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29	Mucciarelli1	Mucciarelli	Implementing new physics in the modeling of the stellar atmospheres
30	Mucciarelli2	Mucciarelli	Evolution of CNOPS elements in the Milky Way
31	Mucciarelli3	Mucciarelli	Reconstructing the mass assembly history of the Milky Way
32	Mucciarelli4	Mucciarelli	Chemical characterization of the Local Group: identifying the chemical DNA of Milky Way satellite galaxies
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34	Nipoti2	Nipoti	Simulations of the collisional evolution of globular clusters with Monte Carlo methods
35	Nipoti3	Nipoti	Global stability of stellar discs with dark matter halos
36	Nipoti4	Nipoti	Probing black holes through gravitational wave and quantum signatures
37	Nipoti5	Nipoti	Hydrodynamic simulations of Terzan 5 and bulge fossil fragments
38	Pallanca1	Pallanca	Exploring binary millisecond pulsars in globular clusters through optical/near-infrared observations.
39	Roccatagliata1	Roccatagliata	Formation and evolution of solar system analogs: gravitational interaction with planets and/or external perturbers
40	Tailo1	Tailo	Investigating stellar rotation in low and intermediate mass stars
41	Talia1	Talia	Exploiting the Euclid Legacy for galaxy evolution with ELSA
42	Vazza1	Vazza	Studying the magnetic connection between the cosmic web and the primordial Universe
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PhD project in ASTROPHYSICS

Title of the Project:

Exploring the nature and feedback of low-power radio AGN in the SKAO era

Supervisor: Marcella Brusa (DIFA)
Co-Supervisors: Marisa Brienza (INAF-IRA)

Scientific Case:

Supermassive black holes at the center of galaxies recurrently accrete gas from their surrounding environment, giving rise to some of the most powerful phenomena in the Universe, visible across the entire electromagnetic spectrum. While it has become clear in recent decades that the energy released by these so-called Active Galactic Nuclei has a considerable impact on the evolution of both galaxies and their surrounding environment — thus becoming a key element in galaxy evolution models— many details of this phenomenon are still not fully understood.

In particular, mostly due to observational limitations, the study of AGN in the radio band has been restricted for many decades to powerful jetted sources extending over scales of hundreds of kiloparsecs. These are typically associated with the most massive galaxies in the Universe and clearly contribute to maintaining their star formation quenched. However, more recently, with the advent of more sensitive and high-resolution radio surveys, it has become clear that these sources represent only the tip of the iceberg. AGN radio outflows on kpc scales, in the form of both winds and jets, are indeed a much more ubiquitous phenomenon in all kinds of galaxies and thus can potentially have a more widespread impact on galaxy evolution. Observations suggest indeed that despite their low power these outflows are able to promote turbulence in the interstellar medium, as well as compress, redistribute, and even expel the gas from the host galaxy, affecting its star formation history. However, a clear characterization of the properties of these radio outflows, including e.g. the **occurrence and origin of jets vs winds**, of the **relationship with the multi-band** counterparts (atomic, molecular, ionized, X-ray gas **outflows**), and of the **connection with the overall properties of the host galaxy and environment** is still to be achieved, from the local Universe to the Cosmic Noon.

Outline of the Project:

The main goal of the proposed PhD project is to address the aforementioned opened questions by exploiting new-generation radio data from SKAO precursors and pathfinders (including JVLA, LOFAR, MeerKAT, VLBI), in combination with multi-wavelength data in the X-ray, IR, optical and mm bands. In particular, the PhD candidate will focus on:

- detailed multi-band investigations of a few archetypical low-power radio AGN to understand the origin of their radio emission (jets vs winds), the connection between the radio outflows and nuclear Ultra-Fast Outflows (e.g. XMM-Newton) and the physics of their interaction with the surrounding interstellar medium (e.g. ALMA, JWST).
- statistical analysis of new samples of low-power radio AGN selected by cross-matching X-ray (e.g. eROSITA) and optical/NIR (e.g. Euclid) surveys with radio surveys.

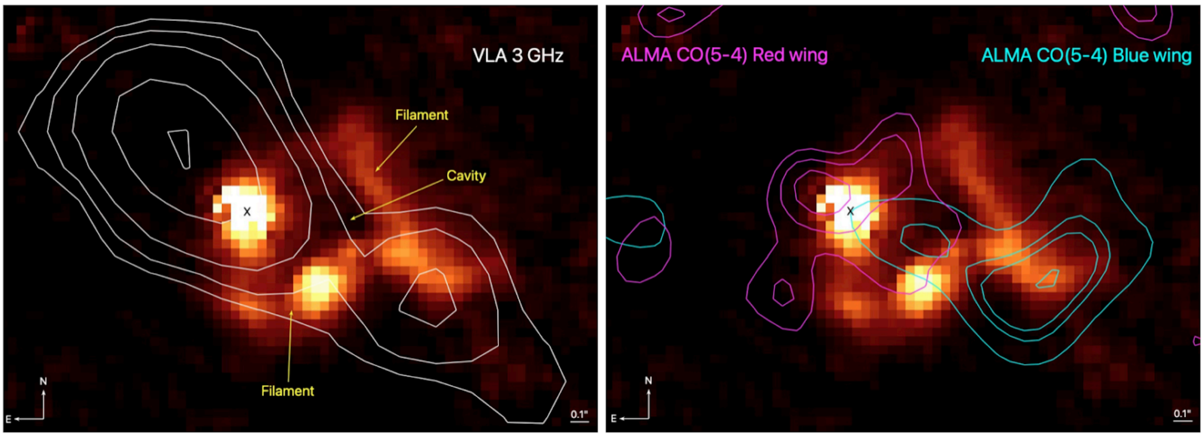

Fig. 1. Example of a powerful quasar with low-power jets (detected by the VLA, white colors on the left), which are interacting with the interstellar medium as probed by JWST (OIII emission in colors) and ALMA (cyan and magenta contours on the right) from Cresci et al. 2023. The PhD candidate will have at their disposal similar or higher resolution data.

Overall, the PhD candidate will be trained in AGN physics, in handling interferometric data and multi-band data catalogs, and in analyzing and interpreting AGN data from different instruments. She/he will also acquire scientific independence by, e.g., writing observing proposals and presenting the results of the work at international conferences. The PhD candidate will join the AGN group at DIFA and INAF-IRA and will have the opportunity to visit renowned research Institutes and Universities abroad through our collaboration network. Generous research funds are available for the entire PhD program.

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PhD project in ASTROPHYSICS

Title of the Project:
New populations of Supermassive Black Holes in the Deep Universe

Supervisor: Marcella Brusa (DIFA)
Co-Supervisors: Marco Mignoli, Roberto Gilli (INAF-OAS)

Scientific Case:
Super massive black holes (SMBHs) at galaxies' centers grow their mass by accreting surrounding gas. During these transient phases, called Active Galactic Nuclei (AGN), part of the gas gravitational energy is converted into radiation that our instruments can detect. Observations at different wavelengths unambiguously indicate that SMBHs primarily grow during hidden AGN phases, when circum-nuclear gas and dust absorb most of the emitted radiation, and that the incidence of nuclear obscuration rapidly increases towards early cosmic times (e.g. Vito et al. 2018). The reasons for this evolution in the obscuration are, however, largely far from being understood. Very recently, the unparalleled capabilities of JWST have in addition uncovered **new, unexpected populations of growing SMBHs in the early Universe**, say z>4, whose observational properties remarkably **differ** from those of known AGN at lower redshift pointing to a significant evolution in the physical properties of the accreting and obscuring matter (e.g. Maiolino et al. 2025).

Understanding the reasons for the increase of nuclear obscuration with redshift and why the new populations of high-z, JWST-detected AGN are so different from low-z AGN are the main objectives of this PhD project.

Outline of the Project:
The proposed project will pursue the objectives above through a **multi-band observational approach**. Our group is heavily involved in the major existing extragalactic surveys (CDFS and COSMOS), and is leading a major effort in the J1030 field. The PhD candidate is expected to **search for and identify distant, obscured AGN** in these fields by applying known obscuration diagnostics and developing new ones based on data from the main international facilities (see e.g. Mazzolari et al. 2024).

The combination of X-ray and radio data in the J1030 field (one of the deep at both wavelength, see http://j1030-field.oas.inaf.it/ for a summary of the data) has allowed selection of promising obscured AGN candidates that have been **recently observed with ground- and space-based spectroscopy by Gemini, LBT, VLT and JWST.** The PhD candidate is expected to reduce and analyze those spectra, measure the redshift, spectral properties and obscuration level of the newly-discovered heavily obscured AGN, and derive their cosmic evolution, probing in turn their contribution to the black hole accretion rate density in the distant Universe.

In addition, the PhD candidate will exploit the available JWST spectroscopic and imaging data to probe **newly discovered AGN populations**, such as X-ray silent broad line AGN and Little Red Dots, to determine their physical properties and abundance, compare with those of 'standard' AGN, and reconstruct how the physics of accretion and nuclear obscuration evolved with cosmic time.

The results from both components of the project will be used to **constrain state-of-the-art cosmological simulations of galaxy(AGN) formation and evolution**, with a focus on the characterisation of the black hole seeds population, and the role of obscuration and Super-Eddington accretion for the growth of supermassive Black Holes in the very early Universe (e.g. Pacucci et al. 2024).

The PhD candidate will be trained in AGN physics and demographics, in handling multi-band data catalogs, and in analyzing and interpreting AGN data from different instruments (e.g. JWST, VLT, LBT and Chandra). They will also acquire scientific independence by, e.g., writing observing proposals and presenting the results of the work at international conferences. The PhD candidate will join the AGN surveys group at DIFA and INAF-OAS and will have the opportunity to visit renown research Institutes and Universities abroad through our collaboration network. Generous research funds are available for the entire PhD program.

References: Maiolino et al. 2025 (A&A in press, arXiv:2405.00504), Mazzolari et al. 2024 (A&A 691, A45), Pacucci et al. 2024 (ApJ 976, 96), Vito et al. 2018 (MNRAS 473, 2378)

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PhD project in ASTROPHYSICS

Title of the Project: Constraining the primordial properties of dense stellar systems

Supervisor: M. Cadelano (UniBo)
Co-Supervisors: E. Dalessandro (INAF-OAS), E. Vesperini (Indiana Univ.), J. J. Webb (Toronto Univ.)

Scientific Case:

Star formation at any cosmic epoch is characterized by the presence of clustered systems such as molecular clouds, massive young clusters, open clusters, and globular clusters. Establishing the link between the origins and primordial properties of these systems is crucial to advancing our understanding of star formation in the context of (1) galaxy evolution, (2) the physical processes governing the formation and evolution of stars and star clusters, and (3) the role of dense stellar systems in producing the gravitational wave events observed today. However, this connection remains poorly understood.

Two key properties of star formation that any predictive theory must account for are the initial distribution of stellar masses, i.e., the initial mass function (IMF), and the fraction of binary/triple systems that form. The IMF is one of the most debated topics in astronomy, particularly regarding whether it is universal or varies with the structural and chemical properties of the star-forming environment. This distinction is critical, as the IMF influences most observable properties of stellar systems, from star clusters to galaxies. Despite extensive efforts to study the IMF across different environments, no consensus has been reached on its universality.

Similarly, stellar binarity is closely tied to the dynamical processes occurring during both star formation and cluster evolution. It has long been recognized that binarity, and stellar multiplicity in general, is a fundamental and inevitable outcome of any star-forming system. Understanding the primordial binary population is essential for studying the formation and evolution of stellar systems, as it governs key processes such as supernova rates, chemical enrichment, and stellar dynamics. Moreover, continuous interactions between binaries and other stars are expected to form hard binaries over time, enhancing the merger rate in these environments. These mergers may hold the key to understanding the gravitational wave events detected by current gravitational wave observatories, particularly in relation to the black hole mass distribution.

The goal of this PhD project is to constrain the primordial properties of dense stellar systems in the Local Group by observing and modeling their present-day properties across different environments. In particular, the project will focus on constraining both the IMF and the primordial binary fraction, which will provide a significant leap forward in our understanding of the physics of clustered star formation.

Outline of the Project:

Recent advancements in N-body and Monte Carlo simulations of star clusters, incorporating a broad range of initial conditions (such as cluster mass, size, primordial binary fraction, black hole retention fraction, and orbital properties), have shown that many present-day cluster properties can be linked to their primordial characteristics. For instance, measurements of radial variations in the present-day mass function serve as a powerful tool for constraining the IMF of dense stellar systems. Similarly, the binary fraction measured across the entire cluster provides a proxy for its primordial value and helps assess the role of the environment in determining how many binaries form, survive, and eventually merge over the cluster's long-term evolution. The synergy between these state-of-the-art simulations and observational data is opening a new window into our understanding of star formation in clusters.

Within this framework, our group has already been awarded more than 150 hours of observing time on different stellar systems using the most advanced ground-based (ESO) and space-based (HST, JWST) facilities.

During the first year, the candidate will learn to perform high-precision photometric analysis of stellar systems. This will allow the characterization of the present-day distribution of stars within clusters and their physical properties. In the second year, the candidate will spend a research period abroad, likely in the US and/or Canada, working with leading experts in dynamical modeling of star clusters through numerical simulations. These simulations, combined with observational results, will provide the foundation for the main goal of the PhD thesis: deriving the primordial properties of dense stellar systems. The third year will focus on consolidating these results and synthesizing them into a comprehensive analysis of the early conditions of clustered star formation environments.

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PhD project in ASTROPHYSICS

Title of the Project: Dynamics of elliptical galaxies

Supervisors : Luca Ciotti – Silvia Pellegrini

Scientific Case: The internal dynamics of elliptical galaxies depends significantly on the anisotropy of the velocity dispersion tensor. The effects of anisotropy are understood quite well in the case of axisymmetric galaxies with a phase-space distribution function depending on the two classical (isolating) integrals of motion, E, and Jz. Much less is known about the case of three-integrals systems, even though observations suggest that this may be the common case. The proposed thesis intends to systematize, clarify, and extends the present knowledge of the field, by the construction of analytical and numerical models of elliptical galaxies, to be confronted with the observational data.

