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3	Bellazzini1	Bellazzini	A space-based re-foundation of optical photometry with Gaia
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29	Vallini1	Vallini	The rise of star formation during the Epoch of Reionization
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PhD project in ASTROPHYSICS

Title of the Project: *The rise of star formation 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), formed stars during the Epoch of Reionization (EoR)? 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: *the Reionization.*

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). 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.

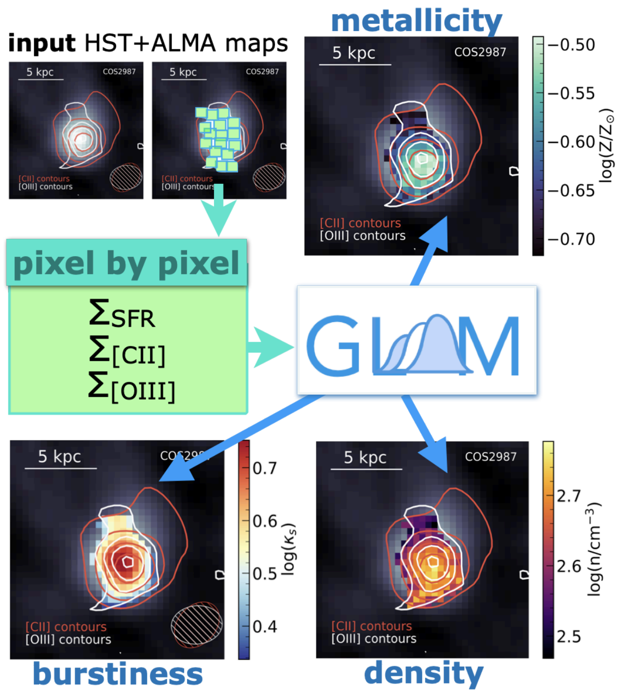
We now have an exceptionally sharp view of the gas, stars, and AGN within high-z sources. However, models that capture the ISM structure, chemistry, and feedback processes are urgently needed to fully leverage the unprecedented quality of ALMA and JWST data.

Outline of the project

The goal of this PhD project is to shed light on how galaxies and AGN formed stars during the first Gyr of cosmic history, 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 right 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 and will acquire the independence needed to successfully continue her/his career at international level.

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 renowned institutes abroad** thanks to collaborations already in place (e.g. Caltech and Flatiron institutes (US), Strasbourg Observatory (France), University of Conception (Chile)).

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PhD project in ASTROPHYSICS

Title of the Project: The outskirts of nearby dwarf galaxies with EUCLID

INAF-OAS Supervisor: F. Annibali

Co-Supervisors: M. Bellazzini, M. Tosi, 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 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.

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) to be 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 a member of the EUCLID Consortium and is actively involved in the science activities of the "Resolved Stellar Populations" and "Local Universe" working groups. The Ph.D. student will have the possibility to work on the EUCLID data before they become public and to lead key studies on dwarf galaxies in the framework of the approved "***Local Volume Resolved Stellar Peripheries*" EUCLID key Project**. Stellar substructures, streams, and merging signatures identified in the EUCLID data will be used to reconstruct the galaxies' merging history through hydrodynamical N-body simulations in collaboration with the Ph.D. thesis co-supervisors.

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:
A combined optical-HI study of nearby dwarf galaxies in the LCDM cosmological framework

INAF-OAS Supervisor: F. Annibali

Co-Supervisors: M. Bellazzini, M. Tosi, R. Pascale

Scientific Case:

Although **dwarf galaxies** are pivotal systems in the history of the Universe, many questions related to their evolution and mass assembling in a Lambda CDM hierarchical merging paradigm remain still poorly understood. Indeed, while studies of merging/accretion phenomena onto dwarf hosts have received little observational attention so far (mostly because of the difficulty in detecting very faint satellites or merger signatures around them), such processes cannot be ignored, as interactions and accretions can strongly affect dwarf galaxies' morphology and kinematics, triggering the inflow of gas and the possible onset of starbursts.

In order to provide new insights on this problem, we propose a Ph.D. project based on a unique sample of 45 nearby (D<10 Mpc) dwarf galaxies for which a highly valuable dataset in optical and HI is available: i) Proprietary deep, wide-field **Large Binocular Telescope** (LBT) **imaging** from the "SSH" Strategic Program (45 hrs, PI Annibali); ii) Proprietary **Hubble Space Telescope data** for a subsample of the SSH dwarfs with merging signatures (38 orbits, PI Annibali); iii) Both proprietary (PI Cannon) and archival **HI data** from different facilities (Very Large Array, Giant Metrewave Radio Telescope, Westerbork Synthesis Radio Telescope).

While the deep, wide-field LBT data and HI data will permit to unveil signatures of accretion or merging events around the dwarfs (e.g. through peculiar gas/stellar features or streams, and/or morphological/kinematical distortions), the superb depth and spatial resolution of HST will allow to infer the galaxies' star formation history (SFH) through modeling of their resolved-star color magnitude diagrams. In the end, the galaxies' optical and HI morphologies, the stellar and gas masses, the HI kinematics, and the spatially-resolved SFH will provide all the ingredients necessary to run tailored hydrodynamical N-body simulations of gas-rich merging dwarfs.
This project will pave the way for future, deeper studies of more distant merging dwarfs with JWST, ELT and SKA. In particular, while JWST will permit to resolve individual stars at much fainter magnitudes than HST, thus reaching larger distances for SFH studies, the extreme resolving power

of MORFEO/MICADO@ELT will permit to study individual stars in the most central and crowded galaxy regions well beyond 20 Mpc, an achievement out of reach of HST and JWST.

Part of the Ph.D project will be devoted to the development and analysis of simulations of resolved stellar populations in dense regions of dwarf galaxies with MORFEO/MICADO@ELT, within the activities that the MORFEO Science Team is currently performing in preparation for the ELT science exploitation under the coordination of the proposed PhD supervisor, who is the MORFEO Project Scientist.

Outline of the Project:

YEAR 1: analysis of the LBT and HST data, with particular focus on resolved star color-magnitude diagrams (CMDs). Lead of proposals (JWST, HST, LBT, VLT) for new observations. Participation to at least 2 refereed papers. Participation to the activities of the MORFEO@ELT science team and involvement into preparatory work for future resolved stellar population studies.

YEAR 2: analysis of the LBT/HST CMDs for the SSH dwarf galaxies (plus new data from successful proposals), derivation of their star formation histories, derivation of associated streams/satellites' properties. Publication of at least 1 paper as first author. Participation to MORFEO@ELT science team activities, simulations of resolved-star science cases.

YEAR 3: finalization of the results in the context of galaxy formation, evolution, and hierarchical merging buildup, also taking into account new results from the collaboration on HI data and N-body hydrodynamical simulations. Publication of at least 1 paper as first author. Participation to MORFEO@ELT science team activities, contribution to updated MORFEO white paper.

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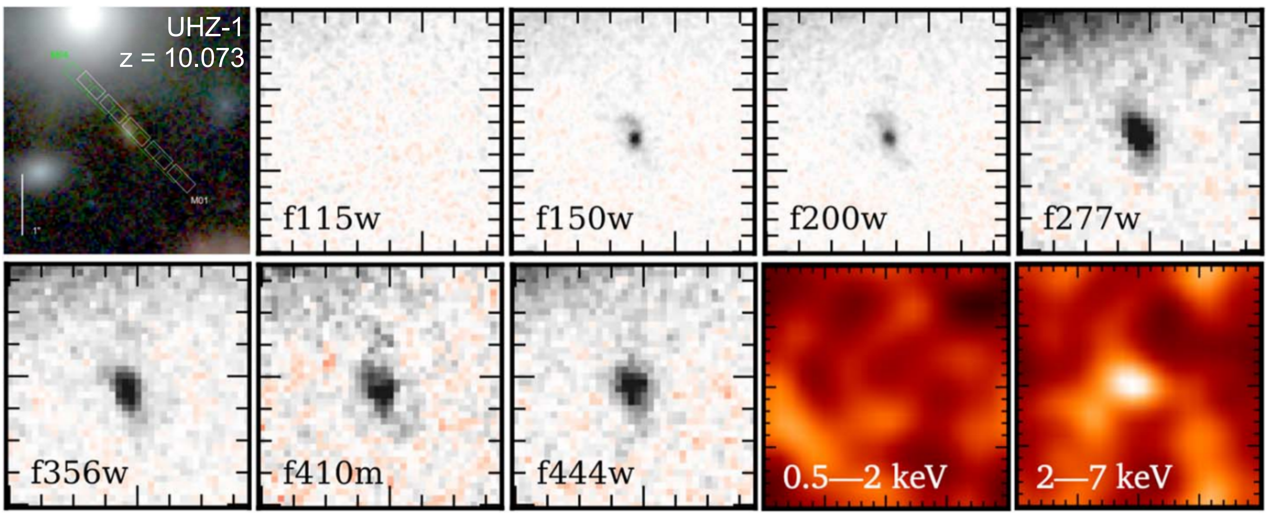
PhD project in ASTROPHYSICS

Chasing the first lights: Supermassive Black Holes in the early Universe

INAF-OAS Supervisor: Andrea Comastri (INAF)

Co-Supervisors: Giorgio Lanzuisi (INAF), Fabio Vito (INAF), Stefano Marchesi (DIFA)

Scientific Case:
Observations with the James Webb Space Telescope (JWST) have revolutionized our knowledge of the light-up and early evolution of black holes powering Active Galactic Nuclei by revealing an emergent population of high-redshift (z=4-10), moderate luminosity (both broad and narrow-line) AGN candidates with weak or absent X-ray emission.
Their number density is approximately one to two orders of magnitudes larger than X-ray and UV-selected quasars, respectively, at similar redshifts, challenging models for Black hole growth. The leading hypothesis suggests supercritical accretion flows (well above the Eddington rate) and/or anomalously low dust-to-gas ratios for broad-line AGN candidates, while heavy absorption by Compton-thick gas could explain the faint X-ray emission in narrow-line AGN. Preliminary results obtained by our group for a small sample of narrow-line AGN discovered by JWST, and for which ultra-deep X-ray exposures are available in the Chandra Deep Field South, indicate the presence of Compton thick obscuration as the most likely explanation of their X-ray weakness. This project aims at exploiting existing and upcoming deep X-ray surveys to systematically characterize JWST-selected high-z AGN emission via advanced stacking techniques and multi-wavelength emission analysis.



