INAF1

INAF-OAS Projects available for PhD cycle 40

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Campana1	Campana	Development, integration, testing and exploitation of high energy astrophysics satellite missions
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Massari1	Massari	Galactic archaeology through the lenses of N-body simulations
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Pozzetti1	Pozzetti	Optimal exploitation with Machine Learning of the first Euclid data for characterizing galaxy & AGN evolution
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Vallini1	Vallini	Unlocking the First Galaxies: a study of the interstellar medium, AGN feedback, and star formation in the Epoch of Reionization
Villa1	Villa	The SOLARIS observatory: a smart Solar imaging system at high radio frequency for continuous Solar monitoring and Space Weather applications
Virgili1	Virgili	Development of technologies for hard X-ray focusing space missions
Vito1	Vito	The large-scale environment of $z > 6$ QSOs
Vito2	Vito	The AGN population in high-redshift protoclusters
Vito3	Vito	Hunting down high-redshift low-luminosity AGN in the deepest X-ray survey

PhD project in ASTROPHYSICS

Title of the Project: A EUCLID view of merging events in nearby dwarf galaxies

INAF-OAS Supervisor: F. Annibali

Co-Supervisors: M. Bellazzini, M. Tosi, R. Pascale, C. Nipoti, F. Marinacci

Scientific Case:

Being the most numerous galaxies in the Universe and the first to have formed, dwarf galaxies are central systems in cosmology, yet many questions related to their mass assembly and star formation are still poorly understood. Indeed, while interaction and accretion phenomena are expected to strongly affect dwarf galaxy morphology and kinematics, triggering the inflow of gas and the possible onset of starbursts, studies of merging events onto dwarf hosts have received little attention observationally so far, mostly because of the difficulty in detecting very faint satellites or merger signatures around them.

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

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

The supervisor of the proposed Ph.D. project is a member of the Euclid Consortium and is actively involved in the science activities of the "Resolved Stellar Populations" and "Local Universe" working groups. The Ph.D. student will have the possibility to work on the Euclid data before they get public and to lead key studies on dwarf galaxies in collaboration with the two aforementioned Euclid working groups. Stellar substructures, streams, and merging signatures identified in the Euclid data will be used to reconstruct the galaxies' merging history through hydrodynamical N-body simulations in collaboration with the Ph.D. thesis co-supervisors.

Outline of the Project:

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

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

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

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PhD project in ASTROPHYSICS

Title of the Project:
A combined optical-HI study of nearby dwarf galaxies in the LCDM hierarchical merging framework

INAF-OAS Supervisor: Francesca Annibali

Co-Supervisors: C. Gruppioni, M. Meneghetti, E. Vanzella

Scientific Case:

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

In order to provide new insights on this problem, we propose a Ph.D. project based on a unique sample of ~50 nearby (D<10 Mpc) dwarf galaxies for which a highly valuable dataset in optical and HI is available: i) Proprietary deep, wide-field **Large Binocular Telescope** (LBT) **imaging** from the "SSH" Strategic Program (45 hrs, PI Annibali); ii) Proprietary **Hubble Space Telescope data** for a subsample of the SSH dwarfs with merging signatures (38 orbits, PI Annibali); iii) Both proprietary (PI Cannon) and archival **HI data** from different facilities (Very Large Array, Giant Metrewave Radio Telescope, Westerbork Synthesis Radio Telescope).

While the deep, wide-field LBT data and HI data will permit to unveil signatures of accretion or merging events around the dwarfs (e.g. through peculiar gas/stellar features or streams, and/or morphological/kinematical distortions), the superb depth and spatial resolution of HST will allow to infer the galaxies' star formation history (SFH) through modeling of their resolved-star color magnitude diagrams. In the end, the galaxies' optical and HI morphologies, the stellar and gas masses, the HI kinematics, and the spatially-resolved SFH will provide all the ingredients necessary to run tailored hydrodynamical N-body simulations of gas-rich merging dwarfs.
This project will pave the way for future, deeper studies of more distant merging dwarfs with JWST, ELT and SKA. In particular, while JWST will permit to resolve individual stars at much fainter magnitudes than HST, thus reaching larger distances for SFH studies, the extreme resolving power of MORFEO/MICADO@ELT will permit to study individual stars in the most central and crowded galaxy regions well beyond 20 Mpc, an achievement out of reach of HST and JWST.

During the Ph.D project, it is expected that the candidate will apply for new observations of dwarf galaxies with JWST and with existing AO instrumentation, such as SOUL-LUCI@LBT or

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

Outline of the Project:

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

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

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

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PhD project in ASTROPHYSICS

Title of the Project: The variable and multi-messenger sky with the CTA Observatory

INAF-OAS Supervisor: Andrea Bulgarelli (INAF/OAS Bologna)

Co-Supervisors:
Nicolò Parmiggiani (INAF/OAS Bologna)
Valentina Fioretti (INAF/OAS Bologna)

Scientific Case:

The Cherenkov Telescope Array Observatory (CTAO), will be the major observatory for very high-energy gamma-ray astronomy over the next decade and beyond. The scientific potential of CTA is extremely broad, exploring the extreme universe, from the origin and role of relativistic cosmic particles to the frontier of physics (dark matter, quantum gravity), to the study of extreme environments and, connected with them, the transient phenomena. A wider field of view and improved sensitivity make CTA a powerful instrument for time-domain astrophysics.
The CTA Observatory will be capable of issuing alerts on variable and transient astrophysical sources. In addition, it will closely interact with complementary astrophysical facilities, accepting triggers from them, enabling multi-wavelength and multi-messenger approaches that will lead to a deeper understanding of the broad-band non-thermal properties of target sources.
To capture these phenomena during their evolution speed is crucial and can be achieved using the Science Alert Generation, a software system for automated and fast identification of flaring events during the CTA observations.
INAF is deeply involved in the development of CTAO, with the responsibility of developing this Science Alert Generation system. In addition, INAF/OAS researchers are participating in different CTA scientific working groups, from extra-Galactic surveys to transients, and have substantial experience in gamma-ray time domain astronomy (AGILE, Fermi, INTEGRAL), in the definition of strategies and systems for fast reaction to transients in the multi-messenger and multi-wavelength context. OAS researchers are also part of the LST1 collaboration, the first large telescope of CTA that is performing observations at La Palma, Canary Islands.

The candidate will work to set strategies for CTA reaction to external transients (i.e. gravitational waves, neutrinos, GRB, gamma-ray binaries, Radio-Loud AGN, etc.); in particular, the purpose is to consider the potential variable sources that CTA may detect, how to identify them with the CTA Science Alert Generation system, and how to select science alerts for the follow-up strategies based on scientific ranking and observatory constraints.

The candidate could also contribute to setting up strategies to discover new sources serendipitously, defining key strategies and defining tools for their identification with the CTA Science Alert Generation system.

The scientific topic will be defined based on the candidate's interest.

The successful candidate will learn high-energy data analysis techniques and use the state-of-the-art gamma-ray analysis tools of CTA and LST1. Based on the availability of the candidate and related scientific collaborations, data analysis techniques and tools of AGILE, Fermi and INTEGRAL could also be used.

The candidate will also gain experience in transient follow-up using the data of the current gamma-ray projects, in particular

1. the candidate will participate in the observing program of LST1 at La Palma, performing one or more nightly shifts of one month each at the telescope site (not mandatory).
2. there is also the possibility of participating in the burst advocate team of the AGILE satellite for the follow-up of gravitational waves for the Ligo/Virgo/Kagra O4 campaign.

Based on the candidate's interests, applying machine-learning techniques to define observational strategies could be an additional benefit.