Outline of the Project: Construction of oblate and prolate galaxy models, supported by two and three integral phase-space distribution functions. Construction of the kinematical (intrinsic and projected) fields, and comparison with observations to constraint the amount and distribution of galactic orbital anisotropy.

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PhD project in ASTROPHYSICS

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

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

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

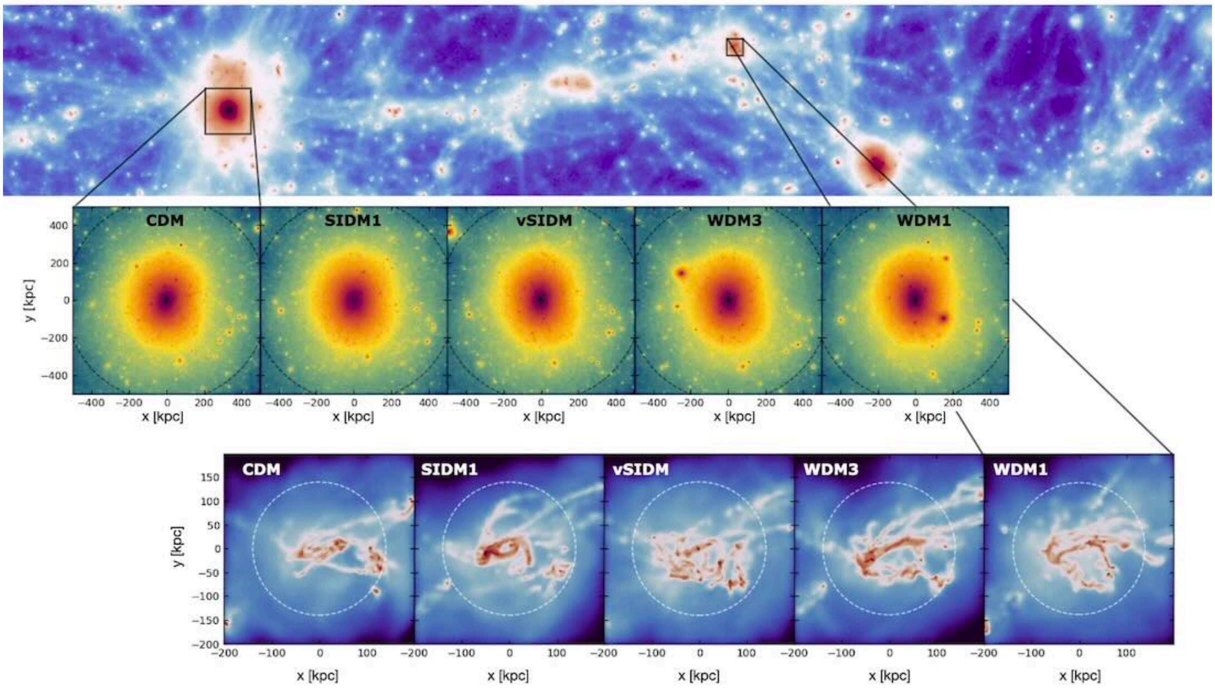

Figure 1. Outline of the new AIDA-TNG runs *(Despali et. al 2025)* that will be used during this project.

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

Outline of the Project:

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

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

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

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PhD project in ASTROPHYSICS

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

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

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

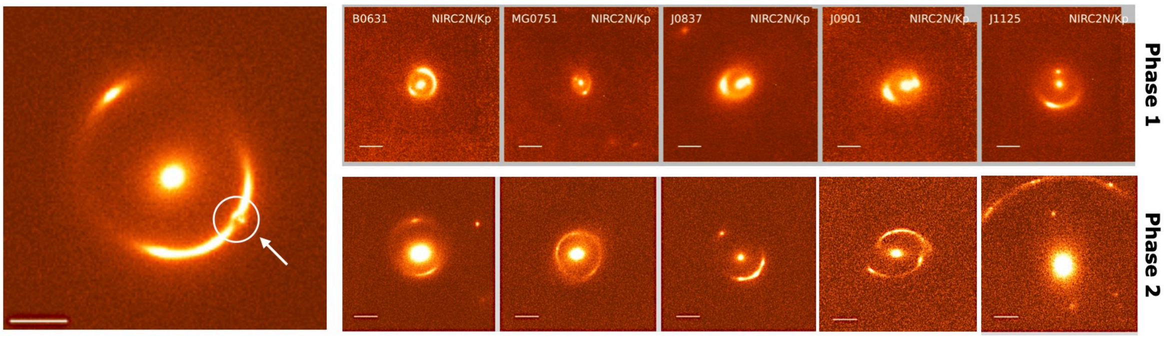
Outline of the Project: The SHARP collaboration and observing program has targeted 40 new systems that have or will be observed soon with the Keck telescope: this is the only new optical sample that targets lensed arcs beyond HST resolution. The current SHARP sample consists of data from two observing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

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

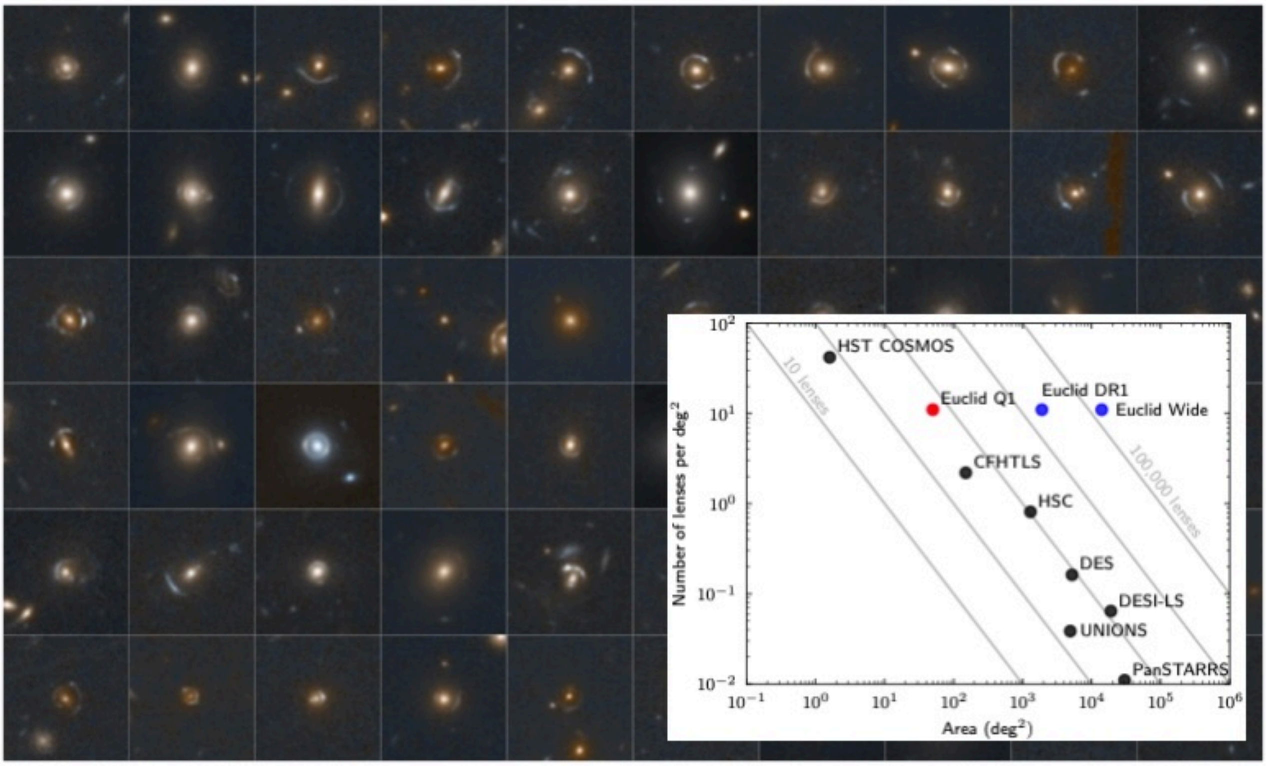
- The PhD student will model the new SHARP lenses, reconstructing the mass and light distribution of the lenses, arcs and sources using existing parallel codes. She/he will then search for smaller satellites, which manifest themselves as surface brightness perturbations.

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

new SHARP lenses



Euclid new lenses



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

PhD project in ASTROPHYSICS

Title of the Project: Searching for Fossil Fragments of the Galactic bulge formation process

Supervisor: F.R. Ferraro **Co-supervisors:** B. Lanzoni, C. Pallanca **Collaborators:** E. Dalessandro (INAF)

Scientific Case: The scenario of galaxy bulge formation is still largely debated in the literature. Among the most credited models, the "merging picture" proposes that galaxy bulges form from the merging of primordial sub-structures, either galaxies embedded in a dark matter halo, or massive clumps generated by early disk fragmentation. Although the vast majority of the primordial fragments should dissolve to form the bulge, it is possible that a few of them survived the total disruption and are still present in the inner regions of the host galaxy, grossly appearing like massive globular clusters (GCs). At odds with genuine GCs, however, these fossil relics should have been massive enough to retain the iron-enriched ejecta of supernova (SN) explosions, and possibly experienced multiple bursts of star formation. As a consequence, they are expected to host **multi-iron and multi-age sub-populations**.
Two of these remnants (disguised as genuine GCs: Terzan5 and Liller1 have been recently discovered (Ferraro et al., 2009, Nature,462, 483) and Liller1 (Ferraro et al, 2021, Nat. Astr., 5, 311), in the bulge of the Galaxy. These systems (1) are indistinguishable from genuine GCs in their appearance, (2) have metallicity and abundance patterns incompatible with those of bulge GCs and well in agreement with those observed in the bulge field stars, (3) host a dominant old stellar population (testifying that they formed at an early epoch of the Galaxy assembly), (4) host at least one young stellar population, several Gyrs younger than the old one (demonstrating their capacity of triggering multiple events of star formation). It is important to emphasise that the multi-age components in both the BFFs identified so far were discovered by analysing proper motion (PM) selected color-magnitude-diagrams (CMDs) obtained by combining HST and AO-assisted ground-based IR images (acquired at ESO-VLT and Gemini; see Fig.2). Here we propose to secure deep second-epoch K_s Gemini images of 11 GC-like stellar systems into the Galactic Bulge to assess their stellar populations thus finally addressing their true nature. *The discovery of other BFFs would add new crucial information on the formation process(es) of the Bulge*

Outline of the Project: In this framework we are using high-resolution and NIR capabilities of GSAOI-GEMS at GEMINI, HST and JWST to secure multi-epoch observations of a sample of globular cluster-like stellar systems in the Galactic Bulge in order to search for other BFFs. 12 hours of observing time at GEMINI South telescope have been already allocated to this project.
With the final aim of providing the accurate characterization of the stellar populations in each of the investigated stellar systems, the student will be in charge of the construction of high-quality differential reddening corrected and Proper motion- selected color magnitude diagrams (CMDs). Proper motions will be obtained from the analysis of multi-epoch observations: in particular the new GEMINI data will provide second-epoch observations for a sample of 11 clusters already observed with HST. Moreover, the combination of near-IR and optical images will provide the appropriate characterization of the extinction law in the direction of each stellar system (Pallanca+19, ApJ,882, 159; Pallanca+21, ApJ, 917, 92). Note that an increasing number of studies is showing that the extinction law can significantly vary along different directions toward the Bulge (e.g., Popowski 2000,ApJ, 528, L9; Nataf+2013,ApJ, 769, 88). Indeed, the correct determination of the extinction law in the direction of each target is crucial, since it is the first, mandatory step for a proper correction of differential reddening, and a solid characterization of the evolutionary sequences in the CMD and it has direct impact on the determination of each stellar system distance.

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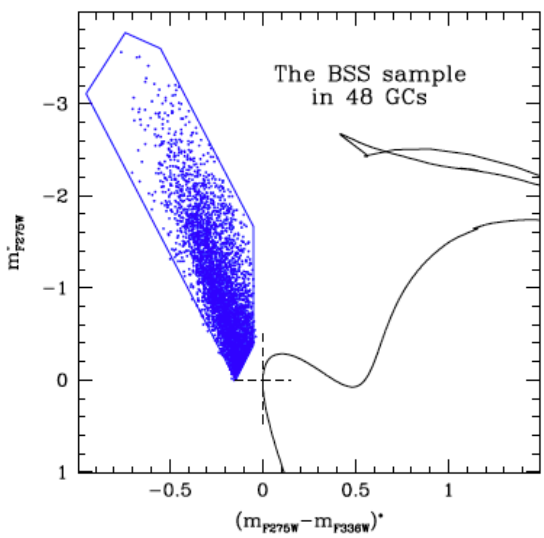
PhD project in ASTROPHYSICS

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

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

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



Outline of the Project: Being more massive than normal cluster stars, BSSs are thought to form either from mass-transfer processes in binary systems or by stellar mergers induced by direct collisions. They also are the brightest and most numerous massive stars in old clusters. Hence BSSs represent the best probe particles for tracing the dynamical history of stellar systems, but their nature and properties are still largely unexplored. By means of a large photometric and spectroscopic database collected by our group (see the Figure), we plan: (i) to measure the BSS physical parameters (i.e. mass, gravity, temperature) of the entire photometric sample comprising more than 4000 BSSs; (ii) to measure the rotation velocity of a sample of BSSs in different environments (clusters with different densities); (iii) to search for chemical signatures of their formation mechanism, thus eventually unveiling their true nature; and (iv) to determine their radial distribution over the entire cluster extension in a number of Galactic GCs with different properties (central density, concentration, mass, etc). Indeed the level of segregation of these stars has been found to be a powerful indicator of the level of dynamical evolution suffered by the parent cluster (thus defining the so-called "dynamical clock" see Ferraro et al, 2012, Nature, 492,393; Ferraro et al. 2018, ApJ, 860, 26; Lanzoni et al., 2016, 833, L29, Ferraro et al., 2019, Nature Astronomy, 3, 1149, Ferraro et al., 2023, ApJ, 950,145).

