Curriculum Teorico Generale

A short presentation of research lines and why you should enroll in it

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The curriculum is the right one for students interested in

- Theoretical physics of fundamental interactions
- Statistical mechanics and complex systems
- General relativity and theoretical astrophysics
- Mathematical physics
- Computational physics and machine learning

Students interested in theoretical aspects of condensed matter or subjects at the boundary of physics and biology should consider the curricula in Condensed Matter and Biosistemi respectively

Curriculum Teorico Generale is very **flexible** as it needs to cover any aspect of theoretical physics:

- leaves a lot of freedom in the choice of the courses
- 2 free choice courses (as all curricula)
- 5 other courses to be chosen in large groups
  (2 in group A and 3 in group B)

In the last years, roughly half of the students of the Laurea Magistrale in Physics have enrolled in it

The curriculum Teorico Generale is formally in Italian:

- few courses are in Italian
- the vast majority of courses are in English

A student not speaking Italian can easily organize its own curriculum (Piano Formativo) containing only courses taught in English

Mandatory courses

- Introduction to quantum field theory (6 cfu)
- Condensed matter physics (6 cfu)
- Physics laboratory 1 & 2 (15 cfu)
- Mathematical physics or <u>Group theory in math phys</u> (6 cfu)
- English language (4 cfu)

Notation: <u>underlined courses are new</u> and can be chosen only by students enrolling starting from academic year 2021/22

Group A

- Statistical mechanics and critical phenomena (1 year, 1 sem)
- Relatività generale (1 year, 1 sem)
- Electroweak interactions (1 year, 2 sem)
- Quantum electrodynamics (1 year, 2 sem)
- Meccanica statistica del non equilibrio (1 year, 2 sem)
- Nonlinear waves and solitons (1 year, 2 sem)
- Statistical mechanics of disordered systems (2 year, 1 sem)
- Statistical physics and machine learning (2 year, 1 sem)
- Quantum field theory (2 year, 1 sem)

All courses have 6 cfu. **2 courses** must be chosen from this group

Group B

- those in group A plus the following
- 1 year, 1 sem: Computing methods for physics, Nonlinear and quantum optics
- 1 year, 2 sem: Theoretical biophysics, Onde gravitazionali stelle e buchi neri, Neural networks, Symmetries and fundamental interactions, Condensed matter physics II, Supercondictivity and superfluidity, Advances machine learning for physics
- 2 year, 1 sem: Many body physics, Physics of complex systems, Quantum information and computation, Weak interactions in the standard model and beyond, Introduzione alla teoria dei processi stocastici, Introduzione alla gravità quantistica

All courses have 6 cfu. **3 courses** must be chosen from this group

How to submit the personal curriculum (Piano Formativo)

A more technical presentation in October, before the opening of the Piano Formativo submission, to illustrate the actual rules

We leave a lot of freedom to the student as long as very reasonable choices are made:

- distribute courses evenly over the 3 semesters
- take courses in the "right order" according to their content
- justify any non-standard choice

These rules will be made explicit in the October presentation

At present, you just need to think (and decide?) whether

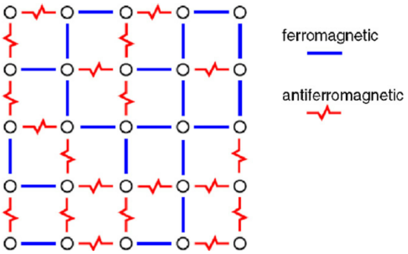
Teorico Generale is the right curriculum

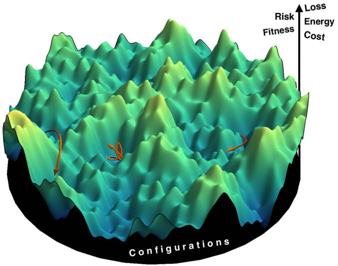
for your interests, according to our research lines

Following is a (too) short sketch of research lines in the Theoretical Physics Group (Gruppo Teorico)

Disorder and frustration lead to very complex physical behaviors

- Spin glasses (prototype of disordered models)
- Structural glasses
- Complex energy landscapes
- Very slow relaxation processes
- Off-equilibrium dynamics (aging)



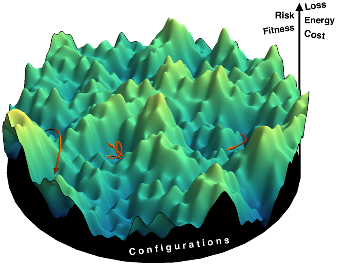


...and applications (Chimera group)

Same problem in many different fields

- Glassy physics (energy relaxation with many metastable states)
- Optimization problems (minimize complex cost fn)
- Machine learning (minimize loss)
- Ecological models (improve fitness)
- Finance and game theory (optimize risk)

Phase transitions play a key role!



