DIFA projects
PhD Cycle 38

DIFA(UNIBO) – Project 1

Testing fundamental physics with numerical simulations of the cosmic large-scale structures

Supervisor: Dr. Marco Baldi

Contact: Prof. Marco Baldi, marco.baldi5@unibo.it

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

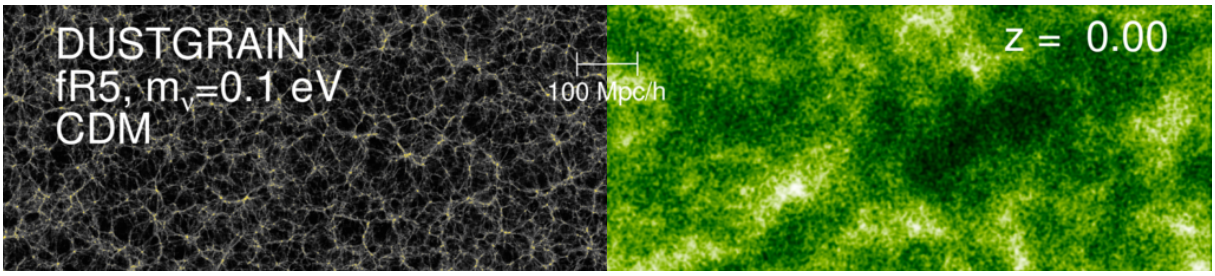
PhD project in ASTROPHYSICS

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

Scientific Case:
The standard cosmological model (known as ΛCDM) has provided 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 models for cosmic acceleration 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 alternative descriptions of cosmic acceleration, such as Dark Energy and Modified Gravity models, 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**, 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;
- **Effective modifications of gravity**: implementing and testing parameterised models of non-linear screening, Interacting Dark Energy, Clustering Dark Energy;
- **General Relativistic Simulations**: extending current Newtonian N-body simulations codes to include a fully relativistic treatment of gravity

The choice of the specific models 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.



The large-scale CDM (left) and neutrinos (right) distribution of the DUSTGRAIN simulations — featuring f(R) Modified Gravity and massive neutrinos — run with the MG-Gadget code

More specifically, the student will:
- **develop highly scalable and memory efficient modules** for one (or more) of the models listed above into the Gadget3 (C) code, or possibly also into the recently-released Gadget4 (C++) code;
- **Run large-scale and high-resolution simulations** (see the example figure above) 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, LSST**: galaxy clustering; clusters and void abundance; weak lensing statistics and cross correlation with clustering statistics; CMB lensing and Integrated Sachs-Wolfe effect

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DIFA(UNIBO) – Project 2

Studying massive quiescent galaxies at z=2 with the James Webb Space Telescope

Supervisor: Sirio Belli

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PhD project in ASTROPHYSICS

Title of the Project:

Studying massive quiescent galaxies at z=2 with the James Webb Space Telescope

Supervisor: Sirio Belli

Scientific Case: The formation of massive galaxies and the "quenching" (i.e., shutdown) of their star formation activity are among the least understood phases in the history of galaxy evolution. The quenching process is likely connected to energetic feedback from supermassive black holes, but may also involve other physical mechanisms, such as galaxy mergers. To understand these processes we need to study the physical properties of massive galaxies close to the epoch of quenching, which is at redshift $z\sim2$, a key epoch called "Cosmic Noon". The optical spectra of these galaxies are redshifted into the near-infrared, where observations are particularly challenging due to the Earth's atmosphere. The launch of the James Webb Space Telescope (JWST) will soon revolutionize near-infrared astronomy, and will enable a detailed study of the spectra of high-redshift galaxies before, during, and after quenching.

Outline of the Project: The *Blue Jay Survey* (PI: Sirio Belli) is a medium-size JWST program approved for Cycle 1. It will collect deep spectra for about 150 high-redshift galaxies and characterize both stars and gas in different types of galaxies. The PhD student will join the *Blue Jay* team (which includes collaborators from USA, Canada, and Australia) and will play a key role in the scientific analysis of JWST spectra. This PhD project focuses on the analysis of a subset of about 20 massive quiescent galaxies, for which JWST will detect several absorption lines. Using advanced spectral fitting techniques based on Bayesian methods, the student will analyze the JWST data and investigate the stellar populations of high-redshift quiescent galaxies, with two major goals:

1) Measure the distribution of stellar ages, and derive the quenching timescale, which is one of the most important constraints for models of galaxy quenching. We will test whether all galaxies have similar timescales or, as suggested by recent observations, galaxies follow either a fast or a slow quenching channel.
2) Measure the abundance of Mg (which is mostly produced in young type II supernovae) and the abundance of Fe (mostly formed in type Ia supernovae). From the ratio of these two elements it is possible to determine the rapidity of galaxy formation, and investigate the phase that preceded quenching.

Given the availability of unique spectroscopic data from JWST, this project will substantially improve our understanding of how massive galaxies formed.

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DIFA(UNIBO) – Project 3

Magnetic fields in galaxy clusters

Supervisor : Annalisa Bonafede Co-Supervisors : Chiara Stuardi, Franco Vazza

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PhD project in ASTROPHYSICS

Title of the Project: Magnetic fields in galaxy clusters

Supervisor : Annalisa Bonafede
Co-Supervisors : Chiara Stuardi, Franco Vazza

Scientific Case:
The advent of new radio facilities, such as LOFAR (the LoW Frequency ARray) and MeerKAT, has opened new windows for the study of magnetic fields on the large-scale structure. At the same time, new techniques have been developed to map the magnetic field on largest scales in our Universe. Galaxy clusters host spectacular radio emission generated by magnetic field interacting with ultra-relativistic electrons. This radio emission comes in a variety of shapes, and is linked to the dynamical status of the cluster. Some merging clusters host radio relics, arc-like structures with the size of ~1 Mpc , linked to shock waves that develop in the intra-cluster medium during mergers. The properties of the magnetic field in these relics and the mechanism for particle acceleration are yet unknown.

Outline of the Project:
The PhD candidate will use radio observations taken with LOFAR and MeerKAT to investigate the properties of magnetic field in radio relics and in their host clusters.
Data will be used in combination with numerical simulations and theoretical models to constrain the properties of magnetic fields, the allowed scenarios for cosmic magneto genesis, and the particle-acceleration mechanisms.
The projects itself is flexible, and different leverage will be given to observational, numerical, or theoretical parts depending on the candidate attitudes and preferences.
The PhD candidate will be part of a larger group built around the project DRANOEL (*Deciphering RAdio NOn-Thermal Emission on the Largest-scale* **https://annalisa-bonafede.myfreesites.net/erc-stg-project-dranoel** *)* financed by the European Research Council (ERC-2016-STG 71425). The PhD candidate will work in close contacts with the other group members and will be part of the LOFAR cluster working group within the Survey key science project. The PhD candidate will also be involved in international working groups, and travels to visit collaborators in the Netherlands, Germany, and USA are planned.

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DIFA(UNIBO) – Project 4

The large scale structure of the Universe at ultra low radio frequencies

Supervisor : Annalisa Bonafede Co-Supervisors: Francesco de Gasperin

Contacts: Francesco de Gasperin fdg@ira.inaf.it

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PhD project in ASTROPHYSICS

Title of the Project: The large scale structure of the Universe at ultra low radio frequencies

Supervisor : Annalisa Bonafede
Co-Supervisors : Francesco de Gasperin

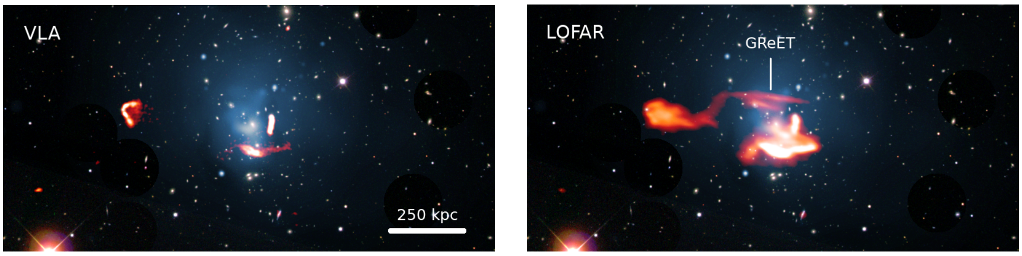
Scientific Case: Within the large scale structure of the Universe, enormous amounts of energy linked to the formation and growth of the cosmic web and the activity of powerful active galactic nuclei (AGN) are dissipated through processes such as turbulence and shock waves. These processes have a fundamental impact on the evolution of galaxy clusters. Their effect can be traced with radio telescopes.
In particular, the ultra-low radio frequencies are unique probes to study galaxy clusters. In this regime, cluster-scale radio sources can be traced for hundreds of megayears, allowing us to explore their long-term impact on the cluster environment. Furthermore, low-efficiency processes, invisible at higher frequencies, shine bright at these wavelengths. However, because of the complexity of the observations, the ultra low-frequencies are one of the last uncharted observational windows of the cosmic electromagnetic spectrum.