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PhD project in ASTROPHYSICS

Title of the Project*:* Probing the early history of the Milky Way formation with the chemical DNA of Bulge stellar systems

Supervisor: F.R. Ferraro **Co-supervisors:** B. Lanzoni, C. Pallanca, L. Chiappino **Collaborators:** L. Origlia (INAF), C. Fanelli

Scientific Case: While observations of the distant Universe show that bulges of spiral galaxies form through multiple mergers of massive clumps of gas and stars, and are subsequently enriched by accretion events, no direct evidence of these processes has been found so far in the Milky Way Bulge. Still, the Galactic Bulge is the sole spheroid where individual stars can be observed, allowing a unique exploration of the debris of those primordial clumps and accreted structures. Indeed, the discovery that Terzan5 (Ferraro et al., 2009, Nature,462, 483) and Liller1 (Ferraro et al, 2021, Nat. Astr., 5, 311), two Bulge systems with the appearance of globular clusters (GCs), host multi-age and multi-iron populations, and share the same "chemical DNA" of Bulge stars strongly suggest that they could be Bulge Fossil Fragments (BFFs), the remnants of the proto-Bulge formation process. Thus, a variety of relics tracing different phenomena are expected to populate the Bulge: BFFs, in-situ formed and externally-accreted GCs, and also nuclear star clusters of cannibalized structures. Each system could provide a piece of information about the Bulge formation and evolutionary history. The signatures of the different origins are imprinted in the kinematic, photometric, and chemical properties of these stellar systems, and can be read with different levels of accuracy.

Outline of the Project: In particular, the chemical tagging is a very powerful tool to unveil the true nature and origin of stellar systems, because specific abundance patterns provide authentic "chemical DNA tests" univocally tracing the enrichment process, hence the environment where the stellar population formed. In fact, the atmospheres of the stars that we observe today preserve memory of the chemical composition of the interstellar medium (ISM) from which they formed, and the chemical abundances of the ISM vary in time if more than one burst of star formation occurs, owing to the ejecta of each stellar generation. Thus, stars formed at different times and in environments with different star formation rates (SFRs) have different chemical compositions, and by analysing the chemistry of each stellar population one can univocally trace the enrichment process of the ISM. Different abundance patterns are expected depending on the stellar polluters, the enrichment timescale and the SFR, with a few specific abundance patterns being so distinctive that they can be used as "DNA tests" of the stellar population origin.
In this framework we are leading a Large Programme at the ESO-Very Large Telescope (VLT) which exploits the superb performances of the spectrograph operating in the near-IR CRIRES+ to perform an unprecedented chemical screening of a representative sample of Bulge stellar systems, with the aim to determine their chemical DNA and finally unveil their true origin. A total of 255 hours of observing time was assigned to this Large Programme (PI: Ferraro).

The student will be in charge of the spectroscopic analysis of the high-resolution CRIRES spectra to derive chemical abundances of several key elements. In particular, beyond the iron, the abundance of many iron-peak elements (like Zinc, Vanadium, etc) and alpha-elements (like Calcium, Silicon, Magnesium, Titanium) will be derived. These abundances will be used to construct powerful chemical DNA indicators as the 'classical" [α/Fe]–[Fe/H] diagram and to test the new-defined DNA test involving [V/Fe] and [Zn/Fe] ratios. The combination of these test will allow a solid distinction between in-situ formed and accreted GCs and the univocal identification of the environment in which the stellar systems formed.

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DIPARTIMENTO DI FISICA E ASTRONOMIA
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PhD project in ASTROPHYSICS

Title of the Project: *Unveiling the physics of Globular cluster cores*

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

Scientific Case: The Universe we live in is dominated by darkness. Indeed, the vast majority of the matter (and possibly of the energy) in the Universe is dark, while only a few percent can be revealed through light signals. Fortunately the presence of dark matter (DM) leaves imprints in the kinematical properties of the luminous mass, revealing invisible structures as DM halos and super-massive black holes. This project is devoted to study the kinematics of sub-galactic stellar systems with the aim of unveiling and probing the existence of non-visible matter at the globular cluster (GC) scales. Finding DM halos in sub-galactic structures would be crucial to alleviate the cosmological "missing satellite problem". Identifying intermediate-mass (10^3-10^5 $M_\odot$) black holes (IMBHs) in GCs could shed new light on the formation processes of the SMBHs observed in galaxies and AGNs already at redshift z>6. Precisely determining the internal structure and kinematics of GCs would also fill our current lack of knowledge about the physics of these stellar systems, which are true astrophysical milestones.

Outline of the Project: To address these issues we propose to perform the most comprehensive study ever attempted to determine the internal structure and kinematics of GCs. Specifically, we propose to determine the projected density distribution, the velocity dispersion profile and the rotation curve, from the very center out to the tidal radius and through unbiased methodologies, for a sample of 36 Galactic GCs well representative of different structural parameters, dynamical stages and environmental conditions. The line-of-sight (LOS) kinematics will be determined from the spectra of several hundreds individual stars located along the entire extension of each GC, by exploiting state-of-the-art technology in a non-conventional way. The data needed to perform this part of the project are already acquired by means the ESO Multi-Instrument Kinematic Survey (MIKiS) that consists of 2 Large Programmes at the ESO-VLT (PI: Ferraro, for a total of 300 hours of observing time). We combine: *(i)* Adaptive Optics (AO) Integral Field Spectroscopy (IFS) in the innermost cluster regions (arcsecond scale), *(ii)* seeing-limited IFS for the intermediate radial range (tens of arcsecond scale), and *(iii)* wide-field multi-object spectroscopy for the most external regions (from one to tens arcminute scales).
A detailed presentation of the survey and first results can be found in: Ferraro et al., 2018, ApJ, 860, 50; Ferraro et al., The Messenger, 172, 18; Lanzoni et al., 2018 ApJ, 865,11; Lanzoni et al., 2018, 860, 95.

PROPER MOTIONS - Accurate proper motions (PMs) of individual stars in the center of each GC will be computed from multi-epoch HST images. This will provide us, for the first time, with the 3D kinematics of dozens of central stars, thus allowing us to reconstruct their orbits and recognize possible high-velocity objects accelerated by an IMBH. Moreover, we will properly sample the very central regions, where the most interesting dynamical processes are expected to occur (but where PMs of stars below the main sequence turnoff are not precisely measurable in most GCs because of crowding; see Watkins et al. 2015, ApJ 803, 29). This is crucial to detect possible central LOS velocity dispersion cusps. The PMs released by the GAIA space mission will complement this information in the external cluster regions, thus providing us with the 3D cluster kinematics along the entire radial extension.

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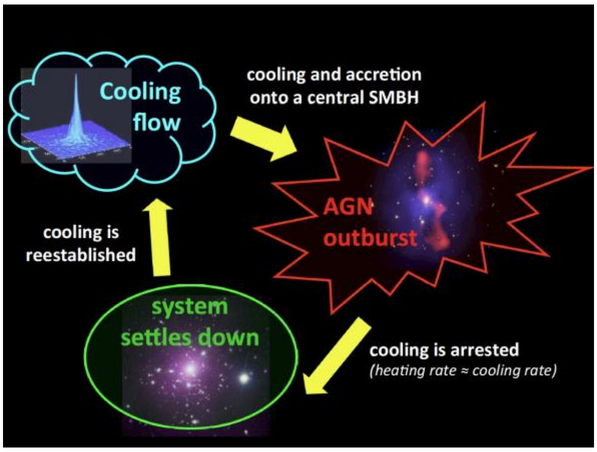
PhD project in ASTROPHYSICS

Title of the Project: *AGN feeding-feedback cycle in cool core clusters with Hα nebulae*

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

Scientific Case:

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



This so-called 'radio-mode' feedback has a wide range of impacts, from the formation of galaxies to the regulation of cool cores, and can in principle explain why cooling and star formation proceed at a reduced rate. However, the details of how the feedback loop operates are still unclear.

Outline of the Project:

To clarify the regulation of the feeding and feedback cycle in cluster cores, it is crucial to perform accurate studies of the cooling and heating processes for a sensible sample of clusters with a prominent cold ICM phase. We have identified a sample consisting of the X-ray brightest, most Hα luminous clusters visible from the Jansky Very Large Array (JVLA). In particular, we selected clusters from the ROSAT BCS sample with 0.1-2.4 keV flux $f_X > 7 \times 10^{-11}$ erg cm^{-2} s^{-1} and Hα luminosity $>10^{40}$ erg s^{-1}. Visibility from JVLA ensures that high resolution radio observations can be used to examine the interaction between radio-loud AGN, ICM and cooling gas. The sample includes some very well-studied systems (e.g., A1835, A1795, A2052), as well as clusters never observed in X-rays and/or with only snapshot radio data (e.g., A1668). In the past years we obtained snapshot *Chandra* and new JVLA data for three clusters which lacked archival X-ray and radio data. Our first results (see Figure) suggest that, in some systems with disturbed morphology showing spatial offsets between the BCG and different gas phases, the cooling process is not currently depositing gas onto the BCG core (*Pasini et al. 2019, ApJ, 885, 111*; *Pasini et al. 2021, ApJ, 911, 66*; *Rosignoli et al. 2024, ApJ, 963, 8*).

The aim of the PhD project is to investigate the feeding-feedback cycle of these strongly cooling clusters and determine whether in systems with spatial offsets the cycle is broken, or if the AGN activation is somehow maintained, for example being driven by the periodicity of the gas motions (sloshing).

We have undertaken an observational campaign to acquire *Chandra* deep exposures and multi-wavelength follow-up observations: in particular, we recently obtained new Atacama Large Millimetre Array (ALMA) CO observations of the clusters A2495, A2207 and A478, as well as MUSE observations of the Hα nebulae in the cluster ZwCl235. The PhD candidate will perform accurate analyses of the ALMA, *Chandra*, JVLA and MUSE data already in hand, that will be complemented by the Hα and CO observations from literature and ALMA archive, to determine the properties of the ICM and the warm gas and the morphology and spectral indices of the central radio sources.

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

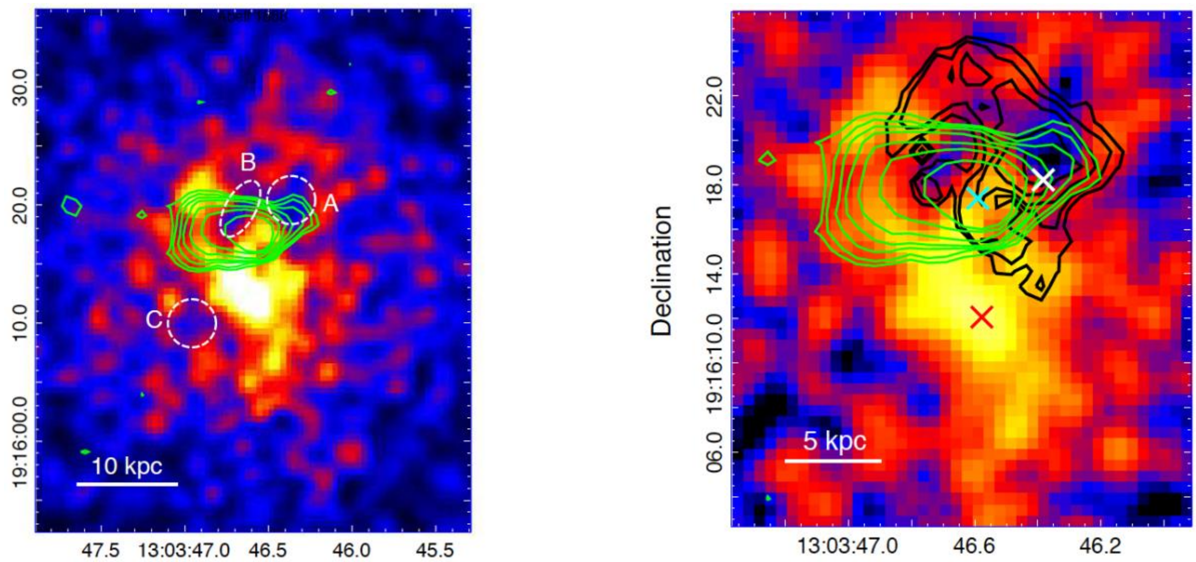


Figure - The results from our snapshot *Chandra* (color map) and 1.4 GHz JVLA observations (green contours) of A1668 indicate that this cluster has a disturbed morphology, showing hints of cavities (A, B and C in the left panel) and spatial offsets between the X-ray peak, the radio BCG and the Hα line emission (in the right panel, the cyan cross is the BCG center, the red and white crosses are the X-ray and Hα peaks, respectively, and the black contours show the Hα line emission). These offsets suggest that the current locus of greatest cooling in the hot ICM is separated from the central galaxy nucleus and raise the question of whether they can affect the feedback cycle. From *Pasini et al. 2021, ApJ, 911*.

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Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: *Radio and X-ray connections in cool core galaxy clusters*

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

Scientific Case:

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

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

Mini-halos show steep spectra ($1 \leq \alpha \leq 1.5$) and amorphous shapes, and typically extend to 100 - 200 kpc from the center (e.g., Gitti et al. 2004, A&A; Feretti et al 2012, A&AR). Their origin is still unclear; among several models, it has been proposed that ICM oscillations ("sloshing") in the cluster potential might power the non-thermal radio emission (e.g., Zuhone et al. 2016, JPlPh), since mini-halos typically appear confined within the sloshing cold fronts (e.g., Giacintucci et al. 2019, ApJ). Alternatively, active galactic nucleus (AGN) feedback may also provide turbulent re-acceleration due to the jets inflating bubbles and driving shock waves in the plasma (e.g., Bravi et al. 2016, MNRAS). A third possibility is a combination of the two: the main driver for the creation of mini-halos could be AGN activity injecting turbulence and relativistic particles in the ICM, while sloshing motions would drive the overall shape of the mini-halos (Richard-Laferrière et al. 2020, MNRAS). The only way to discriminate between the different scenarios is a multifrequency study of these sources: sensitive and resolved radio observations can constrain the properties of mini-halos, while X-ray analysis of the ICM can probe the process injecting turbulence in the clusters' hot medium.

