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PhD project in ASTROPHYSICS

Title of the Project: Reconstructing the hierarchical assembly of dwarf galaxies with EUCLID

INAF-OAS Supervisor: F. Annibali

Co-Supervisors: M. Bellazzini, R. Pascale

Scientific Case:

Being the most numerous galaxies in the Universe and the first to have formed, dwarf galaxies are central systems in cosmology, yet many questions related to their mass assembly and star formation are still poorly understood. Studies of their most external, low surface brightness regions can provide crucial insights into their assembly history, hosting the direct signature of past merging events with smaller satellites. However, direct evidence of satellites' accretion into dwarf galaxies is very poor so far, mostly because of the difficulty in detecting faint companions or merger signatures around them.

The EUCLID satellite, which has been launched in July 2023, is going to revolutionize this field. Thanks to its large field of view and high spatial resolution, EUCLID will provide sharp images of large portions of the sky that will reveal for the first time the low surface brightness extensions of dwarf systems and their faint satellite population.

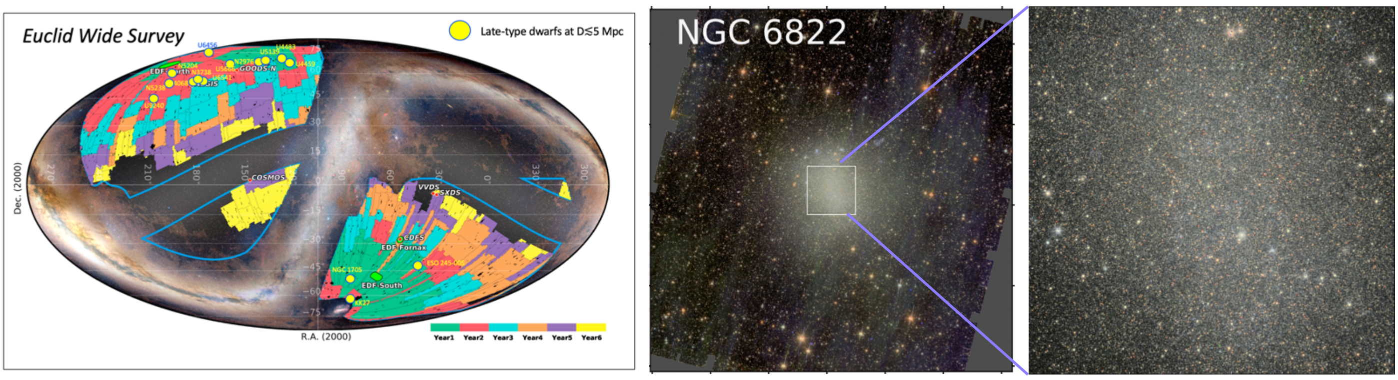

Fig.1: *Left:* Footprint of the Euclid Wide Survey, with colors indicating the sky coverage over the planned 6-year duration. Yellow circles mark star-forming dwarf galaxies observed during the first year. *Middle:* Example of a nearby dwarf galaxy (D = 0.5 Mpc) observed by Euclid. *Right:* Zoom-in of the same system, highlighting Euclid's capability to resolve its stellar population in remarkable detail.

Here we propose a **Ph.D. project** that offers the opportunity to work on **EUCLID data** of nearby dwarf galaxies, starting from the first data release (DR1) delivered internally to the consortium in October 2025. These data will provide an unprecedented detailed and still unexplored view of the formation of **dwarf galaxies** in a hierarchical merging framework. The high angular resolution of EUCLID will permit to resolve individual stars in the outskirts of dwarf galaxies within several Mpcs from us, allowing both to map **stellar streams and faint companions** around them and to characterize their stellar populations through the comparison of color-magnitude diagrams with stellar evolutionary models.

The supervisor of the proposed Ph.D. project is co-lead of the Milky Way and Resolved Stellar Populations working group, and is also actively involved in the science activities of the “Local Universe” working group. The Ph.D. student will have the opportunity to join the Euclid Consortium, work on Euclid DR1 data and, subsequently, DR2 data, and lead key studies, positioning them to drive high-impact research within the scientific community.

Outline of the Project:

YEAR 1: Analysis of EUCLID first data release, with particular focus on resolved star color-magnitude diagrams (CMDs) aimed at identifying stellar streams and merger signatures around dwarf galaxies. Involvement into the EUCLID science working group activities. Expected participation in several papers from the EUCLID collaboration.

YEAR 2: Analysis of the results, characterization of the dwarf galaxy stellar populations, streams/satellites properties' analysis. Publication of at least 1 paper as first author. Involvement into the EUCLID science working group activities, participation in EUCLID papers from the collaboration.

YEAR 3: Finalization of the results, comparison with N-body hydrodynamical models. Publication of at least 1 paper as first author. Involvement into the EUCLID science working group activities, participation in EUCLID papers from the collaboration.

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PhD project in ASTROPHYSICS

Title of the Project: The Next Frontier of Stellar Archaeology: Leveraging HST and JWST Data to Optimize Future ELT Observations of Virgo Galaxies.

INAF-OAS Supervisor: F. Annibali

Co-Supervisors: M. Bellazzini, M. Cignoni, C. Arcidiacono

Scientific Case:

The formation and evolution of galaxies across different environments remain among the most important open questions in modern astrophysics. In particular, understanding how star formation is regulated and quenched in dense environments requires detailed knowledge of the spatially resolved stellar populations within galaxies. However, current facilities are limited by spatial resolution, especially in the inner, high surface brightness regions of galaxies beyond the Local Volume.

The forthcoming **Extremely Large Telescope (ELT),** expected to see first light around 2030, will revolutionize this field. With its 39-m primary mirror, ELT will provide an unprecedented combination of sensitivity and angular resolution. Its first-light instrument MICADO, coupled with the multi-conjugate adaptive optics system MORFEO (a major ground-based project led by INAF), will deliver diffraction-limited imaging over a 50″×50″ field of view, with a uniform point spread function and significantly enhanced sky coverage. This unique capability will, for the first time, allow resolved stellar population studies in the crowded inner regions of galaxies in the **Virgo Cluster** (D ≈ 16.5 Mpc), a key laboratory for studying galaxy evolution in dense environments.

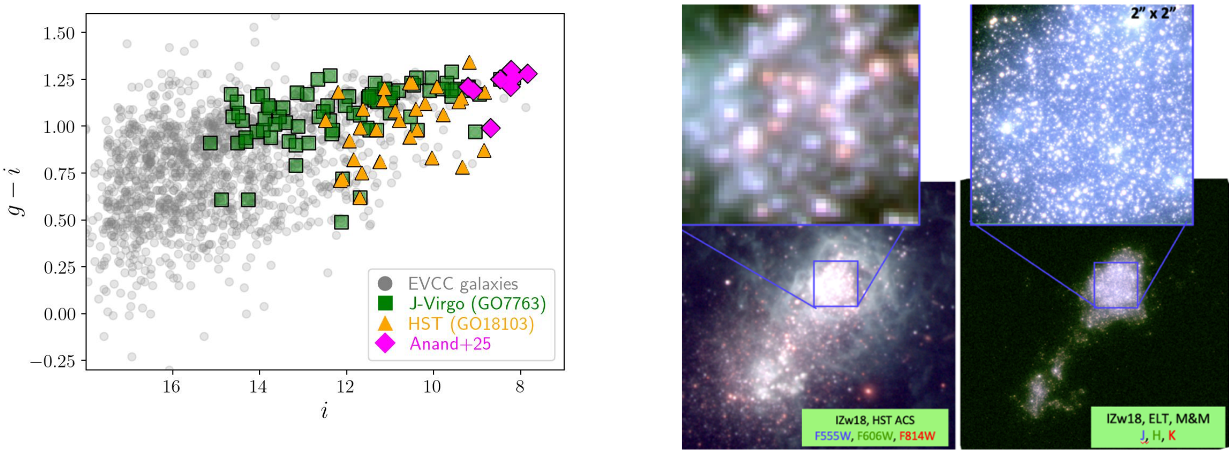

Fig. 1: **Left**: Color-magnitude diagram of galaxies in the Virgo Cluster, highlighting passive (red sequence) and star-forming (blue cloud) galaxies targeted by HST/JWST. **Right:** comparison between original HST data and MORFEO/MICADO ELT simulations for a star-forming dwarf a D ≈Mpc (the IZw18 system taken as a model). The upper panels show a 2" x2" zoom of the central region, highlighting the remarkable gain in resolution provided by the ELT.

Here we propose a Ph.D. project aimed at preparing and optimizing future ELT observations of Virgo galaxies. The project will focus on the study of resolved stellar populations in both early- and late-type systems, with the goal of reconstructing their star formation histories and investigating how environmental processes-such as ram-pressure stripping and galaxy harassment-affect galaxy evolution. The student will combine the analysis of archival **Hubble Space Telescope (HST) and James Webb Space Telescope (JWST)** data with the development of realistic simulations of **ELT** observations, providing a crucial bridge between current facilities and future ELT capabilities.

The supervisor of the proposed Ph.D. project is the Project Scientist for **MORFEO,** a key ELT subsystem which will have access to ≈80 nights of Guaranteed Time Observations (GTO). The Ph.D. student will therefore be embedded in a leading international collaboration and will contribute to defining the scientific strategy for ELT, with the opportunity to lead key studies and play an active role in high-impact research within the astronomical community.

Outline of the Project:

YEAR 1:
Analysis of archival HST and JWST observations of Virgo galaxies, with particular focus on resolved stellar populations in their outer regions. Construction and analysis of color-magnitude diagrams (CMDs) to derive constraints on stellar ages and metallicities. Publication of at least 1 paper as first author based on HST and JWST data. Initial involvement in ELT/MORFEO science activities.

YEAR 2:
Development of realistic simulations of ELT/MICADO observations using tools such as ScopeSim and TipTop, incorporating constraints from Year 1. Assessment of the impact of crowding, PSF variability, and adaptive optics performance on the recovery of stellar populations. Identification of optimal targets and observing strategies. Publication of at least one first-author paper.

YEAR 3:
Finalization of simulations and interpretation of results in the context of galaxy evolution in dense environments. Comparison with theoretical models and predictions. Preparation for future ELT observations and contribution to defining high-priority science cases. Publication of at least one additional first-author paper.

