DiFA Projects available for PhD cycle 42

	Project code	Main supervisor	Title of the project
1	Baldi1	Baldi	Testing fundamental physics and cosmology beyond the standard model with numerical simulations of the cosmic large-scale structures
2	Baldi2	Baldi	Modelling the synergy between Gravitational Waves and Large-Scale galaxy surveys on constraining cosmology and fundamental physics
3	DallOsso1	Dall'Osso	Study of Gamma-ray Burst central engines through theoretical modelling of their broadband light curves
4	Despali1	Despali	What alternative dark matter models do to galaxies: studying galaxy formation in the AIDA-TNG simulations
5	Despali2	Despali	A SHARP view of dark matter in the Euclid era
6	Fiorellino1	Fiorellino	JWST insight on protostellar accretion
7	Gitti1	Gitti	Regulation of the AGN feeding-feedback cycle in cool-core clusters
8	Gitti2	Gitti	Thermal and non-thermal interplay in cool-core galaxy clusters
9	Lanzoni1	Lanzoni	Playing with the physics of Blue Stragglers
10	Marinacci1	Marinacci	The effects of baryonic physics implementation in simulations of galaxy formation and evolution performed with SPH and mesh-based methods
11	Marinacci2	Marinacci	Modeling the thermal balance of the hot CGM in star-forming galaxies: the role of stellar and AGN feedback
12	Marinacci3	Marinacci	Forecasting the gravitational wave signal in cosmological simulations for current and upcoming cosmological surveys
13	Marinacci4	Marinacci	Inhomogeneous chemical enrichment in simulations including single stellar polluters
14	Marulli1	Marulli	Exploring Gravity Models with gravitational redshifts in galaxy cluster environments
15	Marulli2	Marulli	Unlocking the full information content of the Cosmic Web with machine learning
16	Marulli3	Marulli	Cosmological exploitation of the statistical properties of Cosmic Voids
17	Miglio1	Miglio	Stars as laboratories for testing fundamental physics
18	Miglio2	Miglio	A first-principles step forward in red giant asteroseismology with 3D MHD simulations
19	Miglio3	Miglio	Stellar ages as precision cosmological probes: pushing the systematic floor to the percent level
20	Moresco1	Moresco	Exploiting Gravitational Waves as cosmological probes in view of the new upcoming large GW and galaxy surveys
21	Moscardini1	Moscardini	Statistical Tools for Cluster Cosmology Studies in the ESA-Euclid Era Mission
22	Moscardini2	Moscardini	A multi-wavelength view of galaxy clusters from Euclid and XMM-Newton
23	Moscardini3	Moscardini	Detecting Clusters and Voids using Weak Gravitational Lensing
24	Mucciarelli1	Mucciarelli	Chemical characterization of the Local Group: identifying the chemical DNA of Milky Way satellite galaxies
25	Mucciarelli2	Mucciarelli	Evolution of CNOPS elements in the Milky Way
26	Mucciarelli3	Mucciarelli	Implementing new physics in the modeling of the stellar atmospheres
27	Nipoti1	Nipoti	Gravitational waves from black-hole binaries in evolving galaxies
28	Nipoti2	Nipoti	Global stability of stellar discs with dark matter halos
29	Nipoti3	Nipoti	Simulations of the collisional evolution of globular clusters with Monte Carlo methods
30	Pallanca1	Pallanca	Exploring binary millisecond pulsars in globular clusters through optical/ near-infrared observations
31	Roccatagliata1	Roccatagliata	Formation and evolution of solar system analogs: gravitational interaction with planets and/or external perturbers
32	Roccatagliata2	Roccatagliata	Formation of planets in protoplanetary disks
33	Roccatagliata3	Roccatagliata	Planet formation in low-metallicity environments
34	Talia1	Talia	Exploiting the Euclid Legacy for galaxy evolution with ELSA
35	Testi1	Testi	Protoplanetary disks and planet formation in space and time
36	Testi2	Testi	High dispersion spectroscopy of exoplanet atmospheres
37	Vazza1	Vazza	Faraday Rotation to probe the topology of the magnetic cosmic web
38	Vignali1	Vignali	Dual and binary super-massive black holes candidates in the gravitational-wave era
39	Vignali2	Vignali	Shedding light on the physics of the most massive and highly accreting SMBHs up to Cosmic Noon through a multi-wavelength study
40	Vignali3	Vignali	The realm of the high-redshift Universe unveiled by JWST
41	Vignali4	Vignali	AGN physics and demography in the XMM-Newton-Euclid Fornax Deep Field

PhD project in ASTROPHYSICS

Title of the Project: *Testing fundamental physics and cosmology beyond the standard model with numerical simulations of the cosmic large-scale structures*
Supervisor: Prof. Marco Baldi

Scientific Case: The standard cosmological model (known as ΛCDM) has provided us with a surprisingly simple framework to describe and accommodate the vast majority of observational data. Nonetheless, recent **observational tensions** have led to **speculations about possible alternative and more fundamental explanations of cosmic acceleration.** Additionally, the lack of direct detections of Dark Matter calls for **a thorough scrutiny of many possible competing Dark Matter particle candidates**. In such a context, and with the advent of the epoch of so-called "Precision Cosmology", **a detailed investigation of alternative cosmological models and of their impact on the formation and evolution of cosmic structures is essential** for a direct comparison between theory and observations. In this respect, **cosmological simulations play a crucial role**, opening a window on observable properties which cannot be predicted using analytical or simple linear numerical codes, including the statistical and structural properties of cosmic structures at highly nonlinear scales, and **their expected signal in a variety of observational channels** ranging from optical/near-infrared observations (Euclid/VRO), to radio observations (SKA), to gravitational wave surveys (Einstein Telescope).

Outline of the Project: The PhD student will work on **developing, optimising, and exploiting highly efficient and sophisticated numerical codes** to extend their capability of simulating a variety of extensions of the standard cosmological scenario, such as **Dark Energy models, Modified Gravity theories and non-standard Dark Matter candidates, and to extend these (Newtonian) algorithms to General Relativity**. More specifically, the PhD student will work on **the recently-developed PANDA code**, an extension to the state-of-the-art *Gadget4* code for cosmological N-body simulations.

The student will therefore work in the **highly stimulating and rapidly growing field of High-Performance Computing for Cosmology**, developing the research plan described above for one (or more) of the following models:

- **Fundamental modifications of Gravity**: implementing and testing Horndeski Gravity models, K-mouflage models, Growing Neutrino Quintessence, General Relativistic Entropic Forces;
- **Effective modifications of gravity**: implementing and testing parameterised models of non-linear screening, Interacting Dark Energy, Clustering Dark Energy;
- **Non-standard Dark Matter**: extending the capabilities of existing N-body simulations codes including alternative Dark Matter candidates such as Ultra Light Axions or mixed Cold+Warm DM;
- **General Relativistic Simulations**: extending current Newtonian N-body simulations codes to include a fully relativistic treatment of gravity at large scales.

Although some of such models have already been implemented in simulation codes in the past, the continuous technological and methodological advancements in the field of scientific High-Performance Computing demand a new design of most of these algorithms.
The choice of the specific models to consider will be discussed with the student and will be based on both the evolving priorities of the community and the student's interests and attitudes.
More specifically, the student will:

- **Develop highly scalable and memory efficient modules** for one (or more) of the models listed above into the *Gadget4* (MPI/OpenMP, C++) simulations code, following the approach designed in the PANDA module;
- **Run large-scale and high-resolution simulations** for the selected model(s) and test the code performance for large production runs
- **Analyse the results of such simulations**, with a particular focus on the main observables that will be tested by upcoming large-scale surveys such as **Euclid, SKA, VRO-LSST, Einstein Telescope,** namely: **galaxy clustering**; **clusters and voids** properties; **weak lensing** statistics and cross correlation with clustering statistics; **CMB lensing** and Integrated Sachs-Wolfe effect; **Gravitational Waves** source distribution.

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PhD project in ASTROPHYSICS

Title of the Project: *Modelling the synergy between Gravitational Waves and Large-Scale galaxy surveys on constraining cosmology and fundamental physics*

Supervisors: the project will be co-supervised by M. Baldi, F. Marinacci, M. Moresco

Scientific case: The combination of gravitational wave (GW) observations with large-scale structure (LSS) galaxy surveys represents a transformative opportunity for cosmology. Compact binary mergers (such as neutron star and black hole systems) act as “standard sirens”, providing independent distance measurements that can be combined with redshift information from galaxy surveys to probe the expansion history of the Universe. This synergy enables novel and robust constraints on key cosmological parameters, including the Hubble constant, dark energy properties, and potential deviations from General Relativity.

However, fully exploiting this potential requires realistic theoretical predictions that consistently connect GW sources to their large-scale environments. In particular, the astrophysical origin and spatial distribution of compact-object mergers, their relation to galaxy properties, and the impact of observational selection effects must be modeled with high accuracy. State-of-the-art hydrodynamical simulations now offer an unprecedented opportunity to address these challenges, but dedicated efforts are needed to bridge the gap between galaxy formation physics and GW observables.

Outline of the project: This project aims to develop a comprehensive simulation framework to model the joint information from GW events and galaxy surveys and will develop through the following steps:

- First, the PhD student will develop optimized large-scale simulations of structure formation that incorporate the formation and evolution of compact binary systems. This will leverage the recently developed AREPO-GW framework (Marinacci et al. 2025), enabling the generation of GW event catalogs directly from hydrodynamical simulations of galaxy formation (see Fig. 1 below). In parallel, faster semi-analytic techniques will be implemented to populate dark matter halo catalogs from gravity-only simulations. To efficiently target the large volumes required by upcoming surveys, the project will also exploit the latest developments in Dynamic Zoom Simulation techniques (Zangarelli et al. 2026).

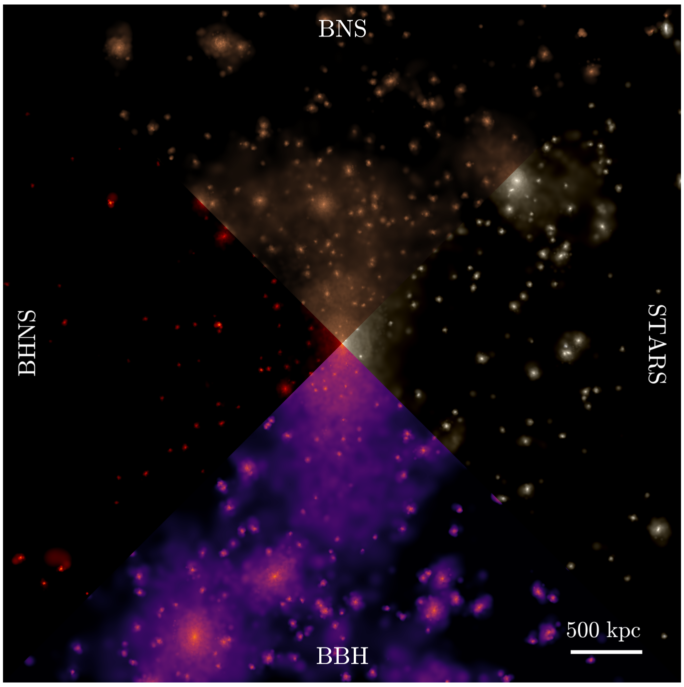

Fig. 1 — The distribution of stellar mass (right quadrant) and of GW events from binary black holes (bottom), black hole-neutron star (left), and binary neutron stars (top) merger events around the most massive halo of the Millennium-TNG simulation (Pakmor et al. 2023), obtained through post-processing with the Arepo-GW code (Marinacci et al. 2025)

- In a second phase, the simulation outputs will be post-processed to generate realistic mock observables tailored to current and next-generation GW detectors (e.g., LIGO-Virgo-KAGRA Observing Run 5, Einstein Telescope) and wide-field galaxy surveys (e.g, DESI, Euclid, WST). This will include modelling instrumental sensitivities, survey geometries, selection effects, and observational systematics, ensuring a direct and robust comparison with real data.

- Finally, the project will exploit the developed simulations with the Bayesian framework developed at DIFA (https://github.com/CosmoStatGW/CHIMERA) to derive quantitative forecasts for the combined constraining power of GW and LSS observations. Different scenarios will be explored, considering a variety of observational setups and different cosmological and fundamental physics models; in this way, the student will assess how this multi-messenger approach can improve constraints on the expansion history, test gravity on cosmological scales, and probe the nature of dark energy.

The PhD candidate will be embedded in major international collaborations in gravitational wave astronomy and spectroscopic surveys, including LVK, Einstein Telescope, Euclid, and the Wide-field Spectroscopic Telescope (WST), with unique opportunities for professional development, first-hand access to the latest datasets, and the possibility to network with leading researchers across the field.

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PhD project in ASTROPHYSICS

Title of the Project: Study of Gamma-ray Burst central engines through theoretical modelling of their broadband light curves

Supervisor : Simone Dall'Osso

Co-Supervisor: Giulia Stratta - INAF/OAS

Scientific Case: Gamma-Ray Bursts (GRBs) are (the most) powerful cosmic explosions capable of launching relativistic jets[1], associated with the formation of stellar-mass compact objects either in the collapse of massive stars, or in the merger of binary neutron stars (BNSs).
GRBs are key laboratories for multi-messenger astrophysics, providing unique probes of the physics of relativistic jets, crucial insights into the equation of state (EoS) of matter at extreme densities, as well as on the cosmic nucleosynthesis of the heaviest elements[2] (beyond the Fe-group). Despite great progress in our understanding of GRBs, in particular after the (first) multi-messenger detection of the GRB 170817A associated with the BNS merger GW170817, key open questions remain about (a) the nature of central engines powering GRBs, i.e. whether they are black holes or fast-spinning NSs, a problem strictly related to the EoS of ultra-dense matter, and (b) the origin of different components of the GRB electromagnetic (EM) emission, directly linked with the physics of relativistic shocks.

Outline of the Project: This project is aimed at calculating broadband GRB lightcurves by extending and generalizing existing models for relativistic shocks in several ways, in order to develop a flexible and general tool for the analysis of multi-wavelength GRB data. The main foreseen improvements concern two points: (i) within a structured-jet scenario[3,4,5,6], calculating jointly the forward and reverse shock emissions expected when the relativistic outflow hits the circumstellar material, and (ii) accounting for a prolonged energy injection from the central engine[7,8] into either shocks, through a physically-motivated model of the shock interaction. In both cases, a careful study of the emission spectrum and of its evolution over time will play a pivotal role. While this represents the minimal set of improvements needed to achieve our goal, the rich and diverse phenomenology of GRB emission lends itself to a much wider spectrum of applications that can be investigated during the PhD (or even beyond its time frame). Through this project we will be able to characterize the observed GRB emission in unprecedented detail, pinpointing the physical origin of different emission components and obtaining new, stringent constraints on the nature of central engines. Moreover, these results will inform follow-up strategies of gravitational wave events, enabling news tests of the EoS of matter at supra-nuclear densities, and the first systematic characterization of the cosmic population of GRB engines.

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PhD project in ASTROPHYSICS

Title of the Project: ***What alternative dark matter models do to galaxies: studying galaxy formation in the AIDA-TNG simulations***

Supervisor : Dr. Giulia Despali
Co-Supervisors : Prof. Lauro Moscardini

Contacts: giulia.despali@unibo.it

Scientific Case: One of physics and astronomy's most pressing questions today is: *"**What is dark matter?**"*. Astrophysical studies have shown that the standard cold dark matter model (CDM) successfully reproduces observed structures in the Universe on large scales and the CDM. Still, tensions with observations persist at the scales of galaxies and below. A solution comes from alternative dark matter models (Warm or Self-interacting) that are able to influence the dark matter distribution at the centre of galaxies and satellites. The next generation of telescopes will bring exceptional progress in the observational domain, providing a much larger sample of galaxies (Euclid, Rubin) and resolving scales down to milli-arcseconds (ALMA, VLBI, ELT): **it is thus the moment to take theoretical predictions to the next level,** by modelling the effects of baryons and alternative dark matter at the same time.
The **AIDA simulations** are a new set of cosmological hydrodynamical simulations based on different dark matter models, including a realistic recipe for galaxy formation: they are the best simulations available to study the nature of dark matter from cosmological scales to

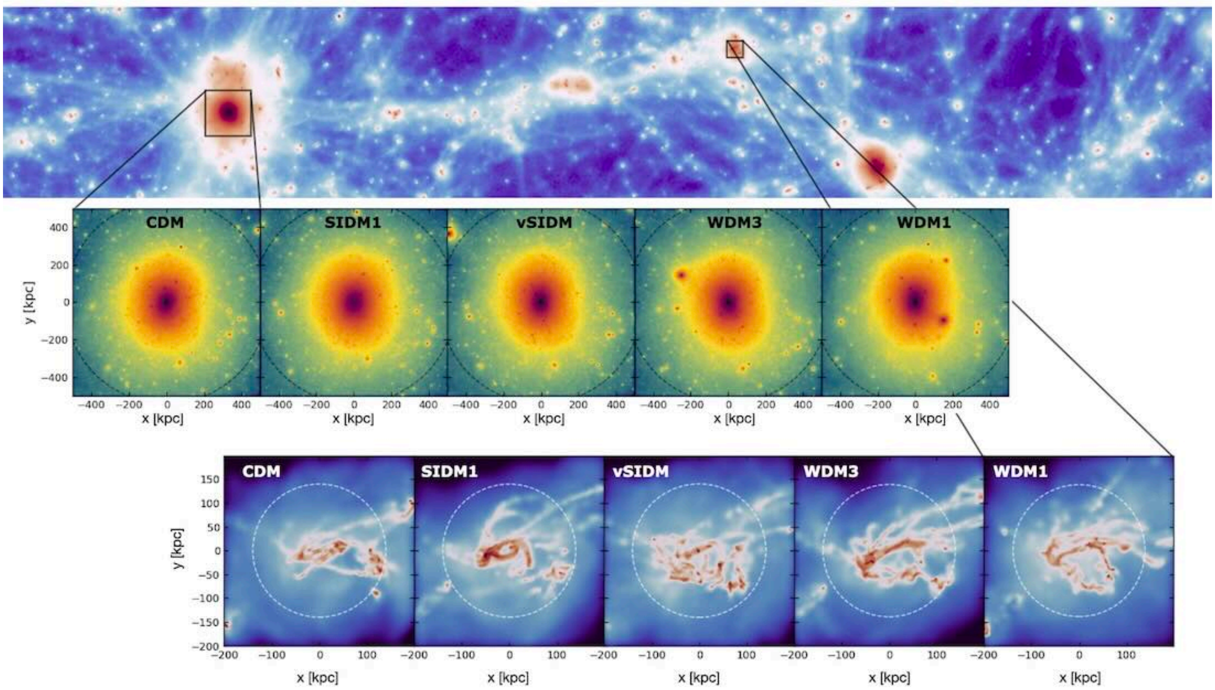

Figure 1. Outline of the new AIDA-TNG runs *(Despali et. al 2025)* that will be used during this project.

dwarf galaxies. Thanks to the high resolution and complexity of the simulations, we will be able to systematically compare the properties of structures, from clusters to dwarf galaxies, and create mock observations in order to find estimators that can lead to new constraints and a better understanding of the physics of structure formation.

