PHD COURSES 2022

ASTROPHYSICS AREA

ADVANCED TOPICS IN ASTROPHYSICS AND PLASMA PHYSICS

Provide advanced analysis and modeling tools for the most recent research topics in astrophysics and plasma physics. The course offers seven modules, each covering 10 hours for 2 CFU. Students will choose one or more modules.

Collective Phenomena in Plasma Physics (2 CFU-10 hours)

M.Romé UNIMI massimiliano.rome@unimi.it

This course provides an introduction to plasma physics in an astrophysical context. Topics include:

- Charged particle motions;
- Magnetohydrodynamics;
- Waves;
- Dynamos;
- Magnetic reconnection.

Fundamentals of Computational Fluid Dynamics in Astrophysics (2 CFU-10 hours)

G.Lodato UNIMI giuseppe.lodato@unimi.it

- Eulerian and Lagrangian methods in computational fluid dynamics;
- Simple examples of numerical solutions to the diffusion equation on a 1D Eulerian grid;
- Smoothed Particles Hydrodynamics (SPH): an introduction;
- PHANTOM: an advanced SPH code for astrophysics.

Cosmology (2 CFU-10 hours)

D.Maino UNIMI davide.maino@unimi.it

- Ganeral relativity and FRW metric;
- Baryogenesis;
- Equation of state;
- Matter-radiation decoupling;
- Spectrum, anisotropy and polarization of the CMB;
- Inflation and alternative.

Observations of the CMB (2 CFU-10 hours)

M.Bersanelli UNIMI marco.bersanelli@unimi.it

- Spectrum, anisotropy and polarization measurements;
- Detector and optics technology;
- Systematic effects;
- Astrophysical foregrounds (galactic, extragalactic);
- State of the art and future perspectives.

Observations and theory of large-scale structure formation (2 CFU-10 hours)

L. Guzzo UNIMI luigi.guzzo@unimi.it

- The large-scale distribution of galaxies, redshift surveys;
- The density field: statistics of large-scale structure;
- Evolution of density perturbations and the origin of galaxies;
- Why we need dark matter.

Bayesian Statistics in Astronomy (2 CFU-10 hours)

M.Lombardi UNIMI marco.lombardi@unimi.it

- Brief overview of basic statistical concepts: random variables, probability distributions, joint probabilities, correlation;
- Formalization of a well-posed problem: the likelihood function and the associated assumptions;
- Bayes' theorem and its interpretation; the role of the prior;
- Bayesian inference of parameters;
- The evidence and its use in Bayesian model selection;
- K-clustering algorithm.

NUCLEAR AND SUBNUCLEAR AREA

ADVANCED TOPICS IN PARTICLE PHYSICS (4 CFU-20 HOURS)

A.Andreazza UNIMI attilio.andreazza@mi.infn.it, L.Serafini INFN luca.serafini@mi.infn.it, R.Turra INFN ruggero.turra@mi.infn.it

Provide advanced analysis and modeling tools for the most recent research topics in cosmology, astrophysics and plasma physics. Prerequisites are the Dirac equation and had a first acquaintance with Standard Model of elementary particles, basic knowledge of the processes of interaction of radiation with matter and some C++ programming experience. The exam consists in solving some exercises assigned during the course and a 30' seminar on a topic, chosen by the student.

Introduction to Particle Accelerators: Physics and Technology challenges (5 hours + 2 hours topical seminar)

- History of the evolution of particle accelerators: ideas, technologies and applications;
- Transverse and longitudinal beam dynamics basics and issues;
- Accelerators for physics, human health and industry;
- Colliders for extreme microscopy while pushing the energy frontier

Reconstruction of charged particle trajectories (5 hours)

- Position sensitive silicon and gaseous detectors;
- Track reconstruction and fitting with Geant4 simulation excercises

Calorimetric techniques for energy measurement (5 hours)

- Calibration and performance of calorimetric systems.
- Simulation of a calorimetric system;

Statistical analysis with exercises (5 hours)

- Hypothesis testing, Likelihood method;
- Estimation of confidence levels.