An example of a JWST-selected (through NIRCam and MIRI photometry) and spectroscopically confirmed (through NIRSpec spectroscopy) narrow-line AGN candidate, one of the few showing a possible direct X-ray detection in the hard band (adapted from Goulding et al. 2023, ApJL, 955, L24).

Outline of the Project:

The thesis will focus on the nature of the population of high-redshift AGN discovered by JWST, extensively using deep and wide observations in the X-ray band and at longer wavelengths.
In addition to ultra-deep archival X-ray observations in the Chandra Deep Fields (CDFS & CDFN) and ancillary multiwavelength surveys, the student will have privileged access to a new Chandra survey over 0.5 sq. deg in the COSMOS field, achieving uniform depth of 0.5Ms on the JWST/NIRCam/MIRI imaging survey (COSMOS-Web), NIRISS NIR spectroscopic survey (COSMOS-3D), and ALMA 1mm survey (CHAMPS).
The exquisite quality, in terms of depth and sky coverage, of the X-ray observations will be fully exploited by developing innovative stacking techniques for detecting faint emissions to constrain the average properties of well-identified homogenous samples of sources.
The conjunction of deeper X-ray data with the unparalleled area and wavelength coverage afforded by the COSMOS, CDFS, CDFS, and other surveys will enable a significantly improved characterization of the physical processes responsible for the observed behavior of supermassive black holes in the early Universe. The results will be used to estimate AGN's luminosity function and early evolution ($z > 4$-5) and their impact on the cosmological context.

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PhD project in ASTROPHYSICS

Title of the Project: The Milky Way assembly as traced by its stars and globular clusters chemistry

INAF-OAS Supervisor: Davide Massari

Co-Supervisors: Alessio Mucciarelli (UniBO); Michele Bellazzini (OAS)

Scientific Case: The recent data release from the Gaia mission has triggered a revolution in our understanding of the assembly history of the Milky Way (MW). Leveraging this unprecedented dataset of nearby stars and globular clusters, a plethora of candidate past merger events between the MW and dwarf galaxies have been discovered (Helmi et al., 2018, Massari et al., 2019). Globular clusters have proven so effective in this respect, that the investigation of their chemistry has also opened the way to investigate the assembly of MW satellites, such as the LMC (Mucciarelli et al. 2021, Nature Astronomy). The next step to understanding the assembly history of the MW and its siblings is to characterise these candidate merger events, using chemical tagging to distinguish dwarf galaxies accreted in the past from structures born in-situ. For the actual merger progenitors, then, it is crucial to reconstruct their star formation histories. The PhD candidate will pursue this ambitious objective by working first with state-of-the-art Gaia DR3 kinematic data, to associate the known Galactic globular clusters with their former galaxy progenitor based on their orbital properties. Then, they will reconstruct the progenitors chemical properties by using proprietary high-resolution spectroscopic data of both stars and globular clusters, to be compared with chemical evolutionary models to reconstruct each galaxy star formation history.

Year 1: dynamical classification of retrograde field stars and globular clusters based on Gaia DR3 and proprietary spectroscopic data;
Year 2: Chemical analysis of inner-halo globular clusters and retrograde field stars;
Year 3: Comparison with theoretical models and reconstruction of the star formation history of past merger events

Dataset (WRS project):
-140 hours of proprietary data taken with PEPSI@LBT (field stars)
-185 hours of proprietary data taken with UVES@VLT (field stars + globular clusters)
-Gaia DR3 kinematic data

External collaborations (possible Marco Polo destinations):
Prof. A. Helmi (University of Groningen, NL)
Prof. P. Bonifacio (Observatoire de Paris, FRs)

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PhD project in ASTROPHYSICS

Title of the Project: Globular clusters as tracers of the Milky Way evolution

INAF-OAS Supervisor : Davide Massari

Co-Supervisors : Alessio Mucciarelli (UniBO); Michele Bellazzini (OAS); Emanuele Dalessandro

Scientific Case: Globular clusters (GCs) are exceptional tracers of the Milky Way evolutionary history, especially in the highly extincted inner regions of the Galaxy or in the far away Halo. Thanks to the GCs orbital properties, we now know that about half of those currently living in the Milky Way were actually born in external galaxies, and were only later accreted. To accurately determine each GC galaxy progenitor, though, additional chronological information in required. This is the objective of the CARMA project (Massari et al. 2023), that aims at determining the age of the entire system of Milky Way GCs with unprecedented precision. As part of the CARMA collaboration, this project will complete the census of GC age, and will use their age-metallicity relation to reconstruct the timeline of the Milky Way merger tree, by estimating the mass and accretion time of each single merger event. Novel data acquired by the Hubble Space Telescope of 34 candidate GCs never studied before (the Hubble Missing Globular Cluster Survey, Massari et al. 2025) will be available, together with exceptional imaging from the Euclid telescope. This fantastic dataset will enable distinguishing actual GCs from open clusters or even ultra-faint dwarf galaxies, thus characterising the last known GCs whose properties and origins are still very poorly understood.

Outline of the Project:
Year 1: determining the age of Milky Way GCs within the CARMA framework;
Year 2: characterizing the unexplored GCs targets of the Missing Globular Cluster Survey and of the Euclid Data-Release 1;
Year 3: reconstructing the Milky Way assembly timeline using the age-metallicty relation of the GCs associated to each merger event.

Dataset:
- The Hubble Missing Globular cluster survey: HST imaging of 34 GCs *never explored before*
- Euclid astro-photometric data
- Gaia DR3 kinematic data

External collaborations (possible Marco Polo destinations):
Dr. A. Bellini (Space Telescope Science Institute, Baltimore, USA)
Prof. C. Gallart (IAC Tenerife, SPA)
Prof. A. Helmi (University of Groningen, NL)

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PhD project in ASTROPHYSICS

Title of the Project: Galactic archaeology through the lenses of N-body simulations

INAF-OAS Supervisor: Davide Massari

Co-Supervisors: Raffaele Pascale, Carlo Nipoti (UniBO)

Scientific Case:

The advent of the Gaia mission, in combination with large spectroscopic surveys such as APOGEE and GALAH, has revolutionized our understanding of the Milky Way assembly history. Thanks to Gaia kinematic measurements and to chemical abundances now available for several millions of stars in the solar neighborhood, we now know that the vast majority of the nearby stellar Halo has originated in a dwarf galaxy, named Gaia-Enceladus, that has been accreted by the Milky Way about 10 Gyrs ago. Other merger events have been identified in the chemo-dynamical space, but their interpretation is far more challenging. In fact, on the one hand recent numerical simulations have shown that debris from the same merger event can develop separate sub-structures in the dynamical space. On the other hand, the stellar debris of past mergers moving on similar orbits now overlap in both the dynamical and chemical spaces. This makes it difficult to disentangle each independent merger and to interpret the complexity of the stellar populations in the Milky Way Halo. To face this challenge, we propose a project that aims at developing suitable hydrodynamical N-body simulations of the Milky Way with the aim of:
1-testing the efficacy of globular clusters as tracers to investigate the outer stellar halo, where our knowledge of the Milky Way assembly is currently very poor.
2-looking for new observational parameters that can help in disentangling the chemo-dynamical complexity, such as stellar age or the initial mass function.

Over the course of three years, the PhD student will develop suitable N-body simulations to investigate the accretion of satellite galaxies, along with their associated globular cluster populations, by the Milky Way. These simulations can be used to: i) explore the correlation between the initial distribution of the accreted satellite's globular cluster population and the distribution of the globular clusters and dismembered satellite in the chemo-dynamical space post-accretion; ii) comprehend the mechanisms that may result in the formation of distinct sub-structures in the dynamical space as a consequence of the same merger event. Subsequently, the simulations will aid in interpreting observational data. The project aims at publishing at least one paper per year, and foresees the participation to international PhD schools and conferences to advertise the related results, as well as a period of collaboration with international researchers.

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PhD project in ASTROPHYSICS

Title of the Project: Gamma-ray Bursts in the Multi-Messenger Era: Progenitors, Full-physics Afterglow Modeling, and Beyond

INAF-OAS Supervisor: Giulia Stratta

Co-Supervisors: **Andrea Rossi, Cristiano Guidorzi, Mattia Bulla, Lorenzo Amati**

Scientific Case: Gamma-ray bursts (GRBs) are cosmic events intimately connected to the formation of neutron stars (NS) or stellar-mass black holes (BH) during the gravitational collapse of massive stars or the coalescence of compact object (NS or BH) binary systems. GRBs are fascinating phenomena *per se,* and in the last years gained further attention as sources of gravitational waves (GWs) after the case GRB 170817, associated with the GW signal from a NS-NS merger system (GW 170817) [1]. The same source produced also the first robust evidence of a kilonova [2,3,4], the elusive optical transient expected to be powered by the radioactive decay of heavy elements synthesized in the neutron-rich matter ejected during the coalescence of compact object (NS or BH) binary systems. To the gamma-ray explosion (0.1-100 s), a multi-band afterglow follows on longer timescales (days-weeks) [5]. Afterglows are powerful probes of the physics at play in these complex events. We aim to validate the current state-of-the-art of the afterglow emission modelling on a sample of GRBs with an exceptionally rich dataset, and to search and characterize the kilonova signals observed in nearby events, focussing on some peculiar GRBs with unexpected gamma-ray properties [6-10]. Results will be used as guidance for detector capabilities of future GRB space missions that will operate in synergy with next generation GW facilities, when dozens of GRB and their GW counterparts will be detected each year.