Outline of the Project:

Warm dark matter influences the number of low-mass galaxies and satellites, while self-interacting models modify the structural properties of dark matter haloes. This PhD project involves both ***creating new simulations*** with such models and ***analysing the existing AIDA-TNG runs***, thus learning the fundamentals of computational astrophysics. Breaking the conventional separation between theoretical and observational works, we will simultaneously learn about dark matter and galaxy formation models. In particular:

- The first phase of the project will consist of an analysis of the cosmological runs, identifying new statistical differences between CDM, WDM and SIDM. For example, scaling relations of galaxies, the number count of haloes and subhaloes, the matter power spectrum, and the evolution of the gas and stellar content of galaxies.
- In a second phase, the PhD student will then run additional boxes or identify systems to re-simulate at higher resolution, to create zoomed versions of a few interesteing galaxies. This will allow us to resolve the galaxy and dark matter structure with increased precision and create realistic mock observations to be compared with real observational data from Euclid and other telescopes (see Fig. 1 for examples of simulated observations).
- The results will be interpreted in the context of the current best data, such as the wide-field survey that will be carried out by the Euclid telescope. In this way, we will derive new constraints on the nature of dark matter.

The AIDA simulations have been developed in an international collaboration that includes DIFA and INAF scientists in Bologna, together wit the IllustrisTNG group: Volker Springel, Annalisa Pillepich, Dylan Nelson and Mark Vogelsberger. This will allow the PhD student to interact with some of the most prominent researchers in the field of numerical simulations. In addition, the student could be involved in the ESA Euclid consortium and the SHARP lensing collaboration, focused on constraining dark matter with lensing. The collaborations mentioned above will also provide the chance to spend a period of 3-6 months abroad.

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Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: **A SHARP view of dark matter in the Euclid era**

Supervisor : Dr. Giulia Despali
Co-Supervisors : Dr. Cristiana Spingola (IRA), Prof. Lauro Moscardini, Dr. Massimo Meneghetti (INAF-OAS)

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Scientific Case: In strong gravitational lensing, the image of a high-redshift source (e.g. a galaxy or a quasar) is distorted and magnified by the presence of an intervening object along the line-of-sight that acts as a lens (see Figure 1). Lensing is thus one of the most promising tools in dark matter studies: the distortion is due to gravity only, allowing one to directly measure the total (luminous and dark) mass distribution of the lens. Besides the main lens, strong lensing can detect low-mass satellites of the main galaxy. These are crucial tests of alternative dark matter: *(i)* their number is the fundamental test of cold and warm dark matter models; *(ii)* self-interacting dark matter can make low-mass structures very dense and thus more easily detectable with lensing.
In galaxy-galaxy lensing, dark subhaloes are detected as localised perturbations to the surface brightness distribution of magnified arcs. This method is, to this day, the only way to detect them beyond the Local Group and has led to detections in ***HST, Keck and ALMA data***. It is easy to understand that the spatial resolution of the lensing images is crucial to detect small structures. This way, we can reach smaller scales and detect perturbers down to $M \sim 10^7 M_\odot$. At the same time, we need a larger sample of gravitational lenses as will be soon provided by the ***Euclid telescope***, launched in July 2023. Following predecessors such as SDSS and DES, the survey data promises to greatly enhance our knowledge of the dark sector of the universe.

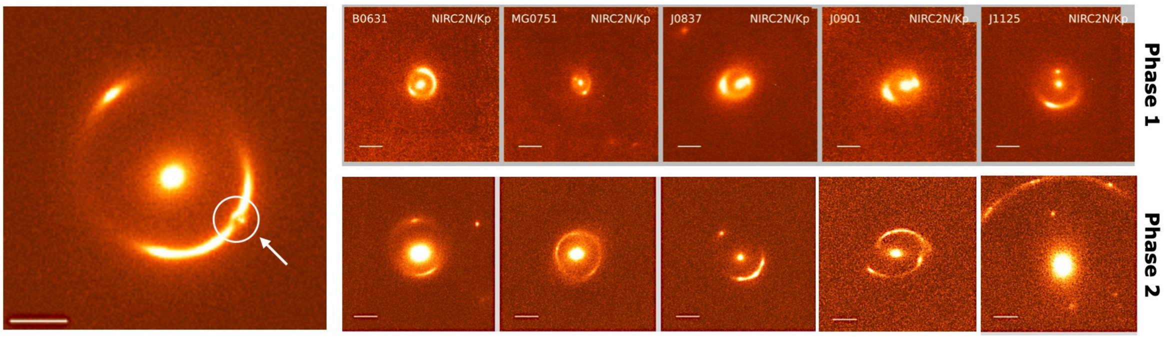
Outline of the Project: The SHARP collaboration and observing program has targeted 40 new systems that have or will be observed soon with the Keck telescope: this is the only new optical sample that targets lensed arcs beyond HST resolution. The current SHARP sample consists of data from two observing runs with the adaptive optics system on Keck, including NIRC2 (H and K' bands) and Osiris. Thus, this program will bring gravitational imaging to the same level of constraints of MW-satellites and flux ratio anomalies and will make combined constraints stronger.

The PhD will combine on the analysis of lensing data from the SHARP sample and follow-up data, with new observations coming from the Euclid mission. In practice:

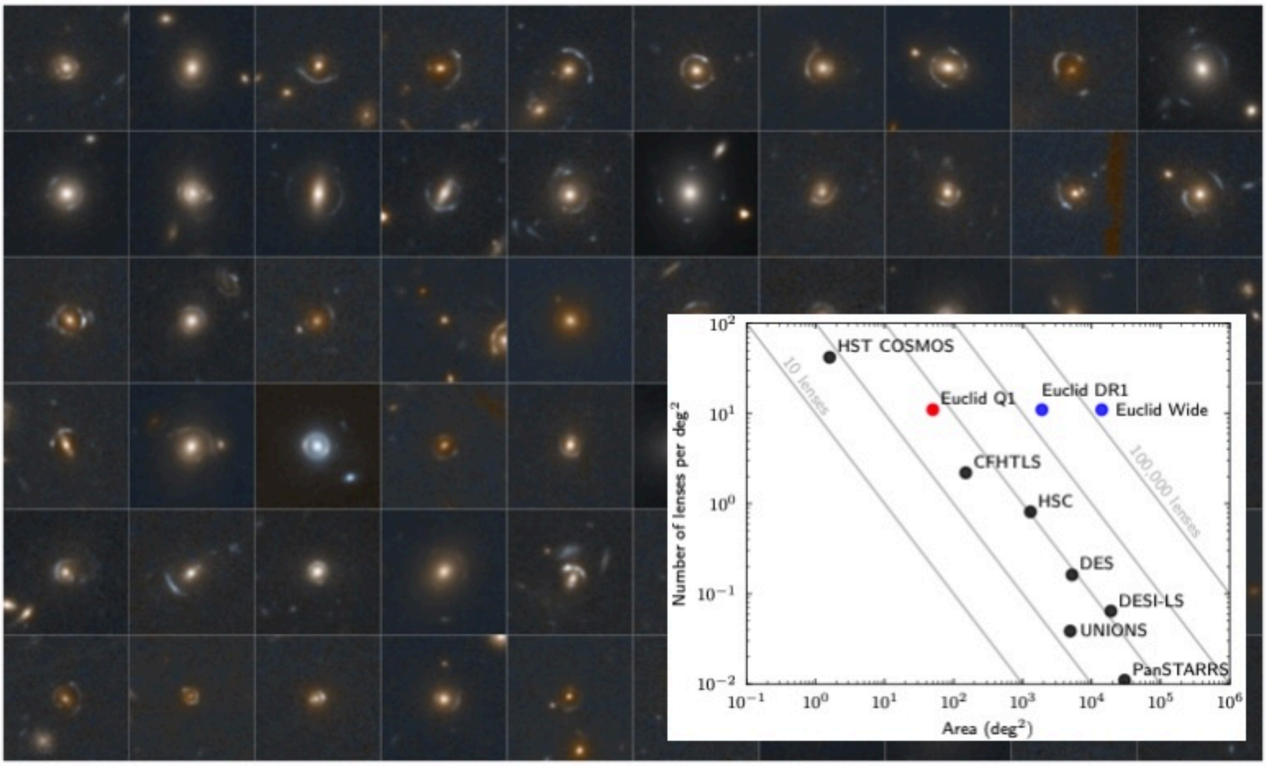
- The PhD student will model the new SHARP lenses, reconstructing the mass and light distribution of the lenses, arcs and sources using existing parallel codes. She/he will then search for smaller satellites, which manifest themselves as surface brightness perturbations.

- We will use Euclid galaxies from DR1 and the following releases to constrain dark matter based on their statistical and individual properties, such as total and stellar masses, half-light radii and sizes, lensing Einstein rings and density slopes, satellite count or matter clustering. All these can be modified by warm and self-interacting models, which alter the distribution of matter inside haloes, the depth of the potential well where the galaxies form, and the timescale of structure formation or merging events. During the first analysis of the Euclid data, we have already found hundreds of new systems which hold great promise for dark matter studies. The PhD student will identify promising systems to analyse and propose follow-up observations.

new SHARP lenses



Euclid new lenses



The SHARP collaboration and Euclid consortium framework will allow the PhD student to interact with the gravitational lensing community. In particular, the SHARP data analysis will be carried out in collaboration with the PI of the SHARP program Prof. Christopher Fassnacht (California UC Davis), and international researchers in Germany and the Netherlands. These collaborations will also provide the chance to spend a period of 3-6 months abroad, visiting partner institutes in Germany or the USA.

PhD project in ASTROPHYSICS

Title of the Project: JWST insight on protostellar accretion

Supervisor : Eleonora Fiorellino - Università di Bologna
Co-Supervisors : Leonardo Testi - Università di Bologna

Scientific Case: The protostellar phase represents the main mass-assembly stage of low-mass stars and sets the initial conditions for planet formation. During this deeply embedded stage, material from the circumstellar disk is accreted onto the forming star while jets and winds remove angular momentum, regulating both stellar growth and disk evolution. The efficiency, geometry, and temporal behaviour of protostellar accretion remain among the least constrained aspects of star formation theory.
Although accretion processes in more evolved T Tauri stars have been extensively characterised through optical and near-infrared diagnostics (Hartmann et al. 2016, Manara et al. 2023), the embedded Class 0/I phases remain poorly understood due to high extinction, envelope contamination, and the difficulty of disentangling stellar, disk, and accretion contributions (Fiorellino et al. 2021b, 2023, Le Gouellec et al. 2024, Testi et al. 2025). This uncertainty directly affects estimates of stellar mass assembly timescales and the physical conditions under which planet-forming disks emerge.

The advent of the James Webb Space Telescope (JWST) has opened a transformative window on protostellar systems. Its unprecedented sensitivity in the near- and mid-infrared allows direct access to deeply embedded protostars across multiple star-forming regions. JWST spectroscopy provides simultaneous diagnostics of accretion and ejection processes. Hydrogen recombination lines (Brα, Brβ, Pfund series) trace hot (T ~10^4 K), dense gas in magnetospheric accretion columns and shocks, while molecular and atomic tracers such as H_2 rovibrational lines, CO fundamental emission at 4.7 μm, and forbidden lines (e.g. [Fe II]) probe jets, disk winds, and inner disk structure. Together, these diagnostics enable a self-consistent investigation of the accretion–ejection interplay during the earliest evolutionary stages.

By quantitatively constraining protostellar accretion rates, and their connection to disk properties, this project aims to bridge the gap between star formation and planet formation, providing fundamental constraints on the physical conditions of young disks at the epoch when planet formation begins.

Outline of the Project: The PhD candidate will analyse a large homogeneous sample (~100) of JWST NIRSpec/MIRI spectra of embedded protostars obtained in multiple star-forming regions. Data are already reduced.

Phase 1 – Accretion diagnostics and stellar parameters
The candidate will derive accretion luminosities and mass accretion rates using established calibrations based on hydrogen recombination lines (Brackett and Pfund series), while also testing updated methodologies tailored to embedded sources. A crucial step in this analysis is to remove the water contamination from the hydrogen emission lines tracing accretion. Stellar

parameters (mass, luminosity, radius) will be determined through self-consistent approaches accounting for extinction, veiling, and disk/envelope contributions. The robustness of classical empirical relations in the protostellar regime will be critically assessed (see Sect. 4 of Fiorellino et al. 2025).

Phase 2 – Accretion–ejection interplay
The project will investigate correlations between accretion tracers and jet/wind diagnostics, including H_2 and CO fundamental emission, looking for quantitatively calibrate accretion/outflow relations in deeply embedded protostars. The geometry and kinematic signatures of disk winds and inner disk gas will be analysed and discussed in the framework of regulating angular momentum transport.

Phase 3 – Evolution and environmental dependence
Results will be compared with brighter protostars observed from ground-based facilities and with samples of more evolved pre-main-sequence stars. This will allow assessment of the evolutionary decline of accretion from protostars to T Tauri stars, the possible role of episodic accretion, and the dependence of accretion efficiency on environmental conditions.

Phase 4 – Disk–accretion coupling
The relationship between mass accretion rate and disk mass will be explored by combining JWST results with (sub-)millimetre disk surveys, i.e. ALMA. This analysis will provide new constraints on early disk evolution and on the initial conditions for planet formation.

This will represent the largest and more complete protostellar accretion survey up to date.

Expected Outcomes

The project will deliver:

- The largest homogeneous spectroscopic study of protostellar accretion with JWST.
- Quantitative constraints on mass accretion rates in deeply embedded sources.
- A critical assessment of empirical accretion diagnostics in the protostellar regime.
- New insights into the coupling between accretion, ejection, and disk evolution.
- Direct implications for the timescales and physical conditions preceding planet formation.

The candidate will gain expertise in infrared spectroscopy, accretion physics, disk evolution, and statistical analysis of large observational datasets, contributing to a rapidly evolving research field enabled by JWST.

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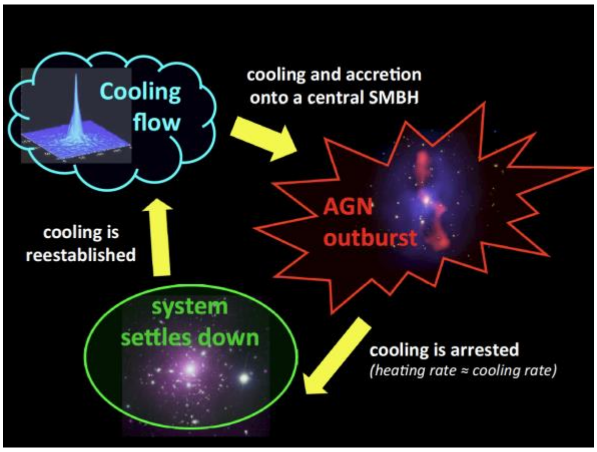
PhD project in ASTROPHYSICS

Title of the Project: *Regulation of the AGN feeding-feedback cycle in cool-core clusters*

Supervisor : Myriam Gitti (DIFA), Fabrizio Brighenti (DIFA)
Co-Supervisor : Francesco Ubertosi (DIFA)

Scientific Case:

In the absence of a heating source, the intra-cluster medium (ICM) at the center of the so-called 'cool-core' galaxy clusters should cool, condense, and accrete onto the brightest cluster galaxy (BCG) and form stars. The end products of cooling, as inferred e.g., from Hα nebulosity, are observed in many BCGs in the forms of cold molecular clouds and star formation, but in quantities at least an order of magnitude below those expected from uninterrupted cooling over the age of clusters (e.g., Peterson & Fabian 2006, Phys. Rep., 427, 1). The implication is that the central gas must experience some kind of heating to balance cooling. The most promising heating candidate has been identified as feedback from energy injection by the central active galactic nucleus (AGN), manifesting in highly disturbed X-ray morphologies (cavities, filaments, shocks and ripples) which often correlates with the morphology of radio jets and lobes (e.g., McNamara & Nulsen 2007, ARA&A, 45, 117; Gitti et al. 2012, AdAst). *This so-called 'radio-mode' feedback has a wide range of impacts, from the formation of galaxies to the regulation of cool cores, and can in principle explain why cooling and star formation proceed at a reduced rate. However, the details of how the feeding-feedback loop operates are still unclear.*



Outline of the Project:

To clarify the regulation of the feeding-feedback cycle in cluster cores, it is crucial to perform accurate studies of the cooling and heating processes for a sensible sample of galaxy clusters with a prominent cold ICM phase. We have identified a sample consisting of the X-ray brightest, most Hα luminous clusters visible from the Jansky Very Large Array (JVLA). Visibility from JVLA ensures that high resolution radio observations can be used to examine the interaction between radio-loud AGN, ICM and cooling gas. The sample includes some very well-studied systems, as well as clusters never observed in X-rays and/or with only snapshot radio data. In the past years we obtained snapshot *Chandra* and new JVLA data for three clusters which lacked archival X-ray and radio data. Our first results (see Figure) suggest that, in some systems with disturbed morphology showing spatial offsets between the BCG and different gas phases, the cooling process is not currently depositing gas onto the BCG core (*Pasini et al. 2019, ApJ, 885, 111*; *Pasini et al. 2021, ApJ, 911, 66*; *Rosignoli et al. 2024, ApJ, 963, 8*).

The aim of the PhD project is to investigate the feeding-feedback cycle in these strongly cooling clusters and, in systems where the BCG nucleus is spatially offset from its fuel sources, to determine whether the cycle is disrupted or whether the AGN activity is somehow sustained.

We have undertaken an observational campaign to acquire *Chandra* deep exposures and multi-wavelength follow-up observations: in particular, we recently obtained new *Chandra* data (>700 ks) and new Atacama Large Millimetre Array (ALMA) observations of CO lines (> 15 h) of several targets, as well as new MUSE observations of the Hα nebulae in one system. The PhD candidate will perform accurate analyses of the *Chandra*, JVLA, ALMA, and MUSE data already in hand, that will be complemented by the Hα and CO observations from literature and ALMA archive, to determine the properties of the ICM and the warm gas and the morphology and spectral indices of the central radio sources.

