DIFA projects – PhD Cycle 37

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Testing Axion Dark Matter Models with N-body cosmological simulations of large-scale structures at different scales
Supervisor: Marco Baldi (email: marco.baldi5@unibo.it)

DIFA(UNIBO) – Project 2
Testing fundamental physics with numerical simulations of the cosmic large- scale structures
Supervisor: Marco Baldi (email: marco.baldi5@unibo.it)

DIFA(UNIBO) – Project 3
Hidden Black Holes in the Deep Universe
Supervisor: Marcella Brusa (email: marcella.brusa3@unibo.it)

DIFA(UNIBO) – Project 4
Black Hole Weather:Unveiling the micro and macro processes of SMBH feeding and feedback
Supervisor: Marcella Brusa (email: marcella.brusa3@unibo.it)

DIFA(UNIBO) – Project 5
"Constraining the expansion of the Universe with the oldest stars"
Supervisor: Andrea Cimatti (email: a.cimatti@unibo.it)

DIFA(UNIBO) – Project 6
"Playing with the physics of Blue Stragglers"
Supervisor: Francesco R. Ferraro (email: francesco.ferraro3@unibo.it)

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AGN feeding-feedback cycle in cool core clusters with Hα nebulae
Supervisor: Myriam Gitti, Fabrizio Brighenti (email: myriam.gitti@unibo.it)

DIFA(UNIBO) – Project 8
"Understanding the role of gas circulation in the evolution of star-forming galaxies"
Supervisor: Federico Marinacci (email: federico.marinacci2@unibo.it)

DIFA(UNIBO) – Project 9
Forming Milky Way-like galaxies in cosmological simulations with explicit ISM and feedback models
Supervisor: Federico Marinacci (email: federico.marinacci2@unibo.it)

DIFA(UNIBO) – Project 10
"Cosmology with Bayesian deep neural networks to learn the properties of the Cosmic Web "
Supervisor: Federico Marulli (email: federico.marulli3@unibo.it)

DIFA(UNIBO) – Project 11
"Cosmology from the combination of multiple observational probes
Supervisor: Federico Marulli (email: federico.marulli3@unibo.it)

DIFA(UNIBO) – Project 12
"Strong Gravitational Lensing: simulating and modelling "
Supervisor: R. Benton Metcalf (email: robertbenton.metcalf@unibo.it)

DIFA(UNIBO) – Project 13
"Weak Gravitational Lensing with the Lyman-alpha Forest "
Supervisor: R. Benton Metcalf (email: robertbenton.metcalf@unibo.it)

DIFA(UNIBO) – Project 14
"Machine Learning Tools for Weak and Strong Lensing by Galaxy Clusters: Paving the Way to the ESA-Euclid Mission".
Supervisor: Lauro Moscardini (email: lauro.moscardini@unibo.it)

DIFA(UNIBO) – Project 15
"Observational cosmology with MeerKAT HI intensity mapping."
Supervisor: Lauro Moscardini (email: lauro.moscardini@unibo.it)

DIFA(UNIBO) – Project 16
"Chemical characterization of the Milky Way merger events: identifying the chemical DNA of our Galaxy."
Supervisor: Alessio Mucciarelli (email: alessio.mucciarelli2@unibo.it)

DIFA(UNIBO) – Project 17
"Very metal-poor stars as local relics of the ancient Universe"
Supervisor: Alessio Mucciarelli (email: alessio.mucciarelli2@unibo.it)

DIFA(UNIBO) – Project 18
"Globular Cluster evolution in dwarf satellites "
Supervisor: Carlo Nipoti (email: carlo.nipoti@unibo.it)

DIFA(UNIBO) – Project 19
"Multi-component models of stellar systems with distribution functions depending on actions "
Supervisor: Carlo Nipoti (email: carlo.nipoti@unibo.it)

DIFA(UNIBO) – Project 20
"Rotating astrophysical fluids with baroclinic distributions"
Supervisor: Carlo Nipoti (email: carlo.nipoti@unibo.it)

DIFA(UNIBO) – Project 21
"Bulge/Disk decomposition of galaxies for the 21th century: characterization of the components, and link with the galaxy properties, using MaNGA kinematics and SDSS photometry."
Supervisor: Silvia Pellegrini (email: silvia.pellegrini@unibo.it)

DIFA(UNIBO) – Project 22
"Simulating the evolution of radiogalaxies in the cosmic web ."
Supervisor: Franco Vazza (email: franco.vazza2@unibo.it)

DIFA(UNIBO) – Project 23

"Tracing the Early Cluster Assembly with Accreting Black Holes."

Supervisor: Cristian Vignali (email: cristian.vignali@unibo.it)

DIFA(UNIBO) – Project 24

"The realm of dual super-massive black holes"

Supervisor: Cristian Vignali (email: cristian.vignali@unibo.it)

DIFA(UNIBO) – Project 1

Testing Axion Dark Matter Models with N-body cosmological simulations of large-scale structures at different scales

Supervisor: Marco Baldi

PhD project in ASTROPHYSICS

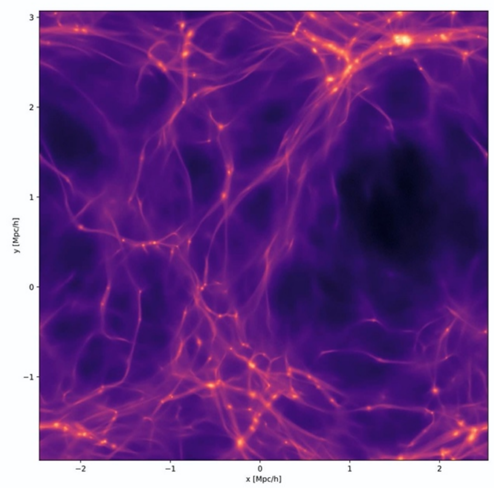
Title of the Project: *Testing Axion Dark Matter Models with N-body cosmological simulations of large-scale structures at different scales*