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Outline of the Project:

- search for long GRB originating from binary neutron star mergers (or neutron star-black hole mergers) rather than from the collapse of massive stars, by exploring their prompt emission properties observed by existing gamma-ray space observatories (e.g. Swift, Fermi, etc.) [11];
- collect their multi-band dataset from the literature and public archives (e.g., Swift/XRT lightcurve repository), or by new follow-up observations obtained via awarded time;
- build a SN Ib/c lightcurve repository using publicly available catalogs;
- build a tool which computes the observed SN lightcurves in the GRB rest frame and allows for estimate of expected magnitude in any filter;
- analyze the multi-band emission of binary-driven long GRB candidates within existing framework, as the "Nuclear Physics and Multi-Messenger Astrophysics" framework (*NMMA, [12]*) to verify presence/absence of a SN or a kilonova;
- explore the existing cc-SN observations in the blue and UV bands in order to extend our analysis to binary driven long GRB candidates at z>1-2 and consider whether we should apply to HST time for additional UV data of new SNe.
- build a sample of a few GRBs according to the following selection criteria: a) known distance; b) good temporal monitoring in all bands, from high-energies (GeV/TeV or X-rays) to radio wavelengths; c) no evidence of extra-features such as plateaus or kilonova emission;
- collect their multi-band dataset
- build a Bayesian framework for inference analysis from which model parameters can be obtained.

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PhD project in ASTROPHYSICS

Title of the Project: Fostering Scientific Citizenship through Creative Learning: Designing and Evaluating Innovative Tools for Astrophysics Education

INAF-OAS Supervisor: Sara Ricciardi

Co-Supervisors: Alessio Mucciarelli

Scientific Case:

Scientific education and the honest communication of frontier research — such as that conducted in astrophysics — play a crucial role in cultivating informed *scientific citizenship*. This project aims to explore how astrophysics, often considered a "gateway science" for its power to spark curiosity and inspire critical thinking, can become more accessible and engaging through creative learning methodologies and can be a gateway for full scientific citizenship.

The core objective of the research is to design and evaluate innovative educational tools that leverage **play-based practices such as Tinkering** and **game-based learning** to promote active, meaningful learning experiences. These tools will aim to simulate and illuminate the scientific research process in astrophysics, enabling learners to grasp not only scientific content but also the epistemic practices of science.

The project may include:

- Research studies to investigate and validate the effectiveness of play-based practices in enhancing learning outcomes and shaping public perceptions of science;
- Dissemination of results through peer-reviewed publications in international Science Education journals.
- The development of communication products such as documentary-style short films showcasing best practices

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PhD project in ASTROPHYSICS

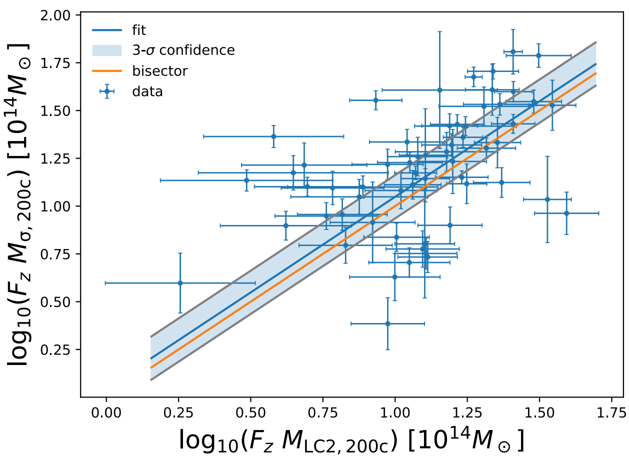
Title of the Project: Co-evolution of dark matter and cold or hot baryons in galaxy clusters as observed with multi-probe scaling relations

INAF-OAS Supervisor: Mauro Sereno

Co-Supervisors: Alberto Cappi (INAF-OAS**),** Rafael Barrena Delgado (IAC, Spain)

Scientific Case: Clusters of galaxies are the nodes of the cosmic web, constantly growing through accretion of matter along filaments or mergers. They are excellent laboratories to study the physics of the gravitational collapse, and the non-gravitational physics that affects their baryonic components. Growth and evolution depend on the underlying cosmology, and clusters are powerful cosmological probes. Many questions are still to be answered: *How does the formation process inform the equilibrium state of clusters? What are the statistical properties of the cluster population? What is the cluster mass scale?* By comparing the co-evolution of dynamical, weak-lensing, X-ray, or SZ masses with optical proxies the student will lead studies to impact our knowledge on (i) the dynamical collapse of baryons and dark matter on different scales (ii) the degree of equilibrium of dark-matter, hot baryons (diffuse gas), and cold baryons (galaxies); (iii) the balance between gravitational and non-gravitational processes in shaping cluster properties. The student will extend the LIRA (LInear Regression in Astronomy, 2016MNRAS.455.2149S) approach and will join the Euclid and the CHEX-MATE collaboration.

*Fig***.** Comparison of dynamical vs weak lensing mass for the CHEX-MATE sample [2021A%26A...650A.104C, 2025A%26A...693A...2S].



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Outline of the Project:

YEAR 1: Development of the pipeline and feasibility studies for Euclid data.
YEAR 2: Scaling relations between optical and weak lensing proxies to infer the co-evolution of cold baryons in galaxies and dark matter.
YEAR 3: Measurement of the thermalisation of galaxy clusters with the analysis of the scaling relations between dark matter, cold baryons, and hot baryons (as observed from X-ray or SZ).

PhD project in ASTROPHYSICS

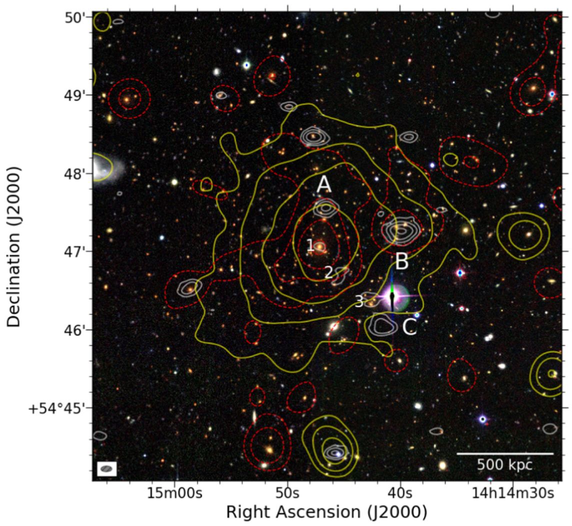
Title of the Project: Multi-wavelength lensing and radio analysis of galaxy clusters and their outskirts in the era of large surveys

INAF-OAS Supervisor: Mauro Sereno (INAF-OAS)

Co-Supervisors: Rossella Cassano (INAF-IRA)

Scientific Case: The connection between diffuse radio emission on cluster-scale, in the form of radio halos and radio relics, and the cluster dynamical state is crucial to understand the evolution and formation of the most massive virialised structures in the Universe. LOFAR and the LoTSS survey opened a new window in radio astronomy showing that radio halos can inhabit diverse clusters [2023A%26A...672A..43C]. Weak lensing can find the signatures of the mass distribution and determine the cluster dynamical state up to large scales [2018NatAs...2..744S]. The student will investigate the connection between the galaxy cluster dynamical status, the mass accretion from the surroundings, and the presence of radio emission. They will develop methods that will be used in the framework of the Stage-IV weak lensing surveys (Euclid e Rubin-LSST). The radio emission will be mainly studied from the exploitation of LOFAR surveys. The candidate would be involved in the Euclid collaboration to exploit its unprecedented weak lensing data-set and they will investigate statistically and theoretically the effect of cluster dynamics on the generation of cluster non-thermal components.

Fig. Radio vs optical emission in the high-redshift galaxy cluster PSZ2 G099.86+58.45 [2019ApJ...881L..18C].



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Outline of the Project:

YEAR 1: Development of tools for inference of accurate mass distributions from gravitational lensing.
YEAR 2: Correlation of morphology from lensing and radio emission for clusters in the sky area covered by LoTTS and Euclid-DR1.
YEAR 3: Study of the emission mechanisms in clusters and constraints on theoretical models.

PhD project in ASTROPHYSICS

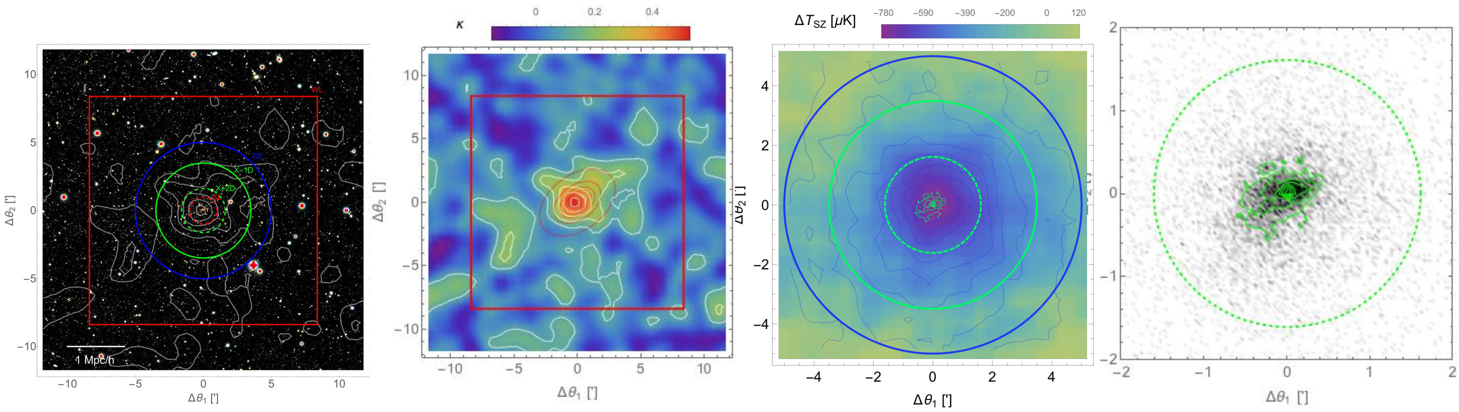
Title of the Project: CLUMP-3D: CLUster Multi-Probes in Three Dimensions of galaxy clusters in the era of multi-wavelength large surveys

INAF-OAS Supervisor: Mauro Sereno

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

Scientific Case: Galaxy clusters can probe large-scale structure, fundamental physics, and cosmology. They form at the nodes of the cosmic web, constantly growing through accretion of matter along filaments or mergers. An unbiased view of their mass distribution, shape, and equilibrium status can be achieved only with a joint study of their optical, X-ray, Sunyaev–Zel'dovich, and radio features to characterise the properties of dark-matter, hot baryons (diffuse gas), and cold baryons (galaxies) at the same time. This is the goal of CLUMP-3D, an international program so far applied to high-quality, targeted samples [2018ApJ...860L...4S, 2023arXiv230704794K]. In the era of ongoing or future multi-wavelength large surveys (Euclid, LSST, HSC-SSP, eRosita, LOFAR-LoTTS, Planck, SPT, ACT), the CLUMP-3D approach has to be generalised to very large samples to explore the low mass and high redshift end of the halo population. We propose a Ph.D. project to study the three-dimensional shape, the equilibrium status, and the non-thermal pressure of large cluster samples covered by survey data. The student will join the Euclid and Rubin-Observatory LSST international collaborations.