NEUTRINO PHYSICS (2 CFU-10 HOURS)

F.Vissani INFN francesco.vissani@lngs.infn.it

Topics of neutrino astronomy: sun, supernovae, geoneutrinos, and high energy neutrinos;

- Introduction to neutrino oscillation;
- Neutrino conversion in vacuum and in matter;
- Experimental evidences of neutrino oscillations;
- Dirac and Majorana mass;
- Neutrinoless double beta decay;
- Extensions of the standard model;
  a) Right handed neutrinos, sterile neutrinos, extended matter and extended higgs fields;
  b) Seesaw;
  c) Grand unified groups;
  d) Neutrino masses in supersymmetric theories;
  e) Connections with other phenomena: mu -> e gamma, proton decay, baryogenesis;

Bibliography:
Bohm Vogel: Physics of massive neutrinos.
Giunti Kim: Fundamentals of neutrino physics and astrophysics.
Fukugita Yanagida: Physics of neutrinos and applications to astrophysics.
Mohapatra Pal: Massive neutrinos in physics and astrophysics.
Strumia Vissani: Neutrino masses and mixings and ..., hep-ph 0606054.
Andrea Gallo Rosso et al: Introduction to neutrino astronomy. 1806.06339.
Guido Fantini et al: Introduction to the Formalism of Neutrino Oscillations. 1802.05781.
Stefano Dell'Oro et al: Neutrinoless double beta decay: 2015 review. 1601.07512.

NUCLEAR STRUCTURE AND NUCLEAR REACTIONS

The course deals with the experimental and theoretical study of modern aspects of the structure of nuclei in the ground state and excited states, and the study of nuclear reactions with heavy ions in the energy interval around the Coulomb barrier. The course offers three modules. Students will choose one or more modules.

Nuclear structure theory: Density Functional methods in nuclear physics (2 CFU-10 hours)

G.Colò UNIMI gianluca.colo@unimi.it

Nuclear structure theory will be discussed with emphasis on the connection with experiment. The course has also an interdisciplinary aspect, in that it highlights common aspects with condensed matter theory and with nuclear astrophysics. After an overview on the current status of nuclear theory, the bulk of the

program focuses on nuclear density functional methods and applications. The course plan, and in particular the last item below, can be changed by agreement with students.
- The nucleon-nucleon interaction and the nuclear many-body problem: a survey.
- Nuclear structure models with emphasis on Density Functional Theory (DFT).
- DFT: the original Hohenberg-Kohn theorem; transferring DFT from electronic systems to nuclei; basics on Skyrme, Gogny and relativistic functionals.
- Applications of static DFT: ground-state properties (masses, radii, deformations).
- Time-dependent DFT and nuclear vibrational states. Giant resonances.
- The nuclear equation of state and applications to compact objects (neutron stars).
- Further topics: nuclear superfluidity, isospin in nuclear physics, exotic resonances.

Nuclear structure studied with stable and radioactive beams (2 CFU-10 hours)
S.Leoni UNIMI silvia.leoni@unimi.it
Lectures will concern the study of modern aspects of the structure of nuclei in the ground state and excited states. Nuclear Structure properties will be discussed from a phenomenological/experimental point of view, mostly in connection with the present use of accelerated beams of stable and radioactive heavy ions. The Course program could be changed by agreement with the students.
Tentative program:
- Production techniques for exotic beams: ISOL and in-FLIGHT methods.
- Examples of facilities and dedicated setups.
- High precision Mass measurements with traps and storage rings.
- Beta decay studies.
- Collective modes of vibration: Giant Resonances (optional).