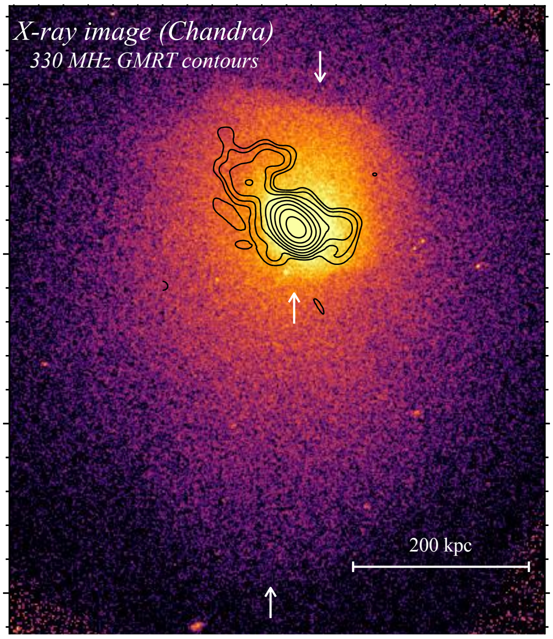

Figure 1: X-ray Chandra image of the cool core cluster Abell 496, with 330 MHz GMRT contours overlaid in white showing the central radio galaxy. Despite the vigorous, ongoing sloshing of the ICM, which produced three cold fronts (white arrows), the existing radio observations fail to reveal a mini-halo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

Outline of the Project:

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

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

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

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PhD project in ASTROPHYSICS

Title of the Project: Leveraging Machine Learning to Decode Multiple Populations in Stellar Clusters

Supervisor: Prof.ssa Carmela Lardo
Co-Supervisor: Prof. Alessio Mucciarelli

Scientific Case: Globular clusters (GCs) are crucial for understanding galaxy evolution, yet the origin of their multiple populations (MPs) remains uncertain. These populations exhibit distinct elemental abundances: some stars are enriched in He, N, and Na but depleted in O and C, while others resemble field stars (Gratton et al., 2012). The first population (P1) has typical chemical compositions, whereas the second (P2) is enhanced in N and Na, likely due to material expelled by earlier generations of stars. While self-enrichment models account for certain trends, they fail to fully reproduce observations, highlighting the need for alternative explanations (e.g., Bastian & Lardo, 2018).

Outline of the Project: The HST's HUGS survey (Piotto et al. 2015) utilised chromosome maps (CMs) to analyse MPs in 57 old Galactic GCs, employing specific filters to trace their chemical composition and revealing correlations between P2 fractions, chemical variations, and GC mass (Milone et al. 2017). While highly effective, CMs are resource-intensive and currently limited to the HUGS clusters and a few in the Magellanic Clouds (Saracino et al. 2020). Their dependence on the F275W filter makes them particularly demanding in HST time, restricting their use for reddened or distant GCs. Moreover, their focus on cluster cores limits our understanding of sub-population distributions, particularly in older GCs (Tiongo, Vesperini & Varri 2019).
Despite advances, understanding MPs requires ever-improving empirical data. Machine learning (ML), with its pattern recognition capabilities, presents a breakthrough in this area. *This project pioneers ML for MP studies, leveraging multi-band imaging to estimate stellar parameters and elemental abundances across GCs, bridging spectroscopy and imaging for large-scale statistical analysis.*
This project adopts a progressively sophisticated approach to deriving stellar parameters and abundances. Initially, it explores approaches based on predicted magnitudes and colors (Lardo et al. 2018). A more advanced phase incorporates simulated space-based images from HST and JWST (e.g., Kuntzer, Tewes & Courbin 2016). Final ML models will be applied to previously unseen data, including photometric catalogs and archival images. The results will enable statistical analyses of MP evolution across time and parameter spaces, aiming to (i) uncover unexpected trends and (ii) establish a foundation for future MP models.

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PhD project in ASTROPHYSICS

Title of the Project: Decoding Multiple Populations - Bridging Star Formation Insights Across Galactic Environments

Supervisor: Prof.ssa Carmela Lardo
Co-Supervisor: Prof. Alessio Mucciarelli

Scientific Case: Globular clusters (GCs), some of the oldest objects in the Universe, offer key insights into star formation and galaxy assembly through their age, chemical, and kinematic data. To fully utilize GCs in studying galaxy evolution, we must first understand their formation processes. The chemical makeup of GC stars holds key information about their origins and the early stages of galaxy formation. Once considered simple stellar populations with uniform age and composition, GCs are now known to host multiple populations (MPs) with variations in helium and light elements such as C, N, O, Na, Mg, and Al, and in some cases, Fe (Milone & Marino 2022). Despite extensive research, the origin of MPs remains uncertain (e.g., Bastian & Lardo 2018).

Outline of the Project: Observations suggest that MP-like chemical signatures extend beyond GCs, appearing in dense stellar systems more broadly. Many Galactic Bulge stars show MP-like chemistry, implying MPs exist beyond dissolved clusters (Schiavon et al., 2017). Evidence of MPs has also been found in an ultra-compact dwarf (UCD; Strader et al., 2013). Na variations in massive early-type galaxies (ETGs) suggest an unusual initial mass function (IMF; Conroy & van Dokkum, 2012), but Na and N fluctuations linked to MPs may mimic IMF differences. The UV upturn in ETG spectra further supports an MP connection, likely influenced by He-enhanced horizontal branch stars.

The proposed project aims to determine whether MPs are unique to GCs or represent a broader mode of star formation across various environments, potentially influenced by observational biases. This will be achieved by developing Stellar Population Synthesis (SPS) models that incorporate MP chemistry to assess their presence in UCDs and ETGs and evaluate their impact on stellar system properties. *This will be the first instance of including MP chemistry in SPS models.* Initial validation will focus on metal-rich GCs. Future stages will compare models with high-quality galaxy spectra. The project will develop SPS models that account for MP chemistry, enabling more accurate interpretations of GC and galaxy properties, especially considering recent JWST discoveries of lensed GCs at high redshift (Mowla et al., 2022).

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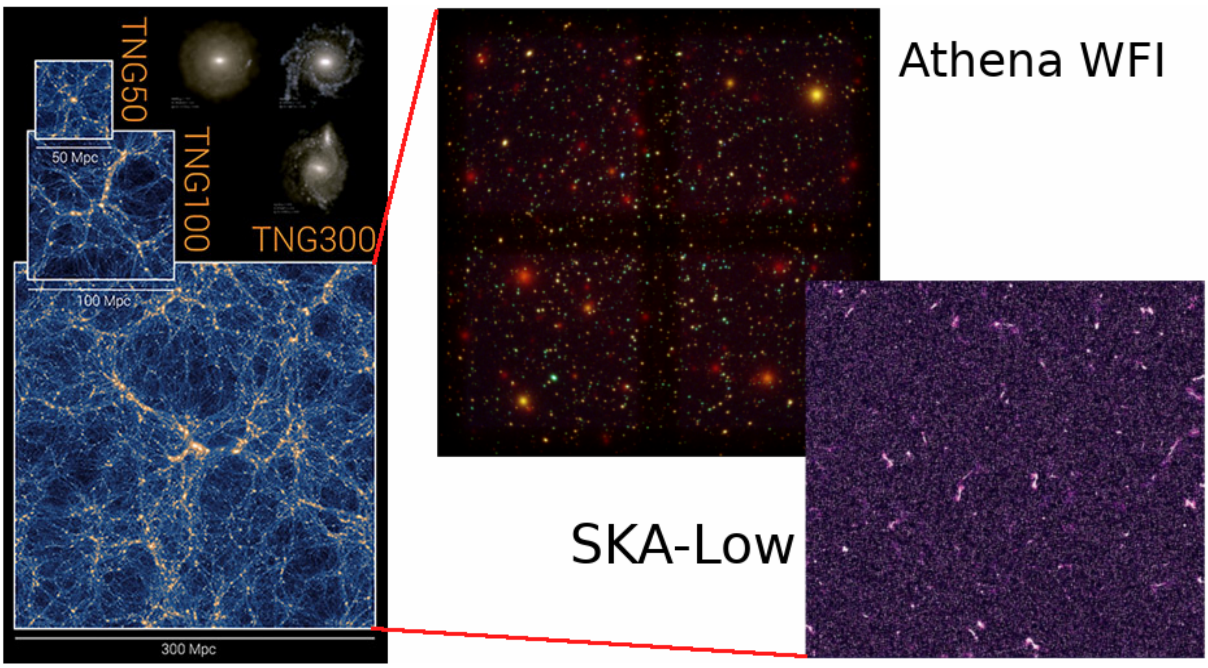
PhD project in ASTROPHYSICS

Title of the Project: Searching for high redshift AGN with current and future X-ray and radio facilities

Supervisor : S. Marchesi
Co-Supervisors : G. Lanzuisi, R. Gilli, A. Comastri

Scientific Case:
This project aims to develop effective methods for identifying the elusive high redshift and obscured Active Galactic Nuclei (AGN) population, to advance our understanding of the formation and evolution of supermassive black holes (SMBHs) and galaxies in the early Universe. By combining the physical properties of accreting SMBH contained in state-of-the-art cosmological simulations and the observed relations beteen accretion and emission in different bands, the project will produce X-ray and radio mock catalogs of AGN. These will be tested and improved against existing/ongoing deep and wide X-ray and radio surveys (COSMOS, CDFS, J1030, XMM-LSS etc). These mocks will then be used to optimize survey strategies for future observations with next-generation facilities, including the Square Kilometer Array Observatory (SKAO), and X-ray missions such as ESA's next large X-ray mission NewAthena and the proposed NASA mission AXIS. Ultimately, this research will enhance our understanding of the first SMBHs and their role in shaping the early Universe while maximizing the scientific impact of forthcoming flagship observatories.



Outline of the Project:

The student will analyse the physical processes that govern SMBHs evolution and accretion in cosmological simulations - such as BH seeding, accretion histories and spin evolution - and assess their impact on the observable properties of high-redshift AGN. The student will define a set of physically-motivated criteria for effectively selecting obscured AGN at high redshift, and then test and refine these selection criteria using data from current/ongoing deep X-ray and radio surveys, in which the host institutions play a leading role: the team is directly involved in the ongoing COSMOS-WebX Chandra Large Program that will more then double the X-ray sensitivity of the central 0.5 deg^2 covered by a variety of deep multi-wavelength data sets, including the JWST COSMOS-Web NIRCam and MIRI survey.

These refined selection criteria will then be applied to optimize the observations and selection strategies for future observatories such as SKAO in the radio and Athena and AXIS in the X-rays. The team is deeply involved in the development of Athena with several Study Team Working Group members, while the supervisor is directly involved as a Co-Investigator of the AXIS study team.

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PhD project in ASTROPHYSICS

Title of the Project: Characterizing the emission mechanisms of extreme high synchrotron peak blazars: towards a new population of CTAO extragalactic emitters

Supervisor: Stefano Marchesi (DIFA)
Co-Supervisors: Cristian Vignali (DIFA)

Scientific Case: Blazars are accreting supermassive black holes (SMBHs), or active galactic nuclei (AGN), whose relativistic jets are pointed in the direction of the observer. Their spectral energy distribution (SED) is characterized by two clear bumps: the first one at lower frequencies/energies, the so-called ``synchrotron peak'', where the synchrotron emission is caused by the relativistic electrons in the jets. The second one at higher frequencies/energies, the ``inverse Compton'' (IC) one, is instead caused by the interaction and subsequent up-scattering in frequency of the synchrotron-produced photons with the same relativistic electrons. The most extreme class of blazars are the so-called "Extreme High Synchrotron Peak" (EHSP) blazars, whose synchrotron peak is observed in the X-ray band, and the IC peak in the Very High Energy (VHE) band, in the GeV-TeV regime that will be observed with unprecedented sensitivity by the forthcoming Cherenkov Telescope Array Observatory (CTAO). A full characterization of the properties of EHSP sources is thus timely, to inform the observing strategy of the CTAO surveys, as well as to select promising candidates for targeted follow-up campaign

Outline of the Project: The main goals of the proposed PhD project are (a) Select targets of interest among a population of X-ray bright EHSPs that lack a counterpart in the Fermi-LAT 4FGL catalog (in the MeV-GeV band). Such sources, while missed by Fermi-LAT, could represent a sample of objects whose SED will peak in the TeV band, and will thus be detected by CTAO; b) Use available X-ray observations from multiple X-ray telescopes (NuSTAR, XMM-Newton, Chandra, Swift-XRT, eROSITA…) to put constraints on the SED at the synchrotron peak, and consequently obtain information on the physical mechanisms behind these extreme emitters; c) Use state-of-the-art models of blazar emission (e.g., AGNPy, JetSet) to make predictions on the shape of the SED in the CTAO energy range, testing a variety of parameters and models. These results will be used to select promising candidates for follow-up observations with CTAO, as well as with current generation Cherenkov telescopes (in particular, the MAGIC-LST1 ones).

The PhD candidate will be trained in the selection and characterization of blazars, fully exploiting the wealth of multi-wavelength data currently available. They will learn how to handle, analyze, and interpret multi-band data, and will gain expertise in proposal writing and presenting the work at international conferences. They will also have the chance of spending a period of time abroad and in other Italian institutions, working with collaborators of the advisors on the topics reported above..