To obtain a good-quality multi-wavelength coverage for the whole sample, the PhD candidate will propose for deeper *Chandra* and JVLA data of those clusters that only have snapshot observations, to be able to perform a thorough investigation of the range of cooling morphologies and interplay with the radio AGN in these clusters. The student will also propose for complementary follow-up ALMA CO and MUSE observations to obtain detailed information on the distribution and kinematics of the molecular gas (as done in e.g., *Russell et al. 2019, MNRAS, 490, 3025*) and optical nebulae (e.g., *Olivares et al. 2019, A&A, 631, A22*). Depending on the student interest, numerical simulations can further be developed to compare the observed data with detailed computational modeling tailored to the specific targets. Comparing these with the X-ray and radio data will allow us, as the final goal of the project, to test key correlations between the different gas phases (plasma - warm - molecular), thus leveraging a multi-frequency approach to investigate the link between the hot ICM, optical filaments and molecular gas within cool cores, and to analyze in detail star formation in the BCG. The PhD candidate would be actively involved in ongoing collaborations with leading international research groups in the field (e.g., SAO-CfA, NASA-Ames), and research visits to these institutions would be encouraged.

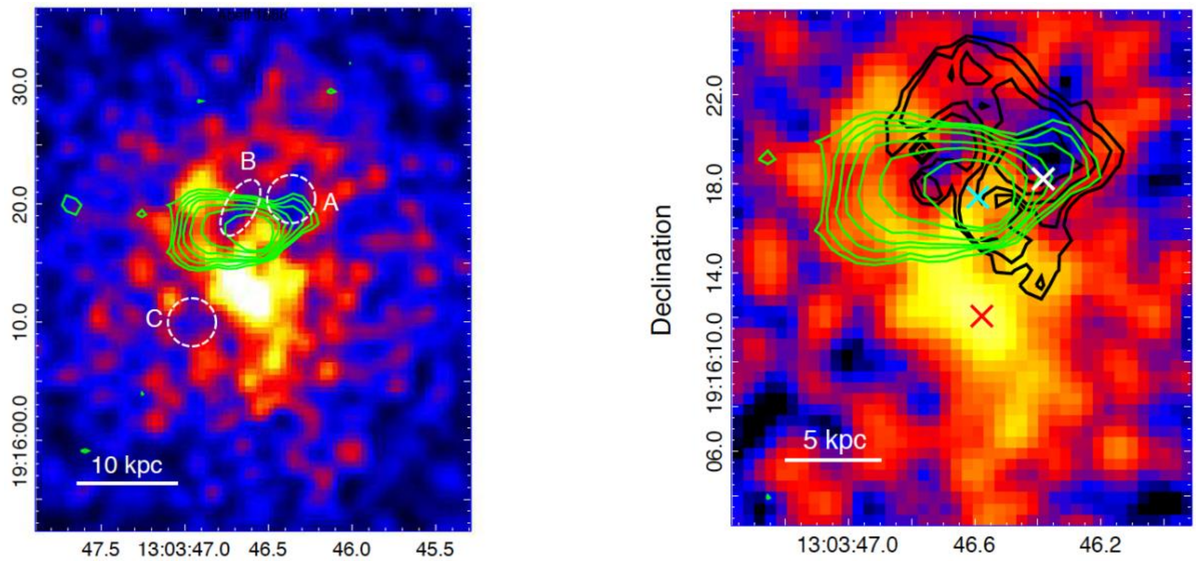


Figure - Snapshot *Chandra* image (~10 ks, color map) and 1.4 GHz JVLA observations (green contours) of the cool-core cluster A1668 (from *Pasini et al. 2021, ApJ, 911*). This cluster has a disturbed morphology (left panel), showing hints of cavities (A, B and C) and spatial offsets (right panel) between the X-ray peak (red cross), the radio BCG (cyan cross) and the Hα line emission (white cross; the black contours show the Hα line emission). The offsets suggest that the current locus of greatest cooling in the hot ICM is separated from the central galaxy nucleus and raise the question of whether they can affect the feedback cycle. The PhD candidate will analyze the new deep *Chandra* exposure (~180 ks).

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Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: *Thermal and non-thermal interplay in cool-core galaxy clusters*

Supervisor: Myriam Gitti (DIFA)
Co-Supervisors: Francesco Ubertosi (DIFA), Fabrizio Brighenti (DIFA)

Scientific Case:

Relativistic particles and magnetic fields permeating the intracluster medium (ICM) of galaxy clusters are best traced by diffuse radio sources extending for hundreds of kpc (*Feretti et al 2012, A&AR*; *Van Weeren 2019, SSRv*). In cool-core galaxy clusters (characterized by a central temperature drop and no signs of recent mergers, e.g., *Hudson et al. 2010 A&A*) it is possible to find "radio phoenices" and "radio mini-halos".

Radio phoenices are extended sources possibly linked to old episodes of activity of cluster-central radio galaxies. The electrons powering the radio emission are thought to have been re-energized by compression due to turbulence in the ICM. The fossil plasma has an ultra-steep spectrum ($\alpha \approx 2$, with flux density $S(\nu) \propto \nu^{-\alpha}$), suggestive of synchrotron aging, and usually has a complex morphology (*de Gasperin et al. 2015, MNRAS*; *Mandal et al. 2020, A&A*). Despite their importance to understand the interplay between thermal and non-thermal phenomena in galaxy clusters, very few sources of these kind are known.

Mini-halos show steep spectra ($1 \leq \alpha \leq 1.5$) and amorphous shapes, and typically extend to 100 - 200 kpc from the center (e.g., *Feretti et al 2012, A&AR*). Their origin is still unclear; among several models, it has been proposed that ICM oscillations ("sloshing") in the cluster potential might power the non-thermal radio emission (e.g., *Zuhone et al. 2016, JPlPh*), since mini-halos typically appear confined within the sloshing cold fronts (e.g., *Giacintucci et al. 2019, ApJ*). Alternatively, turbulence generated by active galactic nucleus (AGN) feedback due to the jets inflating radio bubbles may also re-accelerate the relativistic particles powering mini-halos (e.g., *Bravi et al. 2016, MNRAS*).

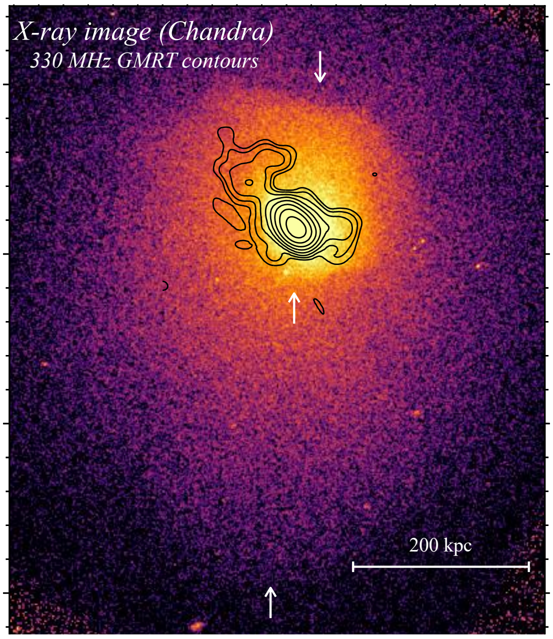

Figure 1: X-ray Chandra image of the cool core cluster Abell 496, with 330 MHz GMRT contours overlaid in white showing the central radio galaxy. Despite the vigorous, ongoing sloshing of the ICM, which produced three cold fronts (white arrows), the existing radio observations fail to reveal a mini-halo (adapted from Ubertosi et al., 2024, A&A). The PhD candidate will search for mini-halos in similar low-mass systems using new radio (JVLA, MeerKAT) observations.

A third possibility is a combination of the two: the main driver for the creation of mini-halos could be AGN activity injecting turbulence and relativistic particles in the ICM, while sloshing motions would drive the overall shape of the mini-halos (*Richard-Laferrière et al. 2020, MNRAS*). The only way to discriminate between the different scenarios is a multifrequency study of these sources: sensitive and resolved radio observations can constrain the properties of mini-halos, while X-ray analysis of the ICM can probe the process injecting turbulence in the clusters' hot medium.

Outline of the Project:

To understand the thermal and non-thermal interplay in cool core clusters it is crucial to combine X-ray data, that probe the thermal properties of the cluster environment, with multi-frequency radio data of radio phoenices and mini-halos, that probe the properties of the non-thermal components of the ICM (relativistic particles and magnetic fields).
The aim of the PhD project comprises two parallel investigations:

1. **Clarify the formation channels of mini-halos**: our group has been a leader research team in the field for two decades, providing both theoretical models and pioneering observational studies (*Gitti et al. 2002*, *2004, A&A*) up to more recent investigations (*Gitti et al. 2018, A&A*). Recently, we investigated Abell 496, a low-mass galaxy cluster that hosts one of the most spectacular sloshing cool cores seen in the X-ray, and yet it showed no mini-halo in past observations (*Ubertosi et al. 2024, A&A*; see Fig. 1). The central cluster galaxy experienced repeated episodes of past AGN activity in the form of two steep-spectrum radio lobes - an abundant source of seeds for reacceleration. The PhD candidate will use recently acquired sensitive JVLA (1 – 2 GHz) and MeerKAT (0.8 – 1.7 GHz) radio observations of Abell 496 and several other low-mass galaxy clusters, in combination with archival X-ray and radio data, to: (a) search for possible faint minihalos in low mass galaxy clusters; (b) verify the sloshing/minihalo connection for clusters of lower masses; (c) understand the possible role of the central radio galaxy in the origin of diffuse radio emission in cool core clusters.
2. **Trace the thermal and non-thermal interplay using radio phoenices**: revived synchrotron sources are excellent probes of reacceleration mechanisms. Our group has worked on different examples of these sources by combining X-ray and radio observations (mainly *Chandra*, *XMM-Newton, JVLA*, GMRT and LOFAR, e.g., *Ubertosi et al. 2021, MNRAS*; *Ignesti et al., 2020b, A&A*; *Rotella et al. 2025, A&A*). A recent case is the galaxy cluster Abell 795, that hosts a 200 kpc diffuse radio source with an ultra-steep spectrum ($\alpha = 2.2$). The PhD candidate will have the opportunity to analyze new deep *Chandra* observations (270 ks) of the ICM in Abell 795 as well as new multi-frequency JVLA data (1 – 2 GHz and 4 – 6 GHz), finally allowing us to understand the connection between the thermal gas of the cluster and the non-thermal plasma constituting the candidate radio phoenix (*Rotella et al. 2025, A&A*). The PhD candidate will analyze the existing observations to measure the morphological and spectral properties of the diffuse radio emission, as well as to determine the dynamical state of the host cluster from the new deep X-ray data.

Overall, ***the PhD project is aimed at understanding the thermal and non-thermal interplay in cool core galaxy clusters, which bears the information on the thermodynamic structure of the ICM, magnetic fields, turbulent reacceleration efficiency, and relativistic particles***. The PhD candidate will measure spectral indices of the diffuse sources, determine radio and X-ray morphologies, and derive ICM temperature, density, and pressure gradients. The activities will be conducted in collaboration with international researchers. The PhD candidate will also propose for X-ray (*Chandra*) and radio (JVLA, uGMRT, MeerKAT, LOFAR) observations of candidate radio phoenices and mini-halos, to push forward the knowledge of these objects and pave the way for future radio telescopes that are expected to detect hundreds of these radio sources (as SKA; e.g., *Gitti et al. 2018, A&A*). They will also propose for complementary follow-up XRISM observations to directly measure the turbulence of the ICM and link this crucial information with the theoretical models of turbulent reacceleration. Depending on the student interests, numerical simulations can be developed to compare the observed data with detailed computational modelling.

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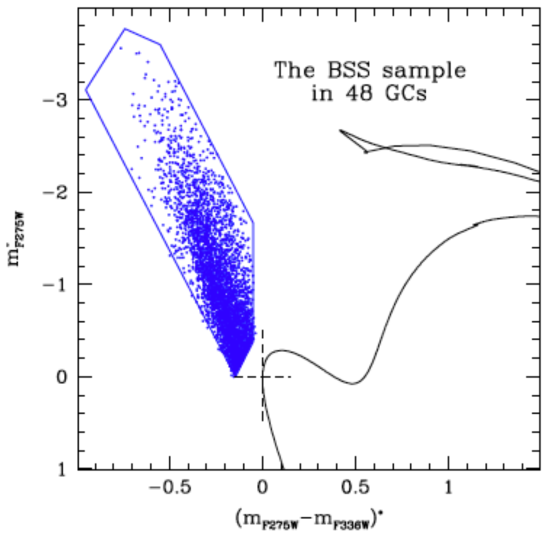
PhD project in ASTROPHYSICS

Title of the Project: *Playing with the physics of Blue Stragglers*

Supervisor: B. Lanzoni **Co-supervisor:** F.R. Ferraro

Scientific Case: Globular clusters (GCs) are among the most beautiful objects in the sky, but their importance goes far beyond their magnificent appearance. They are the best example of simple stellar populations and natural laboratories where to properly test the predictions of the stellar evolution theory. In addition, the large number of stars and the extremely high stellar densities in their center make GCs ideal laboratories to study multi-body dynamics and its effects on stellar evolution. In fact, from a dynamical point of view GCs are the only astrophysical systems that, within the timescale of the age of the Universe, undergo nearly all the physical processes known in stellar dynamics, such as gravothermal instability, 2-body relaxation, energy equipartition, 2-body and higher order collisions, binary formation and heating, etc. Hence, GCs turn out to be key astrophysical laboratories for the simultaneous study of stellar evolution and stellar dynamics, two aspects that cannot be addressed independently: dynamical interactions among stars, as well as the formation and evolution of binary systems play a significant role in the overall evolution of GCs and can considerably modify the observable properties of their stellar populations. Blue Straggler Stars (BSSs) are the most abundant product of this dynamical activity.



Outline of the Project: Being more massive than normal cluster stars, BSSs are thought to form either from mass-transfer processes in binary systems or by stellar mergers induced by direct collisions. They are the most numerous bright and massive stars in old clusters. Hence, BSSs represent the best probe particles for tracing the dynamical history of stellar systems, but their nature and properties are still largely unexplored. By means of a large photometric and spectroscopic database collected by our group, we plan: (i) to measure the BSS physical parameters (i.e., mass, surface gravity, effective temperature) of the entire available photometric sample, which comprises more than 4000 BSSs in almost 1/3 of the entire population of GCs in the Milky Way (see the figure and Ferraro et al., 2026, Nature Comm, 17, 768); (ii) to measure the rotation velocity of a sub-sample of BSSs in different environments (clusters with different densities; see Ferraro et al., 2026, Nature Comm, 14, 2584); (iii) to search for chemical signatures of the BSS formation mechanism, thus eventually unveiling their true nature (Ferraro et al., 2006, ApJL, 647, L53); and (iv) to determine their radial distribution in a number of Galactic GCs with different properties (central density, concentration, mass, etc). Indeed, the level of segregation of these stars has been found to be a powerful indicator of the level of dynamical evolution suffered by the parent cluster (thus defining the so-called "dynamical clock" see Lanzoni et al., 2016, 833, L29; Ferraro et al. 2018, ApJ, 860, 26; Ferraro et al., 2019, Nature Astronomy, 3, 1149).

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PhD project in ASTROPHYSICS

Title of the Project: *The effects of baryonic physics implementation in simulations of galaxy formation and evolution performed with SPH and mesh-based methods*

Supervisor: Federico Marinacci (DIFA)

Scientific Case: Modern numerical simulations of galaxy formation and evolution have reached an impressive degree of accuracy in reproducing the properties of observed galaxies. This achievement is based on their ability of controlling and quenching star formation through very efficient stellar and AGN feedback processes. However, the implementation of these feedback prescriptions must be tailored to the specific code that is being used to perform the simulations and, in particular, to the numerical framework that is adopted to follow the hydrodynamic evolution of the gas. Two main families of techniques are used to model hydrodynamics in galaxy formation simulations: smoothed particle hydrodynamics (SPH) and mesh-based methods. Although it is often argued that the differences in the outcome of the simulations due to the implementation of feedback processes are much larger than the ones induced by the choice of the technique adopted to model the dynamic evolution of the gas, it still unclear whether a specific implementation of feedback processes works “universally” (i.e., regardless of the technique with which hydrodynamics is followed) or might in principle be affected by or mask inaccuracies of the hydrodynamic solver being used. These uncertainties further limit the predictive power of simulations and, more importantly, preclude a detailed theoretical understanding of the key processes at play in shaping galaxies. Therefore, there is an urgent need to analyse and rectify these modelling shortcomings to draw a coherent picture of galaxy formation and evolution.

Outline of the Project: The PhD student will use and extend the scope of application of the SMUGGLE model, an explicit and comprehensive ISM and stellar feedback model, which is currently implemented in the mesh code AREPO. As a first step, to enable the research activities of this PhD project, the student will port the implementation of the SMUGGLE model from the AREPO code to the SPH code Gadget4. Having the same galaxy formation physics model implemented in codes that share the same treatment for gravity, but substantially differ in their treatment of hydrodynamics, will be instrumental to answer the scientific questions outlined above. To do so, after this first phase, the student will design, carry out and analyze state-of-the art numerical simulations of galaxy formation. The simulations will first be performed for isolated galaxies to then scaled up to cosmological zoom-in calculations. The analysis of the simulations will focus on the differences in the results obtained with AREPO and Gadget4, with the ultimate goal of reaching a better understanding of the interactions between modeling techniques and the actual physics of galaxy formation.

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PhD project in ASTROPHYSICS

Title of the Project: *Modeling the thermal balance of the hot CGM in star-forming galaxies: the role of stellar and AGN feedback*

Supervisors: Federico Marinacci (DIFA)

Scientific Case: Modern hydrodynamic simulations of galaxy formation successfully reproduce many observed galaxy properties, yet key uncertainties remain in modeling gas exchange between star-forming galaxies and their environment. In particular, the origin, thermal structure, and long-term stability of the hot circumgalactic corona in Milky Way-like systems are still poorly understood. This hot phase of the CGM is central to galaxy evolution, acting as both a reservoir of baryons and metals and the interface regulating gas inflows and outflows. Its thermal state depends on a balance between heating and cooling processes that are not fully captured in current models. Stellar feedback – through supernovae, stellar winds, and radiation – can drive outflows that transport energy from the disk into the halo, but this may not be sufficient to maintain the hot corona over long (~Gyr) timescales.