YEAR 1:

- Selection of scientific use cases
- Study of gamma-ray data analysis techniques and tools
- Participation in the AGILE burst advocate team

YEAR 2:

- Identification of follow-up strategies with the Science Alert Generation System
- Selection of a scientific case with LST1 data and publication of a scientific paper
- Experience as a shifter at La Palma site for LST1 telescope

YEAR 3:

- Test of follow-up strategies with simulated CTAO data and real LST1 data

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PhD project in ASTROPHYSICS

Title of the Project:

The formation of the first globular clusters in cosmological simulations

INAF-OAS Supervisor: Francesco Calura

Scientific Case:

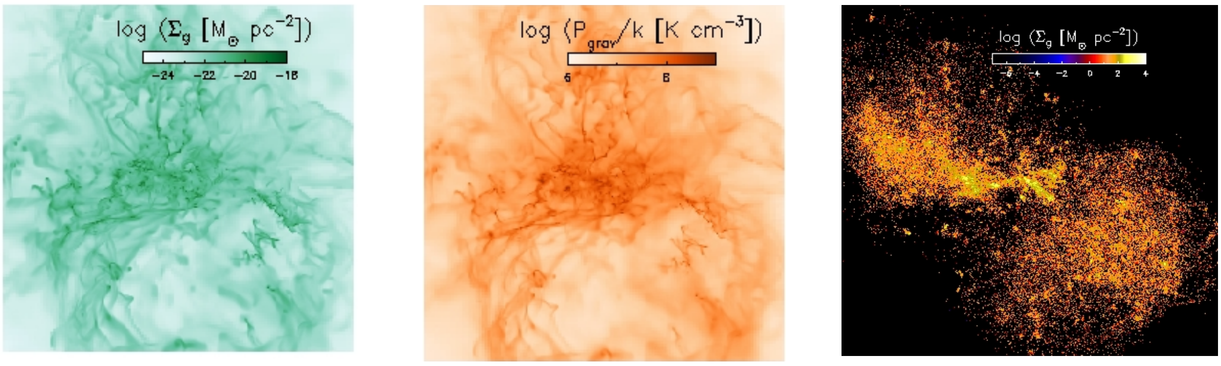
The SImulating the Environments where Globular Clusters Emerged (SIEGE) project (Calura et al. 2022) is a theoretical framework to study the origin of globular clusters in a cosmological context. The unique features of the SIEGE simulations are 1) the very high, sub-parsec resolution, necessary to capture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

Outline of the Project:

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

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

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



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

References

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

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PhD project in ASTROPHYSICS

Title of the Project:
Development, integration, testing and exploitation of high energy astrophysics satellite missions

INAF-OAS Supervisor
Riccardo Campana (co-supervisors: Enrico Virgilli, Ezequiel J. Marchesini)

Scientific Case:
High energy astrophysics, Experimental astrophysics, Space science, Instrumentation, Gamma-ray bursts, High energy transients

Outline of the Project:
The INAF/OAS "Laboratorio Gamma" group is playing a major role in many major space-based experiments, proposed or in development, aiming to vastly increase the discovery space of the high energy transient phenomena over the entirety of cosmic history. Currently, the main space projects with our involvement are:

- HERMES (*High Energy Rapid Modular Ensemble of Satellites,* http://www.hermes-sp.eu) that is an ASI-led project developing a constellation of nanosatellites. The first one was launched in December 2023, and other six satellites will be launched early 2025. The project aims to study the Gamma-Ray Bursts (GRBs) and high energy transient events like the electromagnetic counterparts of gravitational waves.
- THESEUS (*Transient High Energy Sky and Early Universe Surveyor*, https://www.isdc.unige.ch/theseus/), an ESA candidate mission (Medium Class, M7 launch slot around 2036) currently in Phase A, to observe and follow-up transient events in the high energy sky.

For the scientific objectives of these missions, a description of their on-board instruments, and the international context in which they operate the reader is invited to visit the related websites.
For all these missions in an active realization phase, and in several other proposed missions and concept studies, INAF/OAS "Laboratorio Gamma" has a main role in conceiving, developing, realizing, and testing the relevant X and gamma-ray instrumentation, thanks also to several years of experience developed for missions currently operating (e.g., INTEGRAL, AGILE) or proposed (e.g., LOFT, eXTP).
The proposed PhD project will take place in this framework, with specific activities that can be tailored on the candidate main interests and capabilities, in one or all of the following areas:

- Space-borne X-gamma instrumentation design, development, and test.
- Satellite assembly, integration, and testing (AIV) activities
- Simulation and optimization activities.
- Scientific data exploitation.

The ideal candidate should have:

1. Flexibility and willingness to learn
2. Willingness to work in large national and international interdisciplinary teams.
3. A reasonable knowledge of high-energy astrophysics main scientific themes and open issues.
4. Knowledge of basic electronics and computer programming is not necessary but useful.

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PhD project in ASTROPHYSICS

Title of the Project: The Large scale Polarization Explorer - Strip: a ground based instrument to investigate the Cosmic Microwave Background..

INAF-OAS Supervisor: Dott. Francesco Cuttaia

Co-Supervisors: Dott. Luca Terenzi (OAS-INAF); Prof. Leonardo Testi (DIFA – Bologna)
Possible external supervisors from other institutions / universities.

Scientific Case:
Strip, together with SWIPE, is one of the two instruments of the LSPE (Large Scale Polarization Explorer) observation program: both measure the microwave polarization of the sky, the first from the ground (from the Izana Observatory – Tenerife, Canary Islands) and the second from a stratospheric balloon. The LSPE project aims to detect the signatures of primordial gravitational waves - the "B-modes" - emitted at the time of the Big Bang in the cosmic microwave background (CMB). Strip consists of an array of 55 coherent polarimeters coupled to a 1.5 m Crossed-Dragone telescope that continuously rotates around its axis: its two scientific channels, centred at 43 GHz and 95 GHz, allow you to exploit the benefits offered by low-noise HEMT (High Electron Mobility Transistors) amplification technology, cooled to 20 K by a two-stage cryostat, to minimize instrumental noise and maximize sensitivity. The intrinsically coherent nature of the receivers, combined with their pseudocorrelation architecture with double phase modulation, allows the direct simultaneous measurement of the Stokes parameters Q and U, minimizing systematic instrumental and environmental effects. The synergy with other instruments already operational, or which will be active in the future, at the Izana Observatory will also allow us to pursue other objectives, including creating a map of polarized light sources (synchrotron, dust) in our galaxy, improving the measurement of optical depth and study anomalies at large angular scales of the CMB; finally characterize the atmospheric emission - in particular, the fluctuations of water vapour - at the Tenerife site.
Strip has been integrated into the INAF-OAS Bologna laboratories and is currently under testing to optimize and characterize its performance. At the end of the year, it will be integrated with the telescope and finally tested and shipped to the Tenerife site, where it will be installed and observed for at least two years.
The student will participate in the instrument characterization and integration phase and technological and scientific commissioning in operations and data reduction at the Izana site. Collaborations with other CMB-oriented experiments like Quijote (Tenerife) and Litebird satellite will be possible and encouraged.
Depending on the individual skills and interests of the student, to be harmonized with the project's needs, this thesis work may be more oriented either towards purely technological aspects of operations, analysis and data interpretation or a combination of them.

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PhD project in ASTROPHYSICS

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

INAF-OAS Supervisor: Stefano Ettori

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

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

Outline of the Project: The candidate will work on recovering, analyzing, and interpreting the physical properties of these systems. During the 1st year, she/he will approach the problematics and technicalities of the X-ray analysis of extended sources; we will define a 6-months project accordingly to the candidate's interest and some other contingencies (data availability, no conflict with other ongoing work), that will be focused on the thermodynamic properties of virialized structures over two decades in mass. By the end of the 1st year, we expect that the candidate will be able to understand the scientific context of the hierarchical structure formation and the different perspectives to tackle it both observationally and through numerical simulations. During the 2nd and 3rd year, the main topic of the project (on e.g. the distribution of dark matter; the "universality" of the radial profiles of the thermodynamic quantities -such as gas temperature, pressure, entropy; see e.g. Ettori+2023; the scaling laws holding between integrated quantities, like total and gas mass, X-ray luminosity, temperature) will be addressed using both observational (both proprietary and archived, multi-bands) data and cosmological hydrodynamical simulations well suited for this analysis (from our collaborators in Bologna -Dr. Vazza- and in *the300* consortium).

