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Tracing the formation of cosmic structures with hydrodynamical simulations

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Abstract. In this contribution I will report on the activity of our collaboration working in Computational Cosmology. In particular, I will focus on the highlights from the four Key Projects, having as PIs members of our collaboration, which have been approved over the last 5 years, with CPU time allocated within the INAF–CINECA agreement. The results range from the thermal and chemical properties of the intra-cluster medium and of the warm-hot inter-galactic medium at redshift $z \leq 1$, to those of the inter-galactic medium at $z > 2$, to the properties of the galaxy population in different environments and of the diffuse stellar component within galaxy clusters. I will finally shortly discuss the future lines of developments expected for our research activity.

1. Introduction

The study of the formation and evolution of cosmic structures represents one the main challenges of modern cosmology. Now that a number of observational probes (CMB, SnIa, lensing, galaxy clusters, large-scale galaxy distribution) have substantially frozen the underlying cosmological model, the problem has moved to understanding the processes which regulate the behaviour of cosmic baryons as they follow the gravitational instability driven by Dark Matter (DM). Advanced numerical simulations provide the ideal tool to capture the complexity of the relevant gas-dynamical processes and to shed light on the role played by a number of astrophysical processes (e.g., star formation, feedback in energy and metals from SNe and AGN, etc.). Clearly, this a multi-scale problem, in which processes taking place at the parsec scale are expected to leave a significant imprint on the observational properties of cosmic structures at scales up to the Mpc and beyond. The wide range of scales involved necessarely forces cosmological simulations to treat a number of small–scale astrophysical processes through sub–resolution models. As such, processes like star formation and feedback and not self–consistently described in simulations, rather they are accounted for through observationally and theoretically motivated effective models.

The projects described here below are all based on the GADGET2 Tree+SPH code Springel (2005). This is a massively parallel code, which includes a fully adaptive and local time-stepping [1], and an explicit entropy–conserving integration scheme. The version of the code, that we have used, includes the effect of radiative cooling, heating/cooling from a uniform evolving UV background, star for-

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[1] http://www.MPA-Garching.MPG.DE/gadget/

mation and supernova (SN) feedback. The included scheme of star formation converts cold and dense gas particles into collisionless particles, through an effective model which accounts for the multiphase nature of the interstellar medium. Our group has substantially contributed to the development of the GADGET2 code, by including a detailed model of stellar evolution, so as to properly describe the process of chemical enrichment of cosmic baryons from different stellar populations Tornatore et al. (2004, 2007).

In the following, I will provide a short description of the results obtained from the four Key Projects approved to our group, with CPU time allocated within the INAF-CINECA agreement. Due to the limited space available, I will not describe the results obtained with the several standard projects.

2. A summary of the results obtained from the Key Projects

2.1. KP-2003

Within this KP (PI: S. Borgani), we carried out a simulation of a cosmological box having comoving size of 192 h^{-1}Mpc for a concordance ΛCDM cosmological model, and containing 480^3 DM particles and an initially equal number of gas particles. At the time this simulation was campleted, it was the largest cosmological hydrodynamical simulation reaching this resolution and level of description of physical processes (i.e. star formation from a multiphase medium and feedback associated to galactic outflows). The simulation was completed in about 40.000 CPU hours on the IBM-SP4 machine, running on 64 processors.

The simulation was subsequently analysed to study a variety of properties of galaxy clusters and groups, as well as the properties of the large-scale distribution of diffuse cosmic baryons. The published papers focussed on a variety of arguments, ranging from the X–ray and SZ properties of clusters (e.g., Borgani et al., 2004; Ettori et al., 2004; Diaferio et al., 2005; Ameglio et al., 2007) and of the warm-hot intergalactic medium (Cheng et al., 2005; Roncarelli et al., 2006), to the cluster dynamics traced by galaxies (Biviano et al., 2006) and the properties of the intra-cluster light (Murante et al., 2004).

