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Simulating galaxy clusters at high resolution

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Abstract. State-of-the-art cosmological hydrodynamical simulations are able to follow a variety of physical processes, responsible for the formation and evolution of galaxy clusters and of their baryonic component. Given the dynamical range involved, resolving the details of the galaxy population inside the cluster environment is nevertheless challenging and high or very-high resolution simulations are thus required. Here, we investigated the effects of improving resolution on the sub-grid models for feedback and star formation and on the resulting baryonic properties of simulated clusters and their member galaxies, with special focus on a study-case simulated region centered on a massive galaxy cluster.

1. Introduction

With this project we carried out several test runs of cosmological hydrodynamical simulations of galaxy clusters, at high resolution. A primary goal was to test and investigate the effects of improving resolution (10 times better in mass; HR) on the sub-grid models for feedback and star formation, whose calibration is naturally sensitive to the numerical resolution. This is of crucial importance in view of high- and very-high-resolution simulations of production-run samples of simulated clusters, where member galaxies can be well resolved and studied in detail, while keeping under control the sub-grid modelling of the main physical processes in place.

The latest simulation campaign carried out by our group was performed by means of the smoothed-particle-hydrodynamics (SPH) code Gadget3, in a modified version that includes an improved hydrodynamical scheme for better describing gas mixing as well the treatment of various physical processes. Among these, we include models for star formation and detailed chemical evolution, galactic SN-driven winds and a novel scheme for accretion onto black holes powering AGN feedback. This set of simulations provided important results, consistent with observational evidences, on the global thermo-dynamical and chemical properties of galaxy clusters and effectively reproduced their observed cool-core/non-cool-core diversity (e.g. Rasia et al. 2015; Biffi et al. 2017, 2018).

Given the low resolution (LR) of this set of simulations, it is crucial to move to higher resolution in order to investigate in more detail the properties of resolved galaxies within the clusters. The same version of the code, in terms of hydrodynamical scheme and principal physical modules, has been also used to perform the HR tests and full run. From preliminary tests at medium resolution (3-times the

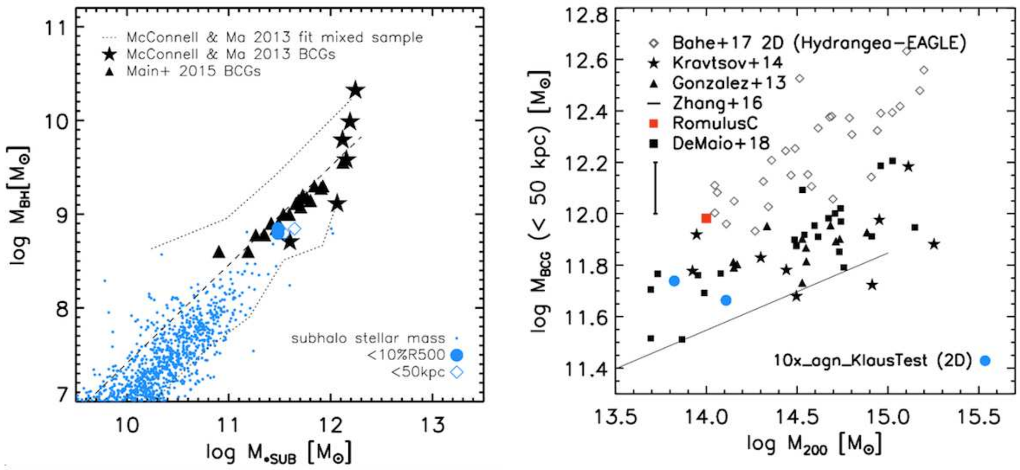

Fig. 1. Relations between the properties of the BH, the BCG and the host haloes, for the Lagrangian region simulated at HR, at $z \sim 1.37$. *Left:* Magorrian relation between the BH mass and the host-halo stellar mass (blue dots and symbols), compared to observational data by McConnell & Ma (2013) and Main et al. (2015) (black lines and symbols). *Right:* relation between the host-halo mass and the BCG mass (computed within the central 50 kpc), compared to observational data as specified in the legend. Simulation data refer to the two most-massive haloes in the simulated Lagrangian region (blue filled circles).

fiducial mass resolution — MR), we could unveil important features of the hydrodynamical models implemented in our code that were not observed in the LR runs and required therefore further investigation. In fact, improving the resolution implies an increase in resolved densities, on which the sub-grid models for evolution of the BHs and AGN feedback depend. A careful re-calibration of these sub-grid models and additional testing was therefore unavoidable. Specifically, we focused on investigating the effects of the BH positioning scheme — especially important for the central BHs in cluster brightest central galaxies (BCGs) and for the resulting impact of AGN feedback on the gas properties — and the presence of a population of "orphan" BHs not associated to any cluster substructure, first at MR and then at HR.

2. Preliminary results and future perspectives

With the computing resources assigned through the INAF-CINECA MoU, we successfully completed a full HR run for one of the 29 Lagrangian regions for which initial conditions are available, were the final best-choice set-up of the code has been adopted. This Lagrangian region has been chosen as a testbed for the HR simulation with the full hydrodynamical set-up of the code, especially because of the variety of different additional tests already available on the same initial conditions.

