PRIMO ANNO CICLO XLI

Advanced topics in astrophysics

S. Covino, F. Haardt, A. Lupi, M. Sormani

(2 credits, 16 hours)

Program:
1. Multiscale simulations: incorporating unresolved physical processes in advanced numerical simulations (Lupi, 4 ore)
2. Search for periodicity in astrophysical time-series (Covino, 4 ore)
3. Structure and dynamics of the Milky Way (Sormani, 4 ore)
4. Atmospheric escape in exoplanets (Haardt, 4 ore)

Period:
Sormani: Week 16-20 of March or the second half in April (4 hours) (to be agreed: mattia.sormani@uninsubria.it)
Covino: February, Wednesday and Thursday are preferred (4 hours) (to be agreed: stefano.covino@inaf.it)
Lupi: end of May, beginning of June (4 hours) (to be agreed: alessandro.lupi@uninsubria.it)
Haardt: June/July (4 hours) (to be agreed: francesco.haardt@uninsubria.it)

Introduction to Nonequilibrium Statistical Mechanics

F. Ginelli

(2.5 credits – 20 hours)

Program: *Classical statistical mechanics describes systems at thermodynamic equilibrium. However, a wide range of natural systems — from climate dynamics to virtually all living matter — are maintained out of equilibrium by external driving and/or sustained fluxes of energy, which is continuously absorbed and dissipated by the system.*

This course introduces key concepts used in the study of macroscopic systems away from thermodynamic equilibrium. Topics include the breaking of time-reversal symmetry, the absence of detailed balance, and entropy production in stationary states. The course will then focus on ***active matter*** *and* ***kinetic roughening*** *as prototypical examples of nonequilibrium systems.*

Texts:

- Paolo Politi and Roberto Livi, *Nonequilibrium Statistical Physics: A Modern Perspective*, Cambridge University Press
- Lecture notes

Assessment
The oral exam is based on the presentation and in-depth discussion of a topic covered in the course.

Period
May (to be agreed: francesco.ginelli@uninsubria.it)

Feynman path integrals

P. Ratcliffe

(1 credit – 8 hours)

Program: *This short lecture series provides a very brief introduction to the Feynman Path Integral approach to quantisation, which represents a completely original and alternative axiomatic basis for quantum theories. While developed within the framework of non-relativistic quantum mechanics, the method is of particular importance (for its clarity and simplicity) in second or field quantisation. However, it finds useful applications in many other areas, as diverse as statistical mechanics and even, for example, financial analysis. Being limited to eight hours of front-on lectures, little attention is paid to mathematical rigour. In other words, a description of the physical basis and significance will be provided, together with some of the interesting applications of the technique of relevance to physics.*

Texts:
Abers, E.S. and Lee, B.W. (1973), Phys. Rep. 9, 1.
Bailin, D. and Love, A. (1993), Introduction to Gauge Field Theory (IOP Pub.), revised edition.
MacKenzie, R. (2000), lectures presented at Rencontres du Vietnam: VI Vietnam School of Physics (Vung-Tau, Vietnam, Dec. 1999).
The above texts are suggested but not necessary, complete notes will be made available by the lecturer.

Period: 4 two-hour lectures, given in April from 11 am to 13 pm, on Tuesday and Thursday, the exact dates to be agreed (contact philip.ratcliffe@uninsubria.it).

Fluorescence Methods in molecular biophysics

L. Nardo

(3 credits – 24 hours)

Program: *Biophysics is a subject intrinsically at the interface between hard sciences and life sciences, and constitutes an ideal bridge within these two fascinating universes. In this teaching module the biophysical approach will be outlined, evidencing its specificities and originality with respect to classical biological subjects.*

The basics of molecular biology will be sketched in "pills". In so doing, the students will be led to mature a deep comprehension of the intimate relationship between biomolecules structures and their biological function. Subsequently, some considerations will be driven about the peculiar thermodynamics of metabolic reactions. Binding reactions will be modelled in details evidencing their crucial role in metabolic regulation.

The main concepts underlying the electronic state transition spectroscopy of molecules in solution will be recalled. The advantages of fluorescence will be discussed and several advanced fluorescence techniques will be presented and applied to the elucidation of binding equilibriums. Particularly, we will focus on time-resolved and fluctuation analyses methods. Further, we will correlate the conformational dynamics of biomolecules with benchmark spectral features, introducing fluorescence resonance energy transfer, both applied on molecular ensembles and at the single molecule level, as a powerful tool to characterize biomolecular structures and interactions.