Nuclear structure and reaction dynamics with radioactive beams (4 CFU-24 hours) - This course takes place in Padua
J.J.Valiente Dobon INFN valiente@lnl.infn.it, A.Di Pietro INFN dipietro@lns.infn.it
- Brief introduction to radioactive ion beams production techniques.
- Nuclear structure studies with ISOL beams.
- Nuclear structure studies with fragmentation beams.
- Experimental problems in reactions with radioactive beams.
- Reaction kinematics
- Resonance elastic scattering: Inverse kinematics thick target method
- Effects of “exotic” nuclear structure on reaction dynamics: elastic scattering, break-up and fusion
- Theoretical models of nuclear reactions
- Design of an experiment with radioactive ion beams.

MATTER PHYSICS AREA (CASTELLI)

QUANTUM THEORY OF MATTER (6 CFU-30 hours)
N.Manini UNIMI nicola.manini@unimi.it, S.Achilli UNIMI simona.achilli@unimi.it, G.Onida UNIMI giovanni.onida@unimi.it, A.Parola UNINSUBRIA alberto.parola@uninsubria.it
This course aims at familiarizing the student with the main theoretical concepts and state-of-the-art methods for the calculation of structural and spectroscopic properties of molecules and solids.

Core topics:
- The Born-Oppenheimer separation, adiabatic dynamics and non-adiabatic terms, adiabatic-diabatic transformation;
- Many-body Theory, second quantization, functional analysis, diagrams;
- Density Functional Theory (static);
- Electron dynamics, excited states and time-dependent phenomena;
- Strong electron correlations: Hubbard models and beyond.

Optional further arguments (can be inserted upon request):
- Time-Dependent Density-Functional Theory;
- The Car-Parrinello method;
- Entanglement of vibrational and electronic motion. Geometric phases;
- Anharmonic corrections to the adiabatic harmonic theory of vibrational properties for molecules and solids.

General Methods and concepts.
- Symmetries in physics and group theory. Subgroups. Group representations. Examples. Product groups. Representation reducibility. Fundamental theorems of the group representation theory. Representation characters.
- Examples and applications to problems in condensed matter and solid state physics

- Born Oppenheimer separation. Diabatic-adiabatic transformation. Examples and applications. Ehrenfest dynamics.

The many-electrons problem

- Many-body Hamiltonian for N electrons and M nuclei. Exponential wall. Summary on the variational principle and its application within the Hartree-Fock method. Electron density and density matrix, and their functional derivatives. Matrix elements of 1 body and 2 body operators. Total energy and double counting. Link with Green's functions and Feynman diagrams.
- Hartree-Fock in second quantized theory. Excitation energies and Koopman's theorem.
- Density Functional Theory (static): Hoenberg-Kohn, Thomas-Fermi, Kohn-Sham. Similarities and differences wrt HF. Case of a single electron; case of the homogeneous electron gas. Local Density Approximation. The self-interaction problem.
- Bandstructure: definition, experiments. Theoretical tools. Charged excitations vs neutral excitations. Janak's theorem. Discontinuity of the exchange-correlation potential.
- Spectral functions. Self energy. Equation for the poles of the one-electron Green's function.
- Perturbative schemes. Comparison with experiments.
- Hedin's equations. The GWGamma scheme. The GW approximation. One-shot G0W0.
- Linearization of the energy dependence of Sigma. Examples: bulk copper. Beyond G0W0: self-consistency and vertex corrections.
- GW implementation in open-source codes.
- Hybrid functionals. Examples.
- Excitonic effects in optical absorption spectra. Bethe-Salpeter equation. Local fields. Examples.
- Usage of the "Quantum Espresso" open-source code suite.

Strongly correlated electron systems

- Role of the electron-electron interaction in the electronic structure of solids. Introduction to the second quantization method. Fock space, creation and annihilation operators, second-quantized Hamiltonian for the electron gas.
- Electronic structure of transition metals. Hubbard model. Mott transition. Strong and small coupling limits of the Hubbard model. Origin of antiferromagetism in condensed matter. The Heisenberg model.
- Metal-insulator transition in the Hubbard model: mean field theory. Hubbard model with attractive interactions: superconductivity. Analogies with the BCS theory.