The first goal is to investigate the details of the simulated region and the thermo-dynamical properties of the main cluster at the center of it. In particular, we started by exploring the position of the central BH in the cluster BCG and the general population of BH in the whole region. In Fig. 1, we show two first tests of the properties of the BHs and their host-haloes, in the HR hydro run at $z \sim 1.37$. We verified that the BHs at the center of the central galaxies in the two most-massive haloes of the region are well centered (residing within the central 0.1 kpc from the center of the halo potential well). As mentioned before, additional tests to explore the properties of the main clus-

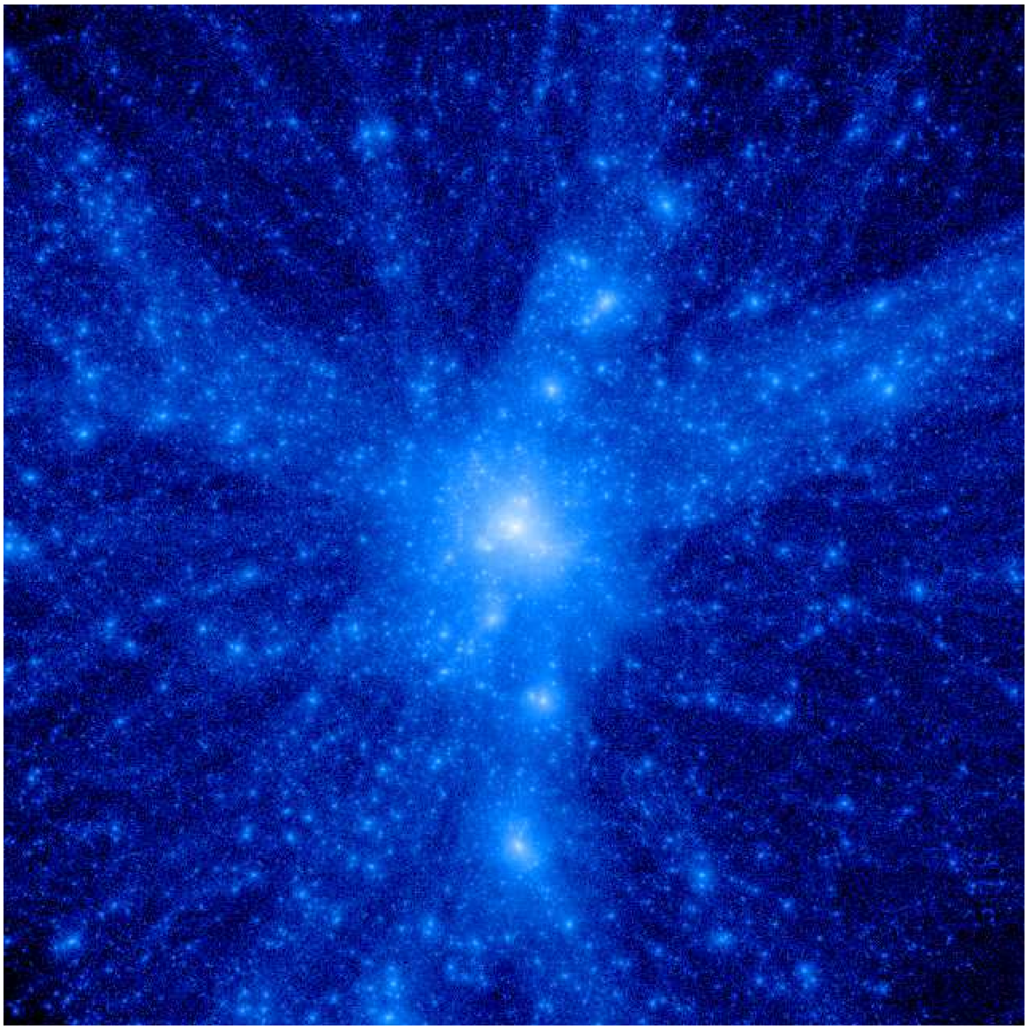

Fig. 2. DM density map at $z = 0$ for one of the 12 cosmological DM-only simulations performed at VHR ($m_{DM} = 10^7\ M_\odot/h$).

ter at the center of the simulated region are still needed. With those, we will further examine the thermo-dynamical profiles in the central core region, most sensitive to the BH positioning, physical feedback and cooling processes implemented. Additionally, part of the allocated budget allowed us to perform very high resolution (VHR) dark-matter(DM)-only simulations of cosmological volumes. Thanks to this computing time we were in fact able to successfully complete a set of 12 DM-only simulations with mass resolution $m_{DM} = 10^7\ M_\odot/h$. An example is visualised in Fig. 2, where the DM density is shown for one of the cosmological simulations at the present time (redshift $z = 0$). The VHR simulations can be then analysed, with the goal of identifying and extracting halo substructures. Eventually, merger trees for halos and sub-haloes in the simulations will be constructed and used as an input for the galaxy evolution semi-analytical model GAEA, developed within the cosmology group at INAF-OATs (see Hirschmann et al. 2016). The combination of these VHR DM-only simulations and the therefrom derived halo merger trees with the GAEA semi-analytical model will allow for studies of the galaxy population within galaxy clusters, providing theoretical predictions on proto-cluster regions to be compared against observational data up to redshift $z > 2$.

The possibility to obtain the requested amount of time and to easily and directly interact with the CINECA and MoU CINECA-INAF committee has definitely been an advantage for the project itself and for the subsequent high-resolution simulation campaign.

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