Master's thesis and internship proposals

This is a non-exhaustive list of thesis and internship proposals. For more details, contact the professor indicated in the corresponding section.

Alberto Parola's group

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- **Thermophoretic force in structured particles (Theoretical/numerical)**

  When a particle is immersed in a fluid with a non-uniform temperature field, it develops a stationary drift velocity whose magnitude depends on the local temperature gradient. This out-of-equilibrium phenomenon is observed in fluid mixtures (Soret effect) and in colloidal suspensions, where it is known as thermophoresis. Despite extensive studies, a theoretical description is still lacking, and predicting the resulting drift remains an open problem in statistical physics. Recently, a microscopic theory has been developed to predict fluid motion in the presence of an interface and a temperature gradient. This thesis aims to apply this framework to thermophoresis, which is assumed to originate from interfacial slip near the colloid surface. The study will be conducted using non.equilibrium molecular dynamics simulations of a single structured particle (an assembly of elementary particles) immersed in a Lennard-Jones fluid under a constant temperature gradient. By fixing the particle position, the "thermophoretic force" exerted by the fluid can be computed and compared with the analytical result

- **Non-isothermal water transport in nanocapillaries (Experimental)**

  Thermal gradients can induce fluid motion near confining surfaces, even in the absence of convection. This phenomenon, known as thermo osmosis, plays an important role in energy conversion, desalination, microfluidics, and biological systems, yet its microscopic mechanisms remain poorly understood. Seminal studies of thermo-osmosis have been performed using two closed reservoirs maintained at different temperatures and separated by a porous membrane. At steady state, the thermo-osmotic flow through the membrane pores generates a pressure difference between the reservoirs, which balances the flow and ensures mass conservation. The resulting pressure gradient is linearly related to the applied temperature difference through a proportionality coefficient that depends on the microscopic properties of both the fluid and the confining material. Despite extensive investigations, those experimental studies often yielded contradictory results, and a systematic microscopic understanding of thermo-osmosis is still lacking. This Master's thesis aims to finalize and characterize a novel experimental setup in which the reservoirs are connected by silica nanocapillaries. By independently controlling the nanotubes dimensions, number, and length, the setup will enable systematic

- **Topological marker for phase transitions in 1D spin systems (Theoretical/numerical)**

  Zero temperature phase transitions between phases in magnetic systems are usually characterized by directly measuring the order parameter, whose definition depends on the specific transition and, in spin models, may be identified as uniform or staggered magnetization, dimer or chiral correlations etc etc. An alternative possibility is to locate the transition by studying a recently introduced topological marker: a local observable which identifies changes in the structure of the many body ground state wavefunction, without a direct connection to the specific transition. This marker has been successfully employed in a one dimensional spin model where its physical meaning becomes transparent due to a variational study. The thesis project is aimed at a better understanding of the physics behind this topological characterization and its implementation in other models.

Francesco Ginelli's group

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- **Population selection via virtual confinement (Theoretical/numerical simulations)**

  This thesis project will investigate whether virtual confinement can act not only as a mechanism for trapping active particles, but also as a selective filter between different bacterial populations. The project builds on recent work on density-protected states in photo-responsive cyanobacteria where bacteria self-organize near the boundary of an illuminated disk, generating a robust confined state. In realistic experiments, however, bacteria may differ in length, swimming speed and, consequently mutual alignment properties. We plan to extend the microscopic model to include two bacterial populations, initially mixed in equal proportion, with possibly different motility and cross-population alignment strengths. The central question is whether the illuminated region can spontaneously become enriched in one population, leading to population selection inside the confined domain. The project will be mainly numerical, with possible interaction with an experimental group and/or extensions toward a two-population mesoscopic theory.

