PhD project in ASTROPHYSICS

Title of the Project: An 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, whose launch is foreseen for 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 soon-available **Euclid** data that 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 preparation 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: Training to data analysis tools on Euclid simulated data. Analysis of the real Euclid 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: *Understanding stellar clusters: synergy among Gaia, large spectroscopic surveys, stellar models, and asteroseismology*

INAF-OAS Supervisor: *Angela Bragaglia*

Co-Supervisor: *Andrea Miglio (DIFA Bologna).*

Collaborators: *WEAVE and 4MOST Consortium members (in particular Ricardo Carrera, Davide Massari, OAS; Antonella Vallenari and Sara Lucatello, OAPd)*.

Scientific Case: *Stellar clusters* are important constituents and tracers of the Galactic structure. Understanding the connection between field stars and their parent cluster is fundamental to figure out the cluster formation and dissolution mechanism and the contribution to the general chemical and dynamical evolution of the Galaxy. Stellar clusters are the ideal site where to *test stellar evolutionary models* and derive *ages*, on whose accuracy ultimately rests most of our understanding of galaxy evolution. We are now in a privileged era, with large surveys from the ground and space missions providing a wealth of information. *i)* The ESA mission *Gaia* is revolutionizing our understanding of the Milky Way, providing a 5-d map of our Galaxy. *ii)* Large spectroscopic surveys from the ground add precise radial velocity, and especially metallicity and detailed chemical composition for a significant fraction of *Gaia* stars of all Galactic components and in particular for clusters of all ages. *iii)* Precise and accurate asteroseismology provided by space missions (*Kepler, K2*, TESS) permits to determine stellar masses and ages and provides stringent test on the physics of stellar models.

Outline of the Project: The Bologna DIFA, INAF-OAS Bologna and OA Padova are involved in *Gaia*, WEAVE, 4MOST, and asteroseismology. The PhD project main steps are: *i)* familiarisation with/use of: stellar clusters, asteroseismology and stellar models (*mostly year 1*); *ii*) analysis of data already in hand, both from large surveys and space missions (*starting in year 1 and up to year 3*); *iii)* interpretation and publication of results (*year 2 and 3 – initial results could be presented at Meetings already from year 1).*

The PhD project will center on (at least) one of the following topics: a) Using stellar clusters as test of evolutionary models; b) Using asteroseismology to derive precise mass/age of stars in clusters in combination with ancillary spectroscopic data. c) Using open cluster as chemical tracers of the disk and its evolution. d) If ESA selects for phase A study the mission HAYDN (PI A. Miglio), devoted to asteroseismology of stellar clusters, the student may be involved in the preparation.

Further developments/projects, also in collaboration with international researchers and stellar modelers, can be devised in agreement with the PhD student.

Framework and data for the PhD project are provided by: the *Gaia* mission results (for which A. Vallenari is deputy chair of the DPAC); the WEAVE survey (started in mid-2023 at the WHT on Canary Islands) in which A. Bragaglia, A. Vallenari co-lead the "Galactic Archaeology-Open Clusters" part and R. Carrera, D. Massari, S. Lucatello play important roles; 4MOST (ESO public survey at VISTA due to start in late 2024) in which A. Bragaglia is co-PI of the Community Survey "Stellar Clusters" (with S. Lucatello and A. Vallenari, while R. Carrera, D. Massari, A. Miglio play important roles); and *Kepler*-*K2* and TESS, whose asteroseismic data are publicly available and for which expertise is available at DIFA (A. Miglio, his group and international collaborations).

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PhD project in ASTROPHYSICS

Title of the Project: The 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.

Outline of the Project:
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 HERMES mission and beyond: towards a compact, distributed network of CubeSats for high energy astrophysics

INAF-OAS Supervisor: Riccardo Campana

Co-Supervisors: Ezequiel J. Marchesini, Enrico Virgilli

Scientific Case:

Outline of the Project:
The proposed thesis is in the framework of the HERMES project (https://www.hermes-sp.eu) which foresees the launch in 2024 of 6 CubeSats, designed and built by a collaboration led by INAF institutes, aiming to detect Gamma Ray Bursts (GRBs) and other high-energy transients.
The PhD candidate will collaborate to the final stages of the payload integration, to the development of the data analysis software, to the analysis of in-flight scientific data and payload health monitoring, and will contribute to the design, simulation, and development (including laboratory testing on prototypes) of new instrument concepts based on the HERMES architecture but suited to interplanetary space environments and/or spectroscopy of planetary surfaces.