Outline of the Project: The candidate will use data from the Low Frequency Array (LOFAR; www.lofar.org) at ultra-low frequencies (<100 MHz or several metre wavelength) to study galaxy clusters and the large scale structure of the Universe. The student will have to work with a massive amount of data, using and developing advanced computing techniques in supercomputers. A certain skill/interest in coding and using novel technologies such as machine learning is an asset.
For the interpretation of the results, and depending on the candidate's attitude, the project can be tuned to leverage the observational (radio, X-ray), computational (MHD simulations) or theoretical (plasma physics and models of radio sources) part.
The PhD candidate will have privileged access to unique data from LOFAR and other radio telescopes as well as from eRosita. The candidate will be part of the LOFAR collaboration that includes >200 scientists from several European countries.

Collaborators: F. Vazza (simulations) and G. Brunetti, R. Cassano (theory).

Contacts:

- Francesco de Gasperin <fdg@ira.inaf.it>
- Annalisa Bonafede <annalisa.bonafede@unibo.it>



Radio observation of the galaxy cluster Abell 1033 at canonical frequencies (1400 MHz, VLA) and at low-frequencies (144 MHz, LOFAR). New phenomena are visible only at LOFAR frequencies. Credits: de Gasperin et al. (2017, Sci. Adv. e1701634)

DIFA(UNIBO) – Project 5

Physics of non-thermal components in galaxy clusters and the LOFAR revolution

Supervisor : A. Bonafede Co-Supervisors : G. Brunetti (IRA INAF)
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PhD project in ASTROPHYSICS

Title of the Project: Physics of non-thermal components in galaxy clusters and the LOFAR revolution

Supervisor : A. Bonafede
Co-Supervisors : G. Brunetti (IRA INAF)

Scientific Case: Galaxy clusters emit diffuse steep-spectrum synchrotron radiation due to relativistic electrons interacting with magnetic fields in their volume. This evidence poses important questions on the origin of non-thermal components and on their interplay with the thermal matter. In the last decade, we demonstrated a connection between the radio emission and the dynamics of galaxy clusters, suggesting that a fraction of the kinetic energy of dark-matter and baryons is channeled into magnetic fields and high energy particles. Mechanisms responsible for powering the non-thermal components involve turbulence and shocks operating in physical regimes that are still poorly explored. Thanks to its unprecedented sensitivity at low frequencies, LOFAR is achieving a breakthrough in the field, allowing us straightforward tests of theories and pushing studies into a completely new regime.
Outline of the Project: We propose two lines for a PhD project which combine data analysis and theoretical interpretation:
1. Formation rate of radio halos in galaxy clusters at different cosmic epochs
LOFAR surveys (LoTSS, LoLSS) are expected to detect about 1000 galaxy clusters extending the limited ranges of masses, redshifts and statistics, that are severely limiting present studies. Data from 5700 square degrees (DR2 area, 27% of the northern sky) are already available to our group. We plan to use the data from the 309 clusters of the PSZ2 catalog that are in this LoTSS-DR2 area to obtain unprecedented information on the statistical properties of diffuse emission in clusters. Importantly, we will investigate the occurrence of radio halos in an unexplored range of clusters masses and redshifts (up to z=1), obtaining fundamental constraints on the magnetic field amplification and particle acceleration, and testing current models.
Coll : R. Cassano, D. Dallacasa
2. Superclusters and radio bridges
LOFAR observations have discovered steep-spectrum diffuse radio emission from bridges of matter that connect pairs of massive clusters in a pre-merger phase. These radio bridges presumably trace dynamically active and vast filaments connecting massive clusters where turbulence amplify magnetic fields and accelerate relativistic particles. A statistical assessment of the occurrence of radio bridges and a firm measure of their radio spectrum is possible only with LoTSS and LoLSS data. During the project we plan to exploit the vast wealth of the available LOFAR data to step into this very new territory and to carry out a comparison with current models.
Stepping on even larger scales, radio emission from super-clusters would allow obtaining important information on the heating mechanisms in the large scale structures and in particular on the physics of turbulence, shocks and magnetic fields in these environments. In this project we plan to study the radio and X-ray emission from super-clusters
Coll : R. Cassano, F. de Gasperin, T. Venturi, D. Dallacasa, F. Vazza
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DIFA(UNIBO) – Project 6

Black Hole Weather:*Unveiling the micro and macro processes of SMBH feeding and feedback*

Supervisor: Marcella Brusa, Co-Supervisor: Massimo Gaspari (INAF)
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PhD projects in ASTROPHYSICS

Title of the Project: ***Black Hole Weather***
Unveiling the micro and macro processes of SMBH feeding and feedback

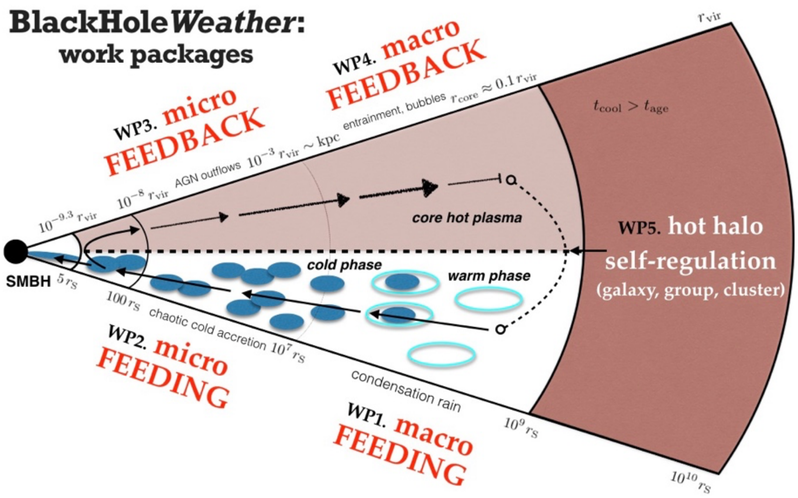
Supervisor: **Marcella Brusa** (DIFA; marcella.brusa3@unibo.it)

Co-Supervisor: **Massimo Gaspari** (INAF OAS; massimo.gaspari@inaf.it)

The project makes use of/develops numerical simulations: yes

Scientific Case: Most of the ordinary matter in the Universe is in the form of a tenuous gas which fills galaxies, groups, and clusters of galaxies (circumgalactic, intragroup, intracluster medium – CGM, IGrM, ICM). These cosmic atmospheres are shaped by complex thermo-hydrodynamical processes – akin to Earth weather – with the central supermassive black hole (SMBH) acting as cosmic thermostat over scales of 10 orders of magnitude. We have entered a Golden Age of multiphase gas detections continuously discovering ionized filaments (optical/UV), neutral gas (IR/21cm), and molecular clouds (radio) which rain/condense out of the hot X-ray halos, or are ejected via SMBH winds and jets. Many key exciting questions are currently matter of intense debate and await to be answered (cf. Gaspari et al. 2020 and references within, for a brief review).

Outline of the Project: *Black Hole Weather* program (PI: Gaspari) aims to tackle key challenges of modern astrophysics. One or more of these interlinked topics/working packages (WP1-5) can be chosen by the PhD candidate (see also the diagram to the right):



- WP1 – **macro feeding**: what is the evolution of the macro condensation out of the diffuse halos (CGM, IGrM, ICM) and tied formation of filaments, stars, and compact objects;
- WP2 – **micro feeding**: how the multiphase rain (a.k.a. chaotic cold accretion) is fed down through the SMBH horizon, e.g., via turbulent and collisional processes;
- WP3 – **micro feedback**: how the gas matter and energy is re-ejected back by the SMBH and deposited via active galactic nucleus (AGN) jets/winds, multiphase outflows, and radiation;
- WP4 – **macro feedback**: what is the role of turbulence, dust, cosmic rays, conduction, viscosity, and/or collisionless plasma physics;
- WP5 – **self-regulation**: how to link the SMBH feeding and feedback loop that shapes galaxies, groups, and clusters throughout the several billion years evolution.

Methods: *Black Hole Weather* includes three synergetic methodologies, which can be also focused on by the PhD candidate, again according to their interests and long-term career vision:

- numerical simulations: development of 3D high-resolution magneto-hydrodynamical (MHD) simulations, carried out with state-of-the-art astrophysical CPU or GPU codes (e.g., FLASH4, Athena++, Gamer2);
- synthetic observations: analysis of the above MHD simulations carried out with state-of-the art synthetic tools that reproduce detailed observations for current/next-generation multi-messenger observatories (e.g., *Chandra*, XMM, *Athena*, XRISM, HST, JWST, MUSE, ALMA, LISA);
- X-ray/optical/radio observations: reduction and analysis of real multiwavelength datasets aimed to tackle the above objectives, in particular studying hot halos (*Chandra*, XMM, *Athena*, XRISM), multiphase gas (HST, JWST, MUSE), and molecular clouds (ALMA) in a diverse range of galaxies, groups and clusters of galaxies.

DIFA(UNIBO) – Project 7

Constraining the expansion of the Universe with the oldest stars

Supervisor: Andrea Cimatti Collaborators: M. Moresco,
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PhD projects in ASTROPHYSICS

Title of the Project: Constraining the expansion of the Universe with the oldest stars
Supervisor: Andrea Cimatti (UNIBO-DIFA). **Contacts:** a.cimatti@unibo.it
Collaborators: M. Moresco, DIFA and INAF-OAS cosmology/galaxy evolution group.