- **Reservoir computing approach to Covariant Lyapunov Vectors (Theoretical/numerical simulations)**

  This thesis project will explore a data-driven strategy to reconstruct Covariant Lyapunov Vectors (CLVs) using reservoir computing. CLVs provide a geometric characterization of chaotic dynamics, identifying the locally expanding and contracting directions in phase space, but they are usually inaccessible in experiments, where the equations of motion are unknown and only time-series data are available. Following reservoir-computing approaches to chaotic prediction, we will train a recurrent neural network to reproduce the dynamics of a target system from observed signals. The CLVs of the trained network will then be computed and compared with those of the original system. The project will test this idea on synthetic data, first considering low-dimensional chaotic models, such as the Lorenz or Rössler attractors, and then moving to spatiotemporal chaotic systems, such as the well-known Kuramoto–Sivashinsky equation.

- **Population selection via virtual confinement**
  (Theoretical/numerical simulations)

  Vectorial active matter models, such as the Vicsek model and active nematics, rely on the spontaneous breaking of a continuous rotational symmetry. This feature plays a central role in their large-scale behavior, in particular through the emergence of Goldstone modes and anomalously strong fluctuations. A useful way to disentangle genuine nonequilibrium effects from those directly tied to continuous symmetry breaking is to replace the continuous symmetry with a discrete one. This strategy led from the Vicsek model to the active Ising model, where flocking-like behavior can be studied without Goldstone modes. In this thesis, we aim to develop an analogous lattice model for active systems with nematic symmetry. The project will investigate how activity, nematic alignment, and discrete symmetry interact at large scales, using numerical simulations and, depending on the student's interests, analytical approaches based on mesoscopic field equations.

Giuliano Benenti's group

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- **Micromaser as a quantum reservoir computing**
  (Theoretical/numerical simulations)

  Quantum reservoir computing is a machine learning framework that exploits complex, nonlinear quantum systems as reservoirs for processing temporal data. In this approach, input signals are encoded into quantum states that evolve under the system dynamics, mapping the information into a high-dimensional Hilbert space, while training is restricted to a simple output layer. In this thesis, we investigate quantum reservoir computing based on the micromaser model, where a train of qubits interacts with a single cavity mode, including the ultrastrong field–matter coupling regime. This platform naturally combines a large Hilbert space with intrinsic nonlinear dynamics, making it a promising candidate for time-series processing tasks. Its predictive performance will be assessed using benchmark problems such as the Mackey–Glass time series, a standard testbed for chaotic dynamics.

Romualdo Santoro's group

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- **Performance characterization of a digital SiPM fabricated in a 110 nm CMOS process**
  (Experimental)

  CMOS technology enables SPAD arrays with integrated quenching and signal processing, forming ultra-fast Digital SiPMs. Unlike conventional SiPMs, they provide individual pixel control and in-pixel signal digitisation. Their scalability and high granularity make CMOS SPADs promising candidates for future high-energy and astroparticle physics experiments requiring picosecond timing resolution.

  The ASPIDES collaboration has developed a monolithic SPAD array with integrated front-end electronics based on a 110 nm CMOS image sensor technology. The device consists of 1024 microcells with a 30 μm pitch and a 50% fill factor. The readout architecture provides on-chip photon counting, sub-100 ps time-stamping capability, and dedicated noise-mitigation strategies. The prototype is expected to be delivered in June 2026, and a comprehensive characterisation campaign will immediately follow. The measurements will focus on key parameters such as photon detection efficiency (PDE), dark count rate (DCR), optical crosstalk, and afterpulsing.

This activity, supported by INFN, is fully integrated within the CERN RD program for future lepton colliders. Both bachelor's and master's students will have the opportunity to carry out measurements and data analysis on this innovative sensor in order to fully characterize its performance. The projects offer the possibility to work in an international research environment.

