DEPARTMENT OF PHYSICS

January 2014-December 2016

SCIENTIFIC REPORT

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

Sapienza Università di Roma

Department of Physics

Sapienza Università di Roma

Dipartimento di Fisica

Scientific Report

2014 - 2016

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The Scientific Report has been edited by Elia Battistelli, Marco Felici, Paolo Pani, and Riccardo Paramatti.

Cover graphics by Fulvio Medici
The Institute of Physics in 1935, "Casabella", 1936, 99 (design by Giuseppe Pagano)
Department of Physics
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Introduction

The Physics Department at Sapienza University of Rome is the largest among this discipline in Italy for number of faculty and students. It is the natural prosecution of the so-called Roman School and it is still worldwide renowned for the high quality of the research carried out in various fields of physics. All this is witnessed by important indicators, such as:

1. The volume of assets deriving from research contracts with organizations and funding agencies such as the EU Community and other institutions. Among others, 11 grants of the European Research Council in the last 3 years are particularly worth of noting;

2. The number of papers published in prestigious international journals (approximately 1900 in the period 2014-2016), especially those with impact factor IF > 10 (50+ in the period 2014-2016);

3. The high percentage of papers published in collaboration with researchers affiliated with foreign institutions;

4. The number and quality of international workshops and conferences organized within the Department, as well as the presence of professors and researchers of the Department who have organized and are part of the scientific committees for numerous international conferences.

These last two aspects in particular demonstrate the high level of internationalization of our community.

The entire research activity of our department has a natural fall out in the number of PhD students and also in our two master's degree courses, with nearly 150 and 30 students choosing our Laurea Magistrale in Physics and in Astronomy and Astrophysics, respectively, and more than 430 new students of the Laurea in Physics every year. Another important element that testifies the quality of the research conducted within the Department of Physics and the vitality of the Roman School is represented by the 7 awards granted in this triennium to members of our community.

In the present report, we show the results of more than 100 research lines, grouped in the subject areas of *Astronomy, Astrophysics and Geophysics*, *Condensed Matter Physics and Biophysics*, *Particle Physics and Fundamental Interactions* and, finally, *Theoretical Physics*, with a summary of the research lines for each area. A relevant number of these research acivities is carried out in continuous collaboration with other institutions affiliated to the Physics Department. The present report gives also a detailed description of the numerous laboratories and experimental and computational facilities that make possibile the development of the entire set of research activities.

To provide a complete insight on the Department activity, this book reports all the Schools, Workshops and Conferences held in this period. The list of published papers in international referred journals divided by year completes the description.

During the last years, the Italian university and research world has experienced many changes and encountered increasing difficulties, mainly due to the general economical crisis. In spite of this critical situation, the Physics Department continues to work while maintaining a level of excellence. I wish to thank the whole body of our scientists that contribute with their enthusiasm every day to these results and all the administrative and technical staff, that make all these results possibile with their professional and personal effort.

Paolo Mataloni

Director of the Department of Physics

The Institute of Physics of Giuseppe Pagano at Sapienza University of Rome*

The scientific activity of the Physycs Department is carried out in the three places shown in the map 1, namely the G. Marconi, E. Fermi and E. Segrè building.

The Marconi building for the Institute of Physics in Rome's university campus is the historical one. It was designed by the architect Giuseppe Pagano and built between 1932 and 1936 and is from then on the seat of Sapienza's Department of Physics. Aiming at a better understanding of the liaisons between this fine building and research in Physics developed by the "Roman School" and in view of the eightieth anniversary since the achievement of the university campus, on October 14th 2016 a seminar was organized to rally physics and architects, flanked by a temporary exhibition of drawings, displayed by the students of Sapienza's School of Architecture, that illustrate the architecture and the research activity it has hosted for decades.

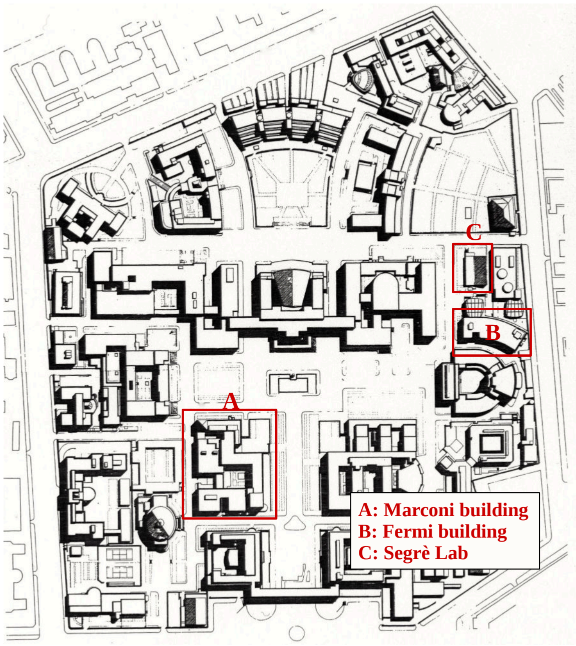

Figure 1: Historic map of the main Sapienza campus displaying the three buildings of the Department of Physics.

Designed in strict observance of the specific needs expressed by the scientists of those times, namely the renown "Ragazzi di via Panisperna" who had already attained sensational scientific discoveries, this was soon acknowledged as a functional, rational and beautiful building. During the postwar years, the Roman scientific community changed radically but was soon able to return within the international research circuit under Edoardo Amaldi's guidance; thereafter, its structures and spaces also had to adapt to drastic changes due to the development in scientific research, to the exorbitant increase of students, and to its essential updating to new regulations.

Eventually, the building has indeed suffered many transformations, responsible of having fragmented the original clearness of the interior distribution and of having hidden its rational character. Changes consist mainly in additions – such as partitions, installations, and minor built-in parts – while removals and demolitions of original parts are of minor importance and encourage to consider the worst alterations as removable, at least in theory. All in all, this masterwork retains its original beauty and functionality, and continues to be considered among the most important pieces of Italian Modern Architecture and, also, a place for research and didactics of excellence.

This assumption and of the growing awareness of the monumental value of Rome's university campus, will ease any future intervention necessary to update this work of art; but, most important, the sense of belonging that it still evokes its daily inhabitants will leverage its conservation and the preservation of this place of successful encounter among Physicists and Architects, and between Physics and Architecture.

*2016, October 14th – Aula Majorana Exhibition and workshop organized by Simona Salvo (Dipartimento di Storia, Disegno e Restauro dell'Architettura). Tables prepared by Giuseppe Pecci, Agnese Riccomagno, Andrea Ramaccini, Martina Renzetti.

Figure 2: *Left:* The Institute of Physics at "Sapienza" University campus in Rome in a picture of 1935 showing the original conditions of the inner courtyard. *Right:* A rendered view of the inner courtyard simulating a restoration project designed by the students of the Architecture Courses at Sapienza University. The drawing proposes to accept some of the major alterations deriving from the constant use of the buildings, but aims at recomposing some of its major features, such as the direct visual and spatial connection between the inner courtyard and the outer context. Italian conservation theory considers monuments as living objects that witness historic and artistic values; these are to be correctly interpreted and may be also recognizable in the current and layered conditions of the building.

Figure 3: The Institute of Physics at "Sapienza" University campus in Rome, survey of the South-West (upper panel) and North-East (lower panel) elevation of the building. The drawings depict the current state of the building, which hosts the prestigious Institute of Physics since 1935, revealing its architectural features and the many alterations received in almost eighty years lifetime; despite the former, this remains among the most significant architectural pieces of Italian Rationalism. Measured drawings and surveys represent an indispensable step of the scientific investigation process that preludes to any conservation work.

In memory of Anna Tramontano

Anna Tramontano, Professor of Computational Biophysics in our Department and one of the most eminent computational biologists in Italy and worldwide, unexpectedly passed away on March 2017.

Anna Tramontano earned her degree in physics at Federico II University of Naples in 1980. After a period at the International Institute of Genetics and Biophysics in Naples, she worked as a post-doctoral scientist at University of California San Francisco where she developed the molecular graphics package InsightII. In 1988 she joined the Biocomputing Programme at the European Molecular Biology Laboratory in Heidelberg to work with Professor Arthur Lesk on the analysis and modeling of immunoglobulins. They developed a method, which is now of general use, to infer the structure of this class of molecules with high accuracy, opening the road to the rational design and engineering of antibodies. In 1990, she returned to Italy as group leader at IRBM, the research Institute of Merck & Co, where later became Director of the Computational Biology and Chemistry Department. Here she managed many projects of pharmaceutical interest, and authored the first experiment of a novel fold designed protein with a tailored function. In 2001, she returned to academia as a full professor at the Sapienza University of Rome where she established the computational biology laboratory, an interdisciplinary research unit, with many different research activities in the fields of structural bioinformatics, genomics and proteomics.

Anna Tramontano has been Vice-president of the International Society for Computational Biology (ISCB), member of the ISCB Board of Directors, the steering committee of the BioSapiens Network of Excellence and the organizational committee for the CASP global experiment. She has been member of the Scientific Advisory Boards of the European Molecular Biology Laboratory, the IIMCB Warsaw, the Max Planck Institute for Molecular Genetics, the European Boinformatics Institute, Centro Nacional de Biotecnologa, Institute Pasteur - Fondazione Cenci Bolognetti, Centro de Regulacion Genomica, the Swiss Institute for Bioinformatics, Scuola Superiore Normale of Pisa, Max Delbruck Center for Molecular Medicine, the EMBO fellowship committee, EMBO Course Committee, Chair of the Evaluation Committee for the FIRB grants of the Italian Ministry, the European Research Council, the National Board of Trustees Research (CNGR).

Throughout the course of her career, Professor Tramontano received many awards and honours. She has been awarded the Marotta Prize - National Academy of Science (2001), the Prize for Natural Sciences of the Presidency of the Council of Ministers (2002), the KAUST Global Research Partnership award (2008), the Minerva Prize (2005), the Tartufari Prize of the Accademia dei Lincei (2010). Her publications include four volumes (Bioinformatics - Zanichelli; The ten most wanted solutions in Protein Bioinformatics - CRC Press; Protein Structure Prediction - Wiley; Introduction to Bioinformatics - CRC Press) and more than two hundred articles in scientific journals.

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°: No longer affiliated to the Department.

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Research areas and affiliations

The research activities have been divided in the following subject areas:

A- Astronomy, Astrophysics and Geophysics: A1-A14

C- Condensed matter physics and Biophysics: C1-C36

P- Particle physics and Fundamental Interactions: P1-P34

T- Theoretical Physics: T1-T19

The authors of the Research Activities, as members of the Department of Physics, are reported at the end of each description. In the case of authors of other institutions affiliated to the Department of Physics, the following numbers have been adopted:

1 - INFN, Istituto Nazionale di Fisica Nucleare

2 - CLNS-IIT, Center for Life NanoScience of the Italian Institute of Technology

3 - CNR-ISC, Institute for Complex Systems, Consiglio Nazionale delle Ricerche

4 - CNR-Nanotec, Consiglio Nazionale delle Ricerche

5 - INAF, Istituto Nazionale di Astrofisica

6 - SBAI, Dipartimento di Scienze di Base e Applicate per l'Ingegneria, Sapienza University of Rome

7 - CENTRO FERMI, Centro Studi e Ricerche Enrico Fermi

8 - ISI Foundation, Institute for Scientific Interchange, Turin

List of research activities

A- Astronomy, Astrophysics and Geophysics:

A1. Constraining Fundamental Physics with Cosmology
A2. Characterization of the HFI instrument on Planck, for measurements of Cosmic Microwave Background Radiation and Milky Way emission
A3. The Q and U Bolometric Interferometer (QUBIC)
A4. CMB polarization: The Short Wavelength Instrument for the Polarization Explorer (SWIPE-LSPE)
A5. OLIMPO: spectral measurements of the Sunyaev-Zeldovich effect
A6. Exploring clusters of galaxies by hydrodynamical simulations and microwave observations
A7. Cosmology and Lensing with Euclid
A8. Unveiling the nature of the first stars and galaxies
A9. Theoretical and Computational Astrophysics
A10. Dynamical evolution of stellar clusters
A11. SiFAP: Silicon Fast Astronomical Photometry activity
A12. Spectroscopy of Transiting Exoplanets
A13. High Resolution study of Anomalous Microwave Emission in astrophysical Galactic and extragalactic regions
A14. Applied meteorology for the assessment of solar ultraviolet radiation at the Earth's surface and human exposure, monitoring of atmospheric ozone and nitrogen dioxide, microclimate analysis for cultural heritage.

C- Condensed matter physics and biophysics:

C1. Superconducting films at strong disorder: Dynamics and Spectroscopy
C2. Soft electronic matter and unconventional superconductivity
C3. Soft electronic matter in oxide interfaces
C4. Spectroscopic studies of layered chalcogenide superconductors
C5. Quest for room temperature superconductivity
C6. Non Linear Terahertz Properties of Topological Insulators
C7. Origin of colossal magnetoresistance in $LaMnO_3$ manganite
C8. Self-assembled molecular magnetic nanostructures on surfaces
C9. Graphene-based nanostructures: from two-dimensional flakes to three-dimensional architectures
C10. Nanomaterials for alternative energy
C11. Semiconductor Plasmonics
C12. Addressing the electronic properties of semiconductor nanowires
C13. Hydrogen-mediated engineering of semiconductor materials and nanostructures
C14. Infrared spectroscopy of solid oxides and interfaces
C15. Low temperature optical and Terahertz spectroscopy: Application to LiF crystals and ancient paper sheets
C16. Ultrafast to ultraslow dynamics in biomolecules and condensed matter
C17. Applications of Infrared Spectroscopy to protein and life-science studies
C18. Resonantly-Enhanced Photo-Thermal Infrared Vibrational Spectroscopy
C19. Surface Enhanced Raman Scattering and its biophysical applications
C20. Investigating matter with radio- and microwave electromagnetic radiation
C21. Confined water
C22. Physics with patchy colloids and DNA-made nano-particles
C23. Self-Assembly-Driven Liquid Crystals
C24. Research activity of PhOBIA group
C25. Optics in conditions of extreme nonlinearity: solitons, rogue waves, scale-free beams and anti-diffracting subwavelength beams
C26. Transverse light confinement in disordered media
C27. Glassy Random Laser and Experimental Measurement of Replica Symmetry Break
C28. Quantum optics for information processing
C29. Quantum Technologies
C30. Strategies for self-propulsion at the micron scale
C31. Computational Biophysics
C32. Codon bias and the organization of bacterial genomes
C33. Economic Complexity
C34. Complexity in techno-social systems
C35. The Statistical Mechanics of Neurons: Imaging, Networks, and Development
C36. Plumes, bubbles and deep vortices in the sea

P- Particle physics and Fundamental Interactions:

P1. The CMS experiment at the CERN LHC
P2. Properties of the Higgs boson
P3. Study of the $H \to \gamma\gamma$ decay at the LHC
P4. Search for exotic resonances at LHC with the CMS detector
P5. Search for new long-lived particles at LHC with the CMS detector
P6. Upgrade of the CMS electromagnetic calorimeter in view of the High Luminosity LHC
P7. Precision time detectors at the High Luminosity LHC
P8. The ATLAS Experiment at the Large Hadron Collider
P9. Precision Standard Model Measurements with ATLAS
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P30. Development of astroparticle detector and a calibration light source device for Cherenkov Telescope
P31. Experiments at the Jefferson Laboratory (JLab - Virginia, USA)
P32. Crystal channeling for high energy hadron beam steering
P33. Dose delivery in Particle Therapy
P34. A novel radio-guided surgery with β^- radiation

T- Theoretical Physics:

T1. Exotic hadron resonances and methods to detect light dark matter
T2. Higher-order perturbative corrections for observables at hadron colliders
T3. Electromagnetic corrections to hadronic decays from LQCD
T4. Some non perturbative aspects of quantum field theory
T5. Weak matrix elements and hadron properties from quantum chromodynamics on a space-time lattice
T6. Theory and phenomenology of quantum-spacetime symmetries
T7. Energetic neutrino and ultra high energy cosmic ray astronomy?
T8. Gravitational waves from astrophysical sources
T9. Tests of gravity with gravitational and electromagnetic waves
T10. Collective behaviour in biological systems
T11. Statistical mechanics of small systems and fast transformations
T12. Equilibrium and nonequilibrium complex quantum systems
T13. Finite-size scaling at quantum transitions
T14. Statistical mechanics of strongly disordered systems
T15. Statistical mechanics of glassy materials: structural glasses, hard spheres jamming, random lasers
T16. Nonlinear waves in complex and quantum systems
T17. On the analytic description via integrable models of two extreme wave phenomena in nature: multidimensional wave breaking and anomalous (rogue) waves
T18. Resonances in quantum mechanics
T19. Markov chains on graphs

List of research activities

Astronomy, Astrophysics and Geophysics

Astronomy, Astrophysics & Geophysics

We are living exciting times for Astrophysics and Cosmology, being able to *measure* electromagnetic signals produced during *all* phases of the evolution of the Universe. Our Department is giving key contribution to this scientific exploration in several areas.

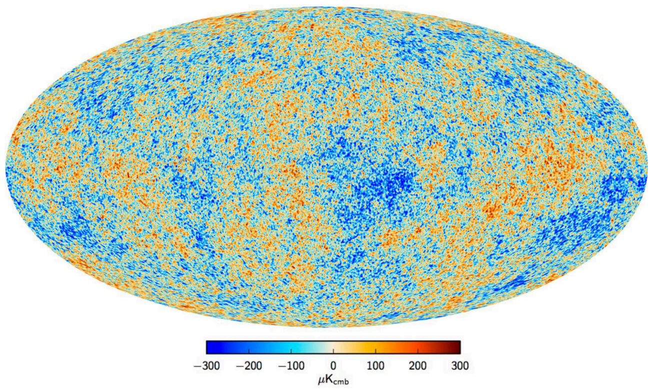

Figure 1: A map of the CMB, measured by the Planck satellite and published in 2015. The faint variations of the brightness temperature (around an average of 2.725K) are due to oscillations of the photon-baryon plasma, 13.7 Gy ago and 380 ky after the big bang. Our Department has contributed to the High Frequency Instrument of the Planck satellite, and to the data analysis of the full Planck dataset.

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 (A1). 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.

The Planck satellite, to which a team of our Department contributed significantly (A2), 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 (see Fig.1), favoring a close-to-scale-invariant spectrum of primordial density fluctuations.

However, 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 (and 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.2).

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 leading the study for a *final* CMB space mission, within the science programme of ESA. Such a mission, the Cosmic ORigins Explorer (CORE), will provide the denitive maps of the CMB polarization anisotropies at large and medium angular scales. In case of a detection of primordial B-modes, CORE 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 ination models remaining after Planck (the so-called large-field class). In addition, the precise measurement of the CMB lensing effect, and of the E-mode polarization over three decades of scale, will bring major improvements in our ability to test and constrain the cosmological model and to assess the need for extensions motivated by developments in other branches of physics.

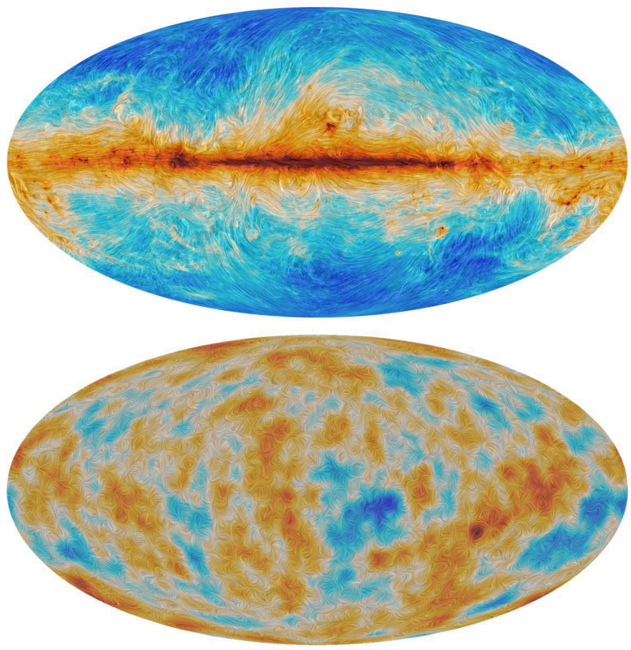

Figure 2: Top: a map of mm-wave emission (colors) and linear polarization (fingerprints) of the sky at mm wavelengths, obtained by the multiband sky survey of the Planck satellite [3]. Bottom: A map of large-scale CMB anisotropy (colors) and polarization (fingerprints) obtained from the Planck data using advanced components separation methods [4].

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-Zeldovich effect in clusters of galaxies, starting from the measurements of the MITO telescope, and now with the leadership of the OLIMPO experiment (A5) and the collaboration to the NIKA instrument and to large-scale structure simulations (A6).

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 (A5). Arrays of KIDs represent the baseline for the focal plane technology in forthcoming European (ESA) space missions for the CMB, like CORE, where our Department has the responsibility for the focal plane section covering CMB frequencies.

Extragalactic Astrophysics

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-Zeldovich effect (A5, A6).

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).

The intriguing period of transition from first stars to first galaxies is vigorously investigated by researchers in our Department, active in observing runs at the most performing telescopes and in the scientific exploitation of the data (A8).

Stellar and Galactic Astrophysics

This activity merges the heritage of the schools of Stellar Astrophysics (developed mainly in the 70s at the Laboratory of Space Astrophysics of Frascati) and of Astronomy (developed mainly at the Institute of Astronomy of our University and at the Observatory of Rome). Stars exist in a variety of forms and systems. They can be considered physics laboratories, where quantum mechanics and nuclear fusion, together with Newtonian dynamics, are the motors of evolution. Actually, in our Department a group has been working for many years on the interconnection between individual star characteristics and the galactic environment where it lives. Stellar systems represent very interesting dynamical systems, whose formation and evolution are studied in our department by analytical and numerical tools, in the framework of galactic dynamics and of general relativity. In particular, we advanced an original interpretation of galactic nuclei activity (Active Galactic Nuclei, AGN) as fed by decayed massive globular clusters in the central galactic regions. This framework has been extensively tested in the frame of sophisticated N-body simulation, field where our department has a long lasting experience and skill (see specific contribution below). A new field presently under development is that of the study of the dynamics of extrasolar planets, especially those around binary star systems. The explanation of the birth of the planets is still debated, being hard to justify the time needed for planetesimal to grow up to the size of a planet in an unstable disk environment around a binary star which exerts a strong tidal distortion (A9 and A10).

An original experimental activity our Department is the development of a fast photometric system (A11) to investigate periodic and impulsive events in our Galaxy.

Researchers in our Department are involved in the extrasolar planets GAPS collaboration, which has been allocated a great amount of observing time at the Galileo 3.6 m national telescope in Canary islands (A9, A10), and contribute to the Ariel mission to search for exoplenets from space (A12).

Researchers in our Department are involved, also, in the CTA (Cherenkov Array Telescope) international collaboration, with the specific aim to use future gamma-ray CTA observation to investigate the processes of annihilation of dark matter particles in dwarf spheroidal galaxies and galactic nuclei (A9).

Researchers are involved in studying our Galaxy by observing dust emission in the infrared and microwave bands using data from balloon-borne experiments (BOOMERanG), the Herschel satellite, and data from large radiotelescopes, including the Sardinia Radio Telescope (A13).

Geophysics

Geophysics research in our Department ranges from atmospheric physics (ozone spettroscopy; ozone, water vapor, clouds and aerosols measurements and modelling in the polar, tropical and urban regions) to environment and microclimate monitoring (see A14).

Organization

All this is accomplished by a staff of 15 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 and Roberto Capuzzo Dolcetta

A1. Constraining Fundamental Physics with Cosmology

Our main activity consists in making use of the recent measurements of Cosmic Microwave Background anisotropies coming from the Planck satellite mission to constrain the main parameters of the standard cosmological model and its possible extensions. In particular, we search for anomalies and inconsistencies that could reveal the presence of new physics.

In [1] we have, for example, showed that the recent Planck data, when combined with other cosmological probes, seems to favour a general late-time interaction between cold dark matter and vacuum energy. This result certainly needs to be confirmed by future measurements, since the indication is only slightly below three standard deviations. Anyway it clearly shows how the presence of new physics is still well possible in current cosmological data.

More recently, we performed an analysis of the Planck data in an extended parameter space, varying 12 cosmological parameters instead of the usual 6. In this extended parameter space we have found that a solution to the current inconsistency of the Planck value of the Hubble constant $H_0 \sim 67$ km/s/Mpc with direct, local, luminosity distance measurements that yield a value of $H_0 \sim 73$ km/s/Mpc, could be invoked by assuming a dark energy equation of state $w < -1$. This kind of value for w would rule out a cosmological constant and prefer even more exotic dark energy scenario as those expected in the so-called phantom models.

The Cosmic Microwave Background can also provide strong limits on the presence of primordial gravitational waves, even at much smaller scales, as those probed by LIGO and VIRGO interferometers. In [2] we have provided new constraints on the GW background using the recent Planck data. Up to date constraints on the GW inflationary background have also been presented.

Future satellite CMB experiments, as PIXIE, will have the potential to probe possible spectral distortions from the black body CMB spectrum. Distortions are expected by several mechanisms, one of them connected to the Silk damping of primordial perturbations. Measuring the distortions induced by this effect can provide strong constraints on the bend of the power spectrum of primordial density perturbations, possibly providing a new confirmation of the inflationary scenario. In [3] we have forecasted the constraints achievable by an experiment as PIXIE on the running and the running of running of the spectral index of inflationary perturbations.

Cosmology can also provide tight constraints on light particles, i.e. with masses below 1 eV since these particles change from the relativistic to a non-relativistic regime after decoupling and therefore leaving key signatures on structure formation. We presented new constraints on neutrino masses and showed that an inverted neutrino hierarchy start to be excluded by some combination of cosmological data. Moreover, we made a comparison of current cosmological constraints with recent data coming from oscillation and long baseline neutrino experiments. Other light particles could be axions, and new constraints on their masses have been presented in [4].

We have also presented new constraints on the neutron lifetime by combined CMB and primordial nuclides measurements. The possibility of solving the "Lithium problem", i.e. the actual disagreement between the theoretical abundance predicted for primordial ^{7}Li assuming standard nucleosynthesis and the value inferred from astrophysical measurements, by assuming an extra sterile neutrino has been investigated.

CMB polarization can be used to constrain cosmological birefringence, the rotation of the linear polarization of CMB photons potentially induced by parity violating physics beyond the standard model. This effect produces non-null CMB cross correlations between temperature and B mode-polarization, and between E- and B-mode polarization. We presented new constraints on cosmological birefringence from Planck. Moreover, we used current measurements of the B mode CMB polarization to to constrain the chirality of primordial gravitational waves in a scale-invariant scenario.

The recent CMB measurements made by the Planck satellite, while providing an impressive confirmation of the standard cosmological model, have also presented interesting hints for anomalies. Also, we have found that the Planck data prefers at 95% c.l. a "modified gravity" structure formation scenario respect to those based on General Relativity.

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Author

A. Melchiorri

A2. Characterization of the HFI instrument on Planck, for measurements of Cosmic Microwave Background Radiation and Milky Way emission

The Planck satellite [1], launched on 14 May 2009, observed the sky continuously from 12 August 2009 to 23 October 2013. Planck's scientific payload contained an array of 74 detectors in nine bands covering frequencies between 25 and 1000 GHz, which scanned the sky with angular resolution between 33 and 5 arc-minutes. The detectors of the Low Frequency Instrument were pseudo-correlation radiometers, covering bands centred at 30, 44, and 70 GHz. The detectors of the High Frequency Instrument were bolometers, covering bands centred at 100, 143, 217, 353, 545, and 857 GHz. Planck imaged the whole sky twice in one year, with a combination of sensitivity, angular resolution, and frequency coverage never before achieved.

The main objective of the mission was the accurate measurement of the anisotropy of the Cosmic Microwave Background (CMB) radiation, which is a direct measure of the distribution of matter and gravitational potential in the early Universe. Figure 1 shows the angular power spectrum of the CMB anisotropy, which encodes statistical information of the CMB map. These data are compatible with a model of the Universe defined by just 6 parameters, the Λ-CDM (Cold Dark Matter with a cosmological constant Λ).

The 2015 distribution of released products, freely accessible via the Planck Legacy Archive interface is based on all the data acquired by Planck during the full mission. The distribution contains items: (i) Cleaned and calibrated data timelines for each detector. (ii) Maps of the sky at nine frequencies in temperature, and t seven frequencies (30–353 GHz) in polarization. Additional products serve to quantify the characteristics of the maps to a level adequate for the science results being presented, such as noise maps, masks, and instrument characteristics. (iii) High-resolution maps of the CMB sky in temperature from four different component-separation approaches, and accompanying characterization products. (iv) High-pass-filtered maps of the CMB sky in polarization from four different component-separation approaches, and accompanying characterization products. (v) A low-resolution CMB temperature map used in the low-ℓ likelihood code, with an associated set of foreground temperature maps produced as part of the process of separating the low-resolution CMB from foregrounds, with accompanying characterization products. (vi) Maps of thermal dust and residual cosmic infrared background (CIB) fluctuations, as well as carbon monoxide (CO), synchrotron, free-free, and spinning dust temperature emission, plus maps of dust temperature and opacity. (vii) Maps of synchrotron and dust polarized emission. (viii) A map of the estimated CMB lensing potential over 70 % of the sky. (ix) A map of the Sunayev Zel'dovich effect Compton parameter. (x) Monte Carlo chains used in determining cosmological parameters from the Planck data. (xi) The Second Planck Catalogue of Compact Sources, comprising lists of compact sources over the entire sky at the nine Planck frequencies. The catalggue includes polarization information. (xii) The Second Planck Catalogue of Sunyaev-Zeldovich Sources (PSZ2), comprising a list of sources detected by their SZ distortion of the CMB spectrum. (xiii) The Planck Catalogue of Galactic Cold Clumps (PGCC), providing a list of Galactic cold sources over the whole sky. (xiv) A full set of simulations, including Monte Carlo realizations. (xv) A likelihood code and data package used for testing cosmological models against the Planck data, including both the CMB and CMB lensing.

The Observational Cosmology group has been particularly involved in the characterization of the High Frequency Instrument (HFI) on Planck. The HFI calibration presented several critical aspects, due to unexpected systematic effects. These have been identified, modeled and removed as described in [2].

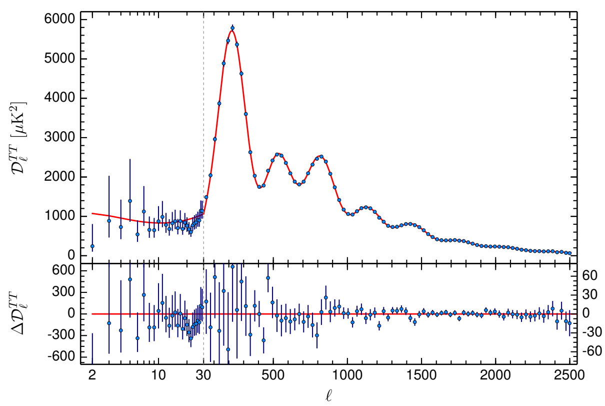

Figure 1: Angular power spectrum of the CMB temperature anisotrpy and residual to the best fit model.

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A3. The Q and U Bolometric Interferometer (QUBIC)

QUBIC [1,2,3] aims to measure the B-mode polarization of the Cosmic Microwave Background. While E-mode polarization, mainly due to anisotropic Thomson scattering of CMB photons at recombination and reionization, has been measured with good accuracy, only upper limits have been found to date for B-mode polarization. If detected, B-modes would offer us an invaluable insight in to what happened immediately after the Big Bang; it will, for instance, allow us to test the inflation theories which state that an extremely rapid exponential expansion occurred during the first 10^{-33} seconds of the Universe. The weakness of the B-mode signal, requires sensitive and accurate experiments. To meet this challenge, the QUBIC collaboration has developed the innovative concept of bolometric interferometry for CMB, combining the sensitivity of bolometric detectors with the systematic effects control allowed by interferometry. The QUBIC instrument is accommodated in a large cryostat (Fig.1), built by the Sapienza group, providing a large volume and cooling power at 4K for extened periods (months or years), using pulse-tubes. The cryostat is open to the sky with a 45 cm diameter window and thermal filters. The first polarization relevant optical element is a cold rotating Half-Wave-Plate (HWP) to modulate the polarization. The cryogenic rotator, operating at 4K, is also built in Sapienza (Fig.2), based on the design developed successfully for the PILOT experiment flown by CNES [4]. An array of 400 corrugated horns (called primary horns designed to be efficient throughout the 150 and 220 GHz bands with a 13 degrees FWHM at 150 GHz) selects the baselines observed by QUBIC. These primary horns are immediately followed by back-horns re-emitting the signal inside the cryostat towards an optical combiner adding on the focal plane the images of each of the secondary horns in order to form interference fringes. Before the focal plane, a dichroic plate splits the signal into its 150 and 220 GHz components that are each imaged on a focal plane equipped with 1024 Transition-Edge-Sensors (TES) cooled down to 320 mK and read using a multiplexed cryogenic readout system based on SQUIDs and SiGe ASIC operating at 4K.

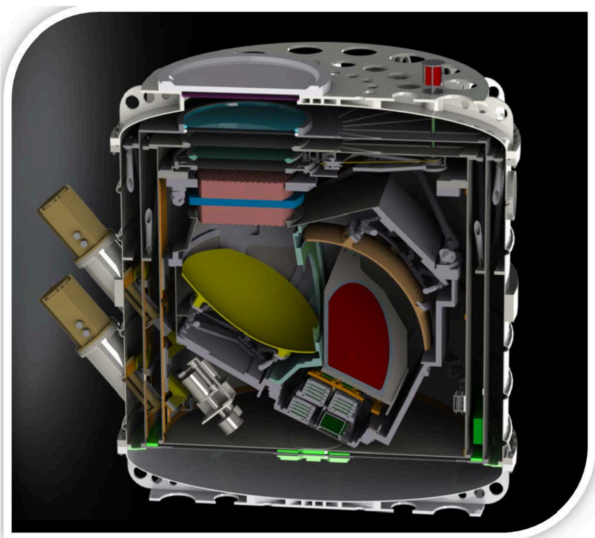

Figure 1: The large cryostat proding the cryogenic operation environment for the QUBIC interferometer

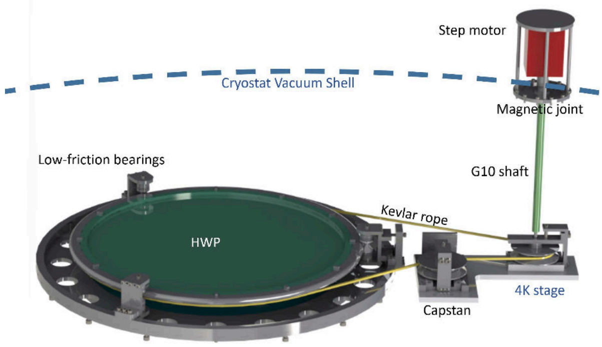

Figure 2: The large cryogenic rotator used to modulate incoming polarization by means of a mm-wave HWP

A demonstrator including the cryostat of the first module is planned to be integrated in 2017. The first module will be installed at the Alto Chorillo (Argentina) close to the LLAMA site. Another module is planned to be installed at the Franco-Italian Dome C Antarctic station (Concordia).

QUBIC is an international collaboration involving several universities and laboratories in France, Italy, the U.K. and the U.S.A., funded in Italy by PNRA and INFN.

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`http://qubic.in2p3.fr/QUBIC/Home.html`

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

SWIPE [1] is a balloon-borne microwave polarimeter, optimized to measure the linear polarization of the Cosmic Microwave Background (CMB) at large angular scales, where a B-modes signal, generated by cosmological inflation in the very early universe, is expected. Small inhomogeneities of the primeval plasma, at the epoch of the last scattering (13.7Gy ago, 380ky after the big bang), induce a small degree of linear polarization in the CMB (E-modes). Gravitational waves produced during inflation, a split-second after the big-bang, also induce linear polarization in the CMB (both E-modes and B-modes). Measuring CMB polarization with high precision one can study the very early universe and the inflation process, happening at energies ($> 10^{16}$ GeV) which cannot be reproduced in the laboratory. The signal from B-modes is extremely small, $< 0.1\mu K$ rms, and is mainly at large angular scales. SWIPE represents the high frequency (120 to 260 GHz) part of a wider program, the Large Scale Polarization Explorer (LSPE), which also includes a ground based measurement (STRIP) operating at 44 and 90 GHz. With this wide frequency coverage LSPE as a synergic program is able to remove accurately any polarized foreground, aiming at both the reionization and recombination peaks in the angular power spectrum of B-modes visible in Fig.1. SWIPE operates as

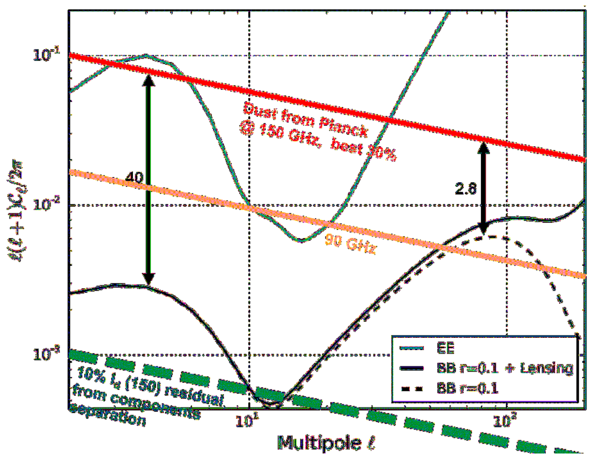

Figure 1: Power spectra of E-mode (blue) and B-mode (black) CMB polarization (normalized to the current upper limits, and expressed in μK^2), compared to the power spectrum of polarized interstellar dust emission at 3 frequencies (color lines). LSPE is able to remove 99% of this foreground emission, aiming at r=0.01.

a long-duration stratospheric balloon during the arctic night, spinning in azimuth to cover a large fraction of the sky (20-25% per flight). 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). A 800000 m^3 balloon is used to lift the instrument at 37 km of altitude. A polarization modulator (rotating HWP [2]) is the first element of the optical chain, to achieve high stability of the polarization measurement and avoid systematic effects [3]. A 60 cm diameter lens follows, focussing on two arrays of 330 multimode bolometers [4,5,6], detecting 8800 modes of the incoming radiation (see Fig.2). 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. The experiment is funded by ASI and INFN and is developed by an international collaboration, led by the group at the Physics Department of Sapienza University of Rome, with collaborators in Tor Vergata, Firenze, Pisa, Genova, Cardiff, Manchester. The first flight is scheduled for December 2018.

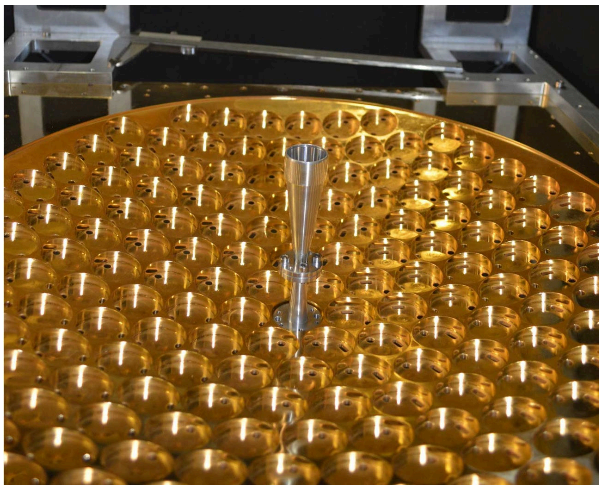

Figure 2: One of the multimode horns of the LSPE-SWIPE focal plane mounted on the 0.3K cold flange of the cryostat

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

A5. OLIMPO: spectral measurements of the Sunyaev-Zeldovich effect

OLIMPO 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. About 1% of the CMB photons gain an energy boost of $\sim 1\%$ from the hot electrons in the 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 with this method.

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 140, 200, 340, 480 GHz). Its 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. Moreover, the use of a Differential Fourier Transform Spectrometer [1, 2] provides low resolution spectroscopy with a rigorous cross-calibration across the entire frequency range. This results in outstanding capability 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). It is composed of a tiltable inner frame, including the telescope, the spectrometer and the detectors cryostat, and an outer frame containing all the other systems and connected to the balloon through an azimuth pivot and the flight chain. The tests carried out show that arcmin stability and sub-arcmin reconstruction can be obtained by a custom Attitude Control System.

Figure 1: The OLIMPO payload ready for a long duration balloon flight in Longyearbyen, Svalbard (July 2014)

The telescope has a 2.6 m diameter primary and a 0.6 m diameter secondary. The telescope has been optimized to scan the sky by tilting the primary mirror around a cross-elevation axis. It is protected by a set of large ground-shields and sun-shields, to limit the effect of straylight and sidelobes. From the focus, inside the cryostat, the beam is reimaged through a set of 3 cold mirrors, the second one being the cold stop of the system, and split by 3 dychroic beamsplitters into 4 arrays of bolometers.

The cryogenic system of OLIMPO is a classical LN/LHe aluminum cryostat with a ^{3}He refrigerator. Its purpose is to cool the detector arrays at 0.3K, and the reimaging optics (filters, mirrors, cold Lyot stop) at 1.6K. The hold time of the system exceeds 12 days.

We have recently implemented new arrays of Kinetic Inductance Detectors (KID) for the four sub-bands of the spectral coverage. These include 22, 39, 25, 43 pixels respectively, and fill a 0.5^o diameter field of view (Fig.2).

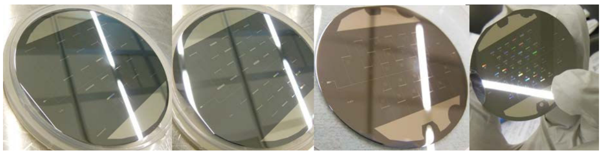

Figure 2: The four arrays of Kinetic Inductance Detectors for the OLIMPO experiment

The experiment is funded by the Italian Space Agency and is developed by an international collaboration, lead by the group at the Physics Department of Sapienza University of Rome. The first flight is scheduled for June 2017. We expect to be produce map-spectrum data-cubes for 50 clusters, and a deep data cube for a $5^o \times 5^o$ blank-sky region.

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

A6. Exploring clusters of galaxies by hydrodynamical simulations and microwave observations

The clusters of galaxies, the largest collapsed structures in the Universe, are useful testbeds to investigate global parameters and evolution of the Universe.

Hydrodynamical simulations are a valuable approach to explore by synthetic clusters the validity of universal approximations based on the self-similarity of those objects. Within the MUSIC collaboration[1] we had the possibility to use one of the largest catalogue of clusters with $10^{13}M_{\odot}<M<10^{15}M_{\odot}$ at redshifts $0<z<9$ generated under the assumptions of purely gravitational equilibrium or adding radiative physics, such as radiative cooling, heating processes, star formation and supernovae feedback and recently with AGN feedback. These synthetic clusters have been studied applying multiwavelength approaches, from visible to X-rays. However observations in the microwaves of the thermal Sunyaev-Zel'dovich effect (SZe), the spectral distortion due to the inverse Compton scattering of the CMB photons with the hot IntraCluster Medium (ICM), are the only ones not affected by the intrinsic dimming usual for emitted radiation. For the first time we extended the Y-M scaling law, the relation linking SZe brightness to the total mass, in the protoclusters regime, Fig.1 [1]. The X-ray properties, and the connected scaling relations with ICM global properties, such as the X-ray temperature and the luminosity, have been then explored in the more massive objects by means of synthetic *Chandra* observations [2]. An estimate of the concentration-mass relation for the CLASH[2] cluster sample has been derived in [3]. Finally the presence of coherent rotation of ICM has been studied in Baldi A.S. *et al.* MNRAS, 2017.

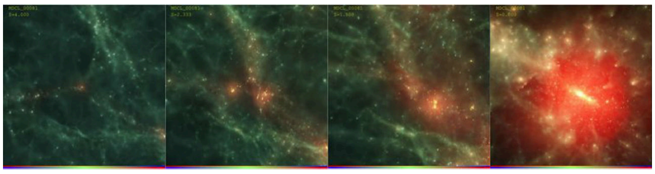

Figure 1: One MUSIC cluster at z=4, 2.3, 1.5 and 0 (from left to right) [1].

Multiband observations of SZe have been used to constraint possible deviation of CMB temperature-redshift relation, $T_{CMB}(z)=T_0(1+z)^{1-\beta}$, a key prediction of standard cosmology. This observational strategy, suggested in the '70 by F. Melchiorri, among others, was applied for the first time with MITO[3] data towards Coma cluster. Recently a subsample of the clusters observed by Planck satellite at $0.01<z<0.94$ from 70 up to 353 GHz has allowed to limit possible deviations on this relation, $\beta=0.012\pm0.016$, still consistent with the standard model [4].

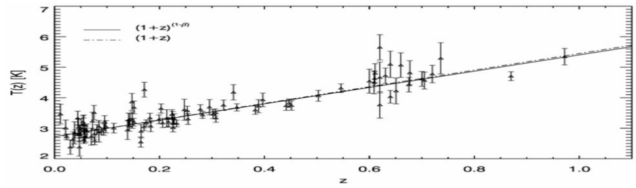

Figure 2: T_{CMB} as a function of redshift [4].

The future of SZe observations resides in high angular and/or spectral resolution observations. While the second ones are going to be explored with the balloon-borne experiment, OLIMPO[4], the high angular resolution is ensured by large dish ground-based telescopes. The NIKA2 camera[5] is completing the commissioning phase at 30-m IRAM telescope: thousaunds of KID detectors are observing at 150 and 260 GHz with 18" and 11" of resolution, respectively. The capabilities of the camera have already been proven with NIKA. A non-parametric pressure profile of ICM was recovered in PSZ1 G045.85+57.71 (F. Ruppin *et al.* A&A, 2017) and a map of the kinetic SZe detected towards MACS J0717.5+3745 (R. Adam *et al.* A&A, 2017), see Fig.3.

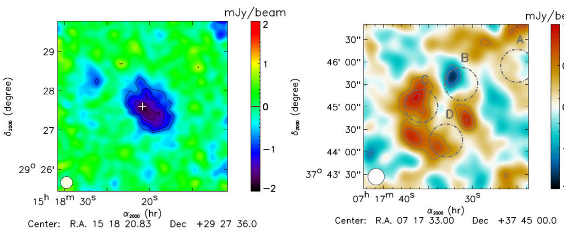

Figure 3: NIKA maps at 150 GHz of PSZ1 G045.85+57.71 (left) and at 260 GHz of MACS J0717.5+3745 (right).

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[2] http://www.stsci.edu/ postman/CLASH
[3] http://oberon.roma1.infn.it/mito
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[5] http://ipag.osug.fr/nika2/

A7. Cosmology and Lensing with Euclid

Euclid is an ESA approved mission scheduled for launch in 2020 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.

The Rome group participates the Euclid collaboration in a non marginal way being part of the Weak Lensing Science Working Group (WLSWG) and the Interacting Science Team (IST). During the years 2014 - 2016, the Rome group has been actively involved in important aspects of the activities carried on within the WLSWG and IST. A brief summary follows.

Impact of shear systematics on cosmological constraints. In order to keep its promises to shed light on the dark side of the universe, the Euclid collaboration must be able to reconstruct the shear field with as less systematics as possible. It is therefore of mandatory importance to first subtract the Point Spread Function contribution modeling it to an accuracy never needed before. As a consequence of the wide filter and the precision required, the wavelength dependence of the PSF is no more negligible so that one has to consider the so called effective PSF which depends on the galaxy Spectral Energy Distribution (SED). Moreover, being the galaxy a two components system, the SED will change along the radial direction so that a colour gradient originates. Neglecting this effect in the reconstruction of the effective PSF and hence in the shear measurement introduces what is referred to as *colour gradient bias.* The Rome group leads the task of estimating and calibrating the colour gradient bias using both simulations and HST images. This is not the only bias possibly affecting shear measurements so that it is important to investigate what the impact is on the cosmological constraints. To this end, the Rome group has developed a method to convert systematics from imperfect galaxy ellipticity measurement and PSF reconstruction into cosmic shear tomography systematics taking care of both the redshift evolution of galaxy properties and the survey observational setup.

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 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 shear and convergence fields providing complementary constraints on cosmological parameters. We have been investigating the use of weak lensing peaks count to constrain modified gravity theories or, for a given cosmology, the parameters of the mass - concentration relation. We lead the higher order statistics package within the WLSWG. This has pushed our attention to other probes which describe the convergence field properties both from a global and a topological point of view. We have considered higher order moments of the convergence probability distribution function (PDF) carrying out a detailed analysis to show that it is possible to match theoretical and observed moments provided some nuisance calibration parameters are introduced. The methodology has been successfully tested on MICE simulation dataset also taking care of problems related to the reconstruction of convergence map from noisy shear data. A Fisher matrix forecast analysis has then been executed to find out how much the constraints on cosmological parameters are improved by a joint use of shear tomography and convergence moments. The same kind of analysis has been carried out using Minkowski functionals as probe of the topology of the field.

Code comparison project. 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, systematics errors). Different codes are available to this end, but it is worth noticing that their consistency has never been verified. Given the high accuracy requested, discordant forecasts can not be accepted. The IST has therefore started a code comparison project which the Rome group is leading.

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Authors

R. Maoli, M. Vicinanza, V.F. Cardone[5], X. Er[5], R. Scaramella[5]

A8. Unveiling the nature of the first stars and galaxies

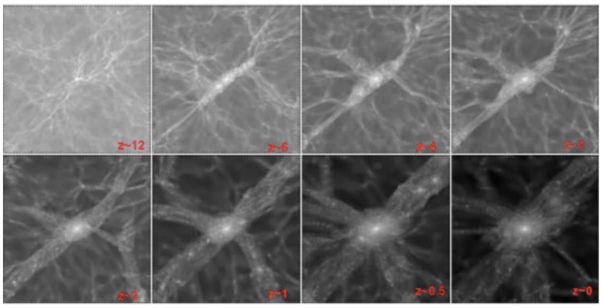

Figure 1: Slice cuts of the dark matter distribution in the Local Group at various redshifts. The images are centered on the Milky Way halo [2].

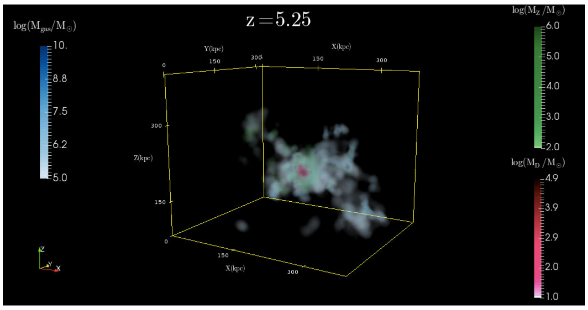

Figure 2: Spatial distribution of gas, metals and dust in simulated galaxy at $z = 5.25$, [6].

Using large ground-based and space-borne telescopes, observations have probed cosmic history all the way from the present-day to $\sim$ 700 million years after the Big Bang. Earlier on lies the remaining frontier, where the initial density fluctuations mapped by the cosmic microwave background radiation grew by many orders of magnitude, paving the way to the formation of the first stars, supernovae and black holes. During this critical phase, the Universe was transformed from its initial simple state to a highly complex system through the injection of the first heavy elements (metals and dust) from supernovae and the emission of light from the first stars and accreting black holes. Data collected in the last decade have revealed that the Universe at redshift $\sim 7-8$ is already mature, with galaxies and quasars already formed. Yet, the nature of the first stars and black holes, and the impact they had on the properties of the first galaxies and quasars remain largely unknown. Our research follows three main lines of investigations:

From first stars to the Local Universe
The most metal-poor stars observed in the Local Group are expected to form out of gas enriched by the first stars, making them the living fossils of the first star formation episodes in the Universe [1]. To assess quantitatively the connection between the first stars and the Local Universe, we have developed GAMESH, a numerical model that couples existing chemical evolution and radiative transfer codes with a high resolution N-body simulation of the Local Group (see Fig.1). Using this tool we plan to investigate a number of astrophysical problems, among which the star formation and the reionization histories of the Local Universe, the formation and coalescence environments of massive black hole binaries, the co-evolution of nuclear black holes and their host galaxies in dwarf-size halos.

From first stars to the first galaxies
To interpret observations taken with current telescopes (HST, ALMA) at very high redshifts ($z \sim 6-8$), we are running detailed numerical simulations with the code dustyGADGET, capable to predict the nature of their dominant stellar populations and the gas and dust content of their interstellar medium [2] (see Fig. 2). The results of these studies will allow us to shed light on the dominant sources of cosmic reionization and metal enrichment [3,9,10] and will provide an important guidance for future observations with the JWST.

From first stars to the first black holes
The existence of $\sim 10^9\ M_\odot$ black holes at $z \sim 6-7$ is a challenge for theoretical models. In the current most popular scenarios, the first black hole seeds form as remnants of the first stars at $z \sim 20-30$, or by the direct collapse of gas at $z \sim 10-15$. We have developed detailed models to track the metallicity of the star forming gas, the intensity of the UV radiation, and the gas accretion rate in order to assess the relative importance of different black hole seed populations [4]. We investigate the role of super-Eddington gas accretion [3] for the early growth of super-massive black holes, and the observability of their black hole progenitors at $z > 6$ [4].

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`www.oa-roma.inaf.it/FIRST`

A9. Theoretical and Computational Astrophysics

Modern theoretical Astrophysics relies crucially on numerical methods. Actually, the strongly non-linear, out of equilibrium, physical stages that characterize the environment of galaxy and star formation, as well as the dynamics of star clusters in an external field and the interaction of stars and a supermmassive black hole (SMBH) are too complicated to be faced with analytic approximations. Consequently, it is compulsory the use of efficient algorithms running on supercomputers. We address the reader to this link http://astrowww.phys.uniroma1.it/dolcetta/HPC.html to know about the HW and SW initiatives of our group ASTRO in the Dep. of Physics which has a long experience in such field and a huge international reputation.

The main topics we dealt with in the 2014-2016 period are: 1. dynamical friction of star clusters in cuspy galaxies; 2. dynamics of Kuiper belt objects upon stellar perturbation; 3. formation and evolution of Nuclear Star Clusters (NSCs) in galaxies; 4. mutual feedback of NSCs and SMBHs in galactic centers; 5. generation of high- and hyper-velocity stars around SMBHs; 6. HR diagram perculiarity of some globular clusters; 7. numerical simulation of a stratospheric balloon launch.

Most of the results obtained in these research topics have been obtained by an intensive use of our group computing facilities, which rely essentially on "hybrid" codes exploiting the joint computing power of CPUs governing various GPUs (Graphic Processing Units) connected via PCI express ports to the host system. The GPUs act as computing accelerators. We have developed both hardware and software aspects, as described in the http://astrowww.phys.uniroma1.it/dolcetta/HPC.html web page.

I will here briefly synthesize the results obtained in the above topics.

1. with the Sapienza PhD student (and later post doc researcher) M. Arca-Sedda we developed a semi-analytical theory of dynamical friction in cuspy (centrally singular) galaxies which avoid the unphysical divergence in the collective deceleration around the host galaxy center (see [1]);

2. with the PhD student D. Punzo (University of Groningen, The Netherlands) and S. Portegies Zwart (University of Leiden, The Netherlands) we showed the effects of the perturbation caused by a passing by star on the Kuiper belt objects of our Solar system. Actually, the encounter itself usually leads towards eccentricity and inclination distributions similar to observed ones, but tends also to excite the low-eccentricity population ($e \leq 0.1$ at around 40 AU from the Sun), depleting this region of low eccentricities;

3. in a wide collaboration involving M. Arca-Sedda, M. Spera (PhD student, Sapienza and later post doc INAF), F. Antonini (CITA, Canada), A. Seth (Univ. of Utah, USA) we continued our long term research program on formation and dynamics of dense stellar agglomerates to form a NSC around the host galaxy center (see [2]);

4. we found that the infall and nerger scenario is working whenever the mass of the central BH is less than $\sim 10^8$ M$_\odot$, above which the tidal disturbance of the SMBH overwhelms the incoming star clusters binding energy and dissolve them before a NSC can form;

5. with G. Fragione (student in the joint Sapienza-Tor Vergata PhD program in Astronomy, Astrophysics and Space Science) we found that the interaction of a massive globular cluster with a SMBH may induce ejection of stars from the cluster at high and very high speed, $v > 800$ kms^{-1} (see [3]);

6. we gave the explanation of the peculiar hook in the HR diagram of the globular cluster ω Centauri (see [4]);

7. in the frame of the FATA project financed by the Regione Lazio (Filas) program coordinated by P. de Bernardis we (R. Capuzzo-Dolcetta and F.G. Saturni, former PhD student in Astronomy, Sapienza) we are testing our code aimed at studying the sub orbital evolution of a balloon to launch at north polare latitudes (launch basis in the Svalbaard islands, Norway). This will constitute the first public tool for planning balloon launches.

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R. Capuzzo-Dolcetta, M. Arca-Sedda, G. Fragione, M. Spera

http://astrowww.phys.uniroma1.it/astro/dolcetta.html

A10. Dynamical evolution of stellar clusters

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. Part of the research has been addressed to the study of the dark energy (DE) effects on the gravitational equilibrium of a cluster of galaxies (CoGs) in the framework of the ΛCDM cosmological model, in order to determine how DE affects the properties of the CoGs. Details on this topic are available in [1]. Moreover, using a direct N-body code to perform numerical simulations, we investigated the effects of the antigravitational action of DE, believed to be the responsible of the accelerated expansion of the Universe, to the dynamical study of the galaxies in a single galaxy cluster. Inspired by some observational works on the Local Group and in other nearby clusters, such as Virgo and Fornax, we studied the role played by DE in shaping the velocity field of galaxies by studying the velocity-distance diagram of the cluster. Our results suggest that the outflowing galaxies reach the observed configuration within a Hubble time, only if some equilibrium initial conditions on the cluster velocity field are relaxed. The observed outflow of the galaxies in the nearby clusters could be caused to the local action of DE [2]. Making use of high-resolution simulations performed, we also analyzed the central region of the cluster, investigating the orbital decay of the galaxies and finding that runaway collisions lead to the formation of a massive central system (MCS). The evolution of a population of Super Massive Black Holes (SMBHs) in the center of a galaxy contributes to the MCS, and it is widely considered that two SMBHs residing in two merging galaxies form a binary system (SBHB). We analyzed this phenomenon and the results are interestingly related to the so-called final parsec problem, by which the hardening of a massive SBHB is limited because of a decrease in the efficiency of SBHB-star scattering [2].

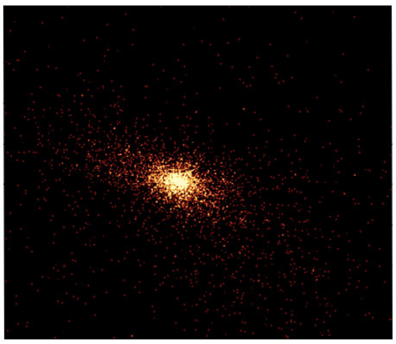

Figure 1: Galaxy in the high resolution simulations.

Another aspect developed in our research is concerning the generalization of the study of the equilibrium of anisotropic models to selfgravitating Fermi gas both in Newtonian and General Relativistic regime [3]. Also in these quantum models the main characteristic is the appearance of a hollow structure for which the density profile shows an increasing behavior at increasing values of radius at sufficiently large level of anisotropy. Moreover, in the limit of full degeneracy, we find a direct expression relating the anisotropy with the mass of the particles composing the system. Relativistic regime may also be applied to the study of superdense neutron stars with anisotropic pressure or super-Chandrasekhar white dwarfs generated by the presence of a magnetic field.

Finally, the study of thermodynamical instabilities of selfgravitating systems, strictly connected with the problem of gravothermal cathastrophe in globular clusters, has reached very important results concerning a new critical value of the onset of thermodynamic instability correcting the one currenty accepted in literature. The presence of an effective potential taking into account the effects of tidal forces induced by the hosting galaxy and producing the evaporation of stars in globular clusters, reduces the evolution time towards the instability and it is able also to explain the conditions for the disruption of the smaller clusters. These results, strengthened by numerical simulations, are confirmed by observational data of GC population in our Galaxy indeed excluding the old critical value introduced by Katz in 1980 [4].

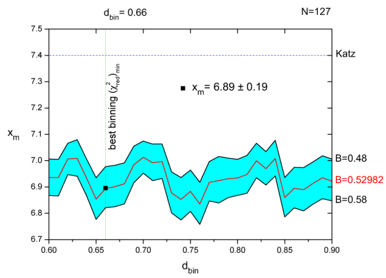

Figure 2: Observational data analysis of GC population.

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M. Merafina, M. Donnari, G. Alberti, D. Vitantoni

A11. 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 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). Great efforts on SiFAP give an integration time down to 20μ us 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 improved during the last three years in order to be able to generate an optical mark to acquire together with the data from the sensors. 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, and they are the same ones used with the previous version of the photometer. The sensors are photodetectors based on the Silicon Photo Multiplier (SiPM) technology. 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 also implemented. Pulsars, rapidly rotating highly magnetized Neutron Stars (NSs), can be found either as isolated or belonging to a binary system. Concerning isolated pulsars, high speed photometric observations on these sources can give detailed information about the processes which lead their emission mechanisms. SiFAP has been developed to compare results from optical observations with those obtained in other bands of the electromagnetic spectrum. In particular, information about the spin period of the pulsar and its temporal derivatives can be obtained. In such a way it is possible becoming able to give some explanations about dissipating and phase shifting processes, which have not yet been understood and quantified. Binary systems are typically classified in two main categories, Low Mass X-ray Binary (LMXB) systems and High Mass X-ray Binary (HMXB) ones depending on the mass of the companion star. In the first case the mass of the star is below one solar mass, while in the second case mass are above five time solar mass. One more class has been recently introduced for such systems: Intermediate Mass X-ray Binary (IMXB), which range of masses varies within the range of two or three times the solar mass. In addition, if we consider a pulsar bounded to a companion star in a binary system, we can retrieve information about orbital parameters (like eccentricity, orbital period with its temporal derivatives, and time of ascending node). In this scenario, 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 recent measurements done last summer 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. Campaigns of measurements on binary systems are going on and soon several publications will be submitted also on this subject.

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A12. Spectroscopy of Transiting Exoplanets

More than 2,650 extrasolar systems have been discovered, hosting nearly 3,500 exoplanets[1]. Ongoing and planned ESA and NASA missions from space such as *GAIA*, *Cheops*, *PLATO*, *Kepler* II and *TESS* 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.

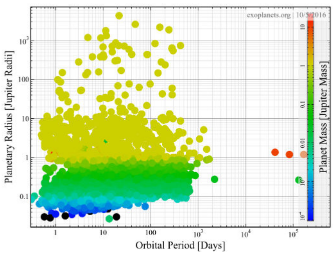

Figure 1: Currently know exoplanets, plotted as a function of planetary radius and orbital period (courtesy of exoplanets.org). The diagram suggests a continuous distribution of parameters – from sub-Earths to super-Juppiters.

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.

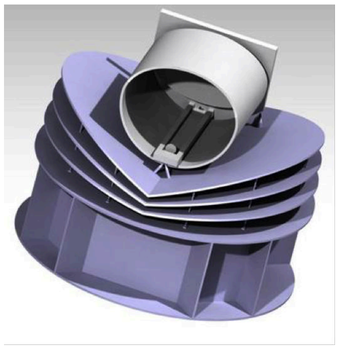

Figure 2: Engineering model of the *ARIEL* spacectraft.

The *ARIEL* space craft (Figure 2) is a dedicated space mission designed with the necessary photometric stability to characterize spectroscopically over 500 exoplanets during a mission life time of 3.5 years [2]. The *ARIEL* sample includes gas-giants, Neptunes and super-Earths with temperatures hotter than 600K, as these types of planets will allow direct observation of their bulk properties, enabling us to constrain models of planet formation and evolution. If selected by ESA for its M4 programme, *ARIEL* will fly in the second half of 2020. 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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Author

E. Pascale

A13. High Resolution study of Anomalous Microwave Emission in astrophysical Galactic and extragalactic regions

The emission budget from astrophysical sources at microwave frequencies is mostly dominated by the well studied free-free, synchrotron, and thermal dust emissions. In addition, the Anomalous Microwave Emission (AME) shows up both as diffuse emission and in selected sky regions. Its physical origin is still far from being fully understood or characterised but the most updated models predict that AME is dominated by electric dipole emission from rapidly rotating small dust grains: the Spinning Dust. AME is spatially correlated to thermal dust emission but peaks at 15-30GHz where the thermal dust contribution is negligible and the emission budget is supposed to be led by free-free and synchrotron. The study of this emission is crucial for understanding the composition of the inter-stellar medium, to study the physics governing our Universe, and to disentangle cosmic signals such as the CMB from foregrounds.

In the experimental cosmology laboratory of Sapienza University we focus on direct observations of selected Galactic regions such as HII regions or Super Nova Remnants (SNR) as well as close-by galaxies. Observations take advantage of the high angular resolution of large radio telescopes. Multi-band intensity and polarisation observations measurements are enabling us to disentangle and validate the different proposed models studying, in addition, the morphology of the selected regions. Among the instruments that are pushing ahead the knowledge of the AME mechanisms, we have been using the Australian 64m Parkes telescope, and the 64m Sardinia Radio Telescope (SRT) in Italy.

Detailed observations toward the RCW175 HII region have been taken with the 64m Parkes telescope in the range 8.4GHz-21.5GHz, in intensity and polarisation, with angular resolution ranging between 1.1' to 2.4' [1]. Our observations confirmed the presence of AME and found the presence of at least two spinning dust components: a Warm Ionized Medium and a Colder Molecular Cloud (see Figure 1). In addition, we derived an excess (spinning dust) map with emission concentrated from one of the source within the RCW175 and got evidence of faint or no polarisation associated to AME.

Analogous observations have been undertaken toward the 3C396 SNR [2]. These showed that the Spectral Energy Distribution arising from this region is dominated by synchrotron with no evidence of AME. In addition, VLA 4.8GHz observations and unpublished GBT 31.2GHz observations of the core of 3C396, together our Parkes observations, allowed us to study the morphology and the spectral index distribution within 3C396 SNR.

In addition to Galactic regions, of great interest is clearly the possibility to detect AME from extragalactic sources as it represents a unique possibility to study astrophysical processes so far mainly studied in our Galaxy. Within the Early Science Program recently opened by

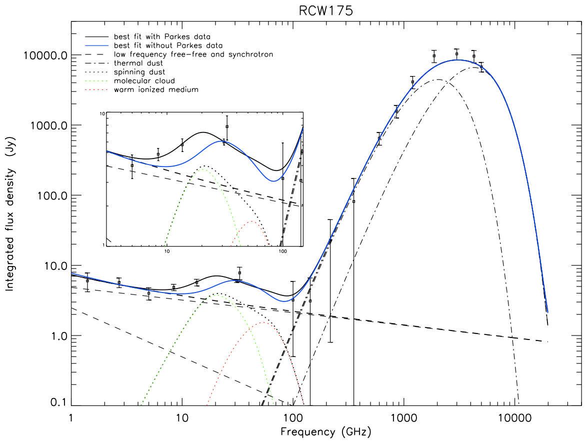

Figure 1: SED of RCW175 obtained with aperture photometry using the Parkes radio telescope. The fit is accounts for free-free, synchrotron, thermal dust emission, as well as various spinning dust models. The overall fit suggests the presence of at least two different components of AME [1].

the SRT, we started an observational program aimed to map entirely M31 galaxy in the C-band (6.7GHz) and in the K-band (22GHz) down to 0.10mJy/beam. The first part of our observations (C-band) has started in June 2016. With these data we can advance in several astrophysical fields including (but not limited to) the study of the AME (E.S. Battistelli *et al.*, in preparation):

- thermal vs non-thermal emission disentangling;
- study of the Star Formation Rate (SFR);
- a study of the AME within M31, both as an overall emission and in specific regions;
- MASERS: 6.7GHz methanol (CH3OH) maser;
- hydrogen Radio Recombination Lines (RRLs).

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http://server2.phys.uniroma1.it/doc/battistelli/

A14. Applied meteorology for the assessment of solar ultraviolet radiation at the Earth's surface and human exposure, monitoring of atmospheric ozone and nitrogen dioxide, microclimate analysis for cultural heritage.

The activity of the Meteorology research group (G-Met) is focused on the following topics:
1) solar ultraviolet (UV) radiation and monitoring of trace gases;
2) microclimate analysis for cultural heritage.

1) The amount of solar radiation reaching the Earth's surface depends on astronomical, astrophysical, geographical and atmospheric factors. In the UV range (200-400 nm) solar radiation is modulated by the amount of atmospheric trace gases, such as ozone and nitrogen dioxide which influence the climate and the terrestrial ecosystem. Since the early 90's the G-Met has been involved in research of solar UV radiation and trace atmospheric gases using measurements provided by a single monochromator spectroradiometer and a broad band UV detector. These intsruments are still in operation and they are located on the roof of the Fermi building within Sapienza Campus. More than 20 years of daily data are regularly checked for their quality and used for short and large-scale studies ([1]). Particular attention has been paid to meteorological conditions that could potentially increase the intensity of radiation at those wavelengths more effective for human erythema, expressed by means of the UVI (Ultra Violet Index, Figure 1). Part of the activity aimed at defining reliable algorithms (empirical, statistical or based on radiative transfer models) for 'the following day' UVI prediction.

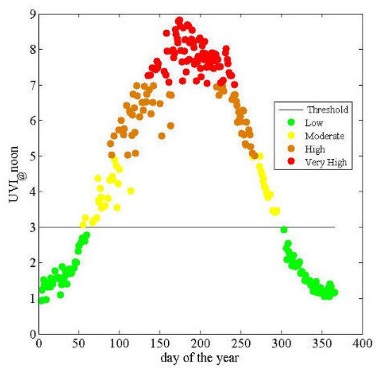

Figure 1: UVI at noon in Rome. The different colors refer to the different risk levels.

The researchers also addressed the challenge to quantify the amount of solar UV radiation received by different human body sites, considering different exposure conditions, geographical sites and exposure durations. Significant contributions to the understanding of the technique, based on the use of small dosimeters built up with UV sensitive polymer films ([2]), were provided. Several dosimetric campaigns with volunteers were carried out to estimate the exposure to solar UV([3]). Since dosimetric data are scarce, the research conducted by G-met has added a huge amount of new data for the assessment of individual exposures.

2) In the last decade a growing number of studies on environmental conditions of museums and buildings housing artifacts have shown that a stable microclimate is benecial for their conservation. Artifacts, depending on their material and age, react to trends and changes in temperature, humidity and lighting. The know-how of the group showed to be essential in the field of cultural heritage, mainly to characterize microclimatic conditions and to evaluate causes of deterioration determined by environmental factors. Through specific measuring campaigns in museums, churches and archaeological sites, the researchers improved existing methodologies both introducing original methods for data analysis and modelling dynamics of indoor environmental conditions (Figure 2) with the use of Computational Fluid Dynamics (CFD) ([4]).

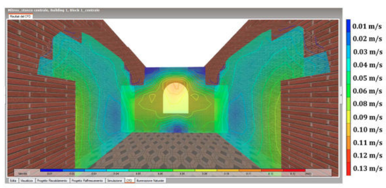

Figure 2: Output of the air velocity distribution from CFD in the Central Hall of the Mithraeum of the Baths of Caracalla in Rome

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www.gmet.eu

List of research activities

Condensed matter physics and Biophysics

Condensed matter physics and Biophysics

The Condensed Matter group at the Physics Department of Sapienza, Universita' di Roma is composed by more than 35 scientists with permanent positions (assistant, associate and full professors) and several affiliated researchers (mostly from CNR) which actively investigate different properties of hard, soft and bio matter, or export ideas developed in condensed matter to new frontiers. This group of scientist collaborates with several post-docs and Ph.D students enrolled in the Vito Volterra Ph.D. school. The condensed matter physics group enjoys a very high reputation in the international scientific community. In the last years, its members have been awarded 7 ERC grants and actively participate to several Horizon-2020 projects.

The following pages introduce the main research lines which are particularly active at the present time within the Physics Department. Additional condensed-matter oriented studies are listed in the Theory section, in all cases in which a predominant theoretical aspect is present. A strong cooperation between the Theory group and the Condensed Matter group has always been a characteristic of our Department. In the following, we present first the hard-condensed matter researches, then the soft-bio matter ones and, last but not least, the condensed matters offsprings.

Following a long-standing tradition, high T_c superconductivity continues to be actively studied theoretically. Under investigation in these days is the behaviour of disordered superconductors and the role of disorder in the superconductor-insulator transition (C1). In particular, the possibility that the disappearing of two-dimensional superfluidity more than the breaking of Cooper pairs could be responsible for the transition in thin films. As discussed in C1, the theory developed in Rome has been able to explain qualitatively, and in some case quantitatively the optical data in ultra-thin films of NbN, in granular Al and SrTiO3 interfaces. It also offer a new perspective for superconductive microwave devices, a field that has grown dramatically over the past decade. Also interesting the approach to unconventional superconductivity (C2) in systems where different phases compete or coexist. An example is found in cuprate high-temperature superconductors in the low-doping regime, where an insulating antiferro-magnetic phase competes with the superconductor. Interestingly, the electrons appear to behave as a soft matter system, forming polymers of charge accompanied by a non-trivial topological structure of the surrounding "solvent" played by antiferromagnetic regions, similar to traditional liquid crystal phases. The concept of soft electronic matter is currently applied also to oxide interfaces (C3) as $LaAlO_3/SrTiO_3$ or $LaTiO_3/SrTiO_3$. These materials host a two-dimensional electron gas with high mobility and gate-tunable electron density n. At the moment, these systems, beside their interest for the superconductivity properties, are also attracting interest as possible hosts for topological states of matter with Majorana fermions. Layered chalcogenide superconductors are discussed in C4. Spectroscopic studies of these materials have been able to quantify the topological spatial distribution of the different electronic phases, revealing a peculiar interconnected conducting filamentary phase that is embedded in the insulating (or normal-metal) texture. Conventional superconductivity is also explored computationally (C5), in the attempt to design, based on density functional information, systems with room temperature superconductivity. Hydrogen rich compounds are good candidates for high T_c, since the pressure required to reach a metallic superconducting state could be much lower than for pure hydrogen. Exploiting a recently developed approach to describe the vibrational and thermodynamic properties of strongly anharmonic systems in the presence of both thermal and quantum fluctuations, very important connections have been discovered between structural properties and superconducting states of H-based materials.