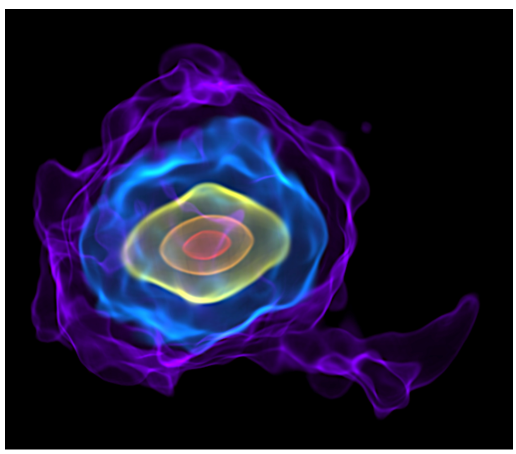
Supervisor: Dr. Marco Baldi
Co-Supervisor: Dr. Matteo Nori
The project makes use of/develops numerical simulations: YES

Scientific Case:
According to the standard cosmological scenario, known as the ΛCDM model, about **80% of the present matter content of the Universe is in the form of Cold and collisionless Dark Matter particles** (CDM). Nonetheless, some lingering inconsistencies at the galactic scales between observations and simulations together with the lack of direct detections of CDM particles provide **strong motivations to explore alternative scenarios** (see e.g. *Bertone et al. 2005*). One intriguing alternative to the standard CDM model involves an *extremely* light dark matter bosonic particle, known as Ultra-Light Axion and generically termed Fuzzy Dark Matter (FDM, see e.g. *Hu et al. 2000*). Such dark matter **exhibits the wave-like behavior typical of quantum systems at cosmological scales**.
Having developed in recent years a new N-body hydrodynamical code for FDM models (AX-GADGET, see *Nori & Baldi 2018*), **we are now able to simulate cosmic structure formation with a fully consistent treatment of FDM dynamics, in order to quantify the FDM impact on specific astrophysical observables**.

Outline of the Project:
The PhD student will make use of the AX-GADGET code to simulate a variety of cosmological and astrophysical systems. Possible specific research directions may involve:

1) Systematic **investigations of the FDM parameter space** with a suite of cosmological simulations of the large-scale structure of the Universe.
2) Studying in detail the **halo and subhalo mass function of FDM models** in a cosmological setup.
3) Investigating **the role of halo mergers in defining scaling relations** of FDM halos
4) Simulate **astrophysical processes (such as galaxy formation and feedback)** in a FDM cosmology.





Representation of the dark matter distribution in numerical simulations of FDM: a density map of a cosmological volume (left) and a 3D rendering of iso-density contours of a single object (right) simulated with the AX-GADGET code (Nori & Baldi 2018)

Contacts: Dr. Matteo Nori, matteo.nori3@unibo.it, Dr. Marco Baldi, marco.baldi5@unibo.it

DIFA(UNIBO) – Project 2

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

Supervisor: Marco Baldi

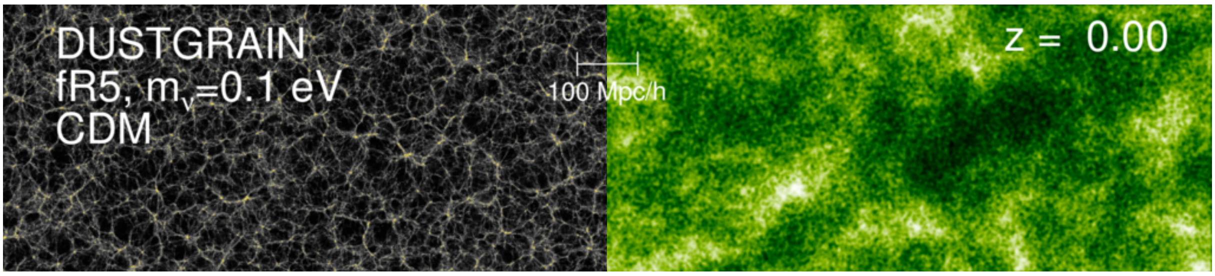
PhD project in ASTROPHYSICS

Title of the Project: *Testing fundamental physics with numerical simulations of the cosmic large-scale structures*
Supervisor: Dr. Marco Baldi **The project makes use of/develops numerical simulations:** YES

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

Contacts: Dr. Marco Baldi, marco.baldi5@unibo.it

DIFA(UNIBO) – Project 3

Hidden Black Holes in the Deep Universe

Supervisor: Marcella Brusa

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

PhD project in ASTROPHYSICS

Title of the Project: Hidden Black Holes in the Deep Universe

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

Scientific Case: Super massive black holes at galaxies' centers grow their mass by accreting surrounding gas. During these transient phases, called Active Galactic Nuclei (AGN), part of the gas gravitational energy is converted into radiation that our instruments can detect. There is now significant evidence that black holes primarily grow during hidden AGN phases, where optical/UV radiation is absorbed by circum-nuclear gas and dust, but the more energetic X-ray radiation is not. Deep X-ray surveys have in fact revealed that most AGN are obscured, and that the obscured AGN fraction is actually increasing towards high redshift, reaching ~80-90% at z~4. Above this redshift we have only a few examples of obscured AGN, mainly because of the current limitations of X-ray instrumentations, whereas hundreds of luminous, unobscured AGN have been discovered at z~6 and above by wide-area optical surveys. Therefore:
- where are the most distant obscured AGN?
- and why is the obscured AGN fraction increasing at earlier cosmic epochs?

Outline of the Project: The main goal of the proposed PhD project is answering the two questions above by exploiting X-ray and multi-band data. Our group is heavily involved in the major existing extragalactic multiwavelength surveys (CDFS and COSMOS), and is leading a major effort in the J1030 field. The PhD candidate is expected **to search for and identify distant, obscured AGN in these fields** by applying known obscuration diagnostics and developing new ones based on X-ray and ancillary data from the main international facilities. The combination of new, deep X-ray and radio data in J1030 is particularly promising (see http://j1030-field.oas.inaf.it/ for a summary of the data).
The PhD candidate will combine the population of obscured AGN that she/he will discover in J1030 with the known AGN populations in the CDFS and COSMOS. She/he will use ancillary data from ALMA to measure the physical properties (eg. density, temperature) of the interstellar medium (ISM) of the AGN host galaxies. These measurements will **enable to probe whether the increased nuclear obscuration measured at early epochs for AGN host galaxies is a consequence of their larger ISM density,** as galaxies were smaller and richer in gas at earlier epochs.