- **Test beam characterization of a fiber sampling dual-readout calorimeter prototype**
  (Experimental)

  Future lepton colliders require highly precise jet energy measurements in order to distinguish between Z, W, and Higgs boson decays. Dual-readout calorimetry, based on the simultaneous detection of scintillation and Cherenkov light, provides improved energy resolution by correcting fluctuations in the electromagnetic component of hadronic showers on an event-by-event basis. In this context, the HiDRa (Highly Granular Dual-Readout Calorimeter) demonstrator has been developed as a modular and cost-effective solution compatible with fully 4π detector geometries.

  The detector combines the dual-readout technique with high-granularity information. It is based on stainless-steel capillary tubes arranged in alternating layers filled with scintillating and Cherenkov fibers, respectively. The light signals are read out using Silicon Photomultipliers (SiPMs), and the detector dimensions are optimised to ensure adequate containment of hadronic showers. The prototype was tested with electron and pion beams at CERN in 2025, and a new test-beam campaign is scheduled to start in June 2026. A dedicated data-analysis effort is currently ongoing to evaluate the detector performance and assess its compliance with the requirements of future lepton collider experiments.

  This activity, supported by INFN, is fully integrated within the CERN RnD program for future lepton colliders. The master's thesis project will focus on the analysis of test-beam data and will offer the student the opportunity to collaborate with both junior and senior researchers in an international research environment.

INSULAB laboratory

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- **Innovative compact electromagnetic calorimeters based on oriented crystals**
  (Experimental)

  Study of the performance of oriented PWO crystals for the application in innovative compact electromagnetic calorimeters for high energy experiments (for instance, forward calorimeters) and on satellites:

  - development of the frontend and readout electronics (using Silicon PhotoMultipliers as photo-detectors)
  - study of the performance of the calorimeter in terms of linearity, energy resolution, particle identification capability in different energy ranges and with different particles (electrons, positrons, photons) on extracted accelerator beamlines (CERN, Frascati, Desy)
  - development of simulation tools including the behaviour of oriented crystals and the strong field effects

  The OREO (ORiEnted calOrimeter) project has been supported by the National Scientific Committee V of INFN and is part of the CERN DRD Calo Collaboration. Both bachelor and master's theses can be performed in this field, featuring one or more of the listed topics.

- **Optimization of crystal radiators for intense photon sources (Experimental)**

  Design and test of optimized crystal radiators for:

  - applications demanding high spectral brilliance, tunability and collimation, such as polarized photon sources, positron production and X-ray generation for life sciences or detector calibration
  - strong-field QED studies and compact gamma sources in accelerator environments

  The CORAL project aims at bridging theory and practical applications, advancing crystal radiators as replacements for conventional bremsstrahlung targets where enhanced intensity and spectral control are critical. The project will study experimentally on beam diamond and tungsten crystals, developing Geant4 simulations to model coherent processes and support the target optimization. Interest on this technology has already been shown by different communities, to substitute the bremsstrahlung targets to generate tens MeV photons for nuclear fission and transmutation or to generate hundreds MeV intense gamma-beam for fundamental physics research.

  Both bachelor and master's theses can be performed in this field, featuring one or more of the listed topics.

- **GEMMA – Gamma-ray Explorer for Multi- Messenger and cosmic Accelerators (Experimental)**

  GEMMA is a proposal to the Italian Space Agency for a small scientific mission for the development of a satellite to target the MeV-GeV domain, the crucial window to probe particle acceleration and radiation processes. This energy range remains one of the least explored regions of the electromagnetic spectrum, leaving a critical gap between hard X-rays, GeV-TeV emission and multi-messenger observations. The GEMMA detector is designed to operate in both the Compton and pair-production regimes from 1 MeV to beyond 1 GeV. The payload includes a Scintillating Fiber Tracker, a highly segmented CsI(Tl) calorimeter, a segmented plastic anticoincidence system. The candidate will work in the development of the detector and in the on beam test of prototypes, becoming part of the collaboration and involved in simulations and data analysis.

Both bachelor and master's theses can be performed in this field, featuring one or more of the listed topics.