Scientific Case

Measuring the expansion rate of the Universe (the Hubble parameter) is one of the key objectives of cosmology and of our knowledge in general. The current results are still limited, and the picture is complicated by the conflicting estimates of the Hubble constant (H_0) which show a >3σ tension. The ages of the oldest stars in present-day objects provide an independent test of the cosmological model as they give a lower limit to the age of the Universe. Accurate parallaxes from *Gaia* space mission and reliable measurements of stellar metallicity provide higher-precision age estimates of Galactic globular clusters and very-low-metallicity stars. These ages constrain the age of the Universe and H_0 independently of the cosmic microwave background. Further constraints come from the globular cluster ages in the oldest elliptical galaxies at z~0. Moreover, passive elliptical galaxies can be used as a function of redshift as *cosmic chronometers* to constrain, free from assumptions on the cosmological model, the expansion rate of the Universe from the relative stellar ages during the past ~8 Gyr of cosmic time (e.g. Moresco et al. 2012).

Outline of the project

This PhD thesis project aims at combining the results of different chronometric probes to reconstruct the expansion history of the Universe. Our group has an extended experience and is involved in international projects. The PhD student will benefit from our expert guidance. The main steps of this work can be outlined as follows.
(1) Collection of a sample of the oldest stars in the Galactic halo and in globular clusters in order to derive the oldest tail of their age distribution. This step will benefit also from the absolute distances derived thanks to the *Gaia* parallaxes.
(2) The ages of the oldest extragalactic globular clusters at z~0 (e.g. in M87) will be estimated through spectral fitting of their integrated spectra and with Lick indices.
(3) The local constraints on the age of the Universe based on steps (1)-(2) will be combined with late-time estimates of Ω_m to obtain a low-redshift (late Universe) H_0 determination that does not rely on assumptions on early Universe physics (CMB). It has been demonstrated that this approach is very promising (Jimenez, Cimatti et al. 2019).
(4) The evolution of the Hubble parameter $H(z)$ at $0<z<1$ will be derived based on the evolution of the relative ages of the oldest and passive envelope of ellipticals selected very carefully to avoid contamination from non-passive galaxies. The stellar ages of these systems will be estimated through a combination of full spectral fitting and Lick indices.
(5) Combination of the results of (1)-(4) with other cosmological probes (e.g. CMB, SNeIa, BAO, weak gravitational lensing) to improve the accuracy on cosmological parameters.

The PhD student will learn how to use *Gaia* data to constrain distances and ages of Milky Way stars, and how to extract metallicities and ages from the spectra of extragalactic globular clusters and passive galaxies. Moreover, she/he will have the opportunity to visit the institutes or universities abroad that are part of our collaboration network.
Overall, the PhD student will acquire the scientific expertise and independence needed to continue her/his career successfully at international level.

DIFA(UNIBO) – Project 8

Dynamics of galaxies in the Cluster Environment

Supervisor : Luca Ciotti

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PhD project in ASTROPHYSICS

Title of the Project: Dynamics of galaxies in the Cluster Environment

Supervisor : Luca Ciotti

Scientific Case: The internal dynamics of galaxies in cluster is affected by the environment, not only through high-velocity encounters with other galaxies, but also through the continuous effect of the cluster tidal field. Several phenomena associated with the interaction of galaxies with the tidal field of the parent cluster have been suggested in the literature, in particular the idea of *collisionless evaporation* (Ciotti & Giampieri 1998, Muccione & Ciotti 2004), in principle an important contributor to the formation of the Intracluster Stellar Population.

Outline of the Project: First part: analytical and numerical study of orbital resonances between stellar orbits in the galaxy outskirts and galaxy librations due to the cluster tidal field, extending the treatment to epicyclic oscillations of the galaxies. Second part: N-body simulations to explore quantitatively the effects of non-linear dynamics in the evaporation process.

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DIFA(UNIBO) – Project 9

The role of relativistic jets in the assembly of the first supermassive black holes: a multi-band approach

Supervisor : Prof. Daniele Dallacasa

Co-Supervisors : Dott. Marcello Giroletti (INAF-IRA), Dott. Giulia Migliori (INAF-IRA), Dott. Cristiana Spingola (INAF-IRA)

Contacts: Prof. Daniele Dallacasa (ddallaca@ira.inaf.it)

PhD project in ASTROPHYSICS

Title of the Project:
The role of relativistic jets in the assembly of the first supermassive black holes: a multi-band approach

Supervisor : Prof. Daniele Dallacasa
Co-Supervisors : Dott. Marcello Giroletti (INAF-IRA), Dott. Giulia Migliori (INAF-IRA), Dott. Cristiana Spingola (INAF-IRA)

Scientific Case:
Little is observationally known for individual objects located above redshift z = 6, when the Universe was young and the first sources (including active galactic nuclei, AGNs) ionised their surrounding gas in the epoch termed “cosmic reionization” (e.g., Zaroubi 2013). The Black Hole within the AGN detected at these cosmological distances has already masses exceeding 10^{8-9} $M_{\odot}$ (e.g., Vito et al. 2019) which are indicative of a fast and efficient growth, challenging supermassive black holes (SMBH) standard formation models (e.g., Volonteri 2012; Wu et al. 2015). About 10% of the entire AGN population is radio loud (Bañados et al. 2015; Padovani et al. 2017). Since they do not suffer from obscuration, they provide a unique opportunity to study the role of jets in the accretion of SMBH (e.g., Volonteri et al. 2015) and their feedback on the host galaxy (e.g., Fabian 2012). Furthermore, they test the cosmic evolution of the AGN radio luminosity function (Padovani et al. 2015) out to the largest distances and can also be used as cosmological probes (e.g., Gurvits et al. 1999). The radio-loud AGNs with their relativistic jets oriented along the line of sight (Urry & Padovani 1995) are termed blazars. Their non-thermal radiation is relativistically amplified, and not obscured along the jet direction. Therefore, they are visible up to high redshifts, allowing the study of the radio-loud AGN population across cosmic time (e.g., Ajello et al. 2009; Caccianiga et al. 2019). Indeed, our team has been recently involved in the identification of the highest redshift blazar (Belladitta et al. 2020), its follow-up at high angular resolution (Spingola et al. 2020), as well as the discovery of relativistic jets also in sources considered radio quiet (Sbarrato et al. 2021).

Outline of the Project:
The proposed PhD project will focus on defining/outlying the properties of the high-z blazar population in a statistically sound sample (as well as a control sample). The main steps of the plan are the following:
1.) Performing a multi-band analysis using state-of-the-art VLBI observations on a sample of radio quasars at z>5 to constrain the actual properties of the pc-scale radio emission in high-z blazars.
2.) Investigating the low-frequency (50-150MHz) emission of the sample. This will to constrain the story/lifetime of the radio emission is npc-scale emission is detected. LOFAR DR2 data have recently been released for ¼ of the northern sky and will be available for the project. The radio spectrum may show a low-frequency turnover, which can be used to assess the physical conditions (e.g. magnetic field) and the radiative mechanisms (e.g. FFA vs SSA) in AGN at these extremely high redshifts.
3.) High energy emission in the X-rays is an important tool to determine the physical properties within the AGN. Hard X-ray data will be used to study the properties of a sample of candidate and confirmed high-z blazars; new soft X-ray data from e-ROSITA will also be publicly available, for a complete view of the X-ray emission.

4.) The typical spectral energy distribution of high-z blazars makes their detection in gamma rays very challenging (current record holder being at z=4.3), with only a handful of blazars discovered at high-energy. All this information (detection/non detection) is however critical in definition of the emission mechanisms. A research on gamma-ray emission from high redshift blazar candidates will be performed, and predictions for future missions and ground-based instruments will complete the PhD Thesis topics.

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Dott. Cristiana Spiungola (spingola@ira.inaf.it)

DIFA(UNIBO) – Project 10

Substructure lensing at milliarcsecond angular resolution

Supervisor: D. Dallacasa
Co-Supervisor: Dr. C. Spingola – Dr. M. Giroletti (INAF-IRA)
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Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project: Substructure lensing at milliarcsecond angular resolution

Supervisor : Prof. Dr. D. Dallacasa (DIFA - UniBO), Dr. C. Spingola – Dr. M. Giroletti(INAF-IRA)

Scientific Case: the high number of low mass sub-halos predicted by simulations and the few dwarf galaxies observed around the Milky Way. This issue has become known as "missing satellite problem". It is unsolved to date. Strong gravitational lensing is a powerful way to investigate directly this problem at any high redshift by means of "anomalies" in the gravitational potential (and its derivatives) caused by the presence of satellites. The angular scale for detecting the astrometric anomalies due to the critical satellite population ($M \sim 10^6 M_\odot$) is of a few milliarcseconds. Currently, such scales can be imaged only at the radio wavelengths with very long baseline interferometry (VLBI). Detecting and quantifying such anomalies in a statistical way provides an ultimate test to the nature of the dark matter particle (cold vs warm particle models).