Additional heating mechanisms may therefore be required. In the Milky Way, observational features such as the Fermi and eROSITA bubbles, suggest that even low-level AGN activity could help offset radiative losses in the inner corona and contribute to its stability. Progress thus requires more realistic models that self-consistently link feedback in the ISM to the thermal evolution of the CGM. Clarifying how energy from stellar and AGN feedback is transferred and maintained in the hot corona is essential to address key open questions, including gas inflow-outflow balance, CGM metal enrichment, and the baryon budget of Milky Way-like galaxies.

Outline of the Project: The PhD student will perform and analyze high-resolution hydrodynamic simulations of galaxy evolution, with the goal of investigating the origin and long-term maintenance of the hot gaseous corona in star-forming systems. The project will employ and further develop the SMUGGLE model for stellar feedback, extending it through the integration of phenomenological coronal heating prescriptions and more physically motivated models of AGN feedback. This approach will enable a self-consistent treatment of the multiphase ISM, its coupling to halo gas via stellar feedback, and the additional heating channels required to sustain the hot CGM.

The project will use controlled, high-resolution galaxy-scale simulations of isolated Milky Way–like systems. These simulations will resolve the multiphase ISM and self-consistently generate galactic outflows, allowing the study of how feedback-driven gas propagates into the halo and interacts with the surrounding medium. A central focus will be the implementation and systematic investigation of coronal heating mechanisms. In addition to stellar feedback modeled with SMUGGLE, the student will explore processes such as shock heating from outflows, thermalization of kinetic energy, and AGN-driven energy injection. Their relative importance will be quantified in setting the thermal structure and stability of the hot ($T \sim 10^6$ K) corona, as well as in balancing radiative cooling.

Finally, the project will establish a self-consistent link between disk-scale feedback and halo-scale thermodynamics, with particular emphasis on how different heating channels shape galaxy evolution. This includes their impact on gas circulation (inflows and outflows), and on the baryon and metal content of galaxies and their CGM. The results will provide physically motivated constraints for calibrating subgrid models in large-scale cosmological simulations.

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PhD project in ASTROPHYSICS

Title of the Project: *Forecasting the gravitational wave signal in cosmological simulations for current and upcoming cosmological surveys*

Supervisors: Federico Marinacci (DIFA), Marco Baldi (DIFA)

Co-supervisors: Micol Bolzonella (INAF-OAS), Lucia Pozzetti (INAF-OAS)

Scientific Case: The detection of gravitational waves (GWs) by LIGO-VIRGO, along with their optical counterpart, has opened a new window into the Universe. GWs can help constrain cosmic expansion, complementing Type Ia supernovae. With optical counterparts providing increasingly precise redshifts, GW-based methods may soon be competitive with or even be superior to traditional cosmological probes. However, accurately determining the distribution of GW events is essential for testing cosmological models and exploring physics beyond the Standard Model. GWs originate from the mergers of compact binaries, which are the end products of stellar evolution within the broader context of galaxy formation. Consequently, predicting the distribution of GWs to forecast their cosmological signal requires modeling highly non-linear astrophysical and cosmological processes. This can only be achieved through advanced numerical simulations combining large-scale structure formation and small-scale stellar dynamics. Moreover, alternative dark matter models or modified gravity theories could influence the evolution of cosmic structures, potentially leaving observational signatures detectable in upcoming GW surveys. These surveys will then become crucial for probing the physics of the dark sector. Recently, our group has developed and implemented a novel method to populate large hydrodynamical galaxy formation simulations (such as Millennium-TNG, the largest of its kind to date) with a self-consistent distribution of GW sources. This approach, based on synthetic stellar evolution calculations, has been integrated into the state-of-the-art hydrodynamical *N*-body code Arepo.

Outline of the Project: The PhD project aims to exploit this recently developed tool to build large 3D catalogues of GW sources forming along (and consistently with) the underlying history of galaxy formation predicted by state-of-the-art hydrodynamical astrophysical models. Additionally, the project will develop methods to populate dark matter halo catalogues, obtained from less computationally intensive collisionless simulations, with a realistic distribution of GW events. These methods may range from simple statistical mapping, such as in Halo Occupation Distribution (HOD) techniques, to more sophisticated approaches including Machine Learning. A possible further goal of the project would be to integrate the GW population model with well-established procedures for generating mock galaxy catalogues from dark matter-only simulations. This integration would enable the creation of self-consistent galaxy and GW catalogues for probe combination and cross-correlation studies in view of the planned future synergies between large galaxy surveys (e.g., Euclid, VRO, Roman Space Telescope, etc.) and GW surveys from existing (Ligo-Virgo-Kagra) or future (Einstein Telescope, Lisa) facilities.

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PhD project in ASTROPHYSICS

Title of the Project: *Inhomogeneous chemical enrichment in simulations including single stellar polluters*

Supervisors: Federico Marinacci (DIFA); Raffaele Pascale (INAF-OAS), Donatella Romano (INAF-OAS)

Scientific Case: Modern hydrodynamic simulations of galaxies successfully reproduce many observed properties across a wide range of scales. However, stellar feedback – the process by which stars inject energy and enriched material into their surroundings – is often implemented in an approximate way even in state-of-the art models. Advancing our theoretical understanding of galaxy formation therefore requires the development of new and more sophisticated feedback prescriptions that capture the multiphase structure of the ISM and take self-consistently into account the energy input and chemical ejecta of various categories of stellar objects. In particular, explaining the large observed scatter in neutron-capture element abundances in the Galactic halo and dwarf satellites of the Milky Way, as well as the large spread in isotopic ratios (e.g., $^{12}C/^{13}C$, $^{14}N/^{15}N$, or $^{17}O/^{18}O$) across the Galactic disk, requires a detailed treatment of stellar polluters. These include asymptotic giant branch stars, supernova progenitors, and binary systems that give rise to nova outbursts and compact-object mergers (neutron star–neutron star or neutron star–black hole).

A more accurate description of stellar feedback is central to addressing major open questions in galaxy evolution, including the balance between gas accretion and outflows, the dynamics and metal enrichment of the CGM, and the baryon and metal budgets of galaxies. In particular, the possibility of accessing these mechanisms at the dawn of the formation of galaxies thanks to *JWST* makes a project focused on the less evolved regions of the Galaxy – the halo and the outer disk – extremely timely.

Outline of the Project: The PhD student will use and further develop the SMUGGLE model, an advanced ISM and stellar feedback framework implemented in the moving-mesh code AREPO. In the first phase, they will design and analyze high-resolution, small-scale simulations to quantify the impact of different stellar feedback channels (radiation, stellar winds, supernova explosions, ...) on the ambient ISM characterized by different physical properties. The student will focus on the chemical abundance signatures of rare events, such as nova explosions and mergers of compact objects, which are usually neglected in high-resolution hydrodynamical simulations.

In the second phase, by using a bottom-up approach, the student will scale up such numerical simulations to investigate the dynamics of super-bubbles and the chemical enrichment in star-forming galaxies, with an emphasis on the properties of the resulting gaseous outflows and chemical inhomogeneities of the stellar populations. Ultimately, this work will enable a self-consistent calibration of feedback parameters within SMUGGLE, improving the fidelity of large-scale cosmological simulations that cannot directly resolve these processes.

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PhD project in ASTROPHYSICS

Title of the Project:
Exploring Gravity Models with gravitational redshifts in galaxy cluster environments

Supervisor: Prof. Federico Marulli
Co-Supervisor: Prof. Lauro Moscardini

Scientific Case:

Current and future wide-field spectroscopic and photometric surveys (e.g., KiDS, *Euclid*, LSST, WST) present a unique opportunity to significantly increase the number of known galaxy clusters and explore previously uncharted territories at both low mass ($M \sim 10^{14}$ M_{sun}) and high redshift ($z > 1$). The scientific interest in these new samples of galaxy clusters is twofold. Firstly, the abundance and clustering of these structures provide crucial constraints on cosmology, as the cluster population carries information about the statistical distribution of initial fluctuations, their subsequent growth, and the dynamics of dark matter halo collapse. Secondly, these clusters serve as invaluable laboratories for studying the evolution of galaxies in dense environments across different epochs.

Furthermore, **galaxy clusters offer natural cosmic laboratories for conducting direct measurements of gravitational redshifts**, enabling tests of gravitational theories on megaparsec scales. Specifically, the gravitational redshift effect can be inferred from the distribution of peculiar velocities of cluster member galaxies as a function of their transverse distance from the cluster center. However, achieving the required precision for definitive tests of General Relativity versus alternative gravity theories has been hindered by the lack of sufficiently large and dense samples of galaxy clusters and associated cluster member galaxies. This limitation is expected to be overcome with the wealth of data from ongoing and upcoming missions, such as the ESA *Euclid* telescope and the NASA *Nancy Grace Roman* Space Telescope, and, in the future, by the planned WST spectroscopic surveys.

The objective of the proposed PhD project is to leverage the new galaxy and cluster spectroscopic samples expected in the near future to conduct **novel tests of gravitational theories using gravitational redshifts in galaxy clusters**. The PhD student will initially construct and characterise new spectroscopic cluster catalogues, focusing on key properties such as cluster centers and the positions of cluster member galaxies. New software tools will be developed to compute these measurements and conduct the necessary statistical analyses. The validity of these pipelines will be verified using simulated catalogues to identify and address potential systematic uncertainties. The newly implemented algorithms will be made publicly available through the CosmoBolognaLib, a comprehensive suite of *free software* C++/Python libraries for cosmological calculations. Ultimately, the PhD student will deliver new constraints on gravitational theories, potentially distinguishing among various alternative gravity frameworks.

Outline of the Project:

The PhD project is organised in the following phases:

- Construction and characterization of **new photometric and spectroscopic catalogues of galaxy clusters and cluster member galaxies** from simulated and real data sets.
- Implementation of **novel algorithms to measure and model the peculiar velocity distributions** of cluster member galaxies.
- Integration of the developed software into the **CosmoBolognaLib**.
- Investigation of all potential **systematic uncertainties** affecting the analysis.
- Application of the model to real data sets to derive **new constraints on gravity theories**.
- Application of the model to mock catalogues of next-generation missions to provide **forecasts** for future analyses.

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PhD project in ASTROPHYSICS

Title of the Project:
Unlocking the full information content of the Cosmic Web with machine learning

Supervisor: Prof. Federico Marulli
Co-Supervisors : Prof. Lauro Moscardini

Scientific Case:

In the last decades, the exponential growth of data has drastically changed the way we do science, leading Cosmology into the so-called Big Data Era. Standard cosmological analyses based on abundances, two-point and higher-order statistics of extra-galactic tracers – such as galaxies, galaxy clusters, and cosmic voids – have been widely used to investigate the properties of the *Cosmic Web*. However, these approaches rely on summary statistics and therefore exploit only a fraction of the total information content available in the data.

Recent methodological developments now enable a more direct extraction of cosmological information. In particular, **simulation-based inference** (SBI) methods allow one to perform likelihood-free inference, while **field-level approaches** enable inference directly on the data or density fields, without relying on summary statistics. These methods provide a natural framework to fully exploit the information encoded in the large-scale structure of the Universe.

The proposed PhD project aims to enhance the scientific exploitation of current and future galaxy surveys by developing and applying modern **machine learning techniques** for cosmological inference. Flexible learning frameworks – including neural density estimators, normalizing flows, and related inference techniques – will be implemented and tested on simulated catalogues in different cosmological scenarios, and then applied to real data sets such as BOSS, eBOSS, and DESI, as well as to upcoming data from the ESA *Euclid* mission.

In parallel, **large language models** (LLMs) will be explored as tools to support the development and optimisation of data analysis pipelines, including code generation, workflow automation, and the construction of surrogate models for cosmological applications.

The primary scientific goals of this project are to provide independent constraints on the **dark energy** equation of state and to **test General Relativity and alternative gravity scenarios**. The PhD student will acquire expertise in advanced statistical techniques for large-scale structure analyses, as well as in modern machine learning methods applied to cosmology. The developed algorithms will be integrated into the CosmoBolognaLib, a large suite of free C++/Python libraries for cosmological calculations.

Outline of the Project:

The PhD project is organised in the following phases:

- **Construction of large sets of dark matter mock catalogues in different cosmological frameworks** using fast approximate methods, such as those based on Lagrangian Perturbation Theory.
- Application of **subhalo abundance matching** and/or **halo occupation distribution** techniques to populate the dark matter catalogues with galaxies and galaxy clusters.
- **Implementation of machine learning and simulation-based inference frameworks** for cosmological analyses, including likelihood-free and field-level approaches.
- Development and validation of **pipelines** to extract cosmological information directly from density fields and galaxy distributions.
- **Training and testing of the inference methods** on mock catalogues, with careful assessment of systematic uncertainties.
- **Comparison** of the cosmological constraints obtained from machine learning approaches with those derived from standard probes, such as two-point and higher-order correlation functions.
- **Application** of the developed methods **to real data sets** to derive new cosmological constraints.
- **Forecasting** the constraining power of next-generation galaxy surveys using realistic mock catalogues.
- **Exploration of LLM-based tools** to assist in pipeline development, automation, and analysis support.

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PhD project in ASTROPHYSICS

Title of the Project:
Cosmological exploitation of the statistical properties of Cosmic Voids

Supervisor: Prof. Federico Marulli
Co-Supervisors: Dr. Sofia Contarini, Prof. Lauro Moscardini

Scientific Case:

A significant fraction of the Universe volume is made up of almost empty space regions, that emerge between the filaments and the walls of the *Cosmic Web*. These low-density patches of the Universe are known as Cosmic Voids and provide one of the most powerful, though yet largely unexplored, cosmological probes. Thanks to their huge sizes – up tens of megaparsec - and low-density interiors, voids constitute unique cosmic laboratories to investigate the physical properties of **dark energy**, as well as **modified gravity theories**, **massive neutrinos**, **primordial non-Gaussianity** and **Physics beyond the Standard Model**. The current and upcoming spectroscopic galaxy surveys will flood us with a huge volume of data, allowing us to significantly enlarge the cosmic void catalogues currently available, up to large redshifts. Cosmic voids are now being recognized as core cosmological probes in next-generation experiments.

This PhD project is aimed at fully exploiting the primary large-scale statistics of the cosmic void population, that is the **size function**, the **density** and **lensing profiles**, and the **spatial clustering of voids**. The PhD student will firstly investigate different void detector algorithms, with the goal of maximising the purity and completeness of the void samples, as well as to accurately characterise the sample selections. Standard statistical methods, as well as the newest Machine Learning techniques will be considered to optimise the data analysis pipelines. New simulated catalogues of cosmic voids shall be constructed in different cosmological scenarios to test the efficiency of the void detectors and check for systematic uncertainties in the cosmological analysis.

The PhD student will then analyse real data sets and provide new cosmological constraints from the probe combination of the main cosmic void statistics. The catalogues will be extracted from both current data sets, such as the final SDSS-III BOSS survey, and ongong galaxy spectroscopic and photometric samples, as the ones from the ESA ***Euclid*** mission.

Outline of the Project:

The PhD project is organised in the following phases:

- Implementation of **new void detector algorithms**, including Machine Learning based methods, and comparison with existing available codes.
- Implementation of new software tools to **measure all primary statistics of cosmic voids: size function, lensing profiles, void clustering**.
- Implementation of **likelihood modules** to extract cosmological information from single void statistics and probe combinations.

- Test of the data analysis pipelines on mock void catalogues extracted from **standard and beyond-ΛCDM cosmological simulations**.
- Construction of **new real cosmic void catalogues**.
- **Cosmological analysis** on real cosmic void catalogues.
- **Forecasting** the constraining power of next-generation photometric and spectroscopic void samples.

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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: Stars as laboratories for testing fundamental physics

Supervisors : Andrea Miglio (DiFA, UniBo), Oscar Straniero (INAF-OAAb)

Scientific Case:

The high temperature and density that develop within the cores of evolved stars, from red giants to supergiants, make them ideal sites to investigate deviations from the standard models describing the behaviour of matter in extreme conditions, which are often not accessible by current laboratory experiments.

In this context, a growing amount of scientific papers discuss peculiar properties of hypothetical weakly interacting particles, by comparing stellar models predictions to several astronomical observables.
For instance, axions are pseudo-scalar particles predicted by several non-standard theories. They provide the most elegant solution to the so-called strong CP problem, i.e, the conservation of the charge-parity symmetry in processes that involve strong interactions. If they exist, axions may have a great impact on cosmology (they are good dark matter candidates) and on stellar evolution. Indeed, they may be produced in hot stellar interiors through their coupling with standard particles, like photons or electrons. In this framework, the most stringent constraints to the strength of the axion-photon coupling comes from the lifetime of core-helium-burning stars (Ayala et al., 2014), while the most stringent constraint to the axion-electron coupling is provided by the luminosity of the red-giant tip (Straniero et al., 2020; Capozzi & Raffelt, 2020). In addition to axions, other feeble particles, e.g., dark photons, may also be produced by thermal processes in stellar interiors and, hence, probed with this technique. The same method may also provide hints on the electromagnetic properties of standard particles, e.g. the neutrino magnetic moment (Capozzi & Raffelt, 2020).

The constraints obtained so far are, however, limited by the effective reliability of our stellar models and by the scarce direct information we have on the internal structure of stars. The situation has now changed, and detailed constraints on the internal structure of red giants are now available thanks to the detection and interpretation of their resonant oscillation frequencies (asteroseismology), offering a unique opportunity to get important hints on various new-physics hypotheses.

Outline of the Project:
During the 3-yr project, the student will:

- Quantify the effect of non-standard particles on the internal structure and evolution of red-giant stars and on their pulsational spectra. The student will familiarise with stellar evolution and pulsation codes and, crucially, with the current uncertainties pertaining to stellar modelling (year 1).
- Devise observational tests needed to set limits on the cross-section describing the interaction of non-standard particles with stellar matter (year 2,3). These tests will

explore both potential direct seismic signature of non-standard particles and indirect signatures that are expected to become significant as a result of reducing, thanks to seismic constraints, other uncertainties in current models (e.g., extension of the convective core, core angular momentum).

The student will be involved in large international collaborations, in particular in the ESA PLATO mission consortium (launch 2026 https://platomission.com/, https://www.esa.int/Science_Exploration/Space_Science/Plato) and in the proposal of next-generation asteroseismic missions such as HAYDN (http://www.asterochronometry.eu/haydn/)

The nature of the project is such that the student should be happy coding and interpreting results from numerical simulations of stellar evolution, analysing and manipulating data. Familiarity with stellar evolution would be highly beneficial.

