DIFA Projects available for PhD cycle 39

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4	Ferraro2	Ferraro	Searching for Fossil Fragments of the Galactic bulge formation process
5	Gitti1	Gitti	AGN feeding-feedback cycle in cool core clusters with Hα nebulae
6	Marinacci1	Marinacci	Simulating super-bubble dynamics in star-forming galaxies with explicit ISM and stellar feedback models
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12	Moresco1	Moresco	Cosmological constraints from the cross-correlation of Gravitational Waves and galaxy catalogs
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19	Mucciarelli2	Mucciarelli	Very metal-poor stars as local relics of the ancient Universe
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28	Vignali2	Vignali	The realm of dual super-massive black holes
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PhD project in ASTROPHYSICS

Title of the Project: *Testing fundamental physics with numerical simulations of the cosmic large-scale structures*
Supervisor: Prof. Marco Baldi

Scientific Case:
The standard cosmological model (known as ΛCDM) has provided us with a surprisingly simple framework to describe and accommodate the vast majority of observational data. Nonetheless, recent **observational tensions** have led to **speculations about possible alternative and more fundamental explanations of cosmic acceleration.** In such a context, and with the advent of the epoch of so-called "Precision Cosmology", **a detailed investigation of alternative cosmological models and of their impact on the formation and evolution of cosmic structures is essential** for a thorough comparison between theory and observations. In this respect, **cosmological simulations play a crucial role**, opening a window on observable properties which cannot be predicted using analytical or simple linear numerical codes.

Outline of the Project:
The PhD student will work on **developing, optimising, and exploiting highly efficient and sophisticated numerical tools** to extend current cosmological simulations codes in order to include a variety of extensions of the standard cosmological scenario, such as **Dark Energy models, Modified Gravity theories and non-standard Dark Matter candidates, and to extend these (Newtonian) algorithms to General Relativity**.

The PhD student will therefore work in the **highly stimulating and rapidly growing field of High-Performance Computing for Cosmology**, in collaboration with the recently established **National Centre for HPC funded by the PNRR**, developing the general research plan described above for one (or more) of the following models:
- **Fundamental modifications of Gravity**: implementing and testing Horndeski Gravity models, K-mouflage models, Lorentz violating gravity, Growing Neutrino Quintessence, General Relativistic Entropic Forces;
- **Effective modifications of gravity**: implementing and testing parameterised models of non-linear screening, Interacting Dark Energy, Clustering Dark Energy;
- **Non-standard Dark Matter**: extending the capabilities of existing N-body simulations codes including alternative Dark Matter candidates such as Ultra Light Axions or mixed Cold+Warm DM;
- **General Relativistic Simulations**: extending current Newtonian N-body simulations codes to include a fully relativistic treatment of gravity at large scales.

Although some of such models have already been implemented in simulations codes in the past, the technological and methodological advancements in the field of scientific High-Performance computing of the last years — that will lead to the new era of Exascale Computing — will require a new design of most of these algorithms.

In any case, the choice of the specific models to consider will be discussed with the student and will be based on both the evolving priorities of the community and the student's interests and attitudes.

More specifically, the student will:
- **Develop highly scalable and memory efficient modules** for one (or more) of the models listed above into the recently-released Gadget4 (MPI/OpenMP, C++) simulations code;
- **Run large-scale and high-resolution simulations** for the selected model(s) and test the code performance for large production runs
- **Analyse the results of such simulations**, with a particular focus on the main observables that will be tested by upcoming large-scale surveys such as **Euclid, SKA, VRO-LSST, Einstein Telescope**: galaxy clustering; clusters and voids abundance; weak lensing statistics and cross correlation with clustering statistics; CMB lensing and Integrated Sachs-Wolfe effect; Gravitational Waves source distribution.

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PhD project in ASTROPHYSICS

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

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

Scientific Case:

Star formation at any cosmic epoch is characterized by the presence of clustered systems such as molecular clouds, massive young clusters, open and globular clusters. Connecting the origins and primordial properties of such systems is paramount to make a step forward in our understating of star formation in the context of galaxy evolution and of the physical processes by which stars and star clusters are formed end evolved. However, such a connection is still poorly understood. For instance, one of the main properties of star-formation that any predictive theory must be able to replicate is the role of stellar multiplicity. In fact, it has been long known that binarity and, more in general, stellar multiplicity is a fundamental and inevitable outcome of any star forming system. Few topics in astronomy are able trigger such vigorous discussions as how many stars are born in binary, triple or multiple systems and their role in the evolution of the host stellar systems. Such a role is of critical importance, as stellar multiplicity influences most of the observable properties of any stellar system (e.g., chemical enrichment, mass-to-light ratio and so on…), from star clusters to galaxies. While significant efforts have been made to study multiple systems in a variety of different environments, no consensus has been reached regarding their formation rate and impact on the long-term evolution of their host systems. Consequently, the knowledge of the primordial fraction of multiple systems is an essential component of any study aimed at understanding the formation and evolution of any stellar systems.

Dense stellar aggregates, such as star clusters, are ideal targets for constraining critical properties of star formation. These systems are found in all types of galaxies, from dwarfs to ellipticals, are populated by many stars and are typically easy to observe. Indeed, the goal of this PhD project is to constrain the primordial properties of star clusters in the Local Group through the observation of their present-day properties, with a particular focus on the properties of multiple stellar systems. This, in turn, will provide the link between star clusters in the local Universe and their high-redshift counterpart and will clarify the role of multiple systems in the cluster long-term evolution. Indeed, the presence of multiple systems in star clusters provides an energy source able to drastically alter the evolution of the clusters. Moreover, the evolution of multiple systems in star clusters produces a large population of exotic objects such as millisecond pulsars, blue straggler stars and so on, which provide a benchmark for stellar evolution under extreme conditions. Finally, interactions among multiple systems trigger merging event visible through both electromagnetic and gravitational waves. Therefore, star clusters are expected to provide the ideal laboratory to test future gravitational waves detectors.

Outline of the Project:

By using the most up-to-date N-body and Monte Carlo simulations of star clusters, accounting for a broad range of different initial conditions (such as cluster's mass, size, primordial binary fraction, black hole retention fraction) and orbits, it has been recently found that it is possible to link a wealth of present-day properties of star clusters to the primordial ones. For instance, the measurements of the binary fraction across the whole cluster extension provide a proxy to the primordial one and allows to constrain the role of the environment in determine how many binaries are formed are survive the cluster long-term evolution. Indeed, the synergy between these cutting-edge simulations and observations is opening a new window in our understanding of the cluster star forming processes. In such a scenario, our group already awarded more than 150 hours of observations of different stellar systems with the most advanced ground-based and space facilities.

During the first year, the candidate will learn how to perform high-precision photometric analysis of stellar systems. This will provide the present-day distribution of single and multiple stars within the clusters and the physical properties of cluster themselves. Then, during the second year, the candidate will spend a period abroad, likely in the US and/or Canada, working with the most experts in the dynamical modelling of star cluster through numerical simulations. These simulations, combined with the results obtained from the observations, will provide the main goal of the PhD thesis, i.e., the derivation of the primordial properties of star clusters, which will be the focus of the third year of activity.

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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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

PhD project in ASTROPHYSICS

Title of the Project: Warm and Self-interacting dark matter constraints from hydrodynamical simulations

Supervisor : Giulia Despali
Co-Supervisors : Lauro Moscardini

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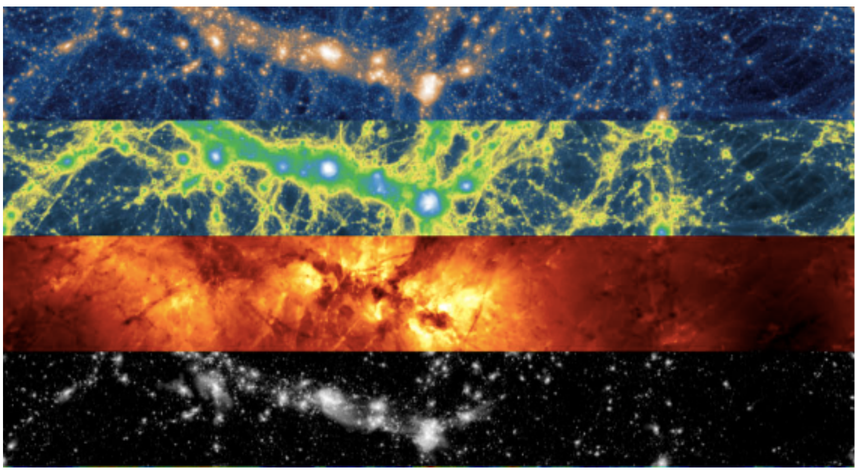
Scientific Case:

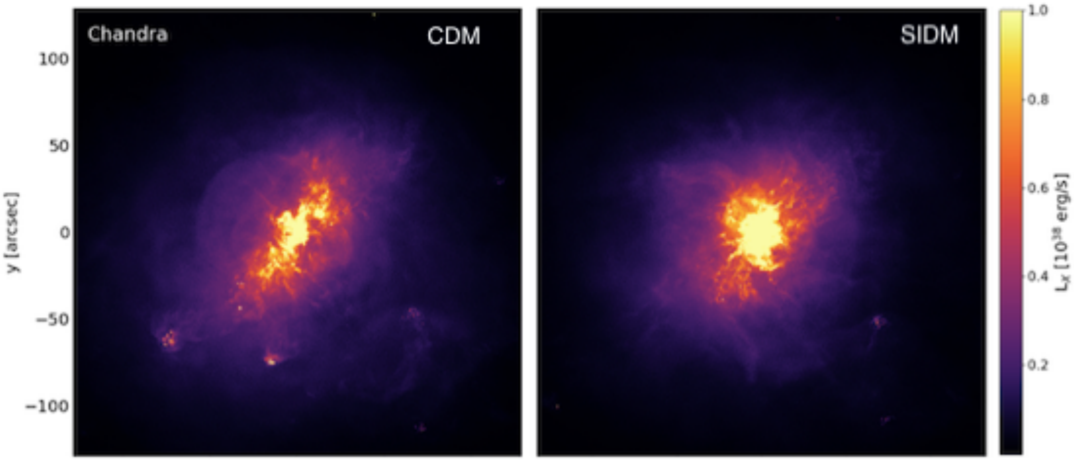
We are at a tipping point in Astrophysics, when numerical simulations are able to reproduce the properties of galaxies with an unprecedented precision. At the same time, the next generation of telescopes will bring exceptional progress in the observational domain, providing a much larger sample of lens systems and resolving scales down to milli-arcseconds: it is thus the moment to take theoretical predictions to the next level. Despite the success of the favoured CDM model in explaining observations of structures on scales larger than 1 Mpc, in reality a wide range of DM models are allowed, motivated to varying degrees by particle physics assumptions, and the tension between the CDM predictions and observations on galactic and sub-galactic scales.
This project will **use and contribute to a new set of hydrodynamical simulations created with the Arepo code** and the TNG galaxy formation model. Cosmological simulations based on **different models of dark matter (Cold, Warm and Self-interacting)** will allow us to study the galaxy population in different scenarios and make prediction on the nature of dark matter through the comparison with observational data.
The aim is to systematically compare the properties of galaxies (galaxy scaling relations, density profiles, shapes, distribution etc) and create mock observations (lensing, optical emission, X-Ray) in order to find estimators that can lead to significant new constraints.

Outline of the Project:

The PhD student will use a new suite of simulations that is currently being created with the AREPO code and in collaboration with international researchers. After an initial period dedicated to learning how to use and analyse numerical simulations, the PhD student will start comparing the **halo and galaxy statistics** in the dark-matter-only and hydrodynamical boxes. This will include, for example, the halo



Distribution of matter in the cosmic-web in the TNG100 simulation: dark matter, gas, velocity field, stars



Simulated X-Ray emission from a massive galaxy evolved in a cold (left) or self-interacting (right) dark matter universe.

and subhalo mass functions and concentration-mass relations in alternative DM scenarios, together with scaling relations of the galaxy population (galaxy-size, galaxy stellar mass function etc). The simulations will be the first self-consistent set, including multiple dark matter models and baryonic physics at the same time, and thus the statistical analysis will lead to the most accurate predictions available in alternative dark matter models. These will be useful for the comparison to new surveys such as **Euclid and LSST**, as well as optical data from HST and Keck.

Based on the results of this first phase, the PhD student will then identify interesting systems to re-simulate at higher resolution and will **run zoom-in simulations of a few individual objects with AREPO**. This will allow us to resolve the galaxy and dark matter structure with increased precision and create **realistic mock observations for strong gravitational lensing**. The mock images will be compared to obsrevational data data, both individually and through a blind analysis of mock samples. This has the purpose of determining the uncertainties of (sub)halo detection in a simulated data-set where the input is known, following the example of similar recent challenges and comparison projects. We will compare the simulations to state-of-the-art lensing observations in optical and radio.

The work activities performed during the PhD period will be based on various international collaborations our group in Bologna has. Moreover, the suite of simulations is currently being developed in an international collaboration that includes the **Illustris/TNG team** and some of the most prominent researcher in the field of numerical simulations, such as Volker Springel, Annalisa Pillepich, Dylan Nelson and Mark Vogelsberger. In addition to the ESA **Euclid** collaboration (https://www.euclid-ec.org), the lensing application will also be discussed within the **SHARP** collaboration, focused on constraining dark matter with lensing. In this way, the PhD student will have great possibilities to interact with diverse scientists that will give her/him/them the appropriate skills for a fruitful career. The collaborations mentioned above will also provide the chance to spend a period of 3-6 months abroad.

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

PhD project in ASTROPHYSICS

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

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

Scientific Case: The scenario of galaxy bulge formation is still largely debated in the literature. Among the most credited models, the "merging picture" proposes that galaxy bulges form from the merging of primordial sub-structures, either galaxies embedded in a dark matter halo, or massive clumps generated by early disk fragmentation. Although the vast majority of the primordial fragments should dissolve to form the bulge, it is possible that a few of them survived the total disruption and are still present in the inner regions of the host galaxy, grossly appearing like massive globular clusters (GCs). At odds with genuine GCs, however, these fossil relics should have been massive enough to retain the iron-enriched ejecta of supernova (SN) explosions, and possibly experienced multiple bursts of star formation. As a consequence, they are expected to host **multi-iron and multi-age sub-populations**.
Two of these remnants (disguised as genuine GCs: Terzan5 and Liller1 have been recently discovered (Ferraro et al., 2009, Nature,462, 483) and Liller1 (Ferraro et al, 2021, Nat. Astr., 5, 311), in the bulge of the Galaxy. These systems (1) are indistinguishable from genuine GCs in their appearance, (2) have metallicity and abundance patterns incompatible with those of bulge GCs and well in agreement with those observed in the bulge field stars, (3) host a dominant old stellar population (testifying that they formed at an early epoch of the Galaxy assembly), (4) host at least one young stellar population, several Gyrs younger than the old one (demonstrating their capacity of triggering multiple events of star formation). It is important to emphasise that the multi-age components in both the BFFs identified so far were discovered by analysing proper motion (PM) selected color-magnitude-diagrams (CMDs) obtained by combining HST and AO-assisted ground-based IR images (acquired at ESO-VLT and Gemini; see Fig.2). Here we propose to secure deep second-epoch K_s Gemini images of 11 GC-like stellar systems into the Galactic Bulge to assess their stellar populations thus finally addressing their true nature. *The discovery of other BFFs would add new crucial information on the formation process(es) of the Bulge*
Outline of the Project: In this framework we are using high-resolution and NIR capabilities of GSAOI-GEMS at GEMINI, HST and JWST to secure multi-epoch observations of a sample of globular cluster-like stellar systems in the Galactic Bulge in order to search for other BFFs. 12 hours of observing time at GEMINI South telescope have been already allocated to this project.
With the final aim of providing the accurate characterization of the stellar populations in each of the investigated stellar systems, the student will be in charge of the construction of high-quality differential reddening corrected and Proper motion- selected color magnitude diagrams (CMDs). Proper motions will be obtained from the analysis of multi-epoch observations: in particular the new GEMINI data will provide second-epoch observations for a sample of 11 clusters already observed with HST. Moreover, the combination of near-IR and optical images will provide the appropriate characterization of the extinction law in the direction of each stellar system (Pallanca+19, ApJ,882, 159; Pallanca+21, ApJ, 917, 92). Note that an increasing number of studies is showing that the extinction law can significantly vary along different directions toward the Bulge (e.g., Popowski 2000,ApJ, 528, L9; Nataf+2013,ApJ, 769, 88). Indeed, the correct determination of the extinction law in the direction of each target is crucial, since it is the first, mandatory step for a proper correction of differential reddening, and a solid characterization of the evolutionary sequences in the CMD and it has direct impact on the determination of each stellar system distance.

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

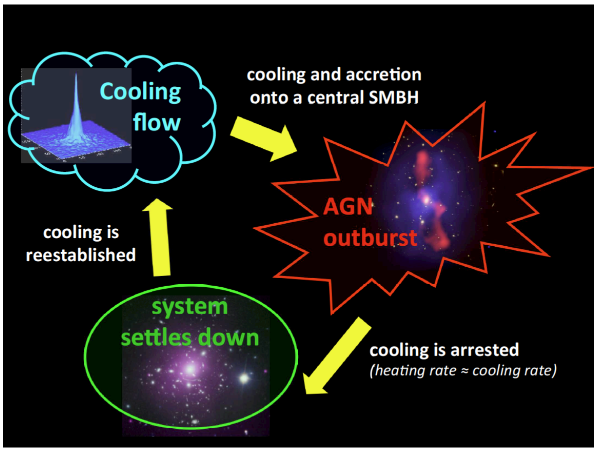
PhD project in ASTROPHYSICS

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

Supervisors : Myriam Gitti (DIFA), Fabrizio Brighenti (DIFA)

Scientific Case:

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



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

Outline of the Project:

To clarify the regulation of the feeding and feedback cycle in cluster cores it is crucial to perform accurate studies of the cooling and heating processes for a sensible sample of clusters with a prominent cold ICM phase. We have identified a sample consisting of the X-ray brightest, most Hα luminous clusters visible from the Jansky Very Large Array (JVLA). In particular, we selected clusters from the ROSAT BCS sample with 0.1-2.4 keV flux $f_X > 7\times10^{-11}$ erg cm^{-2} s^{-1} and Hα luminosity $>10^{40}$ erg s^{-1} . Visibility from JVLA ensures that high resolution radio observations can be used to examine the interaction between radio-loud AGN, ICM and cooling gas. The sample includes some very well-studied systems (e.g., A1835, A1795, A2052), as well as clusters never observed in X-rays and/or with only snapshot radio data (e.g., A1668).

In the past years we obtained snapshot *Chandra* and new JVLA data for three clusters which lacked archival X-ray and radio data, and are now carrying out a follow-up campaign to acquire *Chandra* deep observations.

