Coma Connectivity

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Introduction

As huge concentrations of galaxies (agglomerate of stars, planets and dust) and gas, galaxy clusters are matter concentrations at the nodes of the cosmic web. They are connected between each other through elongated structures, called filaments, made of gas, galaxies and dark matter (nature of most of the matter in the Universe). Their connectivity constitutes a great tool to study the cosmological model ruling our Universe. Among the most studied clusters, the Coma cluster, a gathering of more than a thousand galaxies, is one of the most massive clusters in our cosmic neighborhood. With a mass of more than 10^{15} solar masses, it lies at about 330 million light-years from us. Because of its proximity with us, its connectivity can be studied in detail using galaxy surveys. Multiple scenarios can explain how the cluster came to be connected to the cosmic web and how it accreted and still accretes matters through its connecting filaments. Checking these scenarios relies on cosmological simulations. In such simulations, dark matter particles follow physical law to reproduce the cosmic web statistically.

However, there exists a large variety of clusters even considering solely our cosmic neighborhood. The variety of their cosmic environment and formation history grandly shape their individual connectivity. To fully understand the complex interplay between environment, formation history and connectivity of the Coma cluster, reproducing ''the'' Coma cluster in its cosmological environment is a key ingredient for cosmological studies. Producing such a counterpart of an individual cluster in simulations constitutes though a major challenge. Simulated replicas of local galaxy clusters like Coma can be obtained thanks to new simulations designed to resemble our cosmic Home down to the cluster scale. Within such simulations, replicas of the Coma cluster are therefore formed in the proper environment. They permit assessing the most probable scenario regarding the formation and evolution of the cosmic web around it. This is only possible by modeling a sufficiently large volume of our cosmic neighborhood that includes the Coma cluster and its surrounding. It thus requires the usage of high-performance computing facilities.

Results and Methods

The replica of our local neighborhood is obtained thanks to initial conditions (a set of dark matter particles with initial positions and velocities) that is run forward in time down to redshift z=0, i.e. our cosmological time. To reach our project goal, the box size needs to correspond to about one billion light-years aside at the end of the run. In order to get dark matter particles of sufficient masses (~10^9 times the solar mass) to study the Coma cluster and its surrounding with enough resolution, the box must contain more than 8.5 trillion of them.

Ten million cpu-hours were required to simulate the full formation and evolution of our cosmic neighborhood using the RAMSES code [1] in a dark matter only mode. We used more than 12,000 cores and wrote 228 snapshots using the thin nodes available on SuperMUC-NG at LRZ. They constitute more than 820 TB of data distributed in more than 3.5 million files. These numbers include neither the pre-computing work required to prepare the initial conditions nor the post-computing time necessary to analyze the outputs. Additional preliminary steps permit treating the observational data to obtain constraints for our ''cosmic home initial conditions'' building. More details on the construction of the initial conditions and the resulting simulation can be found in [2] and [3].

Assuming the observer at the center of the box, the dark matter halo, that corresponds to the Coma cluster counterpart in the simulated box, is identified. Figure 1 shows it as a light-orange filled circle. More precisely, on this Figure, the largest dark matter halo representing Coma stands in the middle of smaller dark matter halos (associated to galaxies) that trace the three-dimensional simulated cosmic web. The cube is centered on Coma. Circle sizes are proportional to the halo masses. The gradient of colors from black to grey stands for halos that are further and further away from the front edge of the cube.

We then run a ''cosmic web'' finder that detects the maxima (nodes), minima and saddle points of the three-dimensional density field. Filaments connect the maxima or nodes of the cosmic web. Detected simulated and observed structures reveal that both the observed Coma cluster and its simulated counterpart are connected in a similar fashion The observed cosmic web is reproduced. In particular, lookalikes of the observed North-East and West filaments, named after their position on the sky, are retrieved in the simulated box. These two filaments are highlighted in Figure 2 (orange solid lines named W and NE). This figure shows several slices through the simulation box. These slices are centered on the Coma cluster. Supergalactic (SG) coordinates are preserved unlike on Figure 1 (i.e. the origin of the box is not the Coma cluster but us, the Milky Way).