YEAR 1: Consolidation of the HERMES scientific analysis software. Design and simulation of possible extensions of the HERMES detector concept.
YEAR 2: Exploitation of HERMES scientific data. Laboratory testing on detector prototypes. Further trade-off and design studies.
YEAR 3: Exploitation of HERMES scientific data. Laboratory testing on detector prototypes. Final design of an interplanetary HERMES detector.

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PhD project in ASTROPHYSICS

Title of the Project: Galaxy Evolution with the first Euclid data

INAF-OAS Supervisor: Olga Cucciati

Co-Supervisors: Micol Bolzonella, Lucia Pozzetti, Elena Zucca

Scientific Case: Euclid is a groundbreaking mission within the ESA's Cosmic Vision programme, set to launch in July 2023. Over the course of its six-year nominal mission lifetime, Euclid will make a 3D map of the Universe in 15000deg2, using visible and near-infrared imaging to observe billions of galaxies, as well as near-infrared slitless spectroscopy to study hundreds of millions of galaxies in the redshift range $0.9<z<1.8$. By doing so, Euclid will provide critical insights into the properties of dark energy and dark matter on universal scales.

In addition to its primary mission goals, **Euclid will also be a game-changer for galaxy evolutionary studies**, providing an unprecedented dataset that will enable researchers to investigate the physical processes of galaxy formation and evolution, as well as their **dependence on the environment.** This vast trove of data will be an invaluable resource for researchers in the years to come.

As a PhD candidate working on the Euclid project, you will have the unique opportunity to explore this rich dataset and uncover new discoveries that have been missed in previous surveys. In particular, you will use the first Euclid Data releases to identify and analyze the physical properties of **rare objects**, and to study how their properties (and existence itself) **depends on the environment** that surrounds them (voids, filaments, groups, clusters…). By doing so, you will gain a deeper understanding on the ways in which rare galaxy populations are influenced by their environment.

To help you plan your three-year PhD period, we suggest the following timeline as starting point. This timeline can be re-adjusted, especially after that you gain familiarity with the Euclid data.

Year 1. You will become familiar with the available Euclid data. You will also begin analyzing the data to identify rare objects that could not be found in previous surveys. This will involve developing algorithms and software tools to process and analyze the data.

Year 2. You will use a combination of spectroscopic and photometric data to characterize the physical properties of the rare objects identified during Year 1, and place them into the broader context on how environment affects galaxy evolution for the overall galaxy and AGN populations.

Year 3. You will synthesize your findings into a coherent body of research that sheds new light on the interplay between galaxies and AGN, and their evolution in different environments.

During your PhD, you will be involved in collaborating with other researchers in the field, and presenting your findings at conferences and workshops. Overall, your PhD project will provide an exciting opportunity to contribute to one of the most ambitious astrophysics projects of our time, and to make significant steps forward in our understanding of the Universe.

Local and international context: At INAF-OAS there is a large and active research group on multiwavelength galaxy surveys and observational cosmology involved in Euclid. The researchers deal with many different aspects of the science that will be enabled by Euclid data (e.g. analysis of galaxy environment and clusters of galaxies, in statistical approaches to describe galaxy evolution, in photometric and spectroscopic studies, and on machine learning approaches), playing leading roles. We are also tightly collaborating with researchers at the Physics and Astronomy Department of the University of Bologna, and we have collaborators in many other Italian institutes and foreign countries participating in the Euclid consortium (France, Spain, Germany, US, etc.).