Chimera group members
in Sapienza: Angelini, Cammarota, Marinari, Parisi, Ricci-Tersenghi
in CNR: Leuzzi, Rizzo
+ 6 post-doc + 5 PhD

Systems with Negative Temperature

Do negative absolute temperatures matter physics? It is now possible to provide evidence that we can certainly answer positively to this vexata quaestio. Since more than half a century ago it has been realized that for some interesting physical systems entropy is a non monotonic function of energy, here an incomplete list: $2d$ incompressible fluids, nuclear magnetic chains, lasers, cold atoms and optical waveguides.

It is possible to show that negative absolute temperatures are consistent with equilibrium as well as with non-equilibrium thermodynamics. In particular, thermometry, thermodynamics of cyclic transformations, ensemble equivalence, fluctuation-dissipation relations, response theory and even transport processes can be reformulated to include them, thus dissipating any prejudice about their exceptionality, typically presumed as a manifestation of transient metastable effects.

Response and flux of information in non-equilibrium dynamics

It is well known that entropy production is a proxy to the detection of non-equilibrium, i.e. of the absence of detailed balance; however, due to the global character of this quantity, its knowledge does not allow to identify spatial currents or fluxes of information among specific elements of the system under study. In this respect, much more insight can be gained by studying transfer entropy and response, which allow quantifying the relative influence of parts of the system and the asymmetry of the fluxes.

Statistical mechanics of integrable systems

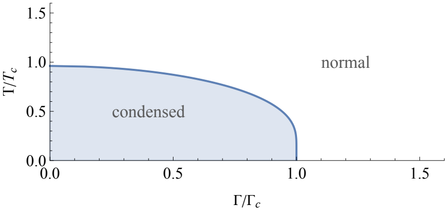
Statistical mechanics allows us to understand the features of macroscopic objects, including intriguing phenomena such as criticality and scale invariance. It is then quite natural to wonder about the origin of such a great success. A paradigmatic and historically crucial example for the problem of statistical mechanics foundations is the celebrated Fermi-Pasta-Ulam-Tsingou (FPUT) problem. Even after many years the true relevance of chaos to legitimate statistical mechanics is still an open issue. Two main different points of view may be traced back to two opposite schools:
i) the "chaotic" one according to which a key role is played by the dynamics and, consistently, the presence of chaos is regarded as the basic ingredient for the validity of the statistical mechanics;
ii) the "traditional" one, following the original Boltzmann's ideas (and then developed by Khinchin, as well as to Mazur and van der Linden) which stresses the role of the large number of degrees of freedom.

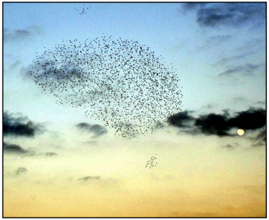
Condensation quantum phase transitions (Presilla)

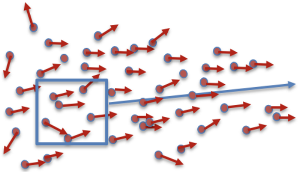
Quantum phase transitions (QPT) are characterized, at temperature $T = 0$, by a competition between two qualitatively different ground states (GSs) reachable by varying the parameters of the Hamiltonian H of the system, as in the paradigmatic case

$$H = \Gamma K + V, \qquad [K, V] \neq 0, \qquad \text{one parameter: } \Gamma$$

Recently, we have introduced a class of first-order QPTs that take place as a condensation, not in the real space but in the space of states $\mathcal{H}$ (Hilbert space). Under not very restrictive conditions, it happens that, when Γ runs below a critical value Γ_c, the system gets locked in a GS confined into a subspace of $\mathcal{H}$, named condensed because its relative dimension with respect to the whole space $\mathcal{H}$ tends to zero in the thermodynamic limit.
By using this sufficient criterion and demanding Monte Carlo simulations, we have demonstrated that the phenomenon of free electron crystallization, predicted by Wigner in 1934 and hitherto remained unproved, is, indeed, a condensation QPT. Work is ongoing to extend the above sufficient criterion to condensation QPTs at temperatures $T > 0$, as in the diagram.







- Living assemblies display collective patterns on the large scale
- Statistical Physics can be used to describe/understand them
- Statistical inference –> data based modelling
- Stochastic dynamics + field theory of collective motion

People: Irene Giardina, Andrea Cavagna + Cobbs group
www.cobbs.it

Some deep questions in fundamental physics involve **gravity**:

- The nature of gravity. Is Einstein (still) right? What building-block principles and symmetries in nature invoked by General Relativity can be challenged? Are there extra fields?
- The nature of neutron stars. How does nuclear matter behave in the extreme conditions present in the inner core of neutron stars? Does exotic physics show up in these objects?
- The nature of black holes. How well classical black holes describe observations? Do more exotic species of compact stars exist? Signatures of quantum gravity near event horizons?
- The nature of dark matter. Is dark matter composed of particles, dark objects, or modified gravity?

We address these questions through GW data which can probe the extreme gravitational fields near black holes and neutron stars.