The spectroscopic properties of topological insulators is discussed in C6. For the case of Bi_2Se_3 an electromagnetic induced transparency is achieved under the application of a strong terahertz (THz) electric field. The high harmonic conversion efficiency (actually the highest in Dirac and massive electron materials), opens the road towards tuneable THz optical devices based on topological insulator systems. The driving forces for generating colossal magnetoresistence in $LaMnO_3$ manganite systems is instead discussed in C7. As well known, magnetoresistance is the change of resistance in the presence of an external magnetic field. In rare-earth manganite compounds, this change is orders of magnitude stronger than usual and it is promising for developing new spintronic and electronic devices.

Bottom-up self-assembly at the nanoscale is central in several researches developed in the Department, both in hard and soft matter. A considerable effort in nanoscience is devoted to design molecular architectures and to guide their directed assembly to generate materials with selected physical properties. The ability to produce two-dimensional networks, made of atomic building blocks and with a precise tuning of size, geometry and composition, allows the engineering of materials with advanced functionalities with possible applications in energy conversion, opto-electronic and spintronic. Contribution C8 shows how magnetic nanostructures can be made from materials that are non-magnetic in the bulk. The final goal is to tailor the spin-polarization transfer, the magnetic order and the magnetic anisotropy of self-assembled spin networks, also to study magnetic frustration as a function of lattice size and symmetry and individual molecules magnetic properties. Contribution C9 discusses the possibility to exploit graphene-based nanostructures for energy storage (battery electrodes) nanoelectronics. Exploiting x-rays photoelectron spectroscopy the Rome scientists have been able to provide an accurate picture of the C hybrid orbitals in nanoporous graphene, an important step in the spatially-resolved analysis of advanced materials. Ionic liquid and metallic membranes at the nanoscale, possible innovative materials with great applicative expectation for energy storage and production, are discussed in contribution C10.

The physics of semiconductors has also a long history in the Physics Department, which has recently evolved toward the study of plasmonic semiconductors (C11), semiconductors nanowires (C12), hydrogen mediated semiconductors (C13). As discussed in C11, a pervasive exploitation of plasmonic nanoantennas for mid-infrared spectroscopy and integrated sensing, requires novel silicon-compatible plasmonic materials. In Rome, nano-antennas made of heavily-doped Ge epitaxially grown on Si that can locally enhance the spectroscopic signatures of molecules by up to two orders of magnitude have been fabricated with techniques that are fully compatible with standard silicon foundry technologies. C12 discusses the light emission and absorption phenomena in nanowires, investigated in Rome by optical spectroscopy techniques based on photoluminescence. These techniques provide valuable information on the band structure of nanowires as well as on their structural properties, which are prerequisites for diverse multi-functionality with augmented performance. C13 addresses the capability of H, an highly mobile and reactive atom, to wipe out energy levels of shallow impurities and defects from the forbidden energy gap. Researchers in Rome are currently investigating how the electronic and optical properties of a semiconductors can be modified by H-atoms. Specifically transition metal dichalcogenides, which are indirect-gap semiconductors, turn into direct-band gap crystals after H irradiation. In turn, hydrogenated transition metal dichalcogenides, become patternable efficient light emitters. Finally, H incorporation has been found to improve the emission properties of Ge quantum dots embedded in Si.

Solid oxides are also investigated by infrared, Terahertz, and Raman spectroscopy in the Department (C14), with particular regard to superconductors, magnetoresistive manganites and multiferroics. In this last class of materials, these studies have identifies a strong electron-phonon interaction, which causes a huge increase in the phonon intensity at low temperature and an anomalous behaviour of the electronic bands, which show a strong softening for decreasing T. A particular effort is also devoted to the study of oxide-oxide interfaces in thin oxide metallic layers. Terahertz spectroscopy is also applied to understand the role of defects, disorder and degradation phenomena in lithium fluoride crystals and polymeric solids, a material used as high sensitivity detectors of ionising radiation (C15). Terahertz spectroscopy, but in the time-domain, is instead employed on the non-destructive but quantitative assessment of the structural modification induced by the aging process on the supramolecular architecture of cellulose polymers in ancient paper sheets.

A smooth cross-over from hard to soft matter is provided by the application of spectroscopic methods to bio and soft matter. In the Department, innovative spectroscopic methods are applied to investigate dynamics in biomolecules and life-science topics. C16 shows how sub-picosecond laser pulses can be used to stimulate and subsequently probe molecular motion in condensed matter and biomolecules. It becomes possible to observe atomic motion during elemental events underlying physical, chemical and biological processes. Similarly, employing Raman spectroscopy through a confocal microscope with ad-hoc sequences of femto/picosecond pulses, it becomes possible to spatially resolve cells, tissues and two dimensional materials. Applications to graphene-based materials and lipid metabolism in hepatic cells are reviewed in C16. Infrared absorption spectra are instead used (C17) to investigate (i) the pathway to amyloid fibril formation, with emphasis on the transient conformational structure of proteins occurring along the fibrils assembly and (ii) the structure of food proteins with low solubility, such as plant proteins in denatured states. Food protein structure impacts the release of bioactive sequences and might play a major role in industrial processing as well as in gastrointestinal digestion. Application of Fourier transform infrared (FTIR) spectroscopy on biological systems, a noninvasive technique able to identify chemical compounds and molecular species thanks to the specificity of vibrational fingerprints, is discussed in C18. The novelty of the studies developed in the Department is the coupling of FTIR with an AFM scanning probe tip to bring the spatial resolution at the nanoscale. Experiments on the bacteriorhodopsin protein assembled in individual membrane patches reveals via the analysis of the amide bands the orientation and location of the proteins. Enhancement of the spectroscopic signal and spatial resolution is also possible with surface enhanced Raman scattering. C19 discusses how this technique can help in early cancer diagnosis. The identification of the specific properties of cancer cells, such as the expression of particular plasma membrane molecular receptors, crucial in revealing the presence and in assessing the stage of development of the disease, will be possibly achieved developing a a single cell screening approach based on SERS micro-imaging.

Dielectric spectroscopy of disordered systems (polyelectrolites, structural glasses, solutions of DNA and carbon nanotubes) in a wide range of frequencies, is discussed in C20. This methodology allows us to investigate a large set of relaxation-phenomena, from the motion of large biological structures such as liposomes, erytrocites or drug delivery vectors to small molecules or even the dynamics of water molecules, which is the common solvent for these systems. Water (in confinement) is also currently investigated (C21) to asses the modifications of the hydrogen-bond dynamics. Confinement is probably the dominant condition under which water plays its role in biology, chemistry, geology or material science. Applications are described to water inside carbon nanotubes, water in ceramics and stones as well as in cellulose fibres of cultural-heritage relevance.

Applied statistical mechanics is at the core of the soft-matter research (C22-C23). Self-assembly of anisotropic or patchy colloidal particles has been investigated in great details. C22 discusses how DNA oligomers can nowadays be assembled to produce a large variety of nanometric constructs, via a cascade of self-assembly processes, each one guided by the length of complementary sequences of distinct DNA strands. It has become possible to build bulk quantities of DNA-made nanoparticles that closely match idealised patchy colloids, transferring modern in-paper and in-silico intuitions into experimental realisations. Experimental work has shown (i) how to exploit limited valence interactions to suppress phase separation enhancing the stability of the equilibrium gel phase (ii) how to exploit competing interactions to generate a material that is fluid both at high and at low temperatures and a solid-like disordered open network structure in between. C23 shows instead how the physics of self-assembly, coupled to a orientational ordering transition, can generate nematic, colesteric and smectic phases in soft materials. C24 discusses instead the physico-chemical mechanisms driving the self-assembly of supramolecular structures in dispersed systems, with special attention to systems of biological interest, as biological cell membranes and model membrane systems (liposomes and lipid monolayers) and complex macromolecules as polyelectrolytes, DNA and polypeptides.

We are now approaching topics which can be classified as offsprings of condensed matter physics, but which retain strong ties with their parent field. Several different evolutions are central in the activities of the condensed matter group in the Department: optics and quantum optics, computational biophysics, active matter, neural networks and economic complexity.

Let's start with optics in conditions of extreme nonlinearity (C25). As well known, wave propagation is strongly affected by nonlinearity. Solitons, wave solutions that propagate undistorted, bouncing obstacles, spiralling around each other, and giving rise to a particle-like behaviour in an otherwise undulatory system are a well know example. C25 discusses the experimental and theoretical description of other nonlinear wave paradigms, e.g. shock-waves which arise when nonlinear steepening causes waves and beams to break up and scatter, and rogue waves, statistically improbable intense wave-perturbations whose origin is still a matter of debate. Waves moving in disordered material may also show localisation phenomena. C26 shows that disordered optical fibre supporting transverse localisation are single mode. This has the important consequence that the transmission channels possess a high degree of resilience to perturbation and invariance with respect to the launch conditions. These disordered and wavelength-sensitive channels may be exploited to de-multiplex different colours at different locations.

Random lasing materials (e.g. powders, porous media, precipitates in solution, or photonic crystals with impurities) are discussed in C27. Here the key challenge is the characterisation of the structure of this network of wave-modes, including the strengths and signs of the relevant random interactions in order to distinguish physical regimes of laser stationary behaviour. Sophisticated statistical models and methods have been proposed to interpret the standard ordered multimode mode-locking lasers and the more recently introduced glassy random lasers. Quantum optics for information processing is discussed in C28. Quantum information is a new scientific field with origins in the early 90s, introduced by the merging of classical information and quantum physics. It is multidisciplinary by nature, with scientists coming from diverse areas in both theoretical and experimental physics (atomic physics, quantum optics and laser physics, condensed matter, etc.) and from other disciplines such as computer science, mathematics, material science and engineering. It has known a huge and rapid growth in the last years, both on the theoretical and the experimental side and has the potential to revolutionise many areas of science and technology. The main goal is to understand the quantum nature of information and to learn how to formulate manipulate, and process it using physical systems that operate on quantum mechanical principles, more precisely on the control and manipulation of individual quantum degrees of freedom. On this perspective completely new schemes of information transfer and processing, enabling new forms of communication and enhancing the computational power, are under development. In Rome (C28), scientists are exploring the possibility to create general multiqubit states, which in turn allow to increase the number of qubits using the same number of particles by exploiting an integrated platform, realised by femtosecond laser writing on a glass chip able to manipulate path-polarization hyperentangled states. Scientists are also developing a technique to restore the entanglement loss, studying a common noise of continuous Amplitude Damping coupled to unitary evolutions. The development of quantum technologies, aiming at identifying experimental platforms suitable for quantum information tasks is discussed in C29. Our researchers report a step forward towards the adoption of photons as information carriers in large size systems exploiting integrated photonics, with the final aim of obtaining an integrated version of a complete optical table. This pave the way for a leap forward in computation, communication and cryptography, as promised by quantum information processing.

Active matter is a novel field of research, focusing on the collective behaviour of nano and microscopic particles with intrinsic motility. The basic *atoms* of active matter are swimming microorganisms or self-propelled colloidal objects both showing peculiar dynamical properties that are very diverse and still not completely understood. In Rome (C30) active particles are exploited as the propelling units for larger and more complex micro-machines, to provide coherent self-propulsion at the micron scale. One of the most recent success is the fabrication of microstructures with a homogeneous light absorbing coating that, when illuminated are able to convert the incident light power into work, reaching an efficiency of conversion about five orders of magnitude larger than previously reported.

Computational biophysics (C31-C32) applies computer technology and biophysical methods to the understanding of biological data. It is an interdisciplinary field, targeting different areas of biotechnology, medicine and life sciences. In particular, in Rome we focus on the development of methods and algorithms to model, design and analyse three-dimensional protein structures with the aim of understanding biological processes at a molecular level. C31 discusses the development of methods and algorithms to model, design and analyse three-dimensional protein structures with the aim of understanding biological processes at a molecular level. A significant effort is also directed (i) to the structural prediction of proteins native states starting from the amino acid sequences and (ii) to the prediction of novel antibody, molecules rapidly becoming essential tools in the clinical practice, given their ability to recognise their cognate antigens with high specificity and affinity. C32 discusses instead a systematic computational study of the codon bias (the different frequencies of expression of synonymous codons) in bacterial genomes to find out how patterns of gene conservation, gene essentiality and gene codon bias can be correlated with the structures of the protein-protein interaction networks.

The statistical mechanics concepts developed in the study of critical phenomena have nowadays been transferred to several distinct fields, including social sciences, fuelled by the recent availability of big data. C33 discusses recent studies on economic complexity, a radically new methodology describing economics as an evolutionary process of eco-systems made of industrial and financial technologies as well as infrastructures that are all globally interconnected. The approach is multidisciplinary, addressing emerging phenomena in economics from different points of view. Application of new metrics has made it possible to provide quantitative assessments of competitiveness and potential of growth of countries, through the concept of Fitness, and products' sophistication and technological content, through the concept of Complexity. Similar algorithms have been developed to quantify the scientific competitiveness of nations. Complexity in techno-social systems is discussed in contribution C34. Here our researchers addresses, with methods originating from statistical mechanics, the dynamics of novelties - a fundamental factor in the evolution of human societies, biological systems and technology - with the aim to unfold and quantify the underlying mechanisms through which creativity emerges and innovations diffuse, compete and stabilise. The same group investigate also vehicular traffic in urban environments, a crucial indicator to provide an optimal planning of the complex processes arising from people collective motion. Statistical mechanics is also currently applied in the Department to the study of neural cells populations. C35 discusses how the Hopfield neural networks model can be used to infer the casual-link between neurones and construct the effective network, to properly predict the collective activation dynamics of specific neural systems. C35 also discusses how neural stem cells collectively form spatially organised tissues, formed of ordered progenitor and differentiated cells, that can be studied as an emergent system with a characteristic phase transition and enucleation process.

The experimental research developed by members of the Physics Department is carried out not only in the laboratories located in Rome, but also in several international facilities (Grenoble, Trieste, Frascati). Very often, our scientists have been members of the groups which have designed and realised the beam lines of these facilities.

Francesco Sciortino

C1. Superconducting films at strong disorder: Dynamics and Spectroscopy

In the last years the behavior of disordered superconductors in the proximity of the superconductor-insulator transition (SIT) got a lot of attention, both theoretically and experimentally. These materials, mainly two-dimensional (2D) thin films, pose the quite interesting problem of competition between localized electrons pairing and long-range phase coherence, such that the SIT is driven by the disappearing of 2D superfluidity more than the breaking of Cooper pairs.

It has been recently suggested [L.B.Ioffe and M.Mezard, Phys. Rev. Lett. **105**, 037001 (2010)] that despite the uniform distribution of disorder the electronic properties of these systems become inhomogeneous and a glassy phase emerges at low temperature, that can explain qualitatively some of the striking experimental findings. The results of L.B.Ioffe *et al.* were obtained on a Bethe lattice i.e. on a graph that has an exponential number of different paths on which it is well known that rare events can appear and dominate the system. It is much more difficult to assess a true glassy behavior in a 2D lattice and show that the system is not visiting its full phase space, being frozen in a subspace of possible realizations. An example we have found is that within the 2D attractive Hubbard model with on-site disorder the currents follow a percolative glassy path [G. Seibold *et al.*, Phys. Rev. Lett. **108**, 207004 (2012)].

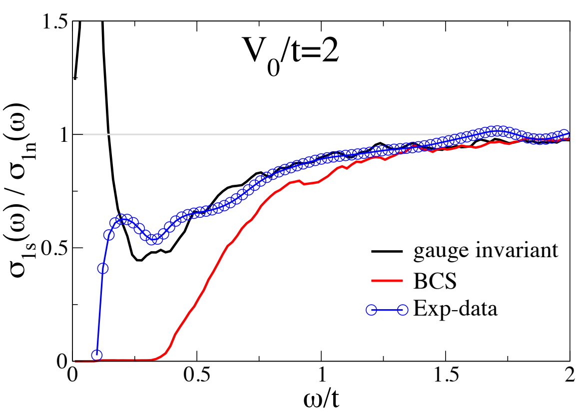

Figure 1: Optical conductivity for the attractive Hubbard model with on-site disorder (strenght $V_0/t = 2$), adapted from Ref. [3]. The experimental data are for a NbN film with $T_c = 3.8$ K, from B. Cheng et al. Phys. Rev. B **93**, 180511 (R) (2016).

Our present focus is on various properties that reflect the strong inhomogeneity of these systems with the aim of finding a clue (if any) to a true glassy superconductivity. This research is by itself full of novelties and intriguing issues. A quite striking prediction concerns the behavior of the optical conductivity. In weakly disordered superconductors the optical absorption, well reproduced by the standard BCS bare-bubble approximation, is due to quasi-particle excitations, which develop only at frequencies larger than twice the superconducting (SC) gap, see red line in Fig. 1. However, at strong disorder an additional subgap absorption appears due to the SC collective modes, included via a full gauge-invariant computation of the current response, see black line. As we have shown in Ref. [1] this effect is due mainly to phase fluctuations of the SC order parameter, which represent for clean systems optically inactive sound-like excitations, but at strong disorder acquire a finite dipole moment. More specifically, we have seen that optically active dipoles are linked to the isolated SC islands, reflecting then the effective granularity of the underlying SC background. It is worth noting that alternative explanations proposed in the literature, focused on the role of the amplitude (Higgs) fluctuations of the SC order parameter, are not supported by our findings. Indeed, we have clearly established [2] that as the SIT is approached the Higgs mode itself becomes unavoidably mixed with the phase mode, which is always dominant at low energies. Our calculations not only explain qualitatively, and in some case quantitatively (see Fig. 1), the optical data in ultra-thin films of NbN, in granular Al and $SrTiO_3$ interfaces, but they also offer a new perspective for SC microwave devices, a field that has grown dramatically over the past decade.

The next step of the research will be the analysis of critical properties. At finite temperature a Berezinsky-Kosterlitz-Thouless transition is expected. So far, the universal jump of the superfluid density has been reported to be almost completely smeared out, and there is not yet a theory for that. Our plan is then to asses whether strong disorder can take the BKT transition out of the low-density regime for vortices, changing its critical behavior. Then we will consider the quantum phase transition at zero temperature, to assess wether the transition to the insulating phase is a possible realization of a Bose glass of Cooper pairs.

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C2. Soft electronic matter and unconventional superconductivity

Soft condensed matter is characterized by gigantic responses to external perturbations. In contrast, hard condensed matter a.k.a. solids respond more weakly to external perturbations but present an enormous richness of interesting phases like metallic, insulating, magnetic, superconducting, ferroelectric, charge ordered, etc. Currently, there is much interest in systems where these phases compete or coexist. It has been known for some time that this phase intermixing can breed new phases like high-temperature superconductivity. More recent is the discovery that this mixing can also bring typical soft-condensed matter phases to the realm of hard matter. A recent example, studied at our Department is that of cuprate high-temperature superconductors in the low-doping regime, where an insulating antiferromagnetic phase competes with the superconductor. In these systems, it has been proposed a ferronematic phase [1]. In this state, electrons form polymers of charge accompanied by a non-trivial topological structure of the surrounding "solvent" played by antiferromagnetic regions [1,2]. These electronic polymers can order in orientation (and direction) as the traditional liquid crystal phases (Figure 1). Interestingly, phenomena of this kind seem common and widespread in diverse materials. The

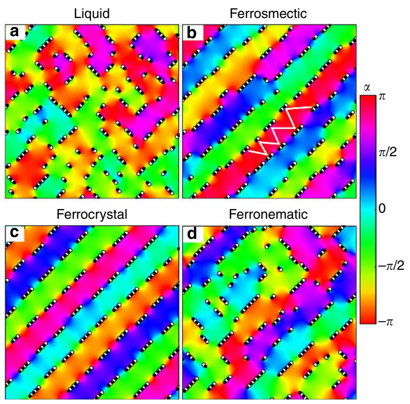

Figure 1: Liquid-crystal-like electronic phases in an underdoped cuprate [1].

above scenario applies in the very underdoped region of the cuprate phase diagram, where the system is insulating and where a strong interplay occurs between the (localized) charges and the antiferromagnetically correlated spin degrees of freedom. Upon increasing the doping, the cuprates become metallic (and eventually superconducting at record high temperatures up to 160 K), but the electronic "softness" seems to persist in various forms. In some materials it seems that the nematically oriented segments merge to form the so-called stripes, an intertwinned form of charge and spin ordering. In other cases the electron softness appear as a simpler tendency to form charge density waves. In any case both stripes and charge density waves may be present in a dynamical, fluctuating form without realizing a truely long-ranged order. Nevertheless the fluctuating waving of the charge may still occur preferentially along one direction thereby breaking the orientational order and again giving rise to a nematic state or to nematic fluctuations. Even in this more elusive fluctuating form, the electronic nematicity may leave distinct signatures in Raman spectroscopy [3] or in other spectroscopic probes.

Another example (among many others) is given by iron-based high-temperature superconductors. Also here recent Raman scattering experiments show that spin fluctuations induce nematic fluctuations where, again, the electronic charge breaks the rotational symmetry and acquires orientational order [4] (Figure 2).

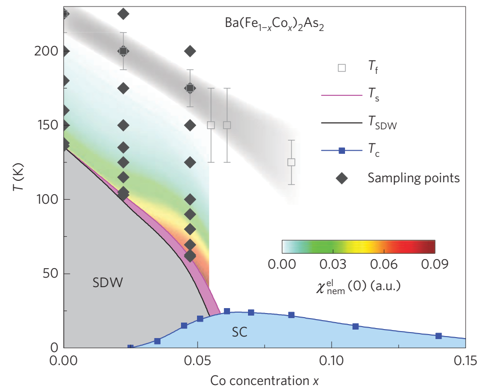

Figure 2: Phase diagram of an iron-based superconductor. The purple region has nematic order [4].

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Authors

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C3. Soft electronic matter in oxide interfaces

Transition metal oxides are intensely investigated, as they are endowed with a broad range of remarkable properties including ferroelectricity, metal-insulator transitions, magnetism, superconductivity. In particular, oxide interfaces like $LaAlO_3/SrTiO_3$ or $LaTiO_3/SrTiO_3$ (LXO/STO) host a two-dimensional electron gas (2DEG) with high mobility and gate-tunable electron density n. Upon varying n, the 2DEG undergoes a metal-superconductor transition. Due to the breaking of inversion symmetry, this 2DEG is also characterized by a sizable Rashba spin-orbit coupling (RSOC), that can be gate-tuned and increases with n.

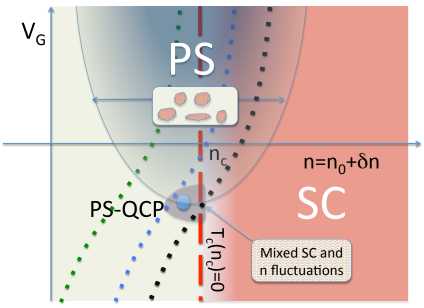

Figure 1: Density n vs. gating V_G phase diagram. The SC critical temperature $T_c(n)$ vanishes along the line of QCPs represented by the red long-dashed line. In the PS region static puddles of denser SC phase (light red) are embedded in a less dense metallic phase (light green). The darker grey shaded area represents the region where the EPS-QCP interplays with the nearby SC-QCPs, giving rise to mixed quantum SC and density fluctuations. The dotted (black, blue, green) lines are the trajectories of real systems having different as-grown densities n_0, when n is varied by gating [3].

We contributed to the understanding of these systems in various respects. First of all, we remarked that several experiments highlight the inhomogeneous character of the 2DEG, and of the resulting superconducting (SC) state, on the nanometer scale [1]. We then identified two, possibly cooperative, mechanisms for electronic phase separation (EPS) [2]: one is based on the dependence of the RSOC on the local electron density and the other is based on the electron confinement at the interface. These results highlight the soft (i.e., highly compressive) character of the 2DEG at these oxide interfaces opening the way to other contributions of our group. Specifically, we investigated the twofold consequences of this softness both on the observed unusual quantum critical behavior of superconductivity in LXO/STO and on possible exploitations to achieve spintronic effects and topological states of matter.

With respect to the first issue, e investigated the effects of temperature, gating, and magnetic field on the EPS leading to the possible vanishing of the critical temperature for EPS (see Fig. 1 and Ref. [3] and references therein). Near this Quantum Critical Point (QCP) the electron density displays quantum fluctuations that are long-ranged both in space and time. Since superconductivity is affected by the local electron density, the SC-QCP interplays with the critically fluctuating electron density, leading to a novel type of quantum criticality.

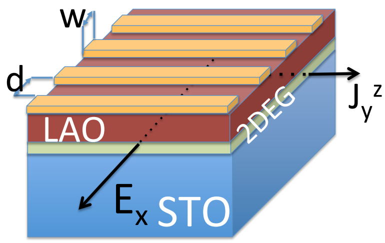

Figure 2: Sketch of a device in which the SHE is enforced in the 2DEG at the LAO/STO interface. Orange stripes represent top-gating electrodes of width w and spacing d [4].

Regarding the second issue, we suggest that, in most of the n vs. V_G phase diagram, the 2DEG is inhomogeneous, opening the way to devices based on suitably patterned states. By designing the top-gating electrodes one can induce a spatially structured RSOC that can display non-trivial spintronic effects. In particular, we identified a striped structure giving rise to a robust Spin-Hall effect (SHE), where an electric field drives a spin current.

At the moment, these systems are also attracting interest as possible hosts for topological states of matter with Majorana Fermions.

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Authors
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C4. Spectroscopic studies of layered chalcogenide superconductors

Functional materials with layered structure are generally susceptible to external stimuli due to fluctuating character of electronic degrees of freedoms. In such cases self organized defects and textures forms with ranging scales in space and time and physical properties of the material getting renormalized. The concept can be exploited to have desirable tuning of layered systems through control over external parameters as doping/intercalation, pressure, strain, electric and magnetic fields etc. Among others, layered chalcogenides are good example of systems that have great potential in various fields and during these years we have studied several of these materials by spectroscopy and microscopy.

Among the iron-based chalcogenide superconductors we have studied structural and electronic phase separation in $K_{1-x}Fe_{2-y}Se_2$. For example, we have used scanning photoelectron microscopy (SPEM) to study the electronic phase separation, providing a direct measurement of the topological spatial distribution of the different electronic phases [1]. The SPEM results reveal a peculiar interconnected conducting filamentary phase that is embedded in the insulating texture (Fig. 1). The filamentary structure with a particular topological geometry could have an important role in the high T_c superconductivity in the presence of a phase with a large magnetic moment in $A_{1-x}Fe_{2-y}Se_2$ materials.

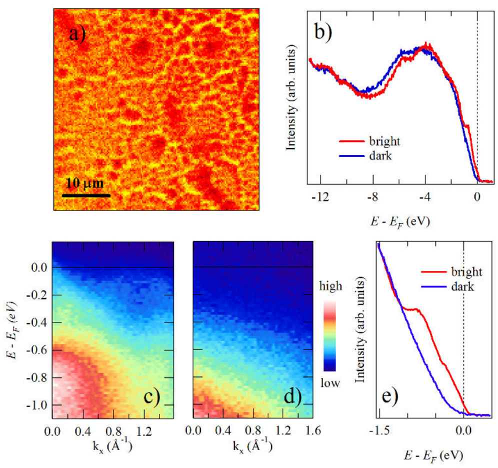

Figure 1: Scanning photoelectron microscopy image and the electronic structure of $K_{1-x}Fe_{2-y}Se_2$ at 40 K [1]. a Overview image with the spatial resolution of 0.3×0.3 μm^2 showing a peculiar topological distribution of an electronic phase with higher DOS. **b** Valence band spectra of the bright and dark regions in the image. Band dispersions along the Γ-M for bright region **(c)** and dark region **(d)**. Spectral weight near the E_F is also shown **(e,)**

Again, in $K_{1-x}Fe_{2-y}Se_2$ system, we have studied local magnetic moment and electronic phase separation in superconducting $K_xFe_{2-y}Se_2$ by X-ray emission and absorption spectroscopy [2]. Unusual temperature dependence of the iron local magnetic moment (Fig. 2) suggests possibility of an interface phase between the metallic filaments and insulating texture in the phase separated $K_xFe_{2-y}Se_2$.

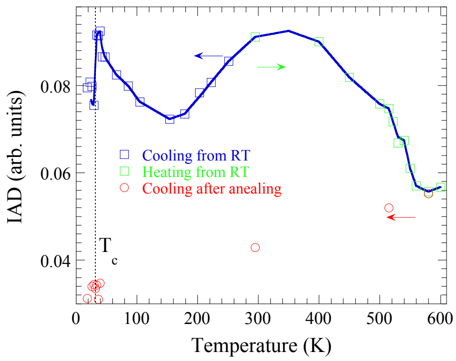

Figure 2: Integrated absolute difference (IAD) representing evolution of local Fe magnetic moment as a function of temperature [2] in $K_{1-x}Fe_{2-y}Se_2$. The thick continuous line is a guide to the eyes.

Another example is $FeSe_{1-x}Te_x$ chalcogenides that have been studied for their nanoscale structure and unoccupied electronic states by X-ray absorption measurements. The local Fe-Se/Te distances determined by different absorption edges fit well in the characteristic Z-plot of random alloys, providing unambiguous support to inhomogeneous nanoscale structure of these systems [3].

In addition, we have extensively studied the newly discovered BiS_2 chalcogenide superconductors characterized by layered structure with active BiS_2 layer intercalated by REO (RE=rare-earth) spacer layers [4]. The materials also have large potential for their tunable thermoelectric properties. By spectroscopy and microscopy studies we have found that physics of these materials is described by large intrinsic disorder in the BiS_2 layer.

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C5. Quest for room temperature superconductivity

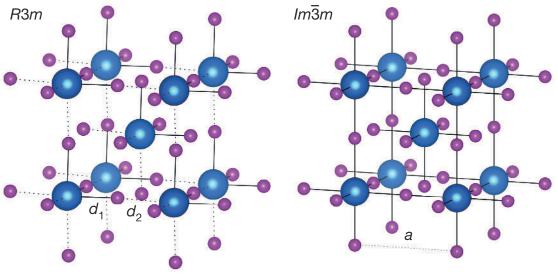

Figure 1: H_3S record superconductor. Crystal structure in the conventional bcc cell of the R3m (left) and Im$\bar{3}$m (right) phases. In the R3m structure, the H-S covalent bond of length d_1 is marked with a solid line and the longer H—S hydrogen bond of length d_2 with a dotted line. In the Im$\bar{3}$m phase, $d_1 = d_2$. The lattice parameter a is marked in the Im$\bar{3}$m structure. Blue and pink atoms represent S and H atoms, respectively.

Cuprates have for many years held the world record for the highest superconducting critical temperature (T_c = 133 K). However, despite almost 30 years of intensive research, the physical mechanism responsible for such a high T_c is still elusive although the general consensus is that it is highly nonconventional. In contrast, for conventional phonon-mediated superconductivity predictive theories, based on first principles calculations, can guide experiments in the quest for higher T_c. Till recently, the highest T_c observed in a conventional superconductor was 39 K, measured in MbB_2. Using first-principles calculations, Ashcroft suggested that metallic hydrogen would be a conventional superconductor at very high pressures (bewteen 350-400 Gpa) with a T_c around room temperature. The metallisation of pure hydrogen is still elusive, but in hydrogen rich compounds the pressure required to reach a metallic superconducting state could be much lower. Following such a path, superconductivity with a transition temperature T_c of up to 203 K, which is the highest record among all known superconductors, was observed in H_xS_y compounds by Drozdov, Eremets, Troyan, Ksenofontov, and Shylin in Nature 525, 73 (2015).

We use first-principles calculations to study to identify the stable phases of H_xS_y compounds [1,2,3] under high pressure and to their structural, vibrational, and superconducting properties [1,2,3]. We paid particular attention to the role of anharmonicity related to the H zero point motion. To this purpose we make use of the stochastic self-consistent harmonic approximation [4] an approach recentely developed by us, capable to describe the vibrational and thermodynamic properties of strongly anharmonic systems in presence of both thermal and quantum fluctuations. Indeed, the quantum nature of the proton can crucially affect the structural and physical properties of hydrogen compounds. For example, in the high-pressure phases of H_2O, quantum proton fluctuations lead to symmetrization of the hydrogen bond and reduce the boundary between asymmetric and symmetric structures in the phase diagram by 30 gigapascals. In [3] we show that an analogous quantum symmetrization occurs in the recently discovered sulfur hydride superconductor. Superconductivity occurs via the formation of a compound with chemical formula H_3S (sulfur trihydride) with sulfur atoms arranged on a body-centred cubic lattice, see Fig. 1. If the hydrogen atoms are treated as classical particles, then for pressures greater than about 175 gigapascals they are predicted to sit exactly halfway between two sulfur atoms in a structure with Im$\bar{3}$m symmetry. At lower pressures, the hydrogen atoms move to an off-centre position, forming a short H-S covalent bond and a longer H—S hydrogen bond in a structure with R3m symmetry. X-ray diffraction experiments confirm the H_3S stoichiometry and the sulfur lattice sites, but are unable to discriminate between the two phases. Our ab-initio density-functional-theory calculations show that quantum nuclear motion lowers the symmetrization pressure by 72 gigapascals for H3S and by 60 gigapascals for D_3S. Consequently, we predict that the Im$\bar{3}$m phase dominates the pressure range within which the high T_c was measured.

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Authors

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C6. Non Linear Terahertz Properties of Topological Insulators

Schrodinger electrons characterized by a quadratic energy/momentum dispersion $E=p^2/2m$ (where m is the band mass), are found in many materials and determine their optical and transport properties. Massless Dirac electrons with a linear energy/momentum dispersion $E=v_F p$ (where v_F is the Fermi velocity), have been only recently observed in condensed matter physics, first in Graphene and after in 3D Topological Insulators (TIs) and Weyl materials.

Dirac electrons are characterized by notable properties like a high mobility, a tunable density and, in TIs, a protection against backscattering through the spin-momentum locking mechanism. All those properties make graphene and TIs appealing for photonics and plasmonics applications [1] . However, Dirac electrons are expected to present also a strong nonlinear optical behavior whose intensity should increases from visible to terahertz spectral range. This should mirror in phenomena like electromagnetic induced transparency and harmonic generation. Here, we demonstrate that in Bi_2Se_3 Topological Insulator, an electromagnetic induced transparency is achieved under the application of a strong terahertz (THz) electric field [E. Chiadroni, *et al.* *Appl. Phys. Lett.* **102** 094101 (2013)].

This effect is determined by harmonic generation in the THz region with a conversion efficiency of about 1 %. The third harmonic generation is shown in Fig. 1 together with the used optical scheme. This measurement was made possible by using a powerful THz source that we developped at the the free-electron laser SPARC at INFN-LNF [2]. In particular, the strong THz radiation from SPARC filtered through a band-pass filter centered at 1 THz has been used for illuminating a thin film of Bi_2Se_3 TI. After the film the third harmonic signal has been captured by a band pass filter centered at 3 THz. The third harmonic generation is a threshold mechanism and starts to be effective above a THz electric field of about 50 kV/cm at which non linear optical phenomena occur. The high harmonic conversion efficiency (actually the highest in Dirac and massive electron materials), opens the road towards tunable THz nonlinear optical devices based on Topological Insulator systems.

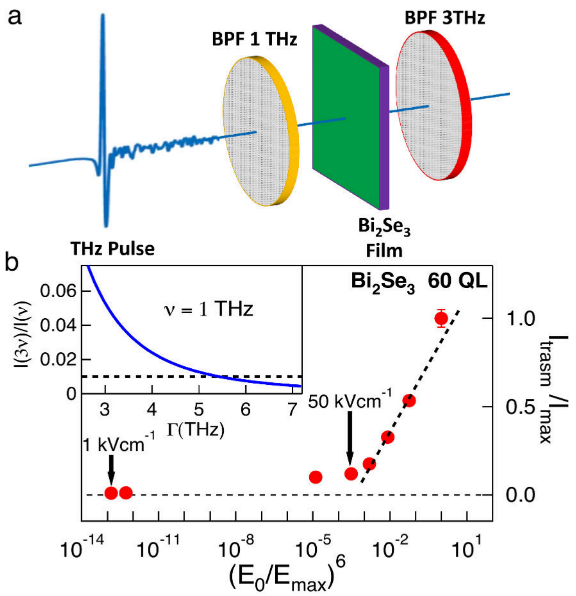

Figure 1: **Third harmonic generation in Bi_2Se_3 Topological Insulator.** Optical scheme for a third harmonic measurement. An bandpass optical filter selects from the broad SPARC THz spectrum a pulse centered at 1 THz and having a full width at half maximum (FWHM) of 0.18 THz. This pulse, with a maximum field of 300 kV/cm, illuminates a 60 QL Bi_2Se_3 film. The transmitted intensity is collected through a filter centered at 3 THz with a FWHM of 0.36 THz and finally measured through a pyroelectric detector (**a**). Above nearly 50 kV/cm the transmitted intensity (normalized to its maximum value) follows a $(E_0/E_{max})^6$ dependence (where E_{max}=300 kV/cm), suggesting a third harmonic conversion process (**b**). In the inset of panel b, the efficiency ϵ of third harmonic generation is represented *vs.* the scattering rate Γ. The measured efficiency of 1 % is obtained for $\Gamma \sim 5.5$ THz.

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F. Giorgianni, M. Autore, and S. Lupi

C7. Origin of colossal magnetoresistance in $LaMnO_3$ manganite

Magnetoresistance is the change of resistance in the presence of an external magnetic field. In rare-earth manganite compounds, this change is orders of magnitude stronger than usual and it is promising for developing new spintronic and electronic devices. In hole-doped rare earth manganite compounds, CMR peaks at a transition from a high-T insulating paramagnetic phase to a low-T conducting ferromagnetic phase. The presence of Mn^{3+} and Mn^{4+} ions together with the site site double-exchange (DE) mechanism appear to capture the essence of this phenomenon. $LaMnO_3$ is the parent compound for many of the most popular and efficient doped CMR manganites. This system displays a complex correlation between structural, orbital, magnetic, and electronic degrees of freedom. At ambient conditions $LaMnO_3$ is a paramagnetic, PM, insulator and is regarded as the archetypal cooperative Jahn-Teller (JT) and orbitally ordered system. It has an orthorhombic structure and it is an antiferromagnetic insulator ($T_N = 140K$). At $T_{JT} = 750K$, $LaMnO_3$ changes from a static orbital ordered state with cooperative JT distortion to an orbital disordered state with dynamic, locally JT distorted octahedra. This transition is accompanied by an abrupt decrease in the electrical resistivity. High Pressure (HP) resistivity and infrared measurements found an insulator to metal transition (IMT) at 32 GPa. Within a well-established collaboration with scientists from Stanford University and Argonne National Laboratory we start to investigate the HP behavior of $LaMnO_3$.

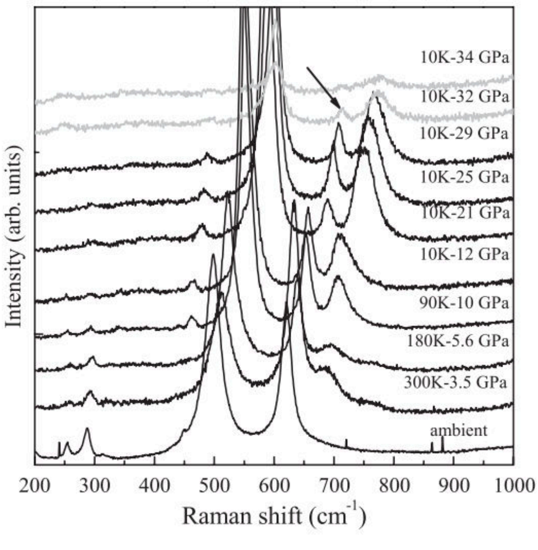

Figure 1: Raman spectra for $LaMnO_3$ collected at several P and T. The gray spectra were collected when $LaMnO_3$ enters the metallic state above 30 GPa [M. Baldini *et al.*, Phys. Rev. Lett. **106**, 066402 (2011)].

Raman measurements up to 34 GPa, collected along several low temperature cycles are shown in fig. 1 [M. Baldini *et al.*, Phys. Rev. Lett. **106**, 066402 (2011)]. Formation of domains of regular octahedra is observed above 3 GPa and coexistence of JT distorted and undistorted MnO_6 units is found over the entire P range providing the rst experimental evidence of the persistence of the JT distortion up to the IMT. in $LaMnO_3$. The nature of the HP mixed state, in particular magnetic, electronic, and orbital properties, claimed for further experimental investigation. We indeed carried out magnetoresistance and resistivity measurements over a large P-T region on a $LaMnO_3$ single crystal [1]. The T-P dependence of the resistivity with a without an applied magnetic field is shown in fig. 2. This results show that we were able to realize CMR in a compressed single-valent $LaMnO_3$ manganite compound. A theoretical investigation shows that pressure generates an inhomogeneous phase constituted by two components: a nonconductive one with a structural distortion and a metallic one without distortion. The CMR takes place when the competition between the two phases is at a maximum. We identify phase separation as the driving force for generating CMR in $LaMnO_3$ and the basic microscopic mechanism in whole family of CMR manganites.

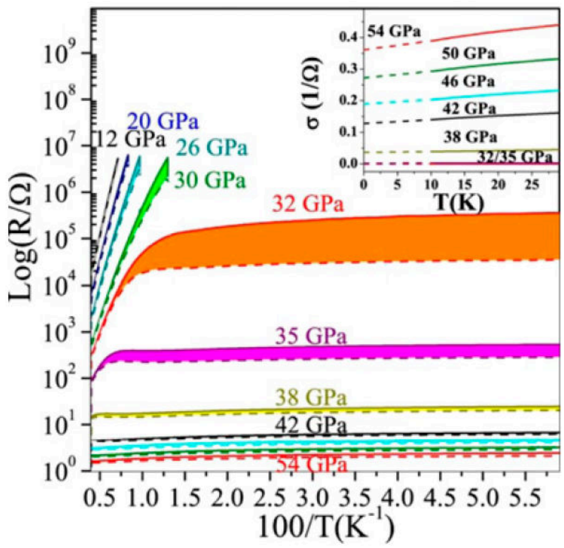

Figure 2: Temperature dependence of the resistance between 12 and 54 GPa. Solid lines data collected at 0 T magnetic field, dashed lines data collected at 8 T. Inset: Temperature dependence of electrical conductivity [1].

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Authors

M. Baldini, P. Postorino, HK. Mao.

http://gruppohps.wordpress.com

C8. Self-assembled molecular magnetic nanostructures on surfaces

A considerable effort in nanoscience is devoted to design molecular architectures at surfaces with novel optical, magnetic and electronic properties. It is well established that nano-aggregates present remarkably different properties with respect to their bulk counterparts. For example, magnetic nanostructures can be made from materials that are non-magnetic in the bulk. The ability to produce two-dimensional networks, made of atomic building blocks and with a precise tuning of size, geometry and composition, allows the engineering of materials with advanced functionalities with possible applications in energy conversion, opto-electronic and spintronic.

The organization of magnetic units on surfaces at the nanoscale offers a unique opportunity to design and tune the properties of their 3D counterparts due to the combined effects of reduced dimensions and enhanced magnetic anisotropy. Single magnetic atoms on surfaces, albeit showing enhanced magnetic anisotropy, 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.

Equally-sized clusters or evenly-spaced molecular networks can be active centers for magnetic functionalities. Magnetic metal atoms embedded into the organic cage of organic oligomers constitute an efficient method to achieve regular networks of magnetic units as, while the organic cage acts as a binding anchor to the surface, the magnetic properties of organometallic molecules are determined by the central metal atoms. The electronic state coupling between the molecule and the metal substrate may be avoided or reduced while maintaining a suitable support for ordered growth by using an appropriate buffer layer, like graphene (Gr).

Self-assembly of Transition Metal Phthalocyanines (TM-Pc) form highly ordered 1D chains (Fig. 1 a-c) on the Au(110) surface [M.G. Betti *et al.*, Langmuir **28** 13232 (2012)], and it can induce a Kondo state due to the interaction of the spin of the central metal ion with the underlying free-electron gas [1].

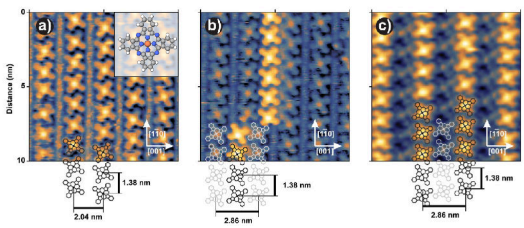

Figure 1: (a)-(c) Scanning Tunneling Microscopy (STM) images for different TM-Pc deposited on the Au(110) surface. Adapted from [M.G. Betti *et al.*, Langmuir **28** 13232 (2012)].

However, due to charge transfer and orbital intermixing between molecular orbital and metallic states, the magnetic activity of the TM-Pc molecules can be reduced [P. Gargiani *et al.*, Phys. Rev. B **87** 165407 (2013)]. Corrugated Gr on metal substrate may efficiently act as a buffer layer, preserving [M. Scardamaglia *et al.*, J. Phys. Chem. C **117** 3019-3027 (2013)] or even enhancing [2] the desired properties of the magnetic units. Furthermore, intercalation of ferromagnetic metallic layers (Co or Fe) between Gr and Ir represents a valuable route for tuning the self-assembly of adsorbed molecules. The surface potential of the Gr layer is modified via intercalation, leading to a moiré superlattice with high height modulations, and TM-Pc's can adsorb in preferential sites with the formation of different 2D superstructures [3,4]. Recently we have demonstrated, by means of x-ray magnetic spectroscopy, that FePc molecules, arranged in a Kagome lattice on graphene, magnetically couple with the intercalated Co layer, with a thermally stable antiferromagnetic coupling (up to room temperature) (Fig. 2).

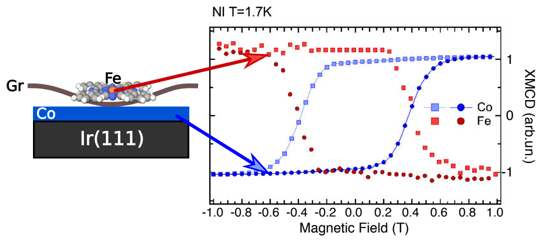

Figure 2: Hysteresis loops for Fe (red) and Co (blue) contribution in the FePc/Gr/Co/Ir sample.

New routes can be explored with different self-assembled molecular networks to study magnetic frustration as a function of lattice size and symmetry and individual molecules magnetic properties. The final goal is to tailor the spin-polarization transfer, the magnetic order and the magnetic anisotropy of these spin networks.

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M.G. Betti, G. Avvisati, S. Mitta

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C9. Graphene-based nanostructures: from two-dimensional flakes to three-dimensional architectures

The honeycomb structure of C atoms in two-dimensional (2D) graphene (Gr) can be arranged in different morphopogical configurations, spanning from a quasi-ideal 2D sheet to 3D architectures. While preserving its 2D properties, it is then possible to build-up more compact structures, constituting a playground to study fundamental physical problems associated to many applications (energy storage, nanoelectronics...). Quasi-ideal Gr can be grown on metal (M) surfaces, like

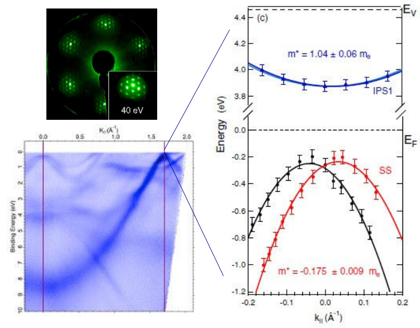

Figure 1: Gr/Ir(111): low-energy electron-diffraction with moirè pattern (top-left); Dirac cone dispersion (bottom-left); confined image potential state and Rashba splitting of Ir states (right), measured by two-photon photoemission [1].

Ir(111) [1], with the linear dipersion of the Dirac cone. The Gr-M interaction is negligible, but Gr influences the properties of the underlying M and the image potential states are pushed down in energy (Fig. 1).

For more practical applications, Gr can be grown from thin SiC films on Si [2] towards integration in Si-based devices, or it can be functionalised by growing Gr nanoribbons through polymerization of small molecular precursors on metals, thus inducing the opening of a small energy band gap [3].

Gr nanoflakes, obtained from the exfoliation of pristine graphite, are an ideal material platform for battery electrodes. Indeed they possess high crystallinity, necessary for fast electron transport, and have small (<100 nm) lateral size, offering larger edge/bulk ratio of C atoms than graphite. We estimated by x-ray photoelectron spectroscopy (XPS) that the alkali uptake for such composites is about 0.5 Li ion *per* C atom [4] (Fig. 2), much more than in graphite-based electrodes.

Nanoporous Gr arranged into a 3D shape retains great potential for alkali metal uptake. We very recently determined how the chemical bonds of C atoms and the electronic response depend on the flatness, borders and edges of the nanostructures, by synchrotron-based spatially resolved XPS. In Fig. 3 we show preliminary spatially resolved (300 nm-scale) C 1s core levels, presenting a perfect sp^2 bonding *vs.* an sp^3-like distorted bond, related to borders and edges. The spatially-resolved XPS

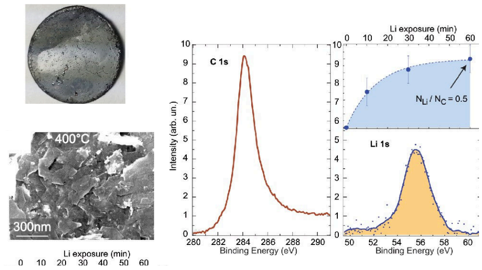

Figure 2: Gr for Li exchange: Gr flake-based electrode (top-left); SEM image of the flakes (bottom-left); XPS data of Li ion uptake *per* C atom (right) [4].

analysis opens new paths in the research field of Gr-based systems, also towards advanced materials for future energy storage applications.

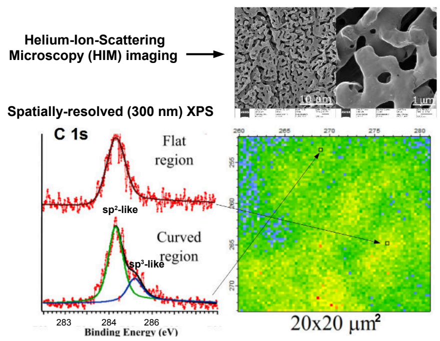

Figure 3: Nanoporous Gr: Helium Ion Microscopy (top); C 1s XPS lineshape taken at sp^2-like and sp^3-like selected spots (bottom-left); 300 nm-spatially resolved C 1s mapping (bottom-right).

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http://server2.phys.uniroma1.it/gr/lotus/index.htm

C10. Nanomaterials for alternative energy

Among all the innovative materials with great applicative expectations for the energy storage and production, we focused on two big issues: the ionic liquids and the metallic membranes.

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. Moreover, these properties can be finely tuned by a proper choice of the composing ions. 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.

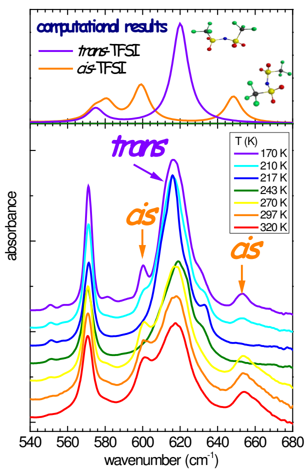

Figure 1: Calculated absorbance spectra of the single ions composing the IL and temperature dependence of the experimental spectrum of PYR14-TFSI [3]

In particular, we studied the two conformers of the bis(triuoromethanesulfonyl)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 ab-initio 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. It turns out that in the presence of cation with shorter chain (N-trimethyl-N-propylammonium, TMPA), in the solid phase the relative concentration of the conformers is strongly shifted toward a predominance of the transoid conformer. On the contrary, the solid IL retains only the cis-TFSI, even if this rotamer is less thermodynamically stable, when the cation has a longer chain (N-trimethyl- N-hexylammonium,TMHA) [1].

The concentration of different conformers of TFSI is strictly related to the possible interactions experienced by the ion, and it is also affected by the interaction with polymer membranes, as we showed for a system composed by TFSI based IL swelling a polyvinylidene-fluoride membrane. Indeed, the interaction with the PVdF chain makes the cis-TFSI energetically favored in the ILs layers in close contact with the membrane [3]. Since this system has been proposed as an innovative separator in batteries, we also studied its thermal properties by means of calorimetric and mechanical analysis techniques with special emphasis on the occurrence of phase transitions [2].

Novel Ni-Nb-Zr amorphous alloys are potential candidates as hydrogen permeation membranes to separate H_2 from CO_2 and other gases obtained from water shift reaction of coal-derived syngas.

The knowledge of the hydrogenation properties of these membranes is fundamental, since the formation of hydrides under certain operation conditions can lead to eventual failure of the membrane because of increased brittleness. To fill the lack of such information, we studied several membranes with different compositions by differential thermal analysis and their hydrogen absorption by volumetric method, providing indications about the hydrogen occupancy in the membrane, which is one of the controlling parameters for the hydrogen permeation through the bulk of the alloy membranes.

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C11. Semiconductor Plasmonics

The last decade has witnessed a pervasive application of plasmonic devices to enhance the capabilities of spectroscopic and sensing techniques. This trend has recently been extended to the mid-infrared range. Absorption spectroscopy in the so-called molecular fingerprint region between 2 and 20 μm wavelength allows direct targeting of the specific vibrational resonances of molecules with purposely designed resonant plasmonic nano-antennas, the optical counterpart of radio-wave antennas realized with nanotechnology methods.

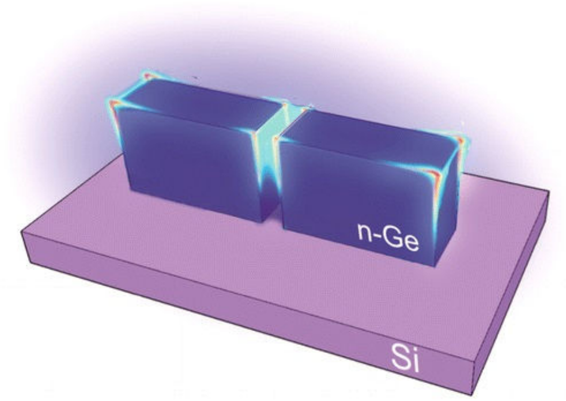

Figure 1: Silicon-foundry compatible infrared nano-antennas made of heavily diped germanium. The colored halos at the apexes represent the simulated electromagnetic field enhancement factor (red: highest value).

A pervasive exploitation of plasmonic nanoantennas for mid-infrared spectroscopy and integrated sensing, however, can only be envisaged if novel silicon-compatible plasmonic materials are introduced. In this framework, group-IV semiconductors (Si, Ge, SiGe, GeSn) represent the ideal platform for the development of integrated mid-infrared plasmonic devices. In fact, while standard semiconductors are known to possess poor conductivity, heavy doping can indeed be exploited to attain semiconductor films that behave as good electrical conductors in the mid-infrared spectral region, below their plasma frequency.

Recently, we demonstrated that nano-antennas made of heavily-doped Ge epitaxially grown on Si can locally enhance the spectroscopic signatures of molecules by up to two orders of magnitude. The nano-antennas were fabricated with techniques that are fully compatible with standard silicon foundry technologies, namely chemical vapor deposition, electron beam lithography, and reactive ion etching. A prototype implementation is formed by two heavily doped Ge rods separated by a small gap, resembling the two-wire dipole antennas commonly used as transmitters and receivers at radio-wave frequencies. The length of each element is set to be resonant with a specific mid-infrared wavelength, while the presence of the gap boosts the localization and enhancement of the field intensity. The enhanced radiation-matter interaction in the antenna gap is studied in the Infrared Spectroscopy Lab of the Physics Department with the Michelson interferometer sketched in the Figure.

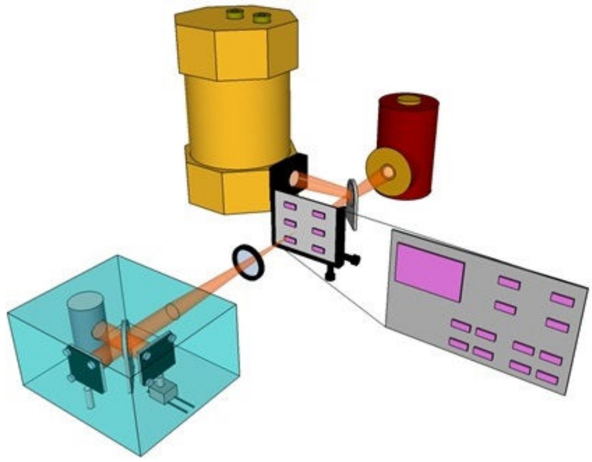

Figure 2: Sketch of infrared spectroscopy experiments on nano-antenna chips.

Beyond biochemical sensing, semiconductor plasmonics will impact other technological fields which exploit infrared radiation: thermal energy harvesting, thermal imaging, night vision, environmental sensing, gas sensing. Current efforts are being devoted to increasing the doping level of Ge thin films, in order to broaden the available spectral window and cover the 3-5 μm range. A key ingredient for the development of group-IV mid-infrared plasmonics is the monolithic integration, on the same Si chip, of Ge nanoantennas and infrared radiation sources and detectors, including those based on SiGe multiple quantum wells such as quantum cascade lasers and detectors.

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C12. Addressing the electronic properties of semiconductor nanowires

Semiconductor nanowires (NWs) are filamentary crystals with several μm in length and diameter ranging from few to hundreds of nm, see Fig. 1. Research in these nanostructures has streamlined into several frontiers, namely nanoelectronics, nanophotonics, electronic-bio interfaces, optoelectronics and energy harvesting/conversion and storage. Pivotal to the success of NWs as versatile building blocks for nanoscience is the knowledge of the nanomaterial fundamental properties. In this context, the activity of our group addresses

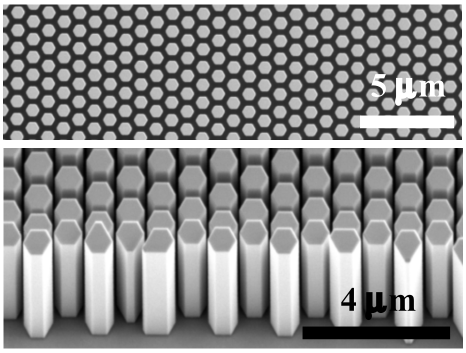

Figure 1: Scanning electron microscopy images in top- and side-mode view of InP wurtzite NWs featuring a high degree of ordering.

light emission and absorption phenomena in NWs investigated by optical spectroscopy techniques based on photoluminescence (PL). These techniques provide valuable information on the band structure of NWs as well as on their structural properties, which are prerequisites for diverse multifunctionality with augmented performance. As an example, we studied the characteristics of absorption and photo-excited carrier relaxation phenomena in III-V (InP and GaAs) NWs with regard to the optimal design of NW-based solar cells and heat dissipation [1]. One of the most exciting properties of NWs is their capability to grow with different crystal phases, known as polytypism, which has provided a platform for fundamental studies and technological applications. Specifically, we investigated the band structure of InP, GaAs and InAs [2] NWs in the wurtzite crystal phase, which is uniquely found in NW materials and is relevant for light polarization-sensitive opto-electronic devices. Fig. 2 sketches an experiment in which light absorption in NWs is clearly dependent on the absorbed photon polarization [3]. Finally, we studied for the first time the transport and spin properties of wurtzite InGaAs, GaAs, and InP NWs and their dependence on chemical composition, crystal phase and size [4]. To this end, we employed PL combined with high magnetic fields (30 T) available, on a competitive base, at the European Magnetic Field Laboratory (EMFL) facilities. Fig. 3 highlights the evolution with magnetic field intensity of the diamagnetism and Zeeman splitting of the carrier energy

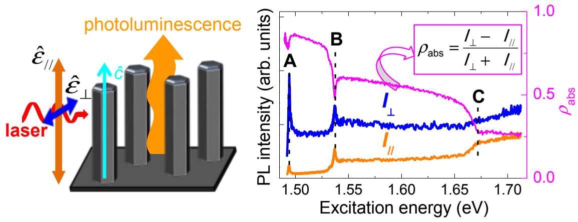

Figure 2: Sketch (left) of the experimental configuration employed to determine the absorbed light polarization degree (right), ρ_{abs}.

states. The analysis of these data leads to the determination of the effective mass and gyromagnetic factor of charge carriers that rule the magnetic, electronic and optical response of NWs to external fields.

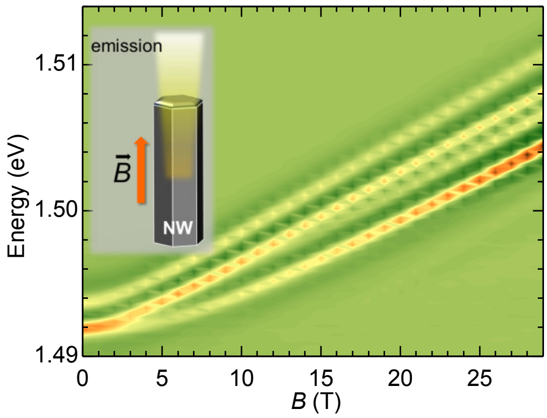

Figure 3: Spectral mapping of PL emission vs magnetic field from wurtzite InP NWs. The inset sketches the experimental configuration.

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C13. Hydrogen-mediated engineering of semiconductor materials and nanostructures

Hydrogen is the smallest atom and one of the most chemically reactive elements. These H characteristics account for its high diffusivity and reactivity in semiconductors, where it can sizeably affect the electrical, magnetic and electronic properties of the material. The incorporation of H in (and its subsequent removal from) p-doped GaN enabled the discovery of white LEDs. H was also recently found to turn highly conductive graphene into an insulator. The capability of H to wipe out energy levels of shallow impurities and defects from the forbidden energy gap has been largely investigated and exploited. In recent years, our group employed low-energy

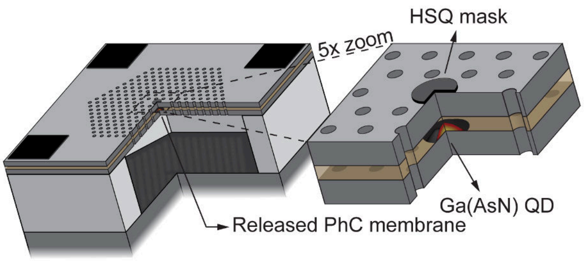

Figure 1: Sketch of a PhC cavity embedding a Ga(AsN) QD obtained by spatially selective hydrogenation.

H irradiation in a large variety of semiconductor materials and nanostructures [1]. One of the most remarkable effects regarded the electronic passivation of N in technologically relevant III-V compounds, such as GaAs and GaP. In Ga(AsN), for example, the formation of N-H bonds leads to a fully tuneable and reversible band gap variation. The subsequent spatial control of this phenomenon via lithographic techniques permits the realization of site-controlled quantum dots (QDs) [2] that can be deterministically coupled with a photonic crystal (PhC) cavity (see Fig. 1), paving the way to a number of light-matter coupling effects of topical interest in quantum photonics. Also of note is the possibility to exploit the lattice expansion associated with the formation of N-H complexes to induce spatially controlled strain modulations [3], thus providing us with an additional "knob" to fine-tune the optical properties of the material.

Another remarkable example of H-driven modification of the electronic and optical properties of a semiconductor has been recently discovered by us. In this case transition metal dichalcogenides (TMDs, *e.g.*, WSe_2, WS_2, $MoSe_2$, and $MoSe_2$), which are indirect-gap semiconductors, turn into direct-band gap crystals after H irradiation. In turn, hydrogenated TMDs become patternable efficient light emitters (see Fig. 2). Finally, H incorporation has been found to improve the emission properties of Ge QDs embedded in Si. In addition, being localised on the atomic scale, H-related effects have permitted to shed light on the microscopic complex responsible for

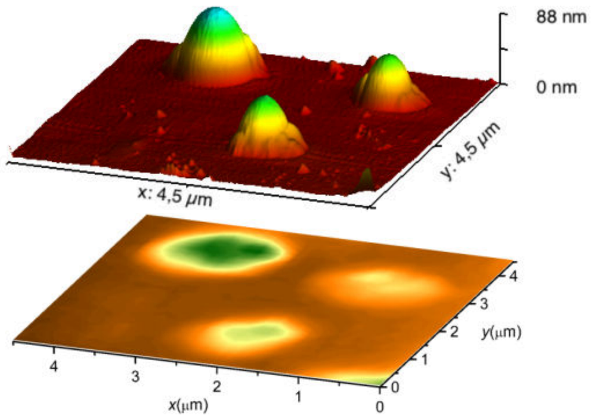

Figure 2: Atomic force microscopy (top) and RT micro-photoluminescence images of hydrogenated WS_2 showing the formation of light-emitting domes after H irradiation.

lasing in group-IV nanostructures based on Ge QDs [4] and shown in Figure 3.

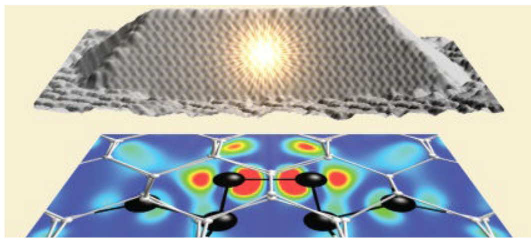

Figure 3: Bottom. Electronic orbital electron density cross-sections in the plane containing the defect responsible for lasing in a Ge QD (top).

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C14. Infrared spectroscopy of solid oxides and interfaces

The IRS group of the Dept. of Physics at Sapienza University has long studied both the lattice and the electronic properties of solid oxides, with particular regard to superconductors, magnetoresistive manganites and multiferroics. Bulk materials, thin films, and, more recently, interfaces, have been investigated by infrared, Terahertz, and Raman spectroscopy. An example of such studies is the investigation of charge ordering in superconductors belonging to the 2-1-4 family, whose main member is $La_{2-x}Sr_xCuO_4$ (LSCO). Recently, we have studied the compound $La_{1.8-x}Eu_{0.2}Sr_xCuO_4$ (LESCO), where we have detected [1] a band characteristic of self-trapped charges at the commensurate doping $x = 0.125$. This opens a pseudogap in the density of states, which can hinder superconductivity being approximately as wide as the maximum superconducting gap of LSCO.

In the domain of multiferroics, i. e., of materials which simulatneously exhibit both magnetic order and electric polarization, we have focused our interest on $Ba_2CuGe_2O_7$ (BCGO), which at low temperature develops helical magnetism of the Dzyaloshinsky-Moriya (DM) type and, under an external magnetic field, also macroscopic electric polarization. This magnetoelectric coupling, even in the absence of spontaneous polarization, is typical of multiferroics. In BCGO we have first measured and calculated the entire phonon spectrum of this compound, along different crystal axes, first for those infrared active [2] and then for the Raman [3] active ones. Our study has also allowed us to point out a strong electron-phonon interaction, which causes a huge increase in the phonon intensity at low temperature. An anomalous behavior of the electronic bands, which show a strong softening for decreasing temperature, was also observed. band acalculatiuons are in progress to explain such effect, in collaboration with ISC-CNR.

In the field of oxide-oxide interfaces, which has raised a growing interest in the last decade, we have studied how thin oxide metallic layers, like those which are grown on insulating oxides to form of electrodes, can affect the phenomenon of incipient ferroelectricity in $SrTiO_3$ (STO). This huge increase in the dielectric constant $\epsilon_1(0)$ of STO is driven by the low-temperature softening of its tranverse optical phonon of lowest energy TO1 through the Lyddane-Sachs-Teller relation

$$\epsilon_1(0)/\epsilon_\infty = \prod_{j=1}^{n} [\Omega^2_{LOj}/\Omega^2_{TOj}] \tag{1}$$

where Ω_{LOj} and Ω_{TOj} are longitudinal and transverse phonon frequencies, respectively, ϵ_∞ is the dielectric function $\epsilon_1(\omega)$ at $\omega >> \Omega_{TOj}$, and the leading term is that with n =1. Studying this effect is very important in the perspective of producing high-permittivity STO microcapacitors. We have shown by Terahertz (THz) reflectivity measurements [4] that ultrathin metallic films on the STO surface, as those which would work as electrodes, cause a partial hindering of such softening - with a consequent reduction in the dielectric constant. We have demonstrated this effect by depositing on STO both a 10-nm-thick film of $SrRuO_3$ (SRO), and a 4nm thick film of $LaAlO_3$, which is known to form spontaneously - at the interface with STO - a conducting two-dimensional electron system (2DES). In SRO/STO, the observed hardening is well explained by the depolarizing action of the SRO free electrons which follow adiabatically the ion motion. In LAO/STO, a weaker TO1 hardening could be detected by patterning the 2DES in the form of microstripes and comparing the response to a polarized THz field parallel ($\vec{E}_\parallel$) or orthogonal ($\vec{E}_\perp$) to the stripes. At 10 K, when TO1 is excited together with the free electrons by $\vec{E}_\parallel$, its absorbance is harder by about 7 cm^{-1} than that measured when TO1 is coupled to the plasmon-polariton confined within the stripes, that is excited by $\vec{E}_\perp$.

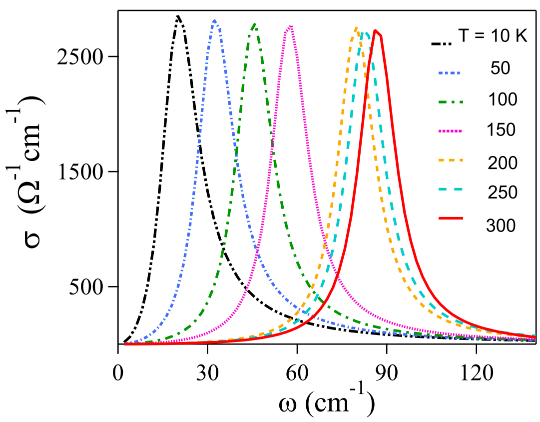

Figure 1: Low-temperature softening of the lowest-energy optical phonon of $SrTiO_3$, which is responsible for the huge increase in its dielectric constant (incipient ferroelectricity) through the Lyddane-Sachs-Teller relation.

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C15. Low temperature optical and Terahertz spectroscopy: Application to LiF crystals and ancient paper sheets

The scientific activity presented here is carried out in collaboration between the Laboratorio di Spettroscopia Applicata ai Beni Culturali and the Laboratorio Basse Temperature. Both Laboratories are aimed to spectroscopic studies of inorganic and organic systems in the ultraviolet, visible and THz wavelength ranges. The synergetic effort allows to investigate physical and chemical properties of materials in a wide temperature range, from 14 to 350K. Present topics of the joint effort are the understanding of the role of defects, disorder and degradation phenomena in lithium fluoride (LiF) crystals and polymeric solids.

LiF has received great attention due to the peculiar optical properties of radiation-induced point defects, known as color centers. Polycrystalline LiF films are used as high sensitivity detectors of ionizing radiation. LiF possesses the largest band gap, ~ 14 eV, of any solid and is particularly suitable for the investigation of lattice defect spectral features by optical spectroscopy. To this aim we measured the optical absorption spectra of gamma irradiated LiF crystals, as a function of temperature in the range $14-300$K. The temperature dependence of intensity, peak position and bandwidth of electronic defect absorption bands (Fig. 1) shows different coupling regimes of the defects electronic levels with the lattice dynamics and a cross-over between localized and delocalized lattice vibrations [1]. Optical spectroscopy

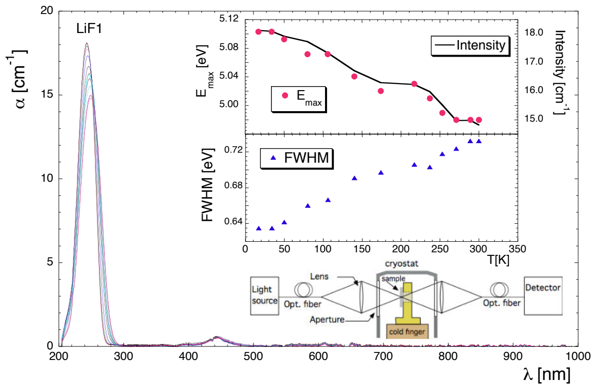

Figure 1: Temperature dependence of optical absorption of a LiF crystal. The experimental set-up is also shown.

has been also used for the study of yellowing of ancient paper. Paper yellowing is due to the development of defects (oxidized groups) acting as chromophores in cellulose polymers. The complexity of cellulose is an obstacle to the interpretation of optical spectra for the characterization and quantification of chromophores induced by ageing. To clarify this problem optical absorption spectra of paper samples were obtained in the temperature range $14-300$K. Their interpretation by *ab-initio* calculations revealed a dominant role of static disorder on chromophores optical response, compared to temperature effect. Our findings are of crucial importance to understand ancient paper degradation processes [2]. By

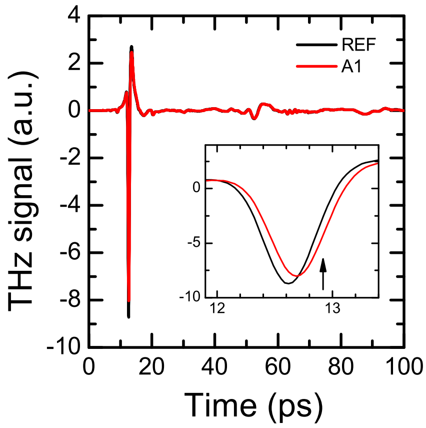

Figure 2: Time signals of the reference and A1 paper sample pulses in the transmission THz-TDS experiment.

using Terahertz time–domain spectroscopy (THz-TDS) we also focused on the non-destructive but quantitative assessment of the structural modification induced by the aging process on the supramolecular architecture of cellulose polymers, directly responsible for their macroscopic mechanical properties [3]. THz photons are particularly suitable to probe the hydrogen-bond that is of utmost importance for biomolecules and it is responsible for cellulose supramolecular arrangements. To this aim, we have developed a method to obtaining a precise determination of the cellulose spectroscopic features using THz-TDS technique (Fig. 2) eliminating the Fabry-Perot effects arising from multiple reflections inside the paper sample. A relation between progressive degradation of cellulose and modification of its supramolecular architecture was evidenced by THz fingerprints and confirmed by *ab-initio* calculations.