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PhD project in ASTROPHYSICS

Title of the Project: *The role of AGN in galaxy transformation*

INAF-OAS Supervisor: Carlotta Gruppioni

Co-Supervisors: Livia Vallini (INAF-OAS), Francesca Pozzi (UniBO-DIFA)

Scientific Case:

One of the main topics in extragalactic astronomy is the exploration of the very early stages of galaxy formation, when the first light arose from the so-called Dark Ages. The present picture tells us that the Universe has experienced a major epoch of intense star formation (SF) activity about 10 Gyrs ago (epoch called “cosmic noon”: $1.5<z<3$), and this turns out to be the best cosmic time to study the SF processes in galaxies, when large gas reservoirs were converted into stars, and a sudden transformation happened in galaxies to quench their SF activity and to give them the shape we observe nowadays. The ubiquity of super massive Black Holes (SMBHs) in the center of galaxies and the large energy release per gram of matter accreted onto the SMBH makes AGN feedback the most promising star formation regulation mechanism. Furthermore, star formation and SMBH growth have similar evolutionary tracks (see, for a review, *Madau & Dickinson 2014* and Figure 1).

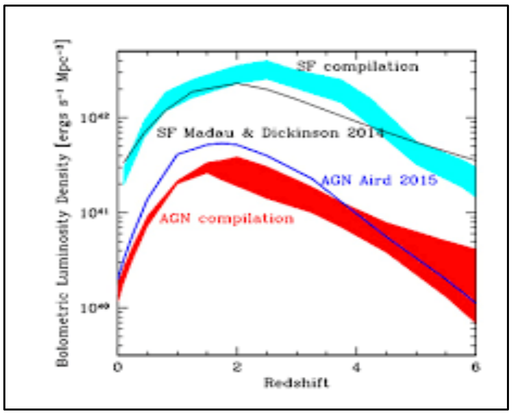

Figure 1. Comparison of growth of galaxies (SFRD, light blue) vs growth of AGN (BHARD, red).

Theory suggests that feedback from growing SMBHs/AGN is able to successfully reproduce the properties of local massive galaxies (see *Silk & Mamon 2012*, for a review) and explain the observed galaxy scaling relations and the quenching of star formation in massive galaxies (e.g., *Silk & Rees 1998*), while, feedback from stars seem to have not enough energy. A key component of models is that the majority of SMBH growth is occurring behind large column densities, $N_H>10^{23}$ cm^{-2}. These obscured sources are difficult to observe, although their contribution to the total number of AGN can be significant. X-ray observations are one of the most reliable methods of selecting AGN and estimating the amount of obscuration, although even some of the deepest X-ray surveys miss a substantial fraction of heavily obscured objects. Obscured AGN can also be identified in the infrared (IR) due to the reprocessing of the obscured UV emission due to dust. The extensive analysis performed on the *Herschel* cosmological surveys provided the evidence that the bulk of galaxies at $1<z<3$ responsible for the SFRD peak indeed host an AGN (i.e., classified **SF-AGN** based on their Spectral Energy Distribution, SED; *Gruppioni, Pozzi et al. 2013*). However, methods of identification based on IR colours are effective mostly for power-law AGN, leaving the obscured population only partially explored. In addition, the high-z obscured and faint AGN population (e.g., $z \gtrsim 2$) is even less explored. Consequently, there is wide disagreement in estimates of the fraction of the AGN obscured population, with our current AGN census being still incomplete. However, a comprehensive census of AGN behavior across a wide range of redshift, luminosity, obscuration level and galaxy properties is necessary to understand the co-evolution of SMBHs and their host systems. This can only be obtained by combining large and deep surveys from the IR to the X-rays. The AGN search with the deepest data from Chandra, Herschel, and Spitzer reached z~3, while the recent results from JWST are pushing the AGN census to fainter luminosities and higher redshifts, identifying obscured and low-luminosity objects up to z~10 (*e.g., Maiolino et al. 2023*).

The main questions we still need to answer, in particular by taking advantage of deep survey data in the infrared (ALMA, Herschel, Spitzer and the recent JWST ones), as well as the deepest X-ray survey to date (i.e., Chandra in the GOODS-S region), are:

1. What shaped the galaxy transformation from the epoch of peak of their star formation (i.e., 10 Gyrs ago) to nowadays?
2. What is the role of AGN in galaxy evolution? Is there a mutual interplay between star-formation and accretion activity?
3. How did the role of AGN in shaping the galaxy properties change from cosmic dawn to cosmic noon and to the local universe?

The main goal of this thesis project is to obtain the most complete census of AGN by collecting all the data available, from Chandra to JWST, in the GOODS-S field, one of the deepest and most extensively studied fields, in order to study the role of AGN in shaping galaxy evolution at all epochs and luminosities.

The PhD project will be structured as follows:

Using all the available information the student will study the main physical properties of the selected AGN (i.e., stellar mass, star formation rate, AGN luminosity, dust obscuration, molecular gas mass), as well as their evolution in the different bands, and their estimated contribution to the X-ray background, interpreting the results within the context of galaxy and AGN formation and (co-)evolution.

First year: During the first months the student will learn how to handle and match large data samples, how to extract physical parameters from data, and will acquire knowledge of the statistical tools needed to study the main source distributions, such as source counts, luminosity functions, redshift distributions. Then, starting from the deepest Chandra catalogue and the new AGN classification by Lambrides et al. (2020), which was able to identify a larger fraction of low-luminosity/obscured AGN based on a multiwavelength analysis, the student will derive the X-ray luminosity function of star forming galaxies and AGN up to cosmic noon and derive the contribution of both populations to the X-ray background.

Second Year: For the Chandra X-ray AGN sample and for that selected by Herschel in the far-IR, the student will collect all the new data, in particular from the ALMA and JWST archive, to study their molecular gas, depletion time, stellar mass, star formation rate, dust mass and morphology. Since the AGN cover a wide range of redshifts and lumniosities, it will be possible to study the evolution of their main properties, to be compared to those of non-AGN galaxies from the literature (or from parent samples).

Third Year: As further analysis, the student will investigate the effects of the AGN on gas and dust within the host galay by studying in detail the morphology and kinematics of dust and gas (both watm and cold) in those previously studied AGN for which ALMA and JWST IFU spectroscopic data are available. This study, crucial for investigating the physical conditions and dynamics in the galaxies responsible for the rise and fall of the SFR and BHAR across the Universe, will be enabled by the combination of Herschel far-IR data matched with optical/mid-IR spectroscopic and ALMA continuum and molecular line data, allowing us to quantify the effects of AGN and SF on the dust and gas within galaxies. ALMA traces the cold ISM component, Herschel traces the cold dust, while the warm dust component, the PAHs and the warm molecular gas rotational emission (H_2 tracing dense enviroments and excited by shocks and X-ray photons) are traced by JWST/MIRI.