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PhD project in ASTROPHYSICS

Title of the Project: *The effects of baryonic physics implementation in simulations of galaxy formation and evolution using Lagrangian and mesh-based hydrodynamic codes*

Supervisor: Federico Marinacci

Scientific Case: Modern numerical simulations of galaxy formation and evolution have achieved remarkable accuracy in reproducing observed galactic properties across various spatial scales. This success largely stems from the ability of simulations to regulate and quench star formation through highly efficient stellar and AGN feedback mechanisms. However, the implementation of these feedback processes must be adapted to the specific numerical code employed and in particular to the method used to model the hydrodynamic evolution of gas. Two primary approaches are used to follow hydrodynamics in galaxy formation simulations: smoothed particle hydrodynamics (SPH) and mesh-based methods. While differences in simulation outcomes are often attributed to variations in feedback implementations rather than the choice of hydrodynamic technique, it remains unclear whether a specific implementation of feedback processes works "universally" – that is independent of the hydrodynamic method adopted – or if they introduce or mask inaccuracies inherent in the hydrodynamic solver. These uncertainties significantly limit the predictive power of simulations and hinder a comprehensive theoretical understanding of the physical mechanisms shaping galaxies. Addressing these modeling challenges is crucial to building a coherent and reliable theoretical framework for galaxy formation and evolution.

Outline of the Project: This PhD project aims to investigate the impact of baryonic physics implementations by employing and extending the *SMUGGLE* model—an advanced interstellar medium (ISM) and stellar feedback framework—currently integrated into the moving-mesh code *Arepo*. The first objective is to adapt and implement the *SMUGGLE* model within the SPH-based code *Gadget4*. By incorporating the same galaxy formation physics module into two codes that share the same treatment of gravitational dynamics but differ in their modelling of hydrodynamic, the project will provide critical insights into the influence of numerical techniques on galaxy evolution predictions. Following this implementation phase, the student will design, execute, and analyze state-of-the-art numerical simulations of galaxy formation. Initial simulations will focus on isolated galaxies, gradually scaling up to cosmological zoom-in calculations. The potential inclusion of AGN feedback in cosmological simulations will also be explored. A key aspect of the analysis will be comparing results from *Arepo* and *Gadget4* to assess how different hydrodynamic approaches interact with the underlying physics of galaxy formation, ultimately improving our understanding of these complex processes.

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PhD project in ASTROPHYSICS

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

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

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

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

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

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PhD project in ASTROPHYSICS

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

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

Scientific Case:
Current and future wide-field spectroscopic and photometric surveys (e.g., KiDS, *Euclid*, LSST, WST) present a unique opportunity to significantly increase the number of known galaxy clusters and explore previously uncharted territories at both low mass ($M \sim 10^{14}\ M_{sun}$) and high redshift ($z > 1$). The scientific interest in these new samples of galaxy clusters is twofold. Firstly, the abundance and clustering of these structures provide crucial constraints on cosmology, as the cluster population carries information about the statistical distribution of initial fluctuations, their subsequent growth, and the dynamics of dark matter halo collapse. Secondly, these clusters serve as invaluable laboratories for studying the evolution of galaxies in dense environments across different epochs.
Furthermore, **galaxy clusters offer natural cosmic laboratories for conducting direct measurements of gravitational redshifts**, enabling tests of gravitational theories on megaparsec scales. Specifically, the gravitational redshift effect can be inferred from the distribution of peculiar velocities of cluster member galaxies as a function of their transverse distance from the cluster center. However, achieving the required precision for definitive tests of General Relativity versus alternative gravity theories has been hindered by the lack of sufficiently large and dense samples of galaxy clusters and associated cluster member galaxies. This limitation is expected to be overcome with the wealth of data from upcoming missions, such as the ESA *Euclid* telescope and the NASA *Nancy Grace Roman* Space Telescope, and, in the future, by the planned WST spectroscopic surveys.
The objective of the proposed PhD project is to leverage the new galaxy and cluster spectroscopic samples expected in the near future to conduct **novel tests of gravitational theories using gravitational redshifts in galaxy clusters**. The PhD student will initially construct and characterize new spectroscopic cluster catalogues, focusing on key properties such as cluster centers and the positions of cluster member galaxies. New software tools will be developed to compute these measurements and conduct the necessary statistical analyses.

The validity of these pipelines will be verified using simulated catalogues to identify and address potential systematic uncertainties. The newly implemented algorithms will be made publicly available through the CosmoBolognaLib, a comprehensive suite of *free software* C++/Python libraries for cosmological calculations. Ultimately, the PhD student will deliver new constraints on gravitational theories, potentially distinguishing among various alternative gravity frameworks.

Outline of the Project:

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

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PhD project in ASTROPHYSICS

Title of the Project:
Cosmology with Bayesian deep neural networks to learn the properties of the Cosmic Web

Supervisor: Prof. Federico Marulli
Co-Supervisors : Prof. Lauro Moscardini, Dr. Alfonso Veropalumbo

Scientific Case:
In the last decades, the exponential growth of data drastically changed the way we do science. This data tsunami led Cosmology in the so-called Big Data Era. Standard cosmological analyses based on abundances, two-point and higher-order statistics of specific extra-galactic tracer populations – such as e.g. galaxies, galaxy clusters, voids - have been widely used up to now to investigate the properties of the *Cosmic Web*. However, these statistics can only exploit a sub-set of the whole information content available.
The proposed PhD project aims to enhance the scientific utilization of current and future galaxy surveys, taking advantage of the newest data analysis techniques to assess the properties of the large-scale structure of the Universe. Specifically, the goal is to **develop new Bayesian deep neural networks for cosmological analyses**. The implemented supervised machine learning infrastructure will be trained and tested on simulated catalogues in different cosmological frameworks, and then applied to current available data sets, such as e.g. BOSS, eBOSS, DESI. In the next future, the developed neural network will be used to analyse the data provided by the ESA ***Euclid*** satellite.
The primary scientific goals of this PhD project are to provide independent constraints on the **dark energy equation of state parameters** and to **test Einstein's General Theory of Relativity**. The PhD student will acquire high-level knowledge on the modern statistical techniques to analyse large extra-galactic data sets and extract cosmological information. Moreover, he/she will become familiar with the latest deep learning techniques for data mining, which will be explored for the first time in a cosmological context. The new implemented algorithms will be included in the CosmoBolognaLib, a large set of *free software* C++/Python libraries for cosmological calculations.

Outline of the Project:

The PhD project is organised in the following phases:

- **Construction of a large set of dark matter mock catalogues in different cosmological frameworks** using fast techniques, such as the ones based on Lagrangian Perturbation Theory.
- Application of subhalo abundance matching (**SHAM**) and/or halo occupation distribution (**HOD**) techniques to populate the dark matter catalogues with galaxies and galaxy clusters.
- Implementation of **new standard and Bayesian deep neural network infrastructures**.
- **Training and testing** of the neural networks on mock galaxy and cluster catalogues.
- **Comparison of the cosmological constraints from neural network and standard probes**, such as e.g. the ones from 2-point and 3-point correlation functions of galaxies and galaxy clusters.
- **Utilization of the new machine learning tools on available data sets** to derive independent cosmological constraints.
- Application of the tools on larger mock catalogues to provide **forecasts for next-generation galaxy redshift surveys**.

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PhD project in ASTROPHYSICS

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

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

Scientific Case:
A significant fraction of the Universe volume is made up of almost empty space regions, that emerge between the filaments and the walls of the *Cosmic Web*. These low-density patches of the Universe are known Cosmic Voids and provide one of the most powerful, though yet largely unexplored, cosmological probes. Thanks to their huge sizes – up tens of megaparsec - and low-density interiors, voids constitute unique cosmic laboratories to investigate the physical properties of **dark energy**, as well as **modified gravity theories**, **massive neutrinos**, **primordial non-Gaussianity** and **Physics beyond the Standard Model**. The current and upcoming spectroscopic galaxy surveys will flood us with a huge volume of data, allowing us to significantly enlarge the cosmic void catalogues currently available, up to large redshifts. Cosmic voids are now being recognized as core cosmological probes in next-generation experiments.
This PhD project is aimed at fully exploiting the primary large-scale statistics of the cosmic void population, that is the **size function**, the **density** and **lensing profiles**, and the **spatial clustering of voids**. The PhD student will firstly investigate different void detector algorithms, with the goal of maximizing the purity and completeness of the void samples, as well as to accurately characterize the sample selections. Standard statistical methods, as well as the newest Machine Learning techniques will be considered to optimize the data analysis pipelines. New simulated catalogues of cosmic voids shall be constructed in different cosmological scenarios to test the efficiency of the void detectors and check for systematic uncertainties in the cosmological analysis.
The PhD student will then analyse real data sets and provide new cosmological constraints from the probe combination of the main cosmic void statistics. The catalogues will be extracted from both current data sets, such as the final SDSS-III BOSS survey, and ongong galaxy spectroscopic and photometric samples, as the ones from the ESA ***Euclid*** mission.

Outline of the Project:
The PhD project is organised in the following phases:

- Implementation of **new void detector algorithms**, including Machine Learning based methods, and comparison with existing available codes.
- Implementation of new software tools to **measure all primary statistics of cosmic voids: size function, lensing profiles, void clustering**.
- Implementation of **likelihood modules** to extract cosmological information from single void statistics and probe combinations.
- Test of the data analysis pipelines on mock void catalogues extracted from **standard and beyond-ΛCDM cosmological simulations**.
- Construction of **new real cosmic void catalogues**.
- **Cosmological analysis** on real cosmic void catalogues.
- **Forecasting** the constraining power of next-generation photometric and spectroscopic void samples.

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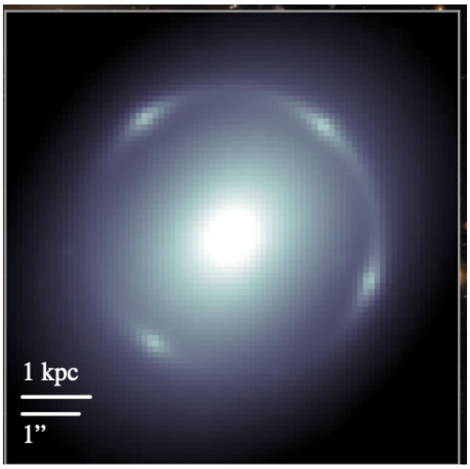
PhD project in ASTROPHYSICS

Title of the Project: The Properties of Strong Gravitational Lenses

Supervisor: Prof. Robert Benton Metcalf
Co-Supervisors : Prof. Giulia Despali



Scientific Case:
The Euclid space telescope has become the world's best strong gravitational lens-finding machine. It has already found hundreds of gravitational lenses and is expected to discover hundreds of thousands over the next few years. Traditionally, these spectacular objects have been studied individually or in samples of just a few. These studies have made discoveries about dark matter, the structure of galaxies, and cosmology. With Euclid, we move into a new regime where the number of lenses is very large, but the information about each one is limited. For the first time, we will be able to use statistically significant samples of the lenses to probe how the distribution of dark matter around galaxies is related to their observable properties. However, to do this, we must overcome some significant challenges involving the bias introduced by the methods used to detect the lenses. Current methods involve Convolutional Neural Networks (CNNs) and crowd-sourced human inspection. These miss some lenses and misclassify others.

Outline of the Project:

The project involves turning the observations of thousands of individual gravitational lenses into constraints on the nature of dark matter, galaxy formation, and cosmology.

Over the past several years, a pipeline for producing realistic simulated images of gravitational lenses has been developed. This pipeline will be further developed to make the images more realistic.

Calibrate the detection algorithms by running them on the simulated images. This involves collaborating with many members of the Euclid collaboration, who are developing Machine Learning (ML) methods for lens detection and modeling.

Develop a simulation-based statistical method for characterizing the selection and for inferring statistical characteristics of the gravitational lens population. For example, how the distribution of dark matter depends on the galaxy type and redshift. Compare these results to the predictions of theories of dark matter and cosmology.

This project involves computer programming and developing machine learning methods.

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PhD project in ASTROPHYSICS

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

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

Scientific Case:

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

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

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

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

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

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

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

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PhD project in ASTROPHYSICS

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

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

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

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

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PhD project in ASTROPHYSICS

Title of the Project: Towards a comprehensive clustering analysis: maximizing the scientific return through the combination of lower-order and higher-order correlation functions in configuration and Fourier space

Supervisor : Michele Ennio Maria Moresco
Co-Supervisors : Massimo Guidi, Federico Marulli

Scientific Case: The analysis of the clustering of galaxies has recently become one of the fundamental tools in Modern Cosmology to probe the distribution of Large Scale Structure. It retains cosmological information of the primordial Universe in the form of peculiar matter over-densities that appear around 100 Mpc/h. These features are called baryon acoustic oscillations (BAOs), and can be used as standard rulers to constrain the expansion history of the universe. In Fourier space, they appear as wiggles in the power spectrum, P(k), while in configuration space, they appear as a distinctive peak around r~100 Mpc/h in the two-point correlation function (2PCF). For these reasons, since the beginning of the century galaxy clustering has become one of the main cosmological probes, and several spectroscopic surveys both from the ground (e.g. BOSS, eBOSS) and from space (e.g. Euclid) have been developed to exploit it at its best.
Historically, the field has been divided into two approaches, either by working in Fourier space (where the modelization is easier, but handling observational effects such as the footprint is more complicated) or in configuration space (with opposite pros and cons). Moreover, up to a few years ago most of the research has been focused on two-point statistics (P(k) and 2PCF), and only a few efforts have been made on higher-orders (bispectrum, B(k), and three-point correlation function, 3PCF).
While it is predictable that to maximize the scientific exploitation and accuracy in cosmological parameter constraint the combination of all these measurements should be combined in a joint analysis, no attempt has been currently made in this direction. Only one work explored the combined constraints on 2PCF+P(k) (Sanchez et al. 2016), finding promising results. Furthermore, recent works have addressed bridging the gap between Fourier and configuration space higher-order modelling. This has opened the path to a comprehensive joint likelihood including lower- and higher-order analysis to mitigate possible systematics and increase the statistical significance of the clustering analysis.
However, in view of the upcoming large spectroscopic surveys that will revolutionize the field with unprecedented statistics of galaxies, it is crucial to take this step.