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C16. Ultrafast to ultraslow dynamics in biomolecules and condensed matter

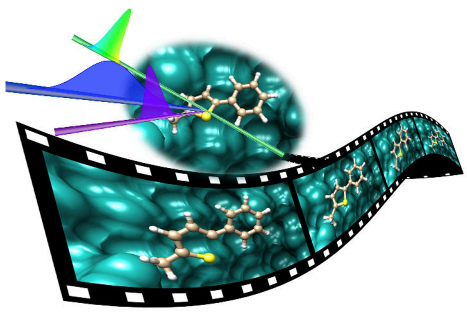
In our group we develop novel experimental tools to study those processes which are too slow, too fast or too small to be observed by the naked eye. To this purpose, we take advantage of complex sequences of sub-picosecond laser pulses to stimulate and subsequently probe molecular motion in condensed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

- **Molecular movies of photo-excited biomolecules.**
  Determining energy redistribution pathways within biomolecules and tracing the detailed nuclear motions underlying chemical reaction from reactant to photoproduct are ambitious challenges. 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: Femtomagnetism.**
  Since IBM introduced the first hard disk in 1956, the quest for more efficient storage has triggered an impressive improvement: the current recording density is more than 50 million times higher than the original prototype. To robustly engrave a single bit, in fact, a relatively large number of extended magnetic domains have to be used, to secure the information against random thermal fluctuations which may accidentally erase the data. This requirement sets the limit for the writing timescale which is possible to achieve in the nanosecond range. That's part of the reason why, in recent years, it emerged a new field of research, named Femtomagnetism, focused on the study of the so called 'exchange interaction', which governs magnetisms on such ultrafast (subpicosecond) time scales. We recently 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 [2].

- **Ultraviscous flow in glass forming materials.**
  For years people have looked at 12th century medieval glass windows and determined that the reason some are thicker at the bottom is that over time gravity causes the glass to "flow" towards the bottom of the frame. Beneath such urban myth a question of panamount importance for glass science stands: does the glass cease to flow at some finite temperature? A direct answer to this question would require ridiculously long observation times. We circumvent this infeasibility by relating the (directly inaccessible) ultraviscous flow of a liquid to the elastic properties of the corresponding glass. Specifically, by means of an ultrashort laser excitation we impulsively generate density fluctuations which we interferometrically detect with a second, time delayed optical probe. Our result indicates the lack of a finite-temperature divergence of the molecular diffusion timescale in a glass [3].

- **Coherent Vibrational Imaging.**
  Performing Raman spectroscopy through a confocal microscope is a powerfol 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. Using ad-hoc sequences of femto/picosecond pulses, Coherent Raman effects can be realized to dramatically reduce pixel dwell times down to video rate imaging. We develop and apply Coherent Raman - based microscopies to a wide variety of cases ranging from rapid characterization of graphenic materials to lipid metabolism in hepatic cells [4].



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

C17. Applications of Infrared Spectroscopy to protein and life-science studies

- **Study of the pre-fibrillar state of proteins.** One of the most discussed problems in life science is the pathway to amyloid fibril formation. Presently indeed, a clear vision of this kinetics is far from being achieved. The presence of fibrils in the infrared spectra is detected by intense absorption bands at 1625 cm^{-1}, close to the amide I contribution. By monitoring these absorption features vs. the solute concentration, the ionic strength of the solution and the temperature, a phenomenological protein-to-fibril pathway might be drawn. The IRS group has recently investigated the transient conformational structure of proteins occurring along the fibrils assembly, binding the proteins with specific molecules that act as stabilizers. We found that dimers of β-lactoglobulin undergo a native-to-fibrillar state through a crossover between β-sheet and unordered secondary structures, that can be drastically reduced when catechins are bounded at the dimer's hydrophobic sites [1]. Insulin in monomeric form, one of the most studied molecule for pharmaceutical uses, is known to form amiloyd fibrils according to a two-stage kinetics: 1) disassembly of the α domains with formation of high β content nuclei 2) coordination of the latter into fibrils. A complete hindrance of the second stage is possible when the monomers bond small hydrophobic molecules such as flavonoids.

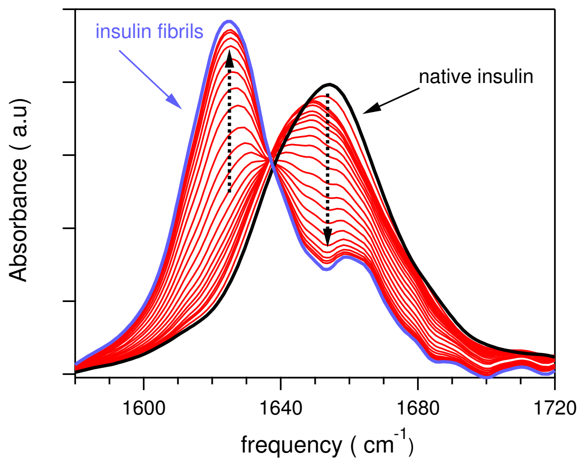

Figure 1: Evolution of the absorption spectra of insulin monomer during fibril formation in the region of the amide I.

- **On-command intracellular pH changes monitored by infrared absorption spectra.** The pH regulation has a fundamental role in several intracellular processes and its variation via exogenous compounds is a tool for intervening in the cytoplasm biochemistry. A new class of compounds (Proton Caged Compounds,PPCs) may efficiently induce intracellular acidification, through the release of protons upon UV irradiation [2]. The IRS group studied the acidification process in the HEK-293 cellular line caused by PPCs upon the UV irradiation, by monitoring the stretching mode of the CO_2 molecule centered at 2343 cm^{-1}, that increases in intensity as a consequence of the cytoplasm pH change. We also studied the efficiency of the intracellular acidification when PPCs are bound to functionalized gold nano-particles: in this case, an increase of the intracellular CO_2 content by two orders of magnitude is detected in UV irradiated HEK-293 cells [3].

- **Infrared spectroscopy of nutritionally relevant proteins.** Food protein structure impacts the release of bioactive sequences and might play a major role in industrial processing as well as in gastrointestinal digestion. The structure of food proteins with low solubility, such as plant proteins in denatured states, has been successfully determined in the IRS group by infrared spectroscopy. The results indicated that high amounts of multimeric complexes are formed from food proteins of plant origin with different mechanisms, depending on the initial content in β-sheet structure. Moreover, the higher the content in β-sheet secondary structure, the higher was the stability of the high-molecular weight complexes: this feature is likely to adversely affect protein utilization and may represent a detrimental factor on the overall nutritional quality [4].

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Authors

A. Nucara, P. Maselli, L.Baldassarre

`http://server2.phys.uniroma1.it/gr/irs/index.htm`

C18. Resonantly-Enhanced Photo-Thermal Infrared Vibrational Spectroscopy

Fourier transform infrared (FTIR) spectroscopy is used on biological systems as a noninvasive technique able to identify chemical compounds and molecular species thanks to the specificity of vibrational fingerprints. FTIR microscopy can also be performed, however only with a poor lateral resolution (comparable with the wavelength $\lambda \sim 5 - 10\,\mu$m) because of the limits imposed by diffraction. Nanoscale resolution can be obtained by shining mid-IR tunable laser beams on the scanning probe tip of Atomic Force Microscopes (AFM) and simultaneously recording either optical scattering signals (as in scattering scanning near field microscopy, s-SNOM) and/or optomechanical signals (as in the AFM-IR photoexpansion microscopy). The latter setup has been implemented at the InfraRed Spectroscopy Group (IRS) by coupling a broadly tunable Quantum Cascade Laser (QCL) to the nanoIR2 from Anasys. Mid-infrared spectra are thus obtained with a lateral resolution of tens of nanometers and with high sensitivity by detecting mechanical forces exerted by molecules on the AFM tip upon light absorption (i.e. a laser pulse).

In the case of thick and complex media, such as biological tissues, bacteria or single cells, the AFM-IR signal originates by the isothermal volume under the tip apex [1]. The size of such volume, that is strongly related to the lateral resolution, depends on the sample itself. In the case of single mammalian cells it has been possible to identify differences in the protein clustering tendency in chemically-stressed HeLa cells if compared to control ones with a lateral resolution of $\lambda/20$ [2].

The sensitivity of mid-infrared photoexpansion nanospectroscopy increases by several orders of magnitude by using a pulsed QCL with the repetition rate resonant with one of the bending modes of the cantilever, and by using a gold-coated tip to exploit field enhancement at the tip's apex. The cantilever deflection amplitude is then amplified by the quality factor of the chosen mode, while a strong electromagnetic enhancement of the optical field intensity is built up in the nano-gap between a commercial sharp gold-coated AFM tip and a gold-coated substrate. This produces a near-field illumination of the sample, allowing for the vibrational study of few molecules. We have tested this experimental condition on the bacteriorhodopsin protein (bR) assembled in individual membrane patches. We compare in Fig. 1(a) the amide I and II absorption lines for a 200 nm- thick film deposited on a flat substrate measured by FTIR with the AFM-IR spectrum of an individual, 5 nm thick, membrane patch. In the upper plot the intensity of the amide II at 1540 cm^{-1} is only slightly lower than that of the amide I band at 1660 cm^{-1}, at variance with what found with AFM-IR. Indeed the amide-I band originates from the C=O bond, aligned vertically with respect to the membrane patch. On the contrary, the amide-II line is due to N-H stretch, that is oriented along the membrane surface and then poorly excited by the radiation field, oriented vertically in the nanogap between the tip and the substrate (see Fig. 1b). This ensures one that the vibrational signal only originates from the 30-nm wide area underneath the tip, with a lateral resolution $\lambda/200$.

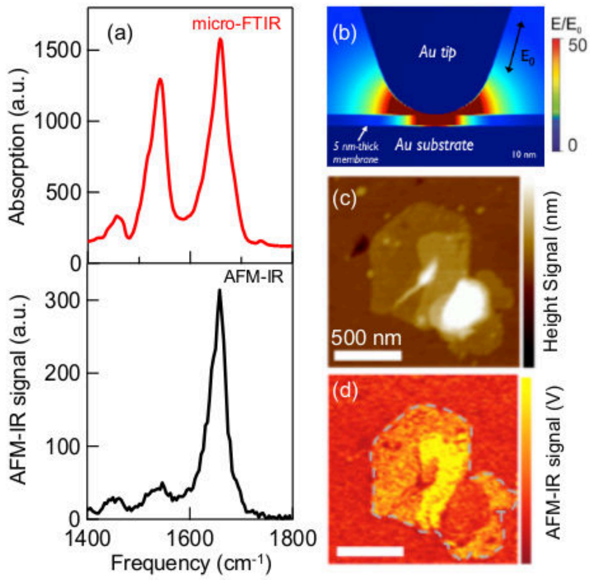

Figure 1: (a) Top: absorption spectra of the amide I and amide II bands as measured by FTIR microscopy on a thick film (200nm) of bacteriorhodopsin membrane patches deposited on a flat substrate. Bottom: AFM-IR signal as recorded on a single membrane patch, 5 nm thick. (b) Electromagnetic field enhancement between the apex of a gold-coated tip and a gold substrate. This situation well describes the condition in which the AFM-IR spectra and nano-imaging measurements are taken. (c) AFM height image of a membrane and (d) corresponding AFM-IR map of the signal recorded at 1660 cm^{-1}.

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Authors

L. Baldassarre, V. Giliberti[2], M. Ortolani, A. Nucara, P. Calvani

http://server2.phys.uniroma1.it/gr/irs/index.htm

C19. Surface Enhanced Raman Scattering and its biophysical applications

In metal nanostructures such as nanoparticles (Nps), the collective oscillation of the free electron gas, namely the surface plasmon, can be excited by electromagnetic radiation, in the visible - near infrared spectral range. The plasmonic excitation causes the localization, close to the Np surface, of an extremely intense electromagnetic field, which can be exploited for spectroscopic investigation of the molecular environment around the Np. In particular, Surface Enhanced Raman Scattering (SERS) consists of the increment of several orders of magnitude (typically from 6 to 10) in the Raman intensity scattered by a molecule close to a metal nanostructured surface (see Fig.1A) [1]. The combination of the strong potentiality of Raman spectroscopy in studying biomolecules (e.g. protein [S. Mangialardo *et al.*, J. Raman Spect. **43**, 692 (2012)]) with the possibility of huge signal enhancement makes SERS spectroscopy an ideal technique for biophysical investigations. SERS can allow the detection of molecules at ultra-low concentrations and the design of nanostructured systems that can interact with cells for diagnostics and therapeutic applications.

We have investigated the plasmonic behaviour of SERS-active Np aggregates obtained by self-assembly from water dispersion. By monitoring the SERS intensity of Raman label 4-aminothiophenol (4ATP), bound to the Nps, we demonstrated that these aggregates behave as single, near-field connected optical entities up to very large sizes (tens of μm^2) [1]. Based on these results, we realized and tested a strategy for developing reproducible and stable 2D gold Np cluster arrays arranged on silicon substrates, to be used for SERS sensing applications. We combined electron beam lithography and molecular functionalization to finely control the shape of the Np assemblies (see Fig. 1B). MicroRaman space resolved measurements were undertaken on the structures and highlighted the full correspondence of the spatial and optical periodicity. The high enhancement capability of the system, together with the standardized fabrication procedure, represent the basis to realize versatile platforms for nano-optical investigation and high-sensitive multiplex sensing [2].

Another potential application of SERS systems deals with the biomedical problem of early cancer diagnosis. The identification of the specific properties of cancer cells, such as the expression of particular plasma membrane molecular receptors, has become crucial in revealing the presence and in assessing the stage of development of the disease. We have developed a single cell screening approach based on SERS microimaging. We fabricated a SERS-labelled nanovector by biofunctionalizing gold Nps with folic acid (FA). After treating the cells with the nanovector, we were able to distinguish three different cell populations from different cell lines (see Fig. 2), suitably chosen for their different expressions of FA binding proteins [3]. The nanovector, indeed, binds much more efficiently on cancer cell lines than on normal ones, resulting in a higher SERS signal measured on cancer cells. These results pave the way for applications in single cell diagnostics and theranostics.

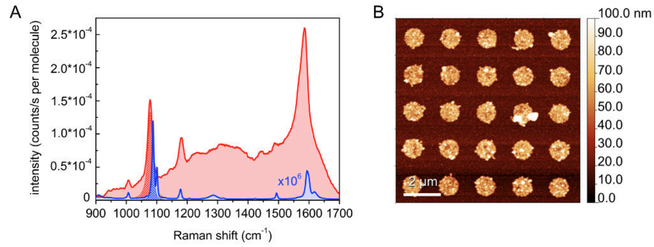

Figure 1: (A) red: 4ATP SERS spectrum from a typical cluster made of 60 nm gold Nps functionalized with 4ATP; blue: Raman spectrum of bulk 4ATP. SERS and Raman spectra are normalized to single molecule contribution. The scale factor of 10^6 is highlighted. (B) AFM imaging of a part the two dimensional array of AuNp clusters with 2 μm spacing.

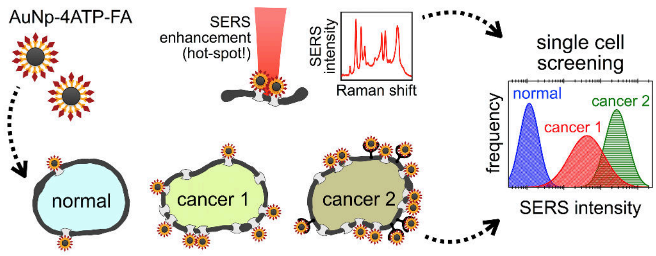

Figure 2: Sketch of the experiment, which consists of: bioconjugation of SERS-active gold nanoparticles with 4ATP and then with FA; treatment of three cellular populations, with different levels of folate receptor expressions (HaCaT normal cells, PC-3 cancer 1 cells, HeLa cancer 2 cells) and selective cellular binding of the nanovector; SERS measurements on the cells, which allowed the discrimination of the cell populations based on the different density of FA receptors and carriers on the membrane.

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C20. Investigating matter with radio- and microwave electromagnetic radiation

My research activity of the last three years has been devoted to different topics, which share a common experimental method: the study of interaction of frequency dependent electromagnetic waves with matter. 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). Different setups allow for measurements of solid or liquid samples, both above 0 °C (up to 100 °C) and at cryogenic temperatures (down to 4 K). These setups has been used to study different physical systems:

- complex liquids: The available experimental setup has been used to perform dielectric spectroscopy (DS) experiments. The wide range of frequencies available allows for te study of a large set of relaxation phenomena, ranging from large biological structures such as liposomes, erytrocites or drug delivery vectors to small molecules or even the dynamics of water molecules, which is the common solvent for these systems. The exepriments can furnish informations both on the solutes (polymeric chains or more complex structures) and on their interactions with the solvent (typically water). A review of some of the information that can be obtained through DS has been reported in (2). Different systems has been studied in the last years (polyelectrolites, structural glasses, solutions of DNA and carbon nanotubes) and the results of these experiments are currently in elaboration.

- Novel materials for accelerating devices: one of the solutions to fulfill the request of increasing field gradients in the accelerating structures is to study novel materials to produce accelerating strucutres able to sustain very high gradients without material degradation. In the last years I took part to the research activity performed in this field by INFN within two specific projects (NOvel Researches Challenges In Accelerators (NORCIA) and DiElectric and METallic Radiofrequency Accelerator (DEMETRA)). My contribution was related to the characterization of molybdenum coatings that should be able to reduce the field reaching the bulk of the cavity structure and at the same time increase the surface hardness of the structure, due to the very high robustness of molybdenum. The main results of this research are reported in (1) and (4).

- Superconductivity: the available 16 T superconducting magnet allows for the study of superconducting properties as a function of both temperature and magnetic field. These properties has been the subject of intense work in the past decades, and the research has been continued also in the last three years, as witnessed by reference (3).

Besides these activity, other research lines are in preparation: in particular, it has been recently approved a research project to study the superconducting properties of some composites of graphene, in which my role will be the measurements of electrical properties as a function of both temperature and magnetic field.

Main collaborations:

Complex liquids: F. Bordi (La Sapienza), B. Ruzicka, R. Angelini, S.Sennato (CNR-ISC), D. Truzzolillo (Universitè Montpellier 2)

Accelerating devices: A.Marcelli, B. Spataro (INFN), S. Lupi (La Sapienza)

Superconductivity: E.Silva, N. Pompeo, K. Torokhtii (Università Roma Tre)

Currently financed projects:

- DiElectric and METallic Radiofrequency Accelerator (DEMETRA - INFN)

- Superconductivity in Li-decorated non-porous Graphene (Ricerca di Ateneo)

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Author
S.Sarti

C21. Confined water

Confinement is probably the dominant condition under which water plays its role in biology, chemistry, geology or material science. Confinement affects structural hydrogen-bond dynamics of water, modifying its properties and making it functional to specific roles. In this view, the DECA laboratory has been studying some basic and applicative issues concerning this topic.

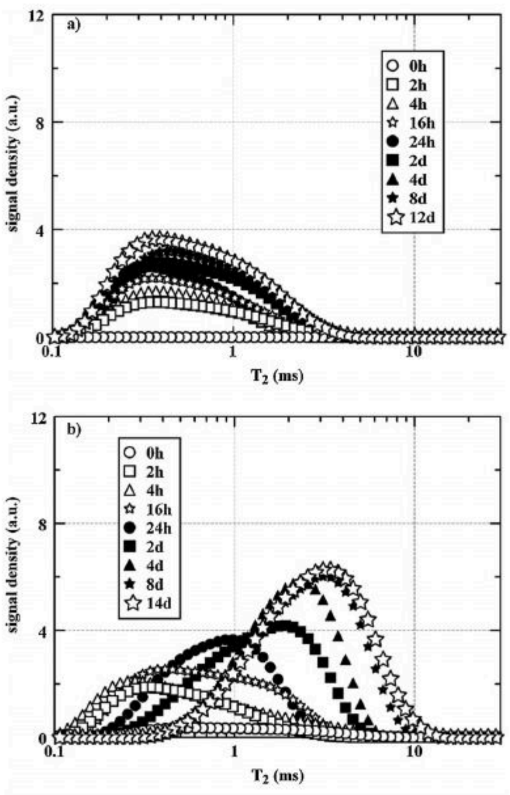

Figure 1: Evolution vs moisture sorption-time of the hydrogen T_2 distribution for a reference (a) and a polluted sample (b) of Lecce stone exposed to humidity [3].

Precisely:

1. The structure of paper has been studied by investigation of its hydration water, in order to develop a quantitative method for monitoring paper deterioration and state of conservation, or the effectiveness of restoration in the case of paper documents of historical and artistic interest [1].

2. The effect of firing temperature or pollution has been studied on water confinement in ceramics and stones of Cultural-Heritage interest (Fig. 1), in order to assess which features give valuable information to both characterize materials production or monitor pollution threat before irreversible damage is caused to artistic or historic artifacts with the purpose of early restoration [2,3].

3. QENS measurements on water confined in carbon nanotubes (CNTs) of about 1.4-nm diameter show that axial confinement make water organize as a filament, or as a molecular single chain (Fig. 2). The very special feature of this configuration is the onset of single-file dynamics, with molecules exhibiting a quasi-free rotor behavior even at very low temperature (10 K) [4]. This peculiar motional regime gives insight into the dynamics of water in biological channels.

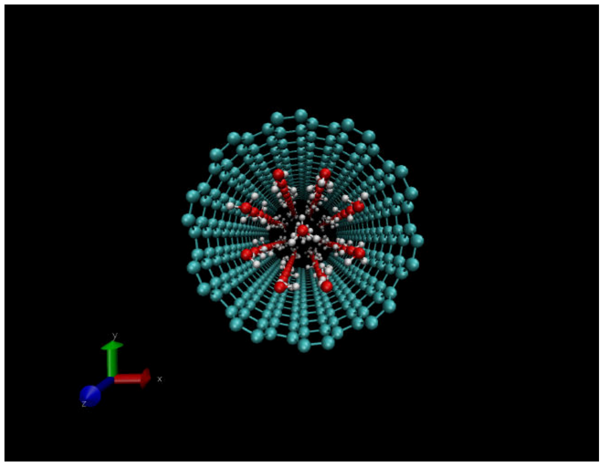

Figure 2: Simulation of water entrapped in a CNT of about 1.4-nm diameter [4].

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A. Conti, G. Poggi, P. Baglioni, F. De Luca, C. Casieri, C. Terenzi, R. Quaresima, G. Quarta, V. Tudisca, G. Briganti, G. Rogati, A. Parmentier, M. Maccarini.

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C22. Physics with patchy colloids and DNA-made nano-particles

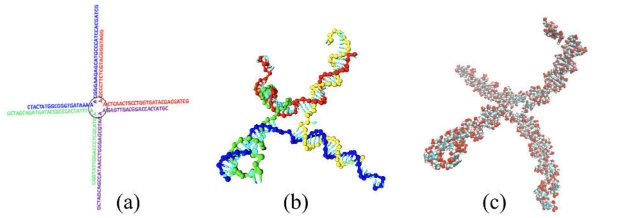

Figure 1: Representation of a tetravalent DNA nanostar (NS) at different levels. (a) The four sequences of bases forming the NS. Each single strand has been represented with a different color. Note the six unpaired bases, acting as sticky ends. (b) The schematic representation of the self-assembled NS, in which each base is modelled as a rigid body. (c) The corresponding full atom representation.

DNA oligomers can nowadays be assembled to produce a large variety of nanometric constructs, via a cascade of self-assembly processes, each one guided by the length of complementary sequences of distinct DNA strands. The majority of the applications in DNA nanotechnology have focused on the ability to design complex self-assembling shapes. Less explored is the use of DNA-made particles as model systems to experimentally verify theoretical predictions based on man-designed interaction potentials. In our research line, 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.

We have started studying experimentally and via simulations trivalent and tetravalent DNA constructs (nanostars, see Fig. 1) to assess the dependence of the gas-liquid phase separation on the maximum number of bonds that each particle can form (also called valence). The experimental work [the result of a collaboration between Milan (Prof. T. Bellini) and our group in Rome, see S. Biffi *et al.*, Proc. Nat. Acad. Science**110**, 15633 (2013)] confirmed that, as predicted by theory and simulation [E. Bianchi *et al.*, Phys. Rev. Lett. **97**, 168301, (2006)], the gas-liquid phase coexistence region can be shrunk by decreasing the valence, providing a novel route for the generation of low-density physical gels, also known as empty liquids. It also strengthens the idea that carefully-designed DNA constructs can be used as experimental realisations of patchy particles, which have recently gained much interest for their ability to self-assemble materials with exotic thermodynamic and dynamic properties, such as the ultrastable liquids [F. Smallenburg and F. Sciortino, Nature Phys. **9**, 554, (2013)].

More recently, we demonstrated the successful selection of short DNA sequences that spontaneously generate all-DNA particles with unconventional phase behaviour by encoding in the DNA sequences not only the required particle shape, but also the desired T-programmable collective properties of the resulting material. In a combined theoretical, numerical and experimental study [1], we reported the successful design of one-pot DNA hydrogel that melts both on heating and on cooling. The sample displays (Fig. 2) a re-entrant phase behaviour [2], providing a neat example of the possibility to rationally design biocompatible bulk materials with tunable properties. Dynamic light scattering experiments show that the gel changes its structural relaxation time by several orders of magnitude in a T range of a few degrees, dissolving both at high and at low T.

In the near future we hope to apply this methodology to two important open problems in the physics of disordered systems: the liquid-liquid transition in network fluids [2] and the reconfiguration of networks via bond swapping mechanisms, by designing and realizing DNA particles with the requested properties.

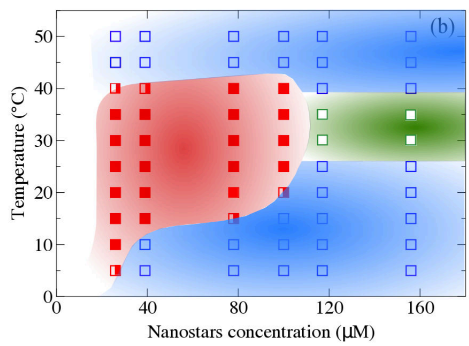

Figure 2: Phase diagram of a re-entrant DNA gel. Filled squares indicate phase separated state points, open squares stable homogeneous solutions, semi-filled squares indicate borderline cases. The red shadow area qualitatively indicates the region of phase-separation, the green area the gel phase while the blue area indicates the fluid phase. The concentration is reported in μM of NSs (1 mg/ml=14.2 μM).

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Authors

F. Bomboi, J. Fernandez-Castanon and F. Sciortino,

C23. Self-Assembly-Driven Liquid Crystals

Self-assembly is the spontaneous formation through free energy minimization of reversible aggregates of basic building blocks. The size of the aggregating units, e.g. simple molecules, macromolecules or colloidal particles, can vary from a few angströms to microns, thus making self-assembly ubiquitous in nature and of interest in several fields, including material science, soft matter and biophysics. Through self-assembly it is possible to design new materials whose physical properties are controlled by tuning the interactions of the individual building blocks. A relevant self-assembly process is the formation of filamentous aggregates (i.e. linear chains) induced by the anisotropy of attractive interactions. Examples are provided by micellar systems, formation of fibers and fibrils, solutions of long duplex B-form DNA, filamentous viruses, chromonic liquid crystals (LCs) as well as inorganic nanoparticles. If linear aggregates possess sufficient rigidity, the system may exhibit liquid crystal phases (e.g. nematic or cholesteric, see Fig. 1b and 1c) above a critical concentration. In order to grasp a physical understanding of this complex behavior, building on the venerable Onsager theory, we developed few years ago a novel theoretical approach for these self-assembly-driven LCs. Noticeably, our theory contains no adjustable nor fitting parameters. Predictions for the isotropic-nematic transition have been carefully tested in two simple model systems, namely bifunctional polymerizing hard cylinders [1] and bent-cylinders [2] by using Monte Carlo simulations.

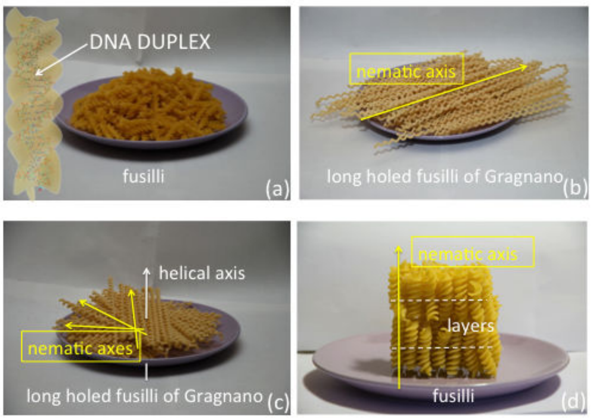

Figure 1: Isotropic (a) and liquid crystal phases ((b) nematic, (c) cholesteric and (d) smectic). In (a) the conformational resemblance between a chiral DNA duplex and a fusillo is evidenced.

Theoretical results for isotropic-cholesteric transition and for helical ordering in the cholesteric phase have been tested in a real system – i.e. a water suspensions of short DNA duplexes – where the chirality of the constituent building blocks induces the formation of a chiral nematic (cholesteric) phase [3]. Among all LC phases observed in self-assembly-driven LCs based on DNA, the smectic one (see Figure 1d) was elusive so far. Building on DNA versatility in creating novel constructs and our former theoretical understanding of self-assembly-driven LC phases we designed three DNA sequences which self-assemble at room temperature into a nanoparticle about 50 nm long comprising of two double-stranded DNA duplexes linked together by a DNA filament 13 nm long. As shown in the Figure 2a, this nanoparticle resembles a nunchaku (see Fig. 2b), which is the traditional weapon of several martial arts, such as kung-fu and ju-jitsu, their size being 30 millions times smaller though. We have provided unambiguous and clear evidence through experiments and numerical simulations that a water suspension of these synthetic DNA nanonunchakus form smectic phases. In addition, computer simulations of a suitable DNA coarse-grained model (see Fig. 2c) allow us to afford some insight into the physical mechanism un

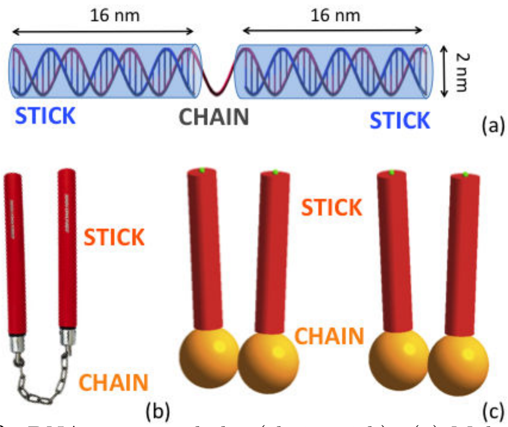

Figure 2: DNA nanonunchaku (chain-stick). (a) Molecular structure created by using 3 distinct DNA sequences. (b) Real nunchaku. (d) Coarse-grained model used in computer simulations.

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Authors

C. De Michele, F. Sciortino, K. T. Nguyen, D. Ancora, A. Battisti, J. K. G. Dhont , E. Stiakakis, G. Zanchetta, T. Bellini and A. Ferrarini

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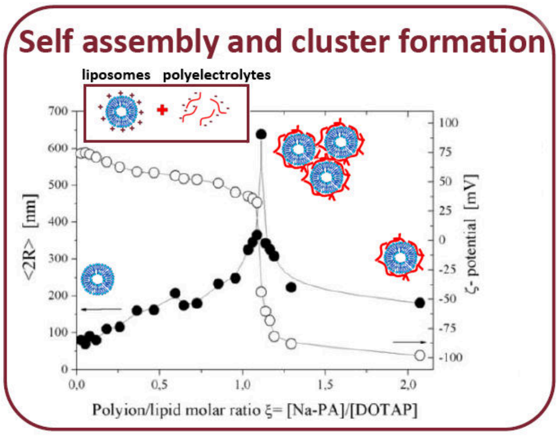
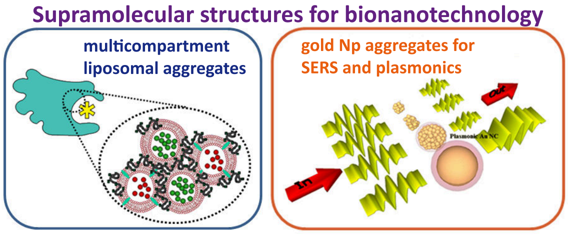
C24. Physics of Bio-Assembly

Our research activity has been devoted to the investigation of physico-chemical mechanisms driving the self-assembly of supramolecular structures in dispersed systems, with special attention to systems of biological interest, as biological cell membranes and model membrane systems (liposomes and lipid monolayers) and complex macromolecules as polyelectrolytes, DNA and polypeptides.

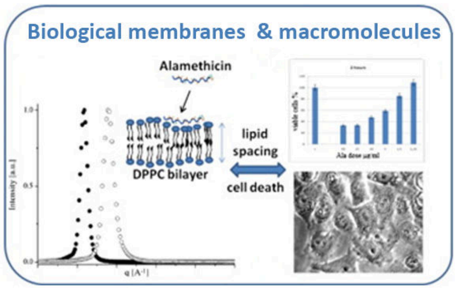
- Self-assembly and cluster formation in liposomes and polyelectrolyte co-suspension: we have extensively investigated the self-assembly phenomena occurring in co-suspension of oppositely charged polyelectrolytes and a peculiar class of colloidal particles (liposomes) yielding to stable aggregates with tunable charge and size [1]. The investigation of this phenomenology and of its dependence on the physico-chemical parameters has converged into a unifying rational description, paving the way for the interpretation of behavior of apparently different mesoscopic systems, as surfactant-DNA stabilized nanotube suspensions, polymeric microgels-polycations and protein-gold colloids aggregates, currently under investigation.



- Supramolecular structures for nanotechnological applications: we are developing innovative drug-delivery vectors for therapy and diagnostic applications (theranostics) based on controlled aggregation of colloids, as macrophage-targeted multi-compartment liposomal aggregates for anti-Tubercolosys therapy and gold-nanoparticles aggregates as SERS-active substrate for bioplasmonic [2].



- Models of biological membranes: we study the structural properties of cell membranes and model membranes systems, as lipidic mono-and bilayers and giant vesicles, to characterize their supramolecular organization and interactions with biological macromolecules, as drug, proteins or DNA, or under different environmental or stress conditions [3].



Main collaborations:
S. Sennato (CNR-ISC), S. Sarti, P. Postorino, S. Lupi (Phys. Dept), M. Carafa (Chemistry and Drug Technology Dept, Sapienza), I. Silvestri (Sapienza Univ), F. Domenici, G Paradossi (Univ. Tor Vergata) D. Truzzolillo (Universitè Montpellier 2, France).

Currently financed projects:

- BRiC 2015 (INAIL) - Ultrasuoni e sicurezza: un nuovo approccio biofisico integrato per la valutazione dell'impatto biologico di tecnologie ad ultrasuoni emergenti
- Ateneo 2015 - Sviluppo di nanovettori biopolimerici ad alta efficienza per la veicolazione della doxorubicina nelle cellule di carcinoma mammario.

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`http://server2.phys.uniroma1.it/gr/PhOBiA/index.html`

C25. Optics in conditions of extreme nonlinearity: solitons, rogue waves, scale-free beams and anti-diffracting subwavelength beams

Wave propagation is strongly affected by nonlinearity. For example, diffracting laser beams inside a self-focusing medium lead to spatial solitons, that is, wave solutions that propagate undistorted, bouncing off obstacles, spiraling around each other, and giving rise to a particle-like behavior in an otherwise undulatory system. While solitons arise when nonlinearity exactly balances diffraction, other nonlinear wave paradigms are shock-waves, which arise when nonlinear steepening causes waves and beams to break up and scatter, and rogue waves, statistically improbable intense wave-perturbations whose origin is still a matter of debate. In conditions of extreme nonlinearity, where anharmonic effects become comparable if not dominant compared to linear phenomena, our understanding of wave behavior is still in the making. In some cases, a dominant nonlinear response can lead to a new effective linear response with altered and unconventional features, such as light that does not diffract, anti-diffracts, obeys equations typical of massive fields [1] (see Fig.1), or even obeys Schroedinger-like equations but with an intrinsic negative mass [2].

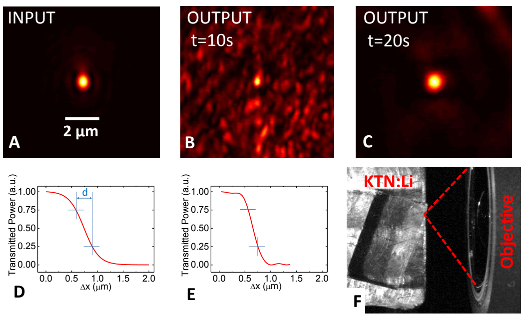

Figure 1: Breaking the diffraction limit in nanodisordered KTN:Li. Subwavelength input beam (a) that shrinks at the output facet (b) and finally relaxes (c). Calibration (d)-(e) and top-view (f) [1].

Experiments into nonlinear optical beams require either intense lasers or highly responsive materials. Extreme nonlinear optics requires such levels of response that can only be observed in metastable or transient conditions. In our investigations, we have developed nonlinear optical crystals with a giant photorefractive and electro-optic response. These are nanodisordered ferroelectrics that, cooled rapidly to their room-temperature ferroelectric-paraelectric phase-transition, manifest a transient non-ergodic phase dominated by polar-nanoregions, that have an anomalously large susceptibility without a concomitant critical opalescence for visible light. The result is a setting for extreme nonlinear beam propagation with entirely new phenomenology, such as spatial rogue waves [3] (see Fig.2) and the emergence of a spontaneous three-dimensional photonic lattice [4] (see Fig.3).

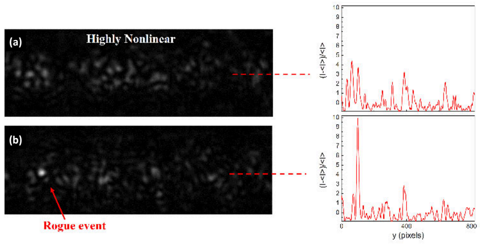

Figure 2: Light transmitted through a critical nanodisordered ferroelectric: (a) speckle-like pattern in the highly nonlinear regime and (b) a rogue event [3].

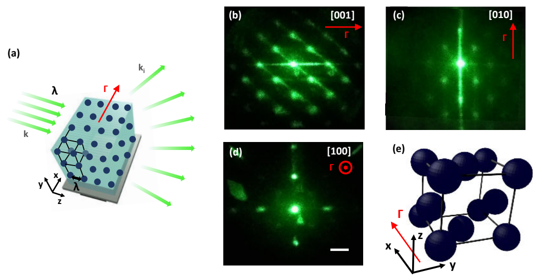

Figure 3: Spontaneous super-crystal. (a) Sketch of scheme and (b-d) 3D superlattice probed along the principal symmetry directions of the crystal (λ=532 nm). (e) Corresponding elementary cubic structure with a micrometric lattice constant [4].

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C26. 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 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.

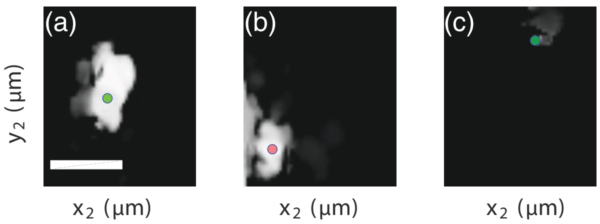

Figure 1: Dwelling areas of the modes located at the azure (a) an pink (b) spots. In c) dwelling area of a location in which a single mode is absent.

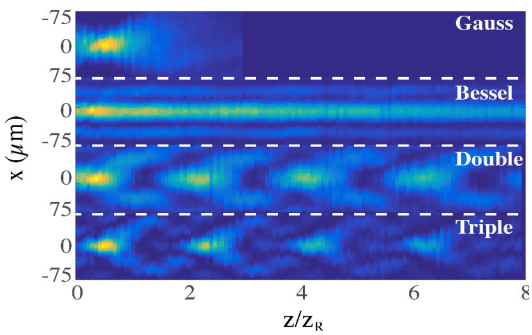

Figure 2: Gauss (a), Bessel (b) and light droplets (c-d) beams.

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C27. Glassy Random Laser and Experimental Measurement of Replica Symmetry Breaking

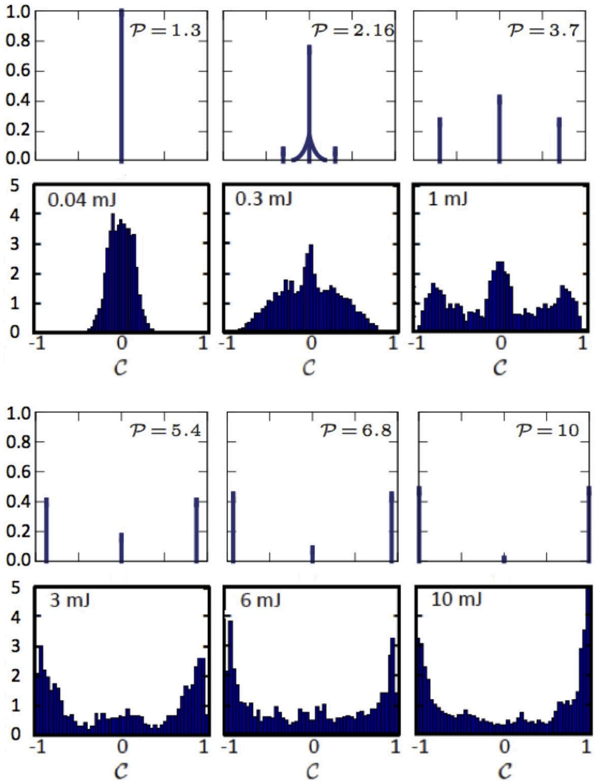

Figure 1: Comparison between theory and experiments in a cavityless random laser. Top row: theoretical IFO probability distributions for increasing pumping $\mathcal{P}$. Vertical lines are Dirac's delta, the height being the probability of the argument value. Different regimes are represented from fluorescence to large pumping random lasing. Bottom row: experimental IFO probability distribution for the same regimes in the amorphous solid oligomeric random laser T5COx [3].

In recent years, random lasing materials (e.g. powders, porous media, precipitates in solution, or photonic crystals with impurities) have been extensively studied experimentally. Pumping energy into these systems causes them to re-emit multi-mode coherent light, with a spectrum displaying randomly arranged peaks in frequency. Starting from the structure and geometry of the atoms and molecules that scatter the light waves, one would eventually want a theory that predicts the onset, the nature and the features of the light modes.

The key questions are connected to the coupling property of the spatial overlap of the electromagnetic fields of the interacting modes. This feature ascribes to the problem of assessing the structure of an interacting network of light-modes in a statistical mechanics representation. Indeed, a set of modes can interact only if their electromagnetic fields overlap in space and, in the lasing regime, non-linear amplification occurs only if the frequencies of the modes satisfy some kind of mode-locking condition. These rules strongly influence the set of feasible interactions in which each mode is viewed as a network node. A key challenge that we address is the characterization of the structure of this network of wave-modes, including the strengths and signs of the relevant random interactions, as is required, e.g., in order to distinguish apart physical regimes of laser stationary behavior. To this aim a Hamiltonian theory has been derived and investigated in systems with different kinds of bond-disorder [1,2], ranging from standard ordered multimode mode-locking lasers to recently introduced glassy random lasers.

The investigation of the glassy behaviour of light in the framework of our theory is made possible by means of a newly introduced overlap parameter $\mathcal{C}$, the Intensity Fluctuation Overlap (IFO) measuring the correlation between intensity fluctuations of waves in random media. This order parameter allows to identify the laser transition in arbitrary physical regimes, with varying amount of disorder and non-linearity [3,4]. In particular, in random media it allows for the identification of the glassy nature of some kind of random laser, in terms of emission spectra data, the only data so far accessible in random laser measurements. The model devised from first principles in whose framework the parameter is defined is the nonlinear phasor statistical mechanical model. This is a generalised complex spherical spin-glass model solvable in the mean-field approximation by Replica Symmetry Breaking theory [2]. IFO measurements are possible in real experiments, recently leading to a validation of the RSB theory and a new characterisation of lasers in terms of spectral intensity fluctuations.

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C28. Quantum optics for 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 novel resources have the potential to revolutionize information processing in terms of speed, security and power. In this context, entanglement, the characteristic signature of quantum world, is the main responsible for the improvement of quantum algorithms with respect to the classical ones.

Within this framework, Quantum Optics represents an ideal experimental platform, since photons are practically immune from decoherence and can be distributed over long distances both in free-space and in low-loss optical fibres. Furthermore the photonic platform allows for great flexibility in the creation and manipulation of quantum states, opening the perspective of encoding qubits over different degrees of freedom (DOFs) of photons, such as polarization, path and frequency.

We exploited an integrated platform, realized by femtosecond laser writing on a glass chip, able to manipulate path- polarization hyperentangled (HE) states. The use of different DOFs opens the possibility to create general multiqubit states, which in turn allow to increase the number of qubits using the same number of particles.

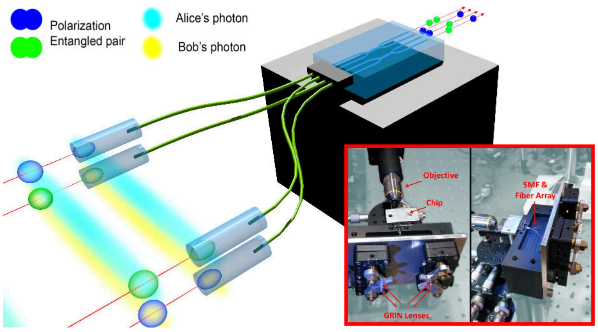

Figure 1: Path-polarization hyperentangled states injected in an integrated device. In the inset the experimental realization of the setup.

This platform has been used to characterize HE states and to generate 4-qubit cluster states, which in turn have been exploited to perform 4-qubit QI protocols such as the Grover's search algorithm [1]. Furthermore, HE states have been used for experiments of fundamental quantum theory, such as addressing the role of local noise on entangled states [2], work extraction protocols in a quantum thermodynamic environment and quantum network analysis using multipartite non-locality witnesses.

In another line of research, our laboratories developed a high quality source of entangled photon, based on two indistinguishable Type-II *Spontaneous Parametric Down Conversions* inside a PPKTP crystal. Each process converts few pumping photons into couples of horizontally (H) and vertically (V) polarized once, and the entanglement emerge when both generations are recombined in a Sagnac interferometer. We can ensure polarization Bell state with fidelities of $F > 0.98$, concurrence of $C > 0.975$ and more than $\frac{60000}{s}$ detected coincidences. This source has been used for experiments regarding Non-Markovian Dynamics (NMD) in which we studied the strength of non-markovianity of a quantum system, either by recovering entanglement through local operation [3] and by applying consecutive environment interactions with one photon qubit from an entangled pair [4].

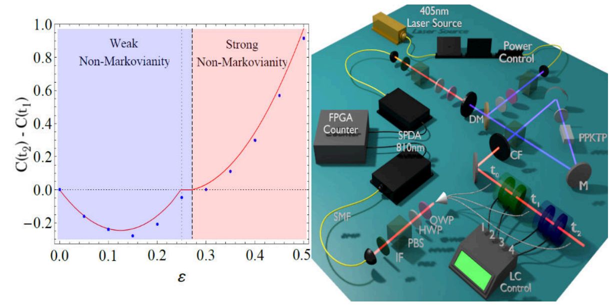

Figure 2: Entanglement source in the NMD experiment, including a caption of the "concurrence information backflow".

Furthermore, we developed a technique to restore the entanglement loss, studying a common noise of continuous *Amplitude Damping* coupled to unitary evolutions, which was experimentally proved in a discrete regime using Entanglement Breaking Channels of order 2 (EB^2). We revealed, in collaboration with the CNR Nano, Lecce, the single exciton-photon coupling (polariton) and its transition to the collective regime, and finally we have successfully tested of a new quantification method for the Quantum Channel Capacity, based on a lower bound, extracted from the *Von Neumann and Shannon entropies* of a noisy channel.

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C29. Quantum Technologies

Quantum information processing holds the promise to allow superpolynomial speedup for several tasks, including computation, communication and cryptography. A significant set of theoretical results have shown that quantum computers should be able to outperform conventional classical computers in specific tasks. However, the realization of a device able to demonstrate this superior computational power is still missing. A strong effort has been then directed towards the development of quantum technologies, in order to identify experimental platforms suitable for quantum information tasks.

Recently, a step forward towards the adoption of photons as information carriers in large size systems has been enabled by integrated photonics, where the final aim is to obtain an integrated version of a complete optical table. This research has been performed in collaboration with Istituto di Fotonica e Nanotecnologie - CNR. Indeed, the technological progresses obtained with this approach made possible to implement interferometers with large number of modes, not achievable with conventional bulk optics. These systems find application for several quantum information tasks. One example is provided by Boson Sampling, a computational model that represents a promising candidate to reach experimentally the regime where a quantum device solves a specific problem faster than its classical counterpart. This task corresponds to sampling the output distribution obtained after the evolution of n indistinguishable bosons through a m-mode linear transformation. In parallel to developing the experimental platform to solve the Boson Sampling task, an open problem in the hard-to-simulate regime is to what extent the correctness of the quantum device can be certified. Such requirement is restricted not only to this specific task, but is common to the whole quantum computation context. We have thus performed Boson Sampling experiments with $n = 3$ photons in integrated circuits up to 13 modes [1]. By applying suitable statistical tests, we were able to show how to discriminate data generated with a correct device from data generated either with distinguishable particles or sampled from the uniform distribution.

A step forward towards certification of genuine multiparticle interference relies on the adoption of multimode interferometers implementing the Fourier transformation. When multiphoton states with a suitable symmetry are prepared, efficiently-predictable quantum distinctive features are observed in the output pattern after the evolution. This occurs only if the input particles are indistinguishable. This mechanism can be thus employed to identified the presence of true multiphoton interference. We have experimentally observed such generalized quantum interference in Fourier interferometers implemented with an efficient architecture [2].

One of the main difficulties in scaling up the complexity of Boson Sampling experiments is the need of reliable

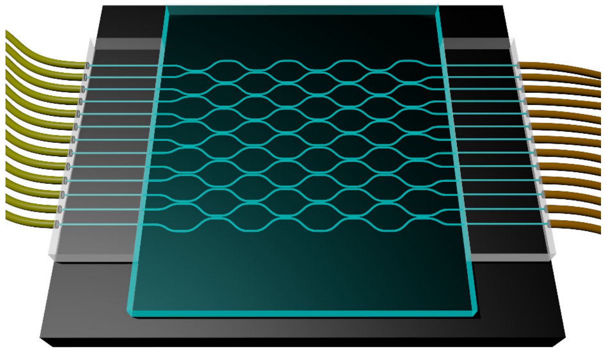

Figure 1: Scheme of an integrated interferometer with $m = 13$ modes for the implementation of Boson Sampling.

and efficient single-photon sources. However, the most commonly employed sources, based on a non-linear process called parametric down-conversion, are probabilistic and present low brilliance. A modified version of the original Boson Sampling problem, named Scattershot Boson Sampling, permits to obtain an exponential boost in the amount of detected signal by involving $k > n$ heralded sources. We have implemented experimentally [3] a first instance of this task with 6 different photon-pair sources.

A different approach to exploit the properties of light for quantum information processing involves the full structuration of light in the transverse plane. This degree of freedom permits to generate a class of states, known as vector beams, presenting peculiar properties that can be employed for several applications such as sensing of data multiplexing. We have investigated experimentally the capability of storing and preserving the quantum information encoded in this class of states by using a multiplexed ensemble of laser-cooled atoms [4].

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C30. Strategies for self-propulsion at the micron scale

The modern tools of nanotechnology allow to shape matter at the micron and nano scale with a high degree of structural and morphological control. In more recent years, researchers have started to investigate possible strategies to "give life" to these structures and provide them with some mechanism for self-propulsion. We have a long experience in building motors at the macroscopic scale but life at the micron scale can look very different from what we are used to see in our everyday experience. There's no inertia, the environment is always very noisy due to thermal fluctuations, surface phenomena can have a dominant role. In this scenario, the search of novel strategies for self-propulsion offers many opportunities for fundamental and applied research. Actuation of microsystem is usually achieved by means of externally generated force fields like magnetic or electrical. The drawback in this approach is that what was meant to be a lab-on-a-chip often looks more like a "chip-in-the-lab": a highly miniaturized machine that requires large and expensive external equipment to drive and control propulsion. For this reason, a large and growing community of researchers is working on the development of novel materials, collectively referred to as "active matter", that are capable of converting locally available energy into directed motion. The basic "atoms" of active matter are swimming microorganisms or self-propelled colloidal objects both showing peculiar dynamical properties that are very diverse and still not completely understood [1]. One of the most fascinating directions in this field is that of using active particles as the propelling units for larger and more complex micromachines. These systems, however, rely on a partial rectification of active particle motions and are in general very noisy and inefficient. We have recently demonstrated that a small and well-defined number of artificial microswimmers can self-organize in highly ordered configurations around a larger passive micro-object and propel it in a steady unidirectional motion [2]. The active component consists of silica particles (5 μm diameter) that are half coated with platinum and that can self-propel in a mixture of deionized water and hydrogen peroxide. The passive component is a microfabricated gear having six asymmetric teeth with an external radius of 8 μm. We have shown that a proper choice of size ratios between gear edges and particle radius leads to the consistent self-assembly of perfectly ordered micromotors starting from randomly distributed building blocks (Fig. 1a) [2]. One drawback in these kinds of strategies is that they rely on internal chemical fuels, like peroxide in the example above, that are progressively consumed resulting in short lifetime. An alternative approach is that of using a cheap and widely available external energy source and design a machine that is capable of converting it into mechanical work. In this respect light represents clearly an extremely interesting option. However, proposed designs require high power levels (generally a focused laser beam) to compensate for the intrinsic low efficiency of commonly used mechanisms for light-to-work conversion. In another recent paper [3], we show that Marangoni forces can be efficiently used to propel micron-sized gears in a continuous way using an incoherent wide-field illumination. We fabricate microstructures with a homogeneous light absorbing coating that, when illuminated, generate temperature gradients in the surrounding fluid. Continuous propulsion is obtained using a gear shape that breaks mirror symmetry so that, when the structure floats at a liquid-air interface, a net torque arises due to surface tension gradients. We demonstrate rotation rates up to 300 r.p.m., which can be quickly, and indefinitely controlled by tuning the incident light power. The observed efficiency of the light-to-work conversion is about five orders of magnitude larger than previously reported effects allowing to generate indefinite rotations at low power densities.

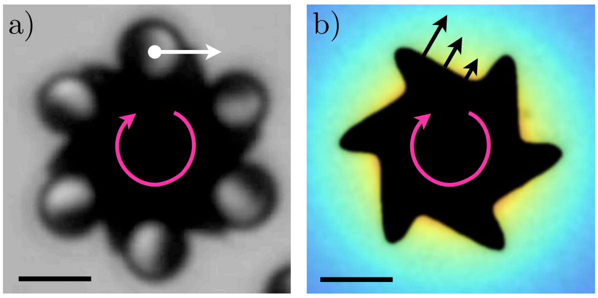

Figure 1: a) Six Janus colloidal particles self assemble into a perfectly ordered configuration leading to the steady rotation of a micro-gear [2]. b) A light-absorbing micro-gear, floating at a liquid-air interface, produces a temperature gradient in the surrounding fluid (color map in the background). As a result, a non uniform surface tension pulls the contact line along the gear's contour (black arrows) giving rise to a net torque [3]. Scale bars in both figures are 5 μm.

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C31. Computational Biophysics

Computational biophysics applies computer technology and biophysical methods to the understanding of biological data. It is an interdisciplinary field, targeting different areas of biotechnology, medicine and life sciences. In particular, we focus on the development of methods and algorithms to model, design and analyze three-dimensional protein structures with the aim of understanding biological processes at a molecular level. The structure of proteins deriving from a common ancestor (homologous proteins) is similar and this observation is the base for inferring the unknown structure of a protein starting from the structure of one of its homologs (homology modeling). When no structure of an homologous protein is available, other methods should be used. We developed a new method for the latter case based on the assumption that the energy global minimum of homologous proteins must correspond to similar conformations, while the precise profiles of their energy landscape, and consequently the positions of the local minima, are likely to be different. In line with this hypothesis, we apply a replica exchange Monte Carlo simulation protocol that, rather than using different parameters for each parallel simulation, uses the sequences of homologous proteins [1].

There is a wide interest in designing peptides able to bind to a specific region of a protein with the aim of interfering with a known interaction or as starting point for the design of inhibitors. We set up a method for the computational design of peptides binding to a given protein surface that only requires the target protein structure and an approximate definition of the binding site as input [2].

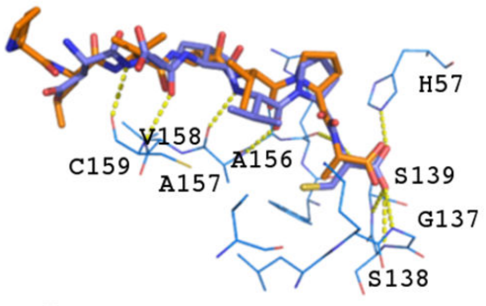

Figure 1: Superposition of a designed (orange) and native (violet) peptide binding to the Hepatitis C protease.

We also developed a new method for inferring the membrane permeability of a drug based on an estimate of the hydropathy and charge distribution of the compound, in turn deduced from the distribution and orientation of the water molecules around it [3].

Another area of interest of the group is the analysis of an important class of biological molecules, antibodies. Antibodies are rapidly becoming essential tools in the clinical practice, given their ability to recognize their cognate antigens with high specificity and affinity, that can be produced at reasonable costs in model animals. Unfortunately, when administered to human patients, antibodies produced in model animals can elicit unwanted and dangerous immunogenic responses. Antibody humanization methods are designed to produce molecules with a better safety profile still maintaining their ability to bind the antigen. This can be accomplished by grafting the non-human regions determining the antigen specificity into a suitable human template. However, this procedure may result in a partial or complete loss of affinity of the grafted molecule that can be restored by a trial and error experimental procedure involving mutation of several amino acids. We developed a method that includes tools for human template selection, grafting, mutation evaluation, antibody modelling and structural analysis, helping the user in all the critical steps of a humanization experiment [4].

We are heavily involved in the CASP (Critical Assessment of Techniques for Protein Structure Prediction) experiment that uses blind testing of modeling methods to assess their capabilities: Participants are provided with amino acid sequences of unknown structures and are asked to deposit structure models. These models are then compared with newly determined experimental structures. The CASP experiment has been conducted every two years since 1994. In the last CASP (in 2014) almost 60,000 models on 100 prediction targets were collected from 207 modeling groups representing about 100 research labs worldwide. Results from recent CASP experiments show impressive progress, especially in contact prediction, refinement, assignment of model accuracy, and modeling of structurally divergent regions.

All the tools we develop are publicly available at `http://www.biocomputing.it/index.php/tools`

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C32. Codon bias and the organization of bacterial genomes

It is quite known that the genetic code is redundant, or degenerate: several amino acids in natural proteins are coded by more than one codon. In every living cell the genetic information, written on the coding DNA via nucleotide triplets called *codons*, is transcribed into mRNA which in turn is translated, on the ribosomes, into proteins, polymer chains made by amino acids. Four alternate nucleotide bases (A,U,C,G) compose mRNA, so there are $4^3 = 64$ codons that code for the 20 naturally occurring amino acids. The genetic code is therefore redundant: while a few amino acids correspond to a single codon, most amino acids can be encoded by more than one codon (on the average by 3). Different codons coding for the same amino acid are known as *synonymous* codons, and in different organisms synonymous codons are used with different frequencies, a phenomenon known as *codon bias*. A consensus view of the biological meaning of codon bias is still lacking, though it is widely believed that it shapes patterns of gene expression, rates of protein synthesis and *in vivo* protein folding [J.B. Plotkin and G. Kudla, Nature Reviews Genetics **12** 32 (2011)].

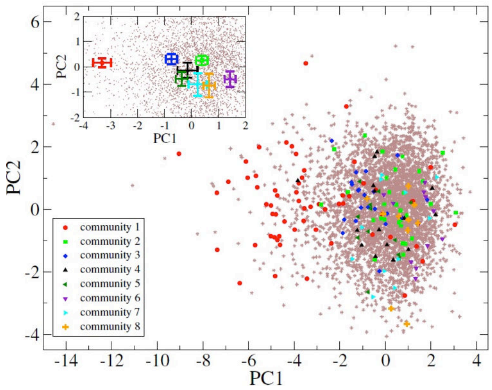

Figure 1: The genes of *E.coli* are projected on the space of the first two principal components of codon bias patterns, as measured by several indices. Genes corresponding to the proteins in the first nine communities of the PPI network (ordered by decreasing density of links) are represented with different colours. The genes belonging to different communities of the PPI make clusters in different regions of the plane, showing that the different communities share common patterns of codon bias. The inset shows that the centroids of the communities are indeed quite separated in this plane, see also [2]

In perspective, our work aims at separating, in the codon bias signal, the regulative part from the structural part; we think that the best way of representing the subtle interplay between: i) the evolutionary drift of the genetic material; ii) the availability of tRNAs; iii) the feed-back by the environment at the protein (phenotypic) level is the use of multilayer networks, which, in principle, combine in a meta-network several networks associated to different descriptive layers [1]. We have recently started a systematic computational study of the codon bias in bacterial genomes; in particular we are studying how patterns of gene conservation, gene essentiality and gene codon bias can be correlated with the structures of the protein-protein interaction (PPI) networks. We have shown in *E.coli* [2] that the more a gene is conserved, as measured by the Evolutionary Retention Index, the more it is likely to be essential and the more it has an optimised codon bias. We have also investigated the correlation of codon bias at the genomic level with the topology of the PPI network. Interestingly, we have shown that the most densely connected communities of the PPI network share a similar level of codon bias and, conversely, a small difference in codon bias between two genes is, statistically, a prerequisite for the corresponding proteins to interact. We are actively working with the genomes of several bacterial species to establish to what extent what we have observed in *E.coli*, can be generalised. In particular, we are searching for robust correlations between patterns of codon bias at the genome level, PPI topologies at the proteome level and the ecology and evolutionary history of the bacterial species.

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Authors
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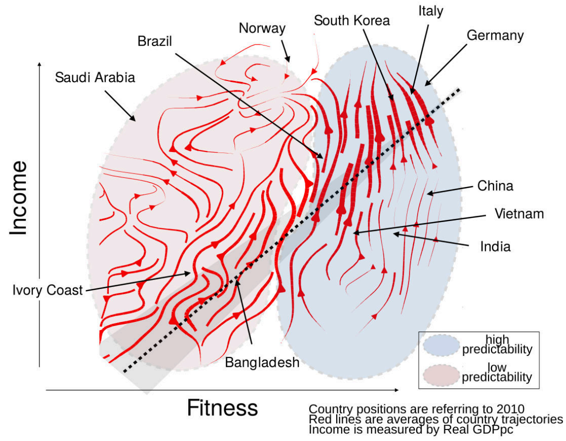
C33. Economic Complexity

Economic Complexity is a radically **new methodology** describing economics as an evolutionary process of ecosystems made of industrial and financial technologies as well as infrastructures that are all globally interconnected. 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** (in the spirit of Google Page Rank and machine learning). 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, that led to collaborations with, among others, the **World Bank**.

- **A new metrics for the fitness of countries and the complexity of products.** We developed and analysed 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 two coupled, non-linear maps which are iterated until the fixed point is reached. This approach is 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 is **heterogeneous** and 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.

- **Quantitative description of Economic Traps.** We have shown that the introduction of the Fitness as a new dimension quantifying the complexity of the industrial structure of countries gives a different insight about their (possible) industrialization process [2]: a high Fitness brings down the barrier to industrialisation. This fosters the fast growth which is the typical sign of the economic transition from the **poverty trap** to the catching up with developed countries.



- **The Product Progression Network.** The Product Progression Network (PPN) is a directed network showing the **natural evolution** from a product to the other in a country [3]. Indeed, the PPN allows for a synthetic representation of the export basket of a country, of the main industrial sectors, and the available and advisable products which can be reached by a given country, containing at the same time 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. The recommendations based on the PPN and the ML predictions can be a useful tool for both investors and policy makers.
- **The scientific and technological competitiveness of countries.** We used the Fitness and Complexity algorithm to quantify the scientific competitiveness of nations [4]. Through **bibliometric** and **patent** data we build a bipartite network connecting countries to scientific and technological areas, whose resulting triangular shape and high nestedness suggest a strong analogy with economic production. This fact points out that successful countries possess an extremely diversified and complex **innovation system**.

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`http://www.nature.com/news/physicists-make-weather-forecasts-for-economies-1.16963`
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`http://pilhd.phys.uniroma1.it/`

C34. Complexity in techno-social systems

Unfolding the dynamics of innovation and creativity Our activity, carried out in the framework of the Kreyon project (www.kreyon.net), addresses the dynamics of novelties - a fundamental factor in the evolution of human societies, biological systems and technology - with the aim to unfold and quantify the underlying mechanisms through which creativity emerges and innovations diffuse, compete and stabilise. The project is timely due to the availability of extensive longitudinal records of human, social, biological and technological evolution. Through a combined experimental (also through our platform for web-gaming and social computation www.xtribe.eu), mathematical and computational framework we aim at providing the scientific community with a quantitative understanding of the determinants of creativity and innovation as well as a solid overarching scientific framework describing creativity in a quantitative and operational way. On the mathematical side we provided one the first modelling framework for the notion of "Adjacent Possible" - introduced by Stuart Kauffman in the framework of biological systems - and tested its predictions in many different social and technological contexts [1]. In this framework we organized two major events, the KREYON DAYS, in September 2015 and October 2016, a unique event of science popularisation, entirely devoted to creativity and innovation, organised in conjunction with The Education Services of Palazzo delle Esposizioni in Rome and patronised by Regione Lazio and Legambiente.

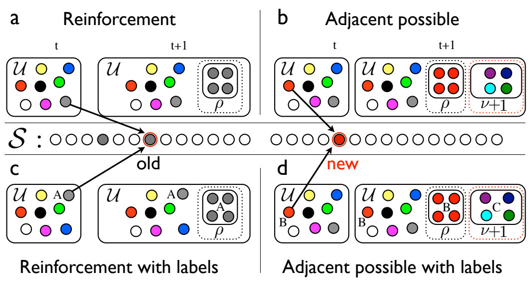

Figure 1: Modelling scheme for the adjacent possible [1].

Learning dynamics Each sphere of knowledge and information could be depicted as a complex mesh of correlated items. By properly exploiting these connections, innovative and more efficient navigation strategies could be defined, possibly leading to a faster learning process and an enduring retention of information. Our activity aims at investigating how the topological structure embedding the items to be learned can affect the efficiency of the learning dynamics. To this end we introduced [2] a general class of algorithms that simulate the exploration of knowledge/information networks standing on well-established findings on educational scheduling, namely the spacing and lag effects. While constructing their learning schedules, individuals move along connections, periodically revisiting some concepts, and sometimes jumping on very distant ones. We highlighted the existence of optimal topological structures for the simulated learning dynamics whose efficiency is affected by the balance between hubs and the least connected items. Interestingly, the real-world graphs we considered lead naturally to almost optimal learning performances. This activity is triggering a panoply of new research directions with concrete applications in deeply rethinking learning approaches and the production of educational material.

Mobility and accessibility dynamics The comprehension of vehicular traffic in urban environments is crucial to achieve a good management of the complex processes arising from people collective motion. Even allowing for the great complexity of human beings, human behaviour 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 optimise 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 a urban context, but also air and trains transportation systems, with the aim to reveal the underlying patterns and uncover the human strategies determining them. In this framework we recently developed a very general interactive web-based platform, www.citychrone.org, that allows to visualise isochrones in many major cities based on public transportation data and draw accessibility maps of different portions or specific features of the city. The possibility for seamless integration of any kind of open data (census, social, medical, financial, etc.) make 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.

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C35. The Statistical Mechanics of Neurons: Imaging, Networks, and Development

Neural cells populations present several interesting scientific questions that can be analyzed from the prospective of statistical mechanics. For example, firing patterns of fully formed neural networks can be studied as complex Hopfield neural networks. Likewise, neural stem cells collectively form spatially organized tissue formed of ordered progenitor and differentiated cells, thus can be studied as an emergent system with a characteristic phase transition and enucleation process. Four neural case are particularly interesting:

- Modeling C. Elegans neural activation pattern in Stimulus/Respose experiments.
- In Vitro Neuron Cultures activation dynamics.
- Human Brain and Resting State Network.
- Neuronal Rosettes Emergence from the differentiation of induced pluripotent stem cells (iPSC).

C. Elegans is a model organism for neuroscience because its micrometric size and its transparent body allow for direct live imaging. Moreover, the known neural network organization (connectome) and its rich repertoire of simple and more complex behavior allows for several experimental conditions. Unfortunately, even if we know the underlying structural network formed of axons and synapses, the directionality and the excitatory/inhibitory nature of these connections are unknown. Namely, we do not know the causal relation between the states of the network, thus we are unable to determine the effective network. Similarly, in vitro neuron cultures placed in the appropriate conditions form functional neural networks. Similarly to the C. Elegans model, the axons form a structural network of which we do not know the casual relations. Both in the C. Elegans model and in the neuron cultures we use techniques such as calcium imaging and capture time-lapse sequences to record neural activation patterns.

On a larger scale, Magnetoencephalography (MEG) data gives us a picture of the activity dynamics of adjacent cluster of cells. Specifically, MEG data from human subjects in a resting state condition present a wide range of activation patterns that show roughly 7-9 separate clusters of neurons that are called functional networks.

In all these cases, we are not able to model the dynamic properties of the neural network, nor predict the experimentally observed activation dynamics. Thus we need a generative model that allows us to infer the effective network and to predict the collective activation dynamics. To this end, we use statistical mechanics models such as Hopfield neural networks to infer the casual-link between neurons and construct the effective network. This approach allows us to construct generative models

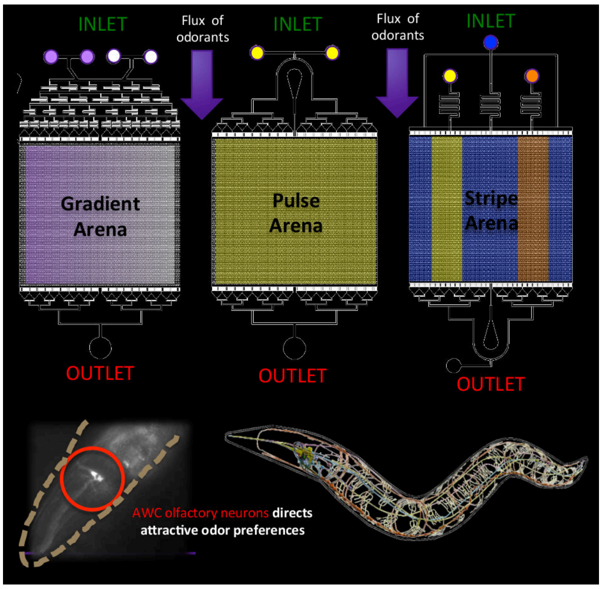

Figure 1: C. Elegans experimental set-up.

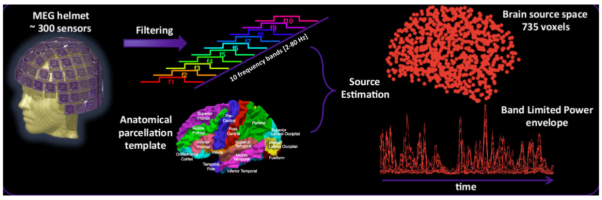

Figure 2: Magnetoencephalography (MEG) data.

that we expect may predict the observed neural network activation patterns.

The last case is the spontaneous formation of neural rosettes. Indeed, when iPSCs are grown in a differentiation culture aimed to generate neural stem cells, these cells recapitulate the early stages of neural development and form emergent structures called neural rosettes. These radially organized regular structures emerge from randomly positioned layers of cells, and mirror the neural tube of a developing embryo. Finally, the evolution of these structures is an example of phase transition in living eukaryotic cells, and is an experimental model of symmetry breaking and enucleation.

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C36. Plumes, bubbles and deep vortices in the sea

The theoretical research line about plumes evolution in the sea, outlined during the previous years has been continued both by field data analysis and experimental laboratory analysis, compared to theoretical models. During this period the research on the subject has been moved along three separated directions:

Bubbles plumes evolution in shallow seas (Main Collaborators: Prof. S. Espa, Hydraulics Dept., Sapienza University, and Dr. G. Caramanna, Earth Sciences Dept., Sapienza Univ. and Dept. of Chemical and Environmental Engineering, Nottingham Univ., UK). Bubble plumes in shallow seas have a complex behaviour, due to the interaction between eddies and bubbles as well as the presence of a stratified environment that strongly influences both the plume pattern and the induced surface flow.The characterization of the dynamics of buoyant plumes produced by a source of bubbles in a liquid is relevant in several contexts including that of the analysis of underwater blowouts as well as in wastewater treatment and destratification of reservoirs. Moreover, a recent interest has developed on the study of CO_2 plumes in the marine realm as a natural analogue for the effect of leakages from sub-seabed CO_2 storage sites. To understand the effects of increased levels of CO_2 on the marine realm, it is possible to study areas where, for natural reasons, there are emissions of CO_2 from the seabed. One of these areas is located east of Panarea Island (Aeolian Islands, Southern Tyrrhenian Sea, Italy). Here, a strong volcanic activity causes a continuous release of CO_2 (up to 98% of the total gas) from several vents on the seafloor in shallow water. Data collected in this area in underwater environment about chemical and physical properties (sea composition, temperature, density, velocity, pH, flux from main gas vents) have been analysed, compared to bubble plumes theoretical analysis. Furthermore, some laboratory experiments in a two-layer stratified fluid have been conducted to under stand the main features of the physical interaction of a gas plume with the surrounding environment. Both field and laboratory experiments show that there is a development of a pseudo-convective cell around the rising plume with the formation of vortices that act as a physical barrier thus reducing the interaction between the plume and the surrounding water but that, in case of CO_2 bubbles, have a mixing effect relevant for the sea acidification process.