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PhD project in ASTROPHYSICS

Title of the Project: *POLARISED CMB ANISOTROPIES: THE SEARCH FOR NEW PHYSICS*

INAF-OAS Supervisor: ALESSANDRO GRUPPUSO

Scientific Case:

The cosmic birefringence effect is the “in-vacuo” rotation of the linear polarisation plane of photons during propagation. In the standard model, such a rotation is null while it is different from zero in parity-violating extensions of the standard electromagnetism. Interestingly, starting from 2020, a series of papers, which exploited the latest Cosmic Microwave Background (CMB) Planck data, made claims of detection of a cosmic birefringence angle of ~0.3 deg at about 3 sigma C.L.. If confirmed in its physical origin, this observation would trace the existence of a yet unknown medium, playing the role of dark matter or dark energy, where the CMB photons propagate through.

The aim of this thesis is to investigate the cosmic birefringence effect, developing/studying theoretical models, building analytic estimators and/or data analysis pipeline to provide constraints on this effect considering available data or realistic simulations to forecast capabilities of future experiments. Other effects impacting on CMB polarisation might also be taken into account.

If desired, the student can be involved in the LiteBIRD collaboration. LiteBIRD is a satellite for CMB observations funded by JAXA, the Japanese space agency, whose launch is expected in 2030. The target of Litebird is to measure the primordial gravitational waves through the specific signature they leave on the polarised pattern of CMB anisotropies. Depending on funds availability, a period of research in Japan might be organised.

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PhD project in ASTROPHYSICS

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

INAF-OAS Supervisor: Davide Massari

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

Scientific Case:

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

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

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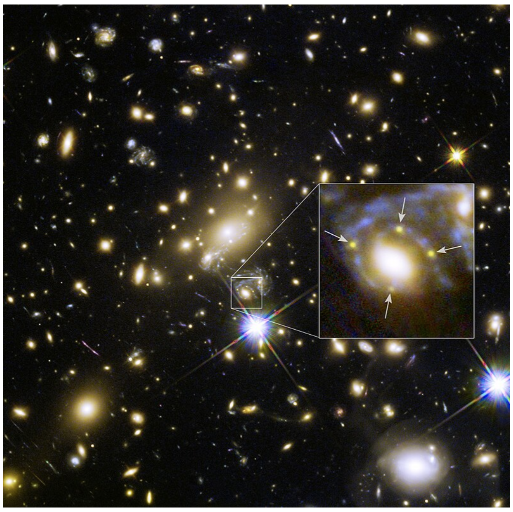
PhD project in ASTROPHYSICS

Title of the Project: *Strong Lensing Cosmography with galaxy clusters in the Euclid surveys*

INAF-OAS Supervisor: M. Meneghetti

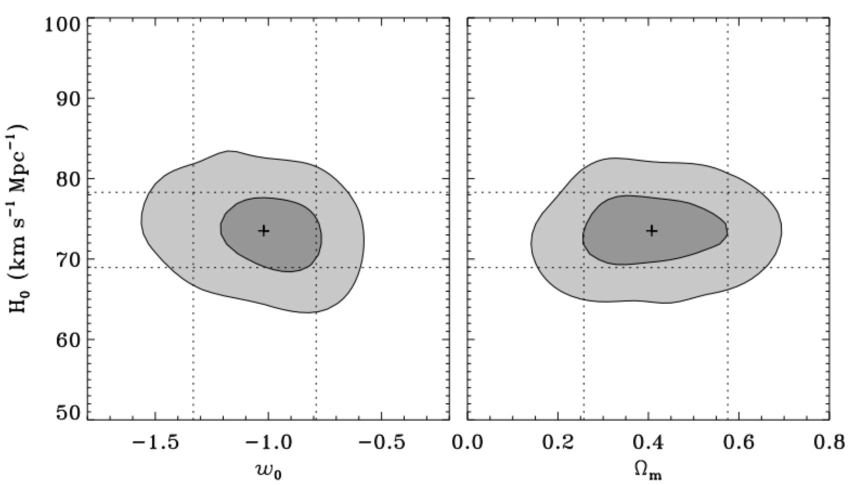
Co-Supervisors: L. Moscardini (UniBO), P. Rosati (UniFE), C. Grillo (UniMI), M. Lombardi (UniMI), C. Giocoli (INAF-OAS)



Scientific Case: The Euclid Mission is poised to revolutionize our understanding of the universe by discovering over 10,000 galaxy clusters through imaging more than 13,000 square degrees of the sky. The exceptional spatial resolution of Euclid, coupled with its notable depth (24.5 AB magnitude in the I_E band at a signal-to-noise ratio of 10 in the wide survey), will facilitate the identification of several thousand strong lensing features within these clusters, including gravitational arcs and multiple images of sources at varying redshifts. Among these lensed sources, we expect to detect numerous QSOs and supernovae (see the HST observation of galaxy cluster MACSJ1149 on the right for a famous example of a strongly lensed supernova — the SN “Refsdal”, Kelly et al. 2014). From 2025, the Legacy Survey of Space and Time (LSST) at the Vera C. Rubin Observatory will supplement these observations with multiband data from the ground in the southern sky. The LSST's observational strategy includes taking pairs of 15-second exposures, or "visits," to survey the entire accessible sky every few nights, aiming for approximately 1,000 observations of the southern sky over a decade, averaging about two visits per week for each sky patch. This will enable monitoring inherently variable sources like QSOs and supernovae by measuring their light curves. For multiply imaged sources, analyzing the light curves of each image can provide measurements of the time delays caused by gravitational lensing. Such measurements, together with observations of image positions and distortions, will allow us to constrain the cluster gravitational potentials and their first and second spatial derivatives. A Memorandum of Understanding is set to be signed between Euclid and the Rubin consortia to facilitate data sharing for these analyses. In parallel to constraining the cluster mass distributions, in clusters where multiple images and time delays are measured, we will employ the strong lensing cosmography method to constrain cosmological parameters. This method utilizes the relative displacement of multiple images from pairs of sources at different redshifts to measure their “distance ratios”. This measurement is sensitive to cosmological parameters like the matter density parameter (Ω_m) and the dark energy equation of state (w), with time delays further sensitive to the Hubble parameter (H_0) (see e.g. Sect. 3.6 from Moresco et al. 2022). Consequently, the synergy between Euclid and Rubin will constrain these cosmological parameters, complementing the results from Euclid's primary probes, such as weak cosmological lensing and galaxy clustering.

Outline of the project

In this Ph.D. project, the candidate will explore the application of strong lensing cosmography for determining cosmological parameters using observations from the Euclid and Rubin surveys. The project is divided into theoretical and observational components. The theoretical segment involves utilizing cosmological hydrodynamical simulations of galaxy clusters from the 300 project (Cui et al., 2018) to pinpoint the most effective mass distributions and image configurations for cosmological parameter estimation. This theoretical investigation will help identify the most suitable galaxy clusters for conducting strong lensing cosmography within the Euclid survey. Moreover, it will assess the number of cluster lenses required to achieve desired levels of precision and accuracy in cosmological parameter measurement. Thus, the first part of the project will consist of simulating Euclid observations, modelling mock data, and performing statistical inference.
In the second part of the project, the candidate will apply findings from the theoretical analysis to select a group of cluster lenses in the Euclid dataset for strong lensing cosmography studies. The project will integrate Euclid imaging with time delay data from Rubin (or other available observations) for multiple imaged QSOs and supernovae. A critical aspect of the strong lensing cosmography analysis will be the simultaneous determination of cosmological parameters and lens mass distribution (see figure below, which shows the cosmological constraints derived from the analysis of the SN “Refsdal” in cluster MACSJ1149, Grillo et al. 2020). To accomplish this, the candidate will employ a cutting-edge parametric mass modeling tool, Gravity.jl (Lombardi et al., in preparation). This code, written in Julia programming language introduces several novelties compared to other modelling codes in the literature, including several lensing models and sources, multi-plane lensing, arbitrary scaling relations for the cluster members, high-parallel and distributed computing.