As a highlight from this simulation, we show in Figure 1 a ray-tracing map of the gas density within the box and a comparison between simulation results and observational data on the relation between X–ray luminosity and temperature of galaxy clusters and groups. Indeed, one of the results of the analysis presented by Borgani et al. (2004) was the demonstration that stellar energy feedback alone is not able to account for the X–ray properties of clusters and another mechanism (i.e. associated to AGN feedback) must be invoked so suppress the X–ray luminosity of poor clusters and groups to the observed level.

2.2. KP-2005

Building on the results obtained from the first KP, described above, we decided to undertake another simulation campaign aimed at resimulating at progressively higher resolution four clusters selected from the original cosmological box, using the Zoomed Initial Condition (ZIC) technique (Tormen et al., 1997). In order to simulate the four clusters at the highest resolution we proposed a second KP (PI: G. Murante), for which 40.000 CPU hours were allocated on the CLX Linux cluster, while lower–resolution runs were carried out on local facilities. The physical processes included in these runs were exactly the same as in the KP-2003 simulation. Also in this case, at the time these runs were completed, they represented the highest resolution simulations of single galaxy clusters and allowed us to perform the first accurate study of resolution on the effect of feedback and star formation.

In particular, these simulations were analysed to study the convergence of the thermal and structural properties of cluster simulations (Borgani et al., 2006) and to study in great detail the dynamical mechanisms leading to the creation of a diffuse intra-cluster stellar component (Murante et al., 2007). The left panel of Figure 2 shows the gas density map of the most massive cluster identified in the original box, resimulated with a 10 times better mass resolu-

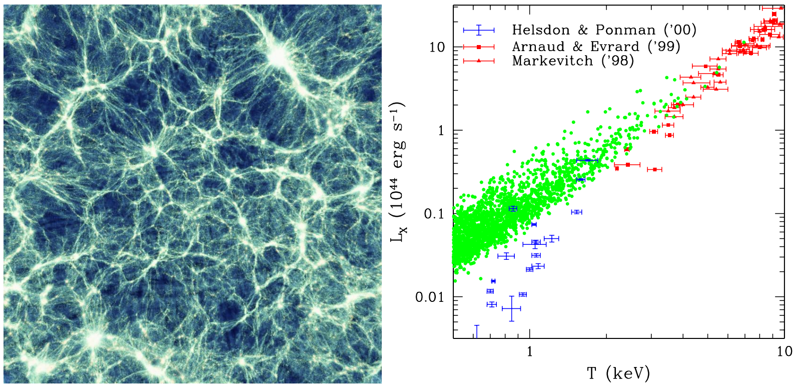

Fig. 1. Results from the KP-2003 (Borgani et al., 2004). Left panel: raytracing map of the gas density field in the simulation box. Right panel: the relation between X–ray luminosity and temperature for the simulated clusters extracted from the box (green circles) and for observational data taken from different authors (points with errorbars).

tion. In the left panel, we show the fraction of diffuse stars produced either by stripping or by the merging process, as a function of the mass of the galaxy from which these stars originated. Quite apparently, the most massive galaxies, which are the main responsible for the generation of diffuse stars, produce this component mainly by the merging process. This prediction of our analysis has been later confirmed by observational data (e.g., Zibetti et al., 2005).

2.3. KP-2007

Having introduced in the GADGET-2 code a module for a detailed treatment of metal production from different stellar populations (Tornatore et al., 2007), we decided to undertake a detailed study of the process of chemical enrichment of the inter-galactic medium at high redshift, $z \geq 2$. This led us to propose a KP (PI: M. Viel) to carry out a simulation of a cosmological box of $20\,h^{-1}$Mpc comoving, using 512^3 DM particles and as many gas particles. For this projects, 200.000 CPU hours were allocated on the BCX machine and the simulation was run on 512 processors. Since the fundamental mode of such a small box undergoes non–linear gravitational instability already at relatively high redshift, and to limit the computational cost, we decided to stop the simulation at $z = 2$. The left panel of Figure 3 shows a map of the optical depth associated to the distribution of neutral hydrogen at $z = 3$ within the simulation box.

