DEPARTMENT OF PHYSICS

January 2017-December 2019

SCIENTIFIC REPORT

Dipartimento di Fisica

Sapienza
Università di Roma

Sapienza Università di Roma

Dipartimento di Fisica

Scientific Report

2017 - 2019

The Scientific Report has been edited by:
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The Institute of Physics in 1935, “Casabella”, 1936, 99 (design by Giuseppe Pagano)
Internal garden and aerial walkway of the department of Physics
Main Campus of Sapienza Università di Roma
Piazzale Aldo Moro 2, 00185 Roma

Contents

Introduction

The Department of Physics of Sapienza, the largest in Italy in this discipline for number of faculties and students, is known throughout the world for the high quality of research, international prestige and variety of educational offer. In our Department an intense research activity is carried out in the major sectors of Modern Physics, both fundamental and applied: Particle Physics, Physics of Matter, Astrophysics and Cosmology, Theoretical Physics, Mathematical and Statistical Physics, Photonics and Quantum Information, Biophysics, Medical Physics, Atmospheric Physics, Physics and Cultural Heritage, with more than 100 research lines.

The Department hosts almost 40 scientific laboratories, besides those directed by researchers of INFN and CNR., and nearly 10 didactic laboratories. Numerous skills are present in these structures, among which those in Particle Physics, Astrophysics, Computational Physics, Physics of Matter, Classical and Quantum Photonics are worth of noting. In recent years, the Department has been a protagonist in some of the most important scientific results achieved in recent years in the various fields of Physics, among which we remember the discovery of the Higgs boson by ATLAS and CMS experiments and the detection of gravitational waves (GW) by part of the LIGO and Virgo experiments. Professors and researchers of the Department carry out these activities within a wide network of international relations, as evidenced a large number of publications almost entirely written in collaboration with authors from various countries. The research activity of the Department is carried out in synergy with national and international research institutions, such as INFN, CNR, INAF, ASI, INGV, in Italy, and also CERN, KEK, PSI, SLAC, GSI, CNRS, BIFI, a international level. The synergy with some of these institutions, in particular with INFN, CNR and INAF, is regulated by appropriate conventions, that allow the members of research institutions to participate fully in the life of the department, including teaching activities and also provide for collaboration for the management of the Department's services.

At the beginning of 2018 the Department of Physics was selected by the MIUR as one of the 180 Italian "Departments of Excellence" based on a project which consisting of the creation of an Interdisciplinary Center for Physics and Astrophysics of Gravitation dedicated to Edoardo Amaldi. The Amaldi Research Center, https://www.phys.uniroma1.it/fisica/amaldi-research-center, involves researchers from different disciplines, from Gravitational Physics and Astrophysics, to Quantum Optics and Materials Science, to consolidate the role of the Department of Physics in Italy and in the international community in gravitational wave research, to contribute to the conception, design and development of third-generation gravitational telescopes, to train a generation of students and researchers with highly transversal skills, and to promote technology transfer to industries and businesses in the coming years. It is aimed at (i) consolidating the role of the Department of Physics and of Italy in the international research community on GW, (ii) exploiting the scientific return of the LIGO/Virgo results, (iii) being protagonists in the conception and development of 3G and LISA gravitational telescopes, (iv) training a new generation of students and researchers with highly transversal skills, (v) being an incubator of new ideas that can cover frequency bands beyond those of current interferometers, (vi) promoting technology transfer to industries and businesses (vii) coordinate outreach activities. A significant improvement in the sensitivity of current instruments requires the development of new measurement strategies, new sensors and experimental equipment based on innovative methodologies, combining transversal skills in the fields of materials physics, quantum optics, cryogenics and superconductivity, represented by research groups that are active within the Department, with internationally recognized excellence. The activities of the Amaldi Research Center of Physics and Astrophysics of Gravitation are organized according to the following lines of development: - Physics and astrophysics of gravitation - Data analysis and multimessenger astronomy - Quantum technologies for the detection of GW - Science of materials for 3G interferometers - 3G Gravitational Wave Laboratory The last two research activities include also the realization of two new laboratories.

The high quality of the research conducted by our Department is evidenced by a series of indicators.

- In the 2017-2019 three-year period, funding was obtained through 55 projects, funded by the European Union, MIUR and other national and international foundations.
- The Sapienza University is the first Italian public university by number of funding from the European Research Council (ERC) and the Physics Department currently hosts 6 of these projects. In the ERC's ten years of life, 16 grants have had a member of our Department as their principal investigator. Some of these grant were obtained by structured members of the Department, others by researchers recruited from abroad or from research institutions, by direct call. Besides, we remember also 4 Proof-of-Concept ERCs obtained by members of the Department, which highlight the Department's propensity to transfer scientific results out of the academic context.

We also remember that one of our teachers, prof. Francesco Mauri, currently appears among the 3 teachers working in Sapienza in the special Highly Cited Researchers ranking: `https://hcr.clarivate.com/#freeText%3Dsapienza`.

- The scientific articles published in prestigious international journals are around 2000 in the three-year period 2017-2019.
- The Department has organized a large number of international events, workshops, schools and conferences (around 40 workshops and international conferences only in the 2017-2019 three-year period). The presence of our professors and researchers in scientific committees is substantial. A further aspect that demonstrates the excellence of our Department is represented by the number of national and international awards and prizes (~ 10) awarded in recent years to members of our community.
- Over the years, members of the department have been called to cover prestigious and responsible positions in the national and international University and Research system, such as, recently, Giorgio Parisi, President of the Accademia Nazionale dei Lincei since 2018, and Luciano Pietronero, recently nominated President of Centro Fermi.
- The Department qualifies in high positions in various international rankings. According to the international Academic Ranking of World Universities 2018, published by the University of Shanghai, our Department ranks 29th in the world and the first in Italy (http://www.shanghairanking.com/), while the QS Ranking ranks it in 39th place in the world, and first in Italy: `https://www.topuniversities.com/university-rankings/university-subject-rankings/2018/physics-astronomy`. Also in 2017, the Center for world university rankings (Cwur) published the classification by subject that places Sapienza in first place in Italy and among the top 10 internationally in 7 scientific disciplines including 4 physics: particle physics; nuclear physics; fluid and plasma physics; mathematical physics (http://cwur.org/). According to the Nature Index 2017, Sapienza ranks third in Italy in Physical Sciences, after the INFN and CNR: `https://www.natureindex.com/annual-tables/2018/institution/all/physical-sciences/countries-Italy`.
- In the context of the third mission we have obtained recognition as a good practice of the MIUR of the Department of Work Alternation project of the Department, LAB2GO: `http://www.istruzione.it/alternanza/_RMPM12000L.html`.

The research activity carried out in the Physics Department is reflected in three doctoral courses (on average 40 students per cycle) in Physics, Astronomy, Astrophysics and Space Science and in Accelerator Physics, as well as in teaching, with degree courses master's degree, in Physics and in Astronomy and Astrophysics, based on a number of students around 150 and 30, respectively. The total number of undergraduate and postgraduate students is around 1200 with a substantial growth in enrolments, up to more than 450 in the last academic years. An aspect that characterises our degree courses is the high number of educational laboratory courses: eight compulsory for 1st level teaching and one, one year long, diversified in the various disciplines, for level II teaching. These courses take place in dedicated facilities, in particular the Laboratories of Mechanics, Thermodynamics, Electromagnetism and Circuits, Optics, Calculus, Systems and Signals, Biophysics and the Physics Laboratory II: Particle and Astroparticle Physics, as well as in research laboratories such as in the cases of the Laboratory of Physics of Matter courses, divided into various addresses, of Astrophysics and Atmospheric Physics. These structures are available to students, three-year and masters, doctoral students and research fellows. The Department also has an important Library. In recent years, this structure has implemented the computerized services primarily for university students, in particular it has allowed the automatic loan to those who are enrolled in the library in front of a fully computerized collective catalog for both periodicals and monographs. The Library of our Department include salso an intense archive activity.

The present report is aimed to give a description of the different aspects of the entire set of research activities. This book reports all the Schools, Workshops and Conferences held in this period. The list of published papers in international referred journals divided by subject area and year completes the description. During the last years a relevant growth of the recruitment of young teachers and professors within Sapienza University has allowed the Physics Department to maintaining a level of excellence. I thank the whole body of our scientists that contribute with their enthusiasm every day to these results and all the technical and administrative staff, that makes possibile all these results with a daily unique effort.

Paolo Mataloni

Director of the Department of Physics

In memory of Saeed Younis

Saeed Younis, a postdoc in the Optical Spectroscopy of Nanostructured Materials Laboratory in our Department, unexpectedly and prematurely passed away in October 2019. Born in Israel, he was about to turn 40.

After obtaining a B. A. degree in Physics and a B. Sc. in Materials Engineering from Technion, in Haifa (Israel), from 2005 to 2009 Saeed worked as a fabrication engineer and physicist at the Ilse Katz Institute for Nanoscale Science & Technology, University of Beer-Shivaa (Israel). Then, he decided to further advance his education, going back to Technion to earn a M. Sc. in Materials Engineering. His M. Sc. thesis dealt with the investigation - mostly by X-ray diffraction, SEM/TEM and tomography - of the structural properties of specific mollusk shells. In 2011 he joined the R&D section of HP Indigo (in Israel), where he mostly worked at the improvement of the properties of electro-ink. However, the call of the academia - and the passion for science - once again proved too strong to resist and in 2015 he moved to Sapienza University, to work as a Ph.D. student within the Marie Skłdowska-Curie Initial Training Network ”PROMIS - Postgraduate Research on Dilute Metamorphic Nanostructures and Metamaterials in Semiconductor Photonics”. He carried out his Ph.D. project under the supervision of Antonio Polimeni and Marco Felici, and he obtained his Doctoral Degree in January 2019, with a thesis titled ”Single-Photon Emitters Based on Selective Hydrogenation of (In)GaAsN”. Immediately afterwards he was hired as a postdoc in our Department, where he kept pursuing his research goals within the framework of the Lazio Innova project ”SINFONIA”.

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Research areas

The research activities have been divided in the following subject areas:
A - Astronomy, Astrophysics and Geophysics A1-A17
B - Biophysics, Medical Physics, and Cultural Heritage B1-B6
CM - Condensed Matter Physics and Physics of Biosystems CM1-CM37
P - Particle Physics and Fundamental Interactions P1-P50
S - Statistical and Mathematical Physics S1-S14
D - Dissemination D1-D4

The authors of the Research Activities, as members of the Department of Physics, are reported at the end of each description with [1].

1 - Dipartimento di Fisica Sapienza

List of research activities

A- Astronomy, Astrophysics and Geophysics:

A1. Microwave observations with 50m-100m class telescopes
A2. Theoretical and Computational Astrophysics
A3. QUBIC experiment
A4. CMB polarization: The Short Wavelength Instrument for the Polarization Explorer (SWIPE-LSPE)
A5. Cosmology with clusters of galaxies by millimetre observations and hydrodynamical simulations
A6. The LiteBIRD CMB satellite
A7. Cosmology and Lensing with Euclid
A8. OLIMPO: spectral measurements of the Sunyaev-Zel'dovich effect
A9. SiFAP: Silicon Fast Astronomical Photometry activity
A10. Tension Cosmology
A11. Stellar dynamics, dark matter and dark energy
A12. Spectroscopy of Transiting Exoplanets
A13. Precision measurement of the Cosmic Microwave Background radiation with the Planck space satellite
A14. Black holes and galaxies at cosmic dawn
A15. The Arctic Climate
A16. The Urban Boundary Layer
A17. Atmospheric physics applied to the study of solar UV radiation and ozone, and to the microclimate analysis for the conservation of cultural heritage

B- Biophysics, Medical Physics, and Cultural Heritage:

B1. Radioguided Surgery with β^- decays.
B2. Artificial Intelligence in Medicine
B3. MRI with ^{19}F: the NEPTUNE project
B4. Nuclear Physics and Particle Therapy
B5. A New Method to Integrate Newtonian N-Body Dynamics
B6. Physics and Cultural Heritage: open labs to artworks

CM- Condensed Matter Physics and Physics of Biosystems:

CM1. Hydrides under pressure: possible room temperature superconductors?
CM2. Phonon-phonon interaction: H-based superconductors, charge-density-waves, thermoelectric and thermal transport
CM3. Charge density fluctuations in high-temperature superconducting cuprates
CM4. Inhomogeneous superconductivity and soft electron matter in two-dimensional systems
CM5. Phase fluctuations in disordered superconductors
CM6. Non-linear effects and time-resolved spectroscopy in electronic systems
CM7. Spectroscopy and microscopy of some emerging superconductors
CM8. Spatial solitons, scale-free optics, and giant broadband optical refraction in disordered ferroelectric perovskites
CM9. Infrared spectroscopy of two-dimensional electron systems
CM10. Spectroscopic investigation of two-dimensional layered materials under pressure
CM11. Physical systems with low-dimensionality studied with infrared spectroscopy: from quantum wells to surface polaritons in layered materials
CM12. Graphene and carbon nano-structures
CM13. Linear and Non-Linear Optical Properties of Quantum Materials
CM14. Magnetic nanostructures on surfaces
CM15. Fabrication of site-controlled quantum dots by light- (and plasmon-)assisted hydrogen removal in Ga(AsN)
CM16. Two-dimensional crystals and their strain engineering
CM17. Quantum Nanophotonics with Semiconductor Nanostructures
CM18. Ultrafast and ultraslow dynamics in biomolecules and condensed matter
CM19. Physics of Simple Molecular Systems under Extreme Conditions
CM20. Tailoring the physical properties of ionic liquids
CM21. Self-assembly and aggregation in colloids for biotechnological and environmental applications
CM22. Testing materials with electromagnetic probes
CM23. Physics and engineering of active matter
CM24. Terahertz spectroscopy in ancient paper sheets and meta-materials
CM25. Infrared spectroscopy of biomolecules: fibril assembly and protein-membrane interaction
CM26. Infrared Nanospectroscopy of Transmembrane Proteins in Cell Membrane Monolayers with Plasmonic Field Enhancement Techniques
CM27. Advanced photonic imaging of 2D-materials and biosystems
CM28. Nanosensors for biosensing and biomedical applications by Surface Enhanced Raman Scattering (SERS)
CM29. Transverse light confinement in disordered media
CM30. Theoretical Modeling of Self-Assembly in Colloids and Macromolecules: a Coarse-Grained Approach
CM31. Computational studies of complex (bio)polymeric systems
CM32. Building Gels with DNA
CM33. Essentiality, conservation, evolutionary pressure and codon bias in bacterial and eukaryotic genomes
CM34. Photonics Quantum Technologies
CM35. Quantum causality and foundations of quantum mechanics
CM36. Quantum Optics for Quantum Information Processing
CM37. Complexity, nonlinearity, topology, and machine learning in photonics

P- Particle physics and Fundamental Interactions:

P1. The ATLAS Experiment at the Large Hadron Collider
P2. Precision Standard Model Measurements with ATLAS
P3. Studies of Higgs Boson Properties with the ATLAS detector
P4. Searches for Dark Matter and Invisible Higgs decays
P5. Search for Dark Matter using Long Lived Particles with the ATLAS Experiment
P6. Artificial Intelligence applications in the ATLAS Experiment
P7. The Level-1 Barrel Muon Trigger of the ATLAS experiment at LHC
P8. The New Small Wheel and the Micromegas chambers for ATLAS
P9. The Computing System of the ATLAS Experiment at the LHC
P10. The CMS experiment at the CERN LHC and its upgrade for HL-LHC
P11. The CMS electromagnetic calorimeter performance in LHC Run2
P12. CMS Mip Timing Detector for High-Luminosity LHC
P13. LYSO crystal characterization for the Mip Timing Detector
P14. Precision measurements of the Standard Model
P15. Properties of the Higgs boson
P16. Search for new heavy particles
P17. Searches for Long Lived Particles
P18. The ALICE experiment at the Large Hadron Collider (LHC)
P19. Discrete symmetries tests with neutral kaons at KLOE-2
P20. Light hadron physics at KLOE-2
P21. Search for Dark Forces at KLOE-2
P22. Beyond the standard model searches with the NA62 experiment at CERN
P23. Dark sector searches with the PADME experiment
P24. Detection of Gravitational Waves
P25. Persistent gravitational waves
P26. Gravitational-Wave Transient Signals
P27. The new detectors on the Earth
P28. Vacuum Fluctuation and Gravity
P29. The search for Majorana neutrinos with the CUORE experiment
P30. The search for matter creation with CUPID
P31. CALDER: Kinetic inductance detectors for Majorana neutrinos
P32. High-Energy Neutrino Astronomy: the ANTARES telescope
P33. Search for high-energy neutrinos from bright GRBs with ANTARES
P34. KM3NeT: a new era deep-sea neutrino telescope
P35. In-situ calibration of the KM3NeT detector
P36. Indirect Dark Matter search with the KM3NeT experiment
P37. The search of charged lepton flavor violation with MEG-II
P38. The CYGNO project
P39. Direct search for dark matter with DarkSide experiment at LNGS
P40. Flavour, CP violation and Matter-Antimatter asymmetry
P41. Weak matrix elements and hadron spectrum from lattice QCD
P42. Directions for New Physics Searches
P43. Higher-Order Perturbative Corrections and Collider Physics
P44. Exotic Hadrons and Light Dark Matter
P45. Tests of gravity with gravitational waves
P46. Testing the nature of compact objects and ultralight dark matter with gravitational waves
P47. Neutron stars: gravitational waves and equation of state
P48. Bent crystals for the Large Hadron Collider beam extraction
P49. Carbon Nanotubes for light Dark Matter searches
P50. Experiments at the Jefferson Laboratory

S- Statistical and Mathematical Physics:

S1. Finite-size scaling at quantum transitions
S2. Statistical Physics of Collective Behaviour in Biological Systems
S3. Statistical Physics Approach to Gene Regulatory Networks
S4. Effective equations for complex systems with multi-scale structure
S5. Equilibrium and non-equilibrium complex quantum systems
S6. Statistical Mechanics of Disordered Systems and of Systems of Biological Interest
S7. A new loop expansion around the Bethe lattice
S8. Statistical physics of optimization and inference problems
S9. Dynamics of processes with innovation
S10. New scenarios for urban systems
S11. Economic Complexity
S12. On the analytic theory of rogue waves in nature
S13. Markov chains on graphs
S14. Negative results in QFT and resonances at finite volume

L- Facilities and Laboratories:

D- Dissemination:

D1. Collaborations with external bodies
D2. Modern Physics for High School Students
D3. Physics with Arduino and Smartphones
D4. International Day of Women and Girls in Science 2019

List of research activities

Astronomy, Astrophysics and Geophysics

Astronomy, Astrophysics & Geophysics

We are living exciting times for Astronomy, Astrophysics and Cosmology, being able to *measure* electromagnetic signals produced during *all* phases of the evolution of the Universe. New precision cosmology measurements are available. The recent direct detection of gravitational waves has revived multimessenger astronomy. Growing knowledge about exoplanets fascinates a new generation of astronomers. Our Department is giving key contribution to this scientific exploration in several key areas of these disciplines.

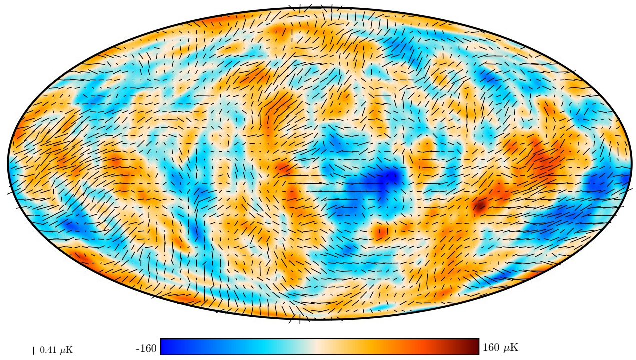

Figure 1: A low-resolution map of the CMB (colors), measured by the Planck satellite and published in 2018. According to the current model of structure formation in the universe, the faint variations of the brightness temperature (around an average of 2.725K) result from quantum fluctuations in the very early universe. The segments represent the linear polarization of the CMB, due to anisotropic Thomson scattering at recombination, 380000 year after the big bang. The polarization pattern has a dominant contribution due scalar (density) fluctuations, and a small contribution (still to be detected) due to tensor (gravitational waves) fluctuations. Our Department has contributed to the High Frequency Instrument of the Planck satellite, and to the data analysis of the full Planck dataset. We are now involved in ultra-sensitive post-Planck measurements of the tensor component of CMB polarization.

Cosmology

400 years ago, Galileo Galilei observed the sky with his first telescope, expanding the radius of our knowledge horizon by several orders of magnitude. Nowadays we have instruments able to collect the faintest fluxes from the farthest sources in the Universe, exploiting the entire electromagnetic spectrum. Our knowledge horizon is not limited anymore by the capabilities of our instruments. When looking very far away, we receive electromagnetic waves produced in the early universe, and we are now samplig the universe so far that we reached the recombination epoch, 13.7 Gy ago, when the universe became transparent for the first time. At earlier epochs, the universe was in its *primeval fireball* state, completely opaque to electromagnetic radiation. This defines our current knowledge horizon.

Our Department, located close to some of Galilei's sites, is a driving partner of this cultural adventure, and played a leading role in mapping the entire last scattering surface, at the recombination epoch, representing the physical firewall between what can be observed electromagnetically and what cannot. At that epoch, in fact, the photons of the Cosmic Microwave Background (CMB) were released from the primeval fireball, and started their long travel across the entire universe to reach the present epoch.

Accurate maps of CMB fluctuations (and their spherical harmonic transforms) represent a powerful tool to constrain cosmological parameters *and* fundamental physics (A10). Using CMB anisotropy data, in combination with other cosmological observables, we have now a baseline *concordance* model, where the Hubble constant and the density parameters for baryonic matter, dark matter and dark energy are now known to sub-% accuracy. This is important, representing the result of many independent and orthogonal observations, but is certainly not the final answer to our cosmological questions. At the very least, we need to understand the physical nature of dark matter and dark energy. But many other questions arise, at the crossroad between fundamental physics and cosmology, which must be further investigated, including the details of structure formation and mass distribution in the universe, the role of massive neutrinos, the very early phases of the universe, and many more (A10).

The Planck satellite, to which a team of our Department contributed significantly (A13), was launched in 2009, and provided strong evidence for cosmological inflation, happening a split-second after the big bang, and relating the structures present nowadays in the universe to quantum fluctuations present in the very early universe. Evidence comes from the power spectrum of CMB anisotropy, favoring a close-to-scale-invariant spectrum of primordial density fluctuations.

One key prediction of inflation, i.e. the production of a background of primordial gravitational waves, remains unproven. Several experiments worldwide are now aiming at the faint B-modes of CMB polarization, a signal produced by such tensor fluctuations. This is the only way to observe signals produced at ultra-high energies ($\sim 10^{16}$ GeV), hence the shared interest of cosmologists and high-energy physicists. For this reason the focus in CMB science is now on CMB *polarization*. The Planck satellite (along with many other experiments) has now mapped E-modes of CMB polarization, mainly due to density and velocity fluctuations present in the primeval plasma at recombination (see Fig.1).

In July 2018 the Planck Collaboration has released a new and improved version of the data acquired by the Planck satellite, which constitutes the official cosmological legacy of Planck, providing our strongest constraints on the parameters of the standard cosmological model and some of the tightest limits available on deviations from that model. The 6-parameter ΛCDM model provides an excellent fit to the cosmic microwave background data at high and low redshift, describing the cosmological information in over a billion map pixels with just six parameters. With 18 well constrained peaks in the temperature and polarization angular power spectra Planck measures five of the six parameters to better than 1% (simultaneously), with the best-determined parameter (θ^*) now known to 0.03%.

While confirming and reinforcing the basic picture of the early universe, the improved accuracy of this data release provides hints for tensions within the simplest ΛCDM model. These will require additional measurements with new, powerful experiments.

Our Department has a leading role in this activity, with the ground-based experiment QUBIC (A3) and the balloon-borne experiment SWIPE-LSPE (A4). Also, we are contributing to the study for a *final* CMB space mission devoted to large-scale polarization, the LiteBIRD satellite of JAXA (A6). Such a mission will provide the definitive maps of the CMB polarization anisotropies at large and medium angular scales. In case of a detection of primordial B-modes, LiteBIRD will allow a determination of the spectrum over the largest possible range of cosmological scales. The sensitivity is such that even a non-detection would allow the rejection of one of the two generic classes of inflation models remaining after Planck (the so-called large-field class).

CMB photons cross the entire size of the observable universe before reaching us, and their interactions with matter can be used to sample its properties. Lensing can be used to constrain the aggregation of dark matter over the entire history of structure formation, as mentioned above. The interaction of CMB photons with hot electrons in clusters of galaxies and other cosmic plasmas can be used to map the hot, low-density universe. Our department has a long-standing tradition of study of the Sunyaev-Zel'dovich effect in clusters of galaxies, starting from the measurements of the MITO telescope, and now with the leadership of the OLIMPO experiment, flown in 2018 for the first time (A8) and the collaboration to the NIKA instrument and to large-scale structure simulations (A5).

These achievements could not happen without a vigorous development program of original experimental methods and instrumentation. The experimental research groups in our Department are contributing to this reserach. For example, they are leading the development of a new generation of detectors for mm/sub-mm/IR photons: Kinetic Inductance Detectors (KIDs). These developments, initially seeded within the INFN-CSN5, have been funded by specific contracts of the Italian Space Agency, and brought to the development of state-of-the-art detector arrays for the OLIMPO stratospheric balloon mission, the first one to use KIDs in space (A8). Arrays of KIDs represent the baseline for the focal plane technology in future space missions for the CMB and are candidates for the focal planes of the future *Stage-4* effort.

Extragalactic Astrophysics

Early on, the Universe consisted of a near-uniform mixture of hydrogen, helium, dark matter and radiation. The emergence of structure from a stochastic background of fluctuations in the period between 400,000 years and 1 billion years after the Big Bang is vigorously investigated by researchers in our Department. This transition from the dark ages in the history of the Universe to cosmic dawn saw the formation of the first autonomous sources of radiation, stars and black holes. We run cosmological simulations to constrain the properties of the first galaxies, their metal and dust content, and the early growth of the first super-massive black holes. Using a coherent theoretical framework, we compare our model predictions with available HST and ALMA data and prepare for the scientific exploitation of future telescopes, such as the James Webb Space Telescope (planned to launch in early 2021) whose sensitivity will enable an unprecedented epochal leap forward (A14). A parallel effort is dedicated to model gravitational wave sources and their formation sites, through cosmological simulations coupled to binary population synthesis models (A14). In addition, researchers of our Department are actively contributing to the theoretical description of some of the most extreme environments in the Universe by running sophisticated dynamical calculations of cosmologically driven black hole mergers, dense nuclear star clusters and stellar dynamics in galactic nuclei. All this is done by accounting for both the classical and relativistic physics involved (A2).

Clusters of galaxies are the largest gravitationally bound objects in the Universe. They form at the intersection of filaments and sheets of galaxies, as evident from large redshift surveys of galaxies and from numerical simulations. A large fraction of the mass of each cluster is in the form of a hot (millions of K), ionized tenuous gas, filling the potential well of the cluster, and producing X-rays. Most of the mass is in the form of dark matter, as evident from dynamical consideration and from lensing measurements on background sources. Researchers in our department estimate the redshift of distant clusters photometrically, using measurements of the spectral energy density from the ultraviolet to the near infrared. In this way they identify very distant clusters and can follow-up with X-ray observations, allowing studies of the evolution of galaxy populations in the clusters. We also study the gravitational lensing produced by clusters and in general by the distribution of dark matter, and study clusters through the Sunyaev-Zel'dovich effect (A5, A8).

The large-scale distribution of galaxies, their redshifts, and their shapes, are fundamental probes for cosmology in general and for the evolution of the Universe. The Euclid mission will provide a comprehensive survey of shapes and redshifts of galaxies and clusters of galaxies over the entire period dominated by dark energy. Our department is actively contributing to the mission (A7).

Stellar and Galactic Astrophysics

Stars exist in a variety of forms and systems. They are actual physics laboratories, where nuclear fusion, which is possible because of quantum mechanical "tunnel" effect, energy transfer and Newtonian and relativistic dynamics are the motors of evolution.

In our Department, a group of theorists has been working for many years on the connection between the large space-time scales characterizing the Galaxy (Milky Way) with the smaller ones of individual stars and star clusters (A2, A9, A11). Stellar systems are ubiquitous in the Galaxy and are example of dynamical systems, where the evolution of the individual members (stars) interplay with the overall evolution of the diffuse environment where the star clusters is embedded in. In our ASTRO research group (sites.google.com/uniroma1.it/astrogroup/home) we have developed a theory of formation and evolution of massive black holes and galactic nuclei, which has been carefully tested via numerical simulations. This theory motivates the formation of massive and supermassive black holes and super dense star clusters in the central region of galaxies by mean of the orbital decay of a set of massive star clusters towards the inner potential well of the hosting galaxy (A2).

Another important field of activity is that of the dynamics of "exoplanets" both when they are still embedded in the protoplanetary disk around a primary star and when they are orbiting around a binary star (a pair of stars gravitationally bound each other). In this framework, some researchers of our Department are involved in the GAPS extra solar planet collaboration, which has been granted of a large amount of observing time at the Galileo 3.6 m national telescope and are involved in the Ariel mission to search for exoplanets from space (A12).

An additional part of work in the galactic context is that aiming to study the dust content and spatial distribution in the Milky Way. This is interesting per-se and because it gives important help to the identification of perturbations over the microwave cosmic background (this is, of course, in strict connection with the scientific activity in Cosmology: A1, A3, A4, A5, A6, A8, A13).

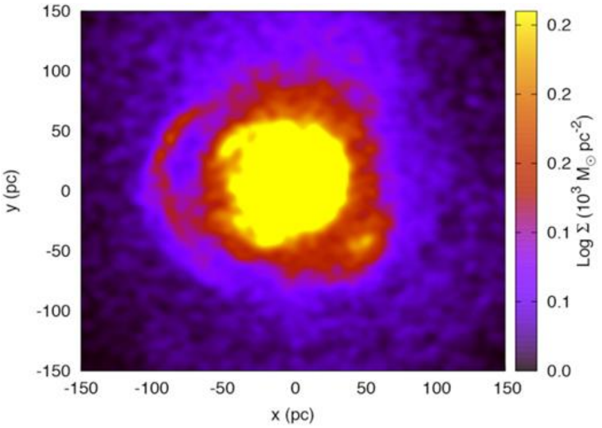

Figure 2: Surface density map of the final state of a globular cluster around super massive black hole binary in a galactic center. A clear arch is visible at ∼100 pc from the galactic centre (x = -100; y = -50, 50), while a clump formed in the bottom right side of the bulge (x = 50; y ≃ -50) (from Arca-Sedda & Capuzzo-Dolcetta, 2018, MNRAS, 484, 520-542).

Planetary Science

Planets are ubiquitous in our Galaxy. More than 4000 exoplanets have been detected in the past 20 years from space and from the ground. Thanks to space missions such as TESS, Cheops and PLATO, and to similar ongoing effort using ground instrumentation, this number is destined to see a dramatic increase over the next decade.

The exoplanets detected have a huge range of masses, sizes and orbits: from rocky Earth-like planets to large gas giants grazing the surface of their host star. This diversity is not seen in our Solar System and the essential nature of these exoplanets remains largely mysterious. There is no known, discernible pattern linking the presence, size, or orbital parameters of a planet to the nature of its parent star. We have little idea whether the chemistry of a planet is linked to its formation environment, or whether the type of host star drives the physics and chemistry of the planets birth and evolution. What are exoplanets made of? How do planets and planetary systems form? How do planets and their atmospheres evolve over time?

The observed diversity of exoplanets can only be investigated by surveying a large parameter space in planetary radii and masses, thermodynamical conditions, chemical properties, and host star types. Researchers in our Department are contributing to the development of the ESA ARIEL space mission (A12), that in a few years from now will allow such a statistical understanding. ARIEL will be placed in orbit around the Lagrange Point 2 (L2), a gravitational balance point 1.5 million kilometres beyond the Earths orbit around the Sun. The mission concept focuses on the spectroscopic observation of warm and hot planets to take advantage of their well-mixed atmospheres which should show minimal condensation and sequestration of high-Z materials. These observations will reveal the planetary bulk and elemental composition (especially C, O, N, S, Si). It is known from Solar System studies that to explore the formation and evolution of planetary bodies requires the characterization of their composition. ARIEL observations of these warm/hot exoplanets will allow the understanding of the early stages of planetary and atmospheric formation during the nebular phase and the following evolution.

Geophysics

Geophysics research in our Department ranges from atmospheric physics to environment and microclimate monitoring (A15, A16, A17).

Specifically, total ozone contents and UV irradiances have been systematically collected at the Solar Radiometry Observatory of Sapienza Universit di Roma since 1992. Such a long (25 years) data collection represents a valuable source of information to study and to assess short and long-term changes and their impact on the planets ecosystem and to verify the effectiveness of the Montreal Protocol measures on substances that deplete the ozone layer.

Concerning microclimate monitoring, the study of the indoor climate in cultural heritage buildings plays a prominent role in their conservation and sustainability.

Organization

All this is accomplished by a staff of 17 academics, and by a larger number of students and Post-Doc, within a network of national and international collaborations. Our Department, in fact, offers a full specific curriculum in Astrophysics, including: the Bachelor's Degree in Physics, with a specific study line in Astrophysics; the Master Degree in Astronomy and Astrophysics; the Ph.D. in Astronomy, Astrophysics and Space Science (see dedicated section below). We have a long-standing tradition of involving students of the two higher degrees quite deeply in research activities and in the related international collaborations. Additional opportunities come from the Ph.D. in Relativistic Astrophysics, also hosted in the Department (see dedicated section below).

Funds for these research activities (detailed in the following) come from Sapienza University, ASI (The Italian Space Agency), MIUR (The Ministry of Education, University and Research), INAF (The National Institute for Astrophysics), INFN (The National Institute for Nuclear Physics), and ERC (the European Reseach Council).

Paolo de Bernardis, Raffaella Schneider, Roberto Capuzzo Dolcetta, Enzo Pascale

A1. Microwave observations with 50m-100m class telescopes

The use of large 50m-100m class telescopes in the microwave band can unveil fundamental astrophysical properties of the interstellar and intergalactic medium thanks to the sensitivity, spectro-polarimetric capability, and angular resolution that such facilities can reach at frequencies ranging from 5GHz to 100GHz.

Among the science goals that benefit from such performance, in the Experimental Cosmology group we focus on the detailed study of the microwave emission (5-30GHz) of Galactic and extragalactic sources with the main goal (but not limited to) of unveiling the nature of the Anomalous Microwave Emission (AME). In addition, the interaction of intracluster medium in galaxy clusters and in systems of clusters of galaxies can be studied through the energy burst provided by the intracluster medium to the low energetic photons of the Cosmic Microwave Background (CMB): the Sunyaev Zel'dovich (SZ) effect.

50m to 100m class telescopes allow us to preform observations of such systems with angular resolution ranging from 1 arminute to a few arcseconds from the microwave band to millimetric wavelengths.

- **Arcmin resolution observations of AME**

The emission budget from astrophysical sources at microwave frequencies is mostly dominated by the well studied and well understood free-free, synchrotron, and thermal dust emission. Nevertheless, observations mainly carried out in our Galaxy have revealed an unexpected excess of emission in the microwave band from 10 GHz to 50 GHz that cannot be explained by standard emission mechanisms or in terms of the CMB. This excess AME is not fully understood yet, but the most convincing models predict that AME is dominated by electric dipole emission from rapidly rotating dust grains (spinning dust, [1]).

Through the use of the 64m Sardinia Radio Telescope [1], we have undertaken an observational program aiming to understand if AME is only originated within our Galaxy or we should expect such emission also outside the Milky Way. We have observed the Andromeda galaxy (M31) at 6.7 GHz and we are currently observing it at 22 GHz. We mapped the radio emission as well as its microwave emission in total power and with spectro-polarimetric capability. This allowed us to estimate the emission budget from M31. Integrating over the whole galaxy, we found strong and highly significant evidence for AME resulting in the highest evidence for AME globally from the entire galaxy detected so far (see Fig. 1, [2]). The high angular resolution details of the emission of M31 at 6.7 GHz and at 22 GHz are currently under study.

- **SZ form the cosmic web**

[1]http://www.srt.inaf.it/

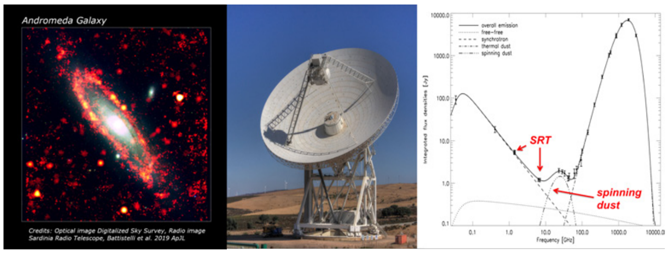

Figure 1: Left: continuum map obtained at 6.7 GHz with the SRT. Center: an image of the SRT. Right: Flux density spectrum arising from aperture photometry over M31.

The baryon distribution in the Universe is an open question for modern cosmology. Hydrodynamical simulations predict that a warm-hot intergalactic medium (WHIM) is arranged in the form of filamentary structures of low density intergalactic medium connecting the clusters of galaxies into the so called cosmic web.

The SZ effect is the distortion of the CMB frequency spectrum due to the energy injection originated from the hot electron gas in galaxy clusters and the surrounding medium. The SZ effect can be used to map the inter-cluster region between galaxy clusters especially in particular cases of superclusters of galaxies and pairs of galaxy clusters in the premerging phase. Such direct detection would be fundamental for the study of filamentary structures between galaxy clusters and shed light on the open problem of the missing baryons in our Universe as well as on the hierarchical structure formation scenario.

We support the possibility of using 50m-100m class telescopes with mm cameras to observe superclusters of galaxies and galaxy cluster pairs in order to map the inter-cluster region between clusters with $\simeq$10" angular resolution. Taking as example the Abell401-Abell399 cluster pair, already observed at low-angular resolution by the Planck satellite, we are undertaking an observational program using bolometric camera MUSTANG2 observing at 3mm, which is coupled with the 100m Green Bank Telescope [2]: an ideal instrument in terms of angular resolution and sensitivity to disentangle different scenarios [3].

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[2]http://www.gb.nrao.edu/mustang/

A2. Theoretical and Computational Astrophysics

- Astronomy, Astrophysics & Geophysics.

Roberto Capuzzo Dolcetta leads group ASTRO. It is a small group active in the field of Theoretical and Numerical Astrophysics.
Recent results concern the dynamical study of astrophysical structures over a wide range of space and time scales, from planets to supermassive black holes (SMBHs).

In different collaborations, we studied:

- the evolution of gaseous disks around single and binary stars with our new SPH code [1];
- the stability of planets revolving on S-orbits in star binary systems [2,3];
- the interaction of of stars hosting planets and the Sgr A* SMBH [4,5,6];
- the stellar black hole binary mergers in open clusters [7];
- the effect of microlensing events on the determination of the inner Galactic bulge [8];
- the future Milky Way-Andromeda galaxy merger [9];
- the SMBH coalescence as mediated by massive perturbers and its implication for gravitational wave emission [10];
- the GW emission as expected by binary black holes around an SMBH [11];

Aside to the work described above, RCD has been active also in the CTA (Cherenkov Telescope Array) collaboration, participating to the paper [12].

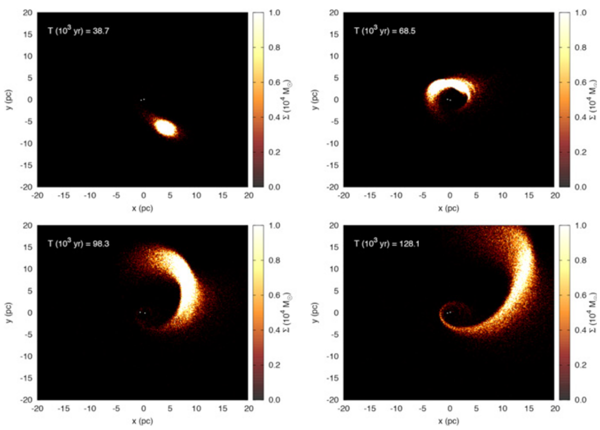

Figure 1: Snapshots, at different times, of the interaction among an infalling globular cluster and a binary SMBH (from [10]).

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R. Capuzzo Dolcetta[1], N. Davari[1], G. De Cesare, G. Navarro[1], A. Marino[1], various colls. of the ARI (Heidelberg, Germany)

A3. QUBIC experiment

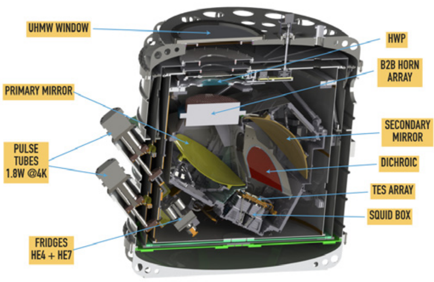

Figure 1: Renderization of a section of the instrument.

The **Q** & **U** **B**olometric **I**nterferometer for **C**osmology (QUBIC[1]) is a cosmology experiment which aims to measure the B-mode polarization of the Cosmic Microwave Background (CMB). Measurements of the primordial B-mode pattern of the CMB polarization is in fact among the most exciting goals in cosmology as it would allow testing the inflationary paradigm. Many experiments are attempting to measure the B-modes, from the ground and the stratosphere, using imaging Stokes polarimeters. The QUBIC collaboration is developing an innovative concept to measure CMB polarization using bolometric interferometry.

- **QUBIC in a nutshell**

In Figure 1, we show a block-diagram of the QUBIC instrument. Polarization modulation is obtained with a Stokes Polarimeter composed of a step-rotating Half Wave Plate (HWP) and a polarizing grid, which are the first optical elements in the optical chain, sky-wise. The polarimeter is followed by the apertures array of the interferometer, consisting of 400 back-to-back (B2B) corrugated feedhorns. Each back-to-back horn includes an independent optical switch, actuated electromagnetically, allowing to open or close the aperture. This feature allows to implement standard radio-interferometry self-calibration techniques. The B2B array is followed by an optical combiner composed of two large mirrors, adding coherently in the focal plane the signals from all the open apertures. The result is a Fizeau interferometer, where the fringes pattern in the focal plane can be controlled opening and closing the aperture's switches. A dichroic splits the beam into two focal planes sensitive to two frequency bands, $150 GHz$ and $220 GHz$. Each detector array is composed of 1024 naked TES bolometers, sampling the pattern of fringes in the focal plane.

- **Calibration phase in progress**

[1] Italian coordinator: Prof.ssa Silvia Masi, Italian Sponsors: INFN and PNRA `http://home.infn.it/it/esperimenti/esperimenti-particelle-2`

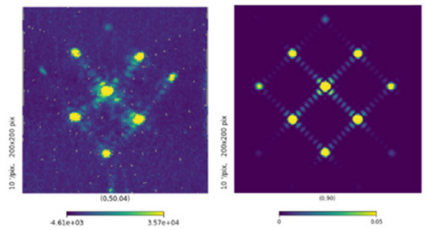

Figure 2: Measured synthesized beam in the 150GHz array of the technological demonstrator, compared with the theory model without spherical abberations.

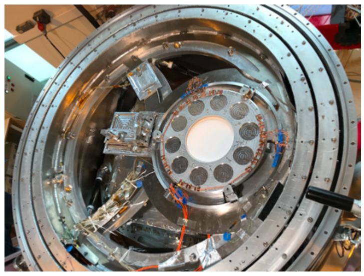

Figure 3: Stokes polarimeter in the QUBIC cryostat

All the parts of the experiment have been finalized in different laboratories. In June 2019 all the subsystems have been delivered at the AstroParticule and Cosmology (APC) in Paris, for the assembly/integration phase. An intensive calibration phase is finished in August 2019. The first impressive results are the measurement of the synthesized beam. In Figure 2 the raw data are shown and compared with the theoretical model. A next step about the polarization calibration will start in October. In Figure 3 the Stokes Polarimeter made by QUBIC Roma team during its installation in the big cryostat at the APC. Within this year the technological demonstrator of the first module of the QUBIC experiment will be delivered to the final destination (Alto Chorillo, Salta, Argentina). The site looks like a desert, at 5000 meters altitude. The first light is expected for January 2020.

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G.D'Alessandro[1], E.S. Battistelli[1], F. Columbro[1], A. Coppolecchia[1], P. de Bernardis[1], M. De Petris[1], V. Gilles , L. Lamagna[1], S. Masi[1], L. Mele[1], A. Paiella[1], F. Piacentini[1]

A4. CMB polarization: The Short Wavelength Instrument for the Polarization Explorer (SWIPE-LSPE)

LSPE (Large-Scale Polarization Explorer) is an experiment to measure the linear polarization state of the Cosmic Microwave Background (CMB). LSPE aims at the detection of the rotational component (B-modes) of the linear polarization field of the CMB at large angular scales (multipoles up to $\ell \sim 200$). This is related to a possible Cosmic Inflation event in the very early universe, throughly investigated by Theorists, and represents one of the few observables related to ultra-high energy physics.

LSPE is implemented through the synergic deployment of a low-frequency ground-based experiment (STRIP in Tenerife) and a high-frequency balloon-borne experiment (SWIPE, the Short Wavelength Instrument for the Polarization Explorer, operating in the Arctic stratosphere). The aim of STRIP is the measurement of the low-frequency (44 GHz) polarized foreground due to synchrotron emission in our Galaxy. The aim of SWIPE is the measurement of the high frequency polarized foreground due to interstellar dust emission in our Galaxy (mainly from two channels at 220 and 240 GHz), and the measurement of CMB polarization (mainly from the 150 GHz channel).

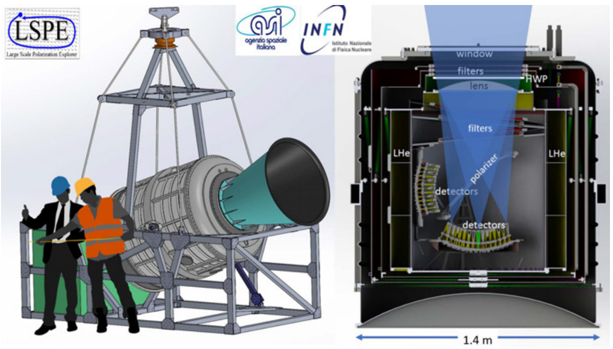

Figure 1: **Left**: rendering of the SWIPE/LSPE payload, with ground shield removed. The large tiltable cryostat contains the cryogenic polarimeter, while the green thermally insulated box contains the instrument electronics and the batteries. The top pivot, based on thrust bearings and a powerful torque motor, allows the payload to spin in azimuth and scan a large fraction of the sky. **Right**: cross-section of the cryogenic polarimeter.

SWIPE (Fig. 1, left) operates on a long-duration (14 days) stratospheric balloon (800000 m^3, 37 km floating altitude), during the arctic night, and is a multi-band, imaging bolometric polarimeter, spinning in azimuth to cover a large fraction of the sky (25-30% per flight). A polarization modulator (rotating HWP, see fig.1, right) is the first element of the optical chain, to achieve high stability of the polarization measurement, beating $1/f$ noise, and avoid systematic effects, as the leakage of temperature anisotropy signals into polarization signals due to small asymmetries of the beams [1,2,3]. A 50 cm diameter lens follows, focussing on two arrays of 330 multimode bolometers [4], detecting 8800 modes of the incoming radiation (see Fig.1, right). The two arrays cover three bands: 140 GHz (20% wide), 220 GHz (5% wide), 240 GHz (5% wide) with an angular resolution of 1.3^o FWHM. The combined sensitivity is 20 $\mu K \times arcmin$ per flight. In Fig. 2 we show examples of custom hardware developed for the instrument. The total mass of the payload is around 2 tons, and the overall dimensions are 5.8m(w) x 3.2m(d) x 4.6m (h). The experiment is developed by an international collaboration, led by Sapienza and funded by ASI and INFN. The first flight is currently scheduled for December 2020.

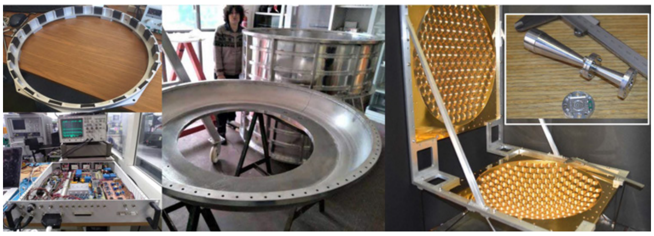

Figure 2: Hardware produced in Sapienza for SWIPE: from left to right: the superconductive magnetic bearing to levitate the 50 cm aperture HWP (top) with its control electronics (bottom); the main cryostat; the two focal plane supports at 0.3K; the back-to-back multimode feedhorn for one of the 330 bolometric pixels.

Comprehensive end-to-end simulations show that in the current configuration, after completion of the component separation procedure, the measurements of CMB polarization from SWIPE will allow to constrain the tensor-to-scalar-ratio r for primordial fluctuations with an uncertainty $\sigma_r \sim 0.01$, a factor 7 better than current upper limits.

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`http://lspe.roma1.infn.it`

A5. Cosmology with clusters of galaxies by millimetre observations and hydrodynamical simulations

Clusters of galaxies science is a powerful way to provide useful cosmological information. The abundance of these objects in the Universe, as function of total mass and redshift, is strictly related to the mean matter density, Ω_m, and the amplitude of matter perturbations at a scale of $8h^{-1}$Mpc, quantified with σ_8. The Sunyaev-Zel'dovich (SZ) effect, mainly the thermal component (tSZ) *i.e.* the inverse Compton scattering of CMB photons with hot electron gas, is a suitable probe to map IntraCluster Medium (ICM) pressure distribution in clusters even at high redshifts. Combining this information with X-ray data it is possible to infer cluster mass, under the assumption of hydrostatic equilibrium.

We approached the study of these objects in two ways: *i*) by observations of SZ in the millimetre spectral band and *ii*) by hydrodynamical numerical simulations.

Full information of the ICM physics is recovered by high angular and/or spectral resolution observations. While the second ones are going to be explored with the balloon-borne experiment, OLIMPO[1], the high angular resolution is exploited by large dish ground-based telescopes. NIKA2 is the new camera with thousands of KID detectors operating at 150 and 260 GHz at the focal plane of the 30-m IRAM telescope at Pico Veleta (Spain) reaching an angular resolution <20", see Fig.1.

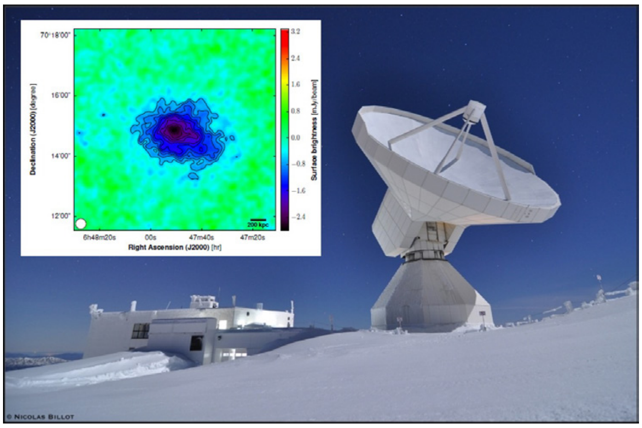

Figure 1: 30-m IRAM telescope at Pico Veleta (Spain). On the top left PSZ2 G144.83+25.11, the first NIKA2 cluster within the SZ LP observed at 150 GHz [2].

After completion of the NIKA2 commissioning phase (September 2017), reported in [1], we started the observations with the SZ Large Program (300 hours of NIKA2 Guaranteed time in 2018-2023). Almost 50 clusters, selected from Planck and ACT catalogues, are being observed. The first observed cluster has clearly demonstrated the effect of resolving the ICM distribution, see the inset in Fig.1 and [2].

[1]http://planck.roma1.infn.it/olimpo/

The collaboration with the Universidad Autonoma de Madrid allows us to work on different datasets of synthetic clusters extracted from cosmological N-body dark matter-only simulation *MultiDark*, a cube of $1h^{-1}$Gpc aside, enriched with gas particles and several physical processes: 1) *Marenostrum MUltidark SImulations of galaxy Clusters* [2] and 2) *Three Hundred Project*.

A few projects using these datasets have been completed during the last 3 years and some are on-going.

The coherent rotation of the ICM is inferred by the kinematic component of SZ. An estimate of the signal and the probability to detect it is reported in [3]. The morphology of clusters was inferred for the first time by SZ maps analysis and so linked to their dynamical state (relaxed or disturbed objects) thus allowing the separation between the two populations in cosmological applications [4]. A twin sample of the SZ LP dataset has been selected among the MUSIC clusters to check the reliability of NIKA2 pipeline in recovering gas pressure radial profiles from simulated realistic observations, see Fig.2. The impact of ICM disturbances is quantified in terms of shape and scatter in the expected profiles [5].

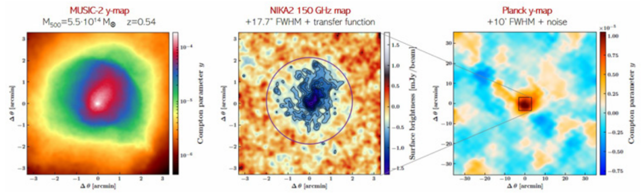

Figure 2: *Left*: SZ map of a MUSIC cluster at z=0.54. *Middle*: simulated NIKA2 tSZ surface brightness map at 150 GHz. *Right*: simulated Planck Compton parameter map [5].

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`https://sites.google.com/a/uniroma1.it/marcodepetris/`

[2]http://music.ft.uam.es/

A6. The LiteBIRD CMB satellite

Inflation is a very early accelerated expansion of the universe which was theoretically devised to solve some critical issues in the original Big Bang theory, like the fine-tuning needed in the early universe to explain the present low curvature of space and its smoothness over large scales. The key prediction of the inflationary paradigm is the generation of a uniform background of gravitational waves, with an amplitude dependent from the energy scale where the inflationary expansion was triggered. The spatial pattern of the polarized Cosmic Microwave Background (CMB) anisotropies at angular scales larger than 1° is affected by such inflationary gravitational waves, getting a curl-like signature at multipoles $2 \leq \ell \leq 200$ called *B-mode*[1]. Evidence of such a signal, if any at all, is quantified by the *tensor-to-scalar ratio* r, but it has been so far elusive.

LiteBIRD[2] is the next generation CMB satellite designed to push to new limits our current capability in constraining the primordial B-modes. It was recently approved by JAXA and it is planned to be launched in 2027.

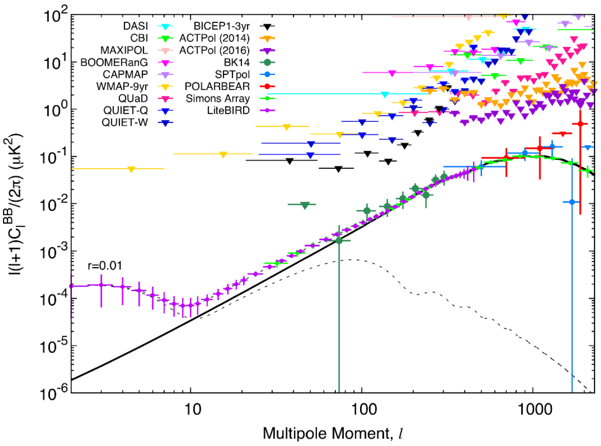

Figure 1: Status of primordial CMB B-modes search and conservative estimate of LiteBIRD sensitivity. The nominal upper limit for $r = 0$ is $r \leq 0.001$ at 95% *c.l.*

Featuring polarization-sensitive superconducting transition edge sensors on its focal planes, it is the first spaceborne instrument designed from scratch for B-mode detection at large scales: it will be sensitive to tiny polarized signals (2.5μK arcmin sensitivity) and robustly calibrated against instrumental systematic effects. The broad spectral coverage (15 photometric bands between 34 and 348GHz) will allow to discriminate CMB from the polarized foregorunds, which could easily leak into false B-mode detections if improperly controlled. The nominal mission is planned to observe the full sky for 3 years, achieving at least 3 orders of magnitude improvement in constraining power with respect to the current generation of observations (fig. 1). Europe is in charge of the design, construction and subsystem-level characterization of the Medium and High Frequency Telescope (MHFT) unit, featuring two independent refractive telescopes. The Sapienza Experimental Cosmology Group is in charge of (or contributing to) the following activities:

- The design and optimization of the optical systems of the two MHFT telescopes. This involves the assessment of many instrumental effects due to non-ideality: lens thickness, absoprtion from lens material, ghosting effects, radiation loading from non-uniform thermalization of the optical elements, etc.
- The design and prototyping of the cryogenic polarization modulation units for MHFT. These are based on rotating metal-mesh half-wave plates and operated through a specialized version of the superconducting magnetic bearing already in development for the SWIPE receiver [3]. They provide the conditioning of the signal from the sky so that the polarized flux is modulated ad 4 times the mechanical rotation frequency. MHFT will modulate polarization at $\sim 1-2$Hz, with a total power dissipation of 4mW over the 4.5K stage of the payload cooler and an operating plate temperature below 20K.
- The optimization of the cold aperture stops for the MHFT telescopes. This involves numerical simulation of optical performance, verification of the absorption, scattering and polarization properties of candidate dielectric absorbers over a bandwidth larger than 1THz in the microwave spectral region, and evaluation of the optical performance of the fully integrated system.
- The development of the analysis and performance forecasting pipeline, which involves feedback from hardware designers and testers in order to understand how instrument systematics propagate from sky radiation to raw detector data, sky maps, power spectra and finally get converted into science results.

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A7. Cosmology and Lensing with Euclid

Euclid is an ESA approved mission scheduled for launch in 2022 aiming at investigating the nature of dark energy and discriminate among General Relativity and modified gravity theories. To this end, Euclid will carry on both an imaging and spectroscopic survey collecting high S/N images of galaxies up to $RIZ < 24.5$ with a number density $n_g = 30$ gal/arcmin^2 and slitless spectra of billion galaxies over a sky area $\Omega = 15000$ sq deg. The imaging survey will allow to reconstruct the cosmic shear field thus making it possible to probe both the background evolution and the growth of structures over the redshift range $0 \leq z \leq 2.5$ providing unprecedented constraints on the cosmological parameters.

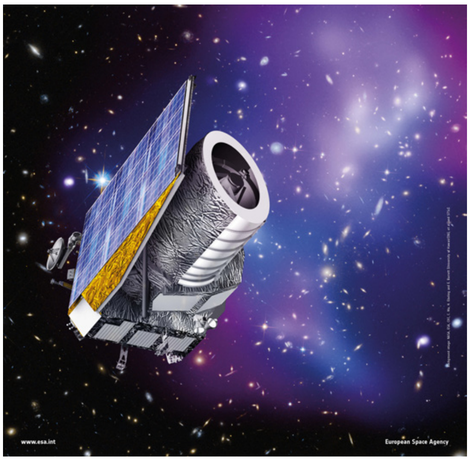

Figure 1: An aritst view of the Euclid satellite

The Rome group participates the Euclid collaboration in a non marginal way being part of the Weak Lensing Science Working Group (WLSWG) and the Inter ScienceWorkingGroup Taskforce for forecasts and likelihood (IST:F and IST:L). During the years 2017 - 2019, the Rome group has been actively involved in important aspects of the activities of these teams as sketched below.

Forecasts and likelihood. A critical role in designing a survey strategy is the optimization procedure needed to guarantee that the desired target will be fit when the full dataset will be available. It is nowadays become common use to rely on Fisher matrix methodology to forecast the accuracy on cosmological parameters for a given observational setup (redshift distribution, survey area, number density, photo - z parameters). The Rome group has played a prominent role in validating and updating the forecasts taking care of the most recent survey specifics and the advancement in theoretical modeling of the matter power spectrum in the nonlinear regime. This activity can be considered as a first step towards the development of a likelihood which allows to dig into the Euclid dataset to infer the constraints on the cosmology. This activity is ongoing within the IST:L which is coled by a member of the Rome group.

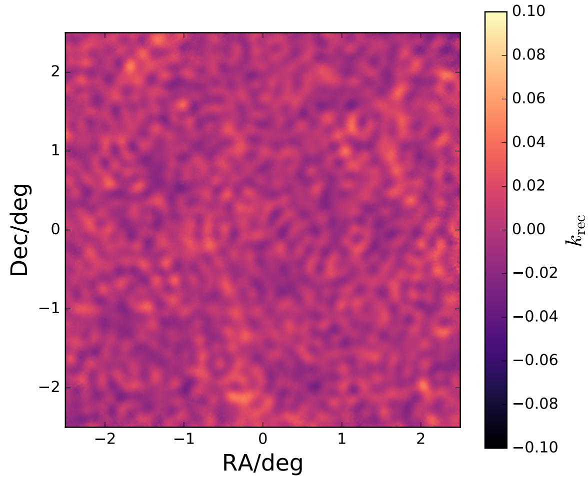

Figure 2: A convergence field from simulated Euclid data

Higher order statistics. Although cosmic shear tomography is the main probe of the Euclid survey, the availability of a large sample of high quality data makes it possible to use higher order statistics (HOS) both as a consistency check and help breaking degeneracies typical of second order statistics. Moreover, going higher order allows to better take into account the non Gaussianity of the lensing fields providing complementary constraints on cosmological parameters. This consideration has motivated the creation of work package (WP) within the WLSWG dedicated to this topic. The Rome group has the responsability to coordinate the activities of this WP. As such, the use of different HOS on WL convergence maps have been investigated. Particular care has been dedicated to the global properties of the convergence map (such as higher order moments), and its topological characteristics (Minkowski functionals and Betti numbers). The Rome group is also involved in a joint effort to calibrate these HOS probes on simulated convergence maps mimicking the expected properties of Euclid data.

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A8. OLIMPO: spectral measurements of the Sunyaev-Zel'dovich effect

OLIMPO (Osservatorio per il Lontano Infrarosso Montato su Pallone Orientabile) is a balloon-borne microwave telescope, aimed at measuring the inverse-Compton effect on Cosmic Microwave Background (CMB) photons crossing the hot gas present in clusters of galaxies and in filaments of inoized matter in the universe. About 1% of the CMB photons gain an energy boost of $\sim 1\%$ from the hot intracluster medium electrons, in a rich cluster. This produces a dip in CMB brightness in the direction of the cluster at frequencies < 217 GHz, and an excess at higher frequencies. This effect has been widely studied photometrically, using ground based telescopes at low frequencies, and by the Planck satellite at high frequency, to the extent that thousands of galaxy clusters have been measured, and hundreds new of clusters have been discovered.

OLIMPO takes advantage of the extreme transparency of the residual atmosphere at balloon altitude (40 km) to cover *spectroscopically* a wide frequency range (from 120 to 500 GHz, in four wide sub-bands centered at 150, 250, 350, 460 GHz). Custom Kinetic Inductance Detectors (KID) arrays have been developed in a close collaboration between the Sapienza team and IFN-CNR [3]. The angular resolution at high frequency ($\sim 1'$) is better than the resolution of Planck, and similar to the resolution of the 10m class telescopes operating on the ground at 140 GHz.

The key original element in OLIMPO is its Differential Fourier Transform Spectrometer (DFTS)[1, 2], which can be inserted in the optical path commanding a movable mirror, providing low resolution spectroscopy with a rigorous cross-calibration across the entire frequency range. This results in outstanding capabilities of extracting the cosmological signal from overwhelming foregrounds.

The payload is 5 m tall and has a mass of about 2 tons (see Fig.1); has been launched from Longyearbyen on July 14^{th}, 2018, and flown in the Arcitc at an altitude of 37.8 km for 5 days.

During the first day of the flight, connection with the payload via the 1 Mbps line-of-sight telemetry allowed us to assess the performance of the instrument, and tune the detectors and the attitude control system.

This is the first time KIDs are operated in near-space, and the excellent measured performance paves the way to their use in satellite missions. In particular, we have demonstrated ([4]) that: • KIDs can be accurately tuned in-flight and an internal calibration transfer is an efficient way to measure their in-flight performance; • if properly designed, KIDs can be retuned in flight to withstand large background changes, as the one introduced by the insertion of a warm DFTS with its emissive wire-grids; • the background of cosmic rays in the stratosphere (not very different, for our purposes, from that in low-earth orbit satellites) contaminates less the $\sim 1\%$ of the measured data

Figure 1: The 2.6 m aperture OLIMPO telescope ready for the long duration balloon flight. Longyearbyen, Svalbard (July 2018)

The DFTS also worked flawlessly during the flight: • the relay mirror mechanism operated well, switching photometric and spectroscopic configurations every hour; • the moving mirrors scanned smoothly the interferogram and their position was accurately monitored; • the instrument was well balanced, producing null-signal interferograms close to the photon-noise limited noise floor of the detectors.

Failure of the satellite-based telemetry did not allow us to operate the instrument after the payload set below the horizon, ~ 1 day after launch, and the line-of-sight connection was lost. For this reason, having demonstrated the excellent performance of the payload, and following the successfull recovery of the payload, we have requested a new flight to the Italian Space Agency.

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S. Masi[1], E. Battistelli[1], F. Columbro[1], A. Coppolecchia[1], G. D'Alessandro[1], P. de Bernardis[1], M. De Petris[1], L. Lamagna[1], L. Mele[1], A. Paiella[1], F. Piacentini[1], G. Presta[1]; see the URL below for a full list.

`http://olimpo.roma1.infn.it`

A9. SiFAP: Silicon Fast Astronomical Photometry activity

Since 2009, the work on SiFAP is still going on at the Laboratory of Silicon Detectors Development of the Department of Physics of Sapienza University of Rome, developing both hardware and software components. SiFAP is composed of thre channels: the first channel is dedicated to study the science target while the second channel is devoted to monitor a reference star in the Field of View (FoV) and the third one is dedicated to monitor the sky.

Great efforts on SiFAP give an integration time down to 20s and a separate electronic chain capable to tag each incoming photon with its own Time of Arrival (ToA) with a time resolution down to 25 ns. Also a new GPS unit able to reach 25 ns accuracy on the rising edge of 1 Pulse Per Second (1PPS) was adopted in order to be able to generate an optical mark to acquire together with the data from the sensors.

The sensors are photodetectors based on the Silicon Photo Multiplier (SiPM) technology. In particular, the detectors used, called Multi Pixel Photon Counters (MPPCs) are supplyed by Hamamatsu Photonics, especially selected from the production batch for this application. SiFAP is a custom ground-based instrumentation working in Optical band (from 320 nm up to 900 nm) realized to detect faint periodic signals coming from variable sources (like pulsars) through high-speed photometry.

In parallel to the hardware part, the software packages in Matlab language were implemented for the data analysis.

SiFAP can perform high temporal resolution measurements of close binary systems. When observing variable sources, Time of Arrivals (ToAs) of incoming photons must be corrected because observations are performed in a reference frame system (that of Earth) which is not inertial. ToAs must be converted in a fixed stable point in an inertial reference frame system identified in Solar System Barycenter (SSB). Once transformed ToAs from a terrestrial clock to the SSB one (Barycentre Dynamical Time), further corrective terms, related to geometrical, relativistic and dispersion effects must be considered. SiFAP was mount at 3.58 m TNG (Telescopio Nazionale Galileo) and 1.52 m Cassini telescope. Very exciting results were obtained for Crab pulsar at TNG [1] and Hz Her/Her X-1 binary system at Cassini telescope [2], respectively. By using two different data analysis approaches, Fourier (implemented on a custom analysis software package called GUIDA [3], (Graphical User Interface for optical Data Analysis) and EFS (Epoch Folding Search), very good agreements between spin periods of the two pulsars (the Crab one and the one belonging to Hz Her/Her X-1 system) observed and expected ones were obtained. Rotational light curves, showing expected shapes, were reconstructed for the two targets. In addition, on measurements done at Cassini telescope, the orbital light curve of Hz Her was also found to be compatible with that available in literature by fitting a simple sinusoid (as a first approximation) on the data points. Keeping in mind that the orbital period of Hz Her (which is not the compact object in the binary system) is about 1.7 d, this result is much more important if taking into account that only four data points (corresponding to four different observations held in four consecutive days) were collected on this system.

After the first observation of the well-known CRAB isolated pulsar using the fast SiFAP photometer, the discovery of the pulsation also in the optical band of a binary millisecond pulsar (J1023 + 0038) is followed [4]. The instrument mounted on the TNG telescope is up-graded for the optical part necessary for the measurement of fast pulsation also in polarized light, both linear and circular [5].

Recently, a long campaign of simultaneous multi-band measurements has allowed us to formulate a physical model for J1023 + 0038. It consists in the first high time resolution observational campaign of this transitional pulsar in the disk state, using simultaneous observations in the optical (TNG, NOT, TJO), X-ray (XMM-Newton, NuSTAR, NICER), infrared (GTC) and UV (Swift) bands [6].

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Authors

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A10. Tension Cosmology

The recent Planck 2018 Legacy data release [1], to which we have contributed significantly, has provided the most accurate measurements of Cosmic Microwave Background anisotropies to date. Thanks to these measurements, very stringent constraints on several cosmological parameters have been presented. However, those constraints have been obtained under the assumption of a theoretical model. Obviously, for the reliability of the constraints, it is mandatory that the values of the parameters inferred by Planck must be consistent with those derived by independent and complementary observables. While good agreement is present between Planck and combined analyses of Baryonic Acoustic Oscillations (BAO, hereafter) a significant discordance is present in the value of the Hubble constant measured using luminosity distances of Type Ia supernovae. Indeed, while under the assumptions of ΛCDM, the Planck dataset provides the value $H_0 = 67.27 \pm 0.60$ km/s/Mpc at 68% C.L., the recent Riess et al. 2019 result [2] gives $H_0 = 74.03 \pm 1.42$ km/s/Mpc at 68% C.L., i.e. in discordance at the level of 4.4 standard deviations.

While undetected experimental systematics can still play a role, the increase during the years of the statistical significance in the Hubble tension suggests a crisis for the ΛCDM cosmological scenario, hinting at the presence of new physics.

In the past three years, we have proposed several possible solutions to the Hubble tension. Among them, probably, the most promising one is to assume a possible interaction between dark energy and dark matter [3]. In Figure 1 we indeed show the probability distribution on the Hubble constant vs ξ, where ξ parametrize the coupling between dark matter and dark energy. As we can see, when the recent measurements of the Hubble constant are included to the Planck data there is a significant evidence for ξ different from zero, i.e. for an interaction between dark energy and dark matter.

The Hubble tension is not, however, the only relevant anomaly from Planck 2018. Another important tension is present in the Planck dataset itself: the Planck CMB angular spectra indeed show a preference for a larger amplitude of the lensing signal with respect to what is expected in ΛCDM at more than three standard deviations. Indeed, parametrizing the amplitude of CMB lensing by the effective A_L parameter, the Planck team has found $A_L = 1.18 \pm 0.14$ at 95% C.L. [1], i.e. at odds of about three standard deviations with the ΛCDM prediction of $A_L = 1$. Also in this case, the discordance is puzzling since the lensing signal obtained again by Planck but in an independent way through measurements of the angular trispectrum is consistent with ΛCDM [1]. Again, several theoretical solutions have been proposed. The simplest one is to allow a positive curved universe and indeed the Planck CMB spectra do provide evidence for curvature at more than 99% C.L. [1]. Curvature, however, places the Planck dataset in strong disagreement with BAO and increases the tension significantly with local measurements, Riess et al. 2019 included. We have recently shown in [4] that since the Planck power spectra prefer a closed universe, discordances higher than generally estimated arise for most of the local cosmological observables, including BAO. The assumption of a flat universe could therefore mask a cosmological crisis where disparate observed properties of the Universe appear to be mutually inconsistent. Future measurements are needed to clarify whether the observed discordances are due to undetected systematics, or to new physics, or simply are a statistical fluctuation.

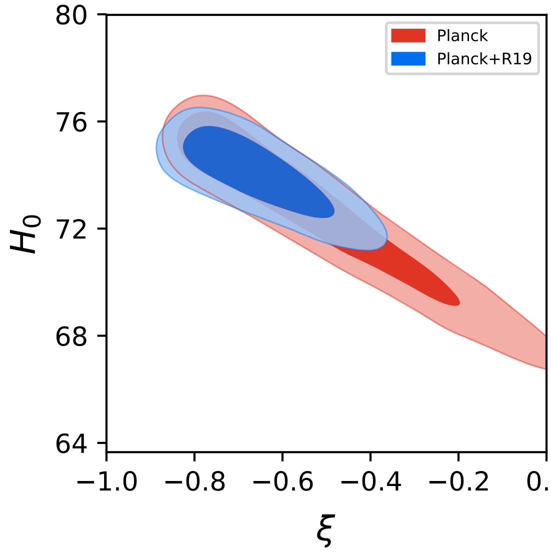

Figure 1: Presence of a possible coupling between dark energy and dark matter, parametrized by the parameter ξ when the Planck data is combined with the recent Hubble constant measurements [3].

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A11. Stellar dynamics, dark matter and dark energy

The main project of our research group is related to the dynamical evolution of stellar systems on different scales, from globular clusters up to clusters of galaxies, dealing with theoretical and numerical approaches.

The study of stellar dynamics of globular cluster was focused on the analysis of the structural parameters of the globular clusters belonging to the Milky Way system which were listed in the latest edition of the Harris Catalogue. We searched for observational evidences of the effect of tidal forces induced by the Galaxy on the dynamical and thermodynamical evolution of globular clusters. The behavior for the W_0 distribution exhibited by the globular cluster population seems to be in contrast with theoretical results in literature about gravothermal instability, and suggests a new limit value smaller than the previous one. This means that core collapse in globular clusters onsets well before than commonly believed, leading to important consequences in the development of the theory, justifying the introduction of an effective potential in the King distribution function in order to take into account the tidal interaction between the cluster and the hosting galaxy [1]. A necessary development of the theoretical analysis is the generalization of the King models to multimass models using a Kroupa mass function. Observational profiles of surface brightness of some clusters are compared and contrasted with the theoretical predictions in new (multimass) and old (single mass) models (see Fig.1). One important aspect of GCs is the spectrum of mass, which is often set aside in simulations and modeling by assuming that all the stars have a constant mass value. In most cases this assumption seems to be in accordance with observations, expecially in the central regions of the clusters, but it moves us away from a correct analysis of the outermost regions of these systems. In fact, stars with heavier masses tends to sink in the core, which is heavier than the single mass case, while the lighter components gain higher velocities and widen the outermost regions. This phenomenon is called mass segregation, which has implication in the evaporation of the stars and the core collapse, and affects the evolution and stability of these systems with respect to tidal disgregation. Nowadays, observational evidences of this phenomenon stand without any question, but the different conclusions about the thermodynamical instability are not yet completely clarified [2].

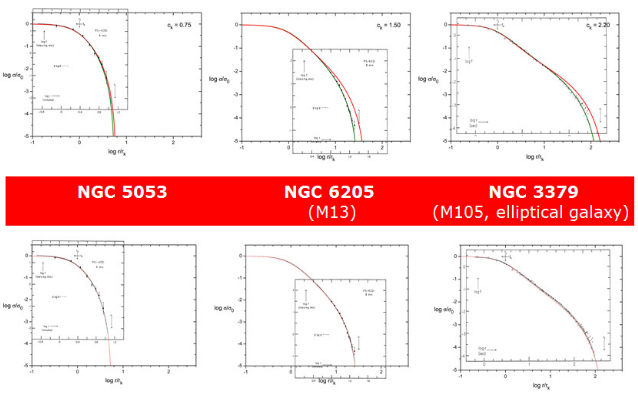

Figure 1: Observational data from three clusters: NGC 5053 and NGC 6205 (globular clusters), and NGC 3379 (elliptical galaxy). Theoretical projected mass densities of both models (multimass/red and King/green) fit data for specific values of the concentration. Fits with King models are due to King.

About the studies on dark matter, we introduced a new family of nonrelativistic, Newtonian non-quantum equilibrium configurations describing galactic halos, taking into account a new possibility to identify particles with masses larger than 1 GeV as no WIMP components of the dark matter. This alternative and fascinating hypothesis involves strange massive particles directly produced in the framework of the Big Bang standard model. We considered $\Lambda^*(1405) \equiv K^- p$ matter as possible constituent of dark matter. As a single particle, it undergoes to strong decay and is therefore highly unstable. Differently, it may become stable in an aggregated state, forming a Λ^* conglomerate which can be considered as a macro-particle with a rest mass $m^* < N m_{\Lambda^*} \sim$ GeV, where $N \sim 10$ or less. This possibility may have important implications on the formation of very massive particles during the Big Bang. The obtained results are in agreement with the requested values in mass and radius in order to be consistent with the rotational velocity curve observed in the Galaxy. Additionally, the average density of such dark matter halos is similar to that derived for halos of dwarf spheroidal galaxies, which can therefore be interpreted as downscaled versions of larger dark matter distributions around Milky Way-sized galaxies and hint for a common origin of the two families of cosmic structures [3].

Finally, part of the research has been addressed to the study of the dark energy (DE) effects on a two body system formed by two galaxies. This particular analysis (very theoretical) comes as last work after a series of papers concerning the DE effects in the galaxy clusters evolution [4].

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A12. Spectroscopy of Transiting Exoplanets

More than 3 000 extrasolar systems have been discovered, hosting more than 4 000 exoplanets[1]. Ongoing and planned ESA and NASA missions from space such as *GAIA*, *TESS*, *Cheops*, and *PLATO* will increase the number of known systems to tens of thousands. Ground based surveys using a variety of direct and indirect techniques will contribute further.

Of all these exoplanets we know very little, i.e. their orbital data and, for some of these, their physical parameters such as their size and mass with a continuous distribution unobserved in our own Solar System (Figure 1).

This diversity makes it only more urgent addressing unanswered fundamental questions. Do atmospheres exist? What are they made of? What kinds of climate do exoplanets have? Can bio-signatures be detected? What does all this tell us about planetary formation and evolution, and the uniqueness or otherwise of the Solar System? Spectroscopy in the medium infrared (mid-IR) portion of the electromagnetic spectrum holds the key to answering these questions [1], as this is the range where the contrast between the star and planet emission grows exponentially.

Exoplanetary science stands on an exciting threshold, similar to our knowledge of the planets in our own Solar System before spectroscopic studies revealed their true nature and started to unravel the story of their formation and evolution. In the past decade, pioneering results have been obtained using transit spectroscopy from space and ground-based facilities, enabling the detection of a few of the most abundant ionic, atomic and molecular species and to constrain the planets thermal structure.

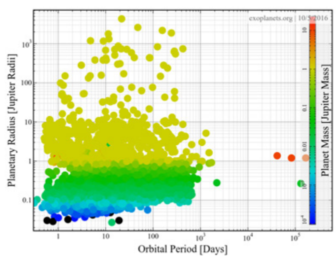

Figure 1: Currently know exoplanets, plotted as a function of planetary radius and orbital period (courtesy of exoplanets.org). The diagram suggests a continuous distribution of parameters – from sub-Earths to super-Juppiters.

A few tens of planets will soon be observed with *JWST* and E-ELT in great detail. However, a breakthrough in our understanding of the processes of planet formation and evolution will only happen through dedicated instrumentation capable of conducting spectroscopic observations covering simultaneously a broad spectral region from the visible to the mid-IR. Because of our own atmosphere, observations over this wide band can only be achieved from space or from high altitude balloon platforms. At "La Sapienza" we are designing the next generation of exoplanet instrumentation, collaborating with scientists and engineers in Europe, US, Canada and Japan.

[1] https://exoplanets.nasa.gov, August 2019.

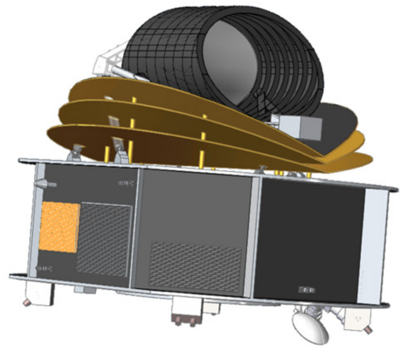

Figure 2: Engineering model of the *ARIEL* spacectraft.

The *ARIEL* space craft (Figure 2) is a dedicated space mission designed with the necessary photometric stability to characterize spectroscopically about 1 000 exoplanets during a mission life time of 3.5 years [2]. The *ARIEL* sample includes gas-giants, Neptunes and Earth-size planets with temperatures in excess of about 600K. These types of planets will allow direct observation of their bulk properties, enabling us to constrain models of planet formation and evolution. *ARIEL* was selected by ESA as the next M4 mission, to fly in 2028. In the meanwhile, stratospheric platforms, capable of lifting scientific instruments in the upper stratosphere (at around 40km of altitude) provide a cost- and time-effective approach [3]. Although not as sensitive as a dedicated space mission, observations from the stratosphere make it possible for the first time wide band spectroscopy of transiting exoplanets in both transmission and emission. These observations will constrain the composition and physical properties such as temperature, pressure and circulation models (through phase curves) of tens of planets.

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Authors
E. Pascale[1]

A13. Precision measurement of the Cosmic Microwave Background radiation with the Planck space satellite

Members of the Observational Cosmology group of this Department have been involved in the research activity of the European Space Agency's *Planck* satellite, which was dedicated to studying the early Universe and its subsequent evolution. The satellite was launched on 14 May 2009, and it scanned the microwave and submillimetre sky between 12 August 2009 and 23 October 2013, producing deep, high-resolution, all-sky maps in nine frequency bands from 30 to 857 GHz. From these maps, it is possible to extract the Cosmic Microwave Background (CMB) radiation, emitted in the early early Universe, 380 000 years after the Big Bang. The last results, published in 2018, present the cosmological legacy of *Planck* which currently provides our strongest constraints on the parameters of the standard cosmological model and some of the tightest limits available on deviations from that model. The 6-parameter Lambda Cold Dark Matter (ΛCDM) model continues to provide an excellent fit to the cosmic microwave background data at high and low redshift, describing the cosmological information in over a billion map pixels with just six parameters. With 18 peaks in the temperature and polarization angular power spectra constrained well, Planck measures five of the six parameters to better than 1% (simultaneously). The 6 parameters, reported in Table 1 are: (a) the density of baryonic matter relative to critical density $\Omega_b h^2$ (h is the Hubble constant $H_0/100$ km s^{-1}Mpc^{-1}); (b) the density of dark matter $\Omega_c h^2$; (c) the angular scale of the sound horizon at recombination epoch (in radians) θ_{MC}; (d) the optical depth of the Universe due to ionized hydrogen after recombination τ; (e) the amplitude primordial of the density power spectrum A_s); (f) the spectral index of the primordial density power spectrum n_s. Among the derived parameters, we report (g) the Hubble constant H_0; (h) the cosmological constant density Ω_Λ; and (i) the age of the Universe. More parameters and deviation from the simplest model are reported in the references.

The Planck data, alone and in combination with other probes, provide stringent constraints on our models of the early Universe and the large-scale structure within which all astrophysical objects form and evolve. In Figure 1 is reported a compilation of the angular power spectra measured by *Planck* and other instruments.

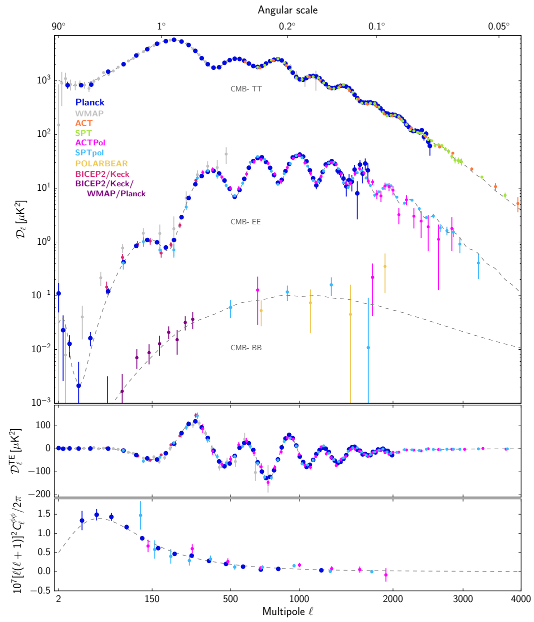

Figure 1: Recent CMB angular power spectrum measurements. Top: temperature and E-mode and B-mode polarization signals. Mid: cross-correlation spectrum between T and E. Bottom: lensing deflection power spectrum. Different colours correspond to different experiments. The dashed line shows the best-fit ΛCDM model to the *Planck* temperature, polarization, and lensing data.

The next parameter to measure will be the tensor-to-scalar ratio r, which quantifies the presence of Primordial Gravitational Waves in the early Universe, originated by the inflationary expansion at the beginning of the Universe. Detection of r is the goal of the forthcoming instrument of the CMB polarization observation, including the space satellite Litebird, and other ground based and balloon based observatories.

Parameter	*Planck* alone	% error
$\Omega_b h^2$	0.02237 ± 0.00015	0.67
$\Omega_c h^2$	0.1200 ± 0.0012	1.0
$100\theta_{MC}$	1.04092 ± 0.00031	0.03
τ	0.0544 ± 0.0073	13
$\ln(10^{10} A_s)$	3.044 ± 0.014	0.46
n_s	0.9649 ± 0.0042	0.44
H_0 [km s^{-1}Mpc^{-1}]	67.36 ± 0.54	0.80
Ω_Λ	0.6847 ± 0.0073	1.0
Age [Gyr]	13.797 ± 0.023	0.17

Table 1: ΛCDM parameters. Only the first 6 parameters are fitted. Other parameters are derived.

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Authors

F. Piacentini, P. de Bernardis, S. Masi, A. Melchiorri

Subject Area

Astronomy, Astrophysics & Geophysics

A14. Black holes and galaxies at cosmic dawn

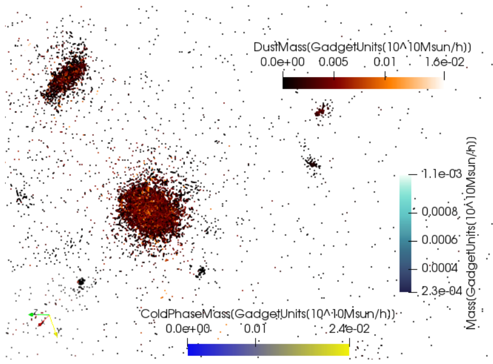

Figure 1: Example of dust, gas, and stellar distribution in a $z = 4$ cosmic region (Graziani et al. in prep).

In the last decades, large data sets, collected using different ground-based facilities and the Hubble Space Telescope, have enabled a characterization of the physical properties and statistical distributions of galaxies and quasars out to $z \sim 8$. While a revolution is just behind the corner with the expected launch of the James Webb Space Telescope in March 2021, our understanding of the assembly history of galaxies and their nuclear black holes at cosmic dawn is still limited. Our work focuses on three main research lines:

Early cosmic pollution in the first galaxies

Recent deep observations of the young Universe ($z > 4$) by the Atacama Large Millimeter/submillimeter Array have revealed that normal star forming galaxies already show a non negligible amount of dust in their interstellar medium (ISM), which is supposed to significantly obscure the light emitted by their young stars and to affect their observed colours. We attempted to characterize the nature of the first stellar sources of dust by running detailed models to quantify the amount of dust formed in core-collapse supernovae, exploring a large grid of progenitor stars with different initial mass, metallicity and rotation rate, [1]. We compared dust enrichment models with the observed dust mass in the Milky Way and with dust scaling relations found in local galaxies. We found that competing processes in their ISM, other than stellar dust production, must be at play to explain the observed trends, [2]. This is being corroborated with sophisticated hydrodynamical simulations, that allow to trace the dust mass and spatial distribution in galaxies with different masses, following their evolution all the way from cosmic dawn down to $z \sim 4$ (Graziani et al. in prep).

The origin of the first super-massive black holes

The existence of black holes with masses $> 10^9\,M_\odot$ at $z > 6$, when the age of the Universe was $< 1\,\mathrm{Gyr}$, is a very challenging theoretical problem. We have investigated the origin and evolution of these first

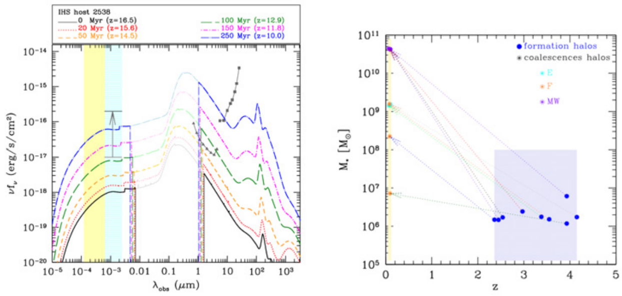

Figure 2: *Left panel:* time evolution of the X-ray to IR spectral energy distribution of a growing black hole at $z \geq 10$, [3]. *Right panel:* evolutionary histories connecting formation and coalescence sites of GW150914-like events, [4], Marassi et al.(2019b).

super-massive black holes in a cosmological framework, exploring the nature of their seeds, their dominant gas accretion mode, their feedback onto the host galaxies and their detectability with future telescopes, operating in multiple bands of the electromagnetic spectrum, [3].

Cosmic archaeology with gravitational waves

The detection of gravitational waves emitted during the coalescence of compact binaries by the LIGO/VIRGO collaboration has opened the era of gravitational wave astronomy. The inferred black hole masses for some of these systems has challenged our current understanding of massive star evolution and require low metallicity gas in their progenitors birth clouds. By coupling binary population synthesis models with cosmological simulations that are able to characterize the properties of high-z, low-metallicity galaxies, we investigated the physical properties of formation and coalescence sites of massive black hole binaries [4], Marassi et al.(2019b). Our results show that some of these systems form well into the epoch of cosmic reionization, opening up the possibility of using gravitational waves to explore star formation at cosmic dawn.

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A15. The Arctic Climate

Authors
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The Arctic region is among the most sensitive to climate change, due to peculiar conditions and some specific phenomena linked to the evolution of sea ice, its influence on the radiation budget and the involved feedback mechanisms. A growing attention has been dedicated in recent years to the study of the role of atmospheric aerosols, and in particular to the phenomenon of the Arctic haze, which may affect the Arctic radiative balance. In 1988, the atmospheric physics group of the Sapienza University of Rome (UR) and the Danish Meteorological Institute (DMI) started planning the installation of a lidar for the investigation of the Arctic stratosphere at Thule Air Base (TAB; 76.5° N, 68.8° W), Greenland. Thule Air Base is a military base of the United States Air Force (USAF), founded in 1951 and located on the north-western coast of Greenland, bordering Baffin Bay (fig.1) The main scientific objective

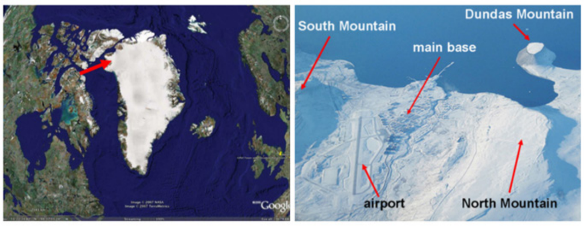

Figure 1: Left: geographical map of Greenland, with the position of Thule Air Base indicated with a red arrow. Right: aerial view of Thule.

was to improve knowledge of the stratospheric ozone depletion phenomenon that was observed to be very intense over Antarctica and anticipated to become important also over the Arctic. During the following ∼30 years, also in the context of large European measurement programs additional instruments were installed, and the collaboration was extended to other Italian (Istituto Nazionale di Geofisica e Vulcanologia - INGV, and ENEA) and US (National Center for Atmospheric Research - NCAR, and Stony Brook University) research institutes. In particular, in January 2009, the participation of DMI, UR, ENEA, and INGV to International Polar Year (IPY) activities were partly supported by the US National Science Foundation, the Italian Antarctic Programme (PNRA) and Ministry for University and Research. The observations carried out by the instruments installed at the Thule High Arctic Atmospheric Observatory (THAAO, http://www.thuleatmos-it.it/) actively contribute to the Network for Detection of Atmospheric Composition Change (NDACC), which is a global network of measurements stations for the monitoring of the atmospheric composition and climate.

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A16. The Urban Boundary Layer

More than half of the planet population lives in big- and mega-cities and is responsible for large modifications of local climate and air quality. A comprehensive description of the atmospheric Urban Boundary Layer (UBL) is a difficult task, due to its complicate three-dimensional structure. The land use and the atmospheric dynamics inside and above the city canopy, formed by buildings, street canyons and green areas, present a large spatial and temporal variability. Human activities, mainly the private and public transportation, are source of unevenly distributed atmospheric pollutants. Despite recent improvements in the observation capability from the satellite-borne instruments and in the modelling of the atmospheric processes, the complexity of the system represents a challenge for achieving an accurate description and understanding of the urban environment. The Atmospheric Physics Laboratory (APL) of the Physics Department established and operates a site for atmospheric monitoring at the Fermi Building inside the University Campus. APL is equipped with more than 10 instruments for atmospheric remote sensing providing data of different nature, that can be used to study the air quality in the UBL, to assess the urban climate evolution, and for calibration/validation of satellite products. In fig. 1 an example of the complexity of the atmospheric dynamics within a range of 3 km from the ground is shown. Convective plumes leave the ground at intervals of few minutes and reach altitudes higher than 1 km, triggering the formation of waves in the overlying stable atmosphere. This is the main process contributing to the vertical dispersion of the pollutants produced near the ground; at higher atmospheric levels they can be transported by the synoptic winds far from the injection point.

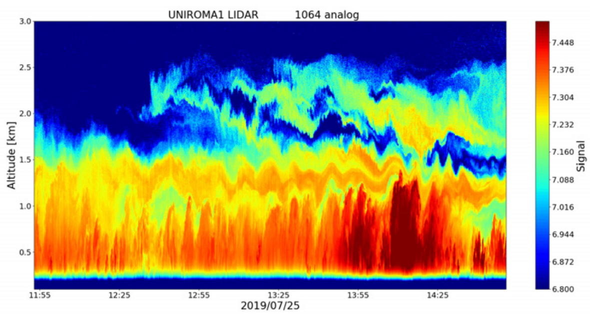

Figure 1: APL LIDAR observation of atmospheric aerosols during the Summer 2019

APL is involved in the BAQUNIN project (Boundary-layer Air Quality-analysis Using Network of Instruments) as the leading partner of a large Supersite that also includes the CNR/ISAC site at Tor Vergata (CNR Institute of Atmospheric Sciences and Climate), in a sub-urban location, and the CNR/IIA site at Montelibretti (CNR Institute of Atmospheric Pollution Research), in a rural environment. The observations at the three sites are accompanied by the outputs from a Mesoscale Numerical Model (WRF-ARW) operated by Sardegna Clima Onlus. ESA (European Space Agency) financially supports the project, which is led by SERCO Italia in terms of Project Management, i.e. the financial/bureaucratic interface with ESA, and scientific/technical support to the BAQUNIN activities, with special focus on APL site. The foreseen duration of the BAQUNIN project is three years, from March 2019 to February 2022. Contact with other space agencies are being developed in order to ensure the BAQUNIN life beyond its nominal closing date.

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A17. Atmospheric physics applied to the study of solar UV radiation and ozone, and to the microclimate analysis for the conservation of cultural heritage

The activity of the Meteorology research group (G-Met) is related to the following topics:
1) monitoring solar ultraviolet (UV) radiation and total ozone and studying their variability at different time scales;
2) microclimate analysis for cultural heritage.

1) Although ozone (O3) is present in small amounts in the terrestrial atmosphere, it plays a crucial role in the attenuation of solar ultraviolet (UV) radiation (200 - 400 nm) reaching the surface and in radiative processes controlling the energy balance on the Earth. The most common ground-based instruments measuring total ozone column (TOC) are spectrophotometers designed to measure ground level spectral intensities of solar ultraviolet radiation attenuated by the ozone absorption. From these spectra, it is possible to retrieve the TOCs. At the Solar Radiometry Observatory of Sapienza Universit di Roma, total ozone column and UV irradiances have been systematically collected by a Brewer spectrophotometer since 1992. This instrument is still in operation on the roof of the Fermi building (Sapienza Campus). Such long (more than 25 years) data sets of TOCs and UV irradiance (Figure 1) allowed to:
validate the satellite-derived products,
investigate the effects of different climatic and meteorological conditions on the long-short term ozone and UV variability,
verify the effectiveness of the Montreal Protocol measures on substances that deplete the ozone layer,
investigate the effects on human health induced by changes in exposure to solar UV radiation.

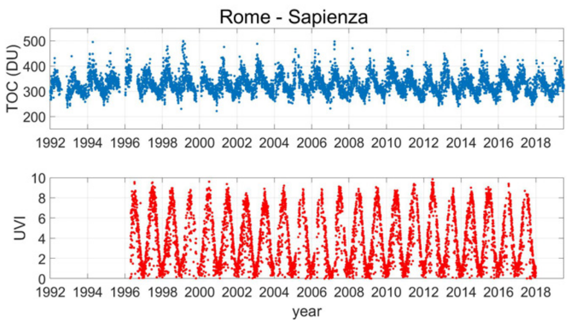

Figure 1: Long time series of TOC and UV Index at noon at Rome.

In the above fields the G-Met collaborates with national and international prestigious groups and participated in two COST Actions in the domain of Earth System Science and Environmental Management. In such a context a relevant number of peer reviewed papers on the above topics were published. To cite a few: [(1,2)].

2) In the last decades, the increasing awareness about the interaction between climate (both outdoor and indoor) and artefacts has led to explore more and more sophisticated methodologies for an effective preventive conservation. It is key to consider the historic environmental conditions (i.e. the climate in which the artefact has been satisfactorily preserved for a long time) and the degradation kinetics of the different materials. In the field of applied meteorology to the conservation of the cultural heritage, the long experience in statistical meteorological data analysis of the G-Met has allowed to obtain successful results in studies on the characterization of the historic climate and in parallel applying the whole-building dynamic simulation ([3, 4]). Both methods represent the best current approach in the implementation of conservation strategies (Figure 2). Currently the G-Met group partecipates in the CollectionCare, a European Commissions Horizon 2020 funded project (grant agreement No 814624), aimed to develop an innovative decision support system for the preventive conservation (www.collectioncare.eu).

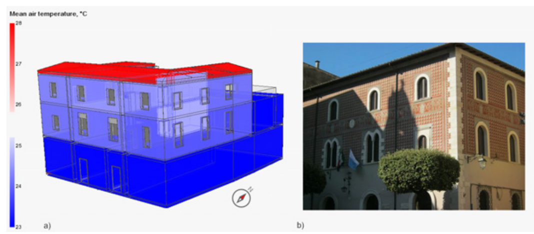

Figure 2: 3D model of the Archaeological Museum of Priverno (Central Italy) with the temperature distribution.

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Authors
A.M. Siani[1], F.Frasca[1], E.Verticchio[1], G.R. Casale, A. Colosimo

List of research activities

Biophysics, Medical Physics, and Cultural Heritage

Applied Physics

The research activities on the constituents and the structure of matter force to develop competences that, utilised in a multidisciplinary environment, can lead to innovative techniques. A huge challenge is therefore how to allow the innovations that arise from pure research to be translated into applications. Such translation requires patenting, interaction with final utilizers of the technique and with producing companies that will have to carry on the engineering phase.

The Department of physics is not traditionally particularly oriented on these aspects, but it has recently acknowledged this aspect as part of its mission. There have therefore arisen also lines of research in applied physics that do the translational effort. Two patents were deposited in the last 6 years and few research contracts with hospitals and companies have been signed.

A delicate aspect of this effort is the identification of the physical aspects that are of interest of the communities that will eventually be the end-users. Without entering into the engineering phase, which does not pertain to the physicist, the activities in the department have posed particular attention in the interactions with the end-users, that in the cases of the researches carried on in the department are the medical personnel and the cultural heritage operators. In particular:

- The Applied Radiation Physics Group (ARPG, http://arpg-serv.ing2.uniroma1.it/) performs research on the medical applications of the techniques developed in the study of elementary particle physics and in particular low energy radiation detectors, electronics, nuclear physics, machine learning and Monte Carlo simulations. In particular, ARPG studies techniques for the profiling of the dose released in adrotherapy, applications of machine learning to tumor stadiation with Magnetic Resonance Imaging (MRI), hardware and software improvements to MRI with ^{19}F, and development of low energy radiation detectors for nuclear medicine applications, including radio-guided surgery (B1-B4).
- A new method to integrate newtonian N-Body dynamic is being applied to molecular dynamics (B5).
- Material science physicists of the department have developed techniques to characterize ancient materials. Such techniques are based on research tools ranging from THz to visible spectroscopy (B6).

In the following the individual research efforts on the topic are detailed.

Eugenio del Re e Riccardo Faccini

B1. Radioguided Surgery with β^- decays.