Our first results (see e.g., Figure below) suggest that, in some systems with disturbed morphology, the cooling process is not currently depositing gas onto the BCG core (Pasini et al. 2019, ApJ, 885, 111; Pasini et al. 2021, ApJ, 911, 66).
The aim of the project is to investigate whether the feeding-feedback cycle of these strongly cooling clusters is broken, or if the AGN activation cycle is somehow maintained, for example being driven by the periodicity of the gas motions (sloshing). In particular, to determine the thermodynamical properties of the ICM and the morphology and spectral indices of the central radio sources, the PhD candidate will perform accurate morphological and spectral analyses of the *Chandra* and JVLA data already in hand, that will also be compared to the Hα nebulae from literature.

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

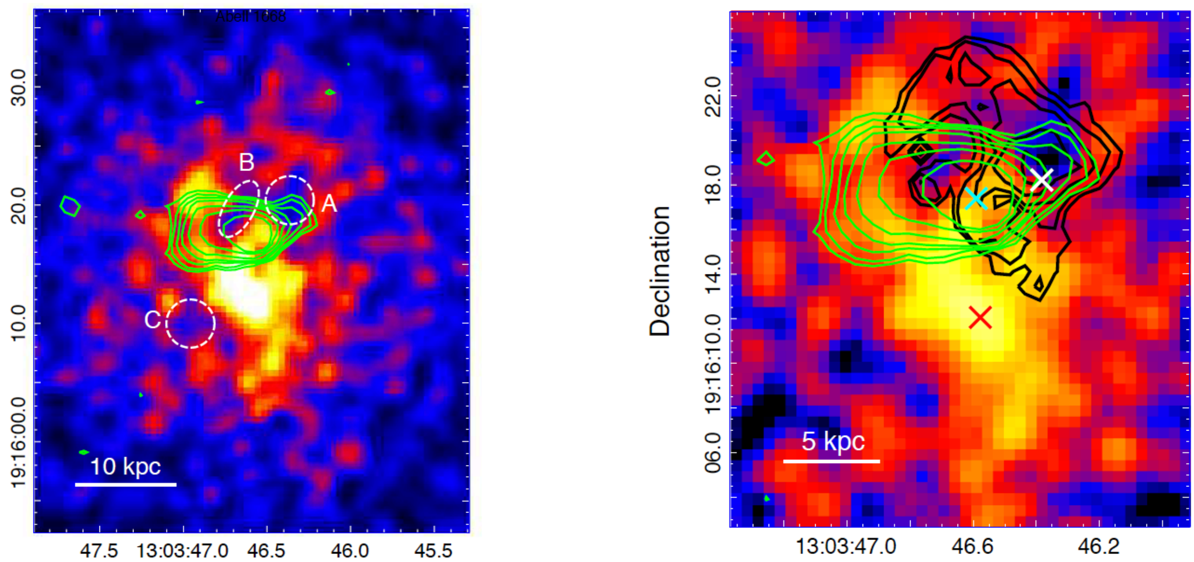


Figure - The results from our snapshot *Chandra* (color map) and 1.4 GHz JVLA observations (green contours) of A1668 indicate that this cluster has a disturbed morphology, showing hints of cavities (A, B and C in the left panel) and spatial offsets between the X-ray emission peak, the radio BCG and the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

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PhD project in ASTROPHYSICS

Title of the Project: *Simulating super-bubble dynamics in star-forming galaxies with explicit ISM and stellar feedback models*

Supervisor: Federico Marinacci

Scientific Case: Modern hydrodynamic simulations of galaxy formation are increasingly successful at reproducing the properties of real galaxies across a wide range of spatial scales, from portions of star-forming disks to cosmological volumes. A large part of this success is based on an efficient implementation of stellar feedback processes that are able to control star formation by ejecting substantial amounts of gas from galaxies. However, many of these feedback prescriptions are affected by severe shortcomings, because they are often implemented in a very crude and approximated way, even in state-of-the art simulations. To make a decisive step forward in our theoretical understanding of galaxy formation it is imperative to overcome these limitations. This can be achieved by the development of new and more sophisticated models that capture the multiphase structure of the interstellar medium (ISM) and self-consistently include the generation of galactic-scale outflows with a numerical treatment that is more faithful to the physical reality. A more accurate understanding of these essential aspects has a direct connection to many open questions in theoretical studies of galaxy evolution, such as the balance between gas accretion and outflows to and from galaxies, the global dynamics and the metal enrichment of the circumgalactic medium and the detailed investigation of the impact of stellar feedback processes on the structure, properties, and metal and baryon budget of galaxies.

Outline of the Project: The PhD student will use and substantially contribute to the development of the SMUGGLE model, an explicit and comprehensive ISM and stellar feedback model implemented in the moving-mesh code AREPO. In the first phase of the project, the PhD student will design, carry out, and analyze small-scale, high-resolution simulations aimed at studying in exquisite detail the effects of various stellar feedback channels (radiation, stellar winds, supernova explosions, ...) on the ambient ISM characterized by different physical properties. After this first phase, by using a bottom-up approach, the PhD student will scale up such numerical simulations to investigate the dynamics of super-bubbles (i.e., large ISM bubbles caused by the stellar feedback of OB star associations) in actively star-forming galaxies and their impact on the evolution of such objects, with an emphasis on the properties of the resulting gaseous outflows. Other than enabling the science described above, the results of this analysis will be particularly useful to calibrate, in a self-consistent way, the parameters of the various feedback channels that will be used by SMUGGLE in large-scale cosmological simulations lacking of sufficient spatial resolution to accurately capture the effects of stellar feedback on the surrounding interstellar and circumgalactic media.

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PhD project in ASTROPHYSICS

Title of the Project: *The effects of baryonic physics implementation in simulations of galaxy formation and evolution performed with SPH and mesh-based methods*

Supervisor: Federico Marinacci

Scientific Case: Modern numerical simulations of galaxy formation and evolution have reached an impressive degree of accuracy in reproducing the properties of observed galaxies across different of spatial scales. This achievement is based on the ability of such simulations of controlling and quenching star formation in simulated galaxies through very efficient stellar and AGN feedback processes. However, the implementation of these feedback prescriptions must be tailored to the specific code that is being used to perform the simulations and in particular to the approach that is adopted to follow the hydrodynamic evolution of the gas. Two main families of techniques are used to model hydrodynamics in galaxy formation simulations: smoothed particle hydrodynamics (SPH) and mesh-based methods. Although it is often argued that the differences in the outcome of the simulations due to the implementation of feedback processes are much larger than the ones induced by the choice of the technique adopted to model the dynamic evolution of the gas, it still unclear whether a specific implementation of feedback processes works “universally” (i.e., regardless of the technique with which hydrodynamics is followed) or might in principle be affected by or mask inaccuracies of the hydrodynamic solver being used. These uncertainties further limit the predictive power of simulations and, more importantly, preclude a detailed theoretical understanding of the key processes at play in shaping galaxies. Therefore, there is an urgent need to analyse and rectify these modelling shortcomings in order to draw a coherent picture of galaxy formation and evolution.

Outline of the Project: The PhD student will use and extend the scope of application of the SMUGGLE model, an explicit and comprehensive ISM and stellar feedback model, which is currently implemented in the mesh code AREPO. As a first step, to enable the research activities of this PhD project, the student will port the implementation of the SMUGGLE model from the AREPO code to the SPH code Gadget4. Having the same galaxy formation physics model implemented in codes that share the same treatment for gravity, but substantially differ in their treatment of hydrodynamics, will be instrumental to answer the scientific questions outlined above. In order to do so, after this first phase, the student will design, carry out and analyze state-of-the art numerical simulations of galaxy formation. The simulations will first be performed for isolated galaxies to then scaled up to cosmological zoom-in calculations. The analysis of the simulations will focus in particular on the differences in the results obtained with AREPO and Gadget4, with the ultimate goal of reaching a better understanding of the interactions between modeling techniques and the actual physics of galaxy formation.

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PhD project in ASTROPHYSICS

Title of the Project: *Paving the way to the next generation of cosmological simulations using the Dynamic Zoom Simulations technique*

Supervisor: Federico Marinacci **Co-supervisor:** Marco Baldi

Scientific Case: To fully exploit the potential of the enormous data volume that forthcoming cosmological surveys (such as Euclid, VRO-LSST, SKA, and Einstein Telescope) will provide, it is imperative for numerical simulations to be able to simulate large volumes of the Universe (to increase their statistical power) at high-resolution (which is needed to faithfully model the galaxy formation physics and the observational properties of the simulated signal). However, these two requirements are in conflict with one another, and lead to a large computational cost which makes carrying out such simulations currently unfeasible. To overcome this issue innovative algorithms, such as the Dynamic Zoom Simulations (DZS), can be used. DZS enables high-resolution, large-volume simulations by selectively coarsening the resolution of the calculations outside the light-cone that is causally connected to the observer. This approach presents major advantages compared to standard, uniformly-sampled cosmological simulations. In particular, the computational cost of a simulation is largely reduced together with its storage requirements. Moreover, a light-cone-like output directly mimics the format of observational surveys, thus facilitating the comparison between simulations and observations. Therefore, the adoption of this technique in the next generation of cosmological simulations of structure formation will be instrumental to increase their predictive power and to investigate the process of galaxy formation and evolution even in non-standard, beyond-ΛCDM cosmological models.