The PhD candidate will be trained in AGN physics and demographics, in handling multi-band data catalogs, and in analyzing and interpreting AGN data from different instruments (e.g. Chandra, ALMA, JVLA). She/he will also acquire scientific independence by, e.g., writing observing proposals and presenting the results of the work at international conferences. The PhD candidate will join the AGN surveys group at DIFA and INAF-OAS and will have the opportunity to visit renown research Institutes and Universities abroad through our collaboration network. Generous research fundings are available for the entire PhD program.
Contacts: marcella.brusa3@unibo.it (office 4S6)

DIFA(UNIBO) – Project 4

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

Supervisor: Marcella Brusa

PhD projects in ASTROPHYSICS

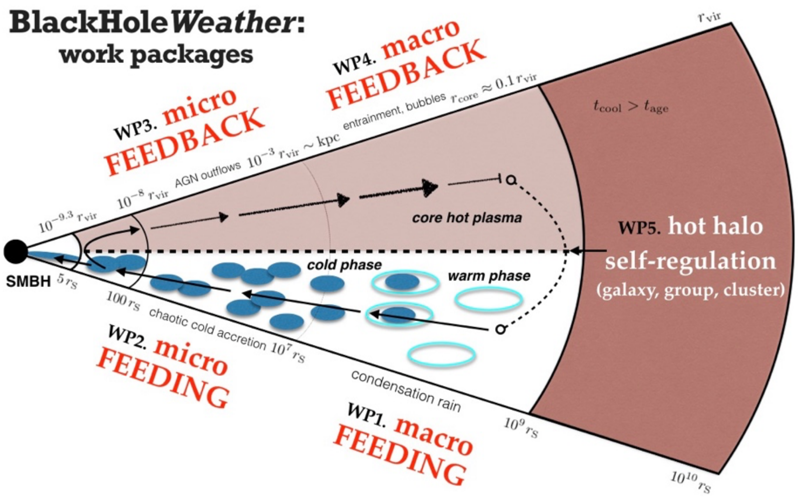
Title of the Project: ***Black Hole Weather***
Unveiling the micro and macro processes of SMBH feeding and feedback

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

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

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 5

“Constraining the expansion of the Universe with the oldest stars”

Supervisor: Andrea Cimatti

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 6

"Playing with the physics of Blue Stragglers"

Supervisor: Francesco R. Ferraro

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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

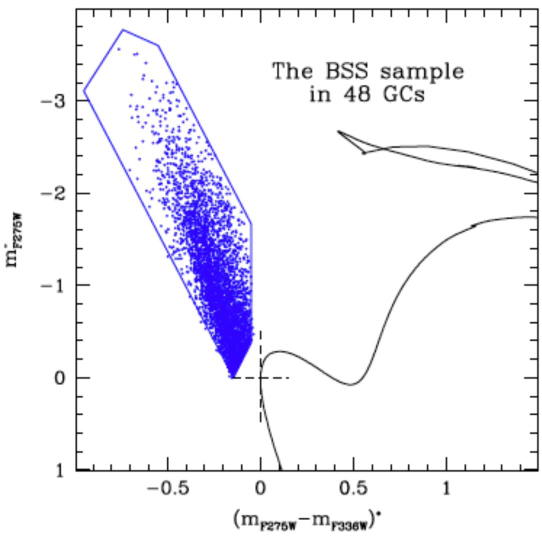
PhD project in ASTROPHYSICS

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

Supervisor: F.R.Ferraro **Co-supervisors:** B. Lanzoni, C. Pallanca, A. Mucciarelli

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 7

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

Supervisor: Myriam Gitti, Fabrizio Brighenti

PhD project in ASTROPHYSICS

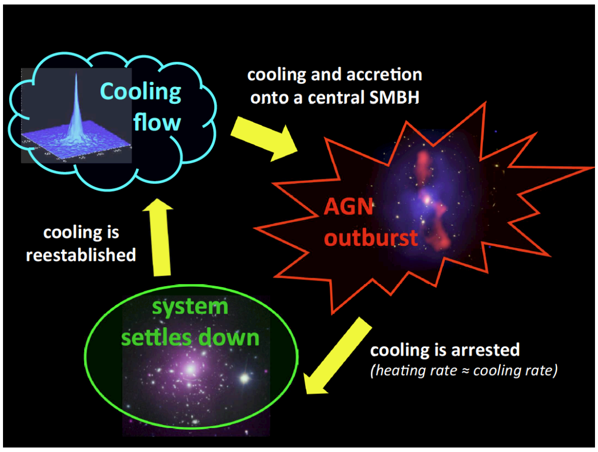
Title of the Project: *AGN feeding-feedback cycle in cool core clusters with Hα nebulae*

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

The project makes use of/developes numerical simulations: no

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.

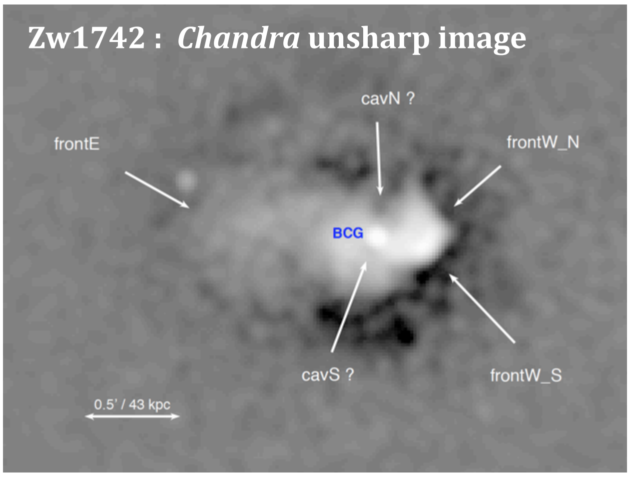
Outline of the Project:

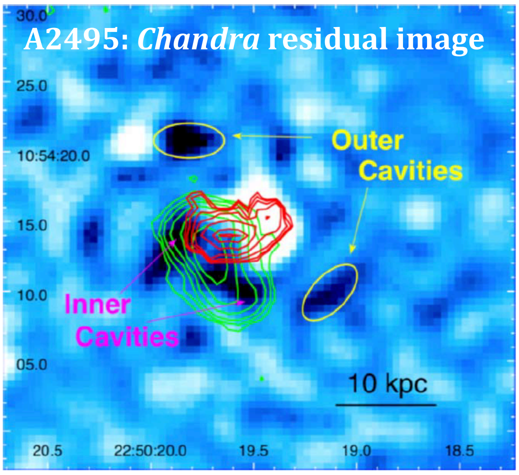
To clarify the regulation of the feeding and feedback cycle in cluster cores it is thus crucial to perform accurate studies of the cooling and heating processes for a sensible sample of clusters with a prominent cold ICM phase. We have identified a sample consisting of the 24 X-ray brightest, most Hα luminous clusters visible from the Jansky Very Large Array (JVLA). In particular, we selected clusters from the ROSAT BCS sample with 0.1-2.4 keV flux $f_X > 7 \times 10^{-11}$ erg 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 (130 ks have already been observed for one cluster).