Fig. Multi-wavelength view of MACS 1206 [2017MNRAS.467.3801S]. From left to right: galaxy distribution; lensing inferred dark matter; SZ map; X-ray surface brightness.



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Outline of the Project:

YEAR 1: definition of a sample of clusters with multi-wavelength data from available surveys. Development and update of the pre-existing python CLUMP-3D pipeline to clusters with shallow or missing data.
YEAR 2: Analysis to constrain clusters shape and thermal status of available data.
YEAR 3: Application to available Euclid data.

PhD project in ASTROPHYSICS

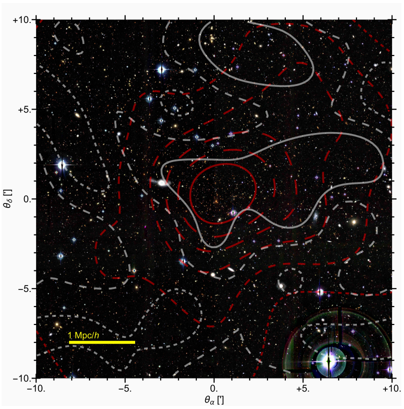
Title of the Project: Gravitational lensing detection of matter distribution at galaxy cluster boundaries and beyond

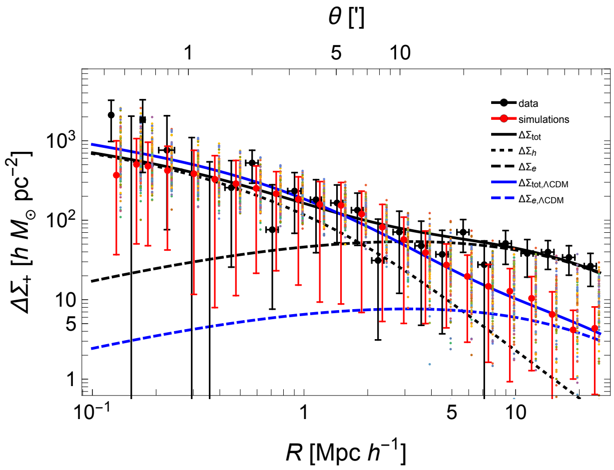
INAF-OAS Supervisor: Mauro Sereno

Co-Supervisors: Carlo Giocoli (INAF-OAS), Federico Marulli (UNIBO), Lauro Moscardini (UNIBO)

Scientific Case: Dark matter halos can probe large-scale structure, fundamental physics, and cosmology. Some of the most promising signals reside near or beyond the virial radius of galaxy clusters [2018NatAs...2..744S, 2022MNRAS.511.1484I]. We propose a Ph.D. project to study the nature and evolution of clusters by looking at their boundaries and beyond. While these scales have recently become observable with multi-wavelength surveys, the matter distribution at large radii has still to be better understood. We propose to measure the weak lensing shear up to large radii and characterise the matter distribution of galaxy clusters and their environment by first exploiting Stage III public lensing surveys, and, then, the first data release of the Euclid survey. The student will develop and apply tools to measure the splashback radius which encloses the main halo and the halo bias of the correlated matter in the cluster environment to test the ΛCDM scenario of structure formation. The student will join the Euclid and Rubin-Observatory LSST international collaborations.

Fig. The galaxy cluster PSZ2 G099.86+58.45 and its surroundings [2018NatAs...2..744S]. Left: optical i-light (red contours) and lensing inferred mass (white) distribution. Right: the signal of the correlated matter beyond the cluster boundaries as inferred from the excess surface mass density profile at 10 Mpc from the cluster center.





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Outline of the Project:

YEAR 1: setting of the theoretical modelling, development and update of the pre-existing pipeline, testing with Stage III surveys (KiDS, HSC-SSP, DES) and Euclid Q1-DR1 data.
YEAR 2: finalisation of the theoretical modelling and of the pipeline, application to Euclid data release and forecasting study for LSST.
YEAR 3: analysis of the Euclid results, release of a public version of the code, finalisation of the thesis.

PhD project in ASTROPHYSICS

Title of the Project: An X and Gamma-ray Imager and Spectrometer for future high energy space missions

INAF-OAS Supervisors: E. Virgilli, R. Campana L. Amati, C. Labanti
Co-supervisors: E. Virgilli, R. Campana, L. Amati, C. Labanti

Scientific Case
The most compact and extreme objects in the Universe, such as black holes and neutron stars, produce violent and energetic phenomena observed in the hard X/gamma-ray bands by satellite instruments. These emissions can be persistent or transient, with events like Gamma-Ray Bursts (GRBs) being particularly interesting.

INAF/OAS, with a strong tradition of collaboration with Italian (ASI) and European (ESA) space agencies, leads the design, development, and testing of hard X-ray detectors for astrophysics. Recently, the X and Gamma-ray Imager and Spectrometer (XGIS) was developed in partnership with universities and research institutions.

The PhD student will join this international collaboration to advance the instrument's technology and assess its performance. Currently, XGIS is part of the THESEUS mission, competing in ESA's 7th medium-size mission (Phase A), with final selection expected in summer 2026.

Outline of the Project
Depending on the attitude of the PhD student the activity could be one of the following:

1) This research will focus on laboratory and environmental tests to characterize the XGIS Demonstration Module Detection Module (DPDM) being developed with OHB-Italy with ESA funding. Key activities include energy resolution measurements, effective area calibration, and environmental testing (thermal-vacuum, vibration, radiation) to ensure optimal performance for space operations.
2) The study will explore improvements in XGIS front-end electronics and readout systems, optimizing noise reduction, signal processing, and radiation hardness. The goal is to enhance detection sensitivity while maintaining low power consumption for long-duration space missions.
3) This work will involve modeling the XGIS response, validating detection efficiency, and refining background rejection techniques. Using both experimental and simulated data, the research will contribute to the analysis of high-energy transient phenomena, such as Gamma-Ray Bursts (GRBs).

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PhD project in ASTROPHYSICS

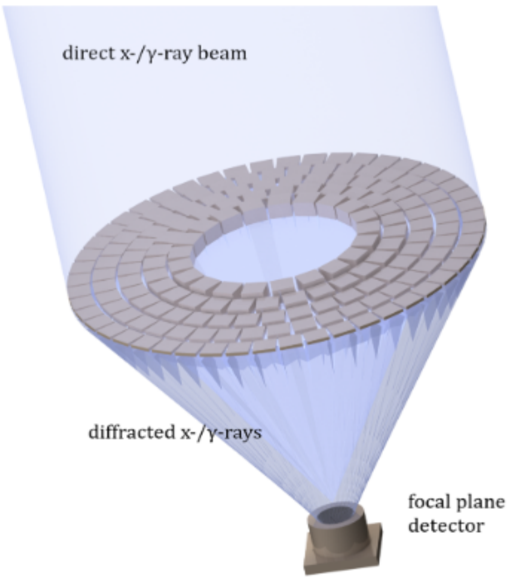
Title of the Project:
Development of technologies for hard X-ray focusing space missions

INAF-OAS Supervisor
Enrico Virgilli
Co-supervisors: N. Auricchio, G. De Cesare, E. Caroli

Scientific Case
High-energy astrophysics aims to explore the most energetic and extreme cosmic phenomena, such as black holes, neutron stars, and gamma-ray bursts. Observing the Universe in hard X-rays and gamma-rays is essential for understanding the physics of these objects, but traditional detection methods suffer from high background noise and limited sensitivity. Focusing optics in the hard X-ray domain (50–300 keV) is a transformative technology that can significantly improve observational capabilities, enabling precise imaging, spectroscopy, and polarimetry of high-energy sources.

Outline of the Project
Main activity is to design and develop technologies for both **hard X-/gamma-ray focusing optics** and **solid-state detectors** as focal plane spectrometers and polarimeters for space missions.

Focusing optics: currently, worldwide there are no technologically mature hard X-/gamma-ray optics available for space astrophysics applications. Nevertheless, such devices would be highly beneficial for enhancing the sensitivity of hard X-ray observations in the energy range 50 - 300 keV. Laue optics are the only method to enable focusing hard X-rays. We develop Monte Carlo simulations and prototypes in order to make this technology mature for space missions.



Focal plane detectors: we also develop, in collaboration with IMEM/CNR and industries, solid-state detectors including CZT and CdTe highly pixelixed detectors, which are ideal systems to enable spectroscopy and polarimetry of hard X-ray sources. Their use will be in the focus of a Laue concentrator.