Radio-guided surgery (RGS) is a technique aimed at assisting the surgeon to reach as complete a resection of the tumoral lesion as possible, while minimizing the amount of healthy tissue removed. Before surgery, the patient is administered with a specific radio-labeled tracer that is preferentially localized in the tumor and a probe sensitive to the signal emitted by the tracer, is used to identify the position of the targeted tumoral cells. As a result, RGS provides the surgeon with real-time information about the location and the extent of the lesion, as well as the identification of tumor margins.

To date, established methods make use of a γ-emitting tracer and a γ radiation detecting probe or a portable gamma camera. Since γ radiation can travel through large amounts of tissue, any uptake of the tracer in nearby healthy tissue represents a non-negligible background, strongly limiting and often preventing the use of this technique.

Within the activities of the ARPG group, to overcome these limits and extend the range of applicability of RGS, our group suggested [1] to use pure β^--emitting radioisotopes. β^- radiation indeed is characterized by a penetration of only few millimeters of tissue with essentially no γ contamination.[1] This novel approach allows to develop a handy and compact probe (see Fig. 1) which, detecting electrons and operating with low radiation background, provides a clearer delineation of the margins of lesioned tissues. For such reasons, a smaller injected activity is required to detect tumor residuals compared to traditional RGS approaches. This also implies that the radiation exposure for the medical personnel becomes almost negligible [1]. In the years 2017-19 our studies have lead to significant steps towards a real application of the technique. In particular

- the possibility to extend the treatment to other types of tumors has been tested by studying the sensitity to radionuclides other than Y^{90}, including β^+ emitters[2] and by developing, in collaboration with Fondazione A. Gemelli, Istituto Superiore di Sanità and Sapienza departments of Chemistry and CTF, novel radiotracers[2]. The studies for the production of new radiotracers required also the development of ad-hoc set of instruments to cover l'entire range of specific activities that can be assumed by the organs.

- the possibility to use other radio-isotopes would allow more radio-tracers and consequently a vaster application. To this aim we have performed feasibility studies with other isotopes, including β^+ isotopes like ^{68}Ga, which open to prostate tumors[3].

- direct use of solid state detectors (e.g.CMOS) for the electron detection has been explored to reduce the minimum detectable electron energy and to reduce the γ contamination, thus broadening the range of useable radio-isotopes[4].

- exploration of the possibility to extend this technique in laparoscopy, where RGS is needed to overcome the limitations in the information on the patient tissues. Studies have been performed to quantify the level of locality of the energy depositions[5].

[1]This idea and the probe design has been patented (PCT/IT2014/000025))

[2]one of them has been patented as RM180321AE80

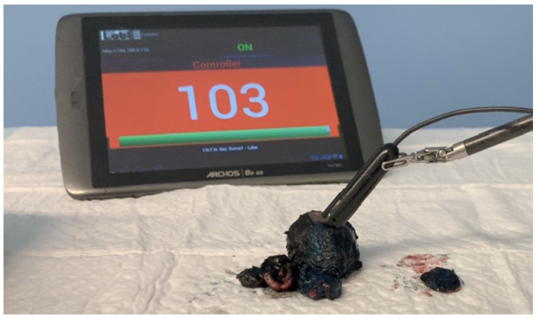

Figure 1: Laparoscopic β probe prototype applied to a prostate tumor by means of a robotic arm.

This activity is highly multidisciplinary and is carried out in collaboration with chemists from "La Sapienza" and nuclear physicians, oncologists and surgeons from several institutes. In particular tests on brain tumors were performed with the Ist. Neurologico Carlo Besta, those on GastroEnteroPancreatic tumors were performed with the Ist. Europeo di Oncologia, and finally tests on prostate cancer with a laparoscopic prototype have been performed with the Leiden University Medical Center (see Fig. 1). With Fondazione Policlinico Gemelli we have then performed tests on animals for biodistribution of radiotracers.

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http://arpg-serv.ing2.uniroma1.it/arpg-site

B2. Artificial Intelligence in Medicine

Machine Learning is among the tools that are routinely used by particle physicists. Within the activities of the ARPG group we have pursued two different projects to develop medical applications of machine learning.

The first project applies machine learning to the analysis of medical images and in particular studies **automatic classification and prediction of tumoral response based on MRI images** in patients affected by Locally Advanced Rectal Cancer (LARC). MRI is considered mandatory for correctly evaluating patients with rectal cancer and stratifying the ones who need preoperative Chemo-RadioTherapy (CRT) before surgical treatment. On the other hand, MRI is not optimal for assessing response to CRT since it is difficult to differentiate fibrosis from residual tumor. It is instead very important to identify patients with pathological Complete Response (CR) after neoadjuvant CRT who might benefit from either less invasive surgical or a wait-and-watch strategy. To this aim we have developed a texture analysis of 3T MRI T2-weighted imaging of LARC patients taken before, during and after CRT to identify imaging biomarkers to be correlated to the efficacy of therapy. The analysis has been carried out on 55 patients with LARC in the context of a funded AIRC project, in collaboration with Policlinico Umberto I. All patients underwent CRT and complete surgical resection; histopathology is taken as the gold standard. Textural features were automatically extracted using an open-source software. Fig. 1, a) shows a MRI image with the entropy map, calculated in the Region Of Interest (ROI, tumoral region) delineated by the radiologist. A sub-set of statistically significant textural features was selected and AI models were built by training a Random Forest (RF) classifier on 28 patients (training cohort). Model performances were estimated on 27 patients (validation cohort) using a ROC curve and a decision curve analysis. The AI model for CR classification showed good discrimination power with mean area under the receiver operating curve (AUC) of 0.86 (95% CI: 0.70, 0.94) in the validation cohort and clinical benefit (Fig. 1). We also developed an AI model to discriminate patients who don't respond to CRT, Non Responder (NR) who could benefit from being addressed to a different therapeutical strategy. The discriminatory power for the NR classification showed a mean AUC of 0.83 (95% CI: 0.71,0.92). Decision curve analysis confirmed higher net patient benefit when using AI models compared to standard-of-care [1].

We are currently extending our work to other clinical problems. We are developing a new method of analysis of MRI of type IVIM-DWI based on a deep learning model to improve the prediction of the HPV status in oropharyngeal carcinoma, in collaboration with the Istituto Nazionale dei Tumori Regina Elena of Roma.

The second project (FILOBLU, funded by Regione Lazio) deals with the use of machine learning for sentiment analysis, i.e. to analyse a text to identify patterns. Patients follow-up at home can bring great benefits both in terms of quality life and of costs and efficiency for the health national system. In this context the collaborations between the doctors and the patients or the caregivers is essential. The aim is to develop an APP for smart-phone that aids the communication to a medical staff of the vital parameters of a patient and of eventual written messages. Our group is developing a tool to label the messages received by the doctor with an attention score based on the text itself and the vital parameters, in order to help the doctor decide in which order to answer the messages.

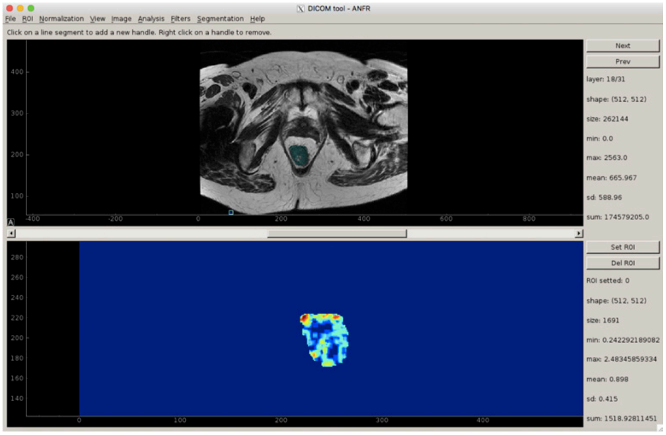

Figure 1: In the upper panel a slice of an axial oblique T2w image is shown with the ROI highlighted in cyan. The lower panel shows the local entropy map of the ROI.

While waiting for data gathering through app usage, synthetic data is generated with HumMod (for physiological parameters) and PolyGen (for the messages) to test operative workflow. We tested multiple deep neural networks architectures used in sentiment analysis to classify patients' messages both alone and in conjunction with vital parameters recordings. When applied to patients the APP will be able to adjust its training based on a feedback from the doctors, utilising a reinforcement learning technique.

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B3. MRI with ^{19}F: the NEPTUNE project

There are several clinical cases that require in-vivo determination of concentration of fluorine. They range from the need of an early diagnostics in Alzheimer desease (which is related to receptivity to β-Amiloyd which can be tagged with fluorinated compounds), to the measurements of the receptivity of tumors to radiosensitizers with fluorine, to eventually the possibility to make a total body search for initial tumors after administering FDG.

Traditionally fluorine concentration is estimated by means of PET, by detecting the radiation emitted by ^{18}F. This tecnique has the disadvantage to use radiactive nuclei and to be able to test only very low concentrations (order of 10^{-16} Moles/ml). An alternative that overcomes both shortcomings is to exploit the fact that the gyromagnetic factor of ^{19}F is close to 1H to perform Magnetic Resonance Imaging (MRI) of the distribution of ^{19}F. The absence of intrinsic signals in living tissues allows indeed in vivo visualization of fluorinated tracers, with a signal-to-noise ratio (SNR) close to that of ^{1}H-MRI even with only 1mMole/ml of ^{19}F. Our group is performing both hardware and software R&D to increase the signal and reduce the background.

From the HW point of view, to reduce the electronic noise of the readout chain and increase the efficiency of the radiofrequency coils,

- in collaboration with the Depts of Chemistry and CTF of the University of Rome "La Sapienza", we are testing ^{19}F-compounds with more 19F identical nuclei and sufficient long T2-relaxation times to increase ^{19}F signal
- we are studying the performances of the RF antennas to design a more performant one and the possibility to improve the amplification stage either by changing components or by introducing cooling
- we are implementing an SDR system in order to be able to test different digital signal reconstructions and optimize the system performances

To test such HW improvements a stand is being setup in the NMR laboratory of Silvia Capuani (CNR), placed inside the Department of Physics. Such test stand is made of a 0.35T scanner and a mobile NMR scanner, both produced by BRUKER and accessible both in input (antenna) and in output (amplifier/SDR). Moreover, to test ^{19}F-compounds a high field MRI scanner is used.

From the SW point of view, the problem to be solved is equivalent to the search of a small signal in a large background. This makes the problem much closer to data analysis in high energy physics rather than traditional NMR imaging. To this aim, we are applying machine learning in three different tasks:

- Noise reduction: one of the main hindrances to clinical application of ^{19}-MRI is the low signal-to-noise ratio. Recent developments in deep learning neural networks based denoisers (DNN) have shown promising results in noise reduction tasks and they may be helpful in maximizing the SNR in ^{19}-MRI.
- co-registration of ^{1}H and ^{19} MRI: Image coregistration is the process of matching and superimposing two or more images taken at different times, with different equipments or different protocols. It is of critical importance in the integration of multiple sources of information in medical image analysis.
- Automated segmentation of anatomical structure in ^{1}H MRI: we plan to identify the set of voxels which make up the volume of the object(s) of interest.

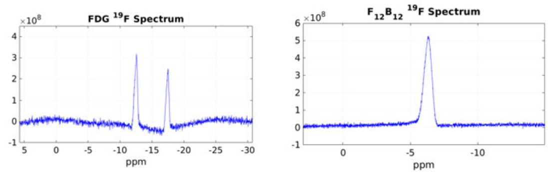

Figure 1: Frequency spectra for 3-FDG (left) and $F_{12}B_{12}$ (right).

The project started in 2019 and it is currently setting up the test-stands: the 0.35T scanner for the HW tests and a 9T small sample scanner equipped with an antenna tuned on fluorine to obtain the images that will be used to test the SW improvements. The first results on the new antenna are on the shape of the signal from several fluorinated compounds. In particular Fig. 1 shows the comparison between the signal from FDG (the most commonly used tracer) and a recently developed molecule, the dodecafluorinedodecaboratedborate $F_{12}B_{12}$. The latter, with a large number of fluorine atoms has a much better resolved peak in frequency. FDG on the contrary presents two structures due to two possible couplings of the fluorine with the rest of the molecule, thus making its use in imaging extremely difficult. Conversely, from these preliminary studies $F_{12}B_{12}$ seems to be an excellent candidate for ^{19}F-MRI.

Authors
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B4. Nuclear Physics and Particle Therapy

The Applied Radiation Physics Group (ARPG) is a group of physicists working on applications of particle radiation in particular (but not only) in the medical field. ARPG was founded in 2011 by physicists from the Sapienza Departments of Fisica and Scienze di Base Applicate per l'Ingegneria (SBAI), expert in high energy physics experiments, both detector development and data analysis. Every year several laurea and Ph.D. thesis have been pursued within the activities of the group. The students found placement both in research, and via the Ph.D. in Physics, in industry and in hospitals, both within the Scuole di Specializzazione in Fisica Medica and in internal research groups.

Within medical applications three major areas have been developed so far: the estimate of the dose delivery in Particle Therapy, described in the following, the development of a novel technique of Radioguided Surgery, and of applications of Artificial Intelligence to radiological exams, detailed in the following pages.

Particle Therapy (PT) has well known advantages in the treatment of solid cancers with respect to conventional radiation therapy, based on X-rays, due to the different mechanism of energy loss in matter. Hadron (proton and ion) beams are characterized by a release of energy localized very close to the end of their range, resulting in the Bragg Peak (BP). The hadron beam energy can be then tuned to be very effective in destroying the tumor, with the BP falling inside it, while sparing the adjacent healthy tissue.

Such high space selectivity of the PT asks for a precise monitoring of the delivered dose to be provided during the treatment (in-beam monitoring) as a fast feedback to the beam. The irradiation of tissues with hadron beams produces nuclear reactions followed by the emission of photons, positrons or charged fragments within few nanoseconds. Several methods have been developed to precisely determine the BP position online by exploiting this diversified secondary particle production.

Furthermore, nuclear reactions have a radiobiological impact on the patient and in particular on its healthy tissues. A complete understanding of these processes is therefore critical.

In this context the ARPG group has been developing several projects:

- a dose profiler for Carbon beams based on the detection of photons emitted in nuclear de-excitations has been developed and tested (INSIDE project[1])
- a device to detect fast neutrons is under development (MONDO project). It is based on the elastic scattering on protons and requires the R&D of ad-hoc, high performance, CMOS-based digital SPAD arrays as light sensor.
- the development of a Monte Carlo so fast to substitute the actually used pencil beam algorithms in Treatment Planning (FRED). It is based on the modellization of the physics processes and parallelization of the execution models on GPU.
- the measurement of the secondary fragments production cross sections in the interactions of C, He and O with targets of interests for medical applications (FOOT project[2]). Accurate knowledge of these cross sections would also be important in the field of radiation protection in space missions.

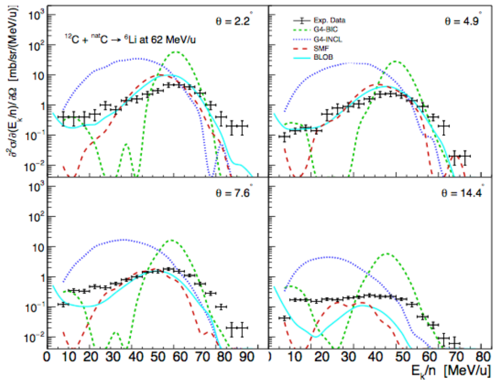

Figure 1: Double differential cross sections of ^{6}Li particle production in the interaction of a 62 MeV/u ^{12}C beam on a thin ^{nat}C target as a function of the kinetic energy of the produced fragment for different angles. The Geant4 models BIC (in green) and INCL++ (in blue) are compared to the model considered in the GeNIALE project: SMF (in red) and BLOB (in cyan).

The main project developed in the department of Physics concerns the study and simulation of the interactions of the ion beams with the nuclei of the patient (GeNIALE project) in the energy domain of interest for PT, i.e below few hundreds of MeV/u. The main goal of GeNIALE is improving the capabilities of the most used toolkit to develop MC simulation in medical applications, Geant4, in simulating these interactions, Fig.1 shows the comparison of the models already available in Geant4 with the models taken into account within GeNIALE interfaced with Geant4, this interface has been developed thanks to this project [3]. Finally, to overcome the main problem of the BLOB usage for medical applications -its running time- we are exploring the possibility of emulating the model using a Deep Learning algorithm: a Variational Auto-Encoder.

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B5. A New Method to Integrate Newtonian N-Body Dynamics

In an inertial coordinate frame, the equations of motion of N point of masses interacting via Newtonian gravity and with given initial conditions descend from the newtonian potential function. As well know, the explicit solution of the classic gravitational N-body problem, does not exist, therefore it is necessary to resort to numerical approximations.

The gravitational, Newtonian, $N-$body problem is chaotic, anyway if dealing with few bodies and restricting to a time "small" compared to the system's Lyapunov time, it can be considered as almost "deterministic". On the other side, when aiming to the study of a many-body motion over a time which is "long" compared to Lyapunov time, what it can be actually looked for is no more an approximation of the "exact" solution, but, rather, only the best possible estimate of the statistical properties of the possible solutions.

In such cases, and which such aims, the defect of classical integration algorithms is that of being unnecessarily *precise*, expensive, delicate, and complex. Consequently, we proposed a totally different type of algorithm (which we will hereafter referred to as *bizarre* method), which, in spite of a loss of (unnecessary) precision, results cheaper, simpler and more robust in giving reliable evaluation of relevant statistical indicators of the $N-$ body system behaviour.

The key idea of this type of algorithm is that of replacing the gravitational potential between two bodies, smoothly varying with the inverse of their distance, with a step-wise potential, kept constant along a certain number of steps. In such a scheme, the gravitational attraction as function of the mutual distance assumes a more bizarre behaviour (which justifies our naming): for almost all distances it is absent except for some distances for which it is infinite.

To test the validity, both in terms of precision and speed, of our algorithm we decided to perform a set of numerical simulations with the aim of providing sufficient statistical reliability, using both our method and the Euler-Cromer method. We exploited time integration of the motion of $N = 100$ equal mass particles, assuming units such that the total mass, M, is the mass unit, and the radius of the sphere containing initially the N bodies, L, is the length unit.

The initial conditions for the $N = 100$ bodies have been randomly sampled from a uniform distribution in both position and velocity spaces.

A comparison with a well established symplectic method is fully positive because both the Lagrangian radii time evolution and that of the virial ratio are very similar.

On a performance side, without any ambition to state clearly about it, we note that the speed of our present implementation of the bizarre method is 60 times that of the Euler-Cromer.

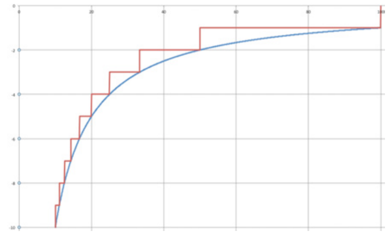

Figure 1: In red we show the step-wise approximation of the body interaction potential (blue).

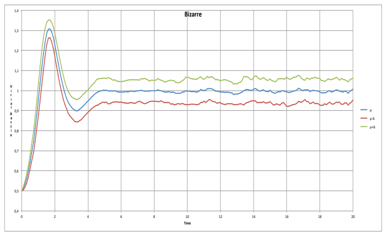

Figure 2: Bizarre method; Virial ratio versus time: the 100 simulations and (above and below) the curves corresponding a standard distance.

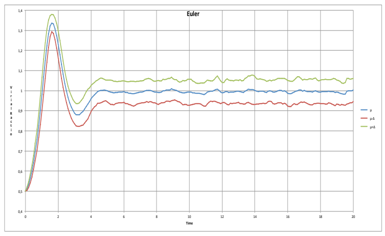

Figure 3: Euler-Cromer method; Virial ratio versus time: the 100 simulations and (above and below) the curves corresponding a standard distance.

As future developments, we are planning to move from astronomical problems to molecular dynamics problems.

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Authors

V. Parisi, R. Capuzzo-Dolcetta

B6. Physics and Cultural Heritage: open labs to artworks

Cultural Heritage includes an enormous number of artworks, made with wide different materials (such as pictorial pigments, metals, paper or wood). Physicists use their knowledge on material science and experimental methodologies to characterize these ancient materials of artistic and historical relevance. The information obtained are complementary to the philological-artistic ones and often crucial for the understanding of the artworks genesis and for their conservation, through the identification of the physico-chemical degradation pathways and the consequent specific recovery strategies. The techniques in use in our Department are based on THz, infrared and visible spectroscopy, mainly aimed at the chemical identification of the materials, also performed through multi-spectral imaging and digital methods. Infrared and Raman spectroscopies were successfully used to identify dyes, pigments, binders and fibres in archaeological, pictorial and contemporary art samples, as shown in Figure 1 [1,2]. In the frame of ADAMO project, promoted by the Excellence Centre at the Lazio Technological District for Cultural Heritage (DTC), a study on new spectroscopic methodologies to selected natural dyes has been performed [3]. THz imaging has a potential application in the nondestructive and noninvasive analysis of the internal structure of historical artworks. The penetration depth of THz radiation can be of several millimeters in the dry organic matter (e.g., painting layers), a depth which is typically opaque to visible and infrared radiation. THz imaging was recently employed to locate buried thin metal foils in a Russian wooden icon dated back between the 17^{th} and the 19^{th} century. Metal foils were used for decoration, and their precise localization under the pictorial layer was relevant information for conservation scientists and restorers.[4]. Mid-infrared and THz-TDS absorption spectroscopy were also employed for the assessment of conservation treatments of paper artworks obtained by using aqueous solution of ionic liquid. Based on the analysis of the bands in the carbonyl/carboxyl region at 1590-1750 cm^1, degradation of cellulose structure caused by oxidation and its improvement due to binding of ionic liquid molecules was investigated. Further, THz-TDS results indicated that the ionic liquid molecules penetrate in the larger size porosity, acting as binders among cellulose fibers to maintain the tensile strength of paper even after aging [5]. Notably, a multidisciplinary laboratory has been recently created in our Department, *Photonics for Humanities*, equipped with confocal microscopes and tools for digital image treatments in the THz spectral region, devoted to the recognition of hidden texts in ancient manuscripts [6]. Moreover, projects in collaboration with the Department of Applied Basic Sciences for Engineering (SBAI) and the Department of Documentary, Linguistic-Philological and Geographical Sciences, are in progress to improve and apply infrared and THz imaging on miniatures in medieval codes. Shared activities with the Institute for Complex Systems of National Research Council on THz-TDS and ultraviolet-visible spectroscopy and imaging are currently in progress. In the field of meteorology applied to the conservation of the cultural heritage, the Physics Department has a consolidated experience in the characterization of the historic indoor climate and in whole-building dynamic simulation.

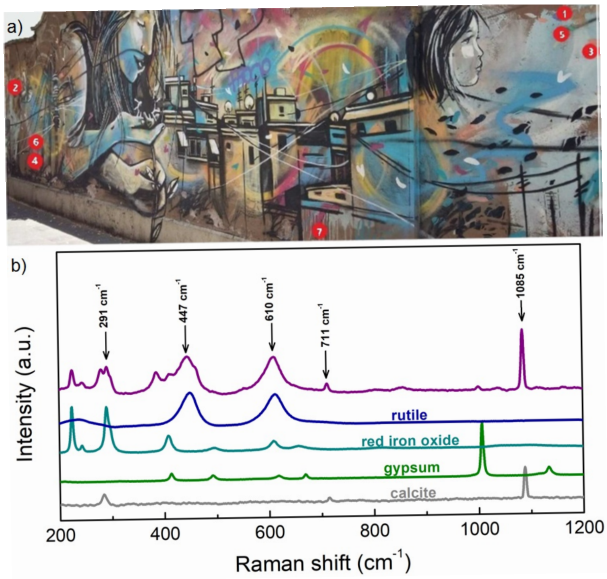

Figure 1: Panel a: mural painting in Via dei Sabelli, Rome; Dots point out the regions studied by Raman and infrared spectroscopy. Panel b: Raman spectrum of the painting preparatory layer, compared with those of different inorganic pigments and extenders.

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List of research activities

Condensed Matter Physics and Physics of Biosystems

Condensed Matter Physics

The Condensed Matter (CM) Physics group at the Physics Department of Sapienza, Università di Roma is composed by about 40 scientists with permanent positions (assistant, associate and full professors) and several affiliated researchers (mostly from CNR) who actively investigate different properties of hard matter, nano-structures, soft and bio matter, photonics and quantum technologies, or even create new frontiers of physics exporting ideas developed in and for CM physics to other (even very far) fields. This group of scientists collaborates with several post-docs and Ph.D students mainly enrolled in the Vito Volterra Ph.D. school and in the Materials Science curriculum of an Engineering Ph.D. School. The CM group enjoys a very high reputation in the international scientific community. In the last few years, some members have been awarded a few ERC grants and actively participate to several Horizon-2020 european projects.

The world around us is formed by macroscopic assemblies of atoms and molecules, which can form ordered or disordered systems: this is the realm of condensed matter, a clearly vast and multiform domain of physics. This domain is customarily split in smaller 'counties' investigating three-dimensional and low-dimensional solids, strongly-correlated materials, the so-called hard condensed matter, and nano-structures, and liquids, gels and sols as well as biological systems and active matter, forming the soft condensed and active matter domains; quantum optics and quantum information are natural derivations of condensed matter in so far they investigate the interplay and coherence of assemblies of photons and their applications.

Interestingly, some of the techniques and paradigms used to describe the collective behaviour of the electronic, photonic, atomic or molecular assemblies have also been transferred into many other fields where many degrees of freedom interact to give rise to emergent properties or strongly fluctuating and hardly predictable systems. This is the case of opinions and disease spreading, economy, network formation and behaviour. This 'leakage' of methods, concepts, and aptitudes typical of physics into far fields like sociology, linguistics, economy, information theory, and so on, is one of the modern declination and spin-off of CM Physics. This last part of the activities of the condensed matter theory group has been collected and reported in the 'Complexity' section in the 'Statistical Physics and Mathematical Physics' chapter. Other theoretical activities in CM Physics have a marked general theoretical character and find therefore their natural description in the 'Theory' section of the present report; a strong cooperation between the Theory group and the CM physics group has always been a characteristic of our Department. Furthermore, many experimental methods and approaches developed in and for CM physics find an application in biophysics, in medical physics and in the cultural heritage field. Finally, the fundamental research questions answered by researchers often require design and development of new advanced instrumentation, in the fields of high-resolution optical and electron spectroscopy. These new systems, albeit developed for fundamental physics questions, are often designed and exploited in prototype devices useful for potential applications, constituting a spin-off of scientific research.

The 'Sapienza' Physics Department hosts a wealth of activities that cover many of these CM physics domains, and all the above different domains of condensed matter involve both experimental and theoretical approaches, highly inter-linked in our Department. In this report, we will introduce these fields of CM physics activities and we will proceed describing the new frontiers extending condensed matter to other fields.

— *Superconductivity, Strongly-Correlated Systems and Functional Materials* [CM1-CM8] —

The scientific activity is focused on the exploration of new phenomena in exotic electronic materials, spanning from high-Tc conventional and unconventional superconductivity, to insulator-to-metal transitions, to materials with strong electronic correlation, low-dimensional superconductors, effects of disorder in low-dimensional electron systems, quantum phase transitions, topological phases of matter, spintronics. Electrons inside a solid are responsible for many of the prominent properties of the material, like, *e.g.*, its insulating or conducting character. Among these properties superconductivity is quite important for both fundamental and applicative reasons and is one of the most actively investigated hard condensed-matter topics in our Department. Superconductivity arises when electrons feel some kind of effective attraction, form pairs (the so-called Cooper pairs), which in turn condense in a single macroscopic quantum state. This condensation is at the basis of the peculiar properties of superconductors (zero resistance, perfect diamagnetism, ...). Depending on the specific investigated system, the research in the field of superconductivity addresses various aspects like the origin of the electron-electron attraction, the way superconductivity disappears (breaking of the Cooper pairs or loss of the quantum coherence of the condensed state), the role of dimensionality, disorder, topology of the electronic states.

The recent discovery of nearly room-temperature superconductivity in hydride compounds under very high pressure has (re)boosted the quest for high temperature superconductors. One of the theoretical groups of our

Department systematically investigates with advanced computational methods the key ingredients of high-Tc conventional superconducting materials and selects the most promising cases for experimental validation. The family of sodalite-clathrate hydrides (like, e.g, YH_{10}) have been predicted to exhibit the highest T_cs among binary hydrides. Another relevant research line in our department is devoted to the anharmonic effects in lattice vibrations, leading to phonon-phonon interactions. These effects are important in hydride superconductors because they stabilise the superconducting state, they are prominent in the presence of charge-density wave transition, a common occurrence in several systems like the transition metal dichalcogenides (TMD), that are of broad and hot interest. Anharmonicity is also important in thermal conductivity of technologically relevant materials.

Modern hard condensed matter devotes a great deal of attention to low-dimensional systems and their peculiar, specific properties: enhancement of electron-electron correlations and of disorder effects, occurrence of competing phases, ... Thus the structurally layered high temperature cuprate superconductors are widely studied both because they have high critical temperatures and because they have quite unusual normal state metallic properties that seem to violate the standard paradigms. According to the scenario proposed by a theory group of our department, these materials are on the verge of a charge-density wave instability and their unusual properties stem from competing phases (metal, superconductor, CDW). This scenario, recently validated by experiments, is part of a more general tendency of electrons to display a large compressibility in low-density and low-dimensional electron systems. This electron *softness* has also been studied in another research line devoted to low-dimensional superconductors (oxide heterostructures, TMD films,..).This may also lead to a filamentary structure of the superconducting phase, a new interesting paradigm for superconductivity in low-dimensional disordered systems.

Disordered superconducting films are also studied in our department under a different perspective: the superconducting condensate can sustain collective phase modes, that are usually invisible in optical experiments. However, disordered conventional superconductors like NbN and InO_x, arrays of Al nanograins or $SrTiO_2-$ based superconducting interfaces, can become intrinsically inhomogeneous leading to a finite coupling between the phase-phase modes and the electromagnetic field with optical absorption in excess with respect to homogeneous systems. The investigation of collective excitations in superconductors is a very active field also in relation to the quest of the Higgs mode, that in superconductors consists in collective fluctuations of the order parameter amplitude and to the observation of Leggett modes (antiphase fluctuations of coupled condensates in multiband superconductors like MgB_2). Inhomogeneity in superconductors is also investigated experimentally in the new emerging BiS_2-based superconductors. The inhomogeneous electronic properties of these systems have been characterised also with spectro-microscopy images at the μm-scale, showing interesting correlations between spectroscopic signal and domains.

Disorder is also a relevant issue for non superconducting materials, and an activity of our department is devoted to the study of periodic compositionally disordered ferroelectric systems, with formation of a 3D ordered mosaic of larger domains, where peculiar optical properties occur, like unprecedented giant refraction.

Our groups are also actively involved in other 'hot' issues like the investigation of topological states of matter, the quest of Majorana fermions in electron systems, the coupling between electron spin and charge transport of relevance for spintronics (the manipulation of spins via charge handles in electronic devices), and so on.

— *Surface Physics and Nanostructures* [CM 9-CM 17] —

The physical properties of condensed matter can be dramatically modified by reducing the size from the bulk limit to the nanometer scale. The design and growth of novel low-dimensional architectures are nowadays opening routes towards the engineering of condensed matter featuring novel functionalities. The groups in this area investigate the structural, vibrational, electronic, magnetic, and optical properties of quantum dots, nanowires, two-dimensional materials (like graphene and other exfoliable and topological materials) and surfaces, by means of advanced spectroscopic techniques with high spatial and temporal resolution. These studies meet the quest for miniaturization and integration of novel functionalities in photonics, quantum information and nanoelectronics.

The researches span from 2D materials, like topological insulators, TMD and graphene-based systems, to ordered 2D adsorbed systems, with intriguing electronic, magnetic and opto-electronic properties. The presence of the 2D electron gas at the interface between topological insulators (Bi_2S_3) and the substrate is brought to light mainly by means of optical spectroscopy, while TMDs are studied also in extreme conditions at ultra-high pressures to modify their structure and consequently the associated electronic properties. The optical properties of Si-Ge quantum well hetero-structures allow to estimate the conduction band offset, as also among van der Waals 2D materials, and the polariton excitation at surfaces is enhanced by the photo-thermal induced resonance technique. Graphene and C-based materials are synthesized and grown also with functionalisation, for changing the intrinsic semimetallic response of graphene, by integrating graphene with h-BN and by hydrogenation of the C bonds towards formation of a planar but semiconducting C layer (*graphane*), as observed by UV and X-ray photoelectron spectroscopy. Vibrational micro-spectroscopy of graphene has also been obtained by short laser pulse excitations of electron-hole pairs followed by the subsequent anelastic Raman scattering lattice excitation. Ultra-thin epitaxial silicon on oxide substrates has been shown to behave as a Dirac-like system by optical studies, as also insulator-to-metal transitions have been induced in vanadium oxide by strong electric field in the THz regime. The interface between graphene and TMD hetero-structures imaging has been studied by photo-excitation and Raman scattering. The magnetic response associated to a mono-layer array of ordered magnetic molecules (metal-phthalocyanines) has been shown to strongly change (from ferro- to antiferro-magnetic) by modulating the 2D thin-layer thickness (from 1 to a few mono-layers) of a magnetic metal intercalated below graphene. These studies, by means of photoemission and X-ray absorption spectroscopy with circulary polarised radiation, demonstrate the possibility of estimating the magnetic moment and of tailoring the ordered magnetic state at the nanoscale.

Low-dimensional materials can also be tailored and engineered towards well defined properties. Groups achieved the formation of III-V-based semiconducting quantum-dots (0D) and quantum-wires (1D) in different ways, from hydrogenation to patterning, to be used as photon generators for quantum nano-photonics applications. A further controlled growth mechanism is the sub-μm-sized formation of patterned bubbles in TMD, by low-energy hydrogen ions, enflating in this way a mono-layer of the 2D material, thus rendering it a direct-gap system, with enhanced optical response. Semiconductor quantum dots and new strain-engineered arrays of TMD-based photon-emitters are currently being developed as site-controlled emitters of single-photon sources.

The experimental methods cover a wide range of energies and probes, from optical and electron spectroscopy to atomic-scale microscopy, to spectro-microscopy. A wide range of excitation photon sources is used, from the THz to the X-ray photon energy range, so as to couple with a wide range of excitations, vibrational, plasmonic and core-levels, by using both elastic and anelastic scattering processes, and also pump-and-probe methods, to determine the dynamics of different processes in low-D materials.

— *Active Matter, Soft Matter and Biosystems* [CM 18-CM 33] —

Advances in non-equilibrium physics, imaging, optics and computer science are creating new pathways and opportunities for the study of soft materials and biological matter. Research activities in this direction range from the spectroscopic investigation of fundamental processes in single biomolecules to the modelling and design of biological and active systems with unique and controllable dynamical behaviour. Our department has a long-standing and top-level tradition in the study of classical soft-matter systems. This involves, for instance the design and creation of new materials with controlled physical properties designed through the spontaneous aggregation of basic building blocks, such as simple molecules, macromolecules or colloidal particles. Examples are provided by micellar systems, formation of fibers and fibrils, solutions of long duplex B-form DNA, epoxy resins, chromonic liquid crystals as well as inorganic nanoparticles.

Investigation of molecules and bio-molecules *via* fast photo-excitation, followed by slower mechanisms involving coupling with lattice/molecular modes, allowed to study the dynamics of these systems, both for condensed structures and bio-molecules. Molecules under extreme conditions (in particular high-pressures) are studied to determine their phase diagram, mainly by neutron, light and X-ray scattering. In these extreme conditions, they produce new physics, like hydrogen metallization and molecular superdiffusion. Optical and microscopy studies are applied to determine the properties of ionic liquids, and also the self-assembly of colloids for studies ranging from bio-technological to environmental applications. Polymers and colloids are characterised by studying their electromagnetic response.

Optical methods are used also for 3D optical micro-manipulation and imaging, so to bring to an integration with patterned micro-machines and engineering of active matter propulsion. These studies investigate and bring to light the basic principles governing non-equilibrium phenomena. Optical spectroscopy in the THz and IR regimes are used for the study and analysis of meta-materials also for cultural heritage applications, they are applied to biomolecules giving important information for the determination of the membrane-protein interaction, and to determine the properties of membrane mono-layers at the nano-scale, the latter overcoming the diffraction limit thanks to plasmonic field enhancement techniques. Coherent Raman imaging of cells and tissues allows to extract direct information about metabolic issues. Surface enhanced anelastic Raman scattering is applied to bring to light the interaction mechanism between DNA and metal nano-particles, revealing a strong potential towards biosensing. Light localisation has been obtained in stronlgy scattering disordered medium, by shaping the incident wavefront through adaptive optics, and a light spot has been demonstrated to penetrate deep in a scattering volume resisting to deflections in the turbid environment, achieving axial resolution comparable to that of Gaussian beams.

The theoretical activities of our department in the field of Active and Soft Matter investigate how complex molecules and polymers aggregate, and the resulting physical properties. One group works theoretically on the properties of chromonic liquid crystals and cholesteric phases of amyloid fibrils by employing simple coarse-grained models where the complex particles are suitably schematised. Also epoxy resins have been successfully described by a coarse-grained model developed in this research group. Regarding polymer aggregations, of particular interest are those polymer-based systems that form complex networks by crosslinking mechanisms, which can be either chemical or physical. In particular microgels are crosslinked polymer networks with sizes ranging from tens of nanometers to tens of micrometers. Their ability to react to a change of the environmental conditions (e.g. temperature, pH, salt concentration) by varying their size make them appealing for both applicative and fundamental purposes. Along similar lines DNA oligomers are studied, which can form a large variety of nanometric constructs, via a cascade of self-assembly processes. In recent years this group exploited DNA oligomers with 2-5 arms (nanostars) as building blocks of gels with specific mechanical and dynamical properties demonstrating the possibility to design biocompatible bulk materials with tuneable viscoelastic properties.

Of course DNA not only is an interesting building block to create new materials and a central ingredient of material science, but is one of the 'traditional' objects of biophysical studies investigating the transfer of biological information. In this framework, our Department hosts interesting theoretical biophysical researches acting along statistical mechanics and/or computational lines. In particular, a theoretical biophysics group in our Department is currently investigating the role of codon's frequency in DNA (codons are DNA nucleotide triplets coding amino-acids) a meta-code that controls gene expression, rates of protein synthesis and in vivo protein folding.

— *Photonics and Quantum Technologies* [CM34-CM37] —

The research activity is at the forefront of photonics with emphasis on the exploration of new phenomena in optics and the development of new tools for quantum information science and technology. This is a very active and growing research area within the Department of Physics, with several groups focusing on: non-linear waves, terahertz technology, ultrafast photonics and non-linear spectroscopy of condensed matter and biomaterials, quantum information and foundations of quantum mechanics, and quantum optics with semiconductor nanostructures, also integrated with optical microcavities.

Photons are an ideal vector for delivering quantum information as they can be produced with negligible decoherence and can travel for long distances. Groups in the Department actively work in this field, and photonic quantum technologies have been used to build complex integrated systems for facing the Boson Sampling problem and to generate high dimensional states with orbital angular momentum. Quantum causality is investigated through production and study of entangled photons. Fundamental problems are accompanied by quantum metrology applications based on the integrated photonic platforms realized in the Department. An experimental all-optical Quantum-Walk has been implemented, also bringing to light the so-called Quantum Darwinism, realizing experiments where the quantum system is correlated with fractions of environment, causing some decoherence. Photons are also used in a wide-field area, by applying the physics of complexity to photonics, and photonic spin-glasses and Ising machines are designed and studied.

CM physics scientists of the Department make use of and contribute to develop the most advanced theoretical and experimental investigation methods. Theoretical approaches span from computational (DFT, Monte Carlo, machine learning, ...) to more analytical, statistical, and field-theoretical schemes. Experimental investigations use the most advanced THz, IR, UV, X-ray and laser sources, as also low-medium energy electron sources, coupled with advanced radiation and electron detectors for high-resolution experiments in the spatial, energy and time domains, as detailed in the laboratory section of this report. A new advanced laboratory for spectro-microscopy investigation of low-D systems has been recently designed and is being installed in the Amaldi Research Center of the Department [http://www.roma1.infn.it/amaldicenter/mat_sci_3G_ifos.html]. This new laboratory is unique in the world, coupling electron spectroscopy (X-ray Photoelectron Spectroscopy, XPS) and optical spectroscopy (Photo-Luminescence and Raman) spatially-resolved techniques. All these techniques are in ultra-high-vacuum and can be exploited at low temperatures, thus allowing the study of the very properties of the low-D systems, without any ambient interference. Furthermore, scientists are also active users and designers/developers of beamlimes at large research infrastructures, like synchrotron radiation, neutron sources and free-electron laser facilities, which constitutes another of the scientifical/technological spin-offs of the CM physics fundamental research of our Department.

Authors

Marco Grilli and Carlo Mariani

CM1. Hydrides under pressure: possible room temperature superconductors?

Last year, superconductivity at 260 K was reported in a lanthanum superhydride, LaH_{10}, four years after another hydride, H_3S, had broken the record for the highest critical temperature (T_c) [1]. Both H_3S and LaH_{10} have little prospects of practical applications, since they only exist and superconduct under Megabar (million of atmospheres) pressures. However, the discovery of two new superconductors with T_c close to room temperature has profound implications for future research: while the discoveries of new superconductors had always preceded their theoretical interpretation, those of H_3S and LaH_{10} were guided by theoretical predictions.

Such a paradigm shift was driven by simultaneous advancements in the theory of superconductivity from first principles, in the prediction of crystal structures, and in high-pressure experimental techniques [2,3]. The synergy of these methods has the potential to produce a substantial acceleration in the discovery of new superconductors: by now, theoretical-computational methods of unprecedented accuracy can systematically explore key ingredients of high-T_c conventional superconductivity and select the most promising cases for experimental validation. Fig. 1 summarizes the spectacular progress in the field of superconducting hydrides after the H_3S discovery: in less than five years, almost all binary hydrides were computationally explored, T_c's exceeding 100 K were predicted for several such compounds and, in the few cases where experiments were performed (H_3S, H_3Se, LaH_{10}), excellent agreement was found [2].

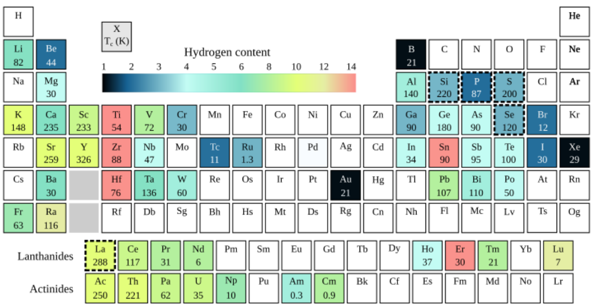

Figure 1: Periodic table of superconducting binary hydrides: for each element the table shows the highest T_c predicted in a pressure range of 1-3 Mbar, and the color scale indicates the corresponding hydrogen content – from Ref. [2].

Our group has investigated several aspects of conventional superconductivity at high pressures, employing theoretical electronic-structure methods for crystal-structure prediction and superconductivity, with the goal of identifying the material-specific aspects underlying the occurrence of high-T_c superconductivity in existing materials, and predicting new ones with improved properties (higher T_c and lower stabilization pressures).

Fig. 2, from Ref. [4], shows the temperature evolution of the superconducting gap of two high-T_c superhydrides, YH_6 and YH_{10}, calculated within a first-principles anisotropic Migdal-Eliashberg theory. They belong to the family of sodalite-clathrate hydrides (SLCH), characterized by large hydrogen cages surrounding a guest atom, which are interconnected to form a dense hydrogen sublattice. SLCH have been predicted to exhibit the highest T_c's among binary hydrides. According to our calculations, YH_{10} should exhibit a T_c exceeding room temperature, thus even higher than its lanthanum counterpart, LaH_{10}. In addition to a rationale for the record T_c of LaH_{10}, our study identified a general trend underlying the stability of hydrogen cages in SLCH, which is governed by the covalent radius of the guest atom. Selecting an element (or a combination of elements) with the appropriate covalent radius, it should be possible to form high-T_c SLCH at pressures well below 1 Mbar.

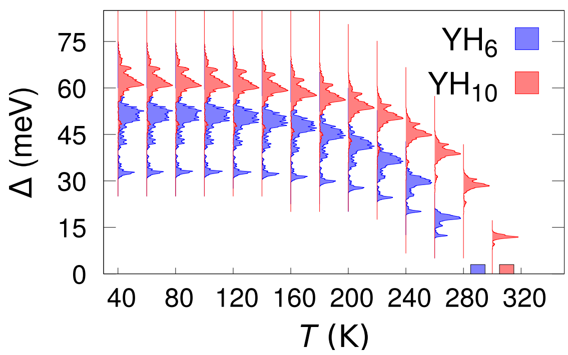

Figure 2: Calculated superconducting gap vs. temperature calculated for YH_{10} and YH_6 at 300 GPa, from Ref. [4].

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CM2. Phonon-phonon interaction: H-based superconductors, charge-density-waves, thermoelectric materials, and thermal transport

Anharmonic effects, namely phonon-phonon interaction, can generally be treated within perturbation theory. Such an approach breaks down when the harmonic solution is dynamically unstable or when the anharmonic corrections of the phonon energies are larger than the harmonic frequencies themselves. This situation occurs near lattice-related second-order phase-transitions such as charge-density-wave (CDW), ferroelectric, and ferroelestic transitions or in H rich materials with large zero-point motion fluctuations (like e.g. in the PdH, H_3S and LaH_{10} superconductors). Interestingly, even in these cases, phonons can be observed and measured. In order to treat such situations, we developed a stochastic implementation of the self-consistent harmonic approximation valid to treat anharmonicity in the non-perturbative regime and to obtain, from first-principles, the structural [1], thermodynamic and vibrational properties [2] of strongly anharmonic systems. We successfully applied our approach to characterise the temperature dependence phonons and the phase diagram of charge density waves metals [3] and of thermoelectric materials (see publications of F. Mauri). Finally, in a recent preprint [I. Errea, *et al.*, arXiv:1907.11916 (2019)] we showed that anharmonic quantum fluctuations of H atoms stabilise a high symmetry cubic structures in LaH_{10}, the superconductors compound with the record transition temperature of 250 K, protecting the superconducting phase against symmetry breaking transitions that lower the electron-phonon interaction [5]. Phonon-phonon collisions also rule the thermal conductivity properties of materials. In particular the thermal conductivity in crystalline solids with well-separated phonon branches (namely with few atoms per unit cell) is well describes by a particle-like Boltzmann Equation for phonons, where the main source of scattering is anharmonicity. In such systems the conductivity decreases with temperature (T), with a 1/T law for T larger than the Debye Temperature (T_D). In amorphous solids the main source of scattering is instead the static and T-independent disorder, well described by the harmonic theory introduced by Allen and Feldman. In these systems the conductivity increases with temperature and, within the Allen and Feldman theory, reaches a constant value for $T>T_D$. Interestingly periodic solids with large super-cells and very low thermal conductivity, relevant for many technological applications, can exhibit an intermediate glass-like behaviour that can not be accounted for by existing theories. Anharmonicity or disorder are the limiting factors for thermal conductivity in crystals or glasses; hitherto, no transport equation has been able to account for both. We derived such equation, resulting in a thermal conductivity that reduces to the Boltzmann and Allen-Feldman limits, respectively, in anharmonic crystals or harmonic glasses, while also covering the intermediate regimes where both effects are relevant [6]. Our approach also solves the long-standing problem of accurately predicting the thermal properties of crystals with ultralow or glass-like thermal conductivity, as we show with an application to a thermoelectric material representative of this class [4].

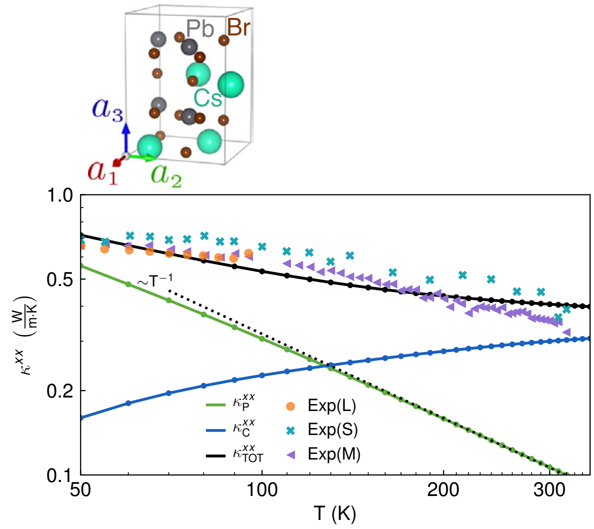

Figure 1: Thermal conductivity of the $CsPbBr_3$, perovskite, a promising materials for thermoelectric energy conversion. The unit cell (upper panel) contains 4 formula units (20 atoms). In the lower panel we report the thermal conductivity as a function of T. Exp(L), Exp(M) and Exp(S) refer to experiments on nanowires with different sections. Green: the conductivity obtained with the standard approach based on Boltzmann equation, with its T^{-1} behaviour. Black: total conductivity from our new unified theory, that perfectly matches the experimental data. Blue: difference between our and the Boltzmann approach, that arises from a wave-like energy-tunneling between different phonon branches.

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CM3. Charge density fluctuations in high-temperature superconducting cuprates

High-T_c superconducting (HTS) cuprates are among the most widely investigated solid-state systems, not only because of their large superconducting temperature, but also because of their unusual normal state properties and rich phase diagram, with several competing phases.

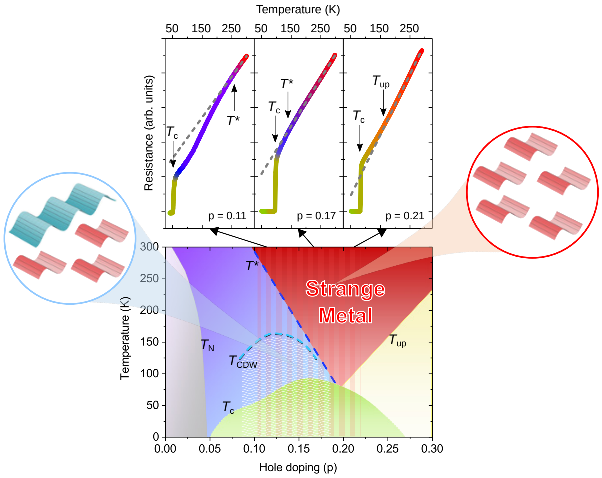

Figure 1: Top: typical resistivity curves for underdoped, optimally doped and overdoped cuprates. Bottom: schematic phase diagram: antiferromagnetic (grey), superconducting (green), pseudogap (blue), and strange metal with MFL behavior (red) regions. RIXS experiments detect CDW (blue waves) and CDF (red waves) in the striped region [1].

The doping-temperature $(p - T)$ phase diagram encompasses the antiferromagnetic and the superconducting orders, and the pseudogap region, where a reduction of the quasiparticle density of states in some sections of the Fermi surface occurs below the cross-over temperature T^*. In this region and up to optimal doping $p \approx 0.17$, short/medium range incommensurate charge density waves (CDWs) emerge as an incipient order weakly competing with superconductivity. There is now increasing consensus that charge modulations are a common occurrence in all families of HTS cuprates. According to an old proposal of ours, recently revised and extended [2], CDWs arise from a quantum critical point (a second-order phase transition at $T = 0$) around optimal doping, but, due to the near two-dimensionality of the CuO_2 planes and competition with superconductivity, they usually stay dynamical without forming long-range order. The unexpected observation of dynamic CDWs even in the overdoped region of some cuprates [3] confirmed their relevance. Thus CDWs in cuprates seem to be a rather pervasive phenomenon.

However, the grand unresolved issue in cuprates is the occurrence of a ‘strange’ metallic state above the pseudogap temperature T^* (red region in Fig. 1). Even though such state has been successfully described within a phenomenological scheme, the so-called Marginal Fermi Liquid (MFL) theory, a microscopic explanation is still missing. Recent resonant inelastic X-ray scattering experiments on $Nd_{2+x}Ba_{2-x}Cu_3O_{7-\delta}$ and $YBa2Cu_3O_{7-\delta}$ films identified charge density fluctuations (CDFs) with characteristic wavevector similar to that of CDWs having low characteristic energies and very short correlation lengths [1]. These CDFs, which are likely ‘aborted’ CDWs that for some reasons (disorder, competition with superconductivity, electron inhomogeneities,...) do not succeed in forming CDWs over distances larger than few lattice spacings. However, CDFs are present over a very wide region of the $(p-T)$ phase diagram and extend well above T^*. We investigated the consequences of CDFs on the electronic and transport properties and found that they can explain the MFL phenomenology [4]. In particular, they can account for the mysterious linear-in-T resistivity (Fig. 2). Therefore, CDFs are likely the long-sought microscopic mechanism underlying the peculiarities of the normal state of cuprates. Thus, CDWs and their short-ranged version, the CDFs, pervade the phase diagram of cuprates and play a key role in their physical properties.

Remarkably, in the underdoped region, the interplay of CDWs and superconductivity may give rise to topologically protected filamentary superconductivity at the boundary between different CDW domains [5].

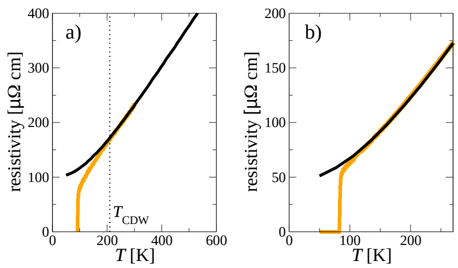

Figure 2: Experimental/theoretical (orange/black) resistivity for an optimally (left) and over-doped (right) cuprate [4].

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CM4. Inhomogeneous superconductivity and soft electron matter in two-dimensional systems

Interesting phenomena occur in two-dimensional (2D) superconducting (SC) thin films or heterostructures, due to the interplay of low dimensionality, phase coherence, and disorder at the microscopic and nanoscopic scale.

Macroscopic and nanoscale studies on NbN SC ultrathin films reveal nanoscopic inhomogeneities of size L_i in the SC properties, uncorrelated to structural inhomogeneity and persisting above the critical temperature T_c as a pseudogap (see Fig. 1). While the thickest films display a 2D behaviour in the SC fluctuations above T_c, paraconductivity in the pseudogap regime of the thinnest films unveils fluctuations of the amplitude of the order parameter, within zero-dimensional (0D) regions of size L_i, resulting from the confinement of SC fluctuations, related to an anomalous diffusion at short distance [1].

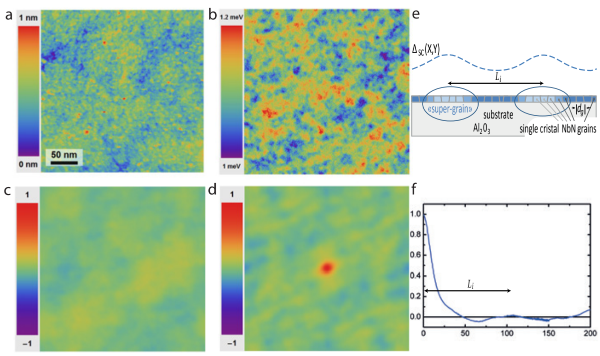

Figure 1: (a) Topographic map of a NbN. (b) SC gap inhomogeneities, on a scale much larger than the size of the structural nanocrystals. (c) Cross-correlation of the topographic and spectroscopic maps. (d) Autocorrelation of the map in (b). (e) Scheme of the relevant length scales. (f) Radial profile extracted from (d). The correlation length $L_i \approx 100$ nm in the present sample. The central peak width, $L_i/2 \approx 50$ nm, gives an estimate of the domain size [1].

In $LaAlO_3/SrTiO_3$ heterostructures, a gate tunable SC electron gas is confined in a quantum well between two insulators. Microwave transport measurements allow to extract the superfluid stiffness and the SC gap energy, showing that a competition between electron pairing and phase coherence is at play. Seemingly, only a small fraction of the electrons condenses into the SC state, corresponding to the weak filling of high-energy d_{xz}/d_{yz} bands in the quantum well, more apt to host superconductivity [2]. Interestingly, when the (110)-oriented heterostructure is studied, evidence is found for a doping-drivem transition from single-condensate to two-condensate superconductivity, which can be related to the Lifshitz transition between $3d$ bands in the quantum well. The SC gap is suppressed while the second band is populated, which might be ascribed to the existence of SC order parameters with opposite signs in the two condensates, due to repulsive coupling [3].

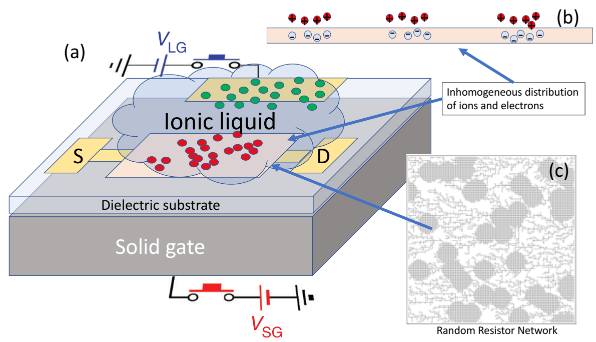

Figure 2: 2D crystalline superconductor (pink) on a dielectric substrate, with a metallic back gate (grey) and a ionic liquid (light blue). Positive (red) and negative (green) ions are shown, together with the ionic-liquid gating (orange). S and D are the source and drain electrodes. (b) Schematic profile of the inhomogeneously doped layer. (c) 100×100 cluster of RRN showing SC filaments and puddles [4].

Tuning the electron density of crystalline thin films, like $TiSe_2$, MoS_2, and ZrNCl, by chemical doping or ionic-liquid gating, a low-temperature metallic state is found, that escapes the SC or insulating fate of standard 2D electron systems. Some experiments also find a tendency to a negative electron compressibility, i.e., an inclination for electron phase separation, resulting in a mild nanoscopic modulation of the landscape, that is compatible with a high electron mobility. This intrinsic inhomogeneity is highlighted by the peculiarity of the metal-to-superconductor transition. Modelling these systems as Random Resistor Networks with SC filaments and puddles embedded in a metallic matrix (see Fig. 2), their resistance vs temperature curves can be fitted. The low-temperature metallic state finds a natural explanation in terms of the pristine metallic background embedding non-percolating SC clusters [4].

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CM5. Phase fluctuations in disordered superconductors

In the BCS theory of superconductivity the spontaneous breaking of the $U(1)$ gauge symmetry at the critical temperature T_c leads to a finite complex order parameter. Its amplitude Δ_0 is responsible for the opening of a gap in the single-particle excitation spectrum, while phase rigidity is responsible for the superfluid response. The phase fluctuations represent the Goldstone mode, which is massless at long wavelengths, and whose frequency is pushed, in the presence of Coulomb interaction, to the plasma energy scale, well above the energy gap Δ_0. In these conditions, its thermal excitation at temperatures well below the superconducting (SC) critical temperature $T_c \sim \Delta_0$ is prevented. In addition, in the long-wavelength limit the phase mode is decoupled from the transverse electromagnetic field, so that it does not contribute to the ac conductivity. For these reasons, within the context of conventional superconductors SC phase modes have been mainly discussed for their role near T_c within the context of effectively two-dimensional (2D) classical models. Indeed, in this case topological vortex-like phase fluctuations becomes entropically relevant and can drive the transition according to the Berezinskii-Kosterlitz-Thouless (BKT) paradigm.

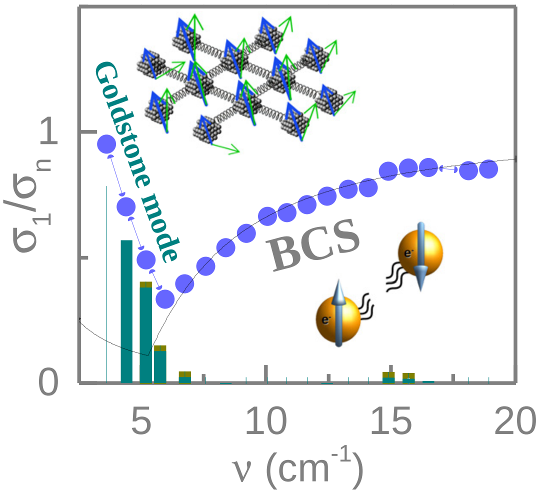

Figure 1: Real part of the optical conductivity of a Al nanograin thin films. The solid line is the BCS fit, which accounts for the optical absorption at $\nu \gtrsim 2\Delta$, due to the breaking of Cooper pairs. The bars document the excess conductivity, due to the Goldstone mode, as computed within an inhomogeneous XY-like quantum model. Taken from [1].

However, recent advances in the growth and control of SC thin films revealed that in several classes of materials, ranging from disordered conventional superconductors like NbN and InO_x to arrays of Al nanograins to $SrTiO_2$-based SC interfaces, the SC background becomes intrinsically *inhomogeneous*, at length scales ranging from tens to hundreds on nanometers. An interesting outcome of the spatial inhomogeneity of the SC properties is that it induces a finite coupling between the Goldstone phase mode and the transverse electromagnetic field. In other words, phase modes become optically active and lead to a finite absorption, that manifest experimental as an excess conductivity with respect to BCS predictions, see Fig. 1. This effect is found both within effective bosonic quantum phase-only models[1], where disorder is introduced at the level of the local phase rigidity, and within microscopic fermionic models[2], where disorder is introduced as a random on-site potential for single-particle excitations.

A related interesting question is also the effect of such fragmented background on the BKT physics. By using Monte Carlo simulations on a classical XY model, whose coupling constants map the "granular" structure of the SC landscape found in [2], we showed [3] that even though the transition ultimately belongs to the BKT universality class, the vortex-antivortex pairs enucleate already significantly below T_c in the bad SC regions. This effect gives rise to a smearing of the expected BKT jump of the stiffness, in good agreement with the experimental observations. A related problem, that we recently started to address in collaboration with the experimental group of P. Raychuadhuri in Mumbai, is how disorder affects the two-step melting of the vortex lattice formed at finite magnetic field. In [4] we recently proved, by means of a combination of real space imaging and transport measurements, that the 2D hexagonal vortex lattice in an amorphous MoGe thin film melts in two steps, as predicted by the BKT theory, refined later on by Halperin, Nelson, and Young: through a transformation from a solid to a hexatic fluid, which retains quasi-long-range orientational order; and then from a hexatic fluid to an isotropic liquid. The new finding is that vortex diffusivity in the hexatic phase is significantly reduced with respect to the isotropic liquid phase. Its theoretical explanation, and the persistence of these effects in an inhomogeneous background, are open question that we plan to address in the near future.

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CM6. Non-linear effects and time-resolved spectroscopy in electronic systems

In the last decade, a significant advance in the investigation of collective modes across phase transitions has been gained thanks to the huge experimental progress in non-linear optics and time-resolved spectroscopy. In the case of superconducting (SC) systems the attention has been focused on two effects: high-harmonics generations and coherent oscillations. In the first case, transmission experiments in conventional superconductors showed that below the critical temperature T_c the power spectrum of the transmitted field has a component at three times the frequency of the incoming radiation, the so-called third harmonic generation (THG), which is strongly enhanced when the incoming pump frequency ω_p matches the value of the SC gap Δ. In the second case pump-probe protocols have shown that the differential probe measured with and without the pump displays below T_c coherent oscillations as a function of the pump-probe delay.

The intensity of the THG can be directly linked to the non-linear optical kernel $K(\omega)$, since $I^{THG}(\omega_p) = K(2\omega_p)$. In a superconductor both the lattice-modulated charge fluctuations and the amplitude (Higgs) fluctuations of the SC order parameter give a resonant contribution to $K(\omega)$ at $\omega = 2\Delta$. While initially in the literature the attention has been put only on the Higgs mode, our work [1] highlighted that charge fluctuations dominate. Indeed the Raman cross-section of the Higgs mode in conventional superconductors is strongly suppressed by particle-hole symmetry, so that the Higgs becomes visible in ordinary Raman spectroscopy only when superconductivity coexists with charge-density-wave order[2]. In addition, both contributions depend in general on the light polarization, and in the case of the Higgs also on the form of the pairing interaction [1].

For what concerns the pump-probe protocols the interpretation of the experiments is more challenging. Indeed, in this case one has to face not only non-linear optical processes, but also with non-equilibrium phenomena on time scales which depend on the characteristics of the experiment. When the system is excited with a visible-light pulse electrons are promoted to conduction bands and they relax in tens of femtoseconds to a thermal distribution at temperatures larger than the lattice, which remains cold. However, when electrons are strongly coupled to some phonon mode the energy can be selectively transferred to it, leading to a very rich and unusual hot-phonon physics, as the one we recently discussed in Ref. [3] in collaboration with the experimental group at EPFL (Lausanne)[3]. In the case of THz pump pulses the perturbation of the system is instead less disruptive, and the same non-linear effects responsible for THG dominate. Taking advantage of the collaboration with the experimental group at PSI (Zurich) we designed an experiment aimed at using THz light to excite the relative phase fluctuations between the two bands – the so-called Leggett-mode– in the MgB_2 superconductor. Indeed, in contrast to the Higgs mode, in MgB_2 the Leggett mode is Raman active, so it contributes to the non-linear optical kernel $K(\omega)$. By using both broadband and narrowband THz pulses we selectively excited coherent oscillations of the Leggett mode, establishing at the same time that the basic excitation mechanism is a sum-frequency analogous of the Raman process, see Fig. 1. On this respect, our work established the general paradigm for coherent control of collective modes, with a high potential for the investigation of a wide variety of quantum states of matter across a phase transition.

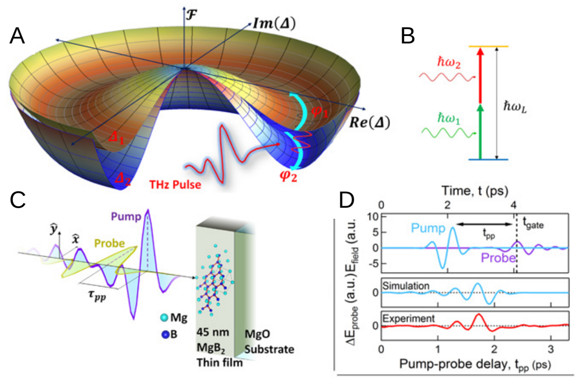

Figure 1: Free-energy for a two-band superconductor, where Δ_1 and Δ_2 are the two complex order parameters. The Leggett mode corresponds to an opposite phase displacement (light blue arrows) between the two coupled order parameters. (B) Two photons of the pump field can excite the Leggett mode at ω_L via a sum-frequency process. (C) Schematic of the experimental setup for the cross-polarized THz pump-THz probe setup (D) Simulation of the nonlinear excitation dynamics of the Leggett mode in MgB_2 in a pump THz field. Taken from [4]

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CM7. Spectroscopy and microscopy of some emerging superconductors

After the discovery of high T_c superconductivity in copper oxides more than three decades ago, layered structures have been a subject of intense research to develop new superconductors with desirable properties. These efforts have resulted in a number of layered superconductors with a variety of superconducting transition temperatures (T_c). Beyond oxides, the most popular materials have been either pnictides or chalcogenides with the examples ranging from the iron-based pnictides/chalcogenides to the Bi-based disulfides. During these years we have studied these emerging superconducting materials by spectroscopy and microscopy.

Among the chalcogenide superconductors, BiS_2-based systems possess a peculiar structural instability and their physical properties are highly susceptible to the external stimuli. Indeed, the instable BiS_2 square lattice is characterized by a coexistence of different low symmetry local structural configurations and hence is intrinsically disordered. Apart from superconductivity, BiS_2-based materials also manifest thermoelectric properties. We have studies the local structure as well the electronic structure of several BiS_2-based systems. Particularly interesting case was of $CeOBiS_2$, studied by scanning photoelectron microscopy (SPEM). The results revealed a direct evidence of electronic phase seperation [1]. Metallic phase was found embedded in the morphological defects and at the sample edges of the stoichiometric $CeOBiS_2$ (Fig. 1). While bulk of the sample is semiconducting, the embedded metallic phase is characterized by the usual electron pocket at X point, similar to the Fermi surface of doped BiS_2-based superconductors (Fig. 1). The embedded metallic phase in the homogeneous insulating texture seems the cause of the recently observed self-doped superconductivity in stoichiometric $CeOBiS_2$ as in granular superconductors. Incidentally, isostructural self-doped $EuFBiS_2$ was also found to show inhomogeneous electronic structure with a phase separation at mesoscale [2]. It was concluded that the local structure of BiS_2-layer plays important role in the electronic phase separation of these self-doped systems. X-ray absorption spectroscopy was combined with spectromicroscopy to explore electronic structure of another BiS_2 superconductor, a self-doped $Eu_3F_4Bi_2S_4$ [3]. A similar work, using a combined analysis of the two techniques, was also carried out to study evolution of Eu valence in $Eu_{0.5}La_{0.5}FBiS_{2-x}Se_x$ system [4].

BiS_2-based systems were also studied for their local structure using X-ray absorption spectroscopy [5]. In particular, the effect of isovalent substitution in $LaOBiS_{2-x}Se_x$ was studied by temperature dependent Bi L_3-edge EXAFS measurements. The results reveal that the BiS_2 sub-lattice is largely distorted in $LaOBiS_2$ (x=0.0), with two in-plane Bi-S1 distances separated by ~0.4 Å instead LaOBiSSe (x=1.0) shows much smaller

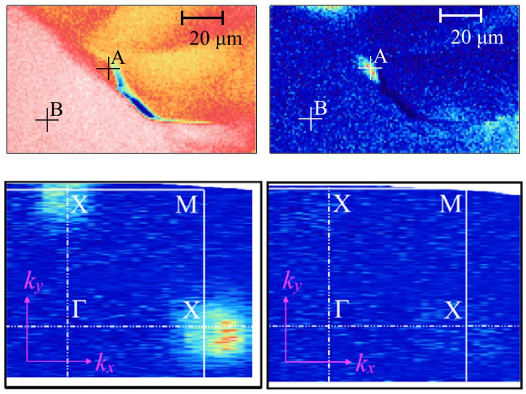

Figure 1: (Upper panels) High resolution (1×1 μm^2) SPEM images measured on $CeOBiS_2$ at 50 K using hν=27 eV. The SPEM images are produced by integrating photoemission intensity within energy interval of -3.5 eV $\leq E - E_F \leq 0.2$ eV (left) and -0.5 eV $\leq E - E_F \leq 0.2$ eV (right). (Lower panels) Fermi surfaces for metallic phase at A-point (left) and those for semiconducting phase at B-point (right), determined by space resolved ARPES measurements [1].

local disorder with two in-plane Bi-Se distances in the plane being separated by ~0.2 Å. Again, the local structure of $LaOBiS_{2-x}Se_x$ was concluded to be an important factor to describe differing electronic and thermal transport of the two compounds.

Another example of emerging superconductors is mechanically exfoliable layered van der Waals (vdW) Zintl phase $NaSn_2As_2$. We have studied the local structure of this system by EXAFS spectroscopy [6]. The anomalous behavior of the local structure suggests that the mechanical exfoliation in this system is likely to be temperature dependent. In addition, we have extensively studied the iron-based superconductors for their local structre and electronic properties.

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CM8. Spatial solitons, scale-free optics, and giant broadband optical refraction in disordered ferroelectric perovskites

Light propagating in disordered out-of-equilibrium materials leads to a great wealth of phenomena whose understanding is still in the making. This is especially true in transparent solid-solution ferroelectric perovskites that allow light to propagate even in proximity of the ferroelectric phase-transition. Here light-matter interaction is so enhanced that both linear and nonlinear waves manifest startling behavior of both a fundamental and applicative importance. Phenomena include spatial solitons, shock-waves, optical turbulence, and a regime called scale-free optics, where diffraction is not simply compensated by self-focusing, but is literally cancelled. In Fig. 1 we report the transition from a conventional spatial soliton propagation to a turbulent propagation with the first observation of replica-symmetry-breaking in wave propagation. The effect is caused by the emergence of strong index of refraction fluctuations associated to the metastable crystal polarization state at the Curie point and enhanced nonlinearity associated to photorefraction. The highly nonlinear light beam propagation

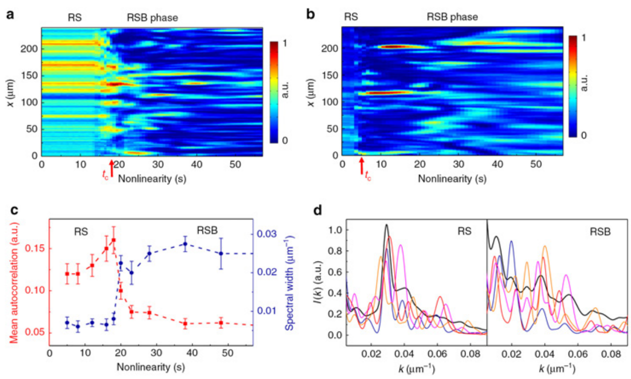

Figure 1: Observation of replica symmetry breaking in disordered nonlinear wave propagation. (a), (b) Intensity distribution for increasing values of beam intensity; (c) evidence of transition in statistics; (d) sample of shot-to-shot fluctuations in the spectrum. [1].

has allowed us to observe up to 3 Fermi-Pasta-Ulam recurrences associated to the formation of Akhmediev soliton breathers, as reported in Fig. 2.

Strong correlation also leads to striking linear propagation effects, principal among which is giant broadband refraction across the entire visible spectrum, reported in Fig. 3. This occurs as nanodisordered ferroelectrics are cooled below the Curie point. Periodic compositional disorder associated to bulk growth techniques leads to the formation of a stable 3D mosaic of ferroelectric domains. The result is a large coherent 3D periodic structure that resembles a crystal, but now with mesoscopic micrometer scales: a ferroelectric super-crystal. Giant refraction is characterized by propagation along the normal of the input facet irrespective of input launch angle, absence of diffraction, and absence of chormatic dispersion, this all in a material that has no resonances in the visible.

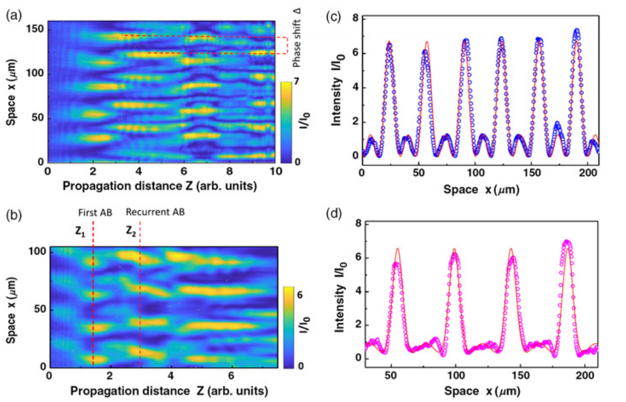

Figure 2: Observation of Fermi-Pasta-Ulam recurrence amd Akhmediev breathers in nonlinear optical beam propagation. (a), (b) intensity dynamics in two different launch conditions; (c), (d) breather soliton profiles [2].

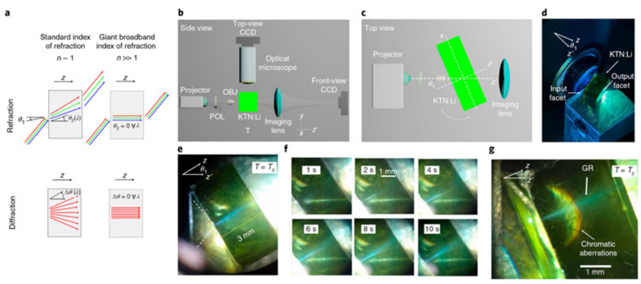

Figure 3: Giant refraction. (a) modified Snell law and diffraction, (b), (c) apparatus, (d)-(g) basic evidence [3].

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CM9. Infrared spectroscopy of two-dimensional electron systems

In the last years there has been an increasing effort aimed at extending infrared spectroscopy (IRS) to the nanometric domain. While lateral resolution has been pushed well below the diffraction limit, in the third dimension the low absorption (which decreases exponentially with the sample thickness) still prevents to study by conventional IRS two-dimensional electron systems like the 2DES which forms spontaneously at the $LaAlO_3/SrTiO_3$ (LAO/STO) interface [1], or the Topological Surface States (TSS) which form at the interface between a topological Insulator and a conventional insulator [2]. To solve this problem, we have applied to the above two systems the Berreman effect (BE), a powerful spectroscopic tool originally used to detect molecules adsorbed on solid surfaces. It is based on the strong enhancement that the in-plane (p) component of the radiation electric field undergoes when crossing the insulator-2DES interface at frequencies close to the zeros of the dielectric function $\epsilon_1(\omega)$. In our experiments, the BE is influenced by the interaction between the 2DES and the longitudinal phonons of the substrate (which provide the zeros in $\epsilon_1(\omega)$) and is detected in the reflectivity at grazing incidence by measuring the ellipsometric angle $\Psi(\omega) = \arctan(R_p/R_s)^{1/2}$. Here, R_p (R_s) is the reflectivity in p (s) polarization. After subtracting the $\Psi_0(\omega)$ of a system without the 2DES, one obtains the $\Delta\Psi(\omega) = \Psi(\omega) - \Psi_0(\omega)$ shown in Fig. 1 for the 2DES of LAO/STO [3]. By fitting the resonance to the Fresnel formulas for a multilayer, one finally obtains the 2DES parameters, like its thickness d (here 4 nm, smaller than the radiation wavelength by three orders of magnitude), the density of electrons n, and their mobility μ.

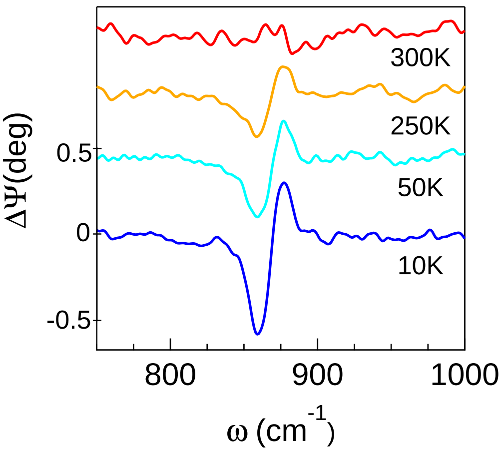

Figure 1: Berreman effect caused by the 2DES at the interface between a film of LAO and STO, as obtained by subtracting from $\Psi(\omega)$ that measured in a LAO/STO system where the 2DES was erased by ion etching.

A similar procedure was applied to the TSS at the interface between an ultrapure film of the topological insulator Bi_2Se_3, grown by molecular film epitaxy, and its sapphire substrate, which provided the longitudinal phonons required by the BE [4]. The BE resonance is shown in Fig. 2 in the proximity of two different phonons of sapphire (Al_2O_3). Suitable fits to data allowed us to determine for the first time the TSS thickness (as small as 0.6 nm) and, once again, n and μ, which turned out to be consistent with previous dc measurements.

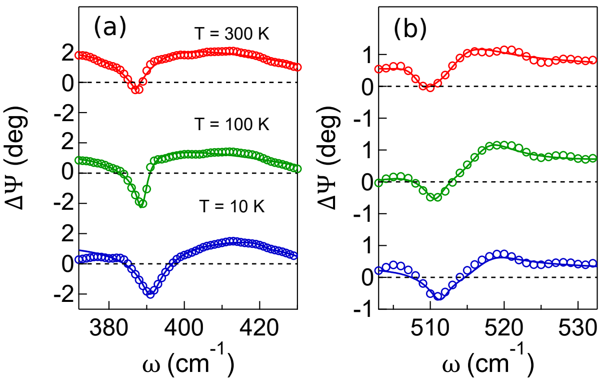

Figure 2: Berreman resonances at two phonon modes of sapphire, caused by the TSS at the interface between the topological insulator Bi_2Se_3 and its sapphire substrate, as obtained by subtracting from the $\Psi(\omega)$ of the whole system that measured on bare sapphire.

This research has been performed in collaboration with P. Roy and J.-B.Brubach of Synchrotron SOLEIL (France), A. Kalaboukhov of Chalmers University (Sweden), and the group of S. Oh of Rutgers University (USA).

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CM10. Spectroscopic investigation of two-dimensional layered materials under pressure.

Owing to the large interest devoted to graphene and graphene-like systems, different layered compounds have been extensively studied with different spectroscopic techniques. Among them, we focused on black phosphorus (BP) and transition metal dichalcogenides (TMDs), which have emerged as two-dimensional materials of particular interest for different opto-electronic applications. We have investigated the strong correlation between structural and electronic properties by analyzing the pressure induced effects.

BP is a high mobility layered semiconductor in which strong covalent bonding determines the structure of the single layers, hold together by weak van der Waals couplings. Recently, BP has attracted attention since its semiconducting gap can be tuned by varying the number of layers or by applying pressure. We studied the structural phase transitions induced by pressure in bulk samples by using both x-ray diffraction for pressures up to 12.2 GPa (performed at the Elettra synchrotron) and Raman spectroscopy up to 18.2 GPa. The obtained results allowed to establish the coexistence between different structural phases in a wide pressure range. An infrared study performed at the Elettra synchrotron allowed to identify the optical signatures of a pressure-induced topological Lifshitz transition around 1.5 GPa. At higher pressures, we observed the optical fingerprints of the two structural phase transitions occurring in the semimetal phase.

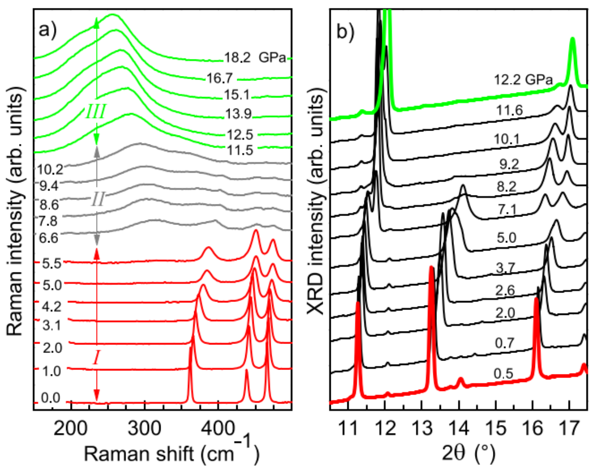

Figure 1: a) Pressure evolution of the BP Raman spectra, vertically shifted for clarity ; b) pressure evolution of the XRD patterns. For clarity, the patterns are vertically shifted and reported in reduced 2θ and intensity scales [1].

TMDs are layered materials with stoichiometry MX_2, where M is a transition metal atom and X is a chalcogen element. Each layer comprises a M plane sandwiched between two X planes (X = Te, Se, S). Their electronic structure, strongly dependent on the inter-layer interactions, can be tuned and studied by varying the number of layers or applying pressure. We focused on $MoTe_2$, of particular interest since its low band-gap energy allows optoelectronic devices in the near infrared range. With the aim of a complete spectroscopic as a function of pressure, we firstly performed Raman measurements at ambient condition on a single crystal. We provided a complete assignment of the observed first- and second-order Raman peaks, which is of basic importance for any further study of pressure induced effects. Recently, we studied the pressure dependence of the electronic properties of bulk $MoTe_2$ by performing transmission measurements in both the far- and near- infrared region up to $\sim$ 20 GPa at SOLEIL synchrotron. We thus obtained new information on the pressure dependence of the $MoTe_2$ metallization.

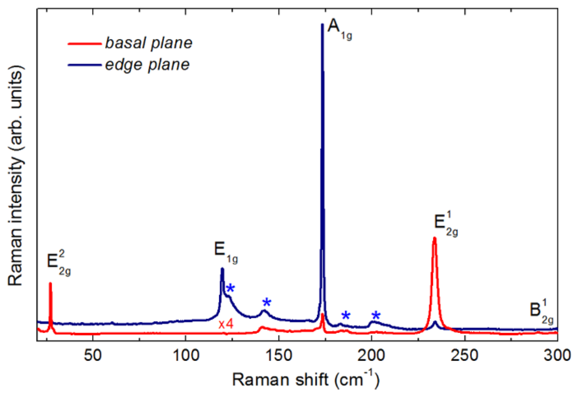

Figure 2: Raman spectra of $MoTe_2$ in two different configurations: *basal plane* and *edge plane*. Stars indicate the second-order Raman contributions [3].

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CM11. Physical systems with low-dimensionality studied with infrared spectroscopy: from quantum wells to surface polaritons in layered materials

The interaction of light with semiconductor heterostructures or van der Waals materials has particularly enabled the understanding of various fundamental phenomena and prompted research to further develop the optoelectronic systems that we rely on today. In the following we will present two different topics: (i) intersubband design and control in SiGe quantum wells (QW) for THz light emission and (ii) polariton excitations in layered two-dimensional (2D) van der Waals materials.

Silicon Germanium quantum wells for THz light emission

Wavefunction engineering in semiconductor heterostructures has led to the development of quantum electronic and photonic devices based on electron tunneling phenomena, such as quantum cascade lasers (QCL). Recently, n- type Ge/Si-Ge heterostructures have been identified as a promising material system to realize CMOS-compatible light emitters leveraging on intersubband (ISB) transitions in the THz range and operating at (or close to) room temperature. these materials would benefit of a (i) weaker electron-phonon interaction in nonpolar semiconductors leading to higher operating temperatures than III-V counterparts; and of (ii) the absence of a spectral range of forbidden propagation (Reststrahlen band), enabling larger emission bandwidth for THz QCLs. Strain-compensated heterostructures are grown within the H2020 FLASH FET-Open project and are studied by means of Infrared spectroscopy, both with laboratory-based sources and at Free Electron Laser facilities. We have studied up to now both the wavefunction tunneling in Asymmetric Coupled QW samples, providing reliable values for the estimation of conduction band offset and are now studying structures designed to yield THz photoluminescence upon optical pumping at higher photon energy. [1]

Polaritons in van der Waals 2D materials

Nanostructures made of layered van der Waals materials are able to sustain several different kinds of 2D collective electromagnetic excitations originating from charge density oscillations (polaritons) due to free-carriers, excitons or polar lattice phonons. Among them phonon - polaritons (PhPs) are attracting interest for applications involving electromagnetic energy transfer at the nanoscale as PhPs can exhibit longer propagation lengths and lower losses than their plasmon-polariton counterparts in conductors. We measured the polariton excitation spectra on hexagonal Boron Nitride (hBN) flakes as thin as 4 nm with the photo-thermal induced resonance technique. Standing wave modes of different circular symmetry appear at different frequencies within the upper

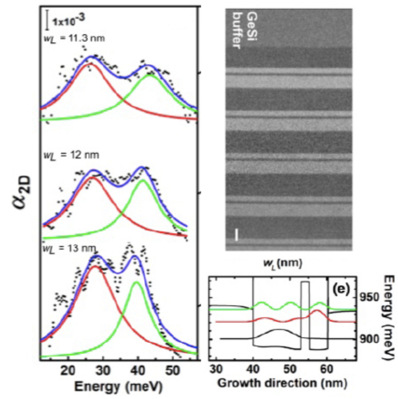

Figure 1: Intersubband absorption spectra of three different Asymmetric coupled QW with three different widths of the large well w_L; STEM image representative of QW structures. Scale bar is 10 nm.; Calculated squared wavefunctions

reststrahlen band of hBN (1370-1610 cm^{-1}), according to thickness and radius of the flakes. The effect of the gold substrate on the polariton dispersion requires further modeling, but a complete polariton screening by free electrons in the adjacent gold layer could be ruled out down to 4 nm thickness of the flakes. The symmetry of polariton standing waves is found to be extremely robust against geometrical imperfections.[2]

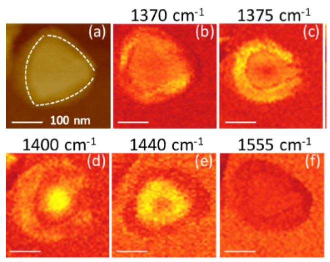

Figure 2: AFM topography and IR absorption maps of a 26 nm thick hBN flake.

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CM12. Graphene and carbon nano-structures

The honeycomb structure of C atoms in two-dimensional (2D) graphene (Gr) can assume different morphopogical configurations, from a quasi-ideal 2D sheet to 3D architectures. While preserving its 2D properties, it is possible to build-up compact structures, constituting a playground to study fundamental physical problems associated to many applications (energy storage, nanoelectronics...). Nano-porous Gr (NPG) is arranged into a 3D shape with a spongy and continuous structure, as shown in Fig. 1 (top).

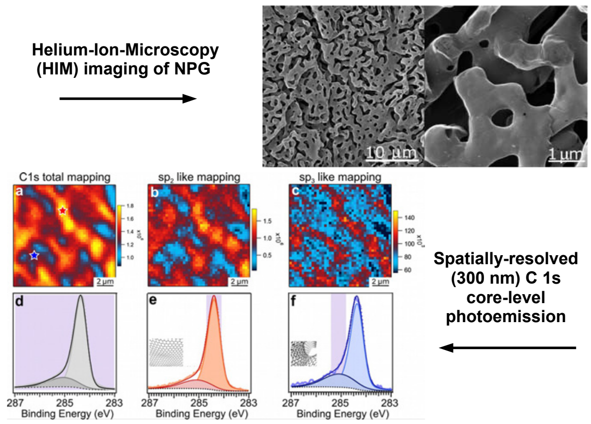

Figure 1: Nano-Porous Gr: Helium Ion Microscopy image (top); 300 nm-spatially resolved C 1s mapping, enlightening the sp^2 and sp^3-like components' spatial distribution (bottom) [1-2].

We recently determined how the chemical bonds of C atoms and the electronic states depend on the flatness, borders and edges of the nanostructures, by synchrotron-based spatially resolved core-level and valence band photoemission [1-2]. The spatially resolved (300 nm-scale) C 1s core level (Fig. 1, bottom) presents the major sp^2 component and an sp^3-like distorted bond, the latter related to the NPG borders and edges. The huge absorption density of porous Gr for alkali metals [3] opens new research paths towards advanced materials for energy storage applications.

Opening of an energy gap in the 2D Gr layer can be pursued through Gr functionalisation with different atomic species into the honeycomb network. In particular, we recently succeeded in achieving boron-carbon-nitride mono-layers using a single molecular precursor [4]. The mono-layers show highly B- and N-doped Gr, and highly C-doped hexagonal BN (Fig. 2).

Further activity is the estimation of anisotropic damage of highly-aligned Carbon Nano Tubes (CNT) by controlled ion-bombardment, through its photoemission and Raman spectral signals [5], as shown in Fig. 3. This is a preliminary step in view of their use as potential detectors in dark matter search [6].

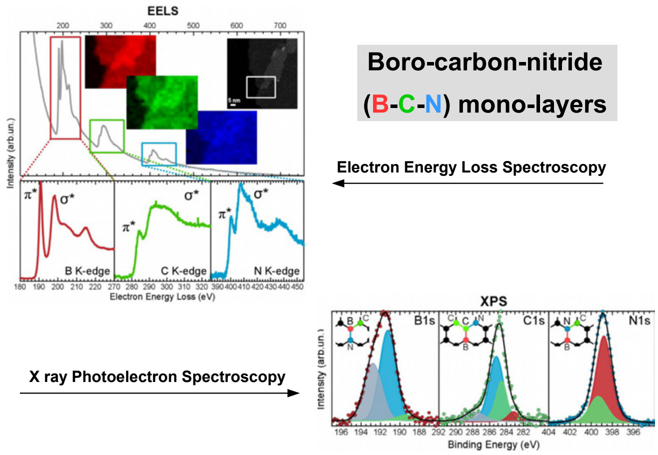

Figure 2: B-C-N mono-layer: electron energy loss spectroscopy data at the B, C and N K edges (top); X-ray photoemission from the B, C and N 1s core-levels (bottom) [4].

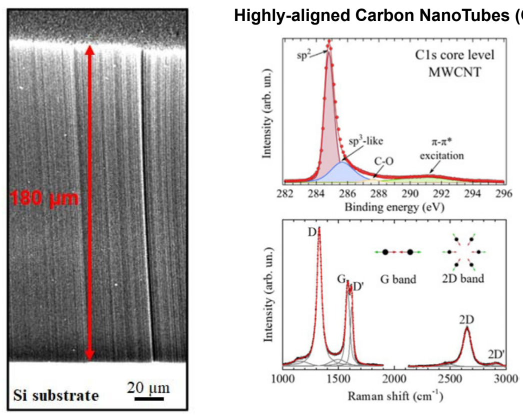

Figure 3: Scanning electron microscopy image of highly-aligned CNT (left); XPS C 1s core-level deconvolved in components (right-top); Raman spectrum (right-bottom) [5].

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CM13. Linear and Non-Linear Optical Properties of Quantum Materials

Although quantum effects can, in many cases, be approximated by a classical description at the macroscopic level, recently there has been growing interest in systems where quantum phenomena manifest over a wider range of temperature, energy and length scales. These systems are called Quantum Materials (QMs) and include High-Tc Superconductors, Graphene and other 2D systems, Topological Insulators, Weyl Semimetals, and Strongly Correlated Electronic Systems. QMs can be used in innovative applications ranging from photonics, fast electronics, and energy storaging. Among QMs, Graphene and Topological Insulators show a linearly dispersive electronic bands and host Dirac-like massless electrons. Weyl systems, instead, are characterized by emergent quasi-particles showing a finite chirality. These represent a condensed matter realization of Weyl fermions never observed in high-energy physics. At TERALAB (Frequency and Time Resolved optical Spectroscopy) we studied the equilibrium optical properties of Silicine, the silicon counterpart of graphene [1]. We have investigated the optical properties of Silicine epitaxially grown on Al_2O_3 substrate from a thickness of a few tens of nm down to the 2D limit. Here, a Dirac-like electrodynamics can be observed in the optical conductivity [1]. A second example of QMs investigation concerns the quantum Insulator-to-Metal Transition (Q-IMT) induced by a strong electric field in the terahertz (THz) range in the V_2O_3 system. In this system, which represents a text-book example of QMs, the application of a MV/cm femtosecond pulsed electric field forces a quantum tunneling between the insulating gap and transforms istantanously V_2O_3 in a metal [2]. A third example of QMs can be observed in 3D Nanoporous Graphene systems in which light is transduced in sound with a high-efficiency by a photo-acoustic quantum effect (see Fig.1) [3]. More specifically, we have demonstrated that a unique emitter based on 3D Nanoporous graphene, is able to product sound from the infrasound (10 Hz) to the ultrasound region (20 MHz) allowing tecnological several industrial applications [4].

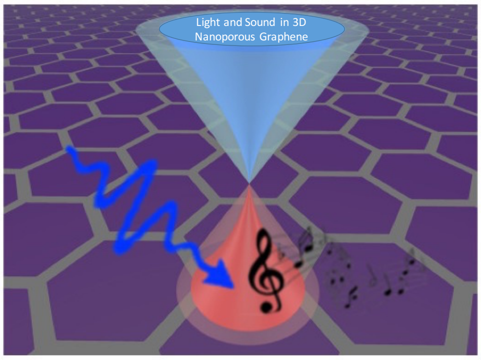

Figure 1: Sound emission through the photo-acoustic quantum effect in 3D nanoporous graphene.

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CM14. Magnetic nanostructures on surfaces

Low dimensional (1D and 2D) systems can present novel optical, magnetic and electronic properties with respect to their 3D bulk counterparts. Magnetic nanostructures can be made from materials that are non-magnetic in the bulk and the assembly of atomic building blocks with a tuning of size, geometry and composition, allows the engineering of nano-materials with applications in magnetic devices and spintronic. Magnetic nanostructures can be promising candidates for high-density magnetic storage, spintronic devices, and permanent magnets if their ground-state preserves the magnetic moment and enhances the uniaxial magnetic anisotropy energy (MAE). The MAE, the energy cost of switching the magnetization from the easy to the hard axis, is crucial for spintronics applications. Magnetic memory devices require that the magnetization can be pinned to a given direction in space, stable against thermal fluctuations at room temperature (RT). Dimension and symmetry reduction in magnetic structures can induce higher spin moments and larger magnetic anisotropy with respect the 3D specimens. We have obtained new (meta)stable magnetic states with a remarkable enhancement of spin and orbital moments and high MAE intercalating a single layer of 3d transition ferromagnetic metals under a graphene sheet. The homogeneous and smooth 3d metal layer, presents an out of plane easy magnetization axis, that switches by only increasing the number of layers of intercalated ferromagnetic alloy, with a strong ferromagnetic state (see Fig.1).

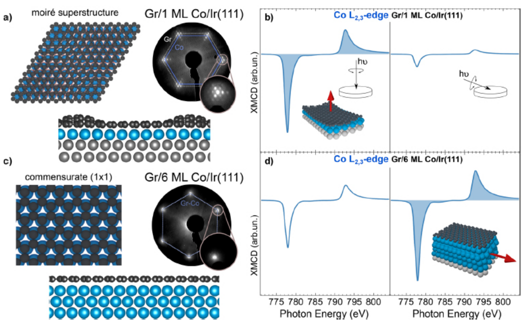

Figure 1: Moiré structure of (a) 1ML Co and (c) 6ML Co intercalated under Gr/Ir(111, confirmed by LEED patterns. (b) and (d): XMCD spectra of Co $L_{2,3}$ absorption edges, for (a) and (b). Magnetic anisotropy switches from perpendicular (1 ML Co, upper panel) to parallel (6 ML Co, lower panel) to the surface plane.

Single atoms on surfaces tend to aggregate on surfaces in clusters, do not form regular patterns and usually present a decreased magnetic response due to the interaction with the surface. A strategy is to assemble molecular networks on surfaces composed by molecules with central magnetic atoms embedded into an organic cage. Spin molecular interfaces of molecules adsorbed on metallic surfaces, exhibiting magnetic remanence at RT can open the route to engineer spin-polarized nanoscale current sources.

We have demonstrated that metal-phthalocyanine of Fe and Cu, can be ferromagnetic (FM) or antiferromagnetic (AFM) coupled (see Fig. 2) up to RT to a cobalt layer by interposing a graphene sheet. It is possible to tune the direction of the magnetic coupling to be either antiparallel or parallel, by choosing the symmetry of the spin-carrying orbital. The peculiar coupling mechanism is determined by the different super-exchange path involving Co, graphene and molecular orbitals. The graphene layer between the active magnetic cobalt layer and the metal-organic molecule protects the molecular orbitals symmetries.

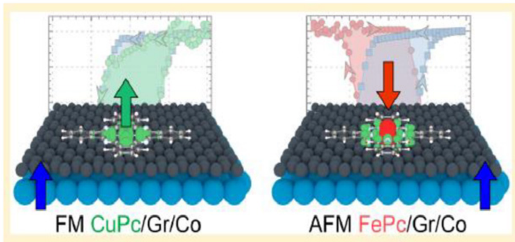

Figure 2: Hysteresis loops of magnetic molecules with a FM or AFM coupling with a Co layer. The magnetic coupling is tuned changing the central metal atom, Cu or Fe.

The choice of an effective super-exchange path can ensure the stability against thermal fluctuations, even at RT, and it can be further optimized with a fine control of the relative orientation of the easy magnetization axes at the spin interface. In perspective, the magnetic remanence at RT of these archetypal spin interfaces opens the possibility to produce future organic-based operational spintronic devices.

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CM15. Fabrication of site-controlled quantum dots by light- (and plasmon-)assisted hydrogen removal in Ga(AsN)

In the last decade, significant efforts have been aimed at the development of nanophotonic devices embedding all the elements required for the on-chip generation, manipulation, and detection of nonclassical light states. A very promising route towards the achievement of this goal is provided by spatially selective hydrogen irradiation of dilute-nitride semiconductors (*e.g.*, GaAsN). Indeed, the formation of stable N-H complexes in these materials fully neutralizes the effects of N on their structural and electronic properties, resulting, *e.g.*, in a large, fully tunable energy-gap redshift. This provides a simple route to the on-chip generation of single photons, via the fabrication of site-controlled GaAsN/GaAsN:H quantum dots (QDs) by H irradiation of lithographically prepatterned samples. These QDs emit single photons and can be easily integrated with nanophotonic devices, *e.g.*, PhC cavities [1].

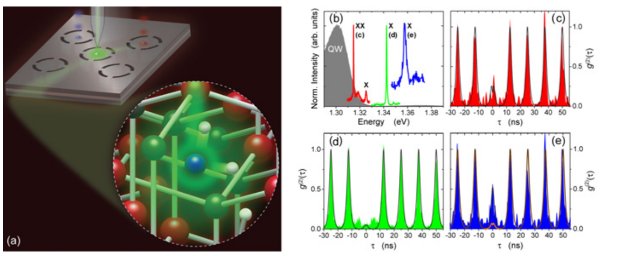

Figure 1: (a) Sketch of the process leading to the fabrication of site-controlled GaAsN/GaAsN:H QDs by spatially selective H removal [2]. (b) Photoluminescence (PL) spectra at 10 K of three QDs, superimposed to the spectrum of the untreated QW (gray area). The labels (c)-(e) indicate the panel wherein the corresponding second-order autocorrelation function, $g^{(2)}(\tau)$, is reported. The value of $g^{(2)}(0) < 0.5$ is a proof of the single-photon emitter nature of the QDs fabricated with this technique.