The analysis of this simulation is now underway and is focused on the following aspects: *(a)* physical and chemical properties of the baryons contained with the DM halos; *(b)* distribution of the neutral hydrogen in the redshift range $z = 2$–4; *(c)* effect of the feedback associated to galactic outflows on the statistical properties of the Damped Lyman- systems (DLAs): e.g., number counts, distribution of column densities, simulations of QSO spectra and comparison with observational data using UV atomic transitions (SiII, CIV, OVI etc.); *(d)* effect of changing the stellar IMF on the distribution of metals around the DM halos and the DLAs. As an example, we show in the right panel of Fig.3 a comparison between the observed and the simulated distribution of DLA column densities. Quite apparently, the simulations are rather successful in predicting the number of the strongest absorbers, while there is a clear deficit at low column densities (Tescari et al. 2008, in preparation).

2.4. KP-2008

Using the same version of the code as for the KP-2007, we decided to move to the study of the inter-galactic medium at low redshift. To

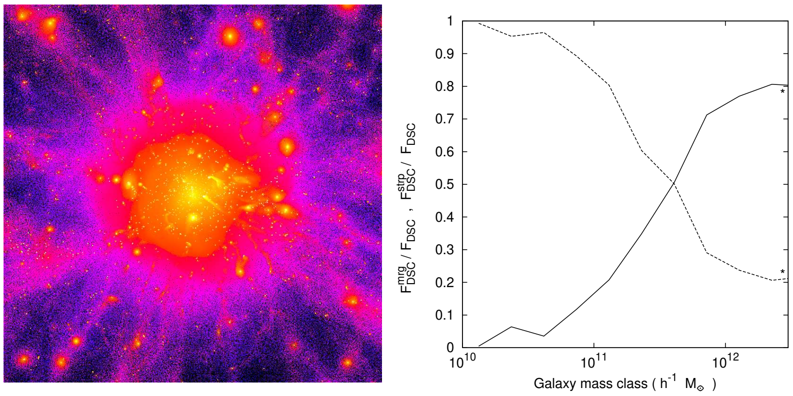

Fig. 2. Results from the KP-2005. Left panel: gas density map of one of the clusters simulated at high resolution. This cluster has a virial mass of about $1.2 \times 10^{15}\, h^{-1} M_\odot$, which is resolved with about two million DM particles and about the same number of gas particles (Borgani et al., 2006). Right panel: the dependence of the fraction of intra-cluster light contributed by merging (solid curve) and by stgripping (dashed curve) as a function of the mass of the galaxy from which it originates (Murante et al., 2007).

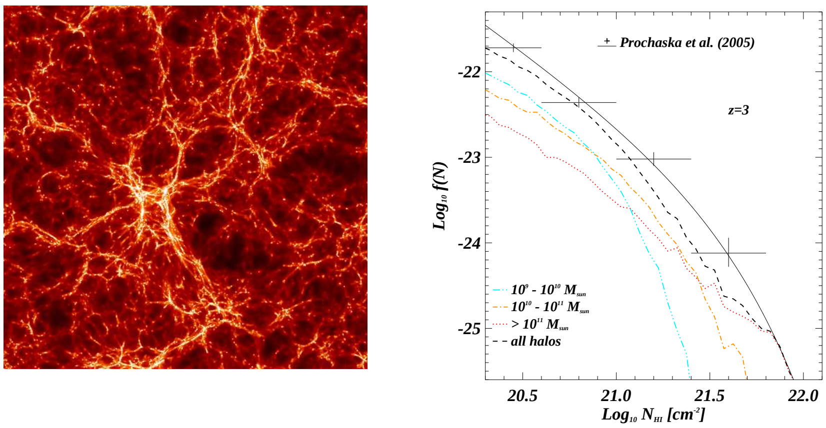

Fig. 3. Results from the KP-2007. Left panel: map of the optical depth associated to the neutral hydrogen at $z = 3$ within the cosmological box of the KP-2007. Right panel: distribution function of the neutral hydrogen column density for DLAs, obtained from 4000 lines-of-sight through the simulation volume at $z = 3$ (Tescari et al. 2008, in preparation). Data points and fit to data are from Prochaska et al. (2005). The dashed curve indicates the distribution obtained from halos having mass $> 10^{11} M_\odot$, with the other two lines for lower mass intervals.