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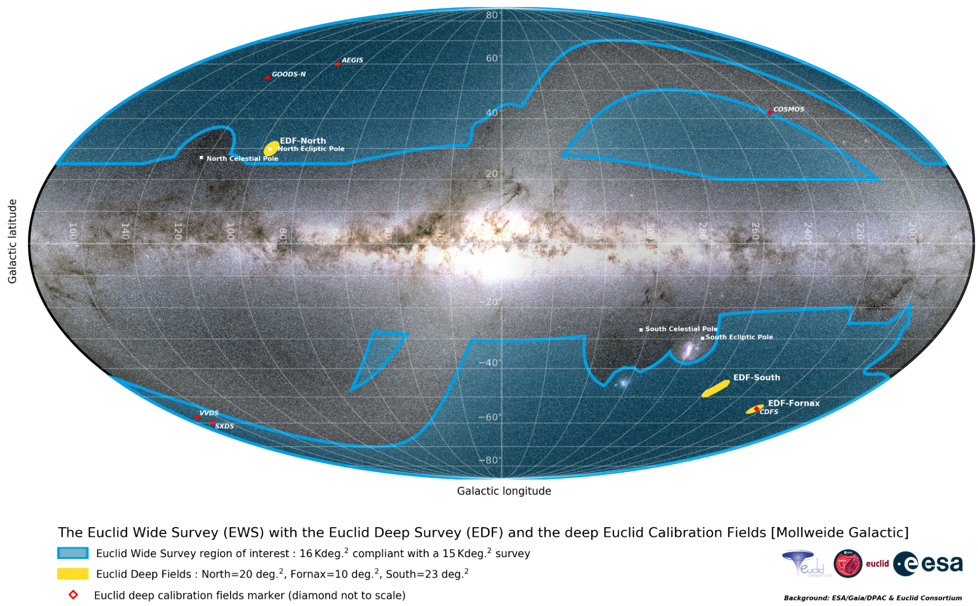

PhD project in ASTROPHYSICS

Title of the Project: Studying AGN ultra-fast outflows with XRISM/Resolve today to paving the way to Athena/XIFU

INAF-OAS Supervisor: Mauro Dadina

Co-Supervisors: Massimo Cappi, Cristian Vignali

Scientific Case: The advent of the first upcoming micro-calorimeter X-ray spectrometer "Resolve" (onboard the JAXA-NASA mission XRISM) and, on a longer term, the revolutionary X-ray Integral-Field-Unit spectrometer (XIFU), onboard the large ESA flagship mission Athena, will take the potentials of high-resolution X-ray spectroscopy to an un-precedent level of investigation, opening a large discovery space. Thus, gaining substantial access to the new-era X-ray spectroscopy data from XRISM-Resolve is of strategic importance, in particular for young Italian astronomers of INAF.
Athena-XIFU consortium and the JAXA-XRISM management team have signed an agreement that grants a large amount of XRISM observing time per year (400 ks/year, half the total amount of the observatory made available on competitive basis to all EU scientists) to the Athena-XIFU consortium. It will be fairly shared among the different communities inside the consortium, according to their relative contributions and leading roles in specific science fields.
The study of ultra fast outflows will be one of the fields in which the Italian community is expected to contribute the most. Here we propose a program aimed at taking full advantage of the un-precedent coupling of energy resolution and collecting area of XRISM-Resolve to investigate the launching mechanism of such energetic winds using state-of-the-art and physically motivated X-ray spectral models based on either radiation pressure or magneto-hydrodynamic mechanisms.

Outline of the Project:
YEAR 1: The first year of the PhD activities will be strongly focused on the learning of XRISM-Resolve data reduction and analysis items. We expect to have access to at least the datasets relative to the observation of one AGN. Moreover, we think that this phase cannot be shorter. In parallel, the candidate will use the physical models of UFOs using CCD observations of nearby AGN.
YEAR 2: Publication of the first results must follow the first part of the work. We expect that this phase will go in parallel with a deep testing of the physical models of winds using the high-resolution data from XRISM-Resolve for all the available AGN.
YEAR 3: We expect that the data from the first available XRISM-Resolve observations of high-redshift QSOs will be available. It will allow testing physical models on such datasets

so as to probe the UFO launching mechanisms at the peak of AGN activity, i.e. when UFOs are supposed to play a fundamental role in shaping the co-evolution path that link the super-massive black-holes and their host galaxies. The information collected from XRISM-Resolve will be used to test the expectations from the Athena-XIFU scientific case.