QUANTUM COHERENT PHENOMENA (6 CFU, 30h)

F.Castelli, fabrizio.castelli@unimi.it (12h), M.Genoni marco.genoni@unimi.it (12h), C.Benedetti, claudia.benedetti@unimi.it (6h)

The course aims to provide the fundamental concepts about the quantum description of the radiation field and its interaction with matter, with a particular attention to advanced developments on quantum states, optomechanics devices and quantum walks.

Topics:
- Fundamentals of radiation quantum theory and quantum coherence;
- Introduction to open quantum systems, master equations and damping;
- Generation and manipulation of optical quantum states;
- Gaussian quantum states and Gaussian quantum operations;
- Stochastic master equations and optical feedback;
- Quantum optomechanics;
- Discrete- vs Continuous-time Quantum Walks (QWs);
- Quantum search Algorithms based on QWs;
- Physical implementations of QWs.

HPC@UNIMI: INDACO FOR MOLECULES AND SOLIDS (3 CFU-15 hours)

G. Fratesi UNIMI guido.fratesi@unimi.it, R. Martinazzo UNIMI rocco.martinazzo@unimi.it, A. Alessi UNIMI alessio.alessi@unimi.it, M. Bensi UNIMI michele.bensi@unimi.it

This course provides an introduction to HPC with special emphasis given at the facilities available within UNIMI (INDACO), and to its application to the calculation of electronic, structural, and spectroscopic properties of molecules and solids.

HPC at Indaco.

Fundamentals of computers and networks, UNIX; installation and configuration of programs to access Indaco; software optimization and management.

The electronic problem.

Introduction: Born-Oppenheimer approximation, potential energy surfaces and their topology, adiabatic vs. non-adiabatic dynamics. Electrostatic Hamiltonian, antisymmetry principle, Slater determinants, spin-symmetry. Methods based on the electronic wavefunctions: Hartree-Fock and post-HF methods. Density functional theory, Kohn-Sham method, Exchange-correlation functionals. Time-Dependent Density Functional Theory.

Methods for molecules.
Atom-centered basis sets. The chemical bond: the hydrogen molecule, valence bond vs molecular orbital theories, localization, natural bond orbitals. Introduction to Gaussian/GAMESS. Electronic structure and molecular properties (with exercises). Geometry optimization, transition-state search, intrinsic reaction paths, normal mode analysis (with exercises).

Methods for the solid state.
The atomic pseudopotential and the projector augmented wave. DFT in a plane wave basis set. Computational issues. Self-consistency and convergence. Brillouin zone integration. Lattice vibrations: frozen phonon and density functional perturbation theory. Introduction to the Quantum-ESPRESSO simulation package. Application to bulk systems. Electronic properties of elemental crystals. Phonons. Application to non-periodic systems: surfaces, molecules. Exercises.

THEORETICAL PHYSICS AREA (FERRERA)

COMPUTATIONAL, SIMULATION AND MACHINE LEARNING METHODS IN HIGH ENERGY PHYSICS AND BEYOND: AUTOMATED COMPUTATIONAL TOOLS (3 CFU-15 hours)

F. Maltoni UNIBO and UCL fabio.maltoni4@unibo.it, -M. Zaro UNIMI marco.zaro@unimi.it

The course is organised in lectures and tutorial sessions where students perform simulations on their own. First, the basics concepts of perturbative QCD relevant for describing events taking place at the LHC experiments are reviewed together with notions of fixed order computations at higher orders, parton showers and their merging/matching. Second, the techniques used for making such computations automatically starting from a generic Lagrangian as well as their implementation in public tools are presented. As practical applications, students will be asked to perform fully-fledged simulations of processes of interest at the LHC, SM as well as beyond the SM, via the use of FeynRules/MadGraph5_aMC@NLO/Pythia/Delphes simulation chain.