Outline of the Project: The PhD candidate will perform the data reduction and lensing analysis of new sensitive VLBI observations at milliarcsecond angular resolution of a sample of radio-loud strong lensing systems that clearly show anomalies in the second derivatives of the lens potential (i.e., flux anomalies). With these observations it will become possible to study also the anomalies in the first derivative of the lens potential (i.e., astrometric anomalies), and combine all of them to study the content of substructure. Some of these systems show hints of faint extended gravitational arcs, which would add tight constraints to the mass density profile. Therefore, the main aim of this analysis is to measure the sub-halo mass function and put stringent limits on the nature of the dark matter particle. Moreover, these data consist of "second epoch" observations, since the VLBI discovery data at the same observing frequencies have been obtained about 15-20 years ago. The candidate will also develop a novel study of relative proper motions in these lensing systems. The long time baselines enable the detection of proper motions as small as few μas/year in the most magnified systems (as demonstrated in a published proof- of-concept work). By using the lens modelling analysis, it is possible to discern if such motions are due to the background radio source (i.e., AGN jets) or the lensing object (i.e., a high redshift galaxy). Therefore, this project has the unique potential to extend the research on the dynamical evolution of galaxies from the Local Group to the early Universe.

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https://ui.adsabs.harvard.edu/abs/2019A%26A...630A.108S/abstract

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DIFA(UNIBO) – Project 11

Searching for water on Mars: global mapping of the dielectric properties at the base of the Martian polar caps

Supervisor: D. Dallacasa

Co-supervisor: Dott. R. Orosei (INAF-IRA)

Contacts: Dott. Roberto Orosei (roberto.orosei@inaf.it)

PhD project in ASTROPHYSICS

Title of the Project:
Searching for water on Mars: global mapping of the dielectric properties at the base of the Martian polar caps

Supervisor : Prof. Dr. D. Dallacasa (DIFA - UniBO)
Co-Supervisors : Dott. R. Orosei (INAF - IRA)

Scientific Case:

After the detection of the presence of liquid water under the southern polar cap of Mars, starting from the data of the MARSIS orbital radar on board the European probe Mars Express, the quantitative analysis of the observations of this experiment in other areas of the planet has become a high-priority scientific goal. The large amount of data and the need to extract information from them using semi-automatic techniques make the task rather challenging, but they provide the basis for a complete mapping of the areas potentially containing liquid water below the Martian polar ice caps.

Outline of the Project:
The development of methods for the Fourier inversion of the signal to identify the presence of water will eventually lead to a global understanding of its origin, of the mechanisms that allow its existence and of its role in constituting a possible habitat for any primitive life forms on Mars. The candidate will be involved into the study and modelling of electromagnetic wave propagation from the probe through the Martian atmosphere and then its soil (and the way back!), in the implementation of numerical simulations and methods for radio signal analysis, and should have at least basic skills in numerical programming languages (Matlab, IDL, etc.) A knowledge of methods for statistical inference and for programming machines for parallel computing is a preferential title. Beyond the mapping of the liquid water under the surface of Mars, characterisation of its atmosphere will be also carried out.

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DIFA(UNIBO) – Project 12

Development of techniques and tools for the image processing of radar signals for the observation of planetary bodies: from the subsurface of Mars to asteroids

Supervisor: D. Dallacasa

Co-supervisor: Dott. R. Orosei (INAF-IRA)

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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:

Development of techniques and tools for the image processing of radar signals for the observation of planetary bodies: from the subsurface of Mars to asteroids

Supervisor : Prof. Dr. D. Dallacasa (DIFA - UniBO)

Co-Supervisors : Dott. Roberto Orosei (INAF - IRA)

Scientific Case:

Radar experiments have been used successfully in the exploration of the Solar System both from orbiting probes and from the ground. The elaboration of the acquired signal allows reconstructing images useful for the characterisation and the geological study of the surfaces and the subsoil of solar system bodies. The problems to be addressed concern the correction of distortion effects caused by the ionosphere, the calibration of the data, range and azimuth processing algorithms, and the extraction of quantitative information from the images thus obtained.

Outline of the Project:

The candidate will learn the basics of these techniques to develop and specialise them according to two projects active at INAF-IRA, namely the observation of the subsurface of Mars using the MARSIS radar on board the European Mars Express probe in orbit around Mars, and the feasibility study for the observation of potentially dangerous asteroids for the Earth (Near Earth Objects - NEO) using ground-based radars. This last project has come to and end in the summer of 2021 but will be the premise for a subsequent development phase currently under planning. The candidate should be interested in the study and modelling of electromagnetic propagation, in the implementation of numerical simulations and methods for radio signal analysis, and should have at least basic skills in numerical programming languages (Matlab , IDL, etc.)

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DIFA(UNIBO) – Project 13

Solar Physics and Space Weather with the Medicina 32-m Radio Telescope: Development, Test and Scientific Exploitation of a Spectro-Polarimetric Imaging System for Solar Radio Astronomy

Supervisor: D. Dallacasa

Co-supervisor: Simona Righini (INAF-IRA), Alberto Paolo Pellizzoni (INAF-OAC)

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PhD project in ASTROPHYSICS

Title of the Project:

Solar Physics and Space Weather with the Medicina 32-m Radio Telescope:

Development, Test and Scientific Exploitation of a Spectro-Polarimetric Imaging System for Solar Radio Astronomy

Supervisor : Prof. D. Dallacasa (DIFA - UniBO)

Co-Supervisors : Simona Righini (INAF-IRA), Alberto Paolo Pellizzoni (INAF-OAC)

Scientific Case:

In the framework of the SunDish Project, a national program devoted to single-dish solar imaging with INAF Radio Telescopes, we propose a challenging Ph.D. program involving technological developments and science exploitation within an innovative and multi-disciplinary approach to Solar Physics applications. The SunDish project is devoted to radio imaging and monitoring of the solar atmosphere at high radio frequencies (at present 18-26 GHz, up to 100 GHz in perspective) through single-dish observations with the Italian radio telescopes.
Mapping the brightness temperature of the solar atmosphere in the radio band allows to reveal plasma processes, mostly originating from free-free emission in the local thermodynamic equilibrium, providing a probe of physical conditions in a wide range of atmospheric layers.
In particular, long-term diachronic radio observations of the solar disk represent an effective tool to characterise the vertical structure and physical conditions of the solar chromosphere, both for quiet and active regions, during their evolution at different phases of the solar cycle. Within this context, the Medicina 32-m and SRT 64-m radio telescopes are increasingly assessing their role in the international solar science panorama.
After a first test campaign aimed at defining and optimising solar imaging requirements for the radio telescopes, the system is ready for systematic monitoring of the Sun to provide:

1. accurate measurement of the brightness temperature of the radio-quiet Sun component, which so far has been poorly explored in the 20-26 GHz range, representing a significant constraint for atmospheric models;
2. characterisation of the flux density, spectral properties and long-term evolution of dynamical features (active regions, coronal holes, loop systems, streamers and the coronal plateau);
3. prediction of powerful flares through the detection of peculiar spectral variations in the active regions, as a promising forecasting probe for the Space Weather hazard network. A fundamental step forward in the project development will be the implementation of spectro-polarimetric capabilities at the Medicina 32-m dish (with the installation of a back-end similar to the one already in use at the SRT), placing our radio telescopes among major international facilities devoted to high-frequency radio monitoring of the Sun.

Outline of the Project:

The Ph.D. candidate will be part, through her/his involvement, in the following activities:

- test and validation of the spectro-polarimeter to be soon installed at the 32-m Medicina dish;
- execution of observations with the Medicina dish;
- development, test and optimisation of data analysis procedures;
- science exploitation of the acquired data (both using data from Medicina and SRT) in the framework of national and international collaborations/networks including both young enthusiastic researchers and affirmed experts in this field.

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DIFA(UNIBO) – Project 14

Playing with the physics of Blue Stragglers

Supervisor: F.R.Ferraro

Co-supervisors: B. Lanzoni, C. Pallanca, M. Cadelano

Contacts: Prof. F.R. Ferraro (francesco.ferraro3@unibo.it)

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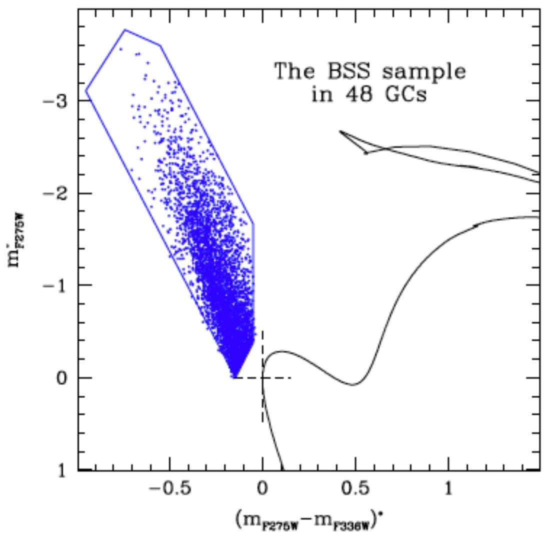
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

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

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

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



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

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DIFA(UNIBO) – Project 15

AGN feeding-feedback cycle in cool core clusters with Hα nebulae

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

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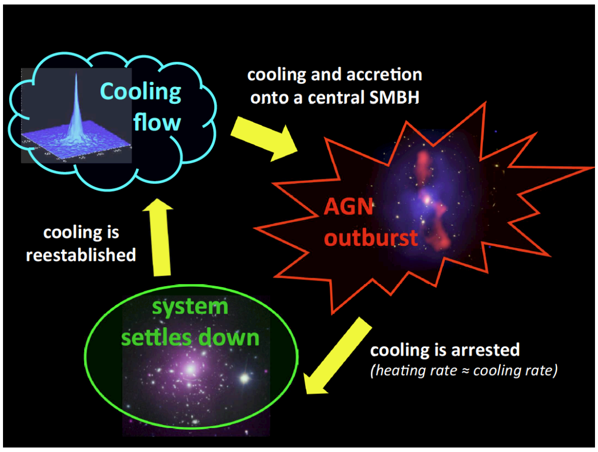
PhD project in ASTROPHYSICS

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 thus 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., A2495, A1668).