All the above topics will be tackled by relying both on examples extracted from the research experience of the teacher and on critical examination of seminal papers from the historical literature. At the end of the course, the students will inherit a comprehensive panorama of time-correlated single photon counting, fluorescence correlation spectroscopy and single-molecule fluorescence resonance energy transfer. Moreover, they will gain some insight on the molecular mechanisms governing life and on the physical laws on which they are based.

Lectures Schedule

Lesson 1. Introduction to the course: "What is biophysics?". March 4^{nd}, h 10.00-13.00

Lesson 2. Molecular biology in pills. Genetic code and protein synthesis. Replication errors, variability and evolution. March 11^{th}, h 10.00-13.00 (for hard-science PhD students who wish to get in touch with molecular biology)

Lesson 3. A (brief and heuristic) sketch of electronic-state transition spectroscopy -1. *An overview of the basic quantum mechanical concept underlying spectroscopy.* March 11th, h 14.30-17.30 (for biomedical sciences students who wish to get the basics to understand the following lessons)

Lesson 4. A (brief and heuristic) sketch of electronic-state transition spectroscopy -2. *A more specific glance on molecular spectra and fluorescence.* March 18th, h 10.00-13.00

Lesson 5. Modelling binding reactions and determining binding affinities through fluorescence analyses. Unravelling the specificities of binding through fluorescence. March 25th, h 10.00-13.00

Lesson 6. Investigating variability at the DNA level through fluorescence April 1st, h 10.00-13.00

Lesson 8. Investigating metabolism regulation mechanisms through fluorescence April 8th, h 10.00-13.00

Lesson 9. Other selected fluorescence applications/question time April 15th, h 10.00-13.00

Assessment of competences

The students will be required to prepare a slide-show in which they discuss some literature articles in which one of the techniques introduced in the lessons will be tackled in more detail. They will expose their elaborate during a brief oral examination and stand some questions on the topic.

Experimental violation of Bell's inequalities

M. Bondani

(2.5 Credits – 20 hours)

Program: *The course offers an in-depth exploration of one of the most profound discoveries in quantum mechanics: the incompatibility of local realism with quantum predictions. The course will provide a theoretical foundation in Bell's theorem, covering key concepts such as entanglement, hidden variable theories, and nonlocal correlations. It will then examine the historical and modern experimental tests of Bell's inequalities, including photon polarization experiments, loophole-free tests, and their implications for quantum information science. A key component of the course is a hands-on laboratory experiment, where students will perform a real-world test of Bell's inequalities using entangled photons, analyze their own data, and compare results with theoretical predictions. Students will also engage with primary literature and discuss the role of Bell's results in quantum technologies, such as quantum cryptography and quantum computing.*

Period: Tuesday 3/3/2026, 14:00-16:00 – frontal lesson;
Thursday 5/3/2026, 14:00-16:00 – frontal lesson;
Tuesday 10/3/2026, 9:00-13:00 and 14:00-16:00 – laboratory;
Thursday 12/3/2026, 9:00-13:00 and 14:00-16:00 – laboratory;

On Tuesday 17/3/2026, 9:00-13:00 data analysis and conclusion

QFT on curved spacetimes

U. Moschella

(4 credits – 32 hours)

Program: *The course is intended as a short introduction to Quantum Field Theory on curved spacetimes. In doing this I will also discuss some topics in General Quantum Field Theory that are not always taught in standard QFT courses. Topics that will be covered are:*
1) Quantization. CCR and CAR algebras. Representations of the commutation rules. The Stone-Von Neumann theorem and its failure.
2) Quantization of fields. Canonical quantization of the Klein Gordon field in Minkowski spacetime. Commutators. Propagators. Two-point functions. Quantum fields as distributions. N-point functions. Reconstruction theorem.
3) The spectral condition and its consequences.
4) KMS equilibrium states. Bogoliubov transformations. Generalized Bogoliubov transformations. The Unruh effect
5) Canonical Quantization of fields in curved spacetimes. General formalism. The Local Hadamard condition. The microlocal spectrum condition. Renormalization. The Casimir effect.
6) Examples. Expanding universes. Bogoliubov transformations. Particle creation by expansion.
7) Thermal equilibrium states. The Hawking effect. 8) Quantum field theory on the de Sitter spacetime. De Sitter invariant vacua. Preferred vacuum. The thermal interpretation. Massless Fields. Applications. Instabilities.
9) Quantum field theory on the anti de Sitter spacetime. The AdS-CFT correspondence.