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PhD project in ASTROPHYSICS

Title of the Project:

The formation of the first globular clusters in cosmological simulations

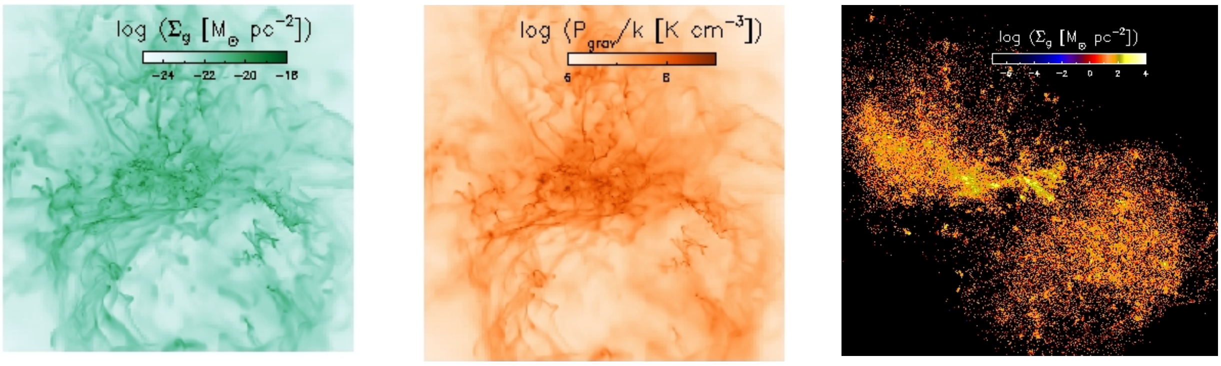
INAF-OAS Supervisor: Francesco Calura

Scientific Case:
The SImulating the Environments where Globular Clusters Emerged (SIEGE) project (Calura et al. 2022) is a theoretical framework to study the origin of globular clusters in a cosmological context. The unique features of the SIEGE simulations are 1) the very high, sub-parsec resolution, necessary to capture the turbulent nature of star formation and the fast, small-range processes acting on the sub-cluster scale and 2) the feedback of individual stars, for the first time included in a grid code in a full cosmological framework. These features offer the possibility to investigate the role of stellar feedback in the formation of the dense clumps that are expected to contain the first Globular Clusters (GCs), recently detected in gravitationally lensed fields at high redshift (Vanzella et al. 2017). They also allow one to include and test the effects of the long-sought-after Population III (Pop III) stars, i.e. the first stars ever born, thought to have a primary role in the formation of the first GCs and in the early metal enrichment of the Universe. This thesis will offer the possibility to study these fascinating topics by means of state-of-the-art tools with unparalleled features and predictive power.

Outline of the Project:
YEAR 1: After having familiarized with the theoretical framework and with the basic instruments, in the first year the student will learn how to run cosmological zoom-in simulations, the best tools to perform high-resolution simulations of early galaxies.
The simulations will be performed with the public hydro-code RAMSES (Teyssier 2002). The initial conditions can be easily generated by means of standard codes. After running low-resolution tests, the student will start performing sophisticated, higher-resolution simulations with various physical ingredients, aimed at addressing the main questions of the thesis, i.e. the formation of the first compact clumps in low-mass dark matter halos. In this regard, stellar feedback plays the most important role and is the most crucial aspect to investigate. Various possibilities will be explored, including the injection of momentum due to stellar winds and supernovae. Alternatively, thermal energy can be injected, with suitable arrangements to prevent overcooling, or both processes can be tested simultaneously.

YEAR 2: The effects of the Pop III stars in the early galaxies are largely unknown. Our simulations are an ideal tool to investigate them, by testing directly how each single star drives the evolution of the star-forming gas and their contribution to primordial metal enrichment. Due to the large uncertainty in their initial mass function and metallicity transition between Pop III and Pop II stars, it will be convenient and feasible to test various choices for some fundamental parameters that regulate their effects, such as the stellar initial mass function and their metal production yields. Suitable, publicly available codes will be used to generate mock images of early systems containing line emission from pop III stars, useful to derive predictions or to simulate observations performed with current and future instruments, such as JWST and the Extremely Large Telescope (ELT).

YEAR 3: In the third year, we will study the effects of ionizing radiation and non-equilibrium cooling on the formation of the first GCs. Ionizing photons from massive stars represent an additional form of feedback and can heat the gas, over-pressurize it and decrease its density, with strong effects on star formation. In addition, in simulations it is generally assumed that gas is in collisional and photo-ionization equilibrium and tabulated cooling tables or functions are used to compute gas cooling rates, based on gas density, temperature, and redshift. However, this represents a strong assumption, as it is not known a priori whether the star-forming gas of primordial galaxies is in equilibrium, and a detailed treatment of non-equilibrium cooling might have important effects on the outcome of the simulations (e. g. Capelo et al. 2018). To investigate such issues, we plan to include in our simulations ionizing radiation and non-equilibrium chemistry and cooling, customizing a version of RAMSES that already takes into account these effects (RAMSES-RT, Rosdahl & Teyssier 2015).



The left, middle and right panel shows a gas density, gas pressure and stellar density map, respectively, in a cosmological simulation from the SIEGE project (Calura et al., in prep.). This model includes stellar feedback in the form of stellar winds and a high star formation efficiency. Several stellar clumps are visible in the right plot, with maximum density up to 10^4 Msun/pc^2, i.e. comparable to the one of local star clusters.

References

Calura F. et al. 2022, MNRAS, 516, 5914
Capelo P. R., et al. 2018, MNRAS, 475, 3283
Rosdahl J., & Teyssier R. 2015, MNRAS, 449, 438
Teyssier R. 2002, A&A, 385, 337
Vanzella E., Calura F., et al., 2017, MNRAS, 467, 4304

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PhD project in ASTROPHYSICS

Title of the Project: Digging into the *dark side* of globular clusters

INAF-OAS Supervisor: Emanuele Dalessandro - emanuele.dalessandro@inaf.it

Co-Supervisors: Enrico Vesperini (Indiana University – USA), Jeremy Webb (University of Toronto, Canada), Mario Cadelano (UNIBO)

Scientific Case: Globular clusters (GCs) are massive ($M=10^4-10^6\ M_\odot$) and compact (few parcsec) stellar systems populating galaxies of any type (from dwarfs to ellipticals) and at any distance. They are formed by stars of roughly the same age and metallicity thus representing the closest example in nature of the so called Simple Stellar Population (SSP). Because of their ubiquity and relative simplicity, GCs are crucial to test and refine stellar evolution models and trace the fundamental parameters of their host galaxies in a wide range of astrophysical processes.

One puzzle yet to be solved in GC studies is the notable discrepancy between theoretical predictions and observations of GC mass-to-light ratios (M/L). In fact, SSP evolutionary models predict that the M/L should increase with metallicity in GCs as they become progressively dominated by *dark* stellar populations. However, several authors found that the observed M/L values in the Milky Way and M31 GCs do not show any significant trend with metallicity and they are actually more than two times smaller than expected for clusters at the metal-rich end. Such a discrepancy can be caused by either stellar cluster internal dynamical evolution and its possible effect on the stellar dark remnants retention fraction and low-mass star loss, or by primordial cluster formation processes leading them to have a non-universal Initial Mass Function (IMF). This dichotomy has key potential implications as SSP models are used to derive stellar masses, star formation histories and metallicities from the integrated light of galaxies and extra-galactic star clusters. Furthermore, the comparison between observed stellar M/L and SSP model predictions has been widely used to constrain the IMF of galaxies.

Outline of the Project: As a matter of fact, while significant efforts have been made to study this issue with a variety of different approaches, no consensus has been reached yet.

Our group has recently defined an innovative tool for breaking the degeneracy between the effects of internal dynamical evolution and of a non-universal IMF by using two directly measurable quantities: the slope of the present-day mass function PDMF (α_G) and its radial variation (δ_α) in a cluster.

The main goal of the project is to use such an innovative tool to finally clarify whether metal-rich GCs formed with a non-standard IMF or their M/L-[Fe/H] discrepancy is the result of significant dynamical evolution. To this aim we will analyze deep and high-spatial resolution proprietary JWST, HST, ESO/VLT and LBT photometric data of a representative sample of Galactic GCs to accurately derive their α_G and δ_α. Observations will be compared with a large suite of *N*-body and Monte Carlo simulations sampling the relevant structural properties and a wide range of IMFs, and designed to follow the long-term dynamical evolution of stellar clusters.

This project promises to finally provide the necessary information to solve one of the most important issues in stellar population studies. In turn, it can potentially shed new light into the processes by which stars form and on its possible environmental dependence.

PhD project in ASTROPHYSICS

Title of the Project - LISCA: Lively Infancy of Star Clusters and Associations

Supervisor OAS: Emanuele Dalessandro - emanuele.dalessandro@inaf.it - phone: +39 0516357325
Main collaborators: Alessandro della Croce (Indiana University – USA), Enrico Vesperini (Indiana University)

Scientific Context | Clustered star formation is the dominant, mode of star formation since the early Universe. In fact, it is widely accepted that most (70-90%) stars are born in groups, clusters or hierarchies and spend some time gravitationally bound with their siblings when still embedded in their progenitor molecular cloud. The possible end-products of clustered star formation, i.e. star clusters, are potentially powerful tracers of the assembly process of galaxies and their main properties are strictly connected with those of their hosts, making them valuable probes for theoretical and observational astronomy across a wide range of disciplines from cosmology to stellar evolution.

To efficiently exploit stellar clusters as tracers of galaxy and large-scale structure formation, we must understand the physical processes setting their initial masses, structure and chemical composition and how they possibly evolve across the cosmic time.

Outline of the Project | The proposed project aims at characterizing cluster formation and early evolution in two local environments: *the Perseus and the Scutum complexes* in the outer and inner Galactic disc, respectively, and the discs of the *Magellanic Clouds*. These systems are characterized by recent star-formation episodes and by the presence of multiple young clusters and associations that show strong signatures of mutual interactions and of ongoing assembly process. Young clusters and associations in local disc/spiral arms are the only recently formed stellar systems close enough to be resolved in individual stars, therefore they represent *the ideal laboratory* for constraining the physical mechanisms at the basis of cluster formation and studying their early evolution with a level of detail that cannot be achieved for distant systems.