Bubbles sound study in shallow seas (Main Collaborators: Dr. S. Buogo, CNR, Corbino Institute of Acoustics, Dr. G. Caramanna, and Prof. S. Espa). It is very difficult to measure the gas flux from the seabeds; this collaboration was meaning to experimentally verify a physical law connecting statistically the sound produced by a gas plume and its flux. It is known that each gas bubble in sea water produces a sound connected to its radius (Minnaert law). So a set of non interacting bubbles can be heard by acoustic sensors. But if the bubbles flux is higher, the interaction among different oscillators is such that the Minnaert law is no more good. A lot of theoretical equations have been used in order to have a flux predictive law by sound measures. But a possible different measure method could be given by the hypothesis that it is connected to the statistics of the measured time series signal and to its hurst exponent: as the flux varies, also the turbulence regime of the bubbles plume changes so as its statistics power law; untill the Hurst exponent is small, the power law gives the quasi-periodicity and the frequency of the bubbles so as the oscillations phase lag; but a transition to a different turbulence regime and a higher Hurst exponent is given at higher gas flux. The collaboration was meaning to verify if a correlation between the Hurst exponent and the gas flux can be got. So a set of experiments in the under water acoustic laboratory pool at IA-CNR were designed, in order to measure acoustic signals of different fluxes of gas bubbles artificially generated in order to determine such a correlation, by working in the hypothesis of a transition from a disordered gaussian signals distribution to a non gaussian one. Unfortunately this research line remained only a project for funds and many other problems.

Analysis of current deep sea data in a Mediterranean site, showing the presence of deep vortices (Main Collaborators: NEMO Group, INFN, Dr. F. Falcini, Univ. of Pennsylvania, Dept. of Earth and Environmental Science, and Prof. A. Rubino, Dept. of Environmental Sciences, Informatics and Statistics, Univ. of Venice). Abyssal temperature and velocity data collected south of Sicily in the Ionian abyssal plain of the Eastern Mediterranean (EM) basin inside the NEMO project for neutrinos detection show for the first time that abyssal vortices exist in the EM, at depths exceeding 2500 m. The eddies consist of chains of near-inertially pulsating mesoscale cyclones/ anticyclones. They are embedded in an abyssal current flowing towards NNW. The paucity of existing data does not allow for an unambiguous determination of the vortex origin. A local generation mechanism seems probable, but a remote genesis cannot be excluded a priori . The presence of such eddies adds further complexity to the discussion of structure and evolution of water masses in the EM, a sea that in the most recent times has had a very strong evolution linked to recent climatic changes.

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List of research activities

Particle physics and Fundamental Interactions

Particle physics and Fundamental Interactions

1 Our fundamental questions about Nature

Understanding the fundamental nature of energy and matter and the birth and evolution of the Universe is the ultimate aim of the Particle and Astroparticle Physics investigations. A vast range of activities is required, including experiments at particle accelerators, experiments in underground laboratories, studies of cosmic rays and cosmological observations. They all have a key role and are complementing each other.

Only few years ago (see our previous issue[1]) the most fundamental questions we were posing were:

1. Does the Higgs boson exist?
2. Quarks and leptons, flavour physics
   - Why are there three families?
   - How to explain the observed pattern of masses?
   - How was the Universe matter and anti-matter asymmetry generated?
3. Physics at the highest scales:
   - How is gravity connected to the other forces?
   - Do all the forces unify at high energy?
4. Neutrinos:
   - Which are the ν masses?
   - Is the neutrino a Majorana or a Dirac particle?
   - Is CP violated in the neutrino sector?
   - Are there additional species? $\rightarrow$ Sterile ν?
5. Dark matter:
   - What is it made of? WIMPs, sterile neutrinos, axions, hidden sector particles?
   - One type or more types?
   - Is it a mere gravitational effect? are there any new interactions?
6. The epochs of Universe:
   - Primordial: is there inflation?
   - Today: what is dark energy?
7. Gravitational waves:
   - Do they exist and can they be directly detected?
   - What is their velocity propagation?
   - Is General Relativity completely true? Was A. Einstein totally right?

At that time, the validity of the Standard Model (SM) strong and electroweak interactions was already experimentally tested with high precision thanks to the success of the LEP and Tevatron experiments and with the first data of the Large Hadron Collider (LHC) experiments.

In the SM, the Brout-Englert-Higgs mechanism predicts the existence of a heavy scalar particle (the Higgs boson, H) which generates the mass values for the W and Z gauge bosons and for the fermion fields via Yukawa-type couplings. Evidence for the H boson was missing and the search for this particle was a highlight of the LHC physics program.

In the summer of 2012 the ATLAS and CMS Collaborations announced the discovery of a new particle decaying to several final states including photon, W and Z boson pairs. A mass of approximately 125 GeV and decay rates consistent with those of the SM H boson were measured. This was a superb achievement in our understanding of the fundamental interactions: the last

[1] http://www.phys.uniroma1.it/fisica/ricerca/scientific-report

missing piece of the great SM puzzle was in fact finally discovered with a positive answer to the first of our questions.

The SM predictions have been almost entirely explored and in principle, the model could be a valid theory up to the Planck scale.

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the CMS and ATLAS experiments at CERN's Large Hadron Collider". In the following years the properties of Higgs boson have been measured by the two experiments.

In these last few years another breakthrough discovery happened: the gravitational waves observation. It represents a beautiful confirmation of Albert Einstein's General Theory of relativity, which predicted the existence of gravitational waves one century ago. At the same time the first observations of a black hole binary system and of the most luminous event ever detected were made. The discovery of gravitational waves opens a new path to the astronomy of the *dark Universe*, based on gravitational-wave detectors located on the Earth and in the space. The answer to question 7 was therefore given.

The missing questions, ranging from 2-6, are still compelling. They are requiring an approach with multiple tools, including high energy colliders, neutrino experiments with short or long baseline, neutrino-less double beta decay, dark matter direct and indirect searches, research and studies of rare or ultra-rare decays. The main questions and the various experimental activities are summarized in Tab. 1.

	High energy colliders	High precision	Neutrino	Dedicated searches
Higgs	✓			
Neutrinos			✓	✓
Dark Matter	✓			✓
Flavour,CP-viol	✓	✓	✓	✓
New particles	✓	✓	✓	✓

Table 1: Fundamental questions of nature and approaches to address them .

These complementary approaches are all needed. Only from their combination we can hope to interpret correctly the signs of possible new physics and build a coherent view of the fundamental interactions. For this same reason, there is no single experiment in future that can give an answer to all the remaining questions.

The Higgs discovery and gravitational waves detection, without any hesitation, will be counted among the most important experimental scientific results of our century. In both of them the Physics Department of Sapienza University played a crucial role we are proud of.

The Physics Department, one of largest in Italy, operates in this field in complete sinergy with the Istituto Nazionale di Fisica Nucleare (INFN) local unit [Pagg. 158-160 of this Report]. People involved in the Particle Physics and Astroparticles experiments are 34 Faculty members (6 Professors, 19 Associate Professors, 9 assistant Professors) 5 post-docs and about ten Ph.D. students. These experiments are located in the most prestigious laboratories in the world:

- CMS [P1-7], ATLAS [P8-16], ALICE [P17], LHCb, and UA9 [P32] at the European Laboratory of CERN, Geneva (Switzerland)
- MEG at PSI,Villigen (Switzerland)
- KLOE2 [P18-20] and PADME [P21] at the Laboratori Nazionali di Frascati (INFN)
- VIRGO [P22-24] at the EGO facility in Cascina (INFN-IN2P3)

- CUORE [P25], LUCIFER [P26], CALDER [P27] at Laboratori Nazionali del Gran Sasso (INFN)
- ANTARES (France) [P28], KM3Net (Capo Passero, ITALY) [P29]
- CTA Instituto de Astrofisica de Canarias (IAC) (Spain) [P30]
- Nuclear Physics at Jefferson Lab (USA) [P31].

In addition, there is an important activity in the space research with the AMS (Alpha Magnetic Spectrometer) on the International Space Station, to measure the cosmic ray composition outside the atmosphere with a unprecedented precision and to look for signals of dark matter from space.

2 Major Research Accomplishments

2.1 Higgs discovery

The Higgs discovery, via its decays to photon, W and Z boson pairs, was based on data recorded in 2011 and 2012 at center-of-mass energies of 7 and 8 TeV (LHC Run1) respectively, corresponding to an integrated luminosity of about 25 fb^{-1} per experiment. Following the discovery, the focus has been on measuring the properties of this Higgs boson. Then, in 2015 and 2016 about 40 fb^{-1} of data (Run2) have been collected at a center-of-mass energy of 13 TeV. All the measurements using the LHC Run1 and Run2 data are consistent with the SM expectation.

The Higgs boson mass, m_H, has been measured independently by the ATLAS and CMS experiments using the Run1 dataset in several decay channels. Channels with the best mass resolution ($H \to \gamma\gamma$ and $H \to ZZ \to 4\ell(\ell = e, \mu)$) are used in the analyses combination of the two experiments. The Higgs boson mass based on this combination is $m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst})$ GeV. The measurement error is dominated by the statistical uncertainty, while the systematic uncertainty is mainly due to the uncertainties on the photon, electron, muon energy and momentum scales and resolutions. The results of the Higgs boson mass measurements performed by the individual experiments as well as the combined values are shown in Fig. 1.

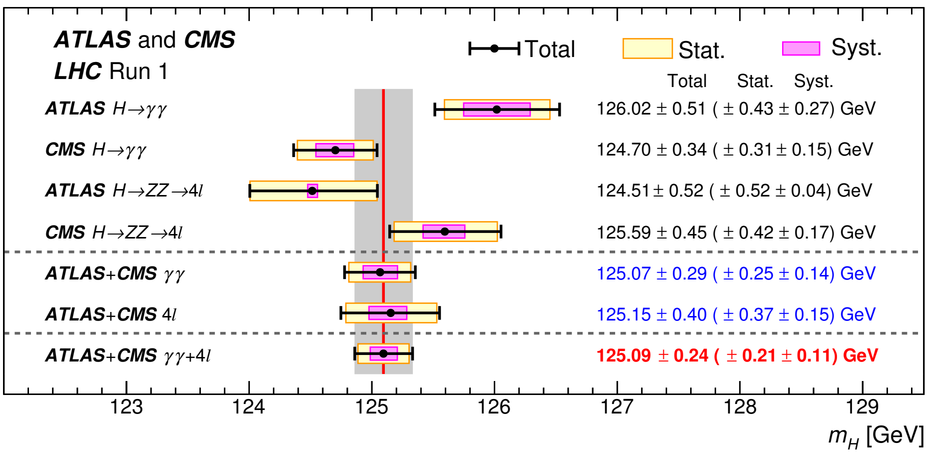


Figure 1: Summary of Higgs boson mass measurements from the individual analyses of CMS and ATLAS and from combined analysis. For all analysis the data correspond to integrated luminosities per experiment of approximately 5 fb^{-1} at $\sqrt{s}$=7 TeV (recorded in 2011) and 20 fb^{-1} at $\sqrt{s} = 8$ TeV (recorded in 2012).

The combined signal yield relative to the SM prediction is measured to be 1.09±0.11, as shown in Figure 2(left). The fermions or weak bosons couplings as a function of particle masses are shown in Figure 2(right) as obtained from the combination of the ATLAS and CMS measurements. All observations are consistent with the SM expectation for a H boson with quantum numbers $J^{PC} = 0^{++}$.

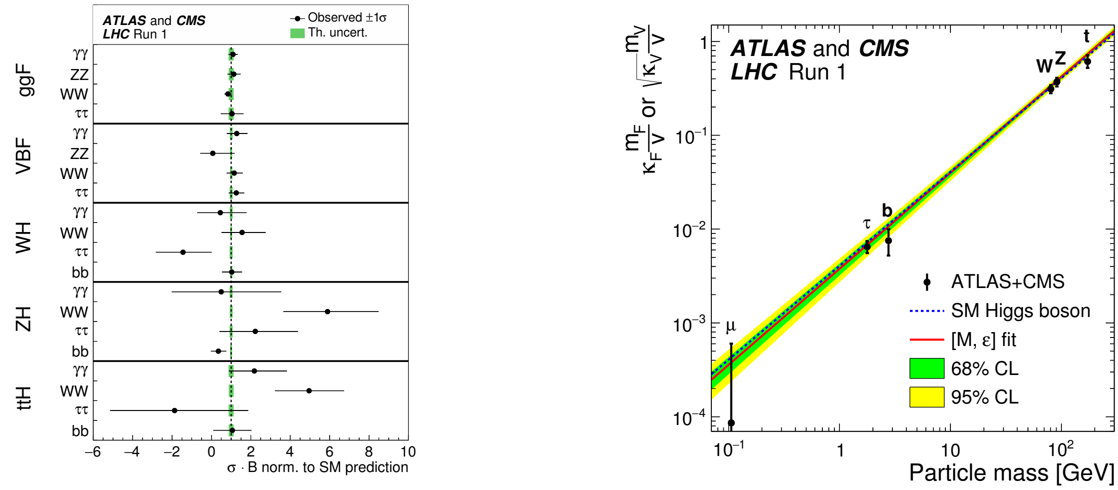


Figure 2: Best fit values of the cross section times branching ratio ($\sigma \cdot B$) normalized to SM prediction for each specific combination, as obtained from the combination of the ATLAS and CMS measurements(left). Two-parameters fit of the fermions or weak bosons couplings as a function of particle masses(right). The integrated luminosities considered is as in Fig. 1.

In 2015 LHC reached the center-of-mass energy of 13 TeV: two events at this energy frontier are shown in Fig. 3, recorded respectively by CMS ($H \to ZZ^* \to 2e2\mu$ event) and by ATLAS (associate production top quarks and Higgs boson $t\bar{t}H$).

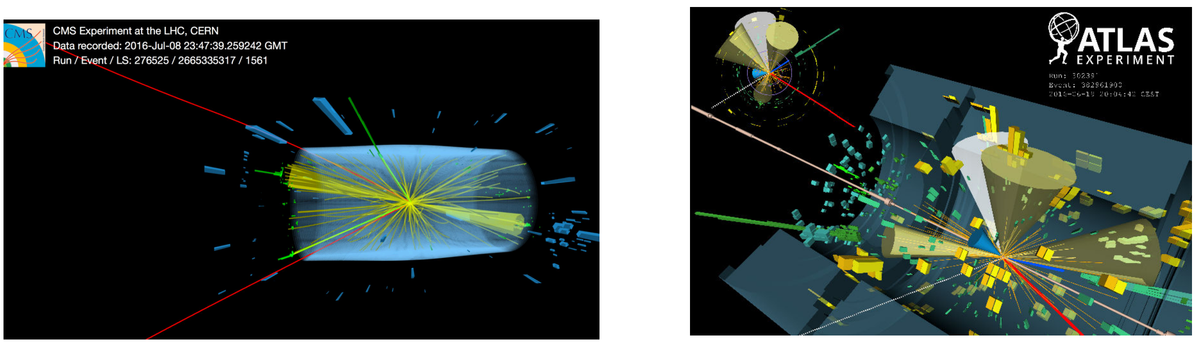


Figure 3: $H \to ZZ^* \to 2e2\mu$ candidate at $\sqrt{s} = 13$ TeV in the CMS detector in which two high-energy electrons (green lines), two high-energy muons (red lines), and two-high energy jets (dark yellow cones) are observed. The invariant mass of 4 leptons is $m_{4\ell} = 124.93$ GeV. (left). Associate production top quarks and Higgs boson candidate as collected by ATLAS experiment, $t\bar{t}H$ in a final state containing $e\mu\tau$ with τ decaying into hadrons. The blue track is the selected electron; the red track is the selected muon; and the white cone is the τ candidate(right).

The new data collected at $\sqrt{s} = 13$ TeV allowed to measure the H cross section at various energies. The increased center-of-mass energy and the larger sample of data expected will give access to other measurements, as for example the Yukawa coupling of the Higgs boson to the top quark, a key SM parameter. This measurement has the potential to identify and disambiguate new physics effects that can modify the $t\bar{t}H$ production cross section relative to the SM expectation.

The increased center-of-mass energy and the expected larger sample of data, up to now 40 fb^{-1} and $100 \div 150$ fb^{-1} expected by the end of 2018, will improve the measurement precision and offers the possibility to detect, until now, unmeasured Higgs boson production and decay channels. The measurements will still be limited by the statistical uncertainties with exceptions in the $t\bar{t}H$ production and $b\bar{b}$ decays with expected larger systematic uncertainties.

The Physics Department of Sapienza University is involved in both ATLAS and CMS. The ATLAS Rome group has made a significant contribution to the construction of the muon spectrometer and to the logic and to the electronics of the muon trigger system. The CMS Rome group has been heavily involved in the project and construction of the electromagnetic calorimeter. Both groups have contributed to the commissioning of their detectors and are currently involved in the data taking.

Both group are deeply involved in the data analysis and played a key role in the Higgs boson discovery: the CMS group with the search of the Higgs boson decaying into a pair of photons and the ATLAS group with the Higgs search through its decay to four leptons.

The subjects of the ATLAS Rome group activity are: several precision measurements of Standard Model processes, of the Standard Model Higgs Properties, searches of new physics beyond the Standard Model, search for Dark Matter and long-lived particles. By exploiting their deep experience on the electromagnetic calorimeter, the CMS Rome group studied the Higgs decaying in photons and possible new di-photon resonances, in the search for a class of the so called *exotic* processes.

Both groups are also involved in the upgrade of their detectors in view of the future runs at $\sqrt{s} = 14$ TeV with a luminosity $3 \div 5 \cdot 10^{-34} cm^{-2} s^{-1}$, exceeding a factor 5 the projected luminosity. The ATLAS Rome physicists collaborate to the construction of *micromega chambers*, covering the pseudorapidity range $1.3 < |\eta| < 2.7$ of the detector and the electronic board for the trigger. The CMS group is actively participating to the upgrade of CMS electromagnetic calorimeter focusing on the reduction of dark current of more than 120000 Avalanche Photo-Diodes(APD) collecting the light of the 61200 barrel crystals and an improvement of time measurement of about 30ps for charged and neutral particles.

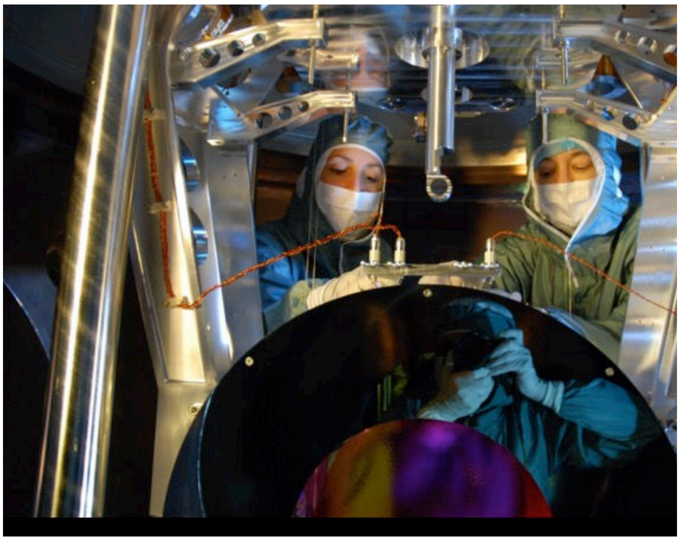
The present physics coordinator of the CMS Collaboration is prof. Shahram Rahatlou, belonging of our Physics Department.

2.2 Observation of Gravitational waves

The Virgo group of Sapienza University of Rome is part of a world-wide collaboration for the direct detection of Gravitational Waves (GW) using Laser interferometer of kilometric baseline, Fig. 4. The network of detectors is formed by the two LIGO detectors in USA and by the Virgo detector in Italy. Since several years the Virgo and LIGO Collaborations are jointly analyzing the data produced by the GW network. The Rome group is involved both in the analysis of the already collected data and in the upgrade to Advanced Virgo, having the full responsibility of the construction of the payloads, the heart of the gravitational wave detector. On 11 February 2016 at Washington D.C. (USA) and at the same time at Cascina (Italy) the LIGO director and the Virgo spokesperson, Fulvio Ricci professor at Sapienza Univ., announced the first direct detection of a Gravitational Wave signal detected at 09:50:45 UTC on the 14 September 2015. This is the start of the new era of Gravitodynamics and Gravitational-Wave astronomy. Up to now physicists and cosmologists explored the Nature thanks to the electromagnetic radiation and the other two fundamental interactions: visible light, X-rays, microwave, radio waves, gamma rays and elementary particles have been the tools to probe the Nature's laws. Since September 2015 Gravitational wave is a new messenger for the exploration of the Universe.

3 Other results in Particle Physics with Accelerators

The activity of the Department at accelerators machines includes as well other activities: heavy ions physics and precision measurements at lower energies.



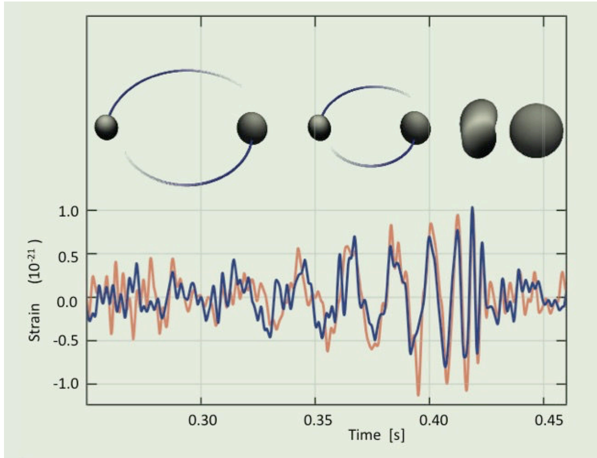


Figure 4: The Advanced Virgo payload during the installation phase (left).The gravitational-wave event observed by the two LIGO detectors. At the top the cartoon shows the interpretation of the dynamical behavior of the system of two black holes emitting gravitational waves (right).

3.1 Heavy Ions physics

In addition to the CMS and ATLAS groups, other physicists are involved in the LHC experiment dedicated to more specific themes: the ALICE group is focused on the study of Quark Gluon Plasma (QGP) in nucleus-nucleus collisions. This search has been performed by exploiting the extremely large energy densities in high energy interactions of heavy ions, Pb-Pb collisions. The ALICE Collaboration is recording, also, p-p and p-nucleus collisions reference data for the nucleus-nucleus collisions. The data have been collected since 2011 to 2012 and since 2015 after the LHC restart. 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 (pp and p-Pb). The Department of Physics (and local INFN unit) group shares with other Italian colleagues the responsibility of the Silicon Drift Detector (SDD) of the Inner Tracker. The ultimate goal of the ALICE experiment is to provide a precision characterization of the high-density, high-temperature phase of strongly interacting matter. To achieve a high statistics of collected data is necessary a detector upgrade to cope with Pb-Pb interaction rates of up to 50 kHz aiming at an integrated luminosity above 10 nb^{-1}. The group of Rome Sapienza and INFN is involved in the analysis studying the jet coming from heavy quarks (like charm and beauty) as *golden channels* to probe the QGP, the space-time evolution of the hadronization process and the phenomena of energy loss (quenching). Concerning the ALICE upgrade, the Rome group is working on the new Inner Tracking System (ITS). All the new ITS will be made of seven layers of Monolithic Active Pixel Sensors (MAPS) with pixel size of $29 \times 27 \mu m^2$. The specific hardware contribution of Rome group is in the development and production of the basic unit named *stave*. The upgrade of the ITS will be accomplished by the end of the LHC Long Shutdown 2 (2021).

3.2 Precision measurements

The Standard Model (SM) of the strong and electroweak interactions has been so far successfully tested in the last decades, but deviations from its predictions can be an indication for new physics. Consequently, detailed studies of known physics represent a path to explore new phenomena. This field, named *flavour physics*, includes the study of the different quark flavours and of the three leptons (e, μ τ and their neutrinos ν_e, ν_μ, ν_τ). Open questions in the lepton sector (see Section 1) involve the values of their masses, their mixing and their Charge Parity symmetry (CP) properties.

The CP violation is a key element to understand the difference in abundance between matter and antimatter. An effect of the presence of yet undiscovered new interactions would be a deviation on the size of CP violation with respect to the SM prediction. This would happen in presence of new particles mediating the CP violating physics processes.

The Department of Physics provides a relevant contribution also in this sector, in particular studying the mixing between lepton families. The existence of processes which violate the lepton flavour number conservation is in fact a clear signal of new physics beyond the SM. The MEG experiment at the Paul Scherrer Institut (Villigen, CH) is totally dedicated to the search for the $\mu \to e\gamma$ decay exploiting the most intense muon beam available in the world. Most models for physics beyond the SM are in fact predicting a branching fraction for this decay in the range of 10^{-12} -10^{-14} that is within the reach of MEG. A group of researchers of this Department and of the local INFN unit took part in this experiment and recently published the analysis of the MEG full dataset. An upper limit on the $\mu \to e\gamma$ branching fraction ($< 4.2\ 10^{-13}$ at 90% C.L.) was set, which is about 20 times more stringent than the previous experiment's best result.
This group is now actively working on the upgrade program (MEG-II), in particular in the construction of a new wire drift chamber. They are planning to push the sensitivity of the experiment to this decay down by another order of magnitude by the end of the current decade.

Always in the framework of precision measurements the Department hosts a group investigating low energy hadron physics. They participate in the run of an experiment (KLOE-2) at the DAΦNE collider in Frascati. Among its many purposes, are the study of neutral kaon interferometry and tests of discrete symmetries, in particular the search for a violation of the Charge-Parity-Time (CPT) symmetry, the study of light mesons spectroscopy and low energy QCD, and the search for dark forces. The improvements with respect to its predecessor KLOE are based on a detector upgrade, mainly the inner tracker with cylindrical GEM technology, and the increased luminosity of the collider. The Rome group of the Department of Physics is involved in the data analysis related to neutral kaon interferometry and η meson physics, and, in general, in the offline reconstruction coordination.
The spokesperson of the KLOE-2 Collaboration, Prof. Antonio Di Domenico, is a member of the Department.

4 Astroparticle Physics

The field of astroparticle physics, or particle astrophysics is relatively new and in great expansion, including the gamma and neutrino astrophysics and studies of neutrino properties. Since reproducible experimental conditions cannot be prepared as in a laboratory, precise knowledge of particle physics is necessary to understand many astrophysical contexts. In this sense, the astrophysical environment therefore constitutes an important laboratory for high energy physicists.

4.1 Gamma and neutrino astronomy

Neutrino Astronomy is a new and unique method to observe the Universe. The weakly interacting nature of the neutrino makes it a complementary cosmic probe to other messengers such as multi-wavelength light and charged cosmic rays: the neutrino can escape from sources surrounded with dense matter or radiation fields and can travel cosmological distances without being absorbed. This specificity of the neutrino astronomy means that in addition to knowledge of cosmic accelerators seen by other messengers, it may lead to the discovery of objects hitherto unknown. For known high energy sources such as Active Galactic Nuclei (AGN), Gamma Ray Bursts (GRB), MicroQuasars (MQ) and Supernova Remnants (SNR), neutrinos will allow to distinguish unambiguously hadronic and electronic acceleration mechanisms and to localize the acceleration sites more precisely than what charged cosmic ray detectors can do. The ability of neutrinos to exit dense sources means that new compact acceleration sites might be discovered. Furthermore, this feature gives an exclusive signal for indirect searches of dark matter based on the detection of high energy products from the annihilation of dark matter particles which might have been accumulated in the cores of dense objects such as the Sun, Earth and the centre of the Galaxy. A diffuse flux of cosmic neutrinos, exceeding the atmospheric component, has been reported by IceCube which started the "Neutrino Astronomy era". The search for distinct point-like sources of neutrinos, such as the examples mentioned above, needs a huge "Neutrino Telescope" with very good angular resolution in order to provide the necessary signal-background distinction. A group of this Department has been promoting the construction of a km^3 scale deep-sea neutrino Cherenkov detector, in the Mediterranean Sea, since the last decade of the past century (the NEMO research and development program). At present it participates to the ANTARES experiment and is one of the stakeholders of the KM3NeT project (partially funded by UE). The Rome group has been responsible for the characterization of Mediterranean deep-sea sites, has developed the electronics for NEMO and for part of KM3NeT detector, and is deeply involved in the data analysis.

Regarding gamma astronomy the participation to the Čerenkov Telescope Array (CTA) is the next generation ground-based observatory for gamma-ray astronomy at very-high energies. With more than 100 telescopes located in the northern and southern hemispheres, CTA will be the world largest and most sensitive high-energy gamma-ray observatory.

4.2 Neutrino Physics

The nature of the neutrino mass (Dirac or Majorana) plays a fundamental role in the framework of particle interactions and in cosmology. The answer could come from the observation of a rare nuclear process called Neutrinoless Double Beta Decay (NDBD) in which a nucleus decays emitting only two electrons. Its discovery would establish the lepton number violation and would shed light on mechanism responsible for matter-antimatter asymmetry in the Universe. Among the several experimental approaches, cryogenic calorimeters (bolometers) stand out for the possibility of achieving excellent energy resolution ($\approx 0.1\%$), efficiency ($\geq 80\%$) and intrinsic radio-purity. Crystals, operating as bolometers, are grown from most of the NDBD emitters, enabling the test of different nuclei. The state of the art of the bolometric technique is represented by CUORE, a 741kg experiment composed by 988 TeO_2 bolometers, presently in its commissioning phase at Laboratori Nazionali del Gran Sasso.

The limiting factor in CUORE resides in the presence of α-decaying isotopes located in the detector structure, producing a flat background. An active background discrimination is therefore needed to further enhance the sensitivity. The CALDER project aims at developing high-sensitivity superconducting light detectors with large area (few cm^2) and 20 eV energy resolution. These devices, coupled to the CUORE bolometers, could detect the tiny (100 eV) Cherenkov light emitted by the electrons and not by the α's, thus enabling an event-by-event background rejection. A different approach, developed by the LUCIFER experiment, makes use of the different light emission properties for the two classes of events in scintillating bolometers. The detector, composed by 26 ZnSe ultra-pure 500g bolometers enriched at 95% in 82Se, is currently taking data at the Laboratori Nazionali del Gran Sasso.

5 Applied physics

The competences acquired in detector design and testing, in data mining and statistical analysis and the knowledge of particle and nuclear physics are exploited for applications, mostly medical. The Applied Radiation Physics Group, founded in 2011, is currently working on the estimate of the dose delivery in Particle Therapy [P33] and the development of a novel technique of Radio-guided Surgery [P34]. Furthermore, recently a new activity on the use of multivariate analysis in radiological imaging for tumor staging has started.

6 Conclusions

In this introduction, a partial review of the Particle physics and Foundamental Interactions activities of the Physics Department has been reported. Following pages present additional information and a deeper and wider overview. This wide range of activities confirms the Sapienza Physics Department high level tradition in the field of Particle and Astroparticle Physics and puts it among the highest ranked Departments in the world.

Simonetta Gentile

P1. The CMS experiment at the CERN LHC

The Large Hadron Collider at CERN (the European Laboratory for Particle Physics), which has been collecting data since 2010, is the highest energy accelerator in the world: it is and will be a unique tool for fundamental physics research for many years to come. In the LHC two proton beams, circulating in opposite directions, collide at four interaction points, where the experiments are located. The collision energy has been increased from 3.5 TeV to 4 TeV and now 6.5 TeV for each beam (centre-of-mass energy $\sqrt{s} = 13$ TeV) in the last years. The CMS (Compact Muon Solenoid) experiment[1] is a general purpose detector to explore physics at this unprecedented energy scale.

The major CMS (and ATLAS) scientific achievement has been the discovery of the Higgs boson in 2012. In years 2013 and 2014, LHC has been upgraded to reach higher energy and luminosity, and data taking restarted early in 2015. Since then, CMS has produced a notable amount of measurements and studies, not only of the Higgs properties and decay modes, but of many other physics channels such as B meson decays, electroweak channels, and top quark production. Furthermore, extensive searches for exotic particles, dark matter, supersymmetry have been carried out, putting new limits on many theoretical models. Finally CMS has produced precision measurements of the parameters of the Standard Model, thanks to the huge amount of Z and W bosons collected.

The integrated luminosity delivered by LHC in the CMS interaction point has been 29 fb^{-1} in Run1 (2010-2012), 4.2 fb^{-1} in 2015 and 41 fb^{-1} in 2016. The peak luminosity of LHC has reached 1.5×10^{34}cm^{-2}s^{-1} in 2016 and is planned to reach 2×10^{34}cm^{-2}s^{-1} in 2017.

Figure 1: Installation of CMS Electromagnetic Calorimeter

The CMS detector measures roughly 22 meters in length, 15 meters in diameter, and 12,500 metric tons in weight. Its central feature is a huge superconducting solenoid, 13 meters in length, and 6 meters in diameter which contains the electromagnetic and hadron calorimeters surrounding a silicon tracking system, allowing a "compact" design. Moreover the high magnetic field (3.8 Tesla) allows for a superb tracker detection system. Muon momenta are measured by gas chambers in the iron return yoke.

Our group contributed to the project and construction of the electromagnetic calorimeter shown in Fig. 1; we have also carried out extensive studies of the calorimeter calibration and optimal reconstruction and identification of electrons and photons [1,2]. We therefore played a major role in the search, discovery and study of the Higgs boson, mainly in the H→ $\gamma\gamma$ channel; the excellent energy resolution of photons in this decay channel is shown in Fig. 2 as a function of pseudorapidity.

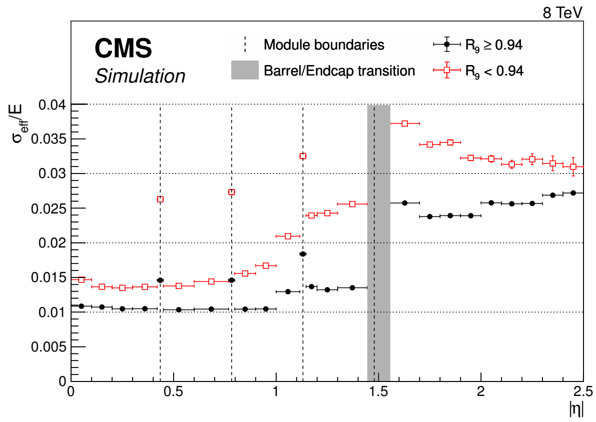


Figure 2: Energy resolution of photons from H→ $\gamma\gamma$ decays. Uncoverted (converted) photons are shown in red (black).

In Run1 the top mass has been measured with great precision, combining jets, lepton + jets, and dilepton decay channels, and resulting as the worldwide most precise measurement: 172.44±0.13(stat.)±0.47(syst.)GeV [3].

The amount of data collected in 2015 and 2016 will allow to improve these studies and reduce the experimental errors. Our group is fully involved in the searches for exotic particles, mainly heavy resonances decaying into two photons and two jets.

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P2. Properties of the Higgs boson

Since the announcement of 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, an impressive program of measurements of its properties has been performed by CMS. The main goal of these measurements is to determine whether the Higgs boson follows the Standard Model (SM) predictions or there are indications for new physics.

A comprehensive analysis [1] combines the CMS measurements of the Higgs boson properties targeting its decay to a pair of photons ($\gamma\gamma$), or vector bosons (WW or ZZ), or a pair of μ or τ leptons ($\tau\tau$, $\mu\mu$) or a b quark and antiquark pair ($b\bar{b}$). Different production modes can also be selected: gluon-gluon fusion, vector boson fusion, and production in association with W, Z, and a top quark-antiquark pair. The broad complementarity of production and decay modes enables a variety of studies on H couplings.

The $H \to \gamma\gamma$ and $H \to ZZ \to 4$ leptons channels play a special role in the mass determination because of the excellent mass resolution of these reconstructed final states. The CMS Rome group has an extended and deep experience in the exploitation of the electromagnetic calorimeter, expressely designed and optimized to detect the $H \to \gamma\gamma$ channel [2].

Figure 1 shows the 68% Confidence Level (CL) regions for two parameters, the H mass (m_H) and the signal strength, defined as the ratio of the measured production cross section to the SM prediction (σ/σ_{SM}), for $H \to \gamma\gamma$ and $H \to ZZ \to 4$ leptons final states and their combination. The best fit value of the mass is determined to be:

$$m_H = 125.02^{+0.29}_{-0.31}\text{GeV}.$$

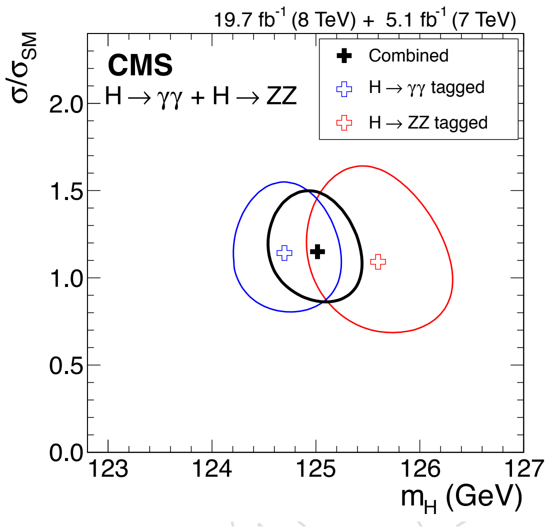

Figure 1: The 68% CL regions for $H \to \gamma\gamma$ and $H \to ZZ \to 4$ leptons final states and their combination.

A distinctive SM prediction concerns the coupling of the Higgs boson to the fermions [3], λ_f, which must be proportional to the fermions masses, and to the weak bosons, g_V, which involves the square of their masses. A two-parameter fit is presented in Fig. 2 [1] with an appropriate transformation for the weak bosons couplings, showing that the H couplings to different particles are correctly related to the masses for more than three orders of magnitude in particle mass.

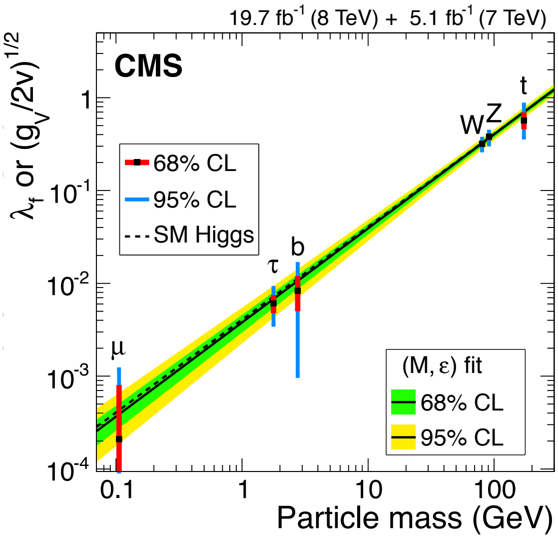

Figure 2: Two-parameter fit of the fermions or weak bosons couplings as a function of particle masses.

The SM Higgs boson is predicted to have even parity, zero electric charge, and zero spin. The experimental observation of the $H \to \gamma\gamma$ decay channel prevents the observed boson from being a spin-one particle because of the Landau-Yang theorem. Other hypotheses are tested studying the angular distributions of the lepton pairs in the $H \to ZZ$ decay channel and looking at anomalous effects in HZZ and HWW interactions [4]. All observations are consistent with SM expectations for the SM Higgs boson with quantum numbers $J^{PC} = 0^{++}$.

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P3. Study of the $H \to \gamma\gamma$ decay at the LHC

In 2012 the ATLAS and CMS Collaborations observed a new boson with a mass of about 125 GeV and properties consistent with expectations from a Standard Model (SM) Higgs boson. In the Higgs search, the $H \to \gamma\gamma$ channel provides, together with $H \to ZZ$, the largest sensitivity. Despite its small branching fraction of $\sim 0.2\%$, the clean diphoton final-state signature allows the mass of the decaying objects to be reconstructed with high precision, thanks to the performance of the electromagnetic calorimeter of the experiment. The resolution of the diphoton invariant mass is of the order of 1% and the uncertainty on the energy scale is at the per-mille level. The selected events are subdivided into classes, depending on the photon kinematics and reconstruction quality, and the presence of extra objects in the event. This approach enhances the overall performance and increases the sensitivity to individual Higgs production mechanisms. Historically, the members of the CMS Rome group have provided a crucial contribution to the study of this channel. Their expertise in the electromagnetic calorimeter has strongly improved the robustness of the diphoton searches.

Later, the analysis of the proton-proton collisions dataset corresponding to the full 2011 and 2012 LHC running periods has further increased the significance of the diphoton channel, reaching a local significance of 5.7σ at a mass of 124.7 GeV (Fig. 1), thus implying the existence of the diphoton decay mode of the Higgs [1].

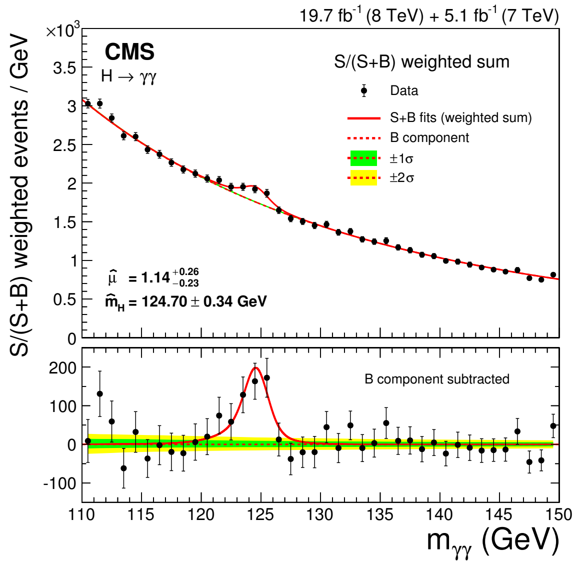

Figure 1: Fit of the diphoton invariant mass distribution. The lower plot shows the residual data after subtracting the fitted background component.

More recently, a number of detailed studies have been performed. The cross section has been measured as a function of the kinematic properties of the diphoton system, and, in events with at least one or two accompanying jets, also as a function of jet-related observables. The resulting differential angular distributions look consistent with the ones predicted by the SM (Fig. 2), confirming that the spin and parity properties are compatible with the ones of the SM Higgs boson [2]. The $H \to \gamma\gamma$ can be further used to search for the production of events with two Higgs, which is predicted by the SM with a small cross section, but may have a large contribution in several scenarios of new physics. The results show a compatibility with the SM [3]. All these studies, also including the ones targeting the measurement of the Higgs couplings, will become more and more crucial when large integrated luminosities at 13 TeV will be collected in future.

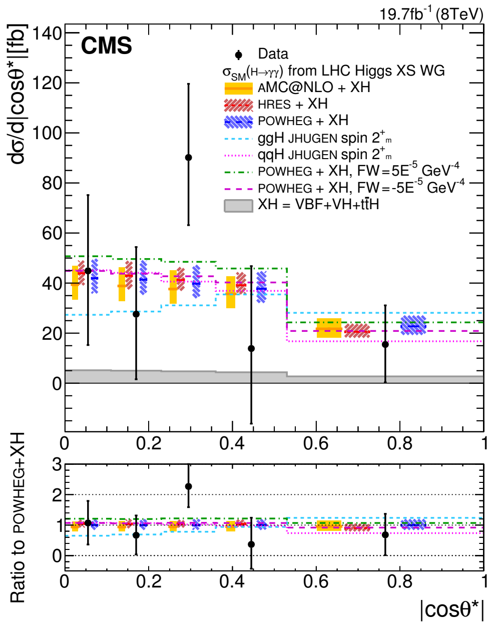

Figure 2: The $H \to \gamma\gamma$ differential cross section as a function of $|\cos\theta^*|$, compared to the SM contributions. The bottom panel shows the ratio of data to theoretical predictions. θ^* is the angle of the photon in the Collins-Soper frame (the rest frame of the $\gamma - \gamma$ system) where the z axis bisects the angle between the incoming proton and the negative direction of the other incoming proton.

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P4. Search for exotic resonances at LHC with the CMS detector

Many extensions of the Standard Model (SM) predict the existence of heavy, unstable resonances that can decay to SM products with a characteristic signature: two or more detectable high energy particles (or jets of particles) whose invariant mass peaks at the new resonance mass. The CMS experiment aims, among other goals, to the discovery of such particles, if they exist. The Collaboration has searched for this kind of resonances over a wide range of masses and final states and, until now, no statistically significant deviation from the SM predictions has been found. The most important signatures explored with the CMS detector are:

- dijets: two high p_T jets are expected in the detector;
- multijets: three or more high transverse momentum (p_T) jets are required in the final state;
- dileptons: in this category a search is made on pairs of electrons, muons or taus;
- $t\bar{t}$: in this case the resonance is expected to decay into a pair of top quarks;
- dibosons: the final state contains two high p_T vector or scalar bosons.

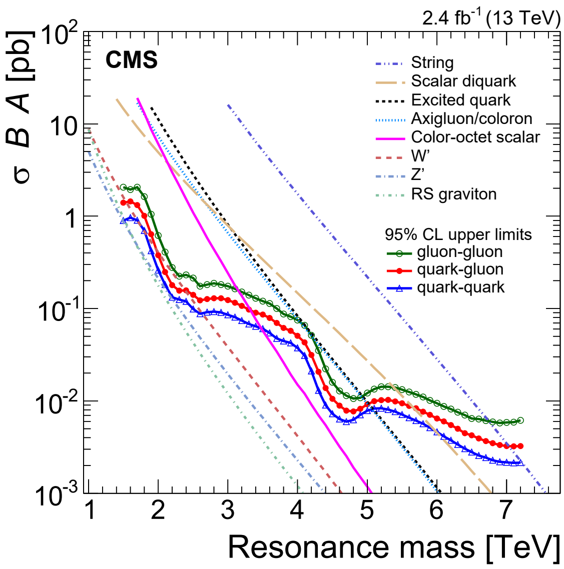

Figure 1: The upper limit on the production and subsequent decay of a resonance into two jets, as a function of the resonance mass.

Since the beginning of the operations, the CMS collaboration published more than 45 papers on this topic[1]. As an example, the results for the dijet search, reported in terms of the upper limit on the production cross section (σ) times the branching ratio (B) and acceptance (A) for a new resonance, are shown in Fig. 1 as a function of the mass [1].

In 2015, the possible existence of a new resonance decaying into two photons with a mass of $m_X \simeq 750$ GeV has received much attention [2]. Later, the analysis of the 2016 dataset disfavoured this possibility. As shown in Fig. 2, the local observed background–only p–value for such a resonance corresponds to about two standard deviations. Taking into account the so–called *look elsewhere effect* the deviation correspond to less than one standard deviation.

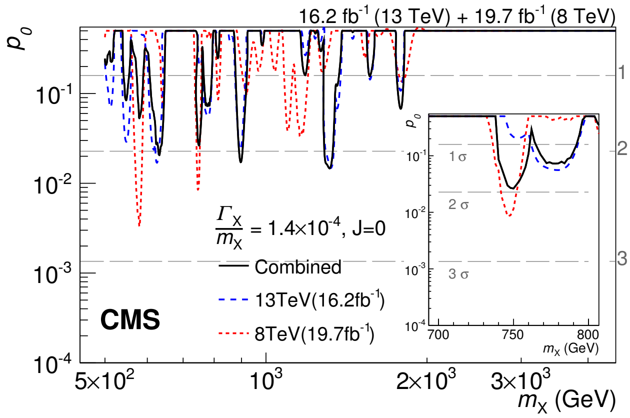

Figure 2: Observed background–only p–values for narrow resonances decaying into two photons.

The search for high mass resonances provide constraints for the possible existence of dark matter. In most cases the SM background is small, but not negligible, hence the shape and the normalisation of the background is inferred from data using signal depleted control regions.

The CMS Collaboration will continue testing new models as well as searching for new excesses in a model independent way, in order to provide important information for the development of new extensions of the Standard Model and/or to identify possible candidates, e.g., for dark matter. The need to provide answers to many open questions makes the search for resonances one of the most important scientific programme of the experiment, to which the Roma Group actively participates.

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P5. Search for new long-lived particles at LHC with the CMS detector

Extensions of the Standard Model (SM) predict the existence of new particles which can be created in high-energy proton-proton (pp) collisions at the LHC. The lifetime of these new massive states is often a free parameter of the theory. If the new particle is long-lived, it will decay far from the pp interaction point and can interact directly with the detector while traveling through it. The experimental signatures of long-lived particles (LLPs) are usually striking but also very different from the short-lived ones, thus requiring dedicated analysis methods.

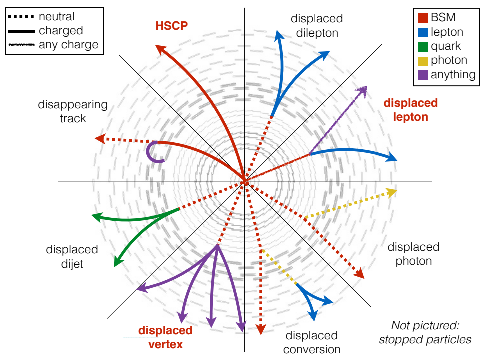

Figure 1: Experimental signatures of new long-lived particles (LLPs) in the CMS detector. LLPs are indicated with the label BSM (beyond the Standard Model). Image courtesy of Jamie Antonelli.

Searches for LLPs have been performed in a wide range of final states with the CMS detector and, so far, no evidence of these signals have been found. The CMS collaboration published 15 papers on this topic [1]. A large number of experimental signatures has been explored, as outlined in Fig. 1, including:

- **Heavy Stable Charged Particles (HSCP)**: at LHC these massive particles are typically produced with β significantly less than 1. They can be identified by unusual rates of energy loss via ionization in the inner tracker material or by their longer time-of-flight to the outer tracking detectors compared to light SM particles (such as muons). Recent results are reported in Ref.[1];
- **stopped particles**: slow HSCPs ($\beta \ll 1$) can lose all their momentum via ionization and stop in the calorimeters. Their decays can be detected out-of-time with respect to the LHC collisions, even hours or days after the pp collision that produced them;
- **displaced vertices**: the LLP can be a neutral particle decaying into SM charged particles (hadrons or leptons) within the inner tracker volume. They can be identified via the reconstruction of decay vertices displaced from the pp interaction point;
- **disappearing tracks**: a disappearing-track signature can be produced by a charged LLP whose decay products are undetected;
- **displaced photons**: a neutral LLP can decay to a photon and a weakly interacting particle. The photon arrival at the electromagnetic calorimeter (ECAL) is delayed, due to extra flight length added by the LLP decay. This time delay, unusual for photons generated by SM processes, can be measured taking advantage of the excellent ECAL time resolution. Displaced photons are foreseen for example by neutralino decays in Supersymmetry. The first search in CMS was performed by the Rome group using data at $\sqrt{s} = 7$ TeV and no deviation from the SM predictions was found [2]. Limits were set on the neutralino mass as a function of its proper decay length, as shown in Fig. 2, extending results from previous experiments.

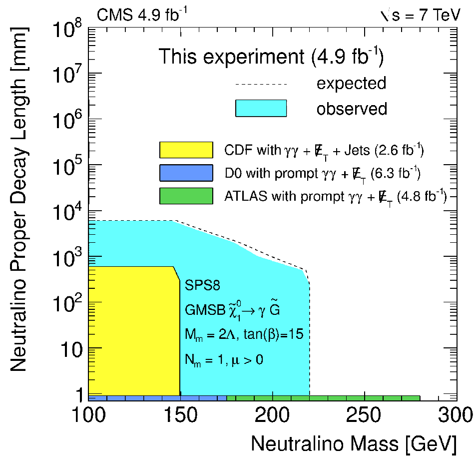

Figure 2: Excluded regions in the neutralino proper decay length ($c\tau$) vs mass plane.

In the next several years, LHC experiments will collect hundreds of fb^{-1} of data at a constant center-of-mass energy of 13-14 TeV. In this scenario of high integrated luminosity and no sign of new physics in the standard prompt decay channels, searches for the exotic signatures of LLPs are expected to become increasingly important.

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[1] `http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/LLP.html`

P6. Upgrade of the CMS electromagnetic calorimeter in view of the High Luminosity LHC

The CMS electromagnetic calorimeter (ECAL) is made of 75848 lead tungstate ($PbWO_4$) scintillating crystals, located inside the CMS superconducting solenoidal magnet. It is made of a barrel part and two endcaps which cover the forward regions. The photodetectors are Avalanche Photo-Diodes (APD) in the barrel and Vacuum Phototriodes (VPT) in the endcaps. The excellent 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.

The design of the ECAL was made to operate with an instantaneous luminosity of $1 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and for an integrated luminosity of 500 fb^{-1}. A new program is being prepared to exploit the full potential of the LHC through a luminosity upgrade, in order to precisely measure the couplings and rare decays of the Higgs boson, self-interaction through the double Higgs boson production and Vector Boson Scattering. The high luminosity LHC (HL-LHC) is expected to provide an instantaneous luminosity greater than $5 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and integrate a total luminosity of around 3000 fb^{-1} by 2035.

This poses new challenges for the experiment both from the point of view of ageing and radiation hardness of the detector components, and from the point of view of the trigger and data acquisition. An upgrade program [1] is then envisaged to take place during the Long Shutdown 3 (in 2023-24). For the calorimeters the planned upgrade consists of replacing the endcap calorimeters, refurbishing the ECAL Barrel electronics and exploting the timing information.

Due to the cumulated radiation in the endcaps, the crystals will develop very low light output. Therefore, CMS plans to replace the endcaps calorimeter with a high granularity calorimeter made of silicon sensors and tungsten absorber.

In the barrel the crystal light output will be sufficient to ensure good performance, but hadron fluence will cause a growth in the APD dark current, and consequently in the electronic noise. The CMS Rome group has qualified the ECAL APDs [2] for radiation hardness up to $2 \cdot 10^{14}$ neutron/cm^2, using the Tapiro reactor at ENEA Casaccia. The APDs were qualified at different temperatures in the thermalized chamber at the LABE (see page 171 of this report). The measurements show that the APDs are still operational at this fluence. Moreover a reduction of the APD dark current of a factor about two could be obtained by lowering the operating temperature of the calorimeter from the present 18°C to about 8°C. This is part of the upgrade strategy of the CMS calorimeter.

The CMS trigger algorithm will be more complex in order to select the good events on top of the high number of concurrent interactions per bunch crossing (pile-up). In particular CMS plans to exploit the track information in the L1 trigger algorithms. A longer processing time, and therefore a longer latency, is expected. The read-out rate will increase by a factor of 10 to allow online filtering of the events in a processor farm, where a better selection will be achieved. The ECAL electronics must be replaced to cope with the increase in trigger latency and in read-out rate. The new design will transmit all the ECAL data off-detector with fast optical links. The upgrade of the electronics also includes a new preamplifier, faster and better matched to the APD dark current increase.

At the HL-LHC instantaneous luminosity, there will be an average pile-up of about 140 (possibly up to 200). The event vertices will be spread in position along the beam axis with a displacement of 5 cm, and in time with a spread of hundreds of picoseconds. This characteristic can be used to mitigate the pile-up using the time-of-flight information, if the calorimeter hits have a precise timing measurement associated to them. The desired resolution is 10-30 ps. Such resolution has been achieved in the past by other types of detectors, but it is unexplored territory for full size (22 cm) scintillating crystals.

A testbeam was carried out by the Rome CMS group in order to study the ultimate timing precision achievable with the crystal calorimeter. In the testbeam setup, 30 $PbWO_4$ crystals were read-out by a prototype of the new amplifier, faster than the present one. High energy electron beams between 20 and 250 GeV were used to study the crystal response. The main result of this testbeam is that a timing resolution of 20 ps is achievable with the ECAL crystals for electron/photon energies above 50 GeV using a signal sampling at 160 MHz. For low energy deposits, and particularly for minimum ionizing particles, the possibility to adopt a dedicated timing detector is being studied (see next page).

In conclusion, several measurements were made by the CMS Rome group to define the upgrade program of the calorimeter for the HL-LHC phase. The planned upgrade of the CMS ECAL will allow to mitigate the ageing and radiation effects, and to cope with the increase in instantaneous luminosity.

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P7. Precision time detectors at the High Luminosity LHC

The high luminosity phase of the LHC (HL-LHC) is expected to provide an instantaneous luminosity exceeding a factor 5 with respect to LHC design luminosity ($> 5 \cdot 10^{34}$ cm^{-2}s^{-1}), with the goal of integrating more than 3000 fb^{-1} by the end of its program. This will allow the experiments to fully exploit the LHC physics potential, with the possibility to measure the Higgs couplings with a few percent level precision or to study rare processes, e.g. double Higgs production or rare Higgs decays ($H \rightarrow \mu^+\mu^-$,$H \rightarrow Z\gamma$, ...). LHC experiments will have to confront these new experimental conditions, far beyond their design goals. An average of 140-200 interactions will pile-up at each bunch crossing; given the proton bunches length and crossing angle, the interaction vertices will be spread over 5 cm along the beam axis and 180 ps in the collision time. In the longitudinal direction, a density of 2 vertices per mm will be reached for 200 concurring interactions.

Pile-up will significantly affect the reconstruction of the hard scattering event. However, it is possible to take advantage of the spread of the vertices in the time dimension to mitigate the effective pile-up contamination. It has been studied with simulations that a time measure with a precision of about 30 ps for charged particles and neutral particles in the acceptance of the LHC detectors will reduce the pile-up of a factor > 5, restoring conditions comparable to the present LHC conditions. Such levels of time resolution are about one order of magnitude better than what is currently achieved by the LHC detectors, thus motivating an R&D study for precise time detectors.

In particular the CMS Rome group is proposing the use of micro-channel plates (MCP) without a photocathode, referred as “i-MCP” (ionisation MCP). The potential advantages of an i-MCP are a robust design, thanks to the removal of the photo-cathode, and an improved radiation tolerance, since radiation damage mostly affects the photo-cathode response. The study of the MCP technology is also motivated by the recent progress of the Large Area Picosecond Collaboration[1] which could result in a significant cost reduction for MCPs production, making this a viable solution to be adopted for large detectors.

In an i-MCP the detection mechanism for charged particles is based on the secondary emission of electrons at the MCP surface. This reduces significantly the amount of charge collected compared to a standard PMT-MCP (exploiting the Cherenkov light emitted in the optical window of the detector). In order to optimise the single particle response of an i-MCP, different geometries have been studied. The ratio between pore size and thickness of the plate or the number of consecutive MCP plates in a MCP stack has been varied. The possibility of a special MCP coating with deposition of thin layers of high secondary emission materials, such as MgO, is being pursued as well. Test beam studies performed both at CERN SPS North Area and LNF BTF have showed that an i-MCP could reach a detection efficiency greater than 70% for a single charged particle with a time resolution better than 40 ps [1]. In Fig. 1 the precision on the time measurement to detect single charged particles is shown as a function of the bias voltage between MCP layers: different i-MCP geometries are compared to a PMT-MCP. It was also demonstrated that i-MCPs could also be exploited for the detection of electromagnetic showers after few radiation lengths with efficiency close to 100% and a resolution better than 30 ps.

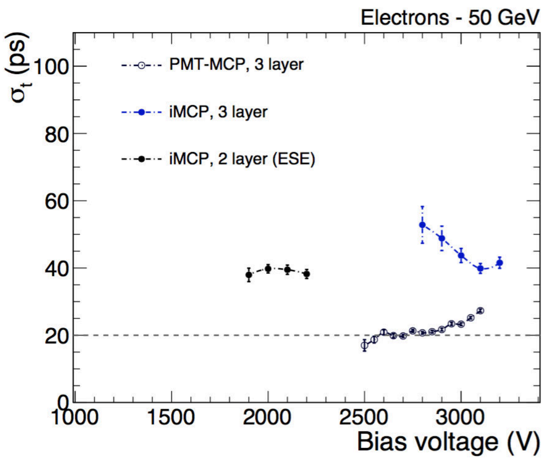

Figure 1: Time resolution as a function of the bias voltage for different i-MCP geometries compared to a 3-layer PMT-MCP

Such devices are being considered within the Phase-II upgrade program of the CMS experiment in view of the HL-LHC conditions. CMS is considering the insertion of a dedicated single layer detector in front of the electromagnetic calorimeter, dedicated to the measurement of the time-of-flight of charged particles produced in the collision. This information will allow to effectively reduce pile-up contamination in the HL-LHC collisions at a level comparable to what is currently observed at the LHC.

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P8. The ATLAS Experiment at the Large Hadron Collider

ATLAS 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 the dimensions of a cylinder, 46m long, 25m in diameter, and sits in a cavern 100m below ground. The four major components of the ATLAS detector[1] are the Inner Detector, the Calorimeter, the Muon Spectrometer and the Magnet System. The Trigger and Data Acquisition System, a specialized multi-level computing system, selects in real time physics events with distinguishing characteristics; the Computing System, specially designed for the experiment, is used to store, process and analyse vast amounts of collision data at 130 computing centres worldwide. ATLAS' scientific exploration uses precision measurement 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. ATLAS physicists test the predictions of the Standard Model, which encapsulates our current understanding of what the building blocks of matter are and how they interact. These studies led to groundbreaking discoveries, such as the Higgs boson [1]. In the future, the experiment will look for physics beyond the Standard Model, to allow for the development of new theories to better describe our universe.

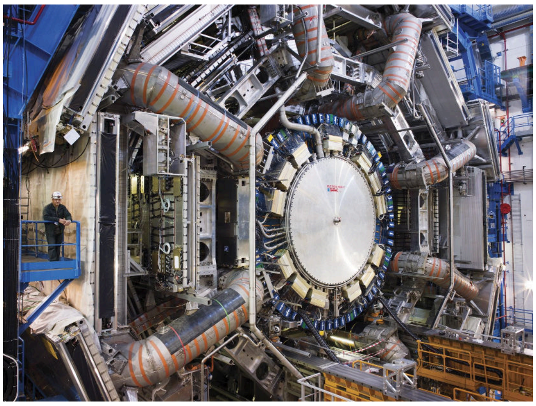

Figure 1: A view of the ATLAS Experiment.

In 2014 the ATLAS experiment underwent a phase of upgrades in order to be prepared for the increase in total energy of the Run-II of the LHC. With the improved detector ATLAS has collected in years 2015 and 2016, at an energy in the center of mass of the proton-proton system of 13 TeV, an integrated luminosity exceeding 40 fb^{-1}. This corresponds to about a factor two the total luminosity accumulated in the whole Run-I of LHC, as shown in Figure 2.

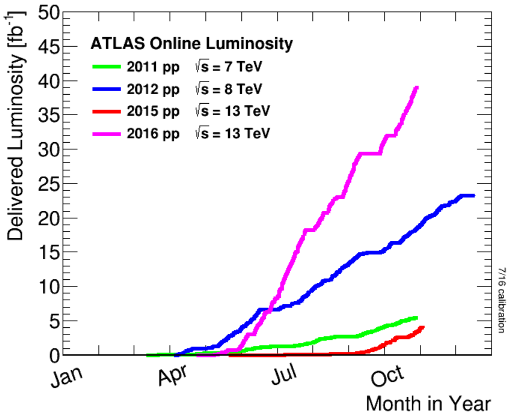

Figure 2: Cumulative luminosity versus day delivered to ATLAS during stable beams and for high energy proton-proton collisions.

The ATLAS group at the Sapienza Università di Roma and at INFN Sezione di Roma (*the ATLAS Rome Group*) has been deeply involved in the design and construction of the precision detectors of the muon spectrometer, the muon trigger, the high level triggers and the data acquisition system, and in the development of the computing system. The group also engaged in a large number of data analyses. These include detector performances assessment, the strong contributions to the searches that led to the discovery and measurement of properties of the Higgs boson [1], precision measurements of Standard Model physics, and searches for exotic processes predicted by theories beyond the Standard Model [2,3]. Currently the group is also captivated by 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.

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`http://www.roma1.infn.it/exp/atlas/`

P9. Precision Standard Model Measurements with ATLAS

Any search for new physics is based on our understanding of the background processes from the Standard Model (SM). A variety of SM processes can be studied at the LHC and some can be calculated with small theoretical uncertainties thanks to the recent developments of perturbative QCD. A precise measurement of these processes gives the opportunity of testing the SM and to search for deviations originating from new phenomena.

A prominent case is the production of lepton pairs, which, at the leading order of perturbative QCD, occurs through the Drell-Yan process $q\bar{q} \rightarrow l^+l^-$. 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. These measurements, to reach small systematical uncertainties, rely on the precise determination of the performance of ATLAS muon spectrometer. Rome group has a leading role in the calibration of the muon reconstruction [1] and trigger [2] and in the determination of the systematic uncertainties associated to the muon measurements.

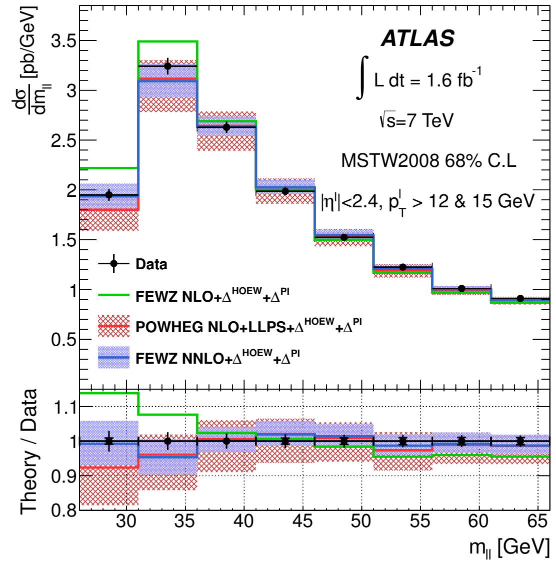

Figure 1: Cross section for lepton pair production in pp collisions at a center-of-mass energy of 7 TeV as a function of the di-lepton invariant mass. Data are compared to QCD calculations at the next-to-leading order (NLO), at the next-to-next-to-leading order (NNLO) and to a calculation at NLO with resummation of leading logarithms through parton showers (NLO+LLPS) [3].

As an example, in Fig. 1, the lepton-pair cross section, measured in the mass region $25 < m < 66$ GeV, is compared to up-to-date QCD calculations. Rome group had an important role in this analysis [3] and is currently working on a new measurement on Run-2 data, extended to lower invariant mass and with improved precision. Such a measurement will provide a unique test of the density of partons carrying a very small fraction of the proton momentum ($x \simeq 10^{-4}$), a regime where new effects beyond the standard Altarelli-Parisi evolution of the parton densities are expected.

The least known parton density in the proton is that of the strange quark. A direct measurement can be obtained from the process $s+g \rightarrow W^-+c$. This process has been measured by ATLAS Rome group [4], producing one of the most stringent constraints to the strange density. This confirmed the previous ATLAS finding that the strange density is closer to that of the light quarks than expected, as shown in Fig. 2.

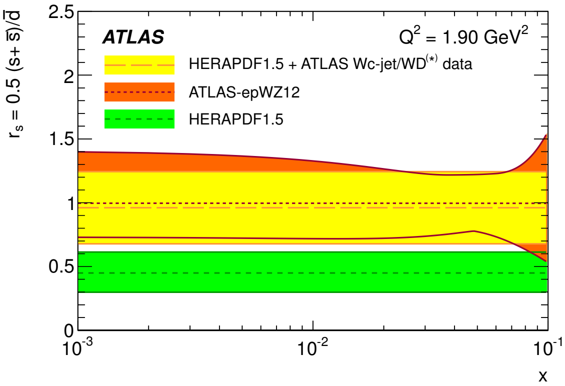

Figure 2: Ratio between strange and d quark densities in the proton extracted from deep-inelastic-scattering data plus the ATLAS Wc production measurement (HERAPDF1.5 + ATLAS $Wc{-}jet/WD^{(*)}$) compared to previous results from ATLAS (ATLAS-epWZ12) and from deep-inelastic-scattering (HERAPDF1.5) [4].

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P10. Standard Model Higgs measurements in ATLAS

The discovery of a new particle in the search for the Standard Model (SM) Higgs boson [1] has been an important step in the understanding of the electroweak symmetry breaking mechanism. The measurements of several properties of the newly observed particle (mass, production strenghts, couplings to fermions and bosons, spin and parity quantum numbers), have until now been consistent with the expectations for the SM Higgs boson.

The ATLAS Rome group has played a central role in all these measurements, both in the analysis of the $H \to ZZ^* \to 4\ell$ channel, and in the combination with the other decay channels of the new resonance. Fig. 1 shows the results for one of the couplings benchmark models, where two coupling scale factors with respect to the SM expectations, κ_F and κ_V, are introduced [2]. The results of the fit to the data are shown for the individual di-boson channels, and for their combination.

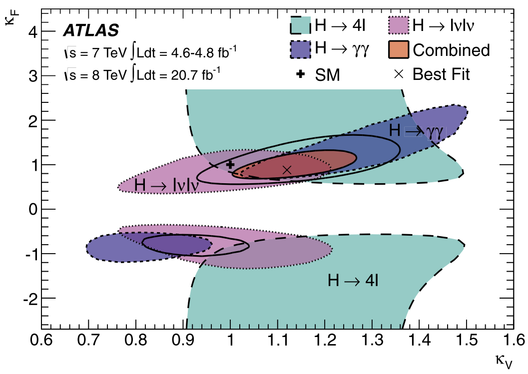

Figure 1: Likelihood contours of the couplings scale factors κ_F and κ_V for fermions and bosons. The best fit result (x) and the SM expectation(+) are also indicated [2].

The measurement of the total and differential cross sections of the Higgs boson production represent another probe of its properties. The measured cross sections can be directly compared to the theoretical modeling of different Higgs boson production mechanisms and can be used to constrain new Physics scenarios. The Rome ATLAS group has taken care of the cross sections measurement in the $H \to ZZ^* \to 4\ell$ channel, and of the combination with the other precision channel $H \to \gamma\gamma$ [3].

The group is also carrying on the study of the Higgs-top Yukawa coupling, studying the associated production of the Higgs boson with a $t\bar{t}$ pair. The final state considered is the multi-lepton one, with two to four light leptons (electrons or muons) and hadronic taus in the final state. This channel includes contributions from the $H \to WW$, $H \to \tau\tau$ and $H \to ZZ$ decays. The results in terms of the fitted signal strength for the channels considered in the analysis are shown in Fig. 2.

In the year 2015 the Run-2 of LHC has started. The center of mass energy of the proton-proton collisions has been brought to $\sqrt{s}$=13 TeV. As an example of the most

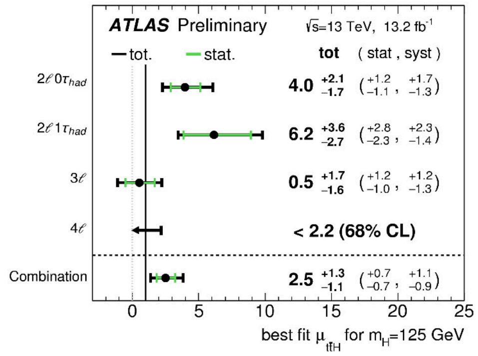

Figure 2: Best fit value of the signal strength parameter $\mu = \sigma_{t\bar{t}H,\mathrm{obs}}/\sigma_{t\bar{t}H,\mathrm{SM}}$, from reference [4].

recent results, the four lepton invariant mass distribution of the candidates selected with the ATLAS experiment in collisions at a center of mass energy $\sqrt{s}$ =13 TeV, in data collected in the years 2015 and 2016, is shown in Fig. 3. A wide range of precision measurements with the Run-2 data of LHC is currently ongoing.

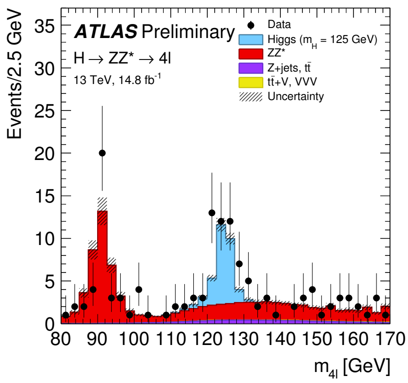

Figure 3: The $m_{4\ell}$ distribution, compared to the expected distributions for a Higgs signal and the backgrounds.

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P11. Beyond the Standard Model Higgs with the ATLAS Experiment

The discovery of a Higgs boson at the LHC marked the beginning of a new era of experimental studies of the properties of this new particle. In the Standard Model (SM), the Higgs boson is a CP-even scalar particle, $J^{CP} = 0^{++}$, theories of physics beyond the SM (BSM) often require an extended Higgs sector featuring several neutral Higgs bosons. Such cases may include the case where the Higgs particle is a mixed-CP state, which would result in observable differences in the kinematics of final-state particles produced in its decays.

The study of the spin and parity properties of the ∼125 GeV Higgs boson has been performed in detail by the Rome ATLAS group using the $H \to ZZ^* \to 4\ell$ decay channel, which is dominating the sensitivity given the possibility to fully reconstruct the decay kinematics. Combined results with other decay channels are published in [1]. Alternative spin and parity assignment for the Higgs boson have been excluded at a more than 99.9% CL in favour of the SM spin-0 hypothesis. In addition, the possible presence of BSM terms in the Lagrangian describing the interaction of the Higgs with W or Z bosons was also investigated, including both BSM CP-even and CP-odd terms. The couplings of the CP-odd and CP-even BSM contributions in an effective field theory approach have been constrained. In particular, constraints on the CP-odd to SM ratio are shown in Fig. 1. These can be expressed as constraints on the relative fractions of the CP-odd contributions, $f_{odd} < 9\%$ or $f_{odd} < 41\%$, for positive or negative coupling constant, respectively.

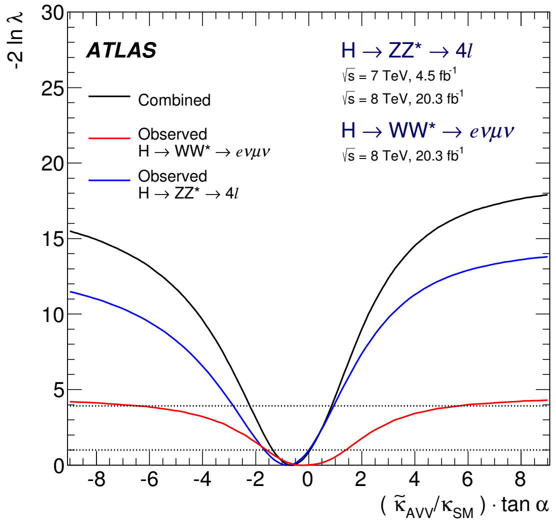

Figure 1: Observed negative log-likelihood from a fit to ATLAS data for $H \to WW \to e\nu\mu\nu$ and $H \to ZZ^* \to 4\ell$ analyses and their combinations for the BSM coupling ratios $\tilde{k}_{AVV}/k_{SM} \cdot \tan\alpha$ [1].