While the possibility to locally remove H by focusing a laser onto the sample surface has been known for many years, we recently demonstrated [2] the possibility to modulate the H concentration profile with a precision of a few nm using a scanning near-field optical microscope, SNOM (see Fig. 1). Starting from a fully hydrogenated GaAs/GaAsN:H/GaAs quantum well (QW), the N-H bonds located within the light spot generated by a SNOM microscope tip are dissociated, resulting in the formation of a site-controlled GaAsN/GaAsN:H QD. By adjusting the laser power density and exposure time, the optical properties of these dots can be finely controlled, tuning the quantum confinement energy over more than 100 meV while retaining the ability to emit single photons. This novel fabrication technique reaches a position accuracy <100 nm and can be easily applied to the realization of more complex nanostructures.

In addition, we are currently working at the fabrication of site-controlled GaAsN/GaAsN:H QDs by exploiting the inherent ability of plasmonic bowtie nanoapertures (NAs) to localize the electromagnetic field at a subwavelength scale (see Fig. 2) [3]. H removal through a bowtie NA —whose presence results in a ∼10-fold field enhancement at the depth of the GaAsN QW— turns out to be much more efficient (by nearly two orders of magnitude) than through the plain surface, thus indicating that bandgap engineering via plasmonic nanostructures could be optimized for the future efficient realization of site-controlled single-photon emitters.

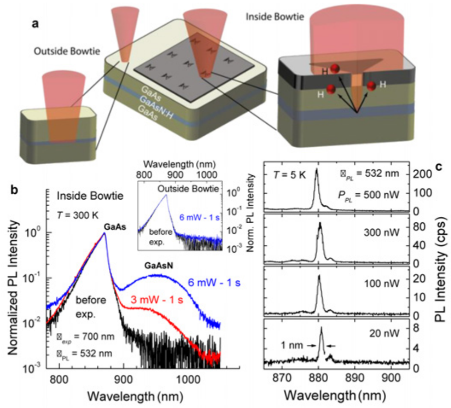

Figure 2: (a) Sketch of the plasmon-assisted H removal process [3]. An array of bowtie NAs is fabricated in an Al layer evaporated on top of a fully hydrogenated GaAs/GaAsN:H/GaAs QW. Laser treatments (with $\lambda_{\mathrm{exp}} =$ 700 nm, matching the resonant wavelength of the NA) are performed through single NAs, selectively removing H. (b) The H removal efficiency is tested by PL investigation of the NAs after the laser treatment exposures. The same treatments are performed also on unpatterned areas for comparison purposes (see inset). The removal of H through the NA is complete for a treatment at 6 mW for 1 s, which does not produce any sizable effect on the unpatterned region. (c) Excitation power dependence of the PL spectrum acquired on a NA after laser treatment at 2 mW for 3 s.

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CM16. Two-dimensional crystals and their strain engineering

The interest of fundamental and applied sciences for two-dimensional (2D) materials —such as graphene, hexagonal boron nitride and transition metal dichalcogenides (TMDs)— is grounded on the wealth of unusual and alluring electronic, optical, transport and magnetic properties these materials exhibit [1]. TMDs (specifically those with chemical formula MX_2, with M: W or Mo and X: S, Se or Te) have received significant attention because they are naturally abundant semiconductors with sizable band gaps that change from indirect to direct in the single X-M-X layer form.

Moreover, the all-surface nature of these 2D crystals makes them particularly sensitive to mechanical deformations, whose related strain fields turn out to be a precious tool to engineer the material's physical properties [2]. So far, most of the approaches to induce strain either require the use of external, bulky devices or rely on spontaneous, yet not controllable, mechanisms whereby curved membranes are formed.

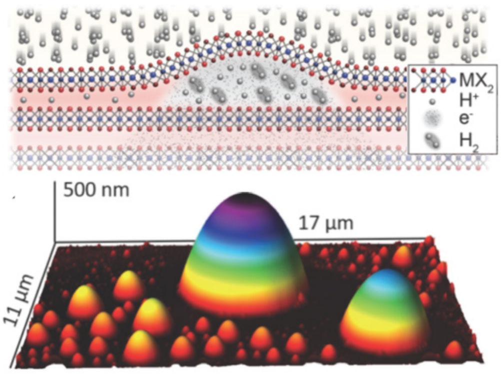

Figure 1: Top: Sketch of the process leading to the local blistering of atomically thin material membranes following proton irradiation and molecular hydrogen formation. Bottom: Atomic force microscope image of a series of WS_2 domes caging highly pressurized (∼10-100 atm) hydrogen.

In our group, we discovered a different, highly flexible method based on low-energy proton irradiation of multi-layered TMDs [3]. Protons (H^+) accelerated by a suitable source penetrate through the sample surface and H_2 forms according to the reaction $2H^+ + 2e^- \rightarrow H_2$ occurring beneath the sample's top surface. As a consequence of the balance between the gas expansion and the van der Waals forces holding the X-M-X planes together, the localized swelling of just one monolayer takes place, thus resulting in the formation of atomically-thin and spherically-shaped domes (see Fig. 1).

The domes feature particularly attractive and peculiar optical properties, caused by the strain fields acting on their surface. Indeed, very efficient light emission is observed (see Fig. 2) accompanied by interference effects (see inset in the same figure), which could be exploited for sensor applications.

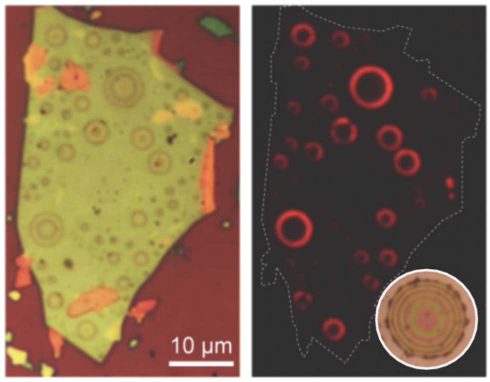

Figure 2: Left: Optical microscope image of a series of WS_2 domes. Right: Corresponding image of the light emitted by the same sample. The inset shows the interference pattern generated by a single dome with 15 μm footprint diameter.

The domes are very robust to aging (3 years), mechanical stress (full indentation has been achieved) and temperature (>200 °C). These structures can be produced in a scalable manner by lithography with size ranging from few tens of nm to few μm and with full spatial control (see Fig. 3).

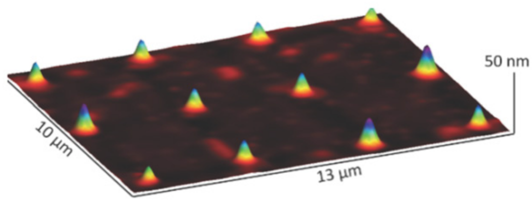

Figure 3: Atomic force microscope image of an ensemble of spatially ordered WS_2 domes.

These micro/nano-domes hold the potential for a wide range of applications ranging from mechanical actuators, to single-photon sources operating at room temperature, to nano-reactors for controlled gas release.

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CM17. Quantum Nanophotonics with Semiconductor Nanostructures

The prospect of using the quantum nature of light for quantum information science and technology keeps spurring the search and investigation of suitable sources of single and entangled photons. Among the others, those based on semiconductor nanostructures are arguably the most attractive, as they can generate photons on demand and are compatible with current photonic integration technologies. The activity of the Nanophotonics group at the Physics Department is focused on the study of the fundamental properties of solid-state-based quantum emitters (QEs), as well as on their exploitation in advanced quantum optics protocols. Two main platforms are currently being investigated: *(i)* Semiconductor quantum dots (QDs) which are regarded as one of the best sources of non-classical light available to date; *(ii)* Quantum emitters in 2-dimensional transition metal dichalcogenides novel sources of non-classical light whose fundamental properties are not yet fully understood.

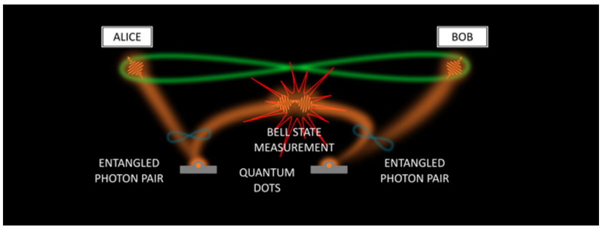

Figure 1: Sketch of the four-photon entanglement swapping protocol with quantum dots.

(i) Our group is well known for works on entangled photons from QDs [1] and, very recently, have used them to implement advanced quantum optics experiments. In a first work [2], we have used single and entangled photons generated on-demand by a single GaAs QD to teleport quantum bits encoded in the polarization state of single photons. The measured fidelities were clearly above the classical limit without the need of temporal and spectral post-selection techniques an important requirement for applications. Building up on this result, we demonstrated for the first time that it is possible to use QD photons for entanglement teleportation (or entanglement swapping) [4]. More specifically, we entangled two photons that never interacted before by interfering (via the so-called Bell State measurement) two photons from independent entangled-photon pair source, as schematically shown in Fig. 1.

(ii) Besides QDs, the Nanophotonics Group is also investigating the fundamental properties of localized excitons in 2-D materials. Several groups have demonstrated that these excitons can be used as single photon sources that can be fabricated with simple and cost-effective methods. However, the physical origin of these QEs is still under debate and it is extremely difficult to attain precise control over their emission properties. Our group has recently developed a novel semiconductor-piezoelectric device in which single layers of WSe2 are integrated onto piezoelectric actuators. We demonstrated that strain fields exerted by the actuator allow the energy of the single photons to be (reversibly) controlled in a spectral range as large as 10 meV and without affecting the single-photon purity [3]. Moreover, we achieved control over the position of 2D-QEs by mechanically transferring single layers of WSe2 onto ordered arrays of micro-pillars made of piezoelectric material (see Fig. 2). Eventually, we demonstrated for the first time that it is possible to use 2-D semiconductors for the fabrication of site-controlled single-photon sources with tuneable energy.

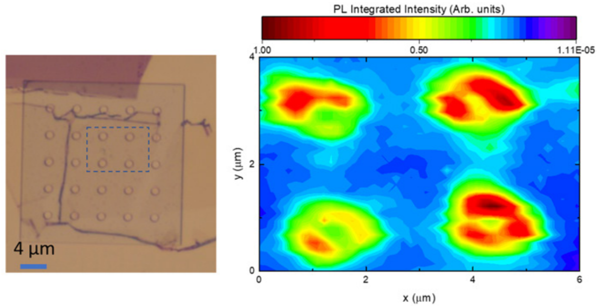

Figure 2: Optical image of an array of micro-pillars covered by a single layer of WSe_2 (left), and LT μ-PL mapping (right) of the area highlighted by the blue dashed square.

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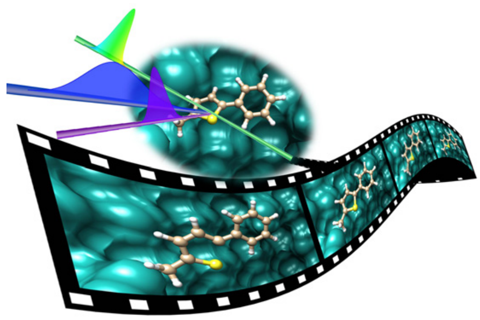
CM18. Ultrafast and ultraslow dynamics in biomolecules and condensed matter

In our group we develop novel experimental tools to study those processes which are too slow or too fast to be observed by the naked eye. To this purpose, we take advantage of complex sequences of sub-picosecond laser pulses to stimulate and subsequently probe molecular motion in condensed matter and biomolecules. The current line of research includes:

- **Molecular movies of photo-excited biological compounds.** Determining energy redistribution pathways within biomolecules and tracing the detailed nuclear motions underlying chemical reaction from reactant to photoproduct are ambitious challenges. In this respect, time-resolved spectroscopy represents a direct way to map how atoms are pushed into action by light absorption. Using ultrashort light pulses, we excite organic compounds in a highly localized manner, promoting the system to an excited out-of-equilibrium FranckCondon manifold. We subsequently observe concurring processes triggered by the photoexcitation, such as excited state dynamics, vibrational energy redistribution and conformational changes along reaction coordinates. This is a first step to establish a general method to animate such time-resolved snapshots making molecular movies, to observe atomic motion during those elemental events underlying physical, chemical and biological processes [1].
- **Ultrafast processes in strongly correlated systems.** A novel class of hybrid semiconducting materials, composed by an inorganic lattice and an organic matrix, has emerged as the prototypical candidates for the next-generation of photovoltaic devices, being able to combine the high efficiencies of silicon-based cells with the low processing costs and flexibility of organic semiconductors. The key property for their high energy conversion efficiency is represented by the long lifetime of the photocarriers, enabling long diffusion lengths. By using femtosecond pulses for injecting photo-carriers and monitoring the subsequent coherent lattice motions employing a time-delayed ultrashort probe pulse, we have unveiled the physical mechanism responsible for the high carriers mobility. Specifically, the generation of an out-of-equilibrium charge upon light absorption represents a peculiar excitation, called polaron, that can be represented as an electron surrounded by a cloud of phonons, and determines a rearrangement of the system to a new geometrical structure, which prevents the charges from relaxing, giving them a high mobility [2]. Besides mapping ultrafast phenomena, we exploit laser pulses also for manipulating and controlling the optical and the magnetic properties of matter. In this respect, a new field of research, named Femtomagnetism, has emerged, focusing on the study of the so called exchange interaction', which governs magnetisms on sub-picosecond time scales. We demonstrated how the exchange interaction can be manipulated using an ultrashort optical stimulus, by observing the subsequent dynamics of the two-magnon excitation in an antiferromagnetic perovskite by means of Femtosecond Stimulated Raman Scattering [3].
- **Ultraviscous flow in glass forming materials.** Amorphous materials, such as glasses and resins, are meta-stable out-of-equilibrium systems: being in an intermediate condition between liquid and solid states, they are subject to slow structural reorganizations, evolving towards more stable configurations over millions of years. By means of an ultrashort laser excitation we impulsively generate density fluctuations, which are interferometrically detected by a second, time delayed optical probe. This allows us accessing elastic properties such as sound velocity, attenuation and vibrational density of states [4]. Furthermore, by an ultrafast transient absorption setup we can access the structural rearrangements occurring over femtosecond timescales. This ultimately allows to connect -in a same material- ultraslow and ultrafast dynamics as function of the glass stability degree.



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CM19. Physics of Simple Molecular Systems under Extreme Conditions

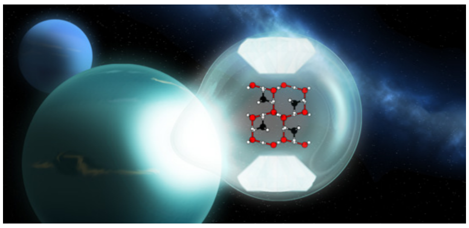

Figure 1: A new phase of methane hydrate has been recently discovered by Raman scattering experiments in diamond anvil cells up to 1.5 Mbar [4]. It is comprised of an ice Ih skeleton hosting in their channels oriented methane molecules, which prevents methane to react and form diamonds. It is believed to be one of the main constituent of giant icy planets such as Uranus and Neptune.

Simple molecular systems, like water, methane, hydrogen, carbon dioxide, and their mixtures are of paramount importance for many fields, ranging from condensed matter to environmental science, and planetary physics. These systems are widespread on Earth and in the extraterrestrial space -outer planets, moons, icy giant planets and comets (ice bodies)- and due to their relatively simple stoichiometry and electronic structure represent key systems for the understanding of more complex molecular systems. Recently a vast effort has been devoted by the community to determining the phase diagram and the exotic properties of these systems up to extreme p-T conditions. With these data, and with those obtained from various space missions, the community is trying to understand the interior of ice bodies, the conditions of temperature and pressure, their chemistry, and ultimately the possibility to host life.

At extreme pressures atoms and molecules are forced to interact in restricted volumes and thus new physics is observed and predicted: enhanced proton tunneling, hydrogen bond symmetrization, superionicity (a spectacular state of ice where oxygens form a cubic crystal while protons freely flow between them), plasticity (a weird cross between a solid and a liquid where molecules form a crystal but are free to rotate), high T superconduction, hydrogen metallization, molecular superdiffusion.

In our group we use neutron scattering techniques-which are particularly sensitive to hydrogenated and light materials- synchrotron radiation and light spectroscopies, coupled to ab-intio molecular dynamics simulations, to probe simple molecular systems - such as H_2, H_2O CH_4, NH_3 and their mixtures under pressures up to millions of atmospheres and hundreds K temperatures.

Unexpected new aspects have emerged from our structural studies on water dense phases: i) we have shown that high pressure ice can build homogeneously into its structure large amounts of host species, like ions, in salty-ice structures [1,2], or small gas molecules, in ice clathrates [3,4]; ii) we have observed that these filled ice structures can survive up to pressures of millions of atmospheres, typical of the interior of giant icy planets, and show conductivity properties far different from that of the pure species; iii) we have finally observed that the electric field generated by the ions included in the water lattice can hinder quantum effects and hydrogen bond symmetrisation in high pressure ice. These filled ice structures thus show radically different thermal and electrical conductivity properties with respect to pure ice, as well as an extremely high gas storage capability. This observation could change the description of planetary interiors, based essentially on the properties of pure ice or ices mixtures.

One of the focusses of our recent research has been the characterization of the the structural and transport properties of natural gas- ice clathrates, a class of non-stoichiometric crystalline systems constituted of large polyhedral cages of hydrogen bonded water molecules encapsulating gas molecules - mainly methane, hydrogen, ammonia, carbon dioxide- that are fascinating for their potential energy and environmental applications. Assessing the technological viability of such energy applications and implementing them require a full understanding of the non-equilibrium phenomena involving gas diffusion, gas-sequestration, and guest-induced formation kinetics. Transport properties of these systems under high pressure are also important in planetary science, as clathrate hydrate are believed to have been the dominant light-gas bearing phase in the nebula from which the outer planets and satellites have been formed.

With the recently patented HP-QENS (high pressure quasi elastic neutron scattering) technique we have observed new intriguing phenomena in these systems such as i) the unexpected hyper-diffusion of methane at the interface of the two main clathrate structures, sI and sII, which exist at the early stages of the methane clathrate formation or during the CO_2-CH_4 exchange process; ii) the existence of concerted tunneling of hydrogen molecules in the large cages of the hydrogen clathrate structure; iii) the locking in and orientation of methane molecules in the ice skeleton under high pressure.

At the core of our program, are fundamental aspects of the hydrogen bond and the quantum nature of the proton, through studies of ion and gas inclusion in ice in a broad range of thermodynamic conditions. These have relevant applications in planetary modeling, as well as energy and hydrogen storage.

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CM20. Tailoring the physical properties of ionic liquids

Ionic liquids (ILs) show many interesting properties, such us high ionic conductivity, low vapor pressure, thermal and electrochemical stability, good solvent capability, which make them extremely promising for many applications, widely ranging from electrochemistry to biomedicine. Indeed, the possibility of tailoring their performance according to the different applicative requirements, is based on a deep knowledge of their microscopic properties. In this framework, our research is strictly fundamental, oriented to the study of the microscopic configurations of the composing ions and their effects on the physical properties of the ILS, which is a key point for the comprehension of the connections between ions composition and macroscopic properties of ILs. These properties are the consequence of competitive microscopic interaction forces, the balance of which can generate an extremely rich scenario. The knowledge of these interactions is therefore fundamental.

In particular, we studied the two conformers of the bis(trifluoromethanesulfonyl)imide (TFSI) anion, the *cis-* and *trans-* conformer, focusing on the changes of the intramolecular structure induced by the phase transitions. The two conformers differ in energy by only 2.2 KJ/mol, so that in the liquid state they are both present. By means of spectroscopic techniques combined to abinitio or DFT calculations of the vibration frequencies, we showed that the relative concentration of the two conformers strictly depends on the chosen cation and on the length of its alkyl chain. Our results clearly show that cations with longer alkyl chains stabilize in the solid phase the less stable cis-conformer of TFSI, likely by means of different balance of forces between anions and cations.

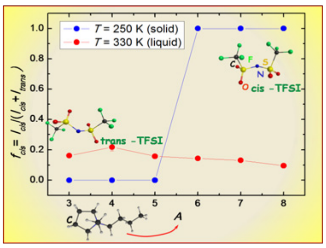

Figure 1: Dependance on the length o cation's alkyl chain of the concentration of *cis-* and *trans-* of the TFSI anion [1]

In a mixed systems, the competitive effect on the stability of the TFSI conformers induced by the presence of cations with different alkyl chains hinders the crystallization process [1]. As a consequence, the competition between the two TFSI conformers at low temperatures can be the origin of the lack of crystalline phases for intermediate concentrations and can be exploited as a valid tool to tailor the physical properties of the mixtures of ionic liquids [2]. The comparison of IR spectra obtained experimentally and computationally, have been also used to study the effect of ether-functionalisation on pure ILs and on mixtures with a suitable Li-salt, to analyze the effect of the Li salt on the polarity and the ion conformers [3].

The fascinating properties of tailoring the ILs properties by mixing with water has attracted a lot of interest in recent years. Indeed, a deep understanding of the interactions between ILs and water is strategic in view of numerous applications, ranging from extractive distillation to synthesis and solutions used in electrochemical devices like fuel cells. Moreover, the structural changes of water in a solution of ionic salts are also interesting from a fundamental point of view. In particular, the modifications experienced by water combined with different systems or confined in nanodomains provide new insight to master their properties.

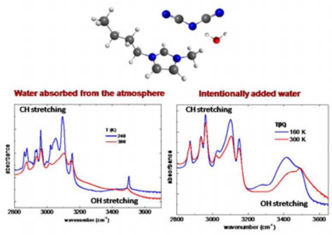

Figure 2: Effects of water on the IR spectra of 1-butyl-3-methylimidazolium dicyanamide [4]

In order to compare the effects of water, either intentionally added or due to absorption from the air, we measured the temperature dependence of the mid-infrared spectrum of an imidazolium based IL, both as synthesized and hydrated, providing evidence of the occurring of phase transitions and of the changes experienced by the microscopic interactions at such transitions [4].

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CM21. Self-assembly and aggregation in colloids for biotechnological and environmental applications

In the last few years our research focused on the characterization of the nanostructures resulting from the self-assembly of oppositely charged macromolecules (polyelectrolytes), or of polyelectrolytes and oppositely charged colloids. These systems not only show a complex and interesting phenomenology that, by the way, still lacks a sound theoretical description, but have a great potential for biomedical and environmental application. DNA (an anionic polyelectrolyte) complexes with different cationic macromolecules (chitosan, for example) are currently employed in some transfection protocol (the process by which a foreign DNA is introduced into a cell), liposomes (cell-membrane like vesicles) and liposomes aggregates are used as drug-vectors, that can target specific cells in an organism. But polyelectrolytes, favoring the aggregation of colloid particles and small charged molecules are also employed in the treatment of water and wastewater.

Self-assembly of finite size clusters in oppositely charged polyelectrolyte-colloid co-suspension. We have extensively investigated this process in different systems, showing that the observed phenomenology is largely independent of the chemical nature of the components depending mainly on their size- and charge-ratio. By tuning these parameters stable and controlled size/charge aggregates can be obtained. We are currently optimizing the process to obtain:

- thermoresponsive microgel clusters [1]
- gold nanoparticle clusters for plasmon-enhanced Raman spectroscopy [2]
- liposome clusters as multi-compartment vectors for the simultaneous delivery of different anti-tuberculous drugs

Using polyelectrolytes as coagulants for natural organic matter (NOM) removal during drinking water and wastewater treatment. NOM is found in all surface, ground and soil waters. The presence of NOM has negative effect on water quality by causing colour, taste and odor problems, results in increased sludge volumes and production of harmful disinfection by-products, promotes biological growth in distribution system. To remove NOM from drinking water the most economically feasible processes is coagulation followed by sedimentation/flotation and sand filtration. Organic polyelectrolytes can be in principle effectively used as coagulating agents and we are currently trying to optimize this process within a project funded by an important industrial player of the sector.

Physical characterization of natural nanoscopic lipid vesicles: the exosomes. Exosomes are extracellular vesicles first described as such 30 years ago and since implicated in cell-cell communication, in the transmission of disease states (possibly in cancer metastasization), in cell and bacteria differentiation, infectious response, etc., and also explored as a means of drug discovery. Exosomes are too small to be resolved by fluorescence microscopy. Exosome release occurring in cell cultures has been imaged by electron microscopic techniques but, more commonly, exosomes are pooled from cellular or bacteria supernatant or biological fluids. However even in this case due to their small size (30-100 nm) it is quite difficult to analyze the preparations in terms of size and composition which is the first important step for whatever further characterization. Currently we are developing an innovative Laser Transmission Spectroscopy (LTS) apparatus that allows to determine the size (and in principle the shape and the refractive index) distribution of the particles in a colloidal suspensions in terms of their absolute concentration. Actually, by measuring the transmittance through the suspension of a laser beam at many different wavelengths, the particles size distribution can be calculated through the Beer-Lambert law and the Mie scattering theory.

Main collaborations:
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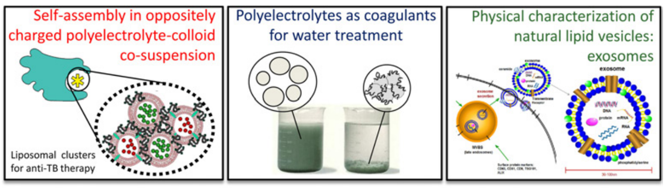

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CM22. Testing materials with electromagnetic probes

The interaction of electromagnetic fields with matter is one of the most powerful and widespread tool to investigate the properties of matter. Any material interacts in a specific way with electromagnetic fields, depending on its microscopic and mesoscopic structure. By testing the material with electromagnetic fields at different frequencies, it is possible to have informations over a very wide parameter set, such as dynamics characteristic times, charge densities, micro/mesoscopic structure and so on. The availability of electromagnetic signals ranging over a wide range of frequency (dielectric spectroscopy, DS) is a key feature when studying different kind of materials: as a rule of thumb, larger objects such as macromolecules or mesoscopic structures respond to relatively low frequency fields, while small molecules or single particles have much shorter relaxation times. The instruments available in my laboratory allow for measurements from the very low frequency tail of the electromagnetic spectrum (a few tens of Hertz) to high frequency microwaves (50 GHz). While single particles (ions, electrons) relaxation times are too short to be studied with this setup, larger structures ranging from macromolecules and colloids to water collective modes and magnetic flux lines in superconductors all fall within the available spectrum.

The main recent research activity is devoted to the study of complex liquids, that is liquids containing different kind of mesostructures (large polymer chains, colloids, vesicles...). For each of these structures, DS can be used to obtain specific informations: for polymers, it is possible to obtain informations on the ionization degree and on the dynamic regime (dilute vs. semi-dilute) as well as on the polymer-solvent interactions. For colloids and vesicles, one may obtain informations on the internal structure of the mesoscopic particles, marking the presence or not of a core-shell structure and giving informations on both of them, if present. In the last three years different liquids has been analyzed: self-aggregate vesicles (ref. 3), complex microgels (ref. 4) and DNA-carbon nanotubes complexes (ref. 6). Similar analysis has been performed also on chemical reagents used for water purification (within the CNR-ISC project "Polywater").

Although complex liquids are the systems that take most advantage from the experimental apparatus used, other systems can also be studied through the interaction of electromagnetic fields. By raising frequency, a progressively thinner layer of a solid sample interacts with the incident radiation (skin effect). This has been used to invent new strategies for the development of novel materials for accelerating devices: in these systems, very high electromagnetic fields are challenging, giving rise to damage of the walls of the accelerating cavities and producing unwanted charges by field induced electron emission. Indeed, at the operating frequency only a relatively thin layer of the cavity walls is exposed to the electromagnetic field, so that the realization of thin layers of appropriate materials can greatly reduce unwanted effects. At the same time, skin effect makes possible to to explore the behavior of the topmost layers of a given sample, if high enough frequencies are used. More, this can be done without the need of electrical contacts, that may damage the sample under study. I took part to the research activity performed in this field by INFN within the project DiElectric and METallic Radio frequency Accelerator (DEMETRA) (ref. 2 and 4). The research activity was also devoted to the realization of novel setups able to perform high precision measurements of the electrical properties of the coatings (ref. 1).

Besides these activity, other research lines are in preparation: in particular, preliminary measurements has been performed regarding the electroacoustic properties of graphene.

Projects financed in 2017-2019:
DiElectric and METallic Radiofrequency Accelerator (DEMETRA - INFN)

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CM23. Physics and engineering of active matter

Dense suspensions of swimming bacteria display striking motions that appear extremely vivid when compared to the thermal agitation of colloidal particles of comparable size. These suspensions belong to a broader class of non-equilibrium systems that are now collectively referred to as active matter [1]. Fundamental research in the physics of active matter investigates the basic principles governing non equilibrium phenomena such as self-propulsion, collective behaviour and rectification. From a more engineering point of view, however, active particles could potentially provide the active "atoms" of a new class of smart materials with unique response characteristics. Using advanced 3D optical imaging, micromanipulation and microfabrication tools, we study complex phenomena in active matter using direct and quantitative methods. Motile cells often explore natural environments characterized by a high degree of structural complexity. Moreover cell motility is intrinsically noisy due to spontaneous random reorientations and speed fluctuations. This interplay of internal and external noise gives rise to a complex dynamical behavior that can be strongly sensitive to details and hard to model quantitatively. In striking contrast to this general picture we showed that the mean residence time of swimming bacteria inside artificial complex microstructures is quantitatively predicted by a generic invariance property of random walks. We tracked bacteria as they moved through microchambers containing randomly distributed pillars (Fig. 1a). We found that, while external shape and internal disorder have dramatic effects on the distributions of path lengths, mean values are constrained by the sole free surface to perimeter ratio [2]. As a counterintuitive consequence, introducing more obstacles doesnt actually increase the average residence time. Instead, it shortens it by decreasing the volume in which the bacteria can swim. Self-propelled bacteria can be integrated into synthetic micromachines and act as biological propellers. We demonstrated that fast, reliable and tunable bio-hybrid micromotors can be obtained by the self-assembly of synthetic structures with genetically engineered biological propellers [3]. The synthetic components consist of 3D interconnected structures having a rotating unit that can capture individual bacteria into an array of microchambers so that cells contribute maximally to the applied torque (Fig.1 c). Bacterial cells are smooth swimmers expressing a light-driven proton pump that allows to optically control their swimming speed. Using a spatial light modulator, we can address individual motors with tunable light intensities allowing the dynamic control of their rotational speeds. Until recently, researchers in active matter have mainly focused on investigating and controlling off-equilibrium phenomena, like collective dynamics and rectification, by shaping the physical world outside active particles, through applied force fields and confinement. We are moving instead into a completely different direction where control on collective shape, structure and dynamics can be obtained by manipulating the biological degrees of freedom inside each cell. By expressing a light-driven proton pump in swimming bacteria, we can use light as a controllable and spatially distributed power source. Self-propelled particles, moving with a speed that is non homogeneous in space, will eventually distribute with a stationary density that is inversely proportional to the local speed value. Using a light projector to display millimetric images on a dense suspension of genetically engineered bacteria, we were able to instruct millions of cells to move in space and produce an accurate miniature replica of Leonardo's Mona Lisa (Fig.1 b) [4].

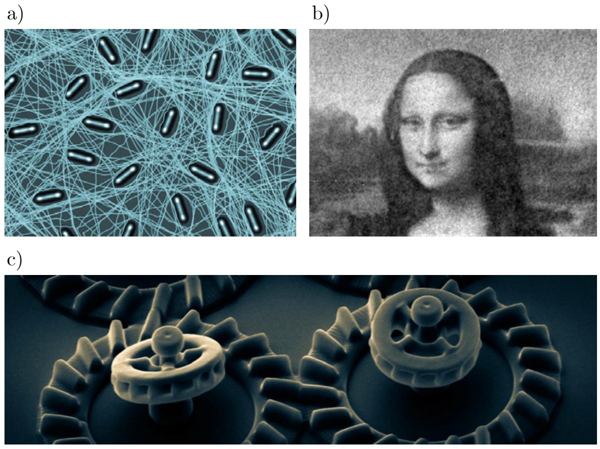

Figure 1: a) Bacteria swimming inside a microstructure containing random obstacles [2]. b) Genetically modified bacteria can be used as a "living" paint controlled by light. [4]. c) 3D printed micromachines that can use swimming bacteria as self assembling propelling units [3].

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CM24. Terahertz spectroscopy in ancient paper sheets and meta-materials

The scientific activity was carried out in collaboration with the Laboratorio di Spettroscopia Applicata ai Beni Culturali (CNR-ISC) and was addressed to the investigation of physical properties of ancient paper sheets and of metamaterials in the THz wavelength ranges.

THz photons are particularly suitable to probe the H-bond that is the main responsible for cellulose supramolecular arrangements. Ancient artifacts made of cellulose pose a significant experimental challenge in the THz transmission spectra interpretation due to their small optical thickness. To this aim, we have developed a method to obtaining a precise determination of the cellulose spectroscopic features using THz-TDS technique eliminating the Fabry-Perot effects arising from multiple reflections inside the sample [1]. Using this method we were able to successfully recover the complex refractive index of cellulose fibers from the THz transmission data obtained on paper sheets (Fig. 1).

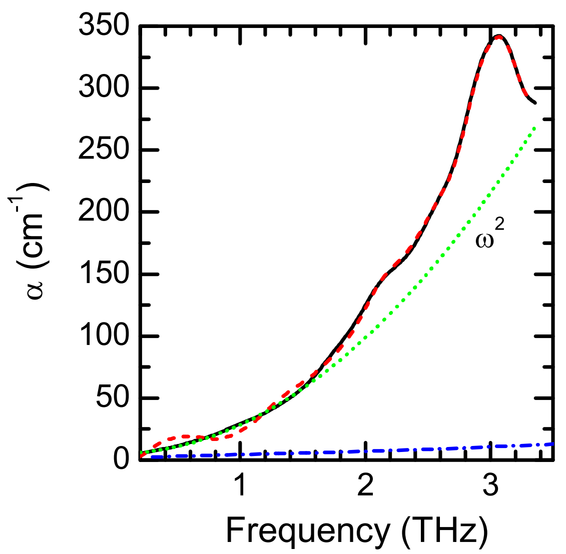

Figure 1: Typical absorption coefficient curves of a paper sample without (dashed red) and with (black) removal of the FP oscillations. A ω^2 fit of the initial curve (green dot line) and an estimation of the bound water contribution (blue dashed line) are also shown.

This allowed us to explain THz absorption spectra in terms of absorption peaks of the cellulose crystalline phase superimposed to a background contribution due to a disordered H-bond network. The comparison between the experimental spectra with THz vibrational properties simulated by DFT calculations have confirmed this interpretation. In this way we demonstrate that evident changes in the THz spectra are produced by the aging of paper, whose final stage is characterized by a spectral profile with only two peaks at about 2.1 and 3.1 THz. The importance of this results lies in the possibility to provide a quantitative assessment of the state of preservation of cellulose artifacts [2].

The THz regime represents a fertile area for the development of metamaterial absorbers (MMAs), which are manmade devices designed to absorb specific bands of the incident electromagnetic radiation constituted of periodic structures with sub-wavelength unit cells. This resonant spectral feature is of particular interest at THz frequencies, where it is difficult to find natural materials with both narrow absorption bands and high absorption coefficients.

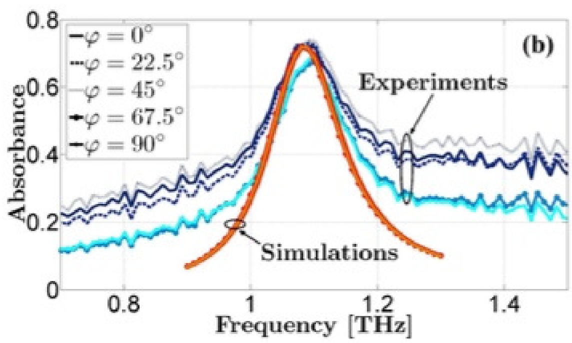

Figure 2: Simulated and experimental absorbance spectra as a function of the azimuthal angle φ.

The presence of a lower metallic ground plate in the sample forces the measurements to be conducted in reflection mode. The quality of the results in this configuration critically depends on alignment of THz optical components, which might result in differences in THz pulses path length and phase errors, altering the measured signals and making difficult the comparison with the theoretical predictions. To overcome al these problems we realize a polarization-maintaining reflection-mode THz-TDS set-up with innovative features that allow us to characterize an ultra-thin MMA device with an extremely selective absorbance spectrum (Fig.2) [3].

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Author

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CM25. Infrared spectroscopy of biomolecules: fibril assembly and protein-membrane interaction

Study on Cytochrome C fibril assembly

Amyloidogenic proteins have the capability to self-assembly into β-sheet organized aggregates (fibrils). First associated to a wide range of degenerative diseases, amyloid fibrils were then recognized to have functional roles in bacterial coatings, branching hyphae in fungi, insect egg envelop protection, catalytic scaffolds and epigenetic transformations [1]. Recently, the study of Cytochrome c aggregation, an evolutionarily conserved heme protein involved in many cellular processes, attracted attention within the scientific community: indeed, the aggregation and fibrillation dynamics of this protein, as well as the mechanisms leading to organized β-rich conformations, are partially known. We performed experimental studies on Cytochrome c aggregates by Scanning Electron Microscopy, fluorescence microscopy, micro-Raman and infrared spectroscopy, aimed at elucidating the morphology, the kinetic of formation and the secondary structure of the aggregates. We found that β-rich aggregates with different morphologies (mature fibrils, spherules and platelets) are built up, after destabilization of the protein from the native fold, through continuous provision of oligomers and/or amino-acids, over timescales varying from tenths to hundreds of minutes [2].

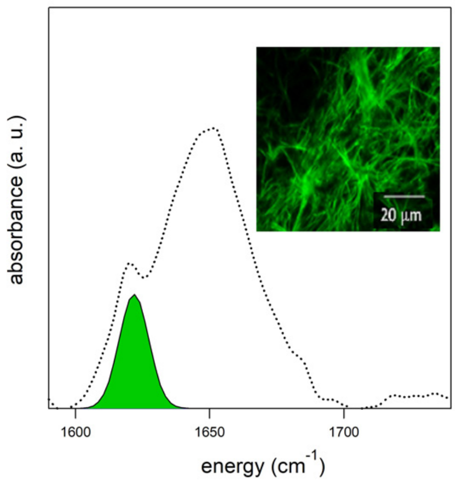

Figure 1: The infrared absorption spectrum of Cytochrome c at pH 9 after thermal incubation at 70° C . The green filled Gaussian at 1617 cm^{-1} is the amyloid fibrils contribution. In the inset, a fluorescence image of fibrils in the same sample is shown.

Study on Cardiolipin-Cytochrome c interaction as a model for mitochondrial membrane functioning

The interaction lipid membrane−protein is an intermediate but crucial step towards the understanding of a class of degenerative diseases. Indeed, at the level of cell cytoplasm, nanofibrils and protein aggregates might be signature of organelles misfunctioning and could themselves induce cytotoxicity [3]. The adhesion of native or mutated proteins to lipidic multilayers provides disordered segments of the CH_2 groups with formation of complexes that remarkably affect the number and the intensities of the infrared vibrational modes of the membrane. Large Unilamellar Vesicles (LUV) of cardiolipin, mimic of the mitochondrial membrane, and Cytochrome c in native and mutated forms, both highly interactive with the lipidic membranes, were used as models. The infrared absorption spectra revealed local distorsions or breakage of the lipid framework and provided insight on the protein-membrane binding mechanism, on the membrane stiffness and on the polarity of the environment as well.

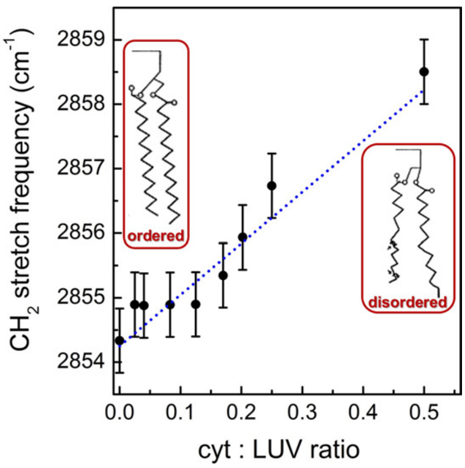

Figure 2: CH_2 symmetric stretching energy in LUV-Cytochrome c solutions as a function of the protein concentration. Dashed line is a guide to the eyes. ATR spectra were acquired at the infrared facility SINBAD of LNF.

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CM26. Infrared Nanospectroscopy of Transmembrane Proteins in Cell Membrane Monolayers with Plasmonic Field Enhancement Techniques

Photosensitive proteins embedded in the cell membrane (about 5 nm thickness) act as photoactivated proton pumps, ion gates, enzymes or, more generally, as initiators of stimuli for the cell activity. They are constituted of a protein backbone and a covalently bound cofactor, e.g. the retinal chromophore in bacteriorhodopsin (BR), channelrhodopsin and other opsins. The light-induced conformational changes of both the cofactor and the protein are at the basis of the physiological functions of photosensitive proteins. Despite the dramatic development of microscopy techniques, investigating conformational changes of proteins at the membrane monolayer level is still a big challenge. Techniques based on atomic force microscopy (AFM) can detect electric currents through protein monolayers and even molecular binding forces in single protein molecules, but not the conformational changes. For the latter, Fourier-transform infrared spectroscopy (FTIR) using difference-spectroscopy mode is typically employed, but on macroscopic liquid suspensions or thick films containing large amounts of purified photosensitive proteins.

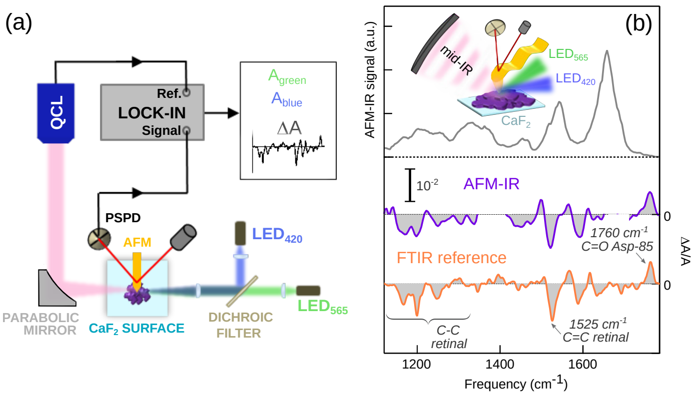

Figure 1: (a) Schematic of the differential IR nanospectroscopy experiment. QCL: quantum cascade laser, AFM: gold-coated atomic force microscope probe producing plasmonic field-enhancement. (b) Top panel: AFM-IR photoexpansion spectrum of a purple-membrane stack of thickness $d = 1$ μm. Bottom panel: AFM-IR difference-spectrum directly measured on a nanoscale sample (violet) and the same quantity indirectly obtained from oblique-incidence FTIR data taken on millimeter-scale samples (orange).

In this work [1] we develop AFM-assisted, tip-enhanced infrared difference-nanospectroscopy to investigate light-induced conformational changes of the bacteriorhodopsin mutant D96N in single sub-micrometric native purple membrane patches. We obtain a significant improvement compared to the signal-to-noise ratio of standard IR nanospectroscopy techniques by exploiting the field enhancement in the plasmonic nanogap that forms between a gold-coated AFM probe tip and an ultraflat gold surface, as further supported by electromagnetic and thermal simulations. IR difference-spectra in the 1450-1800 cm^{-1} range are recorded from individual patches as thin as 10 nm, with diameter of less than 500 nm, well beyond the diffraction limit for FTIR microspectroscopy. We find clear spectroscopic evidence of a branching of the photocycle for BR molecules in direct contact with the gold surfaces, with equal amounts of proteins either following the standard proton-pump photocycle or being trapped in an intermediate state not directly contributing to light-induced proton transport. Our results are particularly relevant for BR-based optoelectronic and energy-harvesting devices, where BR molecular monolayers are put in contact with metal surfaces, and, more generally, for AFM-based IR spectroscopy studies of conformational changes of proteins embedded in intrinsically heterogeneous native cell membranes.

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CM27. Advanced photonic imaging of 2D-materials and biosystems

Over the last decades, photonic imaging and its various applications have undergone major developments that make them essential tools for characterize low-dimensional materials and biomedical research at the microscopic level. In our labs, exploiting coherent Raman spectroscopy, we develop novel approaches tailored for both material science and bio-photonics. The current line of research includes:

- **Coherent Raman Imaging of cells and tissue models.** Performing Raman spectroscopy through a confocal microscope is a powerful method to spatially resolve cells, tissues and two dimensional materials. Chemical specificity, however, comes at the expenses of long acquisition times, due to the inherently small cross section of the spontaneous Raman effect. Such limitation can be circumvented by Coherent Raman spectroscopy: the simultaneous excitation of the sample by two picosecond beams at frequencies ω_P and ω_S, whose difference matches the frequency of a particular molecular vibration, results in the coherent stimulation of the system vibrations, greatly enhancing the detected Raman signal. Coherent Raman effects can be realized to dramatically reduce pixel dwell times down to video rate imaging [1]. On a same setup we are able to collect real-time imaging and single point spectral information to obtain a complete vibrational characterization. Collecting the Coherent Raman signal from lipid droplets in the C-H region $\omega_P - \omega_S \sim 2900$ cm^{-1} can be exploited to follow diverse diseases evolution. Examples include scrutinizing the effect of novel drugs for hepatocarcinoma and monitoring Alzheimers diseased nervous tissues. In the first case we perform a real-time study of the dimension and number of lipid droplets in diseased hepatocytes, in order to extract direct information about lipid metabolism and its alteration under drug administration. In the latter case, we study the lipid concentration in plaques generated by the degeneration of Alzheimers diseased brain and retina tissues.

- **Picosecond Vibrational microspectroscopy of graphene and its heterostructures with transition metal dichalcogenides.** The rise of graphene, followed by the more recent (re)discovery of the vast family of transition-metal dichalcogenides (TMDCs), has fuelled an unprecedented cross-disciplinary research effort. In particular, graphene strongly interacts with visible light being at the same time quasi-transparent due to its monoatomic thickness. This peculiar property, combined with its high electron mobility qualifies graphene as an excellent semimetallic 2D electrode for photovoltaic devices. In our laboratory we perform graphene imaging with vibrational sensitivity, using Spontaneous Raman with pused laser excitation [2] and Coherent Antistokes Raman scattering[3]. This enables real-time methods for the characterization of graphene under out of equilibrium conditions. In particular, CARS can be used for vibrational imaging with contrast equivalent to spontaneous Raman microscopy and signal levels as large as those of the third-order nonlinear response.
Recent demonstrations of hybrid photodetectors, based on gaphene-TMDC van der Waals heterostructures (vdWH), is boosting a rapid progress of this field towards optoelectronic applications. The operation and intrinsic performance of these vdWH-based devices are governed by band alignment, interactions with the underlying substrate, and near-field quantum phenomena, such as photoinduced-interlayer charge transfer (ICT) and energy transfer (IET). To discriminate between ICT and IET effects, we perform pump-probe imaging with two pulses. The first photoexcites (pump) the vdW heterostructures above TMDC (donor) energy gap and the second probes at different time delays upon photoexcitation the response on graphene, which represents the acceptor component in the ICT and IET process. Further, the electronic and vibrational response of graphene is detected as function of pump photon flux and pump photon energy, tuned below and above the MX2 energy gap, as control knobs to facilitate or suppress the transfer process.

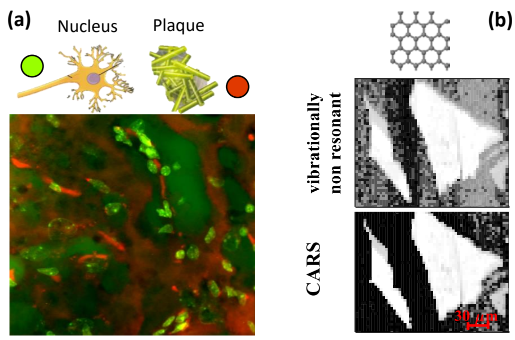

Figure 1: a) Alzheimers diseased brain tissues, observed by two photon fluorescence and Coherent Raman microscopy. (b) non-vibrationally resonant vs CARS signals of graphene.

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http://femtoscopy.phys.uniroma1.it/scopigno/

CM28. Nanosensors for biosensing and biomedical applications by Surface Enhanced Raman Scattering (SERS)

The merging of the molecular specificity of Raman spectroscopy with the extraordinary optical properties of metallic nanoarchitectures is at the heart of SERS spectroscopy, which in the last few decades proved its worth as powerful analytical tool with detection limits pushed to the single molecule level. SERS effect consists of the amplification by many orders of magnitude of the Raman signal of small molecules in proximity of plasmonic nanostructures, owing to their surface plasmon resonance making them effective electromagnetic antennas with nanoscale resolution. SERS-based nanosensors for selective interaction with biological systems, as single cells, and their local spectroscopic probing have been developed and employed for a wide range of applications.

DNA-based nanoarchitectures The programmable assembly of DNA strands is a promising tool for building tailored bottom-up nanostructures. We have proposed a plasmonic nanosystem obtained by the base-pairing mediated aggregation of gold nanoparticles (NPs) which are separately functionalized with two different single-stranded DNA chains. The controlled aggregation of the DNA-NPs has been obtained in solution by a complementary DNA "bridge" sequence. The SERS signature of these systems demonstrates that the action of the DNA bridge molecule yields regular NP aggregates with controlled interparticle distance and reproducible SERS response, with a strong potential for biosensing. Further, SERS can be exploited for directly monitoring the DNA melting process, with a very high sensitivity and an unprecedented spatial resolution [1].

Single cell pH sensing We have reported on the detailed characterization of a SERS-active pH nanosensor, based on the conjugation of Au NPs with the pH-sensitive molecular probe 4-mercaptobenzoic acid (4MBA). The nanosensor pH calibration curve has been derived exploiting the dependence of the SERS spectrum on the protonation degree of the carboxylic group at the edge of the 4MBA molecules. The nanosensor was successfully employed to locally measure the extracellular pH of normal and cancer cells, demonstrating the capability to discriminate between them [2].

Theranostics at single cell level Theranostic SERS nanosensors are nanosized materials capable of tracking cancer cells in complex environments (diagnostics) and of selectively acting against them (therapy). We have reported on antifolate plasmonic nanovectors, made of functionalized Au NPs conjugated with the folic acid competitors aminopterin and methotrexate. Due to the overexpression of folate binding proteins on many types of cancer cells, these nanosystems can be exploited for selective cancer cell targeting. Their strong SERS signature acts as a diagnostic tool, for tracing their presence in biological samples and, through a careful spectral analysis, for quantifying the drug loaded on a single NP and delivered to the cells. The therapeutic action is granted by the strong toxicity of antifolate drugs [3].

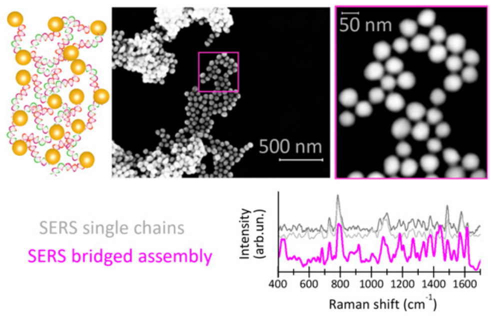

Figure 1: DNA mediated assembly of Au NPs (sketch and SEM images) and their SERS signatures [1].

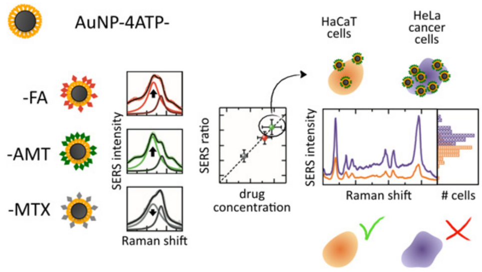

Figure 2: Mechanism of action of folate/antifolate nanovectors, where SERS allows quantifying both the drug concentration on the NPs and the cell targeting efficiency [3].

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CM29. Transverse light confinement in disordered media

The concept of localization was introduced by Anderson starting from the properties of a wave moving in a random potential. The key issue is that disorder can be so strong that the mean free path becomes of the order of the wavelength, yielding to a drastic decrease of the diffusion constant. De Raedt and coworkers [Hans De Raedt *et al.*, Phys. Rev. Lett. **62**, 47 (1989)] introduced a new form of localization of light in which the wave is propagating in one direction but confined in the other two. This “transverse localization” takes place in systems in which the index of refraction is a random function of (x,y) but is constant in the propagation direction z. The lateral diffusion of a wave propagating in such a “random fiber” is negligible.

Localized states play a crucial role in Anderson localization. Some localized states are barely coupled with their neighbours due to differences in wavelength or small spatial overlap, thus preventing energy leakage to the surroundings. This is the same degree of isolation found in the homogeneous core of a single-mode optical fibre. It is possible to obtain a single mode confinement with disorder exploiting a peculiar form of disorder-based confinement: the transverse localization of light. In our experiments we show that localized states of a disordered optical fibre supporting transverse localization are single mode: the transmission channels possess a high degree of resilience to perturbation and invariance with respect to the launch conditions. Our experimental approach allows identification and characterization of the single mode transmission channels in a disordered matrix. These disordered and wavelength-sensitive channels may be exploited to de-multiplex different colors at different locations.

To identify single modes we characterized the modes dwelling areas: the areas where the mode’s intensity pattern is invariant with respect to modification of the launch condition of the fibers. The dwelling areas for two different modes are reported as white spots in Fig. 1 a) and b). In practice by moving the launch beam inside the white areas the output shape is unaffected. In Fig 1 c) we report a the measurement of the dwelling area for a location in which single modes are absent so that the white spot is very small:the output pattern strongly affected by the launch condition as typical for multi mode propagation. Our analysis confirms that these modes, which are resilient to fiber bending and immune to changes of launch conditions, are effectively single modes similar to the ones found in the standard single mode fibers but obtained exploiting disorder.

Another possible origin of light localization in presence of strong scattering is the shaping of the incident wavefront. To this aim we studied light propagation through turbid media by exploiting adaptive optics. We demonstrated diffraction-free self-healing three-dimensional monochromatic light spots able to penetrate

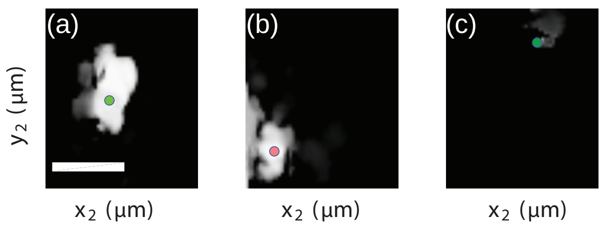

Figure 1: Dwelling areas of the modes located at the azure (a) an pink (b) spots. In c) dwelling area of a location in which a single mode is absent.

deep into the volume of a sample, resist against deflection in turbid environments, and offer axial resolution comparable to that of Gaussian beams. The fields, formed from coherent mixtures of Bessel beams, manifested a more than ten-fold increase in their undistorted penetration, even in turbid milk solutions, compared to diffraction-limited beams. In a fluorescence imaging scheme, we found a ten-fold increase in image contrast compared to diffraction-limited illuminations, and a constant axial resolution even after four Rayleigh lengths. Our results are at the basis of newly conceived three-dimensional microscopy.

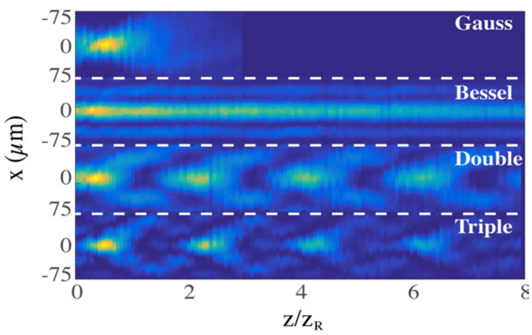

Figure 2: Gauss (a), Bessel (b) and light droplets (c-d) beams.

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CM30. Theoretical Modeling of Self-Assembly in Colloids and Macromolecules: a Coarse-Grained Approach

In several fields, including material science, soft matter and biophysics, new materials with controlled physical properties can be designed through the spontaneous aggregation of basic building blocks, such as simple molecules, macromolecules or colloidal particles. Examples are provided by micellar systems, formation of fibers and fibrils, solutions of long duplex B-form DNA, epoxy resins, chromonic liquid crystals (LCs) as well as inorganic nanoparticles. Simplified coarse-grained models can be very helpful for carrying out exact theoretical calculations of their physical properties. An example is provided by the Wertheim thermodynamic perturbation theory, which can be used in conjunction with detailed two-body simulations to draw phase diagrams of systems made entirely of DNA that are in semi-quantitative agreement with experiments [1].

If through the aggregation process linear aggregates are formed and these possess sufficient rigidity, the system may exhibit liquid crystal (LC) phases, e.g. nematic, cholesteric or smectic (see Fig. 1b, 1c and 1d respectively), above a critical concentration. Building on the venerable Onsager theory, we developed few years ago a novel theoretical approach for these class of LCs.

Recently, we provided theoretical predictions of the phase diagram and elastic constants of chromonic LCs by employing a very simple coarse-grained model where chromonic particles are represented as bi-functional patchy disks [2]. These theoretical results were successfully compared with both numerical and experimental results. We also employed our theoretical approach to gain some physical insight into the formation of cholesteric phases of amyloid fibrils [3]. Amyloid fibrils offer the possibility of controlling their contour length, aspect ratio, and length distribution, without affecting other structural parameters. While longer fibrils lead to highly elongated nematic LCs, only sufficiently shortened amyloid fibrils lead to cholesteric phases. Upon fibrils length increase, we first find experimentally and predict theoretically a decrease of the cholesteric pitch, before full disappearance of the cholesteric phase. The latter is understood to arise from the decrease of the energy barrier separating cholesteric and nematic phases over thermal energy for progressively longer, semiflexible fibrils.

Another relevant aggregation process is the irreversible (chemical) autocatalytic aggregation which occurs in epoxy resins. Autocatalysis, i.e., the speeding up of a reaction through the very same molecule which is produced, is common in chemistry, biophysics, and material science. Rate-equation-based approaches are often used to model the time dependence of products, but the key physical mechanisms behind the reaction cannot be properly recognized. We developed a patchy particle model inspired by a bicomponent reactive mixture (see Fig. 2) and endowed with adjustable autocatalytic ability [4]. Such a simple coarse-grained model captures all general features of an auto-catalytic aggregation process that takes place under controlled and realistic conditions, including crowded environments. We were able to export the analytical description based on this model to real systems, as confirmed by experimental data on epoxy-amine polymerizations, solving a long-standing issue in their mechanistic description.

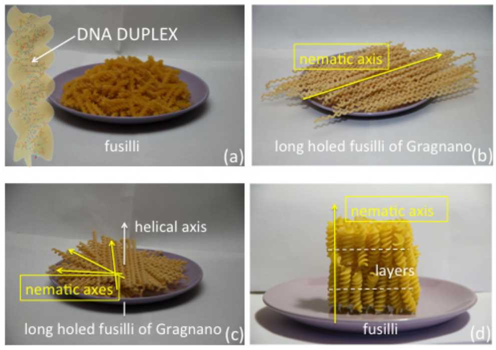

Figure 1: Isotropic (a) and liquid crystal phases ((b) nematic, (c) cholesteric and (d) smectic). In (a) the conformational resemblance between a chiral DNA duplex and a fusillo is evidenced.

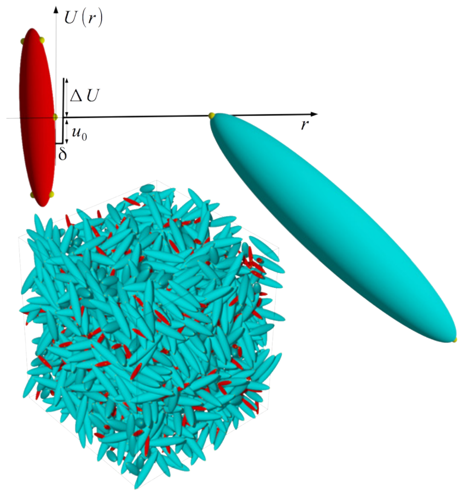

Figure 2: Coarse-grained model of a prototypical epoxy resin where particles are modeled as patchy hard ellipsoids.

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CM31. Computational studies of complex (bio)polymeric systems

Polymers are macromolecules made of many repeating units. From an applicative standpoint, they find widespread use in everyday life as plastics, rubbers and fabrics. However, polymers play a crucial role also in the biological world, as life itself relies on (bio)polymers (DNA, RNA, proteins) to store and retrieve genetic information, to provide structural integrity, to manage the interaction with the environment, *etc.*

Despite many decades of fundamental studies on polymers and on their physics, there are still many questions to be addressed and discoveries to be made. Of particular interest are those polymer-based systems that form complex networks by crosslinking mechanisms that can be either chemical or physical. Particle-based computer simulations can be used to look at these systems with a particularly detailed eye, and have become prominent tools in the field. Here we provide a few examples where we have used a range of numerical tools to better understand the behaviour of selected polymer-based systems, for which we have also developed and refined more coarse-grained methodologies[1].

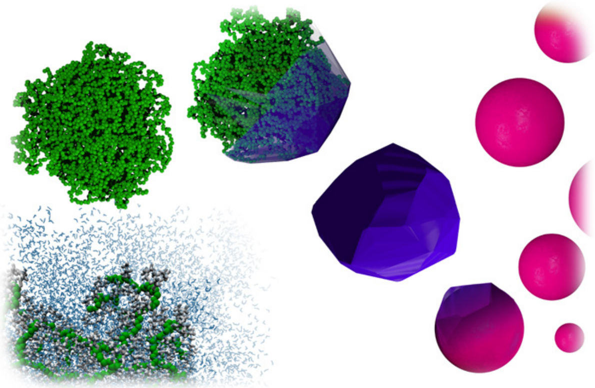

Figure 1: Coarse-graining microgels: each network can be modelled at the atomistic resolution (bottom left), as a single spherical object (right) or with varying degrees of complexity.

Microgels are crosslinked polymer networks with sizes ranging from tens of nanometers to tens of micrometers. Their ability to react to a change of the environmental conditions (*e.g.* temperature, pH, salt concentration) by varying their size make them appealing for both applications (as food additives or units to build photonic crystals, for instance) and fundamental science (*e.g.* to investigate the glass and jamming transitions). Despite their widespread use, there is still much to understand about their microscopic structure, and how this is linked to their bulk behaviour. We have recently put forward a numerical method to extract the single-microgel mechanical properties and compare them with available experimental results[2]. We have used the elastic properties extracted from the simulations to estimate the energy of deformation of pairs of microgels, finding that the classical elasticity theory works well only in a limited regime. This is but the first step towards the development of coarse-grained models[3] that will make it possible to simulate and understand the behaviour of microgels in solution in a multiscale fashion (Fig. 1).

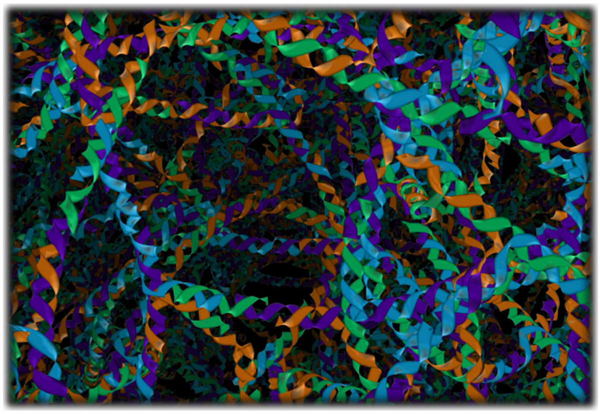

Figure 2: A simulation snapshot of a complex fluid made of DNA nanostars.

Crosslinking in a polymer network can also be reversible. For instance, if the bonding mechanism is affected by external conditions (*e.g.* temperature), the number of crosslinkers, and hence the connectivity of the system, can be changed at will. An interesting example is provided by all-DNA gels: if their sequence is chosen carefully, short synthetic DNA strands assemble into supramolecular constructs that, in turn, form inter-construct bonds that drive the assembly of clusters and, possibly, the formation of a network. The phase behaviour of such systems is, in general, hard to map in experiments as well as in simulations. However, we have devised a method that requires running simple two-body simulations with a detailed model and fed the results to a theoretical framework to access the thermodynamics of the system. In this way we are able to predict the phase behaviour of complicated systems such as binary mixtures of DNA nanostars[4] (Fig. 2).

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CM32. Building Gels with DNA

DNA oligomers can form a large variety of nanometric constructs, via a cascade of self-assembly processes, each one guided by the length of the participating complementary sequences. In our research, we exploit the lesson learned from DNA nanotechnology to build bulk quantities of DNA-made nanoparticles that closely match idealised colloids, transferring modern in-paper and in-silico intuitions into experimental realisations.

More specifically, we study experimentally and via simulations multi-valent DNA constructs (Fig. 1) designed to aggregate on cooling to generate open networks with controlled topology. In previous studies we have investigated the thermodynamics of these gels, providing evidence that the gas-liquid phase coexistence region is controlled by valency, providing a novel route for the generation of low-density physical gels. We have shown that these equilibrium gels are the thermodynamically most-stable lattices. We have also investigated the self-assembly of double strands composed by a small number of bases and the formation of orientationally ordered (nematic) phases.

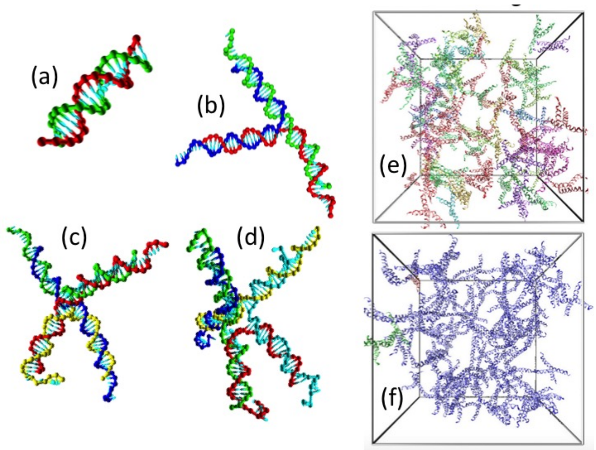

Figure 1: DNA nanostars with different valence: (a) a dimer; (b) a trimer; (c) a tetramer; (d) a pentamer. The arms of the particles end with a single-strand sticky sequence that provides selective bonding with other particles. (e) and (f) show the gel resulting from the self-assembly of tetravalent nanostars at two different temperatures. At room temperature (f), a fully bonded network is observed.

In recent years we have exploited these DNA nanostars as building blocks of gels with specific mechanical and dynamical properties. In Ref. [1], we reported the successful design of one-pot DNA hydrogel that melts both on heating and on cooling. The sample displays a reentrant phase behaviour, providing a neat example of the possibility to rationally design biocompatible bulk materials with tuneable viscoelastic properties. Dynamic light scattering experiments show that the gel dissolves both at high and at low T. In Ref. [2] we reported the observation of a flowing gel (Fig.2). We implemented in the binding base sequences an appropriate exchange reaction which allows links to swap, constantly retaining their total number. The DNA gel is thus able to rearrange its topology (ability to flow) at low temperature while preserving its fully-bonded configuration [2,3]. Last, but not least, we exploit DNA gels as model system for understanding the dynamic arrest associated to gel formation [4].

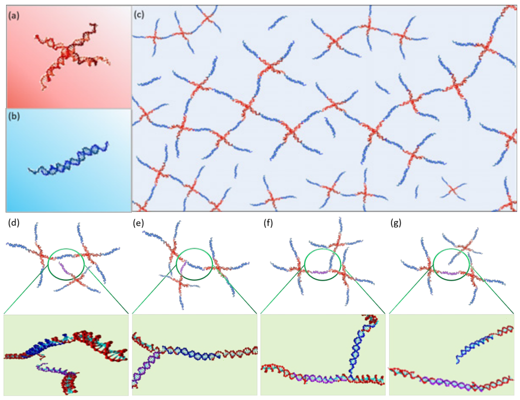

Figure 2: Representation of a tetravalent (a) and a bivalent (b) DNA nanoparticle. (c) Schematic representation of the binary gel, composed by nano-stars connected via dimers. (d-g) Snapshots of the swap process: (d) shows the DNA strands composing the link connecting to nodes (star-arm/dimer/star-arm, coded as red-blue-red) and an incoming free end departing from a close by node (red-violet); (e) shows the incoming free end attached to the toehold; (f) shows the complex after the swap process, with the original dimer still attached to the opposite toehold. (g) The completely swapped configuration; now the node-node connection is provided by the violet strands.

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CM33. Essentiality, conservation, evolutionary pressure and codon bias in bacterial and eukaryotic genomes

Genetic information, is stored in the coding regions of DNA, in nucleotide triplets, the *codons*. The coding regions are *transcribed* into mRNA strands, that are then *translated* into proteins, on the ribosomes. Each one of the 20 amino acids found in proteins is encoded by more than one codon, and since there are 61 codons and 20 amino acids, the genetic code is then 3-fold degenerate. The relative frequencies of the *synonymous codons* that code for the same amino acid, vary significantly in different organisms and this uneven usage is known as *codon usage bias* (CUB). CUB is a hidden meta-code that controls gene expression, rates of protein synthesis and *in vivo* protein folding [1]. We have started, a few years ago, a systematic computational study of the CUB in bacterial and in eukaryotic species, as a phenomenon emerging from the interplay between: i) the evolutionary drift of the genetic material (mutational bias); ii) the availability of tRNAs; iii) the feed-back by the environment at the phenotypic level (natural selection). In particular, we have studied how patterns of gene conservation, gene essentiality and CUB are correlated with the structure of the protein-protein interaction (PPI) networks (interactomes). We have shown in previous studies that densely connected communities of PPI networks share similar CUB levels and, conversely, a small difference in codon bias between two genes is, statistically, a prerequisite for the corresponding proteins to interact, to be connected in the PPI network. Moreover, we have recently shown that in the interactomes of various bacterial species there is a universal topological-functional transition (see e.g. fig. 1), ruled by connectivity [3]. We are trying now to figure out what could be the variational principle behind this phenomenological observation. Essential genes are those which cannot be mutated too much nor lost along the evolution of the species. Within each bacterial genome, we separated two groups of functionally distinct genes, with different levels of conservation and codon bias: i) a core of essential genes, mainly related to cellular information processing; ii) a set of less conserved nonessential genes with prevalent functions related to metabolism. The genes in the first group are more retained among species (conserved), are subject to a stronger natural selection and display a more limited repertoire of synonymous codons. Interestingly, we have also confirmed that essential genes in one species are not necessarily essential in other species. Recently we introduced a new functional classification of intrinsic disorder in the human proteome [4] and we are studying evolutionary pressures and CUB on variants of human disordered proteins [5]. We are actively extending this approach to other eukaryotic proteomes, in particular those of Malaria parasites, looking for general patterns connecting evolutionary pressures, CUB, and intrinsic disorder, focussing on the low-complexity segments, so frequent in Plasmodia.

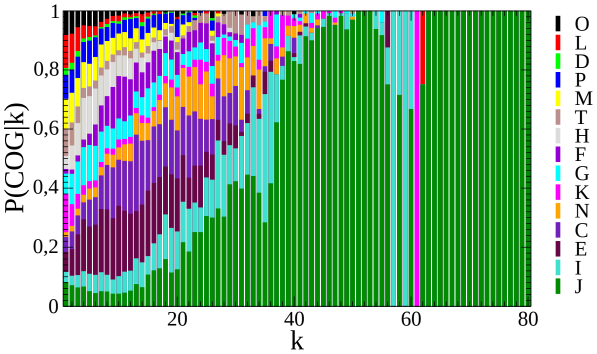

Figure 1: Conditional probability $P(\mathrm{COG}|k)$ that a protein with given degree k belongs to different Clusters of Orthologous Genes (COGs), estimated over 24 bacterial interactomes. COGs are families of genes with strong evolutive and functional similarities. Proteins with low k belong to a variety of COGs, whereas those with $k \geq 40$ mostly belong to COG J (genes related to translational and ribosomal functions) From [3].

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CM34. Photonics Quantum Technologies

Quantum resources promise to provide enhanced capabilities in information processing, with applications ranging in different fields such as computation, simulation, sensing and communication. Within this context, it is fundamental to properly identify appropriate experimental platforms allowing to reach quantum-enhanced performances in desired tasks. Among the currently proposed and developed platforms, photons represent a promising approach given their capability to travel over long distances while experiencing low interaction with the environment.

A first fundamental milestone towards development of large scale quantum technologies would be reaching experimentally the regime of quantum advantage, namely the scenario where a quantum system is capable of solving a given problem faster than any classical platform. In this framework, a promising approach is provided by the Boson Sampling problem, a computational task that consists in sampling from the output distribution of n non-interacting bosons after a random linear evolution. Such task cannot be tackled efficiently with classical resources, while it can be solved naturally by a photonic system which includes sources, multimode linear interferometers and detection. Recent developments in photonic quantum technologies, in particular in the direction of building complex integrated systems, has led to experimental instances of Boson Sampling with progressively larger number of photons and modes. Besides the technological advances, it is fundamental to develop methods to verify the correct functioning of a quantum device that aims at solving this problem. Indeed, the computational complexity of the problem prevents application of direct certification methods. Two different directions can then be pursued. On one side, verification methods that exploit properties of the physical system can be developed, for instance by looking at bunching properties in bosonic systems or at statistical mode correlations [1]. Conversely, other methods can be derived by starting from a computational approach. The main idea in this case is to exploit computational techniques that are capable to identify hidden properties in the measured data. In this context, machine learning techniques can become a powerful tool due to their capability of handling large data sets [2].

Integrated photonics platforms can be also employed as a benchmark system for quantum metrology applications. Within this field, the aim is to measure an unknown set of physical parameters, obtaining higher precision with respect to any classical strategy that employs the same number of resources. A paradigmatic example is provided by phase estimation, where the unknown parameter is a relative phase between the arms of an interferometer. Such problem presents several applications, such as imaging or gravitational wave detection. While the single-parameter scenario has been widely explored, both theoretically and experimentally, several open problems arise when moving to the multiparameter case. It is then necessary to develop suitable platforms to test and develop methodologies in this field. To this end, multiarm integrated interferometers can be used as a benchmark systen [3], allowing to explore multiphase estimation problems in a flexible platform where active reconfiguration capabilities have been recently demonstrated experimentally (see Fig. 1).

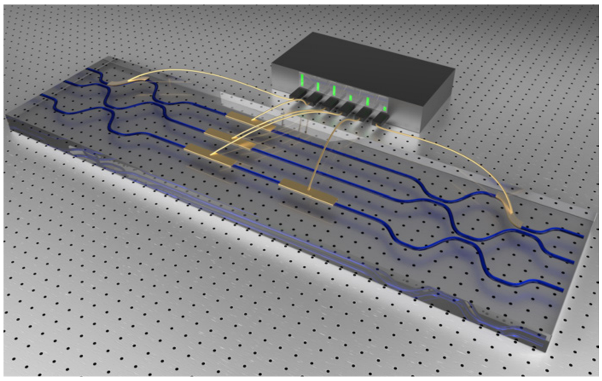

Figure 1: Integrated actively reconfigurable multiarm interferometer in a femtosecond laser-written circuit.

Besides the technological development, a fundamental aspect to address is the characterization of large quantum systems. Indeed, such process is extremely demanding, since the number of parameters grows exponentially with the number of particles. Thus, other methods different from full characterization must then be developed. Such methods should require fewer resources, but should still allow to obtain a significant amount of information. In this direction, it has been recently demonstrated in a photonic platoform the capability of efficient approximate learning of quantum states [4], opening new perspective for the analysis of large scale systems.

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CM35. Quantum causality and foundations of quantum mechanics

Identifying and detecting complex behaviors from different causal structures constitutes a fundamental problem in physics, and in the last decade many efforts have been dedicated to this growing field of research. The recent merging of causality and quantum mechanics provides new theoretical frameworks to analyze the resources underlying quantum information. The physical consequences of entangled states are continuously subject of intensive investigations not only for the corresponding fundamental importance, but also because entanglement represents a powerful resource for technological improvements.

A practical approach to visualize the correlations within a given scenario is through a graphic approach. The Directed Acyclic Graph (DAGs) causal framework allows for the representation of causal and counterfactual relations among variables within a particular scenario. These graphs contains nodes representing random variables, and the (lack of) arrows represent conditional independence assumptions (see Fig. 1), hence providing a compact representation of joint probability distributions. For instance, two (sets of) nodes A and B are conditionally independent given a third set, C, if all paths between the nodes in A and B are separated by a node in C. By contrast, directed graphical models, also called Bayesian networks, have a more complex notion of independence, which takes into account the directionality of the arrows. The results obtained through this methodology have a direct impact on investigating the basic mechanisms that can lead to improvements in quantum cryptography, quantum random number generation and quantum information processing.

From a general perspective, Bell tests represents a resource with a wide range of applications, and many efforts were employed to prove its validity. The causal structure related with the Bell inequality is depicted in Fig.1-a and constitutes a very simple bipartite system. When considering more complex systems, for instance three nodes with two independent hidden variable sources (see Fig.1-b), a broader range of phenomena richer than the one existing within the bipartite system can emerge [1]. Since one of the requirements for a Bell test is the “randomness” of the measurements, Bell himself argued that human “free-will” could be the final solution to overcome this problem. Very recently, a world experiment called “The Big Bell Test” (BBT) allowed to observe for the first time the violation of the bilocality inequality within a quantum network where the choice of the measurements were decided by people around the world [2]. The thirteen experiments performed during the BBT collaboration reject local realism in a wide variety of physical systems.

A step forward towards finding new phenomena was obtained by demonstrating the experimental violation of the instrumental inequality with entangled systems

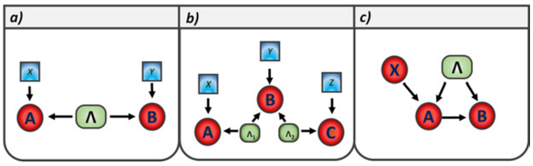

Figure 1: Directed Acyclic Graphs (DAGs). a) Bipartite Bell causal structure. b) Tripartite system corresponding to the bi-local model. c) The instrumental scenario, where X stands for the instrument, A and B are the variables for which we want to estimate causal influences, and Λ represents any latent factor correlating them.

[3]. The causal structure of the instrumental test is depicted in Fig.1-c, and has been exploited to estimate the strength of causal influences between two variables solely from observed data. In [3], it was shown experimentally the violation of such instrumental inequality with feed-forward of information, demonstrating a new form of non-classicality stronger than Bell nonlocality in its usual form. The implementation of more complex systems is crucial to better understand the quantum foundations and quantum modelling of physical reality, and hence future research will be necessary in this field.

Within the foundations of quantum mechanics, the wave-particle duality of a quantum object represents one of its most fundamental nature. While such feature of quantum mechanics and quantum correlations between distant objects have been experimentally observed in different systems, the problem of whether these two properties can be observed simultaneously in the same system is still open. In [4], it was shown experimentally the possibility to observe quantum correlations between the wave and particle states of two different particles. Such result underlies the possibility to encode qubits of information in this wave-particle degree of freedom, leading to its future application in quantum information processing.

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CM36. Quantum Optics for Quantum Information Processing

In Quantum Information theory (QI), physical systems operating on the basis of the quantum mechanical principles are used to formulate, transmit, manipulate and process information. These resources are expected to revolutionize information processing in terms of speed, security and power. Entanglement and superposition principles, the characteristic signatures of quantum world, are the main responsibles for the improvement of quantum algorithms with respect to the classical ones.

Photons are the ideal vectors of quantum information since they are practically immune from decoherence and can be distributed over long distances both in free-space and in low-loss optical fibres. Besides, information qubits can be encoded over different degrees of freedom (DOFs) of the photons.

We have experimentally implemented an all-optical scheme able to reproduce the so called Quantum Walk (QW), namely the quantum counterpart of the Classical Random Walk (CRW). The setup, consisting on a double displaced Sagnac interferometer, exploits multiple passages of light in different parallel directions through a single Beam Splitter (BS) to reproduce all possible paths that the quantum walker can travel [1,2]. Phase stability, assured by the Sagnac configuration, allows us to completely control the evolution of the walker by modifying the phase maps experienced during its evolution. In our experiment we have studied superdiffusion, a phenomenon present in several condensed matter and biological propagation processes. Precisely, when the superdiffusive behaviour is present, the walker is subjected to random disorder, quantified by the percentage p of randomly shifted phases inserted along the evolution. The results of the experiment are given in Fig.1, where we show the variance behaviour vs the number n of steps of the QW for different values of p. Superdiffusivity occurs in the region $0 < p < 1$, between the ordered ($p = 0$) and disordered ($p = 1$) regimes and is identified by the power law $Var(n) \propto n^{\beta}$, with $1 < \beta < 2$ [3].

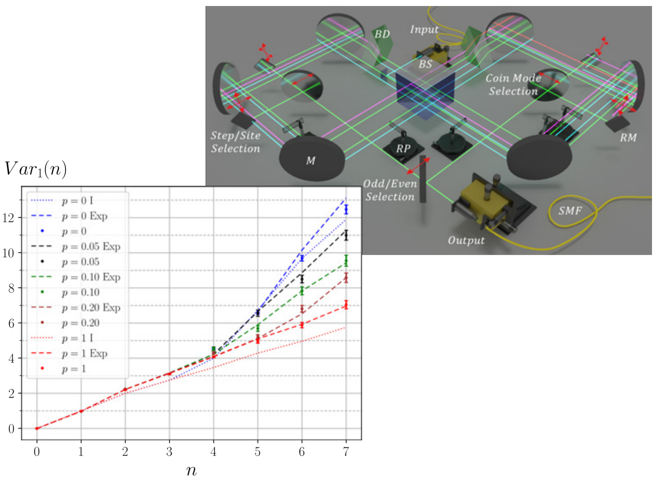

Figure 1: Top: Experimental setup of the all-optical QW scheme. Bottom: Variance behaviour of a walker for five different degrees of disorder.

One of the open questions in the physics of quantum open systems is the quantum-to-classical transition. Usually this feature is explained by the action of decoherence induced by the environment, that constantly monitors the state of a system, thus acquiring information about it. However, Quantum Darwinism retains the role of the environment by focusing on the exchange of information between it and the system. In this picture, the arise of classicality is given by the proliferation of redundant information through correlations between the system and the environment. In Quantum Darwinism, a system is correlated with fractions of the environment, that can be queried by external observers. Under the hypothesis that all the environmental fractions are independent, a plateau in the mutual information between system and environment is to be expected due to the emergence of classicality. Under the presence of intra-environmental correlation, the phenomenology of Quantum Darwinism is not known. We investigated [4] the emergence of Quantum Darwinism in a photonic cluster state as a simulator of tunable interactions between a quantum system and an environment and intra-environmental correlations using a 4-qubit cluster generated by a path-polarization hyperentangled source. We show the experimental mutual information between system and fractions of the environment. Our work demonstrates experimentally for the first time the effect that correlations have in establishing the emergence of an objective reality measured through the redundancy of information that is shared between the system and parts of the environment. We observed that a system correlated with an independent environment give rise to the emergence of an objective reality, as prescribed by Quantum Darwinism. In addition, we observed that intra-environmental correlations give rise to non-trivial back-action effects due to the introduction of multipartite entanglement.

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CM37. Complexity, nonlinearity, topology, and machine learning in photonics

The group aims at studying the application of some of the most essential paradigms in the science of complexity to photonics. The group is headed by the Director of the Institute for Complex Systems of the National Research Council (ISC-CNR), Prof. Claudio Conti, and develops theoretical, numerical and experimental activities involving personnel of Sapienza and CNR.

The most important research directions are:

- Topological photonic insulators. We reported the first theoretical prediction of topological insulator lasers, that is lasers relying on topological edge states in one-dimensional photonic topological insulators with synthetic dimensions.

- Photonic Spin Glasses and Ising machines. We reported the first experimental observation of Replica Symmetry Breaking in photonic spin glasses, i.e., photonic systems described by spin glass Hamiltonians, as linear and nonlinear light waves in disordered systems and random lasers. We apply these ideas to design novel photonic computational devices, as Ising machines.[1]

- Random photonics. We study linear and nonlinear light propagation in disordered systems. We make experiments on "random lasers," disordered electromagnetic cavities which emit coherent radiation. We also study linear and nonlinear light propagation in disordered systems, as multiple scattering surfaces, hydrogels, and soft-matter at optical and THz wavelengths for studying transport and localization phenomena.

- Plasmonics and two-dimensional materials. We theoretically study the nonlinear optical response and processes like spin-orbit coupling in two-dimensional materials, including graphene and transition metal semiconductors.[2]

- Classical and quantum nonlinear waves. We study complex and multimodal dynamics, as in turbulunce, rogue wave generation, and soliton gases at a classical level and in second quantized regimes. We also study classical analogs of fundamental physical process as irreversible quantum mechanics, quantum gravity, and propagation in curved manifolds.[3]

- Biophotonics and graphene oxide photonics. We study the use of graphene for biophotonic applications as the realization of antibacterial surfaces. We also study the nonlinear optical response of graphene oxide for all optical switching applications and random lasers.[4]

- Machine Learning Photonics and Neuromorphic Computing. We study the application of machine learning program interfaces to design classical and quantum photonic devices, as photonic topological insulators, universal quantum gates by random materials, and biosystems a living tumour spheroids.

The group has been founded by several national and international projects, including the Quantum Technologies Flagship, the Templeton Foundation, the Humboldt Foundation, and the European Research Council. Details and further references are available in the group website.

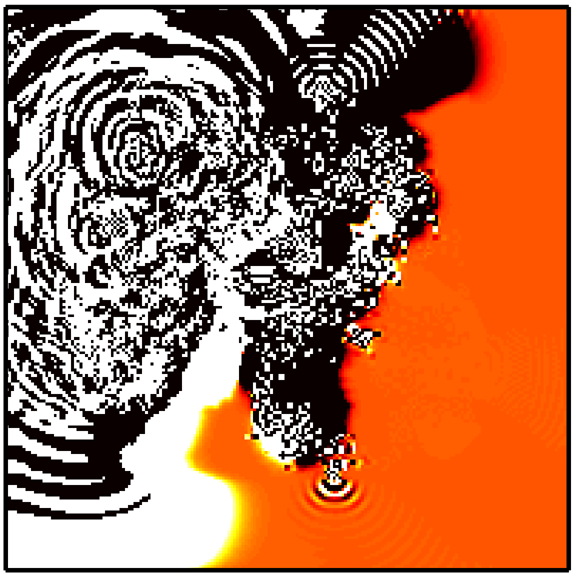

Figure 1: Numerical simulations of a light driven cellular automata (author C. Conti), from the book "Designing Beauty : the Art of Cellular Automata," A. Adamatzky ed., Springer (2016)

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www.newcomplexlight.org

List of research activities

Particle physics and Fundamental Interactions

The Physics of Fundamental Interactions

1 The general picture

Less than a decade ago, in 2012 during the first run of the LHC, the Higgs boson was discovered. This landmark discovery is the most important made in particle physics in recent years. This immense achievement is the result of the successful design, construction and operations of the largest and most powerful accelerator ever built. The discovery and first measurements of the properties of the Higgs boson were mostly relying on the Higgs boson couplings to gauge bosons. During the second run of the LHC, at a higher center-of-mass energy of 13 TeV, experiments have collected larger datasets which have allowed them to observe the direct coupling of the Higgs boson to fermions of the third generation, another landmark result of fundamental importance, along with performing more precise measurements of the properties of the Higgs boson. The experimental profile of the Higgs particle is agreeing with increasing precision with the predictions of the Standard Model (SM).

There are multiple strong motivations to expect new physics beyond the Standard Model at scales reachable at the LHC, from the hierarchy of masses in the Standard Model, the origin of the asymmetry between matter and anti-matter in the universe, inflation, a quantum theory of gravity, to the existence of Dark Matter, which has been introduced to explain the disagreement between the astrophysical observations of the mass of the galaxies and the theory. Hypothetical extensions of the SM theory, addressing these fundamental questions were developed in the past decades and have been actively searched for at the LHC. Another result of great importance of the LHC is that no sign of new physics has been seen so far.

The most striking aspect of this tension is perhaps the puzzling low Higgs mass value, which can to some extent be viewed as the analog of the blackbody ultraviolet catastrophe of our times. If it is unclear, how long it will take to understand what lies behind the striking 'unnaturalness' of the Standard Model as an Effective Theory of our world (where the term un-natural has a precise meaning in the mathematical theory) the LHC has only collected a few percent of its projected complete dataset and can still provide fundamental answers through discoveries.

The LHC community at large, is also very actively pursuing a program to increase its experimental accuracy and that of the theory predictions to perform precision measurements, to both search for indirect manifestations of new physics and in order to increase its sensitivity to potentially tenuous signal. The LHC has produced the single most precise measurement of the W boson mass, a *tour the force* in the complex environment of *proton-proton* collisions.

Studying the finer properties of the Higgs boson, which might even reveal a composite structure, is necessary to give a solution to the deeper questions that the present experimental picture is posing.

The community is also preparing ambitious future collider programs to further probe directly and indirectly new physics beyond the Standard Model.

While the Higgs boson was not a granted discovery, there was little doubt about the existence of gravitational waves. Their direct observation is however a groundbreaking discovery, providing a very powerful tool to study the Universe.

The fact that gravitational waves are found to travel at the velocity of light is severely challenging many recent models extending general relativity, which is now, more than ever, at the experimental test table provided by LIGO and VIRGO interferometra. Despite we might foresee that the theoretical study of GWs is a land of opportunities, we might observe that General Relativity still appears way more robust than the SM of particle interactions and no hints of 'new physics' have been found to the time of this writing.

Going beyond the boundaries of classical physics, gravitational waves are being studied as the tools to understand the nuclear physics of some stars, and can be the way to see all sorts of exotic structures which might populate the Universe, such as bosonic stars. Dark matter itself could be studied with the tool of GWs, as envisaged by some theoreticians.

The existence of dark matter particles and the properties of the Higgs particle (especially its mass) are two prominently urgent questions.

A very elegant and efficient solution to most of the issues of the SM is Supersymmetry. To each fermionic (bosonic) field in the SM, Supersymmetry posits the existence of a bosonic (fermionic) partner field. If the superpartners are not too heavy, this symmetry resolves the naturalness problem and predicts a light stable particle which is a very good candidate for dark matter[1]

In short, Supersymmetry is a way to explain the light Higgs mass with new physics at the TeV scale. The Higgs mass

$$m_H \sim G_F^{-1/2}$$

should be close to the Planck Mass

$$m_{\text{Planck}} \sim G_N^{-1/2}$$

if the SM is *the* theory valid all the way in the high energy domain our modern ultraviolet catastrophe. However Newton and Fermi constants are known to be in the ratio

$$G_N/G_F \times (\hbar^2/c^2) \sim 5.7 \times 10^{-34}$$

Supersymmetry predicts that the SM, as we know it, is not the ultimate theory and gives a precise path to extend it. The new fields, and their particle manifestations, are needed and should appear at the TeV scale.

Similarly the Weakly Interacting Massive Particle paradigm (WIMP) is conceived as a particularly advantageous way to explain the dark matter abundance in the Universe through the existence of some particle interacting with weak force and having a mass in the $\approx$100 GeV region (as known as the 'WIMP-miracle'), where supersymmetric particles could also have been. Supersymmetry offers therefore the unvaluable possibility to explain, with the same physics, the un-naturally light Higgs and dark matter in terms of WIMPs.

Even though we might indulge on the easy statement that 'miracles do not exist', there are good reasons to still search at full steam both WIMPs and Supersymmetry. The so called exclusion plots speak of a hard situation for both of them but still the theoretical motivations for both are so compelling that we cannot trow the towel yet — or maybe the SM model is the final theory and we live in a very special Universe, among an indeterminate number of multiverses, which is the good one to host observers, like us, whereas other universes have

$$G_N/G_F \sim 1$$

which is a rather unsatisfactory anthropic statement.

Many believe by now that it is time to search dark matter particles, experimentally, in mass regions outside the preferred WIMP mass window. The theoretical motivations for most of the light or heavier dark matter particles, exception made for QCD axions, are not as solid as those for WIMPs: the freeze-out mechanism to explain the WIMPs relic abundance is still an extremely well motivated picture. Moreover, abandoning WIMPs, we move from their limited mass window, as suggested by theory, to the mare magnum of 90 orders of magnitude span for all possible mass values.

The KeV-to-GeV mass region, being inaccessible to standard experimental detection techniques, gives the opportunity to explore the interface with modern condensed matter physics, in the search of novel target materials which could reveal the interaction with light dark matter particles in the halo through a variety of phenomena.

[1] It also allows the electromagnetic, weak and strong coupling constants to converge at a higher energy scale, thus providing a framework for a grand unification. Supersymmetry also predicts the existence of a potential partner to the graviton, a spin 3/2 field.

In the last few years several new ideas have been put forward, from the use of carbon nanotubes and the devising of graphene field effect transistors to the use of semiconductors, superconductors and superfluids. Dark matter particles may break pairs in superconductors and excite the Goldstone modes of the superfluid phase of liquid Helium, the phonons. The potentialities of these materials are being studied especially by theorists with a growing interest of an experimental community attracted by the many technological challenges on the table.

This field has at least the very important aspect of bringing together on a common problem particle theorists, condensed matter theorists, and experimentalists from both sides.

The sub-meV axion window represents the border line through which we have to stop thinking in terms of particles and use the wave language instead — the lighter is the dark matter mass, the closer the detectors will be to kind of antennas for scalar waves.

The SM creaks, even though not so loudly, also in the field of flavor physics. The observation of flavor non-universality in the semi-leptonic decays of the B mesons could be a hint of beyond-SM physics. The measurement of the theoretically clean ratio

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \tag{1}$$

shows a departure from $R_K = 1$ which is significant at the level of approximately 2.6σ. Similarly for the R_{K^*}. In recent times, thanks to the efforts of the LHCb collaboration, it has been found that the central values are approaching the SM model ones, but the error bars are getting narrower, resulting in a stable significance of the anomaly.

Such a discrepancy can be the fault in which exotic phenomena, such as Z's' or leptoquarks, might be lurking. The study of precision flavor physics, with particular connection to beyond-SM phenomena, is under strain these days. Irrespectively of what will be the fate of this experimental anomaly, it is worth reminding that flavor physics is an important tool to fathom in depth the SM in the search of signals of new physics which could hide in tiny discrepancies, such as the one briefly described above. One of the pillars of the field relies on the methods of lattice gauge theories, which provide most of the non-perturbative inputs needed in the dedicated phenomenology.

In addition to speculate on the solutions to go beyond our present theoretical understanding of the world, which is certainly the main road for us to follow, we also have to try to understand whatever concrete unexpected phenomenon is observed, even if it is not clear whether or not this study will lead to any disruptive breakthrough.

Mentioning neutrinos, we have to remind here that it is still open the question, of paramount importance, about their nature in terms of Dirac or Majorana particles, which got thrust after the measurement of their tiny mass. The neutrino mass allows to have a non-zero amplitude for the Majorana neutrino chirality flip in neutrinoless double-beta decay. The main feature of this process is the lepton number violation which, in turns, would support the idea that leptons played a role in matter-antimatter asymmetry of the universe.

On the other side, neutrinos can be used to enlarge the Universe observed horizon and to search for the sites where the Ultra High Energy Cosmic Rays are accelerated. Neutrino astronomy has recently entered an exciting period with the discovery, reported by the IceCube Collaboration, of an isotropic high-energy cosmic neutrino flux, the proof that sites where protons are accelerated to extreme energies ($> 10^{18}$ eV) do exist, the flux being caused by the decays of the mesons originated by their interactions with the surrounding matter or radiation. A second important result has been the first evidence of neutrino emission from a known astrophysical source, the blazar TXS0506+056. Recent searches for neutrino emission from the directions of blazars from the 2nd Fermi-LAT AGN catalogue performed by the IceCube Collaboration indicated that blazars contribute less than about 40% to the total observed neutrino flux. These analyses show the strong potential of the search for neutrino sources in the Southern Sky using the joint data sets of the ANTARES and IceCube telescopes. The combination of results obtained by ANTARES and IceCube, which differ in size and location and have complementary view of the sky, allows for an improvement in the sensitivity for different regions of the Southern Sky. KM3NeT, the Mediterranean Cherenkov Neutrino Telescope at present under construction with improved detection effective area and improved angular resolution will allow the detection of high energy astrophysical neutrino sources and will contribute, in a multi-messenger scenario, to the study of the most energetic regions of the Universe.

A remarkable example of experimental discoveries of this kind, is represented by the case of exotic XYZ resonances, which are teaching something deep on the structure of quark matter in hadrons and on strong interactions at low energies.

In the last 15 years, over 20 new hadron resonances have been discovered thanks to the efforts of small groups of experimentalists doing off-main-stream research at electron or hadron colliders. Very recently the LHCb collaboration claimed the discovery of three new pentaquarks with hidden charm.

There is a lively theoretical debate about what we are learning from the XYZ resonances and pentaquarks: are they the manifestation of long range strong forces between mesons or are we observing compact, completely new structures with four, five or more quarks? There are hints that a repulsive force, segregating diquarks from antidiquarks in physical space, might be at work at very short distances and help to explain the very much odd phenomenology of most of these new hadrons.

2 Theoretical Research

The topics touched in the introductory section are mostly covered by researchers in our Department. We have a group on flavor physics and lattice gauge theory and individual researchers on precision physics at the LHC, exotic hadron resonances and light dark matter searches. A theory group on gravitational waves and general relativity follows the most recent developments in that field.

The flavor physics group has a long tradition in the Physics Department, starting with the definitive contributions to the Standard Model given by Nicola Cabibbo, who discovered the celebrated mixing angle, and Luciano Maiani who,starting from the Cabibbo theory, coauthored the Glashow-Iliopolous-Maiani mechanism, another cornerstone of our present understanding of fundamental interactions. Another former member of the Physics Department, Giovanni Jona-Lasinio, together with Yoichiro Nambu, discovered the mechanism of spontaneous symmetry breaking in particle physics, an essential part of the Standard Model.

The flavor precision-physics program, with special attention to the search of new physics phenomena, has been carried on, over the years, by the successful work of the group of Guido Martinelli. These efforts resulted most recently in several contributions investigating the potential role of new physics to flavor and CP violations beyond the leading order in QCD, with the calculation of $\Delta F = 2$ hadronic matrix elements in lattice QCD and the calculation of next-to- leading order anomalous dimensions for the most general $\Delta F = 2$ operator basis. Pioneering work by the same group on the phenomenology of non-leptonic decays are also noteworthy. On the lattice side, the related work of Mauro Papinutto concerns non-perturbative calculations, from weak-matrix elements to the hadron spectrum with advanced techniques, such as the Schrödinger Functional lattice implementation.

On the side of the quest of new physics, Marco Nardecchia leads researches on the very much debated problem of the anomalies in the flavor sector, discussed in the introductory remarks. With his collaborators he is also active on the study of the problem of Dark Sectors of new particles, singlets under the Standard Model gauge interactions, advocated to solve the Dark Matter problem. The way this new particles interact with standard matter is encoded in effective quantum field theories whose phenomenological consequences can be studied at present and future colliders.

The Physics Department has also a renowned tradition in perturbative Quantum Chromodynamics (QCD), from the fundamental work of Altarelli and Parisi which, bringing into QCD some ideas of Fermi, later developed by Weizsaker and Williams, has allowed the flourishing and developing of hadron collider physics as we know it today, to the several contributions to QCD by the Rome group of Martinelli, Maiani and Massimo Testa.

Perturbative QCD, in the last twenty years, has undergone a profound technological advancement, both on the analytic and numerical sides. Monte Carlo techniques for the calculation of the hadron-hadron cross sections have advanced at a terrific rate, from the ALPGEN library [2] to the most recent version of MADGRAPH, POWHEG, MC@NLO and SHERPA which are indispensable computer calculation tools of modern LHC physics. On the analytic side, the technological developments have been tantamount stunning. The frontier of two-loop, multi-leg calculations in QCD is explored vigorously by several groups in the world. The frontier of next- and next-to-next-to leading order calculations in QCD and Electroweak theory is explored in our Department by Roberto Bonciani who is especially concerned with the precision calculation of Standard Model processes at the LHC. Some of these processes are important background to discriminate potential new physics signals at the LHC. Other are of relevance for the finer study of the Higgs boson properties, as discussed in the introductory section.