We will perform the first comprehensive spectro-photometric and kinematic study of the young stars and clusters in the selected star-forming complexes to *i)* characterize the 6D velocity and position phase-space and study their velocity dispersion, rotation and anisotropy profiles and assess the cluster dynamical state, *ii)* compute cluster density profiles and derive their structural parameters (core and tidal radii, ellipticity) and look for evidence of intra-clusters over-densities possibly resulting from mutual interactions, *iii)* measure chemical abundances and abundance patterns and *iv)* derive accurate cluster ages and constrain the possible presence of age spreads.
To this aim, the project will take full advantage of a synergic use of the upcoming Gaia Data Release 4 astrometric catalogs (release date: December 2026) and of a formidable dataset of proprietary photometric and spectroscopic data obtained with JWST, HST and ground-based facilities at the ESO-VLT and TNG telescopes. Eventually, the project will also have access to ESO-VLT/MOONS spectra secured within the GTO Galactic Survey (starting date: mid-2027). We will then use state-of-the-art hydro-dynamical and *N*-body simulations to interpret the observed stellar cluster properties and to constrain the initial physical conditions for cluster formation and evolution.

The characterization of the stellar content of these systems will allow us to test *i)* the role of the environment on cluster formation, *ii)* the relative importance of individual clusters becoming unbound due to gas expulsion as opposed to the hypothesis of hierarchical structure formation and *iii)* the contribution of cluster formation on large scale structures in their host galaxies. Interestingly, the properties of the interstellar medium in the Galactic disc are similar to those in the discs of other nearby galaxies. Hence, the results obtained within the project on star formation and feedback in local young clusters and associations can probe star formation across much of the local Universe.

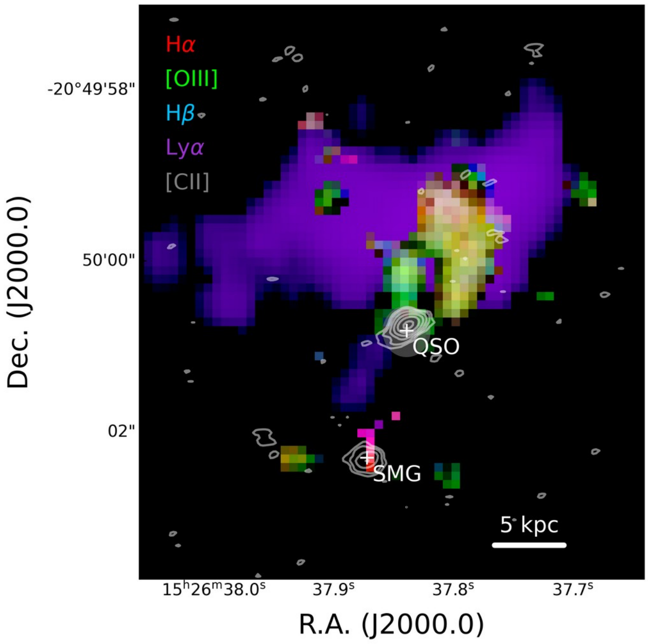
Our team is one of the worldwide leading group in the observational study of stellar populations and star clusters, by using the most updated generation of instruments and telescopes from the ground and space. It also includes major experts of dynamical simulations and modeling and has granted access to the major international computational facilities. Hence, the proposed project will offer a great opportunity 1) to be trained on various aspects of stellar evolution, dynamics and chemical evolution from both the observational and theoretical points of view, 2) to get in contact with national and international experts of the field through meetings, workshops and visit exchanges, 3) and to publish original results and present them to international conferences.

PhD project in ASTROPHYSICS

Title of the Project: ***The baryon cycle in quasars at cosmic dawn***

INAF-OAS Supervisor: Roberto Decarli
Co-Supervisors: Francesca Pozzi (UniBo)

Scientific Case: Quasars at cosmic dawn (redshift z>6, age of the Universe <1 Gyr) are among the most active and massive sources in the early Universe, thanks to rapid (>10 M_{sun} yr^{-1}) gas accretion onto already formed supermassive (10^9 M_{sun}) black holes and intense bursts of star formation (100-1000 M_{sun} yr^{-1}) in their host galaxies. In this PhD project, the perspective candidate will study the baryon cycle of quasars at cosmic dawn using both proprietary and archival ALMA and JWST observations (see an example in Fig.1). The synergy between JWST, ALMA and other facilities enables for the first time to shed light on how gas accretion from the environment feeds the growth of both the galaxy and the black hole, and how the release of energy from these processes redistribute material into the Circum Galactic Medium (CGM) and regulate the gas flow, and hence the future growth of the galaxy.



Figur

Figure 1: The quasar+companion system PJ231-20, observed with ALMA ([CII]), VLT/MUSE (Lya), and JWST (other emission lines). This multi-line investigation shows the interplay of different phases of the ISM, and the cycling of baryons from the CGM to the host galaxy and the central AGN and back again via outflows. Characterizing this interplay is the goal of this PhD project.

The perspective student will join an active team of researchers with strong international collaborations, and work with state-of-the-art data from some of the best astronomical facilities. While data have already been gathered, the perspective student is expected to secure more telescope time via competitive calls, and potentially lead observing runs in telescopes around the world. Interpretative and theoretical spins on the project (e.g., involving radiative transfer computations, or semianalytical modeling of the galaxies and their evolution) are also viable. Generous research funding for traveling will be available throughout the PhD program.

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PhD project in ASTROPHYSICS

Title of the Project: "*Galaxy Groups & Clusters in X-rays: Astrophysics and Cosmology*"

INAF-OAS Supervisor: Stefano Ettori

Co-Supervisors, *depending on the selected topic***:** V. Ghirardini, M. Sereno, M. Roncarelli, M. Meneghetti (OAS); A. Bonafede, M. Gitti, F. Vazza (DIFA)

Scientific Case: The hot plasma of galaxy clusters (Intra-Cluster Medium, ICM) and groups (Intra-Group Medium, IGrM) constitutes their main baryonic component and holds the key to unveil their physical properties. It provides an excellent laboratory to probe the physics of the gravitational accretion and collapse of dark matter and baryons, and how the latter are further shaped by non-gravitational processes, mainly AGN and supernovae feedback. To fully understand the physical process at work, we need robust constraints on the total gravitational mass (dominated by the Dark Matter), on the distribution of the gas over the halo's volume and on its thermodynamic properties for a representative sample of galaxy clusters and groups. In the last few years, we have been able to build such a sample, over two order of magnitude in mass (10^{13}-10^{15} M_{sun}) in the local Universe, through two successful XMM programs: a 3 Msec XMM-Newton Multi-Year Heritage Program in 2017 (with the last exposures acquired in 2022) now titled *Cluster HEritage project with XMM-Newton - Mass Assembly and Thermodynamics at the Endpoint of structure formation* (CHEX-MATE) for 118 galaxy clusters and a 860 ksec Large Program awarded in 2021 named the *X-ray Group AGN Project* (X-GAP) for 49 galaxy groups.
Multi-wavelength data (ranging from radio to optical bands) will be used to complete our understanding of the thermal (and non-thermal) energy budget of these systems.

Outline of the Project: based on the candidate's interests and other contingencies (data availability, no conflict with other ongoing work), we will define at the outset how to articulate the project and which sectors to emphasize, from recovery to analysis and interpretation of the physical properties of these objects. During the 1st year, we will address the challenges and technicalities of X-ray analysis of extended sources and define a 6-month (publishable) study focused on the thermodynamic properties of the ICM/IGrM. By the end of the 1st year, we expect that the candidate will be able to understand the scientific context of the hierarchical structure formation and the different perspectives to tackle it both observationally and through numerical simulations. During the 2nd and 3rd year, the main topic of the project (on e.g. the distribution of dark matter; the "universality" of the radial profiles of the thermodynamic quantities -such as gas temperature, pressure, entropy; see e.g. Ettori+2023; the scaling laws holding between integrated quantities, like total and gas mass, X-ray luminosity, temperature) will be addressed using both (proprietary and archived multi-bands) observations and cosmological hydrodynamical simulations well suited for this analysis (from our collaborators in Bologna -Dr. Vazza- and in *the300* consortium).

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PhD project in ASTROPHYSICS

Title of the Project: Gamma-ray transients with the NASA COSI mission

INAF-OAS Supervisor: V. Fioretti

Co-Supervisors: N. Parmiggiani, A. Bulgarelli

Scientific Case:
The NASA Compton Spectrometer and Imager (COSI), a small mission explorer (SMEX) with a planned launch in 2027, is a wide field of view gamma-ray telescope operating in the 0.2 to 5 MeV. With an order of magnitude better sensitivity than legacy MeV missions, it will open a new observational window to the transient Universe. COSI will be able to download in tens of minutes scientific data to the ground for fast detection, localization, and generation of science alerts to the community by the fast transient pipeline (FasTP). In order to send science alerts, a dedicated satellite system (TDRSS) will send scientific data packets to the ground every time a trigger is detected on board by the anticoincidence system surrounding the telescope.
Using both Compton imaging from the Germanium tracker and time analysis of the anticoincidence system, COSI will perform powerful searches for electromagnetic counterparts to gravitational waves and high-energy neutrinos. INAF OAS is coordinating the development of the FasTP, which will detect, localize and classify GRBs and other types of transients, despite the limited observation window that can be downloaded to the ground, while ensuring fast communications for follow-ups.

Outline of the Project:
This PhD project activity foresees: i) scientific analysis for the COSI mission, both on simulated and real data acquired by COSI after the launch; ii) exploration and development of innovative tools for detection and localization of gamma-ray transients, based on classical or machine learning techniques; iii) contribution to the COSI Fast Transient Pipeline.
The student will be integrated into the space mission team to maintain direct and continuous collaboration with other members with the possibility of spending periods abroad to learn specific analysis techniques and acquire the necessary skills.