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. He/she 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.

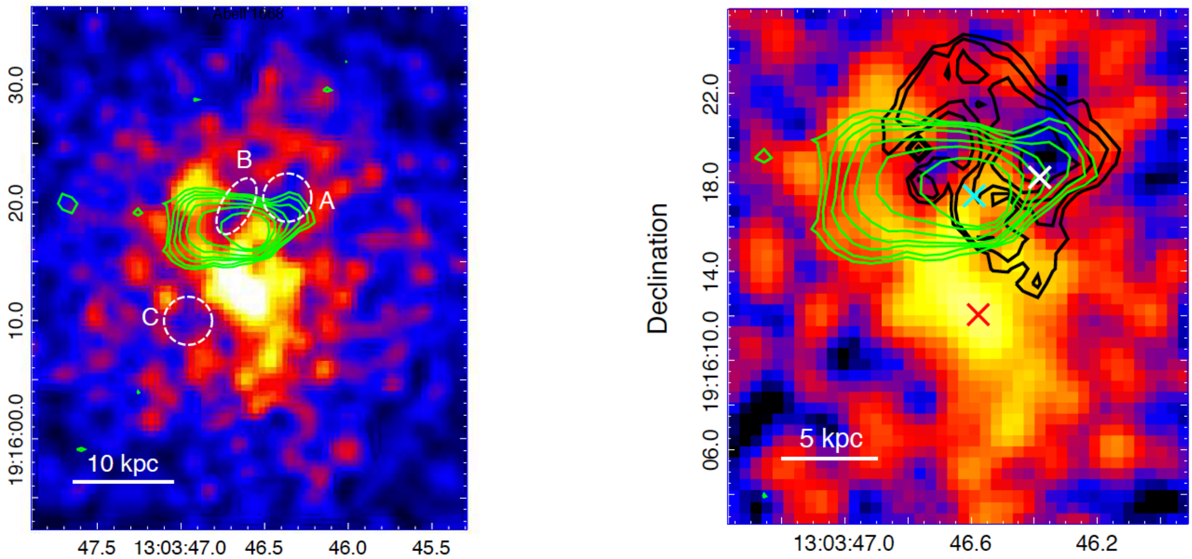


Figure - The results from our snapshot *Chandra* (color map) and 1.4 GHz JVLA observations (green contours) of A1668 indicate that this cluster has a disturbed morphology, showing hints of cavities (A, B and C in the left panel) and spatial offsets between the X-ray emission peak, the radio BCG and the 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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DIFA(UNIBO) – Project 16

Simulating super-bubble dynamics in star-forming galaxies with explicit ISM and stellar feedback models

Supervisor: Federico Marinacci

Contacts: Federico Marinacci (federico.marinacci2@unibo.it)

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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DIFA(UNIBO) – Project 17

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
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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**, which will be launched in 2023.
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 galaxy 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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DIFA(UNIBO) – Project 18

Cosmological exploitation of the statistical properties of Cosmic Voids

Supervisor: Prof. Federico Marulli
Co-Supervisor: Prof. Lauro Moscardini
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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-Supervisor: 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 systematics 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 voids statistics and probe combinations.
- Testing the data analysis pipelines on mock void catalogues extracted from **standard and beyond-ΛCDM cosmological simulations**.
- Construction of **new 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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DIFA(UNIBO) – Project 19

Strong Gravitational Lensing - simulating and modelling

Supervisor: Dr. Robert Benton Metcalf

Contacts: Prof. Robert Benton Metcalf (robertbenton.metcalf@unibo.it)

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PhD project in ASTROPHYSICS

Title of the Project: Strong Gravitational Lensing - simulating and modelling

Supervisor: Dr. Robert Benton Metcalf (robertbenton.metcalf@unibo.it)

The project makes use of/develops numerical simulations: yes
Scientific Case:

Cosmological simulations and astronomical observations have developed over the last few years to the point where they can be directly compared on scales from thousands of Mpc to a few kpc. Comparisons between simulations and observations of strong gravitational lensing are starting to show significant discrepancies on small scales. The radial mass distribution of simulated early-type galaxies do not seem to match the observations of Einstein ring gravitational lenses in detail. Also there are an over abundance of substructure in galaxy clusters that cause small sub-lenses as compared to the predictions from simulations. These are puzzling discrepancies that currently have multiple possible explanation some having to do with variations in the stellar initial mass function, some having to do with feedback from AGN, some having to do with the physics of dark matter and some having to do with numerical limitations inherent to the simulations. Sorting out which of these possibilities the data is consistent with involves further developments of our techniques for realistically simulating gravitational lenses and for extracting information from existing data.

Outline of the Project:

There are multiple projects involved in this topic that the candidate could choose to pursue depending on interest and expertise.

Strong (and quasi-strong) lensing in a cosmological context: My group and I have developed a large base of code called GLAMER to do gravitational lensing simulations on large and small scales. One of the limitations of cosmological simulations is that if they are large enough to give a statistically fare samples they do not have high enough resolution to fully simulate individual lenses well or they do not have baryons in them which are important for strong lensing. They also cannot be quickly rerun with varying prescriptions for galaxy formation. This project would involve better simulating the strong lensing in a large cosmological volume by augmenting the simulation with analytic prescriptions for the distribution of matter in the centres of halos. This would allow us to accurately predict the number and properties of strong lenses and how they depend on cosmological parameters, dark matter properties and galaxy formation prescriptions. It would also allow us to more accurately predict the weak lensing signal on small angular scales. Both these outcomes will have direct relevance to the Euclid Satellite mission to which the student would directly contribute This project involves further developing existing code, running simulations and collaborating with the creators of the cosmological simulations and others

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DIFA(UNIBO) – Project 20

Weak Gravitational Lensing with the Lyman-alpha Forest

Supervisor : Prof. R. Benton Metcalf

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PhD project in ASTROPHYSICS

Title of the Project: Weak Gravitational Lensing with the Lyman-alpha Forest

Supervisor : Prof. R. Benton Metcalf

Scientific Case:

One of the most important questions in cosmology and fundamental physics today is the nature of dark energy, or the cosmological constant, which is causing the expansion of the Universe to accelerate. Weak gravitational lensing has become one of our most important probes of cosmology and of this problem in particular. There are many planned and current surveys that will measure weak lensing using the distortion this lensing has on the images of distant galaxies. This is one of the primary goals of the Euclid satellite mission for example. Weak lensing has also been measured using the Cosmic Microwave Background (CMB) as a source. These measurements will put new constraints on dark energy and possible modifications to General Relativity on large scales.

We have recently discovered that weak lensing should be measurable using observations of the Lyman-alpha forest – the absorption of light coming from quasars, or galaxies, by diffuse hydrogen through the Lyman-alpha line. The necessary Lyman-alpha forest data for this measurement is now being obtained by spectroscopic surveys of galaxies and quasars with other purposes in mind – surveys like eBOSS, DESI , CLAMOTO and LATIS. We will have access to this data through collaborators within some of the surveys. This method would provide a measurement of the cosmological gravitational lensing for sources at a redshift ($z \sim 2$-3) that is not accessible with the traditional galaxy based methods ($z \sim 0.3 – 1.5$) and thus would access a different region of model parameter space. By cross-correlating the signal with foreground surveys information could be gained about the formation of structures in the Universe, the nature of dark matter and alternative theories of gravitation.

Outline of the Project:

The goal would be to detect gravitational lensing using this new method. We have written two papers demonstrating that the signal should be strong in data sets that will be available within about a year – a large number of high quality spectra are needed for high redshift sources that are as dens on the sky as possible. The first task would be to develop the analysis software in Python and/or C++ to analyze the data. We have immediate access to data for developing this method and the data will increase as the surveys continue. The mathematical formalism for doing this is being developed now. The student would need to be comfortable writing computer code and developing mathematical methods and will need to become familiar with spectroscopic data and the techniques used to analyze the Lyman-alpha forest. Once the signal is detected there would be many possible projects to be done on interpreting it and relating it to other cosmological probes. It is likely that the student would work closely with our collaborators in the United States and elsewhere.