Outline of the Project: The successful candidate will develop the numerical techniques with which they will design, carry out and analyze state-of-the-art large-scale simulations of structure formation. In particular, the activities of this PhD project will focus on:

- porting of the DZS method in both mesh-based (Arepo, C) and SPH (Gadget4, C++) simulation codes, including support for baryonic and galaxy formation physics;
- extending this approach to a variety of beyond-ΛCDM cosmological models already implemented in the baseline codes;
- exploring the application of the codes to some specific use cases for large-scale cosmological simulations, for instance to predict the spatial and frequency distribution of gravitational wave sources that will be detected by the future Einstein Telescope experiment;
- developing novel simulation analysis tools tailored to the output format of DZS simulations.

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PhD project in ASTROPHYSICS

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

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

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

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

- **Construction of a large set of dark matter mock catalogues in different cosmological frameworks** using fast techniques, such as e.g. the ones based on Lagrangian Perturbation Theory.
- Application of subhalo abundance matching (**SHAM**) and/or halo occupation distribution (**HOD**) techniques to populate the dark matter catalogues with galaxies and galaxy clusters.
- Implementation of **new standard and Bayesian deep neural network infrastructures**.
- **Training and testing** of the neural networks on mock galaxy and cluster catalogues.

- **Comparison of the cosmological constraints from neural network and standard probes**, such as e.g. the ones from two-point and three-point correlation functions of galaxies and galaxy clusters.
- **Exploitation of the new machine learning tools on available data sets** to provide independent cosmological constraints.
- Application of the tools on larger mock catalogues to provide **forecasts for next-generation galaxy redshift surveys**.

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PhD project in ASTROPHYSICS

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

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

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

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

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

- **Cosmological analysis** on real cosmic void catalogues.
- **Forecasting** the constraining power of next-generation photometric and spectroscopic void samples.

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PhD project in ASTROPHYSICS

Title of the Project: Testing stellar physics in controlled environments: combining astrometric, spectroscopic, and asteroseismic constraints in clusters.

Supervisor : Andrea Miglio (DiFA)
Co-Supervisor : Angela Bragaglia (INAF-OAS)

Collaborators: WEAVE and 4MOST Consortium members (in particular Ricardo Carrera, Davide Massari, OAS; Antonella Vallenari and Sara Lucatello, OAPd), This PhD project will be developed in collaboration with the team working on the ERC-funded project asterochronometry (https://www.asterochronometry.eu).

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 revolutionising 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 modellers, 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 in modelling and analysis is available at DIFA (A. Miglio and collaborators).

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

PhD project in ASTROPHYSICS

Title of the Project: Cosmological constraints from the cross-correlation of Gravitational Waves and galaxy catalogs

Supervisor : Michele Ennio Maria Moresco
Co-Supervisors : Federico Marulli, Andrea Cimatti

Scientific Case: The field of Gravitational Waves (GW) astronomy has been recently exponentially growing. Since the first detection of the electromagnetic counterpart of a GW events thanks to the LIGO and Virgo detection (LIGO Scientific Collaboration et al., 2017), many other events have been discovered. Currently, roughly 90 events have been found, and many more are expected with the improvements of the instruments in the Observing Run 4, and with various GW telescopes planned (Einstein Telescope, Cosmic Explorer). While the standard use of GW as cosmological probes is to use them as standard sirens (see Moresco et al. 2022), recently Mukherjee et al. (2020, 2021) proposed an alternative method that does not rely on directly identifying a redshift counterpart of the GW event. They show that studying the cross-correlation of GW sources with galaxies allows us to break degeneracies in the determination of the distance and redshift of the source, and infer the expansion history from redshift unknown gravitational wave sources. This method is really promising, since it provides a complementary use of GW sources that can be explored in view of the various incoming and planned GW facilities and galaxy surveys.

Outline of the Project: Following Mukherjee et al. (2020, 2021), the aim of this Ph.D. Thesis will be to develop a framework for the combined analysis of GW and galaxy catalog to extract constraints on the cosmological parameters and on the expansion history of the Universe. The project will be developed with the following steps: (i) get familiar with the basics and codes for GW cosmological analyses, to reproduce the constraints on cosmological parameters from standard sirens, (ii) get familiar with the clustering libraries, testing, validating, and optimizing for the case of GW-galaxies the cross-correlation module in the CosmoBolognaLib libraries, (iii) collect all the available data for GWs and galaxies surveys available (both real data and simulations) to build a library of catalogs for the project, (iv) apply the method to real and simulated data to extract constraints on cosmological parameters with current data and provide forecasts for future surveys (with a particular focus on the synergies between the ESA mission Euclid and future GW facilities such as Einstein Telescope), (v) extend the formalism with a Machine Learning approach as an alternative technique, comparing its results with the standard approaches both in terms of accuracy, feasibility, and performances.
The work will be based on the large knowledge of our group of galaxy clustering, starting from the developed libraries CosmoBolognaLib (Marulli, Veropalumbo, Moresco, 2016). In this work, both real and simulated data will be analyzed, taking advantage of the deep involvement of the DIFA cosmology group in the Euclid mission. The Ph.D. student will approach and strengthen knowledges in both galaxy clustering and gravitational waves cosmology and will be also introduced in Italian and international collaborations that study GW (such as Einstein Telescope) and exploit data resulting from the multi-wavelenght EM follow-ups of GW events (such as GRAWITA and ENGRAVE).

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

PhD project in ASTROPHYSICS

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

Supervisor : Michele Ennio Maria Moresco
Co-Supervisors : Andrea Cimatti, Federico Marulli

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

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

In this Thesis we will be explore both tcurrently available and simulated data, taking advantage of the synergies with new spectroscopic surveys such as Euclid, with which our group is heavily involved. Moreover, also the complementarities with other cosmological probes will be studied (see e.g. Moresco et al. 2022), to study how the combination of GW data with independent cosmological probes can be used to break parameter degeneracies and improve cosmological constraints.
The Ph.D. student will be also introduced in Italian and international collaborations that study GW (such as Einstein Telescope) and exploit data resulting from the multi-wavelenght EM follow-ups of GW events (such as GRAWITA and ENGRAVE).

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

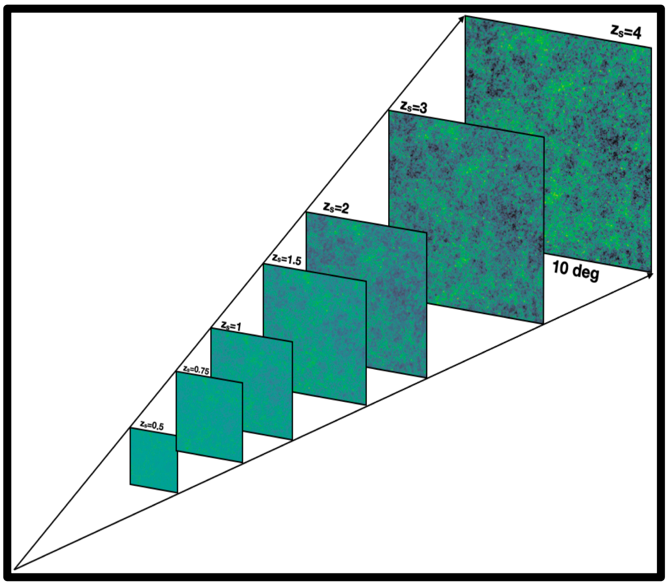
PhD project in ASTROPHYSICS

Title of the Project:
Detection of galaxy clusters and cosmic voids in Weak Lensing Simulations: paving the way to the ESA-Euclid Mission

Supervisor: Prof. Lauro Moscardini
Co-Supervisors: Dr. Carlo Giocoli, Prof. Federico Marulli, Priv.-Doz. Dr. Matteo Maturi

Scientific case:

Future wide-field surveys, like the upcoming **ESA-Euclid Mission, ready to be launched this summer,** will use **weak gravitational lensing** as a primary cosmological probe. The small modification of the intrinsic galaxy shapes, caused by the interposed matter density distribution, allows us to trace the growth of structure during cosmic time. The large number density of galaxies and sky coverage (n_g=30 galaxies per square arcmin observed on 15,000 square degrees) expected to be collected by the ESA-Euclid telescope will allow us to constrain cosmological parameters with unprecedented precision. This will open the possibility of using the weak lensing signal to detect and characterise overdense and underdense regions: galaxy clusters and cosmic voids. The accuracy and precision of these methods require the development of dedicated weak lensing light-cone simulations (see Figure) to improve methods and modellings.



Weak Lensing light-cone simulations that will be used as cosmic reference laboratories in this PhD Thesis. The field-of-view has an aperture of 10 deg on a side and extends up to z=4.

Outline of the Project:

The PhD student will dedicate the initial period of her/his project to construct dedicated **weak lensing Euclid simulations** using the available tools and data-sets available in our group. This will be done using projected matter density distributions from cosmological numerical simulations and shooting rays using the ray-MapSim routine (Giocoli et al. 2015). The constructed shear and convergence maps will be used to extract a Euclid-like shear catalogue of sources assuming the expected nominal depth of 24.5-24 mag in the VIS instrument of Euclid, building up a dedicated database.
Knowing the underlying galaxy cluster population, the PhD student will test the performance of an optimal filter-based algorithm to identify **galaxy clusters** using the shear catalogues. The feasibility of the method has already been demonstrated in a series of works (Pace et al. 2007 - as a pioneering analysis). The tool needs to be scaled and tested on more accurate and updated simulations. This second activity will give us the possibility to construct a cluster weak lensing selection function required to complement the photometric one (Sartoris et al. 2016) and to derive complementary constraints on the main cosmological parameters.
As galaxy clusters trace the overdensities of the projected matter density distribution, cosmic voids delineate the underdensities. As a third activity, the student will develop a new algorithm to **identify and characterise cosmic voids** using weak lensing information, paving the way toward new research topics (Fang et al. 2018, Sanchéz et al. 2017, Melchior et al. 2012).
The work activities performed during the PhD period will be based on various international collaborations our group in Bologna has and framed within different work packages of the **ESA Euclid Collaboration** (https://www.euclid-ec.org). In this way, the student will have great possibilities to interact with diverse scientists that will give her/him the appropriate skills for a fruitful career. A 3-6 month visit for scientific collaboration in one of the international institution involved in the collaboration will be planned during the PhD period.