In the simplest extended Higgs sector model a second Higgs doublet leads to five physical Higgs bosons after the electroweak symmetry breaking. The phenomenology of such a model is very rich and depends, in particular, on the ratio of vacuum expectation values of the Higgs doublets ($\tan\beta$). In general, it is possible to accommodate in the model a Higgs boson compatible to the one discovered at the LHC. In the case where the Higgs potential is CP-conserving, the Higgs bosons after electroweak symmetry breaking are two CP-even (h and H), one CP-odd (A) and two charged ($H^{\pm}$) Higgs bosons. The most stringent limits for the low $\tan\beta$ scenario for both the CP-odd and CP-even neutral heavy scalar have been established using, respectively, the decays into a Z boson and the ∼125 GeV Higgs boson [2] and in Z boson pairs [3], both investigated by the Rome ATLAS group. A summary of these results compared to other searches and to indirect constraints from the ∼125 GeV Higgs boson couplings is shown in Fig. 2, from [4].

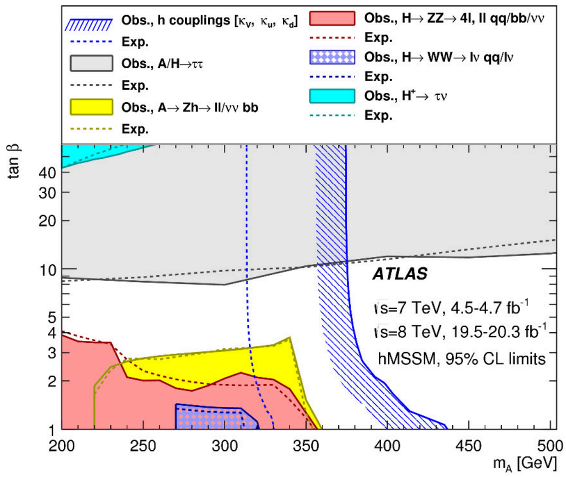

Figure 2: Regions of the $[m_A, \tan\beta]$ plane excluded in the hMSSM model via direct searches for heavy Higgs bosons and fits to the rates of Higgs boson production and decays [4].

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P12. 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, and such states can decay back to Standard Model particles with long lifetimes and sizeable branching fractions. Due to the 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".

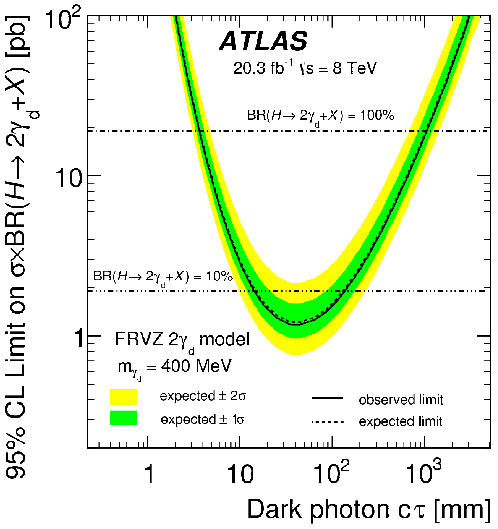

Figure 1: Upper limits on the $\sigma(H \to 2\gamma_\mathrm{d} + X)\times$BR as a function of the dark photon lifetime ($c\tau$) [1].

Neutral particles which decay far from the interaction point into collimated final states 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 "air-core" muon spectrometer. In this context the ATLAS collaboration searched for lepton jets signatures using data collected from proton-proton collisions at LHC at energies between 7 and 13 TeV [1], in a region never explored before, without finding so far any excess over the expected background. Figure 1 shows the results of the ATLAS search in the dataset collected at 8 TeV [1], expressed as upper limit on the Higgs boson decay branching fraction to lepton jets as a function of the dark photon lifetime.

The result is interpreted in the context of the Vector portal model as exclusion contours in the kinetic mixing parameter ϵ vs γ_d mass plane in Figure 2, where it is possibile to appreciate the complementarity between the constraints from the ATLAS searches and those from other experiments.

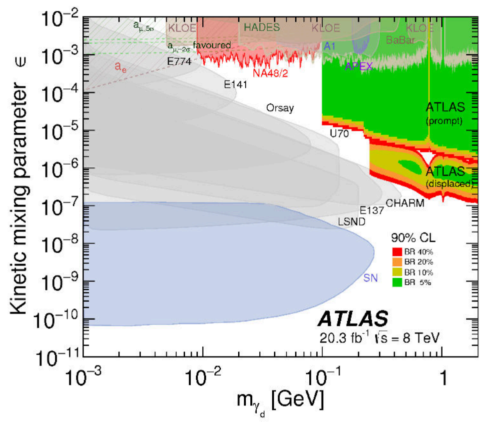

Figure 2: A two-dimensional exclusion plot in the dark-photon mass m_{γ_d} and the kinetic mixing ϵ parameter space, showing the regions excluded by ATLAS [1].

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P13. Search for dark matter and phenomena beyond the Standard Model in jet final states with the ATLAS detector at LHC

One of the primary goals of the LHC physics programme is the search for phenomena beyond the Standard Model. The presence of *Dark Matter* (DM) in the universe, and the apparent unjustified smallness of the Higgs boson mass with respect to the Planck scale (hierarchy problem), provide strong hints that BSM should manifest at the TeV scale. The increase of the LHC centre-of-mass energy from 8 to 13 TeV for the Run 2 in 2015 greatly extended the ATLAS experimental sensitivity to new particles. When a new energy regime opens, final states with jets represent a gold channel to search for new particles. Any particle produced at the LHC must interact with the constituent partons of the proton, and thus it can produce partons, which, after showering and hadronization, manifest as collimated jet of particles in the final state. The total production rates for BSM signals in jet final states can be large, allowing searches for anomalous jet production with a relatively small data sample, even at masses that are a significant fraction of the collision energy. Among the comprehensive BSM search programme carried out by the ATLAS experiment, the Rome group focused on BSM searches in mono-, di-, and multi-jet final states.

In some models of strong gravity, exotic objects such as quantum black holes or string balls can be produced at the LHC. These decay by radiating a number of quarks or gluons, resulting in a final state with many jets with large H_T (defined as the scalar sum of the jet transverse momenta in the event). Such a spectacular final state has been one of the very first signature we searched for with 3 fb^{-1} of integrated luminosity, selecting events with at least 3 jets and $H_T > 1$ TeV. The observed H_T distribution agrees well with SM expectations, and thus the production of black hole is excluded for M_{th} up to 9.0-9.7 TeV depending on the model [1].

Excited quarks, as well as W' and Z' bosons exchanged in the s-channel would produce peaks in the di-jet invariant mass (m_{jj}) distribution. Using data corresponding to an integrated luminosity of 15 fb^{-1}, events with at least 2 central jets, one of which with $p_T > 440$ GeV, are selected. The m_{jj} distribution is then used to search for localized excesses. No deviation from the smooth background parameterization is observed and thus BSM phenomena are excluded between 3.3 TeV and 8.7 TeV depending on the model [2]. These results have been extended also for sub-TeV masses where we are statistically limited by the bandwidth available to inclusive single-jet triggers. To overcome this limitation we carried out a dedicated analysis using the reduced information available from the low-threshold selection that allowed to exclude BSM resonances with a mass as low as 450 TeV. In addition, to be sensitive to possible exchanges of BSM particles in the t-channel as well as to new contact interactions, the distribution of the angular variable $\chi = e^{|y^*|}$ (where y^* is the rapidity difference of the 2 jets) is used. For SM background processes this distribution is approximately flat and independent of m_{jj}, while BSM processes would enhance the low-χ tail. The χ distribution agrees with the SM prediction and contact interactions are excluded for scales Λ below 19.9 TeV and 12.6 TeV for constructive and destructive interference with QCD respectively.

In addition to final states with jets, events with an energetic jet and large missing transverse energy (E_T^{miss}) constitute a distinctive signature of BSM physics. Such a finale state, called mono-jet, is sensitive to large extra dimensions, supersymmetry, and weakly interacting massive particles as candidates for DM [3]. Events are required to have at least one energetic jet and classified according to their E_T^{miss}. Good agreement is observed between events in data and SM predictions, and thus exclusion limits are placed for DM candidates (Fig.1).

No excess over the SM expectations has been observed in any of the jet final states explored so far, thus the most stringent limits to date on several exotics phenomena have been placed.

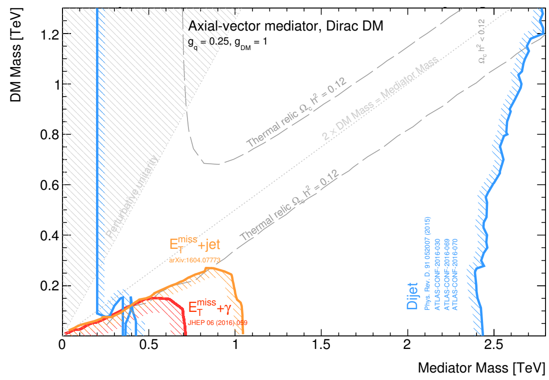

Figure 1: Regions in a DM candidate mass-mediator mass plane excluded at 95% confidence level by a selection of ATLAS dark matter searches, for the lepto-phobic axial-vector mediator DM model described in `[arXiv:1507.00966]`.

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P14. The Level-1 Barrel Muon Trigger of the ATLAS experiment at LHC

The trigger system is an essential component of any collider experiment as it is responsible for deciding whether or not to keep a given bunchcrossing interaction data for later study. The presence of prompt muons in the final state is a distinctive signature for many physics processes in collisions of high energy protons at the LHC, therefore a high-performance muon trigger is essential. The ATLAS system deploys in Run-2 (2015-2018) a two-level trigger strategy: 1) a hardware based trigger at Level-1 using a custom electronics, with a maximum output rate of 100 kHz, of which about 20 kHz are allocated for muon triggers; 2) a software based High Level Trigger (HLT) running on a dedicated computer farm with a final physics rate of about 1.5 kHz of events recorded for offline analysis. About 10% contains Level-1 muon triggers. Muons are identified at Level-1 in the barrel region ($|\eta| < 1$) by the spatial and temporal coincidence of hits in the RPC chambers pointing to the beam interaction region as shown in Figure 1. The low-p_T trigger requires

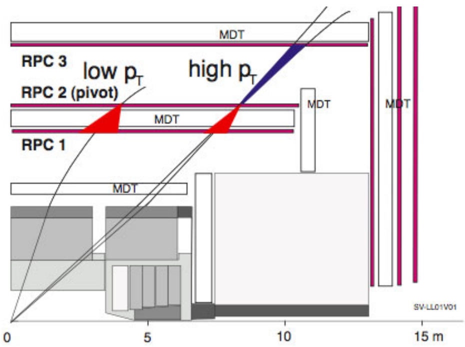

Figure 1: The Level-1 muon trigger in ATLAS in the barrel region ($|\eta| < 1$) makes use of the RPC signals.

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 degree of deviation from the hit pattern expected for a muon with infinite momentum is used to estimate the p_T of the muon. The geometric coverage of the muon trigger in the barrel region is about 80%, due to gaps at around $\eta = 0$ (to provide space for services to the inner detector and calorimeters), the feet and support structures of the ATLAS detector, including two small elevator shafts in the bottom part of the spectrometer. To increase the trigger acceptance in the feet region, a fourth external layer of RPC trigger chambers was installed in 2006 before Run-1 (2010-2012). During the Long Shutdown LS1 (2013-2014), these RPC layers were equipped with trigger electronics. The new feet trigger was commissioned in 2015 and it was fully operational in 2016; Figure 2 shows the trigger efficiency in one of the feet sector with and without the new feet trigger. The total trigger efficiency increased by about 3%.

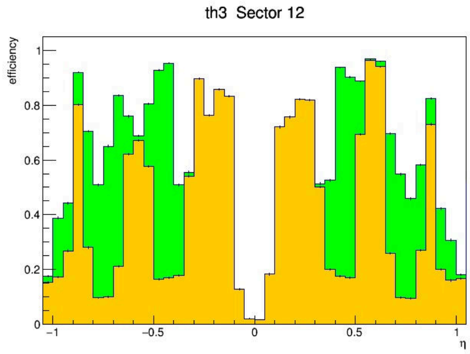

Figure 2: Low-pt trigger efficiency in the feet region as a function of η. In orange is the efficiency of the "old" feet trigger and in green is shown the effect of the new trigger.

Additional RPC chambers were installed during LS1 to cover the acceptance holes corresponding to the two elevator shafts at the bottom of the muon spectrometer. They were partially working in 2016 and we expect to be fully operational in 2017 bringing an increase of trigger efficiency of about 0.8%.

The ATLAS Rome1 group was responsible to build the electronics and the trigger logic of the whole level-1 muon barrel trigger and was in charge of its commissioning in the early years of LHC functioning. During the LS1 shutdown the group successfully installed the completion of the trigger in the lower part of the spectrometer as described above. In the current run, the group is in charge of the maintenance and operation of the full system, including RPC timing calibrations and efficiency measurements.

The current trigger electronics will be used also in Run-3 (2021-2024) where the LHC luminosity will be twice as much the nominal luminosity of $10^{34}\ cm^{-2} \cdot s^{-1}$, but it can not operate for the next LHC upgrade since 2026 onwards, the so-called High Luminosity LHC, with a luminosity increase of about a factor of 5. Therefore the present electronics is going to be completely replaced, leaving the only front-end RPC electronics unchanged. The Rome group is responsible for the design and develop of the new trigger system and it is supposed to play a leading role in the whole trigger system as it did in the past.

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P15. The New Small Wheel and the micromegas chambers for ATLAS

The LHC will start the RUN III in 2020 at 14 TeV energy with a luminosity $3 \div 5 \times 10^{34}\ cm^{-2}s^{-1}$ that exceeds by about a factor 5 the project luminosity. 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 $\pm$ 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

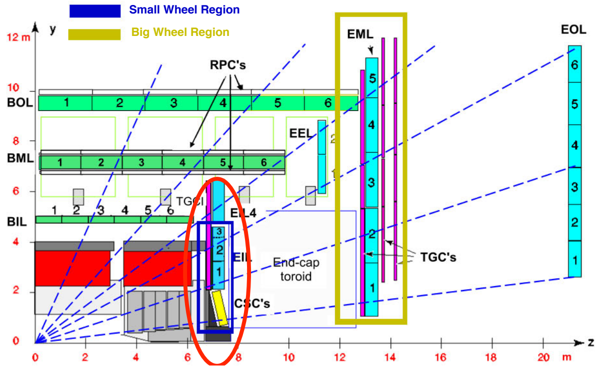

Figure 1: The location of the Small Wheel detectors in the ATLAS Experiment (x-y view of one quarter of the detector).

high rates of particles expected after 2020. 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.

The ATLAS experiment has decided to prepare a new detector, called New Small Wheel (NSW) [1], with 'small-strip Thin Gap Chambers' for the trigger 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 < 100 μm and a similar accuracy is demanded in the assembly of the components of the chamber. Furthermore efficiency and resolution should not degrade because of delta rays, showers and background from neutrons and other particles.

A micromegas chamber is a Micro Pattern Gas Detector built with the modern photolithographic technology. In this detector (Fig. 2) 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 from ionization drift in a 700 V/cm electric field to the mesh and enter in the multiplication gap where in a strong 40 kV/cm field they produce avalanche collected on resistive microstrips. The signals are readout by capacitively coupled metallic microstrips below an insulating layer underlying the resistive microstrips. The resistive strips have been introduced to prevent any damage to the detector in case of discharges due to huge ionization by low-energy alpha particles or slowly moving debris from neutrons interacting in the detector gas or in the detector materials. The resolution in position depends on the microstrip pitch.

MM detectors will have dimensions up to $2\ m \times 2\ m$.

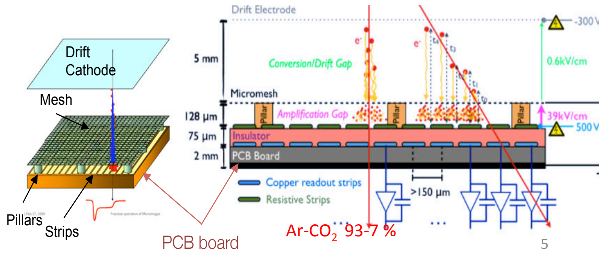

Figure 2: The micromegas detector.

This implies severe mechanical accuracy in the construction to guarantee the thicknesses of the multiplication gap and of the drift gap over such large dimensions and to ensure the positioning of readout microstrips in the chambers as required by the momentum reconstruction. Four micromegas detectors with microstrips of 425 μm pitch are assembled in a MM chamber.

Italian groups from the universities and Sezioni INFN of Cosenza, Lecce, Napoli, Pavia, Roma Sapienza, RomaTRE and Laboratori Nazionali di Frascati dell'INFN will prepare 32 large trapezoidal chambers about $2.2\ m \times 1.3\ m$, that is one quarter of the MM NSW chambers.

In the summer 2016 the first full scale chamber prototype has been assembled and tested on a beam at CERN. The measured resolution in position ($\simeq 80\ \mu m$) and the efficiency ($\simeq$ 98%) are in agreement with expectations from the studies performed on previous small dimension prototypes.

The physicists from Roma will also prepare 32 Trigger Pad Logic Board used to find the tracks for the trigger in the New Small Wheel by the signals readout in the pads of the sTGC chambers.

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P16. 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 2014 and later, in order to finalize the analysis of the data of the Run-1, produce the Monte Carlo data needed for the 2015 run and analyse the data of the Run-2. 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 2014 and the first part of 2015, more precisely in the software domain and the infrastructure. The use of the grid in 2016 has been stable on ∼200k simultaneous jobs, with peaks around the conferences periods above ∼400k, 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 2014 to 2016.

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

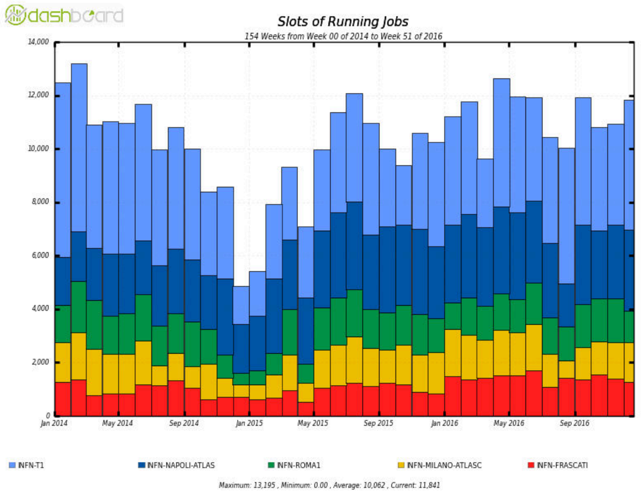

Figure 1: Number of parallel jobs running in the ATLAS Italian Tier1 and Tier2's.

of the ATLAS Virtual Organisation [2], the distribution of the software and its evolutions to CVMFS [3], the access to the condition database via the Frontier System and the remote calibration of the Muon Detectors (Remote Calibration Centers). 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 [4].

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P17. 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 $29 \times 27\,\mu m^2$. 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 whole new ITS will be ready for the installation in ALICE by the end of LHC Long Shutdown 2 (2021).

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S. Di Liberto[1], M. A. Mazzoni[1], F. Meddi, G. M. Urciuoli[1].

`https://www.roma1.infn.it/exp/alice/group.html`

P18. Kaon Physics at KLOE-2

The KLOE-2 experiment is currently taking data at the DAΦNE collider, the Frascati ϕ-factory, and already collected about 3 fb^{-1} of data with the plan to reach at least a total of 5 fb^{-1} in the next ~ 1.5 years. KLOE-2 aims to continue and extend the physics program of its predecessor KLOE, and neutral kaon interferometry and tests of discrete symmetries and quantum mechanics are among the main topics. Improvements with respect to KLOE results will be possible thanks to the increased luminosity and the better quality of reconstructed data, due to the upgrade of the detector with an inner tracker based on cylindrical GEM technology, and small angle calorimeters. In the meanwhile the analysis of the old KLOE data is still going on, and the most recent results about kaon physics are reported in the following, together with new ideas on a novel CPT test.

A violation of CPT symmetry would have a dramatic impact on our present theoretical picture and would definitely constitute an unambiguous signal of a new physics framework, thus strongly motivating both experimental searches and theoretical studies on this subject. In attempts to discuss quantum-gravity scenarios, speculative theoretical models have been considered which may exhibit a CPT-symmetry breakdown. Among them a general theoretical possibility for CPT violation is provided by the Standard-Model Extension (SME), based on spontaneous breaking of Lorentz symmetry, which appears to be compatible with the basic tenets of quantum field theory and retains gauge invariance and renormalizability.

At a ϕ-factory neutral kaon pairs are produced in a pure antisymmetric entangled state, offering new and unique possibilities to study the discrete symmetries and the basic principles of quantum mechanics. What makes the entangled $K^0\bar{K}^0$ pair a really unique system, even with respect to other similar neutral-meson systems (B_d^0, B_s^0, and D^0), is the presence of peculiar mechanisms in the CPT-violation observables, which strongly enhance the sensitivity to CPT-violation effects.

By studying the interference pattern of the entangled neutral kaon pairs in the $\phi \to K^0\bar{K}^0 \to \pi^+\pi^-\pi^+\pi^-$ final state, as a function of sidereal time and particle direction in celestial coordinates, the KLOE-2 collaboration measured the CPT-violation parameters of the SME in the kaon sector by analysing ~ 1.7 fb^{-1} of collected data [1]:

$$\begin{aligned}
\Delta a_0 &= (-6.0 \pm 7.7_{\rm stat} \pm 3.1_{\rm syst}) \times 10^{-18}\ \text{GeV},\\
\Delta a_X &= (\ 0.9 \pm 1.5_{\rm stat} \pm 0.6_{\rm syst}) \times 10^{-18}\ \text{GeV},\\
\Delta a_Y &= (-2.0 \pm 1.5_{\rm stat} \pm 0.5_{\rm syst}) \times 10^{-18}\ \text{GeV},\\
\Delta a_Z &= (\ 3.1 \pm 1.7_{\rm stat} \pm 0.5_{\rm syst}) \times 10^{-18}\ \text{GeV}.
\end{aligned}$$

These results constitute the most sensitive measurements in the quark sector of the SME.

A novel CPT test has been recently studied in the neutral-kaon system based on the direct comparison of a transition probability with its CPT reverse transition [2], rather than comparing masses, lifetimes, or other intrinsic properties of particle anti-particle states; for instance the transition $K^0 \to K_-$ and its CPT conjugated process $K_- \to \bar{K}^0$, with K_- the $CP = -1$ eigenstate. The appropriate preparation and detection of *in* and *out* states in both the reference and the reverse processes is made by exploiting the entanglement of neutral kaons produced in a ϕ-factory and using their decays as filtering measurements of the kaon states, with a careful definition of the involved states. The test is theoretically very clean and model independent, with possible spurious effects induced by direct CP violation in the decay amplitudes and/or violation of the $\Delta S = \Delta Q$ rule well under control. The test is being implemented at KLOE-2.

The absolute branching ratio of the $K^+ \to \pi^+\pi^-\pi^+(\gamma)$ decay, inclusive of final-state radiation, has been measured using ~ 17 million tagged K^+ mesons collected with the KLOE detector. Tagging is performed with $K^- \to \mu^-\nu$ and $K^- \to \pi^-\pi^0$ decays, providing two independent samples of pure kaons for the signal selection and useful for systematic uncertainties evaluation and cross-checks. The result is [3]:

$$BR(K^+ \to \pi^+\pi^-\pi^+(\gamma)) = \\ 0.05565 \pm 0.00031_{stat} \pm 0.00025_{syst}$$

a factor $\simeq 5$ more precise with respect to the previous result. This work completes the program of precision measurements of the dominant kaon branching ratios at KLOE, and is useful in the study of the cusp-like anomaly in $K^+ \to \pi^+\pi^0\pi^0$ decays.

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P19. Light hadron physics at KLOE-2

The KLOE-2 Collaboration is taking data at the Frascati ϕ-factory DAΦNE, with the aim to collect at least 5 fb^{-1} at the peak of the $\phi(1020)$ by March 2018. This luminosity, together with the 2.5 fb^{-1} collected during the first period of data-taking (2001 - 2006) will allow to perform precision studies of the decays of η and π^0 mesons. While collecting the new data, the analysis of the old data is still in progress. In particular the conversion decays of vector mesons into a pseudoscalar and a lepton pair $V \to P\gamma^\star \to P\ell^+\ell^-$ which provide information on the nature of the mesons, are investigated. The coupling of the mesons to the virtual photon is parametrized in terms of a Transition Form Factor (TFF), $F_{VP}(q^2)$, function of the virtual photon 4-momentum corresponding to the dilepton invariant mass ($q^2 = m^2_{\ell^+\ell^-}$). The TFFs are fundamental quantities which play an important role in many fields of particle physics, and in particular in the calculation of the hadronic Light-by-Light scattering contribution to the Standard Model calculation of the muon anomalous magnetic moment. Moreover, recently a discrepancy between the experimental data and the Vector Meson Dominance predictions for the $\omega\pi^0$ TFF has been pointed out.

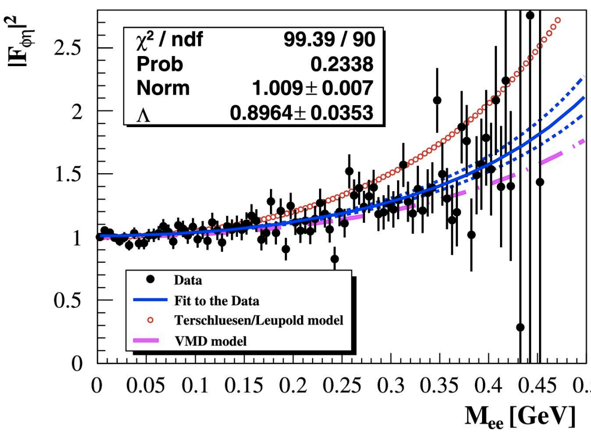

Figure 1: TFF for $\phi \to \eta e^+e^-$, the blue line is the fit, compared with VMD prediction and with other models [1].

From the e^+e^- invariant mass distributions, the branching fractions and the TFF of $\phi \to \eta e^+e^-$(Figure 1) [1] and of $\phi \to \pi^0 e^+e^-$(Figure 2) [2] have been obtained. For the η case, $Br(\phi \to \eta e^+e^-) = (1.075 \pm 0.007 \pm 0.038) \times 10^{-4}$, and the TFF slope is $b_{\phi\eta} = (1.28 \pm 0.10 \pm 0.09)$ GeV^{-2} [1] consistent with VMD. In the π^0 case, $Br(\phi \to \pi^0 e^+e^-) = (1.35 \pm 0.05^{+0.05}_{-0.10}) \times 10^{-5}$, while the TFF slope, $b_{\phi\eta} = (2.02 \pm 0.11)$ GeV^{-2} [2], disagrees with VMD and is better described by other models.

The $\eta \to 3\pi$ decay offers the possibility to constrain the light quark masses. The width is $\Gamma(\eta \to 3\pi) \propto Q^{-4}$, where $Q^2 = \frac{m_S^2 - \hat{m}^2}{m_d^2 - m_u^2}$ ($\hat{m} = \frac{1}{2}(m_u + m_d)$). The Dalitz plot of $\eta \to \pi^+\pi^-\pi^0$ has been measured with a sample of 1.6 pb^{-1}, and is shown in Figure 3 in terms of the

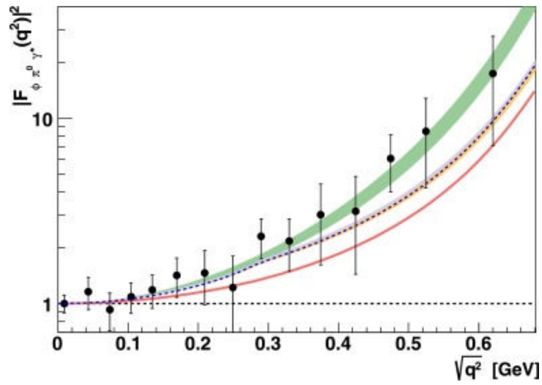

Figure 2: TFF for $\phi \to \pi^0 e^+e^-$, compared with the VMD prediction (red line) and with other theoretical models [2].

variables $X = \sqrt{3}\frac{T_+ - T_-}{Q_\eta}$ and $Y = 3\frac{T_0}{Q_\eta} - 1$, where T_i are the pion kinetic energies of and $Q_\eta = M_\eta - 2M_{\pi^\pm} - M_{\pi_0}$. From a fit the parameters of the Taylor expansion ($|A(X,Y)|^2 = N(1+aY+bY^2+cX+dX^2+eXY+fY^3+gX^2Y+...)$ have been obtained: $a = -1.095 \pm 0.004$, $b = 0.145 \pm 0.006$, $d = 0.081 \pm 0.007$, $f = 0.141 \pm 0.011$, and for the first time also $g = -0.044 \pm 0.016$. The C-violating parameters c and e are compatible with zero.

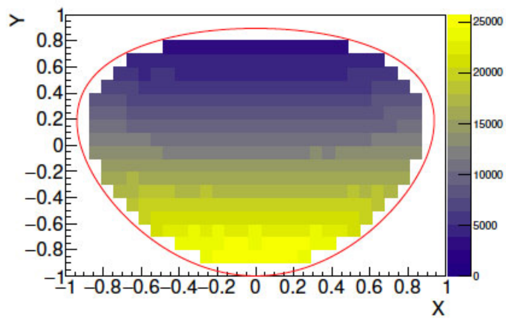

Figure 3: Dalitz plot of $\eta \to \pi^+\pi^-\pi^0$ [3].

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Authors

G. D'Agostini, A. Di Domenico, P. Gauzzi

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

P20. 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 (Figure 1). Recently 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.

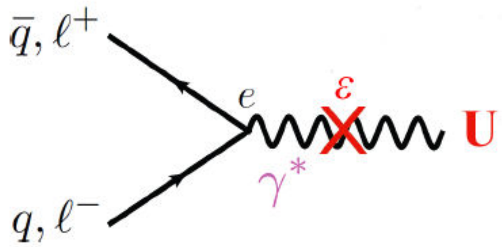

Figure 1: Mixing mechanism of the U boson with the ordinary photon.

KLOE used 240 pb^{-1} of data collected at the peak of the $\phi(1020)$ resonance to look for $e^+e^- \to \mu^+\mu^-\gamma$ events. Both Initial State Radiation (ISR) and Final State Radiation (FSR) contribute to this process, kinematical and geometrical cuts are applied to strongly reduce the FSR. The resulting exclusion region at 90% C.L. is shown by the curve labeled as KLOE$_{(2)}$ in Figure 2. The upper limit on ε^2 is between 1.5×10^{-5} and 8.6×10^{-7} in the U boson mass range $520-980$ MeV. The analysis of the whole data set of the KLOE first period of data-taking is in progress. An improvement of an order of magnitude in the ε^2 upper limit is expected.
KLOE also studied the process $e^+e^- \to e^+e^-\gamma$, by using 1.5 fb^{-1} of data. Also in this case no evidence for a signal has been found and the upper limit is shown by the area labeled as KLOE$_{(3)}$ in Figure 2. This exclusion region partially overlaps with the KLOE$_{(1)}$ one, resulting from a previous KLOE analysis searching for $\phi \to \eta U$, with $U \to e^+e^-$. The upper limit on ε^2 is in the range $10^{-6} - 10^{-4}$ for M_U between 5 and 520 MeV.
More recently KLOE analyzed 1.5 fb^{-1} of data looking for the U boson in $e^+e^- \to \pi^+\pi^-\gamma$. Also in this case a peak in the dipion invariant mass from ISR events is searched for. The resulting upper limit is the curve labeled as KLOE$_{(4)}$ in Figure 2. The $\pi^+\pi^-$ final state allows to compensate the loss of sensitivity of the $\mu^+\mu^-$ case in the region of the $\rho-\omega$ interference, due to the much higher ISR cross section. The 90% C.L. upper limit is in the range 1.8×10^{-5} and 1.9×10^{-7} for U boson masses between 530 and 985 MeV.

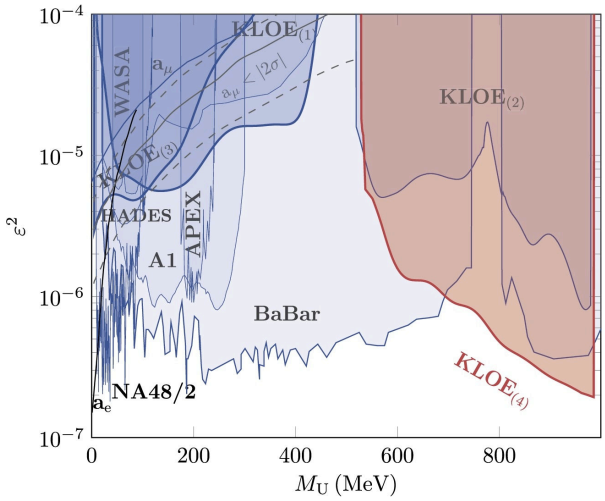

Figure 2: Exclusion plot of ε^2 as a function of the U boson mass.

From the KLOE-2 data-taking an improvement on the upper limit from these processes is expected, but also other decay channels will be exploited: a single photon trigger is under test 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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P21. 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][2]. The main goal of the PADME experiment (Positron Annihilation into Dark Matter Experiment) is to detect the non SM process $e^+e^- \to \gamma + nothing$, *nothing* being any possible exotic particle candidate (A', ALPs, etc.) coupling to electrons and decaying into dark sector particles[3].

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 (see Fig. 1). 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 has been estimated by using a full GEANT4 Monte Carlo simulation for 550 MeV e^+ on target collisions accumulated in $3.15 \cdot 10^7$ s at a rate of 50 Hz with bunches of 40 ns containing 6000 positrons. The expected total statistics depends on the beam characteristics and is $1 \cdot 10^{13}$, $4 \cdot 10^{13}$, and $12 \cdot 10^{13}$ for bunch length of 40ns, 160ns, and 480ns correspondingly. The PADME sensitivity is shown in Fig. 2, details on event selection and background studies are described in [3][4].

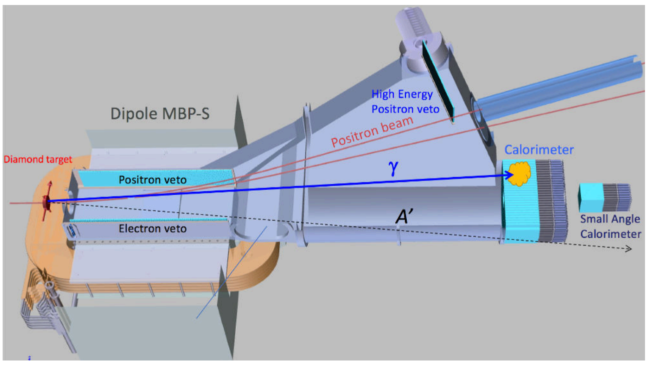

Figure 1: Preliminary layout of the PADME experiment (top view). Beam traveling from left to right.

A competitive sensitivity is also expected for the process $e^+e^- \to \gamma A'$, $A' \to e^+e^-$ by adding the request of two opposite sign in time tracks in the charged particles veto [1]. The possibility of searching for ALPs produced in ALP-strahlung processes and decaying into $\gamma\gamma$ pairs has been recently pointed out and dedicated sensitivity studies are planned.

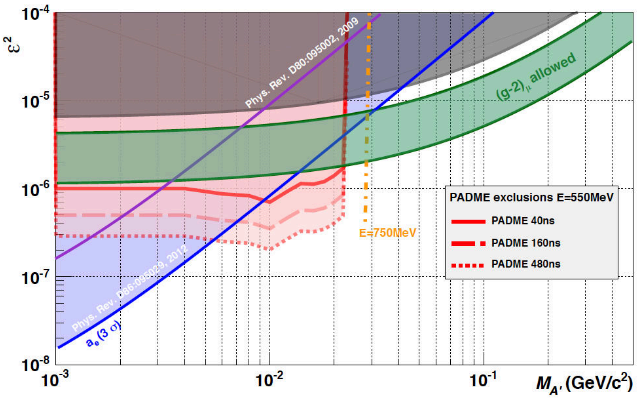

Figure 2: Expected PADME exclusion plot in the invisible channel with a 550 MeV positron beam.

The PADME experiment was approved and financed by INFN CSN1 in late 2015 for a construction program lasting 2 years. The collaboration aims at assembling the detector by the end of 2017 and at starting the engineering run in early 2018. The first beam for physics at PADME is expected for April 2018 lasting 6 month. The Roma group is mainly contributing to the design and construction of the electromagnetic calorimeter. Beside the construction the group is also leading the development of the Monte Carlo simulation, the experiment sensitivity studies, and is coordinating all computing-related activities.

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F. Ferratotto[1], E. Leonardi[1], G. Organtini, M. Raggi, P. Valente[1].

P22. Experimental Gravitation: the search of Gravitational Waves

The Virgo group of the "La Sapienza" Rome University is part of a worldwide collaboration for the direct detection of Gravitational Waves (GWs) using laser interferometer of kilometric baseline. The detector network consists of two LIGO detectors in USA and the Virgo detector in Italy. Since several years, both the Virgo and LIGO collaborations are jointly analysing the data collected by the GW network.

In 2009 LIGO started to upgrade the two interferometers followed by Virgo two years later. The upgrade of LIGO, i.e. Advanced LIGO, was concluded in the spring of 2015, and in September two advanced detectors of the network started the data taking. On 11 February 2016 at Washington D.C. (USA), and at the same time at Cascina (Italy), both the LIGO director and the Virgo spokesperson announced the first direct detection of a GW signal made at 09:50:45 UTC on 14 September 2015. The experimental result was published as an article on Physical Review Letters [1]. The shows also the existence of binary stellar-masse black-hole systems. The two black holes lose energy, largely through GWs and they spiral in towards each other. At the very end of the process, the two objects will reach extreme velocities, and in the final fraction of a second of their merger a substantial amount of their mass has been converted into gravitational energy and travel outward as GWs.

The second GW observation, happened on 26 December 2015, was announced on 15 June 2016 [2].

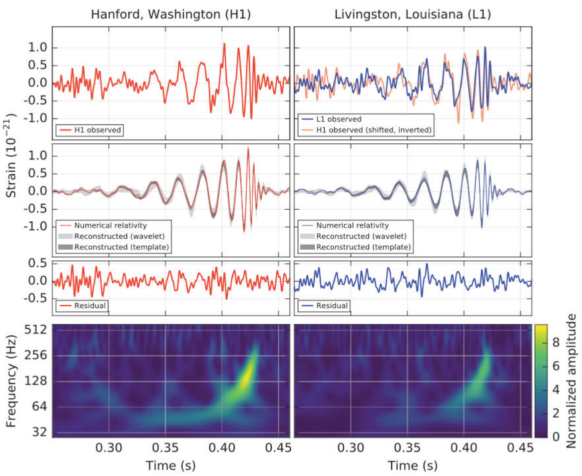

Figure 1: The gravitational-wave event observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. At the top row we report the strain signal in the two interferometer. In the second row the GW strain is projected onto each detector in the 35-350 Hz band. In the bottom row there are the time-frequency representations of the strain data, showing the signal frequency increasing over time.

The first event was detected by the LIGO interferometer at Livingston in Louisiana, 7 ms before the Hanford interferometer in the Washington state. The emitted signal has a peculiar waveform, called chirp: it matches the predictions of General Relativity for a GW emitted from the inward spiral and merger of a pair of black holes of 35^{+5}_{-3} and 30^{+3}_{-4} $M_\odot$, computed in the source frame. The final object is a black hole of 62^{+4}_{-3} $M_\odot$. The mass-energy of the missing (3.0 ± 0.5) $M_\odot$ was radiated away as GWs.

During the final 20 milliseconds of the merger, the power of the radiated GWs was peaked at about $3.6{\cdot}10^{49}$ W, which is 50 times larger than the combined power of all light radiated by all the stars in the observable universe.

On December 26, 2015, the second gravitational-wave event was identified. The source-frame initial black hole masses are $14.2^{+8.3}_{-3.7}$ and 7.5 ± 2.3 $M_\odot$ and the final black hole mass is $20.8^{+6.1}_{-1.7}$ $M_\odot$. We find that at least one of the component black holes has spin greater than 0.2. The location in the sky was even worse of the previous event resulting in an arch of the sky of around 1400 $\deg^2$.

In the near future with Advnced Virgo coming on ine the sky location will be improved significantly.

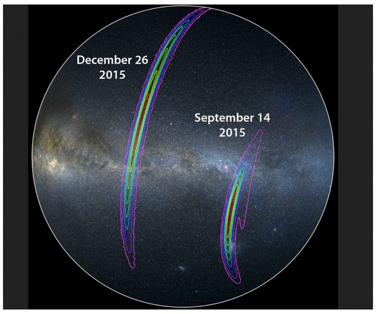

Figure 2: Comparison of the sky localisation for the two gravitational wave events.

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P. Astone[1], S. Frasca, P. Leaci, E. Majorana[1], C. Palomba[1], P. Puppo[1], P. Rapagnani, F. Ricci

P23. The new era of Physics and Astronomy. Continuous wave signals.

Late in the 20th century, the detection of solar neutrinos founded the field of neutrino astronomy, giving an insight into previously invisible phenomena, such as the inner workings of the Sun. The GW observation provides further means to perform astrophysical observations. This is the new era of GW astronomy. Up to September 2015, astrophysicists and cosmologists studied the Universe thanks to the electromagnetic radiation as visible light, X-rays, microwave, radio waves, gamma rays; extra information has been added by the cosmic ray physics through elementary particle-like impinging on the Earth.

Objects such as galaxies and nebulae can also absorb, re-emit, or modify e.m. radiation and particles generated within or behind them. GWs interact only weakly with matter. This is what makes them difficult to detect. It also means that they can travel freely through the Universe, and are not absorbed or scattered. Thus, GWs provide complementary information to that provided by other means. By combining observations of a single event, which are made using different means, it is possible to gain a more complete understanding of the source properties. This is known as multi-messenger astronomy. GWs are used to observe systems that are invisible to be measured by any other means: they provide a unique method to measure for example the properties of black holes.

In addition to black-hole binaries, there are other potential GW sources:

- Binaries systems of two neutron stars or those consisting of a black hole and a neutron star are sources characterised by mechanisms that produce also gamma-ray bursts.
- Supernovae generate high-frequency bursts of GWs that could be detected by both LIGO and Virgo.
- Early universe processes, such as inflation or phase transitions.
- Cosmic strings could also emit gravitational radiation if they do exist. Discovery of these GWs would confirm the existence of cosmic strings.
- Rotating neutron stars are a source of high-frequency continuous waves if they possess an axial asymmetry.

In the following we provide some details related to the search for continuous wave signals emitted by the last class of sources, as to date such kind of signals have not yet been detected.

Continuous GWs are expected to be produced by rapidly rotating neutron stars with non-axisymmetric deformations[1]. The way to search for continuous wave signals depends on how much about the source is known. There are different types of searches:

1. *targeted searches*, where the source parameters (sky location, frequency, frequency derivatives) are assumed to be known with great accuracy (e.g. the Crab and Vela pulsars);
2. *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);
3. *all-sky searches* for unknown pulsars.

Targeted searches are computationally cheap and a fully coherent analysis, based on matched filtering over long observation time, is quite feasible[2]. Some of the most stringent results have been obtained by targeting the Vela and Crab pulsars [3].

It is well-known that all-sky searches for GWs 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 data analysis strategy used to extract the faint continuous wave signals from the interferometric noise data is given by the standard coherent matched filtering method, which is based on the *maximum likelihood detection*. Fully coherent methods based on matched filtering are the approach used in analyses for continuous wave searches over wide parameter space. However, they become computationally undoable when very long data stretches (of the order of months or years) are used and a wide fraction of the parameter space is searched over. Hence, different incoherent hierarchical methods have been proposed, and interesting results have been obtained by using those methods on some of the most recent GW data [4].

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P24. Advanced Virgo

Advanced Virgo (AdV) is an ongoing project to upgrade the Virgo detector to a second generation instrument. It is designed to explore a volume of universe about 1000 times larger than Virgo. The construction started in 2012 and now all the subsystems of the new detector have been installed. The choices of the AdV design were made on the basis of the outcome of the different R&D investigations carried out within the GW community, together with the experience gained by running Virgo, and also taking into account the severe budget constraints. The final configuration of the detector will be a dual recycled interferometer. This configuration will be reached in at a later stage, while the first AdV detector will take data without the signal recycling in place.

The main change of such an upgrade is related to the mirrors: their mass (42 kg) is nearly doubled with respect to the previous Virgo configuration, reducing the impact of the thermal noise in the mid-frequency range of the detector bandwidth. In addition, the spot size of the laser light on the test masses has been enlarged so that the beam waist is placed close to the center of the 3 km Fabry-Perot cavities, whose finesse is increased up to 300. The mirror change required a new design of the whole last stage of both the mirror suspension and its control system, which is a full responsibility of the Virgo group at Sapienza University. The heavy task was concluded also thanks to the strong support of the INFN "Sapienza" branch. The experience gained by running the Virgo detector suggested us to revise the basic configuration of the payload, passing from a branched system, which include a reaction mass used to host the mirror actuators, to a new configuration where the last filter of the super-attenuator supports not only the coils to act on the marionette, but also those acting on the mirror: the Actuator Cage. In this way, we simplified the payload taking out the reaction mass.

This task included the suspension and the alignement of many new items set around the mirrors. The system conceived to compensate the residual thermal effects on the test masses requires that a compensation plate (CP), 350 mm in diameter and 30 mm thickness, is located at 20 cm from the rear surface of input mirrors. A pickoff plate is suspended near the power recycling mirror, and it has a size comparable to the CP. Moreover, the necessity to mitigate diffused light requires the presence of baffles as large as about 1 m close to the front and the rear faces of each mirror. Other elements to be inserted are several ring heaters, positioned close to mirrors, which are used as a further tool to adjust the optical parameters of the interferometer. The assembling operation, under the responsibly of the Rome group of Sapienza, have been carried on keeping the pollution level below a class 100 the payload, going down to class 1 when the installation was concluded. At the time of this writing, the AdV interferometer is completed and in the commissioning phase. soon we will start the data taking. In parallel to this activity, we summarise in the following the ongoing interactions we have with our international partners:

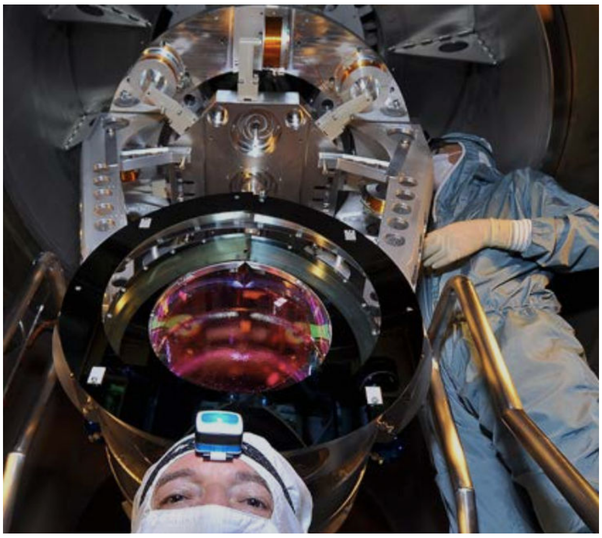

Figure 1: The Advanced Virgo payload during the installation phase.

- we installed in KAGRA, the Japanese detector built in the Kamioka mine, our cryogenic sensors to monitor the environmental noise at very low frequency noise This action was supported by the joint Japanese and European project ELiTes and by INFN.
- the interaction with LIGO is much more extended, both in the hardware and data analysis domain. Our contribution to drive up the publication of the discovery paper was significant as well as the strong contribution on the various data analysis algorithms, which have been developed to perform searches for continuous-wave signals.

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P25. Neutrinoless double beta decay search with the CUORE experiment

In the field of fundamental particle physics the neutrino has become more and more important in the last few years, since the discovery of its mass. In particular, the ultimate nature of the neutrino (if it is a Dirac or a Majorana particle) plays a crucial role not only in neutrino physics, but in the overall framework of fundamental particle interactions. The only way to disentangle its ultimate nature is to search for the so-called Neutrinoless Double Beta Decay (NDBD) $[(A, Z) \rightarrow (A, Z+2)+2e^-]$. 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} y. 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 the commissioning phase at the Laboratori Nazionali del Gran Sasso. 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.

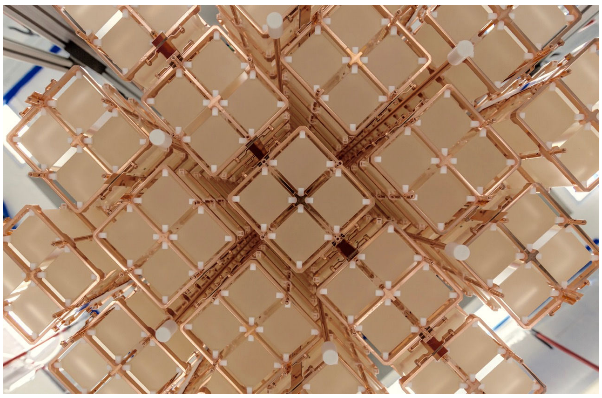

Figure 1: The CUORE detector.

The first tower built following the CUORE procedures, was operated as a stand alone experiment, named CUORE-0 [2] with the goal of validating the CUORE detector performances. The achieved energy resolution (∼5 keV) and background level, confirmed that the CUORE goal is within reach. At the same time CUORE-0 has been a sensitive detector by its own and in two years of data taking it was able to set the world best limit on the half life of ^{130}Te NDBD decay: $T^{0\nu}_{1/2}(^{130}\mathrm{Te}) \geq 4 \times 10^{24}$ y (90% C.L.) [3] (Fig. 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.

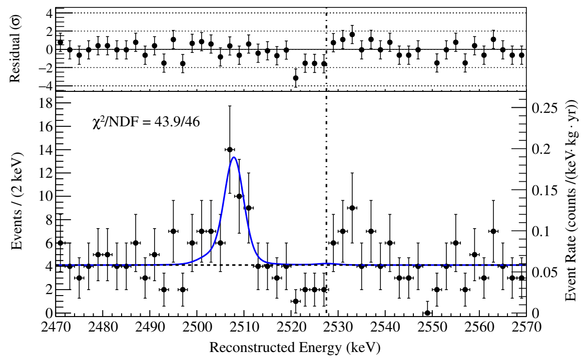

Figure 2: The best-fit model (solid blue line) overlaid on the spectrum of NDBD decay candidates in CUORE-0 (data points); the data are shown with Gaussian error bars. The peak at 2507 keV is attributed to ^{60}Co; the dotted black line shows the continuum background component of the best-fit model. The vertical dot-dashed black line indicates the energy where we expect the NDBD signal[3].

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P26. The Majorana neutrino search with the LUCIFER experiment

Neutrino-less Double Beta Decay (NDBD) is a hypothesized nuclear transition in which a nucleus decays emitting only two electrons. This process cannot be accommodated in the Standard Model, as the absence of emitted neutrinos would violate the lepton number conservation. For this reason, its observation would have several implications for particle physics, astrophysics and cosmology. According to the majority of theoretical frameworks, for NDBD 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 NDBD, cryogenic calorimeters (historically called bolometers) stand out for the possibility of achieving excellent energy resolution ($\sim$0.1%), efficiency ($\geq$80%) and intrinsic radio-purity. Moreover, the crystals that are operated as bolometers can be grown starting from most of the NDBD emitters, enabling the test of different nuclei.

The state of the art of the bolometric technique is represented by CUORE, an experiment composed by 988 bolometers for a total mass of 741 kg, presently in its commissioning phase at Laboratori Nazionali del Gran Sasso. The experience gained during the years of R&D

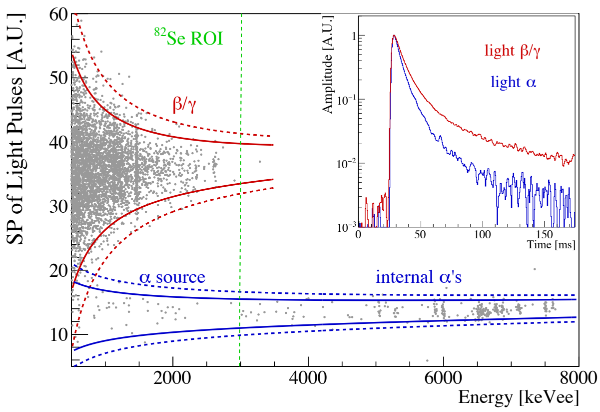

Figure 1: Shape parameter of a light detector as a function of the energy released in ZnSe. The red and blue lines indicate the 2σ (continous) and 3σ (dotted) β/γ and α bands respectively. α events can be easily rejected, in particular in the region of interest for the Se NDBD (green lines). Inset: time development of light pulses produced by β/γ (blue) and α (red) interactions with energy of about 2.6 MeV [2].

activity for CUORE allowed to determine that the ultimate limit in the background suppression resides in the presence of α-decaying isotopes located in the detector structure. The LUCIFER (Low-background Underground Cryogenic Installation For Elusive Rates ERC-AdG n. 247115) project [1] was born to overcome the actual limits. The main breakthrough of LUCIFER is the addition of independent devices to measure the light signals emitted from scintillation in ZnSe bolometers. The different properties of the light emission of electrons and α particles will enable event-by-event rejection of α interactions, suppressing the overall background in the region of interest for NDBD of at least one order of magnitude (see Fig.1). The detector is composed by 26 ZnSe ultra-pure $\sim$ 500g bolometers (see Fig 2.), enriched at 95% in ^{82}Se, the NDBD emitter, and faced to Ge disks light detector operated as bolometers. LUCIFER is hosted in a dilution refrigerator and it will start the commissioning phase in Dic 2016. 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. A success of this project would open the way for an experiment capable of exploring the entire region of the inverted hierarchy of neutrino masses (O(10 meV)).

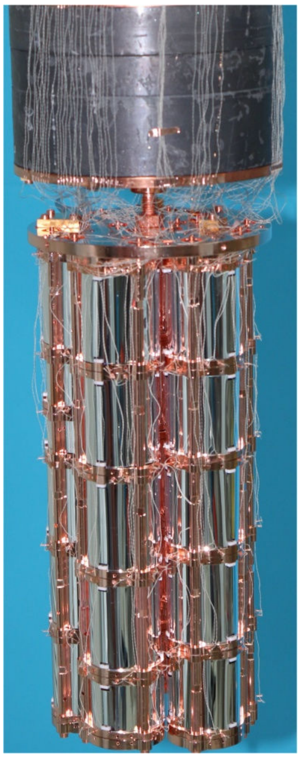

Figure 2: The LUCIFER detector.

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

P27. CALDER: Kinetic inductance light detectors to search for double beta decay

CALDER (Cryogenic wide-Area Light Detectors with Excellent Resolution) wants to contribute in settling two important issues 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".
- What is the dark matter filling the Universe made of? We know that it is different from the ordinary matter, however we still do not know what it actually is.

The goal of CALDER is to develop high-sensitivity cryogenic light detectors for the identification of rare events, such as double beta decay and dark matter interactions with ordinary matter. We are developing 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, characterized 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 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.

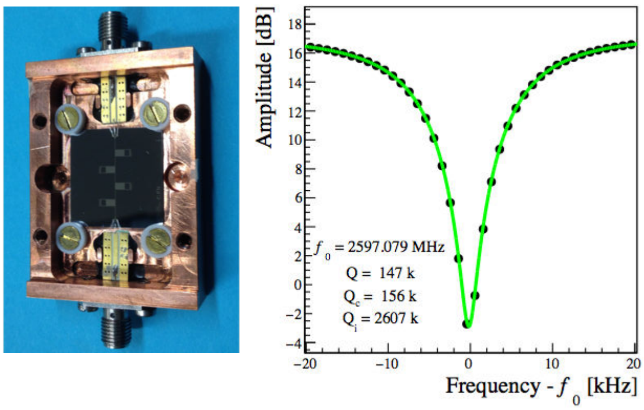

Figure 1: 4-pixel detector made by aluminum lithography on silicon substrate (left) and frequency response of a single KID (right). The detector is cooled down below 200 mK. When a photon is absorbed by the silicon, it is converted to phonons which travel to the KID, break cooper pairs and generate a signal.

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.

We are currently designing and testing the prototypes in the Sapienza/INFN laboratory in Rome. Then the detectors will be installed in the experiments running at the Gran Sasso underground laboratories of INFN to detect Majorana neutrinos and dark matter interactions. CALDER is supported by an ERC Starting Grant (contract No. 335359) started in March 2014.

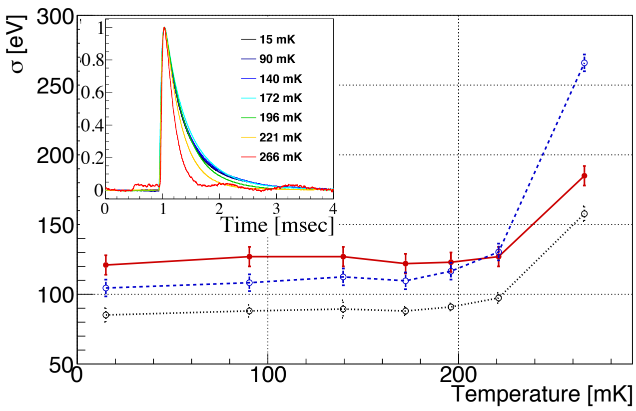

Figure 2: Energy resolution as a function of temperature for amplitude (dashed blue), phase (solid red) readout and their combination (dotted black). Inset: signal shape dependency of the phase readout with temperature.

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`http://www.roma1.infn.it/exp/calder`

P28. ANTARES: search for high energy astrophysical neutrinos

Neutrino Astronomy is a new and unique method to observe the Universe. The weakly interacting nature of the neutrino makes it a complementary cosmic probe to other messengers such as multi-wavelength light and charged cosmic rays: the neutrino can escape from sources surrounded with dense matter or radiation fields and can travel cosmological distances without being absorbed. For known high energy sources such as active galactic nuclei (AGN), gamma ray bursters (GRB), microquasars (MQ) and supernova remnants (SNR), neutrinos will allow to distinguish unambiguously between hadronic and electronic acceleration mechanisms and to localise the acceleration sites more precisely than charged cosmic ray detectors. A schematic view of the ANTARES neutrino telescope [1] is given in Fig. 1. The

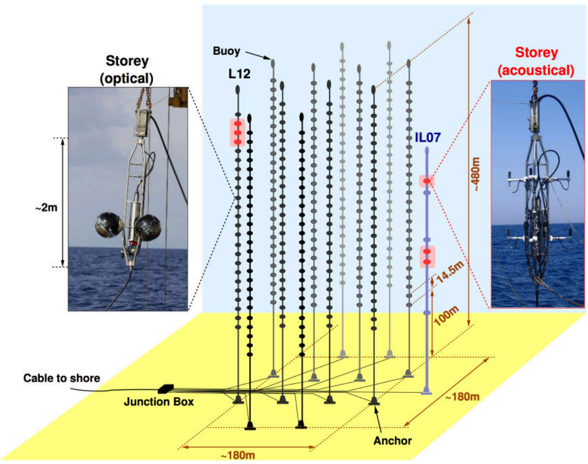

Figure 1: Schematic view of the ANTARES detector.

main channel for the search for astrophysical point-like sources of neutrinos is the muon neutrino [2]. The high rate of downgoing μ from the interactions of cosmic rays in the atmosphere restricts such searches to events coming from below, or only a few degrees above, the horizon. The remaining background is then the flux of atmospheric ν_μ and those few remaining atmospheric μ events misreconstructed as upgoing. The long scattering length of blue light in seawater provides an excellent directional resolution on the ν_μ primary of 0.38° for an E^{-2} source. The effective area of neutrino telescopes such as ANTARES and IceCube to cascade events (neutral-current (NC) interactions, and ν_e and ν_τ charged-current (CC) interactions) is generally lower than that of ν_μ CC interactions, due to the shorter range of the outgoing lepton. Additionally, the angular resolution of the cascade channel is inferior. Nevertheless, including cascade events into the analysed data sample has several advantages: neutrino events are more easily distinguished from the background of atmospheric muons, allowing both up and down-going events to be studied. Furthermore, the energy deposited in the detector is better correlated with the energy of the primary neutrino. The inclusion of the cascade channel has allowed for the first time a combined point-source search using both muon-track and cascade events using 1690 days of effective livetime from 2007 to 2013. After cuts, the sample consisted of 6261 muon-track events, and 156 cascade events, with an estimated contamination of 10% misreconstructed atmospheric muons in each. The resulting skymap is shown in Fig. 2.

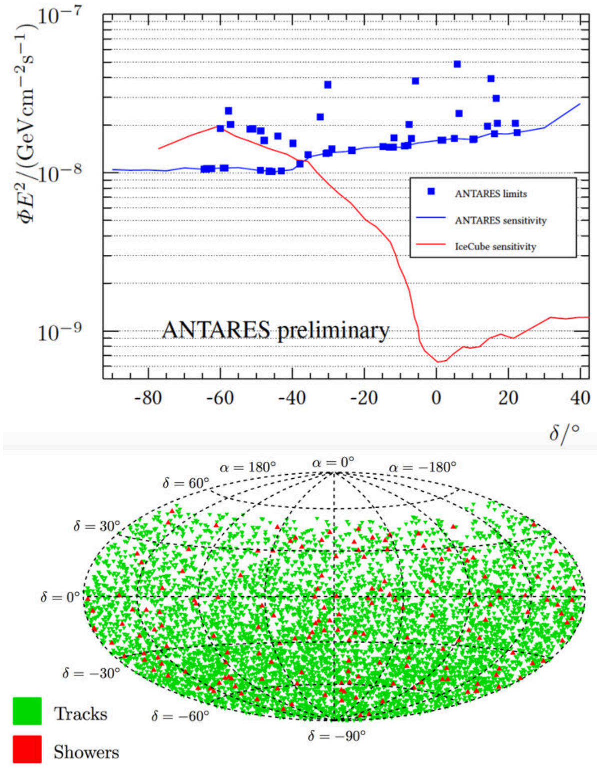

Figure 2: Top: limits and sensitivity of the ANTARES targeted source for flavour uniform neutrino point sources with an E^{-2} spectra in terms of flux per flavour; bottom: arrival directions of events in the all-sky point source analysis.

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F. Ameli[1], A. Capone, S. Celli[1], I. Di Palma, C. A. Nicolau[1], F. Simeone[1]

`http://www.roma1.infn.it/people/capone/ANTARES/indexANTARES.html`

P29. KM3NeT: the future Cherenkov Neutrino Telescope

The main objectives of the KM3NeT Collaboration are the discovery and subsequent observation of high-energy neutrino sources in the Universe and the determination of the mass hierarchy of neutrinos. To meet these objectives, the KM3NeT Collaboration plans to build a new Research Infrastructure consisting of a network of deep-sea neutrino telescopes in the Mediterranean Sea (Fig. 1). The infrastructure will consist of three so-called building blocks. A building block comprises 115 strings, each string comprises 18 optical modules and each optical module comprises 31 photo-multiplier tubes (PMTs) used to detect the Cherenkov light produced by relativistic particles emerging from neutrino interactions. Two building blocks (ARCA: Astroparticle Research with Cosmics in the Abyss) will explore the IceCube signal with comparable instrumented volume, different methodology, improved resolution and complementary field of view, including the galactic plane (GP). One building block (ORCA: Oscillation Research with Cosmics in the Abyss) will be densely configured to precisely measure atmospheric neutrino oscillations and Neutrino Mass Hierarchy (NMH). ARCA will be realised at the Capo Passero site and ORCA at the Toulon site. As a preview to the science objectives of the future Neutrino Telescope, Fig. 2 shows the significance as a function of time for the detection of a diffuse, flavour-symmetric neutrino flux corresponding to the result reported in 2013 by IceCube. A determination of the Neutrino Mass Hierarchy (NMH) with at least 3-sigma significance can be made after three years of operation, i.e. as early as 2023 (Fig. 3). This precedes results of other experiments and provides timely input for experiments aiming at a measurement of the CP-violation phase with high sensitivity. In addition, ORCA will provide improved measurements of some of the neutrino oscillation parameters. A team of the Physics Department and of the local Sezione INFN have contributed so far to the creation of the project, to the design and construction of the electronics and to the definition of the physics case.

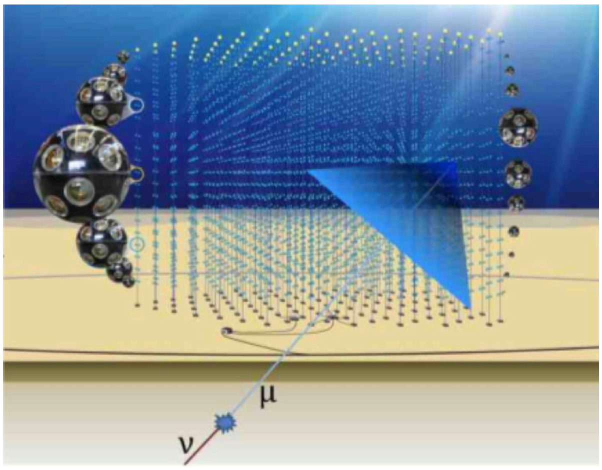

Figure 1: Schematic view of the KM3NeT detector.

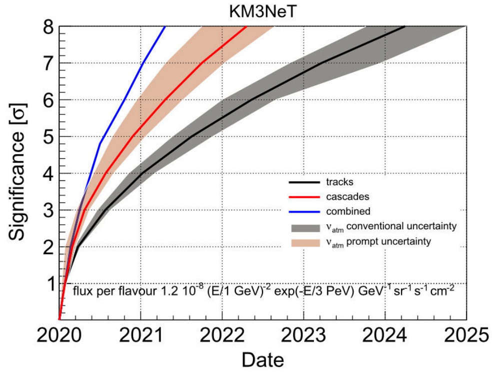

Figure 2: Significance as a function of time for the detection of a diffuse flux of neutrinos corresponding to the signal reported by IceCube, for cascade-like events (red line) and track-like events (black line). The black and red bands represent the uncertainties due to the conventional and prompt component of the atmospheric neutrino flux, respectively. The blue line indicates the result of the combined analysis.

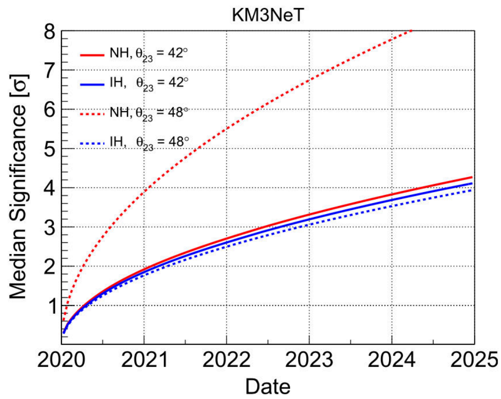

Figure 3: Median significance as a function of time for the determination of the neutrino mass hierarchy. The different lines denote expectations for different combinations of hierarchy and atmospheric mixing angle θ_{23}. Note that the CP-violating phase α_{CP} has been assumed to be zero.

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`http://www.roma1.infn.it/people/capone/ANTARES/indexANTARES.html`

P30. Development of astroparticle detector and a calibration light source device for Cherenkov Telescope

The activity of the group was devoted to complete a prototype to detect cosmic ray particles and build a calibration light source device for a Cherenkov Telescope array.

The detector prototype was proposed as element of a large array, Tauwer, to measure large zenith angle showers produced by high energy neutrino interaction in Earth crust [1]. The prototype, composed by two indentical scintillator counters, 160 cm apart, is still located at Sphinx Observatory Center, Jungfraujoch (3800 m a.s.l) HFSJG Switzerland[1]. By Time Of Flight (TOF) method we discriminate the upward and downward moving particles.

The activity of group, in particulary, was focused to develop the electronics to amplify the signal from a 3x3 mm^2 35 μm microcell Sensl Silicon PhotoMultiplier and its digitization by Domino Ring Sampler Board (DRS4) able to sample at 2GS/s. By fitting the front of the digitized signal the up-down going tracks are selected by TOF. Due to the fact the detector station should work in the harsh enviromental condition we developed a system with Arduino board that records the temperature inside the box with the SiPM and adjusts the breakdown voltage of the sensor to maintain the gain constant. Test results made in the Department of Physics are shown in [2].

A test of a mini array composed by eight of these detectors was also installed in Karlsruhe Institute of Technology (KIT) near the KASCADE array to verify the reconstruction efficiency of vertical shower versus energy compared to the KASCADE data. The data were collected using the trigger performed by KASCADE stations close to the mini array. The results of the analysis are reported in [2].

During the tests at KIT we implemented also a method to separate electron/muon present in the cosmic showers inserting a layer of lead in front of a scintillator plate and measuring the ratio of deposited energy [1]. Part of the electronics developed for the SiPM-SensL used in Tauwer has been also tested to read the light from the inorganic crystal calorimeter (BGO) in PADME detector designed to search dark photons.

At end of 2014 the team joined the Cherenkov Telescope Array (CTA) Collaboration designed to detect, by Cherenkov light produced in atmosphere, high energetic gammas (GeV-TeV) [3].The first prototype of the Large Size Telescope will be installed at Canaria island, La-Palma in fall 2017. The task choosen has been to design and to build a device, named CaliBox, to calibrate the camera sensors. It is located at the center of the mirror plane in front of the camera plane composed by 500 photomultipliers [3]. Being the Cherenkov light spectra peaked at 350 nm the calibration was performed by a UV laser source modulated by reflective neutral density filters that illuminates uniformly the camera plane after to be diffused. All the components, laser, sensors and movement of filter wheels are controlled by a single board, ODROID-C1. The realized device is shown in Fig.1. One of us (MI), member of Central Detector at Fermilab collaboration where he built two subdetectors: muon detector and a preshower has followed the review of some papers [4].

[1] www.hfsjg.ch/wordpress/report/2015/129_UniRom_Iori_cf.pdf

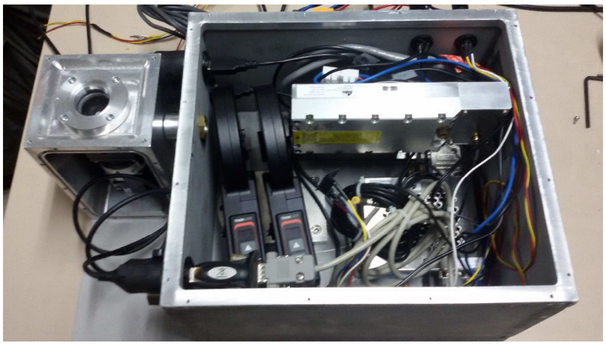

Figure 1: The Calibox. On top is visible the laser and on left side the two filter wheels, the box with the diffuser (left side) where is visible on top the exit window of laser. The ODROID-C1, the power supply are placed on a side of the box.

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Authors

M. Iori, F. De Persio[1], F. Ferrarotto[1], A. Yilmaz

P31. Experiments at the Jefferson Laboratory (JLab - Virginia, USA)

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 the experimental Hall A is being developed. SBS will continue at higher Q^2 values the measurement of the ratio of the nucleon electric and magnetic form factors G_E/G_M that in the previous years has shown an unexpected and dramatic decreasing with Q^2. SBS will continue the measurements of Nucleon Transverse Moment Distributions (TMD) too to allow a three dimensional picture of the nucleon [1]. The Department of Physics of Sapienza University of Rome is involved in the study of the hypernon-nucleon potential and consequently of the structure of the neutron stars too. This study is performed through the electroproduction of hypernuclei and the measurement of their binding energies. It will be possible to determine an 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 would make, according to what is presently supposed to be the hyperon-nucleon potential [2], the Equation Of State (EOS) too soft and would hence forbid the existence of very massive neutron stars. In the field of Dark Matter searches the Department of Physics of Sapienza University of Rome is contributing to the preparation of the experiment APEX, that will search in the JLab experimental Hall A the possible existence of a dark photon responsible of the interactions between dark matter components and weakly coupling with the ordinary Standard Model matter. Thanks to this weakly coupling, this Dark Photon would be produced by electroproduction in target and detectable as a narrow resonance on the background produced by electromagnetic interactions. The activities of the Department of Physics of Sapienza University of Rome at Jefferson Laboratory in the field of the Search for Physics Beyond the Standard Model encompass also the measurements of the Parity Violating Asymmetry [3], that is the fractional difference between the cross-sections of electrons of positive and negative helicity, in several electron scattering processes from nuclei, protons and electrons. These measurements make it possible to enhance the contribution to the processes under study of the weak part of the electroweak potential between electrons and the partons in nuclei. This will make it possible to measure with great precision the weak coupling between electron and quarks [4], the weak charge of the proton and the neutron, the Weinberg angle etc. The Department of Physics of Sapienza University of Rome has a leading role in the experiments PREX too. These experiments are performing, with great precision, the measurement of the neutron radius in the ^{208}Pb and will determine several neutron star features. They will achieve these goals through the measurement of the Parity Violating Asymmetry in the elastic electron scattering from ^{208}Pb. In fact, as quoted above, the contribution of the ^{208}Pb weak charge to the Parity Violating Asymmetry in the electron scattering is enhanced and the neutrons contribute overwhelmingly to the ^{208}Pb weak charge. The measurement of the ^{208}Pb neutron radius will allow a precise determination of the dependence of the symmetry energy on the density. This will improve dramatically our knowledge of the EOS of the neutron rich matter, allowing to determine many features of neutron stars. 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 is based on the construction of a polarimeter made by 46 cells. Each cell is made by a double face microstrip detector, which 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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Authors

F. De Persio, F. Meddi, G. M. Urciuoli[1]

P32. Crystal channeling for high energy hadron beam steering

The Large Hadron Collider (LHC) at CERN is the most powerful circular collider in operation today, able to accelerate beams of protons up to an energy of 6.5 TeV. The LHC layout includes several big superconducting magnets reaching magnetic fields of several Tesla. The CRYSBEAM group in the context of the UA9 experiment at CERN has recently demonstrated how a small and thin bent silicon crystal can be used to manipulate the LHC high energy beams.

Protons (and - in general - charged ions) can in fact be trapped within the crystal lattice planes by the effective electric field of all the ordered atoms in the crystal. This coherent interaction of a charged particle with a whole crystal lattice is known as *crystal channeling*. When a crystal is bent by imparting an external force, its lattice planes result to be bent as well. A trapped particle is therefore emerging from the crystal with a net deflection.