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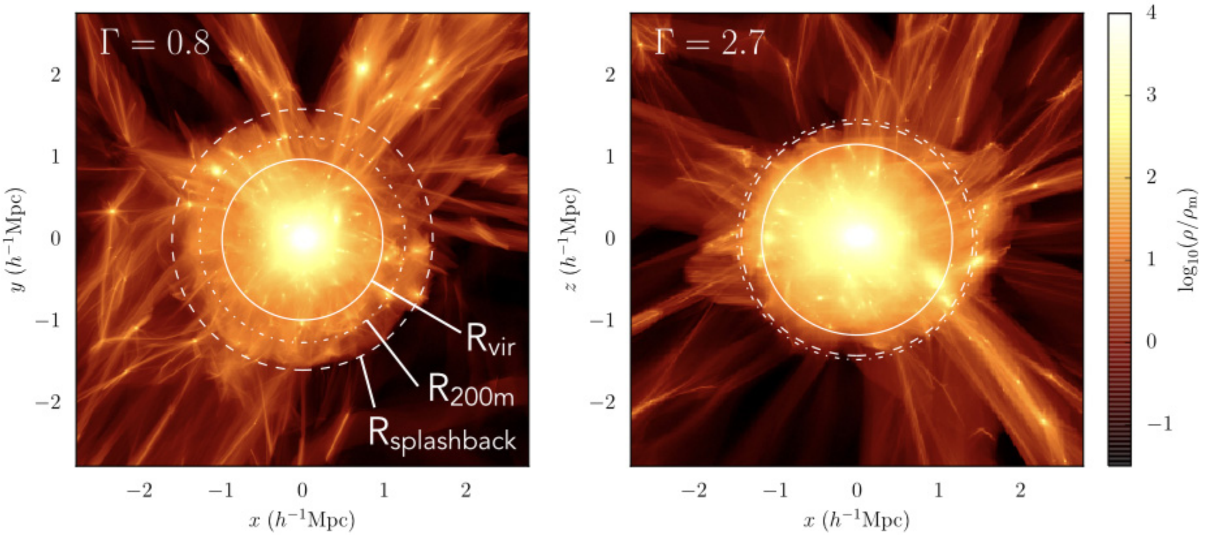
PhD project in ASTROPHYSICS

Title of the Project: Multiwavelength analyses of Galaxy Cluster Boundaries

INAF-OAS Supervisor: Carlo Giocoli

Co-Supervisors: Massimo Meneghetti, Giulia Despali, Lauro Moscardini

Scientific Case:
Galaxy clusters are the largest gravitationally bound structures in the Universe and powerful laboratories to study the interplay between dark matter, baryons, and cosmic accretion. Despite their central role in cosmology and astrophysics, their physical boundary remains poorly defined. Commonly adopted radii, such as R_{200}, are based on spherical overdensity criteria and do not correspond to a true dynamical transition. In contrast, the splashback radius, associated with the first apocenter of recently accreted material, provides a physically motivated definition of the halo edge and a direct probe of the mass accretion rate.
Over the past decade, numerical simulations have established the splashback radius as a key prediction of structure formation, while observational studies have reported evidence for it in galaxy density and weak lensing profiles. However, current measurements remain fragmented and often limited to single tracers, leading to tensions in both the location and sharpness of the splashback feature. In particular, different components of galaxy clusters, dark matter, galaxies, hot gas, and diffuse stellar light, may trace the boundary differently, reflecting the complex, multi-phase nature of structure formation.



A comprehensive, multi-wavelength characterization of cluster outskirts is therefore essential. Weak gravitational lensing provides a direct probe of the total mass distribution,

while optical galaxy surveys trace the distribution of satellite galaxies. The diffuse intracluster light (ICL), originating from tidally stripped stars, offers a complementary tracer of the dynamical evolution of clusters. X-ray observations map the hot intracluster medium, and radio data reveal non-thermal emission associated with shocks and turbulence driven by ongoing accretion.
Despite the availability of high-quality datasets, a unified framework combining these tracers is still missing. This project aims to fill this gap by establishing the splashback radius as a robust, multi-tracer observable of cluster assembly. By combining observational data with state-of-the-art numerical simulations, the project will investigate whether the splashback radius represents a universal halo boundary or a tracer-dependent feature, and how it depends on mass accretion and baryonic processes.
This work is particularly timely in the context of current and upcoming surveys and will advance our understanding of structure formation in the non-linear regime, while providing a foundation for future cosmological applications.

Outline of the Project:
This PhD project will develop a **multi-wavelength, simulation-based analysis of the splashback radius in galaxy clusters, combining observational datasets with numerical modeling to provide** a coherent physical interpretation.
The project will be structured in three main phases.
<u>Phase 1</u>: Foundations and Data Preparation
The student will acquire expertise in weak lensing, galaxy clustering, and multi-wavelength data analysis. A cluster sample with overlapping coverage from KiDS, DES Year 3, CHEX-MATE, and LOFAR will be defined. The student will develop and validate analysis pipelines to measure radial profiles of galaxy density and weak lensing signals, and will begin exploring techniques for extracting intracluster light through stacking methods.
<u>Phase 2:</u> Multi-tracer Measurements
The core of the project will focus on measuring the splashback radius using different tracers. Weak lensing data from KiDS will be used to reconstruct the total mass profile, while DES Year 3 will provide high-statistics galaxy density measurements. The student will extend the analysis to the ICL component, probing the diffuse stellar distribution. Complementary information from CHEX-MATE and LOFAR will be used to investigate the thermal and non-thermal properties of cluster outskirts, enabling a first comparison between different physical components. This will also allow to study the dependence of the cluster boundaries on the accretion rate parameter Γ.
<u>Phase 3</u>: Simulation Comparison and Physical Interpretation
In the final phase, the student will analyze the Three Hundred and AIDA-TNG simulations to identify the splashback radius in dark matter, gas, and stellar components. Mock observations will be constructed to match the observational datasets, allowing a direct comparison and calibration of systematic effects. The student will investigate the dependence of splashback properties on mass accretion rate and dynamical state, and assess whether a universal or tracer-dependent definition of the halo boundary emerges.

Expected Outcomes
The project will provide the student with broad, interdisciplinary training spanning

gravitational lensing, X-ray and radio astronomy, optical surveys, and numerical simulations. The expected outcomes include multiple publications, the development of analysis tools applicable to future surveys, and a comprehensive characterization of cluster boundaries.
The feasibility is ensured by the availability of high-quality datasets and established collaborations, while the modular structure allows progressive scientific results throughout the PhD.

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PhD project in ASTROPHYSICS

Title of the Project: FUNDAMENTAL PHYSICS FROM POLARISED COSMIC MICROWAVE BACKGROUND ANISOTROPIES

INAF-OAS Supervisor: Alessandro Gruppuso

Scientific Case:

The cosmic birefringence effect is the "in-vacuo" rotation of the linear polarisation plane of photons during propagation. While null in Standard Electromagnetism, this rotation is predicted to be different from zero by parity-violating extensions of the Standard Model, such as those involving pseudo-scalar axion-like fields coupled to the electromagnetic field via a Chern-Simons term. Recent analyses (Minami & Komatsu, 2020; Diego-Palazuelos et al., 2022) of the latest CMB Planck Public Release data have reported a tentative detection of a cosmic birefringence angle $\beta \sim 0.3$ deg at about 3σ confidence level. Interestingly, CMB ACT data (Diego-Palazuelos & Komatsu, 2025) found statistically compatible results with similar significance. If confirmed in its physical origin, this observation would reveal the existence of a previously unknown medium through which CMB photons propagate. This would represent a breakthrough in fundamental physics, potentially identifying the nature of dark matter or dark energy.

Outline of the Project:

The aim of this thesis is to characterise the cosmic birefringence effect potentially through a multi-faceted approach, which can be tailored to the candidate's specific background and research interests. The project will be articulated along the following lines:

1) Theoretical modelling. Developing/studying parity-violating models (e.g. axion-like fields) and their impact on CMB observables;

2) Methodology and Data Analyses. Building analytic estimators and/or data analysis pipeline to provide constraints on this effect considering available data;

3) Forecasting and Simulations. Implementing realistic simulations to forecast the capabilities of future experiments, as e.g. the LiteBIRD satellite, with a focus of mitigating or keeping under control systematics of both instrumental or astrophysical origin.

Note that, if desired, the student can be involved in the LiteBIRD collaboration. LiteBIRD is a satellite for CMB observations funded by JAXA, the Japanese space agency, whose launch is expected in 2030s. The target of LiteBIRD is to measure the primordial gravitational waves through the specific signature they leave on the polarised pattern of CMB anisotropies. Within this framework, a period of research in Japan or in other countries participating in the LiteBIRD project (such as France or Spain) can be organised. Furthermore, other international destinations may be considered regardless of the LiteBIRD participation, to foster student's independent research path. INAF-OAS Bologna is strongly connected with the main Italian and international research groups involved in CMB science. This makes the PhD experience an entry point into a wide scientific network, providing a solid basis for future's postdoctoral applications after the PhD program.

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PhD project in ASTROPHYSICS

Title of the Project: Strong and Weak Lensing by Galaxies and Clusters: The Nature of Dark Matter

INAF-OAS Supervisor: Massimo Meneghetti

Co-Supervisors: Carlo Giocoli, Pietro Bergamini, Giulia Despali, Lauro Moscardini

Scientific Case:
The nature of Dark Matter (DM) remains one of the most significant "missing pieces" in modern physics. While the Cold Dark Matter (CDM) model succeeds on large scales, its predictions on galactic scales, specifically the statistical properties of matter toward the central regions, remain largely untested. Gravitational lensing, the distortion of background galaxies caused by the interposed matter density distribution along the line-of-sight, allows us to directly measure the dark matter mass of lens objects, such as galaxies and galaxy clusters, making it an ideal tool for studying dark matter.

Figure 1: ACT-CLJ0411.2-4819 (z=0.424), one of the strong lensing clusters in the Euclid Q1 data release.

The originality of this PhD project lies in the **multiscale and multi-probe approach to mass reconstruction**, designed to connect galaxies and galaxy clusters within a single, coherent gravitational lensing framework. This project is targeted to explore the scientific cases of the Euclid Data Release 1 (DR1).

The Euclid telescope is a European Space Agency (ESA) Mission launched in July 2023, dedicated to studying the growth of cosmic structures over cosmic time. While weak and strong lensing techniques are well established individually, they are most often applied separately and to limited mass ranges. This project moves beyond the state of the art by **jointly exploiting weak and strong lensing across several orders of magnitude in halo mass**, enabling a continuous mapping of dark matter distributions from galactic to cluster scales. A key innovative aspect is the use of the transition between weak- and strong-lensing regimes. The exquisite resolution and data processing of Euclid will give the capability to resolve both giant arcs and cosmic shear within the same field environment. This will allow us to link the inner and outer regions of halos hosting galaxies and clusters. In addition, by applying this modeling analysis to selected objects among **thousands of new strong-lensing galaxies and clusters**, as expected in DR1, the project will provide unprecedented sensitivity to treasure deviations from the CDM, such as core formation or suppressed small-scale structure, that remain invisible to single-scale analyses. The proposal is also original in its focus on dark matter phenomenology driven by **observational data** rather than pure theory. By systematically marginalizing over baryonic uncertainties, using a simulation-based inference and forward modeling approaches, we will compare DR1 observations to a suite of state-of-the-art non-standard dark matter simulations: the magneto-hydrodynamic AIDA-TNG suite.