Outline of the Project: The aim of this Ph.D. Thesis will be to develop a framework for the combined analysis of clustering 2-point and 3-point statistics both in configuration and in Fourier space, namely the 2-point correlation function, the 3-point correlation function, the power spectrum and the bispectrum. Building on the wide expertise of our group on clustering analysis (both on 2-point and 3-point correlation functions) and on the combination of different statistics, the Ph.D. student will base his/her work on the CosmoBolognaLib libraries (Marulli, Veropalumbo & Moresco, 2016), working to extend

these to provide a comprehensive pipeline for the joint analysis of 2PCF+3PCF+P(k)+B(k).
The work will be divided into the following steps:

1. Development of a pipeline for the analysis of 2PCF + P(k) and 3PCF + B(k), starting with a focus on the constraints that can be obtained on bias parameters;
2. Assessment of the cross-covariance between the various statistics (exploiting a theoretical and/or numerical approach);
3. Exploring the constraints that can be obtained on cosmological parameters expanding the modeling through emulators developed with Machine Learning algorithms: this will allow us to explore the constraints at the BAO and/or nonlinear scales;
4. Extend the pipeline for the joint analysis 2PCF+P(k)+3PCF+B(k) analysis;
5. Application of the pipeline to simulated and real data, assessing the gain in constraining power obtained with the full combination and the relative contribution of each term, and providing forecasts and new constraints on bias and cosmological parameters (e.g. exploring Euclid simulation and real data datasets like eBOSS, DESI and catalogs of cluster of galaxies);
6. Test the new developed pipeline on real Euclid data.

The Ph.D. student will approach and strengthen knowledges in galaxy clustering and Large Scale Structure, and will be also introduced in Italian and international collaborations that focus on this field (e.g. Euclid).
This work could provide a fundamental tool not yet explored in view of the large spectroscopic surveys that are taking data in this moment (like Euclid), and will be extremely timely to extend the current capabilities in an uncharted but exciting territory. From this point of view, the developed pipeline will be applied to the state-of-art data that will be available at the time needed.

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PhD project in ASTROPHYSICS

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

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

Scientific Case:

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

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

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

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

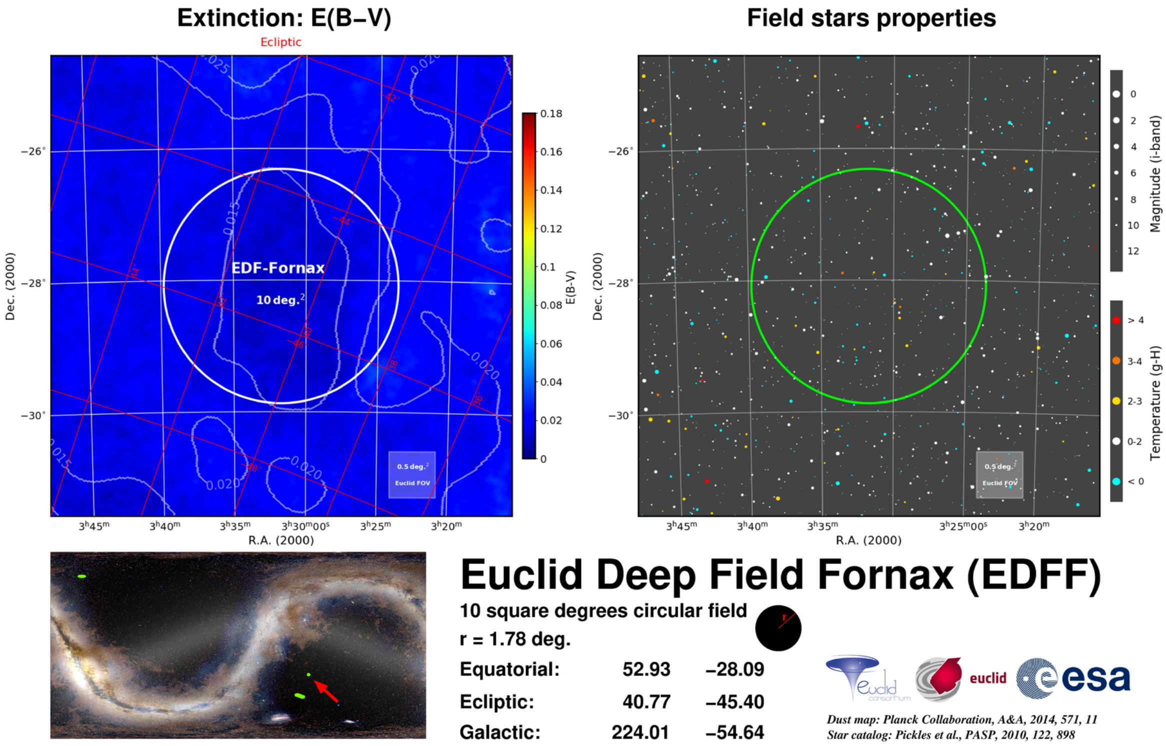
The project will be carried out in the framework of the Euclid collaboration, including ~2000 international scientists. In Bologna (DiFA and INAF institutes) there is a large and lively research group dealing with many different aspects of the science that will be enabled by Euclid data.

Outline of the Project:

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

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

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



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ALMA MATER STUDIORUM
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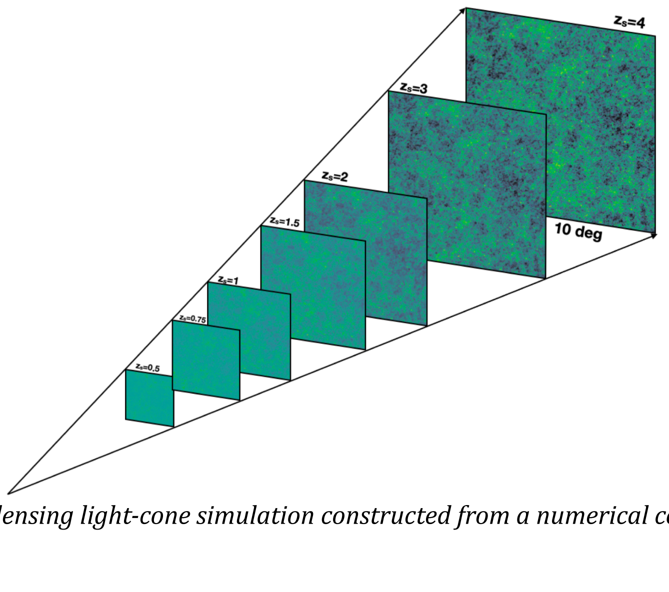
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

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

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

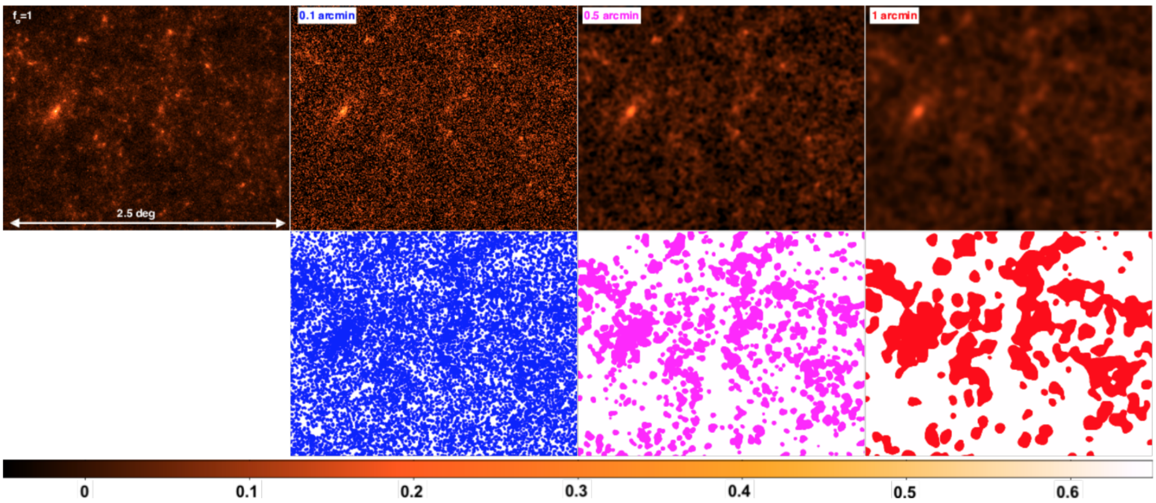
Scientific Case:
Wide-field surveys, such as those conducted by the ESA ***Euclid*** mission and **LSST-Rubin**, will use **weak gravitational lensing** as a primary cosmological probe. The slight distortion of intrinsic galaxy shapes, caused by the intervening matter density distribution, enables us to trace the growth of structure over cosmic time. The high galaxy number density and wide sky coverage expected from these two observatories will allow for **unprecedented precision in constraining cosmological parameters**. This, in turn, will open the possibility of using the weak lensing signal to detect and characterise both dense and underdense regions, such as galaxy clusters and cosmic voids. The accuracy and precision of these methods require the development of dedicated weak lensing light-cone simulations to refine techniques and modeling. In particular, **cluster and void lensing** are expected to be sensitive to **dark energy** equation-of-state parameters, **massive neutrinos**, and **modified gravity**. In this PhD thesis, dedicated weak lensing light-cone simulations will serve as cosmic reference laboratories. The models and results will then be applied to real photometric weak lensing data.



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

Outline of the Project:
During the initial phase, the student will focus on constructing dedicated **weak lensing simulations** using the tools and data sets available within our group. This will involve projecting matter density distributions from cosmological numerical simulations and tracing light rays using the *ray-MapSim* routine (Giocoli et al. 2015). The resulting shear

and convergence maps will then be used to extract the shear catalogue of sources, assuming a nominal depth consistent with expectations from the *Euclid* and LSST-Rubin telescopes.
Knowing the underlying galaxy cluster population, the student will test the performance of an optimal filter-based algorithm to identify galaxy clusters (peaks in the weak lensing convergence and shear maps) using the shear catalogues. The feasibility of the method has already been demonstrated in a series of works (Pace et al. 2007; Trobbiani et al. 2025 - as a pioneering analysis). The tool needs to be scaled and tested on more accurate and updated simulations before being applied to **real data.**
This second activity will give us the possibility to construct a **cluster weak lensing selection function** required to complement the photometric one (Sartoris et al. 2016) and to derive complementary constraints on the main cosmological probes.
As galaxy clusters trace the overdensities of the projected matter density distribution, cosmic voids delineate the underdensities (valleys in the weak lensing convergence and shear maps). As a third activity, the student will develop and optimise a new algorithm to **identify and characterise cosmic voids using weak lensing information**, paving the way toward new research topics (Melchior et al. 2012; Sanchéz et al. 2017; Fang et al. 2018).



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

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

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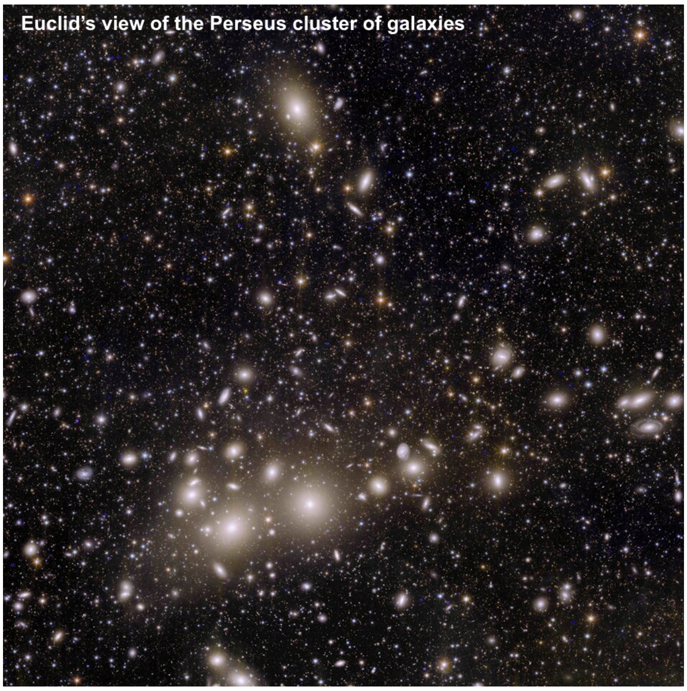
PhD project in ASTROPHYSICS

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

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

Scientific Case:
The successfully launched ESA-Euclid telescope is expected to deliver much data to the scientific community. Galaxy cluster cosmology is expected to increase the constraining power to test general relativity further to the two primary cosmological probes: galaxy clustering and weak gravitational lensing. Thanks to the exquisite data we are already receiving, the developed processing functions will be able to measure with extreme precision both the redshifts and the shapes of the large number density of photometric galaxies – approximately 30 galaxies per square arcminutes. The primary objective will be to measure the clustering and the weak lensing to trace the growth of structures from the present time up to high redshifts: $z \approx 2$. In addition, the Galaxy Cluster Science Working Group has defined the guidelines for using the photometric galaxy catalog to identify groups and clusters of galaxies (Sartoris et al. 2016, Adam et al. 2019) thanks to two algorithms: AMICO and PZWav. The weak lensing data, associated with the tiny distortion of the shape of background galaxies lying beyond the clusters, will be of primary importance in weighting the cluster mass. Using clusters as a cosmological probe, their abundance and their spatial distributions as a function of redshift, rely on the bias and the accuracy with which we can measure their mass and combine them with complementary cosmological data.