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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: A first-principles step forward in red giant asteroseismology with 3D MHD simulations

Supervisors : Andrea Miglio (DiFA, UniBo), Jordan Philidet, Benoit Mosser (LIRA, Observatoire de Paris)
PhD Programme: Joint PhD (Cotutelle) between the University of Bologna and the Observatoire de Paris-PSL

Scientific Case

Red giant stars are key probes of stellar and Galactic evolution, and their asteroseismic properties enable precise determinations of stellar masses and ages. However, current inferences rely on simplified modelling of stellar surface layers and on empirical scaling relations, which introduce systematic uncertainties. In particular, the physical origin and accuracy of the ν_{max} scaling relation, which connects the frequency at which oscillations have maximum power to global stellar properties, the modelling of the outermost stellar layers, and the role of convection in the excitation of oscillation modes remain poorly understood.

Three-dimensional hydrodynamical simulations, such as those computed with CO5BOLD, provide a first-principles description of stellar surface convection and oscillations. Applying these simulations to red giant stars offers a unique opportunity to improve our understanding of surface effects, mode excitation, and their dependence on stellar parameters and metallicity.

In the context of the ESA PLATO mission, which will provide asteroseismic data for tens of thousands of red giants, improving the modelling of these effects is essential. Accurate masses for red giants are crucial not only for evolved stars, but also to calibrate stellar clocks across the Hertzsprung–Russell diagram.

Outline of the Project

During the 3-year project, the student will:

- Perform and analyse 3D hydrodynamical simulations of red giant stars using CO5BOLD (year 1)
- Characterise surface effects and their dependence on stellar parameters and metallicity (years 1–2)
- Investigate the dependence of the νmax scaling relation and the excitation of oscillation modes on metallicity (year 2)
- Explore the connection between convection, pulsations, and mass loss in evolved stars (years 2–3)
- Develop improved seismic diagnostics to infer accurate stellar masses and ages (year 3)
- Contribute to the scientific exploitation of PLATO data, in particular for the expected sample of ~24,000 red giant stars (years 2–3)

The student will be involved in large international collaborations, in particular in the ESA PLATO mission consortium (launch: early 2027: https://platomission.com/, https://www.esa.int/Science_Exploration/Space_Science/Plato), and in the proposal of next-generation asteroseismic missions such as HAYDN (http://www.asterochronometry.eu/haydn/).

The nature of the project requires a strong interest in coding and in the interpretation of numerical simulations. The student will work with MHD simulations, stellar evolution models, and large datasets, and will develop skills in data analysis and modelling. Familiarity with stellar evolution is highly desirable.

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PhD project in ASTROPHYSICS

Title of the Project: Stellar ages as precision cosmological probes: pushing the systematic floor to the percent level

Supervisors : Andrea Miglio (DiFA, UniBo)
Co-Supervisors: Michele Moresco, Andrea Cimatti (DiFA, UniBo)

Scientific Case

The determination of stellar ages underpins a wide range of astrophysical applications, from stellar evolution to Galactic archaeology and cosmology. Space-based asteroseismology has enabled age determinations with ≈10% precision (Montalban et al. 2021, Thomsen et al. 2025). Achieving, testing and improving this level of precision is key to enabling the use of stellar ages as cosmic chronometers to probe the expansion history of the Universe (e.g. Cimatti & Moresco 2023, Tomasetti et al. 2026).

The current limitation lies in systematic uncertainties arising from incomplete modelling of stellar physics. These uncertainties define a systematic floor to the achievable accuracy of stellar ages and limit their use for precision cosmology. Even with high-quality data, different modelling assumptions can lead to systematic shifts in inferred stellar ages at the level of 20–30%, highlighting the need for a robust assessment of the error budget.

The ESA PLATO mission will dramatically increase the number of stars with high-quality asteroseismic data, particularly among low-mass main-sequence, subgiant, and red giant stars. This will enable homogeneous age determinations for tens of thousands of stars, including old and metal-poor populations of cosmological interest. At the same time, future missions such as HAYDN aim to establish the stellar age scale on a robust empirical foundation and to reach percent-level accuracy.
In this context, this project aims to quantify and reduce the systematic floor in stellar age determinations. By combining large asteroseismic datasets with improved stellar modelling, it will be possible to identify the dominant sources of uncertainty and develop strategies to mitigate them. Achieving percent-level accuracy in stellar ages would enable independent constraints on cosmological parameters, providing new insights into current tensions such as the Hubble constant discrepancy.

Outline of the Project

During the 3-year project (lascio in inglese coerente):
- Quantify systematic uncertainties in stellar age determinations by exploring stellar models with different physical assumptions (year 1)
- Develop efficient inference techniques, including machine-learning approaches, to explore large model grids and propagate uncertainties (years 1–2)
- Exploit PLATO asteroseismic data to derive precise and homogeneous stellar ages for large samples (years 2–3)

- Identify the dominant sources of systematic error and develop strategies to reduce them, including contributions to the design and scientific goals of candidate space missions such as HAYDN (years 2–3)
- Assess the cosmological implications of improved stellar ages, using stars as cosmic chronometers (year 3)

The student will be involved in large international collaborations, in particular in the ESA PLATO mission consortium (launch: early 2027 https://platomission.com/, https://www.esa.int/Science_Exploration/Space_Science/Plato) and in the proposal of next-generation asteroseismic missions such as HAYDN (http://www.asterochronometry.eu/haydn/)

The nature of the project is such that the student should be happy coding and interpreting results from numerical simulations of stellar evolution, analysing and manipulating data. Familiarity with stellar evolution would be highly beneficial.

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DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: Exploiting Gravitational Waves as cosmological probes in view of the new upcoming large GW and galaxy surveys

Supervisor : Michele Ennio Maria Moresco
Co-Supervisors : Andrea Cimatti

Scientific Case: Modern cosmology is currently undergoing an exciting yet problematic time. After the discovery of the accelerated expansion of the Universe (Riess et al., 1998, Perlmutter et al. 1999), many of the cosmological probes currently identified as 'main' (Cosmic Microwave Background, Baryon Acoustic Oscillations, Supernovae Type Ia) experienced a period of continuous technological and theoretical development that lead them to percent accuracy; however, as a consequence this lead to a tension between early- and late-Universe measurements, that are currently pointing to values of cosmological parameters at odds by more than 4 sigma (see e.g. Verde et al. 2019). It is therefore now crucial to go beyond standard probes and explore alternative probes that can help to resolve this tension. Gravitational waves (GW) are amongst the most promising emerging cosmological probes in the near future (see Moresco et al. 2022). These astrophysical phenomena provide us a clean measurement of the distance to the source completely independent on cosmological models, only relying on General Relativity. However, to be used as standard sirens, it is necessary to associate to these events a redshift, as firstly proposed by Schutz (1986). This association can be either direct (bright sirens, as for the case of GW170817) or statistical (as for the case of dark sirens, see e.g. Palmese et al., 2021, LIGO Scientific Collaboration et al., 2021). In this Ph.D. Thesis, we propose to explore techniques to maximize the scientific return of analysis of GW as cosmological probes by improving on current analysis by including in the analysis new observational features, exploring the constraints that can be set by current data, forecasting the impact of the new upcoming large GW (e.g. Advanced LIGO-Virgo, Einstein Telescope, …) and electromagnetic observatories (e.g. WST, …), and preparing a framework to be prepared to analyze the expected new data by the LIGO/Virgo collaboration.

Outline of the Project: The field of GW cosmology has recently started and is gaining a growing attention in the cosmological community. For this reason, many different aspects are still worth exploring, especially in the use of GW as dark sirens, like the impact in the derivation of cosmological parameters of the galaxy catalog used to cross-correlate the EM counterpart of the GW, of the accuracy in the redshift estimates, of the completeness of the catalog, of the assumed distribution of BBH masses, of extending the GR framework in the analysis. While some seminal works are being recently published, it is crucial to assess many of these aspects to establish GW as robust cosmological probes. At DIFA, we recently developed a public GW analysis SW (CHIMERA, in collaboration with national and international colleagues), and in this Ph.D. Thesis we propose to extend those by including new features as discussed above, with the following goals: (i) integrate in the GW code improved statistical models, (ii) study and characterize current public catalogs (GLADE+, DESI, …), (iii) analyze the impact of different properties in the catalogs (completeness, accuracy of the redshift estimates) on the cosmological parameters accuracy, (iv) take advantage of the expertise at DIFA in generating mock galaxy catalog (CosmoBolognaLib) to develop a framework to produce ad-hoc simulated galaxy catalogs for GWs to forecast the performance of the combination of future spectroscopic surveys (e.g. Euclid) and GW observatories (e.g. Einstein Telescope), (v) apply the developed framework to current and simulated data, to provide forecasts on the constraints on the expansion history of the Universe, also in combination with other cosmological probes.

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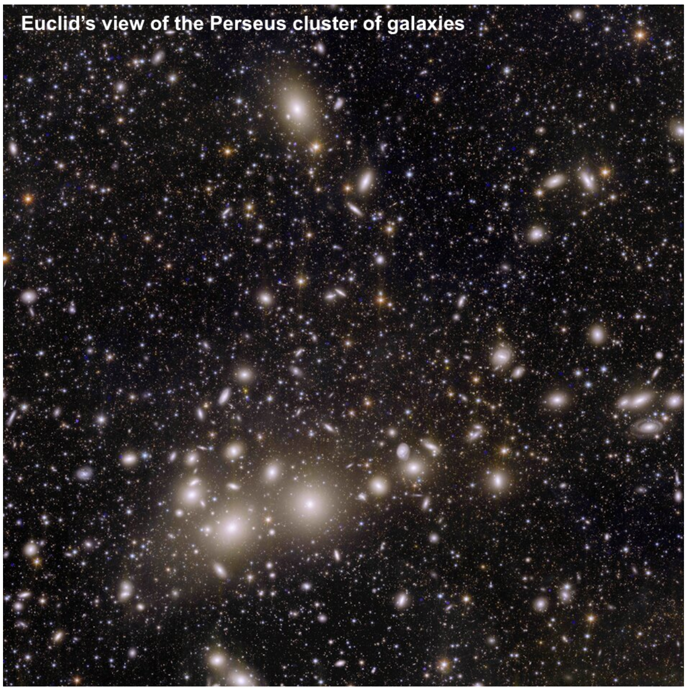
PhD Project in Astrophysics

Title of the Project:
Statistical Tools for Cluster Cosmology Studies in the ESA-Euclid Era Mission

Supervisor: Lauro Moscardini (DIFA)
Co-Supervisors: Carlo Giocoli (INAF-OAS), Federico Marulli (DIFA), MassimoMeneghetti (INAF-OAS)



Scientific Case:
The Euclid mission has successfully entered its operational phase and is already delivering high-quality data to the scientific community, marking a transformative step for observational cosmology. Early data releases have demonstrated the mission's capability to achieve unprecedented precision in both galaxy shape measurements and photometric redshift estimation, with a source density approaching ~30 galaxies per square arcminute. This exceptional data quality establishes a new benchmark for wide-field surveys and opens the way to a new generation of cosmological analyses.
Within this context, galaxy clusters are expected to play a pivotal role as complementary probes to the primary cosmological observables—galaxy clustering and weak gravitational lensing. By combining these approaches, cluster cosmology will significantly enhance our ability to test the validity of General Relativity and to constrain the physics driving the accelerated expansion of the Universe.
The primary scientific objective of this project is to exploit Euclid data to trace the growth of cosmic structures from the local Universe up to redshift (z \sim 2), through joint measurements of galaxy clustering and weak lensing. In parallel, the Galaxy Cluster Science Working Group has established robust strategies for identifying galaxy groups and clusters from photometric data (e.g. Sartoris et al. 2016; Adam et al. 2019, EC: Bhargava et al. 2025), based on state-of-the-art algorithms such as AMICO and PZWav. These methods will enable the construction of large, homogeneous cluster catalogs over an unprecedented cosmic volume.
A key ingredient of this program is the use of weak gravitational lensing to provide accurate and unbiased cluster mass estimates. The subtle distortion of background galaxy shapes induced by foreground clusters offers a direct probe of their total matter content, making weak lensing an essential tool for calibrating mass–observable relations. This calibration is crucial, as the cosmological constraining power of clusters—through their abundance and spatial distribution as a function of redshift—strongly depends on the accuracy and precision of mass measurements, as well as on their combination with complementary cosmological probes.

In recent years, advanced statistical techniques—including Bayesian inference, machine learning, and forward-modeling approaches—have become central to cosmological data analysis. These methods represent the current state of the art and will be fully exploited in this project to analyze Euclid data, mitigate systematic uncertainties, and maximize the scientific return of next-generation wide-field surveys

Outline of the project:
The PhD student will be fully embedded in the scientific activities of the Euclid Consortium, actively contributing to cluster cosmology studies within an international and highly collaborative environment. In particular, they will join the Clusters of Galaxies, Strong Lensing, and Weak Lensing Science Working Groups, gaining direct access to state-of-the-art methodologies, data products, and collaborative expertise.
The first phase of the project will focus on the construction of realistic weak lensing simulations of galaxy clusters. These will be generated by combining clusters extracted from hydrodynamical simulations with fast, flexible pseudo-analytical realizations produced using the MOKA code (Giocoli et al. 2012). Such simulations will be further processed through advanced image simulation pipelines (e.g. SkyLens; Meneghetti et al. 2017) to reproduce realistic observational conditions.
These simulated datasets will serve multiple scientific purposes. First, they will provide a controlled environment to develop and train deep learning models aimed at inferring key cluster properties, such as mass, concentration, and triaxiality, directly from weak lensing observables. The performance of these approaches will be systematically compared with traditional methods based on parametric fits to shear profiles, enabling a robust assessment of biases, uncertainties, and degeneracies.
Through this activity, the student will acquire advanced expertise in weak lensing simulations, multi-wavelength data analysis, and modern statistical and machine learning techniques.
In the second phase, the student will focus on the cosmological exploitation of galaxy cluster catalogs derived from the Euclid mission data. Building upon existing tools within the Consortium—such as the CLOE pipeline—they will contribute to the development and optimization of a forward-modeling framework for cosmological parameter inference.
The project will be carried out within a dynamic international research environment, offering the student extensive opportunities for scientific exchange and professional development. Active participation in the Euclid Consortium will foster collaborations with leading experts in the field and provide exposure to large-scale survey science.
To further strengthen this international dimension, a research visit of 3–6 months at one of the partner institutions will be organized during the PhD. This experience will enhance the student's technical skills, broaden their scientific network, and contribute to building a strong foundation for a future career in astrophysics and cosmology.

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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: A multi-wavelength view of galaxy clusters from Euclid and XMM-Newton

Supervisor: Prof. Lauro Moscardini (DIFA)
Co-Supervisors: Dr. Micol Bolzonella (INAF-OAS)

Scientific Case:
The **Euclid** telescope is a space mission developed by the European Space Agency (ESA) with contributions from NASA, aiming at observing 14000 deg^2 with grism NIR spectroscopy and photometry across visual and NIR wavelengths. While its primary goal is to investigate the mysteries of dark energy and dark matter, Euclid's observations in 3 deep fields promise a lasting legacy across various aspects of astrophysics, from galaxy clusters to AGN. Launched on July 1st 2023, Euclid started the survey operations on February 14th, 2024, marking the beginning of a six-year programme.

XMM-Newton, short for X-ray Multi-Mirror Mission, is an X-ray observatory launched by the European Space Agency (ESA) in December 1999. It is one of the most powerful X-ray telescopes ever built, designed to observe high-energy phenomena in the universe with unprecedented sensitivity and spatial resolution.

Recently, a **XMM Multi Years Heritage programm**e (PI M. Pierre, co-PI M. Bolzonella, B. Maughan, S. Paltani) has been awarded with 3.5Ms to obtain the coverage of the 10deg^2 of the Euclid Deep Field Fornax at 40ks depth.

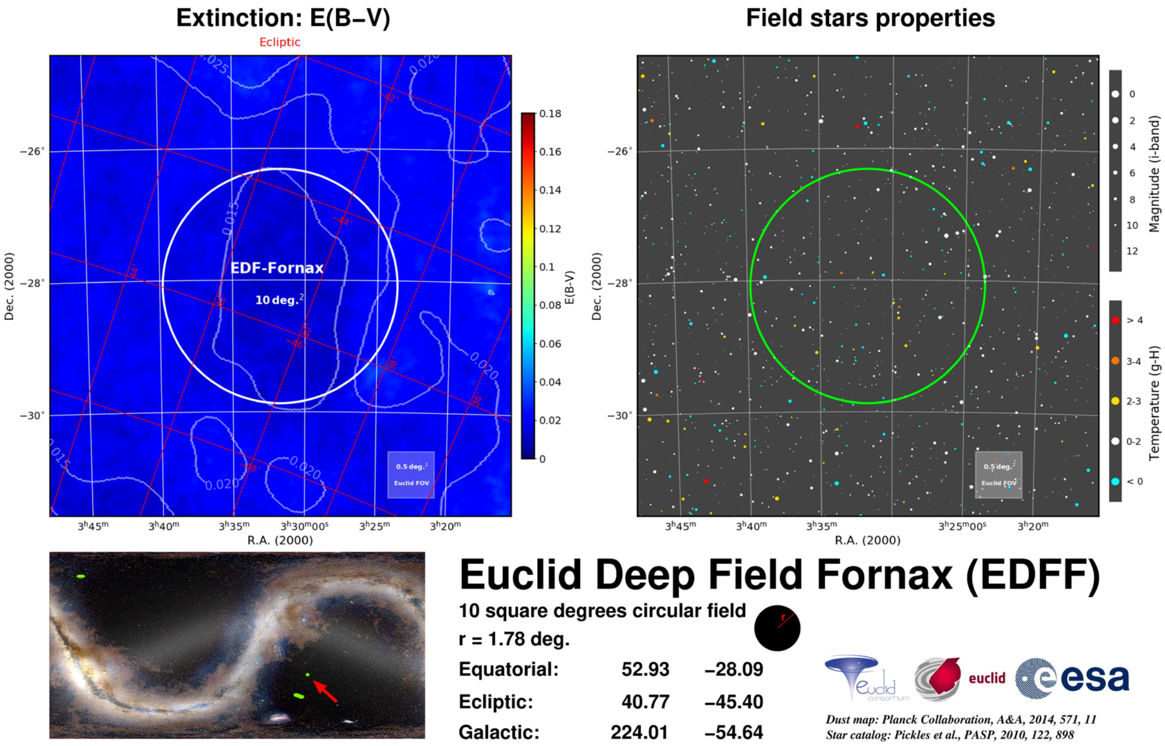
The **Fornax Deep Field** will be the deepest among the 3 Euclid Deep Fields; the concurrent XMM observations promise to deepen our understanding of galaxy clusters, including a deep characterisation of Euclid-detected clusters and their selection function and a robust measurement of cluster scaling relations to $z = 1.5$ and in the galaxy group regime.