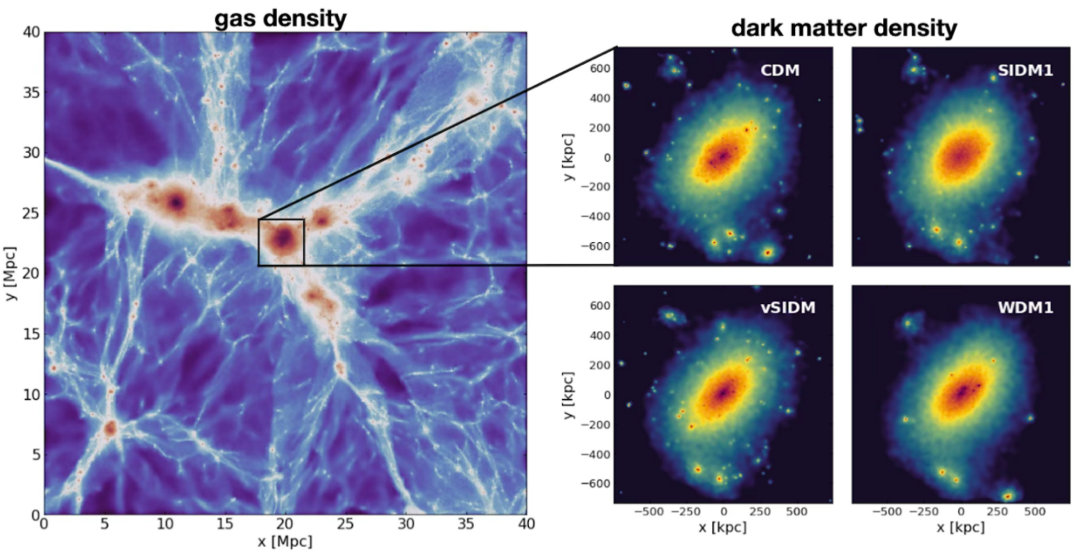

Figure 2: Simulated cosmic structures extracted from the AIDA-TNG simulations. The same halos are simulated in the standard CDM model and in alternative DM scenarios, including self-interacting and warm DM.

Outline of the Project:
The project adopts a multi-disciplinary approach combining observational analysis and Bayesian inference, high-resolution numerical simulations, and deep learning.

Observational analysis: The student will learn how to perform weak and strong lensing mass reconstructions using state-of-the-art free-form and parametric codes. This work will involve the analysis of both simulated observations, to characterize and calibrate the modeling tools, and Euclid DR1 data.

Deep learning methods: Advanced machine learning methods (e.g., convolutional neural networks and latent-space optimization) will be implemented alongside traditional parametric and non-parametric approaches. These tools will be applied to Euclid data to identify lenses and reconstruct the projected mass distribution of galaxies and clusters across multiple scales. We also plan to employ customized Larga Language Models in the process to find new strong lensing features in the Euclid images.

Simulations and mock data: The student will construct realistic lensing simulations using halos extracted from state-of-the-art hydrodynamical runs (e.g., AIDA-TNG) and complemented with fast semi-analytical tools. Baryonic effects (e.g,. AGN and supernova feedback) will be included to ensure accurate modeling. The main output will be a large library of synthetic Euclid-like images (VIS and NIR), catalogs, and measurements of lensing quantities to be used for comparison with the observations.

Cosmological inference: In the final phase, a Bayesian hierarchical framework will be used to compare reconstructed mass maps with simulations. This will enable robust measurements of structural properties (e.g., density profiles, concentrations, substructure content) and provide constraints on dark matter models. Deviations from standard Cold Dark Matter predictions will be used to test alternative scenarios such as Warm or Self-Interacting Dark Matter.

Beyond individual measurements, the project is expected to deliver a fully automated and scalable pipeline for multiscale lens analysis using weak and strong lensing data, applicable to future Euclid data releases. This pipeline will be a lasting legacy of the project and a valuable asset for the cosmology community. Overall, the expected results will significantly improve our understanding of Dark Matter on non-linear scales, strengthen the scientific exploitation of Euclid, and position the PhD candidate at the forefront of observational cosmology and gravitational lensing.

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PhD project in ASTROPHYSICS

Title of the Project: Star clusters at cosmological distances: unveiling their role in galaxy evolution and cosmic reionization

INAF-OAS Supervisor: M. Messa, A. Zanella

Co-Supervisors: E. Vanzella, M. Meneghetti

Scientific Case and outline of the Project:
Thanks to gravitational lensing magnification, galaxy clusters act as natural telescopes, enabling the study of small-scale structures within high-redshift galaxies — such as star-forming complexes and star clusters — at redshifts ranging from z ~ _1 to beyond the epoch of reionization (z > 6).
By leveraging the deepest and most recent data from the James Webb Space Telescope (JWST) in strongly lensed fields — particularly those of the most powerful cosmic telescopes, such as the galaxy cluster MACS J0416 and the cluster PSZ1 G311, which hosts the spectacular Sunburst galaxy (Fig. 1) — we will identify small clumps and, in extreme cases, individual star clusters. Complementing these data with state-of-the-art multi-wavelength observations from ALMA, VLT (e.g., MUSE, ERIS), and Euclid, along with cutting-edge lens models, we aim to estimate their sizes, magnitudes, and colors. This will allow us to derive key properties such as stellar masses, molecular gas masses, ages, ionization power, star formation rate density, and kinematics. These insights will be crucial for understanding star formation efficiency, the impact of feedback, and the role of stellar complexes in both the evolution of their host galaxies and cosmic reionization. Due to their extreme magnification, these systems serve as unique laboratories, providing a glimpse into the questions that will be explored in the future with the Extremely Large Telescope (ELT).
The student will gain expertise in analyzing data from sub-millimeter interferometry, near-infrared photometry and spectroscopy, and optical integral-field spectroscopy (IFS). These skills will be essential in the ELT era, when near-infrared photometric and IFS data will be routinely combined with interferometric observations to study high-redshift clumps. The student will be part of an international collaboration, working closely with leading experts in star cluster formation, galaxy evolution, and strong lensing. The student will also have the possibility of joining the Euclid Consortium. By performing its wide survey of ~15,000 sq. degrees of extragalactic sky, Euclid will discover many highly magnified sources and giant arcs. Studying these sources will require follow-up observations with other facilities, including ALMA, VLT, and JWST. Therefore, the student will be engaged in the preparation of several observational proposals with these instruments.

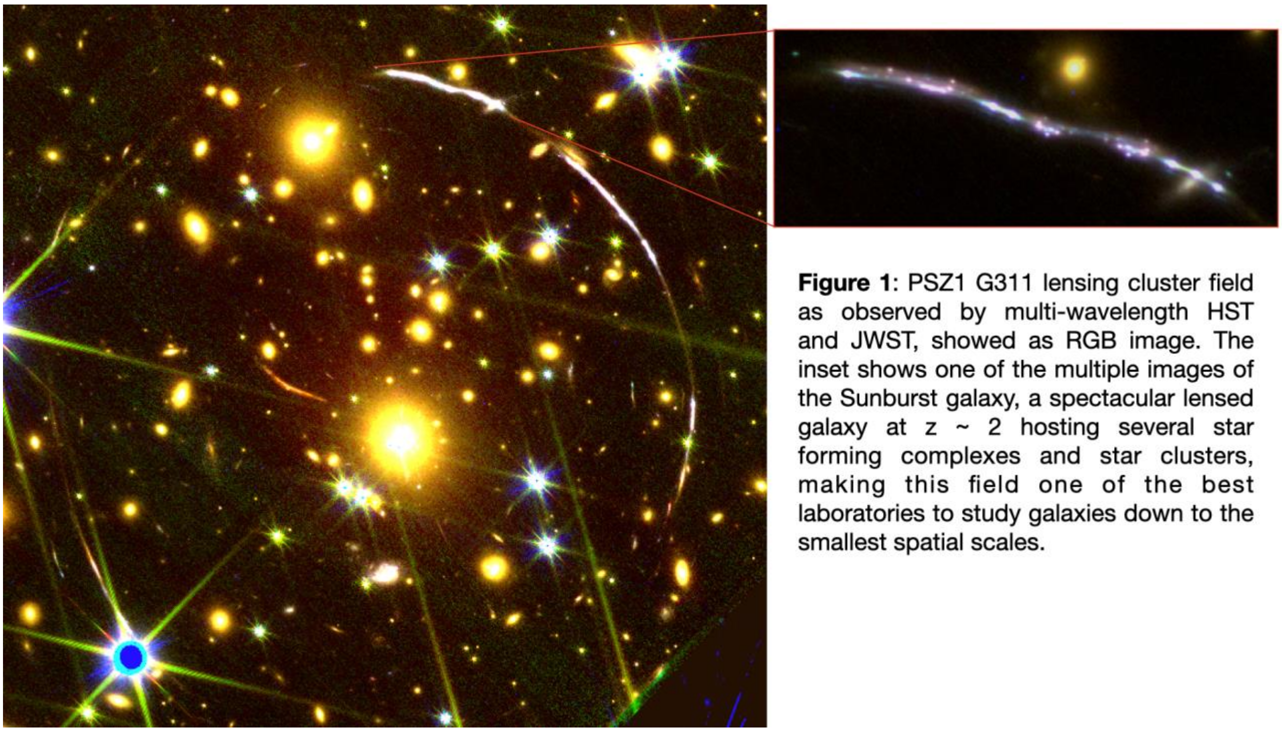

Figure 1: PSZ1 G311 lensing cluster field as observed by multi-wavelength HST and JWST, showed as RGB image. The inset shows one of the multiple images of the Sunburst galaxy, a spectacular lensed galaxy at z ~ 2 hosting several star forming complexes and star clusters, making this field one of the best laboratories to study galaxies down to the smallest spatial scales.

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PhD project in ASTROPHYSICS

Title of the Project: Machine Learning and Deep Learning in the era of large astronomical surveys.

INAF-OAS Supervisor: Tatiana Muraveva

Co-Supervisors: Gisella Clementini (INAF-OAS), Alessia Garofalo (INAF-OAS), Lorenzo Monti (INAF-OAS).

Scientific Case: Astronomy is entering a new era of Big Data science thanks to exponentially growing data volumes from large surveys, such as *Gaia* and the Legacy Survey of Space and Time (LSST) at the Vera Rubin Observatory (VRO). The *Gaia* Data Release 4 (DR4), currently foreseen for December 2026, will provide astrometry and broad-band photometry for over 2 billion sources in the Milky Way (MW) and beyond, along with comprehensive information on variable stars, galaxies, astrophysical parameters, radial velocities, epoch photometry, and spectra. This dataset will be complemented by a 500-petabyte set of images and data products from the LSST@VRO. The extraordinary volume of these data poses novel challenges, since data volumes at these scales have never been encountered by the scientific community before. Thus, the application of advanced Machine Learning (ML) and Deep Learning (DL) techniques, which can provide the level of accuracy and automation required to exploit large datasets efficiently, becomes highly needed and timely.