- **Insulab4School**

  The Insulab group has a long experience in working with schools of all grades and in courses on education for school teachers. The didactics of physics can be performed starting from the nursery school, using adequate materials, selecting the concepts to present, insisting on the power of observation and demonstrating the need to perform hands-on experiments in which students are the real protagonists. Insulab has designed courses for both students and teachers on several topics; the group has investigated misconceptions and their role in the learning process, organized courses on particle and modern physics, designing sets of indicators to understand the efficacy of the courses and of a different way of teaching physics. The candidate will help in defining new courses and indicators, will hold the courses, will develop detectors that can be used in high schools and that can become part of the educational path in the school itself.

INSPECT laboratory

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- **Rational design and evaluation of new conception contrast agents for nuclear magnetic resonance diagnostic imaging (Nardo)**
  (Experimental)

  Nuclear magnetic resonance (NMR) is a powerful diagnostic tool, especially for soft tissues. Contrast agents enhance resolution, reduce acquisition time, and enable selective labelling of tissues. Most current agents use toxic gadolinium, which clears slowly from the body. At DiSAT, novel nanoparticles are being developed as safer alternatives. These are organic molecules that incorporate Fe^{3+} and self-assemble into superparamagnetic aggregates in solution, producing negative-contrast images by quenching water proton magnetization. The student will study the aggregation kinetics by dynamic light scattering as well as tracking UV-vis red shifts and fluorescence quenching, linked to supramolecular assembly and vibrational mode activation in the nanoaggregates. Moreover, the incorporation of the nanoparticles within lipid-based delivery systems will be probed by fluorescence correlation spectroscopy. The morphology of the nanoparticles will be assessed by means of SEM. The performances as contrast agents will be evaluated by means of NMR relaxometry studies.

- **α-Synuclein-dopamine interplay: the molecular bases of Parkinson's disease onset (Nardo)**
  (Experimental + computational)

  This project focuses on understanding the molecular mechanisms behind Parkinson's disease (PD), particularly the aggregation of α-synuclein (αS), a key protein involved in its pathogenesis. αS misfolding and aggregation into oligomers and fibrils is linked to neurodegeneration. Dopamine, the neurotransmitter most affected in PD, appears to modulate αS aggregation, potentially stabilizing toxic intermediates. The project combines biophysics and nanotechnology, employing advanced fluorescence techniques—especially Fluorescence Correlation Spectroscopy (FCS) and Fluorescent Burst Analysis (FBA)—to monitor αS aggregation. It also explores liposome-based systems for controlled αS delivery, integrating experimental work on nanoparticle characterization and protein-vesicle interactions in collaboration with external partners. At present, a large amount of raw data have been already acquired. Besides collecting further statistics, the students will be stirred to devise complex data analysis strategies to handle such data.

- **The molecular bases of energy harvesting and energy production by new-conception solar panels (Nardo)**
  (Experimental)

  Luminescent Solar Concentrators (LSC) have been widely studied for photovoltaics. Both inorganic emitters like quantum dots and organic fluorescent dyes have been considered. The new frontier may lay in combining the two scaffolds within hybrid films. Our synthetic chemist partners provide us with new concept LSC. Electronic state transition spectroscopy, particularly UV-Vis absorption, steady-state photoluminescence and time-resolved fluorescence, are the election techniques to guide the rational design of optimized layers. The student will be in charge of undertaking a full characterization of the new scaffolds starting from the spectroscopy of the single LSC to end with the characterization of the performance of films. Particularly, time resolved analysis will be used to discriminate surface charge recombination from bulk ionization in the photoelectron production process. It will also allow to unravel specific excited-state deactivation pathways of the concentrator and will yield detailed information about the degree of purity of the film crystal structure. Doping is a consolidated technique to enhance the charge migration lifetime through the panel surface, due to the so-called trap effect. The effectiveness of dopers and the fine tuning of their concentration will be evaluated through time-resolved photoluminescence. Spatial homogeneity of the film is one of the main figures of merit to be considered in devices commissioning and will also be assessed by photoluminescence lifetime mapping of the surface.