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PhD project in ASTROPHYSICS

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

INAF-OAS Supervisor: Emanuele Dalessandro

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

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

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

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

Our group has recently defined an innovative tool for breaking the degeneracy between the effects of internal dynamical evolution and of a non-universal IMF by using two directly measurable quantities: the slope of the present-day mass function PDMF (α_G) and its radial variation (δ_α) in a cluster. Indeed, we have convincingly shown that, the combined evolution of δ_α and α_G strongly depends on the cluster's IMF, while being only mildly dependent on the other initial conditions.

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

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

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PhD project in ASTROPHYSICS

Title of the Project: The dusty growth of the first quasars

INAF-OAS Supervisor: Roberto Decarli (OAS)

Co-Supervisors: Francesca Pozzi (UniBo)

Scientific Case: Quasars at cosmic dawn (redshift z>6, age of the Universe <1 Gyr) are among the most active and massive sources in the early Universe. Their luminosity comes from rapid (>10 M_{sun} yr^{-1}) gas accretion onto already formed supermassive (10^9 M_{sun}) black holes. Their host galaxies harbor immense (~10^{11} M_{sun}) gas reservoirs that feed intense episodes of star formation (100-1000 M_{sun} yr^{-1}). In this PhD project, the perspective candidate will work on proprietary ALMA observations of the dust continuum in a sample of z>6 quasars (see Fig.1) with the goal to understand the contribution of the AGN to the energy budget, the distribution of the dust temperature and mass within the host galaxy, as well as the spatial distribution of star formation. The ALMA observations will contribute to a growing dataset on these sources, which include JWST and VLT/MUSE data aimed at characterizing the mass budget of the multi-phase ISM. This study will shed light on the early growth of the host galaxies of the first quasars.

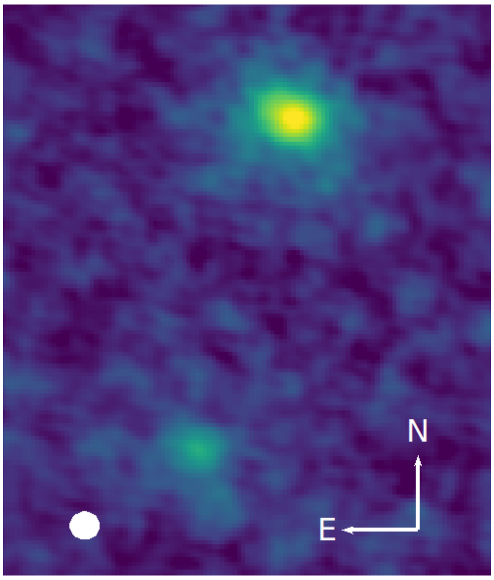

Figure 1: ALMA band 8 observations at 0.13" resolution of a z=6.6 quasar and its companion galaxy. The perspective student will work on these and other on-going matched-resolution observations in band 6 and 4, with the goal to map the dust mass and temperature distribution, and to assess the energy budget and the role of the AGN heating in the system.

Outline of the Project:
YEAR 1: Analysis of the ALMA/ACA data in hand, and comparison with previous band 3 and 6 observations aimed at constraining the global SED of the targeted sources. Design of new observing campaigns.
YEAR 2: Publication of a paper based on the first year's work. Reduction and analysis of the high-resolution observations (first dataset shown in Fig.1) and of the new campaigns.
YEAR 3: Publication of a paper based on the second year's work. Finalization of the observing campaigns, and draft of a third paper. Thesis writing.

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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 formation of the first globular clusters in the SIEGE 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 these enigmatic systems. 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).

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References

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PhD project in ASTROPHYSICS

Title of the Project:

Beyond the current concordance cosmological model with the next galaxy surveys

INAF-OAS Supervisor: F. Finelli

Scientific Case:

A new generation of galaxy surveys will soon be conducting unprecedentedly precise cosmological observations to search for fundamental particles, a breakdown of General Relativity, and signatures of the Universe's inflationary stage. The primary goal of this Ph. D. project is to develop a new set of analytic and numerical tools that increase the likelihood of such breakthroughs, in particular for Euclid, but also other data sets which will become publicly available in the time scale of this Ph.D. project, such as DESI.