The CRYSBEAM team built and tested a number of crystals at the CERN North Area H8 beam test facility, using ultra-relativistic protons, pions, argon and lead ions. One crystal produced in Italy was installed on a special piezo-electric goniometer able to rotate the crystal inside the vacuum chamber of one the two LHC rings. During dedicated tests in 2015 crystals were set in a position to intercept the peripheral particles of the LHC beam (the beam *halo*). In Fig. 1 the beam losses close to the bent crystal are shown as a function of the relative orientation of the crystal lattice planes with the beam halo mean direction. The observed minimum of the interaction rates corresponds to the orientation of crystal channeling when particles are oscillating between the lattice planes and are therefore travelling far from the nuclear sites. This was complemented by the observation of the halo particles deflected by about 50 μrad, that is the designed crystal bending angle [1]. This was an important milestone that was followed by other tests in which it was shown that the crystal can be used to efficiently remove the undesired particles of the halo, working therefore as a beam collimator.

At the same time the CRYSBEAM team designed, built, calibrated and installed on the Super Proton Synchrotron (SPS) accelerator at CERN detectors based on Cherenkov light production and transmission in fused silica bars, critical to monitor the deflected beam inside the ultra-high vacuum beam pipe.

This research activity was in fact complemented by a series of technological advances, for example magneto-rheological finishing of silicon wafers and Cherenkov light production and transmission in micro-machined silica slab with ultra-fast lasers.

During the 2016 the interest for the application of crystals in beam manipulation has grown at CERN. The LHC collimation system for the future upgrade of the accelerator might be based on crystal collimators. Crystals might also be used for the full extraction of the beam

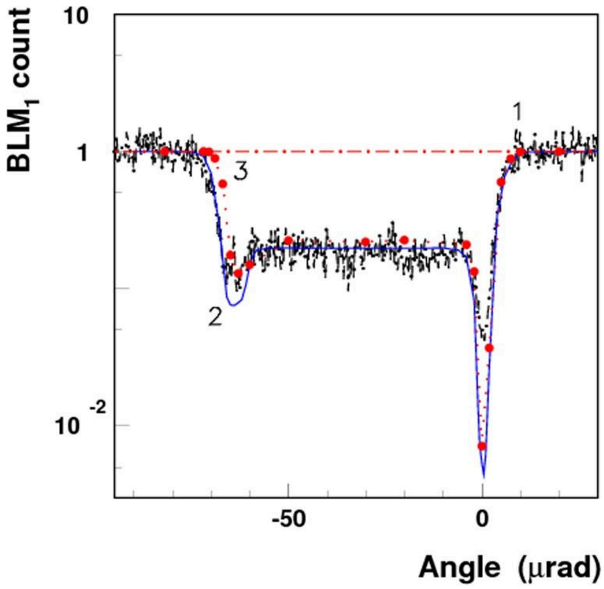

Figure 1: Beam losses due to the inelastic nuclear interactions of protons in the crystal observed with the beam loss monitor downstream of the crystal itself for the LHC coasting beam of 6.5 TeV protons. The recorded beam losses (curve 1) are shown as a function of the crystal orientation angle along with the predictions of two different simulations (solid line 2 and dotted line 3) .

out of the vacuum beam pipe. This would open the possibility of a better exploitation of the SPS extracted beam or of a program of measurement of cross sections of the interactions of the LHC beam with a fixed target. The CRYSBEAM team is now concentrating in building crystals with larger bending angles (up to 1 mrad) that would be useful for the extraction of the beam. New technologies must be studied to have efficient crystals.

Eventually the measurement of the interaction cross sections at the highest energy will be relevant to understand the nature of the high energy cosmic ray showers we observe in the Earth's atmosphere.

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F.M. Addesa, G. Cavoto, L. Ludovici[1], R. Rossi, R. Santacesaria[1], P. Valente[1]

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

P33. Dose delivery in 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. In the past five years almost 30 laurea thesis and 4 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.Within medical applications two major areas have been developed so far: the estimate of the dose delivery in Particle Therapy, described in the following, and the development of a novel technique of Radioguided Surgery, detailed in the next page. Furthermore, recently a new activity on the use of multivariate analysis in radiological imaging for tumor staging has started.

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) shown in Figure 1. 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.

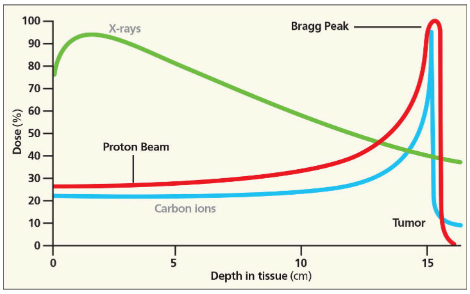

Figure 1: Energy release profile of X-rays, Proton and Carbon Ion beams.

However, the high space selectivity of the PT asks for a new approach to the delivered dose monitoring. The uncertainty on the position of the dose released is of the order of few millimeters possibly larger than the dimension of the BP. A precise monitoring of the dose is then essential for a good quality control of the treatment. Furthermore, the dose monitoring would be particularly useful if provided during the treatment (in-beam monitoring) in order to provide a fast feedback to the beam.

The irradiation of tissues with hadron beams produces nuclear excitations 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 [1].

Our group studies the emission of such radiation in terms of rates and of spectra, with the aim of determining the requirements of the detectors needed for the dose profiling. We are therefore performing a measurement campaign with several types of beams and a wide spectrum of energies [2]. We have also designed and build a profiler capable to simultaneously measure prompt photons and charged particles with the accuracy required in a hadrotherapic treatment.

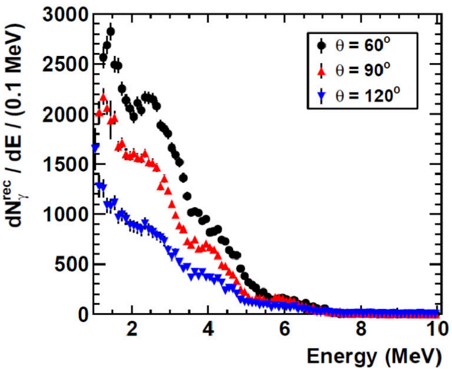

Figure 2: Energy spectra of prompt-γ rays produced by 220 MeV/u ^{12}C ions on a PMMA target measured at different angles with the beam direction [2].

Another critical aspect in PT is the measurement of the secondary fragments produced by the nuclear interactions of the beam with the tissue which significantly contributes to the absorbed dose by the patient. Currently, the predictions of various theoretical models for the fragmentation process differ up to an order of magnitude for double-differential quantities (in energy and angle) and the measurements for light ions in the energy range of interest for hadron therapy applications, between 100 and 500 MeV/nucleon, are scarce or even lacking. Accurate knowledge of fragmentation cross sections would also be important in the field of radiation protection in space missions. ARPG is involved in several measurements of different ions fragmentation cross sections as Carbon, Helium and Oxygen (INFN FOOT Experiment).

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R. Faccini, M. Merafini[7], R. Paramatti, V. Patera[6], D. Pinci[1], A. Sarti[6], A. Sciubba[6], E. Solfaroli Camillocci, C. Voena[1]

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

P34. A novel radio-guided surgery with β^- radiation.

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.

To overcome these limits and extend the range of applicability of RGS, our group suggested [1] to use instead pure β^--emitting radio-isotopes. The 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 [2]. 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].

To explore the applicability of this technique several studies have been performed where the expected signal from the probe prototypes was estimated on the basis of a simulation and tests on phantoms. As a start, the clinical cases were limited to the tumors known to express receptors to a β^- emitting radio-tracer, in particular the ^{90}Y-labeled DOTATOC: brain tumors (meningioma and glioma) [3] and neuro-endocrine tumors. In all cases the expected tumor-to-non-tumor ratios were high enough to allow a detection of 0.1 ml residuals within few seconds of application of the probe.

These studies started from PET images with ^{68}Ga-labeled DOTATOC and, assuming that the bio-distribution of the tracer did not change when labeled with ^{90}Y, with a simulation program (FLUKA) estimated the signal rate on the probe. The relationship between the specific activity in tumor and healthy tissues and the probe counts was tuned by measuring the response of the probe to sealed ^{90}Y sources. Such relationship has been validated in ex-vivo tests on meningioma patients [4].

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

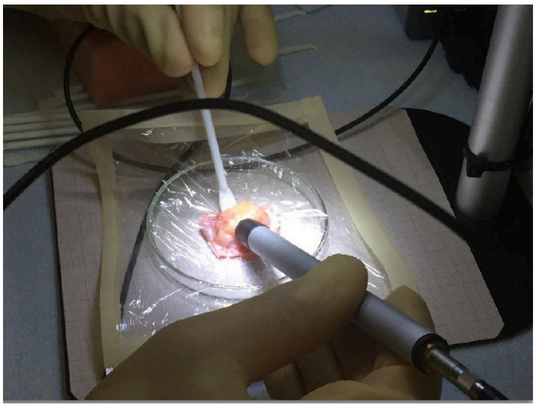

Figure 1: β^- probe prototype applied to a meningioma.

The research activity in this field continues in several paths:

- direct use of solid state detectors (e.g.CMOS) for the electron detection is being explored to reduce the minimum detectable electron energy and to reduce the γ contamination. Such improvement will allow to consider a broader range of radionuclides, and therefore tracers, for this technique;
- 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;
- new tumors of interest and the corresponding radiotracers are being identified. From the particle physics point of view the challenges are the identification of the appropriate radio-nuclides and the study of the optimization of the nuclear reactions that produce them.

This activity is highly multidisciplinary and is carried out in collaboration with chemists from "La Sapienza" and nuclear physicians, oncologists and surgeons from Istituto Neurologico C. Besta, Istituto Europeo di Oncologia, Policlinico Gemelli, Ospedale Pediatrico Bambin Gesù, and Arcispedale di Reggio Emilia.

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List of research activities

Theoretical Physics

Theoretical physics

The Theory Group of the Physics Department in Sapienza is well known world wide for the excellence of its research, and some of its present and former members belong to Italian and foreign Science Academies and have been awarded important international prizes. At present, 15 full professors, 12 associate professors, and 6 assistant professors are permanent members of the group. Moreover, the Department hosts the INFN “Roma1” local unit and several members of research institutes of the CNR and of the IIT. They also actively partecipate in the research activities of the Department, collaborating with several members of the theory group. Finally, a large number of postdoctoral fellows, supported both by Italian and European funds, contribute to the research activities.

The spectrum of the research lines in which the theory group is involved is very broad. They range from very applied investigations, sometimes at the boundary of physics, chemistry, and biology, to more speculative analyses in cosmology, gravitation, and elementary-particle physics. The intense theoretical activity in condensed-matter physics, material science, soft matter, and biophysics is reviewed in the “Condensed Matter Physics and Biophysics” section of this report. Here I will only review those research lines that can be roughly classified in the following four broad categories: **Physics of Fundamental Interactions** (contributions T1-T6), **Cosmology and Gravitation** (contributions T7-T9), **Statistical Mechanics of Complex Systems** (contributions T10-T15), and **Nonlinear Phenomena and Mathematical Physics** (contributions T16-T19). It is clear that, in some cases, the categorization is not so immediate and obvious, and some contributions might equally belong to two different categories or might have been included in the “condensed-matter physics” section of this report as well.

The Physics Department of Sapienza has always been characterized by an intense research activity in the theory of the fundamental interactions. Present and former members of the group have been crucial in the development of the Standard Model, whose predictions have been confirmed by a variety of experiments in the last 50 years. Recently, theoretical research has been spurred by the wealth of results obtained at LHC, which, up to now, all appear to be in good agreement with the theoretical predictions of the Standard Model. Contributions T1-T5 highlight some of the most recent results in this field. Contribution T1 describes the recent activity concerning the theoretical analysis of the nature of exotic hadronic resonances (identified as tetraquark and pentaquark states), which have been discovered and characterized by the LHC experimental collaborations. It also presents the results of an ongoing collaboration with the experimental groups present in the Department, to develop new experimental techniques to detect exotic states of matter, like WIMPs and axion-like particles. Contribution T2 instead reports the ongoing effort in improving the accuracy of perturbative QCD calculations, with the purpose of matching the precision of the experimental measurements of physical observables by the ATLAS and CMS collaborations at CERN. This is also a crucial step for the purpose of identifying new physics signals, as only a combined improvement of the accuracy of experimental and theoretical results allows one to detect deviations from the Standard Model. Improving the accuracy of the theoretical predictions is also the goal of the UTfit collaboration, that involves members of the Physics Department and of the INFN Roma1 unit. Recent results of the collaboration concerning the parameters of the Cabibbo-Kobayashi-Maskawa matrix are reviewed in contribution T3.

Contributions T3, T4, and T5 present nonperturbative QCD results, obtained using the lattice regularization. The activity in this field very much resembles that of HEP experimental groups, with the presence of international collaborations, which share highly sophisticated software, computer time, and jointly use the results of the simulations. At present, there are ongoing collaborations with German, French, and UK Universities and research institutions. Contributions T3 and T4 discuss a new proposal for the calculation of electromagnetic and isospin-breaking effects in lattice QCD. In particular, contribution T3 gives results for the leptonic decay rates of pseudoscalar mesons. Contribution T5 reports recent advances in the computation of QCD matrix elements of composite quark operators between light hadron states. These calculations are a crucial ingredient to obtain theoretical predictions for many quantities relevant in flavor physics.

Contribution T6 presents recent advances in the search of a consistent theory of quantum gravity. In the proposal of the Sapienza group, spacetime is postulated to be noncommutative, i.e., spacetime coordinates have nontrivial algebraic properties that can be schematized using Hopf algebras. Quantum gravity effects are relevant only on very small length scales of the order of the Planck length $\ell_P \approx 10^{-35}$ m, and thus they are typically too small to be observed. The Sapienza group has however shown that a careful analysis of some strong-gravity astrophysical phenomena may allow researchers to identify quantum effects. In particular, γ-ray bursts —and, perhaps, cosmological neutrinos—may give indirect evidence of the short-distance quantum structure of spacetime. Cosmological neutrinos and ultra-high-energy cosmic rays are the subject of contribution T7, in which a new interpretation of the experimental data of the ICECUBE and AUGER experiments is presented.

Contributions T8 and T9 both consider astrophysical processes, with the purpose of better understanding the behavior of stellar matter (T8) and of identifying possible deviations from Einstein's general relativity (T9). Before 2015, the electromagnetic radiation emitted by black holes and neutron stars essentially provided the only data that theorists could use to test their theoretical predictions for several high-energy astrophysical phenomena, like the coalescence of black holes and neutron stars. In 2015, the detection of gravitational waves added a new instrument for the investigation of these phenomena. The relativistic-astrophysics group at Sapienza has always been very active in the study of the structure of neutron stars and black holes, of binary systems and of extensions of general relativity. Contributions T8 and T9 highlight the most recent results. In particular, they show how the analysis of gravitational-wave signals emitted from coalescing neutron binaries can give important informations on the equation of state of neutron stars. Similarly, gravitational and electromagnetic signals produced in strong-gravity astrophysical phenomena can be used to test deviations from general relativity.

Contributions T10-T15 can be generically grouped under the name "Statistical mechanics of complex systems." This is a vast, continuously growing, and strongly interdisciplinary research field. From the methodological point of view, there are strong links with theoretical high-energy physics. For instance, the renormalization-group approach has its roots in quantum field theory, while, vice versa, in the lattice gauge theory approach, QCD is treated as a statistical system. There are also tight connections with condensed-matter physics—historically, many of the techniques were developed to explain the critical behavior of magnetic systems. Recently, statistical mechanics methodologies have been applied to many other disciplines, ranging from biology, computer science, and social sciences. Contribution T10 is an example of the broad scope of statistical mechanics. It analyzes the collective behavior in biological systems, a widespread phenomenon that is observed in (microscopic) cell colonies as well as in (macroscopic) animal aggregations, using the same methods that are applied in the analysis of "physical" statistical systems. Other similar interdisciplinary research lines, strictly related with those presented here, are reported in the "condensed-matter and biophysics" section.

Statistical mechanics, as developed by Boltzmann and Gibbs (just to name two famous names), was meant to provide a microscopic theory for "large" systems in thermal equilibrium. In recent years, however, there has been an increasing interest in the behavior of "small" systems subject to transformations that are faster than typical relaxation times, so that thermal equilibrium is never reached. There are still several conceptual open issues—for instance, the correct definition of temperature in systems with bounded phase space—in the field. Some of them are presently studied by a Sapienza-CNR group. Their most recent results are summarized in contribution T11.

Contributions T12 and T13 consider quantum systems. The first one discusses the behavior of mixtures of chiral molecules and presents rigorous results for the relaxation time to a class of nonequilibrium steady state for a class of many-body models in contact with thermally equilibrated reservoirs. Contribution T12 summarizes recent results on the behavior of small quantum systems, close to a critical or first-order transition. Understanding these finite-size effects is crucial for many experiments, in which relatively small systems are considered (this is the case of recent cold-atom experiments). Contributions T14 and T15 report the activity in the field of strongly disordered systems. Sapienza has always had a world-leading role in the study of these phenomena and is the center of an international research network for the study of spin glasses and of all those phenomena in which randomness and frustration play a crucial role. Contribution T14 summarizes the most recent analytic and numerical results obtained for the Ising spin glass, the paradigmatic model for strongly disordered systems. Large-scale simulations have been performed using the dedicated machines Janus and Janus II, two FPGA-based reconfigurable supercomputers that have been built by an international collaboration involving several Italian—Sapienza is one of them—and Spanish universities and research centers. Contribution T15 discusses other types of glassy materials, the low-temperature behavior of structural glasses and packed hard spheres, and the optical behavior of random lasers. Again, Sapienza, in collaboration with other foreign research groups, has made important contributions in the field. A dynamical field theory has been developed for structural glasses. It has been solved in the mean-field limit and corrections at first-order in a loop expansion around the mean-field solution have been obtained. Analytic results for the jamming of hard spheres in the infinite-pressure limit have been obtained in the mean-field limit. Finally, a new order parameter has been used to characterize the glassy nature of the optical response of random lasers.

Contributions T16 and T17 consider wave propagation in highly nonlinear regimes characterized in some cases by extreme phenomena, for instance rogue waves. They are gigantic waves that arise from no specific excitation and which appear and disappear suddendly. They are rare, unpredictable, and responsible for catastrophic events like tsunamis. Contribution T16 presents analytic, numerical, and experimental results for systems characterized by a nonlinear dynamics and strong randomness, like quantum lasers and cellular automata coupled to electromagnetic waves. Similar problems are also studied in our group from a more mathematical viewpoint. Contribution T17 summarizes the recently obtained rigourous and analytic results obtained for several interesting nonlinear partial differential equations. Two other contributions complete the list of topics discussed in this report. Contribution T18 discusses the properties of resonances in one-dimensional quantum toy models, while contribution T19 presents some results concerning the relaxation properties of different types of Markov dynamics on random graphs.

Andrea Pelissetto

T1. Exotic hadron resonances and methods to detect light dark matter.

Exotic hadron resonances. Hadrons with a number of quarks larger than three are called 'exotic' as they do not fall neither in the category of mesons nor in that of baryons. Several particles of this type have been observed and described in the last ten years [1]. An accredited hypothesis is that they are meson-meson or meson-baryon molecules. Indeed the best experimentally assessed ones have masses close to meson-meson thresholds (in the case of tetraquark particles) but slightly above them. The latter fact speaks in favour of a compact tetraquark interpretation — as proposed by our group since the first experimental indications of a new hadron spectroscopy.

In [2] we show how chromomagnetic interactions among quarks in a tetraquark can reproduce the mass pattern of three observed axial resonances and predict the existence of new scalar and tensor multiplets. This work sets the rules for a systematic description of the observed and expected states.

The high-p_T (transverse momentum) production cross section at the Large Hadron Collider of the best known exotic resonance (the $X(3872)$) also argues in favour of the compact tetraquark hypothesis. Loosely bound hadron molecules, like deuteron and hypertriton, are expected to have production cross sections several orders of magnitude lower at $p_T \gtrsim 15$ GeV, where the X is instead copiously produced.

Recently also a pentaquark resonance has been discovered by the LHCb collaboration, and described in terms of a compact state made of two diquarks and an antiquark in [3]. This is the first experimentally reliable case of a baryon with a multiquark structure.

The problem with our description of the new hadron spectroscopy is in the proliferation of predicted states. The hadron molecule interpretation has the same difficulty. Attempts to find selection rules for the observed states have been proposed [1].

Light dark matter searches. We are in the stage of extending dark matter direct detection searches to lower energy thresholds, and eventually probe the dark matter mass limit of 1 keV.

Our group has proposed two detection techniques, as detailed in some theoretical studies [4]. The first is based on the usage of Carbon Nanotubes (CNT) for the search of light Weakly Interactive Massive Particles (WIMP). The second is the proposal to use microwave radiation sources to detect Axion-Like Particles (ALP).

Assuming that WIMPs have small but finite interactions with matter, carbon ions can be recoiled in WIMP-CNT collisions (for WIMP masses $\gtrsim 1$ GeV) and channeled in the body of single CNTs or in the interstices among parallel CNTs piled in large arrays. This might occur thanks to reflecting potential barriers confining the transverse motion of positive ions. We have studied this behavior with explicit calculations of the scattering processes. Ions guided by CNTs can eventually be detected with appropriate techniques.

The initial kinematic conditions of the scattered ions are decisive for this channeling process to occur, and change with the different orientations of CNT arrays with respect to the direction of the WIMP wind — the Cygnus constellation. The WIMP mass threshold can be lowered studying electron scatterings from nanotubes, with external driving electric fields. INFN is supporting preliminary experimental studies on this mechanism (DeCant project).

ALPs are scalar or pseudoscalar particles which are assumed to have very small couplings to photons and can be produced when photons traverse large external magnetic fields, for example. They might be a component of dark matter.

We have shown that, if we were able to detect photons with few tens of GHz, with single photon efficiency, microwave sources could provide a remarkable opportunity to explore a large portion of the sub-meV mass range of ALPs, improving with respect to running experiments based on LASER sources. In [4] we show how the low energy photon limit can be approached in photon-ALP conversion experiments. INFN is supporting studies on sub-THz photon detection (STAX project).

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T2. Higher-order perturbative corrections for observables at hadron colliders

Precision Physics is, nowadays, of crucial importance, since in the absence of a clear signal of new physics, 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). This is the reason why we are involved in a vast programme of calculations at the fronter of current knowledge in perturbative Quantum Field Theory.

Higgs boson production and decay at NLO and NNLO in QCD [1,4].
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, reveal a strong compatibility of the particle discovered with the Higgs boson of the SM. However, more accurate predictions and measurements and the accurate study of more exclusive observables could reveal peculiar behaviours and point towards some models of 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_T distribution at intermediate and high p_T. Moreover, the exact mass dependence of the cross section at NNLO, being of the same order of magnitude of the current accuracy, is needed to refine the current theoretical prediction. In the last years, we calculated [1,2] analytically the master integrals for the planar contributions to the NLO production of $H + j$, and we are now studying the non planar masters and the planar three-loop massive master integrals for the production of a Higgs in gluon fusion.

Mixed EW-QCD corrections in 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 Standard Model of fundamental interactions (SM). They give acces to the determination of important parameters of the weak sector, as for instance the sine of the weak mixing angle and the W boson mass. 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. For all these reasons, an accurate and reliable experimental and theoretical control on Drell-Yan processes would be of the maximum importance for future physics studies at 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 [2] the two-loop master integrals needed for the evaluation of the mixed corrections to the production of a lepton pair and we are now working on the determination of the relative cross sections.

NNLO 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 the first differential distributions recently appeared, a fast and reliable Monte Carlo (MC) integrator, needed for cross-check and analysis purposes, is still missing. The ingredients to release such a MC are: matrix elements in a form that could be easily evaluated numerically and local infrared subtraction terms that assure a stable and accurate subtraction of the divergences occurring from the integration over the phase space. In the last years, we worked on the analytic evaluation of the two-loop matrix elements and on the infrared subtraction terms in Q_T formalism.

This research programme was carried out in collaboration with the following members of the Department of Physics: Francesco Moriello (PhD student), Matteo Becchetti (PhD student), Simone Lavacca (Master student), Matteo Capozi (Master student), Paul Caucal (ENS internship at the Department of Physics), Valerio Casconi (PhD student).

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T3. Electromagnetic corrections to hadronic decays from LQCD

In Flavor Physics an accurate determination of the parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix represents a crucial test of the Standard Model (SM). Moreover, improving the accuracy on the CKM parameters is at the heart of many searches for New Physics (NP), where we look for rather small effects. The Unitarity Triangle (UT) analysis, for example, allows a rather precise determination of the Wolfenstein parameters $\bar{\rho}$ and $\bar{\eta}$, obtained from a plethora of flavour measurements. This analysis has been performed by several groups, among which our collaboration (**UT***fit*), see for example `http://www.utfit.org` (the results presented here are an update on the "Summer 2016" analysis and they will appear in the web-page as "Winter 2017"). The experimental measurements are mostly taken from `http://www.slac.stanford.edu/xorg/hfag`, while the non-perturbative QCD parameters come from the most recent lattice QCD averages [1]. Using the above inputs a global fit gives $\bar{\rho} = 0.153 \pm 0.013$ and $\bar{\eta} = 0.343 \pm 0.011$, see Figure 1.

For many physical quantities relevant for studies of flavour physics, recent improvements in lattice computations have led to such a precision that electromagnetic effects and isospin breaking contributions cannot be neglected anymore. For light-quark flavours, important examples include the calculations of the leptonic decay constants f_K and f_π and of the form factor $f^+(0)$ in semileptonic $K_{\ell 3}$ decays. These are used to determine the CKM matrix element $|V_{us}|$ and the ratio $|V_{us}|/|V_{ud}|$ at high precision. For such quantities, which have been computed with a precision at the sub-percent level, the uncertainty due to the explicit breaking of isospin symmetry (of the order of $(m_u - m_d)/\Lambda_{QCD} \sim 0.01$) and to electromagnetic corrections (of the order of $\alpha \sim 0.007$) is similar to, or even larger than, the quoted QCD errors. Several collaborations have recently obtained remarkably accurate results in the calculation of the electromagnetic effects in the hadron spectrum and in the determination of quark masses with ab-initio lattice calculations see [2] for a recent review on the subject.

In a recent paper, a new proposal to include electromagnetic and isospin-breaking effects in the non-perturbative calculation of hadronic decays was presented and and fully developed in Refs. [3,4]. As an example of the new method, the procedure to compute $O(\alpha)$ corrections to leptonic decays of pseudoscalar mesons was described in detail. This can then be used to determine the corresponding CKM matrix elements.

Whereas in the calculation of the hadron spectrum there are no infrared divergences, in the case of electromagnetic corrections to the hadronic amplitudes the infrared divergences are present and only cancel for well defined, measurable physical quantities. This requires the development of a new strategy, different than the usual approaches followed to compute the electromagnetic corrections to the spectrum. We proposed such a strategy in Refs. [3,4].

The inclusive decay rate for $P^- \to \ell^- \bar{\nu}_\ell[\gamma]$ can be written as $\Gamma(\Delta E) = \Gamma_0^{(tree)} \times [1 + \delta R_P]$, where $\Gamma_0^{(tree)}$ is the tree-level decay rate given by

$$\Gamma_0^{(tree)} = \frac{G_F^2}{8\pi} |V_{q_1 q_2}|^2 m_\ell^2 \left(1 - \frac{m_\ell^2}{m_P^2}\right)^2 \left[f_P^{(0)}\right]^2 m_P \ , \quad (1)$$

and δR_P the $O(\alpha)$ electromagnetic/isospin correction. Preliminary results for the corrections δR_π and $\delta R_{K\pi} \equiv \delta R_K - \delta R_\pi$ give

$$\delta R_\pi^{phys} = +0.0169 \ (15) \ , \quad (2)$$
$$\delta R_{K\pi}^{phys} = -0.0137 \ (13) \ , \quad (3)$$

where the errors do not include the QED quenching effects. Our findings (2)-(3) can be compared with the corresponding ChPT predictions 0.0176(21) and $-0.0112(21)$[1].

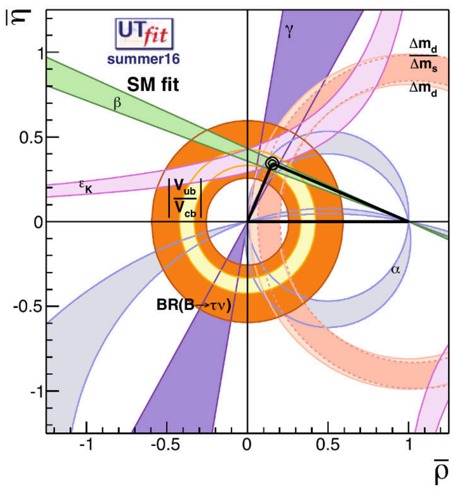

Figure 1: $\bar{\rho} - \bar{\eta}$ plane showing the result of the SM fit. The black contours display the 68% and 95% probability regions selected by the given global fit. The 95% probability regions selected by the single constraints are also shown.

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T4. Some non perturbative aspects of quantum field theory

Quantum Field Theory, in the form of the so called Standard Model, provides nowadays a description of High Energy Physics in complete agreement with all available data. One of the main instruments used to extract predictions from the Standard Model is perturbation theory, whose application is however limited to weakly coupled systems. While this is no obstacle in the treatment of processes involving leptons and intermediate vector bosons, perturbative techniques cannot be applied to the Standard Model sector which describes the strong interaction of quarks and gluons. Processes involving hadrons are treated by so called Lattice QCD, which, using a discretization of space-time, allows a completely non perturbative numerical evaluation of many interesting aspects of strong interaction dynamics. In particular we want to illustrate a couple of recent studies on non perturbative aspects of Quantum Chromodynamics using the lattice regularization:

- Radiative corrections to hadronic processes

  A long standing problem in elementary particle physics is the disentanglement of the contributions of various kinds of interactions to a particular process. The solution of this problem is particularly difficult in the case of electromagnetic effects superimposed to hadronic processes. As an example we may consider the leptonic and semileptonic decays of light or heavy pseudoscalar mesons. The difficulty consists in the fact that, while the electromagnetic interaction can be approximated by low order perturbation theory, the interesting hadronic process receives non perturbative contributions which cannot be easily estimated.

  In the paper [1] for the first time, a method is proposed to compute electromagnetic effects in hadronic processes, such as decays, using lattice simulations. For this kind of processes, the prcedure is complicated by the presence of infrared divergences. In order to compute the physical widths of the decaying system, the diagrams with virtual photons must be combined with those corresponding to the emission of real photons. Only in this way do the infrared divergences cancel as first understood by Bloch and Nordsieck in 1937. The very interesting point is that the implementation of this method, although challenging, is within reach of the present lattice technology and could give a serious contribution to the comparison of physical theories with experiments.

- An interesting problem which also requires a non perturbative treatment is the study of the color structure of the wave functionals of the SU(3) Yang-Mills theory in the presence of a $q\bar{q}$ static pair. In other words, the system under consideration is the non abelian quantum field generated by a static, infinitely heavy quark-antiquark state. The $q\bar{q}$ pair has a fixed position in space, but can evolve in its color content, giving rise to a complicated, interesting dynamics.

  In [2], based on a theoretical formulation by G. C. Rossi and M. Testa, we have performed a numerical study of thos system in a spatial box with periodic boundary conditions. We found that all states contributing to the Feynman propagation kernel are global color singlets and discussed the mechanism underlying this result, and its relation to the adopted periodic boundary conditions.

  The methodology explored in this paper could be important in the study of the effective potentials used to describe the dynamics of heavy quarks.

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T5. Weak matrix elements and hadron properties from quantum chromodynamics on a space-time lattice

The theory of Quantum Chromodynamics (QCD) is today considered the best candidate to describe the strong interactions. Important questions concerning the the Standard Model (SM) - such as the value of the light quark masses, the value of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements or the study of CP violation within the SM and beyond - involve hadron dynamics at low energies. At these scales QCD is non-perturbative and has not been solved analytically: quantitative predictions become thus very challenging. At present, the only first principle approach known which allows non-perturbative computations is called lattice QCD. It consists in regularising the theory on a space-time lattice and computing numerically the functional integral through Monte Carlo methods based on Markov processes. Recent years have witnessed significant progress in the development of algorithms and simulating light quarks on large volumes has become feasible on current super-computers. However, approaching the continuum limit means approaching a continuous phase transition and therefore critical slowing down is to be expected. The severity of the critical slowing down depends on the algorithm and on the observable in question. An observable with notoriously long auto-correlations for virtually all algorithms used for QCD is the topological charge. However, slowly moving modes of the transition matrix of the Markov process couple not only to the topological charge but also to other observables, therefore leading to long auto-correlations. A recently proposed solution to the freezing of these slow modes in the continuum limit consists in using open boundary conditions in the temporal direction.

By joining a collaborative effort called "Coordinate Lattice Simulations" (CLS) we have generated several ensembles of gauge configurations with 2+1 flavors of dynamical quarks (two degenerate light up and down plus the strange quark) with different values of the masses, volumes and lattice spacings. We have used open boundary conditions in the temporal direction and twisted-mass re-weighting to avoid the sector formation due to zero eigenvalues of the Wilson fermions and the resulting instabilities in the simulation [1]. Within this collaborative effort, M. Papinutto has been Principal Investigator of the project "The continuum limit of QCD with three dynamical quark flavours" granted within the 11th PRACE Call with 74 Mega core hours on the IBM BG/Q machine "FERMI" at CINECA (Italy). This computer time has been fundamental in order to generate ensembles with lattice spacing as small as 0.035 fm, the finest one ever simulated with dynamical quarks on large physical volumes.

Typical quantities of interest in flavour physics that need to be computed non-perturbatively by using lattice QCD are matrix elements of composite operators made of quark fields amongst light hadron states. These matrix elements enter, for example, the theoretical prediction of CP violating observables in the $K^0 - \bar{K}^0$ system, within the SM and in models of New Physics. In order to compute non-perturbatively these matrix elements, a very important step is the renormalisation of the composite operators, which also needs to be carried out in a non-perturbative way. At present, two methods exist to compute non-perturbaively the renormalisation constants of composite operators: The RI-MOM scheme and the Schrödinger Functional (SF) scheme. Only the last one however allow for a non-perturbative computation of the Renormalization Group (RG) running down to hadronic scales of few GeV's.

In the case of $K^0 - \bar{K}^0$ (or $B^0 - \bar{B}^0$) matrix elements, the relevant operators are 4-quark operators with a net change of 2 unities in flavour ($\Delta F = 2$). Using the SF scheme, we have thus performed a fully non-perturbative computation of the renormalisation constants and RG running for the complete basis of $\Delta F = 2$ operators (the first such study in presence of mixing) [2].

In order to match the non-perturbative running with perturbation theory at the electroweak scale, the next-to-leading order (NLO) anomalous dimension matrix for the complete basis of operators in the SF scheme was also needed. This has been obtained through a one-loop computation of the matrix of renormalisation constants in the SF scheme [3] and in a new setup called the Chirally Rotated SF which presents several advantages with respect to the standard SF [4]. An interesting byproduct of our computation has been the study the systematic uncertainties related to the use of NLO perturbation theory for the RG running down to hadronic scales, as done usually in the phenomenological literature. Our conclusion was that perturbative truncation effects in the RG running can be significantly large - in particular for the operators which contribute in models of New Physics beyond the SM - therefore posing serious doubts on all the computations of $\Delta F = 2$ matrix elements available at present.

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T6. Theory and phenomenology of quantum-spacetime symmetries

The last century of physics has been primarily characterized by a long list of successes of the quantum paradigm. In a significant part of the literature on the search of a quantum gravity, a theory providing a unified description of both quantum theory and general relativity, researchers are looking for ways to apply this quantum paradigm also to the description of spacetime. This effort is faced by significant conceptual challenges, and perhaps even more sizeable are the experimental challenges, since it is expected that the spacetime quantization should be characterized by a ultrasmall length scale, roughly given by the Planck length $\ell_P \simeq 10^{-35}m$. One of the most popular attempted formalizations of spacetime quantization is spacetime noncommutativity, a formalism that endows the spacetime coordinates of particles with intrinsically nontrivial algebraic properties, whose most studied examples introduce two model-dependent noncommutativity matrices $\theta_{\mu,\nu}$, $\xi^{\alpha}_{\mu,\nu}$

$$[x_\mu, x_\nu] = i\ell_P^2\theta_{\mu,\nu} + i\ell_P\xi^{\alpha}_{\mu,\nu}x_\alpha \, .$$

Amelino-Camelia was one the first advocates of an approach to the study of noncommutative spacetimes which is centered on symmetry analysis, searching for both a suitable formalization and an associated phenomenology programme. Of particular interest are cases in which the symmetries of a noncommutative spacetime require a Hopf-algebra description. The core feature of this novel concept of a Hopf-algebra description of spacetime symmetries resides in the way in which the generators of the symmetries act on states of two of more particles, states which are therefore formalized as elements of a tensor product of multiple copies of the single-particle Hilbert space. For some of the most compelling choices of the noncommutativity matrices one finds an incompatibility between the noncommutativity of spacetime coordinates and the imposition of Leibniz law for the action of the generators T_a of spacetime symmetries on elements of the relevant tensor products,

$$T_a\left(\Psi(x)\Phi(x)\right) \neq \left(T_a\Psi(x)\right)\Phi(x) + \Psi(x)\left(T_a\Phi(x)\right) \, .$$

Some of our most recent theory results [1,2] provide a deeper understanding of Hopf-algebra spacetime symmetries, including the fact that in presence of such symmetries the dimensionality of spacetime, as perceived by probes of Planck-length wavelength, could be smaller than 4, as expected in several other quantum-gravity research programs.

Some of our recent phenomenological studies focused on the laws of propagation of particles in some much-studied quantum-spacetime pictures (including spacetime noncommutativity when the noncommutativity matrix $\xi^{\alpha}_{\mu,\nu}$ doe not vanish), which in particular admit a description of the speed of ultrarelativistic particles of the type

$$v = \eta\ell_P E \pm \delta\ell_P E^\gamma \, . \tag{1}$$

where E is the energy of the particle while η, δ, γ are phenomenological parameters (the notation "$\pm\delta$" reflects the fact that δ parametrizes the size of fuzziness/quantum-uncertainty effects). It is emerging that this sort of effects, even when their magnitude is minute (because of the Planck-length suppression) can be tested meaningfully using observations of gamma-ray bursts, bursts of high-energy photons emitted by sources at cosmological distances. The net result is that one gathers indirect evidence on the short-distance quantum structure of spacetime and its symmetries. In most other contexts Planck-length effects are too small to be observed, but some gamma-ray bursts have a rich structure of space/time/energy correlations and the fact that they travel cosmological distances allows for the minute quantum-spacetime/Hopfsymmetry effects to have in some cases nonnegligible cumulative manifestations. Unprecedented sensitivity levels where exposed in our recent Ref.[3], building on a rather sizable literature focusing on this opportunity, which has been growing over the last decade. We also opened recently [4] a completely new direction for quantum-spacetime phenomenology, exploiting the fact that it became possible, with the IceCube neutrino observatory, to observe cosmological neutrinos. There would be opportunities for a very rich phenomenology if indeed, as expected by the relevant astrophysical models, gamma-ray bursters also emit neutrinos.

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T7. Energetic neutrino and ultra high energy cosmic ray astronomy?

Since recent 2013 the cubic km high energy neutrino detector, ICECUBE, detected a flavor change in highest tens TeVs up to PeVs events. The atmospheric muon neutrino tracks in ICECUBE above 60 TeV are suddenly overcrowded by (electron or tau) shower and cascades. Such an energy neutrino signal change is generally indebted to a new ruling HE neutrino component signals migrating from the atmospheric neutrino noise to a new dominant astrophysical neutrino injection [1]. Prompt atmospheric neutrino might be also polluting: the absence of any tau presence (a double bang imprint) in a dozen of highest hundred TeV events, we suggested, might favor a prompt neutrino role. Indeed most (4:1) of those new HE events are cascades (spherical lightening in ICECUBE) with a poor ($\pm 10^o$) directionality. Rarer muon HE tracks are more precise but rare. No obvious astronomical correlation have been found by few contained muon tracks. We noted that the best astronomical neutrinos could be the highest tracks made by crossing muon, born outside the ICECUBE detector. Indeed the HE tracks originated by primary muon neutrino interactions outside the cubic km volume, whose trajectories are crossing inside the ICECUBE volume, they are originated by a wider larger volume, offering a more abundant rate and a better and sharper source map. We foresaw that such crossing muons may be a leading tool in a few years to HE neutrino astronomy also by self correlation or clustering events, also in connection to UHECR (Ultra High Energy Cosmic Rays) narrow clustering. Recent data seem to confirm our earliest proposal and estimate [2]. Indeed on a complementary astrophysical frame, since two decades, UHECR signals in largest array detectors, as AUGER,TA (Telescope Array) ,AGASA, reached large numbers (hundreds) of events. Because of their energy UHECR, if they are nucleons, they may fly almost unbent and they may trace their sources within a bounded (one percent) of Universe radius. This limit exist because of the cosmic radiation opacity (the so called GZK cut off) due to photo-pion viscosity at highest energies. These last UHECR maps we claimed tell us three main results: the remarkable absence of (otherwise expected) Virgo source (the nearest cluster of galaxy in GZK universe), a twin Hot Spot of UHECR clustering (North and South ones) whose smeared origin has been associated by us to lightest nuclei bending, born around Cen A and M82, the nearest AGNs; the consequent lightest nuclei composition in UHECR, that we did foreseen since nearly a decade suffer of an opacity (the GZK photo-nucleon dissociation) explaining the puzzling Virgo absence. These results have been confirmed by later and last AUGER composition model pointing to lightest nuclei UHECR [3]. Finally among the amazing HE puzzles in ICECUBE data is the (unexpected) absence of any correlation between the HE (TeVs) muon tracks and the GRBs (Gamma Ray Burst) events. This absence make the best GRB candidate somehow surprising by their otherwise (foreseen) huge neutrino signal, based on GRB Fireball hadronic models. In order to overcome the expected Fireball secondaries neutrinos traces, we considered a new version of GRB made by a precessing gamma blazing jet, fed mostly by pure electronic primary electron pairs jet in inverse Compton Scattering. The model is born within a NS-NS (NS, Neutron Star) or NS-BH, (Black Hole), binary system at late spiral and collapse phase. The lightest companion (NS) suffer of neutron escape by tidal stripe tease, in feeding an accretion disk at BH, a disk proton dominated and charged one. The relativistic electron in neutron decay are forced by the disk magnetic field to shrinkage along the magnetic axis accelerating and feeding a GeVs-TeVs electron pairs jet and a consequent collinear gamma jet. Its blazing are seen as GRBs. The late NS final lightest fragment before its final merging sometimes may lead (below 0.2 solar mass) to the NS instability and explosion, during the BH jet blazing to us as a GRB. This may explain the rare (a few percent) and unexplained presence of a GRB burst followed by an (apparent) SN explosion. The new model may explain by its persistence of a thin, precessing, spinning gamma jet the otherwise mysterious X-gamma precursor whose flash is unreasonable and mysterious in Fireball models [4].

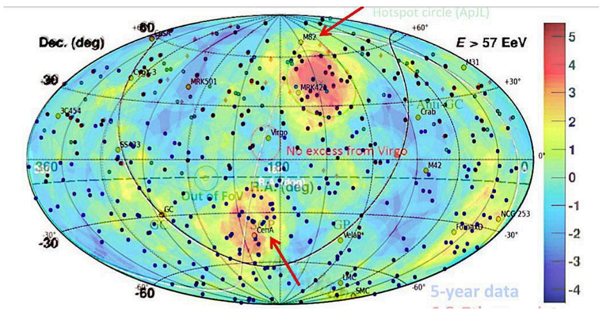

Figure 1: The two main smeared Hot Spot North, South, and the M82 and Cen A tagged sources.

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T8. Gravitational waves from astrophysical sources

After decades of experimental and theoretical efforts and advances, on September 14th 2015 the first gravitational wave (GW) signal – emitted in the coalescence of two black holes (BHs) – has finally been detected, opening a new observational window on the Universe.

One of the most promising sources of GWs are neutron stars (NSs), which provide an ideal laboratory to study matter under extreme conditions of temperature, density and spacetime curvature. Indeed, they are the only environment in the universe where all these conditions can be found, since only their enormous gravitational fields can compress matter well above the nuclear saturation density. In recent years astrophysical observations have improved our understanding of NSs; however, the equation of state (EoS) of matter in such extreme conditions still remains uncertain, mostly due to our lack of knowledge of the non-perturbative regime of quantum chromodynamics. GWs emitted in astrophysical processes involving NSs will allow us to gain a deeper understanding of the NS EoS, providing information both on the gravitational and on the nuclear interaction. Our studies have been focused on the imprint that the EoS of nuclear matter leaves on the GW signals, in different phases of a NS life. ➢**Tidal deformations of neutron stars in coalescencing binaries.** During the latest stages of the coalescence of binaries involving two NSs or a NS and a BH, as the orbit shrinks due to GW emission, tidal interactions become increasingly important, and deform their multipolar structure. This leaves a detectable imprint on the emitted gravitational waveform encoded in the tidal Love numbers, which measures the degree of deformability of the star when it interacts with the tidal field of its companion. Tidal Love numbers carry information on the EoS of matter in the NS interior and have been shown to satisfy some approximately EoS-independent "I-Love-Q" relations, with the moment of inertia I and the spin-induced quadrupole moment Q, which are very useful to remove some degeneracy in the parameter identification of GW signals.

In [1] we have proposed a procedure, based on such relations, to be used to restrict the parameter space searching for GW signals in coincidence with short gamma-ray bursts and to gain information on the EoS of the components. The procedure allows to assign a probability that the emitted GW signal is associated to the formation of an accretion disk massive enough to supply the energy needed to power a short gamma-ray burst.

The theory of tidal deformability of relativistic objects was restricted to static and spherically-symmetric configurations. Since all celestial objects rotate, this theory needed to be generalized to include rotation. We have developed a framework to compute the tidal deformations of a spinning compact object in a perturbative expansion in the angular momentum. We have applied this framework to prove that all tidal Love numbers of a Kerr black hole are zero to second-order in the spin and for an axisymmetric tidal field [2]. Furthermore, we have computed the Love numbers of a NS to first order in the spin, showing that spin-tidal couplings can introduce important corrections to the gravitational waveforms of spinning NS binaries approaching the merger [3].
➢ **GWs from newly born neutron stars.** We have studied the evolution of the rotation rate of a proto-NS, born in a core-collapse supernova, in the first seconds of its life. During this phase, the star evolution can be described as a sequence of stationary configurations, which we have determined by solving the neutrino transport and the stellar structure equations in general relativity, including the angular momentum loss due to neutrino emission [4]. We have determined the emitted GW signal (see Fig. 1), and estimated its detectability by present and future ground-based interferometric detectors. We have also shown that the "I-Love-Q" relation is violated in the first second of the star evolution [5].

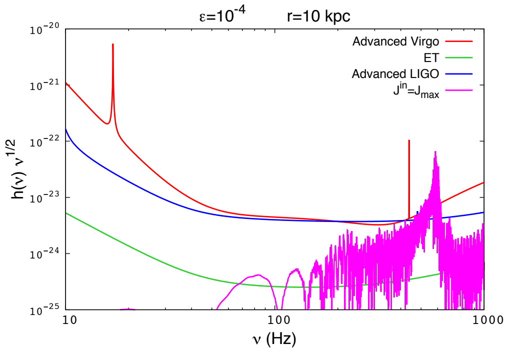

Figure 1: Strain amplitude $\tilde{h}(f)\sqrt{f}$ of the GW signal emitted by a newly born NS with oblateness $\epsilon = 10^{-4}$, at a distance $r = 10$ kpc, compared with the noise curves of Advanced Virgo/LIGO and the third generation detector, ET.

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T9. Tests of gravity with gravitational and electromagnetic 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. Before that detection, we only had tested the weak-field regime of gravity. GW astronomy, together with upcoming large-area X-ray detectors, will allow us to explore the realm of strong-field gravity, and to test whether GR provides an accurate description of the gravitational interaction also in this regime.

To this aim, we have considered simple modifications of GR, such as scalar-tensor theories and quadratic gravity theories, in which scalar fields and bilinear terms in the curvature are included in the gravitational action. We have worked out how these modifications would affect strong-gravity astrophysical processes, such as those involving BHs and neutron stars, and how these effects could be extracted from the GW and electromagnetic signals emitted in these processes.

➢ **Black-hole spectroscopy.** The latest stage of a BH-BH coalescence is characterized by the "ringdown" of the final object. The corresponding GW signal is a superposition of a set of quasinormal modes (QNMs), whose frequencies carry information on the corresponding spacetime and therefore on the underlying theory of gravity: a detection of the BH QNM frequencies would allow to test GR in the strong-field regime. We have studied Einstein-dilaton-Gauss-Bonnet (EDGB) gravity, a particularly well-motivated extension of GR, which includes higher-order curvature terms and a scalar field. We found that BHs are linearly stable also in this theory and investigated how their QNMs can be excited during astrophysical processes. We have also shown that future ringdown detections with a large signal-to-noise ratio would improve current constraints on the coupling parameter of the theory.

➢ **Testing GR with QPOs of accreting BHs.** Quasi-periodic oscillations (QPOs) observed in the X-ray flux from accreting BHs are emitted in the near-horizon region, which is characterized by strong gravitational fields and large curvature. In the near future, very large-area detectors such as LOFT and eXTP will increase the accuracy of QPOs measurements, making it possible to test gravity in the strong-field regime. Using one of the most reliable QPO models, the relativistic precession model, we have determined how GR modifications predicted by EDGB gravity would affect the QPO frequencies, and we have devised a data-analysis strategy to use these observations to discriminate between GR and alternative theories. We have shown that the accuracy of LOFT/eXTP would be sufficient to set constraints on the parameter space of EDGB gravity.

➢ **GW echoes of exotic compact objects.** Theoretical arguments suggest that quantum effects might halt the gravitational collapse preventing the formation of an event horizon (EH). We have discovered that – in these scenarios – the initial ringdown phase is identical to that of a BH, but a smoking gun of new physics at the horizon scale is the presence of "echoes" in the post-merger GW signal of a BH-BH coalescence (cf. Fig. 1). These echoes, produced by GWs trapped near the horizon, are absent in the classical BH picture in which the EH is a one-way membrane. They are slowly radiated through tunneling and produce a modulated train of pulses in the post-merger phase at late times, whose peculiar waveform carries information about the near-horizon deformations, even if the latter are microscopic or Planckian.

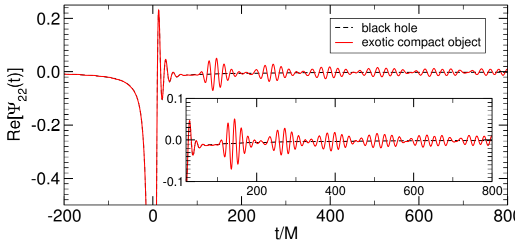

Figure 1: GW echoes of an exotic compact object in which the EH is replaced by a membrane at Planckian distance.

➢ **Testing GR with GW stochastic background.** The GW detection in 2015 has shown that the population of coalescing binary BHs is larger than previously expected. These sources produce an unresolved, potentially observable background of GWs. We have investigated how modified theories of gravity, modeled using a parametrized post-Einsteinian formalism, affect the expected signal, and we have analyzed the detectability of the resulting stochastic background by current and future ground-based interferometers. We have estimated the constraints that Advanced LIGO/Virgo would be able to set on modified theories, showing that they may significantly improve the current bounds obtained from astrophysical observations of binary pulsars.

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T10. Collective behaviour in biological systems

Collective behavior is a widespread phenomenon in biological systems, spanning from the microscopic scale of cell colonies to the macroscopic world of animal aggregations. In many such cases collective behavior is an emergent phenomenon: there is no external leader or common stimulus, rather, the collective patterns are uniquely determined by the mutual interactions between individuals. In this respect, collective behavior in living systems is similar to collective behavior in condensed matter. Statistical physics and field theory have provided a powerful theoretical framework to investigate these phenomena, and much of current research in active matter is focused on living systems at the micro-scale.

As compared to many assemblies living at the micro-scale, animal groups present some distinctive features. At phenomenological level, these groups display a remarkable degree of collective response while maintaining global cohesion and coordination. Somehow they are therefore capable of optimally balancing sensitivity and robustness. At the individual scale, mutual interactions are the outcome of complex cognitive processes, hence a theoretical study of collective behavior in these systems has to rely on effective theories, where inter-particle interactions are schematized. In this respect, we may say that theoretical models of collective behavior are to the real biological phenomenon what the Ising model is to real quantum ferromagnets.

The COBBS (Collective Behavior in Biological Systems) group aims at studying these phenomena using the conceptual framework of statistical mechanics and field theory. In the period 2014-2016 the activity of the group has focused on two main topics: i) discovering how information propagates in biological systems characterized by ferromagnetic order (flocks of birds); ii) characterizing long-range correlations in biological systems in their paramagnetic phase (swarms of insects).

Information propagation in biological groups is crucial for the system to change collective state in a coordinated way. We studied both experimentally [1] and theoretically [2,3] how global changes of directions (namely, turns) propagate in flocks of starlings (Fig.1). We found that information spreads across the flock with constant speed and almost without damping. By introducing a generalized moment of inertia, we have proposed a new dynamic model that fits very well with experimental data and is able to predict the behavior observed in nature.

While in highly coordinated systems like flocks it is obvious that there is collective behavior, in disordered systems like insect swarms it was up to now unclear. It has been known for decades that swarms are formed close to an external landmark (a lamp, a log, a white cloth); this landmark acts as an external field, hence the individuals in these systems could be not even interacting among themselves. We performed experiments on wild swarms of midges and we showed in [4] that connected correlations in these systems are in fact strong, despite the low degree of global order, indicating that swarms are interacting systems. More precisely, performing a finite size analysis on groups of different size and density we showed that swarms are quasi-critical systems. They tune their control parameter and size so as to maintain a scaling behavior of the correlation function: correlation length and susceptibility scale with the system size and swarms exhibit a near-maximal degree of correlation at all sizes [4].

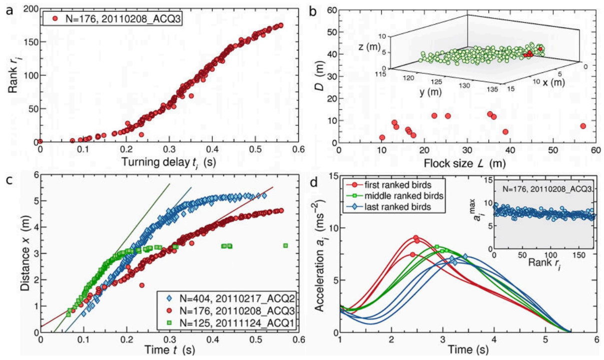

Figure 1: **Propagation of the turn across the flock.** a) The order in the turning sequence is plotted versus the absolute turning delay. b) The first birds to turn (in red) are actually close to each other in space. c) Distance vs. time along the turning sequence. The speed of propagation is the slope in the linear regime. d) The intensity of the peak of the radial acceleration decreases very weakly in passing from the first to the last turning birds. From [1].

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T11. Statistical mechanics of small systems and fast transformations

A challenging fronteer in statistical physics concerns systems with a "small" number N of degrees of freedom, far from the thermodynamic limit: this is motivated by the increase of resolution in the observation and in the manipulation of the micro-nano world. The distinguishing feature of small systems is the relevance of fluctuations, which cannot be neglected. The study of fluctuations of thermodynamics quantities such as energy or entropy goes back to Einstein, Onsager and Kubo, but has recently taken an acceleration with the establishing of new results in response theory and in the so-called stochastic thermodynamics. Such a turning point has received a great impulse from the study of systems which are *far* from thermodynamic equilibrium, and therefore is intimately connected to the problem of fast transformations. For instance, a cyclical transformation - such as the one driving a heat engine - is "fast" when its cycle time τ is shorter than the relaxation times of the system. Fast transformations constitute a key problem in the industry and, for this reason, have been under the scrutiny for many decades. In physics, in the 70's of the last century, several results were obtained in the so-called finite time thermodynamics, one of the foremost being the Curzon-Ahlborn estimate for the efficiency at maximum power. In a nutshell, modern statistical mechanics addresses the finiteness of both transformation's time τ and system's size N.

In our research we have individuated a model for the study of statistical properties of fast and small systems: this model consists in a gas of N simple molecules (e.g. hard spheres) enclosed in a box. One side of the box is a sliding piston which has a finite mass and is submitted to an external force F. The opposite side of the box is a thermostat at temperature T. We have studied the thermodynamic and statistical properties of the system with constant parameters in [1], comparing microcanonical and canonical conditions and deriving a Langevin-like coarse-grained description for the dynamics of the piston. The next step has been to consider a cyclical transformation of the two parameters F and T, in such a way to obtain a heat-engine [2]. In the limit of large cycle time $\tau \to \infty$, the model reproduces the well known results of thermodynamics for quasi-reversible heat engines. At finite τ, on the contrary, different regimes appear: heat engine, refrigerator or heat sink. A comparison with a coarse-grained description of the piston's dynamics shows a qualitative agreement. The finiteness of N and τ leads to non-trivial distribution of fluctuations, in particular of the so-called fluctuating efficiency which is subject of many recent studies. In order to make contact with existing theories on finite-time engines, in [4] we have considered the case of small variations of F and T which (even for finite τ) lead to a linear relation (through a τ-dependent Onsager matrix) between fluxes and thermodynamics forces, as in classical linear thermodynamics.

A second problem in stystems far from the thermodynamic limit is an ambiguity in the definition of temperature in the microcanonical ensemble, which originates from the two possible choices of entropy, the one based upon the density of states in a certain energy shell (informally called Boltzmann entropy, BE) and one based upon the volume of phase space bounded by that shell (informally called Gibbs entropy, GE). The BE-based temperature can be negative for certain systems with bounded phase space, a fact which has been recently verified in experiments with ultracold bosons. Recent studies have harshly criticized the concept of negative temperature and its employment for the interpretation of real experiments. Our research has shown that such a concept naturally arises in statistical mechanics, is well posed and consistent with thermodynamics, and gives precious information about fluctuations and degrees of (spatial) order in the system.

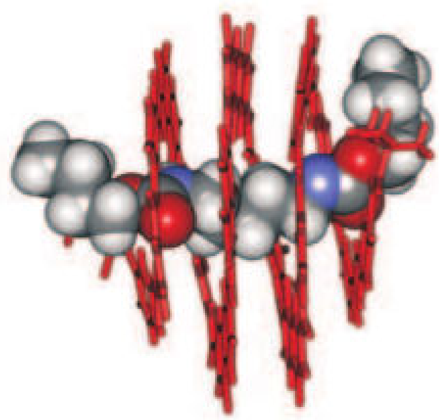

Figure 1: A self-assembled molecular motor with a sliding piston (from Q. Gan et al, Science 331, 1172 (2011)).

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T12. Equilibrium and nonequilibrium complex quantum systems

A common feature of our research is the study of complex quantum systems, i.e., systems where the presence of many, quantum degrees of freedom is the source of phenomena that do not take place at the classical level or for a few degrees of freedom. In some cases we have equilibrium states, more frequently systems out of equilibrium are addressed.

According to quantum mechanics chiral molecules, that is molecules which are not superimposable on their mirror image, should not exist. Chiral molecules correspond to states localized in one minimum of a double-well potential and cannot be stationary states of the Schrödinger equation. A possible solution of the paradox can be founded on the idea of spontaneous symmetry breaking. This idea was behind work we did previously involving a localization phase transition: at low pressure the molecules are delocalized between the two minima of the potential energy while at higher pressure they become localized in one minimum due to the intermolecular dipole-dipole interactions. Evidence for such a transition is provided by measurements of the inversion spectrum of ammonia and deuterated ammonia at different pressures. A previously proposed model gives a satisfactory account of the empirical results without free parameters. We have extended this model to gas mixtures [1]. Also in these systems a quantum phase transition in the internal degrees of freedom takes place at a critical pressure which depends on the composition of the mixture. The interest of this result ranges from the possibility of engineering the phase transition by properly choosing the constituents of the mixture, see Fig. 1, to the comprehension of planetary data.

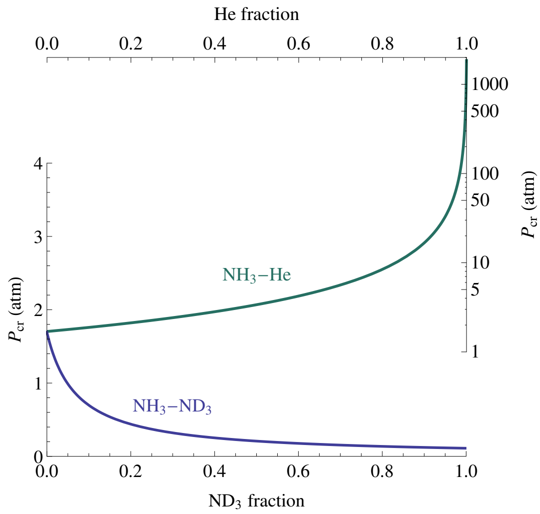

Figure 1: Critical pressure of the localization phase transition in a binary mixture of NH_3 as a function of the fraction of the second constituent chosen as ND_3 (bottom-left axes) or He (top-right axes) [1].

Preparing a quantum system in a target state is a core

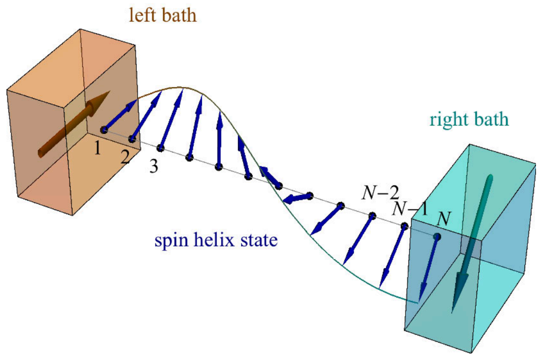

Figure 2: Stationary spin helix state obtained coupling a XXZ Heisenberg chain of N spins to boundary fully-polarizing reservoirs [2].

problem of quantum information science. Mixed coherent and dissipative preparation (MCADP) of pure steady states, well described by a Lindblad master equation, is stable against decoherence and almost independent of the initial conditions. Due to the existence of a unique nonequilibrium steady state (NESS), eventually, the system relaxes to the NESS, and, if the NESS is pure, somewhat paradoxically, the action of the controlled dissipation, instead of destroying the coherence of the system, protects its stability. In the MCADP of a pure steady state, the latter must be an eigenstate of both the coherent and dissipative parts of the dynamics. This greatly limits the nature of the accessible target states. We have shown that working in the Zeno regime, i.e., for infinitely large dissipative coupling, one can generate a pure state by a noncommutative action of the coherent and dissipative parts of the Lindblad equation [2]. This implies that an almost arbitrary target state can be reached as NESS of properly shaped Hamiltonian systems and reservoirs. In particular, we have investigated the case of boundary reservoirs, see Fig. 2.

We have obtained some rigorous results about the relaxation time to the NESS for a class of many-body models in contact with thermally equilibrated reservoirs [3]. Considering blackbody-radiation reservoirs has led us to a many-body revisitation of Fermi's golden rule [4].

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T13. 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, in which relatively small systems are considered (for instance, this is the case of recent cold-atom investigations). Moreover, a clear understanding of finite-size effects is needed in numerical work, as the size of the investigated systems is typically small. Close to a critical point, finite-size effects obey general scaling laws and show universal features that are shared by all systems whose transition belongs to the same universality class. More precisely, a critical 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. In rigorous terms, the FSS theory provides the asymptotic scaling behavior when both $L, \xi \to \infty$ keeping their ratio ξ/L fixed. 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]. This extension is very important, both for theory and experiments, as FOQTs are ubiquitous in low-temperature many-body systems.

In Ref. [2] we present a general FSS theory for a system undergoing a FOQT. We show that the low-energy properties of the quantum system obey general FSS laws, the relevant scaling variable being the ratio of the energy associated with the perturbation driving the transition and the finite-size energy gap at the FOQT point. The size dependence of the scaling variable is therefore essentially determined by the size behavior of the gap at the transition. The theory has broad validity. In particular, it applies to any FOQT characterized by the crossing of the two lowest-energy states in the infinite-volume limit. In this specific case, a phenomenological two-level theory also provides exact expressions for the scaling functions. It is interesting to note that one can use this general theory to predict the FSS behavior at classical first-order transitions, without the need of introducing difficult concepts like, for instance, the interface free energy and the associated correlation length. The general theory also predicts that the behavior at FOQTs is very sensitive to boundary conditions, as they can drastically change the size dependence of the scaling variable. For instance, in Ising systems with periodic boundary conditions the FSS scaling variable at the magnetic transition depends exponentially on L, while, for fixed boundary conditions, FSS depends on a power of L.

The general theory has been applied to a variety of first-order transitions, considering the Potts model [3] and the quantum Ising chain [4]. In particular, we have performed a general analysis of the FSS behavior of the Ising chain in a transverse magnetic field for fixed boundary conditions. We identify a first-order transition, separating a magnetic phase, in which the gap decreases exponentially with increasing size, and a kink phase, in which the gap decreases instead with a power of the size. Using the quantum-to-classical mapping one can identify this one-dimensional quantum transition with the classical two-dimensional wetting transition. Unexpectedly, the analysis of the quantum model provides new analytic results for such very old classical problem in a relatively straightforward way.

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T14. Statistical mechanics of strongly disordered systems

The physical behavior of strongly disordered systems is very different from the one of pure, homogeneous systems. Unfortunately, our understanding of the thermodynamic behavior of strongly disordered systems in the low temperature phase is still limited.

Our research group plays a world leading role in the study of strongly disordered systems. In the period covered by this report we have continued in different directions the study of spin glass models, which are considered the prototype of strongly disordered systems. On the one hand, we have continued large scale numerical simulations of the Edwards-Anderson (EA) model — a three-dimensional short range interacting spin glass model — via the dedicated FPGA-based reconfigurable supercomputer JANUS. Meanwhile we have participated to the realization of the new version of this supercomputer, JANUS II, that started the production in 2016. On the other hand, we have studied analytically mean-field (MF) spin glass models, with the aim of building a loop expansion, that could provide insight on the spin glass physics in finite dimensional models.

We have focused our attention on the study of spin glass models in presence of an external magnetic field. This is a particularly interesting case given that a phase transition in presence of a symmetry breaking field is a very unusual feature of MF spin glass models, related to their infinite number of thermodynamic states. Its presence in finite dimensional models has not been proven or confuted and would have important consequences. In particular the two major competing theories for describing spin glasses (the replica symmetry breaking scenario and the droplet model) have completely different predictions for the behaviour in a field.

Refs. [1] and [2] report the results of large scale simulations run on the JANUS computer of the $3D$ EA model in a field, studied via different numerical techniques. In [1] we simulated the out of equilibrium dynamics of very large systems of linear size $L = 80$ (such that finite size effects are absent and results are practically equivalent to those in the thermodynamic limit) for very long times, closely approaching experimental time scales (up to 0.01 seconds). As shown in Fig. 1, we have been able to measure very large relaxation times, suggesting the presence of a true thermodynamic phase in a field. However none of the existing theory is able to fit well the data.

In [2] we managed to properly thermalize the EA model of linear size $L = 32$ in a field down to $T \approx 0.8T_c$. Our main discover has been that the standard analysis based on averaging over different samples is strongly dominated by a minority of atypical samples, that hide the "silent" majority of samples. Performing a better analysis we have been able to find evidence for a thermodynamic phase transition in a field.

On the analytical side, we are computing loop corrections to MF theories. The main novelty, with respect

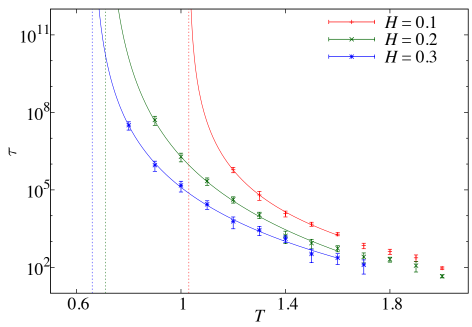

Figure 1: Growth of a relaxation time (τ) at low temperatures (T) in $3D$ spin glass models in a field (from Ref. [1]).

to previous attempts, is that now we are starting from an improved MF theory, the one based on the Bethe approximation which is exact for models on random graph topologies. This MF theory is already very complex, given that any physical observable depends on stochastic fields that have non trivial distributions (to be determined self-consistently via numerical integration).

We have been able to compute leading order loop corrections to the mean-field theory by summing over so-called fat diagrams (i.e. loops in real space). In Ref. [3] we have checked that the leading finite-size correction to the average free energy of disordered Ising models on random regular graphs can be computed as a weighted sum over all non-self-intersecting loops in the graph, the weight being the free-energy shift due to the addition of the loop to an infinite tree.

Recently we have started also the study of strongly disordered models with continuous variables, mainly XY spin models, and their discretized counterpart, the clock model. This kind of models may present new kind of long range order with respect to Ising models. Moreover as shown in Ref. [4] these models are very useful to describe the mode-locking transition of the phases of light modes in lasers at the critical lasing threshold.

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T15. Statistical mechanics of glassy materials: structural glasses, hard spheres jamming, random lasers

It is an empirical evidence that in many systems, the so called *glassy systems*, when we decrease the temperature the relaxation time strongly increases going from picoseconds to more than days. At low temperatures the typical time-scale becomes so large that it cannot be measured in human times. In some specific cases, like for three dimensional spin glasses in zero magnetic field, there is a strong evidence that this time diverges at a critical point and that a real thermodynamic phase transition is present.

In structural glasses the situation is more complex. After a region where the increase of the relaxation time can be fitted with a power law, by decreasing the temperature, before reaching T_c we enter a region where thermally activated processes are important. If we look at a glass on a time scale much smaller than the relaxation time, its microscopic components are frozen inside *cages* formed by the nearby particles that are also frozen inside other cages. The typical escape process is a collective movement of a few particles, whose number becomes larger when we decrease the temperature. One can define a dynamical correlation length (ξ_d) that is related to the size of the spatial regions where these correlated movements take place: this dynamical length (that does not have an equilibrium counterpart) becomes large at low temperature.

There are many questions to be studied in this transition region. In Ref. [1] we introduced a dynamical field theory to describe the glassy behavior in supercooled liquids. The mean-field approximation of the theory predicts a dynamical arrest transition. Beyond the mean-field approximation the theory predicts that the transition is avoided and transformed into a crossover, as observed in experiments and simulations. To go beyond mean-field a standard perturbative loop expansion is performed at first. Approaching the ideal critical point this expansion is divergent at all orders and the leading divergent term at any given order is the same of a dynamical stochastic equation, called Stochastic-Beta-Relaxation (SBR).

An other extreme situation is the zero temperature limit or equivalently the infinite pressure limit for hard spheres. In this infinite pressure limit hard spheres become jammed: the cages shrink to zero. The system freezes in one of the locally stable configurations (selecting a configuration that is close to the initial condition). Jamming of hard spheres is a new critical phenomenon whose exponents are different from those of the other known transitions. These exponents have been recently computed in a mean field approximation: such an analytic theory gives critical exponents that are in very good agreement with the ones obtained by accurate numerical simulations. For example at very large pressure the system is solid: each sphere moves inside a finite region of average squared sizeΔ. In the high pressure limit Δ_{EA} (i.e. the system average of Δ_i^2) behaves as a power of the pressure p, i.e. as $p^{-\kappa}$. The value of the exponent κ as been computed analytically [2] in mean field theory ($\kappa = 1.41574...$) in a remarkable agreement with the data. One of the main prediction of the theory is the existence of a new (Gardner) transition that has been actually observed in [3].

Glassiness can also be found in optical systems, as well, as recently theoretically and experimentally observed. This feature arises in particular in the so-called random lasers, i.e., optically active random media under optical pumping in which the feedback mechanism is provided by molecular randomness itself and the consequent multiple scattering of light. The investigation of the glassy behaviour of light in the framework of our theory is made possible by means of a newly introduced overlap parameter, the Intensity Fluctuation Overlap (IFO) measuring the correlation between intensity fluctuations of waves in random media [4]. This order parameter allows to identify the laser transition in arbitrary physical regimes, with varying amount of disorder and nonlinearity. In particular, in random media it allows for the identification of the glassy nature of some kind of random laser, in terms of emission spectra data, the only data so far accessible in random laser measurements. IFO measurements are possible in real experiments, recently leading to a validation of the RSB theory and a new characterisation of lasers in terms of spectral intensity fluctuations.

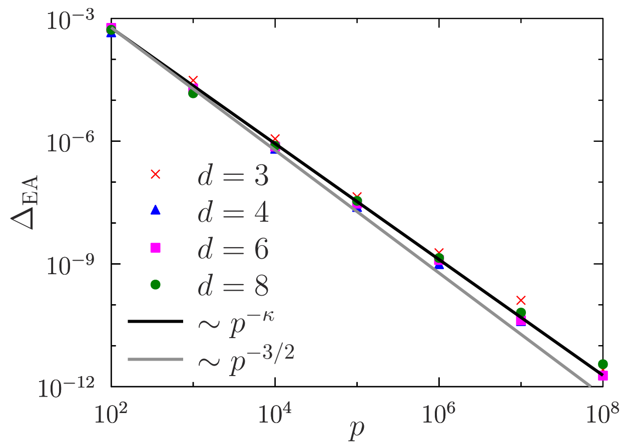

Figure 1: Pressure evolution of the Debye-Waller factor Δ_{EA} in $d = 3, 4, 6, 8$. The black line is a power-law with the theoretical value of the exponent κ . For comparison, we also show a power-law $p^{-3/2}$ as a grey line.

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T16. Nonlinear waves in complex and quantum systems

We study theoretically, numerically, and experimentally wave propagation in systems encompassing structural disorder and nonlinearity. We consider highly nonlinear regimes involving extreme phenomena like shock waves, solitons, and supercontinuum. The interplay between randomness and interaction opens many theoretical problems, as the link between Anderson localization and solitons, or the many-body quantum effects affecting classical nonlinear waves, like intense light pulses or gravitational disturbances.