The PhD candidate will exploit state-of-art ML and DL algorithms to (1) explore the whole data parameter space of the *Gaia* and LSST datasets; (2) classify variable stars based on a combined sample of the time-series data from *Gaia* and LSST; (3) search for chemo-kinematic substructures in the MW using different clustering algorithms.

Outline of the Project:

YEAR 1: Exploration of the *Gaia* and LSST datasets. Collecting training sets.
YEAR 2: Training the models used to classify variable stars on a combined sample of the time-series data from *Gaia* and LSST.
YEAR 3: Application of clustering algorithms to search for chemo-kinematic substructures in the MW. Writing of the thesis and papers describing the main results.

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PhD project in ASTROPHYSICS

Title of the Project: ***The magnetic side of the small scale Universe***

INAF-OAS Supervisor: Daniela Paoletti

Co-Supervisors: Fabio Finelli

Scientific Case: Magnetic fields are observed on cosmological scales everywhere in the Universe. From galaxies, clusters and voids to the hints of their presence also in filaments of the large scale structure, the Universe is permeated by the so-called cosmic magnetism and its origin is one of the key questions in modern cosmology. A possible answer lies in the possible existence of magnetic fields generated in the early Universe, Primordial Magnetic Fields (PMFs). Such fields are a smoking gun of non-standard physics in the early Universe and constraining their characteristics can open a tremendous observational window on fundamental physics at high energies.

PMFs affect all the history of the Universe leaving footprints in several probes, the main ones being the Cosmic Microwave Background (CMB) and the Large Scale Structure (LSS). In the past decade thanks to Planck and the perspective of LiteBIRD the focus has been on the large and intermediate scales (*Finelli+2008, Paoletti+2009, Paoletti and Finelli 2011,2013,2019, Planck Collaboration 2015 XIX, Paoletti+LiteBIRD 2024)*, but recent and future cosmological data from both CMB and LSS are opening a new window in the PMF phenomenology, the small scales.

On small scales the ideal MagnetoHydroDynamics approximation breaks down and cosmological perturbations, including the magnetized ones, enter in a fully non-linear regime. This leads to a non-trivial coupling of the PMFs with the cosmological fluid and in particular baryons and photons, with PMFs expected to be distorted by the backreaction of the fluid, leading to turbulence and baryon clumping - and therefore to inhomogeneous recombination possibly connected with the Hubble tension. The current treatment of these effects (*Jedamzik & Pogosian 2020,2023, Ralegankar 2023, Jedamzik+2026, Ciabattoni, Finelli, Paoletti and Subramanian, in prep 2026*) still lacks a unified semi-analytic description.

The focus of the PhD is the development of a comprehensive semi-analytical approach of these effects, capitalizing on the experience in the quasi-linear treatment within the ideal MHD limit, which can now be considered as a textbook description. We will consider the full MHD coupling of the PMFs with the fluid, including the backreaction and the associated distortions of PMFs, their damping and second order effects. Once developed the treatment, this will be applied to Einstein-Boltzmann codes in order to extend the predictions for CMB anisotropies and LSS probes to smaller scales, both in a LCDM and extended cosmological model context. This will lead also to a quantitative estimation of the baryon clumping and therefore to inhomogeneous recombination. Such treatment will help in shedding light on the early Universe physics, the origin of cosmic magnetism and also the Hubble tension.

The PhD candidate is expected to acquire during the three years skills on the theoretical treatments using also software as Mathematica together with numerical skills in Einstein-Boltzmann codes for cosmological predictions and the software for the constraints to cosmological parameters which will go hand in hand with some High Performance Computing skill development.
The PhD candidate will join our group on the study of primordial magnetism in INAF-OAS Bologna which has been very productive since 2007. In our group we have some of the deepest knowledge on primordial magnetism, having developed the first and only analytical treatment of its effects on cosmological perturbations together with many other different effects. We are involved in the primordial magnetic fields studies in some of the forefront future CMB experiments such as LiteBIRD and FOSSIL. Moreover, we are part of the Euclid collaboration whose data can be the first benchmark for LSS studies within the three years of the Ph. D. We have long term collaborations with some of internationally renowned experts in PMFs as Kandaswamy Subramanian, Josè Alberto Rubino-Martin, Jens Chluba, Chiara Caprini, who can offer a large international context to the PhD candidate.

Outline of the Project:

Year 1 will be dedicated to the study of the damping on small scales of the PMFs with the implementation of different models with increasing complexity. Second order effects on the magnetized cosmological perturbations will be considered (at least one paper).
Year 2 will be dedicated to the study of the interplay of the PMFs with the fluid and in particular the back reaction and the distorted evolution of the spectrum of the PMFs with the associated predictions for cosmological probes (at least one paper).
Year 3 will be dedicated to the application of the treatment to cosmological data such as Euclid, SPT, Simons Observatory as well as forecasts for the future ones. Thesis writing and final papers finalization (should be a couple of papers one on CMB and one on LSS).

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PhD project in ASTROPHYSICS

Title of the Project: *Galaxy and AGN evolution with Euclid: advanced data exploration in the era of big surveys*

INAF-OAS Supervisor: L.Pozzetti, M. Bolzonella
Collaborators: @**INAF-OAS:** L. Pozzetti, M. Bolzonella, E. Zucca, O. Cucciati, S. Bardelli, Z. Mao, X. López-López; @**UniBO:** M. Talia, M. Moresco, A. Enia, S. Quai; + Euclid Consortium and 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, and is currently surveying over a third of the sky with high-resolution imaging and spectroscopy. Euclid, complemented with other multi-wavelength data from X-ray to radio, is providing a data archive increasingly large and rich in information, perfect for studying the history of the formation and growth of galaxies over the age of the Universe. The Euclid Wide Survey and Euclid Deep Fields started observations in February 2024 and the first Quick and Data Release (Q1 and DR1) will already cover about 60 and 1900 square degrees. Traditional approaches are no longer sufficient for the optimal exploitation of this huge amount of data, and it urges the researcher to use new techniques based on Machine Learning (ML). Researchers at INAF-OAS have been appointed to coordinate different key projects with the first major data release (DR1), already available to the Euclid Consortium (EC) since October 2025, and in particular on distribution functions and baryonic cycle as a function of environment.

The goals of the PhD project will be to explore advanced techniques and, in particular, ML methods within one or more of these scientific contexts:
1- ***Recover galaxy and AGN physical properties from photometric and/or spectroscopic data to study their evolution as a function of the environment.*** Traditional approaches, like SED fitting, are well established to derive physical properties of galaxies (stellar mass, SFR, age, dust, and metallicity). The goals of the project will include using and improving advanced techniques and ML: - to speed up the computation of physical properties; - to classify different types of galaxies, e.g. passive vs star-forming and AGN; - to select similar objects and derive their average physical properties from composite SEDs and spectra beyond the observational limits for single objects; - to discover and study rare or yet unseen objects, thanks to the unprecedented datasets that will be available in Euclid; - to study a method to use also spectra and spectral information (emission lines) in addition to photometry to recover galaxy physical properties and AGN fraction; - to assess the impact of physical properties errors on derived scaling relation (SFR-Mass, Mass-metallicity, size-Mass, etc…) and study their evolution, from low-z (z=0.1) up to high-z (z>3), as a function of galaxy type and environment.

2- ***Derive the distribution functions, such as luminosity, stellar, and star-formation functions and their evolution as a function of the environment.*** The project includes: - the use of advanced tools to derive from Euclid photometric data the galaxy and AGN's physical properties, along with their errors and probability posterior; - to explore various techniques (Self-Organizing Maps, or other ML methods) for the selection of potentially interesting subsamples of galaxies; - to derive galaxy and AGN distribution functions and their redshift evolution, using classical methods and machine learning, in particular, to explore methods to assess the impact of physical properties errors; - to make the new tools available to the wider community through their implementation into the ESA datalabs; - to compare the results to state-of-the-art simulations and semi-analytic models (e.g. GAEA), in order to put them into the broader context of galaxy evolution;

The PhD candidate will be involved in the Euclid Collaboration and in the Euclid Legacy Science Advanced Analysis Tools (ELSA), a HORIZON-EU-funded project (PI: M. Talia). The PhD candidate will have the opportunity for collaboration and visibility within the international Euclid Consortium.

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A zoom-in of Euclid's Deep Field South: galaxies of many different shapes and sizes, various huge galaxy clusters, and gravitational lenses are visible in the image.
ESA/Euclid/Euclid Consortium/NASA, image processing by J.-C. Cuillandre, E. Bertin, G. Anselmi

PhD project in ASTROPHYSICS

Title of the Project: *Tracking the First Polluters: Inhomogeneous Chemical Enrichment from Massive Stars in the Early Universe*

INAF-OAS Supervisors: Dr. Donatella Romano, Dr. Raffaele Pascale

DIFA Supervisor: Prof. Federico Marinacci

Scientific Case: Our understanding of the early chemical enrichment of galaxies is currently undergoing a paradigm shift, driven by high-precision abundance measurements in Galactic halo stars and high-redshift observations from the *James Webb* Space Telescope (*JWST*). A central mystery lies in the significant scatter of light-element ratios, specifically [N/O] and $^{12}C/^{13}C$, in metal-poor environments.
Standard stellar evolution models struggle to explain the nitrogen-enhanced patterns observed in some compact systems at high redshift, as well as the high N abundances and low $^{12}C/^{13}C$ ratios observed in some Galactic halo stars. A key solution to this problem is the presence of massive stars with high initial rotational velocity. In these objects, rotational mixing transports nucleosynthesis products from the core to the envelope, drastically boosting the production of ^{14}N and ^{13}C via the CNO cycle.
To decipher the observed signatures, the ability to model the inhomogeneous enrichment of the interstellar medium is fundamental, and to do so, high-resolution 3D simulations that implement stellar feedback on a star-by-star basis are necessary. This allows us to capture the stochastic nature of chemical injection in metal-poor environments, where a single massive rotator can fundamentally alter the "chemical mosaic".