Gravity theory and gravitational-wave (GW) phenomenology

Research group: 2 faculty (Gualtieri, Pani), 6 postdocs, 9 PhD students + master students. https://web.uniroma1.it/gmunu/

Tools: (semi)analytical methods (post-Newtonian expansions, spacetime perturbations); field theory in curved spacetimes; numerical simulations

Research topics:

- GW modelling
  - GW from binary inspirals
  - Quasinormal modes of BHs
  - Param. estimation
- Tests of gravity (GR)
  - GWs from binary BHs beyond GR
  - BH oscillations beyond GR
  - Exotic compact objects
- Neutron-star (NS) physics
  - Quasinormal modes of NSs
  - Multimessenger constraints
  - Tidal deformability & GWs
- Gravity & Astroparticle
  - Ultralight bosons in curved spacetime & BH superradiance
  - Compact objects & dark matter

*Opportunities to collaborate within international networks and join next-generation GW experiments (***Einstein Telescope***,* ***LISA****).*

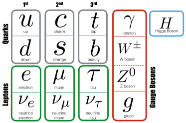
Light Dark Matter searches and Exotic Hadron Spectroscopy (Polosa)

- Theoretical studies of alternative methods for the detection of hypothetical sub-GeV and sub-MeV dark matter particles in target materials such as Superfluid ^4He and carbon nanotubes.
  Example: we developed an Effective Field Theory for describing multi-phonon emissions in Superfluid ^4He from dark matter hits [with A. Esposito (EPFL & IAS Princeton), A Caputo (Tel Aviv)].
- The so called X, Y, Z, P exotic mesons and pentaquarks are parts of a difficult puzzle posed by experimental particle physics. Interpretations range from compact quark structures, exotic hadron molecules, cusp-kinematical effects to un-particles (cuts in correlation functions of a conformal field theory). With group-theory methods we predicted the existence of several of these states. The final picture is still missing. [Several collaborators.]

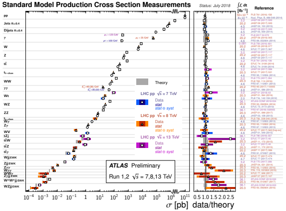
Particle Physics Phenomenology (Bonciani)

The STANDARD MODEL of fundamental interactions is a Quantum Field Theory that describes:

- Ordinary matter, spin 1/2, three families of quarks and leptons
- Strong and Electroweak Force metiators, integer spin
- The scalar Higgs boson field, responsible for the mass generation via the Brout-Englert-Higgs mechanism. Last confirmation 2012 !



In spite of the amazing agreement with experimental data at colliders (it describes with big accuracy Physics up to 10 TeV), the SM leaves a long list of unsolved theoretical issues:



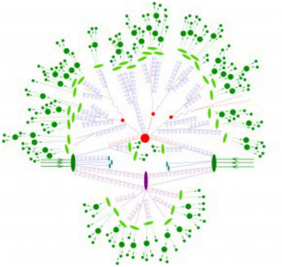
Gravity is still classic, while it should be consistently included in the quantum framework! There is evidence of Dark Matter (and Dark Energy) in the Universe, which is not accounted for in the SM. The SM does not explain the huge difference among spin 1/2 particle masses!! We go from a fraction of eV to the 172 GeV of the top quark mass ... etc.

- The Theory community generally believes that the SM cannot be the “ultimate” Theory. Before the Planck scale something has to happen! The SM is seen as an effective theory, low energy limit of a more fundamental theory.

Particle Physics Phenomenology (Bonciani)

The goal of understanding what there is beyond the Standard Model is afforded by the Theory community with different strategies

- New Theories that can solve the issues of the SM are developed on the basis of theoretical speculation and, where possible, experimental validation
- In the absence of an evident signal of New Physics, we can push the accuracy of the SM theoretical predictions and the experimental measurements at colliders and look for discrepancies between the two



For the next 10-15 years the Large Hadron Collider (LHC) of CERN will play a crucial role in understanding Particle Physics

- The events level of complexity is very high!
- Theoretical predictions must cope with different energy ranges and different regimes: from the hard process to hadronization
- Mandatory: control on the quantum corrections!
  Calculation of Feynman integrals, infrared structure of the theory and Phase-Space integration

Decay of quantum systems in bounded spaces (Aglietti)

Many quantum systems in nature can be described in terms of unstable states or "resonances".
In many physical situations, the available region of space to the initial unstable particle and/or the final decay products is bounded.
New physical phenomena occur in the decays at finite volume. By a quantum generalization of the Poincare' recurrence theorem, the initial unstable state is choherently reproduced at very large times, to an arbitrary accuracy.
Usually, in the infinite-volume case, time evolution completely empties the initial state. On the contrary, at finite volume, it may happen that the decay is "limited", i.e. some particles never decay.

Summary

The research lines presented above represent a good part of the activities of the Theoretical Physics Group (Gruppo Teorico), but they are not exhaustive!

They are meant to give an idea of the research fields where members of the Theoretical Physics Group are active.

You should consider enroll in the curriculum Teorico Generale if you would like to work on any of the above fields of research or on something very much related.