Outline of the Project:

The sensitivity of the new generation of galaxy surveys, either alone or in combination with the measurement of the Cosmic Microwave Background (CMB) anisotropies, will allow us to test the assumptions of the current concordance cosmological model, LambdaCDM, and the relative tensions among different observations. The information contained in galaxy surveys relies on an accurate modelling of non-linear scales. This modelling needs to be computed semi-analytically or fully numerically for different cosmological models. The activity of the Ph. D. student will be conducted at INAF OAS Bologna in contact with members of the relevant Science Working Groups (SWGs) of the Euclid collaboration. This work will focus on more than one of these approaches 1. semi-analytic approximations such as effective theory of large scale structure for Early Universe and modified gravity cosmological models beyond LCDM and implementation of these approximations within the Euclid pipeline 2. N-body simulations of Early Universe and modified gravity cosmological models to inform semi-analytic approximations and eventually train neural networks and machine-learning emulators. 3. preparation and contribution to the Euclid pipeline for the extraction of cosmological parameters from Euclid alone and in combination or cross-correlation with the CMB anisotropy pattern.

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PhD project in ASTROPHYSICS

Title of the Project: *Reconstructing the accretion history of Milky Way dwarf satellites with chemodynamics*

INAF-OAS Supervisor: Dr. Davide Massari

Co-Supervisors: Prof. Alessio Mucciarelli (DIFA), Dr. Michele Bellazzini (OAS)

Scientific Case: According to Λ cold dark matter cosmology, the large galaxies that we observe today have built up hierarchically, via merger with smaller systems. Thanks to the advent of the Gaia mission, that has provided kinematic measurements for more than one billion of stars, and the combination with chemical information provided by large spectroscopic surveys like APOGEE, GES and GALAH, many stellar streams remnant of these merger processes have been discovered in the Milky Way halo (Helmi 2020). Since ΛCDM is self-similar, such a hierarchical growth should have acted in shaping smaller galaxies as well. The best cases to test ΛCDM on these small scales is given by the *Milky Way dwarf galaxies satellites.*
The motion of stars and globular clusters within dwarf galaxies, as well as their chemical composition, are powerful tools to reconstruct their origin, and to understand whether they have formed within the dwarf galaxy itself or if they were accreted from a different environment.
Our group has paved the way for this kind of investigation by discovering for the first time the relic of a past merger event occurring in the Large Magellanic Cloud (Mucciarelli et al. 2021, Nature Astronomy), and is now collecting brand new data with the best telescopes in the world to push forward this novel line of research.

Outline of the Project: The objective of this project is to reconstruct the assembly history of a sample of Milky Way satellite galaxies. This will be achieved by taking advantage of Gaia DR3 data to determine the dynamical properties of these galaxies' stars and globular clusters, in terms of integrals of motion. These will then be combined with chemical abundances estimated from high-resolution spectra obtained at the Very Large Telescope and the Large Binocular Telescope. The chemodynamical properties of the analyzed targets will enable understanding their origin, and in case of accretion the properties of their galaxy progenitor will be reconstructed as well.

Foreseen timetable:
YEAR 1: Ultra-faint dwarf galaxies, at least 1 paper, 1 international conference;
YEAR 2: Large Magellanic Cloud, at least 1 paper, at least 1 international conference, collaboration with international experts in stellar dynamics and spectroscopy;
YEAR 3: Small Magellanic Cloud, at least 1 paper, at least 1 international conference, Thesis submission

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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).

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*, LSST and TESS.
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: Support to the commissioning and first scientific light of the Vera C. Rubin Observatory