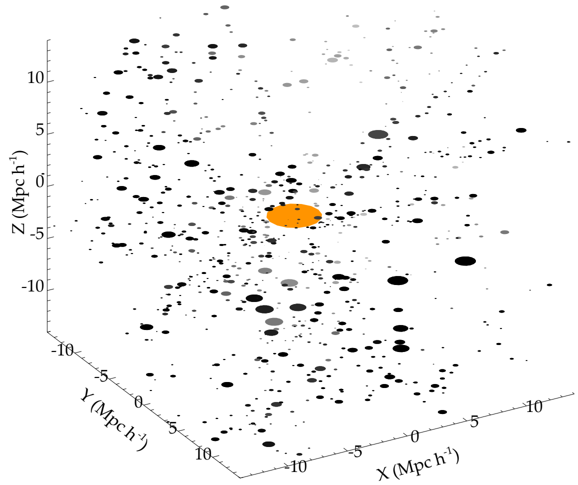

Figure 1: Distribution of dark matter halos in the surrounding of the largest one standing for the Coma cluster. Circle sizes are proportional to dark matter halo masses. The cube is centered on the Coma dark matter halo (orange). Black (grey) dark matter halos are in front of (behind) the Coma cluster in the three-dimensional representation. One megaparsec per h stands for about 5 million light years.

Additionally, we found that, rather than a general isotropic accretion, the Coma cluster of galaxies is indeed fueled in majority alongs the filaments that connect it to the cosmic web. More precisely, dark matter halos falling onto the large halo standing for the Coma cluster have their velocity that tends to align more and more with the filament axes as they get closer and closer to the massive structure. Figure 2 summarizes this result that is detailed in [4]. Indeed, the color gradient, in particular the blue color that highlights the infall onto the Coma cluster, shows that it matches the orange solid lines that stand for the filaments. The black arrows emphasize this aspect.

On-going Research / Outlook

Our next step is to explore in detail Coma evolution via the analyses of higher redshift snapshots. It will permit studying how the Coma cluster came to be connected to the cosmic web and how these connections impact its formation, evolution and growth.

Reproducing observed galaxy clusters, like Coma, with such accurate details permits conducting a large range of projects. For instance, we can also explore the dynamical influence of the local clusters, Coma included, onto the velocity field in detail. These massive structures leave indeed an imprint on the velocity of their neighboring dark matter halos that are galaxy hosts. Investigating the behavior of the line-of-sight (radial) velocities of galaxies in the outskirt of clusters will most probably permit giving a different (from traditional methods) mass estimate of these giant structures to refine their mass measurements [2].

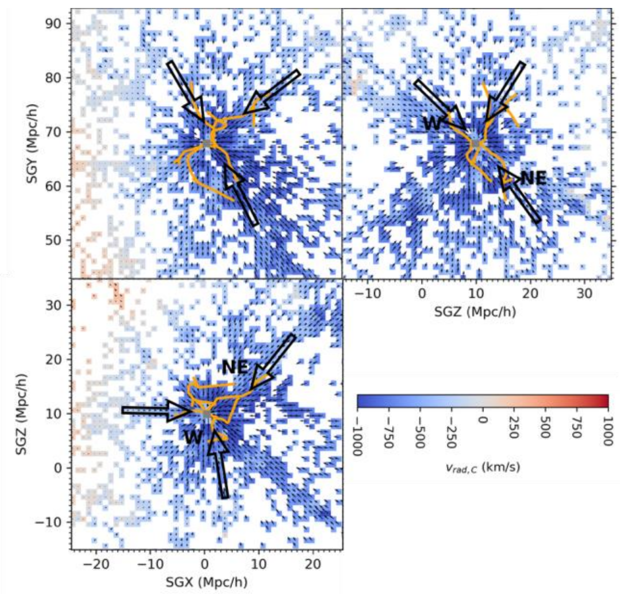

Figure 2: Three 20 Mpc/h (~1 billion light-years) thick Supergalactic slices of the simulated box representing our local neighborhood in the vicinity of the Coma cluster of galaxies counterpart. More precisely, the simulated massive dark matter halo standing for the Coma cluster is in the center of the slices. The orange lines represent the filaments connecting Coma replica to the cosmic web. NE and W stand for the North-East and West simulated filaments lookalike of the observed ones. The gradient of color gives dark matter halo velocity field in Coma outskirt. Black arrows emphasize that matter is mostly fueled into the clusters via the filaments (blue cells alongside orange lines) with increasing collinearity with decreasing distance to the cluster.

References and Links

[1] R. Teyssier, A&A 385 (2002), 337T
[2] J.G. Sorce, MNRAS 478 (2018), 5199
[3] J. G. Sorce, R. Mohayaee, N. Aghanim, K. Dolag, N. Malavasi, arXiv:230101305 (2023)
[4] N. Malavasi, J.G. Sorce, K. Dolag, N. Aghanim, A&A submitted