- **Building and commissioning state-of-art fluorescence microscopy systems (Nardo)**
  (Experimental)

  The group has a long-dating experience on fluorescence spectroscopy, which is routinely applied at the ensemble as well as single molecule level. The recent acquisition of an inverted microscope and a galvanometric beam-sweeping system enables translating such techniques directly into living cells. Two geometries are being considered: scanning-beam confocal microscopy (CM) and total-internal reflection wide-field fluorescence microscopy (TIRF). CM allows acquisition of three-dimensional images of cells and tissues whose organelles and substructures are stained with fluorescent dyes absorbing and/or emitting laser light at different wavelengths. Typical radial and axial special resolutions are about 250 and 750 nm, respectively, making CM one election technique for structural studies on biosystems. Integration of the confocal fluorescence microscope within our time-correlated single-photon counting setup will permit acquisition of fluorescence lifetimes, fluorescence correlation spectroscopy, and fluorescence resonance energy transfer data within selected cell compartments, extending the power of CM to the functional rather than structural domain.

  TIRF exploits the penetration of the evanescent wave in total reflection conditions within a sample. The penetration depth being in the range of 50 to 200 nm, this is a powerful tool to image thin films as well as to probe the conformational dynamics and interactions with substrate of single surface-tethered biomolecules.

- **Optical microcavities for quantum engineering (Lamperti)**
  (Experimental + numerical simulations)

  Optical microcavities provide a versatile platform to study and engineer the interaction between light and matter at the nanoscale. By confining photons in small volumes and for long times, they enhance light–matter interaction and enable applications ranging from quantum information to energy storage. This thesis will explore the realization of microcavities and the usage of innovative colloidal quantum dots, nanometer-sized particles whose optical properties depend on the confinement of the electronic wavefunction in a limited space, to study exotic phenomena ranging from enhancement or suppression of the rate of spontaneous emission, to the realization of quantum devices to study collective properties of matter. The specific thesis goal will be chosen depending on the interests of the student. Beside the experimental activities, numerical simulations using FDTD methods (e.g., MEEP) or open quantum system dynamics (e.g., QuTiP) can be explored.

- **Unveiling DNA-anticancer drugs interactions through Raman spectroscopy (Lamperti)**
  (Experimental + numerical simulations)

  G-quadruplexes (G4s) are non-canonical DNA secondary structures formed by guanine-rich sequences, enriched at telomeric regions and oncogene promoters. Their stabilization by small molecules has emerged as a promising anticancer strategy, making G4–drug recognition an active area of research. In this thesis project, the student will employ Raman spectroscopy to characterize the structural signatures of model G4 oligonucleotides upon binding with selected G4-targeting ligands. By analyzing the vibrational markers of the guanine tetrad core, the work aims to establish spectral fingerprints of drug-induced conformational changes, contributing to a molecular-level understanding of G4–drug interactions. Depending on the student's interest, the project may be extended to include a computational component involving molecular docking and molecular dynamics simulations, enabling a broader screening of candidate compounds for selectivity toward specific G4 topologies.

- **Development of a UV-Resonance Raman spectrometer based on Fourier Transform spectroscopy (Lamperti)**
  (Experimental)

  Raman spectroscopy is a powerful technique to probe molecular vibrations and identify interactions and conformational changes in complex systems. A major limitation of spontaneous Raman scattering is its inherently weak signal, which can be dramatically enhanced by tuning the excitation wavelength to match an electronic absorption of the molecule, a condition known as resonance Raman. Deep-UV excitation is particularly advantageous, as it selectively enhances the Raman response of aromatic and nucleic acid chromophores by several orders of magnitude. In this thesis project, the student will design and build a high-resolution UV Resonance Raman spectrometer based on Fourier Transform detection, exploiting a narrow-linewidth deep-UV laser source. The instrument will be characterized and benchmarked on reference samples, then applied to solutions of G-quadruplex oligonucleotides and other biomedically relevant macromolecules. Depending on the interests of the student, gaseous-phase measurements may alternatively be explored, extending the applicability of the platform to molecular spectroscopy in the gas phase for environmental applications (e.g. study of aerosols or other relevant systems for the physics of the atmosphere).