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DIFA(UNIBO) – Project 21

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

Supervisor:Michele Ennio Maria Moresco Cosupervisors: A.Cimatti

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PhD project in ASTROPHYSICS

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

Supervisor: Michele Ennio Maria Moresco
Cosupervisors: A.Cimatti
Collaborators: DIFA and INAF-OAS cosmology and galaxy evolution groups

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 in order to establish GW as robust cosmological probes. In this Ph.D. Thesis, we propose to make use of public GW analysis SW as gwcosmo (Gray et al. 2019), DarkSirensStat (Finke et al., 2021) and MGCosmoPop (Mancarella et al., 2021), but extending those to include the new features 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 the current public catalogs (GLADE+, DESI, …) and explore new ones (e.g. Euclid) to obtain cosmological constraints with the current and future GW data, (iii) analyze the impact of different properties in the catalogs (completeness, accuracy of the redshift estimates) on the cosmological parameters accuracy, (iv) extend the codes with a wider range of BBH properties (e.g. BBH masses) and assess their impact on the results, (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 both the currently available data will be explored, as well as simulated data, taking advantage and exploring also 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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DIFA(UNIBO) – Project 22

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

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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
Cosupervisors: A.Cimatti, F. Marulli
Collaborators: DIFA and INAF-OAS cosmology and galaxy evolution groups

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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DIFA(UNIBO) – Project 23

21 cm cosmology

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

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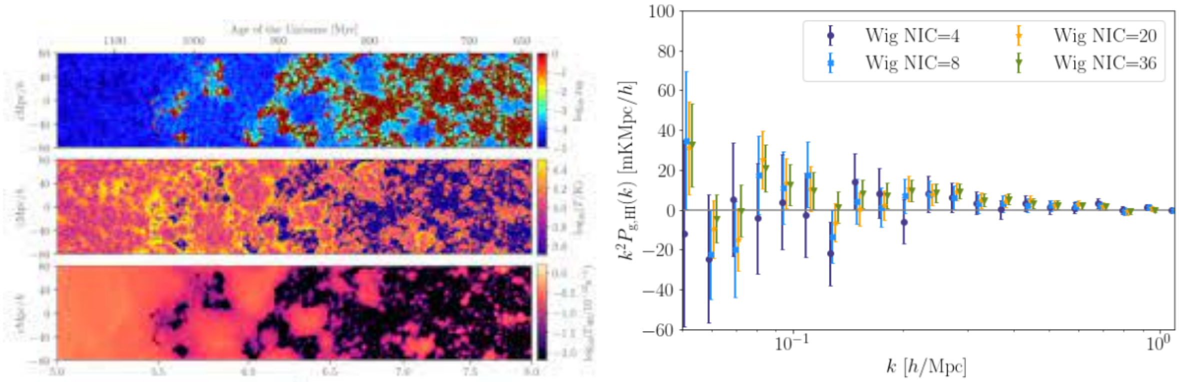
PhD project in ASTROPHYSICS

Title of the Project: 21 cm cosmology
Supervisors: Prof. Lauro Moscardini
Co-Supervisors: Dr. Gianni Bernardi, Dr. Marta Spinelli

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).

This project can therefore take two flavors:

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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DIFA(UNIBO) – Project 24

Cosmology with Galaxy Clusters

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

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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 cluster detection at high redshift in optical surveys*

The project will be based on the cluster finder 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:

- **Optimisation** of AMICO in view of future applications: refinement of the estimation of cluster properties, evaluation of the most appropriate band(s) for the detection, possibility to adapt a scalar-adaptive approach (i.e., not fixing the size of the filter), combination with multiwavelength data (weak lensing data, X-rays, SZ, ...).
- **Application** of AMICO to galaxy catalogues from ongoing and upcoming surveys, with different depths, bands and redshift coverage. These include proprietary KiDS and DES data, and public COSMOS, HSC, SDSS and CFHTLS data. This will allow the detection of previously unknown clusters, as well as the comparison with outputs of other algorithms in well-studied fields.
- 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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DIFA(UNIBO) – Project 25

Detecting galaxy clusters and cosmic voids in Weak Lensing Simulations: paving the way to the ESA-Euclid Mission

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ALMA MATER STUDIORUM
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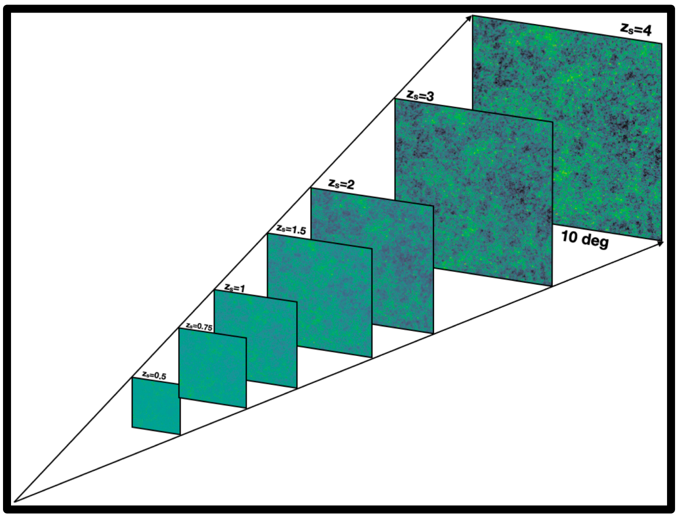
Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

Title of the Project:
Detecting 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,** 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 the 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, but also will open the possibility of using the weak lensing signal to detect and characterize galaxy clusters and cosmic voids. The accuracy and precision of those methods require the development of dedicated weak lensing light-cone simulations (see Figure).



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 by side and extend up to z=4.

Outline of the Project:
The 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 derived 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 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 been already 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 characterize 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.

DIFA(UNIBO) – Project 26

The physical properties of star-forming regions in lensed high redshift galaxies

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

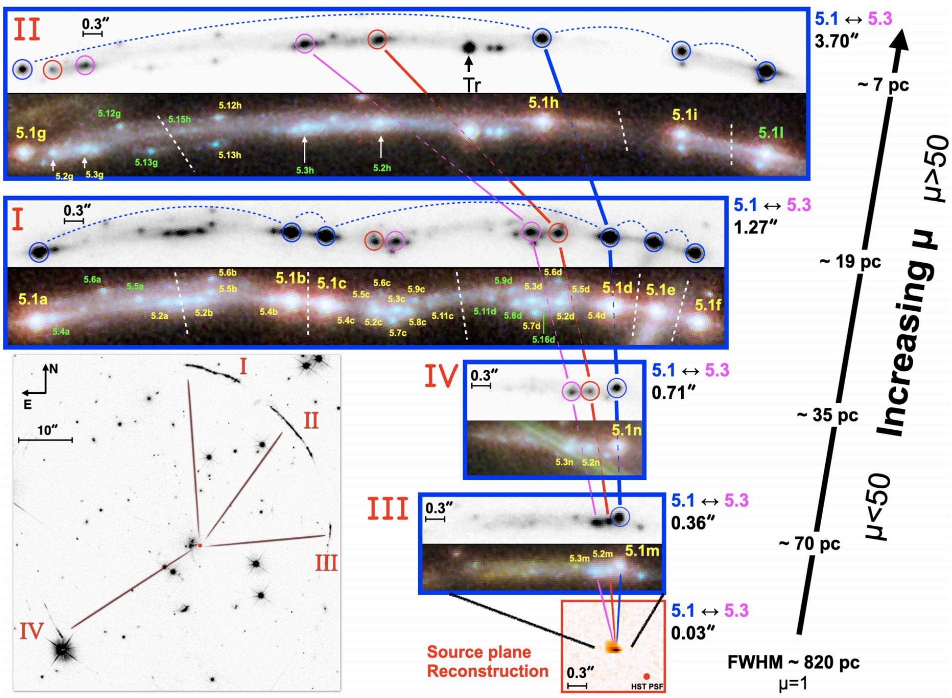

Figure 1: The Sunburst arc complex (z=2.37) in galaxy cluster PSZ1G311 (bottom left). Zooming on the four arc portions we see many star forming complexes which would remain undetectable without lensing magnification (bottom right). The colored lines show associations between multiple images of the same 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 MAORY-MICADO). These simulations will allow us to evaluate how accurately our methods can recover the properties of the sources.

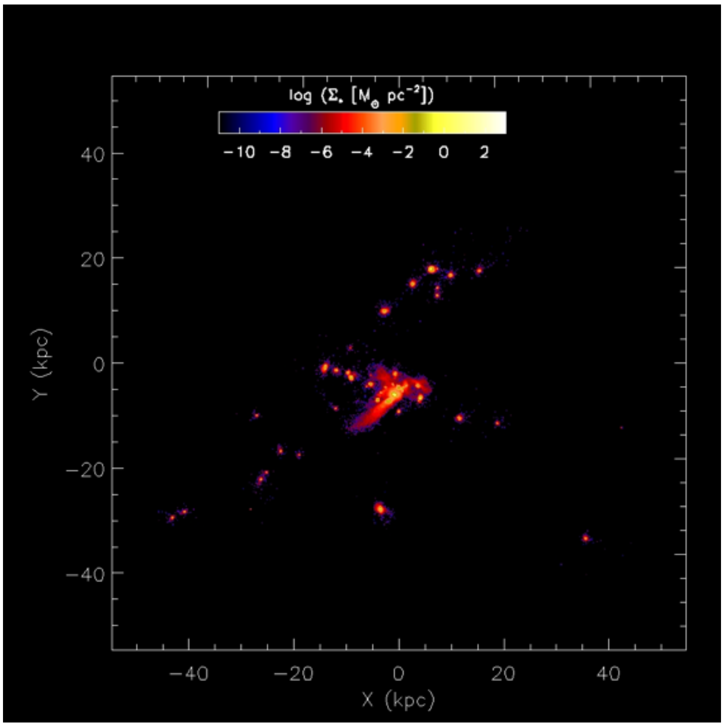

Figure 2: Snapshot (stellar density) at redshift z=6.14 of a sub-pc resolution simulation of a distant galaxy (Calura et al. 2022). Several stellar clumps with masses between $10^4 - 10^5 M_\odot$ and sizes of 10-100 pc are visible. The student will produce mock observations of these high-redshift sources.