The various challenges include explaining and controlling of the so-called extreme events, or "rogue waves:" Gigantic waves that arise from no specific excitation and disappear abruptly; these accompany catastrophic events like tsunamis, or earthquakes, and may be exploited for novel nonlinear optical devices. We demonstrated that rogue waves may originate from the energetic landscape of a large number of interacting solitons. This follows ideas from the statistical mechanics of disordered systems and shows that the probabilistic distribution of extreme events is given by the distribution of minima of a corrugated multidimensional surface.[1]

The link of waves and complexity is also evident in the photon dynamics in the presence of strong disorder and nonlinearity, as it happens in the so-called "random lasers." Light emitted from random lasers is indeed driven by a large number of competing states, and this led to the first experimental observation of the "replica symmetry breaking."[2] We study related phenomena as Anderson localization in curved manifolds (a topic relevant for Bose-Einstein condensation), topologically constrained systems, and long-range interactions.

The coupling of cellular automata with electromagnetic waves is also a fascinating framework. These models concern large-scale biological phenomena, like the moonlight driven coral spawning in the reef, but also new directions as quantum circuits for artificial intelligence. The figures show examples. [3]

A further frontier is testing fundamental principles by highly nonlinear phenomena. This includes modifications in the Heisenberg uncertainty principle, the breaking of time-reversal in quantum mechanics and the need for a new time-asymmetric formulation, and the link between quantum gravity and soliton physics.

We have shown by analytically solvable models and first principle stochastic simulations that a soliton in the integrable quantum nonlinear Schroedinger equation exhibits a number of features strongly resembling black holes and Hawking radiation. Black holes are indeed a special class of solitons. Adopting integrable quantum nonlinear models may furnish novel insights for quantum gravity in the era of gravitational waves.[4]

We employ some of the most advanced theoretical and numerical techniques (including massively parallel computations) to test the fundaments of physics in highly nonlinear, classical and quantum, regimes.

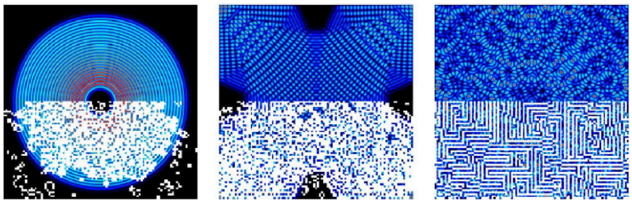

Figure 1: Different scenarios in the interaction between Conway's Game of Life Cellular Automata (CA) and electromagnetic waves in a cavity. The CA living cells are white spots and the wave is given in color scale. When increasing the coupling, the CA start sustaining wave propagation [3].

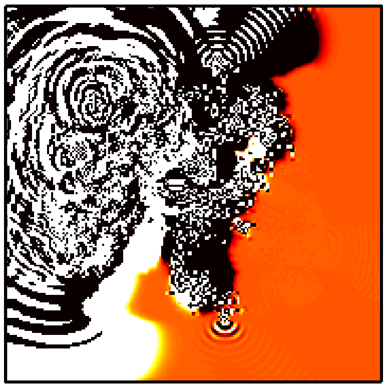

Figure 2: Light driven cellular automata after [3].

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T17. On the analytic description via integrable models of two extreme wave phenomena in nature: multidimensional wave breaking and anomalous (rogue) waves

1) Multidimensional wave breaking

Take any system of nonlinear PDEs i) characterized, for example, by nonlinearities containing quadratic terms and ii) whose linear limit, at least in some approximation, is described by the wave equation. Then, iii) looking at the propagation of quasi one dimensional waves and iv) neglecting dispersion and dissipation, one obtains, at the second order in the proper multiscale expansion, the dispersionless Kadomtsev - Petviashvili (dKP) equation in 2+1 dimensions: $(u_t + uu_x)_x + u_{yy} = 0$. Therefore dKP arises in several physical contexts, like acoustics, plasma physics and hydrodynamics. We remark that the 1+1 dimensional version of dKP is the celebrated Riemann-Hopf equation $u_t+uu_x = 0$, the prototype model in the description of the gradient catastrophe (or wave breaking) of one dimensional waves. Therefore a natural question arises: do solutions of dKP break and, if so, is it possible to give an analytic description of such a multidimensional wave breaking?

dKP is an integrable model arising as the commutation condition of a pair of 2 dimensional vector fields. A novel Inverse Spectral Transform (IST) for 1-parameter families of multidimensional vector fields has been developed in the recent past by our group, and used to construct the formal solution of the Cauchy problem for distinguished examples of nonlinear Partial Differential Equations (PDEs) of Mathematical Physics including dKP. This IST turns out to be an efficient tool to study relevant properties of the solution space of the PDE under consideration: i) the construction of the longtime behaviour of the solutions of the Cauchy problem; ii) the possibility to establish whether or not the lack of dispersive terms in the nonlinear PDE causes the breaking of localized initial profiles and, if yes, to investigate in a surprisingly explicit way the analytic aspects of such a multidimensional wave breaking [1]. More recently, such a formalism has been made rigorous [2], and the role of the nonlocalities in the dynamics completely understood [3].

2) Rogue waves.

Rogue waves (also known as freak waves, extreme waves, and anomalous waves) are large, unexpected and suddenly appearing waves. In oceanography, rogue waves are more precisely defined as waves whose height is more than twice the significant wave height. They present considerable danger for several reasons: they are rare, unpredictable, may appear suddenly or without warning, and can impact with tremendous force. Rogue waves can occur in media other than water. 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 cause for the formation of a rogue wave is Modulation Instability (MI). The nonlinear model describing the amplitude modulation of a quasi monochromatic wave in a weekly nonlinear medium is the celebrated nonlinear Schrdinger (NLS) equation $q_t + q_{xx} + 2|q|^2q = 0$, where q is the complex amplitude of the monochromatic wave and x and t are suitable slow variables, arising in all the above physical contests. NLS is a prototype example of integrable soliton PDE in 1+1 dimensions and exhibits, indeed, MI. Its integrability features allow, in principle, to obtain important analytic informations on the evolution of a rogue wave, from a finite background (f.i., a Stokes wave in a Fluid Dynamical context) perturbed by small waves: an unstable wave may form which "sucks" energy from the background and from other waves, growing to a nonlinear coherent structure whose amplitude is considerably larger than that of the background, before becoming too unstable and collapsing shortly after.

We have recently started a theoretical study of this phenomenon using the integrability features of NLS. In particular, we have already understood how, from fairly general initial conditions of the type described above, one or more rogues waves are generated, their analytic description in terms of elementary functions, as well as their generation, collapse and recurrence times in terms of the parameters associated with the initial data [4].

We also plan to compare, in a collaboration with the nonlinear optics group of this Department, these theoretical findings with actual experiments.

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T18. Resonances in quantum mechanics

A resonance occurs in quantum mechanics when a coupling between a state in the discrete spectrum and a continuum of states is turned on. Such a situation — namely that of a discrete state immersed in a continuum — is quite frequent in virtually any branch of physics and is usually faced by means of perturbative or ad-hoc numerical techniques. Given the relevance of the subject, it is natural to perform a study of the fundamental properties of resonance phenomena by looking at solvable, or "almost" solvable, models. The simplest Hamiltonian model possessing an infinite resonance spectrum is the so-called (Flugge-)Winter model, a one-dimensional quantum mechanical model describing a non-relativistic particle on a half-line subjected to a δ-like potential:

$$\hat{H} = \frac{\partial^2}{\partial x^2} - \frac{1}{\pi z}\delta(x-\pi), \tag{1}$$

with $x \geq 0$ and $\psi(x=0)=0$, where $z \neq 0$ is coupling, to be taken real in order to have an Hermitian Hamiltonian. For $z \to 0$, the potential wall (conventionally located at $x=\pi$) becomes impermeable and the system decomposes in two non-interacting subsystems: a particle in the box $[0,\pi]$ and a particle in the half-line (π,∞). For $z<0$, $|z| \ll 1$, the potential wall becomes weakly permeable, so that a particle initially located inside the cavity $[0,\pi]$ will take a long time to leave it because of tunnelling effect. A infinite spectrum of long-lived resonances therefore emerges out of the box eigenfunctions by turning on the coupling z. In ref.1 it is found that, contrary to previous results, it is not possible to excite individual resonances — with the exception of the fundamental one — by means of simple initial box eigenfunctions. The correct initial wavefunctions are formally obtained from the box eigenfunctions by means of a linear transformation represented by an infinite matrix $A=A(z)$ computed up to second order in z. An approximate, all-order resummation in z is also presented.

Winter model is attached with geometrical, rather than analytic, methods in ref.2, where the Riemann surface S controlling the resonance structure is explicitly constructed. The idea is that of complexify the coupling z and study the emerging multivalued transcendental functions. It is found that each sheet of S is related to a resonance, an antiresonance or a bound state. From this analysis, the limitations of perturbation theory are rigorously established; In particular, the convergence radii R_n's of the perturbative expansions for the frequencies $\omega_n(z)$'s and decay widths $\Gamma_n(z)$'s of the resonances are derived. Such radii are found to be an order of magnitude smaller than previously expected. Non-perturbative results are also obtained. By diagonalizing the non-perturbative mixing matrix $A(z)$ introduced in ref.1, it is found that the eigenfunctions belong to the Lebesgue space $L^2(R^+)$, i.e. are square summable, but not to the Sobolev space $H^1(R^+) \subsetneq L^2(R^+)$, of square summable functions with square summable (weak) first derivative. On physical ground that means that the eigenfunctions have infinite average kinetic energy, so are physically unacceptable: it is not possible to excite exactly one resonance at a time.

In ref.3 a general analytic method to compute resonance wavefunctions in multi-barrier systems is presented, which is based on an expansion in $1/n$, with $n = 1,2,3,\cdots$ the excitation number. The method is based on the observation that the effective coupling of the n-th resonance to the continuum is $\zeta \equiv nz$, rather than z. It is therefore possible to reorganize the double series in n and in z as a series in ζ and in $1/n$ and to obtain closed analytic expressions for the coefficients $\sigma_k(\zeta)$ of $1/n^k$ for $k=0,1,2,\cdots,k_{\max}<\infty$. As a check, the method is first applied to the Winter model re-obtaining some of the the results contained in ref.1 and ref.2, together with some improvements. In particular, a resummed expression for the lowest-order (lo) decay width is obtained,

$$\Gamma_n^{\mathrm{lo}}(z) = \frac{n}{\pi}\ln\left[1+(2\pi n z)^2\right], \tag{2}$$

which interpolates between the fixed-order perturbative result, — namely a truncated expansion in powers of z — and the non-perturbative one for $|nz| \gg 1$ obtained in ref.2. The method is then applied to a double barrier system in the entire real line with arbitrary couplings for the barriers. The final and most complicated application of the $1/n$ expansion is the analysis of a triple-barrier model,

$$\hat{H} = \frac{\partial^2}{\partial x^2} - \frac{1}{\pi z_-}\delta(x+\pi) - \frac{1}{\pi z_0}\delta(x) - \frac{1}{\pi z_+}\delta(x-\pi), \tag{3}$$

with arbitrary couplings z_-, z_0 and z_+, but with equal spacings between the δ's, assumed conventionally to be equal to π. The resonance spectrum of this model is rather rich and presents a double degeneracy for $z_0 \to 0$; oscillation phenomena similar to $k^0 - \bar{K}^0$ mixing are found.

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T19. Markov chains on graphs

Let $\mathcal{G} = (V, E)$ be a connected finite graph with vertex set $V = \{1, 2, \dots, n\}$. 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 $D = \mathrm{diag}(d_1, \dots, d_n)$ 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 [1] 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.

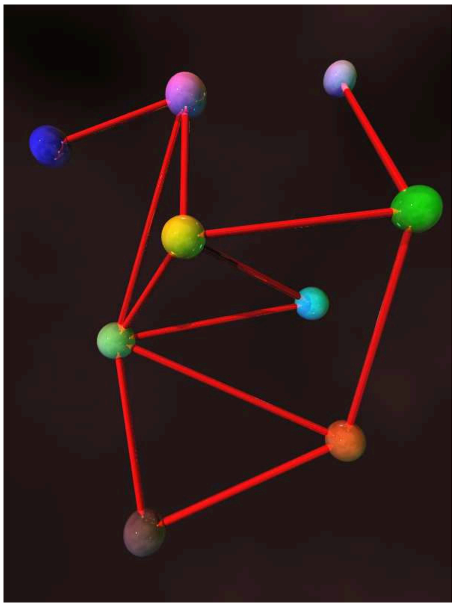

Figure 1: A configuration of the interchange process.

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Author
F. Cesi

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.

PhD in Astronomy, Astrophysics and Space Science

Since its XXVII-th cycle, the Dep. of Physics in Sapienza offers a PhD program in English, in agreement with the 2nd university of Roma Tor Vergata and the Istituto Nazionale di Astrofisica (INAF). Usually, this PhD program offers 14 positions per year, 11 of which are covered by a fellowship.

The coordinator and deputy coordinator are prof. Pasquale Mazzotta (Tor Vergata) and Roberto Capuzzo-Dolcetta (Sapienza).

This PhD program belongs to the V. Volterra doctorate School of Sapienza, that comprises also the PhD programs in Chemistry, Earth Sciences, Mathematics, Physics, Relativistic Astrophysics (see the site `http://www1.mat.uniroma1.it/ricerca/dottorato/ScuolaVolterra/index_en.html`).

Both didactic and scientific activity are in ENGLISH. This allowed our PhD program to have a significant number of foreign students and facilitates significantly our doctors to find easily positions as post doc researchers in foreign countries. As a matter of fact, more than 85 % of our doctors in Astronomy, Astrophysics and Space Science find a post doc position within two months after their PhD title.

The Astronomy PhD program aims to the formation of a young researcher at a highly competitive international level. Such aim will be reached through a didactic and scientific formation along the three years of the PhD program. The PhD student, in his first PhD year, follows at least two specific PhD courses of 16 hours each. During his first year, the student will also attend one of the courses held in an Astronomy School, in Italy or abroad, and will practice in laboratory. With such basic knowledge and competences, which enforce the culture deriving from his laurea magistrale/specialistica (Master of Science), the PhD student is able to reach these objectives: Ability in preparing a research program, with the help and advice of his supervisor; Deep technical competences that, together with his good knowledge of mathematics, physics and computer science, will allow him to work fruitfully in the research program; Good knowledge of English technical and scientific language so as to understand the scientific literature specific of his field of research; Critical attitude, such to be able to identify those problems that deserve further analysis and a deeper approach; Independence in the conduct of research; Ability in working in a team; Skills and confidence in the presentation of results, both in Italian and in English.

The main scientific topics developed in the Institutions involved in this PhD program are:

- Astronomical Techniques
- Classical and Relativistic Gravitation
- Dynamics of Dense Stellar systems and Supercomputing
- Galaxies and cluster of galaxies
- High Energy Astrophysics
- Neutrino Astrophysics
- Observational and Theoretical Cosmology
- Planetology
- Quasars and Active Galactic Nuclei
- Solar System Physics
- Star Formation and Evolution

`http://www.phys.uniroma1.it/fisica/PhD-Astronomy`

The International Ph.D. Program in Relativistic Astrophysics (IRAP-PhD)

In view of the next generation space missions and ground-based observatories, all of them developed as international collaborations, there is the need to develop a new field, the Relativistic Astrophysics, to prepare the new generation of scientists with the knowledge required to manage these observational facilities, to interpret the observational data, and to drive the consequent scientific developments within the theories of general relativity and relativistic quantum and classical field theories. No single university has the expertize required to attain this ambitious goal by itself.

For this reason, it started in 2002 the International Ph.D. Program in Relativistic Astrophysics (IRAP-PhD), coordinated by ICRA and ICRANet, having the University of Rome "La Sapienza" among the Founding Members. The Universities currently Members of the IRAP-PhD, and granting the corresponding joint degree, are the ones of: Bremen (Germany), Ferrara (Italy), Nice Sophia Antipolis (France), Oldenburg (Germany), Rome Sapienza (Italy), Savoie (France). In 2009 the IRAP-PhD was the first program of its kind to receive the sponsorship of the Erasmus Mundus program of the European Commission, and in 2010 they were recruited the first 10 students under this new sponsorship. Last year also the National Academy of Sciences of Armenia joined the IRAP-PhD, and some Brazilian and Colombian Universities are also currently joining. Collaborations are ongoing with many research centres worldwide.

Since its foundation in 2002, the IRAP-PhD saw the enrollment of 120 students from all over the world, as represented in this diagram:

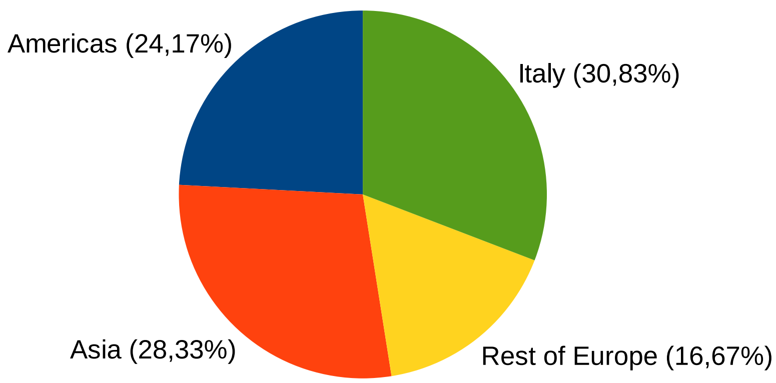

Figure 1: Worldwide distribution of the 120 IRAP-PhD students

http://www.icranet.org/irap-phd
https://en.wikipedia.org/wiki/IRAP_PhD_Program

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 technology 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 shown in Figure 1. 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 foreign 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.

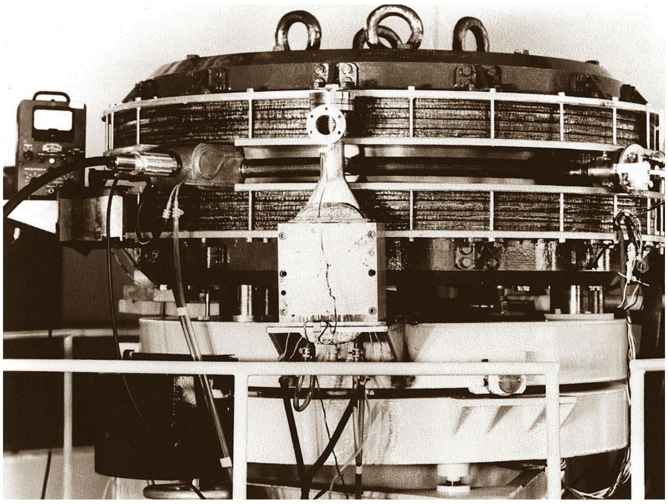

Figure 1: ADA (Anello di Accumulazione): first world wide particle-antiparticle collider, from the intention of Bruno Touschek, build in 1960 at the INFN Laboratori di Frascati.

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 are based at different university physics departments and guarantee 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. 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 100 persons (researchers, technologists, technicians and administrative staff). The people associated to the research activities of the INFN Roma are more than 250. This includes a significative number of PhD (48 in 2015), Msc (37 in 2015) students and Post Docs (27 in 2015).

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.

(a)

(b)

(c)

(d)

Figure 2: Four stamps dedicated to INFN National Laboratories released by Poste Italiane in September 2014

- 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 Higgs Boson discovery by ATLAS and CMS experiments at the Large Hadron Collider (P2, P3, and P10 of this report) and the direct observation of Gravitational Waves by LIGO-VIRGO (P22) have seen an important contribution of the INFN Sezione di Roma and the Physics Department of Sapienza University. 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 (P25). Some experiments are in the construction phase to answer fundamental open questions like the nature of dark matter (DARKSIDE and SABRE) 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, P29).
A set of lively activities is going on in the framework of technological research spanning from medical applications (P33 and P34) like the creation of probes for radio-guided surgery (CHIRONE) and the study of precise methods in dosimetry for hadrontherapy (RDH) to the development of new visionary detectors for future experimental applications (IMCP, DCANT, STAX).
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 (P18−P20) and recently proposed a new experiment, PADME (P21), in order 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 (pages 171−174).

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 Msc thesis. 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 2016 INFN, thanks to its excellent performance in research, was awarded by the Ministry of Research with 73 permanent positions for young researchers which were selected among more than 800 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 will join the Sezione di Roma reinforcing the scientific activities in different fields.

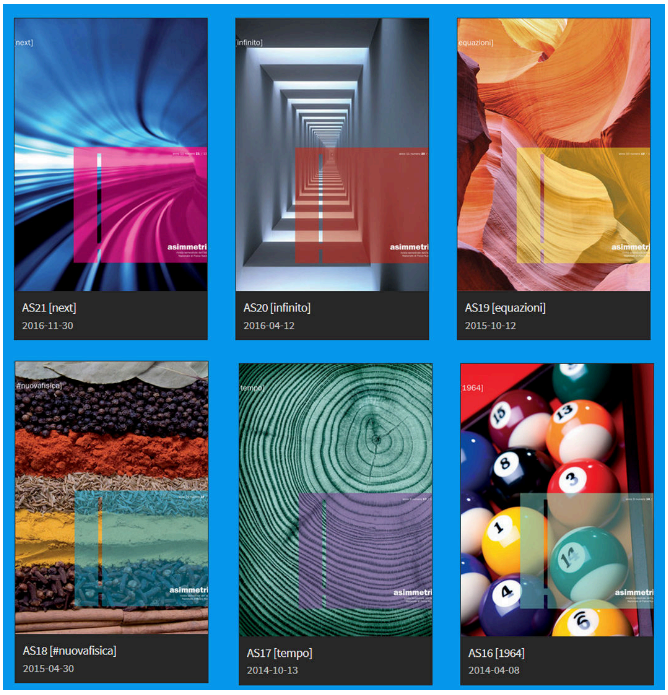

Figure 3: INFN magazine Asimmetrie: covers of 2014-16 issues.

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 2016 INFN Roma and Physics Department launched a new project, LAB2GO (`www.roma1.infn.it/LAB2GO/index.html`), involving students of 19 high schools to classify and repair the existing school's laboratory instrumentation and build a system to share this 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) and the development of infrastructures for GRID and CLOUD. 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 avail themselves of state-of-the-art commercial equipment and, at the same time, foster and support the development of new techniques and instrumentation.

The technological platforms are: Cell culture, Genomics, Bioinformatcs, Bioprinting, Flowo cytometry, Micro and nanofluidics and Microscopy, the latter driven by physicists (G. Antonacci, M. Biasiucci, S. De Panfilis, V. Folli, V. Giliberti, G. Gosti, M. Leonetti, A. Nunn) 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 4 units (Sapienza, Sesto Fiorentino, Tor Vergata, Montelibretti) that in total involve 63 permanent researchers and 28 post-doctoral scientists. In the period 2011-2014, 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.

  Applied Physics(Biomedical Physics, Cultural Heritage)(exp): S. Capuani [LAB], M. Missori [LAB].

- **Complexity**:

  Flocking and animal behaviour (th, exp): A. Cavagna [LAB], S. Melillo, M. Viale.

  Social Dynamics (th): C. Castellano, F. Colaiori, E. La Nave.

  Economic Complexity and Complex Network (th): A. Gabrielli (CRISIS Lab project), A. Scala.

  Granular systems (th, exp): A. Baldassarri, A. Gnoli, A. Petri [LAB], A. Puglisi [LAB] (ERC StG 2008), A. Sarracino.

  Disordered and glassy systems (th): T. Rizzo.

  Cosmology (th): M. Montuori.

- **Quantum Complexity**:

  Graphene, superconductors, and quantum matter (th, exp): L. Benfatto, E. Cappelluti, 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].

`www.isc.it`

CNR Institute of Nanotechnology Unit @ Sapienza

The research activity of the CNR Institute of Nanotechnology (NANOTEC) Unit, [1] named **Soft an Living Matter (SLiM) Laboratory**, mainly concerns advanced tomography, tissue engineering and regenerative medicine, quantitative biology, statistical physics, photonics in random media, soft litography, lab-on-chip technology, microfluidics, active matter, soft matter, olographic micromanipulation, morphologic and optical microscopy.

In the period 2014-2016 the investigation work of the SLiM Lab is primarily shared in four research groups. All groups strongly and actively collaborate with researchers of the Department of Physics.

TOMALab. Supervised by Alessia Cedola, it is primarily focused on development and biological, medical and cultural heritage applications of X-ray physics. `www.sapienza-cnrnanotec.it/tomalab`. The group is funded by the grants: • European Project FET OPEN: "VOXEL - Volumetric medical X-ray imaging at extremely low dose"; • Marie Sklodowska-Curie Individual Fellowships (BiominAB-3D): "Revealing the composition and the formation mechanism of carcinogenic asbestos bodies in humans lungs"; • Biomedical Project of the Italian Healthy Ministry (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). Highlight pubs.: Campi, Acta Biomat. **23**, 309 (2015); A. Cedola, Phys. Med. Biol. **59**, 189 (2014); M. Fratini, Sci. Rep. **5**, 8514 (2015).

Soft litography & imaging. Supervised by Barbara Cortese and Ilenia Viola, it mainly works on nanotechnology, with expertise in molecular nanotechnology and microfluidics, e. g., physics of fluids in confined systems, miniaturization and modulation of functional devices by means of soft lithography (lab-on-chips, OLEDs, organic random lasers), surface control, constructive lithographs, conformational and optical properties of molecular materials by confocal and scanning probe microscopies. Moreover, the group studies cell morphology, distribution of cytoskeleton components (actin microfilaments), Focal Contacts, i.e., the formation of focal adhesion points between cell and substrate, cellular dynamics, in order to measure and monitor cellular responses, changing the mechanical properties of the substrate and/or the topography of adhesion signals. Funding grants: • My First AIRC Grant 2015 n. 16803 (2015-2018): "Role of Electro/Mechanical cues in the control and guidance of Glioma Progression (MFAG)", PI: B. Cortese. Highlight pubs.: B. Cortese at al., J. Mat. Chem. A **2**, 6781 (2014); B. Cortese et al., Integ. Biol. **6**, 817 (2014). F. Di Maria et al., Adv. Funct. Mater. **26**, 6970 (2016).

Microphysics. Supervised by Roberto di Leonardo, the group is focused on investigation of active and soft matter, lab-on-chip and microfluidics with an outstanding expertise in optical trapping. `http://glass.phys.uniroma1.it/dileonardo/` Funding grants: • ERC, Starting Grant: "SMART - Statistical Mechanics of Active Matter", PI: R. Di Leonardo. Highlight pubs.: R. Di Leonardo, Nature Materials **15**, 1057, (2016); C. Maggi et al., Nat. Commun, 6, 7855, (2015).

Statistical physics. 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. Funding grants: • Marie Curie ITN - FP7: "NETADIS - Statistical Mechanics Approaches to Networks Across Disciplines", Coordinator: KCL-UK, CNR-NANOTEC PI: L. Leuzzi; • FIRB - MIUR Futuro in Ricerca: "Statistical Mechanics of Granular Random Lasers", PI: L. Leuzzi; • PRIN2010-2011 (2013-2016): "Statistical Mechanics of disordered and complex systems", Coordinator: Giorgio Parisi, CNR-NANOTEC PI: L. Leuzzi; • PRIN2015 (2016-): "Statistical mechanics and complexity", Coordinator: Giorgio Parisi, CNR-NANOTEC PI: L. Leuzzi. Highlight pubs. F. Antenucci et al., Phys. Rev. Lett. **114**, 043901 (2015); N. Ghofraniha et al., Nature Commun. **6**, 6048 (2015); F. Capuani et al., Sci. Rep. **5**, 11880 (2015). A. Martirosyan et al., PLoS Comput Biol 12, e1004715 (2016).

Furthermore, also the group for **Advanced Photonics**, based in the NANOTEC headquarters in Lecce and funded by the ERC Starting Grant POLAFLOW, carries out research investigation by the NANOTEC Unit at the Physics Department, on Raman enhanced spectroscopy and on optical systems in multimode random fibers - `polaritonics.weebly.com`.

`nanotec.cnr.it`
`cnr-nanotec-rome.weebly.com`

[1] Unit in NANOTEC since its constitution, Jan. 2015. Previously in CNR Institute for Physical and Chemical Processes (IPCF).

Istituto Nazionale di Astrofisica and the INAF Osservatorio Astronomico di Roma

INAF-Osservatorio Astronomico di Roma (OAR hereafter) has an agreement in place with the Sapienza department of Physics since 2009. This agreement has been renovated during 2015 and will be in place up to the end of 2018.

The Astronomy, Astrophysics and Space Science PhD program aims to the formation of a young researcher at a highly competitive international level. Such aim will be reached through a didactic and scientific formation along the three years of the PhD program. The PhD student, in his first PhD year, follows at least two specific PhD courses of 16 hours each. During his first year, the student will also attend one of the courses held in an Astronomy School, in Italy or abroad, and will practice in laboratory. With such basic knowledge and competences, which enforce the culture deriving from his laurea magistrale/specialistica (Master of Science), the PhD student is able to reach these objectives: Ability in preparing a research program, with the help and advice of his supervisor; Deep technical competences that, together with his good knowledge of mathematics, physics and computer science, will allow him to work fruitfully in the research program; Good knowledge of English technical and scientific language so as to understand the scientific literature specific of his field of research; Critical attitude, such to be able to identify those problems that deserve further analysis and a deeper approach; Independence in the conduct of research; Ability in working in a team; Skills and confidence in the presentation of results, both in Italian and in English.

The agreement individuates 6 topics on which OAR and Physics Department researchers are actively collaborating. These topics are listed below.

- Euclid. This is the ESA M2 mission, with a launch foreseen in 2020/2021. 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 structure 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 there is a long-standing collaboration between Dipartimento and OAR reserchers (Roberto Maoli, Roberto Scaramella)
- Compact objects and gravitational waves (GW). Also in this field there is a long-standing collaboration between Dipartimento and OAR researchers (Valeria Ferrari, Raffaella Schneider, Luigi Stella). They developed models for the emission of gravitational waves in astrophysical scenarios including neutron stars, magnetars and black holes.
- Multimessenger astrophysics. Starting from 2013 we set up a working group 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 the first GW events GW20150915 and GW20151226. The OAR staff involved in GRAWITA includes Enzo Brocato (who is the coordinator), Luigi Stella, Silvia Piranomonte and others. The main contact point at the Dipartimento is Fulvio Ricci and his team.
- Advanced numerical calculus. OAR and Dipartimento staff including Marco Limongi, Amedeo Tornambe Paolo Ventura, Roberto Capuzzo Dolcetta, Marco Merafina, studied several application of advanced numerical calculus to different astrophysical scenarios, including the evolution of massive stars, globular clusters and the evolution of AGB stars.
- Gamma Ray Bursts. Giovanni Amelino Camelia, Fabrizio Fiore and Dafne Guetta studied how to use Gamma Ray Bursts to probe the structure of space-time and quantum gravity scenarios.
- AGN galaxies and cluster of galaxies. Dario Trevese, Raffaella Schneider, Fabrizio Fiore, Emanuele Giallongo, Andrea Grazian, Laura Pentericci and Adriano Fontana studied 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.

http://www.mporzio.astro.it/

ICRA and ICRANet

ICRA (International Center for Relativistic Astrophysics) is an international consortium of research institutes in the field of relativistic astrophysics and related areas. ICRA was founded in 1985 by Remo Ruffini (University of Rome "La Sapienza"), Riccardo Giacconi (Nobel Prize for Physics 2002), Abdus Salam (Nobel Prize for Physics 1979), Paul Boynton (University of Washington), George Coyne (former director of the Vatican observatory), Francis Everitt (Stanford University), Fang Li-Zhi (University of Science and Technology of China). ICRA main Seat is located in the Department of Physics at the University of Rome "Sapienza". ICRA current Members are: ICTP - Trieste (Italy); Space Telescope Institute - Baltimore (USA); Specola Vaticana (Vatican City); TWAS - Trieste (Italy); and the Universities of Hofei (China), Insubria (Italy), Rome "Campus Bio-Medico" (Italy), Rome "Sapienza" (Italy), Stanford (USA); Udine (Italy); Washington - Seattle (USA).

ICRANet (International Center for Relativistic Astrophysics Network), founded in 2005, is an international organization promoting research activities in relativistic astrophysics and related areas. The members are the Republic of Armenia, the Federative Republic of Brazil, the Italian Republic, the Vatican State, the University of Arizona (USA), Stanford University (USA) and ICRA. The headquarters is located in Pescara, Italy, and Seats are located in Nice (France), Rio de Janeiro (Brazil), Rome (Italy), Yerevan (Armenia).

Since 2002 ICRA co-organizes every year an International Ph.D. Program in Relativistic Astrophysics, the IRAP-PhD, at "La Sapienza" university. Since 1985, ICRA co-organizes every three years the "Marcel Grossmann Meeting" (MGM) in a different country of the world. Since 2005, both these activities are carried on jointly by ICRA and ICRANet. The 14^{th} MGM was held in Rome at "La Sapienza" (12-18 July 2015) with the participation of more than 1200 scientists from all over the world, including many Nobel Laureates.

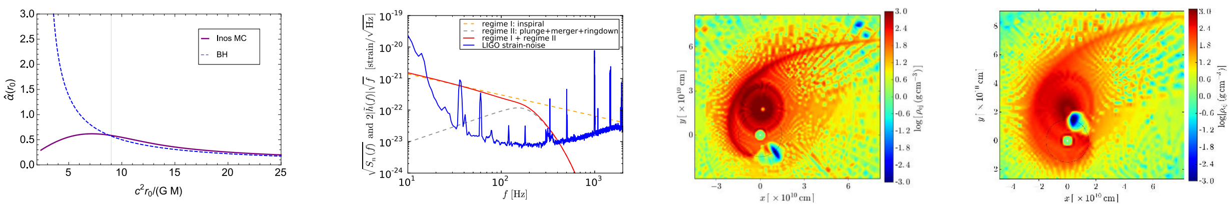

Figure 1: 1^{st} panel: Comparison between BH and fermionic DM quantum core (see Gomez et al., Phys. Rev. D, 94 (2016) 123004 for details). 2^{nd} panel: Comparison of the amplitude spectral density of the GW signal in the different regimes with the one of the LIGO H1 noise (See Rodriguez et al., arXiv:1605.07609, for details). Last two panels: Snapshots of the expanding supernova ejecta which interacts with the companion neutron star. The white dot in the origin is the newly formed neutron star (details in Becerra et al., ApJ, 833 (2016) 107).

One of the recent results obtained by ICRA shows that a self-gravitating system of massive keV fermions in thermodynamic equilibrium correctly describes the dark matter (DM) distribution in galactic halos and predicts a denser quantum core towards the center of the configuration (see Fig. 1 and `http://adsabs.harvard.edu/abs/2016PhRvD..94l3004G`Gomez et al., Phys. Rev. D, 94 (2016) 123004). Concerning Gravitational Waves (GWs), we analyzed the event GW 150914 announced by LIGO, showing that the parameters of the coalescing system and of the newly formed Kerr black-hole can be obtained without sophisticate numerical simulations (see Fig. 1 and Rodriguez et al., arXiv:1605.07609). We are currently examining the GW counterpart of the seven families of Gamma-Ray Bursts (GRBs) recently introduced by ICRANet.

One of the recent results obtained by ICRANet sheds new light on the "hypercritical accretion", which is at the heart of the induced gravitational collapse (IGC) paradigm for GRBs. Detailed numerical simulations of the explosion of an Iron-Carbon-Oxygen (FeCO) stellar core as a supernova and of the hypercritical accretion of the supernova ejecta on a binary neutron star companion has been performed, involving more than one million of particles. These results are supported by numerical simulations done at Los Alamos National Laboratories by Chris Fryer and his group (see Fig. 1 and Becerra et al., ApJ, 833 (2016) 107). Thanks to these results, it is clear that all GRBs originate in binary systems, and that they belong to seven different families, each one connected to a different kind of progenitor binary system (see Ruffini et al., ApJ, 832 (2016) 136).

Full details can be found in the 2016 ICRANet Scientific Report: `http://www.icranet.org/report_2016`

`http://www.icra.it/` `https://en.wikipedia.org/wiki/International_Center_for_Relativistic_Astrophysics`
`http://www.icranet.org/` `https://en.wikipedia.org/wiki/ICRANet`

Facilities and Laboratories

The Physics Museum

The Department of Physics hosts the Physics Museum of Sapienza Università di Roma. The Museum is one of the components of the Polo Mussale 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 1700.

The original nucleus of our Museum comes from the foundation of the *Teatro Fisico* (*Physics Theatre*) in 1748. 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 1891 the *Circolo Fisico* (*Physics Club*) gave the current mission to the Museum: the Club promoted a sort of outreach activities, even if only selected persons were admitted to conferences, presentations and discussions. Later, physics teachers were admitted too these activities and in 1897 the *Società Italiana di Fisica* (Italian Physical Society) was founded.

The first public speaking occurred in 1896 by Quirino Majorana about the discovery of X–rays, when the Physics Department was in a building in Via Panisperna. In 1935 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.

Some of them are particularly valuable, such as the König analyser (Fig. 1) used to determine the frequency spectrum of it (a sort of a modern 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. 2), just to mention a few of them.

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.

Projects for an upgrade of the facility is being evaluated, in order to offer more modern services and experiences to visitors.

Figure 1: The König harmonic analyser for the study of the frequency spectrum of sound.

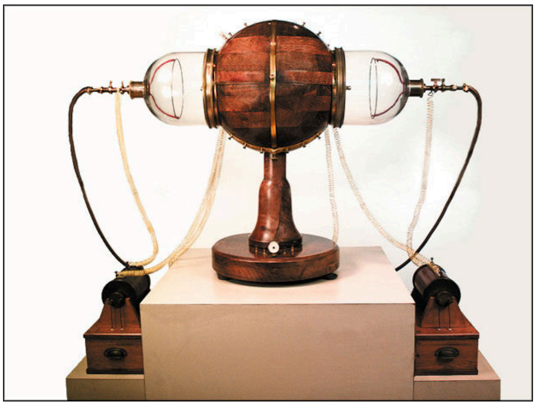

Figure 2: The De La Rive apparatus for the simulation of Northern Lights.

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http://www.phys.uniroma1.it/DipWeb/museo/home.htm

Departmental Library

Along the years, the Departmental Library has undergone a process of transformation both from the structural and logistic point of view, and a throughout modernization of the services. The new location of the Departmental Library was inaugurated in 2005, and consists of a reading room with 84 places, 12 Personal Computers (one of which is specially equipped for the visually impaired) 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 of the access to the wireless network with ones own laptop. These services are offered both to institutional users and to students that visit our University. The catalogue of ancient and modern volumes (approximately 27000 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), so as to allow for the full on-line visibility of the heritage of our Library. The historical collections up to the end of xix-th century, including international journals from the end of xviii-th 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 (approximately 300 articles per year) within the interexchange circuit NILDE, and interlibrary loan with other libraries within the national circuit SBN and within international loan circuits. At the local level, the Library provides the following services: temporary loan for all students and institutional staff member of Sapienza (approximately 5000 loans per year); reservation of internet accesses (12 PCs in the library) for research and consultation of on-line bibliographic resources; wireless connection of ones own laptop. All these services are accessible to all those that enroll as users at the Library (approximately 7000 enrolled users), providing their personal data. These data are stored in a database common to all the libraries of Sapienza and of the territory of the Region Latium (Regione Lazio). 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 charges 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, by means of a magnetic card which is currently released only to institutional users of the Department. Access to the Library is allowed to authorized enrolled users. The premises of the Departmental Library are controlled by a webcam circuit. At present, a new 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 that 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 Departmental Libraries at Sapienza. All volumes will be equipped with a RFID tag that will allow for full traceability and all users will be provided with an identifying card. Thanks to the association of these two elements, each user will be able to loan a book and register the operation in the loan database. The RFID technology will also allow to monitor the handling and recognition of the librarian material, making the procedure simpler, as compared to the long manual procedure of inventory control of the bibliographic material.

Figure 1: Main hall of the Departmental 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.

`http://www.phys.uniroma1.it/biblioteca/eng/home.html`

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.

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http://www.phys.uniroma1.it/fisica/officina-meccanica

The INFN Electronics Laboratory: LABE

The Electronics Laboratory (LabE) in the Physics Departement is operated by the INFN. The team is composed of 7 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, CHIRONE, 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 the Allegro Cadence suite both for printed circuit board (PCB) design and for ASIC development.

In the WORK lab, there are some 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 milling machine used to realize double sided PCBs in a fast way. The milling machine is shown in Fig. 1. 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.

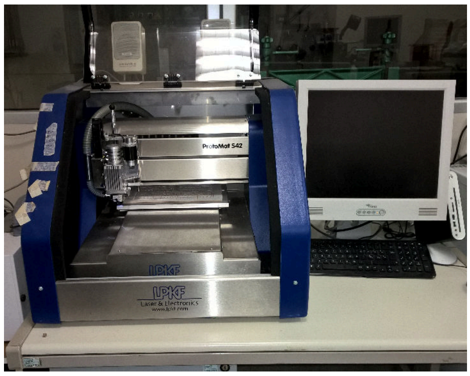
Figure 1: Fast prototyping milling machine used to realize double sided PCBs.

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 rackable VME modules and rack systems. 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.


Figure 2: Thermostatic chamber located in the OPEN LABE area.

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, the ARDUINO system can be controlled by android-based platforms which makes the management of the devices more user friendly. There is also the capacity of FPGA programming, mainly XILINX and MICROSEMI devices. Another important aspect is testing and debugging, which 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 programming 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.

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).

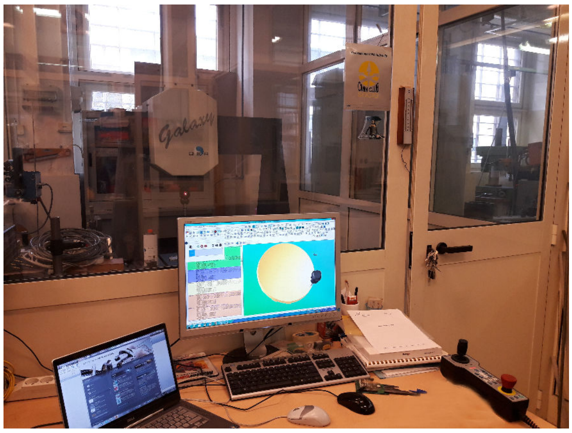

Figure 2: Metrology Lab with CMM machine in controlled environment.

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.

The Infrared Spectroscopy Laboratory - IRS

The InfraRed Spectroscopy (IRS) laboratory is located at the fourth floor of the Fermi Building (doors 415, 416, and 417). 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 functional oxides for electronics such as multiferroics and two-dimensional electron gases at the interface between oxides (see report by P. Calvani). A second line of research focuses on novel materials for plasmonics and nanoantennas, including heavily doped semiconductors (report by M. Ortolani). A third research line concerns infrared vibrational spectroscopy of biological macromolecules including proteins (report by A. Nucara).

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.

`http://server2.phys.uniroma1.it/gr/irs/index.htm`
Related research activities: C11, C14, C17, C18

Soft Matter Laboratory: Light Scattering (CNR-ISC)

The laboratory, located in room 010 at the ground floor of the Fermi Physics Building under the responsability of Barbara Ruzicka, is equipped with three different and complementary Light Scattering set-up running independently:

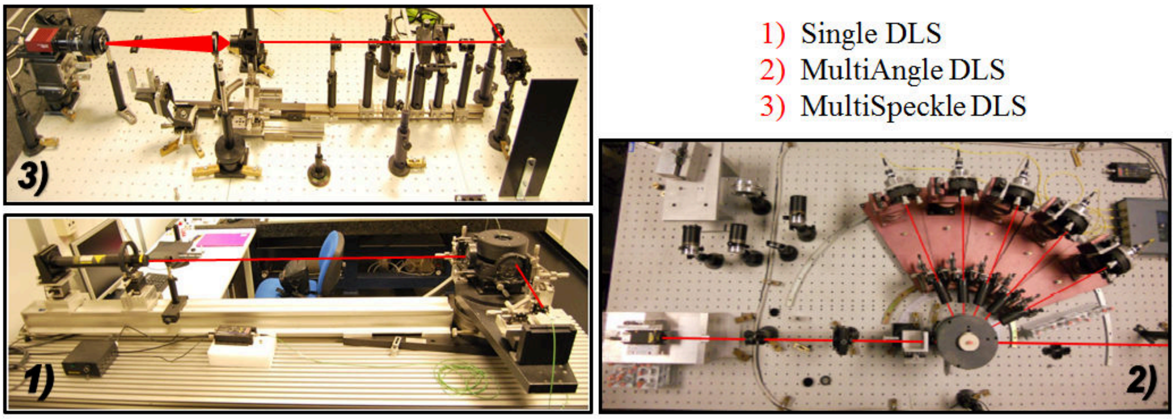

Figure 1: Three different Light Scattering set-up of the Soft Matter Laboratory.

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 different channels where 5 lens-collimator systems couple the scattered intensity with 5 optical fibers connected to 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 (ERC Consolidator Grant, `http://glass.phys.uniroma1.it/Emanuela/`). 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** and **microgels**[1,2].

References

[1] B. Ruzicka *et al., Nat. Mat.* **10**, 56 (2011).
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`http://glass.phys.uniroma1.it/ruzicka/`
Related research activities: C20

Nuclear Magnetic Resonance (NMR) and Medical Physics Laboratory (CNR-ISC)

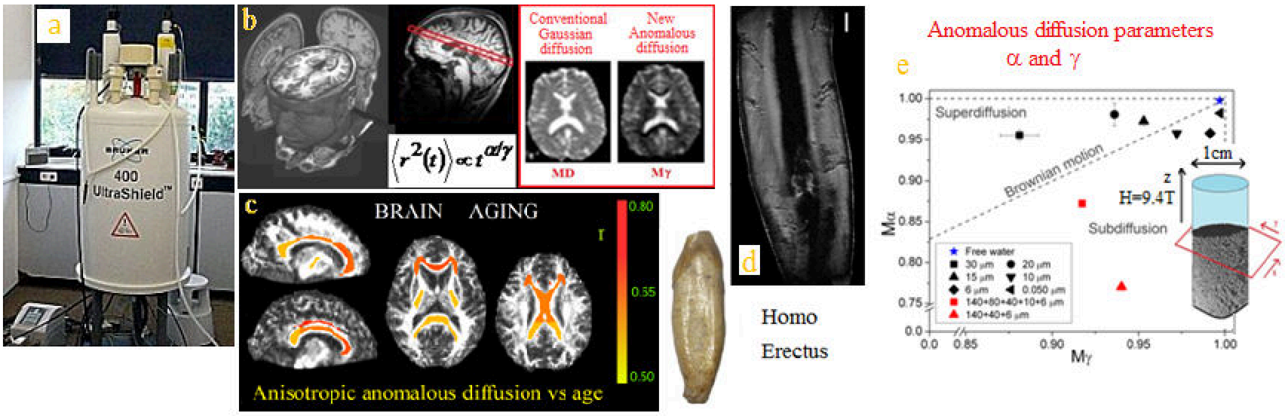

Figure 1: a)9.4T NMR spectrometer, b) diffusion MRI of human brain, c) cerebral microstructural changes with aging, d) microimaging of a fossil tooth, e) anomalous diffusion parameters of water in packed beads samples.

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.

In the NMR and Medical Physics Laboratory directed by Silvia Capuani, there are NMR instruments, workstations and computers linked to a server. Specifically, 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 along the three x,y and z axes) is available (Fig.1) Full processing facilities are available, including 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), Radiology department of Sapienza University, Radiology Department of Tor Vergata University of Rome, 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 and brain aging (Fig.1), tumour-grading for cancer, osteoporosis diagnosis (Fig.1) but also in disorder degree measurement of new materials (Fig.1) and modern and fossil tooth growth (Fig.1).

References:

Palombo et al. JCP 2011; De Santis et al. MRM 2011; Palombo et al. Sci Rep. 2013; Rebuzzi et al. BONE 2013; Zanolli et al. JHE 2014; Caporale et al. Neuroimage 2016.

[1] https://www.researchgate.net/profile/Silvia_Capuani

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.

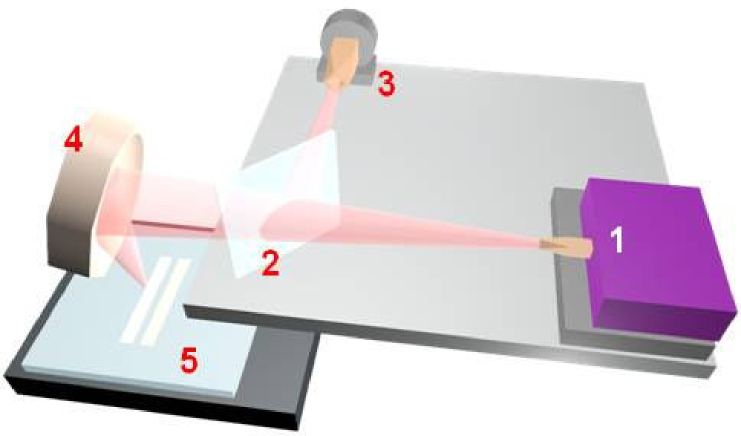

Figure 1: Scheme of the confocal terahertz microscope built in the Terahertz Imaging laboratory. (1) All-electronic terahertz source by Viriginia Diodes, tunable in the range 0.20-0.75 THz. (2) Quartz plate beamsplitter. (3) Waveguide-coupled zero-bias Schottky Diode detector. (4) Focusing ellipsoidal mirror. (5) Sample on a X-Y-Z scanning stage, investigated in reflection mode.

http://sites.google.com/a/uniroma1.it/micheleortolani-eng
Related research activities: C11

Complex Photonics Lab

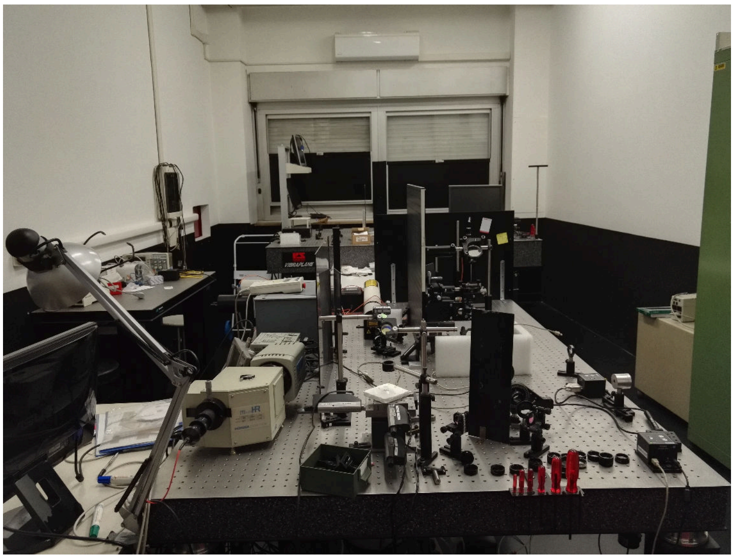

Figure 1: Photonics Laboratory situated at the ground floor of the Fermi Building.

The Laboratory of Photonics headed by C. Conti is situated in room 006 at the ground floor of Fermi building and equipped with scientific instrumentation used in the research of nonlinear optics and photonics in random media. The scheme of the experiments is: different samples are radiated by a laser beam and the light transmitted or reflected by them is collected with several detectors depending on the experiment.

The detailed list of instrumentations is:

- two optical breadboards; 2 personal computers;
- a Q-switched Nd:Yag laser (model Eazy Brilliant-Quantel) working at wavelengths 1064nm, 532nm, 355nm with highest energy of 180mJ, 10 Hz repetition rate and 4ns pulse duration;
- a Continuos Wave laser working at 1064 nm wavelength and 3 Watt maximum power;
- a Continuos Wave laser working at 532 nm wavelength and 1.5 Watt maximum power;
- a Yvon-Jobin spectrograph equipped with electrically cooled CCD array detector; grating density of 1800 mm^{-1} and 600 mm^{-1};
- a 303-mm focal length spectrograph (Andor, Shamrock 303) connected to a low-noise charge-coupled device array (Andor, iDus Spectroscopy CCD);
- 2 Charged Camera Detectors (Thorlabs);
- many optical and opto-mechanical components; several manual and motorized translational stages;
- several photo detectors, including Coherent- Labmax energy meter.

In this laboratory many important experimental results have been obtained, that are published in outstanding journals as Nature Communications, Physical Review Letters, Scientific Reports, etc.

`http://www.newcomplexlight.org`
Related research activities: T16

Complex Nonlinear Optics Lab

Figure 1: Nonlinear Photonics Laboratory situated at the ground floor of the Fermi Building.

The Laboratory of Nonlinear Photonics headed by C. Conti is situated in room 007 at the ground floor of Fermi building and equipped with scientific instrumentation used in the research of nonlinear waves formation and propagation and optotomechanics. The scheme of the experiments is: different samples are radiated by a laser beam and the propagating light in directly visualized with several optical microscopes and Charged Camera Devices (CCD). In the optomechanics experiments a home made Atomic Force Microscope (AFM) is used to detect laser induce surface deflections.

The detailed list of instrumentations is:

- one optical breadboard; 2 personal computers;
- a Q-switched Nd:Yag laser (model Coherent-Surelite) working at wavelengths 1064nm, 532nm with highest energy of 180mJ, 10 Hz repetition rate and 6ns pulse duration;
- a Ti:Shappire oscillator (model Coherent Mantis) with 500 mW power; 80 nm bandwidth, 820 nm center wavelength and 15 fs pulse duration;
- a multi-stage frequency doubled Ti:Sapphire laser system (Coherent Hidra) with 10 Hz repetition-rate, 50 fs pulse duration and 400 nm central wavelength;
- 2 Leica optical microscope with 13X and 4X highest magnification; 2 CCD (Pixelfly and Prosilica)
- a Continuos Wave laser working at 532 nm wavelength and 0.5 Watt maximum power;
- a Spatial Light Modulator (model Holoeye LC2007-R) based on a reflective LCOS microdisplay with a resolution of 1280X768 pixel (WXGA). With a pixel pitch of 20m and a fill factor of 92%;
- many optical and opto-mechanical components; several manual and motorized translational stages; one motorized beam chopper (Thorlabs) and one beam shutter (Thorlabs);
- several photo detectors, including Coherent- Labmax energy meter and power meter.

In this laboratory many important experimental results have been obtained, that are published in outstanding journals as Nature Communications, Physical Review Letters, Scientific Reports, etc.

`http://www.newcomplexlight.org`
Related research activities: T16

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.

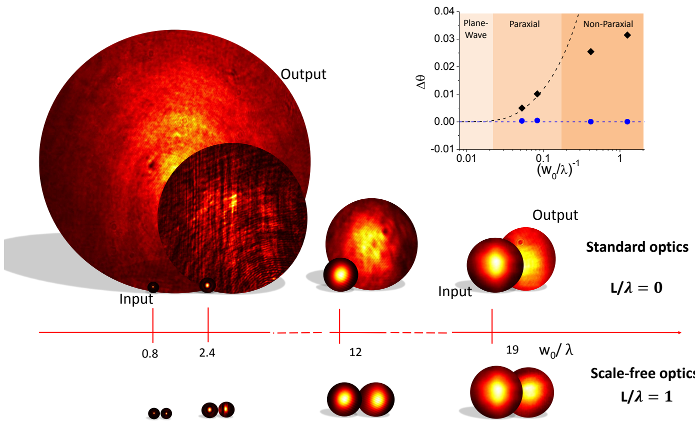

Figure 1: Breaking of diffraction laws in nanodisordered KLTN. Comparison of input versus output beam intensity distribution (see inset) in the standard optics regime (top sequence) and in the scale-free optics regime (bottom sequence), as function of beam-width divided by wavelength (w_0/λ), from F. Di Mei *et al.*, Phys.Rev. A **92**, 013835 (2015).

http://sites.google.com/site/eugeniodelre/Home
Related research activities: C25

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 [7-10]. 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.

References

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[2] N. Ghofraniha *et al.* *Nat. Comm.* **6**, 6058 (2015); I. Viola *et al.* *J. Mater. Chem. C* **1**, 8128 (2013)
[3] R. Angelini *et al.* *Nat. Commun.* **5**, 4049 (2014)
[4] B. Ruzicka *et al.* *Nat. Mat.* **10**, 56 (2011)
[5] R. Di Leonardo *Nat. Mat.* **15**, 1057 (2016)
[6] C. Maggi *et al.* *Small* **12**, 446 (2016)
[7] N. Ghofraniha *et al.* *Adv. Otpic. Mater.* **4**, 1998 (2016)
[8] M. Carbonaro *et al.* *Biochim. Biophys. Acta* **1864**, 766 (2016)
[9] S. Sennato *et al.* Colloids and Surfaces B: Biointerfaces **137**, 109 (2016)
[10] S. Capuani *Micropor. Mesopor. Mat.* **178**, 34 (2013)

Related research activities: C20

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 as response to an applied force, Calorimetry deals with thermal properties of matter. The laboratory therefore aims to study 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 full temperature range. It works in a temperature range -80÷700^{o}C with an accuracy of ± 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 .

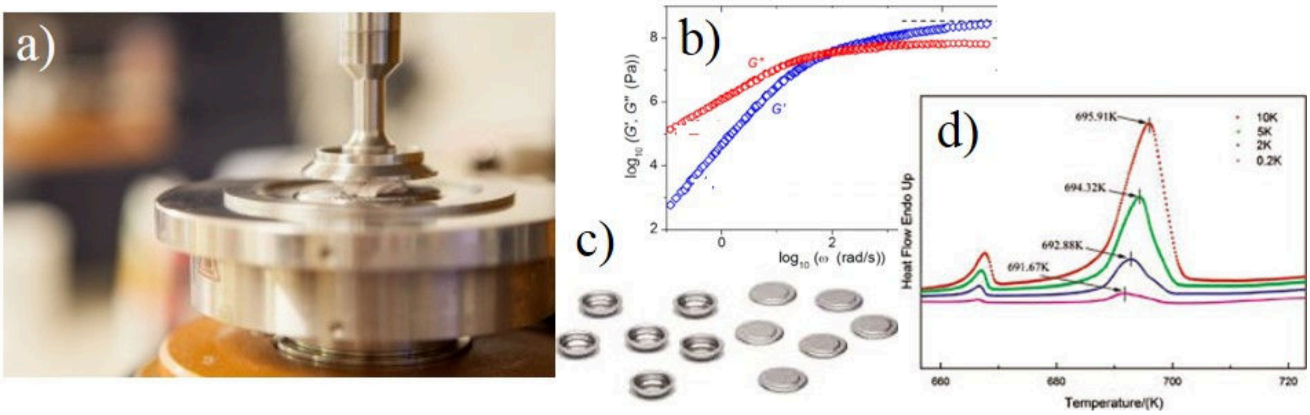

Figure 1: a) Detail of a cone-plate rheometer. b) Example of storage and loss moduli from rheological measurements. c) sample pans for calorimetric measurements. d) Example of thermograms from differential scanning calorimetric measurements.

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 [1-4]. The systems mainly investigated in the laboratory are **charged colloidal clays** and **colloidal microgels** together with biological systems. 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 and complemented with neutron scattering measurements. 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

[1] R. Angelini *et al. Nat. Commun.* **5**, 4049 (2014).
[2] B. Ruzicka *et al. Nat. Mat.* **10**, 56 (2011).
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http://glass.phys.uniroma1.it/angelini/
Related research activities: C20

LoTUS laboratory for the growth of surfaces and nanostructures

The LoTUS laboratory explores electronic properties of low-dimensional systems. The final objective is to identify which physical quantities and scales control the structure and the electronic properties of systems at the nanoscale. It is mainly devoted to the growth with atomic/molecular control of molecular and metallic single layers and thin fims on suitable nano-structured templates. A special effort is dedicated to the growth of graphene on metallic substrates via chemical vapour deposition. The experimental investigation of (i) the chemical state of surfaces and two-dimensional systems is carried out by means of X-ray photoelectron spectroscopy (XPS), (ii) the study of surface crystalline order by means of low-energy electron-diffraction (LEED), (iii) the control of the growth morphology by Auger electron spectroscopy (AES), and (iv) of the adsorption energy by thermal desorption spectroscopy (TDS).

The XPS, LEED/AES and TDS apparatus is contained into an ultra-high-vacuum (UHV, 1×10^{-10} mbar base pressure) 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 (Fig. 1, left panel).

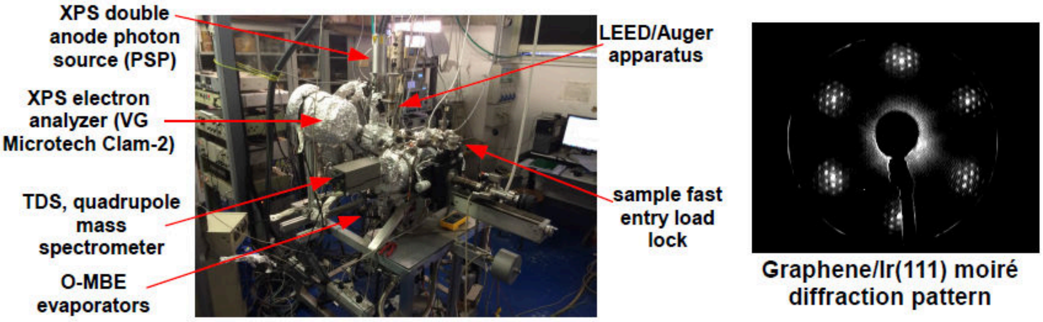

Figure 1: Left: XPS and growth chamber. Right: Low-energy electron-diffraction (LEED) moiré pattern of graphene grown on Ir(111) in the UHV chamber; primary beam energy of 140 eV.

In the following, the main characteristics of the apparatus.

- XPS hemispherical electron analyser: VG Microtech Clam-2, pass-energy 10-200, 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, with cryostat (LN2 77 K), electron-bombardment heater up to 1500 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 for TDS: residual gas analyser SRS RGA 300, 1-300 a.m.u. range; interfaced to produce a linear temperature ramp for TDS acquisition;
- Gas line equipped with several ports, UHV-connected through a leak-valve to the main chamber; oxygen and C_2H_4 sources mounted, the latter for graphene preparation on metals;
- Organic-molecular beam epitaxy (O-MBE) cells, with thermocopule control; quartz crystal thickness monitor; high-temperature electron-bombardment based evaporator for transition metals.

References M.G. Betti *et al.*, Langmuir **28** 13232 (2012); P. Gargiani *et al.*, J. Phys. Chem. C **120** 28527 (2016); Phys. Rev. B **87** 165407 (2013); M. Scardamaglia *et al.*, J. Phys. Chem. C **117** 3019-3027 (2013); S. Lisi *et al.*, J. Phys. Chem. Lett. **6** 1690 (2015); D. Pacilé *et al.*, Phys. Rev. B **90** 195446 (2014); G. Avvisati *et al.*, J. Phys. Chem. C **(**121), 1639 (2017)

`http://server2.phys.uniroma1.it/gr/lotus/index.htm` **Related research activities: C8, C9**

Optical trapping and active matter lab

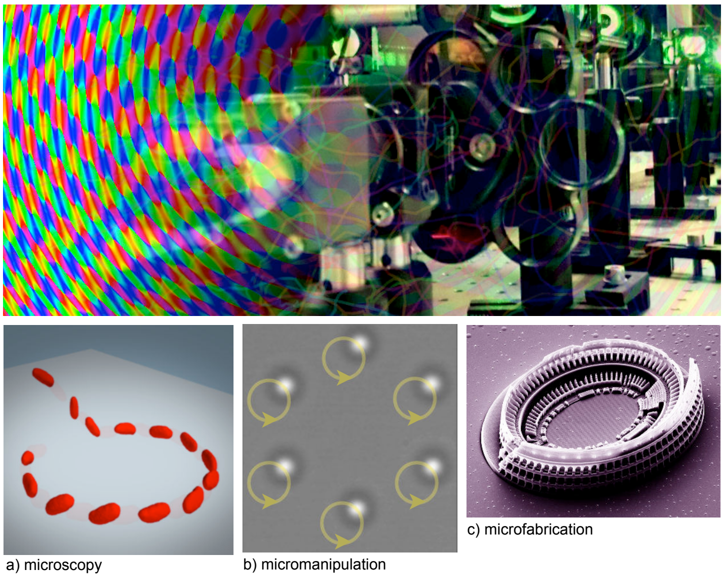

Figure 1: a) 3D reconstruction of a swimming *E.coli* cell trapped by a solid wall [1]. b) Hydrodynamic synchronization of 6 colloidal particles moving over rotating optical landscapes [2]. c) A 3D replica of the Colosseum (scale 1: 2000000).

From bacteria to Brownian motion, during the last three hundred years, the optical microscope has revealed 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 [1] (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 positive 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). We are currently applying this technology to study and control the dynamics of self-propelled bacteria in complex 3D environments.

References:

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`glass.phys.uniroma1.it/dileonardo`
Related research activities: C30

Collective Behavior in Biological System (CoBBS) Laboratory

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. 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, 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.

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.1.

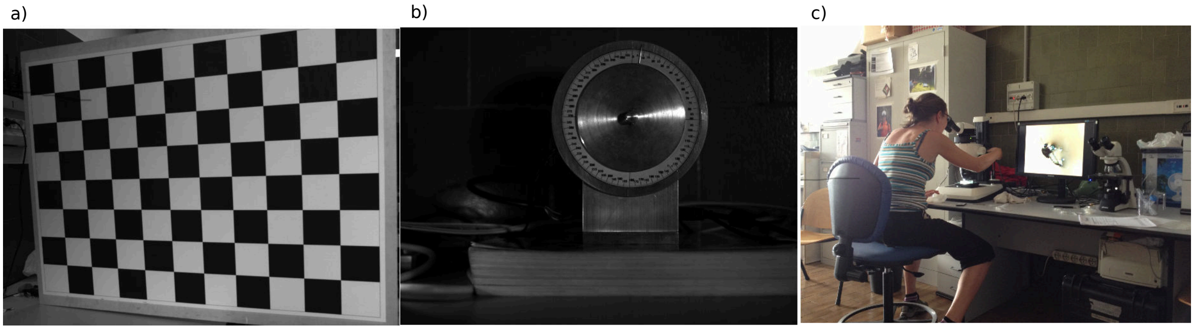


Figure 1: **a. Camera calibration:** 50 images of the checkerboard in different positions are acquired to measure the internal parameters of the cameras. **b. Synchronization tests:** the delay in time between the cameras is periodically measured using the built in home instrument in the picture; the needle rotates at a high speed, so that the time delay can be measured as the difference in the position of the needle in the images shot at the same time step from the three cameras. **c. Insect identification:** insect samples captured in the field are analyzed using two microscopes to determine their taxonomy.

The laboratory is equipped with two systems of three synchronized high speed cameras:

- IDT - M5, 4 Mpx shooting at 170 fps (frame per second);
- IOI Industries - FLARE 12M125-CL, 12 Mpx shooting at 120 fps.

The equipment of the laboratory 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, a set of camera calibration targets, two sets of camera tripods Manfrotto.

CoBBS Lab is also equipped with two microscopes, one stereomicroscope (Leica M125) and a digital one (Optika DM-20), which are used to find out the taxonomy of the insects under investigation, see Fig.1c.

`www.cobbs.it`
Related research activities: T10

LoTUS laboratory for angle-resolved photoelectron spectroscopy (ARPES) of surfaces and low-dimensional systems

The LoTUS laboratory is mainly devoted to the experimental investigation of the electronic band structure of surfaces and two-dimensional systems by means of high-resolution angle-resolved ultraviolet photoelectron spectroscopy (ARPES). The ARPES apparatus, working at high resolution in energy (4 meV) and angle (0.2°), and capable of operating at low temperatures, is contained into an ultra-high-vacuum (UHV, $1{\times}10^{-10}$ mbar base pressure) chamber, UHV-connected to a preparation chamber equipped with several other characterisation methods and ancillary facilities for samples preparation and cleaning, and is provided with a small UHV chamber for a fast load-lock introduction (Fig. 1, left panel).

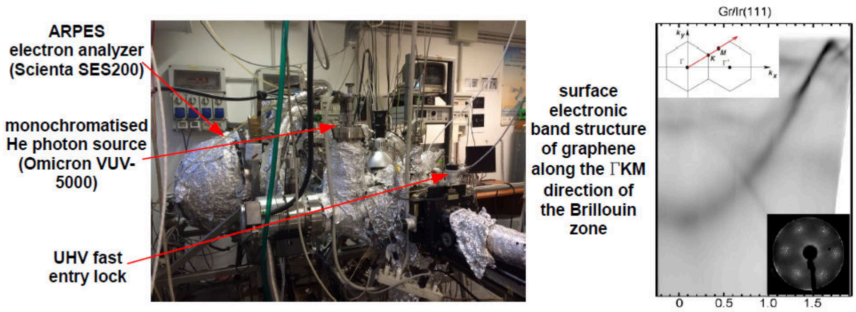


Figure 1: Left: ARPES chamber. Right: Electronic band structure of graphene (Gr) for Gr/Ir(111), along the ΓKM direction of the suface Brillouin zone, excited with the HeI_α photon energy (21.218 eV).

In the following, the main characteristics of the apparatus.

- ARPES hemispherical electron analyser: Scienta SES-200 4 meV best energy resolution, less than 0.2° angular resolution, pass-energy range 1-50 eV, multi-channel detector (MCD, allowing ±8° angular span and 10% of pass-energy energy span); as an example, we report the band structure of Graphene/Ir(111) in Fig. 1, right panel;
- ARPES photon source: Omicron-Scienta VUV-5000 monochromatised micro-wave excited He UV source, main lines HeI_α at 21.218 eV and HeII_α at 40.814 eV photon energy, with low-intensity satellites 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 S. Tognolini *et al.*, Phys. Rev. Lett. **115** 046801 (2015); B. Gupta *et al.*, Nanotechnol. **27** 185601 (2016); L. Massimi *et al.*, Beilstein J. Nanotechnol. **5** 308 (2014); M. Scardamaglia *et al.*, J. Phys. Chem. C **117** 3019 (2013).

`http://server2.phys.uniroma1.it/gr/lotus/index.htm`
Related research activities: C8, C9

Rheology of Disordered Materials (CNR-ISC)

Disorder is crucial in determining the behavior of matter. At the macroscopic level it affects the response to mechanical solicitations, reflecting in physical properties like plasticity, elasticity, viscosity, etc. and affecting inherent phenomena, e.g. fracture generation and propagation. Presently our activity is mainly focused on the dynamics of granular matter. In both natural and industrial world, grains are much more frequently encountered than crystals, however their dynamics is much less understood. They also provide laboratory model systems for studying dissipative, non-linear and non-equilibrium processes, like earthquakes.

One main facility of the lab is aimed at measuring the response of a horizontal granular bed to an applied shear stress. It consists of a mechanical device which can shear the samples at different imposed rotation speeds, a set of sensors with their dedicated channels for data acquisition, and a computer with codes specifically developed for the experiment control and the acquisition and storage of data.

Figure 1 shows the shearing part of the apparatus, consisting of a cylindrical cell made of transparent PMMI, which contains the granular sample. A mobile annular plate on the top can shear the sample in the horizontal and allowing its expansion in the vertical. The shearing rate can be imposed directly, ranging in a wide interval (from 10^{-4} to 10 rads^{-1}), or through a rotating torsion spring. For us this is the most interesting case in which, like in many natural phenomena, shearing can take place in a chaotic way and grains produce *avalanches*, whose statistical properties are the main object of investigation. Through data analysis, avalanche features like size, duration, and velocity are put in quantitative relation among them and with other quantities, like friction, and are used to devise and test stochastic models for the dynamics.

A second main experiment investigates the dynamics of a one dimensional column of beads, shown in fig. 2. (tilted horizontally). The bottom bead (right) is in contact with a piston that supplies energy at controlled amplitude and frequency. A video camera take images at rates up to 1kfps. From image processing, the cinematic of beads is derived and is used to investigate their dynamics and test the validity of different theories.

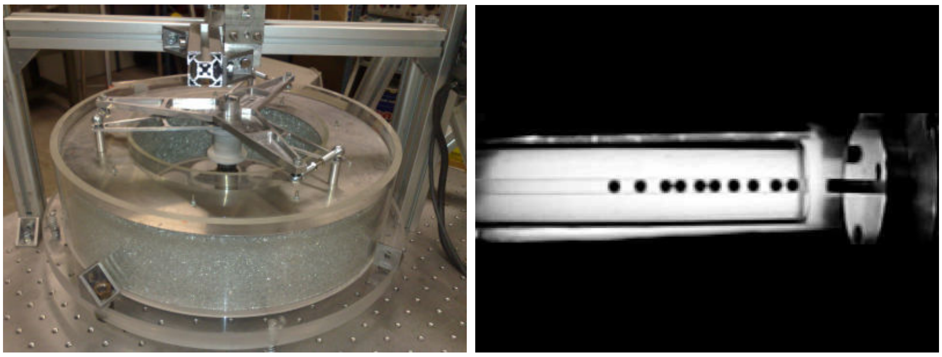


Figure 1: Left: Shear cell for granular matter; Right: One dimensional column of shaken beads.

- Besides usual laboratory instruments (power suppliers, wave generators, amplifiers, oscilloscopes) our facilities includes step-by-step motors, electromagnetic shakers, high frame rate video cameras, angular encoders, multichannel acquisition boards with high dynamics and frequency AD converters, torque and pressure meters, microphones and piezoelectric transducer for acoustic emission acquisition up to 1 MHz in frequency, accelerometers, different digital processors, including PCs, Raspberrys and Arduinos;
- Presently, miniaturized wireless sensors for pressure, temperature and magnetic fields are being developed;
- An optical set up for laser diffusing wave spectroscopy is under implementation.

