PhD project in ASTROPHYSICS - PNRR DiFA1

Title of the Project: **Exploiting the Hubble eyes to probe the exotic populations in Globular Clusters**

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

Scientific Case: Globular Clusters (GCs) are the most populous, old and dense stellar clusters in the Galaxy. They are sub-galactic structures, with typical masses of 10^4-10^6 $M_\odot$, ages as old as the Hubble time, and cores that show the most extreme stellar densities in the Universe, up to several 10^6 stars/pc^3. At odds with what happens in galaxies, where the orbital motion of stars primarily depends on the average gravitational potential, GCs are "alive" (collisional) systems, where two-body interactions cause kinetic-energy exchanges among stars and gravitational perturbations to their orbits, bringing the cluster toward a thermodynamically relaxed state in a timescale that can be significantly shorter that their age. The recurrent gravitational interactions among stars allow heavy objects to progressively sink toward the central region of the cluster (dynamical friction) and modify the structure of the system over the time (the so-called "dynamical evolution"). The internal dynamical activity of GCs is thought to also generate a variety of stellar exotica, like blue straggler stars (BSSs) and binaries containing heavily degenerate objects, as neutron stars (NSs) and black holes. Among these, BSSs are surely the most abundant and the easiest to distinguish from normal stars, since they define a sort of sequence extending brighter and bluer than the cluster main-sequence turn-off (MS-TO) point in a colour-magnitude diagram. Being generated by direct collisions or mass-transfer activity in binary systems composed of non-degenerate companions, BSSs are significantly heavier (1.2 $M_\odot$) than the average cluster population (0.3 $M_\odot$). Hence, they are powerful probes of key physical processes (such as mass segregation and dynamical friction) characterizing the dynamical evolution of star clusters (Ferraro+09,+12). Millisecond pulsars (MSP) are formed in binary systems containing a NS which is eventually spun up through mass accretion from the evolving companion, that, in turn, is expected to become a Helium white dwarf. Although the disk of the Galaxy has a total mass 100 times larger than the Galactic GC system, more than 50% of the entire MSP population has been found in the latter. This strongly suggests that a tight link exists between cluster dynamics and MSP formation: while the only viable formation channel for MSPs in the Galactic Field is the evolution of primordial binaries, dynamical interactions in the ultra-dense environment of cluster cores can favour the formation of binaries suitable for recycling NSs into MSPs. The optical identification of MSP companions, possibly combined with dedicated spectroscopic follow-ups, is fundamental to characterize the origin and the evolutionary paths of MSPs. In principle, the careful examination of the light curve may allow constraining the orbital inclination of the system. This measure, coupled with the mass ratio derived from the velocity curve, leads to a direct estimate of the NS mass, which is expected to be somewhat larger (due to heavy mass accretion) than the canonical 1.35 M_{sun}. In turn, determining the NS mass is crucial to assess its upper limit and tightly constrain the (still unknown) equation of state of matter at the nuclear equilibrium density, thus opening a new window in the domain of Fundamental Physics research.

Outline of the Project: In this PhD thesis we propose to use unprecedented multi-wavelength, multi-epoch, high-resolution datasets already acquired by the Hubble Space Telescope, complemented with new observations with the JWST and UV satellites (e.g., UVIT) to explore the exotic populations of a large sample of star clusters having different structural properties, with the exciting perspective of a huge impact on several branches of the current astrophysics and fundamental physics research. The accurate proper motions measured in the central region of the target clusters using long time-baseline observations will also provide a powerful tool to identify the gravitational action of under-luminous matter aggregations in the cluster centres, thus also probing the existence and providing the mass of the long-sought intermediate-mass black holes.

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

Funded by the European Union
NextGenerationEU

MUR

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

PhD project in ASTROPHYSICS - PNRR DiFA2

Title of the Project: Data-driven approaches to stellar astrophysics in the era of large astronomical surveys

Supervisor : Andrea Miglio
Co-Supervisors : Gisella Clementini, Tatiana Muraveva

Scientific Case:
Stellar astrophysics is entering a new era of Big Data science thanks to exponentially growing data volumes from large surveys, such as the cornerstone European Space Agency (ESA) mission Gaia, the Transient Exoplanet Survey Satellite (TESS), the Legacy Survey of Space and Time (LSST) at the Vera Rubin Observatory (VRO), and the ESA mission Planetary Transits and Oscillations of Stars (PLATO).