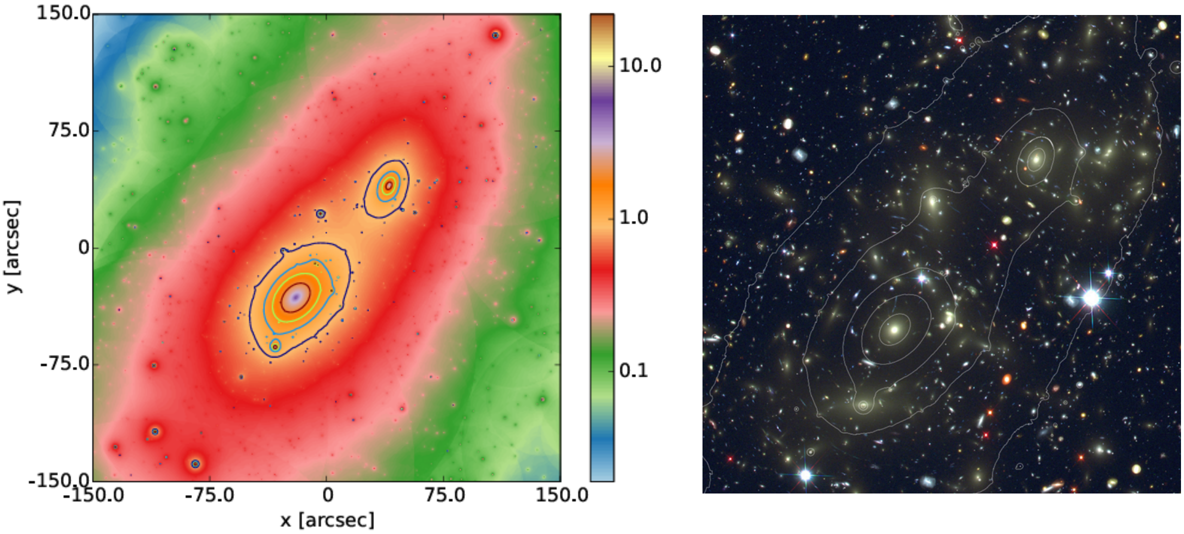


In recent years, the Bayesian, machine learning, and forward model methods have acquired great statistical interest in astrophysics and cosmology. Those represent the state-of-the-art tools that will be used to analyze upcoming data from the approaching wide-field photometric data.

Outline of the Project:

The student will be fully involved in scientifically exploiting the cluster cosmological studies within the Euclid Consortium. She/he will join the Consortium, becoming a member of the Clusters of Galaxies, Strong Lensing, and Weak Lensing Science Working Groups.

The activities will be devoted first to constructing dedicated weak lensing simulations of clusters extracted from hydrodynamical runs and pseudo-analytical realizations using the MOKA code (Giocoli et al. 2012). The image below, from Meneghetti et al. (2017), displays the projected mass density distribution of the cluster mass generated by MOKA (left panel) and the SkyLens image simulation on the right.



The simulations will be useful for several applications. For example, they will be a valuable training set to build deep learning models for the statistical inference of several cluster properties (mass, concentration, triaxiality, etc.) based on the observed lensing signal. In addition, they will be used to study how deep learning methods compare to more traditional methods for measuring the same properties (for example, by fitting projected shear profiles). Furthermore, their analysis will inform us of mass biases depending on other cluster properties. An interesting extension of the lensing simulations could be deriving additional simulated observables for the same clusters (e.g., X-ray emission, SZ signal, optical and near-infrared imaging, etc). Such complementary data would allow us to investigate the impact of possible selection effects on the measurement of cluster structural properties. Thus, by developing the simulated dataset, the student will acquire know-how on weak lensing, multi-wavelength observations, and fast statistical methods.

In a second step, he/she will then improve and optimize the cosmological pipeline starting from the cluster catalogs of the Euclid Collaboration (EC) and develop a mathematical forward model to derive cosmological parameters and combine them with the corresponding clustering and weak lensing constraints (To, Krause et al. 2021). The CLOE pipeline already developed within the EC, together with the results from the first part of the project, will represent the starting point for this section. The student will also be involved in studying and modeling the group and cluster weak lensing profiles using the developed statistical methods and benchmark possible dependencies on cosmology.

The framework of this Ph.D. project within an international scientific community will allow the student to improve his/her expertise, learn new methods, and possibly construct networking for a successful future in science research. A 3-6 month visit for scientific collaboration in one of the international institutions involved in the collaboration will be planned during the Ph.D. period.

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

PhD project in ASTROPHYSICS

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

Supervisor : A. Mucciarelli (DIFA)

Scientific Case:

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

Outline of the Project:

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

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PhD project in ASTROPHYSICS

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

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

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

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

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PhD project in ASTROPHYSICS

Title of the Project:
Reconstructing the mass assembly history of the Milky Way

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

Scientific Case:
The exquisitely precise proper motions and parallaxes provided by the ESA-Gaia space mission are revolutionising our view of the structure and evolution of the Milky Way (MW). In particular, in the lapse of just few years, our understanding of the stellar halo in the surroundings of the Sun has completely changed.
The commonly accepted scenario predicts that a significant portion of the retrograde halo (RH) was created as a result of a merging event between the MW and an ancient relatively massive dwarf galaxy, known as Gaia-Enceladus. Further analyses revealed additional substructures in the RH and led to the conclusion that the RH component could be entirely, or at least for the most part, made up of accreted star. However, the investigation of these sub-structures composing our Halo is still is its infancy and a complete characterization of stars belonging to former satellites needs the combinations of kinematical and chemical properties of individual stars.

Outline of the Project:
The PhD project is aimed at describing the chemistry of Milky Way stars belonging to sub-structures identified accoridng to their kienmatical properties. In fact, the chemical abundance patterns of individual stars carries distinct signatures of the formation process and chemical enrichment histories of each past merger progenitor, and thus crucially helps in differentiate between dwarf galaxies with different mass and star formation efficiency.
The project will benefit from proprietary and archival high-resolution spectra obtained with ground-based telescopes (i.e. VLT, LBT,Subaru,Keck) that will be analysed, together with kinematic data from the Gaia mission, to derive a complete screening of stars in the RH and likely accreted from now dissolved MW satellites.

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

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PhD project in ASTROPHYSICS

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

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

Scientific Case:

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

Outline of the Project:

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

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

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

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

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PhD project in ASTROPHYSICS

Title of the Project: *Local gravitational instability of stratified rotating fluids*

Supervisor: Carlo Nipoti (UniBo)

Scientific Case:
Fragmentation of rotating gas systems via gravitational instability is a crucial mechanism in several astrophysical processes, such as formation of planets in protoplanetary discs and of star clusters in galactic discs. Gravitational instability is fairly well understood for infinitesimally thin discs, but the thin-disc approximation is often not justified. Nipoti (2023) presented new 3D instability and stability criteria, which can be used to determine whether and where a rotating system of given 3D structure is prone to clump formation. For a vertically stratified gas disc of thickness h_z, the instability criterion takes the form Q_3D<1, where Q_3D, depending on h_z and on the local gas properties, is a 3D analogue of the classical 2D Toomre (1964) Q parameter. The Q_3D criterion has been recently applied to observed galactic gaseous discs by Bacchini et al. (2024), and extended to multicomponent discs by Nipoti et al. (2024).

Outline of the Project:
The PhD student will study the local gravitational stability properties both of observed systems and of models. As far as observed systems are concerned, the student will extend the study of Bacchini et al. (2024) by considering the 3D stability and instability criteria to thick multi-component discs for which we have information on the vertical structure, ranging from protoplanetary discs to gaseous galactic discs at low and high redshift.
As far as models are concerned, the student will build numerical (as in Nipoti and Binney 2005) and analytic (as in Sotira 2022) equilibrium models of self-gravitating rotating fluids and will apply to these models the 3D gravitational stability criteria. The analytic results will be complemented by numerical hydrodynamic simulations aimed at studying the non-linear behaviour of the models.

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- Nipoti C., Binney J., 2015, MNRAS, 446, 1820
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Bologna, 21/3/2025

PhD project in ASTROPHYSICS

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

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

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

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

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References:
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- Sollima A., Mastrobuono Battisti A., 2014, MNRAS 443, 351
- Sollima A., Ferraro F.R., 2019, MNRAS, 483, 1523

Bologna, 21/3/2025

PhD project in ASTROPHYSICS

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

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

Scientific Case:

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

Outline of the Project:

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

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Bologna, 21/3/2025

PhD project in ASTROPHYSICS

Title of the Project: *Probing black holes through gravitational wave and quantum signatures*

Supervisor: Carlo Nipoti (UniBo)
Co-supervisor: Roberto Casadio (UniBo)

Scientific Case:
The detection of gravitational waves (GWs) by the LIGO/Virgo/KAGRA collaboration has revolutionized our understanding of the Universe, providing direct insights into the population of compact objects, and in particular stellar mass black holes (BHs). The future GW detectors Einstein Telescope, Cosmic Explorer, and LISA, in synergy with pulsar timing array experiments such as that of the NANOGrav Collaboration, will significantly enhance our ability to detect GWs also from other categories of BHs, such as the supermassive BHs (SMBHs) that seem ubiquitous in massive galaxies, the more elusive intermediate mass BHs (IMBHs) and the exotic population of primordial black holes (PBHs). Depending on the formation scenario, PBHs can cover several orders of magnitude in mass, accounting for possible dark matter particles, and seeds for high redshift SMBHs. Gravitational signatures associated with PBHs formation and evolution can significantly vary, contributing to the cosmic gravitational wave background, together with other sources such as IMBH and SMBH binaries.

Outline of the Project:
The aim of this project is to improve our understanding of some properties of different categories of BHs. For SMBHs we can explore the possibility of using observational constraints on the redshift-dependent galaxy properties and merging hierarchy to sharpen the predictions of low-frequency GW from SMBH binaries (see Ellis et al. 2024). For GWs from IMBH binaries we can investigate models with realistic and redshift-dependent properties of the hosts, which are expected to be globular clusters (or their progenitors) and dwarf galaxies (see Khan et al. 2024). For PBHs one can consider quantum corrections observable in GW signals, focusing on induced GWs (generated at second order by curvature perturbations) or on high-frequency GWs from Hawking evaporation (see Dong et al. 2016 and Franciolini et al. 2023).

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References:

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Bologna, 21/3/2025

PhD project in ASTROPHYSICS

Title of the Project: *Hydrodynamic simulations of Terzan 5 and bulge fossil fragments*

Supervisor: Carlo Nipoti (UniBo)
Co-supervisors: Francesco Calura (INAF-OAS), Francesco Ferraro (UniBo)

Scientific Case

Understanding the origin of globular clusters (GCs) and their multiple stellar populations is a major challenge in modern astronomy. Peculiar cases are represented by the so-called bulge fossil fragments (BFFs) Terzan 5 and Liller 1 that, at variance with ordinary GCs, display multiple sub-populations of stars with large differences in age and in iron content. The complex abundance pattern of these systems indicates an enrichment history characterized by multiple star formation episodes, separated by time intervals as long as a few Gyrs. This non-trivial feature is unexpected for a GC and various explanations have been proposed: besides the possibility that they are remnants of long-lived clumps, most of which eventually merged to form the Bulge, they may also be accreted nuclear star clusters formed in dwarf galaxies (Bastian & Pfeffer 2022) or the result of existing GCs accreting gas and forming a new stellar generation. The aim of the present project is to investigate the latter possibility.

Outline of the Project

To explain the formation of the complex stellar populations of Terzan 5 and its analogues, we propose to use three-dimensional hydrodynamic simulations and model the encounter of an old stellar population with a reservoir of cold gas, such as a molecular cloud.

We propose to use a customized version of the RAMSES code (Teyssier 2002) which includes basic yet realistic physical ingredients, such as radiative cooling, star formation, feedback and chemical enrichment (Lacchin et al. 2021; Calura et al. 2022).

The results of the simulations will be compared with the observational properties of these systems, including their abundance pattern and colour-magnitude diagrams, in an effort to make significant progress in our understanding of the complex history of the BFFs.

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Bologna, 21/3/2025

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DEPARTMENT
OF PHYSICS AND ASTRONOMY
"AUGUSTO RIGHI"

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

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

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

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

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

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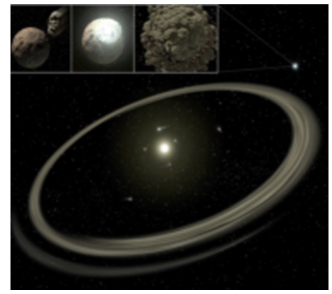
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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

PhD project in ASTROPHYSICS

Title of the Project:



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

Supervisor : Veronica Roccatagliata

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

Outline of the Project: The student will first collect a sample of debris disks highlighting the resolved ones at different wavelengths, and those with planets.
A coherent characterization of the stellar properties of the central star hosting the debris disks will be obtained by the student in clusters and isolated objects. This will be done via spectroscopic analysis and/or via spectral energy distribution. Timescale of collisions in debris disks will be here constrained when multi-epoch observations of the far-infrared excess are available.
Next, the student will develop a comprehensive analysis of the Gaia DR3 (and eventually DR4) astrometric data to reconstruct the flyby experienced by the system during its life. This will be done first with a linear approximation to statistically constrain the frequency of at least one close flyby.
According to the attitude of the student the project will proceed in different ways. One possibility is the proper dynamical reconstruction of the multiple flybys with the relative orbit deviation. Another possibility is the reduction of new high-contrast imaging observations (already available) of the debris disk systems. The student will then led new proposal on a particular sample of debris disks.
The student will be part of the Bologna-based and will also work in collaboration with national and international network of colleagues.