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DIFA(UNIBO) – Project 27

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

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PhD project in ASTROPHYSICS

Title of the Project:
Chemical characterization of the Local Group: identifying the chemical DNA of Milky Way satellite galaxies
Supervisor : Prof. Alessio Mucciarelli (DIFA)
Co-Supervisors : 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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DIFA(UNIBO) – Project 28

Very metal-poor stars as local relics of the ancient Universe

Supervisor: Prof. Alessio Mucciarelli (DIFA) Co-supervisor: Dr. Carmela Lardo (DIFA)

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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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DIFA(UNIBO) – Project 29

Globular Cluster evolution in dwarf satellites

Supervisor:Carlo Nipoti(UniBO)
Co-supervisor:Francesco Calura(INAF-OAS)
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PhD project in ASTROPHYSICS

Title of the Project: *Globular Cluster evolution in dwarf satellites*

Supervisor: Carlo Nipoti (UniBO)
Co-supervisor: Francesco Calura (INAF-OAS)

Scientific Case

The problem of how globular clusters (GCs) and their multiple populations formed is one major, unsolved puzzle of astrophysics. Current scenarios for multiple populations in Galactic GCs envisage a first generation (FG) formed at early times on a very short timescale (<a few Myr), followed by subsequent star formation episodes, occurring on longer timescales. In these models, the second generation incorporates the ejecta of FG polluters, such as AGB stars (Calura et al. 2019). One problem is that, since mass return from old stellar populations is generally very small, in order for subsequent populations to show appreciable chemical signatures of such ejecta the FG has to be assumed very massive, by at least one order of magnitude than the present-day mass. One upper limit to the total mass of FG stars is set by a few Milky Way (MW) satellites containing GCs, such as Fornax and WLM, in which the total stellar mass is 4-5 times the mass in GCs. However, due to their low global mass, such systems might have undergone substantial mass loss, hence the total mass in FG stars at early times could be higher than today.

Outline of the Project

The PhD student will study the evolution of dwarf satellite galaxies in the MW with N-body simulations with up to date realistic models for the MW gravitational potential. The goal of these simulations will be to estimate the maximum stellar mass loss that a satellite can have experienced during its orbit in the MW, for given present-day stellar-mass density distribution and various properties of the tidal streams. This maximum amount of stellar mass loss will be used to constrain models of GC formation (e.g. Khalaj & Baumgardt 2016). The satellite galaxy models used in the simulations will be of increasing complexity, starting from explorative simulations in which the satellite is represented by a single dissipationless component (which in post-processing is separated in a stellar and dark matter components; Nipoti et al. 2021), to more realistic models in which the satellite is represented by a stellar component, a dark matter halo and by its individual globular clusters. The simulations will be used also to address the evolution of the dwarf dark matter component, in light of recent observational indications (Kaplinghat et al. 2019) that the central dark matter density anticorrelates with the pericenter of the dwarf's orbit around the MW.

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References:

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Khalaj P., Baumgardt H., 2016, MNRAS, 457, 479
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Bologna, 28/2/2022

DIFA(UNIBO) – Project 30

Rotating astrophysical fluids with baroclinic distributions

Supervisors: Carlo Nipoti Luca Ciotti (UniBo)
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PhD project in ASTROPHYSICS

Title of the Project: *Rotating astrophysical fluids with baroclinic distributions*

Supervisors: Carlo Nipoti (UniBo) and Luca Ciotti (UniBo)

Scientific Case:
Rotating fluids are widespread among astrophysical objects, ranging from rotating stars, to accretion discs and tori around black holes, to gaseous discs and coronae in galaxies, and possibly to the intracluster medium. A key tool to understand these systems is the construction of stationary models. When stationary models are available, it is important to assess their stability or instability.
While models with cylindrical rotation (barotropic models) are straightforward to construct, the more general (and often more realistic) baroclinic models (in which the angular velocity has a vertical gradient) are more complex and much less studied in the literature (e.g. Barnabè et al. 2006, Sormani et al 2018).

Outline of the Project:
The PhD student will construct new analytic stationary models of fluids with baroclinic distribution aimed at reproducing gaseous components of galaxies (thick gaseous discs, extraplanar gas and galactic coronae), gaseous disc and tori around black holes and the hot gas component of galaxy clusters.
The conditions for the linear stability of these models will be studied under different assumptions. For an unmagnetized fluid the conditions for stability will be derived applying the classical Solberg-Hoiland criterion. For a weakly magnetized fluid, the stability conditions will be derived from the stability criterion that is at the basis of the magneto-rotational instability. 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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Bologna, 28/2/2022

DIFA(UNIBO) – Project 31

Rotation of the intracluster medium: theoretical models and observational perspectives

Supervisor : Carlo Nipoti (UniBO)
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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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Bologna, 28/2/2022

DIFA(UNIBO) – Project 32

Multi-component models of stellar systems with distribution functions depending on actions

Supervisor: Carlo Nipoti
Co-supervisor: Raffaele Pascale (INAF-OAS)
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PhD project in ASTROPHYSICS

Title of the Project:
Multi-component models of stellar systems with distribution functions depending on actions

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

Scientific Case:
Dynamical models of stellar systems are fundamental tools to infer from the observational data the intrinsic properties of galaxies and globular clusters. These stellar systems invariably consist of many components (e.g. different stellar components, different stellar populations, dark matter halo, central black hole). Distributions functions f(J) depending on the action integrals J can be used to build realistic multi-component models and allow a detailed comparison with observations. f(J)-based dynamical models can be used to address several open questions on the intrinsic properties of stellar systems, such as the distribution of dark matter in galaxies and the presence of intermediate mass black holes in globular clusters.

Outline of the Project:
Using the available numerical code AGAMA (Vasiliev 2019), the PhD student will build multi-component f(J) models of stellar systems based on a very general family of distribution functions presented in Vasiliev (2019). In particular, f(J) models of dwarf spheroidal and elliptical galaxies to study the distribution of dark matter (Pascale et al. 2018) will be first tested against available mock observations of model galaxies and then applied to real systems. In the case of elliptical galaxies, the models will allow to infer also some properties of the galaxy stellar initial mass function. With a similar approach the PhD student will produce multi-component f(J) models of globular clusters to study mass-segregation and estimate the contribution of dark remnants to the total globular cluster mass budget.
The stability of the aforementioned multi-component f(J) models will be studied with N-body simulations, whose initial conditions can be generated by sampling the known distribution function.

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Bologna, 28/2/2022

DIFA(UNIBO) – Project 33

A radio perspective on star formation in the J1030 field

Supervisors : Margherita Talia (DiFA); Isabella Prandoni (IRA) Co-Supervisors : Francesca Pozzi (DiFA); Roberto Gilli (OAS)
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ALMA MATER STUDIORUM
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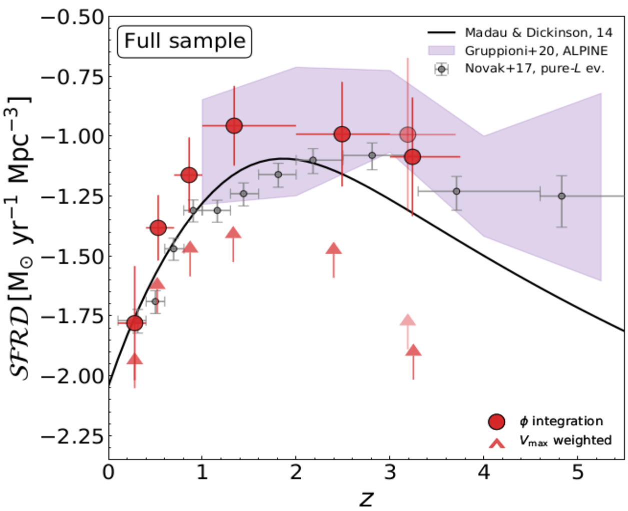
PhD project in ASTROPHYSICS

Title of the Project: *A radio perspective on star formation in the J1030 field*

Supervisors : Margherita Talia (DiFA); Isabella Prandoni (IRA)
Co-Supervisors : Francesca Pozzi (DiFA); Roberto Gilli (OAS)
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. A multi-wavelength observational approach is key to develop a consensus on galaxy formation and evolution. In this context, the radio regime offers an extremely important window toward star formation and supermassive black hole properties of galaxies, as radio continuum emission provides a dust-unbiased star formation tracer and directly probes those active galactic nuclei (AGN) that are hosted by the most massive quiescent galaxies.