COMPUTATIONAL, SIMULATION AND MACHINE LEARNING METHODS IN HIGH ENERGY PHYSICS AND BEYOND: MONTE CARLO METHODS (3 CFU-15 hours)

S.Alioli UNIMIB simone.alioli@unimib.it, E.Re UNIMIB emanuele.re@unimib.it

It will be illustrated the principles on which event generators for hadron colliders are built and the progress that has allowed to increase their precision and reliability. In particular we talk about the showering algorithms, the treatment of coherence in soft radiation, and the hadronization models. It will be also illustrated the CKKW method for interfacing "tree level" array elements with shower generators, and methods to achieve accuracy at next-to-leading order.

- General introduction: basic theoretical and experimental concepts of hadronic collider physics.
- Asymptotic freedom, QCD, jets. Infrared and collinear safe observables.
- Theory of hadronic collisions. Perturbative computation at leading, next-to-leading and next-to-next-to-leading order. Overview of existing tools for automatic computation of physical processes.
- Simulation of hadronic collisions with shower Monte Carlos. Theoretical basics: leading-collinear contributions; soft contributions (Sudakov form factors). Summary of available codes.
- Interface between tree-level matrix elements and Parton Shower (CKKW matching).
- NLO calculations and shower Monte Carlo: MC@NLO and POWHEG.

COMPUTATIONAL, SIMULATION AND MACHINE METHODS IN HIGH ENERGY PHYSICS AND BEYOND: MACHINE LEARNING (3 CFU-15 hours)

S.Carrazza UNIMI stefano.carrazza@unimi.it

An introduction to machine learning techniques including model representation, parameter learning, non-linear models, hyperparameter tune, and an overview of modern deep learning strategies. The seminars will cover the theoretical and mathematical aspects of machine learning followed by practical examples of code implementation using public frameworks.

- introduction to machine learning techniques and model representation;
- parameter learning, non-linear models and hyperparameter tune;
- overview of modern deep learning strategies.

4D AND 3D THEORIES WITH FOUR SUPERCHARGES: FIELD THEORY, D-BRANES, HOLOGRAPHY AND LOCALIZATION (7 CFU-35 hours)

A. Amariti INFN antonio.amariti@mi.infn.it

- 4d supersymmetric QFT: the phase structure of SQCD, 't Hooft anomalies, Seiberg duality, gaugino condensation, supersymmetry breaking, the conformal window, a-maximization. Non-renormalization theorems. ADE classification and accidental symmetries. Quiver gauge theories. S-dualty;
- D-branes: generalities, brane engineering, T-duality, S-duality, Hanany Witten transition and Seiberg duality;
- Holography: general aspects of the gauge/gravity correspondence. The basic example: $N = 4$ SYM and D3 branes in type IIB string theory. AdS_5/CFT_4 correspondence and Sasaki-Einstein (SE) manifolds. Volume minimization and relation with a-maximization. Relation with the KK reduction and gauged supergravity;
- Localization: generalities. The superconformal index.
- Generalization to 3d $N = 2$: Field theory, branes, holography and localization:
  a. Field theory: CS terms, monopoles, parity anomaly. Giveon Kutasov and Aharony duality. Mirror symmetry.
  b. Brane dynamics: CS from $(p; q)$ branes, real masses, monopoles and euclidean D-branes.
  c. AdS/CFT correspondence: the ABJM model and generalization to the SE_7 case. Massive IIA dual. Volume minimization.
  d. Localization: the three-sphere partition function.
  e. Reduction of 4d dualities to 3d using field theory methods, D-branes and localization.

APPLIED PHYSICS AREA (VAILATI)

EXPERIMENTAL METHODS FOR THE INVESTIGATION OF SYSTEMS AT THE NANOSCALE (6 CFU-30 hours)

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The course is focused on the description of experimental methods suitable to manipulate and investigate mesoscopic systems, such as nanostructured materials and interfaces, soft matter, and biological samples. The course is structured as a sequence of self-contained lectures held by specialists in the field. Many of the lectures are accompanied by the experimental demonstration of the method in the research laboratories. Final exam: each student will present a seminar on a topic agreed with one of the lecturers. All the seminars will be grouped within a single session at the end of the course. For general information about the course contact alberto.vailati@unimi.it.