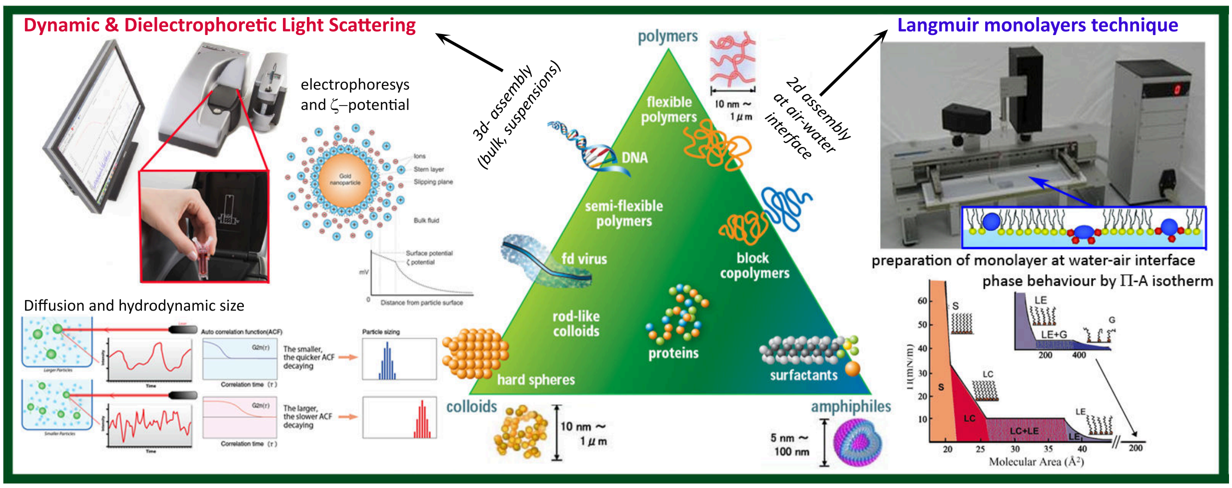
http://lavinia.phys.uniroma1.it

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 they are under the responsibility of Prof. F. Bordi.

The laboratories are equipped with the following complementary instrumentations for the preparation of soft matter self-assembled systems and the further investigation of their self-assembly :

- **Dynamic and Dielectrophoretic light scattering**: two different platforms are available for the investigations of self-assembled systems in bulk, as colloidal suspensions (lipidic vesicles, polymeric vesicles, nanoparticles ...): a Fiber Optique QuasiElastic Light Scattering (FoQELS) Brookhaven, with a portable probe, and a Malvern NanoZeta Sizer, for the simultaneous determination of hydrodynamic size and ζ-potential of particles, within the range 2 nm-10 μm, for both dilute and concentrated samples, in a temperature range from 5 to 120 ^{o}C;
- **Langmuir trough** for the preparation of bi-dimensional monomolecular films at air-water interface and the thermodynamical and electrical characterization of films by surface pressure-molecular area (Π-A) and surface potential-molecular area (Ψ-A)isotherms, at a controlled temperature. It is also equipped with a Dipper for the deposition of films on a solid support, for microscopical (AFM, optical) investigations;
- **Rotavapor and tip sonicator** for preparation of unilamellar vesicles of lipid (liposomes) and surfactant molecules;
- **Vibro-viscosimeter** for the measurement of the viscosity of solutions by tuning-fork Vibration Method with repeatability of 1%, at controlled temperature;
- **Equipments for sample manipulations and preparation** : we dispose of analytical balances with different capability and sensibility (mg and μg), pH-meter, magnetic stirrers, hot-plates, high temperatures oven, ultrasound bath, fridge, a small laminar flow hood and a safety aspirated cabinet for chemicals.
- **Energy-Dispersive X-rays Diffractometer (EDXD)** with a small-angle configuration and operating in conventional BraggBrentano geometry, for the investigation of ordering and thickness in molecular films deposited on a support, as lipid multilayers, in controlled temperature and humidity conditions.



Related research activities: C24

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.

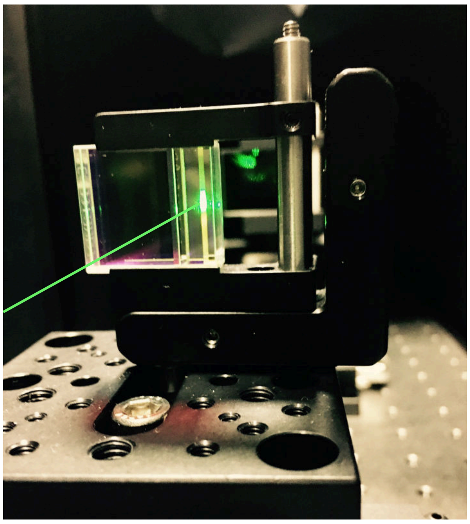


Figure 1: VIPA spectrometer for Brillouin microscopy.

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.

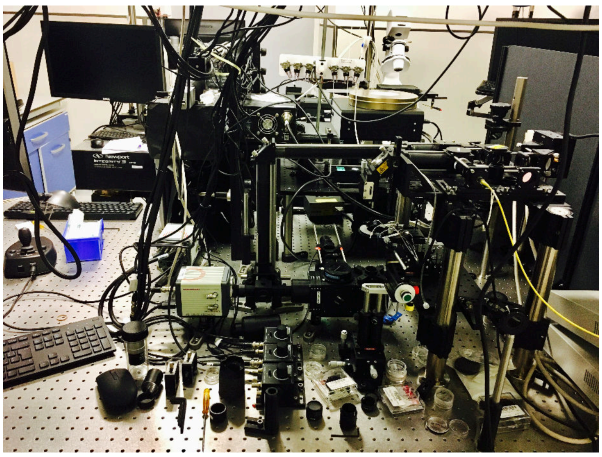


Figure 2: Optogenetics calcium imaging system.

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.

Related research activities: C26, C35

Quantum Optics Laboratory

The Quantum Optics laboratory has been engaged in experimental and theoretical research since more than 15 years with state-of-the-art works in the Quantum Optics and Quantum Information field. At the present time the laboratory is equipped with two optical experiments running independently.

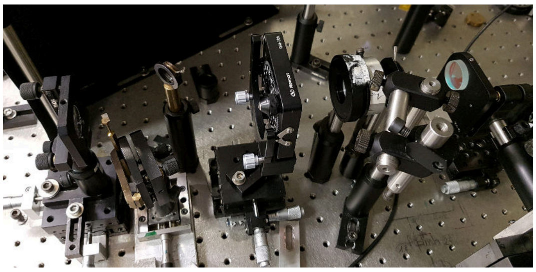


Figure 1: Two photon path-polarization hyperentanglement source

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 crystal's *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.

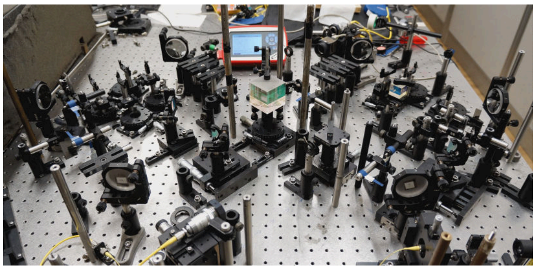


Figure 2: Simulator of open quantum system stroboscopic evolutions

The second experimental activity is dedicated to generate and use two-qubit polarization entangled states with high quality and brilliance, used to study sequential evolutions of open quantum systems, under on demand noise preparations. In our setup, a 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 *Quasi-Phasematching*. The crystal is pumped from both sides, and a coherent recombination of the associated generations inside a closing Sagnac interferometer allows to create intrinsically stable polarization entangled states.

Communication noisy channels are prepared by combining wave retarders, attenuators, and BS's on bulk and fiber optics interferometric configurations. For all the experiments carried out in the laboratory, the processes are revealed by fiber and bulk *Avalanche Photodetectors* to count single and coincident photon events.

`quantumoptics.phys.uniroma1.it/`
Related research activities: C28

Quantum Information Lab

The Quantum Information 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 and contextuality), 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 runs 3 laboratories equipped with several laser systems (including 3 Coherent MIRA, 4 Coherent VERDI, 1 Coherent REGA), more than 30 single-photon counting detectors for the visible range, 3 single-photon detectors in the IR domain, 5 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.

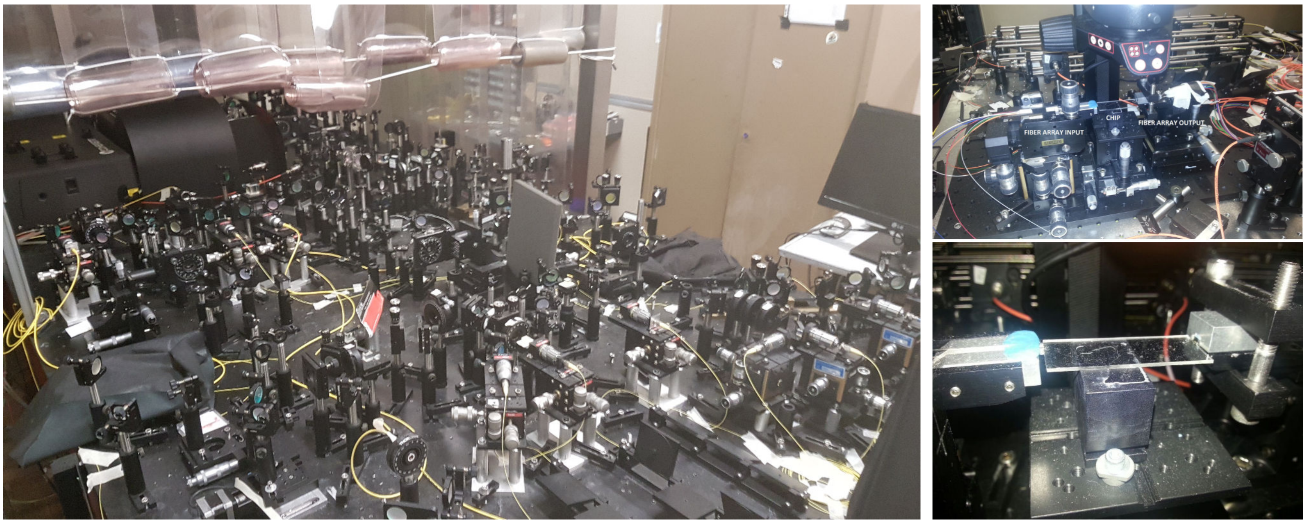


Figure 1: Left: overview of the experimental apparatus for the generation of single-photon states. Top right: equipment adopted to couple single-photons into integrated circuits. Bottom right: highlight of an integrated photonic circuit.

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 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 employs orbital angular momentum of the light as a resource for quantum information and for investigations on the foundations of quantum mechanics. It is equipped with two single-photon sources and spatial light modulators. The laser system is composed of a duplicated Nd:Yag laser (VERDI) pumping a Ti:Sa source of femtosecond pulses (MIRA).

`www.quantumlab.it`
Related research activities: C29

Nanomaterials for energies (Sapienza and CNR-ISC)

The Lab is active on basic research concerning nanomaterials 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 five main experimental stations which can work independently. The anelastic spectroscopy facility allows measurements of elastic energy loss and dynamic modulus in high vacuum in the temperature range between 1.3 and 900 K. Anelastic spectroscopy is a well established experimental technique to quantitatively determine the dynamics and the diffusion parameters of mobile species in solids and the occurrence of phase transitions, including chemical reactions. An external stress, applied to a sample through its vibration perturbs the energy levels of atoms of fractions of meV and induces redistribution of mobile species in the material (defects or lattice atoms) among the perturbed levels. The motion parameters are measured while, by thermal activation, the new equilibrium is being attained. The analysis of the data provides the parameters of the local or long range diffusion processes, like the relaxation rates and their pre-exponential factors, the activation energies for classical processes, or the splitting of the energy levels and the power laws of the relaxation rates for quantum tunnelling phenomena. Moreover, anelastic spectroscopy can sensitively detect structural and magnetic phase transitions through the dynamic elastic modulus, which is extremely sensitive to the formation of new phases or of atom complexes in materials. Anelastic relaxation gives essential information often not obtainable by other techniques and is complementary to neutron scattering, NMR, and NQR.

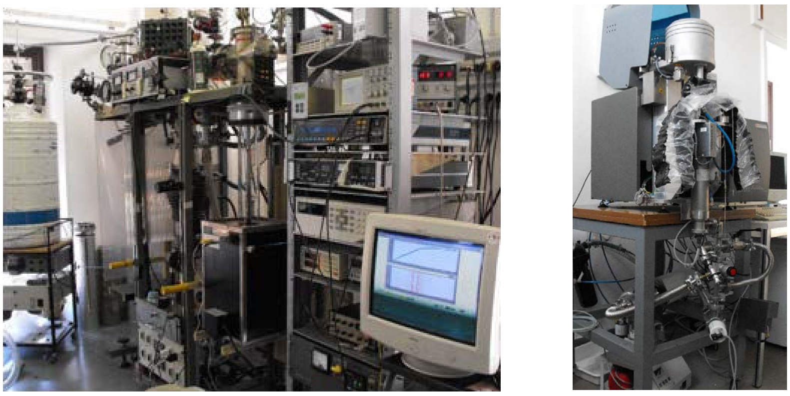


Figure 1: The experimental apparatus for anelastic spectroscopy measurements (left) and the system for concomitant thermogravimetry, differential scanning calorimetry and mass spectrometry (right).

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. Moreover, the Lab is equipped with a commercial Dynamic Mechanical Analyzer, which is able to measure, also in liquid corrosive environments, but at a lower performance level, 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. By the home-made Sieverts apparatus, it is possible to determine the thermodynamic p-c-T curves of the various solid-hydrogen systems, through the volumetric measurement of absorbed/desorbed hydrogen. This system is operative in a wide range of temperatures (80-600 K) and pressures (0-200 bar). Finally, the Lab is equipped with an Infrared Spectrometer allowing measurements in the mid-infrared range, with the possibility to perform experiments above room temperature.

Related research activities: C10

TERALAB

The terahertz (THz) radiation (0.1-10 THz; 0.1- 40 meV; 40-1000 microns) occupies the portion of the electromagnetic spectrum between infrared and microwaves. This spectral range is of crucial importance for the investigation of linear, non-linear and time-resolved spectroscopy in Condensed Matter Physics, in Biomedicine, in Material Science and in Particle-Physics. One can cite, for instance, the investigation of collective modes and the 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 Biomedicine THz imaging being sensitive to water content in tissues, may provide important information about early cancer development. In Particle-Physics THz radiation is an important tool for the characterization of new acceleration cavities, for the diagnostic of femtosecond long electronic beams and for the study of new decay channels for dark matter particles.

The aim of the TERALAB (Frequency and Time Resolved Terahertz Spectroscopy) laboratory of the Department of Physics, Sapienza University of Rome, managed by Prof. Stefano Lupi, is related to the different use of THz radiation in physics. In the TERALAB laboratory many radiation sources have been developped covering a large spectral range from sub-THz to ultraviolet for frequency domain spectroscopy. Femtosecond visible to terahertz sources are also present in the lab providing the possibility to perform pump-probe spectroscopy with time and frequency capability. In parallel to the TERALAB laboratory S. Lupi manages the THz SISSI (Synchrotron Infrared Source for Spectroscopy and Imaging) beamline at the Elettra Synchtron in Trieste (https://www.elettra.trieste.it/elettra-beamlines/sissi.html), where applications of terahertz radiation span from high-pressure material studies, to Biology, and material characterizations. S. Lupi is also co-responsible of the high-intensity THz beamline FEMTOTERA at INFN-LNF. This last beamline provides the possibility to study materials under high-intensity fields (up to 10 MV/cm) accessing to non-linear optical experiments in the THz range.

These three labs, which are also open to external users, provide specialized THz sources for spectroscopy, imaging and time-resolved measurements and represents an unicum in Europe for what concerns THz radiation applications.

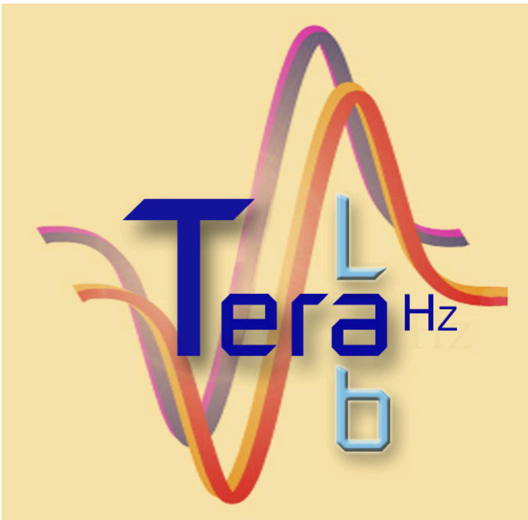


Figure 1: The logo of the TERALAB Laboratory.

http://server2.phys.uniroma1.it/doc/lupi/
https://www.elettra.trieste.it/elettra-beamlines/sissi.html
http://www.lnf.infn.it/acceleratori/sparc_lab/
Related research activities: C6

Laboratory of Spectroscopy Applied to Cultural Heritage (CNR-ISC)

The Laboratory of Spectroscopy Applied to Cultural Heritage (responsible Dr. M. Missori) is mainly focused to the application of ultraviolet (UV), visible (Vis), infrared (IR) and THz spectroscopic techniques to the study of materials found in art objects. Particular importance is given to the study of ancient documents and drawings made of natural fibers of cellulose.

The experimental methods available in the Laboratory are aimed to probe the physical and chemical structure of ancient artifacts in a non-destructive way. The goal is an accurate and quantitative appraisal of the states of preservation of artworks as well as the understanding and the diagnosis of their unavoidable degradation processes.

In the Laboratory is available a setup from Avantes BV (The Netherlands) able to measure diffuse reflectance spectra in the UV, Vis, and near IR (NIR) spectral regions. It consists of a combined deuterium-halogen UV-Vis-NIR source (AvaLight-DH-S-BAL) connected by an optical fiber to an integrating sphere (AvaSphere-30-REFL). This is used to illuminate the sample under study with diffuse radiation and collect radiation reflected from its surface over all angles (Fig. 1, left panel). Radiation from the integrating sphere is sent by an optical fiber to a multi-channel spectrometer equipped with a 2048x14 CCD detector (AvaSpec-2048x14-USB2). Due to the optical fibers the setup is easy movable for on-site measurements. This tools is widely used for quantitative diagnostic of the optical damage induced by degradation in art objects.

Thanks to a collaboration with the Laboratory of Low Temperatures (responsible Prof. R. Fastampa) the optical setup is also used for spectroscopic measurements as a function of temperature in the range 15-350 K. In this case samples are mounted in a He-gas close-cycle optical cryostat while spectroscopic measurement are performed in transmission mode by using an optical line made of UV-transparent CaF_2 lenses.

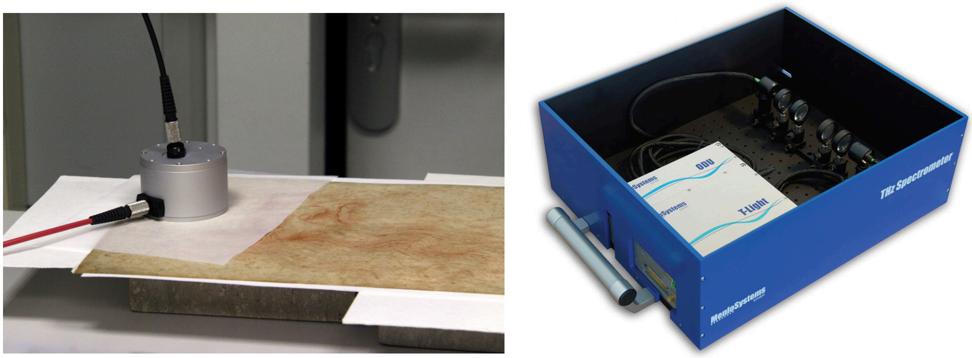


Figure 1: The integrating sphere laid on the Leonardo da Vincis self-portrait during the diagnostic studies carried out at the Central Institute for the Restoration of Archival and Library Heritage in Rome, Italy (left panel); the TERA K15 THz-TDS setup (right panel).

A TERA K15 THz time-domain spectroscopy (THz-TDS) setup from Menlo Systems (Germany) is also available in the Laboratory (Fig. 1, right panel). The fiber-coupled laser excitation of the THz emitter and detector antenna modules is realized by a Menlo System T-Light femtosecond laser. The THz-TDS setup allows spectroscopic measurements in the 0.2-3.5 THz spectral range with a dynamic range $\geq$75 dB and a spectral resolution up to 1.25 GHz thanks to the 825 ps optical delay line. The open architecture of the THz beam line uses plano-convex lenses made of TPX and allows easy operations. Further, two motorized translation stages enable automated THz imaging in transmission mode within a 15cm$\times$15cm scan range.

The Laboratory is also equipped with an atomic force microscopy (AFM) Nanonics Multiview 400 with 70 μm x-y-z scan range and central opening providing clear optical axis for easy integration with optical microscopes. A stereo microscope STMPRO-T BEL Engineering (Italy) equipped with a EUREKAM 3.0 3MPixel camera is also available. Finally, it is possible to perform Fourier Transform IR (FTIR) spectroscopy in transmission and Attenuated Total Reflection (ATR) mode thanks to shared ownership with the ISM-CNR of a Golden Gate MkII Diamond ATR with KRS-5 lenses.

`http://www.isc.cnr.it/staff-members/mauro-missori/`
Related research activities: C15

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 recently purchased 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).

Very recently we also designed and built a setup for photon correlation measurements (both pulsed and CW), which gave us the ability to fully characterize the performance of the investigated nanostructures as single- and entangled-photon emitters. Lastly, hydrogen 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.

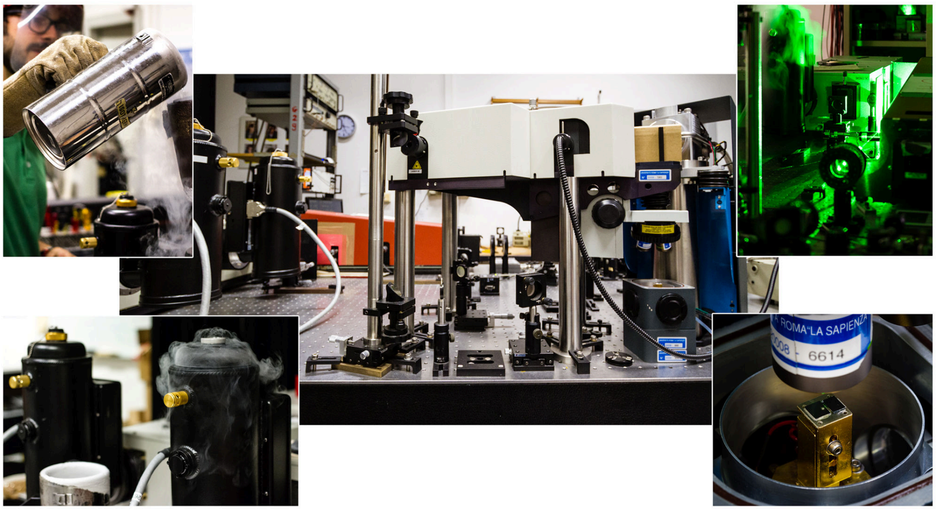


Figure 1: (Center) One of the optical tables available in the OSNM lab, equipped with a state-of-the-art micro-PL setup coupled to a low vibration closed-cycle cryostat. (Bottom right) Zoom-in of the sample chamber of the cryostat, wherein temperatures < 4 K can be reached. The output of one of the several light sources available in the lab (Top left: Beam generated by a frequency-doubled Nd:YVO_4 laser, with wavelength λ_{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/`
Related research activities: C12, C13

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. Light scattering based techniques opens also to a broad range of other applications in the field of nanoscience such as size and shape measurements of nanosized particles and aggregates. The research carried out in our Laboratory is manly focused on spectroscopic studies on the mesoscopic materials belonging either to functional inorganic materials or to soft matter of biological interest. We have two microRaman spectrometers 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 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 as small as few nanoliter and its surface few tens of micron wide. The same apparatus allow to collect both Raman and photoluminescence signal from samples under pressure thus directly monitoring lattice dynamic and electronic structure. Important studies have been caried out in the last years on strongly correlated materials such as high Tc superconductors and colossal magnetoresistence manganites. The instruments are 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. These apparata are remarkably relevant for studying and characterizing emerging low-dimensional materials (few-layers, single layers, heterostructures, nanowires and nanotubes). An example of the results we have obtained by single GaP/Si core-shell nanowire Raman measurements is shown in Panel b and c in Fig.1, together with a typical cross-sectional SEM image in Panel a in Fig.1.

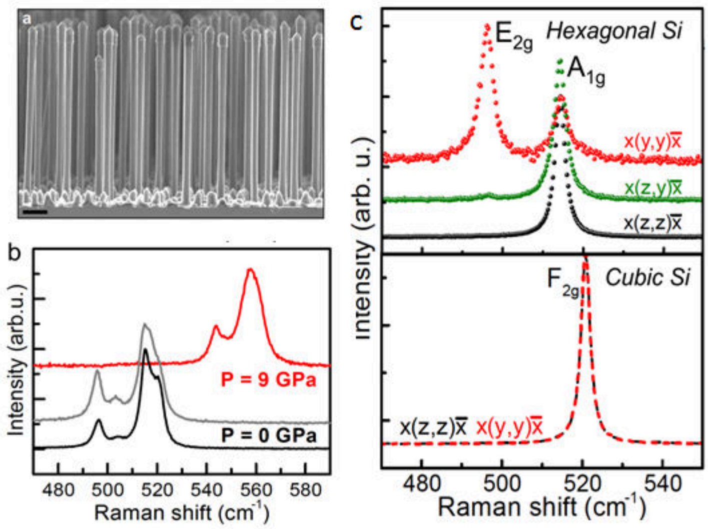


Figure 1: (a) Cross-sectional SEM image of a representative sample of GaP/Si core/shell NWs. Polarized Raman spectra in different scattering congurations (Porto notation).(b) Raman spectrum of an ensemble of hexagonal GaP/Si NWs at different pressures; (c) Upper panel: single hexagonal GaP/Si NW (120 nm shell); lower panel: Si (100) bulk. From: *Hexagonal Silicon Realized* Nanoletters 5855, **15**, (2015)

http://gruppohps.wordpress.com
Related research activities: C7, C19

Laboratorio “GranularChaos” (CNR-ISC)

The laboratory includes two main experimental setups: 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 aluminium 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 colours. The setup A has been used in previous years to achieve a granular 2D fluid (on a rough plate) with number densities in the gas-liquid-glass densities, studying velocity correlations. In a second series of experiments a cylindrical container was used - again in setup A - to get a 3D fluid: a rotating blade was suspended from above in order to observe “granular brownian motion” highlighting the non-linear effects of dry friction and the rectification (“Brownian motor” phenomena) in the presence of some spatial broken symmetry. More recently, the same setup has been used to study the violation of the fluctuation-response relation [1] and the liquid cage effects coupled to long-time superdiffusion at high packing fractions [2]. In the recent months, the setup A has also been used to understand granular rheological properties (average shear stress versus average shear rate) in a wide range of densities and shaking amplitudes [3] and to study the crawling dynamics of 3d-printed synthetic “walkers” with different shapes [4]. Setup B has revelead to be ideal for a closer comparison with granular kinetic theories and hydrodynamics. Such a comparison has revealed an unknown important effect: the presence of thermal convection induced only by dissipative collisions with the lateral walls [5], as put in evidence in the Figure.

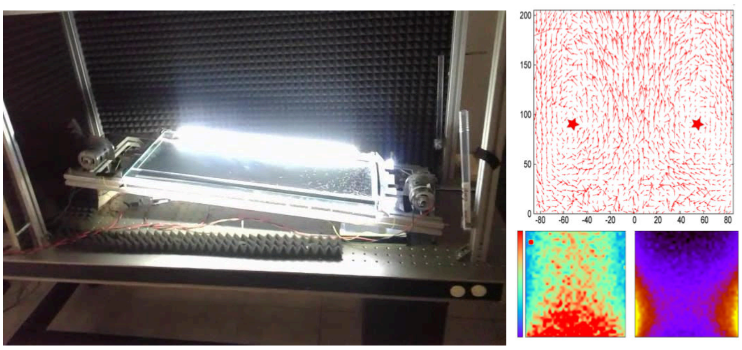


Figure 1: Left: a picture of the experimental setup B of the GranularChaos lab. Right: velocity field (top), temperature field (bottom left) and density field (bottom right) reconstructed by fast-camera particle tracking [5].

[1] A. Gnoli, A. Puglisi, A. Sarracino and A. Vulpiani Nonequilibrium Brownian Motion beyond the Effective Temperature Plos One 9, e93720 (2014)

[2] C. Scalliet, A. Gnoli, A. Puglisi, A. Vulpiani, Cages and anomalous diffusion in vibrated dense granular media Phys. Rev. Lett. 114, 198001 (2015)

[3] A. Gnoli, A. Lasanta, A. Sarracino, A. Puglisi Unified rheology of vibro-fluidized dry granular media: From slow dense flows to fast gas-like regimes Scientific Reports 6, 38604 (2016)

[4] N. Koumakis, A. Gnoli, C. Maggi, A. Puglisi and R. Di Leonardo Mechanism of self-propulsion in 3D-printed active granular particles New J. Phys. 18 113046 (2016)

[5] G. Pontuale, A. Gnoli, F. Vega Reyes, A. Puglisi Thermal convection in granular gases with dissipative lateral walls Phys. Rev. Lett. 117, 098006 (2016)

`http://www.sapienza.isc.cnr.it/index.php/organization/facilities/97-laboratories/200-granular-dynamics-laboratory.html`
`http://tnt.phys.uniroma1.it/~puglisi`
Related research activities: T11

G4-Spectroscopy and microscopy of superconductors and emerging functional materials

Group G4 is actively involved in research activities in the field of spectrsocopy and microscopy 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 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 condensed matter. The group has been using advanced synchrotron radiation facilities for the spectroscopy and 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 complex materials. 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, being used for characterization of new materials for their morphology.

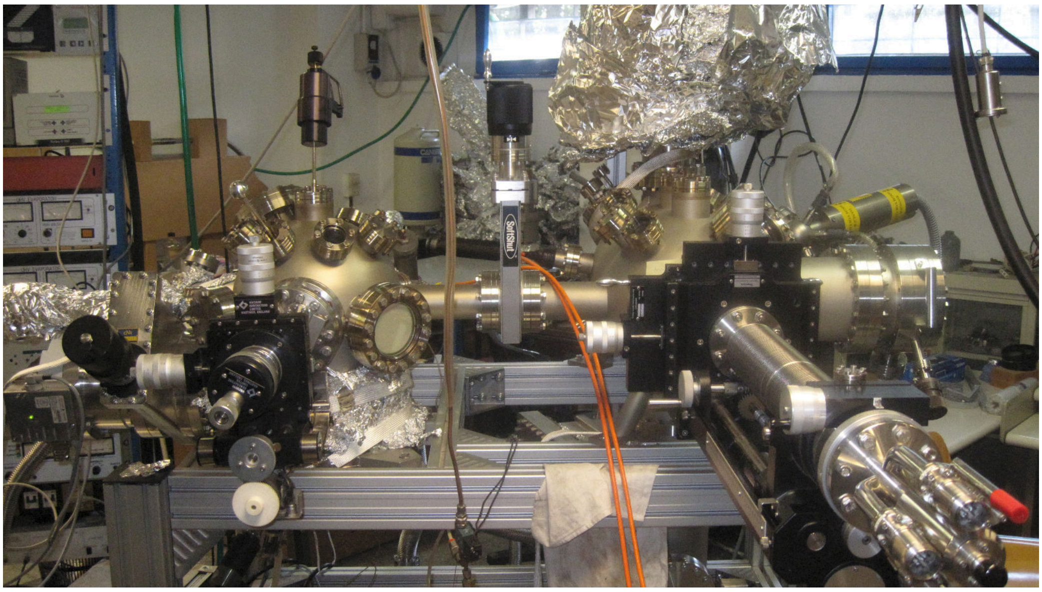
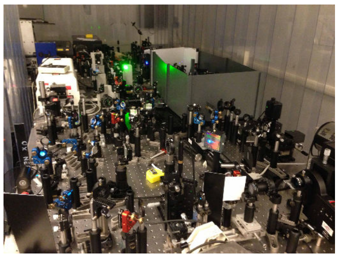


Figure 1: UHV system equipped with the facility of electron spectroscopy.

http://server2.phys.uniroma1.it/gr/g4/
Related research activities: C4

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 wavelength (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/`
Related research activities: C16

High frequency electrical measurements

Instrumentation and methods:

The laboratory is equipped with instrumentation able to measure the electrical response over a very wide frequency range. The available experimental setups allow for measurements on both solid and liquid samples, both at room temperature (liquids and solids) and at cryogenic temperatures (solids). Measurements on solid samples is performed through the Corbino disk geometry, allowing for measurements as a function of frequency over a wide, continuous frequency range (40 MHz-50 GHz). Measurements on liquid samples are perfomed in custom cells, alowing for measurements over an even wider frequency range (from 10 Hz to 50 GHz).

Research activities:

- complex liquids (polyelectrolites, glasses, solutions of carbon nanotubes)
- biological structures (liposomes or drug delivery vectors)
- superconductivity
- novel materials for accelerating devices (in collaboration with INFN)

Collaborations::

F. Sciortino, F. Bordi (La Sapienza), B. Ruzicka, R. Angelini, S.Sennato (CNR-ISC) - complex liquids; A.Marcelli, B. Spataro (INFN), S. Lupi (La Sapienza) - accelerating devices; E.Silva, N. Pompeo, K. Torokhtii (Universita' Roma Tre) - superconductivity

Currently financed projects:

- DiElectric and METallic Radiofrequency Accelerator (DEMETRA - INFN)
- Superconductivity in Li-decorated non-porous Graphene (Ricerca di Ateneo)

Latest pubblications:

- S.Sarti et al. *Hydrogen bond network relaxation in aqueous polyelectrolyte solutions: the effect of temperature* Journal Of Physics-Condensed Matter 24, 284102 (2012)
- K.Torokhtii et al. "Vortex motion in Nb/PdNi/Nb trilayers: New aspects in the flux flow state" Physica C 479,140 (2012)
- Y. Xu et al. *Structural and morphological characterization of Mo coatings for high gradient accelerating structures* ,15TH International Conference On X-Ray Absorption Fine Structure (Xafs15) 430, 012091(2013)
- K.Torokhtii et al. *Microwave Properties of Nb/PdNi/Nb Trilayers* Journal Of Superconductivity And Novel Magnetism 26, 571 (2013)
- S.Bini et al. *Molybdenum sputtering film characterization for high gradient accelerating structures* CHINESE PHYSICS C 37,UNSP 097005 (2013)
- S. Sarti and F. Bordi *Polymeric hollow micro and nanospheres for biotechnological applications: A focused review* MATERIALS LETTERS 109,134 (2013)
- A. Marcelli et al. *Characterization of thick conducting molybdenum films: Enhanced conductivity via thermal annealing* SURFACE and COATINGS TECHNOLOGY 261, 391(2015)
- E. Silva et al. *Wideband Surface Impedance Measurements in Superconducting Films"*, IEEE Transactions on Instrumentation and Measurement 65,1120 (2016)

Related research activities: C20

Low Temperature Laboratory

The Laboratory of Low Temperatures (responsible Prof. R. Fastampa) has a tradition in the field of magneto-resistive measurements in metals and superconductors. Recently a cryogenic system has been set up to also perform optical spectroscopy measurements in the visible range as a function of temperature. As future development the same system will be set up to perform spectroscopy at THz frequencies.

In the laboratory are present a cryomagnetic system Oxford THS 15/17 (see Fig. 1 left) with solenoid superconductor cooled with a system of coupled Dewar containing helium and liquid nitrogen and two workstations each one equipped with Leybold RDK10-320 cryogenerator. One of the two cryogenerators is equipped with optical windows for spectroscopy measurements (see Fig. 1 center) and has been used for transmission measurements in the visible range on Lithium Fluoride crystals thanks to the further optical instrumentation available from Dr. M. Missori (CNR-ISC). All cryogenic systems are equipped by pumping groups able to reach high vacuum levels necessary for establishing the thermal insulation with respect to the external environment.

The cryomagnetic system is able to apply on a sample mounted in a suitable cryogenic insert (46mm sample space) a maximum field of 17 Tesla, covering the temperature range from room temperature up to about 1K by means of a cold helium flow system. A control unit allows to stabilize the temperature within 0.01K. A further control unit also allows to vary the current circulating in the superconducting solenoid in order to set the required intensity of magnetic field. All the operations of the cryomagnet can be controlled by computer, using an IEEE interface.

The cryogenerator-based systems allow to cool samples placed in mechanical contact with the so-called cold finger of the cooling unit (see Fig. 1 right) and to vary the sample temperature in the range $[15 - 350]$K.

Figure 1: Left: Cryomagnet with pump and two reservoirs for cryogenic liquids. Center: Detail of the cryogenerator equipped by optical windows. Right: Inner view of the main body of a cryogenerator. The cold finger is visible on the top of cryogenerator.

Temperature sensors suitably accommodated in the sample holder allow the measurement of the sample temperature. The temperature stabilization within 0.01K is obtained by computerized control (custom software developed in LabView) of the current circulating through a heater coil placed at the base of the sample holder.

The laboratory is also equipped with instrumentation consisting of a nanovoltmeter HP34420A, an EG&G 5302 lock-in amplifier, a current source Keythley K224 and a Keythley K617 electrometer which allow to perform four probes low resistance measurements of high sensitivity (10–100$\mu\Omega$) and two probes high resistance measurements (200$G\Omega$) in all cryogenic systems available in the laboratory. All the instrumentations present in the laboratory can be controlled by computer using the software developed by the laboratory staff in LabView enviroment.

In the laboratory a LENTON furnace equipped with a vacuum-tight quartz tube is also available in order to perform sample annealing in a controlled gas flow up to temperature of 1000 °C. Further a sputtering unit allows to perform thin-film metallic depositions of controlled thickness on suitable substrates.

Related research activities: C15

Laboratory of Silicon detectors development

This laboratory is located on the third floor of the building "G. Marconi" of the Department of Physics of "Sapienza University of Rome". It is equipped with instrumentation able to characterize silicon detectors to detect 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 for silicon detector optical inspection and test is in the laboratory. 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 equipment described above, prototypes of the microstips detectors to be used as front part of the particle tracker of Super Big Bite (SBS) Spectrometer at JLAB (Virginia, USA) were developed. 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 under study. The development of Silicon Fast Photometer (SiFAP) with related custom electronics for the study of variable sources, like pulsars, at 1.5 m (Cassini) and 3.5 m (TNG) optical telescopes is still ongoing.

Related research activities: A11

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`
Related research activities: P14, P15

Laboratory of Accelerator Physics Detectors

The development of gaseous detectors operated with very light Helium-based gas mixture is important for precise tracking of charged particles in magnetic field at relatively low energy (down to few tens MeV energy). This is the case of the search for the ultra-rare decay $\mu \to e\gamma$ where a positron of 53 MeV energy must be measured. Researchers of this Department and INFN involved in the MEG-II experiment at PSI (Switzerland) recently revamped this laboratory for the development of such detectors.

This activity requires the construction of prototypes to be tested with cosmic rays, radioactive source, lasers or particle beams. Prototypes to assess the tracking performances of the MEG-II drift chamber have been built and tested thanks to INFN and MIUR Futuro in Ricerca financing. The ultimate aim of this research is the development cluster counting and cluster timing techniques in order to improve the tracking and particle identification capabilities of drift chambers with light gas mixtures. A small chamber composed of 20 thin-wall (37 μm Mylar) drift tubes with 20 μm diameter gold-plated tungsten wires has been built and is currently under test with cosmic rays, with the goal of reaching a single-hit position resolution around 100 μm. This chamber will be also used in the future as a gas quality monitoring device within the MEG-II experiment (see Fig. 1). A system to measure the stringing tension of the wires during the assembly of the MEG-II drift chamber has been also developed in this laboratory and is currently in operation at INFN Pisa. Moreover, the gas distribution system of MEG-II, now at PSI, has been developed and built here.

The laboratory is equipped with a system for the mixing and distribution of high purity gases at precise stoichiometric compositions, under controlled pressure and temperature conditions; high voltage systems with nA current sensitivity; various kinds of data acquisition devices for comparative studies. In the next future, a Nd:YAG laser system will be installed as a test facility for many kinds of gaseous detectors.

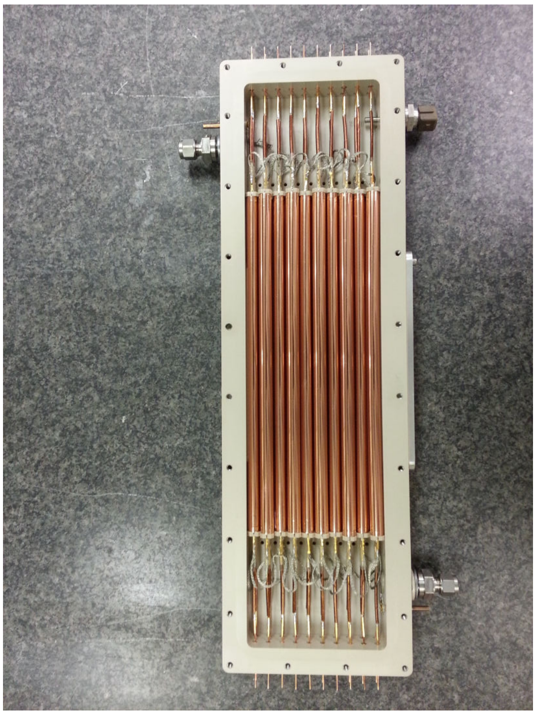


Figure 1: Small test drift chamber for gas monitoring of the MEG-II experiment.

Laboratory of cryogenic detectors (Sapienza and INFN)

The laboratory, supported by both Physics Department and INFN, is used to develop cryogenic detectors for particle and cosmo 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 two RF lines and an optical fiber 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.

Related research activities: P25, P26, P27

ARPG/Chirone Laboratory (INFN)

The ARPG/Chirone Lab located in the Segre' Building at la Sapienza, is devoted to the development, construction and characterisation of new probes prototypes for the Radio Guided Surgery (RGS) proposed by the ARPG group.

The lab is equipped to manage all aspects of the device design/construction/testing steps. A 3D printer and micro machining tools (micro miller, micro lathe) are used to realise the probe mechanics (device body, crystal/sensor holders), crystal cutting and shaping and most of the mechanical components used in our custom test stand.

Standard measurements on the performances achievable with a prototype on β & γ in the energy range of clinical interest are done using an automated test bench and sealed radio active sources. The test bench, actually designed to host pen-like probes with scintillating head will be soon upgraded to manage devices based on CMOS sensors. More specific tests, depending on the clinical environment the probe is designed for are done with custom phantoms reproducing the 3D distribution of the radio pharmaceutical concentration on the tumour remnants to be spotted by the probe and the surrounding healthy tissue.

Phantoms are manufactured on site both by sponge assembly or printed gelatine solids activated with the proper concentration of liquid ^{90}Y. Preparation and handling of the samples are performed in a sealed, shielded environment (glove box).

Figure 1: Preparation of a cylindrical gelatine phantom to test probe performance in an endoscopic environment

Related research activities: P34

The INFN APE Laboratory

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,...). 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.

Current research activities focus on:

a) development of low latency, high bandwidth interconnection network for Hybrid PC cluster (*APENet+*, 3-Dimensional Toroidal network optimized for LQCD computing platform);

b) efficient use of (GP)GPU accelerators in theoretical physics (*QUonG* project);

c) design of FPGA-based, reconfigurable architecture targeted to real-time systems (*NaNet*). NaNet systems implement low latency, high performance read-out systems for detectors at HEP (High Energy Physics) experiments.

In the past, group members participated with leadership roles to EU FP6 (SHAPES) and FP7 (EURETILE) projects in the area of embedded systems and high performance computing.

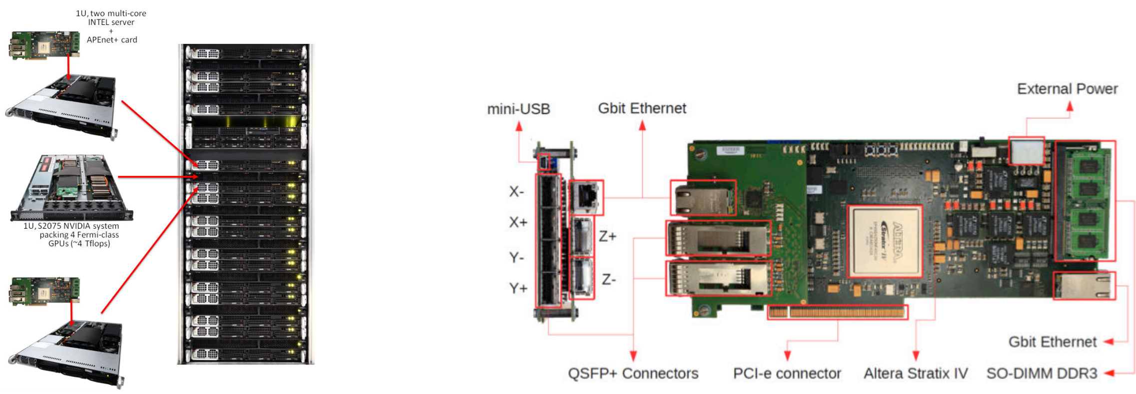
From 2015, in the framework of EU H2020 FET-HPC project *ExaNeSt*, the group has been active in design and prototyping of the next generation supercomputers at extreme scale (ExaFlops, 10^{18} Flops), based on low power microprocessors and custom networking.

Furthermore, in 2016, team members start to coordinate and contribute to *WaveScales* initiative, a sub-project of EU FET Flagship *HBP* (Human Brain Project). WaveScales's main goal is to develop a fast and scalable neural network simulation code to mimic the behavior generated by several tens of billions of nerve cell connections, or synapses.

Figure 1: APENext installation

The APE group is currently composed of 4 staff people and 10 junior researchers with expertise ranging from hardware and 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 to test and develop 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.



(a) (b)

Figure 2: a) QUonG system; b) APENet+ board

http://apegate.roma1.infn.it

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, and is a key partner of the QUBIC collaboration (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 [1,2,3]; b) testing and developing readout low noise electronics; c) cryogenic systems for ensuring low temperatures (down to 100 mK) for detectors and optical systems (see Fig.1); 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 controlled atmosphere chamber (mod. 855 AC by Plas-Labs Inc.), hot press and wire saw. A class 1000 clean room (4m $\times$ 3m) is being assembled in the G31 laboratory;

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 (see Fig. 1).

Figure 1: Dry cryostat with dilution refigerator hosted in the Experimental Cosmology Laboratory on the first floor of the Marconi Building, used to test detectors development. In the background the VNA.

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), 10-20 mW Gunn oscillators for the 90 and 150 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) 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.

g) For the integration of our large volume balloon payloads we have setup externally (hosted by INAF-IAPS Rome) a large industrial tent with a usable internal volume of $10\times8\times6$ m^3. We have a 5 m Gantry-Crane with 2 Ton lift capability inside the tent, and a smooth concrete floor for moving the crane and carts with payloads. This is the largest volume integration facility of our Department. Both the BOOMERanG and OLIMPO payloads have been integrated in this facility.

References

1. A. Paiella *et al.*, JLTP, **184**, 1-2, 97-102 (2016).
2. R. Gualtieri *et al.*, JLTP, **184**, 3-4, 527-533 (2016).
3. G. Coppi *et al.*, JIMTW, **37**, 8, 815-824 (2016).

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

Related research activities: A1, A2, A3, A4, A5, A6, A13

Laboratory of Solar Radiometry and Microclimate for Cultural Heritage

The Laboratory of Solar Radiometry and Microclimate for Cultural Heritage is managed by the G-Met group within the Physics Department and is located both on the third floor of the Fermi Bulding and on the terrace of the same building.

- Measurements of solar UV spectral irradiances in the spectral range from 290 to 325 nm, with a stepwidth of 0.5 nm, have been carried out since 1992. This long UV time series is necessary to assess the influence of solar UV radiation on ecosystems and human health. In addition, erythemal dose rates (i.e. the solar doses dangerous for human skin) have been obtained since 2000 by the broadband UV radiometer (model YES UVB-1). The YES radiometer has a spectral response similar to that of skin erythema and values of erythemal dose rates are retrieved using a calibration matrix as a function of solar zenith angle and total ozone amounts from the Brewer spectrophotometer. Ambient UV radiation is also used in the quantification of human UV exposure by means of polysulphone dosimetry.

Figure 1: A view of the instrumentation on the terrace of the Fermi Building.

- Besides solar radiation in the UV range, global radiation from the Sun in the range 200-3600 nm is regularly measured together with trace gases (ozone and nitrogen dixiode) columnar amounts.
- 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 (such as the thermohygrometers belonging to the TTU600 series) allows to investigate possible sources of degradation for monuments, museums, churches, hypogea and to suggest mitigating measures. Finally, a Minolta Spectrophotocolorimeter is used to detect possible markers of degradation by means of color changes.

`www.gmet.eu`
Related research activities: A14

Grants and Awards

Grants

1 European funding

ERC Advanced Grant FP7-IDEAS-ERC, European Research Council - 2009
"LUCIFER"
Principal Investigator: F. Ferroni
Local fund: 3,294,400 euro

ERC Starting Grant - European Research Council - 2010
"SWARM: Empirical analysis and theoretical modelling of self-organized collective behaviour in three-dimensions: from insect swarms and bird flocks to new schemes of distributed coordination"
Principal Investigator: I. Giardina
Local fund: 1,124,000 euro

ERC Advanced Grant FP7-IDEAS-ERC, European Research Council - 2010
"Critical Phenomena in Random Systems" (CriPheRaSy)
Principal Investigator: G. Parisi
Local fund: 2,080,000 euro

ERC Starting Grant-Consolidator, European Research Council - 2012
"3D-Quantum Integrated Optical Simulation (3D-QUEST)"
Principal Investigator: F. Sciarrino
Local fund: 1,474,800 euro

ERC Starting Grant - European Research Council - 2012
"Statistical mechanics of active matter"
Principal Investigator: R. Di Leonardo
Local fund: 1,448,400 euro

FP7-PEOPLE-IRSES - 2012
"Numerical Relativity and High-Energy Physics" - NRHEP
Local coordinator: L. Gualtieri
Local fund: 23,100 euro

FP7-PEOPLE-2013-ITN - 2013
"Photonic Integrated Compound Quantum Encoding - PICQUE"
Principal Investigator: F. Sciarrino
Local fund: 558,738 euro

ERC Consolidator Grant, European Research Council - 2013
"CRYSBEAM: Crystal channeling to extract a high energy hadron beam from an accelerator"
Principal Investigator: G. Cavoto
Local fund: 2,000,000 euro

FETPROACT-3-2014: Quantum simulation - 2014
"Quantum Simulation on a Photonic Chip (QUCHIP)"
Principal Investigator: F. Sciarrino
Local fund: 431,250 euro

Future Emerging Technology, FP7-FET-2014
"GEMINI: Germanium mid infrared plasmonics for sensing"
Research Unit Coordinator: M. Ortolani
Local fund: 289,500 euro

ERC Proof of Concept, European Research Council - 2014
"VANGUARD : Versatile optomechANical GRaphene Device for bio-tissue engineering"
Principal Investigator C. Conti
Local fund: 150,000 euro

ERC Advanced Grant, European Research Council - 2015
"Photonics of SpinOrbit Optical Phenomena (PHOSPhOR)"
Local Responsible: F. Sciarrino (PI: Lorenzo Marrucci - Federico II Naples)
Local fund: 190,000 euro

ERC Proof of Concept, European Research Council - 2015
"3D-Integrated single photon detector (3D-COUNT)"
Principal Investigator: F. Sciarrino
Local fund: 150,000 euro

H2020-MSCA-RISE-2015
"StronGrHEP"
Node Coordinator: L. Gualtieri
Local fund: 36,000 euro

ERC Advanced Grant, European Research Council - 2016
"Low Temperature Glassy Systems"
Principal Investigator: G. Parisi
Local fund: 1,750,000 euro

ERC Poof of Concept, European Research Council - 2016
"PROCEEDS: Probing Complex Dynamical Structures in Three Dimensions"
Principal Investigator: I. Giardina
Local fund: 150,000 euro

2 Funding from Italian Ministry of Research (MIUR)

The Italian Ministry of Research (MIUR) supports fundamental research in Universities, mainly through the PRIN (Research Projects of National Interest)[1].

2.1 PRIN (MIUR)

PRIN 2010
"GRAF. Frontiere della ricerca sul grafene: comprensione e controllo di funzionalit avanzate"
Principal Investigator: M.G. Betti
Local fund: 146,000 euro

PRIN 2010
"Meccanica Statistica dei Sistemi Disordinati e Complessi"
Principal Investigator: G. Parisi
Local fund: 134,000 euro

PRIN 2012
"RIDEIRON"
Principal Investigator: N. Saini
Local fund: 146,000 euro

[1] Please note that the year appearing in the name of the grant ("PRIN 2015", "PRIN 2014" etc.) does not correspond to the actual funding period of the grant.

PRIN 2014
“Sviluppo di rivelatori a bassissima radioattività per lo studio della massa e della natura del neutrino tramite il doppio decadimento beta”
Principal Investigator: F. Bellini
Local fund: 142,400 euro

PRIN 2014
“Advanced Quantum Simulation and Metrology (AQUASIM)”
Principal Investigator: F. Sciarrino
Local fund: 74,205 euro

PRIN 2015
“ Search for the Fundamental Laws and Constituents”
Principal Investigator: G. Martinelli
Local fund: 924,000 euro

PRIN 2015
“Plasmon-enhanced vibrational circular dichoiroism”
Research Unit Coordinator: Michele Ortolani
Local fund: 101,400 euro

PRIN 2015
“Meccanica statistica e complessità”
Principal Investigator: G. Parisi
Local fund: 133,000 euro

2.2 Other grants from MIUR

Programma per giovani ricercatori “Rita Levi Montalcini” 2010
“Study of the electroweak symmetry breaking mechanism and search for new physics beyond the Standard Model in final states containing a pair of vector bosons with the CMS detector at LHC”
Principal Investigator: F. Santanastasio
Local fund: 219,874 euro

MIUR Futuro in Ricerca 2012-2016
“Rivelatori di luce criogenici ad alta sensibilità per la ricerca di eventi rari”
Local Responsible: F. Bellini
Local fund: 243,926 euro

MIUR Futuro in Ricerca 2012-2016
“Realization of an innovative system for complex calculations and pattern recognition in real time by using commercial graphics processors (GPU). Application in High Energy Physics experiments to select rare events and in medical imaging for CT, PET and NMR”
Local Responsible: A. Messina
Local fund: 214,934 euro

FIRB-Futuro in Ricerca - 2012
“DeLIGHTeD-Accoppiamento deterministico tra nano-emettitori di luce site-controlled e strutture a cristalli fotonici progettate da principi primi Deterministic coupling between site-controlled, nanometer-sized LIGHT emitters and photonic crystal structures Designed from first principles”
Principal Investigator: M. Felici
Total fund: 763,670 euro

SIR-2014
“Mid-Infrared Nano-optics: approaching plasmonics with Doped Semiconductors (MINDS)”
Principal Investigator: L. Baldassarre
Local fund: 423,500 euro

PNRA - 2016
“Kinetic Inductance Detectors for astronomical observations at millimetric and sub-millimetric wavelengths from Antarctica’
Principal Investigator: E. Battistelli
Local fund: 90,200 euro

3 Funding from Sapienza

Ateneo Interdipartimento
“Terahertz and spectroscopy analysis of manuscripts”
Principal Investigator: M. Ortolani
Local fund: 20,000 euro

Progetti Awards
“Anderson localization with classical and quantum photonics systems (PhotoAnderson)”
Principal Investigator: F. Sciarrino
Local fund: 53,000 euro

Progetti di Ateneo 2014
“Caratterizzazione di film sottili per l’ottimizzazione della raccolta di luce di rivelatori criogenici”
Principal Investigator: F. Bellini
Local fund: 13,000 euro

Progetti di Ateneo 2014
“Caratterizzazione di rivelatori superconduttori a bassissime temperature per l’astrofisica, la fisica del neutrino, la ricerca di materia oscura, il calcolo quantistico, lo studio di algoritmi di controllo ottimo”
Principal Investigator: F. Bellini
Local fund: 100,000 euro

Progetti di Ateneo 2014
“Spettrofotomeria solare Brewer per ground-truth dei prodotti satellitari”
Principal Investigator: A.M. Siani
Local fund: 12,000 euro

Progetto di Ateneo 2014
“Development of pattern recognition algorithms for a GPUs cluster in a energy effective real time environment”
Principal Investigator: A. Messina
Local fund: 13,000 euro

Progetto di Ateneo 2014
“Mapping motions and weighing clusters of galaxies with the Sunyaev-Zel’dovich effect”
Principal Investigator: M. De Petris
Local fund: 3,000 euro

Progetto di Ateneo 2014
“Gravitational wave sources”
Principal Investigator: L. Gualtieri
Local fund: 7,000 euro

Progetto di Ateneo 2014
“Simulazioni numeriche delle approssimazioni discrete ai modelli spin glass con variabili continue”
Principal Investigator: F. Ricci-Tersenghi
Local fund: 13,000 euro

Progetto di Ateneo 2015
“Ottimizzazione di sistemi complessi tramite dinamiche biased e l’uso di fluttuazioni quantistiche”
Principal Investigator: F. Ricci-Tersenghi
Local fund: 9,000 euro

Progetti di Ateneo 2015
“Valutazione dei livelli di radiazione solare ultravioletta per indagini sulla salute umana e sulla decontaminazione di acque”
Principal Investigator: A.M. Siani
Local fund: 12,000 euro

Progetto di Ateneo 2015
“Quantum certification of Boson Sampling”
Principal Investigator: F. Sciarrino
Local fund: 13,000 euro

Progetto di Ateneo 2015
“Sviluppo di nanovettori biopolimerici ad alta efficienza per la veicolazione della doxorubicina nelle cellule di carcinoma mammario.”
Principal Investigator: F. Bordi
Local fund: 15,000 euro

Progetto di Ateneo 2015
“Development of an innovative computing device able to execute pattern-recognition algo- rithms in real time and power efficiently on large datasets based on graphical processing units”
Principal Investigator: A. Messina
Local fund: 13,000 euro

Progetto di Ateneo 2015
“The Sunyaev-Zel’dovich Effect: a powerful tool to explore clusters of galaxies”
Principal Investigator: M. De Petris
Local fund: 4,000 euro

Progetto di Ateneo 2015
“Neutron stars and black holes: a laboratory to test the strong-gravity regime of General Relativity”
Principal Investigator: V. Ferrari
Local fund: 13,000 euro

Progetto di Ateneo 2015
“Exploring the tunability of electronic and vibrational properties of few-layer transition metal dichalcogenides via light atom incorporation and intercalation”
Principal Investigator: A. Polimeni
Local fund: 53,000 euro

Progetto di Ateneo 2015
“Development of a GPU-based system for fast analysis of real time data streams.”
Principal Investigator: A. Capone
Local fund: 11,000 euro

Progetto di Ateneo 2016
“Caratterizzazione e test di una sorgente acustica parametrica per la calibrazione di una rete di sensori acustici sottomarini”
Principal Investigator: A. Capone
Local fund: 13,000 euro

Progetto di Ateneo 2016
“Strong gravity tests of General Relativity through gravitational waves , neutron stars and black hole observations”
Principal Investigator: V. Ferrari
Local fund: 15,000 euro

Progetto di Ateneo 2016
“Utilizzo di GPU per la ricostruzione di pattern in sistemi di trigger per esperimenti di Fisica delle Alte Energie basati su algoritmi di apprendimento automatico”
Principal Investigator: M. Bauce
Local fund: 15,000 euro

Progetto di Ateneo 2016
“Caratterizzazione elettrica di dispositivi criogenici superconduttori per la ricerca di eventi rari.”
Principal Investigator: C. Cosmelli
Local fund: 13,000 euro

Progetto di Ateneo 2016
“Detection and detailed study of Anomalous Microwave Emission in astrophysical Galactic and extragalactic sources”
Principal Investigator: E. Battistelli
Local fund: 38,600 euro

Progetto di Ateneo 2016
“Development of a probe for radioguided surgery with beta-decays”
Principal Investigator: R. Faccini
Local fund: 15,000 euro

Workshop Grant - 2016
“New Frontiers in Gravitational-Wave Astronomy”
Local Responsabile: P. Pani
Local fund: 4,000 euro

Grant for Visiting Professors - 2014
Local Responsabile: L. De Petris
Local fund: 9,000 euro

Grant for Visiting Professors - 2016
Local Responsabile: A. Capone
Local fund: 9,000 euro

Grant for Visiting Professors - 2016
Local Responsabile: L. Gualtieri
Local fund: 5,000 euro

Progetti per Avvio alla Ricerca 2016
“Microgel intelligenti per la materia soffice”
Principal Investigator: V. Nigro
Local fund: 1,400 euro

Progetti per Avvio alla Ricerca
“Efficient photon source for telecom wavelength ”
Principal Investigator: N. Spagnolo
Local fund: 2,500 euro

4 Funding from other Italian agencies

Agenzia Regionale per la Protezione dell’Ambiente Valle d’Aosta
“Attività di sorveglianza e di studio dei dati di ozono totale, di biossido di azoto e di irradianza ultravioletta tramite lo spettrofotometro Brewer 066”
Local Responsible: A.M. Siani
Local fund: 42,000 euro

Programma Nazionale Ricerche in Antartide 2013
“CASPER: monitoraggio dell’atmosfera in banda millimetrica/submillimetrica a sostegno di osservazioni cosmologiche dall’Antartide”
Local Responsible: M. De Petris
Local fund: 59,000 euro

Programma Nazionale Ricerche in Antartide (PNRA), Consigio Nazionale delle Ricerche
“QUBIC (Q and U Bolometric Interferometer at Concordia)”
Unit Coordinator: M. De Petris
Local fund: 21,000 euro

Programma Nazionale Ricerche in Antartide (PNRA), Consigio Nazionale delle Ricerche
“Ricerca di Polarizzazione di modo-B nel fondo cosmico di microonde con l’esperimento QUBIC”
National Coordinator: Silvia Masi
Total funds: 293,000 euro; Local Funds: 169,940 euro

Programma Nazionale Ricerche in Antartide (PNRA), Consigio Nazionale delle Ricerche
“QUBIC (Interferometro Bolometrico Q e U a Concordia)”
National Coordinator: Silvia Masi
Total funds: 118,000 euro; Local Funds 43,500 euro

INFN Specific Initiative, 2014
“TEONGRAV”
National Coordinator: L. Gualtieri
Local fund: 83,000 euro

INAIL- BRIC 2015
“Ultrasuoni e sicurezza: un nuovo approccio biofisico integrato per la valutazione dell’impatto biologico di tecnologie ad ultrasuoni emergenti”
Principal Investigator: F. Bordi
Local fund: 60,000 euro

Regione Lazio, 2015
“Facility di Test e Sviluppo Tecnologie Avanzate (FATA)”
Coordinator: Paolo de Bernardis
Local funds: 249,990.40 euro

OLIMPO Svalbard Flight Campaign 2016 - Payload Activities
Italian Space Agency, contract 2016-4-H.0
Coordinator: Silvia Masi
Total funds: 343,027.00 euro

Italian Space Agency, 2016
“Kinetic Inductance Detectors for Space (KIDS)”
National Coordinator: Paolo de Bernardis
Total Funds 397,814 euro; Local Funds 101,400 euro

5 Other International Funding

John Templeton Foundation - 2014
“KREYON: Unfolding the dynamics of creativity, novelties and innovation (www.kreyon.net)”
Principal Investigator: V. Loreto
Local fund: 650,000 euro

John Templeton Foundation - 2015
“Generalized Uncertainty Principle and the Photon”
Principal Investigator: C. Conti
Local fund: 188,000 euro

Simons Foundation 2016
“Simon Collaboration on Cracking the Glass Problem”
Principal Investigator: G. Parisi
Total fund: 9,500,000 euro

Awards

Fabio Sciarrino
Premio Sapio Junior, Senato della Repubblica Italiana, 2014
For developing photonics technologies for quantum information.

Giorgio Parisi
EPS HEP Prize, 2015 (shared with Bjorken, Altarelli, Dokshitzer, Lipatov)
For developing a probabilistic field theory framework for the dynamics of quarks and gluons, enabling a quantitative understanding of high-energy collisions involving hadrons.

Carlo Mariani
Frentano d'Oro, Associazione Culturale Frentano d'Oro, 2015

Paolo de Bernardis
Premio Vittorio De Sica, dell'Associazione Pangea sotto l'Alto Patronato del Presidente della Repubblica, 2015
For his research in Astrophysics.

Fabio Sciarrino
Young Scientist at the World Economic Forum - "Summer Davos", 2015-2016

Fulvio Flamini
Bovetto Prize, Italian Society for Physics, 2016
For his interesting theoretical and experimental contributions to the development of new thermo-reconfigurable photonic devices.

Paolo de Bernardis
Premio Internazionale Giulio Preti, della Regione Toscana, 2015-2016
Awarded to an internationally renowned scientist able to integrate his research activity with enduring commitment to link scientific outreach and democracy.

Paolo de Bernardis
Premio Tuscolanae Scientiae, Associazione Tuscolana di Astronomia, 2016
For his research and outreach activity to promote scientific research in the civil society, becoming a model for the younger generation.

Paolo Pani
SIGRAV Prize, Italian Society for General Relativity and Gravitation, 2016
Awarded every two years to young Italian scientists who have given relevant contributions to General Relativity and Gravitational Physics.

Giorgio Parisi
Lars Onsager Prize in Theoretical Statistical Physics, American Physics Society, 2016 (shared with Marc Mezard and Riccardo Zecchina)
For groundbreaking work applying spin glass ideas to ensembles of computational problems, yielding both new classes of efficient algorithms and new perspectives on phase transitions in their structure and complexity.

Pier Ferruccio Loverre (as a member of the K2K & T2K experiments)
The 2016 Breakthrough Prize in Fundamental Physics for the fundamental discovery and exploration of neutrino oscillations
(Prize awarded to the members of the five experiments Daya Bay, KamLAND, K2K & T2K, Sudbury Neutrino Observatory, Super-Kamiokande)

Alberto Colla, Andrea Conte, Sibilla Di Pace, Irene DiPalma Sergio Frasca, Paola Leaci, Federica Mezzani, Luca Naticchioni, Ornella Piccini, Piero Rapagnani, Fulvio Ricci, (as a members of the LIGO-Virgo Collaboration)
The 2016 Breakthrough Prize in Fundamental Physics for the detection of the gravitational waves
(Prize awarded to the members of the LIGO-Virgo Collaboration)

Outstanding Lecturers ("Premio alla Didattica") awarded by Sapienza University, 2014-2015

Sara Bonella	Marco Grilli	Fulvio Ricci
Antonio Capone	Franco Lacava	Francesco Sciortino
Carlo Cosmelli	Andrea Pelissetto	Massimo Testa
Eugenio Del Re	Antonio Polimeni	
Valeria Ferrari	Paolo Postorino	

Dissemination

Books: 2014-2016

[1] G. R. Casale, *Assessing solar UV exposure Polysulphone dosimetry applied to the quantification of personal exposure to the sun*
Chapter in “Dielectric Relaxation in Biological Systems: Physical Principles, Methods, and Applications”, Scholar’s Press (2014)
ISBN: 978-3-639-71351-0

[2] G. Pettinari, A. Polimeni, and M. Capizzi, *Effects of Hydrogenation on the Electronic Properties of Dilute Nitrides*
Chapter in “Hydrogenated Dilute Nitride Semiconductors Theory, Properties, and Applications”, edited by Gianluca Ciatto, Pan Stanford Publishing, Singapore (2014) ISBN: 978-981-4463-45-4

[3] A. Pelissetto, F. Ricci-Tersenghi, *Large Deviations in Monte Carlo Methods*
Chapter in “Large Deviations in Physics”, Lecture Notes in Physics 885 (2014)
ISBN: 978-3-642-54250-3

[4] R. Trotta, M. Felici, *Technological applications of hydrogenated dilute nitrides and perspectives*
Chapter in “Hydrogenated Dilute Nitride Semiconductors-Theory, properties, and applications”, edited by Gianluca Ciatto, Pan Stanford Publishing, Singapore (2015)
ISBN: 978-981-4463-45-4

[5] A. Maselli, V. Ferrari, *Coincidence Searches of Gravitational Waves and Short Gamma- Ray Bursts*
Chapter in “Gravitational-Wave Astrophysics”, edited by Carlos Sopuerta, Springer Int. Publishing, Switzerland (2015)
ISBN: 978-3-319-10488-1

[6] M. Ortolani, O. Limaj, *Surface Enhanced Infrared Spectroscopy*
Chapter in “Handbook of Enhanced Spectroscopy”, edited by Marc Lamy de la Chapelle, Pietro Giuseppe Gucciardi, and Nathalie Lidgi-Guigui, CRC press - Pan Stanford, (2015)
ISBN: 978-9-814-61332-3

[7] F.Bordi, S.Sarti, *Dielectric properties of polyelectrolytes and lipid vesicles*
Chapter in “Dielectric Relaxation in Biological Systems: Physical Principles, Methods, and Applications”, edited by Valerica Raicu and Yuri Feldman, Oxford University Press (2015)
ISBN: 978-0-19-968651-3

[8] R. Brito, V. Cardoso, P. Pani, *Superradiance*
Springer (2015)
ISBN: 978-3-319-18999-4

[9] Carlo Mariani and Giovanni Stefani, *Photoemission Spectroscopy: Fundamental Aspects*
Chapter in “Synchrotron Radiation; Basics, Methods and Applications”, edited by Settimio Mobilio, Federico Boscherini, and Carlo Meneghini, Springer (2015)
ISBN: 978-3-642-55314-1 (Print) 978-3-642-55315-8 (Online)

Organization of Schools, Workshops and Conferences

Plasmonica 2014
Sapienza University of Rome, Italy, June 30 - July 2, 2014
Members of the Physics Department in the Local Organizing Committee: Michele Ortolani (chair) Leonetta Baldassarre (co-chair)
http://www.sbai.uniroma1.it/conferenze/plasmonica2014/

Spin Glass and Beyond: An old tool for new problems
Institut d'Études Scientifiques de Cargèse, Corsica, France, August 25 - September 6, 2014
Members of the Physics Department in the Local Organizing Committee: Giorgio Parisi and Federico Ricci-Tersenghi
http://www.lps.ens.fr/~krzakala/WEBSITE_Cargese/home.htm

RICAP-14 The Roma International Conference on Astroparticle Physics
Noto, Italy, September 30 - October 3, 2014
Members of the Physics Department in the Local Organizing Committee: Antonio Capone (LOC)
https://agenda.infn.it/conferenceDisplay.py?confId=7620

Compact Objects as Astrophysical and Gravitational Probes
Lorentz Center, Leiden, The Netherlands, February 2-6, 2015
Members of the Physics Department in the Organizing Committee: Paolo Pani
hhttp://www.lorentzcenter.nl/lc/web/2015/675/info.php3?wsid=675&venue=Oort

Top mass: challenges in definition and determination
Laboratori Nazionali di Frascati, Frascati, Italy, May 6-8, 2015
Members of the Physics Department in the Local Organizing Committee: Roberto Bonciani (co-chair)
https://agenda.infn.it/conferenceDisplay.py?confId=9202

Cold Atoms Meet High Energy Physics
ECT* Trento, Italy, June 22-25, 2015
Members of the Physics Department in the Local Organizing Committee: Guido Martinelli
http://www.ectstar.eu/node/1292

PICQUE Roma Scientific School in integrated quantum photonics applications: from simulation to sensing
Sapienza University of Rome, Rome, Italy, July 6-10, 2015
Members of the Physics Department in the Local Organizing Committee: Fabio Sciarrino (chair), Giuliana Pensa (LOC)
http://www.picque.eu/romaschool2015/

Fourteenth Marcel Grossmann Meeting - MG14
Sapienza University of Rome, Rome, Italy, July 12-18, 2015
Members of the Physics Department in the Local Organizing Committee: Elia Battistelli, Paolo de Bernardis, Sergio Frasca, Silvia Masi, Francesco Piacentini
http://www.icra.it/mg/mg14/

VLVnT - 2015 : Very Large Volume Neutrino Telescope
Sapienza University of Rome, Physics Department, Rome, Italy, September 14-16, 2015
Antonio Capone (Conference chairperson).
Members of the Physics Department in the Organizing Committee: Egidio Longo, Chiara Perrina (LOC)
https://indico.cern.ch/event/378423/

101st National Conference of the Italian Society of Physics (SIF)
Sapienza University of Rome, Italy, June 30 - September 21-25, 2015
Members of the Physics Department in the Organizing Committee: Claudio Conti, Eugenio Del Re, Egidio Longo, Francesco Piacentini, Antonio Polimeni, Shahram Rahatlou, Federico Ricci-Tersenghi
`https://agenda.infn.it/conferenceDisplay.py?confId=9263`

School of Analytic Computing in Theoretical High-Energy Physics
Atrani, Italy, October 4-10, 2015
Members of the Physics Department in the Local Organizing Committee: Roberto Bonciani
`https://indico.cern.ch/event/387780/`

RICAP-16 The 6th Roma International Conference on Astroparticle Physics
Villa Tuscolana, Frascati, Rome, Italy, June 21-24, 2016
Members of the Physics Department in the Local Organizing Committee: Antonio Capone (LOC), Irene Di Palma (LOC)
`https://agenda.infn.it/conferenceDisplay.py?ovw=True&confId=10450`

International School of Physics "Enrico Fermi", Summer Courses 2016: Quantum Simulators
Varenna, Como Lake, Italy, July 22-27, 2016
Members of the Physics Department in the Organizing Committee: Paolo Mataloni (Co-Director)
`https://www.sif.it/attivita/scuola_fermi/mmxvi#198`

ECIS 2016 - 30th European Colloids and Interface Society Conference
Sapienza University of Rome, Rome, Italy, September 4-9, 2016
Members of the Physics Department in the Local Organizing Committee: Federico Bordi (LOC),
Members of the Host Istitution ISC-CNR: Simona Sennato (co-chair), Roberta Angelini (LOC), Silvia Capuani (LOC), Nicoletta Gnan (LOC), Mauro Missori (LOC), Emanuela Zaccarelli (LOC)
`http://www.ecis2016.org`

IQIS 2016 – 9th Italian Quantum Information Science Conference
Sapienza University of Rome, Rome, Italy, September 20-23, 2016
Members of the Physics Department in the Local Organizing Committee: Fabio Sciarrino (chair), Giuliana Pensa (LOC), Nicoló Spagnolo (LOC)
`http://www.picque.eu/iqis2016/`

Channeling 2016
Desenzano sul Garda, Italy, September 25-30, 2016
Members of the Physics Department in the Local Organizing Committee: Gianluca Cavoto
`http://www.lnf.infn.it/conference/channeling2016/`

Advances in Dark Matter and Particle Physics 2016
Messina, Italy, October 23-27, 2016
Members of the Physics Department in the Local Organizing Committee: Mauro Raggi
`http://newcleo.unime.it/Events/ADMPP2016/index.html`

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