Outline of the Project The objective of the project will be to study a sample of star-forming galaxies selected at radio frequencies (D'Amato et al.) in the **J1030 field**.
The radio data have been obtained recently by the Bologna research group (PI: I. Prandoni), and the achieved mensitivity makes the J1030 field one of the deepest cosmological fields observed so far. At the center of it is SDSS J1030+0524, a z=6.31 QSO powered by a billion solar mass black hole, that has been the focus of a massive observational campaign in order to study the galaxy overdensity around it.
The PhD student will exploit the great legacy value of the multi-wavelength data acquired so far to understand the star-formation processes from a radio perspective.
The project will consist of the following steps.
(1) Validating the photometric redshifts and estimating the physical properties (stellar mass, SFR…) of the radio-selected star-forming galaxies with SED fitting. (2) Estimating the evolution of the cosmic star formation density (Enia et al. 2022; see figure), with a focus on the contribution of extremely obscured star-forming galaxies at high-redshift (Talia et al. 2021). (3) 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.

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DIFA(UNIBO) – Project 34

Tracing the Early Cluster Assembly with Accreting Black Holes

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

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PhD project in ASTROPHYSICS

Title of the Project: Tracing the Early Cluster Assembly with Accreting Black Holes

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

Scientific Case: Cosmological numerical simulations provide a clear picture of how dark matter (DM) drives the formation and evolution of galaxy clusters across cosmic time. A nascent cluster begins to collapse onto 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 onto 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 finally energy injection from SNe explosions and Active Galactic Nuclei (AGN) into the inter-stellar medium of cluster galaxies and into the intra-cluster 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 $z>1.5$ around powerful AGN selected primarily on the basis of the detection of extended 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 X-ray data in the quest for (i) faint AGN residing within these dense environments 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. The contribution of the AGN to the ionization of the gas of the ELANe will also be evaluated. Finally, stacking X-ray analysis will be tested on the selected sample to shed light on the average physical properties of the diffuse emission, after taking into account the different z range of the systems and characteristics of the underlying DM haloes.
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 the overall incidence of AGN activity in these galaxies. The results will be compared with those in 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*, *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 renown research Institutes and Universities.

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DIFA(UNIBO) – Project 35

The realm of dual super-massive black holes

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

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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. A 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; see Fig. 1). 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 catalogs; (b) an extensive search for dual AGN in some of the deepest X-ray fields currently available, (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, ESO/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 the state-of-the art numerical simulations.

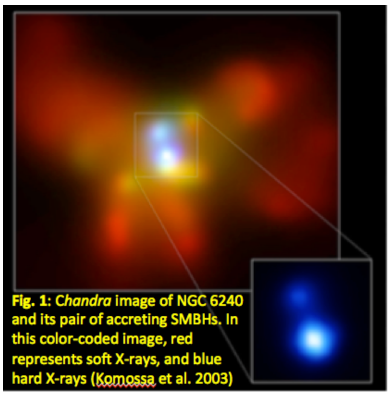
Fig. 1: *Chandra* image of NGC 6240 and its pair of accreting SMBHs. In this color-coded image, red represents soft X-rays, and blue hard X-rays (Komossa et al. 2003)

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DIFA(UNIBO) – Project 36

A systematic search for ultra-bright high-redshift strongly lensed galaxies in Planck catalogues

Supervisor: C. Vignali (DIFA) Co-supervisors: M. Bonato (INAF-IRA)

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PhD project in ASTROPHYSICS

Title of the Project: A systematic search for ultra-bright high-redshift strongly lensed galaxies in Planck catalogues

Supervisor: C. Vignali (DIFA)
Co-supervisors: M. Bonato (INAF-IRA)

Scientific Case: A remarkable, largely unexpected result of Planck sub-mm all-sky surveys was the discovery of ultra-bright, extreme strongly lensed galaxies at $2<z<4$ (Cañameras et al. 2015; Harrington et al. 2016). These objects are of extraordinary scientific interest, since the combination of total brightness, boosted by a factor of μ (typically in the range 10−50), and stretching of images by a factor $\approx\mu^{1/2}$ offers a unique opportunity to pierce into their internal structure and dynamics via high-resolution follow-up observations. It becomes possible to reach spatial resolutions of tens of pc (Cañameras et al. 2017) and measure feedback-driven molecular outflows (Spilker et al. 2018; Cañameras et al. 2018; Jones et al. 2019). Resolved imaging and kinematics of early galaxies is the most direct and powerful way to learn about the complex physical processes governing galaxy formation and evolution and to discriminate among competing scenarios. So far, about 20 strongly lensed galaxies have been found on Planck catalogues, over the limited sky regions covered by Herschel and South Pole Telescope (SPT) surveys. An extrapolation to the full high-Galactic latitude ($|b|>20°$) sky implies a total number of ≈150, an excellent sample to get good or at least sufficient statistics over the peak of cosmic star-formation activity. As a first step towards a complete identification of Planck strongly lensed galaxies, we have selected a sample of 228 candidates with S_{545GHz} > 500 mJy, distributed over the whole high-Galactic latitude sky. We recently observed sub-samples of these objects with the Australia Telescope Compact Array (ATCA; 95 h), with the NIKA2 mm imager at the IRAM 30m telescope (14 h) and with the SCUBA-2 bolometer array at the JCMT (20 h). Each object of our sample has been observed by at least one of such facilities.

Outline of the Project: This PhD project aims at carrying out the reduction, analysis and scientific exploitation of these data, and at starting a systematic program of high-resolution follow-up observations of confirmed strongly lensed galaxies. They will constitute the first statistically significant complete sample of the brightest high-z sub-mm galaxies in the sky. Immediate applications of the new data will provide: i) constraints on the brightest high-z tail of the 545 GHz counts, which constitute tests on the one side of galaxy evolutionary models and, on the other side, of predictions for the high-μ tail of the magnification distribution, which is a probe of evolution of large-scale structure; ii) constraints on the radio−far-IR correlation at high-z; iii) discovery of new high-z candidate proto-clusters of dusty galaxies. The PhD student will then submit proposals for measuring the redshifts of confirmed candidates, for high-resolution observations with sub-mm interferometers (SMA, NOEMA and ALMA), and for deep optical observations to identify the foreground lenses and measure their properties. These observations will allow us to extract unique information on the processes that govern galaxy formation and early evolution.

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DIFA(UNIBO) – Project 37

Exploiting deep radio surveys to assess the growth of black holes and the role of jet-induced AGN feedback in galaxy evolution

Supervisor: Cristian Vignali (DIFA); Co-Supervisor: I. Prandoni (INAF-IRA)
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PhD project in ASTROPHYSICS

Title of the Project: Exploiting deep radio surveys to assess the growth of black holes and the role of jet-induced AGN feedback in galaxy evolution

Supervisor: Cristian Vignali (DIFA); **Co-Supervisor:** I. Prandoni (INAF-IRA)

Scientific Case: Understanding the evolution of galaxies, from the end of the 'dark ages' through to the complexity and variety of systems observed in the local Universe, remains a primary goal for observational and theoretical astrophysics. A crucial piece of the evolutionary picture is the role that active galactic nuclei (AGN) play in shaping galaxies over cosmic time. The energy released by the AGN through radiative winds and/or radio jets is widely believed to regulate the rate of star formation in their host galaxies via AGN feedback. However, the details of how and when this occurs remain uncertain from both an observational and theoretical perspective (e.g., Heckman & Best 2014; Harrison 2017).

It is widely accepted that recurrent jet-mode AGN activity is a fundamental component of the lifecycle of the most massive galaxies, responsible for maintaining these as "old, red and dead" (e.g., Best et al. 2006). There is, however, mounting evidence that at least a fraction (~30%; Delvecchio et al. 2017) of radio-quiet (RQ) AGN host compact AGN-triggered radio cores, possibly associated with mini-jets on (sub-)galactic scale (see also Maini et al. 2016). If mini-jets are a common feature (Jarvis et al. 2019), jet-driven feedback could play a significant role in shaping galaxy evolution even at lower stellar masses. These findings open new very exciting perspectives for next-generation radio-continuum surveys.

Outline of the Project: The co-supervisor is actively participating and has leading roles in international projects involving wide-field and/or deep radio-continuum surveys of some of the most popular extra-galactic fields (e.g., GOODS-N, COSMOS), carried out with SKA pathfinders/precursors (e.g., eMERLIN, JVLA, LOFAR, MeerKAT, ASKAP). At the depths probed by these surveys, the radio sky is dominated by star-forming galaxies (SFGs) and RQ AGN, while powerful radio galaxies (RGs) and radio-loud quasars (RL-QSOs) only represent a minor contribution (e.g., Prandoni et al. 2018). These surveys hence provide a powerful dust/gas-obscuration-free tool to 1) obtain a complete census of AGN, and study how the Type-1/Type-2 AGN fractions evolve with both luminosity and redshift; 2) assess the incidence of mini-jets in RQ AGN populations and shed light on their role in shaping galaxies across cosmic time.

The Phd thesis project will make use of data from one or more of the following surveys: eMERGE with JVLA and eMERLIN; MIGHTEE with MeerKAT; EMU with ASKAP; J1030 field with JVLA, LOFAR, ALMA; LoTSS Deep Fields with LOFAR

which offer complementary views on the faint AGN populations. Through a comparative study of RQ and low (radio) luminosity RL AGN, we will be able to identify common trends and systematic differences, that will shed light on the origin of the radio emission in the radio-quiet population. The study will be carried out adopting a multi-band approach, which is essential to link the radio properties (e.g., radio power, size, spectrum, morphology) to the AGN (e.g., accretion rate, duty cycle) and host-galaxy properties (e.g., stellar and dust mass, star formation rate, redshift, environment).

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