Our first results (see e.g., right panel in the Figure below) suggest that, in some systems, the cooling process is not currently depositing gas onto the BCG core so it cannot fuel the AGN (Pasini et al. 2019, ApJ, 885, 111; Pasini et al. 2021, arXiv:2102.11299).
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 instead 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 student 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 of the whole sample, the PhD student 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 and young stars in the BCG.





Left : Our *Chandra* observation of Zw1742 (Ettori et al. 2013, A&A, 555, A93) found evidence of a minor merger (a cold front ahead of a remnant cool core) and X-ray cavities, but no disruption of rapid cooling in the BCG, as demonstrated by a high Hα luminosity. What is the morphology of the radio BCG? Are there lobes filling the X-ray cavities? Our new JVLA observations will allow us to answer these questions.
Right : The results from our new *Chandra* and JVLA observations of A2495 (Pasini et al. 2019, ApJ, 885, 111) indicate that it has a disturbed morphology, showing hints of cavities and of a cooling wake that is associated with an Hα nebulae (red contours), but is spatially offset from the radio BCG (green contours). This could be explained as a merger or sloshing which has separated the BCG from both the hot gas and the nebular emission, suggesting that cooling may not deposit gas into the BCG core where it can feed the AGN.

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DIFA(UNIBO) – Project 8

"***Understanding the role of gas circulation in the evolution of star-forming galaxies***"

Supervisor: Federico Marinacci

PhD project in ASTROPHYSICS

Title of the Project: *Understanding the role of gas circulation in the evolution of star-forming galaxies*

Supervisor: Federico Marinacci

Scientific Case: The circulation of gas between galaxies and their circumgalactic medium (CGM) is what drives the evolution of galaxies. This gas circulation is particularly important for star–forming disc galaxies like our own Milky Way, which need to accrete a supply of fresh gas from their CGM in order to keep forming stars for the entire age of the Universe. On the other hand, gas within galaxies is also ejected from the star–forming disc as a result of feedback processes associated to star formation. The ejected gas is bound to interact with the material in the CGM and this interaction modifies the thermodynamic state of the CGM gas, its dynamics, and its chemical composition. A fraction of the ejected gas eventually makes its way back to the disc, thus becoming the material from which new stars are born. For these reasons, it is crucial to investigate the gas cycle between galaxies and their CGM to make a decisive step forward in our theoretical understanding of galaxy formation and evolution.

Outline of the Project: This PhD project will investigate how gas circulation between galaxies and their CGM affects their mutual evolution. In short, this project seeks to find an answer to the following open question in theoretical galaxy formation studies:

- How does the gas cycle between galaxies and their CGM influence the properties and the subsequent evolution of such structures? In particular, how does fresh gas in the CGM become accessible to star–forming galaxies so that they can keep forming stars?

To answer this question, this PhD project will investigate in detail the gas flows between galaxies and their CGM by designing, performing and analysing advanced (magneto-)hydrodynamical simulations of galaxy formation and evolution. These simulations will focus on the interaction between the gas lifted from the disc of a star–forming galaxy by feedback processes and the material in the CGM. Moreover, the creation of mock datasets and their detailed comparison to the observations will guide the simulation development and their constant improvement by extensively testing their predictions on the gas properties and dynamics.

The outcome of this PhD project will be instrumental to draw a coherent physical picture on the mechanisms regulating the inflow and outflow of cosmic gas to and from galaxies, thus advancing our understanding of the processes shaping galaxy formation and evolution.

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DIFA(UNIBO) – Project 9

Forming Milky Way-like galaxies in cosmological simulations with explicit ISM and feedback models

Supervisor: Federico Marinacci

PhD project in ASTROPHYSICS

Title of the Project: *Forming Milky Way-like galaxies in cosmological simulations with explicit ISM and feedback models*

Supervisor: Federico Marinacci

Scientific Case: Cosmological simulations of galaxy formation have become increasingly successful at reproducing the properties of real galaxies. A large part of this success relies on an efficient implementation of stellar and AGN feedback processes that lead to the generation of powerful galactic-scale outflows. These outflows, in turn, are able to control star formation by ejecting substantial amounts of gas from galaxies. However, many of these models suffer from severe shortcomings because they are often implemented in a very crude and *ad hoc* way even in state-of-the art cosmological simulations. Therefore, to make a decisive step forward in our theoretical understanding of galaxy formation it is imperative to overcome these limitations. Of particular importance is the development of new models that treat explicitly the multiphase structure of the interstellar medium (ISM) and self-consistently include the generation of galactic-scale outflows. These are essential aspects that have a direct bearing on 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 understanding of the impact of stellar feedback processes on the metal and baryon budget of galaxies.

Outline of the Project: The PhD student will use the SMUGGLE model, an explicit and comprehensive ISM and stellar feedback model implemented in the moving-mesh code AREPO, to perform state-of-the-art zoom-in hydrodynamical cosmological simulations of the formation of a galaxy similar to our own Milky Way. In the first phase of the project, the PhD student will join the ongoing effort of porting the SMUGGLE model from idealized simulations studying the evolution of isolated galaxies to cosmological applications. Once this porting phase is completed, the student will design, carry out and analyse the planned zoom-in cosmological simulations. These innovative simulations will be used to answer key questions in galaxy formation, with a particular emphasis on how stellar feedback influences the properties of galaxies and their circumgalactic medium and the balance between gas accretion and outflows in a full cosmological context. Other than testing the simulations predictions against the available observations, this PhD project will also benefit from a detailed comparison of the simulation results with those of the AURIGA project that simulates the same class of objects by using the same code, but with a different ISM and stellar feedback model.