In addition to astrometry and broad-band photometry already available for about 1.8 billion sources in the Milky Way and beyond, *Gaia*'s Data Release 3 (release date: June 2022) will provide an unprecedented collection of variable stars, galaxies, and asteroids, as well as radial velocities, epoch photometry, and spectra, based on 34 months of Gaia observations. *TESS* is an all-sky photometric survey providing exquisite high-cadence high-precision light curves for hundreds of thousands of bright stars. While TESS' primary aim is the detection of exoplanetary transits, it also represents a goldmine for studying the internal structure of stars via the detection of their global, resonant oscillation modes. These datasets will be complemented by a 500 petabyte set of images and data products from the *LSST@VRO* that is expected to become fully operational in 2024.

The extraordinary volume of these data will pose novel challenges and opportunities as data volumes at these scales have never been encountered by the scientific community before. The application of advanced machine learning (ML) and deep learning (DL) techniques can provide the level of accuracy and automation required to exploit large datasets efficiently, and is thus highly needed and timely. The development of such approaches is also key to the ESA M3 mission PLATO, both in its preparation phase (via a robust characterisation of its prime targets prior to launch) and in exploiting the wealth of data which will be collected during operations (2026-).

Outline of the Project:
The PhD candidate will exploit state-of-art ML and DL algorithms (e.g. regression, K-nearest neighbours algorithms, random forest, principal component analysis, neural networks, and different clustering algorithms) to (1) explore the data parameter space, searching for hidden correlations in the (combined) *Gaia*, TESS and, lately, LSST datasets; (2) infer the missing stellar "labels" (e.g. radial velocity, metallicity, mass, age, evolutionary state, …) from the available datasets, and contribute to PLATO MSte-Sci2 pipeline (Stellar properties determination from preparatory data); (3) scientifically exploit the combination of complementary datasets of variable stars to characterise stellar populations across the Milky Way, including substructures and outliers in the parameters space.

The PhD candidate is expected to contribute to the research projects based on the *Gaia* and LSST data proposed for the Centro Nazionale High Performance Computing (HPC) and Big Data, and will be directly involved in the activities of the PLATO Science Consortium. With support from the Marco Polo fellowship program, they will spend periods abroad at Dipartimento de Inteligencia Artificial, UNED, in Madrid, and at the DPAC data processing centre of the Geneva Observatory.

Contacts: andrea.miglio@unibo.it, tatiana.muraveva@inaf.it, gisella.clementini@inaf.it

PhD project in ASTROPHYSICS - PNRR DiFA3

Title of the Project: Probing the deep cosmos with future gravitational waves and galaxy space missions

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

Scientific Case: Despite the tremendous success gained in recent years by the Λ Cold Dark Matter (ΛCDM) model in describing several astrophysical observables, from the Cosmic Microwave Background (CMB) to the distribution of galaxies in the Large Scale Structure, it is still far from a detailed and complete description of our Universe. In parallel to the still open questions on the unknown component driving the accelerated expansion of the Universe (dark energy) and to debated failures of the ΛCDM cosmological model in describing some phenomena, modern cosmology is currently undergoing a crisis due to the >4sigma tension between measurements of cosmological parameters obtained from late- (Supernovae Ia, Cepheids, ...) or early-Universe (CMB) probes. Whether this is due to some unaccounted systematic in the measurements or it is actually pointing towards new physics, this is still under discussion.

To address all of these questions, several large space missions are currently planned and under development, to explore the cosmos with all-sky maps of galaxies, galaxy clusters, and cosmic voids, e.g. with the European Space Agency (ESA) Euclid mission, and by detecting gravitational waves up to high precisions (e.g. the ESA LISA mission), allowing to measure signals unreachable with current ground facilities. These missions will also significantly benefit the synergy with the next generation ground observatories and telescopes for both galaxies and gravitational waves, like the Vera Rubin Observatory and the Einstein Telescope. It is therefore now fundamental to prepare the exploitation of these future datasets to maximize the scientific return and provide strong foundations for the Italian contribution to these future missions.

Outline of the Project:

The proposed Ph.D. project aims to maximize the scientific exploitation of these planned space data sets, exploiting the newest machine learning data analysis techniques. The volume of data produced will be challenging, requiring to develop efficient data mining strategies. The goal of this project is to implement Bayesian deep neural networks to constrain the cosmological model parameters from the combined analysis of gravitational waves and galaxy catalogues. Accurate simulations will be produced to train the supervised machine learning infrastructure in several beyond-ΛCDM cosmological scenarios. The core scientific achievement of this Ph.D. project will be to exploit these newly implemented data mining pipelines to perform a multi-messenger cosmological analysis, providing new constraints on the expansion history of the Universe. The Ph.D. student will acquire high-level skills in the modern statistical methods of supervised and unsupervised deep learning techniques, which will be investigated for the first time in this context.