Study plan in

Theoretical and Computational Astrophysics

UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

Dipartimento di Scienze Fisiche, Informatiche e Matematiche

M.Sc. program in Physics – Curriculum Theoretical and Computational physics

Overview

Astrophysics explores the fundamental processes governing celestial bodies and the universe. This study plan provides a comprehensive understanding of **modern astrophysics** through a combination of theoretical and numerical approaches, complemented by selected observational techniques. Students will be able to understand the astrophysics of **galaxies, stars, and black holes**, examining their complex interactions and the profound influence they exert on each other over billions of years.

Goal

Students will delve into **recent discoveries** like gravitational waves and feedback mechanisms, gaining insights into these critical astrophysical phenomena. Students will become acquainted with current key theories, such as **special/general relativity**, and their applications to cosmic phenomena. Theoretical **astroparticle** physics bridges particle physics and **cosmology**, addressing the universe composition and the enigma of dark matter. Additional studies cover the physics of elementary particles, quantum interactions in matter, and statistical mechanics, essential for a thorough understanding of astrophysical processes.
Practical skills are developed through courses in high-performance computing, **machine learning** for scientific applications, and **simulation** techniques, all vital for modern astrophysical research. This study plan prepares students for advanced study and research in **astrophysics and astronomy**, providing a robust foundation in key theoretical concepts and cutting-edge methodologies.

More info and suggestions from

Study plan coordinator
Prof. Massimo Gaspari

Program director
Prof. Paolo Bordone

Program website
www.fim.unimore.it/LM/FIS

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Fist year

Astrophysics (R, CC, II) – M Gaspari

A course exploring key modern topics in astrophysics, with focus on the complex universe of multi-scale black holes and their profound influence on galaxies throughout the cosmic evolution. It blends theoretical, numerical, and observational approaches. Students delve into the fascinating areas of extragalactic astrophysics, from the basics to the cutting-edge concepts and recent discoveries, such as gravitational waves and weather-like feedback mechanisms.

Relativity (R, CC, I) – D Trancanelli

Learn the elegant mathematical framework behind Special and General Relativity and apply it to fascinating physical problems, including GR effects on planetary motion, the physics of black holes, gravitational waves and cosmology. The course also provides a first discussion of quantum gravity.

Theoretical astroparticle physics (R, CC, II) – E Bertuzzo

What is the universe made of? We will learn how particle physics and cosmology get together to provide a comprehensive framework. After a recap of the Standard Model of Particle Physics, we will describe the concordance model of Cosmology and its successes. We will then t urn our attention to dark matter, presenting knowns and unknowns about this fascinating component of the universe.

Elementary particles (D, CC, I) – A Bizzeti

A course covering concepts and physical pictures behind various phenomena that appear in vast assemblies of interacting quantum particles. The most widely used many-body methods are presented (many-body perturbation theory, large-scale diagonalization methods, Feynman diagram, and Green's function approaches) and applied to selected physical systems.

Quantum physics of matter (M, I) – R Magri

An advanced course on matter-light and matter-electron interactions, using quantum linear response theory to discuss elementary excitations of material systems and their spectral features: electronic and phonon excitations, excitons, plasmons, polaritons.

Statistical mechanics and phase transitions (M, II) – G Goldoni

An advanced course in statistical mechanics, from theoretical foundations to phase transitions and critical phenomena, including quantum condensates (BEC, superfluids, superconductors). Attendees are introduced to modern theoretical methods, from the Ginzburg-Landau theory to the statistical field theory and the renormalization group approach.

Quantum field theory (M, I) – D Trancanelli, E Bertuzzo

An introductory course on QFT providing the quantization of scalar, spinor and vector fields, and covering the computation of scattering processes and decay rates in ϕ^4, Yukawa and QED theory. The course also provides a first discussion of radiative correction and renormalization.