Since almost two decades, more than twenty exotic hadron resonances have been discovered, whose quark structure is debated. Very recently the LHCb collaboration has presented a new analysis of the pentaquark resonances observed for the first time five years ago, and only few days ago, at the time of this writing, the CMS collaboration has presented a measurement of the $X(3872)$ production cross section showing that the relative yield of this charmonium-like resonance with respect to the standard charmonium $\psi(2S)$, changes completely when passing from proton-proton to Pb-Pb collisions – something further enforcing the idea of a non-standard quark-structure of the X. The phenomenology of the so called XYZ resonances has been studied by Antonio Polosa and Luciano Maiani, former member of the department, since the beginning of this field.

In most recent times, Polosa has been working also in the new research field on light dark matter particles, which is especially oriented on the theoretical examination of the methods for their detection — such has phonon excitations in superfluid helium. Another account on this research line is given in the discussion reported by Gianluca Cavoto, on the use of carbon nanotubes.

Besides the numerous astrophysical applications, and even some incursions in extreme nuclear physics (gravitational waveforms emitted in the late inspiral of binary neutron stars can teach something about the equation of state of nuclear matter in extreme conditions) it is to be understood to what extent Gravitational Waves (GW) can allow progress in fundamental physics. The Rome group of Valeria Ferrari, Leonardo Gualtieri and Paolo Pani is strongly committed to this research program. One direction is that of probing with GWs the consequences of modified gravity models such as massive gravity and Gauss-Bonnet gravity. With GW astronomy strong-field gravity is accessible and this also provides test table of General Relativity, which for the moment appears in very good health.

Ultralight dark matter could also be tested with GW signatures. There are several speculative arguments about the formation of bosonic halos (axions, dark photons, etc.) in the surroundings of spinning black holes. The challenge is that of pinning down specific signals that could unveil these structures at present or future interferometers. Also it seems possible to identify several effects which might be used to distinguish a black hole from a horizonless compact object: the nature of the compact object affects the GWs emitted during a merger.

[2] cohauthored by a member of the Department

3 Experimental Research

In this context, the researchers of the Department of Physics, in close collaboration with INFN, the Italian national institute for the nuclear, particle and astroparticle physics, have given a significant contribution to all the critical lines of research. There are several points of strength of this research activity:

- the activities are pursued in the context of international collaborations, which give a wide visibility to the department and ensure instrumentations and infrastructures that would be inaccessible to the single institutions. The detectors on which the experiments are based are therefore located in international laboratories that guarantee the required infrastructures, resources and personnel. Tab. 1 shows a list of the experiments on which members of the Department work, with the indication of the corresponding Laboratory. A significant part of the activity of the researchers in the department is therefore in these Laboratories, by taking part to the R&D, building, commissioning, operation of the experiments and to the analysis and interpretation of the experimental data. This working model facilitates visibility and contacts in an international environment.

  Each laboratory has its own peculiarities that justifies the presence of an experiment.

  The experiments that make use of accelerators are located at the Laboratories that have the accelerators with the required characteristics. Those performed at the highest energy (ALICE, ATLAS, and CMS) are located at CERN, where since 2018 the LHC, currently in shut-down for upgrades to both the accelerator and the detectors, has produced proton-proton collisions up to a center-of-mass energy of 13 TeV. The energy frontier allows to detect new massive particles, both those predicted by the Standard Model (as it was with the Higgs boson) and those beyond the Standard Model. It allows also precision measurements with an extremely high statistics.

  The NA62 experiment exploits a different CERN beam line that delivers high energy and high intensity kaons, thus allowing the search for the rare $K \to \pi\nu\nu$ decay. Similarly, the MEG experiment makes use of the high intensity muon beam at the Paul Scherrer Institute close to Zurich to search for $\mu \to e\gamma$ decays. Both experiments allow for very stringent tests of the Standard Model and they are therefore a powerful way to investigate new physics.

  At the INFN-LNF laboratories in Frascati, the DAΦNE accelerator yields e^+e^- beams, which collide at a center of mass energy of the Φ resonance, which in turn decays into kaons. The KLOE2 experiment, which took data till 2018, accumulated a huge sample of Kaon pairs produced in entangled states, thus allowing for studies of discrete symmetries. Furthermore, DAΦNE allowed low energy QCD studies. Finally, the PADME experiment exploits the BTF (Beam Test Facility) of LNF in order to have an e^+ beam collide with the electrons of a target and search for dark photons (A') production in $e^+e^- \to A'\gamma$ interactions.

  As far as experiments that do not make use of accelerators, VIRGO is a 3 km long interferometric antenna built in the European Gravitational Observatory (EGO) close to Pisa. Furthermore, the detection of GW signals requires strict collaboration with the LIGO experimental collaboration with two antennas located in the United States. VIRGO is currently in its third run of acquisition of gravitational waves signals. The large number of observed signals from different sources allows to test General Relativity and provide valuable information on physics beyond the Standard model.

  The INFN laboratory under the Gran Sasso (LNGS) is unique in its screening from the cosmic ray background and allows therefore for searches of very rare signals. This feature is being exploited by experiments searching for dark matter candidates and Majorana neutrinos, like DARKSIDE, CUORE, LUCIFER, CUPID and CALDER.

Specific laboratories are built for astro-particle experiments (ANTARES and KM3NET) that measure the spectra of high energy particles of astronomical origin, in particular neutrinos. Such detectors consist in equipping with detectors large undersea areas, utilising marine water as target for the particles under study. The challenge of these detectors is to increase the equipped volumes in order to increase the signal rates and therefore increase the energies at which the experiment is sensitive.

- significant contributions can also be given to these experiments from Rome.

  First, analysis of the experimental data can be performed by remote. In most of the cases the datasets are extremely large (from TB to PB depending on the size of the experiment) and different models can be applied: either the data are in a centralised storage close to the experiment, or diffused in a cloud, or mirrored in local copies of easier access. In all configurations, data analysis is performed from workstations in the department of physics. The analysis of these high statistics data, necessary to observe very low signals, requires very advanced techniques, in particular multivariate analyses and machine learning.

  Next, the design of new experiments or upgrades requires Monte Carlo simulations and feasibility studies that can be performed by working locally. This has been in the years 2017-19 the case of the LHC upgrades, the design of the PADME and KM3NET experiments and the Einstein Telescope for gravitational waves detection. Such studies require vision on the physics and deep knowledge of detector physics, together with competences and computing resources for Monte Carlo Simulations.

  Finally, development of new detectors, both for new experiments or upgrade of existing ones is pursued in the laboratories of the department (see Laboratory and facilities section) equipped with leading edge equipments for R&D of detectors. Such studies typically start with small scale experimental setups to characterise detector prototypes, followed by tests in experimental conditions closer to the final ones (e.g. on test beams in case of accelerator based experiments). Critical is also the production phase: particle physics experiments require typically thousands of replica of the same module and whilst the production is commissioned to industry, laboratories need to be equipped with quality assurance test stands to ensure that the tolerances are respected. In this respect, in 2017-19 the ATLAS group has developed Micromegas detectors and the upgrade of the trigger system, the CMS group MIP timing detectors, the ALICE and JLAB group silicon strip detectors, the KM3NeT group the electronics and the calibration system, the PADME group the electromagnetic calorimeter, the Archimedes group (including VIRGO researchers) is developing a detector to test the interactions between the gravitational field and the vacuum fluctuations.

  The development of new detectors or instrumentations is also in some cases the object itself of the research. This is for instance the case of the CYGNUS and CNT/PTOLEMY projects, that aim respectively at building a demonstrator of a Time Projection Chamber and Carbon NanoTubes for directional Dark Matter searches and of the CRYS-BEAM project that studies the possibility to exploit the properties of bent crystals to improve beam collimators in proton colliders like LHC.

- the excellence of the research in the Department of Physics has been awarded by the "Dipartimento di Eccellenza", a grant that has among the main pillars the study of gravitational waves as probe of the universe and the development of a multi-messanger astronomy.

- the expertise acquired in particle physics experiments in terms of detector, electronics, software, machine learning, Monte Carlo simulations, etc etc ... can have an impact on applications in fields like medicine, cultural heritage, ... There are research groups devoted to the translational effort, i.e. working on the understanding of the requirements from possible users of the developed physics tools and on the possibility of translational research. Such activity is shown in a different section of the report (see Biophysics, Medical Physics, and Cultural Heritage).

Experiment	Research lines	Intl. Laboratory (State)	Contribution
ALICE	SM, QCD	CERN (CH)	P18
ATLAS/CMS	Higgs, SM	CERN (CH)	P1-P17
	Exotica, DM		
KLOE2	SM, QCD	LNF (I)	P19-21
MEG	Exotica	PSI (CH)	P37
NA62	SM, Exotica	CERN (CH)	P22
PADME	Exotica	LNF (I)	P23
VIRGO	GW	EGO (I)	P24-28
CUORE, CUPID, LUCIFER, CALDER	SM, DM	LNGS (I)	P29-31
ANTARES	AstroParticles	Antares NT (F)	P32-33
KM3Net	AstroParticles	Capo Passero (I)	P34-36
CYGNUS, CNT, PTOLEMY, DarkSide	DM		P38-39, P49

Table 1: Summary of the characteristics of the experiments with contributions from the Department of Physics: the name of the international collaboration, the research lines pursued in the Department, the laboratory where the detector is and the reference within this report. The double line separates experiments that require accelerators (above) from those that do not (below).

P1. The ATLAS Experiment at the Large Hadron Collider

ATLAS [1] is the largest volume detector ever constructed for a particle collider and one of the four major experiments at the Large Hadron Collider (LHC) at CERN. It is a general-purpose particle physics experiment run by an international collaboration and is designed to exploit the full discovery potential of physics opportunities that the LHC provides. ATLAS has a cylindrical shape with dimensions 46m in length and 25m in diameter, and sits in a cavern 100m below ground. The four major components of the ATLAS detector are the Inner Detector, the Calorimeter, the Muon Spectrometer and the Magnet System. The Trigger and Data Acquisition System selects in real time physics events with distinguishing characteristics and finally the Computing System allows to store, process and analyse vast amounts of collision data. A view of the ATLAS detector is shown in Fig. 1.

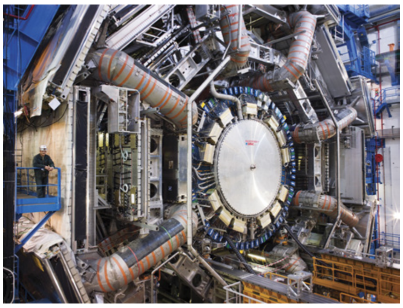

Figure 1: A view of the ATLAS Experiment [1].

The aim of the ATLAS experiment is to push the frontiers of knowledge by seeking answers to essential questions related to the fundamental forces of nature, the composition of the basic building blocks of matter, the problem of *Dark Matter* and the underlying symmetries of our universe.

In the years 2015-2018 during the so called Run2, LHC has delivered proton-proton collisions at a center of mass energy of 13 TeV with an increasing luminosity up to a value of $2{\times}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ a factor of 2 larger than the project value. The ATLAS experiment has collected in these years an integrated luminosity of 160 fb^{-1}. The luminosities collected in the different years are shown in Figure 2. Moreover LHC has delivered lead-lead collisions and proton-lead collisions at the maximum center of mass energies ever reached.

In parallel to the data taking and the wide analysis program, the ATLAS collaboration is carrying out a program of detector upgrades in order to be prepared for the further increase in total energy and luminosity in the forthcoming Run3 and Run4. In 2019 we are entering the so called Long Shutdown 2 (LS2). In this two years period, both LHC and the experiments will undergo a significant upgrade.

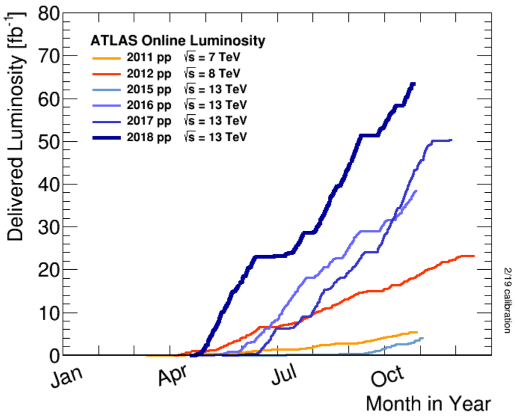

Figure 2: Cumulative luminosity versus day delivered to ATLAS during stable beams and for high energy p-p collisions.

The ATLAS group at the Sapienza Università di Roma and at INFN Sezione di Roma (*the ATLAS Rome Group*) is engaged in a large number of data analyses. These include detector performances assessment, measurement of properties of the Higgs boson, precision measurements of Standard Model physics, and searches for exotic processes predicted by theories beyond the Standard Model. Currently the group is also committed in the detector upgrades and physics studies needed to preserve the ATLAS ability to successfully perform in the challenging environment expected during the High Luminosity program over the coming decade of the LHC machine. The group is deeply involved in the construction of the precision detectors of the muon spectrometer, in the design and realization of the muon trigger, the high level triggers and the data acquisition system, and finally in the development of the computing system.

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[1] ATLAS Collaboration, JINST 3, S08003 (2008).

Authors: F. Anulli, P. Bagnaia[1], M. Bauce[1], C. Bini[1], N. Buscino[1], A. Chomont, M. Corradi, S. De Cecco[1], D. De Pedis, A. De Salvo, C. Dionisi[1], A. Di Domenico[1], S. Falciano, S. Francescato, G. Frattari, P. Gauzzi[1], S. Gentile[1], S. Giagu[1], V. Ippolito, M. Kado[1], F. Lacava[1], I. Longarini, C. Luci[1], L. Luminari, L. Maiani, F. Marzano, A. Nisati, E. Pasqualucci, E. Petrolo, A. Policicchio[1], M. Rescigno, S. Rosati, L. Sabetta, F. Safai Tehrani, C.D. Sebastiani[1], R. Vari, D. Vannicola, S. Veneziano[1]

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P2. Precision Standard Model Measurements with ATLAS

Precise measurements of well-understood Standard Model (SM) processes at the LHC give the opportunity to test the internal consistency of the SM and to search for possible deviations originating from new phenomena. A prominent case is the production of lepton pairs, which can be calculated with small theoretical uncertainties thanks to the recent developments of perturbative QCD. Measurements of lepton-pair production have been performed by the ATLAS Collaboration in a wide range of di-lepton invariant masses and with data collected at different center-of-mass energies [1–3]. To reach small systematical uncertainties, these measurements rely on very accurate lepton reconstruction. The Rome group has an important role in the reconstruction of muons, with a leading role in the muon reconstruction software, in the calibration of the muon spectrometer, and in the muon trigger system. The ATLAS Collaboration has been using dilepton data to measure some of the fundamental parameters of the SM, such as the W-boson mass [4] and the electroweak mixing angle θ_W [5]. Figure 1 shows the ATLAS measurements of the W-boson mass as a function of the top quark mass, compared to indirect results from electroweak fits. Further improvements are expected with the analysis of larger sets of data and from special runs dedicated to precision measurements. The ATLAS Rome group is currently working on an extension of the measurement of lepton-pair production towards small di-lepton invariant masses. Such a measurement will provide a unique test of the density of the constituents of the proton that carry a very small fraction of the proton momentum ($x \simeq 10^{-4}$). In this low-x regime, new QCD effects are expected beyond the standard DGLAP (Dokshitzer-GribovLipatovAltarelliParisi) evolution of the parton densities. These effects may have a large impact in future collider at higher energy. Figure 2 shows a previous ATLAS measurement of the lepton-pair cross section at low mass [6] compared to QCD calculations. A large improvement in precision is expected from the ongoing analysis.

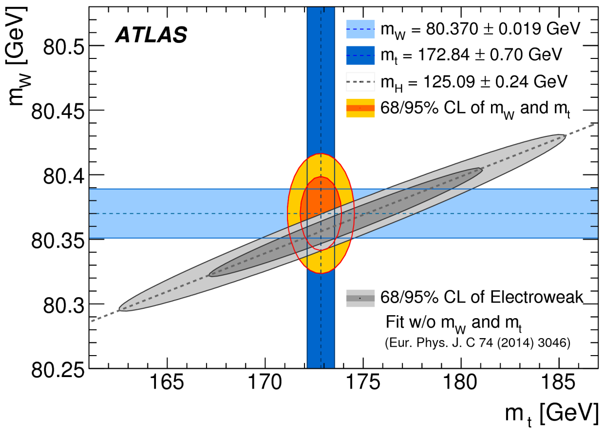

Figure 1: ATLAS measurements of the mass of the W boson and of the top quark, compared to the result from electroweak fits to the Standard Model parameters [4].

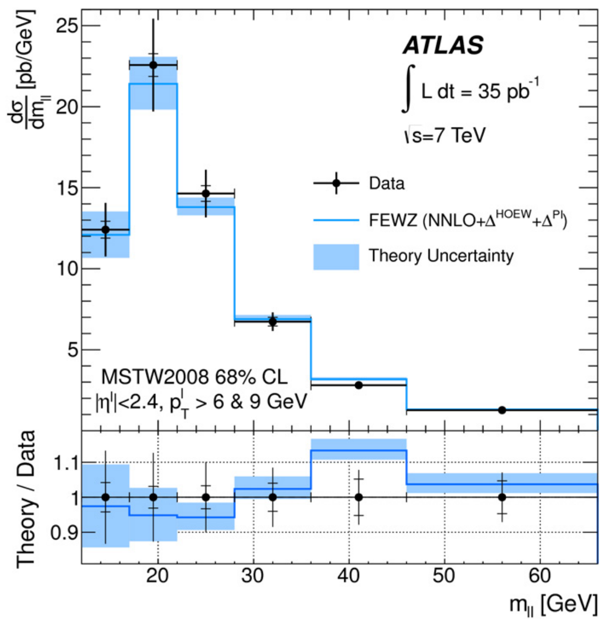

Figure 2: Cross section for lepton pair production in pp collisions at a center-of-mass energy of 7 TeV as a function of the di-lepton invariant mass. Data are compared to QCD calculations at the next-to-next-to-leading order (NNLO) [7].

References

[1] ATLAS Collaboration, Eur. Phys. J. **C** 77:367 (2017) .
[2] ATLAS Collaboration, JHEP **12** 059 (2017).
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[4] ATLAS Collaboration, Eur. Phys. J. **C** 78:110 (2018).
[5] ATLAS Collaboration, "*Measurement of the effective leptonic weak mixing angle using electron and muon pairs from Z-boson decay in the ATLAS experiment at* $\sqrt{s}$ = 8 *TeV*", ATLAS-CONF-2018-037.
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P3. Studies of Higgs Boson Properties with the ATLAS detector

The discovery of the Higgs boson [1] is one of the most prominent and landmark results of the first Run of the LHC. The discovery was made through the three main decays of the Higgs boson to vector bosons (in the diphoton, the ZZ^* in the four leptons, and the WW^* in the two leptons and two neutrinos final states). The discovery itself shed considerable light on the mechanism responsible for the electroweak symmetry breaking. The Rome group has significantly contributed to the discovery and the first measurements of the properties of the Higgs boson in the four-leptons channels [1].

In 2018, the LHC completed successfully its second run at a centre-of-mass energy of 13 TeV, collecting a dataset of approximately 150 fb^{-1}. With the higher centre-of-mass energy and the larger dataset, a vast program to measure with the highest possible precision the properties of the Higgs boson has been carried out. First precision measurements of the coupling properties of the Higgs boson have been carried out, including studies from the four-leptons (ZZ^* channel) [2] and the direct observation of the coupling of the Higgs boson to third generation charged fermions [3].

The Yukawa coupling of the Higgs boson to the top quark happens through the $pp \to t\bar{t}H$ process [3]. Substantial indirect evidence of the coupling of the Higgs boson to top quarks is obtained from its main production mode through the gluon fusion process (proceeding predominantly through a loop of top quarks) and was extensively studied through the discovery channels and therefore also the ZZ^* four-leptons channel.

The direct observation of the $pp \to t\bar{t}H$ production mode is very challenging, both due its low cross section and the complex final state that is produced. The observation required the combination of various decay channels, including the diphoton, the b quark pair, the tau pair, the W boson pair and the four-leptons.

The Rome group has also significantly contributed to the direct observation of this production mode. Consequently the observation in the final state of multiple leptons, originating from the decays of W bosons or tau leptons, has revealed the Yukawa coupling of the Higgs boson to the top quark. The group is leading the analysis team in charge of one of the most sensitive channels in this search: the final state topology where the Higgs boson decays to a pair of taus or W bosons with two same-sign electrons or muons and one reconstructed tau. In these events, in addition to the three aforementioned leptons, events are required to have four jets, two of which tagged with a B hadron.

The observation of the third generation Yukawa couplings is a major and fundamental result obtained with the LHC Run 2 data. It establishes that the Higgs boson responsible for the electroweak symmetry breaking and the masses of the gauge bosons is also responsible for the masses of the fermions.

The larger dataset and centre-of-mass energy delivered at the run 2 of the LHC, and the greatly improved precision of theoretical predictions, have been key to reach a significantly improved precision on the measurement of the Higgs bosons couplings in the combination of all Higgs boson measurement channels. These results are illustrated in Figure [4].

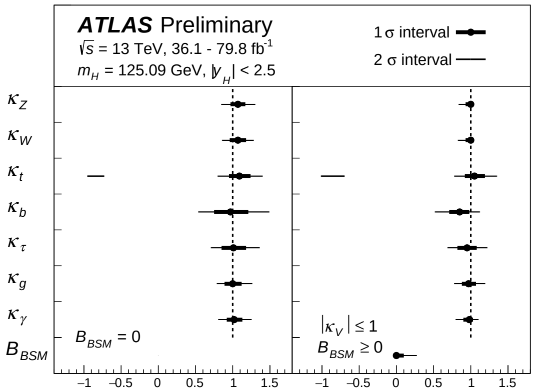

Figure 1: ATLAS measurements of the Higgs boson couplings (to the Z and W bosons, the effective coupling to photons and gluons, and the Yukawa couplings to the top, b quark, and the tau lepton) under two assuptions: (i)-left that only Standard Model particles contribute to the total width of the Higgs boson, and (ii)-right that the coupling of the Higgs boson to vector bosons cannot exceed 1.

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[2] ATLAS Collaboration, "*Combined measurements of Higgs boson production and decay*, ATLAS-CONF-2019-005.
[3] ATLAS Collaboration, Phys. Lett. B 784, 173 (2018).
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P4. Searches for Dark Matter and Invisible Higgs decays

During the Run 2 of LHC operation, at the collision energy in the center of mass of 13 TeV, the ATLAS experiment recorded a high-statistics dataset of proton-proton collisions, corresponding to 139 fb^{-1}. This is currently scrutinized with a wide program of searches for evidence of new phenomena beyond those predicted by the Standard Model (SM). Two particular topics in which the Rome group focused are the searches for evidences of Beyond the Standard Model (BSM) providing a candidate for Dark Matter (DM) and the search for anomalies of the SM in the Higgs boson sector, also through its decay into invisibile particles.

Most of new phenomena initiated by proton collisions must couple any newly produced particle with the constituent partons of the proton, and thus can produce partons, which, after showering and hadronization, manifest as collimated jets of particles in the final state. Signature based on the reconstruction of hadronic jets in the detector can be quite sensitive to new physics evidence.

Exotics particles produced in the collisions, can, on the other side, be weakly interacting with the ordinary matter, therefore resulting as *invisible* in the detector, but whose existence can be inferred from an unbalance in the detector transverse plane energy distribution, called E_T^{miss}.

The search for DM at colliders relies on the Weakly Interacting Massive Particle (WIMP) paradigma, which assumes that in the simplest SM extensions the DM candidate particle is produced via a massive mediator (such as a Z') which couples to it and to SM particles. Two complementary approaches can probe such BSM models: the search for such mediator particle as a new resonance in di-jet events or the search for the decay to DM candidate in events with a large amount of E_T^{miss} and a single hadronic jet radiated from the initial state (ISR) of the collision.

Searches for new resonances decaying to two jets have been carried out in a wide range of mediator masses, considering also events where an additional ISR jet is present or where the two jets from the resonance are merged in a single, wider, object. Given no deviation with respect to the smooth SM background prediction, interpretations in terms of exclusion for different BSM models, besides DM mediators are given: excited quarks, W',Z', excited bosons W^*, quantum black holes [1].

Complementary searches focus on the decay of the aforementioned mediators to undetected WIMPs in association with a single visible object in so-called mono-X signatures. One of the most sensitive searches is considering events with one energetic jet and classifying them based on their E_T^{miss}. Good agreement is observed between events in data and SM predictions, and thus exclusion limits are placed on different DM-related models [2].

The searches mentioned above, as well as other ones has been combined in a publication providing the best constraints on different DM simplified model (Fig.1) [3].

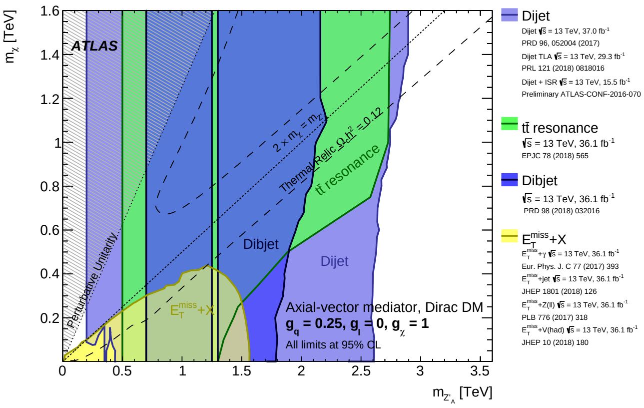

Figure 1: Constraints from different searches on an Axial-Vector mediated DM simplified model, as a function of the main model's parameters [1].

Dark matter particles, if sufficiently light, may be produced in decays of the Higgs boson, therefore searches for the invisible decays of the SM Higgs boson are carried out. Given the invisible decay of the Higgs boson, the detectable signature of such process must be characterized by the presence of visible elements, therefore the Higgs boson production through vector boson fusion or in association with a massive boson W/Z are exploited. A combination of searches in the different production modes has been published, providing constrains on the Higgs branching ratio to invisible particle [3]. The data collected during the LHC run at the center of mass energy of 7, 8, and 13 TeV, corresponding to a total amount of 61 fb^{-1} excluded the invisible Higgs decays with a branching ratio of 0.26, or larger, at 95% confidence level.

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P5. Search for Dark Matter using Long Lived Particles with the ATLAS Experiment

A class of theories beyond the Standard Model, collectively called Dark Sector models, can lead to the production of unusual signatures in detectors at the Large Hadron Collider (LHC), that may include long-lived collimated jets of displaced leptons or hadrons. These signatures allow to evade the current stringent constraints of Standard Model extensions based on more conventional decays, and at the same time can provide a viable solution to important unanswered questions in cosmology and particle physics these days: the Dark Matter problem, the anomalous magnetic moment of the muon, the asymmetries in the electron and positron fluxes measured in satellite experiments, and the recently reported anomaly in ^8Be nuclear decays.

Dark Sector models hypothesize the existence of a hidden sector that is weakly coupled to the visible one. Depending on the structure of the hidden sector and its coupling to the Standard Model, some light unstable neutral hidden states called dark photons (γ_d) may be produced at colliders, for example via Higgs boson decays. The dark photon mixes kinetically with the SM photon and decays back into SM leptons and light quarks with long lifetime. For a small kinetic mixing (ϵ) value, the γ_d has a long lifetime, so that it decays at a macroscopic distance from its production point . Due to its small mass, the dark-photons are typically produced with a large boost producing collimated jet-like structures containing pairs of electrons and/or muons and/or charged pions collectively called “lepton jets”. The lepton-jet signature represent a challenge both for the trigger and for the reconstruction capabilities of the LHC detectors. In the absence of information from the inner tracking system it is in fact necessary to use the muon spectrometer for the reconstruction of tracks which originate from a secondary decay far from the primary interaction vertex, and this is well matched by the high-granularity measurement capability of the ATLAS muon spectrometer.

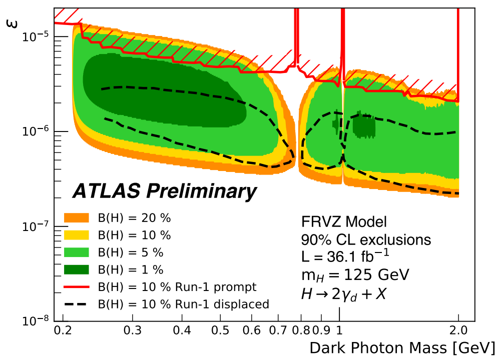

Figure 1: A two-dimensional exclusion plot in the dark-photon mass m_{γ_d} and the kinetic mixing ϵ parameter space, showing the regions excluded by ATLAS [1].

The ATLAS collaboration searched for lepton jets signatures using data collected from proton-proton collisions at LHC at $\sqrt{s}$ = 13 TeV corresponding to an integrated luminosity of 36.1 fb^{-1} [1], without finding so far any excess over the expected background. Figure 1 shows the results interpreted in the context of the Vector portal model as exclusion contours in the kinetic mixing parameter ϵ vs γ_d mass plane, where it is possible to appreciate the complementarity between the displaced and the prompt ATLAS searches.

The enormous amount of data that will be collected by ATLAS during the Run-3 (300 fb^{-1}) and High-Luminosity (3000 fb^{-1}) 14 TeV LHC phase, and the updated ATLAS detector setup, will offer a unique opportunity to probe unexplored regions of phase space in the context of such searches. The sensitivity prospects for Run-3 and HL-LHC [2] are presented in Figure 2.

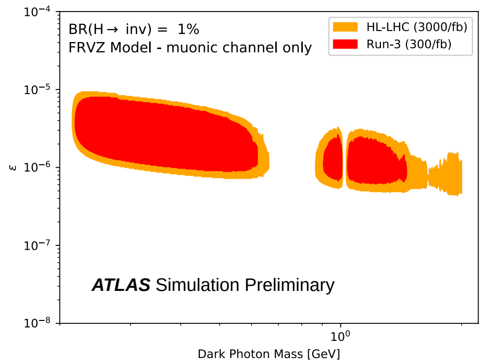

Figure 2: Exclusion plot in the dark-photon mass m_{γ_d} and the kinetic mixing ϵ parameter space, showing the expected excluded regions by ATLAS after Run-3 and HL-LHC [2].

References

[1] ATLAS Collaboration, "*Search for light long-lived neutral particles produced in pp collisions at $\sqrt{s} = 13TeV$ and decaying into collimated leptons or light hadrons with the ATLAS detector*", CERN-EP-2019-140.

[2] ATLAS Collaboration, "*Search prospects for dark-photons decaying to displaced collimated jets of muons at HL-LHC*", ATL-PHYS-PUB-2019-002.

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P6. Artificial Intelligence applications in the ATLAS Experiment

Artificial Intelligence and representation learning emergence in the recent years allowed for machine learning tools which could adeptly handle higher-dimensional and more complex problems than previously feasible.

Traditionally the main problem of the analysis of high energy physics data, characterised by large volumes and high dimensionality, is approached by dimensionality-reduction of data based on a series of analysis steps that operate both on individual collision events and on collections of events. Machine learning, and deep learning in particular, provides an extremely powerful method to condense the relevant information contained in the low-level, high-dimensional data into a higher-level and smaller-dimensional space, and can provide the needed ingredient to overcome the limits of the traditional approach.

The Rome group of the ATLAS experiment is actively involved in the design and development of both state of the art and novel deep learning models for the feature extraction, simulation and analysis of LHC data. This ranges from developing novel low-precision ternary and quantised deep neural network to run in real time on field-programmable gate array (FPGA) processors for next generation fast triggers for the high intensity HL-LHC upgrade, to the study of convolutional neural networks, generative adversarial networks and variational auto-encoders for physics object reconstruction to improve the discovery sensitivity of the ATLAS experiment for new physics beyond the Standard Model. In Figure 1 an example of the ROC curve (QCD multi-jet background rejections VS jet from dark photon decays signal efficiency) obtained by the ATLAS group in Rome in developing Convolutional Neural Network (CNN) in FPGAs for the Phase-2 Level-0 Muon Trigger of the ATLAS detector. The upper figure shows the hits pattern of the signal released by a muon crossing an ATLAS Resistive Plate Chamber detector. The pattern can be interpreted as an image and analysed by a CNN trained to identify the muon and to measure its parameters. The bottom figure shows the efficiency as a function of the transverse momentum of the muon obtained with a ternary CNN that represents an optimal solution for FPGA synthesis, given its low precision weight structure (weight can in fact assume only -1,0,1 values). In Figure 2 the result of the application of deep learning techniques for the offline classification of jets from decays of long lived particles (dark photons) with respect conventional jets from QCD production is shown. Exploiting a deep CNN trained to identify substructures and low level features in the energy deposits in the ATLAS calorimeters, improvements by more than a factor two in the rejection of background have been achieved with respect to the Boosted Decision Trees algorithm used in the previous generation of analysis [2].

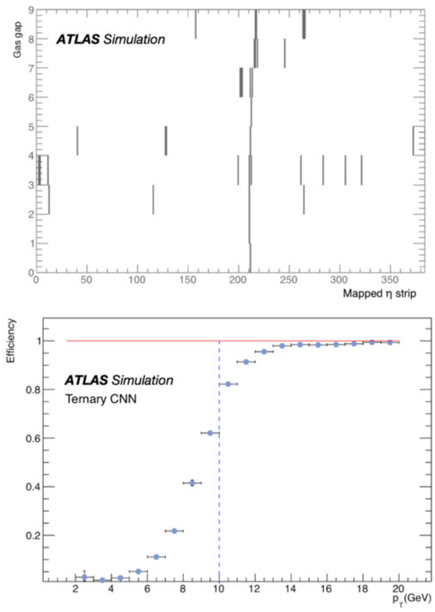

Figure 1: (top) Hits pattern of a muon particle crossing an ATLAS Resistive Plate Chamber detector. (bottom) Efficiency curve (with a threshold at 10 GeV) obtained with a ternary CNN [1].

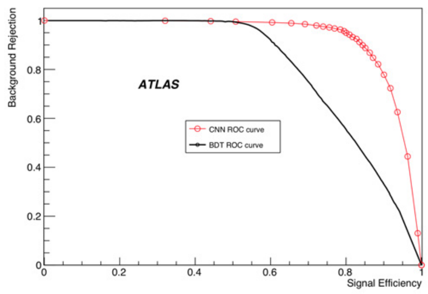

Figure 2: ROC curve obtained with a novel CNN in comparison with a BDT [2].

References

[1] ATLAS Collaboration, "*Fast Deep Learning for Phase-II L0 Muon Barrel Trigger*", ACAT 2019 proceedings.

[2] ATLAS Collaboration, "*Search for light long-lived neutral particles produced in pp collisions at $\sqrt{s} = 13\,TeV$ and decaying into collimated leptons or light hadrons with the ATLAS detector*", CERN-EP-2019-140.

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P7. The Level-1 Barrel Muon Trigger of the ATLAS experiment at LHC

The trigger system of any collider experiment is the essential component responsible of deciding whether or not to keep data from a given bunch crossing interaction for the offline analysis studies. The presence of prompt muons in the final state is a distinctive signature for many physics processes in high energy proton collisions at the LHC, therefore a high-performance muon trigger is essential.

The current ATLAS trigger system is made of a first hardware based system, called Level-1, and a second software based system, called High Level Trigger (HLT). The Level-1 provides 100 kHz data to the HLT for all the physics triggers, including 20 kHz for muon triggers. In turn the HLT selects about 1.5 kHz of events, including about 150 Hz for the muons.

Muons are identified at Level-1 in the barrel ($|\eta| < 1$) by the spatial and temporal coincidence of hits in the Resistive Plate Chamber (RPC) detectors pointing to the beam interaction point, as shown in Figure 1. The low-p_T trigger requires a coincidence in the middle RPC layers while the high-p_T trigger requires a further coincidence of hits in the outer RPC layer. The deviation from the hit pattern expected for a muon with infinite momentum is used to estimate the muon p_T.

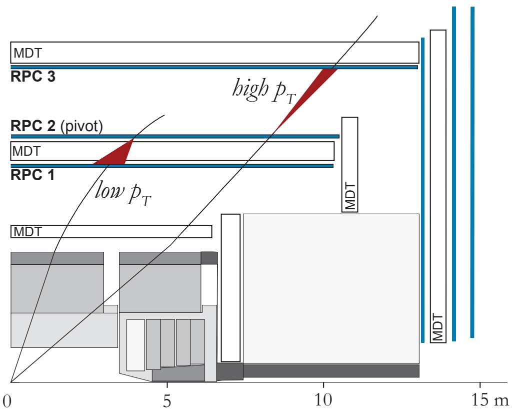

Figure 1: The current and Run3 ATLAS Level-1 muon trigger in the barrel region ($|\eta| < 1$).

The ATLAS-Roma group was responsible of the design, realisation and installation of the Level-1 barrel trigger system and was in charge of its commissioning and data taking in the early years of LHC functioning (Run1, 2011 to 2013) [1]. During the Long-Shutdown-1 (LS1, from mid 2013 to mid 2015) the group successfully installed the completion of the barrel trigger system in the lower part of the spectrometer, which makes use of new additional RPC chambers in regions that previously were not equipped, to recover respectively about 3% and 0.8% geometrical acceptance. During Run2 (2015 to 2018) the group successfully commissioned the new additional trigger regions and continued to be in charge of the maintenance and operation of the full system, including RPC timing calibrations and efficiency studies. A stable and smooth data taking was guaranteed during the full Run2 operations. The current system will be continued to be operated by the Rome group also in Run3 (2021-2024), when the LHC luminosity will be twice the nominal luminosity of 10^{34} cm^{-2} s^{-1}.

Run4 (from 2026, the so-called High Luminosity LHC) will be characterised by an increase of luminosity of about a factor of 5. These high demanding conditions impose to completely replace the current Level-1 trigger system [2]. Figure 2 shows the scheme foreseen for the Run4 new Level-0 barrel muon trigger. The on-detector Data Collector Transmitter boards (DCT) sample and time tag the RPC hits and send the data to the off-detector Sector Logic boards (SL) which perform the coincidence based Level-0 trigger algorithm [3]. The foreseen Level-0 trigger rate is 1 MHz, 50 kHz of which will be allocated for muon events. The Roma group is responsible of the full upgrade of the Level-0 barrel muon trigger system, and it is supposed to play a leading role in the whole trigger system as it did in the past.

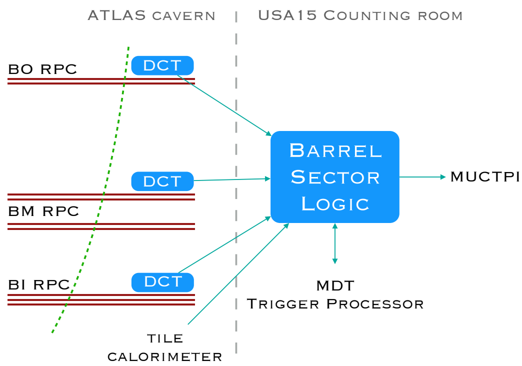

Figure 2: The Run4 Level-0 muon trigger in the barrel.

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[2] The ATLAS Collaboration, *"ATLAS Trigger and Data Acquisition Phase-II Upgrade Technical Design Report"*, CERN-LHCC-2017-020; ATLAS-TDR-029.
[3] The ATLAS Collaboration, *"Technical Design Report for the Phase-II Upgrade of the ATLAS Muon Spectrometer"*, CERN-LHCC-2017-017; ATLAS-TDR-026.

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P8. The New Small Wheel and the Micromegas chambers for ATLAS

In the High Luminosity LHC protons will collide at 14 TeV center of mass energy at a luminosity in the range $5 \div 7 \times 10^{34}\ cm^{-2}s^{-1}$. Such scenario is particularly demanding for the detectors in the forward regions of the ATLAS experiment where large fluxes of particles are expected.

At present in the pseudorapidity range $1.3 < |\eta| < 2.7$, the first stations ('Small Wheel') for the muon detection at ± 7 m from the interaction point, are composed by TGC (Thin Gap Chamber) chambers for the trigger and CSC (Cathode Strip Chamber) and MDT (Monitored Drift Tube) detectors for the position measurement (see Figure 1). These detectors are not adequate for the new high rates of particles expected during HL-LHC. Furthermore a trigger station added in the position of the Small Wheel, and able to track particles with a O(mrad) resolution, will reduce the trigger rate due to fake muons.

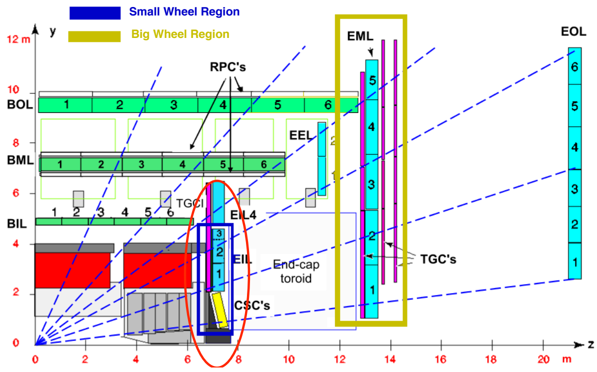

Figure 1: The location of the Small Wheel detectors in the ATLAS Experiment (x-y view of one quarter of the detector).

The ATLAS experiment is presently building a new detector, called New Small Wheel (NSW) [1], with 'small-strip Thin Gap Chambers' as main trigger device and 'Micromegas' chambers (MM) to measure the position of the particles. To achieve a resolution in momentum better than 15% for 1 TeV muons, the position of a track before the Endcap Toroidal magnets in the forward regions, has to be measured with a resolution of about 50 μm. The resolution in position on the single hit in the detectors has to be of the order of 100 μm and a similar accuracy is demanded in the assembly of the components of the chamber.

The ATLAS Rome group is involved in the realization of the Micromegas chambers. This is a Micro Pattern Gas Detector built with the modern photolithographic technology. In this detector the charged particles crossing the detector ionize the gas in a conversion/drift region of a few mm, separated by a thin metal grid (micro-mesh) from a 128 μm thick multiplication gap. Electrons drift to the mesh and enter in the multiplication gap where in a strong 40 kV/cm field they produce an avalanche collected on resistive microstrips. The signals are readout by capacitively coupled metallic microstrips below an insulating layer underlying the resistive microstrips.

The first New Small Wheel (the NSW-A) will be installed in ATLAS before the end of the Long Shutdown 2 (LS2), that is within 2020, while the second Wheel will be installed in a forthcoming shutdown. Seven italian groups from the universities and Sezioni INFN of Cosenza, Lecce, Napoli, Pavia, Roma, RomaTRE and Laboratori Nazionali di Frascati are committed to build 32 large trapezoidal chambers about $2.2\ m \times 1.3\ m$, that is one quarter of the MM NSW chambers and to design and realize the 32 Trigger Pad Logic Boards used to find the tracks for the trigger in the New Small Wheel. Within this project the Sapienza group has already delivered 96 drift panels that are being used for assembling the chambers. At the moment 10 out of 32 chambers have been delivered to CERN and are now under integration. Four of them are shown in Fig. 2 The Italian groups plan to complete the production of the 32 chambers by the summer of 2020.

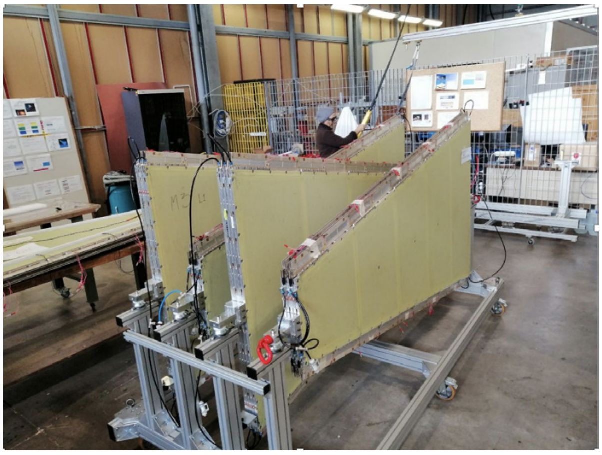

Figure 2: Four Micromegas chambers built from the Italian collaboration

References

[1] ATLAS Collaboration, "*New Small Wheel - Technical Design Report*", CERN-LHCC-2013-006 / ATLAS-TDR-020.

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P9. The Computing System of the ATLAS Experiment at the LHC

The ATLAS Computing System[1] is responsible for the provision of the software framework and services, the data management system, user-support services, and the world-wide data access and job-submission system. The development of detector-specific algorithmic code for simulation, calibration, alignment, trigger and reconstruction is under the responsibility of the detector projects, but the Software and Computing Project plans and coordinates these activities across detector boundaries. In particular, a significant effort has been made to ensure that relevant parts of the offline framework and event-reconstruction code can be used in the High Level Trigger. Similarly, close cooperation with Physics Coordination and the Combined Performance groups ensures the smooth development of global event-reconstruction code and of software tools for physics analysis.

Italy provides facilities to the ATLAS collaboration. The *Tier-1*, located at CNAF, Bologna, is the main centre, also referred as regional centre. The *Tier-2* centres are distributed in different areas of Italy, namely in Frascati, Napoli, Milano and Roma La Sapienza.

The computing activities of the ATLAS collaboration have been constantly carried out in 2018 and later, in order to finalize the analysis of the data of the Run-2, produce the Monte Carlo data needed for the 2018 run and produce the data for the upgrade studies. In this period, the Tier1 and the four Tier2's, have been involved in all the computing operations of the collaboration: data reconstruction, Monte Carlo simulation, user and group analysis and data transfer among all the sites. Besides these activities, the Italian centers contributed to the upgrade of the Computing Model both from the testing side and the development of specific working groups. Several improvements in the Computing Model has been achieved in 2018 and the first part of 2019, more precisely in the software domain and the infrastructure. The use of the grid in 2018/2019 has been stable on 320k simultaneous jobs, with peaks around the conferences periods above 500k, showing the reliability and effectiveness of the use of grid tools.

The contribution of the Italian sites to the computing activities in terms of processed jobs and data recorded has been of about 9%, corresponding to the order of the resource pledged to the collaboration, with very good performance in term of availability, reliability and efficiency. All the sites are always in the top positions in the ranking of the collaboration sites. Figure 1 shows the number of parallel jobs in the Italian Computing System of ATLAS from 2018 to 2019.

The ATLAS group at the Sapienza Università di Roma and at INFN Sezione di Roma has been heavily involved in barely all the Computing activities of the ATLAS ecosystem, since the beginning of the Grid infrastructure in 2000. The members of the group have been pioneers of many subsystem, including the creation

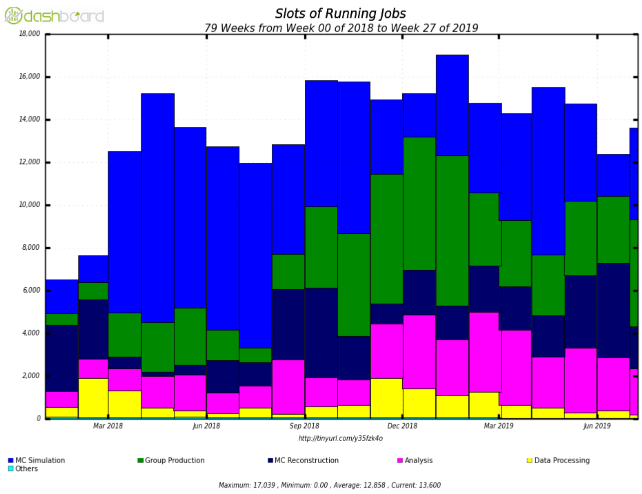

Figure 1: Number of parallel jobs running in the ATLAS Italian Tier1 and Tier2's.

of the ATLAS Virtual Organisation [2], the distribution of the software and its evolutions to CVMFS [3,4], the access to the condition database via the Frontier System [5] and the remote calibration of the Muon Detectors (Remote Calibration Centers) [6]. The ATLAS group operates one of the most efficient Tier-2 infrastructures in the ATLAS Grid and hosts some of the Central Services, like the Installation System services. Currently the group is starting a new project called Harvester to extend the optimisation of the ATLAS resources, by creating a new resource-facing service, to be plugged in the global production system called PANDA [7].

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P10. The CMS experiment at the CERN LHC and its upgrade for HL-LHC

In 2015, the Large Hadron Collider at CERN achieved a center-of-mass energy for proton-proton collisions of 13 TeV, the new world record for particle acceleration. While a small increase in collision energy is planned in the 2021, the main improvement in the sensitivity of the search for physics "beyond the standard model" (BSM) will come from increased luminosity. The current period of LHC operations (Phase-1) will end in 2023. A long shutdown of the machine will then allow to upgrade the optics in the interaction region to produce more tightly focused and overlapping beams at collision. The LHC will resume operations in 2026. The decade following these upgrades is called the High Luminosity (HL-LHC) era or Phase-2 of LHC operations.

For the HL-LHC, the brightness of the beams and the new focusing scheme at the interaction point will enable the accelerator to deliver an instantaneous luminosity of 10^{35} cm^{-2}s^{-1}, five times larger than the Phase-1 value. This rate will largely exceed the capabilities of the existing detectors, which will consequently require significant upgrades to continue working efficiently.

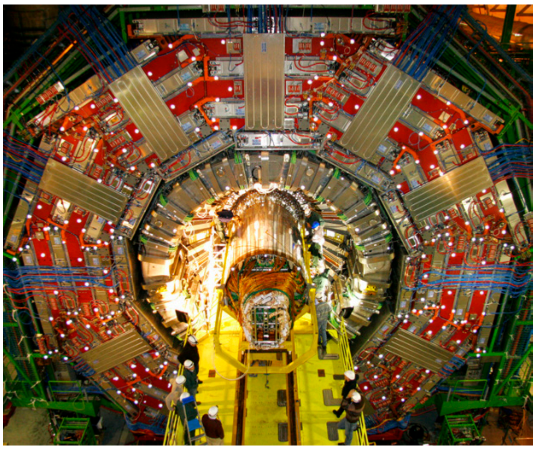

Figure 1: The CMS experiment at LHC.

The CMS detector[1] undergoes an extensive Phase-2 upgrade program to prepare for the challenging conditions of HL-LHC. Hard interactions of interest to CMS, those that probe energy scales ranging from a few GeV to several TeV, occur in less than 1% of the total beam crossings but will always be accompanied, given the increased integrated luminosity, by an average of 140-200 additional interactions. The spatial overlap of tracks and energy deposits from the additional collisions can degrade the identification and the reconstruction of the hard interaction and can increase the rate of false triggers. In addition, the higher collision rate integrated over time results in more radiation damage than can be tolerated by some of the existing subdetectors. The upgraded detector must survive and function efficiently in this much harsher radiation and high pileup environment and must transport a much higher rate of data off the detector to be recorded for analysis. The primary goal of the CMS Phase-2 upgrade is to maintain the current excellent performance of the detector in efficiency, resolution, and background rejection for all final state particles and physics observables of interest in data analysis.

The Rome group has been deeply involved from the beginning to the R&D and the construction of the Electromagnetic Calorimeter (ECAL) of Lead Tungstate scintillating crystals and is now involved in the upgrade of this detector. More recently the group has expanded its interest becoming a leading actor in the R&D of the fast timing detectors and in the construction of CMS Mip Timing Detector (MTD). The MTD is a recently approved new project; its Technical Design Report is currently being reviewed by the LHC Experiments Committee. In the next three pages the activities of the CMS Rome group on the ECAL operations and MTD construction will be described.

At the same time, the CMS Rome group is strongly involved in the physics analysis of 13 TeV data, collected by CMS in the LHC Run 2 (2015-2018). In the following pages a brief summary of the local activities in the Standard Model, in the Higgs boson and in the BSM areas is also presented.

The leading role of the CMS Rome group is recognised by the numerous top management coordination tasks assigned to its members in the last three years: the CMS Physics Coordinator, the ECAL Project Manager, and the MTD national representative are some examples. Moreover the current or recent coordinators of the CMS Higgs analysis group, the CMS Electron and Photon group, the ECAL Performance group and the MTD Performance group are members of the CMS Rome group.

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The CMS Rome Group: L.M. Barone[1], F. Cavallari, M. Cipriani[1], D. del Re[1], I. Dafinei, M. Diemoz, E. Di Marco, G. D'Imperio, E. Longo[1], P. Meridiani, G. Organtini[1], F. Pandolfi, R. Paramatti[1], S. Rahatlou[1], C. Rovelli, F. Santanastasio[1], L. Soffi.

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P11. The CMS electromagnetic calorimeter performance in LHC Run2

The CMS electromagnetic calorimeter (ECAL) is an instrument designed to measure electron and photon energies and position with great precision. It is made of 75848 lead tungstate ($PbWO_4$) scintillating crystals, arranged in a barrel part and two endcaps which cover the forward regions. The energy resolution of the ECAL was optimised using the two-photon decay of the Higgs boson as a benchmark, and it was fundamental to its discovery.

After the LHC Run1 (2010-2012) with proton-proton collisions at center-of-mass energies of 7 and 8 TeV, the CMS ECAL has operated at the LHC Run2 at 13 TeV center-of-mass energy, with a beam collision spacing of 25 ns and instantaneous luminosity of up to $2{\cdot}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The average number of concurrent pp collisions per bunch-crossing (pileup) has reached the value of 60. These high luminosity levels have required a retuning of the ECAL reconstruction algorithm, a careful monitoring of the radiation effects on the crystals and a crystal-to-crystal calibration every year.

The crystal pulse shape convoluted with the electronic shaping has a decay time of about 40 ns. Therefore it is sensitive to pile-up hits of previous and following bunch crossings. For every hit in the crystals, the readout stores the readings of ten consecutive bunch crossings. In Run1 a simple weighted sum of the samples was used to calculate the pulse amplitude (weight method). This method was fast and could be used also in the trigger system, however it was not robust against out-of-time hits. A new method was developed to fit the hit amplitudes of the ten bunch crossings simultaneously, exploiting all the available samples (multi-fit). Common fitting techniques are typically slow and require a large computing power. Using simple assumptions, the problem has been solved with fast matrix inversion techniques, allowing it to be used also at trigger level. Figure 1 shows a typical measured pulse shape with the contributions of the hits of the various bunch crossings as reconstructed by the multifit.

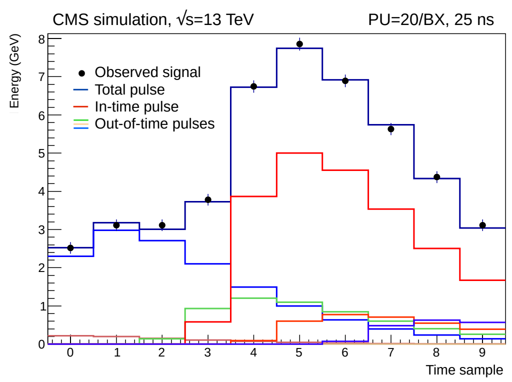

Figure 1: Example of a fitted pulse for simulated events with 20 average pileup interactions and 25 ns bunch spacing.

Due to the high radiation levels, the crystal transparency has decreased, particularly in the forward region of the detector, and the noise has increased. A new algorithm to suppress the noise has been developed. A careful monitoring of the crystal transparency is performed during data-taking using laser light. The laser transparency corrections are computed within 48 hours from data-taking and are used for prompt CMS data reconstruction. During Run2 such corrections were also used for the energy computation at the trigger level.

At the end of Run2, exploiting the full statistics, a full recalibration of the calorimeter has been performed, in order to achieve the optimal performance, which is needed for precision analyses (like for example Higgs boson mass and W boson mass measurements). Improved laser corrections have been derived, drifts of the laser monitoring system have been corrected, and channel-to-channel calibrations have been computed equalizing the channel response using physics signals: $\pi^0 \to \gamma\gamma$ invariant mass, W$\to e\nu_e$ track momentum to ECAL energy ratio, Z$\to$ee invariant mass, and azimuthal symmetry of energy deposits in minimum bias events. Figure 2 shows the energy resolution, obtained for electrons in 2017 data, measured with the initial calibrations, which were available soon after data-taking, and with the optimal calibrations. The improvement is substantial, particularly in the forward part.

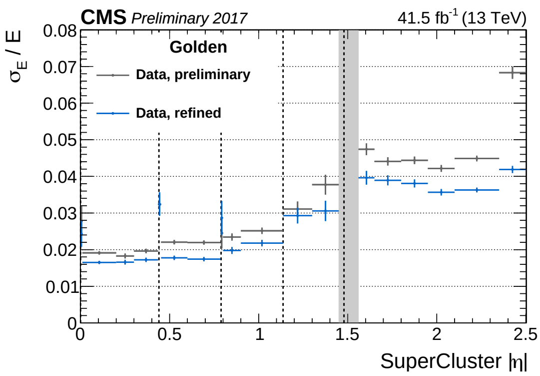

Figure 2: Energy resolution for Z$\to$ee electrons measured in the ECAL in 2017 with the preliminary and refined calibrations.

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P12. CMS Mip Timing Detector for High-Luminosity LHC

For the HL-LHC, the nominal running scenario is to operate the accelerator at a stable leveled luminosity up to 7.5×10^{34} cm^{-2}s^{-1}, with a number of interactions during each bunch crossing (pileup) reaching 200 on average, roughly a factor of 5 higher with respect to the current LHC conditions. The upgraded detectors must survive and function efficiently in this much harsher radiation and high pileup environment.

The CMS Mip Timing Detector (MTD) will help to mitigate the degradation of the performance in the event reconstruction due to pileup effects by assigning a time to each charged tracks with a resolution of about 30 ps. This is much smaller than the crossing time between two colliding proton bunches (180 ps), and allows to separate tracks which overlap in space by using the time coordinate. The use of the timing information for each track will effectively allow to reduce by a factor of about 5 the number of tracks from pileup vertices that are incorrectly associated with the hard-scattering process, restoring conditions similar to what is currently experienced [1].

Mechanical constraints, performance, radiation tolerance, cost and upgrade schedules led to a detector design consisting of a thin layer between the tracker and the calorimeters, divided into a barrel (Barrel Timing Layer, BTL) ($|\eta| < 1.5$) and two endcap sections (Endcap Timing Layer, ETL) covering up to $|\eta| = 3.0$. For the BTL, the sensors will be made by radiation hard scintillating crystals (Lutetium-yttrium oxyorthosilicate, LYSO) read out with Silicon Photomultipliers (SiPMs), which are pixelated avalanche photodiodes operating in Geiger breakdown mode. Instead, for the ETL, which will operate in a much harsher radiation environment than BTL, Low Gain Avalanche Diodes (LGADs), silicon sensors with internal gain of about 10−30, will be used. A sketch of the detector layout is visible in Fig. 1.

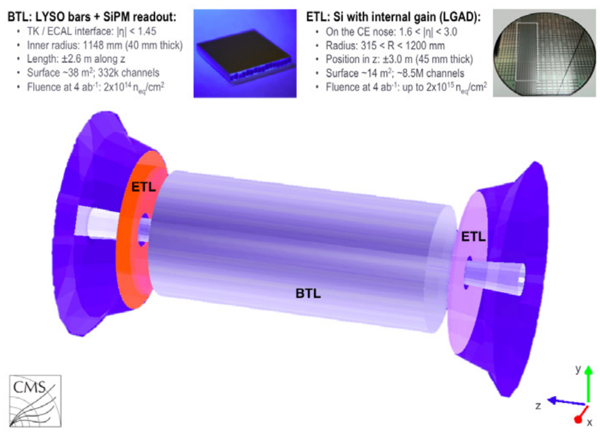

Figure 1: A schematic view of the CMS MTD layout. It comprises a barrel timing layer, BTL, (grey cylinder), at the interface between the tracker and the calorimeter, and two endcap timing layers, ETL, (orange and light violet discs).

MTD is fundamental to maintain good resolution and efficiency to reconstruct physics objects in a high pileup environment, allowing to exploit the full HL-LHC physics potential. For complex final states, such as those exploited in the search for Di-Higgs boson production, the gain in signal acceptance from MTD was estimated to be about 25%, with an increase in signal significance equivalent to running HL-LHC for few additional years. MTD also brings new capabilities to CMS, allowing to measure the speed of charged tracks or the time of displaced vertices. Identification of charged hadrons (pions, kaons, or protons) based on time-of-flight becomes possible up to a few GeV in p_T, providing significant benefits to flavour physics studies. Moreover, this will allow to extend the experimental sensitivity to new phenomena (e.g. production of slow charged tracks or displaced objects) in regions of phase space which would remain otherwise unexplored. The projected performance gains from MTD are summarized in Table 1.

The Rome group has a leading role in the assessment of the performance of the MTD and the corresponding gains for the HL-LHC physics programme. In particular, it is involved in the development of the MTD simulation and reconstruction code.

Table 1: Expected impact of the CMS MTD on some pillars of the HL-LHC physics program

Signal	Gain from MTD
Higgs precision physics	+25% statistical precision
HH	+25% gain in signal yield
SUSY	+40% background reduction
Long Lived Particles (LLP)	New handles for displaced/slow objects
Flavour physics	Combinatorial background reduction

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P13. LYSO crystal characterization for the Mip Timing Detector

The Barrel Timing Layer (BTL) of the CMS MTD is a cylindrical detector with a surface of about 38 m^2. It is designed to detect Minimum Ionizing Particles (MIPs) with time resolution of 30−50 ps. The BTL is located between the ECAL and the Tracker providing a coverage up to $|\eta| = 1.48$.

The sensitive elements consist of Lutetium Yttrium Orthosilicate crystals doped with Cerium (LYSO:Ce). The crystals are shaped in a bar-like geometry of 57 mm length, 3.12 mm width and an average thickness of 3 mm readout by a pair of SiPMs, one at each end, matching the size of the crystal end face for optimal light collection. The choice of this crystal geometry minimizes the SiPM area with respect to the crystal sensitive volume, limiting power consumption and channel count, without loss of light collection efficiency. This is enabled by the light propagating in total internal reflection mode within crystals of such high aspect ratio. This sensor layout exploiting double-ended readout also provides uniform time response across the surface, tracking capabilities and redundancy of time measurements per crystal.

The thickness of the crystals along the detector z axis is optimized to limit the amount of material in front of the CMS ECAL to be as small and uniform as possible ($<0.4\ X_0$, where X_0 is one radiation length) so to have a negligible impact on the ECAL energy resolution. A MIP traversing the crystal volume will produce a number of optical photons along its track proportional to the crystal light yield (LY) defined as the number of photons generated per MeV of energy deposit. A fraction of the photons will be detected at each SiPM. Detected photons will be converted to photoelectrons and amplified by the SiPM, operated with a gain of $O(10^5)$, to generate an electrical signal that can be discriminated and digitized to obtain a measurement of the time at which the MIP crossed the detector.

For precision timing purposes in the BTL environment LYSO:Ce crystals represent an optimal candidate compared to other inorganic scintillators because of their high LY of about 30000 photons/MeV, fast scintillation rise time (<100 ps), and relatively short decay time (about 40 ns). The high density of the material (7.1 g/cm^3) has the additional advantage of minimizing the space required by the scintillator, which is important given the limited space available to BTL. Furthermore, LYSO:Ce is non-hygroscopic, thus avoiding any material effect in case of ambient moisture and it provides scintillation light at a wavelength of 420 nm, matching the sensitive range of the SiPMs. Lastly, LYSO:Ce is a commonly used commodity in medical imaging applications, for Positron Emission Tomography (PET), making it a well-studied material with an abundance of global qualified vendors.

Starting in 2014 the Rome group played a leading role in the R&D on fast timing with iMCP [1]. Since the beginning of 2019 and for the next two-three years the group is in charge of the LYSO:Ce procurement for the BTL. This activity consists in the identification of manufacturers able to produce crystals that best match the physical and optical requirements set by the CMS-MTD Collaboration. This task also implies to precisely define the procedure for the Quality Control of the crystals to be used during the full production. Samples of crystal bars and crystal arrays from different manufacturers (Fig. 1) are being fully characterized in the Segrè Laboratory in Sapienza with three test benches for the following measurements:

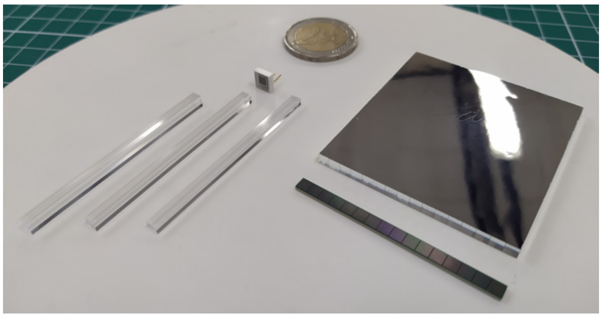

Figure 1: Samples of LYSO:Ce crystals: both single bars and linear assembled array of 16 bars are shown.

- light output and energy resolution with 511 keV photons from a Na22 radioactive source;
- decay time and coincidence time resolution;
- optical isolation of crystals within the array
- crystal density and crystal dimensions with a precision of $O(10\ \mu m)$.

Another key feature of LYSO:Ce is its radiation tolerance, which is required for operation without significant loss of transparency or light output in the high radiation environment until the end of HL-LHC operation. A subset of the crystal samples will be irradiated with photons at Enea - Calliope facility in Casaccia to check the radiation tolerance. Samples will be irradiated to the integrated ionizing dose of 25 kGy, corresponding to the BTL radiation levels at 4000 fb^{-1}. Measurements of light yield and time resolution before and after irradiation will be used to assess the radiation tolerance of the elements.

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P14. Precision measurements of the Standard Model

The Standard Model (SM) of particle physics describes matter in terms of fundamental particles and their interactions mediated by vector bosons. Within the electroweak (EW) theory, the mass of the W boson (m_W) depends on the fine structure constant, the Fermi constant and the mass of the Z boson. It also receives additional contributions from higher order corrections that depend on the gauge couplings and the masses of heavy particles in the SM, such as the top quark and the Higgs boson. A global fit to SM parameters yields an indirect estimate of $m_W = 80354 \pm 7\,\mathrm{MeV}$ (precision of 10^{-4}). The relationship among the measured masses of the W boson, the Higgs bosons and the top quark is shown in Fig. 1. The current world average for the direct measurement of m_W has a total uncertainty of 13 MeV [1].

New particles and interactions, often predicted by theories beyond the SM, could have a non negligible effect on m_W through higher order corrections. Therefore, the precise measurement of m_W with an uncertainty below 10 MeV represents an extraordinary opportunity to test the internal consistency of the SM and probe the possible existence of new physics through indirect searches.

The standard technique to measure m_W uses decays into a charged lepton (muon or electron) and a neutrino. The most precise observable is the charged lepton transverse momentum (p_T^ℓ) distribution, with a Jacobian peak at $p_T^\ell = m_W/2$. The measured distribution in data is then fitted with several simulated templates for different mass hypotheses, and m_W is estimated as the value that minimizes the likelihood ratio.

At the LHC, the largest uncertainties on m_W stem from the theoretical modeling of the W-boson production kinematics. The leading contribution arises from the limited knowledge of the parton distribution functions (PDFs) of the protons. PDFs determine the W-boson helicity (h_W) and rapidity (Y_W) distribution. These reflect in the polarization of the lepton, and result in a modification of the p_T^ℓ spectrum by either shifting or smearing the Jacobian edge.

Theoretical uncertainties can be constrained using data through ancillary measurements of the W-boson kinematics. The deep understanding of the W-boson production at the LHC is a fundamental ingredient for several precision measurements of the SM EW sector, and is paramount to improve the precision on m_W. Measurements of the Z-boson differential cross section are also valuable to test QCD and EW calculations. In particular, the measurement of p_T^Z below 10 GeV, where non perturbative effects make QCD calculations unreliable, is crucial for a better modeling of p_T^W. The measurement of Y_Z at high rapidity plays a significant role in the determination of the weak mixing angle θ_W.

The CMS collaboration aims at measuring m_W using 13 TeV data, targeting a lower uncertainty than the current experimental average. The Rome group has a leading role in the development of this project. To achieve this goal, CMS is also carrying out the measurement of h_W as a function Y_W. The measurement is performed through an innovative technique based on a fit to the lepton p_T^ℓ-η distribution, and is expected to provide in-situ constraints of the PDF uncertainty on m_W. The analysis also targets the measurement of the lepton angular coefficients as a function of Y_W, as well as the W-boson cross section and charge asymmetry differentially in p_T^ℓ-η. These results pave the way towards the full characterization of the W-boson production and decay cross section.

These SM measurements provide stringent tests of perturbative QCD and EW calculations. They will trigger the development of more accurate predictions and help to chart the course for future measurements. At the same time, the Rome group can profit from its expertise in the ECAL performance and help extend the rapidity range for the θ_W measurement using the calorimeter's region above the tracker acceptance. With all these ingredients, an interpretation based on a global fit to SM quantities is foreseen, allowing to unveil possible signatures of new physics in the deviations from the precise SM expectations.

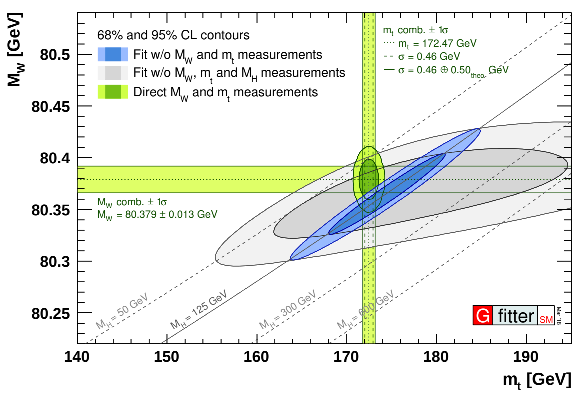

Figure 1: Measured masses of the top quark (m_t), the Higgs boson (m_H) and the W boson (m_W). Within the SM, the green bands and the blue ellipse are expected to cross each other.

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P15. Properties of the Higgs boson

The discovery of the Higgs boson (H) with a mass close to 125 GeV, made in 2012 by ATLAS and CMS Collaborations at the CERN LHC, was the first confirmation of the Brout-Englert-Higgs mechanism to explain the generation of vector bosons mass through the electroweak symmetry breaking.

To establish the Higgs boson role in the fermion mass generation, it is necessary to probe its direct coupling to fermions, determining the so called Yukawa coupling of the Higgs boson to the Dirac field of leptons and quarks. The standard model (SM) predicts that this coupling is simply proportional to the mass of the fermions, while extensions of the SM, including more than one Higgs doublet, allow, e.g., different couplings to up and down fermions. These couplings can be measured from the branching fraction of H decays to any accessible fermion-antifermion pair and can be expressed by the ratios μ_f of these decay rates to their SM prediction.

Data collected in 2016 at a center-of-mass energy of 13 TeV with an integrated luminosity of 35.9 fb^{-1}, combined with data previously collected at 7 and 8 TeV, allowed the CMS experiment to establish the $\mathrm{H} \to \tau\tau$ signal with a statistical significance of more than 5 standard deviations, leading to the first observation of Higgs boson decay to τ leptons by a single experiment [1]. The corresponding μ value is determined to be $\mu_\tau = 1.09^{+0.27}_{-0.26}$.

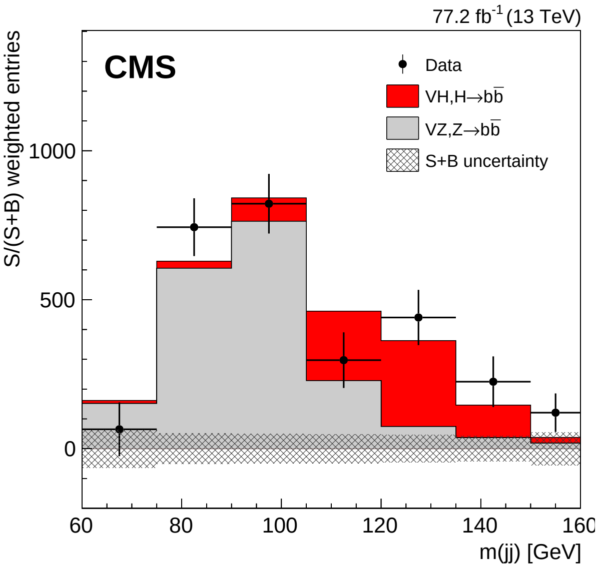

Figure 1: Observed invariant mass distribution for the two b quark jets associated with a vector boson V (W or Z). The Higgs boson signal appears around 125 GeV. The histograms represent the expected distributions for $\mathrm{H} \to \mathrm{b\bar{b}}$ signal events and background from $\mathrm{Z} \to \mathrm{b\bar{b}}$.

The luminosity integrated by CMS was roughly doubled in 2017, allowing the observation of the decay of the Higgs boson to a bottom quark-antiquark pair, $\mathrm{b\bar{b}}$, at 5.6 standard deviations, and establishing the Yukawa coupling of the Higgs boson to the b quark, with a μ_b value of 1.04 ± 0.20 [2]. The invariant mass distribution of the two b jets in the events where either an H or a Z boson are produced in association with a W or Z boson (V) and decay to $\mathrm{b\bar{b}}$ is shown in Fig. 1.

The top quark Yukawa coupling cannot be similarly tested from the measurement of a decay rate, as top quarks are too heavy to be produced in Higgs boson decays. Alternatively, the observation of the production of a Higgs boson in association with a top quark-antiquark pair, through Feynman graphs as those shown in Fig. 2, allows the determination of the Yukawa coupling of H to top quarks. From all the data collected by CMS up to 2016, combining all the accessible Higgs boson decay modes, the direct coupling of the Higgs boson to top quarks has been established for the first time with a significance of 5.2 standard deviations and a μ_t value of $1.26^{+0.31}_{-0.26}$ [3].

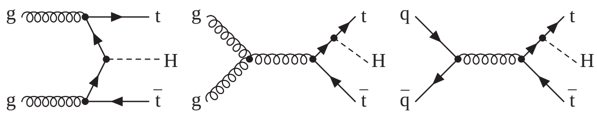

Figure 2: Example tree-level Feynman diagrams for the $\mathrm{pp} \to \mathrm{ttH}$ production process, with g a gluon, q a quark, t a top quark, and H a Higgs boson.

The CMS Rome group has contributed to all these analyses, in particular in the decay channels involving photons (like $\mathrm{ttH}, \mathrm{H} \to \gamma\gamma$) and electrons. These particles are measured in the electromagnetic calorimeter, where the group has an extended and deep experience gained during the design and the construction of the detector. Moreover the coordination of all the CMS Higgs searches in the 2017-18 term has been performed by a member of the CMS Rome group.

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P16. Search for new heavy particles

The discovery of the Higgs boson with a mass close to 125 GeV, made in 2012 by ATLAS and CMS Collaborations at the CERN LHC, was an important milestone in the investigation of the standard model (SM) of particle physics. However, SM still remains incomplete. There are several open issues which may be solved by models of physics extending the SM through new forces and predicting new heavy particles that interact with quarks and gluons. Because of this coupling, the bump hunt in the invariant mass of two hadronic jets (dijet) is a power tool to search for new physics in proton-proton collisions. The strength of the coupling determines the natural width of these particles, which can vary from narrow to wide compared to the experimental resolution in the dijet mass spectrum.

A search for dijet resonances was performed with the data collected in 2016 at a center-of-mass energy of 13 TeV with an integrated luminosity of 36 fb^{-1}. In addition to narrow-width resonances, the search investigated broad resonances with widths up to 30% of the resonance mass and considered different hypotheses for the resonance spin. In a physics model in which dark matter (DM) particles couple to quarks through a DM mediator, the mediator can decay to a pair of jets and therefore can be observed as a dijet resonance.

Hadronic jets from resonances with a mass above 1.5 TeV are selected with standard event selection criteria. At lower masses, due to the high production rate, dedicated event selection and reconstruction algorithms

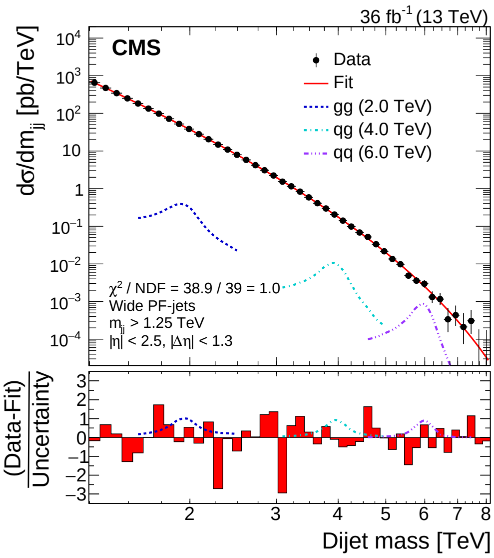

Figure 1: Dijet mass spectra (points) compared to a fitted parameterization of the background (solid curve) for the high-mass search.

were developed to select and store partial information recorded with the CMS detector. The Rome group contributed to the calibration of the energy of the hadronic jets, especially at low masses. In addition, it contributed to the modelling of the large expected background in the SM due to the copious production of hadronic jets. The dijet mass spectrum is shown in Fig. 1.

There is no evidence for a narrow resonance in the data and upper limits are set on the production cross section at 95% CL. The cross section is sensitive to the assumptions about the new particle mass and its couplings to quarks, gluons and DM particles, and hence these limits can provide constraints on these quantities (Fig. 2).

The searches extend limits previously reported by CMS in the dijet channel, resulting in the most stringent constraints on many of the models considered.

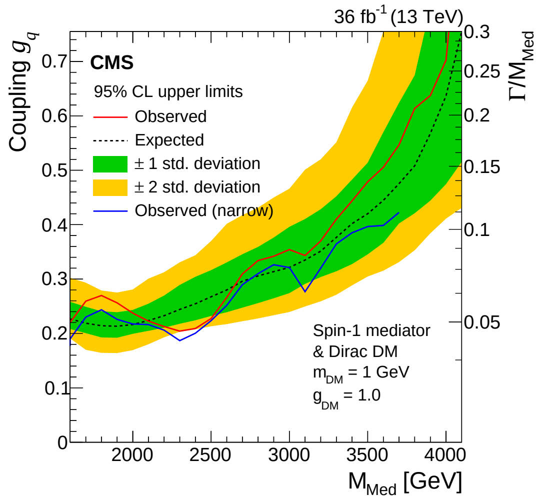

Figure 2: The 95% CL upper limits on the universal quark coupling g_q as a function of resonance mass for a vector mediator of interactions between quarks and DM particles. The right vertical axis shows the natural width of the mediator divided by its mass corresponding to the quark coupling g_q.

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https://cms.cern/
http://www.roma1.infn.it/exp/cms

P17. Searches for Long Lived Particles

Searches for new Long Lived Particles (LLPs) are theoretically well motivated. Many extensions of the standard model allow or require for long lifetimes of particles due to high-dimension operators, very small couplings, heavy mass scales, or suppressed phase space regions. The Rome group actively worked during Run 1 and Run 2 on a search for delayed photons produced in the decay of long lived particle at CMS as main authors of the analysis. The model considered is the Gauge Mediated Supersymmetry Breaking scenario, where the neutralino ($\tilde{\chi}_1^0$) is a massive, long-lived ($c\tau$ from mm to meters) particle, and usually decays to a photon and a stable massless gravitino. In order to be sensitive to short decay path lengths (O(cm)) of the neutralino, the measurement of the time of arrival of the photon is a crucial ingredient of the analysis. The better the timing resolution, the shorter the lifetime that can be probed. The most recent results of this search, shown in Fig. 1, have been obtained at CMS measuring the time of arrival of high energy photons (above 70 GeV) on the ECAL with a resolution of roughly 100 ps [1]. The possibility, at the high luminosity phase of LHC (HL-LHC), to combine a precise measurement of the time of arrival of the photon, made with the upgraded ECAL, with a precise measurement of the timing of the primary vertex where the neutralino has been produced, made with the MTD (global resolution of the order of 30 ps), will provide a powerful ingredient to discriminate the delayed photon signal with respect to the SM background, also in the case of short lifetimes up to neutralino masses of 800 GeV.

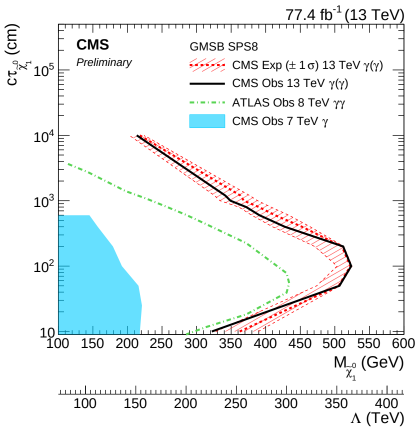

Figure 1: Excluded regions in the neutralino proper decay length ($c\tau$) vs mass plane with Run 2 data.

A broad range of new physics models exist which also foresee the production of heavy long lived particles decaying to hadronic jets. The Rome group is leading the study on an exotic model of extended Higgs sector [2] in which an Higgs boson mediates the production of two long-lived, scalar bosons (X) decaying into quarks which hadronize into jets. While the X are assumed to be neutral, part of the jet constituents is charged, thus leaving a signal in the MTD detector. In cases where the X particles are very displaced, the time of arrival of these signals at the MTD or at the calorimeters would be significantly higher than the time taken by a particle produced in the interaction point. In this context precision timing from the combination of MTD and ECAL detectors can be exploited as a new tool to suppress the large multijet background at the LHC, for which one should expect all tracks inside a jet being in time. Fig. 2 shows the projections of the upper limits on the branching ratio of the $H \to XX$ process for an integrated luminosity of 3000 fb^{-1} with an MTD based measurement. The time discrimination provided by the MTD will bring sensitivity to models with large lifetime particles (decay path lengths O(100m)).

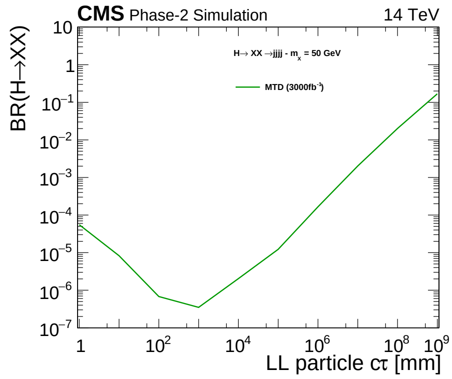

Figure 2: Sensitivity to $H \to XX \to jjjj$ signals expressed in terms of X lifetimes at HL-LHC.

A third interesting search for new long-lived particles to which the CMS Rome group has contributed is the case of Heavy Stable Charged Particles, typically produced with β significantly less than 1 at LHC. They can be identified by unusual rates of energy loss in the inner tracker material or by their longer time of flight to the outer tracking detectors compared to light SM particles. We have shown that the possibility to measure the time of flight of the particle with MTD and hence its β factor with high resolution at HL-LHC will make the difference in the discrimination of such long-lived particles.

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P18. The ALICE experiment at the Large Hadron Collider (LHC)

ALICE is a general-purpose heavy-ion experiment designed to study the physics of strongly interacting matter and the quark-gluon plasma in nucleus-nucleus collisions at the LHC. The detector is designed to cope with the highest particle multiplicities theoretically anticipated for Pb-Pb reactions and has been operational since the start-up of the LHC in 2009 [1]. In addition to heavy systems, the ALICE Collaboration is studying p-p and p-nucleus collisions, which are also used as reference data for the nucleus-nucleus collisions. The 2015 has seen the re-start of the physics program at the LHC, after the upgrade of the machine and the consolidation of the experiments during the Long Shut-down 1 (LS1) from the April 2013 to the end of 2014. During the ensuing run with protons at 13 TeV ALICE operated very smoothly, adjusting the choice of triggers to the evolving running conditions. In the following intensity ramp up phase with 50 and 25 ns bunches spacing, ALICE has been operating at instantaneous luminosities up to 5 Hz/μb collecting 620 M of minimum bias events and integrating 4.35 pb^{-1} of di-muon triggers and 1.81 pb^{-1} of high multiplicity triggers in proton-proton collisions. Many new physics results have been obtained from p-p, p-Pb and Pb-Pb collisions [2,3,4]. In particular no cold nuclear matter effects have been measured in p-Pb collisions, while several signals of collective effects have been unexpectedly observed in collisions of smaller systems (both p-p and p-Pb) triggering a considerable interest in the theorists. The group of Rome is involved in the analysis studying the jet coming from heavy quarks (like charm and beauty) as golden channel to probe the Quark Gluon Plasma (QGP), the space-time evolution of the hadronization process and the phenomena of energy loss (quenching). The group has also the responsibility of the Silicon Drift Detector (SDD) of the Inner Tracker together with the Torino and the Trieste groups (both University and INFN). The long-term goal of the ALICE experiment is to provide a precision characterization of the high-density, high-temperature phase of strongly interacting matter. To achieve this goal, high-statistics, high precision measurements are required, which necessitate upgrading the ALICE detector. The general upgrade strategy is conceived to deal with this challenge with expected Pb-Pb interaction rates of up to 50 kHz aiming at an integrated luminosity above 10 nb^{-1}. The main physics studies rely on new and more precise measurements of heavy flavour (charm and beauty) production in heavy-ion collisions, which address important questions about the QGP properties that cannot be answered with the present experimental setup. In this context, ALICE will apply important changes: a new silicon vertex detector (ITS), a new readout via GEM in the TPC, a forward silicon tracking for muon physics and an upgrade of the readout electronics of all other detectors to 50 kHz. In details, all the new ITS will be constituted of seven layers of Monolithic Active Pixel Sensors (MAPS) with pixel size of 29×27 μm^2. The new ITS will have greatly improved features with respect to the current one in terms of determination of the distance of closest approach of the tracks to the primary vertex, standalone tracking efficiency at low p_T , momentum resolution and readout rate capabilities. The main parts developed under the responsibilities of the Italian teams include: Design of the pixel chip and in particular, of the PLL serializer and driver, and of the digital readout architecture and interface; Development of the test systems for the characterization of the single pixel chip and of the detector components, i.e. modules and staves, during the various phases of the construction process; Characterization of the pixel chip and of the detector module and stave with different sources (radioactive and laser) and in test beams; Development of the Module, the Stave and the Mechanics for the integration in layers of the Outer Barrel; Construction and characterization of a fraction of Modules and Staves for the Outer Barrel, and of the Mechanics for the integration of the four outermost layers; Readout electronics, Data transmission and Power supply system.

Concerning the upgrade, the Rome group is working on the new ITS collaborating specially with the Frascati Laboratory of INFN. The specific hardware contribution of Rome and Frascati groups is in the development and production of the basic unit named stave. The full staves production is completed by September 2019. The assembly of the various barrels it is in progress at CERN. Consequently, the commissioning on surface at CERN is started. The work in the cavern will be on June 2020 with related full detector commissioning. The whole new ITS will be ready for the installation in ALICE by the end of LHC Long Shutdown 2 (2021).

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P19. Discrete symmetries tests with neutral kaons at KLOE-2

On March 30th 2018 the KLOE-2 experiment concluded its data-taking campaign started in November 2014 at DAΦNE, the ϕ-factory collider of the INFN National Laboratories of Frascati (LNF). For the KLOE-2 run an innovative collision scheme based on the *crab-waist* concept has been applied for the first time in presence of a high-field detector solenoid, allowing to achieve the luminosity goal set for KLOE-2, with the experiment successfully acquiring 5.5 fb^{-1} of integrated luminosity.

The KLOE-2 data sample together with the one collected by its predecessor KLOE, in total an integrated luminosity of 8 fb^{-1} corresponding to $\sim$ 24 billions of ϕ-mesons produced, is the largest existing collected at an e^+e^- collider at the ϕ resonance peak. It is very rich in Physics and its analysis provided and will continue to provide a variety of significant scientific results including precision tests of the fundamental discrete symmetries and of quantum mechanics in the entangled neutral kaon pair system produced at DAΦNE.

The asymmetries which can be constructed from the semileptonic decay rates of neutral kaons into the two CP conjugated semileptonic final states, $\pi^-e^+\nu$ and $\pi^+e^-\bar{\nu}$, constitute a powerful probe in the study of discrete symmetries. In particular, the charge asymmetries for the physical states K_S and K_L defined as:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^-e^+\nu) - \Gamma(K_{S,L} \to \pi^+e^-\bar{\nu})}{\Gamma(K_{S,L} \to \pi^-e^+\nu) + \Gamma(K_{S,L} \to \pi^+e^-\bar{\nu})} \tag{1}$$

are sensitive to CP violation effects. At first order in small parameters:

$$A_{S,L} = 2\left[Re\,(\epsilon_K) \pm Re\,(\delta_K) - Re(y) \pm Re(x_-)\right] \tag{2}$$

with $Re\,(\epsilon_K)$ and $Re\,(\delta_K)$ implying T- and CPT-violation in the $K^0 - \bar{K}^0$ mixing, respectively, $Re(y)$ and $Re(x_-)$ implying CPT violation in $\Delta S = \Delta Q$ and $\Delta S \neq \Delta Q$ decay amplitudes, respectively, and all parameters implying CP violation. If CPT symmetry holds then the two asymmetries are expected to be identical $A_S = A_L = 2\,\mathrm{Re}\,(\epsilon_K) \simeq 3\times10^{-3}$ each accounting for the CP impurity in the mixing in the corresponding physical state.

The CPT theorem ensures exact CPT invariance for quantum field theories - like the Standard Model - formulated on flat space-time and assuming Lorentz invariance, locality, and hermiticity. CPT violation effects might arise in a quantum gravity scenario and their observation would constitute an unambiguous signal of processes beyond the Standard Model.

In this context the measurement of the difference $A_S - A_L = 4\,(\mathrm{Re}\,\delta_K + \mathrm{Re}\,x_-)$ is of particular importance as a test of the CPT symmetry. This observable constitutes one of the most precise, robust and model independent tests of the CPT symmetry [1].

At present, the most precise measurement of A_L has been performed by the KTeV collaboration, while the more difficult measurement of A_S – requiring a very pure K_S beam – has been performed for the first time by the KLOE collaboration, exploiting the unique feature of the entangled neutral kaon state produced at a ϕ-factory:

$$|i\rangle = \frac{1}{\sqrt{2}}\{|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\}\ , \tag{3}$$

that allows to *tag* the presence of a K_S with the detection of a kaon at large times (a K_L) in the opposite direction, a technique not possible at fixed-target facilities. The result based on the analysis of a data sample of 1.63 fb^{-1} integrated luminosity is [2]:

$$A_S = (-4.9 \pm 5.7_{stat} \pm 2.6_{syst}) \times 10^{-3}, \tag{4}$$

consistent with the previous determination on an independent data sample of 410 pb^{-1}. The combination of the two results provides [2]:

$$A_S = (-3.8 \pm 5.0_{stat} \pm 2.6_{syst}) \times 10^{-3}\ , \tag{5}$$

which is approaching the level of accuracy necessary to reveal CP violation in the K_S. The combined result (5) together with the KTeV result on A_L yields for the sum and difference of asymmetries:

$$(A_S - A_L)/4 = Re(\delta_K) + Re(x_-) = (-1.8 \pm 1.4) \times 10^{-3}, \tag{6}$$

$$(A_S + A_L)/4 = Re(\epsilon_K) - Re(y) = (-0.1 \pm 1.4) \times 10^{-3}. \tag{7}$$

Using $Re(\delta_K) = (2.5\pm2.3)\times10^{-4}$ and $Re(\epsilon_K) = (1.596\pm0.013)\times10^{-3}$ the CPT violating parameters $Re(x_-)$ and $Re(y)$ are extracted:

$$Re(x_-) = (-2.0 \pm 1.4) \times 10^{-3}, \tag{8}$$

$$Re(y) = (1.7 \pm 1.4) \times 10^{-3}, \tag{9}$$

which are consistent with CPT invariance and improve by almost a factor of two the previous results on these parameters [2].

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Authors
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`http://www.lnf.infn.it/kloe2`

P20. Light hadron physics at KLOE-2

The KLOE-2 Collaboration ended its data-taking in March 2018, by collecting 5.5 fb^{-1} of data at the peak of the $\phi(1020)$ at the Frascati ϕ-factory DAΦNE. This luminosity, together with the 2.5 fb^{-1} collected during the first period of data-taking (2001 - 2006) constitutes the largest sample of data collected at a ϕ-factory, suitable to perform precision measurements on light mesons. During the data-taking the analysis of the old data continued, and one of the fields in which KLOE/KLOE-2 contributed is the measurement of the hadronic cross-section $\sigma(e^+e^- \to \pi^+\pi^-)$ via Initial State Radiation (ISR), by detecting events with $\pi^+\pi^-\gamma$ final state, where the photon is emitted by an initial electron or positron. This measurement is crucial to estimate the hadronic vacuum polarization contribution to the muon anomalous magnetic moment. With the KLOE data, three precision measurements of the hadronic cross-section have been published in 2008, 2010, and 2012. These data have been recently combined, properly taking into account the correlations among the data sets. In Figure 1 the comparison with other measurements is shown. From the KLOE combination a value of the anomaly $a_\mu(0.10 < M^2_{\pi\pi} < 0.95\ \text{GeV}) = (489.8 \pm 5.1) \times 10^{-10}$ is obtained, confirming the 3.5 standard deviation discrepancy between the experimental and the theoretical values of a_μ.

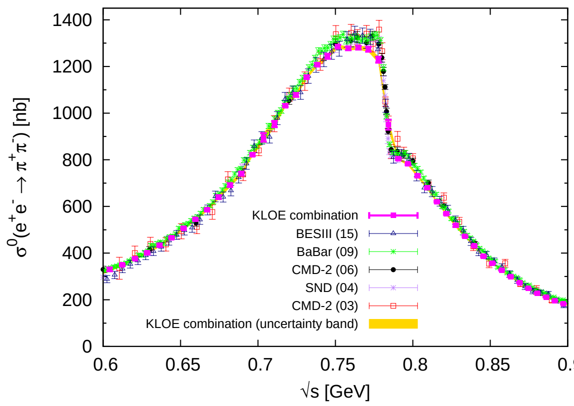

Figure 1: KLOE hadronic cross-section combination compared with the other measurements [1].

The fine-structure constant α_{em} is a running parameter due to vacuum polarization effects, $\alpha_{em}(s) = \frac{\alpha_{em}(0)}{1-\Delta\alpha}$. The value of $\alpha_{em}(s)$ can be extracted from the ratio of the differential cross-section of the ISR process $e^+e^- \to \mu^+\mu^-\gamma$ to the corresponding cross-section with $\alpha_{em} = \alpha_{em}(0)$ obtained from a MC simulation; s is the momentum transfer squared of the reaction. The ratio measured $\left|\frac{\alpha_{em}(s)}{\alpha_{em}(0)}\right|^2$ is shown in Figure 2, compared with the theoretical prediction.

Moreover, $\Delta\alpha$ is a complex parameter in the time-like region. From the optical theorem follows that

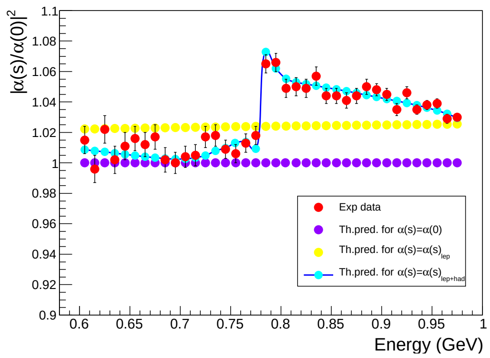

Figure 2: Running of α_{em} showing the $\rho-\omega$ contribution to the photon propagator [2].

$\Im(\Delta\alpha) = -\frac{\alpha}{3}R(s)$, where $R(s) = \frac{\sigma_{hadr.}}{\sigma_{\mu^+\mu^-}}$, and it has been obtained from the quoted above KLOE measurements of the hadronic cross-section. Then the real part of $\Delta\alpha$ (Figure 3) can be determined: $\Re(\Delta\alpha) = \sqrt{\left|\frac{\alpha_{em}(s)}{\alpha_{em}(0)}\right|^2 - [\Im(\Delta\alpha)]^2}$. From a fit to the $\rho-\omega$ interference pattern the $Br(\omega \to \mu^+\mu^-) = (6.6 \pm 1.4 \pm 1.7) \times 10^{-5}$ has been evaluated.

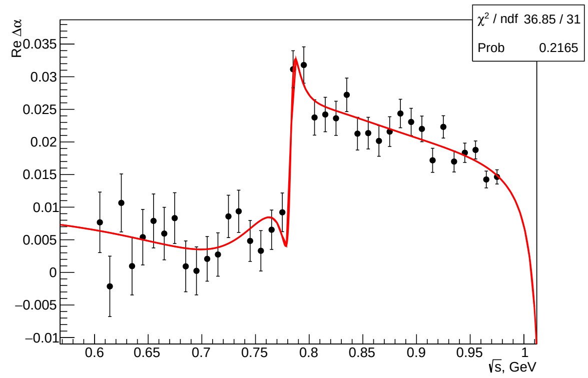

Figure 3: Real part of $\Delta\alpha$ [2]

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http://www.lnf.infn.it/kloe2

P21. Search for Dark Forces at KLOE-2

Dark Matter (DM) existence is now widely accepted, it should account for about 25% of the total energy density of the Universe. Several models have been proposed in which DM consists of new particles belonging to a secluded gauge sector under which the Standard Model (SM) particles are uncharged. In some of these models the new interaction is mediated by a massive gauge vector boson, the U boson (or Dark Photon, also called A′ boson), which can be kinematically mixed with the SM photon. The existence of a U boson of mass of $O(1\text{ GeV})$ and mixing parameter ε in the range $10^{-2} \div 10^{-7}$ has been proposed to explain several astrophysical anomalies (observed by AMS02, PAMELA, INTEGRAL, FERMI, DAMA and other Collaborations). High luminosity e^+e^- colliders, as DAΦNE, are an ideal tool to search for such a U boson, by looking at processes like $e^+e^- \to U\gamma$, with $U \to \ell^+\ell^-$ or $U \to \pi^+\pi^-$. The signal of this hypothetical particle should be a peak in the invariant mass of the particle-antiparticle pair in the final state.

KLOE published three searches for the U-boson decaying into: *(i)* e^+e^- with a sample of 1.5 fb^{-1} of data, *(ii)* $\mu^+\mu^-$ witth 240 pb^{-1}, and *(iii)* $\pi^+\pi^-$ analyzing the whole KLOE dataset, 1.93 fb^{-1}. The searches for the decay into muon and pion pairs, by requiring the Initial State Radiation photon at small polar angle ($\theta < 15^o$, then not detected in the apparatus) cover approxmately the same U-boson mass range in the region 520 - 990 MeV.
Recently the search for $\mu^+\mu^-$ has been extended to the whole KLOE statistics, in Figure 1 the separation of the $\mu^+\mu^-\gamma$ from $\pi^+\pi^-\gamma$ final state is shown. The analysis confirms the absence of signal in the dimuon invariant mass spectrum.

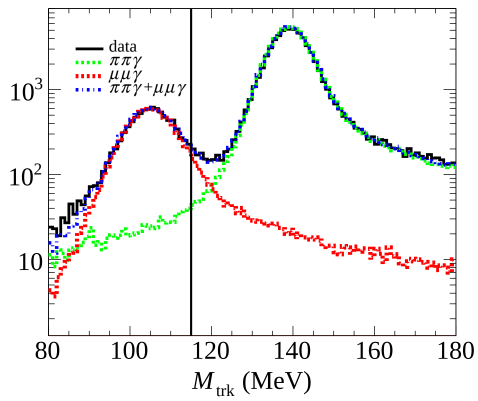

Figure 1: Mass of the charged tracks in the event; data compared with MC simulation.

The obtained limit is comparable with the $\pi^+\pi^-$ one, then the two decay channels have been combined to increase the sensitivity, in particular in the region of the $\rho-\omega$ interference, where thew search in $\mu^+\mu^-$ loses sensitivity.

The combined upper limit, after averaging the statistical fluctuations by a smoothing procedure, excludes values of ε^2 greater than $(13-2)\times 10^{-7}$ in the mass range $519-987$ MeV. The resulting exclusion region at 90% C.L. is shown in Figure 2: the dashed curve represents the updated limit in the $\mu^+\mu^-$ final state, while the dotted curve is the limit obtained with $\pi^+\pi^-$, and the solid curve is the combined exclusion region. The KLOE results are compared with the most competitive limits in this region.

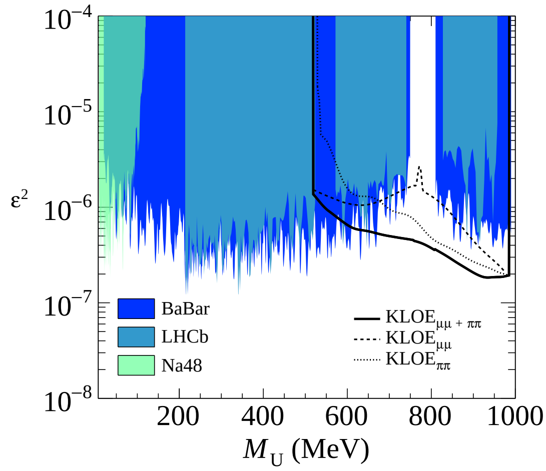

Figure 2: Exclusion plot of ε^2 as a function of the U boson mass [1].