Ultrafast Nonlinear Optics (UNO) laboratory

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- **Laser microfabrication of microfluidics and microelectronics components Silicon Carbide and Diamond for sensing (Experimental)**

  Ultrafast Laser processing technology based on nonlinear multi-photon absorption process is an excellent technique for the formation of microstructures in transparent materials thanks to its high precision, and numerous technological applications have been demonstrated. The goal of the thesis will be to conduct experiments to explore the effects of fs or ps laser pulses in the emerging material of Silicon Carbide (SiC), with the goal of fabricating building block for microfluidics (surface microchannels, micropillars with tailored surface nanostructures), and in-bulk graphitic conductive microstructures to be used for sensing, thanks to the presence of color centers defects that with their triplet spin states are sensitive to different environmental conditions, and can be used for magnetometry. Different laser parameters will be explored, and quasi non-diffracting beams such as Bessel beams will be used, for fast and elongated microstructuring. The surface and internal microstructures obtained will be compared, from the morphological and electrical point of view, to those that can be formed in diamond samples. Different crystallographic orientations will be taken into account for what concerns diamond so as different crystallinity of Silicon Carbide.

Quantum optics laboratory

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- **Generation and characterization of entangled states of light in the mesoscopic regime for underwater communication (Allevi) (Experimental)**

  The experiment involves the realization of two second-order nonlinear phenomena, spontaneous parametric down-conversion and sum-frequency generation, in order to produce optical states characterized by non-classical correlations in the blue spectral region, where water exhibits the lowest absorption coefficient. The light will be characterized, from a statistical point of view, in terms of number of photons using a pair of silicon photomultipliers and a CMOS camera (Orca-Quest) capable of counting photons incident on individual pixels.

- **Production and characterization of pulsed light at telecom wavelengths for applications in quantum communication (Allevi) (Experimental)**

  Through the nonlinear process of white-light continuum generation, light will be produced in the infrared spectral region. This light will then be characterized both spectrally and in terms of photon number by varying the parameters governing its generation (power, beam size, focal position, type of material used). The study of statistical properties will be carried out using the nonlinear process of sum-frequency generation, which will allow the infrared light to be converted into visible light so that it can be measured with a pair of silicon photomultipliers.

- **Implementation of a double homodyne-like scheme for quantum communication protocols (Allevi)**
  (Experimental)

  The scheme is based on a double interferometer and two pairs of silicon photomultipliers. The goal is to produce a stable setup by characterizing the phase noise of the source and implementing an appropriate locking system. The maximum repetition rate at which the system can operate will also be investigated in order to make it suitable for communication applications. Once the experimental setup has been realized and characterized, the possibility of encoding information in the amplitude and phase of coherent states of light will be explored, and the secure key generation rate for the implementation of quantum key distribution protocols will be studied.

- **Foundations of Quantum Optics and characterization of Single-Photon states (Bondani)**
  (Experimental)

  This thesis proposal explores the foundations of quantum optics through the study of parametric down-conversion processes and the characterization of single-photon states using single-photon detectors. Parametric down-conversion is a key technique for generating correlated and entangled photon pairs, widely used in quantum communication, quantum computing, and fundamental tests of quantum mechanics, such as Mandel's experiments and Bell's inequalities. The research aims to investigate how experimental parameters influence the quality of generated photon states by a characterization of these states through measurements of coincidence counting and tomographic reconstruction.