By undertaking this project, the candidate will have the opportunity to join a prominent collaboration like the Euclid Consortium (EC). Their project will contribute to a key project proposed by the Strong Lensing Science Working Group within the EC. As a member of the EC, the candidate will be able to engage with leading experts in strong gravitational lensing and gain expertise in analyzing extensive simulated and observational datasets.

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PhD project in ASTROPHYSICS

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

INAF-OAS Supervisor: Tatiana Muraveva

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

Scientific Case:

Astronomy is entering a new era of Big Data science thanks to exponentially growing data volumes from large surveys, such as *Gaia,* Transient Exoplanet Survey Satellite (TESS) and the Legacy Survey of Space and Time (LSST) at the Vera Rubin Observatory (VRO). The *Gaia* Data Release 3, published on 13 June 2022, contains astrometry and broad-band photometry for about 1.8 billion sources in the Milky Way (MW) and beyond, along with information on large sets of variable stars, galaxies, astrophysical parameters, radial velocities, epoch photometry and spectra. TESS is an all-sky photometric survey providing exquisite high-cadence high-precision light curves for hundreds of thousands of bright stars. While TESS' primary aim is the detection of exoplanetary transits, it has proven to be a goldmine for studies of stellar variability. These datasets will be complemented by a 500-petabyte set of images and data products from the LSST@VRO. The extraordinary volume of these data poses novel challenges, since data volumes at these scales have never been encountered by the scientific community before. Thus, the application of advanced Machine Learning (ML) and Deep Learning (DL) techniques, which can provide the level of accuracy and automation required to exploit large datasets efficiently, becomes highly needed and timely.

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

The PhD candidate is expected to contribute to the research projects proposed for Centro Nazionale High-Performance Computing (HPC) and Big Data. With support from the Marco Polo fellowship program, he/she will spend periods abroad at Dipartimento de Inteligencia Artificial, UNED, in Madrid and/or at the *Gaia* DPAC data processing centre of the Geneva Observatory. Expertise and capacity acquired by the PhD candidate in the application of the ML and DL algorithms can be easily adopted in the world of industry, thus, opening for the successful candidate more opportunities in his/her future career.

Outline of the Project:

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

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PhD project in ASTROPHYSICS

Title of the Project: *Optimal exploitation with Machine Learning of the first Euclid data for characterizing galaxy & AGN evolution*

INAF-OAS Supervisor: L.Pozzetti, M. Bolzonella
Co-Supervisors: **INAF-OAS:** L. Pozzetti, M. Bolzonella, E. Zucca, O. Cucciati; **UniBO:** M. Talia, A. Enia; EC Collaboration and ELSA team members.

Scientific Case:
Euclid is an ESA space telescope launched in July 2023, designed to understand the nature of dark energy and dark matter, and will survey over a third of the sky with high-resolution imaging and spectroscopy. Euclid will provide a data archive increasingly large and rich in information, perfect for studying the history of the formation and growth of galaxies over the age of the Universe. The planned surveys (Euclid Wide Survey and Euclid Deep Fields) have just started in February 2024 and the first Quick and Data Release (Q1 and DR1) will already cover up to 50 and 2500 square degrees. Traditional approaches are no longer sufficient for the optimal exploitation of this huge amount of data, and it urges the researcher to implement new techniques based on Machine and Deep Learning (ML).
The goals of the PhD project will be to explore advanced techniques and in particular ML methods within one or more of these scientific contexts:
1- ***Explore different techniques to recover galaxy and AGN physical properties and their uncertainties from photometric and/or spectroscopic data.*** Traditional approaches, like SED fitting, are well established to derive physical properties of galaxies (stellar mass, SFR, age, dust, metallicity). The goals of the project will include developing advanced techniques and ML: - to improve and speed up the computation of physical properties; - to classify different types of galaxies, e.g. passive vs star-forming; - to select similar objects and derive their average physical properties from composite SEDs and spectra beyond the observational limits for single objects; - to explore the potentiality of super-resolution techniques in correctly recovering the fluxes of objects in multiwavelength observations of the same field, to extend the frequency domain of the feature space and improve the derived physical properties; - to discover and study rare or yet unseen objects, thanks to the unprecedented datasets that will be available in Euclid; - to study a method to use also spectra and spectral information (emission lines) in addition to photometry to recover galaxy physical properties and AGN fraction; - to assess the impact of physical properties errors on derived scaling relation (SFR-Mass, Mass-metallicity, etc…).
2- ***Explore different techniques to derive the distribution functions, such as luminosity, stellar and star-formation functions.*** The project includes: - the use of advanced tools to derive from Euclid photometric data the galaxy and AGN's physical properties, along with their errors and probability posterior; - to explore various techniques (Self-Organizing Maps, SOM, or ML) for the selection of potentially interesting subsamples

of galaxies; - to derive galaxy and AGN distribution functions and their redshift evolution, using classical methods and machine learning, in particular, to explore methods to assess the impact of physical properties errors; - to make the new tools available to the wider community through their implementation into the ESA datalabs; - to compare the results to state-of-the-art semi-analytic models (e.g. GAEA), in order to put them into the broader context of galaxy evolution;

The PhD candidate will be involved in the Euclid Collaboration and in the Euclid Legacy Science Advanced Analysis Tools (ELSA), a HORIZON-EU funded project (PI: M. Talia). The PhD candidate will make use of the acquired expertise to optimally exploit the first Euclid data.

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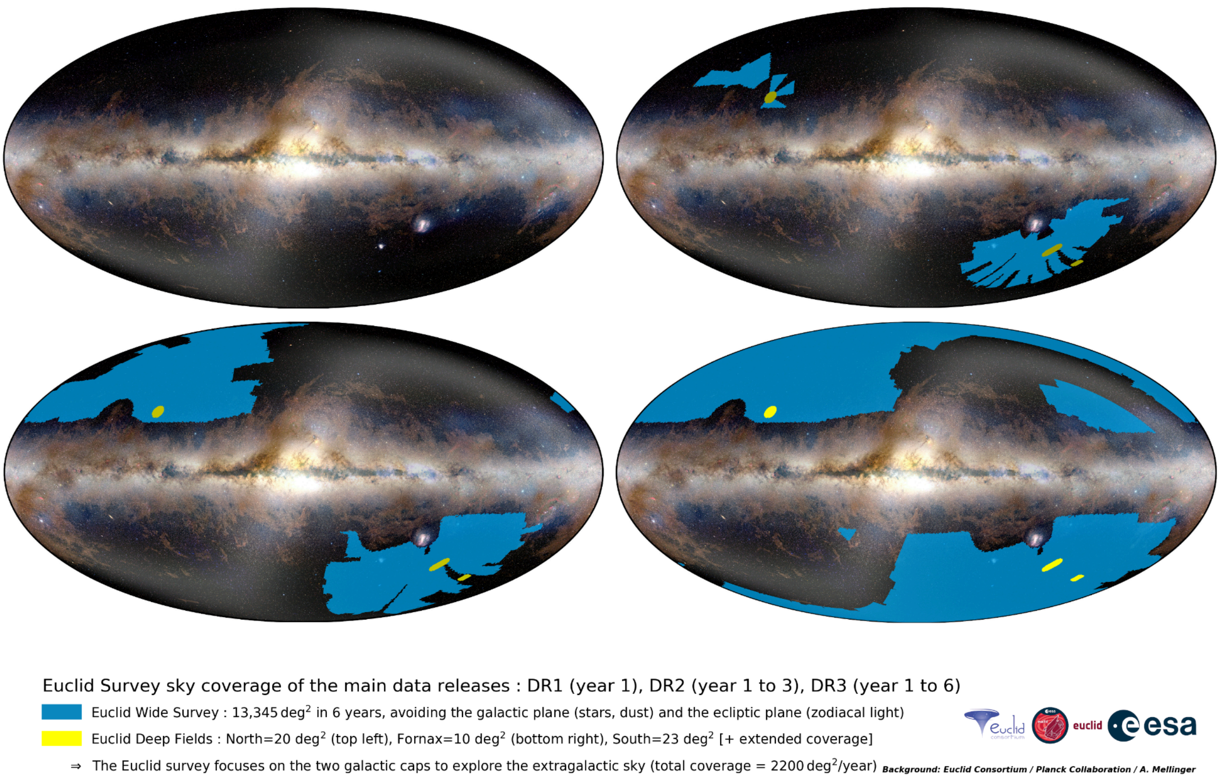