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DIFA(UNIBO) – Project 10

"Cosmology with Bayesian deep neural networks to learn the properties of the Cosmic Web"

Supervisor: Federico Marulli

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

PhD project in ASTROPHYSICS

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

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

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 datasets, 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 2022.
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 knowledges on the modern statistical techniques to analyse large extra-galactic datasets and extract cosmological information. Moreover, he 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 datasets** to provide independent cosmological constraints.
- Application of the tools on larger mock catalogues to provide **forecasts for next-generation galaxy redshift surveys**, such as Euclid and LSST.

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DIFA(UNIBO) – Project 11

"Cosmology from the combination of multiple observational probes

Supervisor: Federico Marulli

PhD project in ASTROPHYSICS

Title of the Project:
Cosmology from the combination of multiple observational probes

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

Scientific Case:
Modern observational cosmology aims at advancing our current understanding of the nature of dark matter and dark energy by exploiting the statistical properties of the large-scale structure of the Universe. The next-generation key breakthrough in this field will involve the joint statistical analysis of different cosmological probes.
The aim of this PhD project is to develop all the required statistical tools to **perform a combined multi-probe analysis** and to apply it to the latest data sets available. The implemented algorithms will be first validated on large sets of mock catalogues in different cosmological frameworks to fully address all the possible issues of probe combination and cross-correlations. The goal is optimize the data analysis methods that will be used to maximize the scientific return of ongoing and future galaxy redshift surveys, like Euclid and LSST, while minimizing systematic uncertainties.
A large data set of different cosmological probes will be collected from available extra-galactic surveys, and the main statistics of cosmic tracers will be be investigated independently and in combination. In particular, this PhD research project will focus on the **joint combination of cosmic void size function and profiles, galaxy cluster number counts, and galaxy and galaxy cluster two-point and three-point correlation functions**. Cross-correlations of voids, galaxies and galaxy clusters will be investigated as well. Constraints from these low-redshift probes will be eventually combined with the cosmic microwave background data.
The PhD student will become familiar with the state-of-the-art techniques of modern observational cosmology, including the management and exploitation of big data. Moreover, he will have the opportunity to obtain new strong constraints on the main standard cosmological model parameters, and to discriminate among alternative cosmological frameworks. He will be also involved in the European Space Agency (ESA) **Euclid mission**, whose core scientific objectives will be achieved by combining galaxy clustering and weak lensing.

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

- **Implementation of numerical algorithms for cosmological probe combination**, including e.g. importance sampling, cross-correlations, cross-covariances, multi-dimensional priors from available posterior distributions.
- **Validation of the probe-combination algorithms** on simulated galaxy, galaxy cluster and void catalogues in different cosmological scenarios.
- Investigation of the potential of probe combination and cross-correlations in **breaking the main cosmological degeneracies**, e.g. between the effects of massive neutrinos, dynamical dark energy and modified gravity.

- **Exploitation of the developed numerical tools on available data sets** to provide new cosmological constraints.
- Multi-probe analysis on simulated and future real data of the ESA **Euclid** wide survey.

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DIFA(UNIBO) – Project 12

"Strong Gravitational Lensing: simulating and modelling "

Supervisor: R. Benton Metcalf

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Department of Physics and Astronomy - DIFA

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.

1) **Development and application of lens modelling techniques in galaxy clusters:** Excellent data exists on galaxy clusters that show small arcs around individual objects in the clusters. Currently these objects have not been fully analysed for lack of a lens modelling codes that can handle them in detail, but they potentially contain a wealth of information about the mass distribution of the galaxies that has not been accessible previously. My former student. Nicolas Tessore, and my group developed a code that can be easily modified to address these cases. This project would involve further developing this code and applying it to real data and simulated data in collaboration with Dr. Tessore, Dr. M. Meneghetti and others. The scientific goal is to learn about the distribution of mass in substructures and to resolve the disagreement between the cosmological simulations and observations.
2) **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 13

"Weak Gravitational Lensing with the Lyman-alpha Forest "

Supervisor: 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 14

"Machine Learning Tools for Weak and Strong Lensing by Galaxy Clusters: Paving the Way to the ESA-Euclid Mission".

Supervisor: Lauro Moscardini

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UNIVERSITÀ DI BOLOGNA

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

PhD project in ASTROPHYSICS

Title of the Project:
Machine Learning Tools for Weak and Strong Lensing by Galaxy Clusters: Paving the Way to the ESA-Euclid Mission.

Supervisor: Prof. Lauro Moscardini
Co-Supervisors: Prof. Massimo Meneghetti, Dr. Carlo Giocoli

Scientific Case:

Galaxy clusters are the largest gravitationally bound structures in the Universe. Their content is dominated by dark matter, which constitutes approximately 85% of their mass budget. Baryons make up the remaining 15%, which is in large part made of hot gas. Only a small fraction (<1%) of the cluster mass is in the form of stars in galaxies.

The upcoming ESA-Euclid satellite will observe 15,000 sq. degrees of the sky to a nominal depth of 24.5-24 mag in the VIS and NIR channels, returning high-resolution imaging of nearly 10,000 galaxy clusters. The quality of the observations, not only in terms of spatial resolution but also in terms of the stability of the PSF, will be ideal to map the content of galaxy clusters using weak lensing measurements. In fact, weak lensing is one of the primary cosmological probes of the Euclid mission. At the same time, several strong lensing features will be detected in the cores of many clusters observed with Euclid. These features will be a fantastic complement to the weak lensing measurements to increase the accuracy of the mass reconstructions in the cluster cores. In particular, strong lensing is widely recognized as one of the most powerful tools to study the inner density profile and substructure content of galaxy clusters.

Figure 1. *Left panel* displays the rendering of the Euclid satellite that will be launched in 2022. *Right panel* shows a high-resolution image of a galaxy cluster (Abel 370) observed by the Hubble Space Telescope. In the outskirt of the system, it is possible to notice the images of slight distorted galaxies due to the weak lensing effect. Toward the center, images are much more elongated, and in some cases multiply repeated, as result of the strong gravitational lensing effect.