Textbooks:
N.D. Birrell, P. C. W. Davies. Quantum Fields Curved Space. Cambridge University Press (1982)
S. A. Fulling. Aspects of quantum field theory in curved space-time. Cambridge University Press (1989)
R.M. Wald. Quantum field theory in curved space-time and black hole thermodynamics. Chicago U. (1995)

Period:
January 14th, 15th , 16th 2026, 11:00-13:00;
January 21th, 22th , 23th 2026, 11:00-13:00;
January 28th, 29th , 30th 2026, 11:00-13:00;
February 4th, 5th , 6th 2026, 11:00-13:00;
February 13th, 18th, 19th , 20th 2026, 11:00-13:00;

Non-Newtonian aspects of general relativity

S. Cacciatori

(2.5 credits – 20 hours)

Program: *This is a 20 hours course, where some specific aspects of the general relativistic dynamics will be discussed, compared to the analogous mechanisms in Newtonian gravity, when allowed. The main arguments included in the course are:*

-Einstein equations and their comparison with Newtonian gravity: time dependence, non harmonicity, tensorial character, non linearity;
-Gravitational waves: generation and detection; weak and strong gravitational waves, effective one-body formalism;
-Dragging effects and weak and strong gravitomagnetism, with applications to the motion of massive bodies and galaxies.

Modifications on the program can be considered on demand, in order to adapt the details of the lessons to the specific needs of the students.

Period:
March 3th, 4th , 5th 2026, 16:00-18:00;
March 10th, 11th , 12th 2026, 16:00-18:00;
March 24th, 25th , 26th , 31th 2026, 16:00-18:00.

SECONDO ANNO CICLO XL

Fundamentals of Machine Learning

M. Landoni

(2 credits – 16 hours)

Program: *The course will cover the state-of-the art algorithms and knowledge about the supervised learning techniques .*
In particular, those topics will be coveres
i) Introduction to classifications problems and methods. Definition of Training Set, Test Set, Validation and metrics to assess the performances of classifiers;
ii) Classification based on parametric model
iii) Classification based on non-parametric model . Decision Trees, Random Forests and linear classified will be presented with the necessary mathematical background and applications in physics/astrophysics.
iv) Classification with Support Vector Machine and Neural Networks
v) Introduction to Deep Learning techniques and architectures of deep neural networks for image classifications.
In order to fully exploit the lessons and the concepts given in the course plan, an introduction to data preparation, features selections and transformation (e.g. principal component analysis) will also be part of the lectures.

Period: September 2025 – January 2026, to be agreed with the lecturer (marco.landoni@inaf.it)

Numerical Methods for Astrophysics

A. Lupi

(2.5 credits, 20 hours)

Program: *The course "Numerical methods for astrophysics" is meant to introduce state-of-the-art numerical modelling techniques employed in astrophysics, and will cover 20 hours. In detail, the following topics will be covered:*
- Newtonian dynamics and the N-body problem (grid-based vs particle-based methods)
- Advanced techniques for computational hydrodynamics: adaptive mesh refinement vs moving-mesh vs mesh-free methods, advantages and limitations
- High performance computing: code development and optimisation

Period: June 2026 (to be agreed with the lecturer: alessandro.lupi@uninsubria.it)

Time series Analysis for Astrophysicists

S. Covino

(2.5 credits, 20 hours)

Time series are ubiquitous in astrophysics. This course is aimed at providing PhD students the main capabilities to extract physical information with state-of-the-art statistical inferences from the available datasets. We will refer to real science cases developed in the astrophysical literature, yet the discussed methodologies could be of definite interest to anyone involved in quantitative analysis of data in a temporal (or spatial) sequence in any field of modern physics, economy, engineering and social sciences.
At the end of the course students will be able to:
• carry out analysis of any statistical problem in a full Bayesian framework;
• properly model time series to derive meaningful statistical inferences about stationarity, short- and long-term memory behavior;
• deal with data irregularly spaced and/or affected by correlated noise;
• apply big-data techniques to carry out the analyses of typical large datasets obtained by modern astrophysical facilities.
More specifically, the main topics of the course are
• Time (and spatial) variability in astrophysics
• Time-domain analysis and auto-regressive processes
• Irregular sampling, Lomb-Scargle periodograms
Case studies: AGN variability
• Advanced topics: non-parametric analysis
• Matching filters
Case study: LIGO/Virgo gravitational wave signals
• Big-data, machine learning and "intelligent" systems for time-series analysis
Case studies: spatial variability (CMB, large scale structure)