From the analysis of the KLOE-2 data an improvement on the upper limit from these processes is expected, but also other decay channels will be exploited: a single photon trigger has been implemented in the last part of the KLOE-2 data-taking to select the possible invisible decay of the U boson. Axion Like Particles will also be searched for in the 3 γ final state events; and other possible DM particles as the leptophobic B boson will be searched for as a peak in the $\pi^0\gamma$ invariant mass distribution in processes like $\phi \to \eta\pi^0\gamma$ and $\eta \to \pi^0\gamma\gamma$.

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`http://www.lnf.infn.it/kloe2`

P22. Beyond the standard model searches with the NA62 experiment at CERN

The flavour-changing neutral current decay $K^+ \to \pi^+\nu\bar{\nu}$ proceeds in the Standard Model (SM) through electroweak box and penguin diagrams, dominated by t-quark exchange. The quadratic GIM mechanism and the small value of the CKM element $|V_{td}|$ make this process extremely rare. Using the CKM matrix elements as external inputs, the SM predicts the branching ratio to be $BR = (8.4 \pm 1.0) \times 10^{-11}$, where the uncertainty is dominated by the current precision on the CKM parameters, while the intrinsic theoretical accuracy is at the 2% level. For this reason the $K^+ \to \pi^+\nu\bar{\nu}$ decay is extremelly sensitive to physics beyond the SM. The E787 and E949 experiments at BNL studied the decay using a decay-at-rest technique, and obtained $BR = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$. The NA62 experiment aims at improving the precision of this measurement using a decay in flight technique.

The choice of the decay-in-flight technique is motivated by the possibility of obtaining a flux of $O(10^{13})$ kaon decays over a few years with a signal acceptance of a few percent, leading to the collection of O(100) SM events. NA62 utilises a 400 GeV proton beam to produce 75 GeV kaon. The boost folds the decay products into a small angular region allowing for a classic fixed target geometry experiment. The detector should measure the incoming kaon and the outgoing pion while reducing background to the level of 10^{-11} of accepted kaon decays. To this end, the detector consists of a collection of sub-detectors, each designed to perform one main task, and with complementary performance. The NA62 beam line and detector layout is described in detail in [1] and shown in Fig. 1

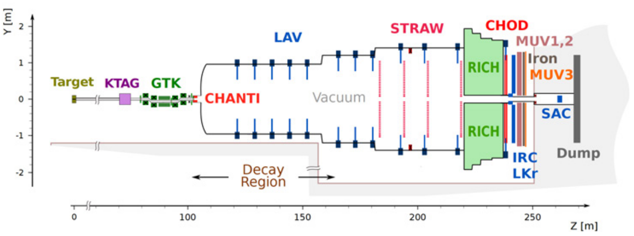

Figure 1: Schematic vertical section through the NA62 experimental setup [1].

The $K^+ \to \pi^+\nu\bar{\nu}$ signature consists of a K^+ with 4-momentum p_K in the initial state, and a π^+ with 4-momentum p_π with missing energy in the final state. The squared missing mass $m^2_{miss} \equiv (p_K - p_\pi)^2$ is used to discriminate kinematically the main K^+ decay modes from the signal. The signal is searched for in two m^2_{miss} regions on each side of the $K^+ \to \pi^+\pi^0$ peak, see Fig. 2. Selection criteria based on m^2_{miss}alone are not sufficient to reduce the backgrounds to the desired level, and additional suppression by π^+ identification and photon rejection is required.

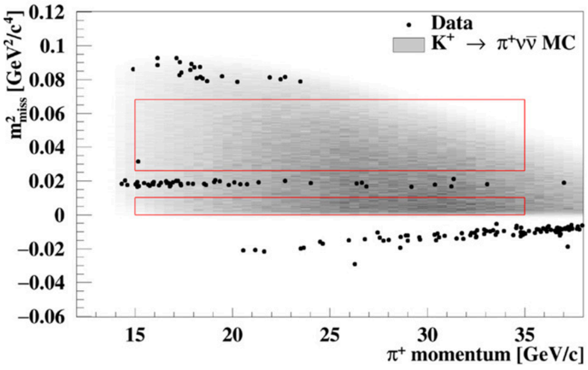

Figure 2: Reconstructed m^2_{miss} as a function of π^+momentum for selected candidates. Red contours define the signal regions.

After a first commissioning period in 2014-2015, the NA62 experiment has accumulated $\sim 1 \times 10^{13}$ kaon decays during the 2016–2018 data taking period. NA62 experiment has recently reported the first search for $K^+ \to \pi^+\nu\bar{\nu}$ using the decay-in-flight technique, based on a sample of $1.21 \times 10^{11} K^+$ decays collected in 2016. The single event sensitivity is 3.15×10^{-10}, corresponding to 0.267 Standard Model events. One signal candidate is observed (see Fig.2) while the expected background is 0.152 events, leading to an upper limit of 14×10^{-10} on the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio at 95% CL [2]. The very high photon rejection capability needed to perform $K^+ \to \pi^+\nu\bar{\nu}$ searches, provides the NA62 with a unique potential in searching for dark sector particles, and in particular for dark photons. NA62 has recently reported the results of a search for π^0decays to a photon and an invisible massive dark photon. From a total of $\sim 4.1 \times 10^8$ tagged mesons, no signal is observed. Assuming a kinetic-mixing interaction, limits are set on the dark photon coupling to the ordinary photon as a function of the dark photon mass, improving on previous searches in the mass range 60-110 MeV/c^2[3]. The Sapienza group is mainly involved on the development of the new L0 trigger processor for the NA62 2021 run, and in the search for dark sectors signatures.

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P23. Dark sector searches with the PADME experiment

The hypothesis that dark matter communicates with the Standard Model (SM) through mediators, particles having quantum numbers of both the dark forces and SM, is becoming increasingly popular [1]. The main goal of the PADME experiment (Positron Annihilation into Dark Matter Experiment) is to detect the non SM process $e^+e^- \to \gamma + \textit{nothing}$, *nothing* being any possible exotic particle candidate (A', ALPs, etc.) coupling to electrons and decaying into dark sector particles [2].

The experiment is composed of a thin (100μm) active diamond target, to measure the average position and the intensity of the beam during a single bunch, a set of charged particle veto detectors immersed in the field of a dipole magnet, to detect the positron losing their energy due to radiation, and an electromagnetic calorimeter to measure/veto final state photons. The calorimeter is composed of 616 21×21×230 mm^3 Bismuth Germanate (BGO) crystals arranged in a cylindrical shape with a diameter of $\sim$ 60 cm. The apparatus is inserted into a vacuum chamber, to minimize the unwanted interactions of primary and secondary particles that might generate extra photons. The rate in the central part of the calorimeter is too high due to Bremsstrahlung photons. For this reason the calorimeter has a hole covered by a faster photon detector, the Small Angle Calorimeter (SAC).

The main goal of the PADME experiment is to search for dark photons decaying into dark matter particles by measuring the missing mass in the process $e^+e^- \to \gamma A'$ in the region of mass below 24 MeV. The sensitivity to A' invisible decays was estimated in [2][3].

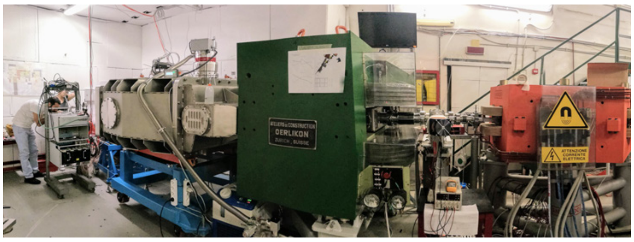

Figure 1: The PADME experiment at the DAΦNE beam test facility. Beam coming from right to left.

The 2017 and early 2018 were devoted to the production and test of the ˜700 scintillating units necessary for the electromagnetic calorimeter assembly. Each unit, made of a refurbished BGO crystal coming from the former L3 calorimeter glued to a photomultiplier, has been characterised using 511 KeV photons from a^{22}Na radioactive source.

The PADME collaboration has started the detector assembly in April 2018. The experiment and data acquisition system were ready in mid September (see Fig. 1), when first tests with the whole apparatus were performed. The PADME data taking was inaugurated on October 4th and lasted up to the end of February 2019 at the DAΦNE Beam Test Facility (BTF). All the detectors have shown the expected performance, and a very stable data taking was achieved after few weeks. BTF bunch lengths up to 250 ns were obtained with an intensity of 25000 positrons/bunch. Average of $\sim 1 \times 10^{11}$ positron on target per day were collected during the entire data taking period see Fig. 2. The total amount of data collected during RUNI exceeds 5×10^{12} positrons on target.

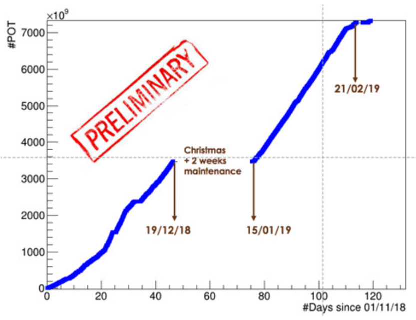

Figure 2: PADME data taking during Run I.

The Roma group is the main contributor to the reconstruction and calibration softwares for the electromagnetic calorimeter. The group is also leading the development of the Monte Carlo simulation, the experiment sensitivity studies, and is coordinating all computing and data taking related activities.

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P24. Detection of Gravitational Waves

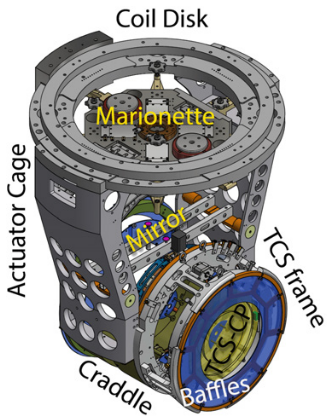

Figure 1: The Advanced Virgo payload in which the super mirror is suspended by four thin silica wires [1].

A worldwide effort is currently being invested in the development of both ground and space based searches for gravitational radiation. The Virgo group of *Sapienza* University is part of a worldwide collaboration for the direct detection of Gravitational Waves (GWs) using laser interferometer of kilometric baseline. Hunted for more than half a century by the group born in our department, thanks due to Edoardo Amaldi, GWs have been finally directly detected. The detector network consists of two LIGO detectors in USA, the Virgo detector in Italy and in few months the Japanese detector KAGRA will also join the network. Data taking runs are organised by synchronising the upgrade activities on the various detector located in different continents.

Gravity has a central role in physics. Astrophysics, Cosmology and Fundamental Physics include gravity as a key ingredient, making it a subject of strong interdisciplinarity. In particular, GWs are the most significant gravito-dynamic phenomena by means of which we can explore even the hidden phenomena of the universe.

The GWs, detected by the LIGO/Virgo Collaborations are relevant for our understanding of both gravity and particle physics. On one side, the gravitational waveforms allow us to test General Relativity and to put constraints on modified theories of gravity. On the other side, the potential detection of GWs produced from first-order phase transitions in the early universe is able to provide valuable information for physics beyond the Standard Model. Many theories beyond the Standard Model lead to a strong first order phase transition, associated with the spontaneous symmetry breaking, when a scalar field obtains a vacuum expectation value. Bubbles of the new broken phase nucleate out of the symmetric phase plasma, expand and eventually collide. Such collisions also produce a stochastic background of GWs.

Harvesting useful information from GW signals and understanding its broader implications require a cross-disciplinary effort. Black Holes (BHs) are the "simplest" astrophysical objects of GR and they harbour predictions such as event horizons and singularities, but the detection of GWs emitted by a BH in a perturbed state may reveal the existence of new fundamental fields and drive us towards a more unified vision of the fundamental laws of Nature. For example, the study of the merger of two BHs into a single Kerr BH provides the first test of the BH area-entropy theorem, better known as the second law of BH thermodynamics. The emitted GWs are coherent and from quantum mechanical point of view are a pure state of zero entropy; the sum of the geometrical entropies of the two merging BHs is nearly equal to that of the final BH. Future studies on similar binary BH events will be critical precision tests of such a statement.

With GWs from BH we should try to answer to fundamental questions:
- How, when and in which environment were BHs formed?
- How fast do they spin and how have some of them grown to become supermassive?
- Can BH mergers tell us on the nature and distribution of dark matter?
- Are there new fundamental degrees of freedom?

GWs can play a crucial role in the debate regarding the universe expansion. There has been an increasing tension between the supernovae, which give a local Hubble parameter today, $H_o \sim 72$ km/s/Mpc, and the inferred value from the Planck CMB measurements which point to $H_o \sim 68$ km/s/Mpc. The tension has recently been quantified at $\sim 4.4\ \sigma$.
This can be due just either to a systematic error in one of the determinations, or the breakdown of the standard ΛCDM cosmological paradigm. GW observations can play a crucial observational role in resolving the H_o tension. This is because merging binaries can act as standard sirens, as the intrinsic (non-redshifted) amplitude of the signal can be recovered from the signal waveform itself, giving a new local measurement of H_o completely independent from the systematics of the local distance ladder used in supernovae observations. Just with the first observation of the Neutron Star (NS) merger done in 2017 by the LIGO/Virgo network we set already a value of $Ho \sim 70 \pm 10$ km/s/Mpc showing as GWs can become competitive with the CMB and supernovae measurements.

The detection of August 17th, 2017 of the two NS merger is considered as the born of the multi-messenger astronomy. These observations have the potential to revolutionise nuclear astrophysics. Moreover, they will improve our understanding of nucleosynthesis, provide insights about the equation of state (EOS) of strongly-interacting matter at high densities. Recent advances in nuclear theory can be combined with the GW observations to extract useful insights about the EOS of matter encountered inside NSs clarifying the role of phase transitions in the NS core and improve our understanding of superdense matter states. Continuous GWs are emitted by NSs with some distortion not along its rotation axis, i.e. a ”mountain”. Various hypotheses have been proposed for the formation of the distortion frozen into the crust or in the core of the star. It can form from material falling onto the star or be produced and maintained though huge internal magnetic fields. The ”mountain” size can also be expressed in terms of the star’s ellipticity, which is a measure of its size as a fraction of the star’s radius. Properties of NSs are largely determined by the EOS of neutron-rich matter and the measurements of the ellipticity through the GW observations can provide crucial information on the dependence of nuclear interaction at high densities.

The core collapse of massive stars [$\sim (10-100)$ $M_\odot$], in particular those producing core-collapse supernovae, was considered a potential source of detectable GWs already at the epoch of resonant bar detectors. GW are emitted by aspherical mass-energy dynamics that include quadrupole or higher-order gravitational contributions. Any core-collapse event generates a burst of neutrinos that releases most of the proto-NS gravitational binding energy. Several neutrino detectors on the Earth are monitoring the sky to look for such a kind of signals trying to repeat the successful observation in the case of the Supernova 1987a. The future supernova event seen by both GW and neutrino detectors will be the most interesting example of multi-messenger astronomy. It will connect the neutrino emission from the core of the proto-NS and the rapid evolution of its inner gravitational field with the consequent GW emission. In addition, the joint observation of the two phenomena will increase the confidence detection of emitted signal and it can be used to solve the supernova explosion mystery.

After the detection of the first GW signals, it is more and more important to improve the performance of the detectors, their sensitivity and reliability for increasing the overall observational time and explore a larger volume of the universe. A program called Advanced Virgo + has been already approved, so that we will alternate time periods of data taking with time devoted to the implementation of new experimental solutions to improve the sensitivity. The application of new experimental solutions will bring the advanced detectors to the limit given by the present infrastructures. Then a new generation of detectors will be built. The Einstein Telescope is a project proposed in Europe for building a new third-generation ground-based GW interferometer, that hopefully will be located in the Sos Enattos mine (Lula-Nuoro) in Sardinia, a location characterised by a very low seismic and environmental noise. In the mean time a robust R&D program, coordinated at international level and carried on by a new generation of researchers, must be carried on.

Despite the simple detection principle, a GW interferometer is an extremely complex instrument. In the figure we show the rendering of the payload used in the current data taking of Advanced Virgo: it includes the super mirror suspended with four fused silica wires. The comprehension of the strategic choices done to achieve the incredible displacement sensitivity lower than 10^{-9} the atom diameter requires a deep knowledge of several different branches of Physics and for this reason the **Amaldi Research Center for Gravitational Physics and Astrophysics** has been recently founded in our department. It is an interdisciplinary Center of Excellence devoted to exploit the scientific results of the present GW network and to play a key role in the design and development of the new GW detectors.

Authors
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https://web.infn.it/VirgoRoma/index.php/en/

P25. Persistent GWs

Interesting GW signals, which have still to be detected and are among the main targets of the LIGO-Virgo collaboration, and in particular of the Virgo group in Rome, are represented by *Continuous Waves* (CWs) emitted by rapidly rotating non-axisymmetric Neutron Stars (NSs), as well as a *Stochastic Background of GWs* (SBGW), either of cosmological or astrophysical origin.

1 CWs

CWs are quasi-periodic signals with a duration longer than the typical detector observation time, which is of the order of months or years.

Part of the activity of the Virgo Rome group is focused on the study, development and application, to both Virgo and LIGO data, of analysis procedures for all-sky searches for isolated stars, targeted searches and narrowband searches for known pulsars, either isolated or in binary systems [1]. The group has also started activities devoted to search for CWs from NSs in binary systems and r-modes or other transients [2]. Furthermore, we also conduct detailed studies of periodic data interferences, especially studying the quality of a given data set for what concerns the presence of narrow noise lines that can dramatically affect CW searches.

The way to search for CWs depends on how much about the source is known. There are different types of searches where we are deeply involved in. Indeed, we have performed the latest following searches on the second advanced LIGO-Virgo observing run, O2[1]:

1. A *targeted* search for 34 known pulsars, including Crab (60 Hz) and Vela (22 Hz). These are searches where the source parameters (e.g. sky location, frequency, frequency derivatives) are assumed to be known with great accuracy (as indeed for the Crab and Vela pulsars). This kind of searches is computationally cheap and a fully coherent analysis, based on matched filtering over long observation time, is feasible [3]. The O2 targeted search has brought us to the best 95% confidence-level (CL) upper limit (UL) on the GW strain amplitude h_0 obtained so far, which is 1.4×10^{-25} for the Vela pulsar. For Crab and Vela our results constrain the GW emission to account for less than 0.017% and 0.18% of the spin-down luminosity, respectively. The spindown limit has been surpassed for 20 young pulsars, including Crab and Vela.
2. A *narrowband* search for 33 known pulsars (including Crab and Vela). In this case we account for a small mismatch between the GW rotational parameters and those inferred from electromagnetic observations. Those searches rely on coherent phase models and wrong ephemeris can introduce phase errors, which would result in a loss of signal-to-noise ratio. In the O2 narrowband search we were able to set the best 95% CL UL for 3 millisecond pulsars and is $h_0 \sim 5.5 \times 10^{-26}$. The spindown limit has been surpassed for 6 pulsars, including Crab and Vela. The UL on the Vela and Crab pulsars has improved with respect to the previous run result by 10% and by a factor of 2, respectively.
3. *Directed searches*, where sky location is known while frequency and frequency derivatives are unknown (e.g. Cassiopeia A, SN1987A, Sco X-1, galactic center, globular clusters). We are currently performing a directed search on data from the ongoing O3 run, which has started on April 1, 2019 for both the two LIGO and Virgo detectors. We are targeting the Galactic center and a few other interesting sources, including CasA, Vela Jr. and other young SNRs, FERMI-LAT/INTEGRAL sources. The methodology we are using consists of fast production of band-limited time series, already down-sampled and cleaned. This flexible general data analysis framework allows us to reduce the computational cost of the analysis by about two orders of magnitude with respect to current procedures. This can correspond, at fixed computing cost, to a sensitivity gain of up to $10\% - 20\%$, depending on the search parameter space.
4. An *all-sky* low frequency [(20-475) Hz] search for unknown pulsars. It is well-known that CW all-sky searches from unknown pulsars over wide-parameter spaces are computationally limited. The reason is that one needs to search for unknown sources located everywhere in the sky, with signal frequency as high as a few kHz and with values of spin-down as large as possible. Long integration times, typically of the order of a few months or years, are needed to build up sufficient signal power. The O2 all-sky search [**?**] allowed us to reach the most sensitive 95% CL UL ever achieved for such a kind of search, and corresponds to $h_0 \sim 1.6 \times 10^{-25}$ at 123 Hz. As regards the astrophysical reach, at 500 Hz we are sensitive to NSs with equatorial ellipticity larger than 10^{-6} and as far away as 1 kpc.

We are currently performing an all-sky high frequency search in the frequency range(500-2000) Hz and using the O2 data set, as well as analysing O3 data.

We plan to perform an O3 search for long CW transient (days-weeks) signals as well as a directed/narrowband search from NSs in binary systems using the generalized 5-vector resampling method. We have also developed a machine learning-based method to search for long duration CW transients, starting with r-modes and generalizing to different transients. This

[1]O2 spans the time period from November 30, 2016, up to August 25, 2017.

ongoing project is based on neural networks and random forests. We are also modifying the FrequencyHough to search for CW transients.

A recent kind of search we are interested in is the search for signal of *post-merger remnant* with unknown frequency and frequency evolution. We have already presented a first model-agnostic search for intermediate-duration ($\leq$ 500 s) GWs considering the NS remnant scenario focusing on signal durations up until the end of O2, i.e. 8.5 days after the coalescence of GW170817. No signal candidates were found. The search sensitivity was estimated for several GW emission mechanisms: oscillation modes of a short-lived hypermassive NS, ba$r$-mode instabilities, and rapid spindown powered by magnetic-field induced ellipticities. For all mechanisms, a realistic signal from a NS remnant of GW170817 could only have been detected with at least an order of magnitude increase in detector strain sensitivity. We consider, however, fundamental to have pipelines ready to perform a post-merger remnant search.

We are currently finalizing a comprehensive study of the effectiveness of Convolution Neural Networks to detect long duration transient GW signals lasting (lasting for hours - days) from isolated NSss.

Furthermore, we are developing a Doppler-agnostic segmentation of GWs in time-frequency multi-detector RGB spectrograms using a Residual U-Net with real, complex and hypercomplex weights. The current method is so general that it can be applied to all kind of CW searches described above.

An additional O3 search we are currently working on is the search for CWs emitted by ultralight boson clouds around spinning black holes. As a consequence of superradiant instability induced in Kerr black holes, ultralight boson clouds can be a source of persistent GWs. These signals are expected to be nearly monochromatic, with a small steady frequency increase (spin-up).

2 GW Stochastic Background

The SBGW consists of a random accumulation of signals from thousands or millions of individual sources and is expected to contain unique information from throughout the history of the universe that is unavailable through standard electromagnetic observations, making its study of fundamental importance to understand the evolution of the universe.

As regards the SGWB, the most stringent upper limits are those obtained by a directional search, pointing sources emitting GWs at a single frequency, targeting the directions of Sco X-1, SN 1987A, and the Galactic Center. The best ULs on the strain amplitude of a potential source in these three directions range from $h_0 < (3.6 - 4.7) \times 10^{-25}, 1.5$ better than previous limits set with the same analysis method.

Other interesting and very recent results are those obtained from cross-correlating data from O1[2] and O2. No evidence for SBGW is found, but stringent 95% CL ULs on the normalized energy density in GWs ($\Omega_{\rm GW}$) are obtained and are: $\Omega_{\rm GW} < 6.0 \times 10^{-8}$ for a frequency-independent (flat) SBGW and $\Omega_{\rm GW} < 4.8 \times 10^{-8}$ at 25 Hz for a background of compact binary coalescences [4].

Finally, a novel project we are working on is an efficient joint analysis that makes use of the fast and consolidated SGWB cross-correlation algorithm to quickly identify CW signals, which need to be properly followed up with ad hoc CW pipelines. We are currently focusing on the development and the implementation of an end-to-end pipeline, which will be tested on simulated data before to be ran on O3 and beyond. Using fake data will make possible direct sensitivity assessments and concrete code optimizations, which will result in performing searches at an affordable computational cost.

[2] O1 covers the time period starting from September 12, 2015 up to January 19, 2016.

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P26. Gravitational-Wave Transient Signals

Gravitational-waves (GWs) can be classified into transient or (virtually) persistent, depending on their duration. A possible detection strategy for transient GW signals is to launch a deep search whenever a violent astrophysical phenomenon takes place. This is known as an externally triggered search, where the "trigger" denotes an observation of electromagnetic or neutrino radiation from a high-energy astrophysical event. The rationale behind externally triggered searches is that such events involve asymmetric, relativistic motions of dense matter and are therefore efficient GW sources. Further, the GW signal must be consistent in time and sky-position with the external trigger. This constraint enables the formulation of GW searches that are more sensitive than the all-sky, all-time ones. The combination of a triggered GW detection and the trigger itself constitutes a multi-messenger observation of an astrophysical event.

The GW Group at "Sapienza" focuses on searches for the GW emission associated with gamma-ray bursts (GRBs) and core-collapse supernovae (CCSNe).

Gamma-ray bursts — GRBs are high-energy transients of cosmological origin that are observed at an average rate of more than once per day. Among them are short GRBs, with durations $\lesssim 2\,\mathrm{s}$, which have taken more than half a century to explain: the detection of the GW transient GW170817, a NS binary merger, in temporal and spatial coincidence with the short GRB 170817A provided evidence at $5.3\,\sigma$ Gaussian-equivalent significance that binary neutron star mergers can ignite short GRBs [1] (see Fig. 1). Among other results, this single multi-messenger observation also yielded an impressive fundamental physics constraint: the difference between the speed of gravity and the speed of light was measured to be between -3×10^{-15} and $+7 \times 10^{-16}$ times the speed of light. Because GRB 170817A was 2 to 6 orders of magnitude less energetic than other GRBs with measured redshift, its joint observation also opened new questions, such as (i) was this event unexpectedly dim, and (ii) is there a population of unobserved short GRBs with similar luminosities and distances?

Answering these questions will require more joint GW-GRB observations. The GW Group at "Sapienza" holds a leadership position at worldwide level in devising and conducting GW searches triggered by GRBs, and it is at the forefront of building strategies to extract novel physical information from future joint observations [2].

Core-collapse supernovae — The non-spherical mass-energy dynamics that takes place during the collapse of the core of massive stars (~ 10–$100\,M_\odot$) emits GWs that encode information about the core dynamics of these events. In particular, if this dynamics is present in the pre-explosion stalled-shock stage of CCSNe, a triggered GW search offers the possibility of shedding light on the currently unknown mechanism that drives these violent deaths by observing them in the gravitational channel.

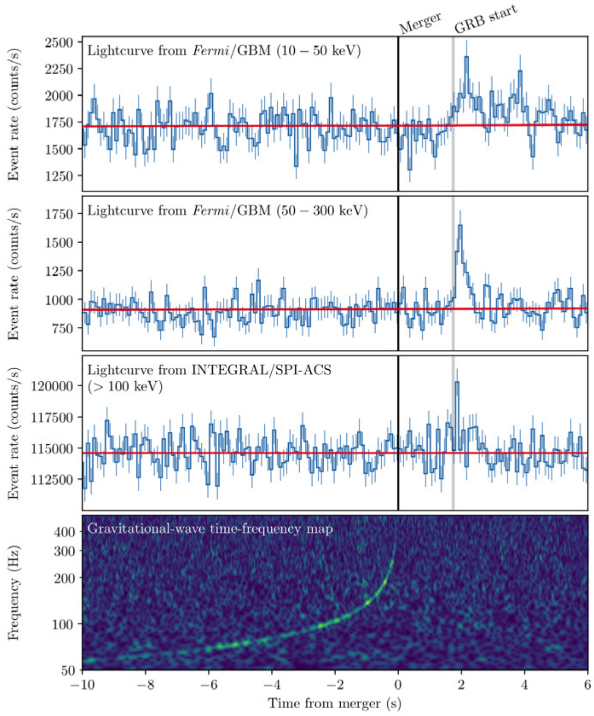

Figure 1: Joint, multi-messenger detection of GW170817 and GRB 170817A performed by *F*ermi Gamma-ray Burst Monitor (top two panels), INTEGRAL (third panel), and LIGO-Virgo (bottom panel). See [1] for further details.

The GW Group at "Sapienza" formulated a new method to analyse data of the GW interferometer network that enhances the detection efficiency of GW signals from CCSNe. The method exploits a peculiarity of the GW signal emitted by a CCSN; it is based on a convolutional neural network classifier of time-frequency images of the GW data that is trained to perform the signal recognition task [3]. This method was shown to be able to identify GW signals from simulated CCSNe better than the current algorithms devoted to the CCSN triggered search.

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P27. The new detectors on the Earth

The exploration of a larger volume of the Universe and the deep study of new phenomena by means of the GW observation implies to increase further the detector sensitivity.
At the present time LIGO and Virgo are both giant quantum optics devices to circumvent the limitation of the Heisenberg principle by using light squeezed vacuum. The present configuration has the advantage to increase the sensitivity in the high frequency range at the cost of a noise increase at low frequency range. Further quantum optics studies are needed to overcome this limitation. Thermal noise associate to the suspension and mirror vibration modes is flighted by studying the material properties of the suspension wires and the super mirror coating, a typical domain of the surface science expert. In addition, we are developing non-perturbative methods to cool the system at low temperatures, a way pursued also by KAGRA colleagues. Advantages emerge from cooling at very low temperature, one based on macroscopic quantum effect, namely superfluidity and superconductivity, the latter permitting the development of low noise sensors and actuators, and others associated to the general reduction of effects as thermal expansion and creep.

Seismic and Newtonian (direct gravitational coupling of the random motion of the ground to the mirror) noise are deeply investigated to get a significant increase of the interferometer sensitivity in the low frequency range, so crucial for the search of continuous GW signals emitted by the rotating NSs. Geological activity affects the interferometric detectors and conversely, for the same reason, the interferometric detectors can be used to extract information on the geological activity. For example searching for the propagation direction of the seismic disturbances has as potential application the improvement of the early warning systems for earthquakes.

Some of these new experimental solutions can be implemented in the existing facilities and for this reason the Advanced Virgo + project has been approved recently. Others require a completely new facility, a detector of third generation as the Einstein Telescope [1].

1 Advanced Virgo+

Advanced Virgo Plus (AdV+) is an upgrade of Advanced Virgo to be realised in two phases named Phase I and Phase II. The installation of AdV+ Phase I will take place between the observation runs O3 and O4 and, according to the present plan, this should be between April 2020 and October 2021. The installation of AdV+ Phase II will take place between the observation runs O4 and O5 and it this should happen between October 2022 and March 2024.

Broadly speaking the main goal of AdV+ Phase I is to reduce the quantum noise of the interferometer light by means of
- the implementation of the signal recycling technique by reshaping the quantum noise spectrum to increase the detector bandwidth;
- the increase of the laser power injected into the interferometer by a factor of two;
- the implementation of auxiliary optical activity external to the main interferometer, with the function to introduce a frequency dependence of the squeezed vacuum state which is injected in the inteferometer via its output port; this method, called frequency dependent squeezing, will permit to reduce further the shot noise without increasing the radiation pressure noise at low frequencies.

AdV+ Phase I will be the occasion to deploy also an array of seismic sensors in the central and end buildings to test Newtonian noise cancellation techniques. In parallel with the deployment of the array of sensors, an effort will be done to reduce the environmental noise coming for the air conditioning system.
The combination of all these improvements outlined should increase the sensitivity the detector such that we should detect in Virgo for coalescing binary neutron stars at distances of the order of 100 Mpc.

AdV+ Phase II instead will be focused on the reduction of the mirror thermal noise. To do so the beam on the end mirrors will be enlarged to about 20 cm diameter while keeping the same size in the central area of the interferometer. This implies the use of larger mirrors at the two ends of the interferometer, 55 cm in diameter and 100 kg in weight, with a significant impact on the whole suspension system that we have to review and rebuild. To further reduce the mirror thermal noise the best available coatings available will be used and, to this purpose, the development of coatig with lower thermal noise should be and activity to be carried on already during the AdV+ Phase I. Finally the change in the beam divergence will require to change also the two cavity input mirrors, the power recycling mirror and the signal recycling mirror. These mirrors will use substrates of the same size as the ones currently in use (35 cm in diameter).

The combination of the improvements allow to push the binary neutron star horizon of Virgo above 200 Mpc. To achieve the goals of Phase II, several tasks needs to be started during Phase I as
- the design of the beam geometry in the interferometer arms;
- the upgrade of the LMA infrastructure to be able to coat and characterise 55 cm diameter mirrors;
- the procurement of super-polished substrates to be ready for the mirror coatings in 2022;
- the study of new payloads and of super-attenuators upgrade to suspend 100 kg mirrors;

- the development of advanced coatings with lower thermal noise.

2 The 3G GW Detector Einstein Telescope

The Einstein Telescope (ET) project aims to build a crucial research infrastructure in Europe, a third generation Gravitational Wave Observatory, ten times more sensitive than the current gravitational wave interferometers, Advanced LIGO and Advanced Virgo, which are the second generation of detectors after the initial one [2].

As it is well known, the Advanced Interferometers succeeded in detecting gravitational waves in 2015. Since then, gravitational waves events have become another powerful probe to observe the universe and test physics at extreme energy scales. Currently, these instruments are detecting signals from coalescing black hole binaries at a rate of a few per month, and from coalescing neutron stars binaries at a rate of a few per year. However, it is evident that the signal-to-noise (SNR) of these detections is still too low for precise studies of the GW sources, and, in order to fully exploit the potential of this new instruments it is necessary to increase their sensitivity by at least a factor ten. This is the goal of the Einstein Telescope and of other third generation gravitational wave observatories which are now being proposed in the USA.

Indeed, the ET project started in 2008 as a Design Study funded by the European Union. The project evolved in the following years, and was ready to start the design phase when gravitational waves were first detected in 2015. As a third generation detector, ET will include several developments to the the design of the current interferometers, to reduce the fundamental noises that today limit their performance. In order to reduce the seismic noise at low frequencies (between 3 and 100 Hz), ET will be located underground at a depth of about 100-200 m. The competing noises depending on laser power, i.e. radiation pressure and shot noise (as power increases, radiation pressure noise increases and shot noise decreases) is overcome splitting the detector in two interferometers, one for the low frequencies (2-40 Hz), and one for the high frequencies (up to a few kHz), each interferometer adopting different, optimal technologies (xylophone configuration). To improve the sensitivity at low frequencies, we shall operate the mirrors at cryogenic temperature to suppress the thermal noise, while the seismic and gravity gradient will be decreased by installing the interferometer underground (ETc). At high frequencies the sensitivity will improve thanks to the progress done in operating the second generation detectors at high power and with the frequency dependent squeezing (ETb).

Moreover, the new interferometers will have arms 10 km long, more than twice the length of the arms of current detectors, with a proportional increase in sensitivity. The topology of each interferometer will be the dual-recycled layout with Fabry-Perot arm cavities. An important feature of the ET laboratory is that it is conceived as an observatory capable of hosting more than one GW detector. In this way ET will be usable for many decades, while the implemented detectors will undergo successive upgrades or replacements according to the progress in the state of the art of interferometer technologies. In the complete configuration, ET will consist of three nested detectors, each in turn composed of two interferometers in xylophone configuration. In this way, the detector will have a wider antenna pattern and a better angular resolution to identify the position in the sky of a gravitational wave source.

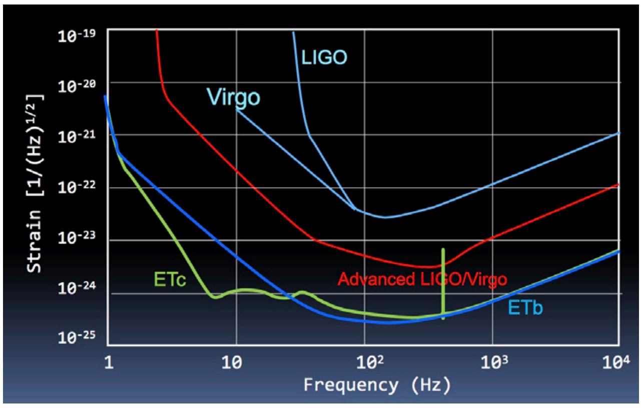

Figure 1: The sensitivity curves of ETc and ETb compared with those of initial LIGO and Virgo and the sensitivities of their advanced version.

The GW group of this department is fully engaged in straightening both the science case of this ambitious project and studying the experimental challenges of this new detector. In particular we are fully engaged in the characterisation of the proposed underground sites [3] and all the issue regarding the operation of the detector at low temperature. For instance, we are going to study crystalline mirrors with new coatings insuring less optical and mechanical losses as well as new silent refrigeration strategies to cool the mirrors without adding further acoustic noise.

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E. Majorana, L. Naticchioni[1], C. Palomba, A. Paolone, P. Puppo, F. Pannarale[1], P. Rapagnani[1], F. Ricci[1]

P28. Vacuum Fluctuation and Gravity

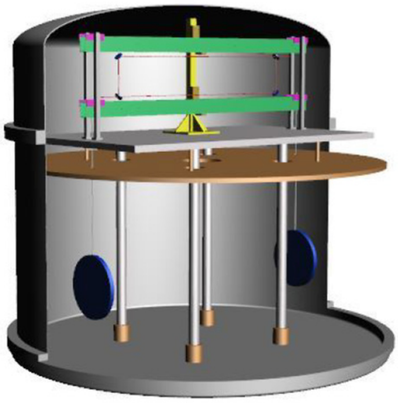

Figure 1: The balance to test the weight of the vacuum.

Vacuum fluctuations and macroscopic observables are among the most intriguing topics of the modern physics, particularly when considering the interaction with the gravitational field. The theoretical understanding and experimental evidences are still not completely satisfactory and require more efforts to reach a deeper consensus.

Archimedes is an experiment [1] conceived to shed light on the interactions between the gravitational field and the vacuum fluctuations. The experiment will measure the force exerted by the gravitational field on a Casimir cavity, whose vacuum energy is modulated with a superconductive transition, by using a balance as a small force detector.

Casimir effect is known as one of the evidences of the vacuum energy. Such an evidence is the attractive force between two plane conductors placed very close together. This force is due to the difference between the pressure of the vacuum e.m. modes outside and inside the cavity. Due to the boundary condition set on the e.m. field by the conducting planes, only some frequencies can resonate between them. Although the modes outside and inside the cavity are infinite, their resulting difference is a finite value called Casimir energy E_c. If this energy interacts with gravity, the Casimir cavity loses the weight of a quantity $g(E_c/c^2)$, where c is the speed of light and g the gravitational acceleration on the Earth. As a consequence, an upward force results, recalling the Archimedes buoyant force.

How to generate the effect and measure it? The idea is to modulate the Casimir effect by modulating the conductivity property of the planes . The use of superconductors is then straightforward and the modulation can be done by moving their temperature around the critical value. The high T_c layered superconductors (like YBCO cuprate) are natural multi Casimir-cavities thanks to their molecular structure, where the planes are set at distances of the order of nanometers. The Casimir energy is proportional to the inverse of the third power of the layers distance, and a sort of constructive interference between the adjacent layers is present. As a consequence, at these distances, the Casimir effect is enhanced with respect to other quantum effects, like a sort of multilayer coating mirrors. Moreover, in normal state the planes that will become superconducting are a very poor conductors enhancing the Casimir energy change at the transition. With these kinds of materials, typically with 10^6 layers, the expected force is of the order of 10^{-16} N a value of the same order of what it has been achieved in the GW detectors.

The experiment sensitivity of 10^{-16} N can be achieved by using a very sensitive balance and the force signal can be modulated by inducing a periodical transition from normal to superconducting state by a temperature change with a time constant ranging between $1 - 100$ mHz, typical values of the thermal processes.

Indeed, some requirements must be fulfilled to modulate the temperature. The idea is to change the sample temperature of a few K around T_c via radiative exchange, to limit all the other interactions that could mask the vacuum energy change. To this aim the design of the cooling system must proceed in parallel with the design of the mechanical part. Thermal times depend on the thermal properties of chosen materials, and as the radiative is privileged as the heat exchange mechanism, an optimisation is needed to reduce the transition times and increase the frequency bandwidth.

The Rome group of Archimedes experiment has setup a test bench for the modulation of the YBCO sample temperature around its critical temperature. The main difficulties are related to heating samples with mass of hundreds of grams within thermal transition time scales of hundreds of seconds. To reduce the transition times and increase the frequency bandwidth, the choice of the sample shape and of the heating system is crucial. On the base of a finite element analysis we have obtained a temperature modulation of about 5 K on a 100 mm diameter 3 mm thick. The shape is compatible with the present YBCO technology and is useful to get a signal within the expected sensitivity. The system will be hosted in a liquid nitrogen cryostat and the modulation will performed around $T_c = 91$ K, the typical value of YBCO critical temperature.

Balances, by means of which we should measure forces of the order of 10^{-16} N modulated at $1-100$ mHz, should be suitable tuned and operated with an excellent seismic isolation. A mechanical challenge is to design the balance with the center of mass set on its bending point in order not to re-inject the seismic noise in the system, so that the major sources of noise should be at the best its thermal noise. The read-out system will be either an optimised optical lever or an interferometric sensor and the data will be collected for several months, permitting to increase a high signal-to-noise ratio.

The Archimedes experiment, a INFN six-year project funded by INFN, is a collaboration between the two Virgo groups of *Sapienza* and Napoli Federico II universities and the integrated apparatus must be installed in a very seismically quiet site. SAR-GRAV is a new laboratory under construction in the Sos Enattos mine located the Sardinia. This site is a candidate to host the Einstein Telescope GW detector thanks to the very low seismic noise, the ideal environment for carrying on Archimedes, a null force experiment.

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P29. The search for Majorana neutrinos with the CUORE experiment

In the field of fundamental particle physics the study of the neutrino properties played a key role since the discovery of its mass. The ultimate nature of the neutrino (if it is a Dirac or a Majorana particle) is a portal for physics processes beyond the Standard Model. The only way to disentangle the neutrino nature is to search for the so-called Neutrinoless Double Beta Decay (NDBD) $[(A, Z) \rightarrow (A, Z + 2) + 2e^{-}]$ a lepton- number-violating decay. The NDBD is an extremely rare process, if it exists at all. It has never been observed so far and its half life is expected to be higher than 10^{25} yr. CUORE searches for NDBD in a particular isotope of Tellurium (^{130}Te), using thermal detectors. A thermal detector is a sensitive calorimeter which measures the energy deposited by a single interacting particle through the temperature rise induced in the calorimeter itself. This is accomplished by using suitable materials for the detector (dielectric crystals) and by running it at very low temperatures (in the 10 mK range) in a suitable cryostat (e.g. dilution refrigerators). In such conditions a small energy release in the crystal results in a measurable temperature rise. This temperature change can be measured by means of a proper thermal sensor, a NTD germanium thermistor applied in contact with the detector.

The CUORE (Cryogenic Underground Observatory for Rare Events) detector is a close-packed array of 988 5×5×5 cm^3 TeO_2 bolometers arranged in 19 towers, each one containing 52 TeO_2 crystals, disposed on 13 floors. The total detector mass is 741 kg, containing 206 kg of the isotope of interest for NDBD (^{130}Te). The detector (Fig. 1) is presently in data taking at the Laboratori Nazionali del Gran Sasso and represents a significant advancement in this technology. CUORE will reach a sensitivity on the ^{130}Te NDBD half life of 10^{26} y, thus starting to cover the inverted neutrino mass hierarchy region [1].

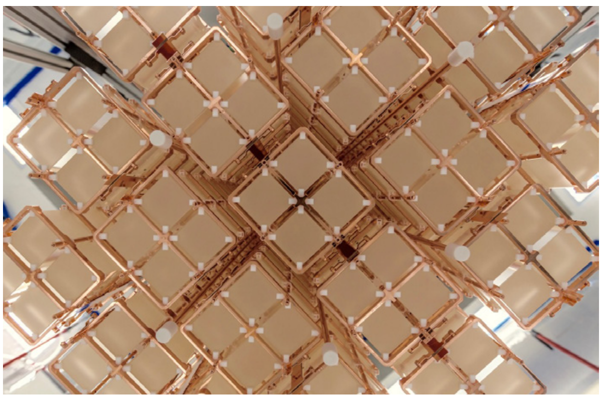

Figure 1: The CUORE detector.

Examining a total TeO_2 exposure of 369.9 kg yr, characterised by an effective energy resolution of about 8 keV FWHM and a background in the region of interest of $(1.37 \pm 0.07) \times 10^{-2}$ counts/(keV kg yr), we find no evidence for NDBD decay. Including systematic uncertainties, we place a 90% credible interval lower limit on the decay half-life of $T_{1/2}(^{130}\text{Te}) > 2.3 \times 10^{25}$ yr [2].

Within the CUORE collaboration, our group has been in charge of several crucial tasks, among them the design and procurement of the CUORE tower assembly line in clean room and ultrapure atmosphere and the software for the analysis of the experimental data. Our main expertise though is in the crystal developments. Our group was responsible of the entire process of crystal procurement from specifications to final acceptance tests through the qualifications of the materials.

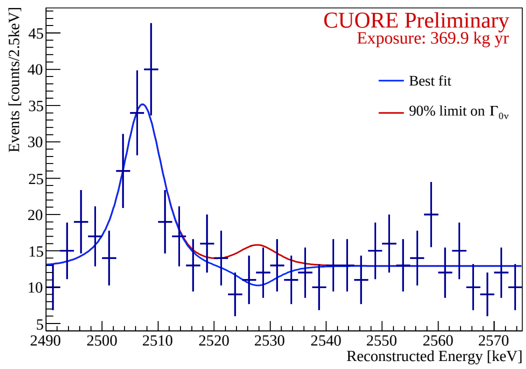

Figure 2: The best-fit model (solid blue line) overlaid on the spectrum of NDBD decay candidates in CUORE (data points); the data are shown with Gaussian error bars. The peak at 2507 keV is attributed to ^{60}Co [2].

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F. Bellini[1], L.Cardani, N. Casali[1], C. Cosmelli, I. Dafinei, F. Ferroni[1], S. Morganti, V.Pettinacci, C.Tomei, M. Vignati[1]

P30. The search for matter creation with CUPID

Neutrino-less Double Beta Decay ($0\nu\beta\beta$) is a nuclear transition in which a nucleus decays creating two electrons: $(A,Z) \rightarrow (A,Z+2)+2e^-$. This process cannot be accommodated in the Standard Model, as the absence of emitted neutrinos would violate the lepton number conservation. Its observation would have several implications for particle physics, astrophysics and cosmology. According to the majority of theoretical frameworks, for $0\nu\beta\beta$ to happen neutrinos must be Majorana particles. This means that, in contrast to all the other known fermions, they must coincide with their own antiparticles. Among the several experimental approaches proposed for the search of $0\nu\beta\beta$, cryogenic calorimeters (bolometers) stand out for the possibility of achieving excellent energy resolution, efficiency and intrinsic radio-purity. Moreover, the crystals that are operated as bolometers can be grown starting from most of the $0\nu\beta\beta$ emitters, enabling the test of different nuclei.

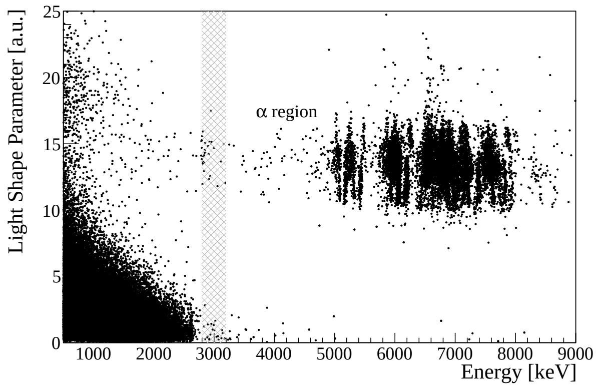

Figure 1: Light Shape Parameter as a function of the heat released in the ZnSe. The dashed region identifies the 400 keV region centered around the ^{82}Se Q-value [1].

The state of the art of the bolometric technique is represented by CUORE, a ton-scale experiment, presently in data taking at Laboratori Nazionali del Gran Sasso (LNGS). The CUORE sensitivity is currently limited by the background induced by the presence of α-decaying isotopes located in the detector structure. CUPID (CUORE Upgrade with Particle IDentification) starts from the CUORE technical expertise, material selection, background model, excellent energy resolution, and combines it with the capability to eliminate the backgrounds from α particles using scintillating crystals. The first CUPID prototype, CUPID-0 is composed by 26 ZnSe $\sim$ 500g bolometers, enriched at 95% in ^{82}Se, the $0\nu\beta\beta$ emitter, and faced to Ge disks light detector working as bolometers. CUPID-0 is taking data at LNGS. Thanks to the dual read-out (Fig.1), the background is reduced by an order of magnitude, down to $\sim 10^{-3}$ cts/(keV kg yr) [2].

With a collected statistics of only 9.95 kg yr of Zn^{82}Se we set a 90% credible interval lower limit of $T_{1/2}^{0\nu\beta\beta}$(^{82}Se) $> 5\times 10^{24}$ yr [2]. Moreover, we measure the $2\nu\beta\beta$ decay half-life of ^{82}Se with an unprecedented precision level. The very high signal-to-background ratio, along with the detailed reconstruction of the background sources allowed us to identify the single state dominance as the underlying mechanism of such process, demonstrating that the higher state dominance hypothesis is disfavoured at the level $> 5\ \sigma$ (Fig. 2 [3]).

Our group has been in charge of the Se enrichment, the whole crystal growth, the assembly of the detector and the developments of sophisticated analysis techniques for the background abatement.

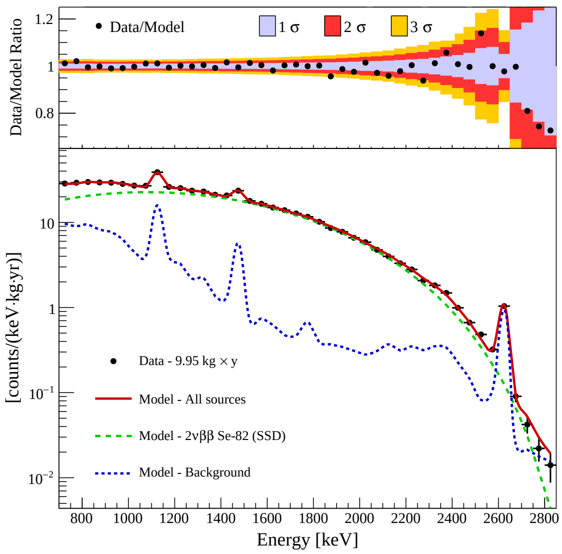

Figure 2: Energy spectrum of the events collected by CUPID-0 (black dots). Only three γ-lines are clearly visible over the continuum due to $2\nu\beta\beta$: ^{65}Zn at 1116 keV, ^{40}K at 1461 keV, and ^{208}Tl at 2615 keV. The solid red line is the results of the Bayesian fit reconstruction. The green line represents the $2\nu\beta\beta$ component. The blue line is the sum of the background sources [3].

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P31. CALDER: Kinetic inductance detectors for Majorana neutrinos

CALDER (Cryogenic wide-Area Light Detectors with Excellent Resolution) wants to contribute in settling an important issue that particle physics is now facing: Is the neutrino a standard particle or is it equal to its own antiparticle, as predicted by Ettore Majorana? The answer is of fundamental importance in the global framework of particle interactions and in cosmology, and could come from the observation of a rare nuclear process called "neutrinoless double beta decay". The goal of CALDER is to develop high-sensitivity and fast cryogenic light detectors for the identification of the double beta decay with a new technology based on superconducting detectors called KIDs (Kinetic Inductance Detectors).

KIDs base their working principle on the kinetic inductance. In superconducting materials the Cooper pairs, characterised by a binding energy smaller than 1 meV, move through the lattice without scattering, thus featuring a zero DC impedance. Nevertheless the AC impedance is non-zero. If a radio or microwave frequency is applied, the pairs change continuously their direction, and the inertia due to their mass generates an impedance. If the superconductor is inserted in a resonant RLC circuit with high quality factor ($Q > 10^3$), the density variation of the Cooper pairs is detectable as it produces changes in the transfer function of the circuit.

The detector is made via superconductor lithography on a silicon substrate. When photons hit the silicon they are absorbed and converted to phonons. Phonons scatter through the silicon until they are absorbed by the KIDs, break the Cooper pairs and generate a variation of the circuit transfer function. This variation is detected as an amplitude or phase modulation of the wave transmitted past the circuit.

On a sensible area of 2x2 cm^2 we demonstrated record sensitivity and response time of 25 eV and 20μs, respectively. We are now closing the project with larger light detectors featuring a sensible area of 5x5 cm^2, sensitivity of 100 eV or better and response time of 50 μs.

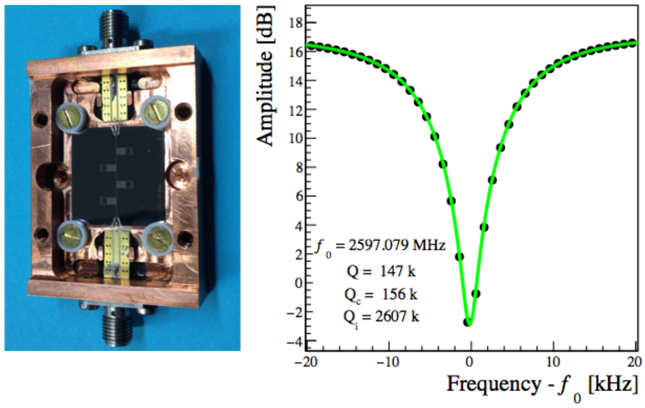

Figure 1: 4-pixel detector made by aluminum lithography on silicon substrate (left) and frequency response of a single KID (right). The detector is cooled down at 20 mK. When a photon is absorbed by the silicon, it is converted to phonons which travel to the KID, break cooper pairs and generate a signal.

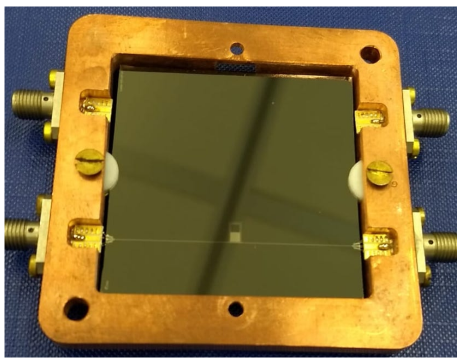

Figure 2: Picture of a 5x5 cm^2 detector made by a silicon absorber and a single aluminum KID coupled to a coplanar wave guide.

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CALDER was supported by an ERC Starting Grant (contract No. 335359) started in March 2014 and finished in February 2019.

http://www.roma1.infn.it/exp/calder

P32. High-Energy Neutrino Astronomy: the ANTARES telescope

Neutrino Astronomy is a new and unique method to observe the Universe. The weakly interacting nature of the neutrinos identifies them as a complementary cosmic probe to other messengers as photons, charged cosmic rays and gravitational waves. Neutrinos are ideal messengers as they can travel cosmological distances without being deflected or absorbed. As they are only produced in the interactions of hadrons, neutrinos will allow to distinguish unambiguously between hadronic and leptonic acceleration mechanisms in high-energy sources. In addition, neutrinos can escape from sources surrounded with dense matter or radiation fields: this implies that new compact acceleration sites might be discovered. This feature also gives rise to a unique signal for indirect searches of dark matter based on the detection of high energy products from the annihilation of dark matter particles possibly accumulated in the cores of dense astronomical objects. A diffuse flux of cosmic neutrinos, exceeding the atmospheric component, has been reported by IceCube that in this way started the "Neutrino Astronomy era". The search for individual point-like sources of neutrinos needs a km^3-scale neutrino telescope with good angular resolution in order to provide the necessary signal-background distinction.

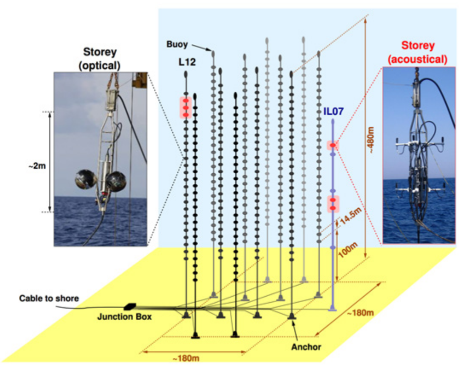

Figure 1: A schematic view of the ANTARES detector.

The ANTARES neutrino telescope is at present the largest deep-sea Cherenkov neutrino telescope in the Northern hemisphere [1] (see Fig. 1 for a schematic view). The main channel in the search for astrophysical point-like sources of neutrinos is the muon neutrino charged current interaction allowing for an excellent directional resolution on the primary ν_μ of less than 0.5°. The high rate of atmospheric μ restricts such searches to events coming from below the horizon. The background affecting this selected sample of "up-going" muon tracks is then mainly due to atmospheric ν_μ and few remaining atmospheric μ events misreconstructed as up-going. In the search for astrophysical neutrino sources, angular clustering requirements yield a strong suppression of both backgrounds. Improving the angular resolution allows to strongly suppress the background. The telescope is optimized to detect up-going high energy neutrinos (> 100 GeV) by means of 12 vertical lines equipped with a total of 885 photo-multipliers looking downwards at 45°. The latest searches for point-like neutrino sources are based on the combined analysis of data from both ANTARES and IceCube. The combination of the two detectors, which differ in size and location, opens a window in the Southern sky where the sensitivity to point-like sources improves by up to a factor of two compared to individual analyses. Using data recorded by ANTARES from 2007 to 2012, and by IceCube from 2008 to 2011, in both the track and cascade channels, a search for sources of neutrino emission was performed, as shown in Fig. 2. No significant excess over background has been found and flux upper limits for the candidate sources are derived [2]. These results appear promising for the next generation km^3-scale detector, currently under construction in the Mediterranean Sea, KM3NeT.

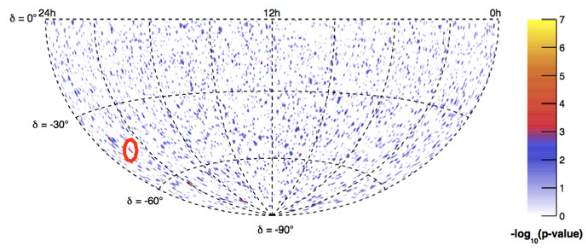

Figure 2: Skymap of pre-trial p-values for the combined ANTARES 2007-2012 and IceCube 2008-2011 point-like source analyses. The red circle indicates the location of the most significant cluster (0.7σ post-trial significance in the one-sided sigma convention).

A group of this Department is at present participating to the ANTARES experiment and is one of the stakeholder of the KM3NeT project (partially funded by UE). The Roma group has been responsible for the characterization of Mediterranean deep-sea sites and is deeply involved in the ANTARES data analysis.

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A. Capone[1], S. Celli, I. Di Palma[1], P. Fermani, A. Zegarelli

`http://www.roma1.infn.it/people/capone/ANTARES/indexANTARES.html`

P33. Search for high-energy neutrinos from bright GRBs with ANTARES

Gamma-Ray Bursts (GRBs) are irregular pulses of [100 keV−1 MeV] radiation, constituting the most energetic explosion of the Universe. Their characteristic energy release of $10^{51} - 10^{54}$ ergs is in the form of collimated mildly-relativistic jets lasting for a typical timescale shorter than one minute. Their isotropic distribution in the sky, as shown in Fig. 1, indicates an extra-Galactic origin. The observed non-thermal energy distribution implies that the photons are originated by particles accelerated into the source. For these reasons, GRBs are considered promising candidate sources for the production of the Ultra-High-Energy Cosmic-Ray (UHECR) flux observed at Earth.

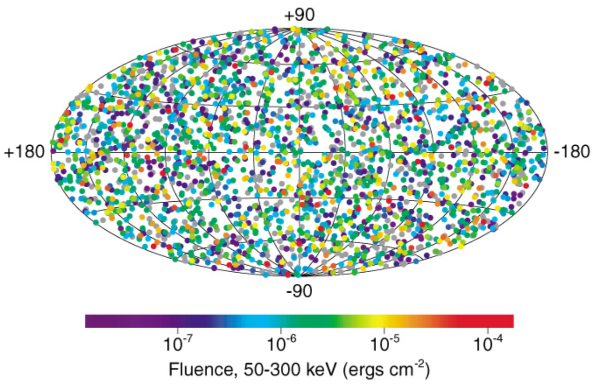

Figure 1: Sky distribution in Galactic coordinates of 2704 GRBs measured by BATSE onboard of the Compton Gamma-Ray Observatory and relative gamma-ray fluence [1].

In the so-called $p\gamma$ interaction, mesons are produced, which then decay generating neutrinos and gamma rays, with respectively $\sim$ 5% and $\sim$ 10% of the proton energy. In the following, the NeuCosmA simulation [2] is adopted to predict the neutrino flux produced at shocks internal to the jet: these predictions rely on several assumptions, including: i) the ratio between the internal energy channeled into protons and electrons (also called baryonic loading), fixed to $f_{\rm p} = 10$, and ii) the Lorentz factor of the overall jet, assumed to be $\Gamma = 10^{2.5}$.

We searched for high-energy neutrinos within ANTARES data, in temporal and spatial coincidence with the prompt emission of GRBs originated in correspondence of internal shocks. Assuming that the neutrino flux scales with the gamma-ray flux, bright sources represent promising targets. We selected long GRBs with gamma-ray fluence larger than 10^{-4} erg cm^{-2} exploding between 2007 and 2016, whose redshift was measured. In order to look for up-going muon tracks, the golden channel for astronomical purposes among the event types of neutrino telescopes, only those GRBs located below the horizon of the ANTARES telescope at the trigger time were selected. Four bright GRBs fulfilled these criteria: GRB 080916C, GRB 110918A, GRB 130427A and GRB 130505A [3].

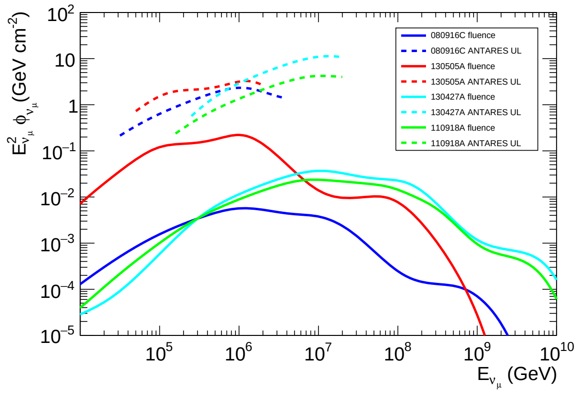

Figure 2: Expected $\nu_\mu + \bar{\nu}_\mu$ fluences for the selected GRBs (solid lines) and ANTARES 90% confidence level upper limits (dashed lines) [3].

After optimizing the data analysis for the track quality, a search in ANTARES data was performed within i) an angular window centered on the bursts position with an aperture of 10°, and ii) a temporal window slightly larger than the GRB duration. No neutrinos survived the analysis cuts, and we obtained an upper limit to the neutrino flux emitted by each of these sources, as indicated in Fig. 2. These limits allow to constrain the parameter space of the model, and they currently suggest a low neutrino production efficiency in bright GRBs because large values of Γ are still allowed. This circumstance may work against the detection of high-energy neutrinos, as their production in the jet of the most fluent GRBs seems to be compensated by a high Lorentz factor and possibly by a low baryonic loading. We are extending this work towards a population study of GRBs, in order to constrain the contribution of this class of sources to both the diffuse astrophysical neutrino flux measured by IceCube and to the UHECR flux.

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`http://www.roma1.infn.it/people/capone/ANTARES/indexANTARES.html`

P34. KM3NeT: a new era deep-sea neutrino telescope

KM3NeT is the new network of submarine Cherenkov neutrino telescopes under construction in two different sites of the Mediterranean Sea, whose physics goals are: 1) the discovery of high-energy neutrino sources in the Universe; 2) the determination of the neutrino mass hierarchy. The KM3NeT infrastructure will consist of three building blocks, as schematically shown in Fig. 1 [1]. At the Italian site, a two block detector named ARCA (Astroparticle Research with Cosmics in the Abyss) will be devoted to the detection of high-energy astrophysical neutrinos coming from cosmic sources in the Universe. At the French site, a single block detector named ORCA (Oscillation Research with Cosmics in the Abyss), similar to ARCA for the technology but much more compact, will exploit the sample of atmospheric neutrino interactions to determine the neutrino mass hierarchy.

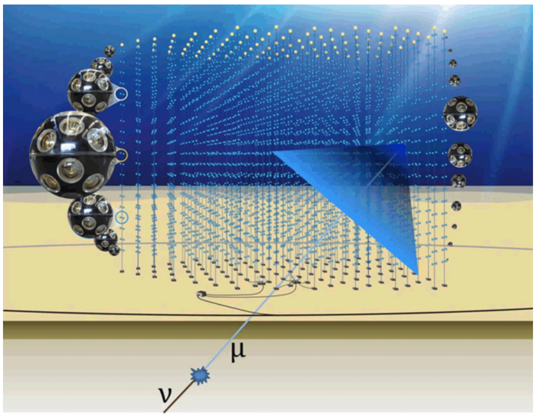

Figure 1: An artistic view of the KM3NeT detector.

Each block is an array of 115 flexible strings instrumented with digital optical modules (DOMs) hosted within pressure-resistant glass spheres, each housing 31 3″ photomultipliers tubes and their readout electronics. This multi-PMT design has been adopted to improve the directional information on the detected particles. The geometry of the detectors has been adapted to their physics goals: ARCA, optimised for the high energies, will be sparsely configured, while ORCA, dedicated to the low energies, densely configured. Thus every block will constitute a 3-dimensional array of photosensors able to detect the Cherenkov light produced by relativistic particles emerging from neutrino interactions.

Fig. 2 shows the significance as a function of time for the detection of a diffuse, flavor-symmetric neutrino flux at the level of that reported by IceCube in 2013 by ARCA. The excellent angular and energy resolutions, combined with its large effective mass, provide a significant discovery potential to find neutrino sources in the Universe. After three years of ORCA operation a determination of the neutrino mass hierarchy with at least 3-sigma significance will be achieved, as shown in Fig. 3. In addition, ORCA will provide improved measurements on some of the neutrino oscillation parameters.

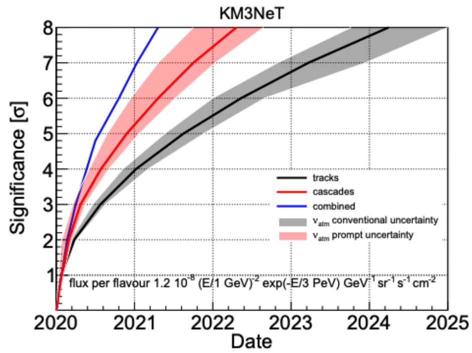

Figure 2: Significance as a function of time for the detection of a diffuse flux of neutrinos corresponding to the signal reported by IceCube, for cascade-like events (red line) and track-like events (black line). The black and red bands represent the uncertainties due to the conventional and prompt component of the atmospheric neutrino flux, respectively. The blue line indicates the result of the combined analysis.

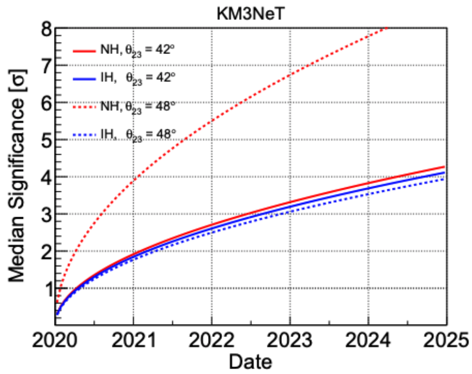

Figure 3: Median significance as a function of time for the determination of the neutrino mass hierarchy. The different lines denote expectations for different combinations of hierarchy and atmospheric mixing angle θ_{23}. Note that the CP-violating phase δ_{CP} has been assumed to be zero.

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P35. In-situ calibration of the KM3NeT detector

The basic element of the submarine Cherenkov neutrino telescope KM3NeT is the Digital Optical Module (DOM, Fig. 1), a complex instrument made by 31 PMTs (3″) inserted into a pressure resistant glass sphere together with the read-out and control electronics. 18 DOMs are installed on a Detection Units (DU), a vertical string kept tough by an anchor and a buoy. The PMTs allow to measure the detection time of Cherenkov photons induced by the path in water of charged particles originated in neutrino interactions. The total charge measured by each PMT gives also an indication of the energy deposited in water. Accurate measurements of the charge and the time of arrival of photons together with a precise real-time knowledge of the positions and orientations of the PMTs are required to have an excellent angular resolution: better than 0.3° for tracks and about 3° for cascades. To achieve the best angular reconstruction a unique clock, and time definition, has to be used for the whole detector: the PMTs have to be inter-calibrated with a nanosecond precision [1].

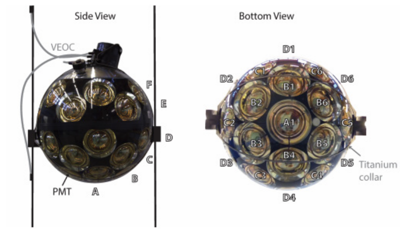

Figure 1: Views of a KM3NeT DOM.

The PMTs time calibration is obtained by a combination of several steps: 1) intra-DOM, 2) inter-DOM; 3) inter-DU. Prerequisite for the time calibration is the definition of the PMT High-Voltage (HV): for all PMTs in a DOM the HV is set in order to have the same gain (3×10^6). In KM3NeT the PMT charge is deduced by the "Time Over Threshold"(ToT) and the HV tuning is performed selecting, for each PMT, the HV values that produces the selected ToT for a single photon. The ToT distribution obtained for one PMT varying the HV is shown in Fig. 2. For each PMT we fix as, working point, the HV value that provides an average ToT=26.4 ns for a single photon signal [2].

KM3NeT DOMs allow to select atmospheric muons looking for local coincidences between the PMTs. A vertical muon passing close to a line will be seen by several DOM's allowing for the track reconstruction. From the time residuals of the track fit we will inter-calibrate the PMTs of different (adjacent) DOMs. The decay of a ^{40}K in the vicinity of a DOM, causes the majority of coincidences on 2 PMTs installed in the same DOM, in a time window of 25 ns. For the hits due to ^{40}K in PMT$_\mathrm{i}$ and PMT$_\mathrm{j}$ we do expect that the distribution of the hit-time

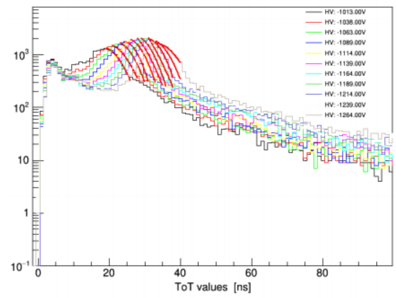

Figure 2: ToTs for one PMT and several HV offset values.

difference Δt_{ij} follows a Gaussian distribution (Fig. 3). A central value different from 0 means that the PMT time offset has to be adjusted. The width of the distribution is related to the PMT transit time spread while its integral is proportional to the product of the PMT efficiencies [3].

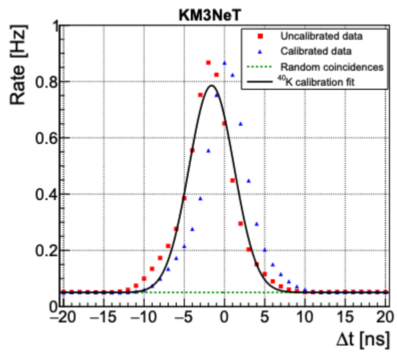

Figure 3: Coincidence rate vs Δt for 2 adjacent PMTs.

As expected, the mean of the calibrated time difference distribution is zero [4]. Muons traveling in water and detected by several DUs will allow and inter-DU time calibration. The results of the calibration analysis show the capabilities of the Cherenkov technique in sea water.

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P36. Indirect Dark Matter search with the KM3NeT experiment

Nearby one century ago F. Zwicky, while performing a systematic study of the velocity of galaxies in the Coma Cluster, reached the conclusion that the external galaxies were moving too fast to be in equilibrium with the estimated total mass of the cluster. This was the first hint for the hypothesis of the existence of Dark Matter (DM). Various astrophysical environment today suggest the presence of this kind of invisible matter. We still don't know what dark matter is: if it is made by particles, for sure they cannot be part of the Standard Model. A widely accepted model proposes the existence of the lightest DM particle, called WIMP (Weak Interactive Massive Particles) χ, that can interact only gravitationally. For this reason, WIMPs are supposed to feel the attraction of massive astrophysical object (like the Sun or the Galactic Centre in our Galaxy), where they would accumulate and self-annihilate producing neutrinos, either directly or as secondary products.

Large neutrino telescopes, like ANTARES and KM3NeT, are optimised to observe the more energetic annihilation channels, like:

$$\chi\chi \longleftrightarrow b\bar{b},\ W^+W^-,\ \mu^+\mu^-,\ \nu\bar{\nu}$$

where each interaction is supposed to have a 100% BR. From simulations, it is possible to obtain the energy spectra (dN_ν/dE_ν) of the various annihilation channels, which allow to compute the number of neutrinos isotropically emitted per energy and per WIMP annihilation. In order to evaluate the probability for the WIMP to be captured by a massive object, it is necessary to know their thermal relic density of DM in our Galaxy, that is described by the J-factor function:

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int \rho^2 dl$$

where Ω is the extension of the source, l is the distance between the Earth and the source of DM annihilation considered and ρ is the DM density profile. The latter is one of the key ingredient for predicting the neutrino fluxes from DM annihilation, and several models exist in the literature for it (e.g. NFW, Einasto etc.). Hence, the observed neutrino fluxes can be parametrised as:

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi M_\chi^2}\frac{<\sigma_A v>}{2}\frac{dN_\nu}{dE_\nu}J(\Delta\Omega)$$

where the thermally averaged annihilation cross section $<\sigma_A v>$ among the WIMPs with velocity v and mass M_χ appears. The preferred sources to be investigated for an indirect DM search with neutrino telescopes are i) the Sun, ii) the Galactic Centre and iii) the Earth, but also iv) low luminosity (dwarf) galaxies.

The theory gives little guidance for the WIMP mass or whether their interaction with matter is spin-dependent or spin-independent. Looking in the direction of one of these possible source of DM, the evidence of an excess of neutrino events over the isotropic atmospheric neutrino background can be considered as an indirect probe of the existence of DM. In Fig. 1 and Fig. 2 the sensitivity of KM3NeT-ORCA on the DM annihilation cross section after 3 years of data taking is reported, in comparison with the other DM searches.

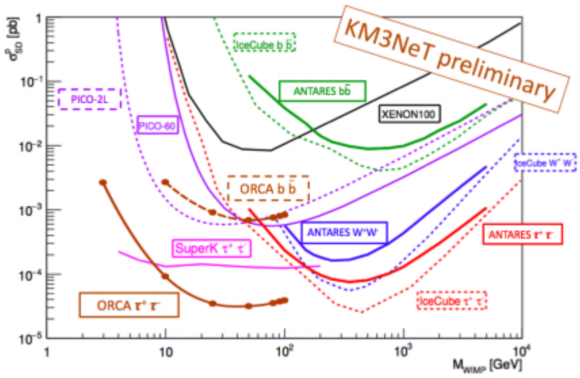

Figure 1: 90% C.L. limits on the spin-dependent cross-section after 3 years of ORCA data taking, based on counting both ν_μ and ν_e events coming from the direction of the Sun.

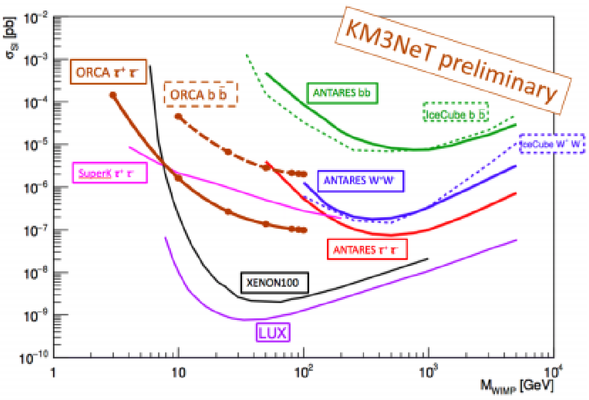

Figure 2: 90% C.L. limits on the spin-independent cross-section after 3 years of ORCA data taking, based on counting both ν_μ and ν_e events coming from the direction of the Sun.

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P37. The search of charged lepton flavor violation with MEG-II

The searches for lepton flavor violation in charged lepton decays play a crucial role in the hunt for physics beyond the Standard Model of particle interactions (SM). Historically, the negative results of these searches led to the formulation of the lepton flavor conservation as an "accidental" symmetry of the SM. The discovery of neutrino oscillations already demonstrated that lepton flavor is not an exact symmetry, although the impact on the charged lepton sector is negligible, predicting, for example for the $\mu \to e\gamma$ decay, a branching ratio (BR) of about 10^{-54}, far away from any experimental sensitivity. This symmetry is generally broken in many New Physics (NP) models, sometimes leading to predictions just below the present limits (see [1] for a review). Thus, an observation of charged lepton flavor violation would be an unambiguous evidence of NP, while upper limits can be used to constrain NP models.

The present best limit on the $\mu \to e\gamma$ decay, BR$(\mu \to e\gamma) < 4.2 \times 10^{-13}$ at 90% C.L [2], has been obtained by the MEG collaboration at the Paul Scherrer Institut (PSI, Switzerland). The MEG experiment has been upgraded (MEG-II) to increase the sensitivity by one order of magnitude i.e. with a design sensitivity of 6×10^{-14}.

In a $\mu \to e\gamma$ experiment muons are stopped in a target in order to exploit the clean signature of a decay at rest: an e^+ and a γ in coincidence moving collinearly back-to-back with their energies equal to half of the muon mass ($m_\mu/2 = 52.8$ MeV). Positive muons are used to avoid interferences due to the negative muon capture in nuclei. The dominant background is due to an accidental coincidence of a positron from a Michel muon decay ($\mu \to e\nu\bar{\nu}$) with an high energy photon, whose source might be either a radiative muon decay (RMD, $\mu \to e\nu\bar{\nu}\gamma$), the annihilation in flight of a positron in a Michel decay or the bremsstrahlung from a positron. The other source of background is the RMD when the positron and the photon are emitted almost back-to-back while the two neutrinos carry off little energy. To separate signal from background events, four discriminating observables are commonly used: the positron and photon energy (E_{e+} and E_γ) the relative angle ($\Theta_{e+\gamma}$) and the relative time ($T_{e+\gamma}$), usually combined in a maximum likelihood analysis to enhance the sensitivity.

The MEG-II [3] experiment is an upgraded version of the MEG experiment. The basic idea of MEG-II is to achieve the highest possible sensitivity by making maximal use of the available muon intensity at PSI with the same detection principles of the MEG experiment but with improved detectors.

A monochromatic beam of μ^+ is extracted from the πE5 channel of the PSI high-intensity proton accelerator complex, as in MEG, but with an intensity of 7×10^7 muons/s, more than twice of that used in MEG. After the MEG beam transport system, μ^+ are stopped in a target, which is thinner than the MEG's one to reduce multiple scattering of the emitted positrons.

The e^+ momentum is measured by a magnetic spectrometer, composed by an almost solenoidal magnet (COBRA) with an axial gradient field and by an ultra thin single volume cylindrical drift chamber. The e^+ timing is measured by two matrices of 256 plastic scintillators pixels read out with silicon photomultipliers (Timing Counter). The γ energy, direction and timing are measured in a 800 l volume liquid Xenon scintillation detector by means of multi-pixel photon counters on the inner face and photomultipliers on the lateral faces. All the detector resolutions and efficiencies are improved by a factor $\sim$2 with respect to MEG. A schematic overview of the MEG-II detector is shown in Figure 1.

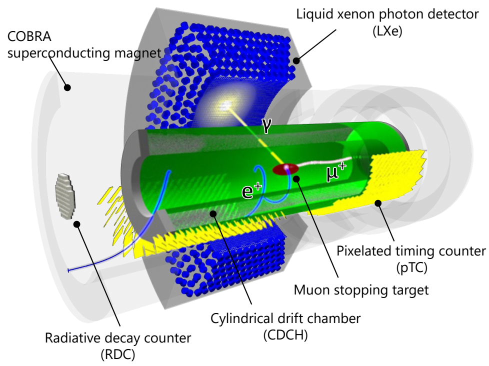

Figure 1: Schematic view of the MEG-II detector

The experiment is in an advanced commissioning phase. The detector integration has been completely tested in 2018, and at the end of 2019 an engineering run is scheduled; the beginning of data taking is foreseen in 2020 and the MEG-II experimental goals are within reach in three full years.

The Rome group is involved in the drift chamber construction and calibration. The group is also responsible for the target monitoring system and contributes to the final analysis, to the Monte Carlo simulation, and to the experiment sensitivity studies.

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P38. The CYGNO project

The CYGNO project is aiming at the construction of a 1 m^3 gas Time Projection Chamber (TPC) for the Directional Search of light Dark Matter (DM) [1].
The TPC technology, developed for High Energy Physics experiments, can provide a complete information about interaction events occurring in the sensitive gas volume:

- 3D reconstruction of the particle tracks;
- evaluation of the energy release profile along the particle trajectory;
- acquisition of large volumes with a relative small amount of readout channels.

A recent proposal [2] aims to develop an Optical Readout of Gas Electron Multipliers (GEM) based on CMOS sensor for the gas TPC.
The optical readout approach has several advantages:

- sensors can be installed outside of the sensitive volume reducing the interference with the GEM high voltage operation and reducing the gas contamination;
- the use of suitable lenses allows to image large surfaces to small sensors;

In particular the large granularity and very high sensitivity of the CMOS technology, allows the detection of few photons per pixels. A sensitivity to events with an energy releases in the gas in the keV range has been recently demonstrated [3].

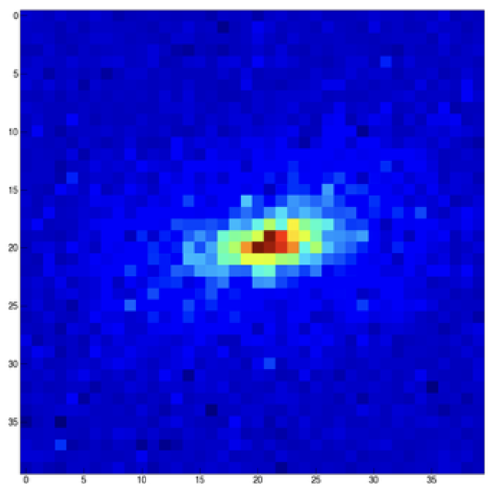

Figure 1: Example of an event of Helium nuclear recoil induced by neutron scattering acquired with a 10 l prototype developed within the the CYGNO project.

The use of Helium-based gas mixtures allows an efficient momentum transfer for DM particles with a mass in the GeV range.

The application of this technology in the DM search will provide high efficiency in the identification of nuclear recoils induced in the gas by DM scattering. Moreover, the possibility of reconstructing the recoil direction offers a crucial handle to rejecting background events due to natural radioactivity [4]. After about two years of R&D activity, during 2019 the CYGNO collaboration is finalising the design of the 1 m^3 detector (Fig. 2) and will start its construction in 2020.

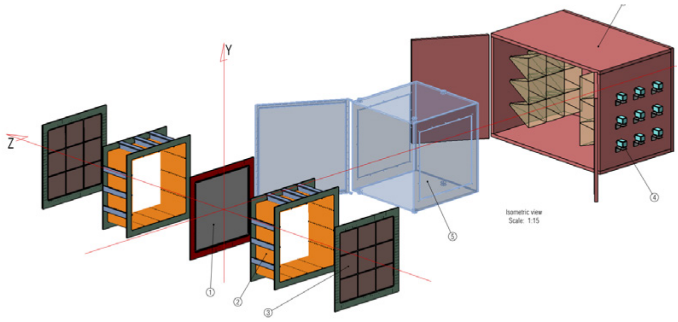

Figure 2: Exploded view of the CYGNO 1 m^3 module and radioactivity shields.

The apparatus will be composed by a 1 m^3 gas volume filled with a He/CF_4 60/40 gas mixture (1.6 kg total mass) kept at atmospheric pressure and subdivided in two 50 cm long parts separated by a central cathode with a drift electric field of about 1 kV/cm. Each gas volume is equipped with a 3×3 matrix of triple-GEM structures and a CMOS sensors. The active apparatus will be contained in a massive structure meant to shield it from the external gamma rays and neutrons. The installation underground at the National Laboratories of Gran Sasso is foreseen for 2022. CYGNO will behave as a demonstrator of the this optical readout technology in order to prepare a proposal for a 30-100 m^3 experiment.

This activity is carried out in the framework of the CYGNUS-TPC project that aims at building a system of multi-ton gas targets distributed in underground laboratories around the world using the TPC-based techniques for Directional Dark Matter searches.

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P39. Direct search for dark matter with DarkSide experiment at LNGS

There is strong evidence from astronomical and cosmological observations for the existence of dark matter in our Universe. Weakly Interacting Massive Particles (WIMPs) are a well-motivated dark matter candidate. The observation of WIMPs with masses in the range from 1 GeV up to about 1 TeV is a major future experimental challenge. Direct and indirect DM detection techniques allow for a search program complementary to the one at colliders. Direct detection of DM via elastic scattering of galactic WIMPs from a liquid argon target is a demonstrated technique capable of probing masses well above the reach of the LHC. Liquid argon (LAr) is a particularly favorable target thanks to its excellent discrimination capabilities. Scintillation light initiated by particles recoiling off atomic electrons (ER) has a time constant of about a microsecond, to be compared to nanosecond time scale for scintillation light expected in WIMP-nuclear recoil event (NR). Exploiting this effect via pulse shape discrimination (PSD), an ER background rejection of 10^9 was achieved by DEAP. Additional discrimination was demonstrated by Darkside-50, using a two-phase time projection chamber (TPC) to measure both the prompt scintillation light and the delayed one from ionized electrons. DarkSide-50 performed a blind search and observed no background events over a run period in excess of two years [1].

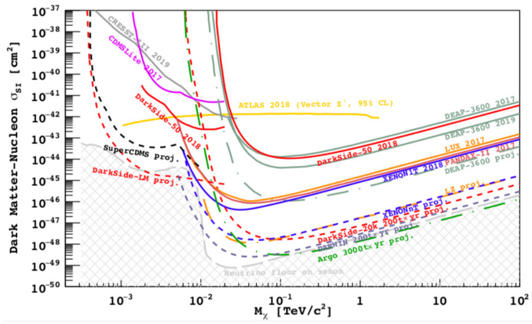

Figure 1: 90% C.L. exclusion limits showing leading results (continuous) on direct DM searches compared with future sensitivities for Ge-, Xe-, and Ar-based projects (dashed).

In addition to sensitivity to WIMPs with high masses, the two-phase DarkSide-50 detector has extended its reach to low WIMP masses by detecting single ionization electrons extracted from the liquid argon volume, resulting in the best world limit below 6 GeV [2]. With control of the ER backgrounds and the reduction of the ^39Ar component by the use of underground Ar (URANIA project) and by further distillation (ARIA project), a ton scale LAr detector (DarkSide-LM) will have the potential to reach the "neutrino floor" in this low-mass range (see Fig. 1). All major groups using LAr to search for DM (ArDM, DarkSide-50, DEAP, and mini-CLEAN) joined the Global Argon Dark Matter Collaboration (GADMC) to build the DarkSide-20k two-phase underground argon (UAr) TPC detector, which will operate in the LNGS Hall-C, and the ultimate 300t ARGO in a later stage.

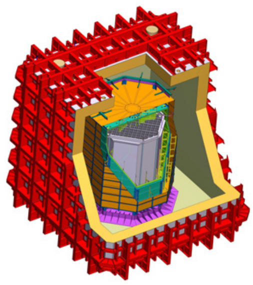

Figure 2: Rendering of the DarkSide-20k detectors: TPC (gray), outer Veto (green) and copper cage (orange), all contained in the protoDUNE-like cryostat (red).

Fig. 2 shows a 3D schematic view of the DarkSide-20k detector consisting of two nested detectors, the inner dual phase argon TPC and the outer Veto, housed within a protoDUNE-like membrane cryostat. The TPC is contained in an acrylic vessel and filled with 50t UAr. SiPM-based PhotoDetector arrays will view the argon volume on top and bottom planes. The active outer veto detector surrounding the TPC is made of Gd-loaded acrilic shells moderating and capturing neutrons providing an efficient veto of NR background. The DarkSide-20k detector will have ultra-low backgrounds and the ability to measure them *in situ*, resulting in an expected sensitivity to WIMP-nucleon cross sections with projected sensitivity better than currently-published results and other planned experiments (Fig. 1). DarkSide-20k is foreseen to begin operations in 2023 and will either detect WIMP DM or exclude a large fraction of favored WIMP parameter space. The Sapienza & INFN Roma group is actively involved in both the DarkSide-50 physics data analysis, namely in the low mass DM search result, and also in the R&D and construction of DarkSide-20k project, in which : A. Messina Software trigger L2, V. Ippolito is Offline L2, M. Rescigno is Trigger and DAQ L1, and S. De Cecco is DarkSide-20k deputy project leader.

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P40. Flavour, CP violation and Matter-Antimatter asymmetry

In spite of the extraordinary experimental programme of LHC, which led to the discovery of the Higgs particle and to the measurements of many interesting processes, we are still confronted by a number of fundamental questions which are not answered by the Standard Model (SM) of particle physics as, for example, the nature of dark matter or the mechanism which generates the baryon-antibaryon asymmetry of our universe. Our expectations (prejudices) about the existence of particles with masses in the TeV range, due to physics Beyond the SM (BSM), were all deceived. Thus we do not know which processes or measurements, and at which energy scale, will provide evidence for BSM physics. *Ça va sans dire* that searches of new light or heavy particles, more accurate determinations of the properties of the Higgs boson and further progress in our knowledge of quark and lepton weak interactions, in particular regarding the Charge-Parity (CP) symmetry violation, will be the focus of experimental and theoretical investigations in the near future.

Flavour is the name generically used to identify the fundamental fermions which are grouped in three families, $(u_{L,R}, d_{L,R}, e_{L,R}, \nu^e_L,)$, $(c_{L,R}, s_{L,R}, \mu_{L,R}, \nu^\mu_L)$ and $(t_{L,R}, b_{L,R}, \tau_{L,R}, \nu^\tau_L)$. So far we do not have direct evidence of the existence of right handed neutrinos, although the measurement of their mass difference is a strong signal that they should exist. The fermions within a given family have different quantum numbers with respect to strong, weak, and electromagnetic interactions. On the other hand, across the three families the particle content is exactly the same except for the masses. The heaviest fermions decay into the light ones under the action of weak interactions which violates flavour conservation. Several fundamental questions then arise: why there are three almost identical replicas of one family and what is the origin of the bizarre mass matrix and of the weak couplings - the Cabibbo-Kobayashi-Maskawa (CKM) matrix that we observe in nature. We expect that the explanation of this puzzle will also give the key to solve the question of the baryon-antibaryon asymmetry in the universe. Since in the SM the mass of the fermions are strongly correlated to their coupling to the Higgs we may also expect to improve our knowledge on the nature of the Higgs field from a study of flavour physics.

In the past, due to its sensitivity to high scales, flavour physics played a major role in developing and understanding the SM, providing signals of the presence of new particles well before these were directly observed (this was the case for charm and top quarks from $K_L \to \mu^= \mu^-$ decays, K^0-$\bar{K}^0$ and B^0-$\bar{B}^0$ mixing, respectively). After decades of intense experimental and theoretical investigation we now know that the bulk of flavour physics is due to the SM CKM mechanism.

A deeper scrutiny of the SM expectations for the anomalies recently observed in semileptonic $B \to D^{(*)}\ell\nu_\ell$ decays and in $B \to K^{(*)}\ell^+\ell^-$ decays, pointing to a possible violation of Lepton Flavour Universality (LFU), together with other processes such as rare kaon decays, radiative decays of heavy mesons and neutral meson mixing, could in the future establish the presence of NP even with modest improvements of the accuracy. A fundamental step in this direction is the control of radiative decays, including hard photon emissions, in weak decays. There is a large complementarity between HL-LHC, Belle-II, and dedicated experiments at muon beams searching for $\mu \to e\gamma$ as well as with the flavour diagonal probes such as the measurements of the $g-2$ of the muon and the electric dipole moment of the neutron (electron). A related unsolved problem is that of strong CP violation, the solution of which with the axion could also provide the dark matter of the Universe.

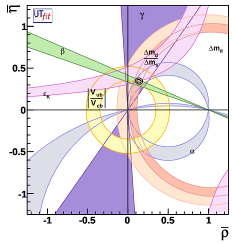

Figure 1: Constraints on the Wolfenstein parameters $\bar{\rho}$ and $\bar{\eta}$ from the Unitarity Triangle analysis [3].

Our group has a world-leading role in these directions, obtained with studies of NP contributions to flavour and CP violation beyond the leading order in QCD, with the calculation of $\Delta F = 2$ hadronic matrix elements in Lattice QCD, with the computation of Next-to-Leading order (NLO) anomalous dimensions for the most general $\Delta F = 2$ operator basis, with combined analyses of flavour and CP violation in the SM and beyond. It has also pioneered the phenomenology of non-leptonic decays, devising several strategies to estimate the SM uncertainty in a reliable, mostly data-driven way, as well as new methods to extract short-distance information from non-leptonic decays. More recently important results on radiative, rare decays and $g-2$ have been obtained, with accurate predictions which will certainly help in the quest for physics BSM see [1]-[3] and references therein.

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Authors
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P41. Weak matrix elements and hadron spectrum from lattice QCD

The theory of Quantum Chromodynamics (QCD) is considered the best candidate to describe the strong interactions. Important questions concerning the value of the parameters of the Standard Model (SM) and of models of new physics involve hadron dynamics at low energies. At these scales QCD is non-perturbative (NP) and has not been solved analytically: quantitative predictions become thus very challenging. At present, the only first principle approach known which allows NP computations is called lattice QCD and consists in regularising the theory on a space-time lattice and computing numerically the functional integral. Typical quantities of interest that need to be computed NP by using lattice QCD are matrix elements of composite operators made of quark fields amongst light hadron states. Matrix elements of $\Delta F = 2$ 4-quark operators enter, for example, the theoretical prediction of CP violating observables in the $K^0 - \bar{K}^0$ system, within the SM and beyond. In order to compute NP these matrix elements, a very important step is the renormalisation of composite operators, which also needs to be carried out in a NP way. The Schrödinger Functional (SF) is the only scheme which allow the NP computation of the Renormalisation Group Running (RGR) down to hadronic scales of $\mathcal{O}(\Lambda_{\rm QCD})$. We thus have applied this technique to the $\Delta F = 2$ operators, for the first time in presence of mixing.

Such a computation can be divided in two parts: the fully NP computation from the hadronic scale ($\approx \Lambda_{\rm QCD}$) to the electroweak scale ($\approx M_W$) and the next-to-leading order (NLO) perturbation theory (PT) computation above the electroweak scale (where PT at the NLO should be safely applicable). The second part of the computation requires the knowledge of the NLO anomalous dimension matrix for the complete basis of operators in the SF scheme. This has been obtained through a one-loop computation of the matrix of renormalisation constants [1]. We have thus proceeded with the first part, by computing NP (with 2 flavours of sea quarks) the RGR between two scales $\mu/2$ and μ. Iterating this computation for various scales ranging in the interval $[\Lambda_{\rm QCD}, M_W]$ and combining with the NLO PT computation above M_W, we have been able to construct the full RGR down to the hadronic scale [2]. An interesting byproduct of our computation has been the study the systematic uncertainties related to the use of NLO PT for the RGR down to hadronic scales, as done usually in the present literature. Our conclusion is that PT truncation effects in the RGR can be significantly large - in particular for the operators which contribute in models BSM - therefore posing serious doubts on all the computations of $\Delta F = 2$ matrix elements available at present.

In order to compute the RGR with 3 flavours of sea quarks we have used a modification of the SF scheme called the Chirally Rotated SF, which presents several advantages with respect to the standard one. We have performed the NLO PT computation in this scheme [3] and we have started the NP computation of the RGR in the interval $[\Lambda_{\rm QCD}, M_W]$ [4].

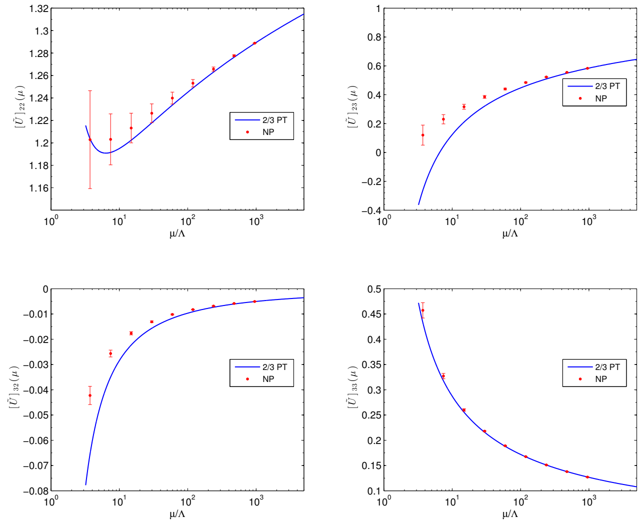

Figure 1: NLO PT (blue) and NP (red) RGR for two operators of the $\Delta F = 2$ basis which mix under renormalisation

We have also tackled the problem - crucially related to the long standing problem of the exponential reduction of the signal-to-noise ratio in euclidean time - of the precise determination of the baryon spectrum and of baryon matrix elements. We have developed a new type of extended interpolating fields (IFs) built by introducing "quenched" 3-Dimensional (3D) fermions living on the time slices where the source and the sink of the correlator are placed. Contrary to the previously used extended IFs obtained from smearing techniques, renormalisation properties of the new extended 3D IFs are under good theoretical control, allowing the continuum limit to be taken in a controlled way. Moreover, the short distance behaviour when two of them approach each other is greatly improved with respect to both point sources and smeared IFs. The use of the new extended 3D IFs can thus be very helpful when solving the generalised eigenvalue problem by creating a wider basis of operators which couple to the low lying states [5].

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Authors

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P42. Directions for New Physics Searches

Two solid messages can be extracted from the experimental results from the LHC experiments: a spin-0 state so far matching the properties of the Standard Model (SM) Higgs boson has been discovered and no clear sign of the long sought New Physics (NP) associated with the solution of the hierarchy problem have been found. Nevertheless there are intriguing hints of physics beyond the SM in the form of lepton flavour universality (LFU) violation in semileptonic B decays both in charged and in neutral currents, while various extensions of the SM formulated to address evidences such as the existence of Dark Matter (DM), neutrino masses and baryogenesis predict new dynamical degrees of freedom at a mass scale testable at the LHC. The search for NP thus continues and various directions can be pursued.

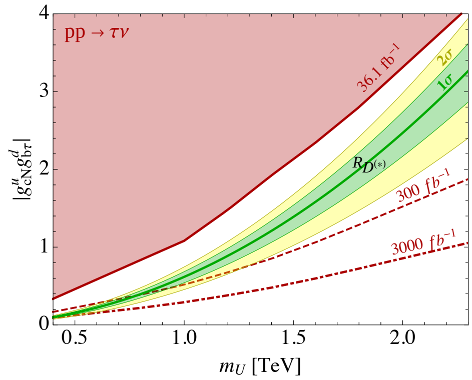

Figure 1: Present and projected LHC limits on the mass of the U_1^μ LQ. Shown in green and yellow the 68% and 95% confidence intervals around the central values of $R(D^{(*)})/R(D^{(*)})^{\mathrm{SM}}$. See [1] for details.

Anomalies in the flavour sector [1, 2]

NP models which are able to explain the discrepancy in the measurements of the charged current $R(D^{(*)}) = \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\ell\nu)$ ratio face various challenges due to the doublet nature of the SM neutrino. Adding a new right-handed sterile state, N_R, which contribute to the $R(D^{(*)})$ anomaly through the effective operator $(\bar{c}_R\gamma^\mu b_R)(\tau_R\gamma_\mu N_R)$, allows to avoid stringent experimental constraints. This effective operator can be generated only via the exchange of a charged vector boson, $W'_\mu \sim (\mathbf{1},\mathbf{1},+\mathbf{1})$, a scalar leptoquark (LQ), $S_1 \sim (\bar{\mathbf{3}},\mathbf{1},+1/3)$ or a vector LQ, $U_1^\mu \sim (\mathbf{3},\mathbf{1},+\mathbf{2/3})$ [1]. Interestingly, models where the mediator is the U_1^μ LQ can also provide a solution to the charged current $R(K^*) = \mathcal{B}(B \to K^{(*)}\mu^+\mu^-)/\mathcal{B}(B \to K^{(*)}e^+e^-)$ anomaly whereas if only the $R(D^{(*)})$ anomaly is addressed the N_R state can be a DM candidate. Also without the inclusion of the N_R sterile state, models with the U_1^μ LQ can provide a combined explanation of both charged- and neutral-current anomalies and full-fledged ultraviolet complete theories can be formulated. Crucially, the LHC will be directly testing these LQ mediator through their on-shell production with already $\mathcal{O}(300\ \mathrm{fb}^{-1})$ of data in all almost all the model parameter space that can explain the $R(D^{(*)})$ discrepancy, see Fig. 1.