On-going international collaborations: the PhD student will work in an international context with potential internships at other institutes in Europe (e.g. DTU Copenhagen, CEA Paris-Saclay, LIP Coimbra), primarily focusing on the development of focal plane detectors and/or for the advancement of hard X-ray Laue concentrators.

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Osservatorio di Astrofisica e Scienza dello Spazio
OAS – Bologna

PhD project in ASTROPHYSICS

Title of the Project: A space-based re-foundation of optical photometry with Gaia

INAF-OAS Supervisor : Michele Bellazzini

Co-Supervisors : Paolo Montegriffo (OAS-Bo), Davide Massari (OAS-Bo)

Scientific Case: The ESA-Gaia mission, among its many scientific achievements, is providing the observational basis for a complete and revolutionary re-foundation of optical photometry, that, indeed, has already started. Gaia is producing all-sky space-based photometry (G, G_BP and G_RP bands) and spectrophotometry (from absolutely calibrated low resolution BP and RP spectra, hereafter XP spectra, for brevity) for billions of sources with unprecedented accuracy and precision, on such a huge scale. In one of the Data Release 3 (DR3) *Performance Verification Papers* by the Gaia Collaboration (Montegriffo, Bellazzini, De Angelis, et al., 2023, A&A, 674, A33) it has been demonstrated that any space-based or ground-based photometric system whose passbands are enclosed in the 330-1050 nm range can be effectively reproduced to a great level of accuracy and excellent precision by synthetic photometry on XP spectra. This lead to several powerful scientific applications (see, e.g. among many others, Martin et al., 2024, A&A, 692, A115; Bellazzini & Pascale 2024, A&A, 691, A42) and to the definition of a new standard for the absolute calibration of photometry. In practice any new or ongoing survey, either from the ground (e.g., *SDSS, DES*, *S-PLUS*, ecc.) or from space (e.g, *Euclid*) is using Gaia photometry and/or spectrophotometry for relative and/or absolute calibration and/or validation of their optical photometric products, and the first application to the calibration of instruments on board of spacecrafts aimed at the exploration of the Solar System has been recently presented (Munaretto, Cremonese, Bellazzini et al., 2025, A&A, 693, A115). However, *the best has still to come*: Gaia DR4 (2026) will double the amount of observations released in DR3 and will made possible to obtain synthetic photometry for all the sources in the Gaia catalogue (>2 billion sources instead of the 220 millions whose XP spectrum was released in DR3), and Gaia DR5 (2030) will double again the amount of observations processed wrt DR4 (i.e., ×4 wrt DR3).

Outline of the Project: We propose a PhD thesis to work with the INAF-OAS Bologna group within the "Photometric Processing" coordinating unit (CU-5) of the Gaia Data Processing and Analysis Consortium (Gaia-DPAC). The programme is twofold. The main goal and the bulk of the activity would be to test and explore the capabilities of DR4 photometry and spectrophotometry in scientific applications and in the standardisation of photometric systems. In addition to this, the candidate would contribute to the refinement of the absolute calibration of Gaia photometry and spectrophotometry, helping the Gaia CU5 team at INAF-OAS Bo in the development of innovative solutions to improve the performances of the photometric products of the Gaia mission and, hence, of the long lasting heritage of the mission. The candidate will become an official member of the Gaia-DPAC for the period of her/his PhD.

Datasets: Gaia DR3 and DR4 catalogues. DR5 processing data.

External collaborations (possible Marco Polo destinations):
Dr. F. De Angeli (IoA – Cambridge, UK), Prof. R. Ibata (Obs. Strasbourg, FR)
Dr. R. Andrae (Max Planck Institute for Astronomy, Heidelberg, DE)

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PhD project in ASTROPHYSICS

Title of the Project: *Understanding stellar clusters: synergy among large spectroscopic surveys and asteroseismology*

INAF-OAS Supervisor: *Angela Bragaglia*

Co-Supervisors: *Andrea Miglio (DIFA Bologna).*
[in collaboration with WEAVE, 4MOST, PLATO consortia]

Scientific Case: *Stellar clusters* are important tracers of the Galactic structure and the connection between field stars and their parent cluster is fundamental to figure out the cluster formation and dissolution mechanism and the contribution to the general chemical and dynamical evolution of the Galaxy. Stellar clusters are ideal to *test stellar evolutionary models* and derive *ages*, on whose accuracy ultimately rests most of our understanding of galaxy evolution. We have at our disposal *i)* The ESA mission *Gaia* which provides a 5-d map of our Galaxy; *ii)* large spectroscopic surveys from the ground which add precise radial velocity, and especially metallicity and detailed chemical composition; *iii)* precise and accurate asteroseismology provided by space missions (*Kepler, K2*, TESS) which permits to determine stellar masses and ages and provides stringent test on the physics of stellar models.

Outline of the Project: The PhD project main steps are: *i)* familiarisation with/use of: stellar clusters, asteroseismology and stellar models (*mostly year 1*); *ii*) analysis of data already in hand, both from large surveys and space missions (*starting in year 1 and up to year 3*); *iii)* interpretation and publication of results (*year 2 and 3 – initial results could be presented at Meetings already from year 1).*
The PhD project will center on (at least) one of the following topics: a) Using stellar clusters as test of evolutionary models; b) Using asteroseismology to derive precise mass/age of stars in clusters in combination with ancillary spectroscopic data; c) Using open cluster as chemical tracers of the disk and its evolution. *Further developments/projects, also in collaboration with international researchers and stellar modelers, can be devised in agreement with the PhD student.*
Framework and data for the PhD project are provided by: the *Gaia* mission results; the WEAVE survey (due to start in 2025 at the WHT on Canary Islands) in which A. Bragaglia co-leads the "Galactic Archaeology-Open Clusters" part; 4MOST (ESO public survey at VISTA due to start in 2026) in which A. Bragaglia is co-PI of the Community Survey "Stellar Clusters" (while A. Miglio plays an important role connected to asteroseismology); and *Kepler-K2*, TESS, whose asteroseismic data are publicly available, plus PLATO (to be launched in 2026) and for which internationally acknowledged expertise is available at DIFA (A. Miglio, his group and international collaborations).

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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.

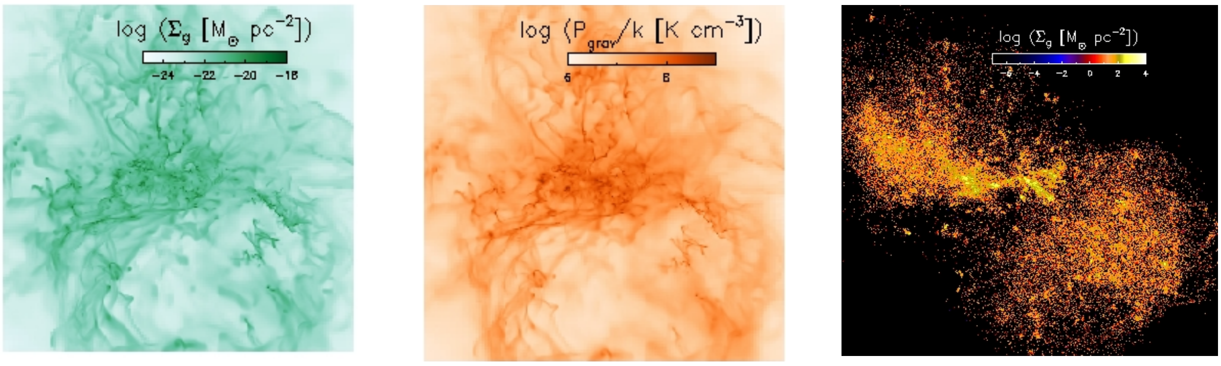
Outline of the Project:

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

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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: ***Stellar families that defy time: The internal dynamics of Milky Way Open Clusters in the Era of Gaia and Spectroscopic surveys***

INAF-OAS Supervisor: Ricardo Carrera

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Co-Supervisors:

Scientific Case:

Open clusters are families of stars born together from the same molecular cloud, sharing the same age, chemical composition, and initial dynamics (Friel 2013). But these families do not remain eternally bound—on the contrary, they are constantly being disrupted by internal gravitational interactions, stellar evolution, and external forces like giant molecular clouds and galactic tides (Krumholz et al. 2019).

Yet… some survive. Roughly 8–10% of known open clusters in the Milky Way live longer than theory predicts—lasting billions of years (Cantat-Gaudin et al. 2020; Hunt & Reffert 2023)., when simulations suggest they should dissolve within one (e.g. Baumgardt & Makino 2003; Lamers et al. 2005a; Bastian & Gieles 2008). Therefore, two critical questions emerge:

1. **Why do some star clusters defy death? What shields these ancient clusters** from the relentless mechanisms that dismantle their peers? Is it initial conditions—mass, density, or orbit—or some yet-unidentified stabilizing factor?
2. If clusters inevitably lose stars, **how have these "stellar families" shaped our Galaxy?** What's their true legacy in the Milky Way's disc?

This PhD project explores these mysteries using a new generation of astronomical data—from Gaia, WEAVE, 4MOST, etc.—to study the internal dynamics, evolution, and structure of open clusters across the Galactic disc. By analysing their motions, compositions, and phase-space features, you will help answer fundamental questions about stellar evolution, cluster longevity, and the history of our Milky Way.

Outline of the Project:

1. *Membership Determination:*
    - Use Gaia DR3 (and DR4 when available around mid-2026) to assign membership based on proper motion and parallax, applying clustering and machine learning techniques (Kallimanis *et al., in prep.*).
    - Incorporate radial velocities and chemical abundances from massive spectroscopic surveys WEAVE/4MOST/etc.
2. *Study Internal Dynamics:*
    - Derive Radial density and velocity dispersion profiles.
    - Model dynamics using advanced codes like LIMEPY (for tidally limited systems; Gieles & Zocchi 2015) and SPES (including mass segregation and escaping stars; Claydon et al. 2019).
    - Analyse core-halo structures, looking for signs of collapse or central remnants (e.g. black holes).
3. *Physical interpretation:*
    - Trace tidal tails and signatures of past interactions.
    - Compare surviving clusters to disrupted ones to uncover survival factors. (e.g. Alvarez Baena *et al.* 2024).
    - Estimate the contribution of open clusters to the nowadays disc stellar populations, contributing to the broader field of Galactic Archaeology.