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Fields of specialization

- Astrophysics
- Astronomy
- Cosmology
- Astroparticle Physics
- High-Performance Computing
- Machine Learning

Opportunities

This study plan is linked to ongoing research activities carried out by FIM astophysicists in collaboration with several research centers worldwide, including Princeton University (USA), MIT (USA), NASA (USA), INAF (Italy), NTU (Taiwan), CfA (USA), and UniBo (Italy). Potential **thesis projects** are carried out within the group of theoretical astrophysics at the FIM department and/or in international research groups, with several opportunities connected with the ERC-COG led by Prof. Gaspari (`BlackHoleWeather').
Students may also opt for the **Double Degree program** and spend the 2nd year on a research project at the Radboud University (NL).

Employment

The acquired skills will enable the student to pursue employment in research of advanced astrophysics and astronomy at national/international and private public institutes. This degree is vital to apply for a PhD, within the **Graduate School in Physics and Nanoscience** at UniMoRe or in other Universities. The acquired programming skills are very highly requested by modern jobs at High Performance Computing centers and in industrial R&D departments, especially in booming sectors such as artificial intelligence and quantitative finance.

Notes

Interested students may deepen the computational aspects of the field choosing from a list of modern courses in computational techniques. Ask the study plan coordinator for further suggestions on other available courses to tailor the program to your interests.

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Advanced quantum mechanics **(M, I)** – M Gibertini

A self-contained course addressing several aspects of quantum mechanics relevant to modern developments of physics, from condensed-matter theory to particle physics and their fundamental interactions. Emphasis will be given to the concept of Berry phase, the path integral formulation, and scattering theory.

Quantum many-body theory **(D, II)** – A Ferretti

A course covering concepts and physical pictures behind various phenomena that appear in vast assemblies of interacting quantum particles. The most widely used many-body methods are presented (many-body perturbation theory, large-scale diagonalization methods, Feynman diagram, and Green's function approaches) and applied to selected physical systems.

Laboratory of quantum simulation of materials **(D, I-II)** – A Ruini

Frontal lectures and hands-on tutorial sessions introduce attendees to theoretical/computational techniques for the electronic structure simulation of condensed matter systems. Special emphasis is given to Density Functional Theory, the present state-of-the-art, parameter-free and atomistic scheme for the predictive description of materials.

Second year

High Performance Computing for physical sciences **(F, CC, II)** – P Bonfà

A course which combines lectures and hands-on projects to exploit modern computers in diverse fields, from high-throughput material screening to climate modeling to black holes formation, introducing to general concepts of parallel computing and practical approaches based on OpenMP, MPI, and GPU programming.

Machine learning for scientific applications **(F, CC, II)** – F Grasselli

An introduction to key ideas and techniques in machine learning for applications in physics, from basic principles to advanced topics in supervised and unsupervised learning, including worked hands-on examples. Subjects include Gaussian Process Regression, Bayesian Inference, Kernel methods, Deep Neural Networks, Convolutional Neural Networks, and Encoder-Decoder models.

Synchrotron radiation: basics and applications **(D, I)** – S D'Addato

A course on the working principles of synchrotrons and the use of emitted radiation, from description of single ultra-relativistic particles sources to essentials of storage rings, bending magnets, wigglers and undulators, free electron lasers, beam lines. Examples of ensuing popular techniques, as X-ray diffraction, scattering, absorption and X-ray microscopy, are discussed and a visit to to ELETTRA labs in Trieste ends the course.

Legend: **M** mandatory course for this curriculum; **D** chosen within distinctive (*caratterizzanti*) courses; **R** chosen within related (*affini*) courses; **F** selected as a free choice course; **CC** core-choice course; **I/II** term

This study plan is a suggested set of courses, chosen within the curriculum, to ensure an in-depth professional training combined with the broad spectrum of skills required to modern scientists. Mandatory, distinctive and related courses provide the natural background of this study plan. However, the study plan can also be tailored to the students' scientific interests, see the complete list of courses. Ask the study plan coordinator for further indications.