NP not related to the hierarchy problem [3]

Theories with new vector like matter charged under a confining QCD-like sector have gained renewed attention due to the possibility of having an accidental $U(1)$ global symmetry that guarantees the stability of the lightest baryon of the new gauge group, thus possibly providing a DM candidate. These theories have been so far overlooked from the experimental side, up to the point that new resonances with a mass of $\mathcal{O}(100\ \mathrm{GeV})$ are still allowed by current constraints. Typically, meson of the new gauge group are pair produced and each decay into a pair of SM gauge bosons. Multibosons final state such as $3\gamma W$, $2\gamma 2W, 2ZW\gamma 2\ldots$ thus provide striking and clean signatures to be looked for at the LHC. These can be used to effectively test these theories up to masses of the new strong sector resonances of $\mathcal{O}(1\ \mathrm{TeV})$.

[1] In parentheses the quantum number under $SU(3)_c \times SU(2)_L \times U(1)_Y$ are indicated, with $Q_{\mathrm{em.}} = T_L^3 + Y$.

Dark Matter via Dark Sectors [4]

The present picture can motivate the idea that the NP responsible for DM may arise in a Dark Sector (DS), made up of new particles which are singlets under the SM gauge interactions. The DS can eventually interact with the SM via portal-type interactions, mediated by heavy messengers which can communicate tree-level interactions between the SM and the DS fields. This can give rise to low-energy effective interactions between SM and DS particles induced by higher-dimensional operators, the latter being suppressed by the characteristic scale of the messenger fields. A quite heavy messenger sector might then naturally explain why the NP, and in particular the DM sector, is still escaping all direct and indirect searches. A rich phenomenology arises from this framework that can be scrutinized at present and future colliders (see *i.e.* [4], and references therein).

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P43. Higher-Order Perturbative Corrections and Collider Physics

In the absence of a clear signal of new physics in the high-energy regime, Precision Physics is of crucial importance since it represents the only possibility we have to reveal a discrepancy of the measured observables with the predictions of the Standard Model of fundamental interactions (SM).

Higgs plus jet production at NLO in QCD [1].
After its discovery in 2012 at the LHC, the Higgs boson has been in these years the subject of a wide number of experimental and theoretical physics studies. The accurate measurements of the Higgs cross sections in all the possible decay channels, done by ATLAS and CMS collaborations at CERN, reveal a strong compatibility of the particle discovered with the Higgs boson of the SM. Accurate predictions and measurements and an accurate study of more exclusive observables are important to reveal peculiar behaviours and to highlight possibly the effetcts due to new physics. In order to reach the needed accuracy in the theoretical predictions, higher-order perturbative corrections have to be taken into consideration. In particular, NLO QCD corrections to the production of a Higgs along with a jet, with the complete dependence on the mass of the heavy quark running in the loops, is essential for the study of the Higgs $p_\perp$ distribution at intermediate and high $p_\perp$. In the last years, we calculated analytically the master integrals for the planar contributions to the NLO production of $H+j$. We have now completed the calculation of one of the two families of non planar diagrams, important for the completion of the cross section.

EW-QCD corrections to Drell-Yan processes [2].
The Drell-Yan production of Z and W bosons is one of the standard candles for physical studies at the LHC. Due to the big cross section and clean experimental signature, Drell-Yan processes can be measured with small experimental uncertainty and, therefore, allow for very precise tests of the SM, giving acces to the determination of important parameters of the weak sector. Furthermore, Drell-Yan processes constitute the SM background in searches of New Physics, involving for instance new vector boson resonances, Z' and W', originating from GUT extensions of the SM. An accurate and reliable experimental and theoretical control on Drell-Yan processes would be of the maximum importance for future physics studies at hadronic colliders. The NNLO QCD corrections to Drell-Yan processes are known in the literature and they are combined with NLO EW corrections. At the moment the main source of uncertainty is due to the mixed QCD-EW corrections, which affect in particular the distributions used for the extraction of the W mass. In the last years, we calculated the two-loop master integrals needed for the evaluation of the mixed corrections to the production of a lepton pair and we now completed the determination of the total cross section of production of an on-shell Z boson in the quark-antiquark channel.

NNLO QCD contributions to $t\bar{t}$ production cross section at hadron colliders [3].
Although the NNLO QCD corrections to the total cross section of production of $t\bar{t}$ pairs at hadron colliders are already known and many differential distributions recently appeared, a fast and reliable Monte Carlo (MC) integrator, needed for cross-check and analysis purposes, is still missing. The last missing ingredient to release such a MC is the completion of the evaluation of the two-loop matrix elements in a form that could be easily evaluated numerically. Recently, we completed the analytic evaluation of the master integrals needed for the quark-antiquark channel and the still missing two color factors of the relative cross section.

Double Higgs production and $p_\perp$ expansion [4].
In view of a detailed study of the properties of the Higgs boson, a very important role is played by the tri-linear coupling of the Higgs field. The process in which a pair of Higgs bosons are produced in hadronic collisions gives access to this parameter. Therefore, precise predictions for the double-Higgs production cross section is of maximal importance for the run II of the LHC. Recently, we computed the NLO QCD corrections to such observable using a new technique based on an expansion of the analytic cross section in powers of the Higgs $p_\perp^2$.

This research programme was carried out in collaboration with the following members of the Department of Physics: M. Becchetti (PhD student), S. Lavacca (PhD student), V. Casconi (PhD student), C. Brancaccio (Master student), F. Vitale (Master student).

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P44. Exotic Hadrons and Light Dark Matter.

Exotic Hadrons. The XYZ hadron resonances are a class of very well experimentally confirmed exotic particles, with quantum numbers and decay modes suggesting a multiquark nature [1].

Hadrons composed by more than three quarks indicate that unexpected low energy quantum chromodynamics (QCD) phenomena are at work: either long range forces between standard mesons, allowing, for example, the production of molecules at high transverse momenta in multi-TeV proton-proton collisions notwithstanding their very low binding energy, or special arrangements of the color forces between quark lumps, compatible with multiquark structures and with the surprising decay patterns observed.

We are working on a model of low energy QCD interactions in hadrons based on the emergence of a short range repulsion between diquark-antidiquark pairs. The tunneling through the resulting potential barrier can be studied with quasiclassical methods and a very simple and solid explanation of the decay phenomenology of X and Z particles is found [2,3].

We have recently shown that it is possible to formulate a QCD version of the hydrogen molecule bond with a set of configurations comprising the above mentioned repulsion. With the same method we confirm that doubly-heavy open-beauty tetraquarks are stable against strong decays, as envisaged in several recent papers.

The analog of the H_2^+ ionized molecule is a doubly heavy baryon, compatible with those observed by the LHCb collaboration, whereas a doubly heavy tetraquark is the analog of the H_2 molecule. Heavy quarks are taken in place of protons and light quarks in place of electrons. The non-abelian nature of the color forces produces, on the other hand, a number of peculiarities which are specific to these multiquark systems.

We introduce the notion of QCD 'orbitals': two body, heavy-light, quark-quark or quark-antiquark lumps held together by the QCD Coulomb-like interaction plus a linear confining term with the appropriate string tension.

The pair forming an orbital, except for the case of the baryon, is in a superposition of color representations with the same triality, e.g. $\bar{\mathbf{3}}$ and $\mathbf{6}$. Orbitals with non-vanishing triality have to be confined by the appropriate linearly rising potential. Triality zero orbitals are not confined. This is the first step for the definition of the wave functions of the orbitals and a QCD version of the Born-Oppenheimer approximation in molecular physics is used to find the spectrum of states [3].

The next frontier is trying to understand pentaquarks in the same scheme.

Light Dark Matter. In the last few years an intense program of investigations devoted to propose methods for the direct detection of light dark matter has started.

The Weakly-Interactive-Massive-Particle paradigm, in terms of left-over particles from the thermal freeze-out, is strongly challenged by data on hypothetic dark matter particles with masses above 1 GeV.

This is motivating an intense discussion on the possibility of sub-GeV and even sub-MeV candidates, very difficult to be detected with available technologies.

In this field, theoretical research meets the experimental one in the attempt to imagine new ways to detect light and very weakly interacting particles.

Several proposals have been formulated, from the use of two-dimensional materials (graphene and carbon nanotubes[1]) to superconductors, semiconductors and superfluids. In all cases, a very detailed understanding of the physics of the proposed target material is needed to confront with the challenge posed by the extremely low energy recoils expected.

An extremely difficult mass region is that between the KeV and the MeV. In this range there is the possibility that superfluid Helium could be advantageous: the light dark matter probe can produce long-lived single or multi-phonon excitations in the medium which might eventually be detected with bolometric techniques.

We have shown how a relativistic effective quantum field theory for the superfluid phase of ^{4}He can replace the standard methods used to compute the production rates of low momentum excitations due to the interaction with an external probe. The rate of emission of two-phonons, the Goldstone modes of the effective theory, gets strongly suppressed for sub-MeV dark matter particles as a consequence of a fine cancellation, in the limit of small exchanged momenta, between the polar and seagull diagrams with two phonons in the final state. It is also found that the angular distributions for the emission of two phonons can be used to measure the mass of the hypothetical dark matter particle hitting the helium target [4].

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[1]See the report from G. Cavoto in this same volume

P45. Tests of gravity with gravitational waves

General Relativity (GR) has successfully passed several tests: solar system tests, binary pulsar tests and, in 2015, the historical detection of a gravitational wave (GW) signal from a coalescing black hole (BH) binary system. With GW astronomy we can explore the realm of strong-field gravity, testing whether GR provides an accurate description of the gravitational interaction also in this regime. To this aim, we need to model the coalescence of BH binaries in modified theories of gravity.

We have considered different classes of simple GR modifications: quadratic gravity theories and massive gravity. In quadratic gravity theories a scalar field, coupled with bilinear terms in the curvature tensor, is included in the gravitational action. Such theories provide the simplest modifications of the large-curvature regime of GR. In particular we studied *scalar Gauss-Bonnet (sGB) gravity*, which is the only quadratic gravity theory with second-order field equations (a further motivation comes from the fact that these theories arise from string-theory compactifications). In *massive gravity theories*, instead, the graviton has a tiny mass which affects its propagation properties.

We have worked out how these modifications would affect strong-gravity astrophysical processes, such as those involving binary BH coalescences, and how these effects could be extracted from the emitted GW signals.

➢ **Spontaneous BH scalarization in sGB gravity.** We have found [1] that some sGB gravity theories exhibit the phenomenom of *spontaneous BH scalarization*, i.e. they admit the stationary BH solutions of GR but, if the mass lies in certain bands, these solutions are unstable and a non-trivial scalar field configuration develops. The scalar field would affect the properties of the BHs, and in particular the GW emission in binary inspirals. We have also found under which conditions these scalarized solutions are stable. A generic feature of these theories is the presence of a minimum value of the mass, below which no stable, stationary BH solution can exist.

➢ **GWs from BH mergers in sGB gravity.** The most promising astrophysical process to test GR in the large-curvature regime is the merger of two BHs. While the inspiral and the ringdown (i.e. the oscillations of the final BHs) can be modelled using approximation and perturbative techniques, the stage of the merger (which shows the largest curvatures) can only be described by fully non-linear numerical relativity (NR) simulations. We have performed, for the first time, a NR simulation of a binary BH merger in sGB gravity in the limit of small coupling [2]. In this limit, we have found the waveforms of the scalar field and of the gravitational field during the late inspiral, the merger and the ringdown (see Fig. 1). We have found that GW observations can set the strongest constraints to this class of GR deviations.

➢ **GWs from extreme-mass ratio inspirals (EMRIs) in massive gravity.** EMRIs are among the primary targets for space interferometers like LISA. In these systems a small body orbiting around a much more massive one performs thousands of cycles on eccentric trajectories before the plunge. This evolution translates into an accurate map of the spacetime geometry, that is encoded within the gravitational signal. In [3] we analysed the GW emission by an EMRI in massive gravity, focusing on characterieristic features of this theory such as the presence of extra radiative modes which are not excited in GR. We found that dipolar radiation emitted by binary BHs is dominant with respect to the leading quadrupolar component in Einstein's gravity. Our results show that future observations of such dipolar modes may lead to unprecedented constraints on the mass of the graviton.

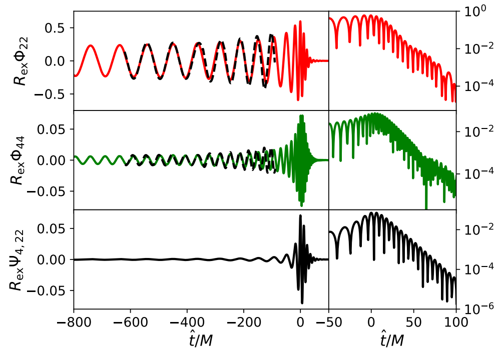

Figure 1: Scalar and gravitational waveforms emitted in a binary BH merger in sGB gravity, obtained with a NR simulation [2].

➢ **Tests of gravity from the ringdown.** GWs emitted after the coalescence of binary BHs are arguably the most promising tool to test GR. Such signals features a series of damped quasi normal modes (QNMs), which are uniquely determined in Einstein's theory. In [4] we have developed a data-analysis approach to find GR-deviations in QNMs for spinning BHs. We have analysed the detectability of these modifications by current/future detectors, showing that our approach is able to accurately identify the imprint of new physics from the incoming GW observations.

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https://web.uniroma1.it/gmunu/

P46. Testing the nature of compact objects and ultralight dark matter with gravitational waves

The landmark detection of gravitational waves (GWs) has opened a new era in physics, giving access to the hitherto unexplored strong-gravity regime, where spacetime curvature is extreme, matter is well above nuclear density, and the relevant velocities are close to the speed of light. In parallel to their countless astrophysical applications, these discoveries can also shade new light on fundamental physics. Outstanding open issues such as the quantum extension of Einstein's General Relativity (GR), the nature of dark matter (DM) and the existence of new fundamental interactions, the nature of black holes (BHs) and the fate of spacetime singularities, might finally be addressed.

➢ **GW signatures of ultralight DM.** In the presence of ultralight bosons (e.g., axion, dark photons, etc), spinning BHs can be unstable against the formation of a bosonic cloud through a process known as rotational superradiance. Bosons with masses in the range $(10^{-21} - 10^{-10})$ eV have a Compton wavelength comparable to the radius of astrophysical BHs in the supermassive to the stellar mass range, and hence can form bound states of up to $\sim$ 10% of the mass of the BH. This cloud disperses over long timescales though the emission of nearly-monochromatic GWs with frequencies that could range from 10^{-6} Hz up to 10^4 Hz, depending on the boson mass (see Fig. 1). We showed that these GW signals would be observable both individually or as a very strong stochastic GW background [1]. Furthermore, extreme mass ratio inspirals (EMRIs) detectable by the future space mission LISA will be able to probe the geometry of these boson clouds, probing a region not excluded by continuous GW searches [2].

➢ **Tests of the nature of compact objects.** Event horizons are the defining feature of BHs in classical GR and constitute a causal boundary: information can propagate from the exterior universe to the BH's interior, but at the classical level nothing can cross in the other direction. This conflicts with the semiclassical prediction that BHs evaporate, carrying information from inside the hole to the exterior. The "information paradox" resulting from BH evaporation suggests that the classical picture of BHs is at least incomplete. Most attempts to solve this paradox invoke drastic changes at the horizon, either in the form of new physics or of regular horizonless geometries (e.g., fuzzballs). The latter might also solve the long-standing singularity problem of GR.

We have identified several effects which might be used to distinguish a BH from a horizonless compact object [3]. The nature of the compact objects affects the dynamics of a binary system and the GW emitted during a merger. We found that the tidal effects can be used as a strong discriminator of the nature of BHs, especially for highly-spinning supermassive binaries in the LISA band [4]. Furthermore, we have characterized in

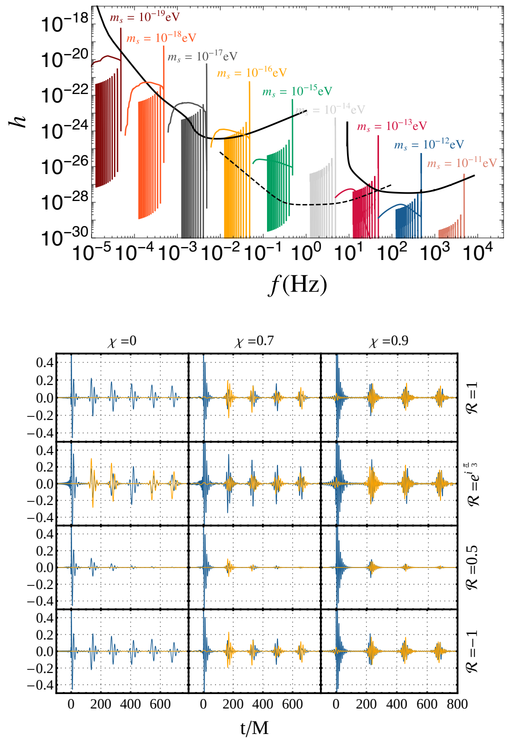

Figure 1: Top: Signal of BH-axion condensates [1] compared to the sensitivity curves of LISA (left) and LIGO/Virgo (right). Bottom: Slideshow of our analytical echo [3] template for various spin (χ) and reflectivity ($\mathcal{R}$) parameters.

detail the "GW echoes" signal that is predicted to occur after the merger in some of these scenarios, including near-horizon quantum structures, exotic states of matter in ultracompact stars, and certain deviations from GR. We have developed an analytical template describing the post-merger ringdown and the echo signal of a spinning ultracompact object. This template will be implemented to perform a matched-filter based search for echoes with current and future detectors.

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`https://web.uniroma1.it/gmunu/`

P47. Neutron stars: gravitational waves and equation of state

Neutron stars (NSs) are natural laboratories to test physics under conditions which can not be reproduced with terrestrial experiments. The stellar core of a typical NS can have densities up to ten times larger than the nuclear saturation point, $\rho_0 \simeq 2.67 \cdot 10^{14}\,\mathrm{g/cm^3}$, and offers the unique opportunity to investigate the properties of the equation of state (EoS) of nuclear matter in extreme regimes. Although there is a general consensus on the EoS for densities smaller than ρ_0, for larger values a variety of models do exist that depend on the specific model used to describe hadronic interactions in such regimes. Current observations in the electromagnetic band are not accurate enough to solve this degeneracy.

Gravitational waves (GWs) emitted by NS binaries offer a new window to constrain the EoS of nuclear matter. The gravitational waveform emitted in the late inspiral of binary neutron stars depends on a set of constants, the tidal Love numbers, which encode the deformability properties of the star and thus depend on the NS EoS. Extracting the values of these parameters provides important constraints on the stellar composision. In practice this is a challenging task, which requires accurate theoretical waveforms to compare against the datastream coming from the detectors.

➢ **Improved PN waveforms.** Current theoretical models of tidal deformations in coalescing binaries are accurate enough for current, second-generation GW detectors, but could be unadequate for 3^{rd} generation detectors. In [1] we have extended the theoretical models of NS tidal deformations in coalescing binaries to include the rotation of the NSs. We have computed the contribution of spin-tidal couplings to the gravitational waveform emitted by a compact binary system, at the leading order in the post-Newtonian framework and to linear order in the spin. In [2] we have assessed the impact of these terms in the data analysis from present and future ground-based interferometers. We have found (see Fig. 1) that if the spin of the NSs is at least $0.1GM^2/c$, these terms will be relevant in the data analysis of 3^{rd} generation detectors such as the Einstein Telescope.

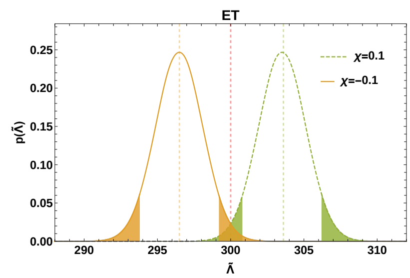

Figure 1: Probability distribution of the rescaled quadrupole Love number for a binary NS spinning at $J = \pm 0.1GM^2/c$, assuming the Einstein Telescope noise sensisivity curve, in the case of a GW170817-like observation with optimal orientation [2]. The solid areas define the 90% credible intervals.

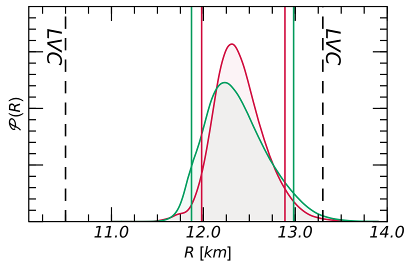

Figure 2: Posterior distributions for the radii of the two NSs of GW170817 (solid curves) derived through the multi-messenger approach devised in [4], and compared against the 90% confidence interval inferred by the LIGO/Virgo collaboration (dashed vertical lines).

➢ **Multi-messenger constraints to the NS EoS.** Multi-messenger approaches aimed to combine NS observations in both the gravitational and the electromagnetic band provide a new powerful tool to constrain the nuclear EoS. Using an approach developed in [3], we have performed for the first time a Bayesian analysis combining the Love numbers measured by LIGO/Virgo for the binary event GW170817, and the stellar radii estimated from spectroscopical observations of accreting X-ray binaries [4]. These measurements belong to two independent events, characterised by very different environments and dynamical regimes, and therefore are expected to provide complementary information on the EoS. We have inferred the probability distributions of the parameters which characterise the EoS beyond the nuclear saturation point, reconstructing the macroscopic properties of the two NSs of GW170817. Fig. 2 shows how our multi-messenger approach dramatically improves the bounds on the stellar radius derived by LIGO/Virgo alone, leading to the strongest constraint on the stellar structure available so far.

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`https://web.uniroma1.it/gmunu/`

P48. Bent crystals for the Large Hadron Collider beam extraction

Particle accelerators are complex machines able to increase the velocity of electrically charged elementary particles (like protons) up to a value very close to the speed of light. The Large Hadron Collider (LHC) at CERN is the most powerful machine in operation today, able to accelerate beams of protons up to an energy of 6.5 TeV (that is equivalent to a velocity 99.9999991% times the speed of light !).

Such accelerated particles are usually handled with very special and big magnets. Instead, by using small and thin bent crystals a novel way to manipulate these high energy beams has been studied by the CRYSBEAM team in the context of the UA9 experiment at CERN. Protons (or charged ions) are in fact trapped within the crystal lattice planes by the effective electric field of all the ordered atoms in the crystal. This phenomenon is very effective in mono-crystal of very high quality and it is known as *crystal channeling*.

Since the macroscopic bending of the crystal also causes a bending of the lattice planes, the trapped particles are emerging deflected at a well-defined angle. The CRYSBEAM team built and tested a number of crystals at the CERN beam test facilities. One crystal installed on the LHC was successfully proved to be able to deflect the LHC beam by 50 μrad at the end of 2015. In the recent years the bent crystal technology was sharpened to produce crystals with larger bending angles (up to 1 mrad) but still efficient in deflecting the beam. In Fig. 1 samples of bent silicon crystals are shown.

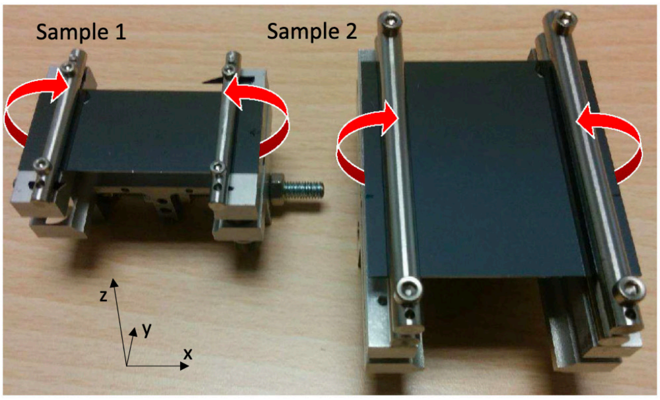

Figure 1: Two samples of silicon bent crystals installed on a holder that is imparting a deflection as indicated by the red arrows. Along the y direction an anticlastic curvature is generated that is used to steer charged particles.

The crystal curvature is finely characterized with white light interferometry and high resolution X-ray diffraction [1]. This will have a large impact for future projects at CERN including new experiments and new experimental facilities to manipulate high energy beam. In future, bent crystals will be employed for instance to extract high intensity beam for dark matter searches or to study the properties of heavy baryons.

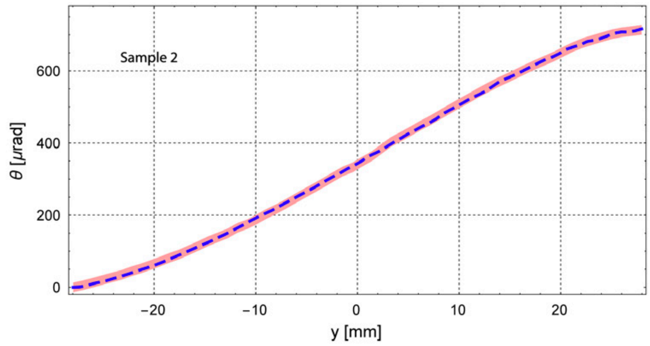

Figure 2: X-ray measurement of the anticlastic deformation along the y direction. The red stripes represent the instrument uncertainty, while the dashed lines represent the corresponding interferometric measurements.

At the same time detector prototypes able to monitor the deflected beam inside the ultra-high vacuum beam pipe of the accelerator and to absorb it to measure inclusive inelastic cross sections were developed. They were designed, built, calibrated and installed on the SPS accelerator at CERN by the CRYSBEAM team. More recently a detector based on the production of light due to the ultra-relativistic Cherenkov effect was employed to measure the flux of the deflected particles by a bent crystal [2]. This has been used in various dedicated data-taking periods at the SPS, showing a sub-nanosecond timing resolution and sub-mm position resolution that were critical to understand the features of the extracted beam. Moreover, a massive smart absorber of particles was also employed to study how hadron particles are interacting with low Z materials as carbon. This was the final aim of the CRYSBEAM project, that is the development of a prototype apparatus that could eventually steer with a bent crystal the multi-TeV LHC hadron beam to a target made of light materials. This would in fact mimic what hadrons do in the Earths atmosphere when they are coming from the sky in the form of cosmic rays. The particle showers they are producing are in fact evolving according to cross sections that the CRYSBEAM apparatus can measure, eventually helping to shed more light into the nature of the ultra-high energy cosmic rays.

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P49. Carbon Nanotubes for light Dark Matter searches

The particle nature of Dark Matter (DM) is still totally unknown. Hypothetical weakly interacting massive neutral particles (named WIMPs) with a mass in the 10-100 GeV range has been searched in our Galaxy with no conclusive proof of their existence. Currently, lighter (i.e. with a MeV mass) DM candidates are largely unconstrained but still theoretically motivated. A new experimental program is needed to look for them. However, in this range of masses novel types of detectors based on new concepts are needed - in particular those able to detect a very low energy electron recoiling after a scattering with a DM particle. Moreover, given our motion with the Sun in the Galaxy, DM particles would be seen on Earth with an apparent velocity that is mostly directed towards the Cygnus constellation.

We therefore started to investigate a technique for the directional detection of DM with a mass as low as few MeV by studying the electron recoils in large arrays of parallel carbon nanotubes (CNT). CNT are an intriguing one-dimensional nanostructured material which can be engineered in ordered CNTs-based architectures having predefined alignments, such as vertically aligned carbon nanotubes (VA-CNTs).

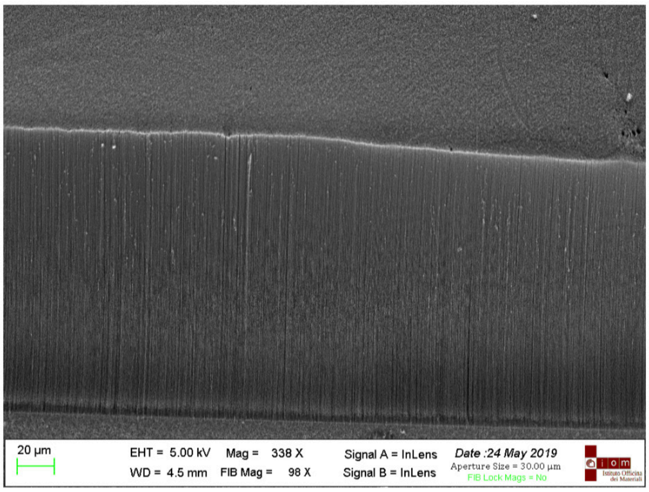

Figure 1: Vertically Aligned CNT grown on a transparent fused silica substrate. These VA-CNT are more than 150 μm tall, a world record.

An easy, low cost and reproducible synthesis method for growing VA-CNTs on transparent substrate (i.e. fused silica) following an iron nanoparticle-catalyzed Chemical Vapor Deposition process (CVD) has been used, in collaboration with CNR Trieste (see Fig. 1). Notably, in our synthesis method, although no metal other than iron has been used as catalyst layer and even if the growth time was limited to merely four minutes, the yield, reproducibility, and density of the produced CNTs are comparable to similar structures grown by using more sophisticated and time-consuming techniques. The low cost and high versatility of the here presented CVD-based synthesis process, together with the possibility to create on the supporting substrate patterns of any arbitrary shape of CNTs, open up new opportunities in the perspective of adopting them as potential targets for DM particles.

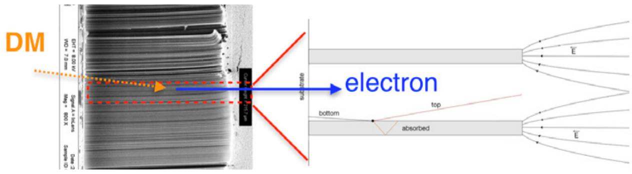

Figure 2: DM interacting with electrons in VA-CNT. The VA-CNT act as a filter selecting preferentially the electron scattered along the CNT axis. An electric field is then applied to collect the emerging electrons and focus them to an instrumented anode.

In a scattering process with a lattice electron, a DM particle might transfer sufficient energy to eject it from the nanotube surface. An external electric field can be added to drive the electron from the open ends of the array to the detection region (see Fig. 2). The anisotropic response of this detection scheme, as a function of the orientation of the target with respect to the DM velocity, has been calculated. Significant regions of the light DM cross section and mass region might be excluded (see [1]). A compact sensor, in which the cathode element is substituted with a dense array of parallel carbon nanotubes, could serve as the basic detection unit. An R&D study is currently progressing towards a first prototype for this detector- in the context of the ATTRACT *NanoUV* project (P.I. F.Pandolfi, INFN) and of the INFN CNS2 Ptolemy project. The scattering of a DM particle on a carbon ion has been also investigate theoretically [2] [3]predicting an effect of collective channeling in the VA-CNT. A number of experimental test has been recently conducted by bombarding the CNT with Ar ions reporting an anisotropic behaviour of the VA-CNT with respect to the Ar ion direction [4].

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P50. Experiments at the Jefferson Laboratory

The activities of the Department of Physics of Sapienza University of Rome at Jefferson Laboratory encompass several areas. In the area of the nucleon structure studies, the construction and installation of the Super BigBite Spectrometer (SBS) in Hall A is in progress. SBS will continue at higher Q^2 values the measurement of the ratio of the proton electric and magnetic form factors: $\mu_p G_{E_p}/G_{M_p}$ that has shown an unexpected and dramatic decreasing with Q^2[1] and the measurements of Nucleon Transverse Moment Distributions (TMD) needed to obtain a three dimensional picture of the nucleon. In the field of Dark Matter searches the Department of Physics of Sapienza University of Rome has contributed to the preparation of the experiment APEX, that run in spring 2019 and is searching for the possible existence of a dark photon responsible of the interactions between dark matter and the ordinary Standard Model matter. The Department of Sapienza University of Rome is involved also in the experiments PREX-II, in which has a leader role, and CREX. These two experiments are running from June 2019 to March 2020 and are measuring the difference between the neutron radius and the proton radius in the nuclei ^{208}Pb and ^{48}Ca respectively. These measurements are being performed through the measurements of the Parity Violating Asymmetry, that is the fractional difference, mostly sensitive to the neutron distribution in the nucleus, between the cross-sections of electrons of positive and negative helicity in elastic electron scattering off ^{208}Pb and ^{48}Ca respectively. PREX-II, that will complete, increasing the statistics, the experiment PREX that run in 2010[2], will have an enormous impact on our knowledge of neutron star features, because the difference between the neutron and proton radius in ^{208}Pb is directly correlated to the symmetry energy dependence on density and hence to the Equation Of State (EOS) of nuclear matter. Neutron star features like crust thickness, way of cooling and possible existence of exotic states of matters in neutron star core depend on their turn on EOS. PREX-II results will confirm or rule out some signatures about neutron star composition derived by the recent observations of gravitational waves. The experiment CREX will have an impact on nuclear theory. In fact, the difference between the neutron and the proton radius in ^{48}Ca depends on the isovector sector of the nuclear interaction, so far poorly constrained because of lack of measurements sensitive to it. The Department of Physics of Sapienza University of Rome has a leading role in the hypernuclear physics program being carried out at JLab too[3]. Important part of this program is the study of the hypernon-nucleon potential, that will also have a big impact on our knowledge of neutron star composition and will be performed through the measurement of binding energies of the hypernuclei $^{40}_{\Lambda}$K and $^{48}_{\Lambda}$k. It will be possible this way to determine a hypothesized repulsive (at high densities) three body component of the force hyperon-nucleon that would explain the existence of neutron stars of big (up to two solar) masses. In fact, the existence of hyperons in neutron stars, that should be "natural" because of neutron star core high density, would make, according to what is presently supposed to be the hyperon-nucleon potential, (EOS) too soft and would hence forbid the existence of very massive neutron stars. Another important part of the hypernuclear physics program at JLab is the study of a possible Charge Symmetry Breaking in the interaction hyperon-nucleon. An experiment investigating the possible existence of a neutral bound state nnΛ generated in the reaction $^3H(e,e)nn\Lambda$ run in autumn 2018 and its analysis is in progress. The existence of this hypothetic resonance is possible only if the neutron-Λ interaction is 5% bigger than the proton-Λ interaction. At last, but not least, the Laboratory of Silicon Detectors Development of the Physics Department of Sapienza University of Rome is developing a project to measure, in a satellite, the polarization of high energy cosmic rays (between 20 and 1000 MeV). The project[4] is based on the construction of a polarimeter made by 46 cells. Each cell is made by three double face microstrip detector. The first detector will act both as a converter of the gammas in electron positron pairs and as a detector of the coordinates of the points where the gamma conversions take place. The other two silicon microstrip detectors will measure respectively the X and Y coordinates of the tracks of the electrons and positrons produced by the gammas. The distribution of the azimuthal angle of the positrons (electrons) relative to the direction of the incident photons is function of the degree of the gamma linear polarization and will be hence make it possible its measurement. Just to quote an example, a polarization measurement of the gammas from the Crab pulsar and the Crab nebula with an accuracy of 6% will be possible in one year long observation.

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List of research activities

Statistical and Mathematical Physics

Statistical and Mathematical Physics

Statistical and Mathematical Physics have produced some of the most fertile theoretical advancements of the last fifty years, such as the theory of critical phenomena and dynamical systems theory, to name just a few examples. More recently, the theoretical approach and the mathematical tools developed within these disciplines have been progressively extended beyond the realm of physical systems to address a variety of multidisciplinary problems, from computer science to biology and economics. The reason for such surprising flexibility and descriptive power lies in the very core objectives of statistical physics: to derive the large scale properties of a system starting from the interactions between its microscopic constituents; to incorporate the effect of noise and fluctuations; to address the role of nonlinearities. These aspects are clearly relevant for physical systems, but are equally important for many biological and social networks, where individual units influence each other on non-trivial interaction structures, and evolve in the presence of complex and noisy environments. As a consequence, Statistical Physics is nowadays a vital and growing field, where research spans a broad range of topics, from fundamental issues in condensed matter and non-linear phenomena to interdisciplinary applications in complex systems. The activity at the Department of Physics well reflects such variety, as the contributions in this report illustrate. At present the area of Statistical Mechanics and Mathematical Physics comprises 4 full professors, 4 associate professors, 2 assistant professors, 2 untenured researchers, and a large number of postdoctoral fellows, PhD and master students. Moreover, the Department hosts the INFN "Roma1" local unit, the Sapienza units of the Institute for Complex Systems and of the Nanotec Institute of CNR, as well as the Rome unit of the Italian Institute of Technology. Many researchers of these Institutes routinely collaborate with members of the Department in joint laboratories and research groups. Here below we summarize the research activity performed at the Department and the major scientific achievements of the last two years, which are described in more details in the individual contributions following this brief Introduction.

One of the main topics in Statistical Physics is the theory of phase transitions and critical phenomena. Despite a long-standing activity on this subject, there are several important open issues. Finite Size Scaling (FSS), for example, has been studied for a long time in classical systems, and provides one of the most effective techniques to numerically estimate critical properties. Still, generalizations to the quantum case have been scarce until recently. Contribution S1 describes how the FSS approach can be extended to quantum transitions, both continuous and discontinuous. Besides, it also describes how dynamic FSS - originally developed for continuous transitions in classical systems - can be studied for first-order transitions, and how the classical results can be further generalized to quantum systems.

Surprisingly, a field-theoretic approach based on the theory of critical phenomena can also be used to investigate collective behavior in biological systems. As discussed in contribution S2, animal groups like bird flocks and insect swarms not only exhibit large scale correlations, but also obey static and dynamic scaling laws. These experimental findings indicate that a statistical physics approach to these systems is fully justified and provide a benchmark for theoretical predictions. The authors in S2 have indeed developed a novel dynamical field theory for swarming and, using a Renormalization Group (RG) approach, they found a value for the dynamic critical exponent close to the one measured on natural swarms of insects. This contribution provides a clear instance of the wide applicability of statistical physics and suggests that important concepts like renormalization and universality can be used in biological systems to define classes of behaviour.

A further example of how field-theoretic techniques can be used to investigate problems of biological relevance is described in contribution S3. The authors use statistical field theory to analyze the statistics of the information flow in gene regulatory networks. Here the problem is to understand how regulatory circuits in living cells optimize their noise-processing capabilities. In particular, the work focuses on ensembles of regulatory motifs, particularly relevant in extended networks or in populations of cells.

Contribution S4 addresses another fundamental problem in statistical mechanics: how, and under what conditions, a coarse-grained description for some relevant effective variables - such as hydrodynamic fields or slow modes - can be derived starting from the microscopic dynamics. The authors investigate two instances particularly relevant for systems exhibiting a multi-scale structure: one case with non-standard Hamiltonian dynamics (the kinetic term is non quadratic) and a non-Hamiltonian system (granular Brownian motion). They show how to derive the effective diffusivity constant and how, in some cases, additional slow time scales emerge, requiring a more complex effective description.

The question of timescales is also crucial in contribution S5. Here, the authors describe how to obtain a consistent thermalization scenario for a quantum system using a Lindblad-based approach, which takes into account the interaction of the system with the environment. In their work they show that it is possible to provide a separation of the thermalization time into dissipation and decoherence time and, in some specific models, they study in detail the relaxation dynamics towards the (generally nonequilibrium) steady state.

The statistical description of a system gets enormously enriched, both at the phenomenological level and in terms of the theoretical treatment, when disorder is present. Strongly disordered systems indeed exhibit a broad spectrum of non trivial properties, with multiple ergodic phases, metastability and out-of-equilibrium glassy dynamics. With their 'rugged' energy landscape, these systems are often considered as an archetype of complex systems. Research in this field has traditionally been very strong at the Department, with major contributions to the physics of spin-glasses, structural glasses, and interdisciplinary applications to computer science and biological networks. The extensive activity on these topics is described in contributions S6-S8. Contribution S6 reports the most recent results on spin-glasses obtained by an international italian-spanish collaboration. Using the Janus supercomputer, researchers have performed large scale simulations on finite dimensional models, investigating response behavior to small perturbations, and more recently focusing on film-like spin glasses. In the same contribution some interesting applications to diffusion in random environments, post-transcriptional genetic regulation and metabolic networks are also mentioned. Contribution S7 addresses the important theoretical problem of how to develop an appropriate RG approach for finite-dimensional disordered systems. It is indeed well-known that an expansion around the mean-field solution leads in many cases to wrong results. The authors of S7 propose a new method, where a loop expansion is performed around the Bethe lattice solution. In the Bethe lattice, contrary to mean-field, local observables have a non-trivial distribution, a crucial property of finite dimensional systems. For this reason, one can hope that such a loop expansion could actually work. First results on spin-glasses in magnetic field and in the Random Field Ising model are promising in this respect. The physics of disordered systems also provides an excellent framework to address optimization problems. A prototypical case are Constraint Satisfaction Problems, where one has to find a configuration of many variables satisfying a given number of constraints. Solutions of the problem can be mapped to ground states of statistical physics models, typically with complex landscapes, where phase transitions occur as the number of constraints per variable is varied. Contribution S8 investigates the connection between such phase transitions and algorithmic thresholds, by appropriately reweighting solutions according to their algorithmic reachability. Applications to inference problems on random graphs are also addressed.

As already mentioned, statistical physics is nowadays used to investigate several problems in social and economic networks, also thanks to the recent availability of large data-sets on all sorts of human activities. Contributions S9-S11 offer a nice perspective on such applications. In contribution S9 the authors investigate the dynamical processes underlying the evolution of systems featuring innovations. The model they introduce, which mathematically formalizes the concept of 'adjacent possible space', allows to statistically treat the occurrence of innovations and to devise inference schemes in the case where new events are possible. Contribution S10 illustrates the results of a collaboration between the Department of Physics and the Sony Computer Science Lab in Paris. The objective is to gather and analyze statistical data related to mobility in large cities, in order to devise functional strategies for urban development. Two platforms have been created that quantify in accessibility maps data from vehicular and public transportation. In contribution S11 the authors introduce a new methodology - Economic Complexity - that describes economics as an evolutionary process of ecosystems. Crucial to the method is a new data-driven metrics quantifying the competitiveness of a country, and therefore allowing to define a fitness. Predictions based on this method have been extremely well performing and offer a promising framework to investors and policy makers.

The last three contributions (S12-S14) describe some recent results in mathematical physics. Contribution S12 focuses on Rogue Waves, large and apparently unexpected waves that form due modulation instabilities and non-linearities. The simplest model for such waves is the focusing nonlinear Schroedinger equation, a prototype of integrable nonlinear PDE. The authors were able to solve the periodic Cauchy problem for rogue waves, and to describe analytically their dynamics with different initial conditions. Predictions have also been verified in a nonlinear optics experiment. Contribution S13 deals with dynamical processes occurring on connected finite graphs, a problem of relevance in many applications. From a mathematical perspective, it is interesting to understand how the dynamical relaxation on the graph is related to its geometric properties. Contribution S13 discusses how some recent rigorous results obtained for random walks can be generalized to more complex Markov chains. Finally, contribution S14 reports a number of recent theoretical results in Quantum Field Theory. The first two results are 'negative', in the sense that they rule out theories with certain features due to the inconsistencies they lead to. The authors formulate a no-go theorem with main application in quantum gravity; and present an argument in favor of the general unsolvability of interacting bosonic quantum field theories. A third result concerns the decay behaviour of resonances in finite volume, investigated in a one-dimensional quantum mechanical model.

Irene Giardina

S1. Finite-size scaling at quantum transitions

Finite-size effects in critical phenomena have been the object of theoretical studies for a long time. Indeed, their understanding is crucial in many experiments and numerical simulations, in which relatively small systems are considered. Close to a critical point, a finite statistical system shows a universal finite-size scaling (FSS) behavior, when the correlation length ξ is large but still of the order of the size L of the system. The FSS behavior is only controlled by the universality class of the model and allows one to determine several quantities characterizing the transition, like the critical exponents and the critical temperature. The FSS approach is one of the most effective techniques for the numerical determination of the critical quantities. While infinite-volume methods require the condition $\xi \ll L$ to be satisfied, FSS applies to the less demanding regime $\xi \sim L$. FSS also holds at first-order transitions, with some very unusual features, like anisotropic scaling.

FSS was originally formulated in the classical framework. However, it also holds at zero-temperature quantum transitions, in which the critical behavior is driven by quantum fluctuations. This can be easily shown, using the well-known classical-to-quantum mapping in which a quantum d-dimensional system is mapped onto an anisotropic $(d+1)$-dimensional classical system. In particular, all concepts that are routinely used in the analysis of classical spin systems, like correction-to-scaling exponents, non-linear scaling fields, etc., can be generalized to quantum transitions [1]. It can also be extended to first-order quantum transitions (FOQT) [2,3]. This extension is very important, both for theory and experiments, as FOQTs are ubiquitous in low-temperature many-body systems. One specific feature of FSS at first-order transitions is its strong dependence on the boundary conditions. For continuous transitions, boundary conditions only affect scaling functions but have no influence on the scaling behavior of bulk quantities (for example, the scaling variables depend only on the infinite-volume critical exponents). This is no longer true for first-order transitions [2,3].

Beside the equilibrium behavior, FSS also applies to dynamical phenomena. The behavior of statistical systems driven across phase transitions is a typical off-equilibrium phenomenon. Indeed, the large-scale modes present at the transition are unable to reach equilibrium as the system changes phase, even when the time scale t_s of the variation of the system parameters is very large. Such phenomena are of great interest in many different physical contexts: One observes hysteresis and coarsening phenomena, the Kibble-Zurek defect production, etc. At continuous transitions, thermodynamic quantities obey general off-equilibrium scaling laws as a function of t_s, controlled by the universal static and dynamic exponents of the equilibrium transition. We have studied the same issue for systems undergoing a thermal first-order transition [4,5]. The numerical results for periodic boundary conditions show evidence of a dynamic transition [4], where the FSS functions show a spinodal-like singularity: the general mean-field picture is qualitatively recovered, provided the time dependence is appropriately (logarithmically) rescaled. A different scaling behavior is instead observed if the boundary conditions favor one of the two phases [5]. In this case, a power-law dynamic scaling emerges, associated with a mixed regime where the two phases are spatially separated.

We have also generalized the classical results to quantum systems [6,7]. In Ref. 6 we investigated the quantum dynamics of systems subject to local (i.e., restricted to a limited space region) time-dependent perturbations. If the system crosses a quantum phase transition, an off-equilibrium behavior is observed, even when the driving is very slow, which can be characterized by universal scaling laws. In first-order transitions some scaling functions can be computed exactly. For continuous transitions, the scaling laws are controlled by the standard critical exponents and by the renormalization-group (RG) dimension of the perturbation. In Ref. 7 we derived a general dynamic finite-size scaling theory for the quantum dynamics after an abrupt quench, at both continuous and first-order quantum transitions. For continuous transitions, the scaling laws are controlled by the critical exponents and the RG dimension of the perturbation. In the case of first-order transitions, the universal scaling is controlled by the size behavior of the energy gap between the lowest-energy levels.

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S2. Statistical Physics of Collective Behaviour in Biological Systems

Collective behaviour emerges in the living world across several scales of space and time, from cell colonies up to mammal herds. As in statistical physics, collective behaviour displays two phases: one in which all individuals synchronize, giving rise to a non-zero order parameter (paradigm: *flocks*), and one in which local patterns emerge with zero order parameter (paradigm: *swarms*). Experimental data show that strongly correlated collective behaviour in biological systems is completely consistent with short-range local interactions [1]. This fact justifies the approach adopted by our group, namely a field-theoretical study of collective biological systems, inspired by the statistical physics of critical phenomena. The success of the theory of critical phenomena is based upon a simple observation: systems with very diverse details behave in strikingly similar ways when correlations are sufficiently strong. This experimental fact eventually crossed over into theory with the formulation of phenomenological scaling laws, whose key idea is that the only relevant scale ruling the critical behaviour of a system is the correlation length, ξ. Eventually, the renormalization group explained why different systems shared so much at the macroscopic level (universality) and provided a method to calculate experimentally accessible quantities. The aim of our group is to retrace the path correlation–scaling–renormalization, and laid the foundations of a theoretical physics of biological systems.

A key experimental discovery of our lab and of other groups has been that in all instances of collective behaviour in biological systems correlations are unusually strong: the correlation length, ξ, is always much larger than the microscopic length scales of the system and in some cases ξ scales with the system's size, giving rise to scale-free correlations [1]. A particularly important discovery made by our group, is that one finds scale-free correlations also of degrees of freedom *without* spontaneous continuous symmetry breaking, a case for which our group developed a novel theory of marginal ferromagnetism [2], able to account for scale-free correlations of speed fluctuations in bird flocks. Motivated by the emergence of strong correlations, our group conducted an intense experimental effort to look for evidence of scaling laws in collective biological systems. We succeeded, finding clear empirical proof of the validity of dynamic scaling in natural swarms, although with unusual values of the critical exponents [3]. Dynamic scaling is truly noteworthy, as it links spatial correlation to temporal relaxation through critical slowing down, a core mechanisms of statistical physics (see Figure 1).

The validity of dynamical scaling in natural swarms, together with the fact the previous models and theories do not fit the data, motivated our group to develop a novel dynamical renormalization group approach to the study of collective behaviour. This is what we have recently done in [4]: we studied a novel field theory which

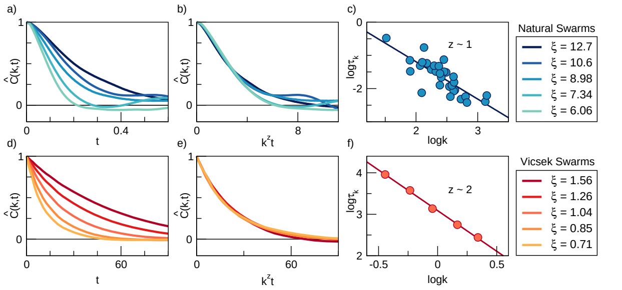

Figure 1: **Dynamical scaling laws in natural swarms.** Upper panel: Data from natural swarms [3]. The spatio-temporal correlation function (left) depends on time t, momentum k, and static correlation length ξ; however, by rescaling the data with a suitable value of the dynamical critical exponent z, one finds a collapse of all correlations functions (center), indicating that dynamical scaling works. Lower panel: Data from simulations [3]. Relaxation in the Vicsek model of collective biological dynamics is quite different: the shape of the correlation function is exponential (unlike in swarms) and the dynamical exponent z has a completely different value. This discrepancy calls for more theoretical work to be done.

included mode-coupling terms in the dynamics. By using momentum-shell at one loop, we find $z = 3/2$, a value significantly closer to the experimental value $z \approx 1.2$, than the previous theoretical determinations ($z = 2$).

The fact that dynamical scaling laws apply to collective biological systems and that the renormalization group can calculate some of the critical exponents does not imply that such systems are at equilibrium. In fact, we found evidence of anomalous, non-equilibrium fluctuations that account for the emergence of spontaneous collective changes of direction in real flocks [5].

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S3. Statistical Physics Approach to Gene Regulatory Networks

Gene expression is a complex process that should be regulated in each cell of every organism in order to ensure the proper functioning throughout its life. The regulation is generally performed by networks of molecules (proteins or RNAs) that interact with each other, often defined regulatory networks (GRNs). The simplest GNR is made by a single input node, representing e.g. a transcription factor or a regulatory RNA, controlling N targets, see Fig. 1. The targets interact through the controller exclusively, i.e. there is no direct coupling between targets. Regulatory process in living cells are universally subject to noise, due to the low copy number of molecules or to their diffusive motion inside the cell, that impose physical limits to the reliability of regulation. In many cases, it is essential that stochastic fluctuations affecting an upstream node of the regulatory network (e.g. a transcription factor, a cell-surface receptor, etc.) are not amplified as the biochemical cascade triggered by its activation (e.g. RNA transcription, a specific signalling pathway, etc.) proceeds to downstream nodes (e.g. proteins). Indeed, efficient modulation of the cell's response in changing extracellular and/or endogenous conditions requires the output to be controllable with sufficient accuracy. In this light, noise processing appears to be a central task of regulatory circuits, and quantifying their noise-processing capability is an important theoretical question.

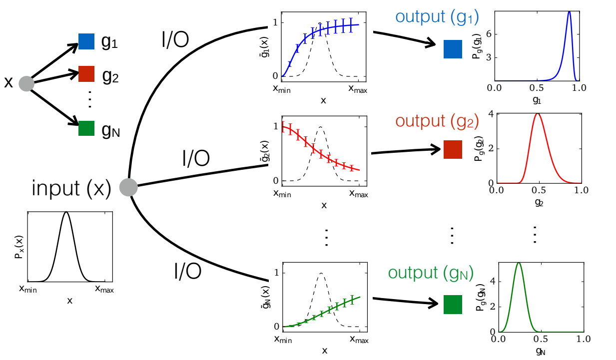

Figure 1: Scheme of one controller regulating N independent targets. $P_{\mathrm{x}}(x)$ is the probability distribution of the controller level x, the dashed black lines in middle panels. The channel is represented by the mean target levels $\{\bar{g}_i(x)\}_{i=1}^{N}$, the solid lines in middle panels. The controller can either activate or repress each of the N targets. The error bars represent $\pm\sigma_i(x)$, where $\sigma_i^2(x)$ is the intrinsic noise variance of the i-th target. The presence of noise induces a probabilistic relationship between controller level x the target levels g_i: the outputs of the regulatory network are the probability distributions $\{P_{\mathrm{g}}(g_i)\}_{i=1}^{N}$, whose shape depends on the matching between the controller distribution and the noisy channel.

During the past decade many studies have addressed this issue within an information theoretic framework in different contexts, see e.g. [1]. The general idea behind this line of work is that optimal effectiveness of a regulatory module is achieved when the mutual information between input and output nodes is maximised. While individual motifs may operate under non-trivial trade-offs in extended regulatory networks or even in populations of cells, optimal properties establish fundamental limits to noise processing by regulatory circuits. To this aim we have extended the current theoretical picture to the analysis of the statistics of optimal information flow in ensemble of regulatory motifs using tools of statistical field theory [2,3]. Their quantification allows in principle to isolate and characterise the physical ingredients that constrain information flow, that can be tested either in experiments, see Fig. 2, or via transcriptional or proteomic data analysis.

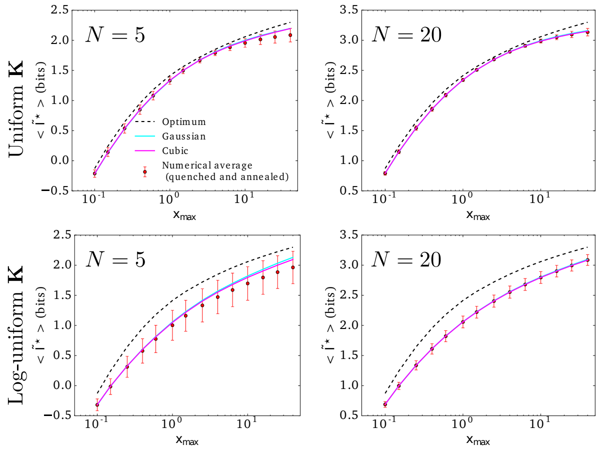

Figure 2: Comparison between numerical results for the average capacity (markers) and analytical results obtained from different approximations for $N = 5$ and $N = 20$ targets. Vectors $\boldsymbol{K}$ of the Hill function parameters, parameterising the mean target level, are sampled from a uniform (top panels) and uniform in log-scale (bottom panels) distributions in $[x_{\min}, x_{\max}]$. The dashed line gives the absolute maximum value of information at the given $x_{\max}$ [From [2,3]].

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S4. Effective equations for complex systems with multi-scale structure

In statistical physics the systems of interest include many coupled degrees of freedom. A complete description of all variables is usually out of reach and this is the main reason why simplified or coarse-grained models are introduced [1]. Often in these models a few relevant variables, usually the slowest ones or those associated to macroscopic behavior, are individuated. This task is not always straightforward, since relevant variables can also be non-trivial combinations of microscopic degrees of freedom, for instance hydrodynamic fields or slow dynamical modes. Even in the lucky case where the relevant variables are known, the reconstruction of an effective description for their dynamics is a complex task. A further complication arises when the total number of degrees of freedom is not huge and fluctuations can be relevant. The paradigm of effective description in this context is the so-called Langevin (or stochastic differential) equation [1]. In the literature of the past century only a few cases exist where the effective equations are deduced through a rigorous procedure starting from the microscopic (e.g. Hamiltonian) dynamics, for instance the case of Brownian Motion in chains of coupled harmonic oscillators (by Rubin, Turner, Ford, Mazur, Zwanzig and others in the '60s or later). In the recent years a series of novel physical phenomena have attracted the attention of statistical physics. Those systems have non-standard Hamiltonian dynamics or, in certain cases, they even lack a Hamiltonian description. Some of the former have a non-quadratic form of the kinetic energy, for instance in effective models of cold atoms interacting with some kind of underlying (e.g. optical) lattice: they are interesting because they may display *negative absolute temperature*. Examples of non-Hamiltonian systems include for instance granular matter (where interactions are dissipative, because of friction).

With the aim of investigating the dynamics of systems with different time-scales in non-trivial contexts, our research has focused on particular instances of the two above categories [2,3,4]. First we have considered the problem of a Langevin description for Hamiltonian systems with a generalized kinetic term $K(P) = Mf(P/M)$ where M and P play the role of the mass and momentum of the slow variable respectively and the function f in the standard case takes the simple form $f(x) = x^2/2$. Among other relevant cases one has $f(x) = 1 - \cos(x)$ which admits absolute negative temperatures. Our general results show that a Langevin description is possible under suitable but quite general assumptions, of the form $\dot{P} = -D\beta f'(P/M) - U'(Q) + \sqrt{2D}\eta$ (D is a diffusivity constant, β is the inverse temperature, U is the external potential which depends on the position Q and η is white Gaussian noise of unitary variance) [2]. In a more recent work we have relaxed most of the mentioned hypotheses showing that in the general case D can be spatially dependent $D \to D(Q)$ and $U(Q)$ is replaced by an effective potential, similar to a free energy [3]. While in this more recent paper we have also shown a constructive procedure, similar to the classical Chapman-Enskog procedure for hydrodynamics, to derive $D(Q)$ from the microscopic dynamics, in the previous work we have adopted a different protocol based upon numerical data extracted from microscopic simulations. This data-driven approach, which is more refined than a simple fitting procedure, has been also applied to data coming from a granular Brownian motion experiment [4]. In this case we have shown that when the granular "bath" surrounding the Brownian particle is very dense, additional slow time-scales may emerge which determine a more complex effective description, in terms of two or more coupled Langevin equations.

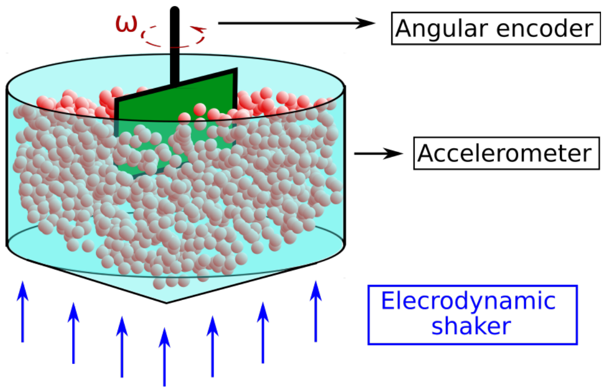

Figure 1: Sketch of the experimental setup for granular Brownian motion whose data have been analyzed in [4].

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S5. Equilibrium and non-equilibrium complex quantum systems

Usually, a quantum system is well described by a Lindblad master equation (LME) which, under a Markov assumption, takes into account the unavoidable interaction of the system with its environment. It follows that, starting from the complex whole, the reduced density matrix (RDM) of the system undergoes a coherent and dissipative evolution. If the coherent and dissipative parts of LME do not depend on time, then, after a transient, the system reaches a steady state, which is unconnected to its initial conditions and, under very mild assumptions, unique. Depending on the nature of the environment, we may have an equilibrium or a nonequilibrium steady state.

In the equilibrium case, the correct choice of the Lindblad operators, representing the system-environment interaction, is crucial. In principle, a microscopic derivation is possible. A celebrated example is the quantum optical master equation, which describes the thermalization of a system via dipole interaction with a blackbody radiation. However, in the microscopic derivation a series of approximations is introduced in order to reach an equation for the RDM that belongs to the Lindblad class. Even if these approximations are physically sound, their validity is, in general, out of control. The resulting thermalization dynamics reveals a number of serious pathologies, possibly including a lack of ergodicity.

We have obtained a consistent thermalization scenario by introducing a Lindblad-based approach (LBA), in which the Lindblad operators are established as the elements of an operatorial basis with squared amplitudes fixed by imposing a detailed balance condition and requiring their correspondence with the dipole transition rates evaluated under the first-order perturbation theory [1]. Within the LBA, it is possible to provide a clear-cut partitioning of the thermalization time into dissipation and decoherence times. For these times, we have derived explicit formulas in the case of a system consisting of an ensemble of noninteracting, arbitrarily complex, elementary subsystems. We have used the LBA approach to study the thermalization of the Lipkin-Meshkov-Glick model [2].

For general environments and arbitrary but time-independent system-environment interactions, the system reaches, at long times, a nonequilibrium steady state (NESS). In this case, we have a double aim: to study the relaxation dynamics but also to engineer the environment to the purpouse of realizing a target NESS. In the latter case we have investigated in detail the realization of spin-helix pure states in spin chains strongly coupled to two boundary environments [3].

Even if the NESS is trivial, the relaxation dynamics may not be: specially if a large dissipation-free subspace exists, the NESS can be approached through a complicated multistage evolution. As an example, we have investigated the time evolution of a system described by a LME with dissipation acting only on a part of the degrees of freedom $\mathcal{H}_0$ of the system, and targeting a unique state of $\mathcal{H}_0$. We have shown that, in the so called Zeno limit of *strong* dissipative coupling with the environment, the RDM of the system traced over the dissipative subspace $\mathcal{H}_0$, evolves according to an auxiliary LME, with renormalized effective Hamiltonian and *weak* effective dissipation [4]. Three stages of relaxation, occurring at different time scales, are then well distinguished. On the shortest time scale, only the degrees of freedom directly affected by the dissipation relax to their stationary values. On the second, intermediate time scale, an effective coherent evolution takes place, governed by the renormalized effective Hamiltonian. Finally, on the longest time scale, the remaining degrees of freedom of the system relax to their stationary values.

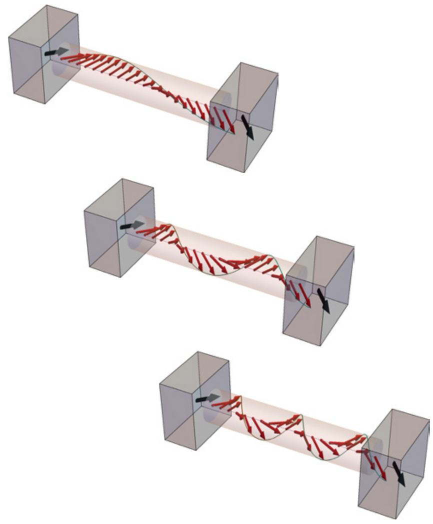

Figure 1: Multi-winding spin-helix states in a spin chain attached to two fully polarizing boundary environments [3].

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S6. Statistical Mechanics of Disordered Systems and of Systems of Biological Interest

The work that our group has been doing in the period considered in this report touches two main areas. The first area is "pure" statistical mechanics of disordered systems (with a strong attention to numerical simulations and to dedicated, optimized computers). The studies of spin glasses, the prototypical materials giving rise to phenomena of high complexity, are at the center of this analysis. The second direction has been towards using methods of statistical mechanics and theoretical physics to study systems of biological interest.

Let us start from the statistical mechanics of disordered systems, where we have been working in different directions. One is more based on small scale numerical simulations and analytic developments, while the second uses dedicated computers, that our groups have designed and build, to run very large scale numerical simulations, and to introduce all the needed ideas and formalism useful to analyze them.

As a first specific point we will quote the study of the "quasi critical" behavior of two dimensional spin glasses when T goes to zero. This is important from a fundamental point of view, but also, and we will come back to that, since new, modern spin glasses experiments analyze "film" like models, that smoothly interpolate among 2D and 3D systems.

Large scale simulations of spin glass systems have allowed us to reach very close to experimental scales (fractions of seconds of the order of 1/10). We used the Janus supercomputer, that we have designed and built in a collaboration among Italian and Spanish physicists. We analyzed a recent set of experiments (by Orbach group at San Diego, USA), by focusing on fluctuation-dissipation relations, and on the response of the spin glass system to small perturbations. We have also analyzed the "aging behavior" of spin glasses, and try to quantify the relevant scaling laws. As we have said we have dedicated a good amount of attention to "film" like spin glasses, by analyzing the transient from a pure to 2D system up to a 3D system by adding layers in this third direction. We have analyzed a peculiar and interesting phenomenon, the "Mpemba effect", and we have established its presence in the behavior of spin glass systems, and explained in detail its functioning. We have also been studying simple, paradigmatic models (the so called trap and step models) to describe basic aspects of disordered physical systems. Phase transitions in integer linear problems can also be studied, as we did, in the same framework. We have applied some of these ideas to superconducting mesoscopic islands.

A last sector of analysis into the field of disordered systems has been about power spectra of complex systems. This can have a strong experimental relevance. We have studied a Sinai like motion (random walk in a random environment), where the random potential is periodically repeated. We have analyzed the power spectrum of a single (or few) trajectories of Brownian motion and for fractional Brownian motion, also by analyzing a number of different sets of experimental results.

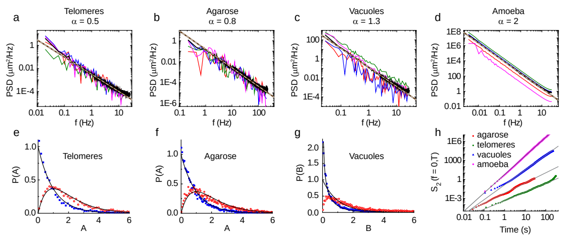

Figure 1: Comparison of theoretical results and experimental data fro the power spectrum of fractional Brownian motion like systems.

As far as systems of biological interest are concerned we have been involved in three different lines of research. The first concerns microRNA and post transcriptional genetic regulation. Phenomena like cross-talk are very reminiscent of the physics of collective phenomena, and we have investigated them in good detail. The second feature that has been of interest for us is related to the metabolic functioning of cells and the so called Flux Balance like approaches. We have both tried to clarify the true nature of the optimization principles that govern the cell functioning (the "Pareto front") and analyzed what thermodynamics can teach us about these phenomena. At last our third field of work has been more connected to neural networks and neurosciences: we have analyzed a learning model where synapses are bound by a hard threshold.

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S7. A new loop expansion around the Bethe lattice

The renormalization group method was introduced many decades ago to characterize second-order phase transitions. To compute the critical exponents in finite dimensions, one usually writes the Landau-Ginzburg (LG) Hamiltonian associated to the chosen model. Its bare terms lead to the solution of the fully-connected (FC) mean-field (MF) version of the model, while the loop expansion of the field theory gives the critical exponents in finite dimensions. This expansion around the FC model leads to very good results in some cases. There are however some known models (usually disordered ones) for which the usual LG expansion cannot be applied, or its application leads to wrong predictions for the finite-dimensional version of the models.

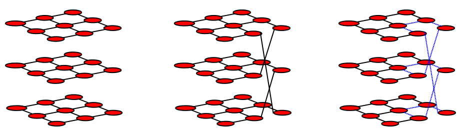

Figure 1: Qualitative representation of a M-layer construction for a 2D regular lattice with $M = 3$. (left) the original lattice replicated M times; (center) for a specific edge in the original graph, a possible permutation of its M copies; (right) a simple loop in the M-graph (dashed lines)

In Ref. [1] we introduce a new loop expansion, around the so-called Bethe lattice (BL). The BL is a particular type of lattice in which the average connectivity c is finite, and two spins are connected with high probability by a unique linear path: the average length of closed loops diverges logarithmically with the system size. Concerning critical phenomena, a phase transition on the BL is mean-field in nature and the model is usually solvable. To build this new expansion we introduce the Bethe M-layer construction, summarized in Fig. 1, composed of the following steps:
1-Take a model on a finite-dimensional lattice
2-Replicate the lattice M times
3-If a link (i, k) was present in the original model, randomly permutate the links between the M layers.
In this case, the large M limit of the theory will be given by the Bethe solution while the $1/M$ expansion will result in a topological loop expansion. Compared to FC models, that are typically simpler to solve, the BL has the advantage of being more similar to realistic finite-dimensional models due to its finite connectivity.

In some cases, the transition that we want to study in finite dimensions is just not present in the FC model. This is the case for the spin-glass (SG) in an external field. In the FC model, there is a transition line in the field-temperature plane, that tends to an infinite value of the field when $T \to 0$: at $T = 0$ there is not a transition in a field and the system is always in the so-called SG phase. This is not the case in finite dimensions, where we know that at $T = 0$ and high enough field there is no SG phase. While we lack proof of the existence of an SG transition in a field and the subject is an active research theme, it is well-known that things are different from the FC case and more similar to the BL one. In fact, on the BL at $T = 0$, there is a transition at a finite field h_c and we can perform an expansion around it to understand the fate of this transition in finite dimensions. In Ref. [2] we show that the expansion around the BL gives exactly the same results of the LG expansion for the SG in a field at $T \neq 0$ and large connectivity. We plan to see if the two expansions lead to different results for $T = 0$.

In some other cases, the transition in the FC model is present but has significant differences with respect to the one in finite dimension. This is the case for the Random Field Ising model (RFIM). In this case, the FC expansion implies dimensional reduction meaning that the critical exponents of RFIM in D dimensions are the same as a pure ferromagnet in $d = D - 2$ dimensions. However, for low enough dimensions dimensional reduction is not valid: the breaking is due to non-perturbative effects. The FC and the BL transitions are deeply different. In the BL the local order parameter fluctuates, contrary to what happens in the FC model, where the distribution of the observables is essentially peaked around a mean global value. The existence of a non-trivial distribution for local observables is a crucial property in common between finite-dimensional lattices and BL. One possibility is that the loop expansion around the FC fixed point leads to wrong results because it does not account correctly for the presence of multiple solutions for the local magnetization and expanding around the BL could give different results. In Ref. [3] we compute the first order of the expansion around the BL for the RFIM. We obtain that at this order Dimensional Reduction is still valid. However, we additionally succeed to predict some important phenomena, like the existence of avalanches, unpredictable with the use of the usual LG expansion. We plan to compute the next order in the Bethe expansion to see if the breaking down of Dimensional Reduction takes place.

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S8. Statistical physics of optimization and inference problems

In *constraint satisfaction problems* (CSP) one is asked to find a configuration of N variables satisfying αN constraints. These problems are prototypical *optimization problems* and correspond to the zero temperature limit of statistical physics models where the energy counts the number of violated constraints, such that a zero energy ground state corresponds to a solution to the CSP. In the last decade many zero temperature *phase transitions* have been found in random CSP varying the constraints per variable ratio α. These phase transitions have been uncovered thanks to the use of sophisticated tools developed by statistical physicists, and they currently play an important role in the challenging task of understanding the behavior of algorithms searching for solutions. However the exact connection between thermodynamical phase transitions in the space of solutions and *algorithmic thresholds* is still not clear, mainly because algorithms are out of equilibrium processes and thus do not sample any equilibrium Gibbs measure.

It has been observed that many algorithms do not sample solutions uniformly but are more likely to converge to solutions with some specific features. A better way to describe the dynamical behavior of these algorithms is to *reweight* solutions, so that the reweighted measure is dominated by solutions that are more likely to be reached by the searching algorithms. We have implemented in [1] this strategy for a very hard CSP (bicoloring random hypergraphs). We have studied a reweighted measure where the constraints that are satisfied only thanks to the assignment of a single variable (and thus force that variable not to change its value) have a smaller weight equal to $1-\epsilon$. The phase diagram in the (α, ϵ) plane shown in Fig. 1 clarifies that by using the reweighted measure, $\epsilon > 0$, the grey region where ergodicity is not broken (and thus algorithms can find solutions easily) moves to larger α values. We also uncovered that finding solutions by simulated annealing is much easier if the measure with $\epsilon > 0$ is used.

Understanding which class of algorithms may be more effective in solving basic optimization problems is still a largely open question. In [2] we have made a thorough study of algorithms to find the largest independent set in random regular graphs: this a fundamental problem that corresponds to the physical problem of achieving the densest packing of spheres. We have found that parallel tempering is definitely the algorithm performing best, although a theory explaining its behavior is still lacking.

In *inference problems* one is asked to find a signal hidden by some noise. In statistical physics these problems are mapped to *planted models*, where the planted configuration is the signal and the noise generates a glassy phase. Random ensembles of planted models show phase transitions varying the signal to noise ratio.

In [3] we have presented a complete theory for phase transitions in inference problems defined on sparse random graphs, finding phases that were unknown before. The behavior of algorithms that are able to achieve the Bayes optimal solution is expected to be directly related to the phase transitions taking place in the posterior measure and we have checked this expectation by running large scale numerical simulations. Fig. 2 summarises the phases available in these problems and the corresponding behavior of a Bayes optimal algorithm.

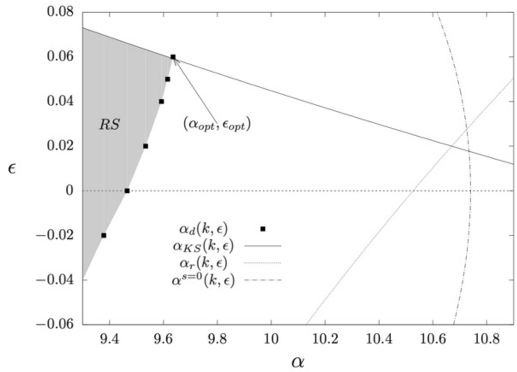

Figure 1: The phase diagram of a reweighted CSP shows that the grey region where ergodicity is not broken can be moved to larger α values by using $\epsilon > 0$. Reprinted from [1].

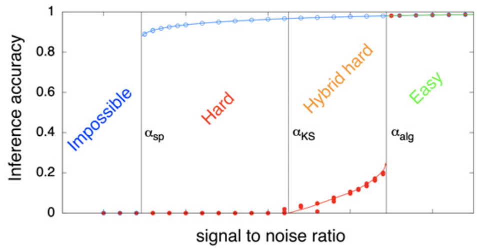

Figure 2: Different phases in inference problems on sparse random graphs as computed analytically (full lines) and from the behavior of a solving algorithm (points) [3].

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S9. Dynamics of processes with innovation

The analysis of large databases, mirroring human activities, allowed, in recent years, to highlight shared statistical patterns. This result points to a kind of universality in the complex dynamical processes underlying the evolution of systems featuring innovation. This universality was firstly grounded in the Zipfs' and Heaps' laws, describing respectively the relative abundance of different elements in a system and the rate at which innovation occurs. More recently, various measures are under investigation to reach a deeper comprehension of the underlying phenomena.

Recently, we introduced a modeling framework [1] that accounts for many of the universalities highlighted so far. The model translates in mathematical terms the concept of the *adjacent possible* space - roughly speaking, the space of events that are reachable in the near future given the present situation - and its key feature of being dynamically restructured while its boundaries get explored, i.e., conditional to the occurrence of new events. The model has been further progressively enriched to account for higher-level statistical properties [2], and, when extended to a multi-urns formulation, was able to account for both microscopic and macroscopic features in the dynamics of growing networks related to human activities [4].

Relation with bayesian inference. This modeling framework has been recognized [3] to be a generalization of well known stochastic processes, namely the one and two parameters Poisson-Dirichlet processes. Those processes have an extensive history in the mathematical and computer science literature, being at the basis of many inference problems.

Those processes are related for instance to the so-called "Sampling of Species Problem," reformulated in the context of population genetics by Ewens: if we sample genes from an evolving population, which is the probability to sample at each observation a brand new gene, or a specific one among those already observed? This knowledge is relevant, for instance, to decide whether one can safely end a sampling procedure.

Mathematically, all these problems correspond to estimate the rate at which new events occur, and this is a very tough problem because it implies estimating the probability of events never happened before. This is the general problem one faces when studying what is new: estimating its probability implies to be able to make accurate predictions about unseen events. The typical problem of inference is that of estimating the probabilities of future events based on the observation of the past. When brand new events are possible, the inference scheme has to be revised.

Due to their suitability to make inference in the presence of novelties, hierarchical formulations of the Poisson-Dirichlet processes are at the basis of state-of-the-art methods in bayesian non-parametric inference, for instance in topic models. Still, these processes produce exchangeable sequences: the probability of a sequence is assumed to be independent on the order of the elements, e.g., a text is considered as a bag of words. The reformulation of these processes in term of a Polya's urn model opened the way to straightforward generalizations that include, for instance, the possibility of accounting for correlations in the microscopic dynamics, thus going beyond exchangeability. This reformulation was crucial to reproduce patterns of correlations observed in many real systems related to human activities [1]. The challenge we take is that of building Bayesian inference schemes based on our generalized Polya's urn modeling framework.

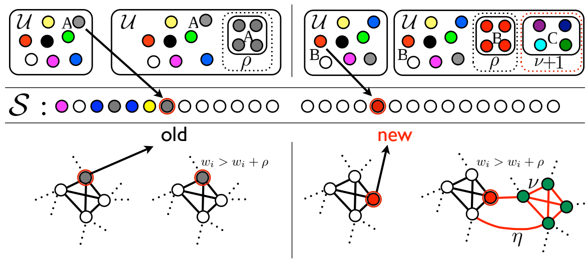

Figure 1: Left: An element that had previously been drawn from the urn, is drawn again: the element is added to $\mathcal{S}$ and it is put back in the urn along with ρ additional copies of it (reinforcement of known events). Right: An element that never appeared in the sequence is drawn: the element is added to $\mathcal{S}$, put back in the urn along with ρ additional copies of it, and $\nu + 1$ brand new and distinct balls are also added to the urn (an innovation triggers further innovations: the adjacent possible expands conditionally to the actualization of an innovation). Bottom: the urn model can be rethought as a random walk in an expanding and dynamically weighted graph.

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`http://www.socialdynamics.it/`

S10. New scenarios for urban systems

The intrinsic complexity of the emerging challenges that human beings collectively face, requires a deep comprehension of the underlying phenomena in order to plan effective strategies and sustainable solutions: from the planning of urban infrastructures to rethinking cities and their interactions, from containment strategies for pandemics to the impact of political campaigns, to measures against information pollution and misinformation. In all these cases, decision-making processes have to be supported with meaningful representations of the present situations along with accurate simulation engines to generate and evaluate future scenarios. Instrumental to all this is the possibility to gather and analyze vast amounts of relevant data and visualize them in a meaningful way. Understanding the present through data is often not enough, and the impact of specific decisions and solutions can be correctly assessed only when projected into the future. This implies the need of developing suitable modeling schemes allowing for a realistic forecast of how a change in the current conditions will affect and modify the future scenario ("what if" games). In this area, our Department has a tight collaboration with the Sony Computer Science Lab in Paris (https://csl.sony.fr/).

Mobility and accessibility dynamics The comprehension of vehicular traffic in urban environments is crucial to achieving proper management of the complex processes arising from people collective motion. Even allowing for the high complexity of human beings, human behavior turns out to be subject to strong constraints - physical, environmental, social, economic - that induce the emergence of common patterns. The observation and understanding of those patterns is key to setup effective strategies to optimize the quality of life in cities while not frustrating the natural need for mobility. In our activity, we focus on mobility, both vehicular and public transportation in an urban context, but also air and trains transportation systems, to reveal the underlying patterns and human strategies determining them. In this framework, we recently developed a web-based platform, Citychrone++ (http://whatif.cslparis.com/citychrone.html), that allows to visualize isochrones in many major cities based on public transportation data and draw accessibility maps of different portions or specific features of the town. The possibility for seamless integration of any open data (census, social, medical, financial, etc.) makes the system suitable to reveal underlying patterns in social dynamics. This kind of tools turns out to have the potential to become powerful instruments for learning at all levels, planning, and simulation of scenarios and decision making.

The future of Electric Mobility The transition towards private electric mobility has been already started across the world, pushed forward by the need of independence from fossil fuels and of preserving proper levels of

Figure 1: Maps of the *velocity score* in km/h for six different cities: Paris, New York, Madrid, Montreal, Sidney, Boston. The great variability of the colors reveals a strong dissimilarity of performances of the public transports across cities.

air quality in urban centers. In this context, it is necessary to provide instruments to foresee the effects that a massive introduction of electric vehicles might have on urban environments in terms of the amount of electricity and infrastructures needed to their functioning. The platform E-Mobility (http://whatif.cslparis.com/e-mobility.html) exploits a data-driven approach combining different data sources: demographics data, GPS data about cars traveling within an area, environmental data (e.g., solar radiation to provide solar energy to recharge station) and so on. The platform not only allows to visualize the present, through the available data but, crucially, allows for the construction of suitable scenario simulation models to project the system into the future and assess the sustainability of different solutions.

Modeling urban systems A lot is known about scaling-laws in cities. While the identification of the mechanisms behind the emergence of scaling laws is important to understand the evolution of cities, the current research lacks studies aimed at understanding how different indicators interact among them. Our research is aimed at filling this gap and developing models that reproduce the dynamics of cities and the interrelation between their socio-economic indicators. We adopt a panoply of tools ranging from Complexity Science to Maximum Entropy (ME) inference principle.

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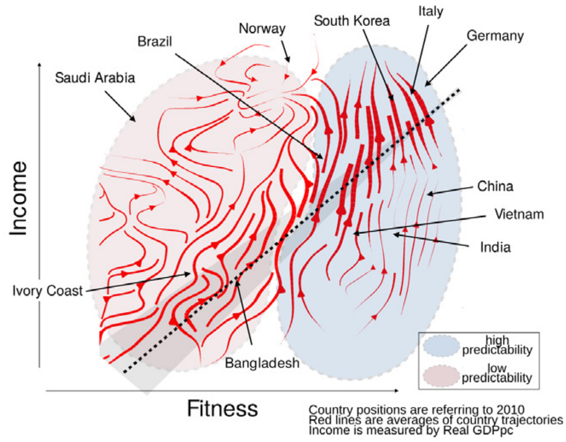
S11. Economic Complexity

Economic Complexity is a radically **new methodology** based on a bottom up, data driven approach, describing economics as an evolutionary process of ecosystems. The approach is **multidisciplinary**, addressing emerging phenomena in economics from different points of view: analysis of complex systems, scientific methods for systems and the recent developments in **Big Data**. This approach offers new opportunities and a new paradigm to constructively describe technological ecosystems, analyse their structures, understand their internal dynamics, as well as to introduce new metrics. In the following we will briefly illustrate the main scientific achievements we obtained using the Economic Complexity approach. It led to collaborations with, among others, the **World Bank**, which adopted this methodology for the study of more than 70 countries.



- **A new metrics for the fitness of countries and the complexity of products.** We developed a new metrics which is able to give quantitative assessments of both countries' competitiveness and potential of growth, through the concept of **Fitness**, and products' sophistication and technological content, through the concept of **Complexity**. These two quantities are calculated using a methodology completely different from the standard economic approach, which takes into account a large number of subjectively weighted macroeconomic indicators. On the contrary, the Economic Complexity approach is data-driven and gives results using **zero parameters**, results which can be scientifically tested.

- **Selective Predictability Scheme.** The coupling of these non monetary measures with standard monetary quantities such as the GDP allows a radically new approach to macroeconomic **forecasting** [1]. Making use of concepts borrowed from dynamical systems we have built a novel perspective in which the ability to forecast depends on the location of countries in the **Fitness-GDP plane**. This evidence naturally leads to the so called Selective Predictability Scheme, a framework which uses the dynamical evolution of suitable analogues to predict the future movements of countries. According to a recent report by Bloomberg, this methodology systematically outperforms standard methods [i.e., IMF], despite requiring much less data.

- **Quantitative description of Economic Traps.** The introduction of the Fitness as a new dimension quantifying the complexity of the industrial structure of countries gives a different insight about their industrialization process [2]: a high Fitness brings down the barrier to escape from the **poverty trap**. This fosters the fast growth which is the typical sign of the economic transition towards the developed countries.

- **The Product Progression.** The Product Progression Network (PPN) is a directed network showing the **natural evolution** of countries from a product to the other [3]. Indeed, the PPN allows for a synthetic representation of the main industrial sectors of a country and the available and advisable products it can reach, containing information about the time evolution during industrialisation. In parallel, we have developed a **Machine Learning** (ML) technique to forecast the industrial sectors in which a country will become competitive in the following years [4]. The recommendations based on the PPN and the ML predictions can be a useful tool for both investors and policy makers.

- **The innovation system of countries** The space in which scientific, technological, and economic developments interplay with each other can be mathematically shaped using pioneering **multilayer** network techniques. We build the network of these human activities (scientific, patenting, and industrial production) and study their interactions [5]. We can measure the time needed to transform, for instance, the technological know-how into economic wealth and scientific innovation, being able to make predictions with a very long time horizon. We find empirical evidence that, at the aggregate scale, **technology** is the best predictor for industrial and scientific production over the next decades.

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S12. On the analytic theory of rogue waves in nature

Rogue Waves (RWs) (also known as anomalous, freak, or extreme waves) are large, apparently unexpected and suddenly appearing waves. In oceanography, they can present considerable danger, since they can impact with tremendous force. RWs can occur in media other than water. Indeed they appear to be ubiquitous in nature and have also been reported in liquid helium, in nonlinear optics and Bose-Einstein condensates.

The main physical causes for the formation of a rogue wave is Modulation Instability (MI) and nonlinearity. The simplest nonlinear model describing the amplitude modulation of a quasi monochromatic wave in a weekly nonlinear medium and exhibiting MI as well, is the celebrated focusing nonlinear Schrdinger (NLS) equation $A_t + A_{xx} + 2|A|^2 A = 0$, where $A(x,t)$ is the complex amplitude of the monochromatic wave and x and t are suitable slow variables. The background solution $A_0 = a\exp(2i|a|^2 t)$ of NLS, describing Stokes waves in water waves, constant light intensity in nonlinear optics, and constant boson density in a Bose condensate, is unstable under small perturbations of sufficiently large wave length, and a number of nonlinear coherent structures are produced from this instability, and can eventually interact constructively generating RWs.

NLS is also a prototype example of integrable nonlinear PDE in 1+1 dimensions, and few years ago we started with P. G. Grinevich (Landau Institute, Chernogolovka, Russia) a theoretical study of the RW phenomenon, using the integrability nature of NLS. In particular, we have recently solved, to leading order, the periodic Cauchy problem of the RWs, for a generic initial perturbation of the unstable background, describing analitically, in terms of elementary functions of the initial data, the RW dynamics [1-5] (see the figure below). If the periodic initial data excite only a finite number of unstable modes, the theory is fully deterministic. The techniques used range from the finite-gap method (a nonlinear analogue of the method of the Fourier series for linear PDEs) to matched asymptotic expansions. In the simplest case of a single unstable mode, the dynamics is described by an exact RW recurrence [1-3], and these theoretical findings have been recently tested successfully in a nonlinear optics experiment [6]. Since NLS describes reality to leading order, the exact RW recurrence of the integrable model becomes a good example of Fermi-Pasta-Ulam recurrence [7] in nature.

At the moment, we are investigating 1) RW dynamics with a large number of nonlinear unstable modes, when the established deterministic theory should be replaced by a suitable statistical analysis; 2) RWs in field theories on the lattice and in relativistic field theories (with the PhD student F. Coppini).

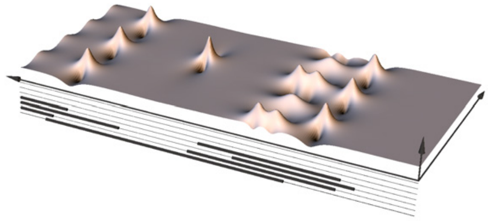

Fig. The Plot of $|A(x,t)|$ in the (x,t) plane (the x axis is the short one), where $A(x,t)$ is the leading order approximation of the solution of the Cauchy problem, as described by the theory in [1-5], when the initial data excite the first four unstable modes (the lines below indicate the time intervals in which each mode is "visible"). It is important to remark that this plot agrees "pixel to pixel" with the corresponding numerical experiment.

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S13. Markov chains on graphs

Let $\mathcal{G} = (V, E)$ be a connected finite graph with vertex set $V = \{1, 2, \ldots, n\}$. The *Laplacian* of $\mathcal{G}$ is the $n \times n$ matrix $\Delta_{\mathcal{G}} := D - A$, where A is the adjacency matrix of $\mathcal{G}$, and $D = \mathrm{diag}(d_1, \ldots, d_n)$ with d_i denoting the degree of the vertex i, *i.e.* the number of edges originating from i. Since $\Delta_{\mathcal{G}}$ is symmetric and positive semidefinite, its eigenvalues are real and nonnegative and can be ordered as $0 = \lambda_1 \leq \lambda_2 \leq \cdots \leq \lambda_n$. There is an extensive literature dealing with bounds on the distribution of the eigenvalues and consequences of these bounds. Of particular importance for several applications is the second eigenvalue λ_2 which is strictly positive since $\mathcal{G}$ is connected. The Laplacian $\Delta_{\mathcal{G}}$ can be viewed as the generator of a continuous-time random walk on V, whose invariant measure is the uniform measure on V. In this respect, λ_2 is the inverse of the "relaxation time" of the random walk, a quantity related to the speed of convergence to equilibrium. λ_2 is also called the *spectral gap* of $\Delta_{\mathcal{G}}$. There are several results which estabilish relationships between the spectral gap and various geometric quantities associated with the graph. Among these we should mention upper and lower bounds on λ_2 in terms of the Cheeger isoperimetric constant, a result closely related to the Cheeger's inequality dealing with the first eigenvalue of the Laplace–Beltrami operator on a Riemannian manifold.

One can consider, besides the simple random walk, more complicated Markov chains on the same graph $\mathcal{G}$. We mention two widely used processes: the exclusion process and the interchange process. In the interchange process each vertex of the graph is occupied by a particle of a different color (Fig. 1), and for each edge $\{i, j\} \in E$, at rate 1, the particles at vertices i and j are exchanged. The exclusion process is analogous but with only two colors, say k red particles and $n-k$ green particles (particles with the same color are considered indistinguishable).

The interchange process on $\mathcal{G}$ can be considered as a random walk on a larger graph with $n!$ vertices corresponding to the configurations of the process. This graph is nothing but the Cayley graph of the symmetric groups S_n with generating set given by the edges of $\mathcal{G}$, where each edge $\{i, j\}$ is interpreted as a transposition. We denote this graph with $\mathrm{Cay}(\mathcal{G})$. It is easy to show that the spectrum of $\Delta_{\mathcal{G}}$ is a subset of the spectrum of $\Delta_{\mathrm{Cay}(\mathcal{G})}$. By consequence

$$\lambda_2(\Delta_{\mathcal{G}}) \geq \lambda_2(\Delta_{\mathrm{Cay}(\mathcal{G})})\,.$$

Being an $n! \times n!$ matrix, in general the Laplacian of $\mathrm{Cay}(\mathcal{G})$ has many more eigenvalues than the Laplacian of $\mathcal{G}$. Nevertheless David Aldous formulated in 1992 a neat conjecture which states, equivalently:

1. If $\mathcal{G}$ is a finite connected simple graph, then

$$\lambda_2(\Delta_{\mathcal{G}}) = \lambda_2(\Delta_{\mathrm{Cay}(\mathcal{G})})\,.$$

2. If $\mathcal{G}$ is a finite connected simple graph, then the random walk, the exclusion process and the interchange process on $\mathcal{G}$ have the same spectral gap.

Aldous's conjecture has been proven for trees in 1996. In 2010 we found a proof for complete multipartite graphs using a tecnique based on the representation theory of the symmetric group. Shortly after the appearence of our result, a general proof of the Aldous's conjecture was found by Caputo, Liggett and Richthammer. Their proof is a subtle combination of two ingredients: a nonlinear mapping in the group algebra which permits a proof by induction, and a quite hard estimate named the octopus inequality. In a successive paper we present a simpler and more transparent proof of the octopus inequality, which emerges naturally when looking at the Aldous' conjecture from an algebraic perspective.

In [1] we extend the validity of Aldous' conjecture to the B_n family of Weyl groups. From a probabilistic point of view this is equivalent to considering a "spin 1/2" version of this conjecture, where each vertex carries, in addition to its color, a ± 1 valued spin variable.

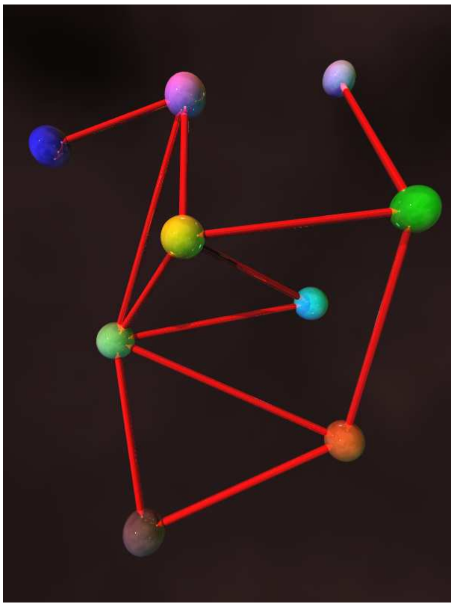

Figure 1: A configuration of the interchange process.

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S14. Negative results in QFT and resonances at finite volume

1. No-go theorem in quantum gravity
As far as quantization is concerned, gravity is substantially different from the other fundamental forces in nature; it describes the interaction of spin two massless particles — the gravitons — via a coupling with a negative mass dimension[1], the Planck scale. The quantization of electromagnetism, for example, has produced the well known Quantum-Electro-Dynamics (QED), a renormalizable theory[2]; no modification of the classical Maxwell equations has been required by quantization. On the contrary, Einstein's equations of General Relativity (GR) lead, upon quantization, to a non-renormalizable theory. One has therefore to modify GR at small distances in some way. The principles of renormalizability, unitarity[3] and microcausality[4] are at the root of the Standard Model of the strong and electroweak interactions. It is difficult to formulate a consistent quantum theory of gravitation by retaining all the above principles and, in particular, there is not any sound reason to keep microcausality. Microcausal theories have particle propagators with poles in the II and IV quadrant only of the complex energy plane. In the sixties of last century, T.D. Lee and G. Wick proposed a generalization of QED with propagators containing poles also in the I and III quadrants, which violate microcausality in a "controllable way" by means of (at least) one new large mass scale, which can be tuned at will. In collaboration with Prof. D. Anselmi of Pisa University, we basically formulated in ref. 1 a no-go theorem in quantum field theory, with main application in quantum gravity. In the paper it is shown that theories containing higher-order box operators ($\Box^2, \Box^3, \cdots$), giving rise to free propagators with poles in all the quadrants, are not consistent if they are quantized directly in Minkowski spacetime, as they give rise, at one loop, to non-local ultraviolet divergences both in two-point correlation functions (propagators) and in three-point correlators (vertices).

2. Unsolvability argument in QFT
Solving exactly a "realistic" Quantum Field Theory (QFT) — such as, let's say, an interacting scalar theory or a non-abelian gauge theory in four space-time dimension — is the dream of high-energy theorists since the fifties of last century. Despite different ingenious attempts by many great scientists (G. t'Hooft, G. Veneziano, A. Polyakov, A. Migdal, K. Wilson, E. Witten, just to name a few), no interacting bosonic quantum field theory has ever been exactly solved. In ref. 2 I present an argument, based on Dyson-Schwinger (DS) equations on the lattice, in favor of the general unsolvabilty of these theories. The argument also applies, as its simplest case, to the quantum anharmonic oscillator, which can be considered an interacting bosonic quantum field theory in one space-time dimension (space dimension = 0). The idea is that, even after solving the DS equations and the symmetry equations of the quantum field, one ends up with a set of "primitive" or "master" correlators (the basis set) which grows up exponentially, rather than power-like, with the number of lattice points. Furthermore, any conceivable evolution equation aimed at calculating any primitive correlator, involves, in general, all of them.

3. Resonances at finite volume
An impressive number of complicated dynamical phenomena in virtually any branch of quantum physics — high-energy physics, nuclear, atomic, molecular, solid-state physics, etc. — can be described to a good approximation as the formation and the subsequent decay of a narrow resonant state[5]. Understanding the decay of a resonance in a large but finite space volume (in the quasi-continuum, if we work in momentum rather than configuration space), apart from an interest of principle, is crucial for studying unstable particles in lattice Quantum-Chromo-Dynamics. In ref. 3 I study this general problem in a specific model: the extension of Winter or δ-shell model to finite volume (length). Standard Winter model is a simple one-dimensional quantum-mechanical system possessing an infinite, non-degenerate resonance spectrum. Because of its simplicity, also its finite-volume extension can be studied, to some extent, analytically, by means of ordinary or resummed perturbation theory (multi-scale method). In general, a resonance at finite volume is related to a compression of two or more spectral lines; for specific values of the parameters of the model, it is related to a degenerate or quasi-degenerate doublet in the spectrum.

[1] Like the old phenomenological theory of E. Fermi for the weak interactions.

[2] That is an infinite theory in the limit in which the ultraviolet regulator is removed, with a finite number (usually very small) of free parameters.

[3] A fundamental theory has to explicitly describe any possible outcome of a scattering event, so that the probabilities of all final states has to sum up to one. Unitarity is non trivial (order by order) in perturbation theory.

[4] The field operators exactly commute at space-like, whatever small, separations.

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[5] For a general definition of a resonance, see for example my contribution to the previous Department report.

Philosophy Doctorates

PhD in Physics

The Physics PhD Program at Sapienza is finalized to train scientific researchers with a wide spectrum of scientific knowledge: we expect them to be flexible with regards to all possible job related choices, and to be able to easily reach a high professional level in all fields where physics research is active.

All fields of experimental and theoretical physics are represented. The Ph.D program enrolls each year about 15 students with fellowships provided by Sapienza and by some affiliated institutions (INFN and IIT). These students are selected with a written and oral exam, and can freely choose as thesis advisor any professor or researcher of the Department or of other institutions affiliated to the Department in any subject of physics. In addition, about 7 students per year join the program within international, or bilateral PhD programs or supported by the research grants of individual groups of the Department. On average 3% of the students are not Italian. The board of the PhD (Collegio Dottorale) includes 17 members of the Physics Department and 5 professors/researchers of European institutions outside Italy.

The program lasts three years. The first year the students must follow about 120 hours of classes chosen among the courses offered by the Laurea Specialistica or directly by the PhD program and pass the corresponding exams. In addition, the students must present the advancements of their research activity to the PhD board during the second and third year of the program. This PhD program belongs to the V. Volterra doctorate School of Sapienza, that comprises also the PhD programs in Astronomy-Astrophysics and Space Science, Chemistry, Earth Sciences, Mathematics, Physics, Relativistic Astrophysics.

Accelerator Physics PhD

Accelerators were initially developed to investigate elementary particles but they are now also a common tool for applications ranging from medical therapy to cultural heritage and agrifood. The Departments of Fisica and of Scienze di Base Applicate all'Ingegneria of the Università "La Sapienza" together with INFN, the National Institute for High Energy Physics, are set to grow the new generation of Accelerator Physicists.

In this context, the PhD school in Accelerator Physics aims to prepare young researchers to Accelerator Physics , profiting of the high level facilities both in the University and in the INFN. The covered topics span from Theory Models and simulations, both with Monte Carlo and Particle in Cell codes, to R&D of new accelerating techniques. Research in new beam diagnostic tools and radioprotection issues is also included. Finally, the Ph.D. theses range from research on next generation circular and linear accelerators to the bleeding edge of laser plasma acceleration. The course is unique in Italy and has therefore national coverage.

In the first year the lectures are devoted to improve the knowledge of the Physics acquired in the graduation courses to the principles of the Accelerator Theory and to their applications in the different domains of this science. The students will be required to follow both theoretical lectures and practical training in accelerator based laboratories all around the world from the INFN labs in Frascati, Legnaro and Catania, to CERN in Switzerland, to KEK in Japan. Lessons can be attended, via e-learning, also from remote, to guarantee a national dimension to the course.