Why this project?:

This is your chance to tackle one of the biggest unsolved puzzles in stellar dynamics: ***why do some star clusters beat the odds?*** With cutting-edge data, innovative methods, and deep implications for our understanding of the Galaxy, your work will be at the frontier of modern astrophysics.

Whether you're passionate about star formation, dynamical modelling, or Galactic structure, this project offers a rich and rewarding journey through the cosmos—guided by data, driven by questions, and inspired by discovery.

PhD project in ASTROPHYSICS

Title of the Project: Massive star clusters across the cosmic

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

Main collaborators: L. Origlia (INAF-OAS), A. Della Croce (INAF-OAS), E. Vesperini (Indiana University – USA), A. Sills (McMaster University – Canada), M. Cadelano (UNIBO)

Scientific Case: The proposed research project is set in the wide context of stellar population and galaxy assembly studies and it is focused on the use of low-mass stellar systems within the rapidly evolving landscape of near-field cosmology. Emphasis is given to globular clusters (GCs) in light of recent discoveries about their peculiar chemical, kinematic and structural properties.

The key scientific goal of the project is to make a quantum leap in our understanding of GC formation and early evolution. Indeed, despite the extensive study of massive stellar clusters, the physical processes driving their formation and their earliest evolutionary phases are yet to be fully understood. Arguably this is one of the most exciting open questions in modern astrophysics and it has important implications in many astrophysical fields, ranging from the ionization budget of the early universe, to the global stellar mass assembly of galaxies and formation of the so-called multiple populations, all to way to the scales of the star formation process itself.

Outline of the Project: The proposed project aims at tackling this long-standing problem from an innovative standpoint which is based on the use of the present-day kinematic and chemical properties of local of local young (<100 Myr) clusters, including both the so-called young massive (~10^5 M_{sun}) clusters (YMCs) and the sparse and low-mass (10^2- 10^3 M_{sun}) sub-clusters/clumps, in the outer and inner Galactic disk and in the Magellanic Clouds.
The rationale behind this approach is that YMCs may represent young analogs of the old GCs. This picture has been recently strengthened by James Webb Space Telescope (JWST) and Hubble Space Telescope (HST) observations of high redshift proto-GCs (down to z~10). In addition, local young clusters 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 for studying their early evolution.
The key open questions we will be addressing are: *is there a single, scalable formation mechanism applicable to all clusters? Or are additional mechanisms required to accumulate such a large gas mass in a small volume to form the most massive clusters?*

The project is structured in two synergic activities that cover the entire path from the construction of the required observational framework to the development of the necessary theoretical background to model the dynamical evolution of star clusters.

1. ***Perform the first comprehensive spectro-photometric and kinematic study of the young stars and clusters in the selected regions.*** To this aim the project will take full advantage of a synergic use of available and near-future Gaia astrometric catalogs and of state-of-the-art proprietary photometric and spectroscopic data obtained with HST and ground-based facilities at the ESO-VLT and TNG telescopes. The project will also have access to ESO-VLT/MOONS spectra secured within the GTO Galactic Survey.
2. ***Use proprietary state-of-the-art hydro-dynamical and dynamical (N-body and Monte Carlo) simulations*** following the early evolution of clusters to interpret the observed stellar cluster properties and to constrain the initial physical conditions for cluster formation and evolution.

This project will allow us to move the first key steps towards the definition of a true *Rosetta Stone* of the entire process of cluster formation thus potentially addressing one of the most relevant questions in modern astrophysics.

PhD project in ASTROPHYSICS

Title of the Project: Bridging observations and models: stellar populations with a variable IMF

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

Main collaborators: M. Cadelano (UNIBO), E. Vesperini (Indiana University – USA), J. Webb (York University – Canada)

Scientific Case: One of the main properties of star-formation that any predictive theory must be able to replicate is the initial distribution of stellar masses, i.e. the initial mass function (IMF). Few topics in astronomy initiate such vigorous discussions as whether or not the IMF is universal or instead depends on the structural and chemical properties of the star formation environment. The distinction is of critical importance, as the IMF influences most of the observable properties (e.g., chemical composition, mass-to-light-ratio) of any stellar system, from star clusters to galaxies. Hence detecting variations in the IMF can provide deep insight into the process by which stars form.

While significant efforts have been made to study the IMF in a variety of different environments, no consensus has been reached regarding its universality.

Outline of the Project: In principle, globular clusters (GCs) are ideal targets for constraining critical properties of the IMF. These systems are found in all types of galaxies (from dwarfs to ellipticals), are well populated, and typically easy to observe. Moreover, the old GCs (t > 10 Gyr) formed during the very first phases of cosmic structure assembly and therefore their study opens the door for understanding the formation and evolution of their host galaxies. However, in GCs we can directly measure only the present-day mass distribution of stars, which can be shaped by either long-term internal dynamical evolution effects or by primordial cluster formation processes leading them to have a non-universal IMF.
Interestingly, our group has recently designed an innovative tool for breaking such a degeneracy and constraining the IMF of GCs by using quantities that can be directly measured by using deep and wide-field photometric observations sampling the entire extension of stellar clusters and state-of-the-art dynamical *N*-body simulations.

The goal of this project is to extensively use such an innovative tool to understand whether the IMF of GCs is universal and, in case it is not, whether IMF variations are connected to the environment where GCs formed. To this aim, we will target a representative sample of genuine Galactic and accreted GCs by making use of a dedicated proprietary large data-set composed by a combination of very deep Hubble Space Telescope high-resolution images and ground-based ESO/VLT-FORS2 + LBT-LBC wide-field observations. These data will allow us to homogeneously sample both the innermost and most crowded regions of the target GCs as well as their outskirts down to a stellar mass of $\sim 0.2 M_{sun}$ along the main sequence. Observational results will be then combined with a large suite of tailored-made dynamical simulations that will provide the interpretative ground of the project.

The results of this project promise to open a new window on our understanding of the role of the properties of the star formation environment, such as gas density or chemistry, on the primordial mass distribution of stars in any stellar systems with major implications in multiple fundamental astrophysical fields.

Our team is one of the worldwide leading groups 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 it has granted access to the major international computational facilities. Hence, the proposed project will offer a great opportunity i) to be trained on various aspects of stellar evolution, dynamics and chemical evolution from both the observational and theoretical points of view, ii) to get in contact with national and international experts of the field through meetings, workshops and visit exchanges, iii) and to publish original results and present them at 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.

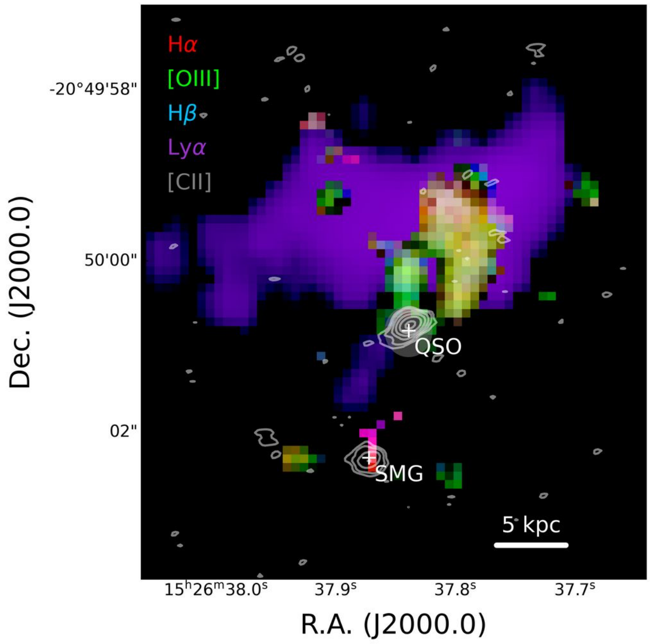

Figure 1: The quasar+companion system PJ231-20, observed with ALMA ([CII]), VLT/MUSE (Lya), and JWST (other emission lines). This multi-line investigation shows the interplay of different phases of the ISM, and the cycling of baryons from the CGM to the host galaxy and the central AGN and back again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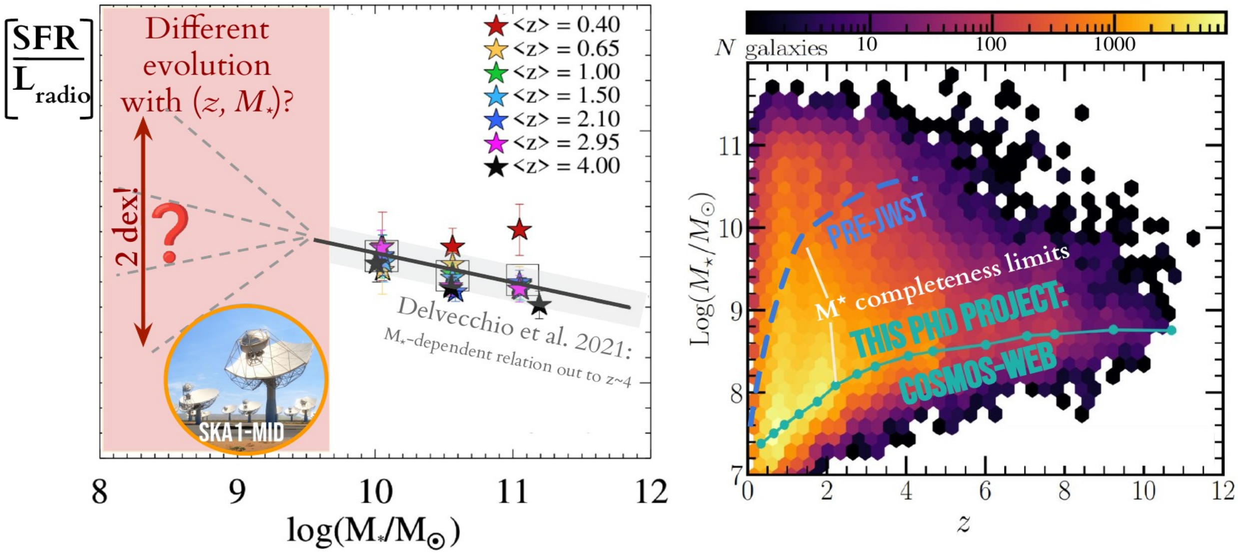
PhD project in ASTROPHYSICS