Outline of the Project: The PhD candidate will investigate the chemical evolution of low- and high-density metal-poor environments by bridging the gap between stellar nucleosynthesis and galactic-scale hydrodynamics. The student will implement a sophisticated chemical enrichment module within the moving-mesh code AREPO that treats stellar polluters as individual sources. This represents a major improvement over typically adopted methods, which average yields across stellar populations (SSPs). The core of the research will focus on the evolution of Nitrogen and Carbon isotopes. The first step will consist in quantifying how the inclusion of rotation-enhanced yields affects the spread of the [N/O] ratio in metal-poor regimes, as well as in predicting the scatter of $^{12}C/^{13}C$ in the Galactic halo and comparing these results with spectroscopic surveys of extremely metal-poor (EMP) stars. In the final phase, the student will use these high-resolution "zoom-in" simulations to provide a theoretical framework for *JWST* observations. By simulating the first stages of galactic assembly, the project will determine if the chemical inhomogeneities seen in our own Galactic halo are consistent with the integrated light signatures of galaxies at $z > 6$.
The project addresses two major open questions at the intersection of galactic astrophysics and stellar chemistry: can the observed chemical scatter in the Milky Way be used as a fossil record to constrain the initial rotation distribution of the first stars? And are the anomalous chemical patterns in the early Universe a natural consequence of stellar rotation and inhomogeneous mixing?

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PhD project in ASTROPHYSICS

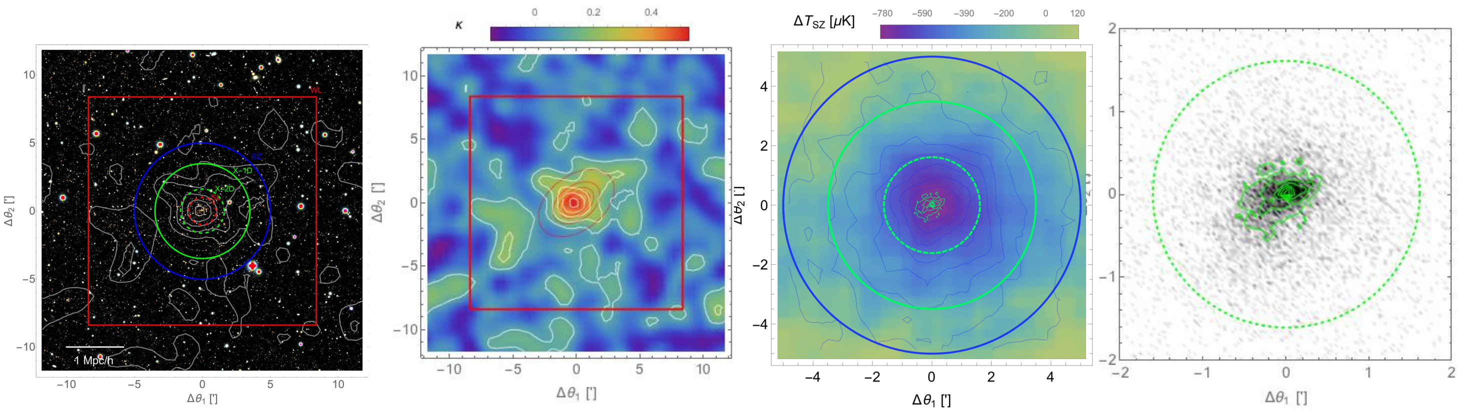
Title of the Project: CLUMP-3D: CLUster Multi-Probes in Three Dimensions

INAF-OAS Supervisor: Mauro Sereno

Co-Supervisors: Jack Sayers (Caltech, USA), Junhan Kim (KAIST, Korea)

Scientific Case: Galaxy clusters can probe fundamental physics and cosmology. They form at the nodes of the cosmic web, constantly growing. Their full picture can be taken only with a joint study of optical, X-ray, Sunyaev–Zel'dovich, and radio features. This is the goal of CLUMP-3D, a project to describe at the same time the three-dimensional shape, distribution, and equilibrium status of dark-matter, hot baryons (diffuse gas), and cold baryons (galaxies) in galaxy clusters. We propose a Ph.D. project to apply the method to deeply targeted haloes (CHEX-MATE) or very large samples covered by large surveys (Euclid, DESI, LSST, HSC-SSP, eRosita, LOFAR-LoTTS, Planck, SPT, ACT) and to explore the low mass and high redshift end of the halo population. The student will join the CHEX-MATE, Euclid, or Rubin-Observatory LSST international collaborations.

Fig. Multi-wavelength view of MACS 1206. From left to right: galaxy distribution; lensing inferred dark matter; SZ map; X-ray surface brightness.



Outline of the Project: Year 1: Update of the pre-existing CLUMP-3D pipeline. **Year 2:** Analysis to constrain shape and thermal status of targeted samples (CHEX-MATE). **Year 2-3:** Application to survey data.

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PhD project in ASTROPHYSICS

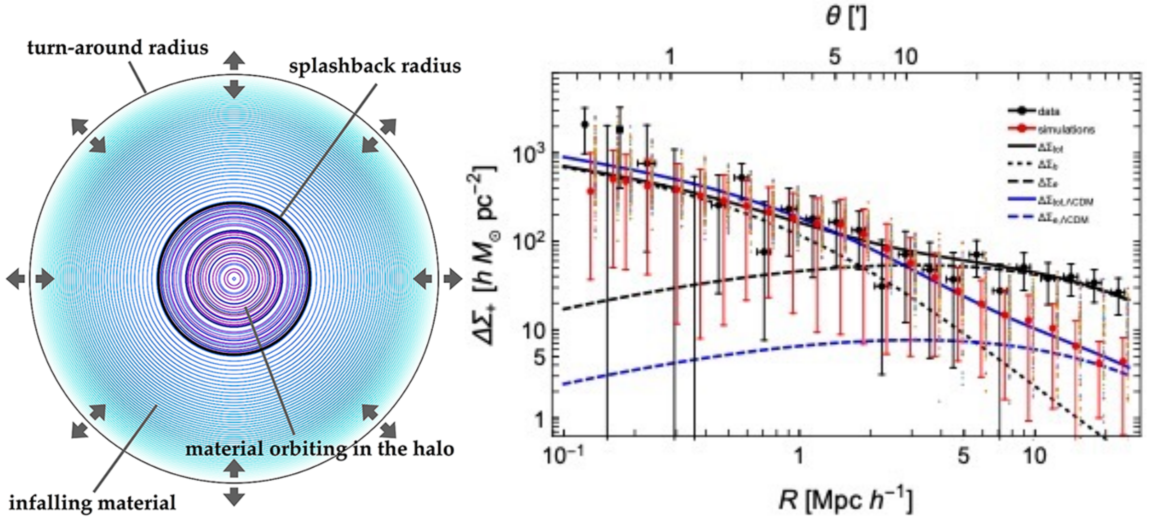
Title of the Project: The frontier of galaxy clusters in time and space

INAF-OAS Supervisor: Mauro Sereno

Co-Supervisors: Mario Radovich (INAF-OAPd)

Scientific Case: In the standard theory of matter growth, cosmic structures form hierarchically and self-similarly from smaller clumps. As the latest, still growing, most massive nearly virialised haloes to form, galaxy clusters put important constraints on formation theories. The current frontier of cluster science is beyond z~2 in time, closing in on the era of formation of the first massive haloes when the universe was only ~3 Gyr old, and beyond r~3 cMpc in space, looking at the accretion region. Here, we propose to constrain the cluster properties at the splashback and up to turnaround radius. We want to provide an animated image of the cluster outskirts to picture where the matter is, where it is going, and if it is infalling as expected in ΛCDM. The mass distribution will be characterised with weak lensing. The dynamics and orbits of cluster members will be constrained with the projected phase-space diagram of rest-frame velocities vs. distances. The Ph.D student will exploit Stage-III and IV lensing (Euclid, HSC-SSP, DES, KiDS) and spectroscopic (Euclid, DESI, SDSS) surveys to test or discard theories of gravity.

Fig. (*Left*) Idealised spherical collapse in the expanding Universe. (*Right)* The lensing measured excess surface density of PSZ2 G099.86+58.45 up to large radii.



Outline of the Project: Year 1: Development of the pipeline. **Year 2:** Testing and data analysis. **Year 2-3:** Data analysis and interpretation.

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PhD project in ASTROPHYSICS

Title of the Project: Electromagnetic Counterparts of Binary Neutron Star Mergers

INAF-OAS Supervisor: Giulia Stratta INAF-OAS)

Co-Supervisors: Andrea Rossi (INAF-OAS), Simone Dall'Osso (Università di Bologna)

Scientific Case: *Binary neutron star (BNS) mergers are key laboratories for multi-messenger astrophysics, providing insight into the physics of relativistic jets, compact objects, and kilonova (KN) emission. Key open questions remain on the diversity of kilonova emission properties, on the nature of the merger remnants, and on the link between merger and host galaxy properties. This project is aimed at modelling the GRB afterglow and kilonova emission with state-of-the-art tools, constraining the kilonova luminosity distribution, and studying correlations between kilonova and host galaxy properties. Overall, this project will provide new insights into the diversity of BNS electromagnetic counterparts and of their host galaxies, contributing to a more complete understanding of compact object mergers, and to the refinement of follow-up strategies of gravitational wave events in the multi-messenger era.*

Outline of the Project:

- *We will first model GRB afterglow and associated kilonova emission using state-of-the-art tools (e.g., NMMA, FIESTA, Redback etc., see e.g. Singh et al. 2026), expanding past works on newly discovered and/or previously unmodelled events, including systems with possible long-lived remnants (e.g., magnetar-powered emission). This will allow a consistent comparison of afterglow and KN properties across different mergers.*
- *We will then constrain the luminosity distribution of kilonovae, building a homogeneous framework to assess their diversity, and compare the predicted fluxes at different distances with the capabilities of current and future observational facilities.*
- *Finally, we will study the properties of host galaxies (e.g., star formation rate, stellar mass, extinction, and stellar population age) of GRBs with an associated KN (i.e. with confirmed BNS merger progenitor) and investigate potential correlations with kilonova parameters such as the mass and velocity of the ejecta. These results will be compared with theoretical predictions, and will be used to identify the most likely host galaxies of BNS mergers among the large number of candidates contained within the wide sky error region provided by gravitational wave interferometers in future follow-up campaigns.*

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PhD project in ASTROPHYSICS

Title: *Rise and shine: the star formation law during the Epoch of Reionization*

INAF-OAS Supervisor: Dr. Livia Vallini

Co-Supervisors: Dr. C. Gruppioni (INAF - OAS), Prof. F. Pozzi (DIFA)

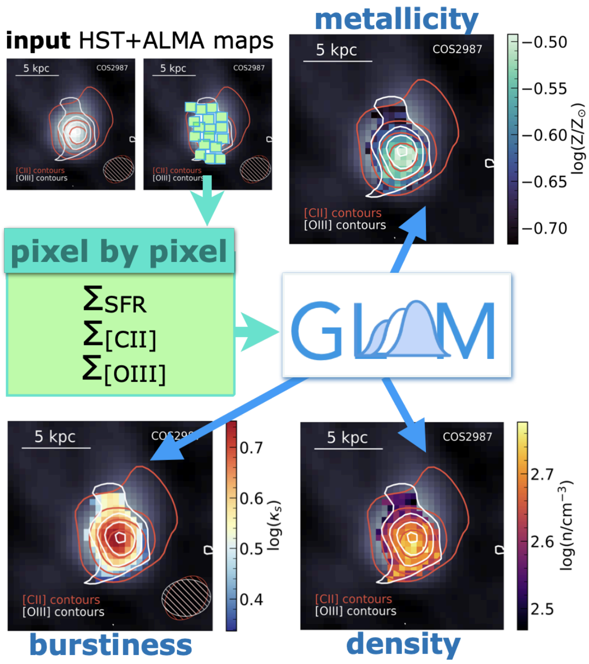
Scientific Case
How do galaxies, with and without an Active Galactic Nucleus (AGN), form stars during the Epoch of Reionization? Was the Kennicutt-Schmidt law, connecting the star formation rate to its fuel, already established in the EoR? Answering these questions is essential for clarifying the evolution of the Universe's last fundamental phase transition and shed light on the galaxy mass assembly in the first 500 million years of the Universe.