Outline of the Project:

Measuring the distribution of dark matter and baryons and understanding the interplay of these cluster constituents is of fundamental importance for comprehending the nature of dark matter and the physical mechanisms that regulate the formation and evolution of galaxies in dense environments. When dealing with the huge amount of data that Euclid will deliver, the major obstacle will be to find the optimal way to automatize a large part of the analysis process to measure relevant cluster properties. This Ph.D. thesis will develop novel techniques to exploit weak and strong lensing by clusters observed with Euclid. In particular, the candidate will work on:

- developing deep learning algorithms to measure cluster structural properties, such as their mass, concentration, density profile, substructure content, etc., from weak lensing maps (e.g. shear maps);
- developing methods to automatize the search for strong lensing features in galaxy clusters. These will include multiple images of background sources and gravitational arcs produced mainly by the lensing effects of the cluster dark matter halo, and small scale strong lensing events produced by cluster galaxies;
- combining weak and strong lensing measurements using methods based on hybrid parametric, free-form, and AI-driven approaches.

The candidate will use large sets of semi-analytic and full-hydrodynamical simulations to produce mock Euclid observations usable for training and validating the methods mentioned above. In addition, they will apply their techniques to existing observational datasets.

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DIFA(UNIBO) – Project 15

"Observational cosmology with MeerKAT HI intensity mapping."

Supervisor: Lauro Moscardini

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

PhD project in ASTROPHYSICS

Title of the Project: Observational cosmology with MeerKAT HI intensity mapping

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

Scientific Case:

Mapping the large-scale structure of the Universe by covering increasingly larger volumes and earlier cosmic epochs is essential to understand the role of dark matter and dark energy in the evolution of structures and, ultimately, for unveiling the nature of these dark components. A promising candidate to this scope is the cosmic neutral hydrogen (HI), observed by radio telescopes through its redshifted 21 cm line. The HI distribution in the post-reionization Universe can be measured in large enough volumes within reasonable amounts of telescope time by exploiting the technique of Intensity Mapping (IM). Indeed, HI IM aims at integrating the signal in large sky pixels without resolving individual HI galaxies, which would be too faint for a direct detection using traditional methods.
The measurement and interpretation of the HI IM signal is the next open challenge in cosmology and one of the main observational programmes at the MeerKAT telescope, located in the Karoo outback in South Africa (Figure 1). MeerKAT has recently started its observing campaign (MeerKLASS) that will eventually lead to exquisite measurements of the growth of structures, the angular diameter distance and the Hubble rate.

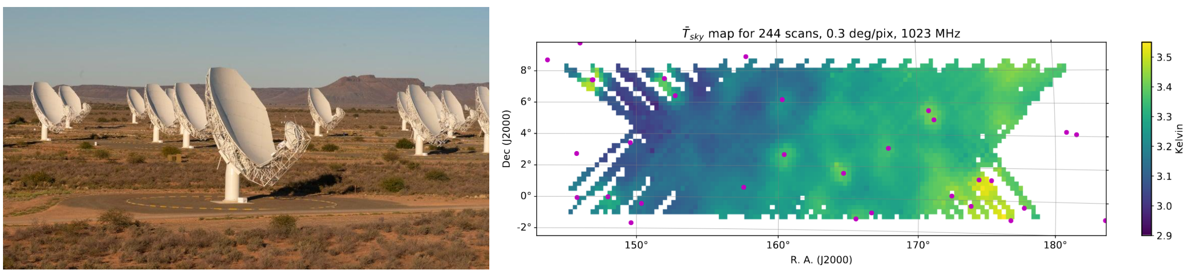

Figure 1: (*Left*): the South African radio telescope MeerKAT, a precursor of the Square Kilometre Array (SKA) telescope. (Right): sky image at 1.023 GHz from the first MeerKLASS observations (Wang et al., 2020).

Outline of the Project:

The project goal will be the measurement of the HI distribution up to redshift 0.5 from the MeerKLASS power spectrum. The power spectrum amplitude constrains the HI bias and the HI density. A measurement of the bias would shed light on the nature of collapsed halos in which HI resides and the properties of the hosting galaxies. The success of HI IM observations heavily relies on the ability to separate the cosmological signal from the strong foreground emission which can be up to five orders of magnitude stronger than the expected HI signal. The candidate will work on the foreground separation using techniques borrowed from the CMB data analysis and will carry out simulations to test the accuracy of the subtraction.
The candidate will also explore the cross-correlation of HI maps with optical galaxy surveys in order to enhance the detection significance by suppressing systematic effects.

The strategies developed within this project will be timely to provide a realistic and complete pipeline for IM data analysis and will allow the candidate to take a leading position in future cosmological observations with the SKA.

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DIFA(UNIBO) – Project 16

"Chemical characterization of the Milky Way merger events: identifying the chemical DNA of our Galaxy."

Supervisor: Alessio Mucciarelli

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

PhD project in ASTROPHYSICS

Title of the Project:
Chemical characterization of the Milky Way merger events: identifying the chemical DNA of our Galaxy
Supervisor: Prof. Alessio Mucciarelli (DIFA)
Co-supervisor: Dr. 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 neighbourhood (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 advent of the Gaia mission has allowed to identify globular clusters formed in situ, as well as clusters born in different structures, and only later accreted onto our Galaxy. Gaia kinematic measurements enabled the association of each of these accreted cluster to its likely progenitor (Massari et al. 2019), completely changing our comprehension of the Milky Way globular cluster systems.
Clusters formed in different progenitors of the Milky Way keep memory of the chemical composition of their past environment in their atmospheres. From the chemical composition of these clusters, we can therefore reconstruct the chemical DNA of their progenitors. Even if these progenitors are now completely dissolved within the Galaxy, their clusters can tell us about their chemical enrichment histories, provided that the derivation of the chemical composition is performed in a homogeneous and systematic-free manner.

Outline of the Project:

The PhD project is aimed at describing for the first time the chemistry of each individual accreted dwarf galaxy that contributed to build-up the Milky Way. In order to reach this goal, we plan to perform the most complete and homogeneous screening of the chemical properties of several tens of globular clusters associated to different Milky Way merger events.
For all of these globular clusters high-quality, high-resolution spectra are available in the ESO and Keck archives, providing a goldmine of information ready to be exploited.
The Gaia data of each spectroscopic target will be exploited in order to assess its membership to the different globular clusters. For each cluster then, the chemical abundance of the main groups of elements (i.e., alpha, slow and rapid neutron-capture elements) will be measured and compared with state-of-the-art chemical evolutionary models to (1) reconstruct the chemical enrichment history of each progenitor and (2) characterize from a chemical point of view the sequence of merger events that has shaped our Galaxy.