Intensity Fluctuation Spectroscopy (Vailati)

- Brownian motion and fluctuations;
- Homodyne and heterodyne detection;
- Spatial coherence;
- Polarized and depolarized Dynamic Light Scattering;
- Hambury- Brown and Twiss interferometry.

Coherent imaging (Paroli)

- Radiation emission and propagation;
- Spatial and temporal coherence;
- Illuminating a sample - coherent and incoherent imaging;
- X-ray imaging - phase sensitive imaging methods;
- Tomography;
- Holography.

Quantitative microscopy (Giavazzi)

- Theory of image formation;
- Anatomy of a microscope;
- Scattering- vs fluorescence-based microscopy;
- Overcoming the diffraction limit;
- Microscopy vs scattering;
- Real vs reciprocal space;
- Laboratory activities.

Rheology and micro-rheology (Zanchetta)

- Stress and strain;
- Different types of response to an imposed deformation: elastic solids, viscous fluids,...everything in between!
- Rheological tests;
- Yield stress;
- The importance of micro-structure;
- Micro-rheology: real-space and Fourier-space methods;
- One-point and two-points micro-rheology;
- Passive and active micro-rheology.

Fluorescence methods in biophysics (Buscaglia)
Introduction:
- spectroscopic properties of fluorophores;
- standard analytical instrumentation.

Advanced methods:
- fluorescence quenching as a probe for inter- and intra- molecular diffusion and conformation;
- fluorescence resonance energy transfer as a nanometer-scale ruler;
- fluorescence correlation spectroscopy and single molecule techniques to directly observe structural and dynamic heterogeneity;
- Laboratory activities.

Molecular Beams (Piseri)
- Introduction to molecular beam concepts: effusive sources; free jet sources; seeded expansions;
- Molecular beam techniques and methods: molecular beam apparatus; devices and instruments; selected experiments and applications;
- Synthesis of nanostructured systems by molecular beam deposition.

Scanning probe microscopies (Podestà)
- Scanning Probe Microscopies e Atomic Force Microscopy. Basic principles;
- Beyond topography. Applying and Measuring forces at the nanoscale;
- Experiments in the lab.

Laser Sources (Cialdi)
- Single mode and multimode lasers;
- Pulsed lasers (Q-switched and mode locked);
- Laboratory activities.

Nanomagnetism (Arosio)
Introduction to Nuclear Magnetic Resonance:
- Larmor precession and Bloch equations;
- Longitudinal and transverse nuclear relaxation times;
- NMR spectra.

Few concepts of magnetism:
- Diamagnetism, paramagnetism and ferromagnetism;
- Superparamagnetism.

Laboratory:
- The pulsed NMR apparatus;
- Most typical pulse sequences;
- Measurements of 1H NMR spectra, T1 and T2 on reference oil;
- Fast-field Cycling technique: an example of profiles.

Photoemission Spectroscopy (Lenardi)
Theoretical arguments:
- Surface Physics: motivations to study the electronic properties of surfaces in nanostructured materials;
- Photoemission spectroscopy (XPS, UPS, AES): analysis of the structure of the core levels and the valence band, elemental analysis, chemical shift, spectromicroscopy with synchrotron radiation;
- Instrumentation: experimental apparatus equipped with X-ray and UV sources, electron analyzer, detector.

Laboratory:
- Acquisition of a wide spectrum of a sample in low resolution;
- Acquisitions of core edges in high resolution;
- Data analysis: peak recognition, quantification of elements and chemical bonds.

Static light scattering and its applications (Carpineti)
- Basic concepts: light scattering, absorption and extinction;
- The scattering problem;
- The case of a single particle and of many independent particles;

- Scattering and index of refraction: the extinction formula;
- Rayleigh and Rayleigh-Gans approximations;
- The scattered intensity and its relation with the sample properties;
- Correlated particles: the pair correlation function, with examples;
- The light scattering instrument;
- Laboratory activities especially related to the last three points.