INAF ISTITUTO NAZIONALE DI ASTROFISICA

OSSERVATORIO DI ASTROFISICA E SCIENZA DELLO SPAZIO DI BOLOGNA

OAS BOLOGNA

PhD project in ASTROPHYSICS

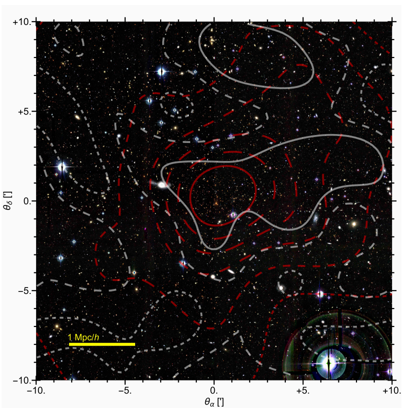
Title of the Project: Gravitational lensing detection of matter distribution at galaxy cluster boundaries and beyond

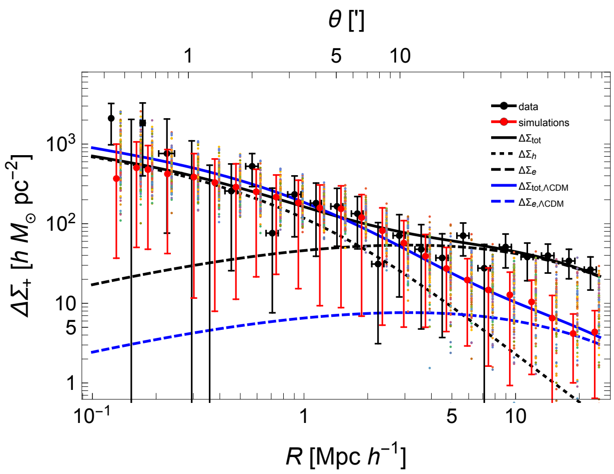
INAF-OAS Supervisor: Mauro Sereno

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

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

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





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Outline of the Project:

YEAR 1: setting of the theoretical modelling, development and update of the pre-existing pipeline, testing with Stage III surveys (KiDS, HSC-SSP, DES) and Euclid PV/ERO data. At least one expected paper submitted on Stage III surveys.
YEAR 2: finalisation of the theoretical modelling and of the pipeline, application to first Euclid data release and forecasting study for LSST. At least one paper on LSST forecast.
YEAR 3: analysis of the Euclid results, release of a public version of the code, finalisation of the thesis. At least one paper on the Euclid data.

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PhD project in ASTROPHYSICS

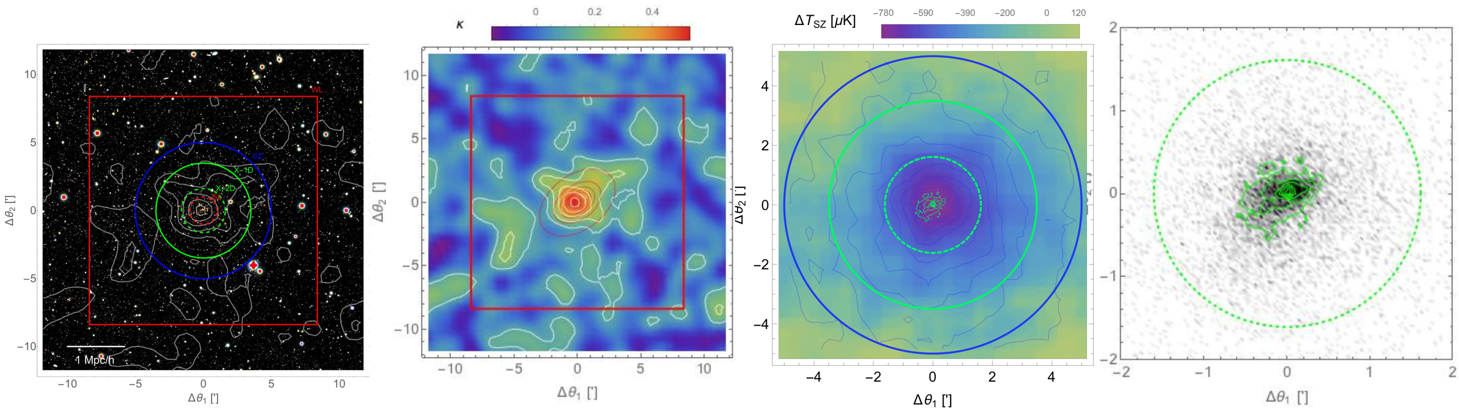
Title of the Project: CLUMP-3D: CLUster Multi-Probes in Three Dimensions of galaxy clusters in the era of multi-wavelength large surveys

INAF-OAS Supervisor: Mauro Sereno

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

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

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



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Outline of the Project:

YEAR 1: definition of a large sample of clusters with multi-wavelength data from available surveys. Development and update of the pre-existing pyhton CLUMP-3D pipeline to clusters with shallow or missing data. At least one paper
YEAR 2: Analysis of the year 1 sample to constrain clusters shape and thermal status. At least one paper.
YEAR 3: Application to Euclid data (at leat one paper).

PhD project in ASTROPHYSICS

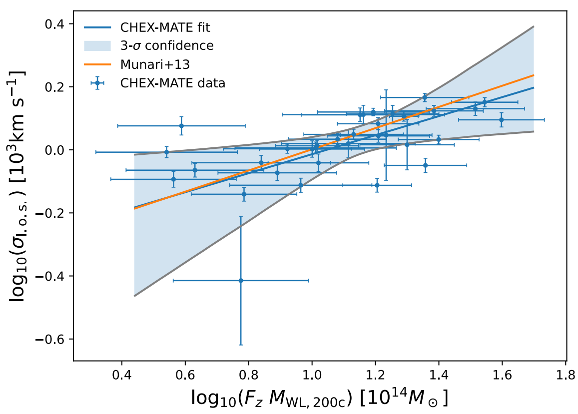
Title of the Project: Dynamics and kinematics of the CHEX-MATE galaxy clusters

INAF-OAS Supervisor: Mauro Sereno

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

Scientific Case: Clusters of galaxies are the nodes of the cosmic web, constantly growing through accretion of matter along filaments or mergers. They are excellent laboratories to study the physics of the gravitational collapse, and the non-gravitational physics that affects their baryonic components. Growth and evolution depend on the underlying cosmology, and clusters are powerful cosmological probes. Many questions are still to be answered: *How does the formation process inform the equilibrium state of clusters? What are the statistical properties of the cluster population? What is the cluster mass scale?* CHEX-MATE is an XMM-Heritage project to study a large, signal-to-noise limited sample of 118 clusters drawn from the Planck PSZ2 catalog [2021A%26A...650A.104C]. Combining primarily spectroscopic data (including proprietary data from FORS2@ESO and WEAVE - Cosmological Clusters Survey) with multi-wavelength observations available to the project, the student will lead studies to impact our knowledge on (i) the dynamical collapse of baryons and dark matter on different scales (ii) the degree of equilibrium of dark-matter, hot baryons (diffuse gas), and cold baryons (galaxies); (iii) the balance between gravitational and non-gravitational processes in shaping cluster properties. The student will also join the Euclid international collaboration to explore the potential of the spectroscopic sample for studies of dynamics and kinematics of galaxy clusters.