The unprecedented details captured by ALMA and JWST observations indicate differences in the interstellar medium (ISM) of EoR galaxies compared to local ones. EoR sources were dense and compact (Tacchella+2023), they were turbulent due to frequent mergers, yet showed signs of already ordered disk-like structures. ALMA's findings of unexpectedly low surface brightness in neutral gas lines, relative to ionized ones (Harikane+2020), suggest bursts of star formation depleting the cold gas (Vallini+2021,2024,2025). Additionally, the cutting-edge JWST spectroscopy is uncovering an increasing number of AGN in the first galaxies (Übler+2023) which were completely undetectable by previous instruments. While these AGN are less luminous than high-z quasars detected pre-JWST, their higher occurrence likely played a role in the evolution of their hosts (Koudmani+2022) possibly causing the emergence of quiescent galaxies (Carnall+2023). This discovery also opened a debate on the AGN contribution to Reionization, either direct through ionizing photon production, or indirect, due to their feedback on star formation. We now have an exceptionally sharp view of the gas, stars, and AGN within high-z sources. However, models that capture the ISM structure, chemistry, and feedback processes are urgently needed to fully leverage the unprecedented quality of ALMA and JWST data.

Outline of the project
The goal of this PhD project is to shed light on how galaxies and AGN formed stars in the Epoch of Reionization, and disentangle the impact of star formation on line emission from the ISM. This ambitious goal will entail the following steps:
1) Implementation of AGN Effect on Line Emission in the FIR and Optical/UV: This task will be accomplished by developing tailored and self-consistent radiative transfer models that account for the ionized, neutral, and molecular gas phases in the ISM of galaxies. The student will utilize all available observational data regarding the SED shape (both stellar and

AGN) in typical EoR sources. The PhD student will study the evolution line emission ratios, equivalent widths, the impact of metallicity, gas density profiles, and turbulence, and finally achieve a self-consistent framework for interpreting line emission from EoR sources.

2) Integration of Step 1 Results into a Semi-Analytical Model: This step will facilitate a convenient and rapid analysis of observational data from ALMA and JWST using an enhanced version of the semi-analytical tool GLAM ([Galaxy Line Analyzer with MCMC]). The GLAM model (Vallini+2020, 2021,2024; **see the Figure**) is a Bayesian method for inferring ISM properties (density, deviation from the KS relation (called burstiness), metallicity) from ALMA maps of FIR lines. The PhD student will enhancev GLAM's capabilities by incorporating nebular lines, and the effects of AGN radiation into the analytical tool. The enhanced GLAM code will be then used to interpret JWST data.



3) Derivation of the Impact of the star formation law on Observational Diagnostics in order to characterize with UV/Optical/FIR line emission key quantities such as the fraction of UV photons that escape from galaxies and contribute to the reionization. The work will also aim at disentangling and assessing the contribution of galaxies versus AGNs to reionization.

During the PhD course the student will learn how to model line emission from different gas phases in galaxies and AGN, and how to interpret ALMA and JWST data in the highest redshift galaxies so far discovered. He/she will build up fundamental skills in **data processing** and **data analysis** by using his/her model for post-processing cosmological zoom-in simulations producing mock emission maps. Finally, he/she will learn how to write proposals for state of the art facilities such as ALMA and JWST.

Generous travel funding will be available, through the INAF Minigrant RISE (PI: Vallini) International mobility is already planned as we **envisage that part of the work will be carried out in institutes abroad** thanks to collaborations already in place (Caltech and Flatiron institutes (USA), Strasbourg Observatory (France), University of Concepcion (Chile), University of Geneva (Switzerland)).

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PhD project in ASTROPHYSICS

Title of the Project:
Development of Next-Generation Technologies for Hard X-ray Focusing Space Missions

INAF-OAS Supervisor Enrico Virgilli

Scientific Case
High-energy astrophysics serves as our window into the most violent and extreme phenomena in the cosmos, including black holes, neutron stars, and gamma-ray bursts. While observing the Universe in hard X-rays and gamma-rays is fundamental to unlocking the physics of these objects, current traditional detection methods are hindered by high background noise and restricted sensitivity.
The implementation of focusing optics in the hard X-ray domain (50–300 keV) represents a transformative leap in technology. By concentrating photons, we can drastically improve signal-to-noise ratios, enabling unprecedented precision in spectroscopy, timing and polarimetry of high-energy sources. This project will address the scientific and technological requirements for PHEMTO (Polarimetric High Energy Modular Telescope Observatory, see Fig. 1) a mission proposal for the ESA M8 call, which aims to revolutionize our understanding of the polarized high-energy sky.

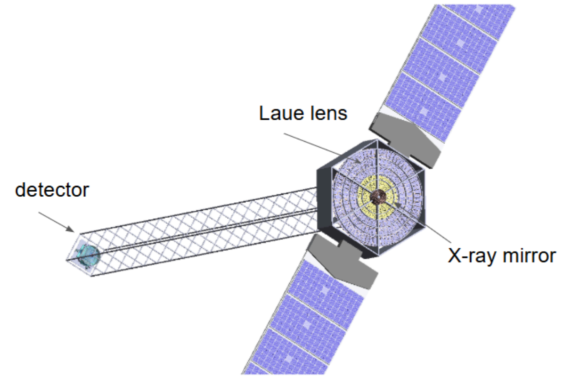

Fig. 1. PHEMTO preliminary design

Outline of the Project
Depending on the attitude of the candidate, one or more of the following activities will be addressed.

1) Advancing technology for X-ray mirror and Laue lens. While INAF holds the expertise in X-ray mirrors (1 - 70 keV), there are currently no technologically mature hard X-ray optics available worldwide for space applications. Laue optics represent the only viable method for focusing in the 50–300 keV range. INAF also has the leadership in the design and prototyping of Laue lenses. The PhD candidate will utilize Monte Carlo simulations and prototype development to bring this technology to flight-readiness.

2) Cutting-edge focal plane detectors: In collaboration with national and international institutes the project involves also developing high-density pixelated CZT and/or CdTe solid-state detectors.

3) Mission requirements and mission profile definition: the candidate will contribute to defining the scientific and technical requirements for a mission based on X-ray optics. This includes A) mission profile: defining the orbital parameters (e.g., L2 or Low Earth Orbit) to minimize background radiation. B) evaluate sensitivity and polarimetric capability of the instrument; C) analyzing the trade-offs between focal length, mass, and power consumption

On-going International Collaborations

The PhD student will be involved in an international research environment. This includes potential internships and collaborative work at European institutes such as DTU (Copenhagen), CEA (Paris-Saclay), LIP (Coimbra).

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PhD project in ASTROPHYSICS

Title of the Project: Development, testing, and exploitation of next-generation X and Gamma-ray space missions (ESA, NASA, ASI) for multi-messenger astrophysics

INAF-OAS Supervisors: Enrico Virgilli, Riccardo Campana

Scientific Case: The modern era of astrophysics is defined by multi-messenger observations, where the study of the most extreme objects in the Universe, such as merging neutron stars and black holes requires the simultaneous detection of gravitational waves and high-energy electromagnetic signals. These cosmic events produce violent, transient phenomena like Gamma-Ray Bursts (GRBs), which serve as powerful probes of the early Universe and the physics of matter under extreme conditions.

The proposed PhD research is integrated into a roadmap of high-energy space missions designed to vastly increase the discovery space of transient phenomena. This includes the development and performance assessment of **THESEUS (Transient High-Energy Sky and Early Universe Surveyor)**, a candidate for the ESA M7 mission slot currently in Phase A, which aims to monitor the high-energy sky for GRBs and early Universe transients. Other mission opportunities which are now under evaluation are **GEMMA (Gamma-ray Explorer for Multi-Messenger and cosmic Accelerators)** and **GECO (Galactic and Extragalactic Compact-objects Observatory),** being proposed as the next Italian small-scale scientific mission (call ASI-INAF), focusing on monitoring for multi-messenger targets. Furthermore, the PhD project will explore the possible Italian involvement (both scientific and technological) in **XTRA (Xplorer for Time-domain Relativistic Astrophysics)**, a potential NASA MIDEX mission in the hard X-ray domain designed to provide unprecedented sensitivity for transient detection. All these mission concepts are fundamentally based on (or are adaptations of) the **XGIS (X and Gamma-ray Imager and Spectrometer)** instrument concept. The XGIS is an advanced instrument which has been designed at OAS Bologna and it is currently being optimized and characterized through laboratory tests and simulations to ensure optimal performance for these future space missions.

Outline of the Project: depending on the attitude of the PhD student, the activity will focus on one or more of the following research topics:

– Experimental characterization: focus on laboratory and environmental tests (thermal-vacuum, vibration, radiation) to characterize detector modules, including energy resolution measurements and effective area calibration.

– Electronics and readout systems: research into improving front-end electronics and readout systems, specifically optimizing noise reduction, signal processing, and radiation hardness to enhance sensitivity while maintaining low power consumption.

– Simulation and data exploitation: modeling instrument responses, validating detection efficiency, and refining background rejection techniques to analyze high-energy transient phenomena using both experimental and simulated data.

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