INAF-OAS Supervisor: Gabriele Rodeghiero

Co-Supervisors: Felice Cusano, Maurizio Pajola

Scientific Case: The Vera C. Rubin Observatory (formerly known as Large Synoptic Survey Telescope, LSST) is a cornerstone astronomical facility developed by Aura, DoE and SLAC aiming to conduct a 10-year legacy survey of the Southern sky between 0.3 and 1 micron. The Rubin telescope is located at the Cerro Pachón in Chile and it is currently entering its final phase of Assembly Integration and Verification (AIV) with the goal of achieving the first light by the end of 2024. The decadal survey that Rubin will conduct is based on four main science cases: i) the comprehension of the dark energy and matter, ii) the observation of the optical transients, iii) the study of the Solar System minor bodies and iv) the mapping of the Milky Way. The possibility of participating to the integration of an 8 m class astronomical telescope along its way towards the first light (technical and scientific) is a unique opportunity offered to the PhD candidate. The achievement of the first light is the milestone that unlocks the astronomical observations and the on-sky commissioning to assess the system performances before releasing it to the scientific community. The project time schedule well matches the 3-years PhD timeframe, allowing a progressive involvement in the telescope AIV phases in the first part of the PhD and a confluence into the science observations at the end of the telescope commissioning. Besides the exciting opportunity of taking part in key operations of commissioning and science data verification with a newly born telescope, the collaboration with the Rubin Observatory offers a diverse and multi-cultural working environment with periodic trips to the Chilean telescope observing site.

Outline of the Project:
PART 1 (1.5 years): The first year and a half of the PhD will be engineering-oriented and it will support the commissioning activities of the telescope before and during its first light. The engineering work will expose the candidate to the modern techniques of the optical and system engineering with a cutting-edge astronomical facility. The main activities foreseen concern the testing of the secondary mirror cell, the telescope alignment sequence and the wavefront error control strategy (supervisor Gabriele Rodeghiero).
PART 2 (1.5 years): The science-oriented phase will take place at the end of the engineering operations. With this work-package the candidate will scrutinize the first images taken by Rubin in its early operations phase. Concerning the science topics, a free choice among two main stream science cases can be offered: i) the study of the stellar optical transients and their photometric variability with time (reference Felice Cusano); ii) the

photometric and astrometric study of the Solar System minor bodies population such as asteroids and Trans-Neptunian objects (reference Maurizio Pajola).

The position requires the availability of sustaining periodic visiting shifts to Chile. In addition, a good knowledge of written and spoken English is required. Candidates are encouraged to contact the reference person for any inquiry.

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PhD project in ASTROPHYSICS

Title of the Project: "Unveiling the earliest phases of massive galaxy evolution in the era of ALMA and JWST"

INAF-OAS Supervisor: Dr. Donatella Romano

Co-Supervisors: Dr. Roberto Decarli (OAS), Prof. Francesca Pozzi (UniBO)

Scientific Case: This PhD project aims at studying the formation and evolution of quasar (QSO) host galaxies at high redshift by means of chemical evolution models that implement detailed stellar nucleosynthesis prescriptions and dust production/destruction mechanisms. Multi-line observational studies exploiting the extraordinary capabilities of ALMA and JWST allow to characterize the chemical properties of the ionised, neutral, and molecular gas of several quasar hosts (e.g., Decarli et al. 2023). Chemical evolution models are the ideal tool to connect such observations to the physical processes driving galaxy formation, such as gas accretion, star formation, energetic feedback from stars and QSOs, chemical enrichment from stars (Romano et al. 2017; Zhang, Romano et al. 2018).