*Fig***.** The preliminary comparison of galaxy velocity dispersion vs weak lensing mass for the CHEX-MATE sample supports the self-similar scenario for clusters formation and evolution.



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Outline of the Project:

YEAR 1: data reduction and analysis of proprietary and archival data of the CHE-MATE sample. At least one paper. Feasibility studies for Euclid data.
YEAR 2: The candidate will measure the thermalisation of galaxy clusters to unprecedented accuracy with the analysis of the scaling relation between kinetic energy and potential energy in the CHEX-MATE sample (at least 1 paper).
YEAR 3: Dynamical investigations, e.g. based on the Jeans analysis or the caustic technique, will be performed on the CHEX-MATE sample to provide detailed mass profiles, substructure detections, orbit and anisotropy analyses. At leas one paper. Dynamical study of the Euclid clusters (1 paper).

PhD project in ASTROPHYSICS

Title of the Project: *Unlocking the First Galaxies: a study of the interstellar medium, AGN feedback, and star formation in the Epoch of Reionization*

INAF-OAS Supervisor: Dr. Livia Vallini

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

Scientific Case: *How do galaxies, with and without an Active Galactic Nucleus (AGN), formed stars during the Epoch of Reionization (EoR, 6<z<30)? Was the Kennicutt-Schmidt law, connecting the star formation rate to the gas surface density, already established in the EoR?* Answering these questions is essential for shedding light on the evolution of the Universe's last fundamental phase transition: *the Reionization process.*

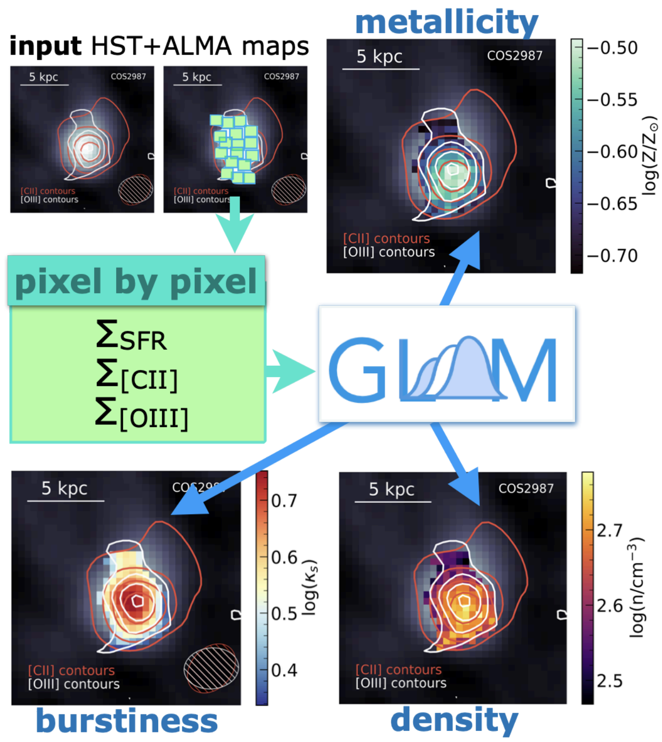
Recent observations indicate notable differences in the interstellar medium (ISM) of EoR galaxies compared to local ones. EoR sources were dense and compact (Tacchella+2023), they were turbulent due to frequent mergers, yet showed signs of already ordered disk-like structures. ALMA's findings of unexpectedly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

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

Outline of the project:
The goal of this PhD project is to **develop self-consistent *models* to characterize the law governing star formation in EoR sources, by leveraging the imprint of star formation and AGN feedback on line emission from different gas phases.** To achieve this goal the work will be structured as follows:

1) Implementation of AGN Effect on Line Emission in the FIR and Optical/UV: This task will be accomplished by developing tailored and self-consistent Cloudy models that account for the ionized, neutral, and molecular gas phases in the ISM of galaxies. The student will utilize all available observational data regarding the SED shape (both stellar and AGN) in typical EoR sources. The PhD student will study the evolution line emission ratios, equivalent widths, the impact of metallicity, gas density profiles, and turbulence, and finally achieve a self-consistent framework for interpreting line emission from EoR sources.

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



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

To summarize, during the project the PhD student will learn how to model line emission from different gas phases in galaxies and AGN, and how to interpret ALMA and JWST data in the highest redshift galaxies so far discovered. Moreover, he/she will build up fundamental skills in **data processing** and **data analysis** by using his/her model for post-processing cosmological zoom-in simulations producing mock emission maps. Finally, he/she will learn how to write observational proposals for getting all the proprietary data needed to tailor the models. During the PhD programme she/he will acquire the independence needed to successfully continue her/his career at international level.

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PhD project in ASTROPHYSICS

Title of the Project: The SOLARIS observatory: a smart Solar imaging system at high radio frequency for continuous Solar monitoring and Space Weather applications

INAF-OAS Supervisor: Fabrizio Villa (INAF-OAS)

Co-Supervisors: Leonardo Testi (UNIBO), Francesco Cuttaia (INAF-OAS). Sara Ricciardi (INAF-OAS)

Scientific Case: Solaris is a scientific and technological project to develop a smart Solar monitoring system based on single-dish imaging techniques at microwave frequencies. It combines implementing a dedicated and interchangeable 100 GHz receiver on existing small radio telescope systems (1.5/2.6m class) available in Milano, at Testa Grigia Valle d'Aosta (MITO) and Antarctica (OASI). The Solaris Observatory offers unique observing conditions and unprecedented Solar monitoring in the radio W-band. This will be achieved through state-of-the-art single-dish imaging techniques at radio frequencies that allow the mapping of the entire solar disk in less than 30 minutes with a spatial resolution of a few arcminutes. This opens for the identification and spectral analysis of Active Regions before, after and during the occurrence of Solar flares. These system features will allow Solaris to explore cutting-edge aspects of Solar Physics (e.g. chromosphere dynamic monitoring) and Space Weather applications (e.g. flare forecast).
Solaris can perform continuous Solar imaging observations for nearly 20h/day during Antarctic summer, exploiting the observation facility OASI in East Antarctica at Mario Zucchelli Station. The Solaris observatory will be the only Solar facility offering continuous monitoring at 100 GHz, and it will be able to collect and disseminate data in synergy with the existing national and international network of Space Weather facilities.

INAF-OAS is responsible for system engineering for Solaris and developing a 100 GHz receiver based on the existing prototype. The receiver will be optimized for solar observation through simulations and laboratory measurements from a radiometric (noise/gain/linearity) and an optical point of view (beam pattern). This PhD project aims to develop and build an optimized receiver for solar observations to follow the project from a system engineering point of view and ultimately install the receiver at Testa Grigia, Milano and Antarctica to conduct solar observations. Moreover, observations at the Medicina Radio Telescope and Sardinia Radio Telescope may be possible, as well as participation in the outreach activities within the Solaris collaboration.
Solaris has been approved as a permanent observatory in Antarctica by the PNRA (Progetto Nazionale Ricerche in Antardite). It is supported as a project by the Space Weather group at INAF. The work will be carried out within the 'Laboratorio di Tecnologie Astrofisiche' agreement between DIFA and INAF-OAS.
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Osservatorio di Astrofisica e Scienza dello Spazio
OAS – Bologna

PhD project in ASTROPHYSICS

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

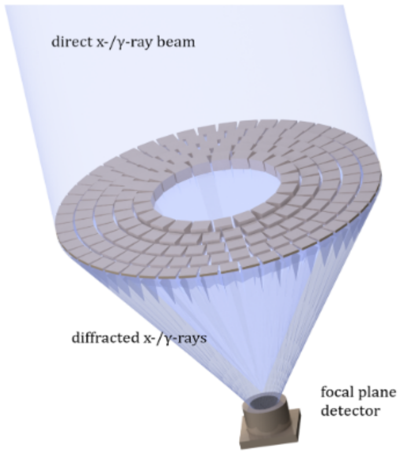
INAF-OAS Supervisor
Enrico Virgilli

Scientific Case:
Experimental astrophysics, High energy astrophysics, detection and study of high energy astrophysics transient, hard x-ray spectro-polarimetry

Outline of the Project:

Introduction: One of the activities of the high-energy group at INAF OAS is the design and development of technologies for both **hard X-/gamma-ray focusing optics** and **solid-state detectors as focal plane spectrometers and polarimeters** for space missions.