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

PhD project in ASTROPHYSICS

Title of the Project: The physical properties of star-forming regions in lensed high redshift galaxies

Supervisor : Lauro Moscardini
Co-Supervisors : Massimo Meneghetti, Eros Vanzella, Francesco Calura

Scientific Case: In the first billion years of the Universe's lifetime, galaxies undergo a rapid assembly phase, changing their properties quickly. The period between redshift $z = 3 - 6$ represented a critical transition phase from the primordial Universe ($z > 6$) when the first sources ionized neutral hydrogen in the Inter-Galactic-Medium (IGM) and the peak of cosmic star formation rate when galaxies are mature ($z \sim 2 - 3$). **Studying this early epoch is essential to understand how galaxies assemble their mass** while building up the structures (star clusters, disks, bulges) observed in the local sources. Unfortunately, ***the bulk of galaxies at*** $z > 4$ ***cannot be resolved with current instrumentation, including the HST, preventing the study of their internal structure and individual star-forming complexes.***

These limits can be overcome using the magnification power of strong lensing galaxy clusters. They are entities of mass $\sim 10^{14} - 10^{15} M_{\odot}$, whose composition is ~85% DM and ~15% baryons. About ~90% of the baryons are hot, fully ionized gas, observable at X-ray, millimeter, and radio wavelengths. The remainder ~10% of baryons are in the form of stars. Being so massive, galaxy clusters are the most efficient gravitational lenses in the Universe. Their enormous gravitational potential can produce tens to hundreds of multiply lensed images of background sources, that sometimes appear as giant arcs. The lensing magnification provided by galaxy clusters makes background sources brighter and more prominent in the sky. Indeed, ***strong lensing can boost both the signal-to-noise ratio and the effective resolution of HST up to a few tens of pc***, enabling morphological analyses impossible in blank fields with the same observational set-up.

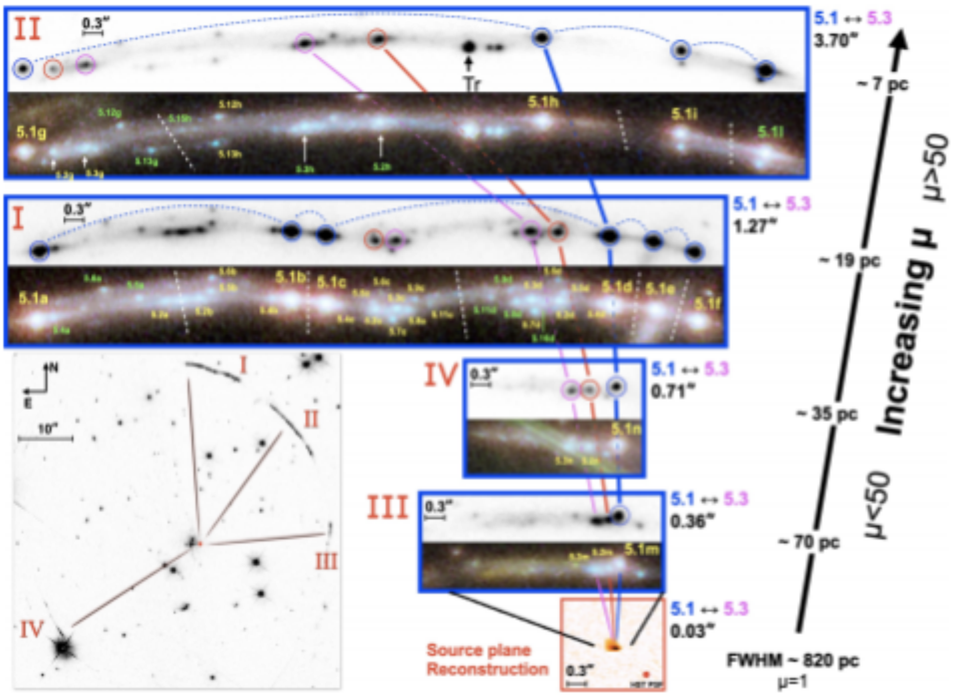

Figure : The Sunburst arc complex (z=2.37) in galaxy cluster PSZ1G311 (bottom left). Zooming on the four arc portions we see many star forming complexes which would remain undetectable without lensing magnification (bottom right). The colored lines show associations between multiple images of the same stellar clumps. From Vanzella et al. (2021)

The following years will open unprecedented opportunities to exploit cluster lenses for studying the distant Universe, thanks to upcoming experiments and instruments. For example, Euclid will discover several thousands of giant gravitational arcs like the one in Fig. 1. Other instruments, such as the James Webb Space Telescope (JWST) or even ground-based facilities equipped with new adaptive optics systems such as MAVIS@VLT and HARMONY and MAORY-MICADO at the E-ELT, will follow-up in great details these incredibly magnified sources.

Outline of the Project: This project aims at developing an analysis framework for studying and characterizing sources highly magnified by galaxy clusters.

1) By modeling a large set of strong lensing features, one can recover the mass distribution of cluster lenses down to galaxy scale. High-resolution mass mapping is the key to use galaxy clusters to de-lens high redshift sources and investigate their intrinsic physical properties. In this project, the candidate will work on developing high quality lens models of galaxy clusters using data from HST and MUSE@VLT.
2) The candidate will investigate what is the best approach to de-lens the magnified sources and measure their un-magnified properties using the lens models. For example, they will use the lens models to perform a forward modeling of the lensed sources or use other estimators of the lens magnification.
3) Very often, the lensed galaxies contain plenty of stellar clumps, whose properties (sizes, stellar masses, star formation rates, etc.) are particularly relevant to understand the mechanisms that drive galaxy formation and evolution in the early universe. Are they the remnants of merging galaxy satellites, or are they forming through gravitational instability of the galaxy discs? The candidate will identify star clumps in magnified sources and will study their properties to answer these questions.
4) Researchers in Bologna have developed sub-pc resolution cosmological hydrodynamic simulations of high redshift galaxies to resolve the star-forming regions fully (Fig. 2). The candidate will simulate the strong lensing effects of these galaxies and produce mock observations. We will focus on instruments that we will use to follow up exciting sources like, e.g., JWST or future telescopes with extreme adaptive optics systems like VLT/MAVIS or the E-ELT facilities (e.g., HARMONI and MORFEO-MICADO). These simulations will allow us to evaluate how accurately our methods can recover the properties of the sources.

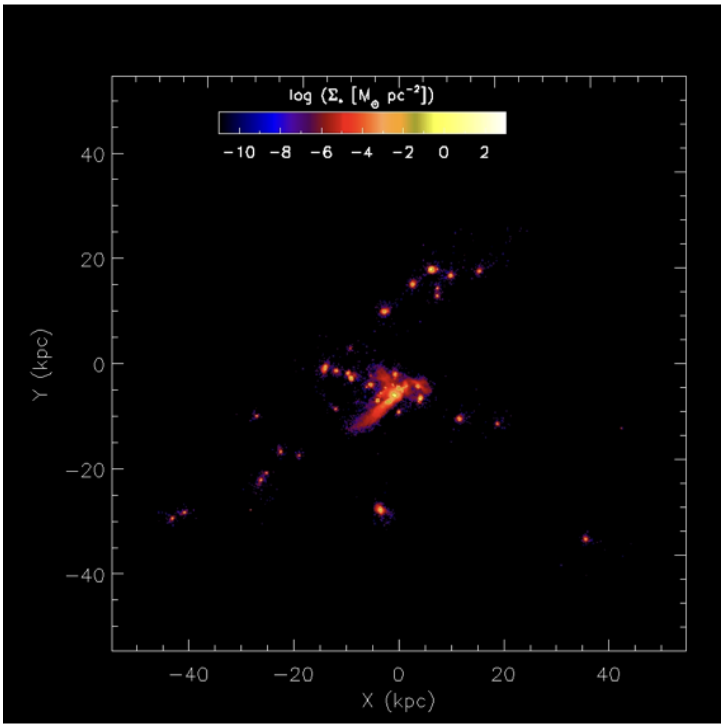

Figure : Snapshot (stellar density) at redshift z=6.14 of a sub-pc resolution simulation of a distant galaxy (Calura et al. 2022). Several stellar clumps with masses between and sizes of 10-100 pc are visible. The student will produce mock observations of these high-redshift sources.

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

PhD project in ASTROPHYSICS

Title of the Project:
Cosmology with Galaxy Clusters

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

Scientific Case:

Current and future wide-field photometric surveys (e.g. KiDS, Euclid, LSST) will provide the opportunity to increase dramatically the number of known clusters of galaxies, and explore new regimes at low mass ($M \sim 10^{14}\ M_{sun}$) and high redshift ($z > 1$). The scientific interest for these new samples of galaxy clusters is two-fold. On one side, the abundance and clustering of these structures constrain cosmology, because the cluster population bears the imprints of the statistical distribution of initial fluctuations, their subsequent growth and the dynamics of the collapse of dark matter haloes. On the other hand, the population of these clusters will be a unique laboratory where to study the evolution of galaxies in dense environments at various epochs.