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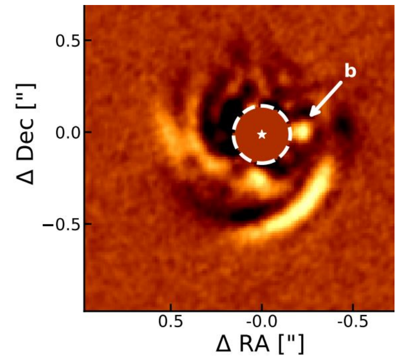
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS



Title of the Project:

Formation of planets in protoplanetary disks

Supervisor : Veronica Roccatagliata

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

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

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PhD project in ASTROPHYSICS

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

Supervisor : Margherita Talia <margherita.talia2@unibo.it>
Collaborators : ELSA team members

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

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

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

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

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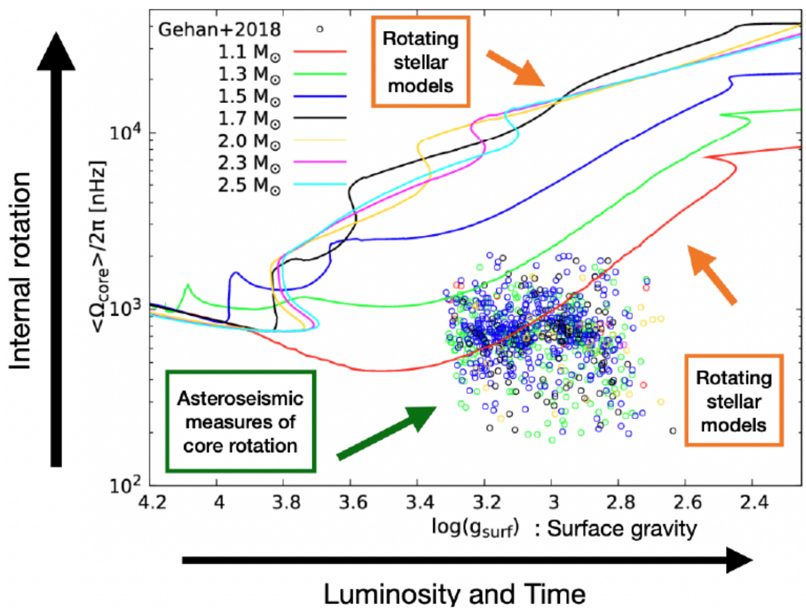
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: Investigating stellar rotation in low and intermediate mass stars

Supervisor : Marco Tailo
Co-Supervisors : Andrea Miglio

Scientific Case: Stellar evolution (SE) is fundamental in astrophysics, astrobiology, and planetology. This is further underscored by the fact that stars are the main building blocks of galaxies and the source of the elements essential for life and planets. Understanding stellar evolution relies on comparing observational data with theoretical models, but these models still have significant limitations. A key example is the discrepancy between the observed stellar rotation rates, which are at least three times lower than predicted by the most advanced models (see the figure in this section). Solving this issue is crucial, especially for low- and intermediate-mass stars (LIMS), which make up the majority of stars in the universe.



Accurate modeling of LIMS is essential for many fields: from understanding dust emission and galaxy evolution, to the study of globular clusters - where, at the time of this writing, explaining the formation of their multiple stellar populations remains a major challenge — and the calibration of "chemical clocks" used in galactic archaeology. However, the interaction between core rotation, element transport, and surface chemistry is still poorly explored and could offer new perspectives in astrophysics and hydrodynamics.

Outline of the Project: The aim of this project is to study rotation in stars of low and intermediate mass and how it affects the surface chemistry and the physical features of these stars. The research activities needed for its completion will be performed within the framework of the Asterochronometry group, led by Prof. Andrea Miglio.
The project can be roughly divided into three main parts.

- Phase One: the student will start learning stellar evolution by using the powerful MESA code and other essential tools for modeling and analysing stellar models with rotation. These new skills will be used right away, with a hands-on theoretical investigation into how surface abundances in stars are shaped by rotational mixing—or its absence—and by the various physical prescriptions available in MESA.

- Phase Two: The focus shifts to evolved stars, exploring how rotation influences their evolution and properties. Special attention will be given to core helium-burning stars, whose unique characteristics play a crucial role in the galactic ecosystem.
- Phase Three: The final stage broadens the horizon to a comprehensive study of stellar rotational velocities and the mechanisms that govern them. The spotlight will be on the internal structure of stars and how it shapes asteroseismic signals—key for interpreting data from upcoming space missions like PLATO and HAYDN.

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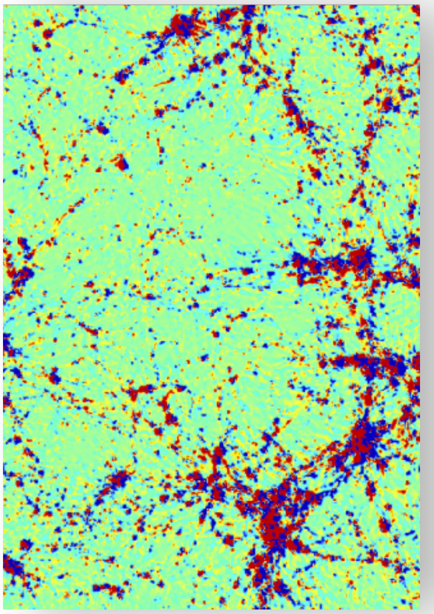
PhD project in ASTROPHYSICS

Title of the Project:
Studying the magnetic connection between the cosmic web and the primordial Universe
La connessione magnetica tra il cosmic web e l'Universo primordiale
Supervisor : *Prof. F. Vazza (Università di Bologna)*
Co-supervisor*: Dr. E. Carretti (IRA/INAF)*



Scientific Case: New radio observations of the Faraday Rotation effect from distant galaxies shining polarised radio emission through the cosmic web have lead to a tantalising detection of the signature of primordial magnetic fields (Carretti, Vazza et al. 2024).
A robust detection of primordial magnetic fields in the local Universe is of pivotal importance, since primordial magnetic fields could only be generated during out-of-equilibrium transitions in the very early Universe, like the Electro-Weak phase transition or before the confinement of Quarks, in the Quark-Gluon plasma stage of the Universe (less than a *micro-second* after the big bang). Primordial magnetic fields have also been proposed as a plausible explanation for the detected background of stochastic gravitational waves (Neronov et al. 2021), and hence can represent a very powerful probe of extremely early high-energy cosmological processes, extending our observational capabilities much beyond the epoch probed by photons of the cosmic microwave background.

In order to accurate model the Faraday Rotation of the cosmic web, **advanced and realistic cosmological are required**, so that the magnetic contamination from evolving galaxies and radio jets can be removed, and the primordial signal can be best extracted. To best match the large volume and level of detail proved by new radio surveys, like from LOFAR, ASKAP and in preparation to the future ones by the Square Kilometre Array (from 2029), new and ambitious cosmological simulations should be deployed on High Performance Computing facilities. Thanks to new simulations, the PhD candidate will be able to test different realistic scenarios for the origin of cosmic magnetic fields, with the final goal of selecting those compatible with radio observations and produce a key result towards the understanding of cosmic magnetism.

Outline of the Project: The PhD candidate will work at the design, testing and production of new large cosmological simulations optimised to run on large HPC facilities like LEONARDO at Cineca. By robustly constraining the amplitude and spectral shape of allowed primordial magnetic fields, **the candidate will be able to produce a key scientific results which can connect cosmology of the primordial Universe, with local large-scale structures**. This project calls for candidates with experience (or curiosity) in numerics, theory and large-scale structure dynamics.

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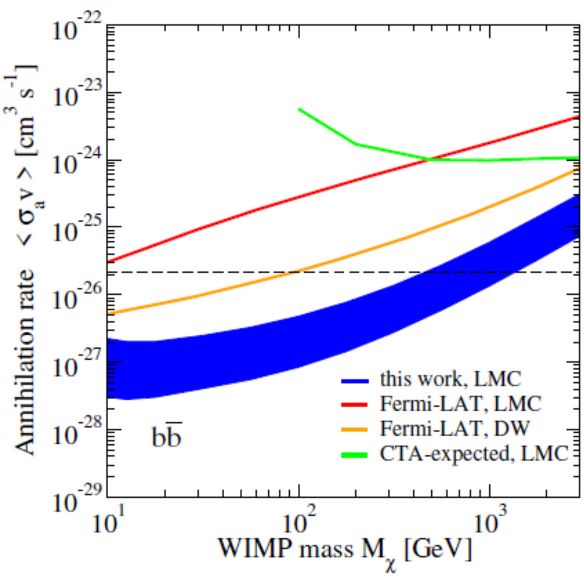
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project:
Unveiling the nature of dark matter from radio observations with SKA precursors
Rivelare la natura della materia oscura da osservazioni radio con i precursori di SKA
Supervisor : *Prof. F. Vazza (Università di Bologna)*
Co-supervisor*: Dr. G. Bernardi (IRA/INAF), Prof. M. Regis (Università di Torino)*

Scientific Case: Most of the matter in our universe must be non-baryonic. Observations accumulated over the last few decades show that some form of dark matter (DM) is the invisible scaffolding that holds the visible universe together. The remarkable and indisputable evidence is still accompanied by an aura of mystery about the particle origin of dark matter. Weakly Interacting Massive Particles (WIMP) and axion-like particles are best-motivated dark matter candidates. WIMPs can annihilate producing electron/positron pairs which, in turn, can generate synchrotron emission in the presence of magnetic fields. Axion-like particles can decay into radio waves. The search for the DM radio signature has led to no detection to date, and the most recent observations started to place significant constraints, probing theoretically well-motivated WIMP and axion models.



The advent of a new generation of sensitive radio interferometers spanning a large range of frequencies like LOFAR, MeerKAT and ASKAP, offers the opportunity to improve current upper limits on the DM mass and, ambitiously, to attempt a detection of the DM radio signal.

Outline of the Project: The PhD candidate will work on:

- LoFAR observations of galaxy clusters. Clusters are the most massive bound systems in the Universe and their very extended halos can be targeted to probe a possible non-gravitational emission from particle DM. The PhD candidate will use targets from the publicly-available, all-sky, LoFAR LoTSS survey (or deeper observations on single targets available in the archive)
- ASKAP and MeerKAT observations of dwarf spheroidal galaxies (dSph). DSph are the galaxies with the largest mass-to-light ratio, offering a target nearly free of astrophysical backgrounds where to perform particle DM searches. The PhD candidate

will use candidates from the publicly-available, all-sky ASKAP RACS/EMU surveys, complemented MeerKAT archive data;

- MeerKAT and JVLA observations of the Galactic center. The aim is to study the radio/gamma-ray correlation at the Galactic center and explain the gamma/ray excess observed by the Fermi-LAT telescope as a DM signal or a (so far unknown) population of Galactic objects. The PhD candidate will use data available from both MeerKAT and VLA archives in order to provide the most sensitive radio images of the Galactic centre region to date.

The PhD candidate will develop the theoretical framework to predict the DM-induced radio signature from each target, also using cosmological numerical simulations tailored to reproduce the mass distribution of targets (dwarf galaxies and clusters of galaxies). With numerical simulations, the PhD candidate will also investigate the possibility that electrons and positrons injected by DM can seed additional large-scale radio emissions, detectable with future radio surveys using the Square Kilometre Array.

Although radio images are the publicly available data products from the aforementioned surveys, we anticipate that further reprocessing will be needed in order to achieve better sensitivity on the angular scales of the DM signal. We also anticipate that the search of DM-induced radio emission may include early surveys carried out with the SKA, whose timing is aligned with the proposed PhD project.

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PhD project in ASTROPHYSICS

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

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

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

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

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PhD project in ASTROPHYSICS

Title of the Project: Shedding light on the physics of the most massive, highly accreting SMBHs at cosmic noon through a multi-wavelength study

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

Scientific Case: While the physics of accretion in quasars at low redshift has been widely investigated in the last decades and has provided a generally accepted picture, at high redshift the situation is far less clear. Probing accretion in luminous quasars at z=2−4 is fundamental to investigating the strict interplay between the disc UV emission and that of the X-ray emitting corona at the highest accretion rates, verifying whether different accretion-disc solutions may be at play, and assessing, from a physical and demographic perspective, the role of quasar-driven feedback in shaping galaxies in the early times of the Universe.

Outline of the Project: In this project, accretion physics is tackled starting from the sample of WISE/SDSS selected hyper-luminous ($L_{bol}>10^{47}$ erg/s) quasars at z~2−4. All of these quasars are characterized by large Eddington ratios, thus probing accretion at its 'extremes', and have multi-wavelength data allowing for a comprehensive investigation of their properties. Among the many possible open issues related to nuclear accretion at cosmic noon, we would like to focus on (a) the nature of X-ray weak quasars at z~3 (~30% of the population) and their occurrence at earlier cosmic epochs, thus providing an interpretation in the context of accretion-disc physics of highly accreting SMBHs; (b) the origin of the recently found correlation between parameters linking the mid-IR emission and the optical-UV to X-ray emission; (c) the properties of quasar host galaxies (e.g., star-formation rates, molecular gas content) via SED fitting and millimeter (ALMA) observations; (d) the link between quasar accretion and nuclear extinction in the path to properly investigate the claimed blow-out (feedback) phase. Further extension of this work may include a systematic spectral analysis of z~2−4 quasars (selected also using the recently available DESI data) in archival Chandra and XMM-Newton observations, and the luminous quasars at z>6 of the HYPERION sample. The properties of the analyzed quasars will be finally compared with those of local AGN to get a comprehensive view of accretion across cosmic time. Proprietary XMM-Newton data should also be available.

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

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

PhD project in ASTROPHYSICS

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

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

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

Outline of the Project: The main goals of the proposed PhD project are (a) to provide a physical characterization of the AGN thus far discovered at high redshift (z>4) by JWST using X-ray data (hence, not only catalogs) and the available rich ancillary multi-band datasets; (b) place constraints on the accretion-related activity in the LRD and galaxy population using X-ray data coupled with multi-band SED fitting; the comparison between the X-ray emission and the one in radio/mid-IR has been proven to be effective in providing indications of obscuration. This approach will then allow us to unveil the thus-far still poorly investigated population of obscured AGN candidates at the highest redshift; (c) provide an updated census of the dual and offset AGN population at high redshift through a multi-wavelength approach. The recently JWST-derived higher fraction of dual AGN at high redshift compared to low redshift, if confirmed, needs to be interpreted using the most up-to-date model predictions, and the mechanisms driving the likely enhancement at high redshift (larger molecular gas content? higher merger rates?) should be investigated.
Overall, the proposed strategy will shed light on the emergence of nuclear accretion activity in the first two billion years of the Universe and allow us to reach a comprehensive picture of the black hole accretion rate density at z>4.

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

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PhD project in ASTROPHYSICS

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

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

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

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

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