The intrinsically international nature of the community behind Accelerator Physics implies that most of the students spend a significant amount of time abroad, in very high profile research infrastructures, like for instance, CERN.

External Institutions

Istituto Nazionale di Fisica Nucleare and the INFN Sezione di Roma

The National Institute for Nuclear Physics (INFN, `www.infn.it`) is the Italian research agency dedicated to the study of the fundamental constituents of matter and their interactions, under the supervision of the Ministry of Education, Universities and Research (MIUR). INFN performs theoretical and experimental research in the fields of subnuclear, nuclear and astroparticle physics. All of the INFN's research activities are undertaken within a framework of international competition, in close collaboration with Italian universities on the basis of solid academic partnerships spanning decades. Fundamental research in these areas requires the use of cutting-edge technologies and instruments, developed by the INFN at its own laboratories and in collaboration with industries.

Physicists from the universities of Rome, Padua, Turin, and Milan founded the INFN on 8th August 1951. In the last years of the 50s the INFN designed and built the first Italian accelerator, the electron synchrotron developed in Frascati, where its first national laboratory was set up, and few years after the ADA (Anello di Accumulazione) the first world wide particle-antiparticle (electron-positron) collider. During the same period, the INFN starts its participation to the research activities of the the European Organization for Nuclear Research, CERN, in Geneva. Besides research at CERN, the INFN is a major contributor to experiments at other leading international laboratories including FERMILAB, SLAC, BNL, and JLAB (United States); PNPI, BINP and JINR (Russian Federation); CIAE and IHEP (China); RIKEN and KEK (Japan); BARC (India), DESY and GSI (Germany), ESRF (France), PSI (Switzerland) etc.

INFN employs some 5,000 scientists whose work is recognized internationally not only for their contribution to various European laboratories, but also to numerous research centres worldwide. The INFN carries out research activities at two complementary types of facilities: divisions (Sezioni) and national laboratories. The four national laboratories, based in Catania, Frascati, Legnaro and Gran Sasso, house large equipments and infrastructures available for use by the national and international scientific community. Each of the 20 divisions is based at different university physics departments and guarantees close collaboration between the INFN and the academic world. The present President of INFN is Prof. Fernando Ferroni belonging to the Physics Department of Sapienza University (end of mandate fall 2019). In the past, illustrious physicists of this Department holded the same task: Prof. Amaldi, Prof. Salvini, Prof. Cabibbo and Prof. Maiani.

The INFN Sezione di Roma (`www.roma1.infn.it`) is located in the Physics Department and counts a staff of 125 persons (researchers, technologists, technicians and administrative staff). More than 250 scientists are associated to the research activities of the INFN Roma division. This includes a significative number of PhD (53 in 2019), Msc (25 in 2019) students and Post Docs (27 in 2019).

The scientific activity of INFN is organized in five lines of research coordinated by five National Scientific Committees (CSN):

- CSN1 studies fundamental interactions of matter in experiments using particle accelerators.
- CSN2 deals with research in the field of astroparticle physics.
- CSN3 studies the structure and dynamics of nuclear matter.
- CSN4 is concerned with theoretical physics research.
- CSN5 develops technological research and promotes the use of fundamental physics instruments, methods and technologies in other sectors.

Experiments belonging to all these five lines of research are present in the Sezione di Roma.

In particular in these years the study of the Higgs Boson discovered by ATLAS and CMS experiments at the Large Hadron Collider (P1-P17 of this report) and the investigations after the direct observation of Gravitational Waves by LIGO-VIRGO (P24-P28) have seen an important contribution of the INFN Sezione di Roma and the Physics Department of Sapienza University. Detailed studies for future accelerators (Future Circular Collider shown in Fig.1 and Muon Collider), to which scientists of the Sezione are actively contributing, are going on in the international community. The aim is to push, in the next decades, the energy frontier toward new unexplored territories.

Figure 1: The location planned for the tunnel of 100 km of the new FCC accelerator project is shown and compared to the present LHC proton-proton collider.

Other research activities are going on with a leading participation of INFN Roma and Physics Department and will produce results in the forthcoming period about neutrino's nature with CUORE at Laboratori Nazionali del Gran Sasso (P29). Some experiments are in design or construction phase to answer fundamental open questions like the nature of dark matter (CYGNO, PTOLEMY, DARKSIDE and SABRE, P38-P39) or investigate distant astrophysical sources such as supernovae, gamma ray bursters or colliding stars looking at cosmic neutrinos in order to open a new window on our Universe (KM3NeT, P34−P37).
A set of lively activities is going on in the framework of technological research spanning from medical applications to the development of new visionary detectors for future experimental applications.
A special link exists with the nearby Laboratori Nazionali di Frascati where the scientists of INFN Roma and Physics Department are very active in KLOE2 (P19−P21) and PADME (P23), an experiment to reveal the mysterious dark photon a new hypothetical elementary particle.
An important role is played by the theoretical research active in several areas like flavour physics and LHC phenomenology (T1−T4) as well as more formal subjects. A complete list of the experiments can be found at `www.roma1.infn.it/main/exp.html`. The INFN Sezione di Roma supports its experiments with technical services: a computing center (including a T2 for LHC computations), an electronics laboratory, a mechanical workshop and a service for mechanical design (see Laboratory and Facilities section of this book).

INFN takes great care of young generations of scientists. The international context of INFN activities gives important opportunities of gaining experience abroad and in big laboratories already during the Mater thesis. In 2017 INFN Roma promoted an award for the best six students of the 3rd year course of Nuclear and Subnuclear Physics. The students are exposed to a three days visit to CERN guided by young INFN Roma researchers. A snap-shot of the 2018 visit is shown in Fig. 2. INFN supports each year with three grants the PhD program in physics of the Department and a specific PhD course of three years in Accelerator Physics (`www.roma1.infn.it/direzione/dottorato/index.html`) it's organized in collaboration between Sapienza University (through the Physics and Engineering Departments) and INFN (that finances 6 grants). The career of young Post Docs is supported with grants in Italy and in international laboratories like CERN. Permanent job opportunities are uncommon and the competition is high but the possibilities offered by the field are worldwide. In 2018 INFN, thanks to its excellent performance in research, was awarded by the Ministry of Research with 39 permanent positions for young researchers which were selected among more than 500 young scientists performing their activity in Italy and around the world. Most of the winners have less than 5 years of Post Doc activity, some of them joined the Sezione di Roma reinforcing the scientific activities in different fields.

Figure 2: The students selected in 2018 are visiting the LHC accelerator. The LHC tunnel is accessible during the shut-down periods.

INFN has a strong engagement in outreach initiatives. The INFN magazine Asimmetrie (`www.asimmetrie.it`), directed by Prof. Egidio Longo of the Sapienza Physics Department, is published twice a year and each issue is dedicated to an important aspect of particle physics. The Sezione di Roma is very active in the popularization of particle physics through the organization of events for a wide public (from children to senior people), in organizing orientation courses for high school students and training courses for their teachers. Every year INFN Roma jointly with Physics Department contributes to the International Masterclass Program (`www.physicsmasterclasses.org/index.php`).
More than 10.000 high school students in 46 countries come to one of about 200 nearby universities or research centres for one day

in order to unravel the mysteries of particle physics. Lectures from active scientists give insight in topics and methods of basic research at the foundations of matter and forces, enabling the students to perform measurements on real data from particle physics experiments themselves. In 2019 INFN Roma and Physics Department launched for the third year the project LAB2GO (`www.roma1.infn.it/LAB2GO/index.html`), involving students of 31 high schools to classify and repair the existing school's laboratory instrumentation and build a system to share these resources among the involved schools in order to enrich the possibilities of experimentation.

The INFN Sezione di Roma has a long tradition in technological research in the fields of particle acceleration, particle detectors and medical applications. In more recent years, under the push of computing needs both in experiments and theory, there has been a dedicated effort towards the design of computing systems for High Performance Computing (HPC). In the framework of technological research, coordinated by CSN5, each year six grants are awarded to young scientists proposing three years projects on innovative technologies; the grant consists in the salary of a post doc position for the proponent and the money to develop the project. Young scientists working in the Sezione di Roma have been often successful in this program thanks to the lively activity of researchers in this field.

CLNS-IIT @ Sapienza
Center for Life NanoScience of the Italian Institute of Technology

The Center for Life NanoScience revolves around two topics of biomedical interest where technological innovation is key to reach the goals. The first regards neurodegenerative disorders, hereditary and sporadic conditions characterized by progressive nervous system dysfunction. The focus of the second is brain tumours, the most life-threatening diseases of adulthood and childhood. These challenging projects benefit from the establishment and convergence of common technological platforms. They employ state-of-the-art commercial equipment and, at the same time, foster and support the development of new techniques and instrumentation.

iit @SAPIENZA ISTITUTO ITALIANO DI TECNOLOGIA CENTER FOR LIFE NANO SCIENCE

The technological platforms are: Cell culture, Genomics, Bioinformatcs, Bioprinting, Flowo cytometry, Micro and nanofluidics and Microscopy, the latter driven by physicists in tight connection with the Department of Physics.

The Microscopy platform sits in six laboratories, two of them host the "imaging core facility", including commercial state-of-the-art instrumentation, aimed at providing a complete panorama of techniques to tackle biomedical research activities (Single and two-photon laser-scanning confocal microscopy, spinning disk confocal microscopy, structured light microscopy). The other labs are devoted to the development of new techniques and new instrumentation. These activities include the study and the development of : *(i)* New imaging tools based on disordered optical fibers; *(ii)* Nano-phosphors crystals for multi-spectral fluorescence microscopy; *(iii)* Non-linear microscopy for CARS and SRS imaging; *(iv)* Nano-IR microscopy; *(v)* Nano-Raman microscopy; *(vi)* Plasmon-based scanning probe microscopy; *(vii)* Brillouin microscopy; *(viii)* Long working distance Bessel beam microscopy; *(ix)* New approach to optogenetics based on calcium imaging on large field of view and digital optical olography.

The experimental activities are complemented and supported by different numerical and theoretical studies (inference techniques for the determination of neural networks in C. Elegans and in neurons culture, and of functional network from MEG data; study of the neural stems cells and their differentiation in nervous structure; theory for propagation and localization in disordered optical fibers).

Overall, the CLNS employed 32 Post Docs (out of them eight are physicists) and about 20 PhD students (seven new entry every year) from different PhD schools (one every year from the Physics PhD program). The center has been established in 2011, started its experimental activities in 2013 (Bio) and 2014 (Technological), it is now in the steady state concerning personnel (beside the Post Docs and PhD students there is one director, G. Ruocco, four staff, two administrative and two technicians, and about ten associate scientists from Sapienza) and budget (the center institutional budget is now stable around 3 MEuro/year, with a total investment of 18.5 MEuro in the period 2011-2016). The scientific production is still growing, reaching in 2015 about 100 papers (about 3 pub/year/res).

`http://lns.iit.it/`

Institute of Complex Systems @Sapienza

The scientific mission of the **Institute of Complex Systems** (**ISC**) of the Research National Council (CNR) is the study of the science of complexity, from fundamental issues to applications. Complex systems are composed by interacting elements which exhibit some emergent properties, ranging from simple particles to entire communities and networks and their study has profound implications in modern physics. The activity includes theory and experiments, not only in the fields of condensed matter but also extending to economics, animal behaviour, neuroscience, soft-matter, photonics, and social dynamics.

The Institute has 2 units (Sapienza, Sesto Fiorentino) that in total involve 70 permanent researchers and 20 post-doctoral scientists. In the last period, ISC collected more than 10 million euros from research grants, published 787 papers with more than 6000 google-scholar citations with h-index 39. The publications include 25 articles in Nature journals and 58 Physical Review Letters.

Figure 1: Institute of Complex System @Sapienza.

The main unit of the institute is settled at and strictly collaborates with the Department of Physics of Sapienza University to which the Director, Prof. Claudio Conti, belongs. Young scientists, forming the leading groups in ISC, are worldwide recognized, highly productive, strongly committed to teaching, to master and phD tutoring and to outreach activities. The research is fully described at `www.isc.cnr.it` and is both theoretical (th) and experimental (exp) with ISC laboratories [LAB] (described in other pages of this Report) located in the Physics Department. It can be summarized in the leading modern directions like:

- **Soft-matter**:

  Self-assembly, gels and glasses, smart materials (th, exp): R. Angelini [LAB], N. Gnan, B. Ruzicka [LAB] (head of the ISC Sapienza Unit), S. Sennato, E. Zaccarelli (ERC-CoG 2015).

  Active and biological systems (th): L. Angelani, F. Cecconi, M. Cencini. S. Melchionna, A. Taloni.

  Applied Physics(Biomedical Physics, Cultural Heritage)(exp): S.Capuani[LAB], M.Missori[LAB].

- **Complexity**:

  Flocking and animal behaviour (th, exp): A. Cavagna [LAB] (ERC AdG 2017), S. Melillo, L. Parisi, M. Viale.

  Social Dynamics (th): C. Castellano, F. Colaiori, E. La Nave.

  Economic Complexity and Complex Network (th): G. Cimini, A. Scala (CRISIS Lab project).

  Granular systems (th, exp): A. Baldassarri, A. Petri [LAB], A. Puglisi [LAB] (ERC StG 2008).

  Disordered and glassy systems (th): T. Rizzo.

  Cosmology (th): M. Montuori.

- **Quantum Complexity**:

  Graphene, superconductors, and quantum matter (th, exp): V. Brosco, R. Larciprete, J. Lorenzana.

  Complex photonics and quantum complexity (th, exp): C. Conti [LAB] (ERC StG 2008), S. Gentilini, N. Ghofraniha, L. Pilozzi.

  Nanomaterials for the energy (exp): O. Palumbo, A. Paolone [LAB].

INAF and Osservatorio Astronomico di Roma

INAF-Osservatorio Astronomico di Roma (OAR hereafter) has an agreement in place with the Department of Physics of La Sapienza University since 2009. This agreement has been renovated twice in 2015 and in 2018; it is now in place until the end of 2021. The agreement involves several topics on which OAR and Physics Department researchers are actively collaborating; most important are summarized below:

Euclid. This is the Cosmology ESA M2 mission to last six years, with a launch foreseen in 2022. Euclid is a space telescope designed to explore the dark Universe. The mission will map out the large-scale structure of the Universe across 10 billion light years, revealing the history of its expansion and the growth of cosmic structures during the last three-quarters of its history. One of the techniques used to achieve this goal is the accurate measure of the weak gravitational lensing. On this topic and the theoretical aspects there is a long-standing collaboration between Dipartimento and OAR researchers (A. Melchiorri, V. Cardone, R. Maoli, R. Scaramella)

Accretion, emission processes and gravitational waves (GWs) from compact objects. Also in this field there is a long-standing collaboration between scientists at the Physics Department (V. Ferrari, L. Gualtieri, P. Pani, F., Meddi, S. Frasca, P. Astone, C. Palomba, P. Leaci) and at OAR (L. Stella, A. Papitto and others). This includes the development of advanced models for accretion of matter, radiation processes and emission of gravitational waves in collapsed objects such as, different classes of neutron stars (including magnetars and transitional millisecond pulsars) and black holes. Innovative observational programs of neutron star systems (such as candidate steady gravitational wave sources and millisecond pulsars) are also carried out which exploit the SiFAP fast optical photometer and world-class astronomical facilities (such as MAGIC, XMM/Newton, Swift, NICER GranTeCan).

Multimessenger astrophysics. Starting from 2013 a working group was set up with the aim of studying the possibility of searching for the electromagnetic counterparts of GW events. This effort led to the creation of GRAWITA, which allowed Italian scientist to be at the forefront in the search for electromagnetic counterparts of GW events since the earliest detections (GW150914 and GW151226) and in the discoveries made possible by the identification and study of the Gamma Ray Burst and Kilonova associated to the merging double neutron star event GW170817. The OAR staff involved both in GRAWITA and in Multimessenger astrophysics includes E. Brocato, L. Stella, S. Piranomonte, A. Papitto, A. Stamerra, L. A. Antonelli and others. The main contact point at the Dipartimento is F. Ricci and his team.

Indirect Dark Matter searches. L. A. Antonelli, S. Lombardi and R. Capuzzo Dolcetta are collaborating in the search for the signal from Dark Matter at the very high energies in dwarf spheroidal galaxies selected by dynamical properties of their stellar populations.

The first galaxies and AGN in the early universe. R. Schneider, E. Giallongo, L. Pentericci and A. Fontana collaborate on several projects to study AGN and galaxy evolution with particular regard to the first galaxies and the first accreting black hole and their role in the reionization of the Universe. In particular at the Observatory we work on large observational surveys, carried out primarily with the ESO-VLT and the Hubble Space Telescope and in the future we will acquire data from the upcoming JWST space telescope.

INAF and the Department of Physics of La Sapienza carry out, in collaboration with the Department of Physics of the University of Tor Vergata, the ”Astronomy, Astrophysics and Space Science PhD Program” to breed a new generation of young researchers at the highest international level. The three-year program consists of both teaching and scientific training. In the first year of the program PhD students follow at least two monographic courses of 16 hours each, attend one of the courses taught in the Italian Astronomy School, either in Italy or abroad, and carry out laboratory activity. The additional knowledge gained in this way by PhD students complements the one they acquired in previous programs and degrees (Laurea triennale, Laurea Magistrale). Students then go on to work on their PhD thesis research program, with the help and advice of their supervisors. The program is aimed at developing state of the art technical and scientific competence that can allow them to work effectively in cutting-edge astrophysics research. This includes also: a good knowledge of the scientific literature specific to their research field; the development of a critical attitude capable of identifying key problems that deserve further attention and analysis; independence in the conduct of research; ability to work in a team; skills and confidence in the presentation of results, both in Italian and in English. In advance, every year up to 10 students from the Department of Physics carry out their Master Thesis under the supervision of OAR scientists.

CNR NANOTECH

The research activity of the CNR Institute of Nanotechnology (NANOTEC) Unit, named Soft and Living Matter (SLiM) Laboratory, mainly involves research fields ranging from advanced physics for biomedicine, statistical physics, photonics in random media and active matter. In the period 2017-2019 the investigation work of the SLiM Lab has been primarily shared among the four research areas. All groups strongly and actively collaborate with researchers of the Department of Physics.

Cellular micro-environment and nano-environmental materials (I. Colantoni, B. Cortese, O. Ursini) The group studies the cellular microenvironment, tweaking dynamically and mechanically the microenvironment to influence, control and direct cell behavior, focusing on the understanding of the interactions between materials, proteins and cells; the molecular control and chemical engineering of biomaterials and polymers for the development of supportive scaffolds; and the chemio-physical properties of materials, as bulk or as a surface, and how they influence cell response. Also superwetting/self cleaning micro/nano-engineered materials are developed as promising potential candidates for treating oil/solvent-water emulsions to tackle energy and environmental challenges.
Funding Grants - (MFAG) My First Start Grant n 16803.
Highlight Pubs: Palam I.E., et al., Cancers, 11(5), 643; (2019). Caschera D, et al., Applied Surface Science 427 (PA) 81-9, (2018). D' Amone S., et al.,, Int. J. Adv. Res. 6(9), 924-940, (2018).

Advanced imaging for bio-medical investigation (I. Bukreeva, A. Cedola, M. Fratini, I. Viola)
TomaLab (http://www.tomalab-cnr nanotec.it/index.html) supervised by Alessia Cedola, it is primarily focused on the biological and medical applications of X-ray physics and Functional Magnetic Resonance Imaging. In particular the scientific activity is dedicated to the study of neurodegenerative diseases by means of X-ray Phase Contrast Tomography and MRI. *Funding grants:* - European Project FET OPEN: "VOXEL - Volumetric medical X-ray imaging at extremely low dose"; - Young Researcher Project of the Italian Ministry of Health (GR-2013-02358177): "Multimodal experimental and theoretical approach for the study of the Spinal Cord in healthy and diseased subjects"; - COST Project MP1203: " Advanced X-ray spatial and temporal metrology"; - Project ESA-BION M2 (2016-2019). - COST Project CA16122 BIONECA, - Progetto Bilaterale Italia- Russia 2018-2020.
Highlight pubs.: Bukreeva et al, Scient. Rep. 7, 41054 (2017); Cedola et al. Scient. Rep. 7, 5890 (2017); Massimi et al. Phy. Med. Biol. 63 (2018); S Tommasin et al., Neuroimage 179, 570 (2018); Massimi et al., Neuroimage 184 (2019); A Tourni et al., Science Advances 5 (2019).
Soft lithography & imaging Supervised by Ilenia Viola, it mainly works on molecular nanotechnology and microfluidics, conformational and optical properties of molecular materials by confocal and scanning probe microscopies. Reaserch investigation is mainly carried on confined dynamics of soft materials and nanoparticles; modulation of emitting properties at the interface of photonics materials and quantitative investigation of the interface behavior of biological systems-molecules. *Funding grants:* - "ELITE - Etichette Laser IntelligenTi per la sicurEzza" (Prot. 85-2017-15111), project of Regione Lazio, Progetti Gruppi di Ricerca.
Highlight pubs.: De Nicola et al, Sci. Rep. 9, 13386 (2019); Zizzari et al. Anal. Chem. 90 (2018); Bianco et al. Sens. Act. B. Chem. 265 (2018); Arima, et al. European patent n. 18177715.2 (2018); Arima, et al. Italian patent n.102017000071008 (2017); Zizzari et al. Coll. Surf. Sci. 532 (2017)

Active and soft matter (S. Bianchi, C. Maggi, F. Saglimbeni)
Supervised by Roberto Di Leonardo, the group is focused on investigation on propulsion mechanisms at the micron scale of synthetic and biological swimmers. The group is also interested on the study of light-controlled of

genetically engineered bacteria. The experimental techniques used in the lab include optical microscopy, optical trapping, 3D two-photon lithography (http://glass.phys.uniroma1.it/dileonardo/) *Funding grants*: - ERC, Proof Of Concept: "ADMIRE, A holographic microscope for the immersive exploration of augmented micro-reality", - ERC, ATTRACT: "PROTEUS, A virtual reality platform for live micromanipulation of cells with holographic optical tweezers"; - ERC, Advanced Grant: "SYGMA"
Highlight Publications: S. Bianchi et al., Phys. Rev. X, 011010, (2017); G. Vizsnyiczai et al., Nature Communications, 8, 15974, (2017); G. Frangipane et al., eLife, 7, e36608 (2018); S. Bianchi et al., Nature Communications, 9, 4476 (2018); G. Frangipane et al., Nature Communications, 10, 2442, (2019)

Statistical physics (A. De Martino, L. Leuzzi)
The group, supervised by Andrea De Martino and Luca Leuzzi, carries out theoretical investigation mainly in four research areas: Statistical Mechanics of disordered systems, Photonics in Random Media, Computational Biology and Scientific Computing & Big Data. Systems biology and physics of living systems c/o Joint Lab Nanotech-IIGM (Torino) carries out investigation of the physics of living systems across a broad range of scales, from single cells to populations, which are studied by mathematical models and through the development of novel algorithms for high-throughput data analysis. Current focus is on the energetics of cancer development and sustainment, RNA networks and the adaptation of microbial populations to complex environments.
Highlight pubs.: A Martirosyan et al, Springer Methods in Molecular Biology, vol 1912 (2019); M Mori et al, Nat Sys Biol Appl 5, 16 (2019); M Miotto et al; PLoS Comp Biol (2019, to appear).
Statistical mechanics of disordered systems investigates the modeling of systems with instrinsic, non-perturbative randomness in diverse material frameworks, from glasses to lasers. Both the direct approach, the modeling of systems to predict their behaviors, and the inverse approach, through Bayesian inference of the system properties are developed.
Highlight pubs.: A Marruzzo, et al., Scientific reports 7, 3463 (2017); Phase transitions in integer linear problems, S. Colabrese et al., JSTAT 093404 (2017); Basic I Viola et al., Physics and Recent Developments of Organic Random Lasers in Organic Lasers, 151-192 (2018). Funding grants: - ERC, Advanced: " LotGlassy - Low Temperature Glassy Systems"

Facilities and Laboratories

L1. The Physics Museum

The Department of Physics hosts the Physics Museum of Sapienza Università di Roma, a part of the Polo Museale Sapienza: an integrated system of museums of the various disciplines studied in our University. The Physics Museum owns an important collection of scientific instruments dating back to the end of 1 700.

The original nucleus of our Museum comes from the foundation of the *Teatro Fisico* (*Physics Theatre*) in 1 748). At that time the purpose of the Museum was both to perform public demonstrations and for teaching physics with the help of experimental activities.

In 1 891 the *Circolo Fisico* (*Physics Club*) promoted a sort of outreach activities, even if only selected persons were admitted to conferences, presentations and discussions. Later, physics teachers were admitted to these activities, too, and in 1 897 the *Società Italiana di Fisica* (Italian Physical Society) was founded.

The first public speaking occurred indeed in 1 896 by Quirino Majorana about the discovery of X–rays, when the Physics Department was already moved in a building in Via Panisperna. In 1 935 the new University campus was ready and all the faculties moved there, where they currently are. The Physics Museum was among those institutions who moved in the new location, even if the current organisation dates back to the middle of the XX century.

The Physics Museum collections include a set of instruments for the study of acoustic waves, optics, spectroscopy, mechanics, electricity and magnetism, as well as an important set of objects belonged to Enrico Fermi. In particular, we still preserve the original instrumentation used by Fermi and his group for the discovery of artificial radioactivity induced by neutrons, that yielded to him the Nobel Prize in 1 938.

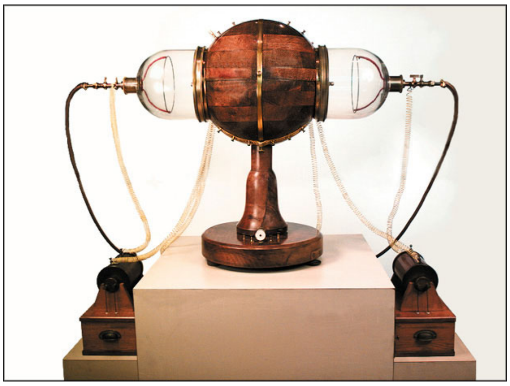

Figure 1: Left: The König harmonic analyser for the study of the frequency spectrum of sound.
Right. The De La Rive apparatus for the simulation of Northern Lights.

Some of them are particularly valuable, such as the König analyser (Fig. 1 Right) used to determine the frequency spectrum of sounds (a sort of a spectrum analyser), a Becquerel phosphoroscope, large Littrow spectrographs for the study of UV radiation, a very accurate Atwood machine and a very rare apparatus made by De La Rive to simulate Northern Lights (Fig. 1 Left), just to mention a few of them.

The collection of instruments for the study of acoustic waves is one of the largest in the world. We own unique instruments like a value Armonium made by the german constructor Appunn and designed by Pietro Blaserna in 1 887 as a tool to study consonances and dissonances. For his studies, Blaserna was appointed as the Director of the institute for the conservation of the standard tuning forks, still preserved and displayed in our Museum.

The Museum is open for visits few days per week. The opening schedule can be found on the Physics Department web site. The admission is free of charge and groups can ask for guided tours. It is usually visited by schools, not only from Italy. The Museum also hosted few scholars from all over the world and presented a poster at the UMAC (*University Museums and Collections*) conference in Kyoto in 2019 about the restoration of the Blaserna's Armonium and the acquisition of the beam splitter of the Virgo experiment used during its commissioning phase.

`http://www.phys.uniroma1.it/DipWeb/museo/home.htm`

L2. Physics Department's Library

Along the years, the Physics Department's library has undergone a process of transformation both from the structural and logistic point of view, and an overall modernization of the services. The new location of the departments library was inaugurated in 2005, and consists of a reading room with 90 seats, 2 personal computers with direct access to the internet. The library offers a series of services, from the traditional ones, like consulting and loan, to advanced ones, like reservation of work sessions on the pcs of the library, or the access to the Sapienza wireless network with one?s own laptop. These services are offered both to institutional students and to students who visit our University. The catalogue of ancient and modern volumes (approximately 30.000 books) is now fully automated. The catalogue of subscribed and historical journals (approximately 500 titles) is also automated. The bibliographic records are inserted into two important national databases (ACNP and SBN) to allow the full on-line visibility of the heritage of our library. The historical collections up to the end of XIX century, including international journals from the end of XVIII century and ancient volumes, has been digitalized and can be consulted by accessing the electronic catalogue of the Sapienza University. The library provides document delivery within the inter-exchange circuit NILDE, and interlibrary loan with other libraries within the national circuit SBN and within international loan circuits. At local level, the library provides the following services: temporary loan for all students and institutional staff member of Sapienza. All these services are accessible to all those who enrol as users at the library, providing their personal data. These data are stored in a database common to all the libraries of Sapienza. The departmental library takes active part to the national project of automation SBN, since 1990. This allows to share data and provide services to the users, without direct changes for the structure, but thanks to the centralized financial support of Sapienza, via the SBN project. The automation process includes an experimental activity, aimed at improving the services offered to the users. It is already possible to access to the library after the closing time, using a magnetic card which is currently released only to institutional users of the Department. The access to the library is allowed only to enrolled users. The premises of the Physics department?s library are controlled by a webcam circuit. Since 2009, a service for the automatic loan by means of the RFID technology is available. Thanks to the computer science competences of the Department of Physics, a software is being developed: it will allow to download data from the database SEBINA/SBN and process them with the help of dedicated hardware, fully exploiting the RFID technology. Once tested , this software might be released and made accessible to other Department libraries at Sapienza. All volumes will be equipped with a RFID tag that will allow full traceability and all users will be provided with a Sapienza card. In the 80?s the Department?s history of Physics Group began to show a growing interest for the collection and the preservation of the personal documents belonged to the most important scientists of the last century who were related to our Institute. These papers, whose number increased with the addition of other papers belonging to other important scientists, were collected in order to avoid their dispersion or damage and then to be available for researchers. These documents are in the library storage and we are working to reorganise, inventory and computerise them. We are digitalising the most relevant archives. Now, almost 10.000 records have been inserted in the Department Archive. Archival holdings are made of 21 personal archives (as Amaldi, Conversi, Cabibbo and Touschek) and two collections between which 14 archives and one collection are already available on our portal *https://sapienzadipfisica.archiui.it/*.

Figure 1: Main hall of the Department's Library, with the front desk and the shelves displaying the latest issues of the subscribed journals. The reading room is located beyond the glass divider.

https://www.phys.uniroma1.it/fisica/biblioteca

L3. The Machine Shop of the Physics Department

The machine shop of the physics department is a small ($\sim$ 80 m^2) but well equipped facility, aimed at solving the mechanical problems that research groups face in everyday activity, build custom mechanical devices required in research experiments and laboratory teaching, and fix/improve precision mechanical devices used for research.

The machine shop is equipped with three drill machines, two mill machines with precision electronic XYZ readout, to machine parts up to 0.5m in size, and two lathes, also with electronic readout, to machine parts up to 0.4m in diameter. A welding station and standard ancillary equipment (shearing machine, ribbon-saw, marking gauge and levelling table etc., with a very wide variety of cutting tools) complete the equipment (see figure 1, left).

One expert technician, Mr. Giorgio Amico, works full time in the machine shop, and is in charge of design verification and actual machining.

Jobs submitted are first checked for feasibility, and then for production time, and finally included in the production queue if compatible with the capabilities and the available time resources of the machine shop; otherwise are submitted to external machine shops.

The machine shop of the physics department has finalized precision mechanical systems for all the experimental groups of the physics department and several other groups of the Sapienza Atheneum, manufacturing parts for positioning, optics, cryogenics, vacuum, electronics, space.

In figure 1 (right), we display a few examples of parts produced by this facility.

Figure 1: *Left:* equipment of the machine shop of the physics department. *Right:* sample productions of the machine shop of the physics department.

http://www.phys.uniroma1.it/fisica/officina-meccanica

L4. The INFN Electronics Laboratory: LABE

The Electronics Laboratory (LabE) in the Physics Departement is operated by the INFN. The team is composed of 8 staff technicians who have wide and diverse competences in electronics field, as briefly explained later.

This laboratory supports the local experimental groups in the design, development, implementation and debug of electronics circuits. In the past three years, work has been carried out for LHC experiments as well as VIRGO, PADME, MEG, CHIRTWO, KM3NeT, UA9, CRYSBEAM, JLAB, and many others. The high number of different applications requires a wide knowledge and a big experience in many fields.

The LabE is divided in three areas: the CAD room, the WORK lab, and the OPEN LABE room. In the first room, board design and software programming is accomplished, using various SW suites for Printed Circuit Board (PCB) design: Altium, Cadence, KiCAD, and, in the next future, also Mentor Graphics.

In the WORK lab, there are tools intended for PCB maintenance and rework and also some mechanical tools. There are two soldering stations for Surface Mounting Device (SMD), one microscope, a rich stock of integrated circuits and passive components which can be useful for prototypes and tests, and a brand new milling machine, shown in Fig. 1, used to realize double sided PCBs in a fast way. There is also a small mechanical workshop with tools that help in the realization of mechanic elements for the electronics: a milling machine, a lathe, a bender, a drill, and others.

Figure 1: Fast prototyping milling machine used to realize double sided PCBs.

The OPEN LabE is so called since it is accessible to external users and students that are supported in their thesis work. The room is equipped with up to date instruments, like digital scopes, function generators, a spectrum analyzer, multimeters, hardware protocol interfaces to VME, I2C, CANbus, SPI, and GPIB; there are also some racks with rackable VME modules. In this space a thermostatic chamber is installed, which allows to make tests in a temperature controlled environment. A picture of the chamber is shown in Fig. 2.

The expertise provided by the LABE is mainly focused on hardware: design of front end electronics for SiPM and phototubes reading and conditioning, analog design for fast and slow signal acquisition, digital expertise for complex FPGA based boards, high speed data transmission up to 10 Gb/s, clock dejittering and distribution systems, microcontroller based boards. Along all these items, there is also the experience to program devices both at high and low level: ARDUINO based systems are well known and used since many years; recently, ARDUINO systems have been controlled by android-based platforms which makes the management of the devices more user friendly. There is also the expertise for FPGA programming, mainly XILINX and MICROSEMI devices.

Figure 2: Thermostatic chamber located in the OPEN LABE area.

Since 2017 the LABE contributed to the project, design, realization and programming of a 12-channel digitizing board with 14 bit ADCs running up to 250 MHz. The board is intended as a general purpose acquisition system for whatever experiment could need it. Since 2019 a complex "glove box" system is under development, based on Off-The-Shelf PLC arranged and programmed by LABE staff.

Another important aspect is testing and debugging, tasks that are implemented in the OPEN LABE area taking advantage of the instrumentation and of the many work tables and tools. In past years, customized testing systems have been developed to qualify commissioned hardware destined to experiments.

The LABE staff is also capable to carry out complex cabling systems, both in the planning phase and in the implementation step. Up to date tools are available to make a various number of standard cables and connectors.

The LABE manages a pool of instruments available to whoever requests it; year after year, this pool is continuously updated with modern and increasingly performing devices, while older ones are constantly maintained, often by the LABE itself.

Last, but not least, the LABE gives also support, both hardware and software, to some university courses.

L5. SOM and SPM of INFN–Roma

The mechanical workshop (SOM - Servizio Officina Meccanica) plays a fundamental role for the experimental activities on-going at INFN division and Physics department of Sapienza University. It's significantly engaged in the prototypes and end-use part productions, being able to have highly skilled manpower (also working directly in building and commissioning parts of experimental systems both on-site and around the world), several kind of machineries installed including the most recent and advanced technology, such as additive manufacturing systems (3D printer). Almost all most common materials are daily treated (metallic alloys, polymers, composites) including polymers able to be processed through fused deposition modeling (FDM).

In details, the SOM facility is equipped with:

- n.4 lathes, two of which are high precision tooling machines: conventional high precision lathe Shaublin 150 and the Shaublin 180-CCN (high precision lathe with n.3 simultaneous axes with numerical control by Fanuc - R-T version for turning with a turret with 8 stationary tools);
- n.4 milling machines: one of them is the C.B.Ferrari A15 working on five axis with a CNC control and a precision of 20 microns over a range of 30 cm;
- Metrology laboratory for quality control, equipped with CMM Dea Hexagon Galaxy Diamond 3D Measuring Coordinate Machine (measuring volume: 0.5 m3 , precision 2 μm) and a Mitutoyo L.H. 600 linear height meter (precision 1 μm, range 972 mm);
- 3D printer (polymers): FDM machine Fortus360mc processing Polycarbonate (white) and ASA (black) - both materials Stratasys brand: it's an high-level production system with a dimensional accuracy close to 0.1 mm, a large working table/volume (about 35x25x25 cm), and one of the best and most powerful preprocessing software (Insight).

Figure 1: 3D printer (FDM) installed.

Moreover, in the shop area two clean rooms are located: a class 10000 (ISO 7) clean room which has been used to integrate parts of ATLAS, AMS and ALICE experiments, and a class 100 clean room, with a hut where the class 1 is reached. The class 100 (ISO 5) room has been built to develop Virgo payloads and is used now to study new parts for second and third generation gravitational wave interferometers.

Another service available in the mechanical workshop, is the welding station (Plasma, T.I.G., soft welding) with patented operators, that is crucial for several applications. The workshop staff is commonly using the most advanced CAD/CAM softwares on the market, in order to work on the automatic machineries (such as Autodesk Inventor and Mastercam).

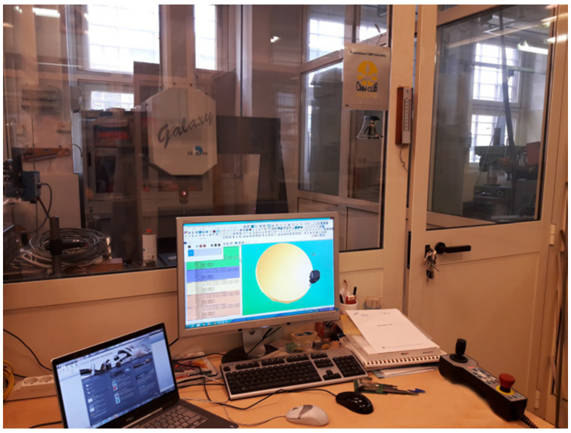

Figure 2: Metrology Lab with CMM machine in controlled environment.

The mechanical design service (SPM - Servizio Progettazione Meccanica) provides support to mechanical needs of the experiments (infn/university groups) in which researchers are involved. The design is assisted by professional CAD (Catia, Nx Siemens) system and numerical code (fea Ansys) for structural calculation, choosing suitable materials and specific techniques for realization.

The Computing and Network Service of INFN

The Computing and Network Service of INFN manages the computing network, both wired and wireless, serving the local INFN branch, the Physics Department of Sapienza University of Rome and the Tier-2 computing center mainly dedicated to process data produced by the LHC experiments at CERN. It also manages the connection of the local network to the GARR infrastructure.
The INFN computing center, located at the ground floor of the Guglielmo Marconi building of the Physics Department, hosts all the network services (DNS, e-mail servers, web servers, DHCP, print server, distributed disk space through AFS, ...), the central servers for users' access and the main services of the Physics Department. It also hosts the computing facilities of theoretical and experimental groups collaborating with INFN and the GARR PoP, to which the local network is directly connected.

The INFN Computing and Network Service:

- Manages the computing network in the Physics Department and its connection to the GARR netowrk
- Manages users' account on central servers and e-mail service
- Manages network security policies
- Offers an help desk service
- Manages software licences centrally purchased by INFN
- Offers support to install commercial software licenced to INFN
- Offers support to install commonly used operating systems (Windows, Linux e Mac OsX) on users' machines
- Manages print service and public printers
- Offers technical support for hadware procurement
- Develops web pages for special events
- Offers video streaming service for scientific events
- Supports audio and video conference equipment

`http://www.roma1.infn.it/sic/home.htm`

The Tier–2 LHC Computing Centre of INFN–Roma

The ATLAS and CMS experiments at LHC produce a huge amount of data. In fact, proton–proton collisions at the collider happen with a rate up to 40 MHz, such that the probability to produce interesting events (usually having a small cross section) is reasonably high.

In order to select interesting events, suitable trigger systems act on detectors to select only those events having non trivial kinematics, potentially useful for precise measurements or for the discovery of new physics. Trigger systems reduce the acquisition rate down to 300 Hz.

Despite the trigger systems reduce the acquisition rate of many orders of magnitude, the number of events collected every year is of the order of 5×10^9. Given the average event size between 1 and 2 MB, each experiment produces up to $5 \times 10^9 \times 2 \times 10^6 = 10^{16}$ B/year= 10 PB/year.

Physicists must submit their analysis jobs to the system such that they can analyse the whole set of data. They do that using the *grid*: a worldwide distributed computing infrastructure composed of several data centres distributed in many countries. The grid is hierarchically organised: the *Tier–0* centre resides at CERN and collects all the data produced by the experiments, distributing them to few tens of *Tier–1* centres. Each Tier–1 centre hosts a fraction of the whole dataset: one of them is run by the CNAF Laboratory in Bologna. From Tier–1 centres, data are distributed over hundreds of *Tier–2* centres. Roma runs one of such Tier–2 centres.

Jobs submitted by the physicists to the grid are automatically distributed to the data centres hosting the required data. The sub–jobs are then executed in parallel on CPUs sitting in the same data centre and the results are automatically collected and sent to the submitter.

The Roma Tier–2 centre has ten water refrigerated racks made by Knürr. Each rack is closed on each side. At the bottom, a heat exchanger in which it's injected water at 12°C produced by three Stulz chillers tears down the air temperature inside the rack. Three fans on the back side of the racks produce a pressure drop between the front and the back of the rack: refrigerated air tends to flow in the front part of the rack, where it is drawn through the servers by their inner fans and expelled from the back where it returns to the heat exchanger. This way, servers are always at constant temperature (18°C) irrespective of external meteorological conditions. Moreover, air conditioning is limited to the volume of the rack and the temperature of the room is maintained at comfortable values for technicians and physicists.

The solution has been found to be good also from the energetic point of view. The PUE (Power Usage Effectiveness) of typical data centres, defined as the ratio between the total energy needed to run it and the energy needed for servers, is always greater than 2 and is typically 3 or more. The PUE of our data centres is about 1.3: only 30 % of the total energy is used for ancillary services like air conditioning, lighting and so on. It is considered among the *greenest* existing data centres.

Few hundreds of servers are hosted in the ten racks, as well as storage servers for a total of 2 PB and 2 500 computing cores. In other words, our centre guarantees the concurrent running of as many jobs in parallel giving access to about 20 % of the data collected by the experiments every year. The UPS has also a filtering function, removing fast transients from the power taken from the electrical grid.

The Internet connection is provided by two redundant, high speed networks through the Sapienza Department of Physics router and the GARR one. The connection speed reaches 10 Gbps and we are part of the LHCOne, a collection of access locations that are effectively entry points into a private network to the LHC Tier–1/2/3 sites.

L8. The Infrared Spectroscopy Laboratory - IRS

The InfraRed Spectroscopy (IRS) laboratory is located at the fourth floor of the Fermi Building. Established in the Seventies of the last century, it is now devoted to the experimental study of the optical properties of solids in the infrared (IR). After having performed core studies on high-T_c superconductivity and colossal magnetoresistance, the focus is presently on (i) low-dimensional systems (such as quantum wells and novel two-dimensional materials), (ii) novel materials for plasmonics and nanoantennas, including heavily doped semiconductors, (iii) vibrational spectroscopy of biological macromolecules including proteins (iv) functional oxides for electronics such as multiferroics and two-dimensional electron gases at the interface between oxides.

The IRS lab is equipped with three research-grade vacuum interferometers by Bruker Optics (two IFS66v and one new Vertex70v with time-resolved spectroscopy capabilities), covering the spectral range from the sub-Terahertz to the near-IR; two mid-IR microscopes with 15x and 36x Cassegrain objectives; one grating spectrometer working from the near-IR to the visible and the UV. Available detectors include a liquid-He cooled far-IR bolometer, photovoltaic MCTs and pyroelectric detectors for the mid-IR, and a CCD for the near-IR to UV. These instruments allow one to collect spectra on crystals, thin films, powders and solutions in transmittance, normal-incidence, grazing-incidence and diffuse reflectance modes, with spectral resolution better than 0.5 cm^{-1}, either in vacuum down to 1 mbar, or in H_2O and CO_2 free environment, granted by distribution pipelines connected to pumping units and to a purge-gas generator, respectively.

All spectrometers are equipped with cryogenic systems capable to cool the samples down to liquid-He temperatures. Lithographic polarizers are available for linear dichroism spectroscopy e.g. of intersubband transitions in quantum wells or of anisotropic crystals. Crystals and substrates can be cut and polished in an adjacent room. Sample materials are provided by leading groups of crystal and thin-film growers (from Italy, USA, Japan, Sweden, UK). Biochemistry sample solutions are inserted in vacuum-tight fluidic cells of variable thickness equipped with transparent windows for the entire far-IR to UV range.

Figure 1: One of the three FTIR spectrometers at the IRS laboratory, coupled to an infrared microscope, equipped with a liquid-Helium flow cryostat and a cryogenic mid-infrared detector.

L9. Soft Matter Laboratory: Light Scattering (ISC-CNR)

The laboratory, located in room 010 at the ground floor of the Fermi Physics Building under the responsability of Dr. Barbara Ruzicka (ISC-CNR) (`http://www.roma1.infn.it/~ruzickb/`), is equipped with three different and complementary Light Scattering set-up running independently:

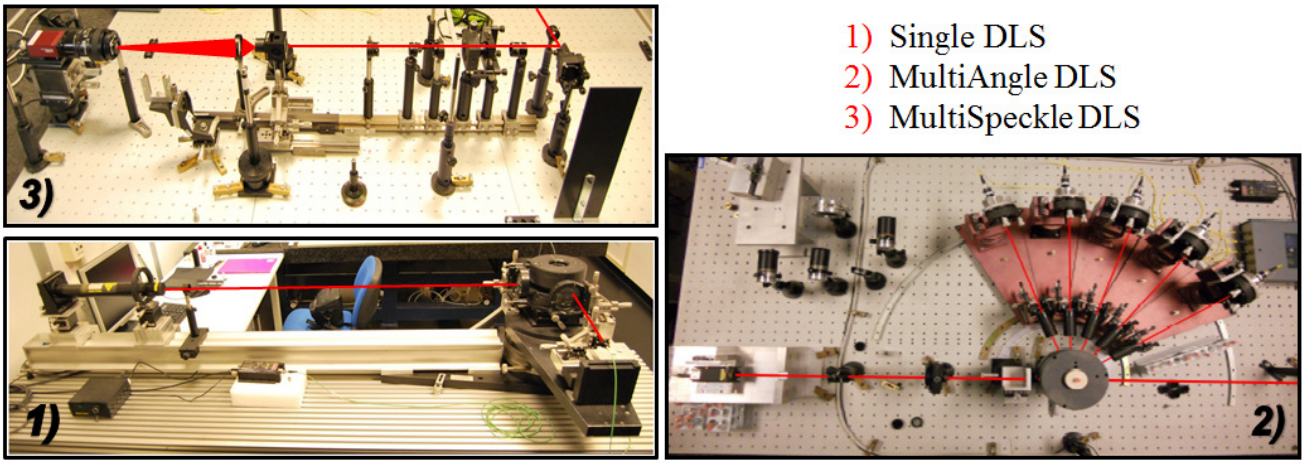

Figure 1: Three different Light Scattering set-up of the Soft Matter Laboratory.

1) **Dynamic Light Scattering (DLS)** set-up: a He-Ne laser (λ=632.8 nm) of 10 mW is focused on the sample in the centre of a vat mounted on a goniometer. The temperature of the sample is controlled by a cooler-heater. The scattered light is focused and collected by a singlemode fiber connected to a photodiode detector. The photoncounts are analysed by an home made software that provides a logarithmic correlation of the data. The use of single mode fiber permits to obtain time-intensity autocorrelation functions with a very high signal to noise ratio. Measurements at various scattering vector Q (varying the collecting angle) and in a time correlation window between 1 μs and 2 s can be performed.

2) **Multi Angle Dynamic Light Scattering (MultiAngle DLS)** set-up: a solid state laser (λ=642 nm) of 100 mW is focused on the sample in the centre of a vat. The temperature of the sample is controlled by a cooler-heater. The scattered light is focused and collected simultaneously by 5 different channels where 5 lens-collimator systems couple the scattered intensity with 5 optical fibers connected to 5 photodiode detectors and time-intensity autocorrelation functions are computed by an home made software that provides a logarithmic correlation of the data. Simultaneous measurements at 5 different scattering vectors Q (between 10^{-3} to 10^{-2} nm^{-1}) and in a time correlation window from few μs to 1 s are obtained.

3) **Multi Speckle Dynamic Light Scattering (MultiSpeckle DLS)** set-up: a solid state laser (λ=642 nm) of 100 mW is focused on the sample. The scattered light is collected by a charge-coupled device (CCD) and intensity autocorrelation functions are calculated by ensemble rather than time average, rendering possible the measurements of non ergodic samples. Measurements at different scattering vectors Q (between 10^{-4} to 10^{-3} nm^{-1}) and in a time correlation window from 0.03 to 60 s are obtained.

The Laboratory is dedicated to the investigation of the microscopic dynamics of soft matter and more in details of colloids such as clays, polymers and biological systems. These are characterized by a non stationary dynamics that slows down (aging), letting the system to pass from a fluid (ergodic) to an arrested (non ergodic) state of gel and/or glassy nature. The use of complementary X-rays and neutron techniques performed in Large Scale Facilities permits to extend the accessible time and length scales and to investigate also the structure of the systems. The activity is in strict collaboration with the experiments carried out in the Soft Matter Laboratory: rheology and calorimetry of Roberta Angelini and with the theory and simulations performed by the group of Emanuela Zaccarelli. In the last years the investigation through experiments with different techniques, simulation and theory has permitted to deeply investigate several systems such as **colloidal clays** [1], **microgels**[2] and **vescicles**[3].

[1] A. de Melo Marques et al. J. Phys. Chem. B **121**, 4576 (2017).
[2] V. Nigro et al. J. of Mol. Liq. **284**, 718 (2019).
[3] A Grimaldi et al. Front. Cell. Neurosci. **13**, 41 (2019).

L10. Nuclear Magnetic Resonance (NMR) and Medical Physics Laboratory (CNR ISC)

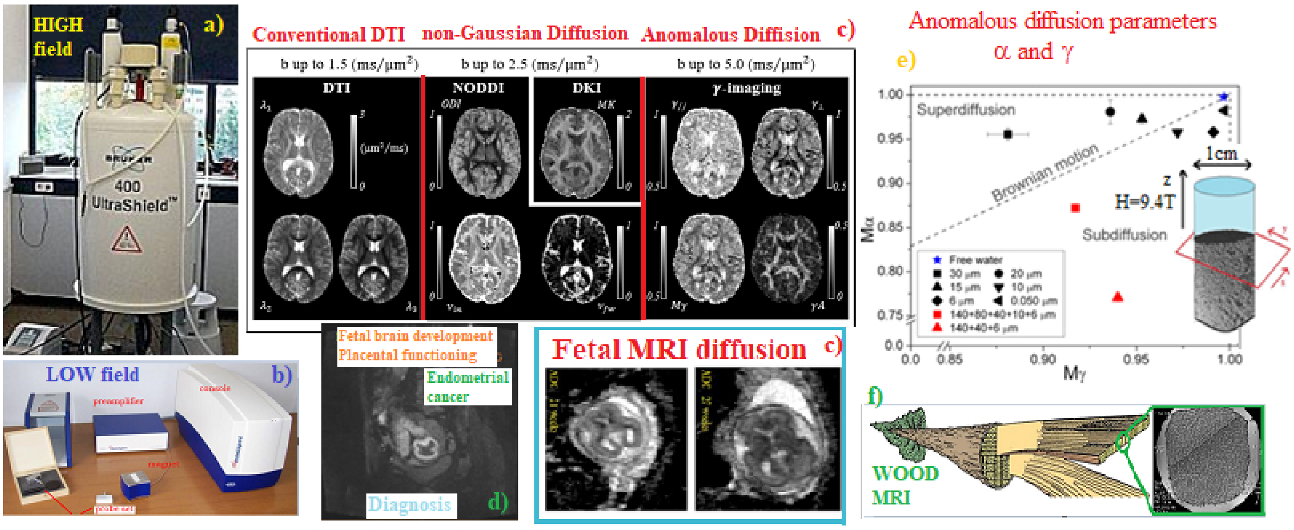

Figure 1: a)9.4T NMR spectrometer; b) low field spectrometer for cultural heritage; c)and d) cerebral microstructural changes with development and aging; e) anomalous diffusion parameters of water in packed beads samples; f) wood imaging

The research in Nuclear Magnetic Resonance (NMR) and Medical Physics Laboratory focusses on molecular diffusion studies by NMR, Magnetic Resonance imaging (MRI) and spectroscopy (MRS) in materials, biological tissues and in humans (healthy and patient cohorts), optimization for biomedical imaging and image analysis, diagnosis in biomedicine and cultural heritage field. The work involves both ends of the imaging pipeline: designing novel imaging techniques with sensitivity to new image features, and extracting new information by using different molecular diffusion models: Gaussian, non Gaussian and Anomalous diffusion models. 19F MRI development. In the NMR and Medical Physics Laboratory directed by Silvia Capuani, there are: a 9.4T Bruker Avance spectrometer for in vitro experiments (equipped with a microimaging, multinuclear probe and high performance gradients with maximum magnetic gradient strength equal to 1200 mT/m (Fig.1 a)and a low field portable spectrometer for cultural heritage investigations (Fig.1 b). Full processing facilities are available, workstations and computers linked to a server for data storage and a grid engine for parallel computing (currently 18 CPUs, in expansion to 66+ CPUs) for the most demanding computational tasks. Software facilities include the main neuroimaging tools (SPM, AFNI,FSL, etc.), and general computation tools (IDL, Matlab, Consol). Thanks to active collaboration with the neuroimaging laboratory of IRCCS Santa Lucia foundation (Rome) and Radiology department of Sapienza University, several hours of machine time is available on human NMR scanners operating at 3T.

Measuring tissue microstructures, such as cell size, shape and packing density or disorder degree, traditionally requires invasive biopsy and microscopy, but diffusion MRI offers the potential for non-invasive histology with major advantages for diagnosis and monitoring of disease. In particular, by using molecular diffusion weighted images, it is possible to extract from each image voxel microstructural and topological information of heterogeneous and complex materials and human tissue (such as brain). Key applications are in neurological diseases, brain development and aging (Fig.1 c), tumour-grading for cancer (Fig.1 d) but also in disorder degree measurement of new materials (Fig.1 e) and modern and archeological wood(Fig.1 f).

// **References:**

Palombo et al. Sci Rep. 2013; Capuani et al. Placenta 2017; Caporale et al. Neuroimage 2017; Guerreri et al. Neuroimage 2019

`laboratoryXXX.site3.it`

L11. The Terahertz Imaging Laboratory

The Terahertz Imaging laboratory is located at the ground floor of the Fermi Building (room 009). Established in 2015 as the Photonics for Humanities Laboratory, a collaboration between the Physics and the Humanities Departments of Sapienza University for the digital imaging of ancient and modern manuscripts in the visible and terahertz ranges of the electromagnetic spectrum, it is now devoted to the development of advanced terahertz imaging schemes. Terahertz radiation (1 THz = 1000 GHz) is located between the microwaves/millimeter waves and the far-infrared range. A typical definition of terahertz radiation corresponds to the frequency range where no electronic nor laser radiation sources are easily available at low cost and with high output power. This corresponds to the range between 300 GHz and 5 THz (wavelengths netween 1 mm and 70 μm), which is in turn not yet exploited for scientific and technological applications, although it has been used by astronomers and condensed matter physicists in the past. Important features of terahertz radiation are: it is insensitive to scattering by microparticles, hence it penetrates through paper, plastic, tissue, fog, dust; it is non-ionizing hence safe for human health; it is absorbed/reflected by metals and water so it presents important imaging contrast for material science and biological tissues; it features better imaging resolution than any microwave device, including in near-field and super-resolved schemes. In the last decade, the development of the body scanner for airport security, of imaging arrays based on nano- and micro-electronic devices with extremely high cutoff frequency up to 1 THz, and of the Terahertz Quantum Cascade Lasers have made possible to devise applications of terahertz imaging for civil uses. These potentially include medical diagnostics, nondestructive material evaluation and all-weather vision.

The THz imaging lab is equipped with a Virginia Diodes tunable amplifier-multiplier chain capable of emitting up to 3 milliWatt of free-space radiation through horn antennas in the range 200-750 GHz. A Terasense imaging array with 1024 receiving pixels is used for testing advanced imaging schemes in the frequency domain, including super-resolved terahertz imaging and confocal terahertz imaging. Precise multi-axis motor stages are used to scan the sample or the illumination beam position. Schottky diode detectors, liquid helium cooled bolometers and in-house developed field-effect rectifiers are all employed for radiation detection. Parabolic and ellipsoidal reflectors are preferred to polymeric lenses because they provide no optical aberration, and are therefore available in the Lab in all sorts of shapes, dimensions and focal lengths.

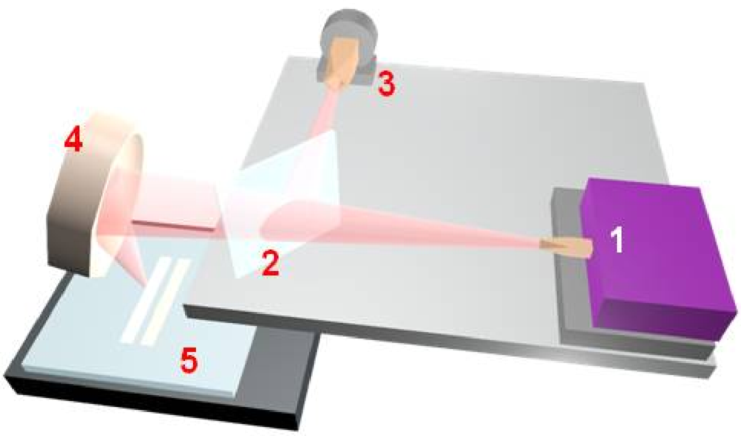

Figure 1: Scheme of the confocal terahertz microscope built in the Terahertz Imaging laboratory. (1) All-electronic terahertz source by Viriginia Diodes, tunable in the range 0.20-0.75 THz. (2) Quartz plate beamsplitter. (3) Waveguide-coupled zero-bias Schottky Diode detector. (4) Focusing ellipsoidal mirror. (5) Sample on a X-Y-Z scanning stage, investigated in reflection mode.

`http://sites.google.com/a/uniroma1.it/micheleortolani-eng/`

L12. Nonlinear Optics and Complex Photonics Lab

The Laboratory of Nonlinear and Complex Photonics (responsible C. Conti) involves researchers of Sapienza University and CNR. The Laboratory is situated in rooms 006 and 007 at the ground floor of Fermi building and it is equipped with scientific instrumentation used in the research of nonlinear optics, photonics, and spectroscopy of random media. The scheme of the experiments is: different samples are radiated by laser or THz beam and the light transmitted or reflected by them is collected with several detectors depending on the experiment.

The detailed list of the main instrumentations is:

- nanoseconds Q-switched Nd:Yag lasers working at 1064, 532, 355nm wavelengths with highest energy of 180mJ (model Eazy Brilliant-Quantel and model Surelite-Coherent);
- femtoseconds Ti:Sapphire laser systems (model Mantis-Coherent and model Hidra-Coherent);
- several Continuos Wave lasers working at 405, 532, 635 and 1064 nm wavelengths and power ranging from 0.5 to 3W;
- a Spatial Light Modulator (model LCR-720-Holoeye) with a resolution of 1280X768 pixel, 20 μm pixel pitch;
- a Yvon-Jobin spectrograph equipped with a cooled CCD array detector and two grating of 1800 and 600 mm^{-1} density;
- a 303-mm focal length spectrograph (Andor, Shamrock 303) connected to a low-noise CCD array (Andor, iDus Spectroscopy CCD);
- 3 optical stereo microscope with magnification ranging from 13X to 4X;
- several detectors inlcuding CCD Cameras (Thorlabs, Retiga, Pixelfly and Prosilica), multirange power and energy meters and integrating spheres;
- a fiber optics based setup (Avantes) able to measure spectra of random media in the UV, Vis, and near IR;
- THz time-domain spectroscopy setup from Menlo Systems working in the 0.2-3.5 THz range with a dynamic range $\geq$90 dB;
- large equipment of optical and opto-mechanical components including manual and motorized translation stages.

Many important experimental results have been obtained, that are published in top level journals as Nature Communications, Nature Photonics, Physical Review Letters, Scientific Reports, etc. Below selected publications of the last two years.

R. Prizia et al., "Soret reverse saturable absorption of graphene oxide and its application in random lasers", JOSA B **36**, 19 (2019).

D. Pierangeli et al., "Large-scale photonic Ising machine by spatial light modulation", Phys. Rev. Lett. **122**, 213902 (2019).

D. Pierangeli et al., "Observation of replica symmetry breaking in disordered nonlinear wave propoagation", Nature Comm. **8**, 1501 (2017).

V. Palmieri et al., " Reduction and shaping of graphene-oxide by laser-printing for controlled bone tissue regeneration and bacterial killing", 2D Materials, **5**, 015027 (2017).

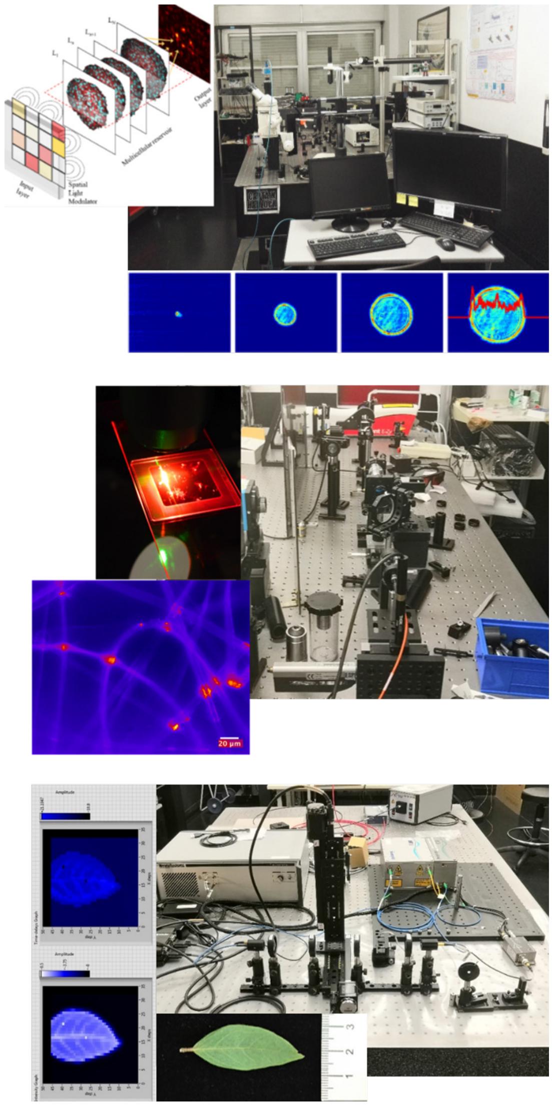

Figure 1: From top to bottom. Picture of the instrumentations in room 007 and images acquired during nonlinear optics experiments. Setup, sample and image of a random laser experiment. Terahertz spectroscopy setup and images obtained by means of motorized translation stages systems.

L13. Soliton Propagation Laboratory - Photonics Group

In nonlinear optical materials, light can locally change the properties of the sample leading to optical self-action and nonlinear waves. The result is an altered and unconventional scenario in which light beams violate the basic laws of linear optics, such as diffraction, interference, and refraction. In the Soliton Propagation Laboratory, light beam propagation is inspected using high-resolution beam profiling systems both along the propagation axis and detecting scattered light from lateral directions, using optical microscopes and super-resolution techniques. Typical experiments involved visible laser sources working in continuous-wave mode, ranging from low power Helium-Neon gas lasers to more powerful doubled Nd-YAG solid state lasers. Nonlinearities include saturated Kerr-like nonlinearities in electrically biased photorefractive crystals, diffusive nonlinearities in near-transition nanodisordered ferroelectrics, and artificial nonlinearities in liquid-crystal micro-arrays. Dissipative nonlinearities are also investigated, such as those encountered in VCSELs (Vertical-Cavity-Light-Emitting-Diodes) leading to cavity solitons.

The Laboratory focuses on the investigation of giant nonlinear response in innovative composite and microstructured ferroelectrics. Studies are carried out using beam propagation, polarization rotation experiments, and optical scattering experiments. Typically, a compositionally disordered ferroelectric of the ABO_3 type is grown in non-stechiometric conditions by the partner laboratory of Nonlinear Optics at the Hebrew Universtity of Jerusalem (A. J. Agranat). The samples manifest a dielectric response dominated by polar-nanoregions that align on the basis of an external bias field or on consequence of an optically generated electric field. The result is an optical response that is history-dependent, is greatly enhanced, beyond all electro-optic responses of conventional materials, and allows the study of extreme optical response, such as that leading to scale-free optics, rogues waves, and Klein-Gordon Optics.

A specific apparatus is dedicated to the study of electro-holography and electro-activation, that is, the ability of creating and reconfiguring electro-optically volume integrated optical circuits. Here, the feasibility of the use of optically written waveguides is investigated also for light beams at the single-photon level. Present demonstrations include a miniaturized electro-optic intensity modulator, a phase-modulator, and a micrometric Gaussian-beam to Bessel-beam generator.

Finally, a setup is dedicated to the study of giant broadband refraction and ferroelectric super-crystals (see Fig.1).

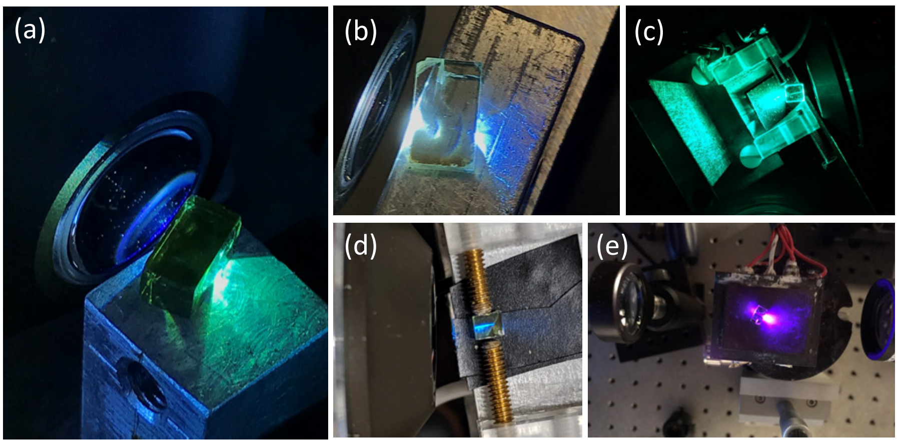

Figure 1: Giant broadband index of refraction in a ferroelectric super-crystal. (a) Ideal imaging, white-light from a commercial projector, (b)-(d) giant refraction experiments and (e) enhanced second-harmonic generation experiments.

http://sites.google.com/site/eugeniodelre/Home

L14. Chemical Laboratory for sample preparation (CNR-NANOTEC)

The chemical laboratory is located in room 020 at at the ground floor of the Fermi Physics Building. This facility is available since the beginning of 2011 and in few time it has considerably increased its activity. The main success achieved in this period is having brought together physicists, chemists, biologists, engineers who shear their technical and scientific knowledge. It has become therefore a meeting point to learn the experimental chemical basics, to exchange information and to start collaborations. It is attended from the CNR researchers, both of the Institute of Nanotechnology (NANOTEC) and the Institute of Complex Systems (ISC), from the Physics Department professors and researchers, from thesis and PhD students supervised by tutors and from allowed collaborators. Currently the Laboratory is under the responsibility of CNR-NANOTEC, and operationally managed by Dr. Ilenia Viola (CNR-NANOTEC) and Dr. Roberta Angelini (CNR-ISC).

Figure 1: Snapshot from the Chemical Laboratory of the Physics Department.

The laboratory is focused on different research areas and equipped with the following workstations:

- **Soft Litography** techniques for the fabrication of Lab-on-Chip functional devices for Life Science, fluidics and photonics(CNR-NANOTEC) [1]
- **Self-assembly** for processing and manipulation of molecular and polymeric organic materials (CNR-NANOTEC) [2]
- **Soft Matter** for synthesis and basic characterization of colloidal and biological systems (CNR-ISC) [3-4]
- **Active Matter** (Physics Department) [5-6]

It is also complemented by many other important scientific activities [7-9]. It is provided with laminar flow hood, safety aspirated cabinet for chemicals, glove box for sample preparation under clean atmosphere, ultra pure water system, oxygen plasma chamber, spin-coater, analytical balances with different capability and sensibility (mg and μg), pH-meter, magnetic stirrers, hot-plates, high temperatures oven, ultrasound bath, fridge, laboratory freezer ($-80°C$). The Chemical laboratory is therefore fully furnished for: self-assembly techniques of molecular, bio-hybrid, colloidal systems and nanocrystals; controlled deposition of thin film from liquid phase; optimization of energetic properties at the interface; photo and soft-lithography; fabrication of functional device for tissue engineering; fabrication of optoelectronic plastic devices.

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[3] F. A. De Melo Marques et al. J. Phys. Chem. B **121**, 4576 (2017).
[4] V. Nigro et al. J. Mol. Liq **284**, 718 (2019)
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[7] R. Prizia et al. J. Opt. Soc. Am B **36**, 19 (2019)
[8] V. Nigro et al. J. Colloid Interface Sci **545**, 210 (2019)
[9] R. Sinibaldi J. Tissue Eng. Regen. Med. **12**, 750 (2018)

L15. Soft Matter Laboratory: Rheology and Calorimetry (CNR-ISC)

The Soft Matter Laboratory: Rheology and Calorimetry is located in room 010 at the ground floor of the Fermi Physics Building and it is under the responsibility of Dr. Roberta Angelini (CNR-ISC). Rheology studies the flow and deformation of matter in response to an applied force, Calorimetry deals with thermal properties of matter. The laboratory therefore is focused on the study of mechanical and viscoelastic properties of matter and its phase transitions and phase diagrams. It is equipped with two instruments:

- a **differential scanning calorimetry (DSC)** from Perkin Helmer composed of independent dual furnaces of platinum-iridium alloy with independent platinum resistance heaters and temperature sensors with furnace mass less than 1g. The temperature is measured through Platinum resistance thermometers for best linearity. Measurements are performed under Nitrogen atmosphere over the full temperature range. It works in a temperature range -80÷700^{o}C with an accuracy of $\pm$ 0.1^{o}C and a sensitivity of 0.2 μW.
- a **cone-plate rheometer** from Anton Paar with 50 mm diameter plate and cone angle of 2^o. It can measure viscosity in the range $10^{-6} \div 10^7$ Pa·s and it is equipped with a water cooled Peltier temperature device for temperature control in the range -40÷200^{o}C .

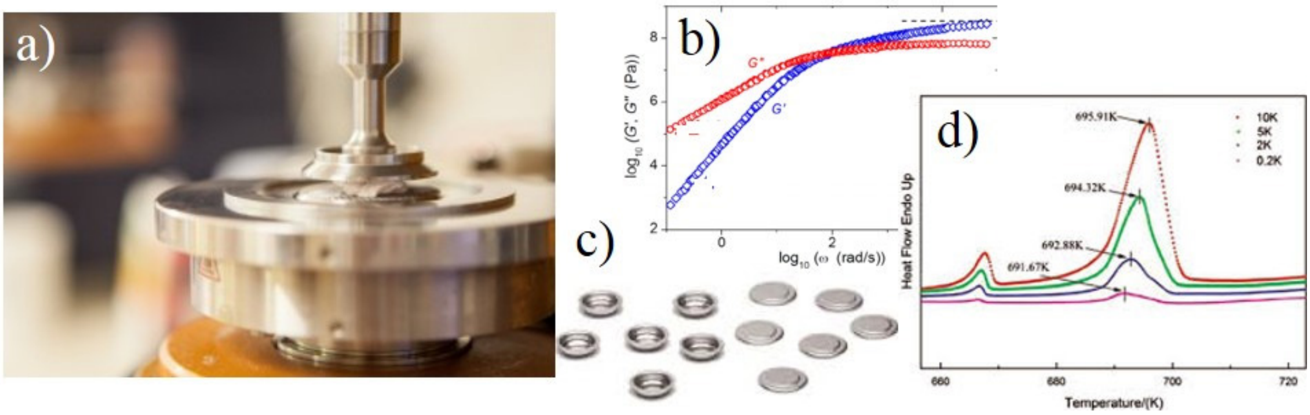

Figure 1: a) Detail of a cone-plate rheometer. b) Example of storage and loss moduli from rheological measurements. c) sample pans for calorimetric measurements. d) Example of thermograms from differential scanning calorimetric measurements.

The laboratory is focused on the experimental study of structure and dynamics of soft materials and in particular on the understanding of equilibrium and non equilibrium states of matter. In this context an important role is played by colloidal suspensions that offer the possibility to observe unusual phase diagrams, multiple arrested states, such as gels and glassy states and glass-glass transitions. The systems mainly investigated in the laboratory are **charged colloidal clays**[1] and **colloidal microgels**[2-3] together with biological systems[4]. Alongside rheometric and calorimetric techniques, synchrotron-based methods are powerful tools used to compare and extend, to wide spatial and temporal scales, the measurements performed in this laboratory. This part of work is developed mainly in large scale facilities like the European Synchrotron Radiation Facility (ESRF) for x-rays complemented with neutron scattering measurements performed at the ISIS and ILL neutron sources. The experimental work is developed, in collaboration with Dr. Barbara Ruzicka (CNR-ISC) of the Soft Matter Laboratory: Light Scattering and in collaboration with Dr. Emanuela Zaccarelli (CNR-ISC) for comparison with theory and simulations.

References
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[2] V. Nigro et al. Soft Matter **13**, 5185-5193 (2017).
[3] V. Nigro et al. J. Colloid Interface Sci. **545**, 210-219 (2019).
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`http://www.roma1.infn.it/~angerob/`

L16. Nanostructures at Surfaces laboratory

The aim of the laboratory is to investigate how physical properties arise when solid state systems shrink to the nanoscale. It is mainly devoted to atomic level controlled growth of molecular systems, low dimensional structures with desired morphology and spacing on suitable nano-structured templates. A special effort is dedicated to the growth of graphene on metallic substrates via chemical vapour deposition, graphene nanoribbons by molecular precursors, graphene nano- and micro-porous systems (see Fig. 1, right panel). Of the nanostructures grown on surfaces we study: (i) the bonding state of the elements by means of X-ray photoelectron spectroscopy (XPS), (ii) the 2D crystalline order by low-energy electron-diffraction (LEED), (iii) the control of the growth morphology by Auger electron spectroscopy (AES), and (iv) the adsorption energy by thermal desorption spectroscopy (TDS).

The XPS, LEED/AES and TDS apparatus is contained into an ultra-high-vacuum (UHV) chamber, UHV-connected to a small chamber for a fast load-lock introduction, along with several other characterisation methods and ancillary facilities for samples preparation and cleaning, atomic/molecular beam epitaxial evaporators.

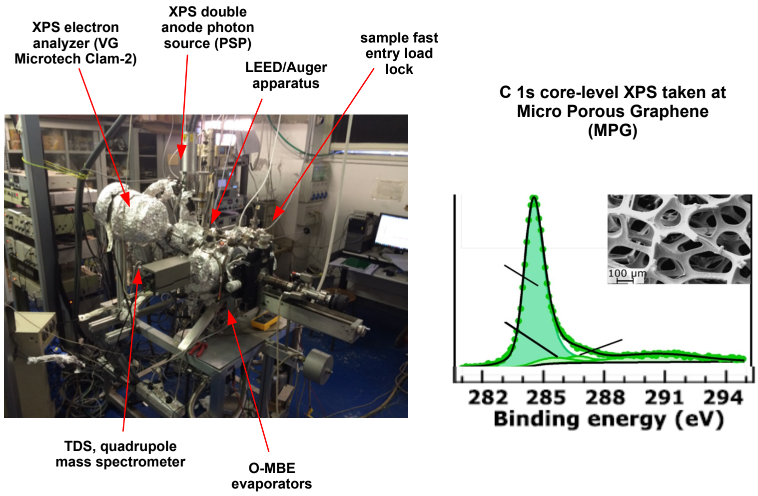

Figure 1: Left: XPS and growth chamber (5×10^{-11} mbar base pressure). Right: XPS C 1s core-level at MPG.

In the following, the main characteristics of the apparatus.

- XPS hemispherical electron analyser: VG Microtech Clam-2, pass-energy range: 10-200 eV, single-channel detector;
- XPS photon source: PSP double-anode X-ray source, emission lines Al_{K_α} (1486.6 eV) Mg_{K_α} (1253.6 eV);
- XPS UHV manipulator: 4-degrees of freedom, cryostat (>77 K), electron-bombardment heater ($\leq$1200 K);
- Low-Energy Electron Diffraction (LEED): Omicron SpectaLEED system, with LEED and Auger modules;
- Ion Gun: Omicron ISE10 0.2-5 keV energy range, Ar ion source;
- Mass Spectrometer: residual gas analyser SRS RGA (1-300 a.m.u.); linear T ramp for TDS acquisition;
- Gas line equipped with several ports, UHV-connected through a leak-valve to the main chamber; O, H and C_2H_4 sources;
- Organic-molecular beam epitaxy (O-MBE) cells, with thermocouple control; quartz crystal thickness monitor; high-temperature electron-bombardment based evaporator for transition metals.

References I. Di Bernardo *et al.*, ACS Omega **2** 3691 (2017); Carbon **131** 258 (2018); M. Iacobucci *et al.*, Nanotechn. **29** 405707 (2018); G. D'Acunto *et al.*, Carbon **139** 768 (2018); F. Leardini *et al.*, 2D Mat. **6** 035015 (2019).

https://sites.google.com/uniroma1.it/nano-surface-physics/home

L17. Optical trapping and active matter lab - DIPFIS

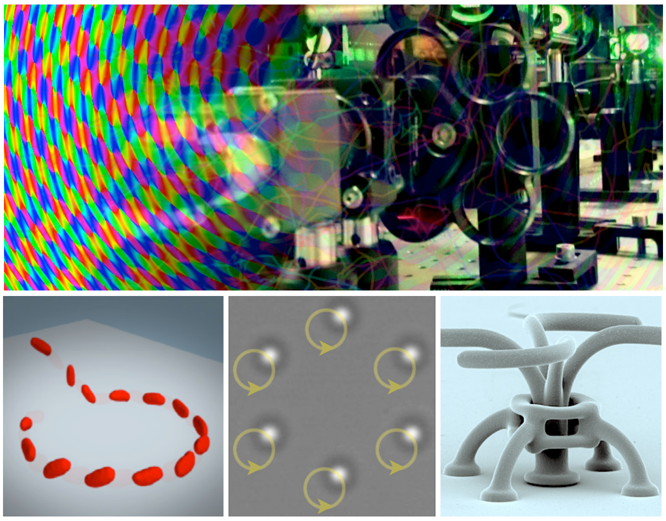

Figure 1: a) 3D reconstruction of a swimming *E.coli* cell colliding and being trapped by a solid wall [1]. b) Hydrodynamic synchronization of 6 colloidal particles moving over rotating optical landscapes [2]. c) The light sprinkler: a 3D printed microstructures that can reroute an incoming flow of optical energy to exploit light's momentum for torque generation [3].

From bacteria to Brownian motion, during the last three hundred years, the optical microscope has revealed to us an image of the world at the micron scale that is far more interesting and rich than what we could have expected based on our experience of macroscopic phenomena. Although the "anatomy" of an optical microscope has not evolved much in the last century, more recently the photonics and digital revolutions have radically changed the way we generate, detect, and design light fields using lasers, LEDs, digital cameras and spatial light modulators. The modern optical microscope integrates optical, photonics and computer hardware in a powerful and ever expanding instrument. For instance, replacing the microscope lamp with a coherent light source like a laser, one obtains sample images that at a first sight look like intricate and apparently meaningless interference patterns. However, once captured by a digital camera and converted to arrays of numerical values, these 2D holograms can be rendered as 3D volumetric reconstructions by means of numerical backpropagation on a computer. We have recently proposed an implementation of Digital Holographic Microscopy called 3-axis DHM that uses three independent and tilted illumination beams to improve axial resolution to an extent that allows high speed 3D imaging of the prolate body of an *E.* coli cells (1 μm thickness) while it swims through a large three dimensional field of view (Figure 1a). Lasers have not just expanded the possibilities of imaging with light but have radically transformed the microscope from a passive observation tool to an active instrument that can use the radiation pressure of a focussed laser beam to trap colloidal particles or cells, move and arrange them into precise 3D configurations and also perform extremely sensitive force measurements. Our lab is very active in the field of holographic optical trapping and has contributed both technical development and applications to the fields of microfluidics, soft matter, statistical mechanics and microhydrodynamics (Fig. 1b). A microscope objective can be also used to focus a pulsed laser beam down to a diffraction limited spot that can produce localized photopolymerization of a negative photoresist by a two-photon absorption mechanism. By accurately scanning the sample along a 3D trajectory this beam can be used for direct laser writing in a sort of 3D printer with submicron resolution. Our lab has developed a custom TPP setup, equipped with a spatial light modulator that allows to multiplex writing beams and fabricate arrays of identical 3D structures in parallel (Fig. 1c).

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`glass.phys.uniroma1.it/dileonardo`

L18. Collective Behavior in Biological System Laboratory - CoBBS

The aim of the CoBBS Lab is to bring together in one single research effort experiments on collective biological systems and physics-inspired theory. Collective behaviour in biological systems runs wildly across scales in both space and time, from bacteria and cell clusters, to insect swarms, bird flocks and up to vertebrate groups.

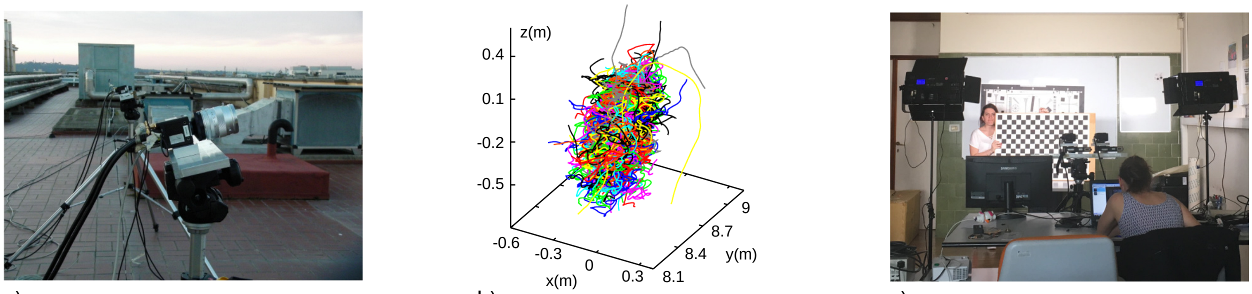
The CoBBS Lab is focused on collective behavior in flocks of starlings (*Sturnus vulgaris*) and swarms of non-biting midges (*Chironomidae* and *Ceratopogonidae*) in their natural environment, to understand the fundamental interaction rules between individuals. The Lab has ongoing collaborations to perform experiments on Vaux's swift (*Chaetura Vauxi*), malaria mosquitoes (*Anopheles Gambiae*) and stem cells (bone marrow stromal cells).

From an experimental point of view, the study of collective behavior is very challenging: the aggregations tend not to be stationary and the exhibited behaviour cannot be predicted, so that the experimental procedure has to be continuously adapted to the environmental constraints.

We collect data on insect swarms during summer in public parks of Rome where swarms are likely to be found, due to the presence of small lakes. Data on bird flocks are instead collected from the roof of *Palazzo Massimo alle Terme* near Termini Station in Rome see Fig.1a, where starling use to roost during winter.

The experiment is performed using a system of three synchronized high speed cameras recording the same flocking/swarming event from different points of view. Image sequences are then analyzed to reconstruct the three dimensional trajectory of each individual within the group. We developed and tested a sophisticated algorithm, GReTA (Global and Recursive Tracking Algorithm), which is able to correctly identify and track thousands of animals with negligeable switches of identity see Fig.1b.

The activities of CoBBS Lab are not limited to the field experiments. Many experimental activities, such as the calibration of the internal parameters of the cameras (i.e. focal length, position of the centre of the image, distortion coefficients) as well as tests on the synchronization and the accuracy of the camera system, need to be periodically performed in the laboratory to guarantee the high quality of the data, see Fig.1c.



a) b) c)

Figure 1: **a. Experimental setup:** for starling flocks on the roof of *Palazzo Massimo alle Terme*. **b. Midges swarm 3D trajectories:** reconstructed by our tracking algorithm GReTA. **c. View of the lab:** during the calibration and synchronization test of the system.

The laboratory is equipped with several systems of high speed cameras. The most advanced ones is composed by three IDT OS10s 10Mpx cameras able to shoot at 155fps. The equipment of the laboratory also includes several sets of lenses with different focal length which are used depending on the experimental set-up, a built-in-home instrument to measure the delay in the synchronization of the cameras and two microscopes that are used to identify the taxonomy of the insects under investigation.

Nowadays a great effort is made to bring the experimental configuration from a system of fixed cameras to one in which the cameras are able to follow the movement of the objects of interest. In this way it will be possible to collect data for a longer period of time keeping the objects in the cameras field of view for longer.

To achieve this goal each camera will be mounted on a rotary stage remotely controlled by a computer. For each instance time, a software will analyze the scene by calculating the movement that each rotary should perform in order to keep the objects centered in the field of view of each camera. Therefore the cameras will be independently free to move following the group and expanding the acquisition time.

http://www.cobbs.it

L19. Nanostructures at Surfaces laboratory for angle-resolved photoelectron spectroscopy (ARPES)

The laboratory is devoted to the experimental investigation of the electronic band structure of surfaces and two-dimensional (2D) materials by means of high-resolution angle-resolved ultraviolet photoelectron spectroscopy (ARPES). The ARPES apparatus, working at high energy and angle resolutions, operating at low temperatures, is contained into an ultra-high-vacuum (UHV) chamber, UHV-connected to a preparation chamber equipped with several other characterisation methods and ancillary facilities for samples preparation and 2D materials growth, and is provided with a small UHV chamber for a fast load-lock introduction (Fig. 1, left panel).

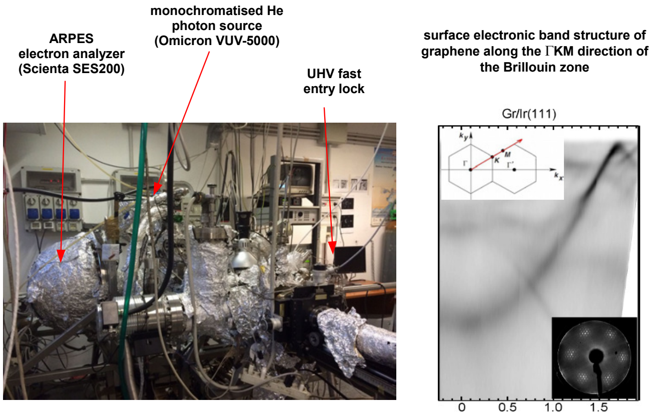


Figure 1: Left: ARPES chamber ($1{\times}10^{-10}$ mbar base pressure). Right: Electronic band structure of graphene (Gr) for Gr/Ir(111), along the ΓKM direction of the suface Brillouin zone, excited with the HeI_α photon energy (21.218 eV).

In the following, the main characteristics of the apparatus:

- ARPES hemispherical electron analyser: Scienta SES-200, 4 meV best energy resolution, <0.1° angular resolution, 1-50 eV pass-energy range, multi-channel detector (MCD, ±8° angular span and 10% of pass-energy energy span); Graphene band structure in Fig. 1, right panel;
- ARPES photon source: Omicron-Scienta VUV-5000 monochromatised MW-excited He source, main lines HeI_α at 21.218 eV and HeII_α at 40.814 eV, up to HeII_δ at 52.241 eV;
- ARPES manipulator: 5-degrees of freedom UHV manipulator, with precision rotation of the azimuthal and polar angles, cryostat to liquid nitrogen temperature, electron-bombardment heater up to 1200°C;
- Low-Energy Electron Diffraction (LEED): Specs retractable ErLEED system, with LEED and Auger modules;
- Ion Gun: Omicron ISE10 0.2-5 keV energy range, Ar ion source;
- Mass Spectrometer: residual gas analyser SRS RGA 300, 1-300 a.m.u. range;
- Gas line, equipped with several ports for small bottles and UHV-connected through a leak-valve to the main chamber; oxygen and C_2H_4 sources mounted, the latter for graphene preparation on metals *via* temperature programmed growth;
- Organic-molecular beam epitaxy (O-MBE) cells; high-temperature electron-bombardment based evaporator for transition metals; quartz crystal thickness monitor; cleaver, other ancillary facilities for sample preparation, etc.

References I. Di Bernardo *et al.*, ACS Omega **2** 3691 (2017); I. Di Bernardo *et al.*, Carbon **131** 258 (2018).

`https://sites.google.com/uniroma1.it/nano-surface-physics/home`

L20. TERALAB

The electromagnetic spectral range between terahertz (1 THz= 4 mV) and ultraviolet (UV, 6 eV) is of crucial importance for the investigation of linear, non-linear and time-dependent properties of Quantum Materials. One can cite, for instance, the study of collective modes and superconducting (single particle) gap in superconductor (charge-density-wave) materials, the phonon and vibrational modes in insulators, the low-energy electrodynamics across the metal-to-insulator transitions in strongly correlated materials. The Dirac electron gas confined at the surface in graphene and Topological Insulators.

Figure 1: The Time-Resolved Spectroscopy laser facility of the TERALAB laboratory.

TERALAB (Frequency and Time Resolved Optical Spectroscopy of Quantum Materials) is constituted by two experimental facilities in the Physics Department of Sapienza University: The first, based on frequency-domain optical spectroscopy in a wide range of frequency (terahertz to ultraviolet, 1 meV- 6 eV), allows the study of the equilibrium electrodynamics of Quantum Materials providing information about their microscopic optical response functions like the optical conductivity and the dielectric permittivity. Avalaible experimental apparatous consist in two Bruker Michelson interferometers, an infrared microscope and a JASCO spectrophotometer. The second facility (Fig. 1), allows the study of non-equilibrium properties of Quantum Materials through pump-probe, high-field experiments (10 MV/cm) on femtosecond time scale.This second facility is based on a Coherent Legend Laser Amplifier (1 KHz, 7 mJ, 35 fs), an OPA system and several terahertz apparatous. The experimental facilities at Sapienza are further supported by the beamline SISSI (Synchrotron Infrared Source for Spectroscopy and Imaging) at the Elettra Synchrotron in Trieste managed through a collaboration between CNR-IOM Sapienza (S. Lupi) and Elettra Sincrotrone Trieste, allowing the study, through an innovative spectrometer, of the optical properties of Quantum Systems with a nanometric spatial resolution [2].

[1] https://sites.google.com/a/uniroma1.it/teralab/
[2] https://www.elettra.trieste.it/it/lightsources/elettra/elettra-beamlines/sissi/sissi.html

L21. Laboratory of Physics Of BioAssembly - PhOBiA

The laboratories of Physics of Bio-Assembly are located in room 316, third floor, and in room 421, 4th floor, of the Fermi Physics Building, and Prof. Federico Bordi is the person in charge of the laboratories.
The main activity of the group concerns the physical characterization of bio-nanoparticles and biological colloids, and the experimental study of the self-assembly in these complex systems. To this aim our laboratories are equipped with the following instruments:

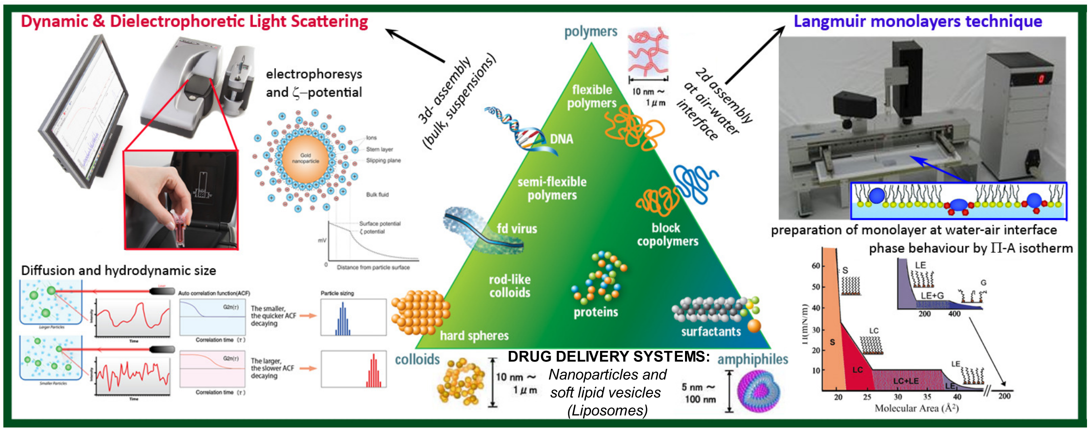
Dynamic, Static and Dielectrophoretic Light Scattering Dynamic Light Scattering (DLS) allows to measure the translational diffusion coeffcient of particles and supramolecular aggregates in colloidal suspensions and hence to determine their hydrodynamic size and size distribution (within a range from a few nm to about one μm). Static Light Scattering (SLS) is used to determine the molecular weight of macromolecules and macromolecular assemblies, while Dielectrophoretic Light Scattering (DiLS) measures particles electrophoretic mobility and gives an estimate of the ζ-potential (the electrical potential) and of the electrical charge at the particle-solvent interface. In our laboratory we have two different light scattering apparatus a Fiber Optic Quasi-Elastic Light Scattering (FOQELS) Brookhaven, equipped with a dip-in fiber-optic probe, and a Malvern NanoZeta Sizer, for the simultaneous determination of hydrodynamic size and ζ-potential. Both the instruments work in backscattering geometry (137 and 173 °C, respectively) that allows to use rather concentrated suspensions, and with the possibility of controlling the sample temperature in a range from about 5 to 120 (FOQELS $\approx$ 200) °C

Langmuir-Blodgett trough for the thermodynamical characterization of monomolecular films at the solvent-air interface and their deposition on solid supports (for example for their microscopic characterization).

Small Angle Energy-Dispersive X-rays Diffractometer (EDXD) operating in conventional Bragg-Brentano geometry, for the investigation of ordering and thickness in molecular films deposited on a support, such as lipid and or macromolecule multilayers, in controlled temperature and humidity conditions.

Laser Transmission Spectroscopy (LTS) apparatus for the simultaneous determination of the size distribution and of the absolute concentration of nanoparticles in colloidal suspensions

The laboratory is also equipped with the facilities and the small instrumentation needed for the manipulations and the preparation of colloids and biological samples, i.e. analytical and preparative balances, pH-meter, magnetic stirrers, hot-plates, high temperatures oven, ultrasound bath, fridge, a chemical hood, a laminar flow hood and an aspirated safety cabinet for chemicals. We also have a humidity controlled box, a glove-box, a small centrifuge, a temperature controlled bath, a rotavapor and a tip sonicator for the preparation of unilamellar lipid vesicles (liposomes).



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[4] F. Domenici *et al.*, J Colloid Interf Sci **540**, 1 (2019).

L22. Imaging Lab (CLNS - IIT)

The Imaging laboratory at the Center for Life Nano Science (CLNS) of the Istituto Italiano di Tecnologia (IIT) is primarily involved in the development of novel state-of-the-art imaging systems aimed to provide early diagnosis and a better understanding of human diseases. The lab combines advanced optical instruments, such as ultrafast lasers and high-sensitivity cameras, with the latest experimental approaches that gain physical information about matter.

One of the primarily goals at the CNLS Imaging lab is to seek new ways to image in-depth regions of biological samples, which standard imaging techniques cannot investigate due to both diffraction and scattering. As such, we are developing peculiar beams that, similarly to Bessel beams, are non-diffractive and self-healing. These light beams are generated through spatial light modulators (SLM) that control either the amplitude or the phase of the incident coherent light beam.

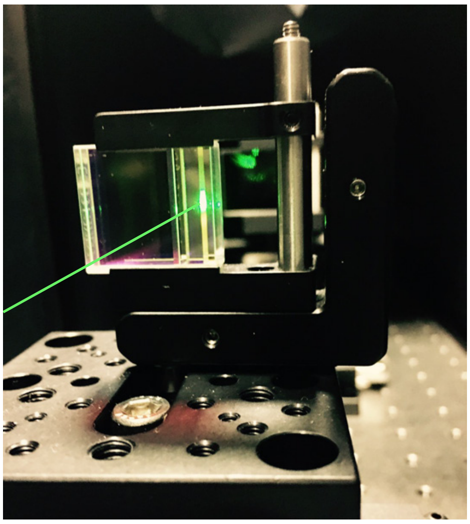


Figure 1: VIPA spectrometer for Brillouin microscopy.

Spectroscopy plays a central role in our experiments. Whilst commonly used fluorescent techniques require sample labelling with toxic fluorescent molecules, spectroscopy provides a label-free approach to gather fundamental information about the sample. We are developing a non-contact and label-free confocal Brillouin microscope that is capable of acquiring three-dimensional mechanical images of specimens. A single-longitudinal-mode Coherent Verdi V12 laser is used to ensure ultra-narrow (< 1 MHz) spectral linewidth and a virtually imaged phased array (VIPA) spectrometer spectrally resolves the weak Brillouin peaks. The Brillouin microscope together with an Atomic Force Microscope (AFM) already present in our lab can furnish a true picture of the system's mechanical properties, which are found to play a pivotal role in the pathophysiology of several diseases such as atherosclerosis, cancer and glaucoma. In parallel, an imaging system scopy with an AFM microscope is currently under development to obtain chemical and structural information of biological systems with a spatial resolution down to the nanometer scale.

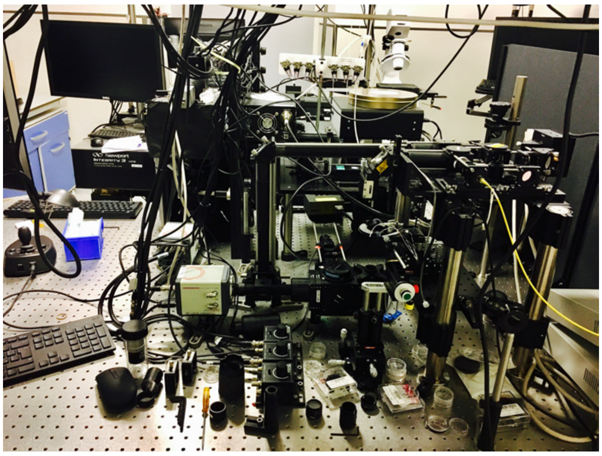


Figure 2: Optogenetics calcium imaging system.

The lab is equipped with advanced optical instruments and ultra-fast CCD cameras to perform optogenetics, where the primarily goal is to investigate neuronal activity using calcium imaging. In particular it is possible to monitor with different experimental approaches (calcium imaging or off-axis holography) the activity of large ensembles of cells (usually neurones) at the same time enabling the investigation of high order/long range correlations in neural networks cultures. In parallel, cell differentiation is currently investigated with a fluorescent scheme involving a motorized stage and a temperature-stabilized incubator.

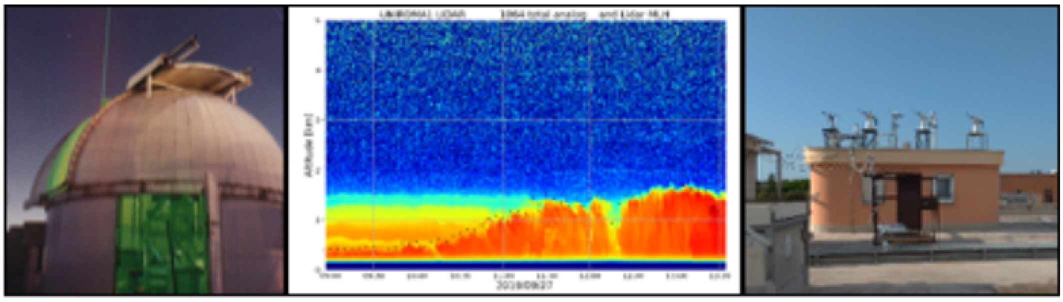
Further lab facilities include a two-photon fluorescence microscope with a three-channel light source, a fast spinning disk confocal microscope and a structured light super-resolution microscope for biomedical imaging.