- **Teaching Quantum Physics concepts in High Schools (Bondani)**

  This thesis proposal explores innovative approaches to teaching quantum physics concepts at the undergraduate level by integrating the two-state formalism, quantum technologies, and educational games. Quantum mechanics is often perceived as highly abstract due to its mathematical complexity and counterintuitive principles such as superposition, measurement, and uncertainty. The study aims to investigate whether introducing simplified two-state systems as instructional models can help students better understand fundamental quantum concepts before addressing more advanced topics. It also examines how connections to emerging quantum technologies, such as quantum computing and quantum communication, can increase student motivation and relevance. Additionally, the research evaluates the use of game-based learning tools and interactive activities to enhance engagement and conceptual understanding. A mixed-method approach involving tests, interviews, and classroom observations will assess the effectiveness of these strategies in improving quantum physics education.

- **Laboratory-Based Learning and teacher training in Physics (Bondani)**

  This thesis proposal examines the effectiveness of laboratory-based instruction in improving problem-solving skills among physics students while emphasizing the importance of teacher training in organizing practical activities. Practical experiments help learners connect theoretical knowledge with real-world applications, yet many institutions face challenges such as inadequate laboratory equipment, limited instructional time, and insufficient teacher preparation. The study aims to develop simple experiments and assess how trained teachers can design and implement effective laboratory activities that enhance student learning outcomes. Data collection methods will include tests, observations, teacher interviews, and student feedback. The research will contribute to improving physics instruction by highlighting the role of teacher professional development in successful laboratory education.

Quantum and Ultrafast Photonics (QUP) laboratory

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- **Quantum-enhanced two-photon absorption (Experimental)**
- **Quantum-enhanced spectroscopy (Experimental)**

INAF / Brera Astronomical Observatory

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- **Thesis Opportunity in Time-Domain Astrophysics**

  We offer a graduation thesis project (Master and Bachelor) focused on the study of transient and/or highly variable high-energy phenomena, including gamma-ray bursts (GRBs) and active galactic nuclei (AGN). The work will involve the analysis of X-ray and gamma-ray observations from space-based missions, with emphasis on time series analysis, spectral characterization, and the physical interpretation of rapid variability. Students will gain hands-on experience with real astronomical data and modern computational tools. A background in physics or astrophysics and an interest in high-energy phenomena and data analysis are welcome.

Mattia Sormani's group

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- **Analytic rotating models of the circumgalactic medium (Theoretical/numerical simulations)**

  The Milky Way is surrounded by hot rotating atmosphere known as the "Galactic corona", or the circumgalactic medium. This atmosphere can be assumed to a first approximation to be in a rotating equilibrium. There are not many realistic models available in the literature that include rotation. The goal of this project is to develop realistic rotating analytic model of the Galactic corona constrained by cosmological simulations of galaxy formation. The models will be useful when future x-ray missions will be able to detect the rotation of the corona through spectroscopic measurements.

Haardt and Lupi's group

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- **Dynamical Evolution of Massive Black Hole Binaries (Lupi) (Theoretical/numerical simulations)**

  Massive black holes (MBHs) are commonly found in galaxy centres and form binaries during mergers. Their evolution depends on interactions with stars, gas, and feedback from accretion, which can affect coalescence times and gravitational-wave detectability. This project aims to model early binary evolution through numerical simulations of galaxy mergers, including advanced prescriptions for MBH accretion and feedback. The candidate will study how environmental properties influence orbital decay and the transition toward the gravitational-wave regime, improving predictions of merger rates and observable signals.

- **Electromagnetic Counterparts of MBH Binaries (Lupi) (Theoretical/numerical simulations)**

  MBH binaries shrink through interactions with stars and gas, potentially producing electromagnetic counterparts. In the bachelor project, the candidate will implement a semi-analytic model of stellar hardening in numerical simulations, following approaches such as Franchini et al. (2021). In the master project, the focus shifts to gas-rich environments, with on-the-fly radiation transport in simulations of binaries embedded in circumbinary discs. The goal is to study how accretion and radiation influence gas dynamics and to identify observable electromagnetic signatures at different evolutionary stages.