This project can take two different flavors:

1. *Probing the spacetime structure of the Universe with Gravitational Redshifts in Galaxy Clusters*

Clusters of galaxies provide natural cosmic laboratories to perform direct measurements of gravitational redshifts, thus allowing us to **test the gravity theory on megaparsec scales**. Specifically, the gravitational redshift effect can be extracted from the **distribution of peculiar velocities of the cluster member galaxies** as a function of the transverse distance from the cluster centre. Extremely large and dense spectroscopic samples of galaxy clusters and associated cluster member galaxies are required to reach a sufficient precision to definitively discriminate the Einstein theory of General Relativity from alternative gravity theories. This prevented an extensive exploitation of this method in the past, but the situation is about to change thanks to the big wealth of data that will be provided by incoming missions, such as the ESA Euclid Telescope and the NASA Nancy Grace Roman Space Telescope.
The goal of the proposed PhD project is to take advantage of the new galaxy and cluster spectroscopic samples that will be available in the next future to perform new tests on the gravity theory with gravitational redshifts in galaxy clusters. The PhD student will first construct new spectroscopic cluster catalogues and characterize their main properties, in particular the cluster centres and the position of the cluster member galaxies. New software tools have to be implemented to compute this kind of measurements and perform the required statistical analysis. The pipelines shall be validated on simulated catalogues to check for all possible systematic uncertainties that might affect the analysis. The new implemented algorithms will be released within the CosmoBolognaLib, a large set of *free software* C++/Python libraries for cosmological calculations. The PhD student

will eventually provide new constraints on the gravity theory, possibly discriminating among alternative gravity frameworks.

Outline of the Project:

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

2. *Improving cosmological tools for cluster optical catalogues*

The project will be based on the galaxy cluster optical catalogues obtained with the code **AMICO** (Adaptive Matched Identifier of Clustered Objects), developed in Bologna and Heidelberg (Prof. Maturi). AMICO is based on the **Optimal Filtering technique**, which allows to maximise the signal-to-noise ratio of the clusters. AMICO has been selected as the first cluster detection code by the Euclid Consortium, and it is currently being used in different surveys (KiDS, COSMOS, JPAS, HSC, ...). The PhD project will consist of several steps.

Outline of the Project:

- **Application** of AMICO to galaxy catalogues from ongoing and upcoming surveys, with different depths, bands and redshift coverage. These include the first release of the **Euclid survey** (launch in July 2023), proprietary data (KiDS and DES), and public data (COSMOS, HSC, SDSS and CFHTLS). This will allow us to detect previously unknown clusters, as well as to perform a comparison with outputs of other algorithms in well-studied fields.
- **Optimisation and application of the cosmological pipeline**, which, starting directly from the AMICO catalogues and measurements of cluster counts and clustering properties, allows us to derive constraints on the main cosmological parameters through the different steps: selection function, likelihood, calibration of the relation between richness and mass, etc.
- Evaluation of the performances of the AMICO algorithm in identifying **protoclusters and galaxy clusters at very high redshifts;** optimisation of the code using suitable mock catalogues extracted from cosmological simulations.

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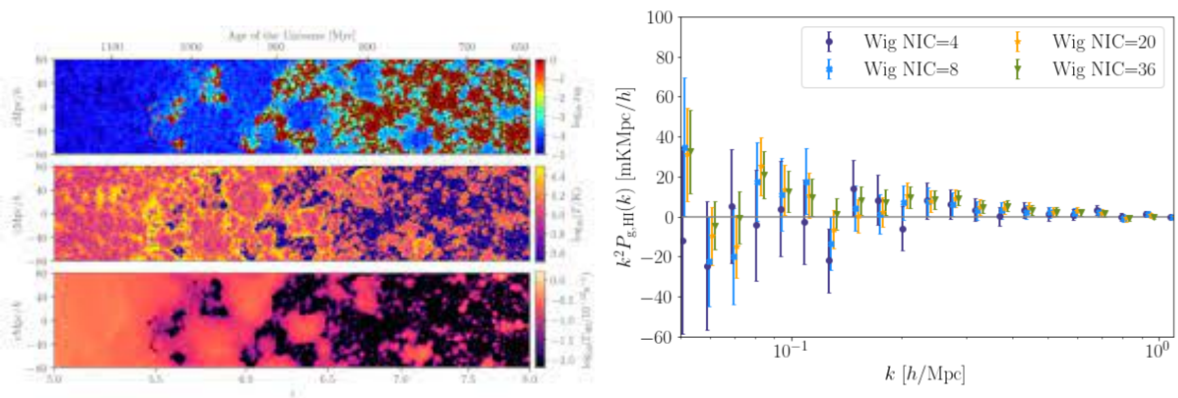
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: 21 cm cosmology

Supervisor : Prof. Lauro Moscardini
Co-Supervisors : Dr. Gianni Bernardi, Dr. Marta Spinelli

Scientific Case: Observations of the redshifted 21 cm line from neutral Hydrogen (HI) is one of the most powerful cosmological probes. At high redshift ($6 < z < 35$) the 21cm line allows to study cosmic reionization and the birth of the first stars and galaxies. At lower redshifts ($z < 6$) observations trace the cosmological distribution of dark matter web and, eventually, dark energy.



(*Left*): Example of a cosmological 21 cm simulation: evolution of the neutral hydrogen fraction (top), temperature of the intergalactic medium (middle) and photo-ionization rate emitted by galaxies (bottom). (Right): The detection of the HI signal using the cross-correlation of foreground cleaned GBT 21cm maps and WiggleZ galaxy survey (Wolz et al. 2021).

The two following projects are available for the candidate.

1. Characterization of the Cosmic Dawn and Epoch of Reionization.

This project is focused on observations of the 21 cm emission to constrain the thermal and ionization evolution of the intergalactic medium (IGM) in the $6 < z < 30$ range. The student will analyze state of the art observations taken with dedicated telescopes (HERA, LEDA, REACH) in order to detect (or place the most stringent upper limits on) the (so far undetected) signal. A detection will open up a new window on the first billion years of the Universe's history, allowing us to derive the properties of stars and galaxies in the first billion years (their mass, luminosity, dark matter halo function), their evolution and the timing of reionization.

Project outline:

- analysis of observations using existing pipelines, initial power spectra, assessment of systematic limitations due to systematic effects;
- development of techniques for improved foreground subtraction/modeling systematic effects;
- re-analysis to obtain improved power spectra and parameter constraints evolution (in particular in the $12 < z < 30$ range): evolution of the temperature and ionization of the IGM, constraints on the heating mechanism of the early IGM, measurement of the DM halo mass function.

2. Unveiling the large scale structures using 21cm Intensity Mapping.

Large cosmological volumes can be probed within reasonable amounts of telescope time by exploiting the technique of Intensity Mapping (IM): the signal is integrated in large sky pixels without resolving individual HI galaxies, too faint for a direct detection. The measurement and interpretation of the HI IM signal is the next frontier of cosmology and one of the main observational programmes at the MeerKAT telescope, located in the Karoo outback in South Africa. MeerKAT has recently started its observing campaign that will eventually lead to exquisite measurements of the growth of structures, the angular diameter distance and the Hubble rate. The success of HI IM observations heavily relies on the ability to separate the cosmological signal from the strong foreground emission. The student will work on the foreground separation and will carry out simulations to test the accuracy of the subtraction. The candidate will also explore the cross-correlation with optical galaxy surveys in order to enhance the detection significance by suppressing systematic effects.

Project outline:

- construction on MeerKAT specific mock 21cm intensity maps and use of existing mock galaxy catalogues for cross-correlation;
- exploitation of existing foreground sky models to be adapted to IM frequencies and application of state-of-the art cleaning techniques on simulations;
- cosmological parameters forecasts;
- application of cleaning techniques on 21cm data: power spectra and detection/upper limits.

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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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

PhD project in ASTROPHYSICS

Title of the Project:
Chemical characterization of the Local Group: identifying the chemical DNA of Milky Way satellite galaxies
Supervisor : Prof. Alessio Mucciarelli (DIFA)
Co-Supervisors : Carmela Lardo (DIFA), Davide Massari (INAF)

Scientific Case:

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

Outline of the Project:

The PhD project is aimed at describing the chemistry of Milky Way satellites (like the Sagittarius dwarf galaxies, the Large and Small Magellanic Clouds), nearby isolated dwarf galaxies and ultra-faint dwarf galaxies. The chemical DNA of these galaxies will be compared with that of the Milky Way. In particular, the chemistry of field and globular cluster stars of these galaxies will be used to reveal possible past merger events occurring in their history and to shed new light on the chemical composition of the past merger events contributing to assembly our Galaxy.
The project will benefit from proprietary and archival high-resolution spectra obtained with ground-based telescopes (i.e. VLT, LBT,Subaru,Keck) that will be analysed to derive a complete screening of the chemical properties of these stars (see Minelli et al. 2021a,b for some examples of the adopted approach).