Title of the Project:
Calibrating radio emission as a star formation rate tracer towards the SKA era

INAF-OAS Supervisor: Dr. Ivan Delvecchio

Co-Supervisors: Prof. Margherita Talia (UniBo), Dr. Isabella Prandoni (IRA)



Outline of the Project:
Radio-continuum observations are nearly insensitive to gas obscuration, hence the radio luminosity (L_{radio}) of star-forming galaxies has long been used as a star formation rate (SFR) tracer (Condon 1992). However, our knowledge of the radio-SFR relation is limited only to massive galaxies (stellar mass $M_*>10^{10}$ M_{sun}) and up to z~4 (Delvecchio et al. 2021, A&A, 647, 123), showing a significant decrease of the ratio [SFR/L_{radio}] with increasing M_* (left Figure), which is not yet understood. In the upcoming years, the SKA1 (MID) will routinely detect ultra-faint (~10 nJy) radio sources in low-M_* galaxies and at z>4, but their star-forming content totally relies upon uncertain extrapolations (by 2 dex at $10^{8.5}$ M_{sun}) of the radio-SFR relation not yet backed up by data. This proposed PhD project capitalizes on state-of-the-art JWST surveys to get M_*-complete samples down to $10^{8.5}$ M_{sun} at z~8 (right Figure, Shuntov et al. 2025), using the largest JWST/NIRCam survey to-date: "COSMOS-Web" (which the supervisors are members of). From JWST-selected galaxies, the PhD candidate will perform image stacking in deep infrared and radio bands - reaching stacked flux levels comparable to those of future SKA detections - run SED-fitting of stacked photometry and radio-AGN removal, in order to infer accurate SFR and L_{radio} estimates in every bin of (M_*, z). The newly calibrated SFR-radio relation will become a benchmark in the SKA era, enabling accurate data-model comparisons, better radio-quiet AGN identification, and an independent assessment of the SFR density in the early Universe. The (co-)supervisors have full expertise and all core-data already in-hand to ensure a complete accomplishment of the project.

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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); F. Brighenti, 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 the underlying population 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.

Outline of the Project: The candidate will work on recovering, analyzing, and interpreting the physical properties of these systems. During the 1st year, she/he will approach the problematics and technicalities of the X-ray analysis of extended sources; we will define a 6-months project accordingly to the candidate's interest and some other contingencies (data availability, no conflict with other ongoing work), that will be focused on the thermodynamic properties of the ICM/IGrM over two decades in mass. 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 observational (both proprietary and archived, multi-bands) data 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: Testing new physics beyond LCDM with a joint analysis of Euclid and CMB data

INAF-OAS Supervisor: Fabio Finelli

Co-Supervisors: If interested, Daniela Paoletti and Alessandro Gruppuso, as well as others, are welcome to join.

Scientific Case:

The DESI 2025 3yr baryonic acoustic oscillation (BAO) results released last week point to departures from the LCDM cosmology in combination with Planck. The combination with ACT DR6, also released last week and therefore not studied yet, could further worsen the tension with LCDM. At the same time, the cosmological constraints on the neutrino mass, allowed to vary in addition to LCDM parameters, clash with the normal hierarchy lower bound from neutrino oscillation experiments. These two issues could be connected, given the role of low redshift measurements in constraining the neutrino mass. One of the workhorse models to alleviate this tension, a redshift dependent parameter of state for dark energy, (w_0, w_a), also introduced as a diagnostic for scientific capability of galaxy surveys by the Dark Energy Task Force, and now preferred to the LCDM by the combination of Planck BAO data at 3.4 σ, is a phenomenological model, considered by some theoretically unsatisfactory.

Outline of the Project:

The Ph. D. student will work on the phenomenology beyond general relativity which could reconcile these CMB and BAO measurements, and other cosmological observations such as the joint galaxy clustering-galaxy lensing information (3x2pt), also extended to include CMB lensing (6x2pt), SN (calibrated and uncalibrated data) and complementary data. Its work will focus on the most general scalar-tensor theory (Horndeski or beyond Horndeski) and will take advantage of also working with proprietary data of the Euclid collaboration towards DR1 and DR2 releases. Previous works have shown that these models, well founded from the theoretical point of view, can fit CMB and BAO data better than LCDM. The theoretical predictions of scalar-tensor theories of gravity for cosmological observables have been studied for more than a decade here at INAF IASF Bologna/INAF OAS. The Ph. D. student will work either with specific models and also with the non-parametric reconstruction of the Newton constant and the parameter of state directly from the data.

The timing of this Ph.D. thesis is somewhat ideal.

The Ph.D. XVI cycle (2025-2028 with a discussion of the thesis in 2029) overlaps with the proprietary data analysis for the Euclid DR1 (~ 2000 deg^2) expected in October 2026 and in the preparation of Euclid DR2 expected in 2028 (~ 7000 deg^2).

The Ph.D. student will have the possibility to work within the Euclid collaboration, mainly within the Theory and CMB cross-correlation Science Working Groups of the Euclid consortium in which OAS members are strongly involved, even with positions of scientific responsibility (F. Finelli, lead of the Theory SWG). Note that the 3x2pt from the photometric survey will lead to the tightest Euclid DR1 results, and this will be augmented by the 6x2pt, whose Euclid forecasts are coordinated at INAF OAS. The Ph. D. work will focus on data analysis and interpretation. A prototype of the likelihood code inside the Euclid collaboration has just been released and the internal release of DR1 within the Euclid collaboration is planned for October 2025. The possibility to work with proprietary data within the Euclid collaboration will either allow the student to participate in the Euclid releases and put her/him in the position to lead papers with eventually a smaller number of authors which can give him the visibility necessary to proceed with the postdoctoral experience.

The last Ph. D. student in Astrophysics I supervised, Matteo Braglia, XXXIII cycle, has received two honorable mentions for his Ph. D. thesis, within ”Premio Lions RICERCA SCIENTIFICA ED INNOVAZIONE TECNOLOGICA 2021” and within Livio Gratton 2023.
I am therefore confident to supervise a Ph. D. student at the best of his capabilities, given the current exciting time in cosmology and the opportunity to work within the Euclid collaboration when data are available.

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PhD project in ASTROPHYSICS

Title of the Project: Artificial Intelligence for gamma-ray data analysis: the NASA COSI mission

INAF-OAS Supervisor: Valentina Fioretti
Co-Supervisors: Nicolò Parmiggiani, Andrea Bulgarelli

Scientific Case:

The observation of the Universe in the MeV band is particularly challenging because of the high background, the low efficiency of the dominant physics processes (Compton scattering and pair production), the complexity of the signal reconstruction and the need for space-based technologies. For this reason, the MeV region is still fairly unexplored, with no significant progress for more than 20 years. INAF, with the support of the Italian Space Agency (ASI), is involved in the next generation of gamma-ray missions such as the NASA Compton Spectrometer and Imager (COSI), a Compton space telescope that will observe in the 0.2 - 5 MeV band, to be launched in 2027. Future MeV missions will increase the sensitivity in the MeV band by more than 10 times what achieved in the past, opening the possibilities to new discoveries (e.g. GRBs, blazars, magnetars) thanks to new and advanced artificial intelligence models for the signal reconstruction and event detection. The INAF OAS team has a huge heritage in high-energy space missions and artificial intelligence, actively contributing to the simulation and analysis software for the COSI mission, the Compton-pair new-ASTROGAM ESA mission proposal, and the ASI AGILE space mission, launched in 2007 and terminated in 2024.

Outline of the Project:

This PhD project activity foresees: i) high energy mission simulations using Geant4 to evaluate the scientific performance and prepare datasets for the training of machine learning models; ii) exploration of innovative artificial intelligence architectures (e.g. physics informed neural networks) to classify and reconstruct the astrophysical signal iii) development of new tools for the scientific analysis, based on classical or machine learning techniques; iv) evaluation of developed tools with real data acquired by COSI after the launch.

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: Low-mass galaxies with a soft X-ray spectrum: a path to IMBHs and new multi-messenger transients?

INAF-OAS Supervisor: Giorgio Lanzuisi

Co-Supervisors: Riccardo Arcodia (MIT/Harvard BHI), Cristian Vignali (UniBo/DiFA) Micol Bolzonella (INAF-OAS)

Scientific Case:

Accretion onto black holes (BHs) at the center of galaxies is a key channel to study BH growth. As the innermost regions of BH accretion flows shine bright in X-rays, observations in this band provide a unique channel to study their properties. Typically accretion and growth of BHs and their co-evolution with their host galaxies are well-studied in massive galaxies, such as our own Milky Way up to much larger ones. In comparison, much less is known about galaxies at lower masses, e.g. with a mass lower than the Milky Way, and the typical accretion mode of their comparably smaller BHs (called "massive" BHs, MBHs, or "intermediate-mass BHs", IMBHs). This low-mass regime has gathered significant interest in the last years through the discovery of nuclear transients, for instance, caused when a star ventures too close to the MBH and gets torn apart by its gravity, producing a tidal disruption event (TDE). Even more recently, a new class of transients has been discovered: quasi-periodic eruptions (QPEs) are sharp, soft X-ray flares that last and repeat on the timescale of several hours to a few days, which are thought to be the electromagnetic counterpart or precursor of extreme mass ratio inspirals (EMRIs) that emit gravitational waves (GWs) detectable by the recently-adopted LISA. Intriguingly, TDEs and QPEs have several aspects in common: they ignite MBHs/IMBHs in low-mass galaxies, and they show a soft X-ray spectrum indicative of an active compact flow around relatively small MBHs, in contrast with the typical hard X-ray spectrum of canonical AGN (Fig. 1).