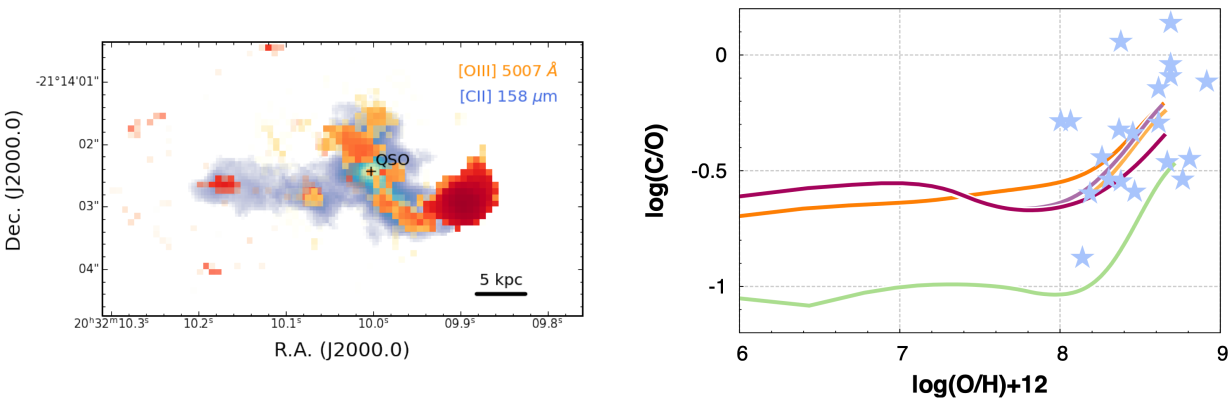

Figure 1. Left-hand panel: JWST and ALMA observations of the quasar+companion galaxy merging system PJ308-21 at z = 6.23. The quasar resides at the core of a massive (~10^{11} $M_{\odot}$) galaxy which is merging with multiple satellite galaxies. A plethora of emission lines arising from different elements and molecules unveil precious information on the thermodynamics, excitation, ionization budget, and abundances of the gas in this rapidly assembling system at cosmic dawn. **Right-hand panel:** The run of C/O versus metallicity as predicted by a chemical evolution model for a massive elliptical galaxy under different assumptions about C and O nucleosynthesis in stars (coloured lines) compared to data for local star-forming galaxies (symbols).

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The abundance models developed in this PhD program will be crucial in order to interpret the observed line emission in systems emerging from the cosmic dark ages, and to connect these high-redshift observations with their local counterparts.

Outline of the Project:
YEAR 1: During the first year, the student will get familiar with our proprietary chemical evolution code and will start implementing new routines to take into account the mechanisms of dust production/destruction.
YEAR 2: During the second year, the student will complete the implementation of the new routines and start the comparison of the model predictions with the observations. During the second year the student is expected to submit a first paper.
YEAR 3: In the third year, the student will build a bridge between the local and high-redshift observations. At least a couple of papers should be submitted at this stage. The last three months will be fully devoted to writing the PhD thesis.

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PhD project in ASTROPHYSICS

Title of the Project: VHE gamma-ray astronomy: the early science of CTAO and the Astri-MiniArray

INAF-OAS Supervisor: Eleonora Torresi

Co-Supervisors: Roberta Zanin (CTAO & INAF-OAS), Vito Sguera (INAF-OAS) and Paola Grandi (INAF-OAS)

Scientific Case:

Very-high energy photons are tracers of relativistic particle acceleration in the most extreme environments known in the Universe - such as in supernova explosions, black holes, and neutron star mergers. The next generation of VHE gamma-ray instruments will give us access to a wide variety of extreme events in our Galaxy and beyond.
Pulsars and their surroundings are sites where particles are accelerated to relativistic energies. One of the main open questions in high-energy astrophysics is related to the origin of the most energetic cosmic rays in our Galaxies, reaching energies of the order of the PeV (10^{15} eV).
The hunt for the astrophysical sources capable of accelerating particles up these energies, dubbed as PeVatrons, is a key objective of the current and future gamma-ray facilities. At the same time, pulsars became one of the hottest topics of gamma-ray astronomy when it was proven, against any theoretical expectation, that they can accelerate particles up to TeV energies. If current facilities have just looked at the tip of the iceberg, we would expect a completely new paradigm to emerge from pulsar observations by the upcoming instruments like CTAO.
Accreting black holes ejecting relativistic plasma (jets) are ideal candidates for studying acceleration processes. The radio galaxies M87 (recently targeted by the Event Horizon Telescope) and 3C 84 (where Space VLBI observations have resolved the jet base), and the blazar TXS 0506+056 (where it was proven the coincidence of a VHE flare the detection of a cosmic neutrino) are a few representative examples of a population of relativistic jets that CTAO will detect and study in detail.
The Cherenkov Telescope Array Observatory (CTAO) is the next-generation gamma-ray instrument that will significantly increase the discovery space, paving the way to new questions and paradigm-changing discoveries thanks to its greatly improved sensitivity when compared to the current facilities, along with enhanced angular and spectral resolution.