Foreseen milestones and deliverables

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

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

PhD project in ASTROPHYSICS

Title of the Project: *Very metal-poor stars as local relics of the ancient Universe*
Supervisor: Prof. Alessio Mucciarelli (DIFA)
Co-supervisor: Dr. Carmela Lardo (DIFA)

Scientific Case:

The Big Bang essentially produced H, He, and a small amount of Li. Metals (e.g. elements heavier than He) are produced by stars and recycled from one stellar generation to the next within galaxies. As a result, more and more of all elements were made with cosmic evolution. The first stars ever formed (Pop III stars) ended the Dark Ages of the Universe, with their fresh input of light and ionising radiation. In spite of their importance, most of our knowledge of Pop III stars is only based on theoretical models and numerical simulations, simply because they cannot be observed directly.
The most metal-poor objects born from the ashes of the first stars, formed when the cosmos was almost devoid of metals (e.g., the most metal-poor star detected so far has ~1/10’000’000 of the solar iron abundance) and they are the oldest objects we can reach. *As a matter of fact, the oldest, most metal-poor stars in the field of the Milky Way (MW) offer us our most detailed view on the physical and chemical conditions of primordial star formation through their kinematics and chemical abundances.*

Outline of the Project:

The investigation of the properties of long-lived stars in the MW provides complementary insights into key processes (e.g. the physical conditions at the earliest times, the nature of the first stars, and the formation of the elements along with the involved nucleosynthetic processes) that cannot be obtained by studying distant and faint objects at high-redshifts.
Many open issues of modern astrophysics can be tackled thanks to the accurate chemical tagging of metal-poor stars:

- By coupling chemical abundances with kinematics from Gaia, we can gain an understanding of the Halo formation process and the assembly mechanism of the Galaxy.
- Dwarf galaxies contain a significant fraction of the known metal-poor stars. By comparing their abundances to those of stars in the MW Halo, we can directly test whether primordial chemical evolution was an universal process and understand the relation between dwarfs and the *building blocks* of the Halo.
- Abundances of very metal-poor stars can be compared with theoretical Pop III supernova yields to constrain star formation at high redshift and the properties of the first supernovae. A detailed chemical analysis of neutron- (*n*-)capture elements is key to work out details of *n*-process nucleosynthesis (e.g., the contribution of rapid *n*-capture to the abundances of post iron-peak elements, frequency of neutron star mergers, mass transfer in binary systems).

Finally, the proposed project will benefit from high-quality spectra collected at the Very Large Telescope and data from the Gaia space mission. Also, the state-of-the-art techniques for abundance analysis of high-resolution spectra will be employed to derive precise stellar parameters and abundances for a statistically significant sample of very metal-poor stars.

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PhD project in ASTROPHYSICS

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

Supervisor: Carlo Nipoti (UniBo)

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

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

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References:

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- Sotira, S., 2022, Master Thesis, University of Bologna
- Toomre A., 1964, ApJ, 139, 1217

Bologna, 20/2/2023

PhD project in ASTROPHYSICS

Title of the Project: *Hydrodynamic simulations of Terzan 5 and BFFs*

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

Scientific Case

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

Outline of the Project

To explain the formation of the complex stellar populations of Terzan 5 and its analogues, we propose to use three-dimensional hydrodynamic simulations and model the encounter of an old stellar population with a reservoir of cold gas, such as a molecular cloud.
We propose to use a customized version of the RAMSES code (Teyssier 2002) which includes basic yet realistic physical ingredients, such as radiative cooling, star formation, feedback and chemical enrichment (Lacchin et al. 2021; Calura et al. 2022).
The results of the simulations will be compared with the observational properties of these systems, including their abundance pattern and colour-magnitude diagrams, in an effort to make significant progress in our understanding of the complex history of the BFFs.

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References:

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Bologna, 20/2/2023

PhD project in ASTROPHYSICS

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

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

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

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

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References:

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

Bologna, 20/2/2023

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

PhD project in ASTROPHYSICS

Title of the Project: ***Rotation of the intracluster medium: theoretical models and observational perspectives***

Supervisor : Carlo Nipoti (UniBO)
Co-Supervisor : Stefano Ettori (INAF-OAS Bologna)

Scientific Case:
The intracluster medium (ICM) is mainly supported against gravity by pressure. However, due to the relatively poor spectral resolution of the currently available X-ray spectrographs, the available observational constraints leave open the possibility that the ICM rotates with significant rotation speed, which is also expected on the basis of cosmological hydrodynamic simulations. Rotation of the ICM could be an important ingredient in understanding the so-called hydrostatic mass bias, i.e. the mismatch between cluster mass estimates based on hydrostatic equilibrium and the true underlying mass as evaluated by less biased proxies like the gravitational lensing. But also the stability properties of the ICM can be drastically modified in the presence of rotation, with important implications for the dynamics and evolution of the central gas distribution of the galaxy clusters with cool-core.

Outline of the Project:
The student will build models of rotating ICM in equilibrium in a cluster dark matter halo of given gravitational potential, considering both cool core and non-cool core clusters. The dark matter halo will be modelled as physically consistent analytic axisymmetric density-potential pair, with density distribution consistent with theoretical expectations and observational findings. The ICM models will be required to be realistic in terms of ellipticity, gas density and temperature profiles. The student will realize mock X-ray observations of the ICM models to compare them to currently available images and spectral data of observed clusters and to make predictions for future X-ray instruments, such as those that will be onboard the XRISM (expected launch in 2023) and the next ESA Large Mission Athena (launch in 2030s) satellites. The linear stability of the models will be studied taking into account the combined effect of rotation, stratification, radiative cooling and thermal conduction, in the presence of weak magnetic field. For linearly unstable models the consequences of the instabilities will be studied either analytically or numerically (with hydrodynamic simulations), focusing in particular on the evolution of the central regions of cool core clusters.

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Bibliography:
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Bologna, 20/2/2023

PhD project in ASTROPHYSICS

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

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

Scientific Case:

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

Outline of the Project:

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

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References:

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- Efstathiou, G., Lake, G. and Negroponte, J., 1982, MNRAS, 199, 1069-1088
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Bologna, 20/2/2023

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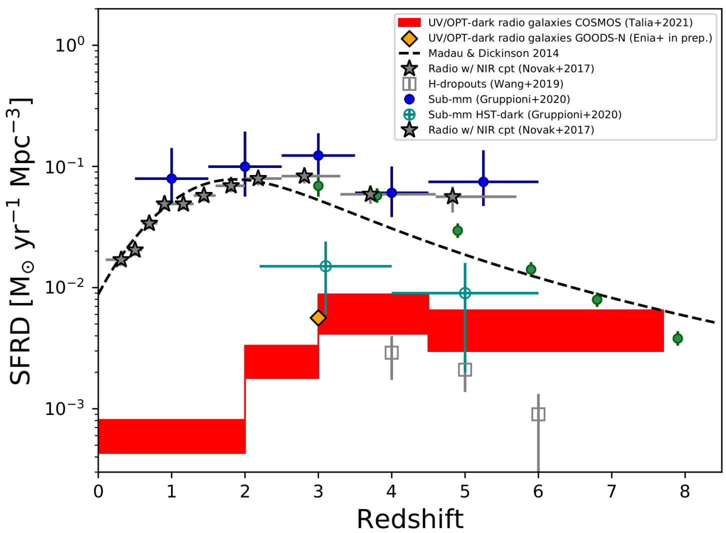
DIPARTIMENTO DI FISICA E ASTRONOMIA
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: *Illuminating the Dark Side of Cosmic Star Formation*
Supervisor : Margherita Talia (DiFA) margherita.talia2@unibo.it;
Co-Supervisor : Francesca Pozzi (DiFA)
Collaborators : galaxy evolution groups at UNIBO-DIFA, INAF-OAS and INAF-IRA.

Scientific Case One of the main questions in modern astrophysics is understanding the formation of galaxies and their evolution through cosmic time. Our current knowledge of cosmic star-formation history during the first two billion years is mainly based on galaxies identified in rest-frame ultraviolet light. However, this population of galaxies is known to under-represent the most massive, dust-obscured galaxies, whose contribution to the star-formation is still largely unknown, especially at high redshift (z>3). In recent years, the quest for such galaxies has been carried on by adopting various selection criteria at different wavelengths, from mid-infrared (Wang et al. 2019), to sub(mm) (Franco et al. 2018, Gruppioni et al. 2020) and radio (Talia et al. 2021, Enia et al. 2022), but a consensus has not been reached yet.

Outline of the Project The objective of the project will be to determine the contribution of dust-obscured, massive galaxies to the cosmic star-formation rate density and to study their physical properties and evolutionary path.
The project will consist of the following steps.
(1) A search for galaxies that are invisible at optical and near-infrared wavelengths using two different approaches: the so-called H-dropout technique (Wang et al. 2019) and a radio selection (Talia et al. 2021). In particular, the search will be conducted in the Euclid deep and calibration fields by exploiting both the public Spitzer data from the Cosmic Dawn Survey (Moneti et al. 2022), the private radio data from the MIGHTEE survey (Hale et al. 2023), complemented by the wealth of multi-wavelength data available in those fields.