- **Eccentric Binaries and Thin Discs Close to Coalescence (Lupi) (Theoretical/numerical simulations)**

  The gas properties around MBH binaries near coalescence are poorly constrained, due to limited observations and incomplete simulations. This project uses a GRMHD numerical scheme to simulate binaries from Newtonian scales to the relativistic regime. The candidate will explore the role of orbital eccentricity and thin circumbinary discs on gas dynamics and radiation. The aim is to provide improved predictions of electromagnetic signatures associated with coalescing binaries and support multimessenger studies.

- **Modelling the Broad Line Region of Super-Eddington MBHs (Lupi) (Theoretical/numerical simulations)**

  Recent observations suggest that many high-redshift MBHs accrete above the Eddington limit, affecting the structure of the broad line region (BLR) and potentially biasing mass estimates. In the bachelor project, the candidate will model BLR emission using disc radiation and different cloud distributions (e.g. with SIROCCO). In the master project, GRMHD simulations will be used to determine disc structure and continuum emission self-consistently.

- **Airglow in Exoplanet Atmospheres (Lupi + Haardt) (Theoretical/numerical simulations)**

  Airglow is produced in planetary upper atmospheres by recombination of molecules ionised by stellar radiation. While well known on Earth, it may be detectable in exoplanets with future facilities such as the Extremely Large Telescope. Variations in airglow can provide information on atmospheric composition, thermodynamics, and possibly geological activity. The candidate will develop semi-analytic and 1D hydrodynamic models to study how atmospheric properties affect airglow emission. The goal is to assess its observability and diagnostic potential.

- **Atmosphere and Water Retention in Close-in Rocky Exoplanets (Haardt) (Theoretical/numerical simulations)**

  Close-in rocky exoplanets experience intense stellar radiation that can drive atmospheric escape. This project investigates the conditions under which such planets can retain atmospheres and water over long timescales. The study uses analytical and hydrodynamic escape models, considering planetary properties (mass, radius, magnetic field) and stellar activity. It also examines secondary atmospheres from volcanic outgassing and the role of magnetic shielding. The impact of tidal locking on atmospheric circulation and water distribution, including cold traps, will be explored. By combining models with observations from Kepler, TESS, and JWST, the project aims to identify conditions for atmospheric retention and potential habitability.

Oliver Piattella's group

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- **Cosmological tensions and limits of the ΛCDM model - Critical study of the main observational discrepancies (H0, S8) and analysis of possible theoretical and systematic explanations**
  (Theoretical)
- **Dynamic dark energy and scalar fields in general relativity - Exploration of models beyond the cosmological constant, such as quintessence and k-essence, with time-varying equations of state**
  (Theoretical)
- **Modified gravity - study of the extension of general relativity in cosmology and astrophysics**
  (Theoretical)
- **Axions and dark matter beyond the Standard Model - Theoretical study of axions as a solution to the strong CP problem and as candidates for cosmological dark matter**
  (Theoretical)
- **Primordial black holes as dark matter - Analysis of the possible formation of black holes in the early universe and the observational constraints limiting their mass and density**
  (Theoretical)
- **Effective quantum gravity and primordial cosmology - Study of quantum corrections to general relativity in the low-energy regime and their possible effects on the dynamics of the early universe**
  (Theoretical)
- **Quantum fluctuations and the origin of cosmic structures - Analysis of how**

quantum fluctuations during inflation transform into the spectrum of perturbations observed in the CMB
(Theoretical)

- **Alternatives to particle dark matter - We propose to study alternatives to particle dark matter that simultaneously explain observations of galaxy velocity curves, dynamics in galaxy clusters, and the formation of post-recombination structures**
  (Theoretical)