Curriculum Teorico Generale

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

July 14th, 2022

The curriculum is the right one for students interested in **every** aspect of theoretical physics:

- Theoretical physics of fundamental interactions
- General relativity and theoretical astrophysics
- Theoretical aspects of condensed matter
- Statistical mechanics and complex systems
- Computational physics and machine learning
- Mathematical physics
- Theoretical modelling of biological systems

Introduction

Research lines related to

- Theoretical physics of fundamental interactions
- General relativity and theoretical astrophysics
- Theoretical aspects of condensed matter

have been already presented.

Below are briefly described research line related to

- **Statistical mechanics and complex systems**
- **Computational physics and machine learning**
- **Mathematical physics**
- **Theoretical modelling of biological systems**

Introduction

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

- leaves a lot of freedom in the choice of the courses
- 2 free choice courses (as in any curricula)
- 6 other courses to be chosen in large groups
  (3 in group A, 2 in group B an 1 in group C)

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

The curriculum Teorico Generale is formally in Italian, but

- only one course is taught in Italian,
- a student not speaking Italian can easily organize its own *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 Group theory in math phys (6 cfu)
- English language (4 cfu)

Group A

- Statistical mechanics and critical phenomena (1 year, 1 sem)
- General relativity (1 year, 1 sem)
- Theory of fundamental interactions (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)
- Quantum field theory (2 year, 1 sem)
- Statistical physics and machine learning (2 year, 1 sem)

All courses have 6 cfu. **3 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, Gravitational waves, compact stars & black holes, Neural networks, Strong interactions & QCD, Condensed matter physics II, Superconductivity & superfluidity, Advances machine learning for physics, Physical cosmology
- 2 year, 1 sem: Many body physics, Physics of complex systems, Quantum information and computation, Phenomenology of the standard model, Theory of stochastic processes, Physics of solids

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

How to submit the personal curriculum (Piano Formativo)

A technical presentation at the end of September, 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 September presentation

At present, you just need to decide whether

Teorico Generale is the right curriculum

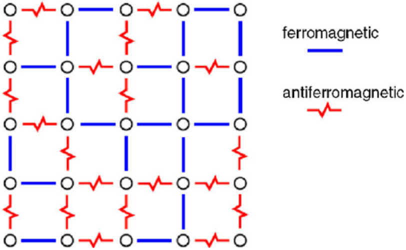
for your interests, according to our research lines

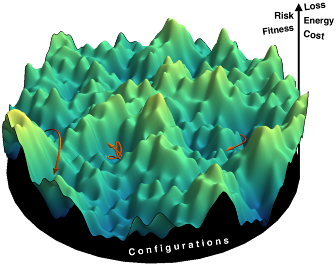
Theoretical research lines in fundamental interactions have been already presented by Marco Nardecchia (curriculum Fundamental Interactions).
Theoretical research lines in condensed matter have been already presented by Lilia Boeri (curriculum Condensed Matter Physics).

Following is a very short sketch of the remaining 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)



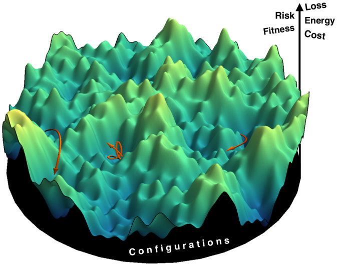


...and applications (Chimera group)

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.

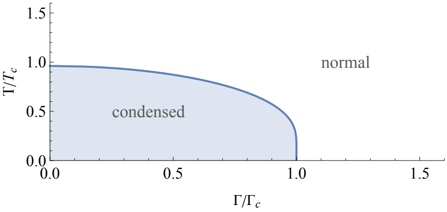
Condensation quantum phase transitions (Presilla)

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

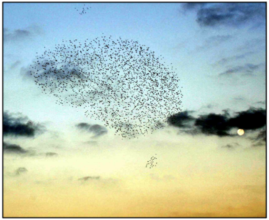
$$H = \Gamma K + V, \qquad [K, V] \neq 0, \qquad \text{one parameter: } \Gamma$$

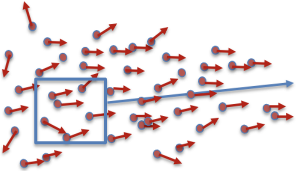
Recently, we have introduced a class of first-order QPTs that take place as a condensation, not in the real space but in the space of states $\mathcal{H}$ (Hilbert space). Under not very restrictive conditions, it happens that, when Γ runs below a critical value Γ_c, the system gets locked in a GS confined 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.



Collective Behaviour in Biological Systems (Cobbs)





- 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

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.

For any further question write to
Federico Ricci Tersenghi `federico.ricci@uniroma1.it`