The CTA Observatory is a distributed facility with headquarters in the Bologna Astrophysics Area and two telescope arrays on the Canary Islands of La Palma and Paranal (Chile). The Observatory, including 51 imaging Cherenkov telescopes, will start to be built in 2024, and the data from the first installed telescopes will be available straight away.
In parallel, the CTAO pathfinder, Astri-MiniArray, including 9 imaging Cherenkov telescopes, is being built in Tenerife (Spain) with the main scientific mission of searching for and characterizing PeVatrons.

In preparation for the scientific exploitation of these facilities, it is critical to understand and characterize the new instruments as soon as the first telescopes become operational **AND** to prepare the future observations of the Key Science Projects (KSPs), including their multi-wavelength follow-up. The KSPs are large programs, as, for instance, surveys, aiming to deliver legacy data sets that are produced in a coherent fashion on key science cases, such as those briefly described above, promising major breakthroughs.

The Ph.D. thesis will offer the possibility to analyze the first-ever scientific data recorded by the first CTAO/Astri-Mini Array telescopes in operation and to prepare for the upcoming observations via extensive simulation of the Very High Energy gamma-ray sky.

Outline of the Project:

YEAR 1: The candidate will learn the basis of gamma-ray astronomy, practice with data analysis, and in particular, will learn how to analyze the data recorded by the LST-1, the prototype CTAO Cherenkov telescope that is already taking data in La Palma. The student will have the unique possibility to participate in the data taking and learn the low-level analysis. This is something that, once the Observatory will be operative, will be done automatically by the observatory staff. The science target is chosen at the beginning of the first year with the supervisor: it can span from pulsars to binary systems, active galactic nuclei, and transients in general. During the first year, the student will be assigned some LST1 data already recorded on the agreed target and trained to prepare their proposal for the CTAO early science.

In parallel, the student will be able to participate in the CTAO science data challenge, whose data release is expected to happen in mid-2024. These are simulated science-ready data of the very-high-energy sky as CTAO is expecting to see it. The student could select the targets of interest and run perspective studies on the subject.

YEAR 2: The candidate will continue their scientific study by interpreting and publishing the obtained LST1 results in a peer-reviewed paper. In parallel, the candidate will learn how to analyze the data of different telescopes that, by that time, will be accepted by the CTAO and start operations.

This will provide another interesting opportunity for the student that will be at the forefront of the commissioning of these telescopes acquiring all the expertise needed to exploit the instruments as soon as the early science phase starts. The analysis of the commissioning data will lead to a publication to verify the scientific capabilities of the new instruments.

The student is expected to spend a considerable fraction of the second year abroad joining a group with worldwide recognized expertise in the phenomenological interpretation of the obtained results.

YEAR 3: The student will wrap up and conclude the started projects focusing on the writing of the thesis. In parallel, they will be able to analyze and interpret the data of the proposal submitted the previous year on the available LST telescopes.

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PhD project in ASTROPHYSICS

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

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

Scientific Case
The most compact and extreme objects in the Universe, such as black holes and neutron stars, give rise to some of the most violent and energetic phenomena which are observed in the hard X / gamma-ray bands, through instruments on-board satellites. These cosmic emissions can come from persistent or transient emitters. Particularly interesting are transient events like Gamma-Ray Bursts (GRBs). Thanks to a long standing tradition and collaboration with Italian (ASI) and European space agencies (ESA), INAF/OAS holds the leadership in the design, realization and test of hard X-ray detectors for astrophysics. In recent years, an X and Gamma-ray Imager and Spectrometer (XGIS) has been developed in collaboration with several Universities and other scientific and technological Institutions. The PhD student will join the collaboration working in an international context for further technological developments of the instrument and for its performance estimation. At present, the XGIS has been adopted for the mission THESEUS proposed for the 7^{th} medium size mission of ESA which is now in the first stage for selection among other competitive science missions.

Outline of the Project
The outline of the project strongly depends on the selection process of the THESEUS mission by ESA. In case of selection for the following Phase A (lasting 3 years) the PhD activity will be entirely related to further studies and technological developments to optimize the performance of the instrument. In case the mission will not be selected by ESA for further study, other mission opportunities will be explored in the international context including the collaboration with the U.S Agency NASA and the Japanese Agency JAXA.

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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, 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, 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.

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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

Co-Supervisors:

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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