L23. Atmospheric Physics Laboratory-APL

APL is located in rooms 503-518-519-520 and on the roof of the Fermi Physics Building and dr. Marco Cacciani is the person in charge of the laboratory. The main APL activities are observations and studies of the Urban Boundary Layer, of the Tropospheric and Stratospheric Aerosol and Clouds, as well as of the calibration/validation of Earth Observation Satellite products. APL is involved in the BAQUNIN supersite together with the CNR/IIA, CNR/ISAC, Sardegna Clima Onlus and SERCO Italia. APL is equipped with the following instruments:

- **Elastic-Raman LIDAR** for the observation of the aerosol and water vapor atmospheric vertical profiles;
- **Triaxial SODAR** for the observation of the wind-vector and atmospheric turbulence vertical profiles;
- **POM-1** (PREDE) spectrophotometer for the retrieval of the spectral optical depth, size distribution, single scattering albedo and Angstrom exponent of aerosol contained in a column of atmosphere. This instrument is a member of Europe Skynet Network;
- **PANDORA** (SciGlob I&S) spectrophotometer for the retrieval of aerosol and trace gases atmospheric content. This instrument is a member of PANDONIA Network
- **CIMEL CE318-T** (Cimel Electronique) spectrophotometer for the retrieval of the spectral optical depth, Angstrom exponent and fine/coarse fraction of aerosol contained in a column of atmosphere and Precipitable Water. This instrument is a member of AERONET Network;
- **MFRSR MFR-7** (YES) spectrophotometer for the retrieval of optical depth of aerosol contained in a column of atmosphere;
- **ALL-SKY CAMERA** (Alcor System) for the observation of the total cloud coverage;

APL equipment includes pyranometers, meteo-stations and sonic anemometers installed in different locations in the Fermi Building.



Left): LIDAR. Center): evolution of the Istantaneous Unstable Boundary Layer above APL. Right): CIMEL, PANDORA and POMs are measuring the direct sun radiance

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L24. Materials for energies (Physics Dept. and ISC-CNR)

The Lab is active on basic research concerning materials potentially applicative in the field of energy storage and transformation. The main research themes include: solid state hydrogen storage, electrodes and electrolytes for innovative lithium batteries, hydrogen purification. In order to study these materials, we chose an approach based on investigations by means of a large variety of experimental techniques, which are available in the Lab. Indeed, the Lab is equipped with four main experimental stations which can work independently.

A commercial Dynamic Mechanical Analyzer is able to measure, also in liquid corrosive environments, the elastic moduli and the elastic energy dissipation of solid samples in a wide temperature range, between 78 and 900 K. This system is particularly well suited for the study of polymers, but we also succeeded in using it to measure relaxation processes and phase transitions in liquids.

The group uses a flexible system for concomitant measurements of thermogravimetry and differential scanning calorimetry. This apparatus can operate both in inert gas atmospheres and in high vacuum, and the exploitable temperature range is between 300 and 1300 K. The system is complemented by a quadrupole mass spectrometer which allows the identification of the released gaseous species.

A home-made Sieverts apparatus allows to measure the thermodinamics and kinetics of the absorption of gases (mainly hydrogen and deuterium) in solid samples. The system is based on a volumetric principle and can operate in a wide range of temperatures (80-600 K) and pressures (10^{-4} bar up to 200 bar), thanks to a large variety of pressure transducers.

Finally, the Lab is equipped with a Agilent Cary 660 Infrared Spectrometer allowing measurements in the mid-infrared range. Different cells provide various environments for conditioning the samples in a wide temperature range (80-1000 K). Moreover, above room temperature, gas pressures as high as 60 bar can be introducted in a properly designed cell to allow reactions with the sample to occur. Both transmittance and reflectance mode measurements are possible.

Figure 1: The Infrared Spectrometer (left), the Sieverts apparatus (center, above), the Dynamic Mechanical Analyzer (center, below) and the system for concomitant thermogravimetry, differential scanning calorimetry and mass spectrometry (right).

L25. Laboratory of Solar Radiometry and Microclimate for Cultural Heritage

The Solar Radiometry Observatory and Microclimate for Cultural Heritage is managed by the G-Met group at the Physics Department.

- Since 1992 at the Solar Radiometry Observatory of Sapienza Universit di Roma, total ozone contents and UV irradiances have been systematically collected by the Brewer spectrophotometer 067. Measurements of solar UV spectral irradiances are carried out in the spectral range from 290 to 325 nm, with a stepwidth of 0.5 nm. Total column ozone is retrieved by measuring of both direct sunlight and polarized radiation scattered from the zenith sky. Direct-sun and zenith sky measurements are carried out at specific solar zenith angles throughout the day. Since its installation, the instrument has been regularly calibrated by intercomparison with the traveling reference Brewer 017 every one or two years. This latter Brewer is in turn calibrated against the World Brewer Reference Triad in Toronto. Thus, the ozone calibration of Rome spectrophotometer is also traceable to the Brewer Reference Triad. Ozone data are regularly submitted to the WOUDC (World Ozone and Ultraviolet Radiation Data Centre) and took part to the COST Action ES1207 EUBREWNET. In 2016 Brewer 067 has been included in The Boundary-layer Air Quality-analysis Using Network of Instruments (BAQUNIN) Super-Site for Satellite Atmospheric Chemistry Products Validation.

Figure 1: Brewer 067 on the terrace of the Fermi Building (Sapienza Campus).

- The G-Met is also involved in monitoring the main microclimatic parameters, such as outdoor and indoor air temperature and relative humidity, which are fundamental to assess if ambient conditions are suitable for conservation purposes. Monitoring such parameters with well maintained instrumentation allows to investigate possible sources of degradation and to suggest mitigating measures. Finally, a Minolta Spectrophotocolorimeter is used in order to detect possible markers of degradation by means of color changes. The G-Met group is one of 18 partners in the CollectionCare project funded by the European Unions Horizon 2020 Research and Innovation Programme under the grant agreement No 814624. The aim of the project is to develop an innovative preventive conservation decision support system targeting the needs of small-medium sized museums and collections.

https://www.collectioncare.eu/

L26. Optical Spectroscopy of Nanostructured Materials

The members of the Optical Spectroscopy of Nanostructured Materials (OSNM) Laboratory have decades of experience in the optical characterization of semiconductor materials and nanostructures. The OSNM lab is equipped with state-of-the-art facilities for optical spectroscopy, including:

- Several continuous wave (CW) and pulsed light sources, covering a wavelength range from 266 nm to 2200 nm;
- Double (75 cm) and single (0.16, 0.3, and 1 m) monochromators, equipped with light detectors operating from the UV (down to ∼300 nm) to the infrared (IR, up to ∼5 μm);
- Two closed-cycle cryostats for conventional photoluminescence (PL) measurements and a He-exchange cryostat equipped with a superconducting magnet (fields up to 14 T), for magneto-PL measurements;
- Two micro-PL setups: the first one, based on a He-flux cryostat, is optimized for measurements in the IR range (up to 5 μm), whereas the second one, designed for measurements from the visible to the near IR (350 nm to 1.8 μm), is built around a low vibration closed-cycle optical cryostat (see Fig. 1). This system allows for the optical characterization of single nanostructures in the 4-350 K temperature range, without the need for liquid He and with a spatial resolution <500 nm (limited by diffraction).

Recently we also designed and built setups for time-resolved micro-PL and photon correlation measurements, which gave us the ability to characterize the dynamics of the investigated nanostructures and their performance as single- and entangled-photon emitters. Lastly, hydrogen (and deuterium) irradiation of semiconducting samples can be performed by means of a low-energy (1-500 eV) Kaufman source, operating at temperatures ranging from room temperature to 600 °C.

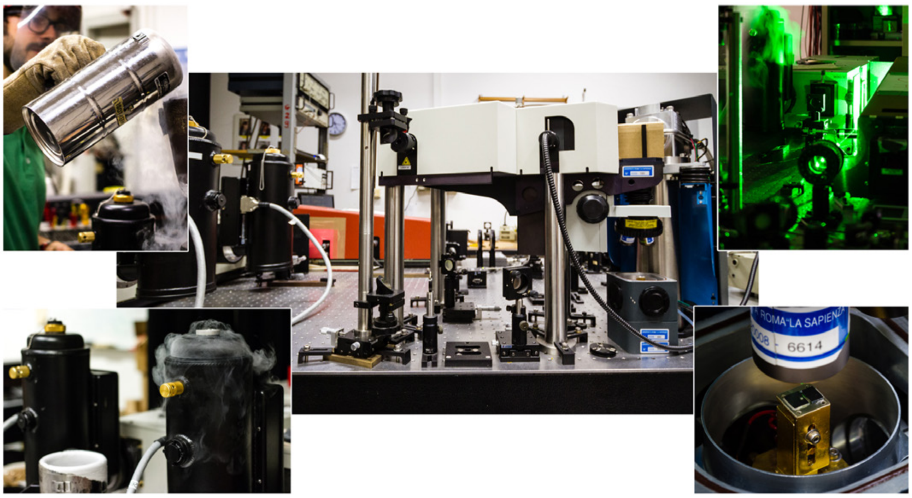

Figure 1: (Center) One of the optical tables available in the OSNM lab, equipped with a state-of-the-art micro-PL setup coupled to a low vibration closed-cycle cryostat. (Bottom right) Zoom-in of the sample chamber of the cryostat, wherein temperatures < 4 K can be reached. The output of one of the several light sources available in the lab (Top left: Beam generated by a frequency-doubled Nd:YVO_4 laser, with wavelength $\lambda_{ex} = 532$ nm and maximum power = 8 W) is focused on the sample with a microscope objective (spot size <500 nm). Samples are mounted on a two-axis nanopositioning system (minimal step size ∼10 nm), so that individual nanostructures can be precisely placed in the optical path. The resulting micro-PL signal is collected through the microscope objective and dispersed and detected with a single or double 75-cm monochromator, coupled to a N_2-cooled (Top left: Detail of the cooling procedure) light detector (Bottom left: Si CCD camera and InGaAs linear array detector). (All photographs by Alessandro Cerè, `http://www.alecere.com/`).

`http://antoniopolimeni-physics.weebly.com/`

L27. Optical Micro-Spectroscopy Lab - High Pressure Spectroscopy Group

The development of micro-spectroscopic systems opened up a whole new dimension of optical spectroscopy in the field of mesoscopic physics. A highly spatially resolved spectroscopy is indeed a fundamental need for a number of research fields and applications ranging from the investigation of matter under extreme temperature and pressure conditions to surface enhanced spectroscopies, from the evaluation of optical properties of inhomogeneous material to cultural heritage. The research carried out in our Laboratory is manly focused on spectroscopic studies on functional inorganic/hybrid materials or to soft matter and nanosystems of biological interest.

We have a microRaman spectrometer with multiple laser lines for excitation, coupled with confocal optical microscopes which, at the best, can provide a sub-micrometric lateral spatial resolution and a micrometric resolution along the optical axes. Confocal microscopes can be optically coupled with available diamond anvil cells to investigate the properties of matter under extreme pressure (0-50 GPa) and temperature (4-1000 K) conditions. The possibility of sampling the spectral response on a micrometric spatial scale is necessary since the sample volume in high pressure experiment can be as small as few nanoliter, and its surface few tens of micrometer wide. The same apparatus allows collecting both Raman and photoluminescence signals from samples under pressure thus directly monitoring lattice dynamic and electronic structure [1, 2].

The instrument is equipped with a sub-micrometric mapping stage and thus imaging and stratigraphic analysis are easily available. Moreover, state-of-the-art volume Bragg gratings allow to collect Raman spectra very close to the excitation frequency, well within the Terahertz region. This kind of apparatuses are remarkably relevant for studying and characterizing emerging low-dimensional materials (few-layers, single layers, heterostructures, nanowires and nanotubes) [3].

Terahertz Raman measurements can provide crucial information on the structure and dynamics of complex functional materials such as hybrid perovskites, which are well known for their potential in photovoltaic applications. These materials are characterized by an inorganic scaffold with octahedral shape, embedding organic cations. Their peculiar properties arise from the interplay between the inorganic structure and the organic elements, and the relationship between structure and physical behavior is subject of intense investigation. A recent experimental study performed by our group on the effect of pressure on the dynamics of the organic methylammonium (MA) cation in methylammonium lead bromide ($MAPbBr_3$) perovskite is reported in Figure 1.

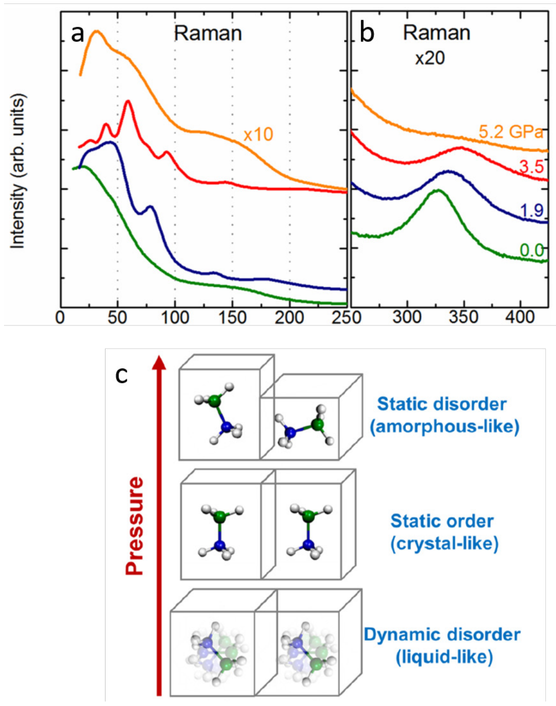

Figure 1: Low-frequency Raman (panels a and b) spectra of $MAPbBr_3$ hybrid perovskite at four selected pressures, representative of the different high-pressure phases of the system. (c) Pictorial representation of the three methylammonium dynamical regimes within the inorganic cage (full lines) on increasing the pressure.

References

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L28. "GranularChaos" Lab: statistics and rheology of macroscopic disordered materials (CNR-ISC)

The laboratory includes two main experimental setups for granular dynamics: A) Vertical vibration (granular experiments in 2D and 3D): an electrodynamic shaker LDS V455, which can reach a maximum acceleration of 105g, powered by a PA1000L power amplifier. The amplifier receives the signal from a signal generator board. Particle tracking data are collected by a fast camera (MIKROTRON EO-SENS CL) which reaches 506 frames per second at full resolution (1280x1024). B) Inclined plane with vibrating pistons (granular experiments in 2D at reduced gravity): the inclined aluminum plane has a variable tilt-angle to control effective gravity, lateral lighting, two vibrating pistons (actuated by rotating engines) on the short sides (usually the topmost and the lowest ones) inject energy. Particle images are collected by a fast camera (Photron MiniUX50) which gets 1.3Mp at 2Kfps with colors.

The setup A has been used in previous years to obtain a granular 2D fluid (gas-liquid-glass densities), studying order in the velocity field. In a second series of experiments with setup A a cylindrical container was used to get a 3D fluid and study "Brownian motor" phenomena, the violation of the fluctuation-response relation, the liquid cage effects coupled to long-time superdiffusion, and general granular rheological properties in a wide range of densities and shaking amplitudes. Setup B has revealed to be ideal for a closer comparison with granular kinetic theories and hydrodynamics, including the presence of thermal convection induced only by dissipative collisions with the lateral walls [1]. More recently setup A (in 3D dense configuration) has revealed that there is an optimal frequency of vibration where the viscosity in a fluidized granular medium is minimal [2]. The complex rheological phenomena seen in the dense 3D fluid in setup A have been also analyzed in terms of coupled Langevin equations, revealing the existence of relevant variables with a very slow dynamics [3]. The results of this experiment have been also compared with detailed numerical simulations leading to the discovery of collective rotational motion inside the granular medium itself [4]. In the last month a new tracking method to trace the motion in the 3D bulk is being validated, based upon a magnetic tracer perceived by an array of magnetic sensors.

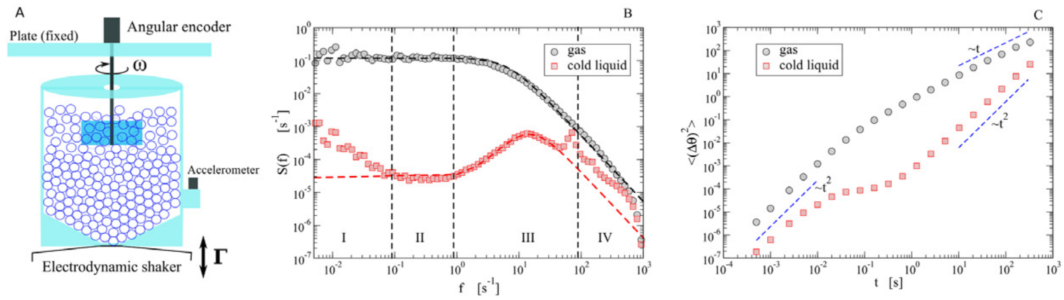

Figure 1: A: Sketch of the experiment reported in [3] and [4]. B: Experimental data of the velocity power density spectrum for the gas case and the cold liquid case, together with predictions (dashed lines) from a theoretical model [3]. C: Experimental data of the MSD for both cases, together with dashed lines useful as guides for the eye.

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http://tnt.phys.uniroma1.it/~puglisi

L29. G4-Spectroscopy and microscopy of superconductors and emerging functional materials

Research activities of Group G4 are mainly focussed on spectrsocopy and microscopy studies of superconductors and emerging functional materials. The goal is to develop new materials by knowledge of structure function relationship through an experimental approach based on the manipulation of materials properties. In particular, the recent research activities are focussed on layered systems showing superconducting and related functional properties. Exploiting high energy spectroscopy as a tool of fundamental electronic structure, combined with structural tools of nanoscale structure, the group has been active in the frontier research with a direct implication of our understanding of complex quantum matter. The group has been using advanced synchrotron radiation facilities for the spectroscopy and spectral imaging of the new materials. The main experimental techniques include X-ray absorption and emission spectroscopy, photoemission spectroscopy and microscopy, in addition to the diffraction based imaging techniques. The synchrotron radiation based experiments are combined with in-house spectroscopy and microscopy measurements to characterize new materials with functional properties. The group has contributed significantly on the role of nanoscale structure in the physical properties of systems hosting quantum phenomena as the superconductivity.

The G4 laboratory is equipped with various instruments for the materials characterization. There is dedicated ultra high vacuum (UHV) facility equipped with a preparation chamber and the analysis chamber for spectroscopy (Fig. 1). The analysis chamber is equipped with a dual anode X-ray source and an ultra violet radiation source, in addition to the high resolution multi channel Omicron EA 125 electron analyzer, permitting to perform XPS, AES and UPS measurements on the materials of interest. All these measurements are possible down to about 20 K using liquid He cooled sample holder attached to the Omniax manipulator. Surface structure and morphology can be studied using the LEED/Auger system mounted in the analysis chamber. The laboratory also has muffle furnaces and a furnace for Czochralski growth, being used for samples treatments. For the transport properties, a complex conductivity measurement system equipped with Heliox3 cryostat, is used down to very low temperature. In addition the laboratory is equipped with an ambient pressure AFM/STM system, used for characterization of materials for their surface morphology.

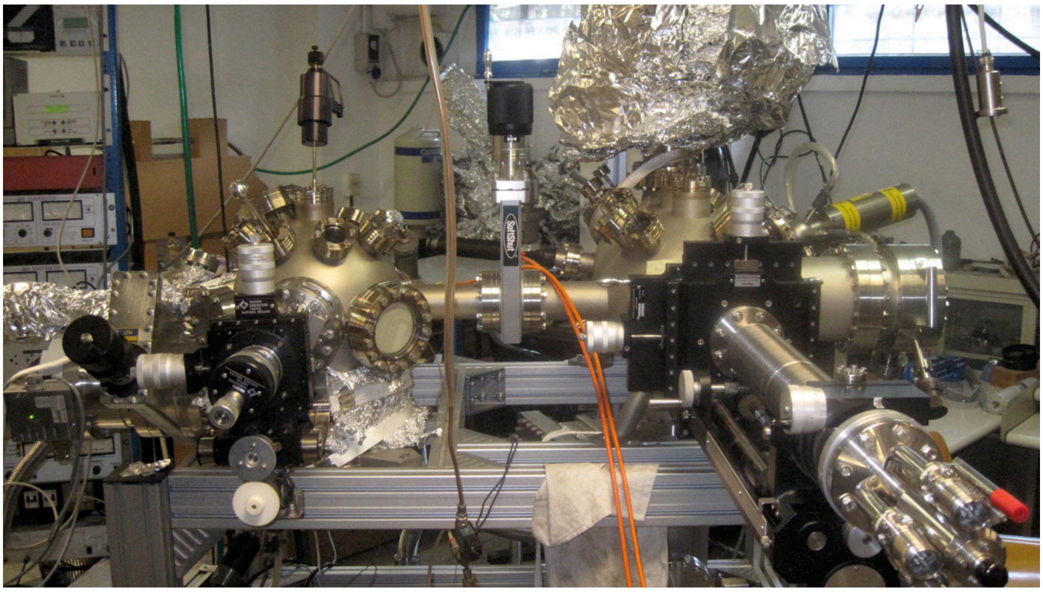
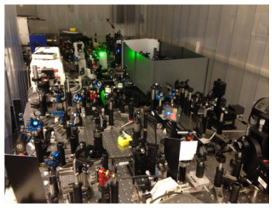


Figure 1: UHV system equipped with the facility of electron spectroscopy.

http://www2.phys.uniroma1.it/doc/saini/

L30. Femtoscopy Labs



In our labs we perform time-resolved non-linear optical spectroscopy and coherent imaging experiments, using ultrafast laser sources with wide tunability range in frequency and pulse duration. The strategy used in time resolved spectroscopies is the pump-probe scheme, where a single pulse emitted by a laser source is split into an intense pump beam, exciting the system under investigation, and a weaker probe pulse, which detects the optical proprieties of the sample upon photo-excitation. The basic principle of coherent imaging is the combination of multiple pulsed beams, to spatially resolve the label-free vibrational fingerprints of cells, tissues, and two-dimensional materials. The following techniques are available:

- **Linear and non-linear absorption and luminescence**: the simplest way to characterize a sample is to measure its linear absorption spectrum. Moreover, we are able to reveal luminescence emission upon ultrafast excitation, exploring single and multi-photon absorption regimes.
- **Ultrafast transient absorption (TA)**: it allows mapping the out-of-equilibrium intermediates of a system. Two pulses interact with the sample, acting as pump and probe. The former is tuned in resonance with an electronic transition of the system, which is then promoted to an excited state. Time-dependent properties are investigated by monitoring changes in the probe's linear absorption. A key feature of our setup is the use of a wavelength-tunable pump to access a wide range of electronic transitions, from the near UV (260 nm) to 800 nm, and a broad white light continuum ($350 - 1300$ nm) to probe, in a single shot, the optical modification at different wavelengths.
- **Femtosecond stimulated Raman spectroscopy (FSRS)**: FSRS is powerful technique able to access vibrational spectroscopy at the sub-picosecond time scales, both in molecular compounds and condensed matter. The FSRS concept is to combine a narrowband picosecond beam, which ensures an high spectral resolution, with a broadband femtosecond pulse, acting as a probe on the sample trough a stimulated Raman scattering (SRS) process. Since the SRS mechanism requires the presence of both the fields overlapped on the sample, vibrational coherences are triggered with a temporal precision dictated by the shortest (femtosecond) pulse. The addition of a femtosecond actinic pump (AP) pulse to this layout makes possible to induce a photo-reaction, which can be probed by the SRS detection scheme with ~ 100 fs of time resolution.
- **Impulsive Vibrational Spectroscopy (ISRS)**: the ISRS experiments exploit a time-domain probe protocol consisting of two temporally separated laser fields: a ~ 10 fs pump pulse impulsively excites the Raman active modes of a system, and, then, a femtosecond broadband probe measures at variable time delays the optical transmission, which is temporally modulated by the coherently stimulated vibrations. By Fourier transforming the signal to the frequency domain, the transient Raman spectrum can be retrieved.
- **Picosecond photo-acoustics (PA)**: This technique allows to measure the mechanical response of amorphous materials in an unexplored frequency region (30-300 Ghz), located between Brillouin and inelastic X ray scattering accessible windows. In the experimental setup a pump pulse launches a traveling longitudinal acoustic wavepacket, detected by a time-delayed broadband probe.
- **Coherent Vibrational Imaging (CARS, SRS, RIKES)**: the experiments are based on the application of two pulsed beams to obtain label-free imaging, exploiting the vibrational fingerprint of the sample. The ability to obtain hyper-spectral CARS images combining picosecond and femtosecond pulses with different time delays is the main feature of our setup.

The following instrumentation is available at the Femtoscopy labs:

- ◇ An 80 MHz, 50 fs at 800 nm oscillator (Coherent Micra)
- ◇ A regenerative amplifier (Coherent Legend Elite) with 1 kHz, $40 - 120$ fs time duration and 3.5 mJ energy;
- ◇ A 40 MHz Er doped fiber laser with four outputs: i) 1 ps, 782 nm and 135 mW; ii) 1 ps and tunable wavelenght (830-1100 nm); iii) 90 fs, 1560 nm and 400 mW; iv) < 25 fs, broadband ($980 - 1400$ nm), 13 mW.
- ◇ several monochromators coupled to Optical Multichannel Analyzers.
- ◇ several commercial and home-built optical parametric amplifiers (OPAs) to synthesize wavelength tunable pulses in the range 260-1600 nm with time duration down to 10 fs.
- ◇ Inverted microscope with galvo laser scanning system.

http://femtoscopy.phys.uniroma1.it/scopigno/

L31. Laboratory of Silicon detectors development

This laboratory is located on the third floor of the building “G. Marcon” of the Department of Physics of “Sapienza University of Rome”.

It is equipped with instrumentation able to characterize silicon detectors for the detection of both minimum ionizing particles (microstrips) and photons (Silicon Photo Multiplier, SiPM).

The experimental activity concerns also the development of fast electronics based on Field Programmable Gate Arrays (FPGA) and microprocessors. A manual Probe station with 8 inches chuck is located in the laboratory and used for both optical inspection of silicon detectors and tests.

A set-up to test silicon microstrip detectors with cosmic rays as well a set-up to perform tests with a laser beam on these detectors are present. For data acquisition both Standard VME based and fully custom set-ups are used. A Pattern generator and a Logical state analyzer support the debug phase. Thanks to the pieces of the equipment described above, were developed prototypes of the microstips detectors (50 μm pitch, 10 cm $\times$ 10 cm area, manufactured by Hamamatsu Photonics) to be used as front part of the particle tracker of Super Big Bite (SBS) Spectrometer at JLAB (Virginia, USA).

The development of a polarimeter for cosmic gammas in the energy range from 20 MeV to 1000 MeV using silicon microstrip detector planes to be included on a satellite is in the preliminary phase of study.

Since 2009, the Laboratory started developing the Silicon Fast Astronomical Photometry (SiFAP). SiFAP is a custom ground-based instrumentation working in Optical band (from 320 nm up to 900 nm) realized to detect faint periodic signals coming from variable sources (like pulsars) through high-speed photometry. SiFAP in its first version is basically composed of two channels; the first channel is dedicated to study the science target while the second channel is devoted to monitor a reference star in the Field of View (FoV). The sensors are photodetectors based on the Silicon Photo Multiplier (SiPM) technology. Up to now, the detectors used, called Multi Pixel Photon Counters (MPPCs) are provided by Hamamatsu Photonics, especially selected from the production batch for this application. The work with SiFAP started at 1.5 m (Cassini) and then moved on 3.5 m (TNG) optical telescopes and it is still ongoing.

L32. The ATLAS TDAQ Laboratory

The ATLAS Rome group is deeply involved in the TDAQ activities of the experiment. The group is currently responsible and coordinates the activities of:

- the first level trigger (overall coordination);
- the first level muon trigger system in the barrel region;
- the data acquisition system for the MDT detector;
- the MUCOMB (Muon Combined) high level trigger algorithm at the event filter.

Furthermore the group is involved in several TDAQ activities for the future upgrades of the experiments, like:

- realisation of the Pad trigger board for the first level muon trigger of the New Small Wheel region, for the sTGC detector, to be used for Run-3 starting in 2021;
- realisation of the optical interface board between the barrel Sector Logic board and the Muon Central Trigger Processor Interface (MuCTPi) board, to be used for Run-3;
- complete upgrade of the first level muon trigger system in the barrel region for Run-4, starting in 2026;
- studies of first level trigger algorithm implementation using FPGA based boards;
- studies of High Level Trigger (HLT) algorithm implementation using GPU based boards.

The TDAQ Lab for the ATLAS experiment is used by students and staff to test current and future software and hardware infrastructures for the trigger and data acquisition system of the experiment.

A slice copy of the barrel trigger system is available, as well as different evaluation and prototype boards based on FPGAs or GPUs.

A remote control room shift station has been installed in the laboratory. It is configured to control and monitor the muon detector, as the muon desk in the experiment control room; it is also used to monitor the calibration data processing.

http://www.roma1.infn.it/exp/atlas

L33. Laboratory of cryogenic detectors (INFN and Sapienza)

The laboratory develops cryogenic detectors for particle physics. It has been inaugurated at the end of 2016 and hosts a Oxford Triton 200 dilution cryostat. The cryostat is able to cool down an experimental volume of 24 cm diameter and 44 cm height to a base temperature of 10 mK. It uses a dry system based on a pulse tube to reach 3 K and then a 50 liters ^{3}He-^{4}He mixture to reach the base temperature. Two sets of thermal shields are available, one completely closed and the other open through windows to illuminate the detectors. The system is completely automated, it can be operated remotely and it enables fast operations: a full cool down and warm up requires about 2 days. A high-sensitivity leak detector is also available for debugging.

The laboratory is equipped with several electronic instruments, in particular for RF analysis. Among them we highlight: 9 GHz Vector Network Analyzer (VNA) and Spectrum Analyzer (SA), 9 GHz Local Oscillator with ultra-low phase noise, 4 low noise cryogenic amplifiers (LNA), Rubidium frequency standard, cryogenic circulators, generic RF electronics including amplifiers, attenuators and mixers.

The main activity of the lab is currently the development of Kinetic Inductance Detectors (KIDs). The cryostat is equipped with 4 RF lines and 2 optical fibers to calibrate the detectors with a room-temperature LED. The KID readout uses FPGA-based electronics, DAC, ADC and analog low-noise electronics.

Figure 1: From left to right: pumping rack, control rack, Oxford Triton 200 cryostat, magnetic shield, electronics rack.

The APE Laboratory (INFN)

The APE group is involved in research and development of High Performance Computing Architecture dedicated to engineering and theoretical physics applications (LQCD Lattice Quantum Chromodynamics, complex systems, Brain modeling). Several generations of parallel supercomputers, known as *APE machines*, have been built from the middle of 80's. The last APE custom supercomputer, *APENext*, showing a peak performance equal to 10 TeraFlops (10^{13} Floating Points Operations per second), has been installed in our department in 2006 and decommissioned in 2012.

More recently several different research lines have been followed and a number of new projects were launched focusing on:

a) HPC (High Performance Computing) system co-design: development of HPC-oriented low latency, high bandwidth, 3D Toroidal network (*APENet+*[1]) for hybrid PC clusters accelerated by Nvidia GPGPU (*QUonG* project) and scalable computing systems based on low power processor (*ExaNet* architecture);

b) HEP (High Energy Physics) computing: design of FPGA-based, reconfigurable architecture targeted to real-time systems (*NaNet*[2]). NaNet systems implement low latency, high performance detector read-out systems and low levelo trigger computing at HEP experiments.

c) Brain modeling and simulation: study of cortical learning and cognitive functions using fast and scalable simulation engine (*DPSNN code*) and analysis tools for experimental electrophysiological data (*SWAP tools*).

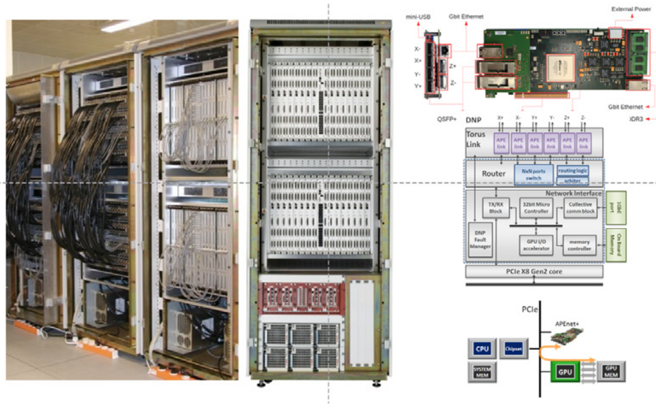


Figure 1: APE MPP and APEnet network card

In the past, group members participated with leadership roles to EU FP6 (SHAPES) and FP7 (EURETILE) projects in the area of embedded systems and HPC. From 2015, in the framework of EU H2020 FET-HPC project *ExaNeSt*[3] and *EuroEXA* the group has been active in design and prototyping of the next generation supercomputers at extreme scale (ExaFlops, 10^{18} Flops), based on low power microprocessors and custom networking.

In addition, NaNet activities allowed to assess the feasibility of GPU adoption for real-time track reconstruction in the online trigger system of the HEP experiment (*NA62*) at CERN and latterly, to push for the development of new generation FPGA-based high performance level-0 trigger system in the same experiment.

Furthermore, in 2016, team members start to coordinate and contribute to *WaveScales* and *WaveScales2*[4], sub-projects of EU FET Flagship *HBP* (Human Brain Project) a EU-funded research initiative involving more than 100 institutions all over Europe. WaveScales's aim at investigating the role of the different expressions of electrophysiological activity of the brain cortex during deep sleep. Current technological research efforts are in the area of hardware/software co-design for distributed spiking neural network simulations on parallel computing platforms and neuromorphic computing systems.

The APE group is currently composed of 9 staff researchers and 5 junior researchers with vertical expertise ranging from hardware and system software design to scientific applications coding and optimization.

The laboratory is equipped with storage and computing servers hosting CAD software to support ASIC, FPGA and hardware design. Multiple high end PC clusters are also present allowing for test and development of application software. A complete soldering station as well as real-time high performance oscilloscopes, logic analyzer and PCI Express protocol analyzer are used to test and verify hardware prototypes.

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http://apegate.roma1.infn.it/

L35. G31 Laboratory - Observational Cosmology

The Experimental Cosmology laboratory produces and tests instrumentation for observations of the sky at submillimeter and millimeter wavelengths. The group was funded by prof. Francesco Melchiorri and is involved, since 1980, in many experiments carried out different observational sites: ground-based, balloon borne and satellite. In this laboratory has been developed and actually built hardware for the MITO observatory on the Alps, the BRAIN experiment in Antarctica, the BOOMERanG balloon and the High Frequency Instrument aboard of the Planck satellite of ESA.

The laboratory is now leading the balloon-borne projects OLIMPO and LSPE, the COSMO experiment in Antarctica, and is a key partner of the QUBIC (ground-based in Argentina) and LiteBIRD (satellite) collaborations (see specific contributions).

The laboratory is equipped with facilities for: a) developing and assembling radiation filters and new technology detectors, like KIDs, specifically for mm-bands; b) testing and developing readout low noise electronics; c) cryogenic systems for ensuring low temperatures (down to 100 mK) for detectors and optical systems; d) calibrating photometers, polarimeters and spectrometers in the sub/mm spectral range.

Noticeable facilities are:

a) an evaporation chamber (Jep 600 by RIAL Vacuum) with gauge controller, thickness monitor and pumping systems; an optical microscope (Leica Wild M3Z), a lapping and polishing machine (mod. 920 by South Bay Technology Inc.), a wire saw, a hot press to produce polyethylene-embedded quasi-optical devices for the mm/submm range.

b) A small (4m $\times$ 3m) class 1000 (ISO-6) clean room is present in the G31 laboratory for operations with detector wafers and large focal planes. A microscope with micromanipulator, a wedge-bonder (model 5-0427-100B Bondtec), and a laser writer for maskless litography (MicroWriter ML3 from Duhram Magneto Optics Ltd) are the main instruments available in the clean room.

c) lock-in amplifiers (SR 850 and SR 830), oscilloscopes, AC and DC power suppliers, spectrum analysers, 24 bit data acquisition units. For the KIDs development we have a 20 GHz vector analyzer, a 40 GHz CW synthesizer, and a dedicated cryogenic system with low-noise HEMT amplifiers, and FPGA-based readout electronics (NIKEL and Roach). The VNA analyzer has an extension for the W band (75-110 GHz) for direct characterization of detectors.

d) Wet cryostats (Infrared Labs, QMC Ltd and self manufactured), cryogens transfer tubes, different size dewars for liquid nitrogen and liquid helium, 3 leak detectors (Alcatel and Pfeiffer). Three dry cryostats based on pulse tube refrigerators (Cryomec, Sumitomo, Vericold). Two of them include ^{3}He fridges for continuous operation at 0.3K without the need of ordering liquid Helium and liquid nitrogen, and one of them includes a dilution fridge for operation down to 55 mK.

e) lamellar grating Fourier transform spectrometer (mod. LR-100 by RIIC 50 mm stroke of the moving mirror); Large throughput Martin Pupplett Iterferometer (600 mm stroke of the moving mirror), 5-30 mW Gunn oscillators for the 90,150 and 220 GHz bands, 30 mW BWO source for the 350 GHz band, a 1-m in diameter off-axis parabolic f/2 mirror for generating plane mm-waves, cold and hot blackbody sources.

f) An all-purposes cryogen-free bolometer system from QMC instruments, covering the 100-1000 GHz band and operated with a PT refrigerator has been recently acquired, and is used for a variety of photometric, spectroscopic and polarimetric mm/submm wave measurements.

g) In the laboratory is also present a small machine shop including a combo mill-lathe and a drill press with accessory tools, for quick modification of mechanical parts.

Figure 1: *Left:* Class 1000 clean room. *Center:* Vector Network Analyzer and W–band extension. *Right:* Liquid–free 100mK refrigerator.

http://oberon.roma1.infn.it/

L36. NanoPhotonics Lab

Figure 1: Main lab of the NanoPhotonics group situated at the third floor of the Marconi building.

The labs of the NanoPhotonics group, established in 2018 and led by Rinaldo Trotta, are situated at the third floor of the Marconi building, Department of Physics. The current research activity focuses on the possibility of using semiconductor nanostructures, in particular semiconductor quantum dots and quantum emitters in two-dimensional materials, as sources of non-classical light for quantum information science and technology. The labs are equipped with state-of-the-art facilities for advanced quantum optics experiments with single and entangled photons, including:

- three optical tables, with three dedicated work-stations;
- Several continuous wave lasers and one pulsed Ti:Sa laser working in the $680-1080$ nm wavelength region with 80 MHz of repetition rate, 150 fs pulse duration, and 4 W of peak power at 800 nm;
- one closed-cycle cryostat working from 4 K to 350 K, and equipped with a low temperature objective (0.9 NA) and piezoelectric movements (x, y, z directions) with minimum step size of the order of 100 nm;
- one liquid helium flow cryostat working from 4 K to 300 K;
- One 750 mm monochromator equipped with a liquid-nitrogen cooled CCD and with three gratings with 300, 1200, and 1800 grooves per mm;
- 18-channel correlation electronics and several single photon detectors with time resolutions of 100 or 350 ps and quantum efficiency above 60% in the near-IR region;
- Two low-ripple high-tension (up to 1000 V) voltage supplies;
- One Michelson Interferometer.

https://trotta-nanophotonics.weebly.com/

L37. The Gravitational Wave Laboratory: Virgo

The VIRGO laboratory was conceived to develop crucial components to build the detectors devoted to the direct observation of gravitational waves. These are complex opto-mechanical systems, which must measure coherent states of oscillation of macroscopic objects such as the super mirrors of the Virgo interferometer: the goal is to measure displacements one thousandth smaller than the proton radius (10^{-18} m). The frequency range of the vibration measurements carried out in this laboratory covers an interval ranging from 30 mHz up to 2 MHz. To cover such a wide range, the laboratory is equipped with a large variety of sensors, both commercial and developed ad hoc by our research group. Vibration measurements are made using piezoelectric ceramics and optical systems. For the development of this type of sensors the laboratory is equipped with a 1.8 $m \times 1$ m optical bench and infrared laser with high stability in frequency and amplitude. The signals of these sensors are amplified and detected through dedicated acquisition systems that change according to the frequency range considered.

In the Virgo lab our scientific activity is devoted - to develop optical configurations to circumvent the quantum limit of the detector via the production of squeezed electromagnetic vacuum; - to beat the thermal noise of the detector by studying the dissipation mechanisms associated to the last stage of the mirror suspension (the Virgo payload).

The first scientific goal is pursued by developing a opto-mechanical system installed on a dedicated optical bench hosted in a vacuum chamber of around 3 m^3. The set-up is a Michelson interferometer with high finesse Fabry - Perot (FP) arms and suspend optical elements. In particular, to reduce the thermal noise, the FP mirrors are suspended with silica fibers.
The laboratory is equipped with others high vacuum chambers used to test or single components or even the entire Virgo payload. The volumes of these vacuum containers are respectively
- ~ 10 m^3 equipped with rotary pumping systems / roots / molecular turbo,
- ~ 5 m^3 equipped with scroll / molecular turbo pumping systems,
- ~ 1 m^3 equipped with rotary/ molecular turbo pumping systems.

In addition two cryogenic systems are interlocked with pulsed tube refrigerators (PT), which permit to carry on studies down to 4 K:
- the first PT is inserted in a free cryogen fluid cryostat, which includes a vacuum chamber hosting the sample. The cryostat is equipped with an active compensation system of the vibrations generated by the PT in the frequency range around 1 Hz. The experimental apparatus, developed by our group and called Vibration Free Cryostat -VFC, permits to carry on measurements in a quite cryogenic environment, free from residual vibrations;
- the second is a smaller and simpler cryostat, but it is also equipped with another PT. This system is mainly dedicated to test material properties of the suspension elements of the payload. We used it to qualify thermal conductivity and dissipation of amorphous and crystalline samples. In the last month we tested also the elastic joints of low temperature inclinometers produced via additive manufacturing technique in collaboration with the department of Mechanics and Aerospace of our university.

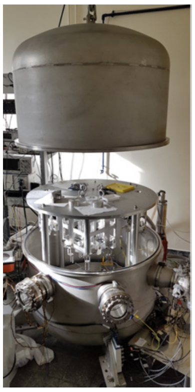

Figure 1: On the left the FabryPerot-Michelson suspended interferometer hosted in the 1 m^3 vacuum chamber; on the right the Vibration Free CryostaT equipped with a Sumitomo Pulse Tube .

To complement this instrumentation, the laboratory is equipped with vertical cryostats for liquid helium, built in fiberglass and equipped with a vacuum chamber immersed in the cryogenic liquid. In this way the samples being measured can be inserted in a volume available in high vacuum or in an inert atmosphere. These volumes vary according to the type of cryostat considered The largest has a useful volume for the sample of ~ 0.5 m^3 and a capacity of the liquid helium pocket of ~ 200 lt. In this cryostat we will carry on the thermal modulation test of the superconducting sample that we will use in *Archimedes*, the experiment conceived to measure the weight of the electromagnetic vacuum.

L38. Laser Transmission Spectroscopy Laboratory

The study of biological matter by optical spectroscopies can provide valuable information on the composition, behaviour and interaction of biomolecules and biosystems in complex environments. In this framework, it is relevant to carry out the experimental investigation at conditions as close as possible to the physiological ones. The Laser Transmission Spectroscopy (LTS) laboratory is dedicated to the study of the optical properties of biomolecules and biosystems (vescicles, bacteria and cells), in liquid environment and at controlled temperatures.

At the core of the LTS setup is a tuneable laser source, emitting ns light pulses at wavelengths from the ultraviolet-visible to the infrared. The LTS technique allows determining the density distribution of colloidal suspensions by measuring the transmittance spectrum of the laser beam through the suspension. The particle density distribution as a function of their size can be calculated through the Beer-Lambert law. Compared with traditional scattering techniques (static and dynamic light scattering), LTS allows not only to assess the size and shape of the particles in suspension but also to determine their absolute concentration [1].

This is very powerful for both soft matter physics and biophysics. In particular, the high sensitivity of the technique enables the study of lipid nanovesicles (*e.g.* nanocarriers, exosomes) at very low concentrations, opening new scenarios in therapeutic and diagnostic applications [2,3].

In our laboratory a LTS apparatus, combined with a high-sensitivity, high-resolution conditioning optoelectronic system, is available [1]. The system is capable of measuring very small changes of the light power transmitted through the sample under analysis. Measurements on drug carrier liposomes have allowed to derive the vescicle concentrations in relation to the expected concentration, based on the synthesis paramenters [3]. Some results are displayed in Figure 1. The ultimate upgrade of the setup, carried out in the Spring 2019, grants the extension of the laser tunability down to 200 nm wavelengths. This is expected to boost the detection limit in terms of size ($d < 20$ nm) or concentration ($c < 10$ aM) [4].

Moreover, a setup dedicated to the measurement of Raman scattering and fluorescence emission on liquid samples is currently under construction. Various continous-wave laser lines, spanning over the whole visible range, are available for the sample excitation, allowing in principle the combined measurement of both fluorescence and Raman spectra. Controlled sample environment, in terms of temperature and pressure, is available.

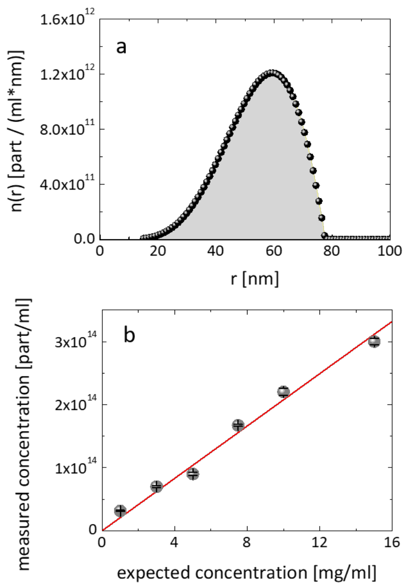

Figure 1: (a) Density distribution as extracted from LTS measurements on a suspension of drug carrier liposomes. From the integral of the function (gray area) one obtains the absolute vesicle concentration in the dispersion. (b) Correlation between the vescicle concentration estimated by LTS measurements and that expected by the growth parameters adopted for their synthesis.

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L39. Quantum Optics Laboratory

The Quantum Optics laboratory has been engaged in experimental and theoretical research during the last 20 years with state-of-the-art works in the Quantum Optics and Quantum Information field. The laboratory is equipped with two optical experiments running independently.

The first experimental activity is aimed at the generation and manipulation of multiqubit path and polarization hyperentangled states. An UV laser (GENESIS, Coherent Inc., Santa Clara, USA) of 100mW, wavelength 355nm, Continuous Wave (CW) operation, $< 10GHz$ bandwidth, vertically polarized, is used to excite a non-linear crystal (NC), which produces by Type-I Spontaneus Parametric Down Conversion (SPDC) pairs of horizontally polarized photons of 710nm, emitted over a cone defined by the crystals Phasematching (PM). A double passage scheme is exploited to generate polarization entanglement while a mask selecting four modes on the PM cone produces path entanglement. This source effectively produces a four-qubits hyperentangled state encoded over two photons. This laboratory is equipped with photonic integrated Beam Splitters (BS) fabricated by the femtosecond laser writing technique. The hyperentangled state is injected into the chip through a custom made support for a 4-independent fibers array, and Graded Indexed lenses are used to couple the photons into the single mode fibers.

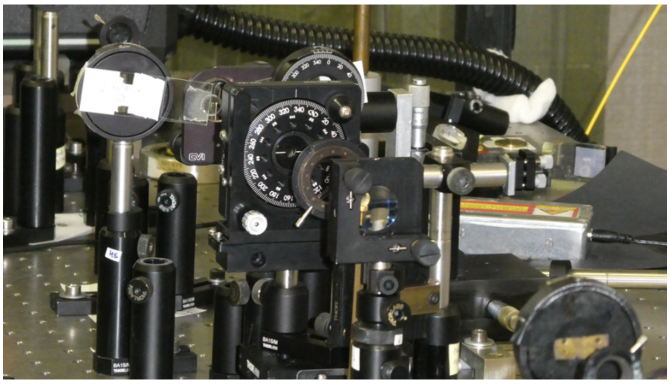

Figure 1: Two photon path-polarization hyperentanglement source.

The second experimental activity is focused on the implementation of an all-optical Quantum Walk. The setup consists of two displaced-multi-pass Sagnac interferometers (SIs) connected to each other through a common BS, as shown in Figure 2. Here, all beam trajectories are initially prepared in a collinear regime, and after a single mirror translation in the first SI (SI1), one obtains the displaced loops lying in a single transmission plane. This configuration is equivalent to a chain of Mach-Zehnder interferometers (MZIs), with intrinsically stable phases that can be addressed independently in each mesh of the chain. The number of consecutive passages of light through the BS of Figure 2 determines unambiguously the length of the chain. The one-dimensional QW can be realized including as a further spatial dimension the vertical direction, perpendicular to the horizontal plane of Figure 2. This is achieved by using suitably-designed beam displacers (BDs) intercepting some of the light trajectories in both SIs, namely clockwise trajectories in SI1 and counter-clockwise ones in SI2. For each passage of light through the BD, the number of QW sites grows by one unit, and the number of possible paths that the walker can go through is equal to 2N, where N is the total number of steps.

Thus, our scheme exploits the three dimensions of the same BS to increase the number of sites and steps of the QW. Individual phases can be easily addressed by using independently-rotating thin glass plates (RPs) in each QW mesh point. In the system, BDs are realized by properly-oriented glass prisms. Additionally, the output radiation of each step can be extracted for measurement by a set of moving mirrors. One or two photons can be injected in the setup. In order to generate them, single mode CW diode laser (TopMode-405, Toptica, Munich, Germany) with 25mW, at 405nm, is injected inside a periodically poled NC. Then, by Type-II SPDC photon pairs of horizontal and vertical polarization are generated at 810nm and emitted collinearly in one intersection of two cones determined by $QuasiPhasematching$.

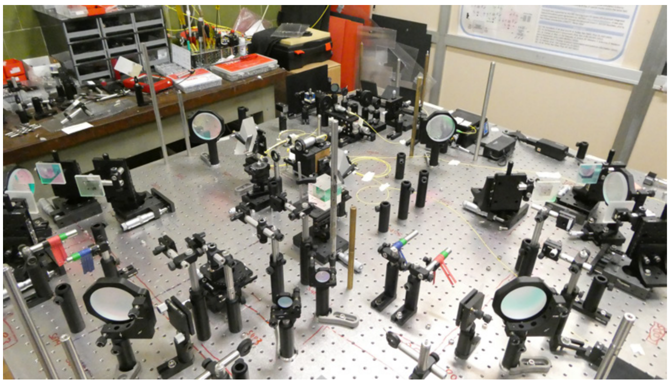

Figure 2: All optical Quantum walk reproduced in the lab.

L40. Quantum Information and Technology Lab

The Quantum Information and Technology Lab, led by Fabio Sciarrino, is based at the Department of Physics. The research group has pioneered the use of photonics for quantum information. Significant contributions in the last few years include investigations on the foundations of quantum mechanics (including entanglement, contextuality and causal structures) and quantum information with orbital angular momentum of photons. Recently, the group has introduced, in team with Istituto di Fotonica e Tecnologie - CNR, the use of fs-written for quantum photonics. This allowed to carry out several implementations of quantum information and simulation protocols on chip, including the first Boson Sampling experiments, both in the visibile range and at telecom wavelenghts.

The Quantum Information and Technology Lab runs 4 laboratories equipped with several laser systems (including 3 Coherent MIRA, 4 Coherent VERDI, 1 Coherent REGA), more than 30 single-photon detectors for the visible range, 3 single-photon detectors in the IR domain, 6 counting modules (from Id Quantique). Each laboratory is equipped with advanced optical and mechanical precision instruments, including optical fibre and waveguide coupling, spatial light modulators.

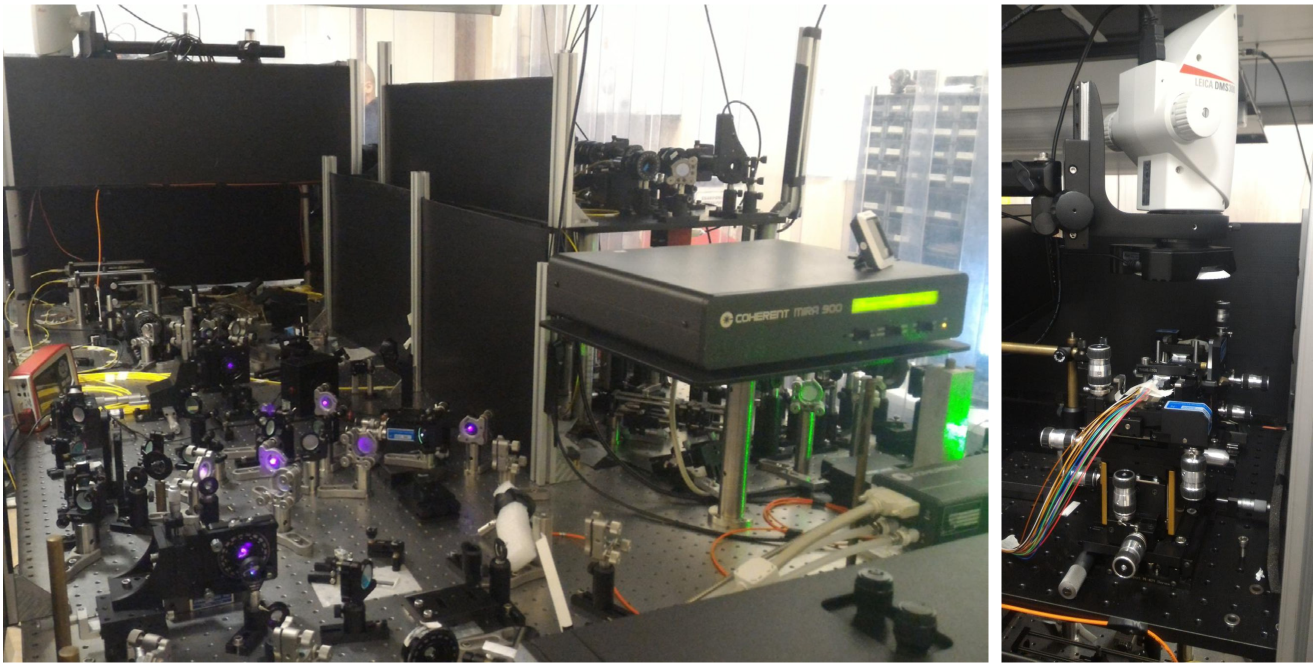

Figure 1: Left: overview of the experimental apparatus for the generation of single-photon states. Right: equipment for manipulation of integrated circuits.

One laboratory is dedicated to advanced investigations on multiphoton interference. The laser system is composed of a 18 W duplicated Nd:Yag laser (VERDI) pumping a Ti:Sa source of femtosecond pulses (MIRA). The output field is a train of 250 fs pulses at a repetition rate of 76 MHz, achieving an output power of 2 W. The laboratory includes three photon-pair sources based on non-linear crystals that can operate simultaneously, and an advanced coupling stage for integrated devices.

A second laboratory is dedicated to quantum simulation and quantum metrology protocols, and to the implementation of quantum information tasks at telecom wavelength. The laser system is composed of a 18 W duplicated Nd:Yag laser (VERDI) pumping a Ti:Sa source of femtosecond pulses (MIRA HP). The output field is a train of 250 fs pulses at a repetition rate of 76 MHz, achieving an output power of 3.5 W. The laboratory includes a photon-pair source for the visible range, and a photon-pair source at telecom wavelength, with two independent advanced coupling stages for integrated devices.

The third laboratory is dedicated to the investigations on the foundations of quantum mechanics. It is equipped with two single-photon sources, spatial light modulators for manipulation of orbital angular momentum, and a full coupling stage for integrated devices. The laser system is composed of a duplicated Nd:Yag laser (VERDI) pumping a Ti:Sa source of femtosecond pulses (MIRA).

The fourth laboratory is currently dedicated to quantum technologies, and in particular it focuses on engineering quantum states in the orbital angular momentum degree of freedom. It is equipped with a Sagnac-based polarization-entangled photon-pair source in the visible range, and optical components for the manipulation of orbital angular momentum including spatial light modulators.

http://www.quantumlab.it/

Dissemination

Outreach and Technology Transfer

The so called "third mission" of the University is defined as to encourage the application, dissemination and transfer of knowledge and technologies to contribute to the social, cultural and economic development of society. The Physics Department promotes these activities consisting in the organisation of events for schools, training for teachers, outreach activities for the general public and collaboration with industries.

Traditionally, the most important and well consolidated activities are those aimed at students and teachers. However, the Department is open to collaboration with industries and companies and has recently started to encourage the organisation of meetings between all the possibly interested actors, such as students, researchers and industry representatives.

The main lines of actions are summarised below.

- So called "**third parties**" (*conto terzi*) consists of activities made in the interest of third parties customers, such as industries or companies, compatible with the research interests of the Department. Because, traditionally, scientific bodies and manufacturers were not well connected in the past, only few contracts of this kind were signed in the recent past. However, the Department is open to a more strict collaboration with third parties for the economic growth and foster new collaborations.

- As an example of the activities aiming at reinforcing the connection between science and production, we organised events dedicated to our students inviting former physics students now working for the industry to give advices for the development of new careers. New technologies, in fact, are making possible for physicists to develop new career paths to apply their knowledge in fields traditionally not covered by our students, such as finance, artificial intelligence, data mining, etc.. Those events also represented a way to establish and maintaining contacts between us and third parties.

- The activities dedicated to schools, whose aim is mainly to guide the choice of the students to the best university career, are numerous and diverse. In particular, we currently support two main programs: "Lab2Go" [1] and "Art & Science Across Italy". The first consists in collaborating with high schools for keeping the documentation of the physics laboratory updated and making it public, such that we now have a network of more than 80 schools whose laboratory is fully documented and open to collaborations with other schools (`https://web.infn.it/lab2go/fisica`). The second is a project of INFN and CERN to pursue the STE(A)M paradigm for a better and more integrated scientific education, of which our Department is an important partner, together with Accademia di Belle Arti di Roma. The project (`https://web.infn.it/artandscience/index.php/it`) consists of a first phase of physics and artistic education, after which students design and realised an artwork to be shown during a public exhibit that will take place in an important location in January 2020. Artworks will be evaluated by a local committee. The best 8 artworks will be part of a national event in Napoli, in May 2020, where an international committee will choose 10 among the artworks coming from the various Italian sites, whose authors will spend a week at CERN for a master.

Figure 1: The closing ceremony of the Lab2Go 2018 project at Sapienza.

- Besides the main projects, two events are now part of the tradition: the "Masterclass of Particle Physics" (`https://physicsmasterclasses.org`) and the "International Cosmic Day" (`https://icd.desy.de`). The first, coordinated by IPPOG worldwide, each year involve more than 13 000 high school students in 55 countries for one day in order to unravel the mysteries of particle physics. Lectures from active scientists give insight in topics and methods of basic research at the fundaments of matter and forces, enabling the students to perform measurements on real data from particle physics experiments themselves. At the end of each day, like in an international research collaboration, the participants join in a video conference for discussion and combination of their results. The International Cosmic Day will bring students, teachers and scientists together to talk and learn about Cosmic Rays. During the International Cosmic Day (ICD) students will carry out measurements and observations and get in contact with groups all over the world.

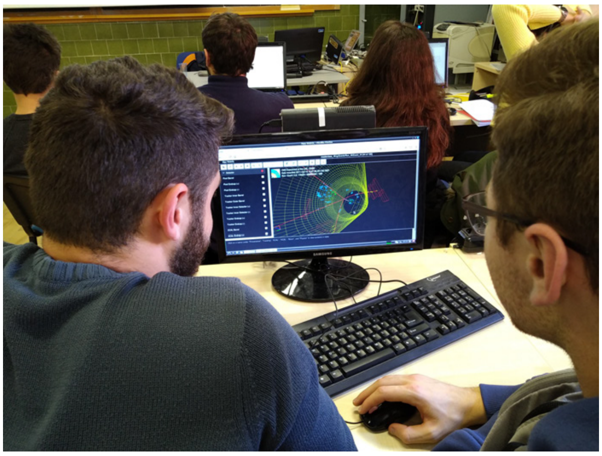

Figure 2: Students working on events collected at LHC during the masterclass on particle physics.

- Activities dedicated to teachers consists of a series of seminars about modern and contemporary physics, often in collaboration with the Department of Mathematics. Another important goal of our actions is to promote laboratories activities among students. To this purpose we organise events during which we perform experimental activities. In particular, the "Schools of Physics with Arduino and Smartphones" are now an internationally recognised event consisting in teaching Arduino programming during a three days workshop. In this workshop teachers are asked to design, make and document quantitative experiments to be realised using Arduino and/or smartphone, together with readily available materials.

Figure 3: Teachers participating at the III edition of the School of Physics with Arduino and Smartphones.

- We collaborated with external bodies such as Accademia di Belle Arti di Roma, either as content providers (see, e.g. the "FisicaMente" project - `http://www.wunderbarproject.it/2018/05/07/fisicamente-eureka-roma-2018-dipartimento-fisica-sapienza-roma`) or as a partner for our projects (such as in the case of "Art & Science Across Italy). We also collaborate with AIF (`https://www.aif.it`) to practise high school students to the participation to the Physics Olympiads (`http://ipho.org`).

- Many events are dedicated to the general public. In particular, we cite two activities that was part of the "Eureka" project during the last two years: "I mille nomi di Fermi" dedicated to the celebrations of the 80 years from the Nobel Prize to the Italian scientist, and "ICARO2019" to celebrate 50 years from the landing on the Moon. FISICAST [2] is a popular podcast about physics realised under the coordination of our physicists.

- As part of the university involvement in the school–work experience, many researchers of the Department proposes activities to high school students ranging from the analysis of data to the documentation of scientific work.

Our Department hosts, since its constitution in 2018, the AMALDI Research Center, an interdisciplinary center for both Gravitation Physics and Astrophysics. Besides the scientific activities, the AMALDI Research Center is involved in outreach activities, in cooperation with the Department of Physics, the most notable of which was a seminar by the Nobel Prize Barry Barish open to the public.

Finally, even if not formally part of the Department, the Physics Museum of Sapienza is integrated into it and managed by physicists. The museum receives annually many visits, especially from schools (even foreign ones). Schools can profit from free guided tours within the museum collections that are among the richest ones in the world and claims several rare instruments as well as some unique ones as, e.g., the harmonium designed by Pietro Blaserna for the study of the musical scales that was recently restored.

The Physics Museum also holds all the instruments originally used by Enrico Fermi and his group to discover the artificial radioactivity induced by neutrons and the beam splitter of the Virgo experiment used in the preparation run before the discovery of the first gravitational wave.

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G. Organtini
Outreach and Technology Transfer, G. Organtini[1]

`https://www.phys.uniroma1.it/fisica/node/10049`

Collaborations with external bodies

The Department of Physics collaborates with several external bodies for outreach activities, either at institutional level as well as via the collaboration of single physicists.

Events for high school students

Besides periodic activities devoted to guide high school students towards the choice of their undergraduate studies, like **Porte Aperte**, **Incontri di Orientamento** and training for **Olimpiadi della Fisica**, the Department of Physics is committed with several activities for the dissemination of the scientific results, in collaboration with other subjects, both for students and for general public, as, e.g., the **European Research Night**.

Art and Science across Italy is an INFN [1] nationwide project within the framework of the CREATIONS [2] EU project to which local branches of 10 cities participate: Firenze, Genova, Milano, Napoli, Padova, Pisa, Potenza/Matera, Roma, Torino and Venezia. The project in Roma is supported by the local branch of INFN, as well as from the Department of Physics and Accademia di Belle Arti di Roma [3] and aims at disseminating scientific knowledge among students irrespective of their initial attitudes towards scientific disciplines, by means of art, inspired by the STE(A)M movement.

During the first year of the project, students attend seminars and lectures about scientific and artistic topics, visit museums and laboratories, etc.. Then, they are asked to design an artwork (of any kind: paintings, sculptures, videos, literature, etc.) that will be exposed at an important location of the city during a public exhibit. For Roma, this is foreseen on January 2020 in the *ex Mattatoio* museum. A panel of experts will evaluate the artworks and will select 8 of them to be exposed at a nationwide exhibit in Napoli. There, a second panel will declare ten winners who will be hosted for a week at CERN for a master on art and science.

The project started in 2018 with 17 schools in the roman area. 1 058 students were involved in the first phase, while 65 artworks are expected for the 2020 exhibit.

Events for the general public

In 2018 we celebrated the 80^{th} anniversary of the Nobel Prize to Enrico Fermi with a series of initiatives called **I Mille nomi di Fermi** together with Teatro Mobile [4], a theatrical company, with which we organised a set of ten events composed of a guided tour around physics laboratories, designed as a theatrical performance, followed by a seminar on a given aspect of the Fermi's findings. The last event comprised a stage performance.

With Accademia di Belle Arti di Roma we offered a set of seminars to students of the Accademia as well as to general public about the interrelationship between Art and Science, with the participation of artists and scientists (**FisicaMente**). The final event was realised by the students of Accademia di Belle Arti who designed an original tour of the Physics Museum where selected pieces of the collections were illustrated by artistic performances.

In 2019, Teatro Mobile the space exploration was celebrated with a new project together with Teatro Mobile called **ICARO 2019**, during which the public could be introduced to multimessenger physics.

Nobel Prize Prof. Barry Barish was hosted for an event in 2018 (**Gravitational Wave Day**) in collaboration with the Amaldi Research Center [5]. The event was attended by not less than 500 persons and comprised an experimental session during which we performed experiments to explain the behaviour of waves to introduce the seminar about gravitational waves by Prof. Barish.

A series of lectures, open to the public, made by important scientific figures are organised each year about a selected topic under the auspices of the **Cattedra Fermi**. These lectures were given by Luciano Maiani, Gabriele Veneziano, Roberto Car, Francesco Sette and Giovanna Tinetti.

We collaborated with the **Media Art Festival** and provide speakers for various **Caffè Scientifici**. Scientific theatre was also an activity conducted by physicists of the Department of Physics, as well as the running of a podcast (**FISICAST**) [6], in which the authors talks about physics in an original style, using an informal language, but still preserving scientific rigour.

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Authors
G. Organtini[1]

Modern Physics for High School Students

The Department of Physics of Sapienza Università di Roma organises several activities dedicated to high school students. These activities are intended to provide enough information to students to let them choose consciously which university career to pursue as well as to complete their physics education with topics usually not covered in schools.

Most of these activities are done under the auspices of "Piano Lauree Scientifiche" (PLS): a ministerial plan to encourage enrolment in scientific faculties. In particular, two activities have been appreciated by both students and teachers for their international character and because they are strongly motivating. They are the **International Masterclass of Particle Physics** and the **International Cosmic Day**.

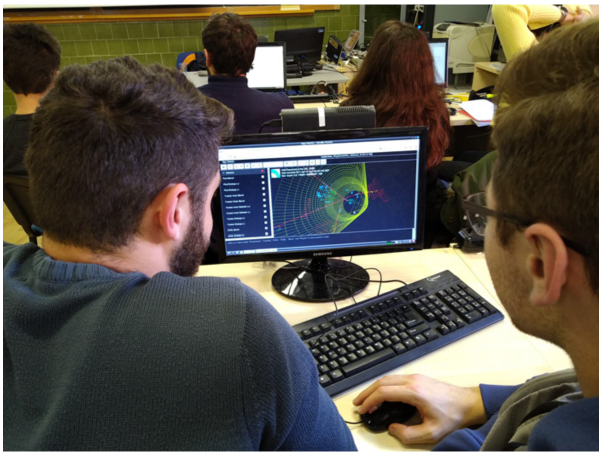

Figure 1: Students selecting proton–proton collision events during the International Masterclass on Particle Physics.

The first consists in a full day in which up to 80 students are welcome in the Department. During the morning session, they attend lectures and seminars about the standard model of the particle physics, the physics of particle accelerators and that of particle detectors. They are then trained on the working principles of a specific LHC detector: ATLAS or CMS, depending on the year.

After lunch, students are assigned to groups of two students in a laboratory. Each group has a PC in front of it, where real proton–proton collision events collected at LHC can be analysed by means of a visualisation tool that draws particle trajectories and graphically represents the interactions of the particles with the detector. Students, based on the information received, must identify the type of particles produced in the events. Each group analyses a different set of data, then results are collected together to derive real measurements. For example, one can measure the mass of new particles spotted in the events, such as the J/Ψ, the Υ, the Z boson or the Higgs boson. Once can also measure the ration of W^+ over W^- production as well as the ratio between the weak coupling constant of muons and electrons with intermediate vector bosons.

At the end of the day results are compared with those obtained in other four or five sites in Europe during a videoconference moderated by CERN. The activity is coordinated by IPPOG [1].

Figure 2: Students attending lectures during the International Cosmic Day.

During the **International Cosmic Day** (ICD) [2], students attend lectures and seminars about the physics of cosmic rays and its history.

This activity is internationally coordinated, too, by the DESY laboratory in Germany. With respect to many other places, Roma is different since the ICD is very popular among our schools and participation is very wide. Typically more than 200 students attend this event and that precludes the possibility for them to make some hands on activity.

However, our ICD is organised such that students can look at real cosmic rays passing through a spectacular spark chamber provided by INFN that shows the tracks of cosmic particles in a stunning fashion. Moreover, we usually show data taking using ArduSiPM: a compact and cheap device developed by INFN to detect cosmic particles using an Arduino board, coupled with a small plastic scintillator paired with a silicon photomultiplier (SiPM).

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Physics with Arduino and Smartphones

One of the most successful activities performed under the auspices of the *Piano Lauree Scientifiche* (PLS), especially in terms of effectiveness, is the organisation of the **schools of physics with Arduino and smartphones** for teachers.

Smartphones are currently so pervasive that we can easily assume that every student have at least one portable device in his/her pocket, while Arduino boards can be regarded as affordable and easy to use tools for data acquisition. We then started a training program for teachers consisting in the organisation of three full days activities during which teachers can learn how to use smartphone and Arduino boards to perform interesting, precise and accurate physics experiments. Since the third edition, the school has been configured as a **Corso di Alta Formazione** that leads to an official recognition of the merits for the participants.

Figure 1: A moment during the school of physics with Arduino and smartphones.

The school is organised together with **Fondazione Mondo Digitale** [1] and **INFN** [2]. In particular, Fondazione Mondo Digitale provides a FabLab where the activity is done as well as technicians to operate the FabLab tools, when needed.

The first half day, participants attend lectures about Arduino programming and the usage of the sensors in the smartphones as physics instruments. We support a team in Aachen who developed a dedicated App (`PhyPhoX`) to this purpose, for which we act as *Ambassadors* in Italy. Starting from the afternoon of the first day, activities are all hands-on. Teachers, divided in small groups of two or three teachers, are asked to design an experiment on any aspect of physics. Tutors (among which there are few physics students as well as previous participants) help teachers in properly designing the experiment strategy.

The first part of the morning of the second day is devoted to the *shopping session*. The whole group visits an emporium where teachers have a small budget to buy whatever they need to perform their experiments.

Figure 2: Group photo of attendees at the School of Physics with Arduino and Smartphones.

We deliberately do that to show that good physics experiment can be done using commonly available materials. After the shopping session, we return to the FabLab where teachers starts assembling the experiments. Here, they receive the help of tutors (especially on programming the boards) and FabLab technicians that can rapidly realise mechanics assemblies, if needed.

The whole second day, as well as the third morning, are then devoted to the construction, execution and analysis of the experiments. The last afternoon each group presents its experiment to the others. Moreover, each group is asked to provide a standardised documentation to be published on the website of the Department of Physics [3].

This activity is going to be exported in several countries all around the world. We have contacts in France, Germany, Norway, USA, Uruguay and Cuba. The network is rapidly growing and exchange of good practice is frequent. Often, foreign guests are invited to give a short talk to the school. The second edition of the school had the honour of hosting David Cuartielles, one of the Arduino inventors, as a speaker.

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4. Organtini, G. (2018). Arduino as a tool for physics experiments. Journal of Physics: Conference Series. 1076. 012026. 10.1088/1742-6596/1076/1/012026.

Authors

G. Organtini[1]

International Day of Women and Girls in Science 2019

February 11 was named "International Day of Women and Girls in Science" by the United Nations with the aim to "... achieve full and equal access to and participation in science for women and girls, and further achieve gender equality and the empowerment of women and girls". To celebrate this important occasion, in 2019 the Department of Physics of Sapienza has organized an event for students, researchers, and all interested people with the aim of sharing data, highlighting stereotypes and discussing positive actions through comparison with others national and international realities. Female PhD students and postdoctoral fellows of the department have promoted and organized the exhibition: "da Roma al Mondo" to underline how some women scientists who studied at the Department of Physics in Sapienza achieved outstanding results in different fields of physics. Individual interviews allowed to discuss the difficulties and successes encountered during their career paths and provided illuminating advices for young scientists.

Finally, we have edited the booklet: *Physics@Sapienza: the women's view* reporting on the research activity of all staff women scientists working in the Department. The booklet shows the women's rich and original contribution to the research activities of the Department and may represent a useful reference for female students and an inspiration for young women who aspire to a career in science.

Figure 1: *Left:* The GIPSI group *Right:* Valeria Ferrari moderates the round table in a crowded Amaldi lecture all.

Authors
GIPSI (Gender and Diversity in Physics at Sapienza)
`https://sites.google.com/uniroma1.it/gender-and-diversity-physics/home`

Grants and Awards

1 European funding

ERC Starting Grant 2017 - European Research Council
DarkGRA ”Unveiling the dark universe with gravitational waves”
Principal Investigator: Paolo Pani
Local fund: 1,340,000 euro

H2020-MSCA-IF-2017
FunGraW ”Fundamental physics in the era of gravitational-wave astronomy”
Principal Investigator: Paolo Pani, Researcher: Richard Brito
Local fund: 169,000 euro

RISE (Research and Innovation Staff Exchange)
Name: StronGrHEP
Principal Investigator: U. Sperhake; Local coordinator: L. Gualtieri
Local Funds: 27,000 euro

ERC Advanced Grants 2018 - European Research Council
SYGMA
Principal Investigator: Roberto Di Leonardo
2.397.500 (1.020 Dip Fis) ATTRACT.eu, PROTEUS, Roberto Di Leonardo, 100.000 euro

ERC Proof of Concept 2017 - European Research Council
ADMIRE
Principal Investigator: Roberto Di Leonardo
Local fund: 150,000 euro

H2020-MSCA-ITN-2018
ACTIVE MATTER
Node Coordinator: Roberto Di Leonardo
Local fund: 261,500 euro

ERC Starting Grant 2017 - European Research Council
CALDER
Principal Investigator: Marco Vignati
Local fund: 420,000 euro

Subcontratto di Servizio con SERCO per ESA
Satellite Calibration/Validation and Urban Environment Monitoring Super-Site: Boundary-layer Air Quality-analysis Using Network of INstruments (BAQUNIN)
Principal Investigator: Marco Cacciani
Local Funds:108,000 euro

H2020 FET Quantum Technologies
PhoQus
Principal Investigator: Claudio Conti
Local fund: 150,000 euro

ERC Consolidator Grant - European Research Council
CRYSBEAM
Principal Investigator: Gianluca Cavoto
Local fund: 2,000,000 euro

ERC Proof of Concept (2016-2018) - European Research Council
PROCEEDS
Principal Investigator: Irene Giardina
Local fund: 150,000 euro (fondi su CNR)

ERC Advanced Grant - European Research Council
Cripherasy
Principal Investigator: Giorgio Parisi
Local fund: 2,098,800 euro

ERC Advanced Grant - European Research Council
LoTGlasSy
Principal Investigator: Giorgio Parisi
Local fund: 1,760,000 euro

ATTRACT–EU
NANOUv
Principal Investigator: Gianluca Cavoto
Local fund: 20,000 euro

Marie Skodowska-Curie Individual Fellowship (2019-2021)
"Strain Engineering of Light-Emitting Nanodomes (SELENe)"
Researcher: Alessandro Surrente, Supervisor: Marco Felici
Local fund: 171,473.28

MatWork
Principal Investigator: Prof. Sergio Frasca
Local fund: 25,000 euro

NEWS 2018
Principal Investigator: Fulvio Ricci
Local fund: 11,000 euro

NEWS 2019
Principal Investigator: Fulvio Ricci
Local fund: 10,770 euro

2 Funding from Italian Ministry of Research (MIUR)

Rita Levi Montalcini Fellowship
Principal Investigator: Francesco Pannarale
Local fund: 197,973 euro

Rita Levi Montalcini Fellowship
Principal Investigator: Lorenzo Rovigatti
Local fund: 211,173 euro

PRIN 2017
FERMAT
National Principal Investigator: S. Barone (SISSA); Local Principal Investigator: Carlo Mariani
Local fund: 155,000 euro

PRIN 2017
Advanced techniques for a next generation cryogenic Double Beta Decay experiment
Principal Investigator: Fernando Ferroni
Local fund: 244,000 euro

PRIN 2017
LISA - PHASE A: Gravitational Waves from Massive Black Holes in The Gravitational Universe
National Principal Investigator: Monica Colpi - Local Coordinator: Paolo Pani
Local fund: 211,000 euro

PRIN 2017
Principal Investigator: Carlo Mariani
Local Funds: 155,202 euro

PRIN 2017
QUANTUM2D
Principal Investigator: Francesco Mauri
Local Funds: 257924 euro

PRIN 2017
PELM
Principal Investigator: Claudio Conti
Local fund: 183,543 euro

PRIN 2017
COSMO - COSmological Monopole Observations
Principal Investigator: Paolo de Bernardis
Local fund: 258,541 euro

PRIN 2019
ENIGMA
Principal Investigators: Luca Naticchioni, Paola Leaci
Local fund: 118,000 euro

Contratto di Ricerca per PNRA
CLouds And Radiation in the Arctic and Antarctica, CLARA2
Principal Investigator: Marco Cacciani
Local fund: 181,500 euro

Grant, PLS (Piano Lauree Scientifiche)
Principal Investigator: Josette Imm (CT)
Local fund: 30,000 euro

3 Funding from Sapienza

Ateneo 2017
Observational Cosmology at millimeter wavelengths
Principal Investigator: Paolo de Bernardis
Local fund: 37,000 euro

Ateneo 2017
"Tailoring the electronic properties of transition-metal dichalcogenides via hydrogen-assisted phase, strain, and band gap engineering"
Principal Investigator: Marco Felici
Local fund: 13,400 euro

Ateneo 2017
Principal Investigator: Riccardo Faccini
Local fund: 13,500 euro

Ateneo 2017
Gravitational waves as probes of fundamental physics
Principal Investigator: Paolo Pani
Local fund: 13,700 euro

Ateneo 2017
OBSERVATIONAL COSMOLOGY AT MILLIMETER WAVELENGTHS
Principal Investigator: Paolo de Bernardis
Local fund: 37,000 euro

Ateneo 2017
CNT for Dark Matter
Principal Investigator: Gianluca Cavoto
Local fund: 60,000 euro

Ateneo 2017
Principal Investigator: Irene Rosana Giardina
Local fund: 35,750 euro

Ateneo 2017
High-Tc Superconductivity at Extreme Pressures in Ternary Hydrides
Principal Investigator: Lilia Boeri
Local funds: 12,000 euro

Ateneo 2017
Principal Investigator: Fulvio Ricci
Local fund: 25,000 euro

Ateneo 2017
Study of memory effects in the long time out of equilibrium dynamics of spin glass models
Principal Investigator: Vincenzo Marinari
Local fund: 13,800 euro

Ateneo 2018
Caratterizzazione di calorimetri criogenici per la ricerca del neutrino di Majorana
Principal Investigator: Fabio Bellini
Local fund: 12,500 euro

Ateneo 2018
Principal Investigator: Riccardo Faccini
Local fund: 38,500 euro

Ateneo 2018
Sviluppo di algoritmi innovativi di Deep Learning per dati altamente sparsificati e applicazione all'identificazione di particelle prodotte nei decadimenti del bosone di Higgs negli esperimenti a LHC
Principal Investigator: Stefano Giagu
Local fund: 12,500 euro

Ateneo 2018
Isotropic and anisotropic spectral distortions of the Cosmic Microwave Background: data analysis for the COSMO and OLIMPO experiments
Principal Investigator: Silvia Masi
Local fund: 10,000 euro

Ateneo 2018 Principal Investigator: Antonio Polimeni
Local fund: 40,000 euro

Ateneo 2018
"Search for new resonances in unexplored trijet final states at LHC"
Principal Investigator: Santanastasio Francesco
Local fund: 12,500 euro

Ateneo 2018
Complex nonlinear rogue waves and replica symmetry breaking

Principal Investigator: Claudio Conti
Local fund: 13,400 euro

Ateneo 2018
Principal Investigator: Vincenzo Marinari
Local fund: 10,000 euro

Ateneo 2018
New high-pressure phases of complex hydrides: high-temperature anharmonic superconductors
Principal Investigator: Lilia Boeri
Local funds: 12,500 euro

Grandi Attrezzature 2018
A Scalable Artificial Intelligence system for Machine and Deep Learning Research and Training at Sapienza Universia di Roma
Principal Investigator: Stefano Giagu
Local fund: 300,000 euro

Bando Progetti H2020 - ERC
Synthetic photo-biology for light controllable, active matter
Principal Investigator: Roberto Di Leonardo
Local fund: 27,000 euro

Bando per la cooperazione allo sviluppo
Principal Investigator: Giovanni Organtini
Local fund: 10,000 euro

Grant for Visiting Professors 2017
Proposer: Lilia Boeri

Grant for Visiting Professors 2019
Proposer: Giovanni B. Bachelet

4 Funding from other Italian agencies or institutions

POR FESR Regione Lazio
FILOBLU
Prof. Riccardo Faccini
Local fund: 105,000 euro

MAECI (Ministero degli Affari Esteri e della Collaborazione Internazionale)
collaborative Italy-India project SuperTop-PGR04879, January 2017- December 2019
Prof. Lara Benfatto (Principal Investigator)

MIUR Programma Nazionale Ricerche in Antartide
Winter long duration stratospheric balloons from Polar regions
Prof. Francesco Piacentini
Local fund: 120,000 euro

Progetti di Ricerca della Regione Lazio
Trattamento sicuro dei dati mediante linformazione con singoli fotoni a richiesta
Prof. Antonio Polimeni
Local fund: 149,000 euro

Regione Lazio, Lazio Innova
3DGATE

Prof. Roberto Di Leonardo, 149.829 Local fund: 149,829 euro

Progetto Premiale - ASI 2017-42-H0
Qualifica nello spazio di nuovi rivelatori e polarimetri criogenici per microonde
Prof. Paolo de Bernardis (Principal Investigator)
Local fund: 817,253 euro

5 Other International Funding

SIMONS FOUNDATION
Prof. Giorgio Parisi
Local fund: 619,000 euro

6 Awards

Breakthrough Prize 2016 per la rivelazione delle Onde Gravitazionali, come membro del gruppo Virgo (include I. Di Palma, S. Frasca, P. Leaci, L. Naticchioni, F. Pannarale, P. Rapagnani e F. Ricci).

2016 Gruber Cosmology Prize for the first direct detection emitted from collision of two black holes, as member of the Virgo Collaboration (include I. Di Palma, S. Frasca, P. Leaci, L. Naticchioni, F. Pannarale, P. Rapagnani e F. Ricci).

Somiya Award for international collaboration for Semiconductor Nanowires: Growth, Characterization, Processing and Optoelectronic Devices a Antonio Polimeni, 2017 Kyoto, Japan.

2017 Premio Nazionale di Cultura "Benedetto Croce" per la Letteratura Giornalistica a Paolo de Bernardis.

Ludwig-Genzel Prize 2018 "for advancing the theoretical understanding of the dynamical response of interacting electronic systems, in particular superconductors" a Lara Benfatto.

2018 Gruber Cosmology Prize, as member of the Planck Team (include Paolo de Bernardis, Silvia Masi, Alessandro Melchiorri e Francesco Piacentini).

2018 Marcel Grossmann Award to the Planck Collaboration (include Paolo de Bernardis, Silvia Masi, Alessandro Melchiorri e Francesco Piacentini).

Pomeranchuk Prize, 2018 a Giorgio Parisi.

2018 Commendatore della repubblica Italiana per meriti scientifici a Fulvio Ricci.

Premio Le Ragioni della Nuova Politica, XVI edizione 2018 assegnato per meriti scientifici dall'associazione "L'alba del Nuovo Millennio" a Fulvio Ricci.
APS Outstanding Referee in 2019 a Sergio Caprara e Federico Ricci-Tersenghi

Premio Alfredo di Braccio per studiosi in Fisica, Accademia dei Lincei (2019) a Lorenzo Rovigatti.

2019 Giuseppe and Vanna Cocconi Prize - European Physical Society, as member of the Planck Team (include Paolo de Bernardis, Silvia Masi, Alessandro Melchiorri e Francesco Piacentini).

International Leibnitz-Institut fur innovative Mikroelectronik "Wolfgang Mehr" Fellowship Award 2019 a Leonetta Baldassarre

7 Outstanding Lecturers (Premio alla Didattica) awarded by Sapienza University, 2017-2019

Antonio Capone, Riccardo Faccini, Stefano Giagu, Raffaella Schneider

Books: 2017-2019

1. A. Ali, L. Maiani, A.D. Polosa, *Multiquark Hadrons,*
Cambridge University Press
ISBN-10: 110717158X, ISBN-13: 978-1107171589

2. G.B. Bachelet, V.D.P. Servedio, *ELEMENTI DI FISICA ATOMICA, MOLECOLARE E DEI SOLIDI* II EDIZIONE
Aracne 2017
ISBN 978-88-548-9894-3

3. L. M. Barone, E.Marinari, G.Organtini, F. Ricci-Tersenghi, *Programmazione Scientifica* 2 ed.,
Pearson, 8891909130

4. L. Boeri, *Understanding Novel Superconductors with Ab-initio Calculations*
published in Springer Handbook for Materials Modelling, Eds. Sidney Yip and Wanda Andreoni, Springer (2018),
ISBN 978-1-4020-3286-8

5. Antonio Capone, Paolo Lipari and Francesco Vissani, *Multiple Messengers and Challenges in Astroparticle Physics*
Chapter: "Neutrino Astronomy", pages195-356,
Editor: Springer, ISBN 978-3-319-65425-6, DOI: 10.1007/978-3-319-65425-6

6. R. A. Capuzzo Dolcetta, *Classical Newtonian Gravity*
entire monography published in the Unitext for Physics series
Springer Nature (Switzerland), ISBN 978-3-030-25846-7
G. Parisi, P. Urbani, F. Zamponi, *Theory of simple glasses: exact solutions in infinite dimensions*
Cambridge University Press

7. P. de Bernardis, *Radiazione Cosmica Primordiale - Collana Viaggio nell' Universo*
volume 20 - Corriere della Sera - Novembre 2019

8. C. Mariani, *La cultura, la scienza, la formazione*, pp. 102-103 in Una scuola che guarda lontano Il Liceo Scientifico Galileo Galilei da 50 anni a Lanciano,
by R. Crisanti, E. De Berardinis, R.A. Testa, Casa Editrice Carabba Srl, 2019. ISBN: 978-88-6344-564-0

9. E. Marinari, *La Fisica dei Sistemi Complessi*
chapter: A. De Martino, D. De Martino and E. Marinari, "The Essential Role of Thermodynamics in metabolic network modeling: physical insights and computational challenges" in "Chemical kinetics beyond the textbook"
edited by Katja Lindenberg, Ralf Metzler and Gleb Oshanin (World Scientific, Singapore 2019)

10. F. Ricci, *Le onde gravitazionali*
volume 1 - Corriere della Sera - Ottobre 2018

11. F. Ricci, *Alla scoperta delle onde gravitazionali*
published by Dedalo
ISBN: 9788822068804

Organisation of Schools, Workshops and Conferences

International School of Physics "Enrico Fermi": Quantum Simulators (course 198)
Varenna, Italy, July 22-27, 2016
Members of the Physics Department in the Local Organizing Committee: Paolo Mataloni
https://www.sif.it/corsi/scuola_fermi/mmxvi#198

New Frontiers in Gravitational-Wave Astrophysics
Sapienza University of Rome, Italy, March 19-22, 2017
Members of the Physics Department in the Local Organizing Committee: Valeria Ferrari, Leonardo Gualtieri, Paolo Pani
https://agenda.infn.it/event/12616/?ovw=True

Light Dark Matter at Accelerators LDMA 2017
La Biodola - Isola d'Elba, Italy, May 2428, 2017
Members of the Physics Department in the Local Organizing Committee: Mauro Raggi and P. Valente

Characterisation of Photonic Materials and Devices
Sapienza University of Rome, Italy, June 14-16, 2017
Member of the Physics Department in the Local Organizing Committee: A. Polimeni
https://promis-photonicmaterials.weebly.com/

Strong Gravity Universe
Sao Miguel (PT) July 3-7 2017
Scientific Committee: E. Barausse, V. Cardoso, L. Gualtieri, C. Herdeiro, U. Sperhake
https://centra.tecnico.ulisboa.pt/network/grit/sgu17/

Liquid Matter Conference 2017
Ljubljana, Slovenia, July 17-21, 2017
Member of the Physics Department in the Local Organizing Committee: Roberto Di Leonardo
http://liquids2017.ijs.si

DATA-DRIVEN METHODS FOR MULTI-SCALE PHYSICS AND COMPLEX SYSTEM
Sapienza University of Rome, Italy, 2017, July 24 - August 4
Members of the Physics Department in the Local Organizing Committee: Claudio Conti and Eugenio Del Re
http://faculty.washington.edu/kutz/page5/page21/

CERN TH Initiative – Dark Sectors 2017 – Probing the dark sector and general relativity at all scales
CERN, Switzerland, August 14-25, 2017
Member of the Physics Department in the Local Organizing Committee: Paolo Pani
https://indico.cern.ch/event/614097/

Scuola di Alta Formazione in Fisica con Arduino e Smartphone
Sapienza University of Rome, Italy, September 6-9, 2017
Members of the Physics Department in the Local Organizing Committee: Giovanni Organtini and Shahram Rahatlou
https://www.phys.uniroma1.it/fisica/Arduino-Smartphone-Esperimenti

2017 WORKSHOP OF THE PHD PROGRAM IN ASTRONOMY ASTROPHYSICS AND SPACE SCIENCE
Sapienza University of Rome, Italy, September 25-27, 2017
https://www.phys.uniroma1.it/fisica/archivionotizie/workshop-phd-program-astronomy-astrophysics-and-space-science

Wilhelm und Else Heraeus Seminar on ab-initio Electronic Structure Theory for Solids in the 21st Century
Physikzentrum Bad Honnef, Germany, 2017, October 30 - November 3
Member of the Physics Department in the Local Organizing Committee: L. Boeri, I.I. Mazin, T. Saha-Dasgupta, R. Valenti

https://itp.uni-frankfurt.de/ valenti/heraeus-seminar/index.html

Stato e prospettive della fisica delle Astroparticelle
Sapienza University of Rome, Italy, November 23, 2017,
Members of the Physics Department in the Local Organizing Committee: Antonio Capone (chair), Manuela Vecchi
https://agenda.infn.it/event/14311/

Current Problems in Theoretical Physics
Vietri Sul Mare, Italy, March 24-28 2018,
Organizing Committee: S. Capozziello, E. Ercolessi, P. Facchi, V. Ferrari, L. Gualtieri, L. Rosa
http://paft18.sa.infn.it/

RomeSC2018, Workshop on Electronic Structure of Superconductors and Novel Materials
Sapienza University of Rome, Italy, May 2325, 2018
Member of the Physics Department in the Local Organizing Committee: G.B. Bachelet, L. Boeri, R. Gonelli, R. Valenti

ATLAS Exotics Workshop
Sapienza University of Rome, Italy, May 29, 2018 - June 1, 2018
Members of the Physics Department in the Local Organizing Committee: S.Giagu, M.Bauce, V.Ippolito, L.Nisati
https://indico.cern.ch/event/710748/

International Workshop on 2D Superconductivity "SuperTop2018"
Sapienza University of Rome, Italy, June 22, 2018,
Members of the Physics Department in the Local Organizing Committee: Lara Benfatto. LOC: Jose' Lorenzana. Secretary: Alba Perrotta
https://supertop2018.wordpress.com/

Solar Radiation Based Established Technique (SORBETTO)
July 2-6, 2018
Members of the Physics Department in the Local Organizing Committee: Monica Campanelli (ISAC/CNR), Anna Maria Siani (Sapienza), Stefano Casadio (SERCO Italia)
sorbetto2918.artov.isac.cnr.it

Channeling 2018
Ischia, Italy, September 23-28, 2018,
Members of the Physics Department in the International Advisory Board: Gianluca Cavoto
https://agenda.infn.it/event/14872/

2018 Worskshop of the PhD program in Astronomy, Astrophysics and Space Science
Sapienza University of Rome, Italy, September 24-26, 2018
https://astrophysicsworkshop.files.wordpress.com/2018/09/workshop2018_timetable9.pdf

Il nucleare, una questione scientifica e filosofica dal 1945 a oggi. Nuclear (power), a scientific and philosophical question from 1945 to today
Sapienza University of Rome, Italy, September 24-25, 2018,
Members of the Physics Department in the Local Organizing Committee: Orietta Ombrosi Irene Kajon Carlo Cosmelli

Fundamental Physics with LISA
Arcetri, Italy, November 12-14, 2018
Member of the Physics Department in the Local Organizing Committee: Paolo Pani
http://www.ggi.infn.it/showevent.pl?id=305

On the crest of a wave: a four-decade long scientific journey in honor of Valeria Ferrari
Sapienza University of Rome, Italy, February 22, 2019,
Members of the Physics Department in the Local Organizing Committee: Leonardo Gualtieri, Paolo Pani,
https://agenda.infn.it/event/17768/

Scuola di Alta Formazione in Fisica con Arduino e Smartphone
Sapienza University of Rome, Italy, February 22-24, 2019
Members of the Physics Department in the Local Organizing Committee: Giovanni Organtini and Shahram Rahatlou
https://www.phys.uniroma1.it/fisica/Arduino-Smartphone-Esperimenti

Theoretical Aspects of Astroparticle Physics, Cosmology and Gravitation
Sapienza University of Rome, Italy, March 11-22, 2019
Organizing Committee: N. Bartolo, N. Fornengo, D. Grasso, L. Gualtieri, G. Miele, E. Lisi
https://agenda.infn.it/event/17246/

Light and Technology: the frontier of emergent systems
Sapienza University of Rome, Italy, March 18-20, 2019,
Members of the Physics Department in the Local Organizing Committee: Lara Benfatto and Naurang Saini. Secretary: Alba Perrotta
http://www.roma1.infn.it/ lbenfat/maeci_website/workshops_maeci.html

Quantum Information and Measurement (QIM)
Sapienza University of Rome, Italy, April 4-6, 2019
Members of the Physics Department in the Local Organizing Committee: Gonzalo Carvacho, Giuliana Pensa, Nicol Spagnolo
https://www.quantumlab.it/qim2019/

Breakdown Of Ergodicity In Isolated Quantum Systems: From Glassiness To Localisation
Arcetri, Italy, JUne 37, 2019
Member of the Physics Department in the Local Organizing Committee: Giorgio Parisi
https://www.ggi.infn.it/showevent.pl?id=318

22nd International Conference on General Relativity and Gravitation and 13th Edoardo Amaldi Conference on Gravitational Waves
Valencia (SP) 7-12 July 2019
Two Scientific Organizing Committees: one for GR22 (including Leonardo Gualtieri), one for Amaldi13 (including Fulvio Ricci)
https://www.gr22amaldi13.com

CYGNUS 2019
Sapienza University of Rome, Italy, July 10-12, 2019
Members of the Physics Department in the Local Organizing Committee: Gianluca Cavoto
https://agenda.infn.it/event/18542/

Lost in gravity
Saint Flour, France, August 28-30 2019
Members of the Physics Department in the Local Organizing Committee: Andrea Maselli, Laura Bernard, Miguel Zilhao
https://centra.tecnico.ulisboa.pt/network/grit/lostingravity2019/

SuperTop2019: Emergent phenomena at low dimensions
Sapienza University of Rome, Italy, September 4-6, 2019,
Members of the Physics Department in the Local Organizing Committee: Lara Benfatto (chair), Marco Grilli, Jose' Lorenzana, Pratap Raychaudhuri. Secretary: Alba Perrotta
https://supertop2019.wordpress.com/

Scuola di Alta Formazione in Fisica con Arduino e Smartphone
Sapienza University of Rome, Italy, September 6-8, 2019
Members of the Physics Department in the Local Organizing Committee: Giovanni Organtini and Shahram Rahatlou
https://www.phys.uniroma1.it/fisica/Arduino-Smartphone-Esperimenti

40 years of Replica Symmetry Breaking: a conference about systems with many states

Sapienza University of Rome, Italy, September 10-13, 2019,
Members of the Physics Department in the Local Organizing Committee: Giorgio Parisi, Federico Ricci-Tersenghi
https://sites.google.com/view/rsb40

2019 WORKSHOP OF THE PHD PROGRAM IN ASTRONOMY ASTROPHYSICS AND SPACE SCIENCE Sapienza University of Rome, Italy, September 17-19, 2019
https://astrophysicsworkshop.wordpress.com/

Disordered serendipity: a glassy path to discovery
Sapienza University of Rome, Italy, September 19-21, 2019,
Members of the Physics Department in the Local Organizing Committee:Giorgio Parisi, Federico Ricci-Tersenghi
https://sites.google.com/site/disorderedserendipity/

ShareScience
Sapienza University of Rome, Italy, October 28-30, 2019,
Member of the Physics Department in the Local Organizing Committee: R. Faccini (chair)
https://agenda.infn.it/event/19596/

Artificial Intelligence: Art or Science?
SISSA, Trieste, Italy, November 1213, 2019
Member of the Physics Department in the Local Organizing Committee: Federico Ricci-Tersenghi
https://www.sissa.it/calendar-event/artificial-intelligence-art-or-science

Light Dark Matter at Accelerators LDMA 2019
Fondazione Querini Stampalia - Venezia, Italy, November 2022, 2019
Members of the Physics Department in the Local Organizing Committee: Mauro Raggi and P. Valente
https://agenda.infn.it/event/18184/overview

Publications – Year 2017

1. V. Khachatryan et al., CMS Collaboration *"Measurement of electroweak-induced production of W gamma with two jets in pp collisions at root s=8TeV and constraints on anomalous quartic gauge couplings"* J. High Energy Phys. (2017) DOI: 10.1007/JHEP06(2017)106

2. V. Khachatryan et al., CMS Collaboration *"Measurement of the differential inclusive B+ hadron cross sections in pp collisions at root s=13TeV"* Phys. Lett. B **771** (2017) DOI: 10.1016/j.physletb.2017.05.074

3. M. Aaboud et al., ATLAS Collaboration *"Measurements of the production cross section of a Z boson in association with jets in pp collisions at root s=13 TeV with the ATLAS detector"* Eur. Phys. J. C **77** (2017) DOI: 10.1140/epjc/s10052-017-4900-z

4. F. Acernese et al. *"Status of the Advanced Virgo gravitational wave detector"* Int. J. Mod. Phys. A **32** (2017) DOI: 10.1142/S0217751X17440031

5. V. Khachatryan et al., CMC Collaboration *"Search for top quark decays via Higgs-boson-mediated flavor-changing neutral currents in pp collisions at root s=8 TeV"* J. High Energy Phys. (2017) DOI: 10.1007/JHEP02(2017)079

6. A. M. Sirunyan et al., CMS Collaboration *"Measurement of the top quark mass using single top quark events in proton-proton collisions at root s=8 TeV"* Eur. Phys. J. C **77** (2017) DOI: 10.1140/epjc/s10052-017-4912-8

7. M. Aaboud et al., C Collaboration *"Performance of the ATLAS Transition Radiation Tracker in Run 1 of the LHC: tracker properties"* J. Instrum. **12** (2017) DOI: 10.1088/1748-0221/12/05/P05002

8. M. Aaboud et al., ATLAS Collaboration *"A measurement of the calorimeter response to single hadrons and determination of the jet energy scale uncertainty using LHC Run-1 pp-collision data with the ATLAS detector"* Eur. Phys. J. C **77** (2017) DOI: 10.1140/epjc/s10052-016-4580-0

9. R. Adam et al. *"Mapping the kinetic Sunyaev-Zel'dovich effect toward MACS J0717.5+3745 with NIKA"* ASTRONOMY & ASTROPHYSICS **598** (2017) DOI: 10.1051/0004-6361/201629182

10. R. Capuzzo-Dolcetta et al. *"On the relation between the mass of Compact Massive Objects and their host galaxies"* Mon. Not. R. Astron. Soc. **472** (2017) DOI: 10.1093/mnras/stx2246

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