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 17

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

Supervisor: Alessio Mucciarelli

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Department of Physics and Astronomy - DIFA

PhD project in ASTROPHYSICS

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

Scientific Case:

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

Outline of the Project:

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

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

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

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DIFA(UNIBO) – Project 18

"Globular Cluster evolution in dwarf satellites "

Supervisor: Carlo Nipoti

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Department of Physics and Astronomy - DIFA

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), in order to avoid substantial pollution from type II supernova ejecta in the stellar chemical composition, 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 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 in their orbit, hence the total mass in FG stars at early times can have been larger than today. With this thesis, we plan to address the problem of mass loss in satellites and in their globular clusters by means of N-body simulations.

Outline of the Project: The PhD student will study the evolution of dwarf satellite galaxies in the Milky Way with N-body simulations. 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 Milky Way, 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.

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References:
Calura F., D'Ercole A., Vesperini E., Vanzella E., Sollima A., 2019, MNRAS, 489, 3269
Khalaj P., Baumgardt H., 2016, MNRAS, 457, 479
Nipoti C., Cherchi G., Iorio G., Calura F., 2021, submitted to MNRAS (arXiv:2012.06600)

Bologna, 26/2/2021

DIFA(UNIBO) – Project 19

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

Supervisor: Carlo Nipoti

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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

PhD project in ASTROPHYSICS

Title of the Project:
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 the distribution functions presented in Pascale et al. (2019). In particular, f(J) models of globular clusters with central intermediate mass black hole (IMBH) will be first tested against available mock observations of model globular clusters and then applied to real globular clusters to constrain the mass of putative central IMBHs. The PhD student will produce multi-component models of globular clusters to study mass-segregation and estimate the contribution of dark remnants to the total globular cluster mass budget.
With a similar approach the PhD student will study the distribution of dark matter in dwarf spheroidal galaxies (see Pascale et al. 2018) with multiple stellar populations plus dark-matter halo. 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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References:
Pascale R., Posti L., Nipoti C., Binney J., 2018, MNRAS, 480, 927
Pascale R., Binney J., Nipoti C., Posti L., 2019, MNRAS, 488, 2423
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Bologna, 26/2/2021

DIFA(UNIBO) – Project 20

"Rotating astrophysical fluids with baroclinic distributions"

Supervisor: Carlo Nipoti

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:
Barnabè M., Ciotti L., Fraternali F., Sancisi R., 2006, A&A, 446, 61
Sormani M.C., Sobacchi E., Pezzulli G., Binney J., Klessen R.S., 2018, MNRAS, 481, 3370

Bologna, 26/2/2021

DIFA(UNIBO) – Project 21

"Bulge/Disk decomposition of galaxies for the 21th century: characterization of the components, and link with the galaxy properties, using MaNGA kinematics and SDSS photometry."

Supervisor: Silvia Pellegrini

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: *Bulge/Disk decomposition of galaxies for the 21th century: characterization of the components, and link with the galaxy properties, using MaNGA kinematics and SDSS photometry.*

Supervisors: Silvia Pellegrini (DIFA, UniBo), Michele Cappellari (Dept. of Physics, Univ. of Oxford, UK)

Scientific Case: The development of the integral-field spectroscopy (IFS) produced a major advance in our knowledge of the dynamical properties of galaxies of the local universe. For example, the ATLAS^{3D} project, focused on early-type galaxies, provided a new classification of these objects based on their kinematical properties. The project analyzed a sample of 260 galaxies within z = 0.01 and produced the first 2D characterization of their dynamical properties (e.g., mass-to-light ratio, dark matter content, angular momentum of the stellar component). One of the outcomes of the project was the finding of a close link between bulge fraction, as approximately traced by the velocity dispersion, and the galaxies stellar population. This finding provides important clues for our knowledge of the formation (and evolution) path followed by these galaxies (e.g., Cappellari 2016 for a review). More recently, a new much larger IFS survey mapped galaxies of all morphological types at $0.01 < z < 0.15$: the MaNGA Survey (Mapping Nearby Galaxies at APO, Bundy et al. 2015). This project, that just completed the data acquisition part, provides spatially resolved spectroscopy for ~10000 galaxies, the largest sample to date. This means that MaNGA will allow for a major extension of previous studies.

Outline of the Project: The thesis project is divided into two main parts. In the first one, photometric data from the SDSS, and IFS kinematic data from MaNGA, will be jointly used to develop a novel method to perform a simultaneous photometric + kinematic bulge/disk decomposition. This part will make use of some existing software to model the galaxies dynamics (e.g., JAM; Cappellari 2008), but some significant new components will be developed. The new method, combining photometry and kinematics, aims at removing the degeneracies currently affecting the traditional photometric bulge/disk decomposition (e.g. Galfit) and will be nearly insensitive to inclination effects; it is then expected to become useful for the entire community, and the package that will be built could be made publicly available. In the second part, taking advantage of the improved characterization of the various components, the project will revisit the main correlations involving the properties of these components, as for example the relations between the Bulge/Disk and the age, metallicity of the stellar population, environment.

References:
Bundy, K., et al. 2015, ApJ 798, 7
Cappellari, M., 2008, MNRAS 390, 71
Cappellari, M., 2016, ARA&A 54, 597

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DIFA(UNIBO) – Project 22

"Simulating the evolution of radiogalaxies in the cosmic web ."

Supervisor: Franco Vazza

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: Simulating the evolution of radiogalaxies in the cosmic web

Supervisor : Prof. F. Vazza (DIFA)

Scientific Case:
Radio Galaxies are one of the most spectacular example of how astrophysics couples spatial and temporal scales separated by many orders of magnitude, and they also are a key ingredient of galaxy formation. A small (<%) fraction of the energy accreted onto their central supermassive black hole on is fed back onto the surrounding medium, replenishing it with thermal energy, relativistic particles and magnetic fields.
The long-term evolution of relativistic plasmas, mixing with the surrounding gas, depends on a complex sequence of loss and re-energisation events, which start to be routinely detected by low-frequency radio observations, often highlighting complex morphologies and spectral emission properties which are yet challenging to understand.

Despite their pivotal role for the evolution of their host environment, no self-consistent and large simulation of radiogalaxies has been performed so far, also because this requires the development of advanced numerical models and the access to very large simulations.

