Project Title: Cosmology with High-Performance Computing: simulating cosmic structures at different scales

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Project Description

Numerical simulations of cosmic structure formation offer nowadays the most advanced tool to fully capture the complexity of the formation of galaxies, clusters of galaxies and of the large-scale cosmic web. Advanced codes for cosmological simulations are able to optimally exploit the computing capabilities of the most advanced High-Performance Computing (HPC) infrastructures and, in turn, need to be continuously adapted to keep the pace with rapidly evolving HPC architectures. Thanks to the continuous improvement of simulations' software and HPC hardware, the future generation of simulations promise to describe the processes of formation and evolution of cosmic structures, from the ~100 parsecs (pc) to the ~1 Gigaparsecs (Gpc) scale, with an unprecedented level of realism. Two examples of such simulations are shown in Fig. 1, where we show a simulated galaxy cluster and a simulated disk galaxy, as arising within the standard ΛCDM cosmological model.

Cosmological simulations have two distinctive aspects that make them one of the toughest challenges in the field of modern HPC. First, gravity is the main driver of structure formation at cosmological scales. Since gravity is a long-range force, its effect on the scales relevant for galaxy formation, ~ Megaparsec, depends of the structure of the tidal field out to much larger cosmological scales. Second, astrophysical processes relevant for galaxy formation, such as star formation, explosions of supernovae, gas accretion onto super-massive black holes (SMBHs) hosted at the center of galaxies, and the ensuing feedback from Active Galactic Nuclei (AGN) all take place at scales that cannot be resolved in such simulations, but produce effects on ~Mpc scales, that are instead explicitly resolved. Therefore, such effects need to be included in simulations as phenomenological sub-resolution models, whose degree of realism can only be judged by their capability of predicting the observed properties of cosmic structures.

The line of research proposed for this PhD project will focus on the development of new models to describe the processes of star formation and feedback from SMBHs. Such models will be implemented in the OpenGADGET3 (OG3) simulation code, that is developed by the research team formed by the supervisors and the collaborators. In its infrastructural part, OG3 describes gravity through a Tree-PM N-body integration, while the hydrodynamics of cosmic baryons is described by Smoothed Particle Hydrodynamics (SPH). After developing in OG3 and testing such novel models of star formation and feedback, the PhD student will carry out simulations at unprecedented resolution, to describe the formation of galaxies from high to low redshift, both in the extreme environment of galaxy clusters and in the field. The interaction between galaxies and the surrounding diffuse cosmic baryons permeating the inter-galactic (IGM) and intra-cluster (ICM) media will be studied to shed light on the physical processes determining their properties observed by telescopes operating both from ground and from space at different wavelengths, from radio/millimetric, to optical, to X-rays.

The PhD student will be exposed to both theoretical/numerical and phenomenological/observational aspects of cosmic structure formation. From the numerical side, the student will need to get acquainted with parallel coding and with the use of massively parallel HPC facilities, besides acquiring skills on techniques of big-data analysis, including Machine Learning methods. From the astrophysical side, the student will acquire expertise on both phenomenological and theoretical aspects of galaxy evolution and its interplay with diffuse cosmic baryons. Finally, the development of a background knowledge of observational cosmology will also be required in order to compare predictions of simulations to observational data.

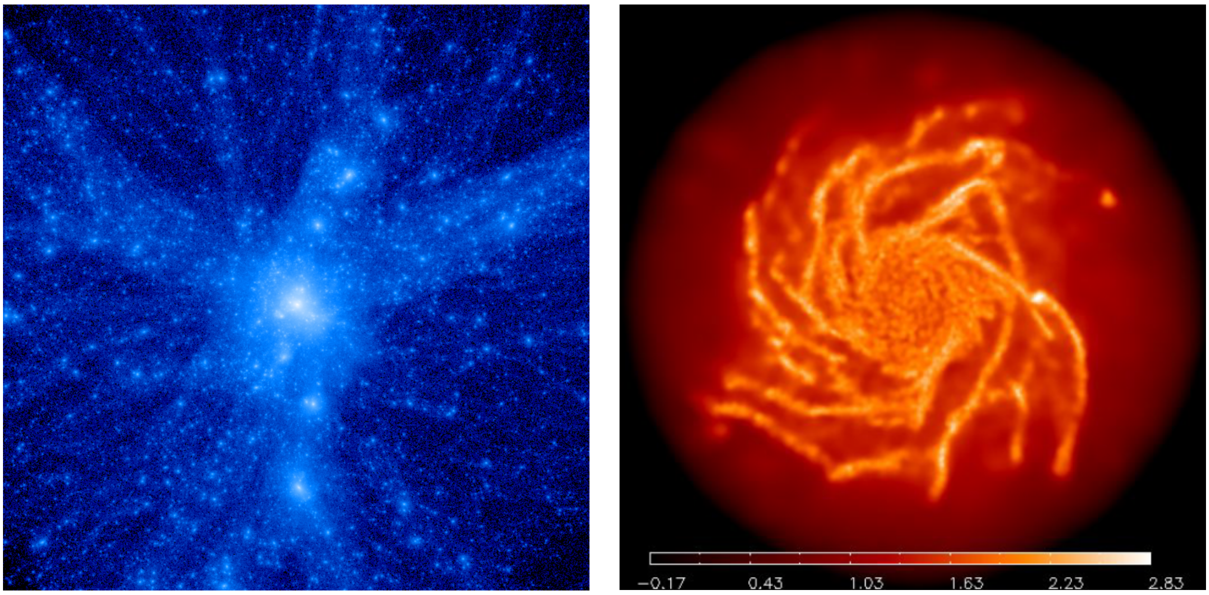

Figure 1. Left: the dark matter density field in a cosmological simulation of a galaxy cluster. The box has a side of about 15 Mpc. Quite apparently, the cluster forms at the intersection of filaments along which it accretes matter and galaxies forming in correspondence of small-scale density clumps. Right: face-on image of the gas distribution in a simulation of a spiral galaxy. The box has a side of about 30 kpc. Knots of high gas density within realistic spiral arms trace the location where stars form.