The project will be carried out in the framework of the Euclid collaboration, including ~2000 international scientists. In Bologna (DiFA and INAF institutes) there is a large and lively research group dealing with many different aspects of the science that will be enabled by Euclid data.

Outline of the Project:
The project, to be discussed with the PhD candidate, can include some of the following aspects.

- Characterisation of X-ray and optical properties, their differences to analyse the systematics affecting the selection at different wavelengths, and comparison with simulated ones;
- Cross-identification of clusters identified in Euclid and XMM to constrain both the baryonic and dark matter components;
- Predictions and analysis of the scaling relations (between temperature, luminosity, richness) to study the feedback and the connection between the cooling of ICM, fuelling of star formation, accretion of AGN, and presence of energetic outflows; these feedback processes are fundamental to understand the

galaxy stellar mass function and are a critical ingredient of cosmological simulations.



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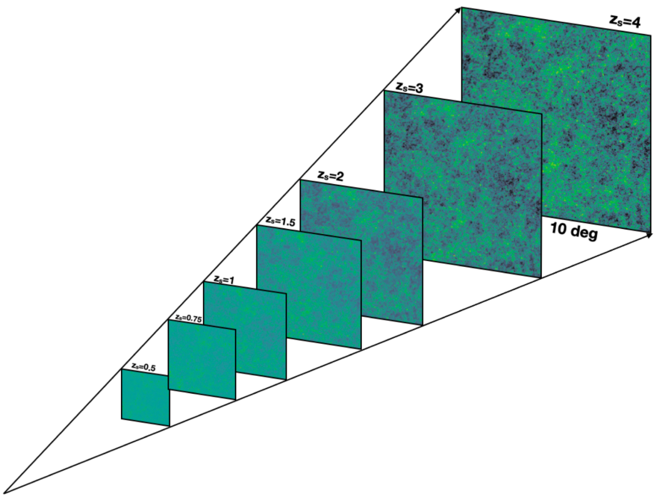
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project:
Detecting Clusters and Voids using Weak Gravitational Lensing

Supervisor: Lauro Moscardini
Co-Supervisors: Carlo Giocoli, Federico Marulli, Giulia Despali

Scientific Case:
Wide-field surveys such as Euclid mission and the Vera C. Rubin Observatory will establish weak gravitational lensing as a cornerstone probe of modern cosmology. The small distortion of galaxy shapes induced by the intervening projected matter distribution provides a direct and unbiased tracer of the growth of large-scale structure across cosmic time. The combination of high galaxy number density, accurate photometric redshift and extensive sky coverage expected from these surveys will deliver unprecedented statistical precision in the measurement of cosmological parameters.
This large data set will enable the exploitation of weak lensing beyond traditional two-point statistics, allowing for the detection and characterization of both overdense and underdense environments, such as galaxy clusters and cosmic voids. Fully exploitation of this potential requires highly accurate modeling of the lensing signal, supported by dedicated and realistic light-cone simulations.
In this context, the PhD project will develop state-of-the-art weak lensing light-cone simulations, designed to act as controlled "cosmic laboratories" for testing analysis pipelines and mitigating systematic uncertainties. Particular emphasis will be placed on cluster and void lensing, which provide complementary sensitivity to key extensions of the standard cosmological model, including the dark energy equation of state, massive neutrinos, and modified gravity scenarios. The validated modeling will then be applied to forthcoming photometric weak lensing data, enabling robust and high-precision cosmological inference.

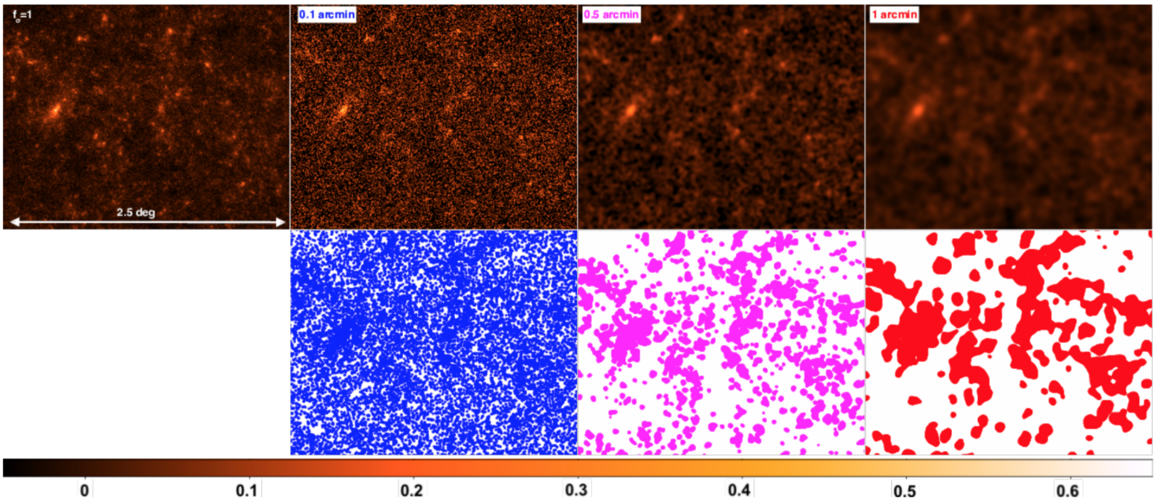


An example of the weak lensing light-cone simulation constructed from a numerical cosmological simulation.

Outline of the Project:
During the initial phase of the project, the student will focus on the construction of dedicated weak lensing simulations, exploiting the tools and data sets available within the host group. This activity will build upon established methodologies, including the projection of matter density fields from cosmological numerical simulations and the subsequent ray-tracing of light paths using the *MapSim* pipeline (Giocoli et al. 2015). Particular attention will be given to incorporating recent methodological advancements, such as those presented in Maggiore et al. (2025), which significantly improve the realism and accuracy of weak lensing light-cone reconstructions. The resulting convergence and shear maps will be used to generate mock shear catalogues, assuming source distributions and depths consistent with expectations from the Euclid mission and the Vera C. Rubin Observatory.
Building on these simulations, the student will investigate the identification of galaxy clusters directly from weak lensing observables. Leveraging the knowledge of the underlying halo population, they will test and optimise an optimal filter-based algorithm designed to detect peaks in the convergence and shear fields. The feasibility of this approach has been demonstrated in previous studies (e.g. Pace et al. 2007; Trobbiani et al. 2025), but its application to next-generation data requires validation on more accurate and higher-resolution simulations. This step will be crucial to assess completeness, purity, and selection biases in a controlled framework.

A key outcome of this analysis will be the construction of a weak lensing-based cluster selection function, which will provide an essential complement to photometric selection methods (Sartoris et al. 2016). The combination of these approaches will enable improved cosmological constraints by reducing systematic uncertainties and enhancing the statistical power of cluster-based probes.

While galaxy clusters trace the overdense regions of the matter distribution, cosmic voids probe its underdense counterpart, corresponding to minima in the weak lensing maps. As a third major activity, the student will develop and optimise a novel algorithm for the identification and characterization of cosmic voids directly from weak lensing data. This effort will extend existing methodologies (Melchior et al. 2012; Sánchez et al. 2017; Fang et al. 2018, Maggiore et al. 2025) and open new avenues for exploiting void lensing as a complementary cosmological probe, shading more light into the dark setctor of our Universe.



Noised and smoothed convergence maps considering different choices for the filter scale. The top left panel displays the original convergence map. Moving from left to right, the other top panels show the convergence maps with artificial noise added and filtered, using filter sizes of 0.1, 0.5, and 1 arcminute. The bottom sub-panels display the regions in the corresponding maps that are above the noise level.

The work activities performed during the PhD period will be based on various **international collaborations** that our group in Bologna has, framed within different work packages of the ESA *Euclid* Collaboration (https://www.euclid-ec.org) and LSST-Rubin. In this way, the student will have great opportunities to interact with a diverse group of scientists, gaining the appropriate skills for a fruitful career.

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PhD project in ASTROPHYSICS

Title of the Project:
Chemical characterization of the Local Group: identifying the chemical DNA of Milky Way satellite galaxies

Supervisor : A. Mucciarelli (DIFA)
Co-Supervisor : D. Massari (INAF-OAS)

Scientific Case:

According to the Λ cold dark matter cosmological paradigm, structure formation proceeds bottom-up, as small structures merge to build up the larger galaxies we observe today. The Milky Way is a prime example of this formation mechanism, as first demonstrated by the discovery of the Sagittarius dwarf spheroidal galaxy in the process of disruption (Ibata et al.1994), then by halo stellar streams crossing the solar neighborhood (Helmi et al. 1999), and more recently by the discovery of stellar debris from Gaia-Enceladus, revealing the last significant merger experienced by our Galaxy (Helmi et al. 2018). As a result of such merger events, not only stars, but also globular clusters were accreted.
The chemical composition of stars is a powerful tool to reconstruct the history of the parent galaxies and their possible merger events. In fact, the amount of different metals in a star acts as a powerful "*DNA probe*" that allows us to trace the genealogy of each star and to distinguish those formed in other galaxies and only later added to the main building. This approach has been recently used to identify for the first time the relic of a past merger event occurring in the Large Magellanic Cloud (Mucciarelli et al. 2021, Nature Astronomy).

Outline of the Project:

The PhD project is aimed at describing the chemistry of Milky Way satellites (like the Sagittarius dwarf galaxies, the Large and Small Magellanic Clouds), nearby isolated dwarf galaxies and ultra-faint dwarf galaxies. The chemical DNA of these galaxies will be compared with that of the Milky Way in order to reconstruct the chemical enrichment history of these galaxies. Two key questions will be addressed in this project,

- **Assembly history of the massive satellites -** the chemistry of field and globular cluster stars of the most massive Milky Way satellites (i.e. the Magellanic Clouds) will be used to reveal possible past merger events occurring in their history and to search for the missing satellites of these galaxies, predicted by Λ cold dark matter simulations. The search for past merger events in these galaxies is an exciting hot topic in modern astrophysics that is taking its first steps, only one merger event has been discovered so far in these galaxies (Mucciarelli et al. 2021).
- **The early evolution of the interacting satellites** – the chemical properties of long-lived, metal-poor, old stars provide detailed insights into the early ages of these galaxies when they evolved in isolation and before they start to interact each other. These rare stars will allow us to understand the impact of first supernovae in different galactic environments and enhance our comprehension of the first Gyr of life in these systems.

The project will benefit from proprietary and archival high-resolution spectra obtained with ground-based telescopes (i.e. VLT, LBT,Subaru,Keck) that will be analysed to derive a complete screening of the chemical properties of these stars (see Minelli et al. 2021a,b for some examples of the adopted approach).

Foreseen milestones and deliverables

- at least one refereed paper per year in the best impact-factor astronomical journals.
- dissemination of the project results at international astronomical conferences.
- collaboration with world-renowned experts in spectroscopy of resolved stellar populations

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ALMA MATER STUDIORUM
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DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project:
Evolution of CNOPS elements in the Milky Way

Supervisor : A. Mucciarelli (DIFA)
Co-Supervisor : D. Romano (INAF-OAS)

Scientific Case:
Carbon, nitrogen, oxygen, phosphorus, and sulphur (hereinafter the CNOPS elements) are the building blocks of all life on Earth. Understanding their formation in stars and evolution in the Milky Way is a fundamental step to the definition of the "Galactic Habitable Zone" and its evolution in time and space in the Galaxy.
This PhD project is part of the international collaboration SPONGE (Sulphur, Phosphorus, Oxygen, Nitrogen and carbon Galactic Evolution) that aims to address the fuzziest aspects of CNOPS evolution by means of both novel spectroscopic observations and cutting-edge galaxy formation and evolution models.

Outline of the Project:
The PhD candidate shall reduce, analyze, and provide theoretical interpretations of proprietary data already in hand, while also being involved in the preparation of next observational campaigns by the team. Indeed, within SPONGE we are obtaining high-resolution stellar spectra to measure the C and O isotopic ratios (12C/13C, 16O/18O) of unevolved stars - the sole that can effectively constrain Galactic chemical evolution models, because their atmospheric abundances are unaffected by mixing processes typical of later stellar evolutionary phases. It is worth noticing that none of past, current, or planned large spectroscopic surveys can provide such data, so our effort nicely complements that of the community.
Moreover, the student will have access to complementary molecular cloud data (12C/13C, 14N/15N, 16O/17O, 16O/18O, 32S/33S, 32S/34S) obtained in the framework of several international collaborations, which will allow him/her to study the variation of the isotopic ratios not only in time in the solar neighborhood, but also across the Milky Way disc at the current time. All of this, jointly to the availability of a proprietary Galactic chemical evolution code that is maintained and constantly upgraded in Bologna, will put him/her in the prime position of being able to obtain and interpret unique data, with an assured large impact on the community.

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DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project:
Implementing new physics in the modeling of the stellar atmospheres

Supervisor : A. Mucciarelli (DIFA)

Scientific Case:
A model atmosphere is a numerical model that describes the physical state of the plasma in the outer layers of a star, and is used to compute observable quantities, such as the emerging spectrum or colours. The level of realism in the physical treatment of these models has a fundamental impact on the chemical abundances derived from spectra, as well as on the photometric colors or the integrated spectra predicted for complex populations such as galaxies. All the model atmospheres widely adopted are based on the assumptions of local termodynamical equilibrium and one dimensional geometry. These assumptions are not always valid leading to significant variations in the chemical abundances that we derive.

Outline of the Project:
The goal of the project is to implement new physical processes in public computational codes for model atmosphere and spectral synthesis. Several physical processes need to be introduced or updated in the calculation of both the atmosphere model and the emerging flux, for instance: (1) an appropriate treatment of the non local thermodynamical equilibrium in spectral synthesis, (2) the impact of three-dimensional geometry on the model atmospheres, (3) updated physics for collisional broadening in the calculation of the line profile, (4) the impact of non standard chemical mixtures in classical one dimensional models.
The candidate will have the opportunity to develop various aspects of the project, interacting with astronomers from other European institutions who are experts in NLTE and 3D models atmospheres.

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DIPARTIMENTO DI FISICA E ASTRONOMIA
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PhD project in ASTROPHYSICS

Title of the Project: *Gravitational waves from black-hole binaries in evolving galaxies*

Supervisor: Carlo Nipoti (UniBo)

Scientific Case:
The detection of gravitational waves (GWs) by the LIGO/Virgo/KAGRA collaboration has revolutionized our understanding of the Universe, providing direct insights into the population of compact objects, and in particular stellar mass black holes (BHs). The future GW detectors Einstein Telescope, Cosmic Explorer, and LISA, in synergy with pulsar timing array experiments such as that of the NANOGrav Collaboration, will significantly enhance our ability to detect GWs also from other categories of BHs, such as the supermassive BHs (SMBHs) that seem ubiquitous in massive galaxies, the more elusive intermediate mass BHs (IMBHs). The occurrence and evolution of binary SMBHs and IMBHS depends crucially on the BH-galaxy connection and on the galaxy merger history.

Outline of the Project:
The aim of this project is to improve our understanding of some properties of different categories of BHs. For SMBHs we can explore the possibility of using observational constraints on the redshift-dependent galaxy properties and merging hierarchy to sharpen the predictions of low-frequency GW from SMBH binaries (see Ellis et al. 2024). For GWs from IMBH binaries we can investigate models with realistic and redshift-dependent properties of the hosts, which are expected to be globular clusters (or their progenitors) and dwarf galaxies (see Khan et al. 2024). IMBHs hosted by satellite stellar systems orbiting larger galaxies can coalesce and emit GWs if dynamical friction is efficient (Giunchi et al. 2025), while they would survive as wandering BHs if the satellites are disrupted in the host's outskirts (Nipoti 2025). The relationship between galaxy-evolution processes and GW emission will be studied with state-of-the-art numerical codes such as KETJU (Mannerkoski et al. 2023).

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References:

- Ellis, J. et al., 2024, Phys. Rev. D, 109, 2, L021302
- Khan, F. et al. 2024, ApJ, 976, 1
- Giunchi E., Marinacci F., Nipoti C., et al. 2025, A&A, 701, A129
- Nipoti C., 2025, A&A, 697, A74
- Mannerkoski M., Rawlings A., Johansson P.H., et al., 2023, MNRAS, 524, 4062

Bologna, 6/3/2026

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DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: *Global stability of stellar discs with dark matter halos*

Supervisors: Carlo Nipoti (UniBo), Luca Ciotti (UniBo), Silvia Pellegrini (UniBo)

Scientific Case:

Thin stellar discs are prone to global instability and bar formation. The formation and evolution of the bar is an open research field, addressed by means of N-body simulations since the early 1970s (e.g. Ostriker and Peebles, 1973). Some criteria have been studied to understand the conditions for the development of global instabilities in the stellar disc leading to bar formation. The most common global stability parameter, due to Ostriker and Peebles (1973), is $t=T/|U|$, where T is the ordered kinetic energy of the system and U is the total gravitational energy. An alternative global stability parameter has been proposed by Efstathiou et al. (1982): $t^*=T^*/|W^*|$, where now T^* is by definition the stellar order kinetic energy and W^* is the trace of the gravitational interaction energy tensor of the stars in the total gravitational potential.
Whether either of these parameters is sufficient to describe the global stability of stellar discs in the presence of dark matter halos is still debated (see Romeo et al. 2023).

Outline of the Project:

In this project, the student will study the global stability of stellar discs in the presence of dark matter halos, using high-resolution N-body simulations. Following the approach of the preliminary explorations of Caravita (2022) and Cantarella (2023), the student will construct N-body realizations of equilibrium two-component galaxies, with stellar disc and dark matter halos. The considered systems will differ greatly ranging from simpler cases of thin discs with "frozen" dark matter halos to more realistic cases of thick discs with "live" dark matter halos, for which a careful study of the distribution functions will be necessary. The stability of these systems will be studied by following their evolution with N-body simulations. The results of the simulations, combined with the measurement of the parameters t and t* of the initial conditions, will allow to draw conclusions on the proposed stability criteria and possibly also to construct new stability criteria.