Outline of the Project:
This PhD project is aimed to develop a physically motivated algorithm for the evolution of radio galaxies and of the relativistic plasmas injected by them, with the cosmological Eulerian code ENZO. The code developments will be used to produce new, large simulations of radiogalaxies across cosmic environment, as well as to accurately model the relativistic processes associated with the ageing and the re-acceleration of relativistic particles in the cosmic web. Synthetic radio observations of simulations will also be routinely produced to closely compare with existing or future radio surveys.

Given its topic and workflow, this project calls for candidates who are comfortable with *coding and numerics*, as well as candidates with some background in *relativistic physics*.

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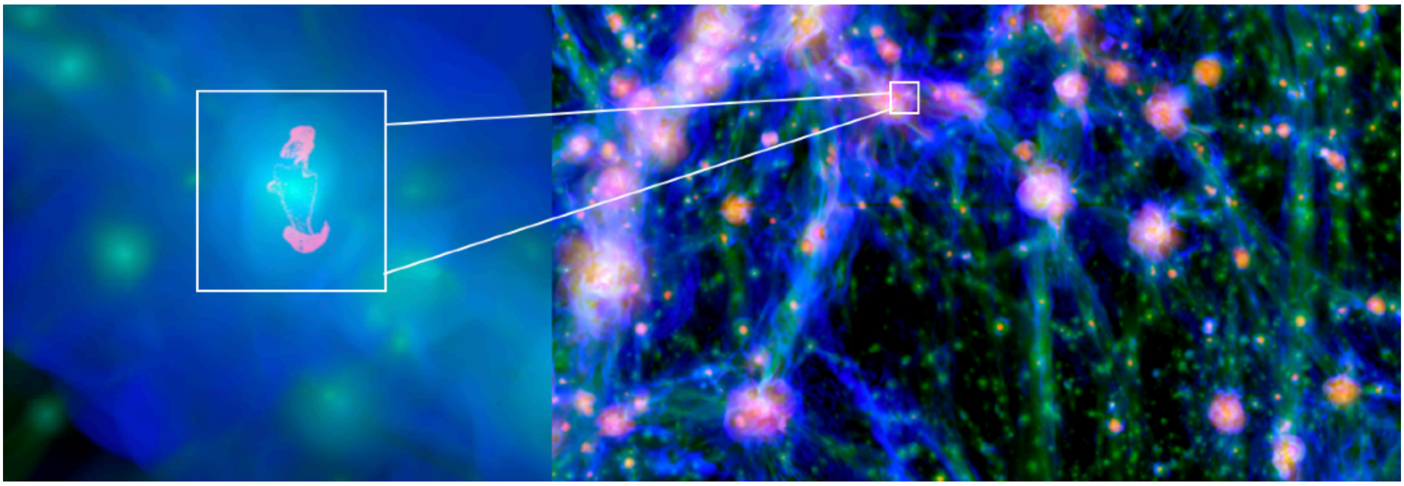

DIFA(UNIBO) – Project 23

"Tracing the Early Cluster Assembly with Accreting Black Holes."

Supervisor: Cristian Vignali

PhD project in ASTROPHYSICS

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

Supervisor: Cristian Vignali (DIFA)
Co-Supervisors: Marco Mignoli, Roberto Gilli (INAF-OAS)

Scientific Case: Cosmological numerical simulations give us a clear picture of how dark matter 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", i.e. the ancestors of today's massive clusters, are usually identified as large galaxy overdensities in the first three-four billion years of cosmic history ($z>1.5-2$). 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 itself.

Outline of the Project: The main goals of the proposed PhD project are i) understanding how supermassive black holes form and grow within early cosmic structures, and ii) 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 that have been discovered by our group (e.g. the Jackpot nebula) and where a wealth of multi-band information has been already collected, including data from Chandra, VLT/MUSE, HST and ALMA. She/he will start from the analysis of the X-ray data to search for i) faint AGN residing within these dense environments and ii) signatures of X-ray diffuse emission that may give insight on both AGN feedback and on the dynamical status of the structure. The same analysis will be extended to Chandra and/or XMM archival observations of similar systems.
For the protoclusters with the richest multi-band coverage, the candidate will also investigate the physical properties of the population of non-active galaxy members (star formation rate, stellar mass) and determine the overall incidence of AGN activity in these galaxies. The results will be compared with those in the literature that have been obtained in similarly overdense structures and in the field, i.e. in average density regions, as well as with the expectations from numerical simulations.

The PhD candidate will be trained in observational cosmology, in particular in the formation and assembly of galaxy clusters, 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 gain expertise in observing proposal writing, acquire scientific independence, present the work at international conferences, and have the opportunity to visit renown research Institutes and Universities abroad through our collaboration network and thanks to the research fundings available to our group.

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DIFA(UNIBO) – Project 24

***"The realm of dual super-massive black holes*"**

Supervisor: Cristian Vignali

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: The realm of dual super-massive black holes

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

Scientific Case: Searching for dual/multiple 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) an extensive search for dual AGN in some of the deepest X-ray fields currently available, (b) an intensive study of the currently known dual AGN in terms of BH mass ratio and host galaxy (and environment) properties (including a multi-wavelength study of the interstellar medium), and (c) the occurrence of dual and offset AGN by cross-matching large-area optical survey galaxy pairs with *Chandra* and XMM catalogs. Finally, (d) the derived demography and physical properties will be interpreted and placed in a coherent picture using the available numerical simulations. The PhD student will also be introduced to the state-of-the-art analyses using MUSE/ALMA/HST data to fully characterize dual AGN and their hosts.

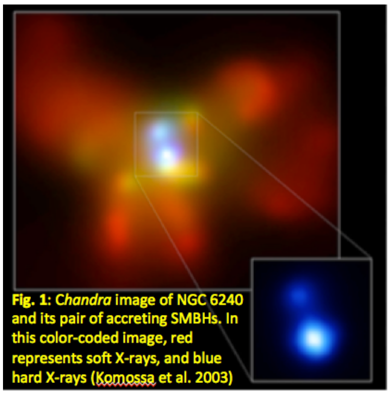

Fig. 1: *Chandra* image of NGC 6240 and its pair of accreting SMBHs. In this color-coded image, red represents soft X-rays, and blue hard X-rays (Komossa et al. 2003)

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