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



Focal plane detectors: our group is also engaged in the detection of these focused photons using appropriate devices. The ideal detector is a high Z sensor with significant stopping power for such energetic photons. Solid-state detectors, including CZT or CdTe detectors segmented into millimetric pixels, represent the ideal system to be coupled with Laue concentrators. Germanium detectors are also under investigation for this application, despite the drawback of requiring a cooling system to operate in space. Independently of the detector's nature, enabling hard x spectro-polarimetry is of primary interest.

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

Preferred Candidate's qualities:
– Ability to work in an experimental laboratory environment and in an international context;
– Initiative and problem-solving skills;
– Basic knowledge of space technologies used in space and main astrophysical open questions;
– Basic computer programming knowledge and familiarity with CAD software will be viewed as advantageous qualities for the PhD candidate;

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PhD project in ASTROPHYSICS

Title of the Project: The large-scale environment of $z > 6$ QSOs

INAF-OAS Supervisor: Fabio Vito

Scientific Case: In the last decades, hundreds of luminous quasars (QSOs) powered by supermassive black holes (SMBHs) with masses up to $10^{10}\,M_{\odot}$ have been discovered at $z > 6$, but theoretical models struggle to explain their existence. One of the few predictions common to nearly all such models is that the formation of the BH seeds and the efficient SMBH accretion are highly favoured in the peaks of the dark-matter distribution, characterized by large gas reservoirs, high-rates of galaxy interactions, and galaxy densities in excess to the average field. A direct and testable prediction is that $z > 6$ QSOs should be surrounded by galaxy overdensities on scales up to 10 Mpc, with a radial profile likely dependent on the feedback produced by the central QSO itself.

Outline of the project: the student will reduce and analyze deep optical/IR photometric observations of a sample of $z > 6$ QSOs that are being obtained as part of a Large Binocular Telescope (LBT) INAF Strategic Program for the purposes of this project, and select galaxy candidates at the same redshift of the QSOs. Then, the student will study the enhancement of galaxies in the QSO fields as a function of several parameters, like QSO luminosity, radio loudness, SMBH mass, and distance from the central QSO. The results will be compared with predictions from theoretical models and numerical simulations of SMBH formation and growth. The student will complement the optical/IR data with other existing multi-band datasets from, e.g., JWST and XMM-Newton to study the multiwavelength properties of the discovered galaxies. As part of the project, optical/IR/mm spectroscopic follow-up observations will be proposed to confirm the redshift of the high-z galaxy candidates.

The project will obtain the first statistically solid view of the typical environment and feedback effects of high-redshift QSOs, as well as possible dependences on BH mass or radio loudness, thus providing tight constraints to models and numerical simulations of SMBH formation and growth in the early Universe. The student will acquire precious technical and scientific skills in an astrophysical field in which the international community is highly active, and which is being revolutionized by cutting-edge facilities such as JWST and ALMA.

Main local collaborators:
Roberto Gilli (OAS), Marco Mignoli (OAS)

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PhD project in ASTROPHYSICS

Title of the Project: The AGN population in high-redshift protoclusters

INAF-OAS Supervisor: Fabio Vito

Scientific Case: Environment is a major driver of galaxy and supermassive black-hole (SMBH) evolution across cosmic time. In the densest large-scale regions of the high-redshift (z>2) universe, i.e., galaxy protoclusters, the availability of massive gas reservoirs and the high rate of galaxy mergers are thought to promote SMBH growth. As a result, powerful active galactic nuclei (AGN) feedback may be produced, affecting the entire galaxy structure, as inferred from galaxy clusters in the local Universe. However, this scenario has been tested beyond the low-redshift universe with only a few structures

Outline of the Project: the project aims to constrain the physical link between protocluster environment and fast SMBH growth by 1) measuring the AGN fraction in high-redshift protoclusters and comparing the results with the field environment, 2) constraining possible evolution with redshift and trends with the structure masses, and 3) studying in details the physical properties of AGN of particular interest (e.g., highly luminous and heavily obscured). The PhD student will analyze proprietary ALMA and Chandra datasets that our team has recently obtained on z~4 protoclusters to identify AGN among the structure galaxies, study the physical properties of their host galaxies (e.g., gas mass and kinematics), and investigate possible evidence for AGN feedback in the structures(e.g., outflows). The student will also use public observations of z>2 protoclusters with major astronomical observatories (e.g., JWST, Chandra, ALMA, VLT-MUSE) to constrain the dependence of the AGN population with protocluster properties and with redshift .

The study of high-redshift protoclusters is a fast growing astrophysical field which will also benefit from future facilities such as Euclid and Vera Rubin Observatory. The PhD student will acquire significant expertise in the formation and properties of protoclusters, as well as in AGN physics and demographics. The candidate will also be trained in the reduction and analysis of multiwavelength observational data obtained with major observatories. The project will benefit from the expertise of a wide network of collaborators at INAF-OAS (e.g., R. Gilli, M. Mignoli) and other Italian and international institutes.

Main local collaborators: Roberto Gilli (OAS), Cristian Vignali (DIFA)

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PhD project in ASTROPHYSICS

Title of the Project: Hunting down high-redshift low-luminosity AGN in the deepest X-ray survey

INAF-OAS Supervisor: Fabio Vito

Scientific Case: The physical mechanisms driving the formation and fast growth of supermassive black holes (SMBHs) in the early Universe represent one of the most pressing unsolved mysteries in modern astrophysics. Large efforts have been put in theoretical works and numerical simulations to address such an issue, but the required observational constraints are largely lacking. One of the very few observational tests for theoretical models of SMBH formation consists in the measurement of the space density of low-luminosity AGN at high redshift ($z > 3$), which shape and normalisation depend on the physical parameters driving the formation of the first SMBH seeds.

Outline of the Project: The proposed project will exploit optical (VLT/FORS-2, ~80h) and sub-mm (ALMA, ~5h) observations of the best sample of z=3-6 low-luminosity X-ray selected AGN candidates in the Chandra Deep Field-South, the deepest X-ray survey to date, to improve significantly their spectroscopic identification completeness, and constrain their space density to a currently unmatched precision. The observations have been obtained for exactly these purposes, and are already fully available. Archival ALMA observations in the field (which is one of the most intensively studied extragalactic regions) will provide the required datasets to study the properties (e.g., gas mass) of the host galaxies of the identified AGN. The PhD candidate will also investigate possible evidence for AGN activity in faint and high-redshift (up to z~10) galaxies discovered with deep JWST, ALMA, and MUSE observations in the field, via cross-match with the Chandra sources and X-ray stacking analysis. The results will be compared with theoretical models of SMBH formation in the early Universe and results from cosmological simulations.

The PhD candidate will be trained in AGN physics and demographics, in reducing and analysing observational data from major observatories (JWST, ALMA, VLT, Chandra), and in handling multi-wavelength catalogs. The student will join the large and active AGN community in INAF-OAS and Unibo-DIFA, and will collaborate with researchers in other Italian and international institutes.

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