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References:

- Ostriker, J. P. and Peebles, P. J. E., 1973, ApJ, 467-480
- Efstathiou, G., Lake, G. and Negroponte, J., 1982, MNRAS, 199, 1069-1088
- Romeo A. B., Agertz O., Renaud F., 2023, MNRAS, 518, 1002
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Bologna, 6/3/2026

PhD project in ASTROPHYSICS

Title of the Project:
Simulations of the collisional evolution of globular clusters with Monte Carlo methods

Supervisor: Carlo Nipoti (UniBo)
Co-supervisor: Raffaele Pascale (INAF-OAS)

Scientific Case:
Globular clusters are the perfect environment to study the evolution of stellar systems over timescales where the effects of collisionality on their dynamics cannot be neglected. Indeed, globular clusters are dynamically old, dense agglomerates of stars with relaxation time (i.e. the time needed by the stars to redistribute efficiently their energy due to two body encounters) way shorter than the age of the Universe, which makes them susceptible to processes of energy equipartition, mass segregation and gravitational evaporation. In this context, Monte Carlo (Henon 1971) algorithms are a special family of methods, alternative to and less computational expensive than N-body simulations, suited to follow the long time, dynamical evolution of stellar systems once the integrals of motion of their tracers are perturbed to account for two-body interactions.

Outline of the Project:
The PhD student will develop a novel version of the orbit-averaged based Monte Carlo method presented in Sollima and Mastrobuono Battisti (2014), optimized to model spherical stellar systems as globular clusters with the inclusion of binaries, stellar evolution and external tidal force fields (e.g. Sollima and Ferraro 2019,). The code, first developed in Fortran77, will be partially ported in Python and complemented by flexible tools to handle the statistical and graphical analysis of typical outputs of the codes, as well as new features to account in the models for central intermediate massive black holes, a continuous mass spectrum in the initial distribution of stars, and more general initial conditions. From the model it is possible to compute observables to be directly compared with observations of real globular clusters. The software will be then used to model the dynamical evolution of a set of globular clusters orbiting around the Milky Way to study mass segregation and the effect of massive dark remnants (e.g. black holes) at the center of the system.

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References:
- Hénon M.H., 1971, ApSS, 14, 151
- Sollima A., Mastrobuono Battisti A., 2014, MNRAS 443, 351
- Sollima A., Ferraro F.R., 2019, MNRAS, 483, 1523

Bologna, 6/3/2026

PhD project in ASTROPHYSICS

Title of the Project: Exploring binary millisecond pulsars in globular clusters through optical/near-infrared observations.

Supervisor: C. Pallanca
Co-Supervisors: M.Cadelano, F.R. Ferraro, B. Lanzoni

Scientific Case:
Globular clusters (GCs) are old, compact and dense gravitationally bounded stellar systems. They are collisional systems and are the main efficient factories of peculiar stellar populations, as millisecond pulsars (MSPs). In fact, the number of MSPs per unit mass in the Galactic GC population is significantly larger than in the Galactic field. MSPs are stable and fast rotating neutron stars, emitting a collimated radio periodic signal (e.g. usually described with the "lighthouse" model) with typical periods of milliseconds. The main formation scenario of these object is commonly known as the "recycling scenario", according to which a NS is spun up by mass accretion in a binary system. In this context MSPs companions are expected to be He-white dwarfs (WD, i.e. the residual cores of the peeled companions that recycled the pulsars). However, even if several He-WD companions have been already identified as companions to MSPs, a zoo of unique objects is emerging. This is not surprising considering the host environment. Indeed, the active innermost regions of GCs may perturb the canonical evolution of these binary systems.

Outline of the Project:
The unprecedented power of recent radio telescopes (e. g. MeerKAT and FAST) is propelling MSPs detection into a thriving era. Taking advantage of this significant improvement, the Galactic globular cluster MSP population has increased by >80% in the last years. Therefore, the time is ripe for a thorough study of companions to binary MSPs in GCs. A photometric search for companions to binary MSPs hosted in GCs will be performed. For each target, the astrometric position, the CMD location and the presence of variability will be investigated. To achieve these goals, multi-filter and multi-exposure data-set at high spatial resolution, such as proprietary and archival JWST and HST observations, will be used. The optical identification of the companion stars to MSPs will bring key information on the nature, the physical parameters, the evolutionary processes and the recycling mechanisms occurring in these systems. Secondly, the full characterization, in synergy with radio and X-ray studies, of binary MSPs will enable a wealth of groundbreaking scientific applications, such as testing general relativity and alternative theories of gravity, studying stellar and binary evolution and constraining the equation of state of matter at the nuclear equilibrium density, thus eventually opening a new window in the domain of Fundamental Physics research. Finally, linking the current properties of the MSP population to the internal dynamical status of the host cluster, will clarify the role that the most massive objects/binaries play in the evolution of GCs, and, vice versa, the role that internal dynamical processes play in the evolutionary path of these objects. Such a project will set the stage of our understanding of the population of MSPs.

Main external Collaborators: Emanuele Dalessandro (OAS-Bo), Paulo Freire (Max Planck Institute, Germany), Craig Heinke (Alberta University, Canada), Scott Ransom (NRAO, USA), Alessandro Ridolfi (Bielefeld University, Germany)

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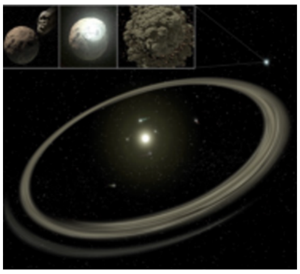

Title of the Project:

Formation and evolution of solar system analogs: gravitational interaction with planets and/or external perturbers

Supervisor : Veronica Roccatagliata

Scientific Case: Solar system analogs host a remnant of the protoplanetary disks around the central star, the so-called debris disks. These are formed as a by-product of planet formation and consist of planetary remnants such as dust, gas, and planetesimal belts. Due to dust's short lifespan, it requires continuous replenishment through planetesimal collisions. Moreover, substellar companions can significantly influence dust and planetesimal dynamics through gravitational effects. Even small planets can leave distinctive marks on debris disk structures, while misaligned planets or those with elliptical orbits may reveal past gravitational interactions, also during a flyby. N-body simulations, SPH simulations, and collisional evolution models of debris disks predicted peculiar substructures induced by planet-disk interaction which might be potentially observable. Flybys can also be responsible of a perturbation of the dynamical interaction in the debris disk system. However, recent observations suggest the close encounters can be fundamental even for the formation of the debris disk systems themselves.

Outline of the Project: The student will first collect a sample of debris disks highlighting the resolved ones at different wavelengths, and those with planets.
A coherent characterization of the stellar properties of the central star hosting the debris disks will be obtained by the student in clusters and isolated objects. This will be done via spectroscopic analysis and/or via spectral energy distribution. Timescale of collisions in debris disks will be here constrained when multi-epoch observations of the far-infrared excess are available.
Next, the student will develop a comprehensive analysis of the Gaia DR4 astrometric data to reconstruct the flyby experienced by the system during its life. This will be done first with a linear approximation to statistically constrain the frequency of at least one close flyby.
According to the attitude of the student the project will proceed in different ways. One possibility is the proper dynamical reconstruction of the multiple flybys with the relative orbit deviation. Another possibility is the reduction of new high-contrast imaging observations (already available) of the debris disk systems. The student will then led new proposal on a particular sample of debris disks.
The student will be part of the DIFA research group "Origin and evolution of planetary systems", and will work in collaboration with a national and international network of colleagues.

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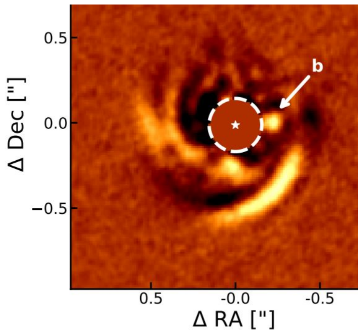
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS



Title of the Project:

Formation of planets in protoplanetary disks

Supervisor : Veronica Roccatagliata

Scientific Case: High angular resolution observations of dust continuum at millimeter wavelengths (with ALMA) and high contrast imaging observations of scattered light in the near-infrared obtained spectacular observations of protoplanetary disks, revealing the presence of sub-structures in the dust and gas distribution, such as inner dust cavities and ring-like structures, vortices and spirals. Several mechanisms have been proposed to explain the origin of such sub-structures such as: dynamical interaction between the disk and protoplanets; magneto-rotational instability, condensation fronts or photoevaporation.
Confirmed evidence of two young protoplanets have been obtained so far only in the dust cavity of the disk around PDS 70.
A new instrument at the VLT, ERIS, provides a unique opportunity to study these structures at high angular resolution using coronagraphic imaging. As member of the INAF/GTO team, we are conducting a large program to look for thermal emission from protoplanets in structured protoplanetary disks at different stages of their evolution. Data obtained in open time are also available.

Outline of the Project: In the first step, the student will analyze coronographic observations of AS 209 obtained with two different coronographs of ERIS, the vector Apodizing Phase Plate (vAPP) and the annular groove phase mask (VORTEX) coronagraphs. This will allow a training of the student in the calibration and reduction of the data, using the available pipeline and comparing data obtained with broad and narrow band filters. The data post processing will proceed with different techniques as, the angular differential imaging (ADI) and the annular principal component analysis (PCA) based algorithm which emphasizes the non axisymmetric structures in the disk, as well as point like sources. Other sophisticated post-processing will be explored by the student, with the possibility of visiting the developers of those techniques. The student will have the possibility to go to Paranal to perform the observations planned in the next years. The student will be hence responsible few systems, combining the results obtained with ERIS with the resolved substructures resolved in the disk at different wavelengths. He/She will also be encouraged in leading new proposals on a particular sample of disks.
This thesis will make the student one of the few experts around the world on high-contrast imaging. This expertise will be particularly important also for the new instruments on ELT, where both, APP and VORTEX coronographs will be mounted e.g. on METIS and MICADO.
The student will be part of the DIFA research group "Origin and evolution of planetary systems", and will work in collaboration with a national and international network of colleagues.

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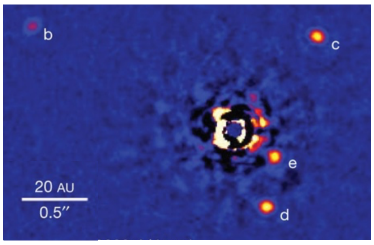
PhD project in ASTROPHYSICS



Title of the Project:

Planet formation in low-metallicity environments

Supervisor : Veronica Roccatagliata

Scientific Case: A peculiar class of systems is represented by λ Bootis stars are one of the most metal poor classes of nearby objects. These chemically peculiar late B to mid F stars show a depletion in metals heavier than Si but with solar abundances of C, N, O and S. Uniformly distributed among the evolutionary phases, the origin of their chemical peculiarity is still under debate: they are uniformly located in the solar neighborhood, which is a metal rich environment, but they are poorer than the Sun in elements heavier than Si. Such a peculiarity is likely due to a selective mechanism which can reproduce underabundances only of heavy metals.
In the so-called *accretion scenario* for the λ Bootis stars, the refractory elements heavier than the Si are locked in the dust while lighter elements are gaseous and are being accreted onto the star. According to the core accretion model of planet formation heavy metals will remain trapped in dust grains which will form the core of a proto-giant planet. This mechanism may lead to a metal depletion of the disk from which the star accretes metal-poor gas.
In some λ Bootis stars a low-mass companion and even a planetary system has been detected (e.g. HR 8799). A possible relation to planet formation of this class of object needs to be explored in a homogenous way.

Outline of the Project: A radial velocity survey of about 100 λ Bootis stars has been obtained to look for close-in low mass companions. The student will first analyze the available optical high-resolution spectra obtained with the FEROS spectrograph. As soon as the project will start, he/she will lead follow up proposal to complete the λ Bootis looking for short period candidates, as well as re-observe sources with observations already available to look for companions with longer periodicity. With an ad-hoc cross-correlation technique specifically extended to early type stars, radial velocities will be computed with an accuracy better than 25 m/s. He/she will determine: the radial velocity variation, the projected rotational velocity, and the stellar activity of these stars. Moreover, the high S/N and large wavelength coverage of the spectra will allow us to determine the abundances of several elements, including e.g. Na, Mg, Ca, Ti and Fe.
According to the attitude of the student, for the closest objects the project may include also the search for planetary companions at higher distances for the host star than those detected via RV using high contrast imaging (as the case of HR 8799) and/ astrometry (using the Gaia DR4). The student will be part of the DIFA research group "Origin and evolution of planetary systems" and will work in collaboration with an international network of colleagues expert on metal poor stars and planet search.

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DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: Exploiting the Euclid Legacy for galaxy evolution with ELSA

Supervisor : Margherita Talia
Collaborators : ELSA team members

Scientific Case:
Euclid is an ESA space telescope launched in July 2023, designed to understand the nature of dark energy and dark matter. To achieve this, Euclid is observing over a third of the sky with high resolution imaging and spectroscopy, which will establish "the" reference map of the extra-galactic celestial sphere for decades to come. The giant archive produced will be a goldmine to study the history of the formation and growth of galaxies over the age of the Universe, driving answers to many fundamental science questions on the co-evolution of galaxies and supermassive black holes, the interaction between stars, gas, and galactic nuclei in galaxies at cosmic noon, and excelling in the discovery of rare objects including gravitational lenses.

Outline of the Project:
The main objective of this project will be the update/development of existing/new tools for spectro-photometric analysis (i.e. combining both spectroscopic and photometric data) and their application to Euclid data from the first and second data releases (DR1-DR2) in order to extract a wide range of physical parameters, including star formation history, dust emission, and metallicity, providing a complete understanding of the physical and chemical properties of the galaxies observed by Euclid.
The project will consist of the following main steps:

1) Do a complete census of existing spectro-photometric codes, to be tested and adapted to Euclid data using custom simulated photometric catalogues and spectra. If needed, develop a new tool for spectro-photometric analysis specifically tailored to the analysis of very large datasets. The application of machine learning algorithms will also be explored.
2) Test the feasibility of spectro-photometric analysis on individual galaxies and select a suitable sample from the Euclid dataset. Build stacked datasets using the codes already developed at DiFA (Quai et al., in preparation) in order to extend the analysis to the faint tail of the parameters space.
3) Perform spectro-photometric analysis on individual and stacked Euclid data and derive physical properties for different galaxy populations (i.e. "normal" star-forming galaxies, passive galaxies and AGN). Study the evolution of scaling relations (e.g. mass-age, mass-metallicity) with redshift and the possible dependence on environment.
4) Compare the results to state-of-the-art theoretical models (e.g. GAEA), in order to put them into the broader context of galaxy evolution.
5) Publish the scientific results and make the new tools available to the wider community through their implementation into the ESA datalabs.

The PhD project will be carried out as part of the Euclid Legacy Science Advanced Analysis

Tools (ELSA) program, an HORIZON-EU funded project (PI: M. Talia) aimed at exploring new methodologies and creating cutting-edge pipelines, tools and algorithms in order to maximally exploit the legacy value of Euclid spectroscopic data for galaxy evolution studies. In particular, the successful applicant will work in the framework of the Work Package 2 (1D-spectra) and in close collaboration with ELSA team members both in Bologna (namely S. Quai at DiFA and L. Pozzetti and M. Bolzonella at INAF-OAS) and in the other institutes that are part of the collaboration. ELSA membership will give access to reserved computational resources of the cluster inside the Open Physics Hub (OPH) at DiFA. Also, the PhD student will enter the Euclid collaboration and gain priority access to all the data collected by the telescope.

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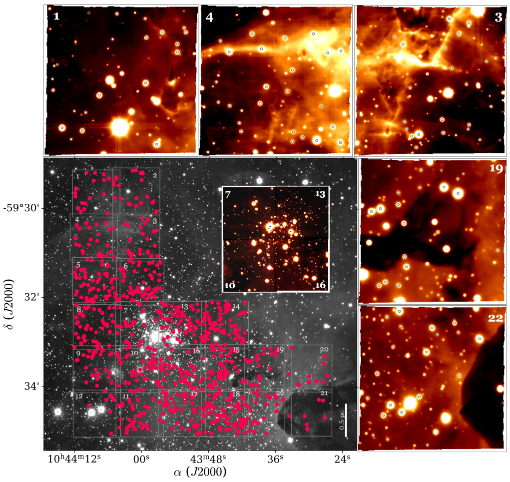
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: ***Protoplanetary disks and planet formation in space and time***

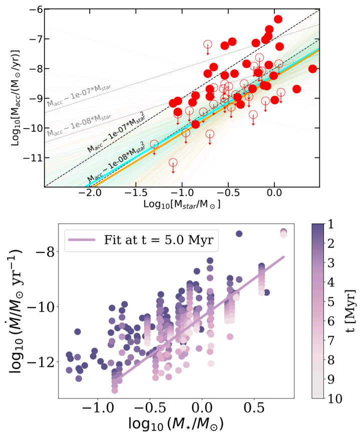
Supervisor: Leonardo Testi (DIFA/UniBo)
Partners: Giuseppe Lodato (UniMi), Carlo Manara (ESO), Megan Raiter (Rice University)

Scientific Case: Exoplanetary systems show a vast variety of architectures, and the Solar System seems to be a rare occurrence. Nevertheless, the basic physical and chemical processes that shaped our own cosmic home appear to be common, but the devil is in the details: how diverse are the evolutionary path that lead to fully formed planetary systems? Planet formation is mostly observationally constrained by its effect on the protoplanetary disk, and the eventual outcome is determined by the interplay between disk initial conditions, disk evolution, and disk-planet interaction. We are engaged in a multifaceted project that includes the development and use of a disk population synthesis code, large ALMA/VLT surveys of disk populations in different galactic environments, and innovative machine learning tools to analyse the simulated and observed datasets. The final goal is to use this diverse set of data and tools to constrain the timeline of planet formation as a function of stellar and environment properties.



VLT/MUSE survey of young stars with disks in the Tr14 cluster (Itrich+2024)

Outline of the Project: The student will analyze spectroscopic integral field data from the VLT/MUSE instrument, obtained as part of a large survey of young stellar objects with disks in different star forming regions. The data analysis will be carried out by applying, and in some cases improving upon procedures developed within our group (e.g. Itrich+2024, Kang+2023, 2024). The bulk parameters of protoplanetary disks populations as a function of age and environment will be compared with population synthesis analysis, also developed by our group (Testi+2022, Somigliana+2023, 2024). Depending on the inclinations of the student and the progress of the research project, the emphasis of the activity could lean more on the observations or population synthesis, but both aspects will be included. The final goal of this project will be to derive a solid statistical understanding of the disk properties as a function of age, an essential constraint on the outcome of the planet formation process.