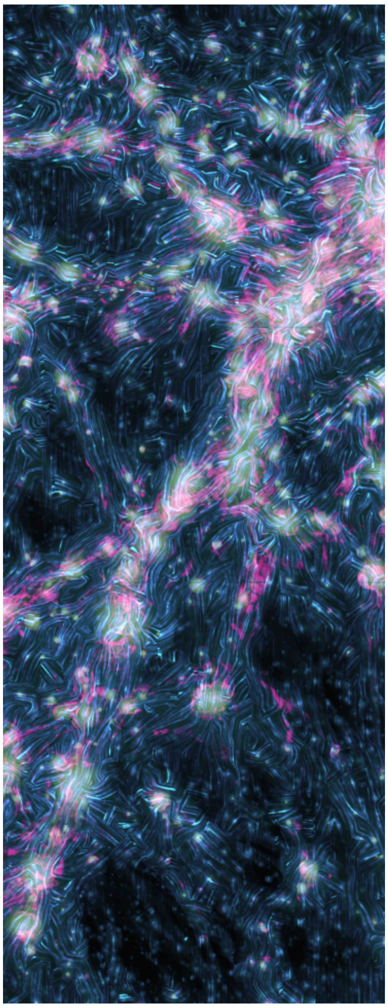
(2) Estimating redshift and physical properties (LIR, SFR, stellar mass, extinction, dust temperature) of the selected galaxies with SED fitting.
(3) Estimating their contribution to the cosmic star formation density (see Figure) and comparison with theoretical models (Illustris, Millennium) to investigate the evolutionary links with present-day ETGs.
The PhD student will learn how to make the best use of multi-wavelength data and to interpret them to constrain galaxy physics and evolution. Moreover, he/she will gain expertise in observing proposal writing and will acquire the scientific expertise and independence needed to continue her/his career successfully at international level.

PhD project in ASTROPHYSICS

Title of the Project: **Simulating the Relativistic Universe on Supercomputers**
Simulazioni dell'Universo Relativistico con Supercomputers

Supervisor : Prof. F. Vazza
Co-Supervisors : Dr. C. Gheller

Scientific Case: Several exciting recent low-frequency radio observations of the cosmic web (e.g. Vernstrom et al. 2023; Cuciti et al. 2022; Govoni et al. 2019) call for an update of theoretical models to study how relativistic electrons are seeded on the largest scales in the Universe. Cosmological simulations are the ideal tool to test new acceleration theories, and the next generation must couple the evolution of galaxies to their relativistic feedback output (via jets or winds) as well as to the modelling of diffuse acceleration processes ("a la Fermi") acting on the accreted plasma. To match the large sky volume and level of detail proved by new satellites (e.g. Euclid, JWST) and colossal facilities on the ground (e.g. the Square Kilometre Array) we need to deploy new, ambitious cosmological simulations capable to scale on the largest High Performance Computing facilities and adopt innovative numerical approaches.
In this project, the PhD candidate will work at the testing, design and production of simulations of relativistic processes (like injection of relativistic electrons from shocks, radio jets and galactic activity) tailored to scale on tens of thousands of computing nodes equipped with modern Graphic Processing Units (GPU), and study the observable properties of state of the art models of the relativistic particle content of our Universe.



Outline of the Project: The PhD candidate will work at the design, testing and production of new large cosmological simulations optimised to run on large HPC facilities like LEONARDO (Cineca), and increase both the variety of physical mechanisms, and the total statistics of simulated objects.
The candidate will learn new numerical methods to evolve families of cosmic rays, account for their dynamical impact on the surrounding gas, and compute their observational signatures in the radio and gamma-ray band.
The candidate will be involved in the ongoing observational and numerical activities of the PI's group (https://cosmosimfrazza.eu/erc-magcow) and will have the chance of producing new exciting numerical simulations on some of the largest Supercomputers in the world. This project calls for candidates with experience (or curiosity) in numerics, theory and large-scale structure dynamics.

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PhD project in ASTROPHYSICS

Title of the Project: Tracing the Early Cluster Assembly with Accreting Black Holes in Enourmous Lyα Nebulae at z>2

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

Scientific Case: Cosmological numerical simulations provide a clear picture of how dark matter drives the formation and evolution of galaxy clusters across cosmic time. A nascent cluster begins to collapse in the highest peaks of the matter density field and then grows hierarchically through a process of accretion and mergers of small haloes streaming along Mpc-sized filaments. Such "proto-clusters" (the ancestors of today's massive clusters) are usually identified as large galaxy overdensities at z>1.5−2. Their study provides a window into the early baryonic processes that led to the formation of today's massive galaxies and their transformation in dense environments. These processes involve galaxy mergers and interactions, fueling and growth of supermassive black holes (SMBHs) at their centers, and energy injection from SNe explosions and Active Galactic Nuclei (AGN) into the interstellar medium of cluster galaxies and the intracluster medium.

Outline of the Project: The main goals of the proposed PhD project are (a) understanding how SMBHs form and grow within early cosmic structures and (b) whether and how AGN feedback processes affect the transformation of these structures across cosmic epochs. The PhD candidate will consider proto-clusters at z>2 around powerful AGN selected primarily from the detection of enourmous (>200 kpc) Lyα nebulae (ELANe); for these structures, a wealth of multi-band information, including data from Chandra, VLT/MUSE, HST, ALMA and SCUBA2, has been already collected. She/he will start from the analysis of the proprietary Chandra data (large program; PI: F. Vito) in the quest for (i) faint AGN residing within these dense environments, thus providing a complete census of the AGN population and measuring their contribution to the ELAN powering, and (ii) signatures of diffuse X-ray emission that may give insight on both AGN feedback and on the dynamical status of the structure, as recently carried out for the Jackpot nebula at z=2.
For the proto-clusters with the richest multi-wavelength coverage, the candidate will also investigate the physical properties of the population of non-active galaxy members (e.g., star formation rate, stellar and molecular mass) and determine whether and how the presence of AGN activity in the same region affects their properties. The results will be compared with those in the literature that have been obtained in similarly overdense structures and in the field, i.e. in average density regions, as well as with the expectations from numerical simulations.

The PhD candidate will be trained in the formation and assembly of galaxy clusters, and AGN physics and demography. She/he will learn how to handle multi-band data catalogs and to analyze and interpret data from different instruments (e.g., Chandra, XMM-Newton, VLT/MUSE, HST, ALMA, JWST). She/he will gain expertise in proposal writing, acquire scientific independence, present the work at international conferences, and have the opportunity to visit renowned research Institutes and Universities.

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

PhD project in ASTROPHYSICS

Title of the Project: The realm of dual super-massive black holes

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

Scientific Case: Searching for AGN signatures in dual super-massive black holes (SMBHs) and characterizing their nuclear activity in the multi-messenger era.

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

The current PhD project will focus on (a) the occurrence of dual and offset AGN by cross-matching large-area optical/near-IR survey galaxy pairs/multiplets with Chandra and XMM-Newton catalogs and infer the level of nuclear activity via multi-wavelength data; (b) an extensive search for dual AGN in some of the deepest X-ray fields currently available, expanding the view to high redshifts; (c) an intensive study of the currently known dual AGN in terms of BH mass ratio and host galaxy (and environment) properties. The PhD student will also be introduced to the analysis of MUSE, ALMA, HST, VLT data to fully characterize dual AGN and their hosts. The derived source demography and physical properties obtained through multi-wavelength data will be interpreted and placed in a coherent picture using state-of-the-art numerical simulations.
The PhD student will gain significant expertise in data analysis and interpretation and writing proposals; she/he will acquire scientific independence, present the work at national/international conferences, and have the opportunity to visit renowned research institutes and universities inside the collaboration.

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

PhD project in ASTROPHYSICS

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

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

Scientific Case: While the physics of accretion in quasars at low redshift has been widely investigated in the last decades and has provided a generally accepted picture, at high redshift the situation is far less clear. Probing accretion in luminous quasars at z=2−7 is fundamental to investigating the strict interplay between the disc UV emission and that of the X-ray emitting corona at the highest accretion rates, verifying whether different accretion-disc solutions may be at play (with relevant consequences for the seed black hole topic), and assessing, from a physical and demographic perspective, the role of quasar-driven feedback in shaping galaxies in the early times of the Universe.

Outline of the Project: In this project, accretion physics is tackled by adopting a twofold approach, namely using (a) the sample of WISE/SDSS selected hyper-luminous ($L_{bol}>10^{47}$ erg/s) quasars at z∼2−4 and (b) the sample of hyper-luminous quasars at the epoch of reionization (HYPERION, z>6), which were recently granted a multi-year XMM-Newton Heritage program (PI: L. Zappacosta). All of these quasars are characterized by large Eddington ratios (L_{bol}/L_{Edd}), thus probing accretion at its 'extremes', and have multi-wavelength data allowing for a comprehensive investigation of their properties. We aim at studying (a) the nature of X-ray weak quasars at z∼3 (∼30% of the population) and their occurrence at earlier cosmic epochs, thus providing an interpretation in the context of accretion-disc physics of highly accreting SMBHs; (b) the relations among the X-ray luminosity, the disc/corona emission and the blueshifted velocity of the CIV line, which have direct implications for the launching mechanism of accretion-disc winds; (c) the relations between the presence of broad absorption line features in UV spectra and the multi-band spectral and photometric nuclear properties; (d) the properties of quasar host galaxies (e.g., star-formation rates, molecular gas content) via spectral energy distribution fitting and millimeter (ALMA) observations.
Further extension of this work may be provided by a systematic spectral analysis of the quasar properties at z∼2−4 from serendipitous archival Chandra and XMM-Newton observations. The overall properties of the analyzed quasars will be finally compared with those of local AGN to get a comprehensive view of accretion across cosmic time.

The PhD student will gain invaluable expertise in multi-wavelength data analysis and interpretation, in preparing observing proposals, and in presenting the work at national/international conferences. She/he will join the WISSH and HYPERION collaborations and take advantage of the interactions with researchers of Italian and foreign institutes, thus extending her/his knowledge in this research field, which has a brilliant future in the era of forthcoming ground- and space-band facilities (e.g., Vera C. Rubin Observatory, Roman Space Telescope, Athena).

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