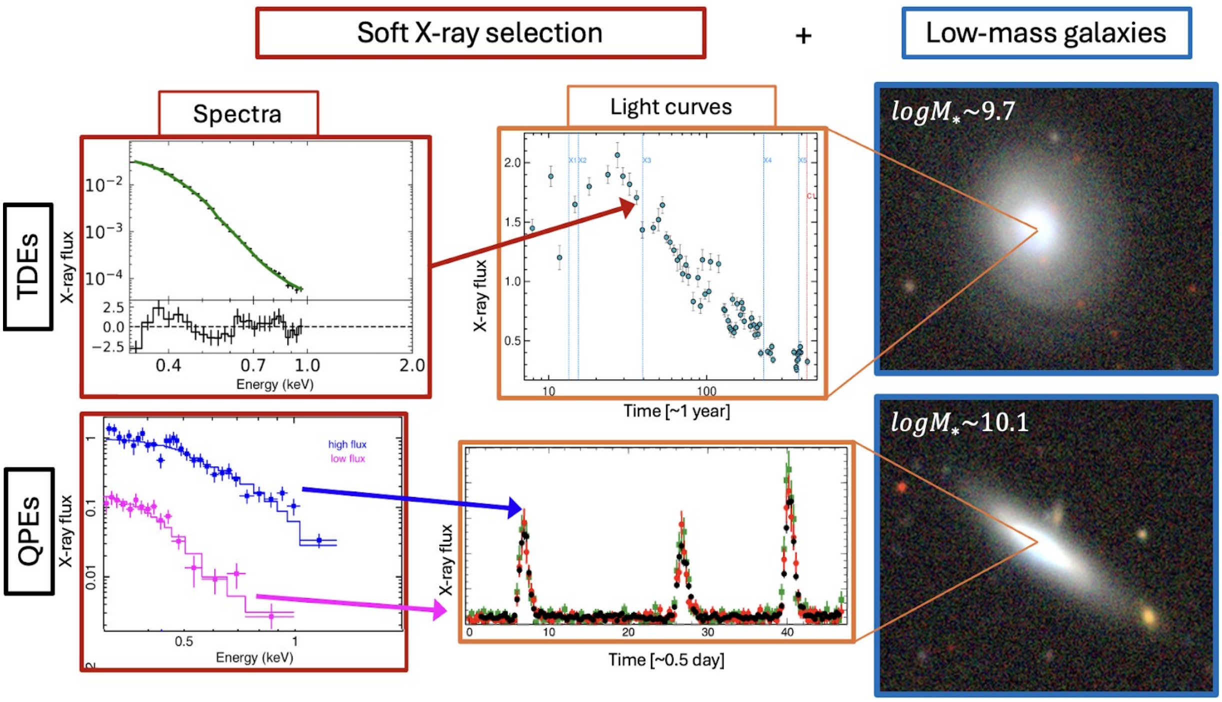

Fig. 1: X-ray spectra (left), X-ray light curves (center) and optical images (right, Legacy surveys) of a known TDE (top panels) and QPE (bottom), selected via soft X-ray emission from two low-mass galaxies. Plots adapted from Pasham et al., (2018), Giustini et al., (2020), Guolo et al., (2024).

Outline of the Project:
The final goals of this project are to find more candidate IMBHs, TDEs, QPEs in existing multi-wavelength archival data. We will achieve this by selecting low-mass galaxies (with stellar masses lower than in the Milky Way) with a soft X-ray spectrum, which indicates the presence of a radiatively efficient accretion disk around the central BH. For this, the candidate will use data from multiple X-ray missions (XMM-Newton, eROSITA, Chandra, Swift), from optical-IR missions (Euclid, Gaia, Legacy Surveys) and at other wavelengths (WISE, VLA) that cover the full sky, including the exquisite multi-mission coverage of the Fornax field (e.g XMM-Newton and Euclid). The goal is to study this large sample characterising the X-ray properties of the BHs (luminosity, spectral shape) as a function of galaxy properties (e.g. morphology, light profiles, star formation rate, stellar mass). This sample will contain, among others, candidate IMBHs, TDEs, and QPEs (e.g. see Fig.1), and the PhD candidate will compile their multi-wavelength properties to rank them in tiers and obtain follow-up data to confirm their nature. This project is a collaboration between different institutes and will allow the student to carry out part of the research program with Dr Arcodia at Harvard's Black Hole Initiative.

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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.

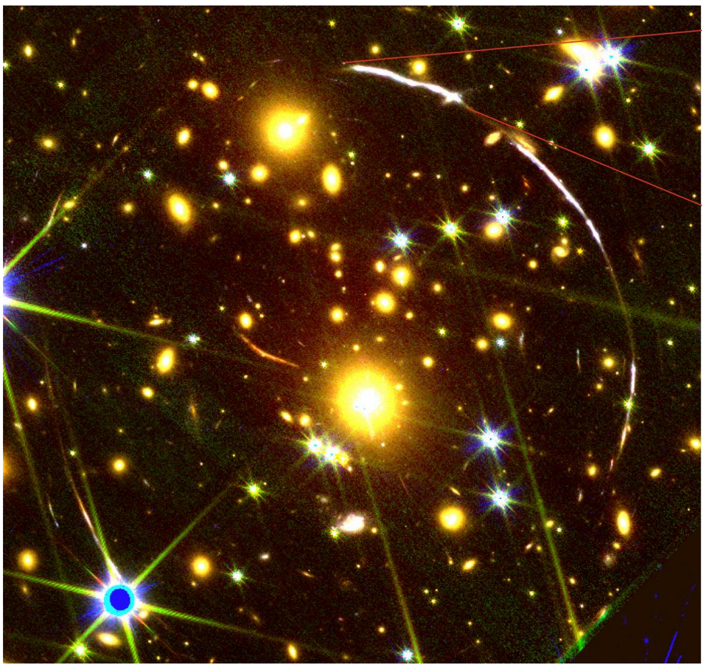


Figure 1: PSZ1 G311 lensing cluster field as observed by multi-wavelength HST and JWST, showed as RGB image. The inset shows one of the multiple images of the Sunburst galaxy, a spectacular lensed galaxy at z ~ 2 hosting several star forming complexes and star clusters, making this field one of the best 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 3, published on 13 June 2022, contains astrometry and broad-band photometry for about 1.8 billion sources in the Milky Way (MW) and beyond, along with information on large sets of 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 (in particular neural networks) 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: *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), available to the Euclid Consortium (EC) in 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: EVOLUTION OF CNOPS ELEMENTS IN THE MILKY WAY

INAF-OAS Supervisor: Dr. Donatella Romano

Co-Supervisor: Prof. Alessio Mucciarelli

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.

This PhD project is part of the international collaboration SPONGE (Sulphur, Phosphorus, Oxygen, Nitrogen and carbon Galactic Evolution, PI: D. Romano) that aims to address the fuzziest aspects of CNOPS evolution in stars and galaxies by means of both novel spectroscopic observations and cutting-edge galaxy formation and evolution models. The PhD candidate shall reduce, analyze, and provide theoretical interpretations of proprietary data already in hand, while also being involved in the preparation of the next observational campaigns by the team. In particular, within SPONGE we are currently obtaining high-resolution stellar spectra that will allow us to measure the C and O isotopic ratios ($^{12}C/^{13}C$, $^{16}O/^{18}O$) 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 that alter the original chemical composition of the stars). ***It is worth noting that none of past, current, or planned large spectroscopic surveys will provide such data, so our effort nicely complements that of the community.***

The student will also have access to complementary molecular data ($^{12}C/^{13}C$, $^{14}N/^{15}N$, $^{16}O/^{17}O$, $^{16}O/^{18}O$, $^{32}S/^{33}S$, and $^{32}S/^{34}S$ isotopic abundance ratios in cold gas spanning the full range of Galactocentric distances) obtained in the framework of several international collaborations, which will allow him/her to study the variation of the isotopic ratios not only in the solar neighbourhood, but also across the full Milky Way disc. 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.

Outline of the Project: Below we give an outline of the development of the project over three years that can be adjusted basing on the candidate specific interests. This outline is meant to provide a structured approach to the PhD project, ensuring that the candidate has clear goals, methodologies, and timelines for their research on the evolution of CNOPS elements in the Milky Way.

Year 1: Familiarization and Preliminary Analysis:

- **Training and Skill Development.** Learn to use the abundance analysis tools and chemical evolution code.
- **Initial Data Analysis.** Start analyzing proprietary high-resolution stellar spectra of subgiant and main-sequence stars.
- **Collaboration and Networking.** Engage with SPONGE (regular teleconferences + one yearly meeting in person) and other international collaborators.

Year 2: Research and Publication:

- **Data Analysis and Interpretation.** Finalize the analysis of isotopic ratios from stellar data and compare with molecular data and model predictions.
- **Publication of Papers.** Present findings on the isotopic ratios in unevolved stars. Discuss implications for stellar evolution and nucleosynthesis and Galactic chemical evolution.
- **Study of Stellar Ejecta Mixing.** Investigate processes of mixing between stellar ejecta and the interstellar medium (ISM) that lead to the scatter observed in the data.
- **Leadership in Observational Proposals.** Develop and submit proposals for new observational campaigns.

Year 3: Advanced Research and Thesis Writing:

- **Continued Data Analysis.** Further analysis of data and isotopic abundance ratios across the Milky Way disc.
- **Publication of Additional Papers.** Focus on broader implications of findings across Galactocentric distances. Discuss the broader impacts on understanding the Galactic Habitable Zone.
- **Thesis Writing and Defense.** Compile results, findings, and interpretations into a coherent thesis document. Prepare for thesis defense, including presentation and publication of results.

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