Examples of observed (top, Testi+2022) and simulated (bottom, Somigliana+2024) protoplanetary disk populations

The student will be part of the DIFA research group "Origin and evolution of planetary systems", and will work in collaboration with an international network of colleagues from Italy, Germany and USA.

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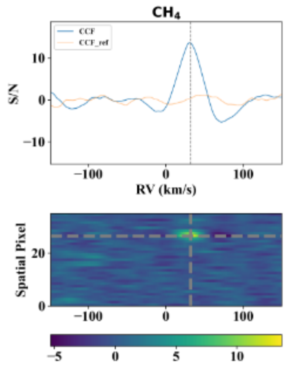
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

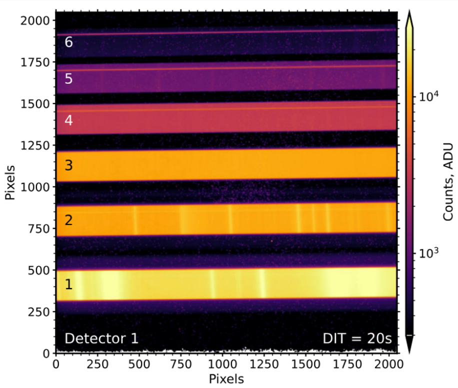
Title of the Project: ***High dispersion spectroscopy of exoplanet atmospheres***

Supervisor: Leonardo Testi (DIFA/UniBo)
Partners: Lorenzo Pino (INAF-Arcetri), Giulia Roccetti (ESA)



Detection of CH4 in the ßPictoris b exoplanet atmosphere (Peng+2026)

Scientific Case: Exoplanetary Science is rapidly evolving from detection of planets to the characterization of their physical properties, especially their atmospheres physical and chemical properties. Following the initial studies of atomic species in the optical, high dispersion spectroscopy in the infrared is now allowing the analysis of the presence and abundance of molecular species like H_2O, CO, and CH_4, and detection of SiO and CO_2 in the thermal infrared are also possible. In the future, the goal of this research is to constraint the chemistry of atmospheres, including N-bearing and S-bearing molecules, to search for "habitable" atmospheres around temperate planets, and eventually define strategies to detect biosignatures in exoatmospheres. For the latter topic, understanding the observable signatures of the Earth atmosphere is one key step.



VLT/CRIRES+ observations of ßPictoris at 4um, which allowed the first detection of SiO in the planetary atmosphere (the planet is too faint to be visible in these raw images, Parker+2025)

Outline of the Project: For this research topic, the student can chose to focus on one of three separate avenues of research: analysing observations of planet Earth, analyse observations of exoplanet atmospheres, or development of hardware, software, and simulations for future instruments aimed at characterizing exoplanetary atmospheres. Earth observations are collected using space probes or through the observation of Earthshine on the Moon (e.g. Roccetti+2025). Exoplanetary atmosphere observations are collected mostly using high dispersion spectrographs at the TNG and VLT (e.g. Pino+2022, Parker+2024). Design and construction of instrumentation for this purpose is primarily targeting the next generation instruments for the ESO VLT and ELT observatories.

The student will be part of the DIFA research group "Origin and evolution of planetary systems", and will work in collaboration with an international network of colleagues.

Contacts: Leonardo Testi (leonardo.testi@unibo.it)

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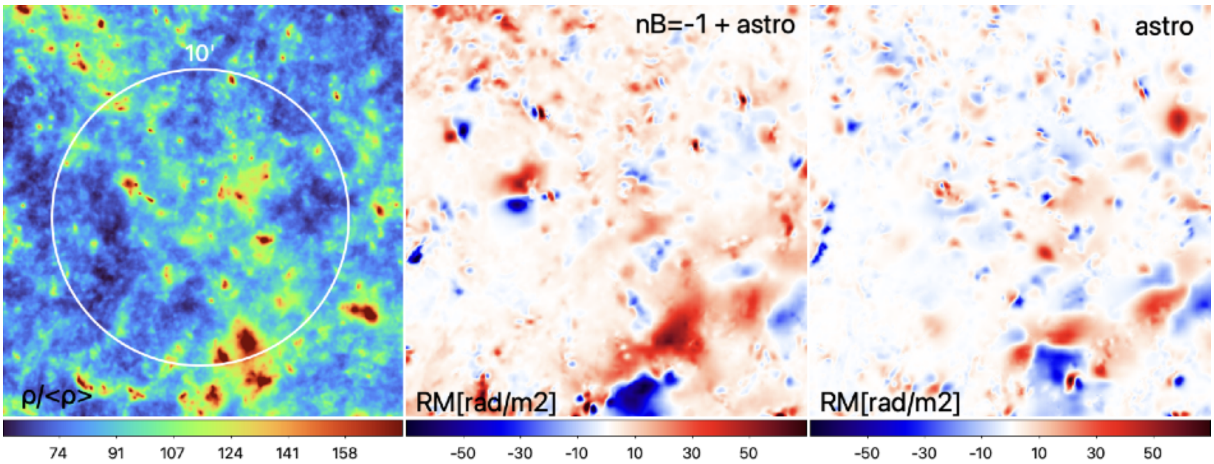
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project:
Faraday Rotation to probe the topology of the magnetic cosmic web
La Rotazione di Faraday per sondare la topologia della rete magnetica del cosmo

Supervisor : *Prof. F. Vazza (Università di Bologna)*
Co-supervisors*: Dr. E. Carretti (IRA/INAF), Dr. S. Mtchedlidze (Università di Bologna)*

Scientific Case: the Faraday Rotation effect on the polarised emission from distant radio galaxies has been proven to be a powerful probe of intergalactic magnetic fields, and is one of key observable quantities measured by all modern radio surveys. Indeed the recent analysis of the LOFAR LOTSS radio survey has led to the detection of Faraday Rotation increasing with the redshift of sources, which can only be explained by the presence of widespread magnetic fields, compatible with large-scale magnetic fields generated in the very early Universe (e.g. Carretti, Vazza et al. 2024). However, disentangling the actual contribution to Faraday Rotation from the cosmological component from the local one by the host radio galaxies, and from the Milky Way foreground is challenging, and several statistical techniques are being tested (e.g. Mtchedlidze et al. 2026). Accurate cosmological Magneto Hydro Dynamical (MHD)



Simulated baryon density (left) and Faraday Rotation from two different models of cosmic magnetism in a recent cosmological simulations produced for the case of the Square Kilometre Array.

simulations are fundamental to test physically motivated models for the evolution of magnetic fields in the Universe (including primordial and astrophysical seeding scenarios) and to predict the signals which can be tested with the current generation of radio telescopes: e.g. with LOFAR at low frequencies or ASKAP at high frequencies already now, or with the the Square Kilometre Array starting from 2032.

Outline of the Project: the PhD candidate will produce and analyse new cosmological MHD simulations and also perform post-analysis on real radio survey data, which are and will be publicly available during the project, in order to study cosmic magnetism on largest possible range of redshift and volume. The final goal is to design and refine new observational strategies to constrain the topology of cosmic magnetic fields through the analysis of Faraday Rotation from extragalactic polarised sources, and produce timely results which can be immediately of use to the rest of the astrophysical community. The PhD candidate will have the opportunity to build a unique scientific profile, combining the expertise in High Performance Computing simulations of the cosmic web with the analysis and interpretation of actual radio data from modern radio telescopes. This project calls for candidates with some experience in numerics, in data modelling and statistics, and a strong curiosity to explore new ways to study magnetism across cosmic epochs and connect it to cosmology and fundamental processes in the very Early Universe.

The PhD candidate will work in a collaborative environment, in close contacts with the other members of Prof. Vazza's group, both at the University of Bologna and with other closely related groups at the Universities of Paris, Stockholm and at CERN.

Contacts: franco.vazza2@unibo.it

PhD project in ASTROPHYSICS

Title of the Project: Dual and binary super-massive black holes candidates in the gravitational-wave era

Supervisor: C. Vignali (DIFA)
Co-supervisors: P. Severgnini (INAF-Brera), A. De Rosa (INAF-IAPS)

Scientific Case: Hierarchical models of galaxy formation predict that galaxy mergers represent a key transitional stage of rapid super-massive black hole (SMBH) growth. Merging SMBHs are among the loudest sources of gravitational waves (GWs) in the Universe and will be detectable with the future large ESA mission LISA. Yet, the connection between the merging process and enhanced AGN activity (hence the triggering and the level of nuclear emission) remains highly uncertain, affected mainly by the lack of a thorough census of dual AGN over cosmic time. Precise demography of dual SMBHs and the occurrence of AGN activity is currently hampered by the adopted detection techniques, sensitivity and spatial resolution issues, and the increasing evidence that dual AGN at kpc scales are more heavily obscured than in isolated systems (e.g., De Rosa et al. 2019). Despite the intensive observational efforts to search for dual and offset AGN (where only one member of the pair is active) in the last decade, how common they are and the link with their host galaxy properties and close environment are still open questions. It is therefore mandatory to overcome the current limitations through an optimal exploitation of the complementarity between observations and numerical techniques.

Outline of the Project: The current PhD project will investigate some of the following topics: (a) the occurrence of dual and offset AGN by cross-matching large-area optical/near-IR survey galaxy pairs (including SDSS, LEGA-C, and the recently released DESI catalog) with Chandra and XMM-Newton catalogs and inferring the level of nuclear activity via multi-wavelength data and X-ray spectral analysis; (b) the presence of dual AGN in some of the deepest X-ray fields currently available (CDF-S, CDF-N, COSMOS, Abell2744), expanding the view to high redshift; (c) the content of dual AGN, likely associated with intermediate-mass BHs, in dwarf galaxies using spatially resolved BPT diagrams; (d) binary AGN candidates using X-ray and optical monitoring programs. Eventually, the PhD candidate will be able to conduct an intensive study of the currently known dual AGN in terms of BH mass ratio and host galaxy and environment properties. The derived source demography and physical properties obtained through multi-wavelength data will be interpreted and fitted into a coherent framework using state-of-the-art numerical simulations. The PhD student will also be introduced to the use of MUSE, ALMA, HST, VLT, and JWST data to fully characterize dual AGN and their hosts, and will be included in some of the major GW collaborations (LISA, LGWA, ET).
She/he will gain significant skills in data analysis and interpretation and proposal writing, develop scientific independence, present her/his work at national/international conferences, and have the opportunity to visit renowned research institutes and universities as part of the collaboration.

Contacts: C. Vignali – DIFA (cristian.vignali@unibo.it); P. Severgnini – INAF-Brera (paola.severgnini@inaf.it); A. De Rosa – INAF-IAPS (alessandra.derosa@inaf.it).

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PhD project in ASTROPHYSICS

Title of the Project: Shedding light on the physics of the most massive and highly accreting SMBHs up to Cosmic Noon through a multi-wavelength study

Supervisor: C. Vignali (DIFA)
Co-supervisors: E. Piconcelli, L. Zappacosta (INAF-Osservatorio Astronomico di Roma)

Scientific Case: Understanding the physics of accretion in highly accreting systems across cosmic epochs requires studying the tight coupling between the UV emission of the disc and that of the X-ray emitting corona. This, in turns, is crucial for studying the incidence of winds and assessing, from a physical and demographic perspective, the role of quasar-driven feedback in shaping galaxies up to Cosmic Noon.

Outline of the Project: In this project, accretion physics is tackled starting from the sample of WISE/SDSS selected hyper-luminous (L_{bol}>10^{47} erg/s) quasars at z∼2−4. These quasars are characterized by large Eddington ratios (λ_{Edd}), thus probing accretion at its 'extremes', and have multi-wavelength data allowing for a comprehensive investigation of their properties. Among the many possible open issues related to nuclear accretion at Cosmic Noon, we would like to focus on (a) the properties of quasar host galaxies (e.g., star-formation (SF) rates, molecular gas content) via spectral energy distribution (SED) fitting and millimeter (ALMA) observations; (b) the nature of X-ray weak quasars at z∼3 (∼30% of the population) and their occurrence at earlier cosmic epochs, thus providing an interpretation in the context of accretion-disc physics of highly accreting SMBHs; (c) the link between quasar accretion and nuclear extinction in the path to properly investigate the claimed blow-out (feedback) phase. The properties of the analyzed quasars will be compared with those of local AGN to obtain a comprehensive view of accretion across cosmic time. To this end, the candidate will investigate the broad-band (SED and CO spectral-line energy distribution) properties of PDS456, a highly-accreting quasar at z=0.18 that can be considered a low-*z* analogue of WISSH quasars; for this source, the recently available JWST data will provide clues about accretion and star formation, and their relative role in the observed feedback. Finally, to further investigate accretion in highly accreting quasars, the candidate will also evaluate the properties of relatively faint X-ray quasars selected among the highest-λ_{Edd} sources in the SDSS-DR14 catalog and provide the most accurate overview possible of the accretion processes, thus paving the way for the X-ray mission NewAthena.

The PhD student will gain invaluable expertise in multi-wavelength data mining, analysis, and interpretation, in preparing observing proposals, and in presenting the work at national/international conferences. She/he will join the WISSH collaboration, take advantage of the interactions with researchers of Italian and foreign institutes, and do preparatory work for the forthcoming ground- and space-based facilities (e.g., Vera C. Rubin Observatory, Roman Space Telescope, NewAthena).

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PhD project in ASTROPHYSICS

Title of the Project: The realm of the high-redshift Universe unveiled by JWST

Supervisor: Cristian Vignali (DIFA)
Co-Supervisors: F. Vito (INAF-OAS), S. Marchesi (DIFA)

Scientific Case: In the last few years, the James Webb Space Telescope has revolutionized our view of the high-redshift Universe through the discovery of a significant number of galaxies and Active Galactic Nuclei (AGN) up to very high redshift, probing the first hundreds million years of the Universe. Among its main discoveries, JWST has been able to detect black holes down to about 10^6 $M_\odot$ at $z>5$, i.e. three orders of magnitude lower than probed by the SDSS; interestingly, most of the current JWST-detected AGN (and candidates) are host in under-massive galaxies (compared to local relations), which suggest a complex path for AGN and galaxies in reaching the local `Magorrian relation'. Claims of accretion-related activity have been formulated for the Little Red Dot (LRD) population, i.e. faint AGN candidates detected by the deep JWST surveys, associated with red compact sources experiencing episodes of star formation. What is currently partially missing is a proper and systematic broad-band characterization of both AGN (candidates) and LRD populations taking advantage of the deep X-ray exposures in e.g. the CEERS, JADES, and Abell 2744 fields.

Outline of the Project: The main goals of the proposed PhD project include <u>some</u> of the following topics: (a) to provide a physical characterization of the AGN thus far discovered at high redshift ($z>4$) by JWST using the available rich ancillary multi-band datasets; (b) place constraints on the accretion-related activity in the LRD and galaxy populations using X-ray data coupled with multi-band SED fitting. At present, the paucity of X-ray emission in high-z JWST-selected AGN points towards either significant obscuration or super-Eddington accretion; in-depth investigations are crucial to clarify the situation. (c) provide an updated census of the dual and offset AGN population at high redshift through a multi-wavelength approach. The recently JWST-derived higher fraction of dual AGN at high redshift compared to low redshift, if confirmed, needs to be interpreted using the most up-to-date predictions coming from simulations, and the mechanisms possibly driving the enhancement at high redshift (larger molecular gas content? higher merger rates?) should be investigated.
Overall, the proposed strategy will shed light on the emergence of nuclear accretion activity in the first two billion years of the Universe and allow us to reach a comprehensive picture of the black hole accretion rate density at high redshift.

The PhD candidate will be trained in the selection and characterization of AGN, fully exploiting the wealth of multi-wavelength data currently available. She/he will learn how to handle, analyze, and interpret multi-band data, and will gain expertise in proposal writing and presenting the work at international conferences. Besides, she/he will have the opportunity to collaborate with international research groups, thus gaining invaluable experience for a career in astrophysics.

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PhD project in ASTROPHYSICS

Title of the Project: AGN physics and demography in the XMM-Newton-Euclid Fornax Deep Field

Supervisor: Cristian Vignali (DIFA)
Co-Supervisors: E. Piconcelli (INAF-Osservatorio Astronomico di Roma), M. Bolzonella (INAF-OAS), L. Barchiesi (University of Cape Town)

Scientific Case:
The Euclid mission's twofold observing strategy – a Wide Survey covering 14000 deg^2 with near-IR grism spectroscopy and photometry across visual and near-IR wavelengths, and a Deep Survey going two magnitudes fainter over 50 deg^2 – will allow, among the multiplicity of scientific goals, to systematically study large-scale structures, clusters of galaxies, and Active Galactic Nuclei (AGN) across cosmic time. The awarded XMM-Newton Multi-Year Heritage program (3.5Ms) has recently started observing at 40ks depth the 10 deg^2 of the Euclid Deep Field Fornax, centered on the Chandra Deep Field South; coupled with the current and forthcoming multi-wavelength coverage (e.g., ultra-deep Rubin-LSST), this field will be a benchmark for astrophysics in the years to come. On the AGN side, ~7000 AGN will be detected in X-rays, including ~100 at $z>3$; under conservative assumptions, about 2000 AGN will allow moderate-to-good quality X-ray spectroscopy for proper source characterization. It will then be possible to (i) trace obscured accretion up to high redshift, (ii) study the co-evolution of AGN and their host galaxies and the role of feedback, (iii) determine the presence of AGN in clusters of galaxies at different redshifts, and (iv) search for proto-clusters and large-scale structures at high redshift using AGN as tracers of massive halos.

Outline of the Project: The main goals of the proposed PhD project are (a) to create a catalog of obscured AGN using spectral energy distribution (SED) fitting and hardness-ratio analysis (in the low X-ray photon regime); for about one-third of the X-ray AGN, it will be possible to adopt physically motivated models, providing insights on the geometry and thickness of the absorbing medium. This search will allow us to derive a reliable census of the black hole accretion rate density over a wide range of environments and across cosmic time, thus overcoming the limitations of previous studies in terms of area, depth, sample size, and cosmic variance; (b) to investigate the quasar evolutionary sequence of SMBH/host galaxy co-evolution and the claimed transition of quasars from an initial heavily dust-enshrouded phase to a 'blow-out' phase, when radiation and outflows (hence 'feedback' processes) from the accreting SMBH blow away the dust and gas to reveal a blue quasar hosted in a quiescent galaxy.

The PhD candidate will be trained in all the project steps, from AGN selection to their physical characterization, using the available multi-wavelength data, *in primis* XMM-Newton and Euclid. She/he will learn how to handle, analyze, and interpret multi-band data, and will gain expertise in proposal writing and presenting the work at international conferences. The student will be granted collaborations with internationally recognized and active research groups.

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