Period: June 2026 (details to be agreed: stefano.covino@inaf.it)

Advanced Astrophysical Fluid Dynamics

M. Sormani

(2.5 credits – 20 hours)

Program:
- Rotating equilibria and thick discs: barotropic equilibria and Taylor-Proudman theorem, baroclinic equilibria, Solberg-Hoiland stability criterion

- Accretion discs: inviscid thin disc, viscous evolution of a thin disc and spreading of a thin ring, steady-state viscous thin discs, angular momentum transport, Shakura-Sunyaev alpha-disc "standard" model, emitted spectrum, the Eddington limit, angular momentum transport in discs

- Effects of rotation on waves, epicyclic frequency and Lindblad resonances, density waves in discs, Toomre instability, Papaloizou-Pringle instability

Period: June 2026 (to be agreed, contact: mattia.sormani@uninsubria.it)

Non equilibrium Statistical Physics: kinetic roughening and active matter

F. Ginelli

(2.5 credits – 20 hours)

Program: *Classical statistical mechanics describes system at thermodynamic equilibrium. However, a wide range of natural systems, ranging from climate to virtually all living matter, are kept out of equilibrium by external driving and/or fluxes of energy which is constantly absorbed and dissipated through the system.*
This course focuses on two prototypical classes of non-equilibrium systems: (i) kinetic roughening of driven interfaces and (ii) active matter. Kinetic roughening is relevant to the description of many interfacial problems under non-equilibrium conditions (deposition at the solid-gas interface, flame front propagation, wetting, etc.), while active matter is a nonequilibrium paradigma capable of explaining the behavior of many biological systems, from bird flocks to bacteria colonies and cellular migration to cite a few examples.

Texts:

- Paolo Politi and Roberto Livi, *Nonequilibrium Statistical Physics: A Modern Perspective*, Cambridge University Press
- Lecture notes

Assessment
The oral exam is based on the presentation and in-depth discussion of a topic covered in the course.

Period
May 2026 (to be agreed: francesco.ginelli@uninsubria.it)

Laser-driven Radiation Sources: Science, Technology and Applications

M. Clerici

(1.5 credit – 12 hours)

Program: This short course introduces students to the technological aspects and applications of laser-driven sources of radiation, one of the most active areas of research in laser physics today. The course begins with a brief introduction to ultrafast lasers, followed by an overview of the science, technology, impact, and applications of state-of-the-art secondary sources. These include parametric amplifiers (mid-infrared sources), optical rectification or photoconductive switching (THz sources), and non-perturbative light-matter interactions (high-order harmonic generation).

Period: June 2026 (to be agreed, contact: matteo.clerici@uninsubria.it)

Fundamentals and Applications of Optical Metrology

L. Caspani

(1.5 credit – 12 hours)

Program: This short course introduces students to the basic concepts of optical metrology and provides an overview of the current state-of-the-art for some of its most advanced and widespread applications. The course begins with an introduction to the theoretical aspects of optical metrology and the physical mechanisms underpinning its applications. It then analyzes examples of transformative metrological applications, such as interferometry (empowering the observation of phenomena like gravitational waves), spectroscopy (e.g., time-resolved spectroscopy with unparalleled sensitivity), and dual-comb spectroscopy (used e.g., for astrophysical observations).

Period: June 2026 (to be agreed, contact: lucia.caspani@uninsubria.it)

Complements of theoretical physics

S. Cacciatori

(2.5 credits – 20 hours)

Program: *This is a 20 hours course, with the aim of presenting some advanced topics in theoretical physics, related with the physics of the standard model and/or general aspects of theoretical physics.*
The main arguments proposed by the course are:
-Symmetries in quantum field theory: Lie groups, spontaneous symmetry breaking of global symmetries and local symmetries, symmetries in path integral formalism, anomalies.
-Feynman integrals in classical and quantum theories. Methods of computation of the Feynman integrals and related twisted cohomology;
-The geometry of the Standard Model of Particles and possible extensions to grand unification models.
According to the interests of the participating students, it is possible to consider a short introduction to all such arguments, or to develop more deeply one of them if needed.

Period:
April 14th, 15th , 16th 2026, 16:00-18:00;
April 21st, 22th , 23th 2026, 16:00-18:00;
April 28th, 29th , 30th 2026, 16:00-18:00;
May 5th 2026, 16:00-18:00.