this purpose, we proposed to carry out a series of three simulations in which we varied both the initial mass function (IMF) for star formation (and therefore the history of chemical enrichment) and the resolution. The resulting KP (PI: S. Borgani) requested 400.000 CPU hours to simulate two cosmological boxes of $75\, h^{-1}$Mpc aside with a 2×512^3 particle resolution, done by assuming two different shapes for the IMF. We also carried out a simulation with 2×400^3 particles within a two times smaller box size. Furthermore, we also carried out simulations on such smaller box sizes, using 2×256^3 particles, using local resources. The combination of these simulations allows us to have under control the effect of changing the model of chemical evolution, of resolution and of simulation volume on the final results. These simulations are being currently analysed to study in detail the properties of the WHIM and of groups and poor clusters of galaxies (Tornatore et al. 2008, in preparation). In Figure 4 we show a gas density map for one of the two simulations performed within the larger box. The high resolution reached in this simulation will allow us to address the following questions: *(a)* How do the different phases (hot, cold and warm) of the cosmic baryons evolve with redshift and how does this evolution depend on the processes of feedback and chemical enrichment? *(b)* How do the predicted thermo- and chemo-dynamical properties on the intragroup medium compare with the most recent observational data from the XMM and Chandra satellites? *(c)* Which is the dependence of the optical/near-IR properties of galaxies on the environment and how do these properties evolve with redshift?

3. Looking at the future

On the light of the above overview of the results so far obtained within our collaboration, we are convinced that this has been possible thanks to the access we had to both local supercomputing facilities, like those available at the University of Trieste and at the Astronomical Observatory of Catania, and to the large facilities available at CINECA. We are also convinced that a point of strength of our collaboration is the close contact with observers, which allowed us to make the best use of simulations in term of comparison with data. On the other hand, although we have contributed to the development of the simulation code by uncluding modules to describe specific astrophysical processes, we are conscious that much more can (and should) be done to increase the level of our contribution in this aspect.

The question then arises as to which are the steps that we have to undertake to maintain our position in the international competition in the field of computational cosmology. Taking as examples what is done at present within the major groups working in Germany, UK and North America, it is clear that we can not hope to lead the field in terms of the accessible supercomputing power. On the other hand, original results in computational cosmology can often be achieved in these days only the development of innovative simulation codes, which either include novel physical processes or integration schemes. It is clear that providing a significant contribution to the development of a highly competitive simulation code requires planning the activity over a medium-long term, with the involvement of young researchers. This can not be pursued by opening short-term positions. The need for enforcing a culture of code development is made even more pressing in view of the acquisition by CINECA of a new critical-capacity supercomputing facility. Besides keeping the pace with the continuous development of the general structure of the GADGET-2 code, a few examples of the directions of code development that we foresee for our group can be summarized as follows.

(a) Development of a novel scheme for star formation in a multi-phase interstellar medium and of the resulting SN feedback, which will replace the so-far adopted scheme by Springel & Hernquist (2003).
(b) Substantial refinement of the AGN feedback scheme, originally introduced by Springel et al. (2005), in order to better describe the process of gas accretion onto the black holes and the thermalisation of the extracted energy.
(c) Implementation of alternative SPH formulations, like that based on a Godunov-type Riemann solver (Cha & Whitworth, 2003), so as to avoid the introduction of an artificial viscosity term.

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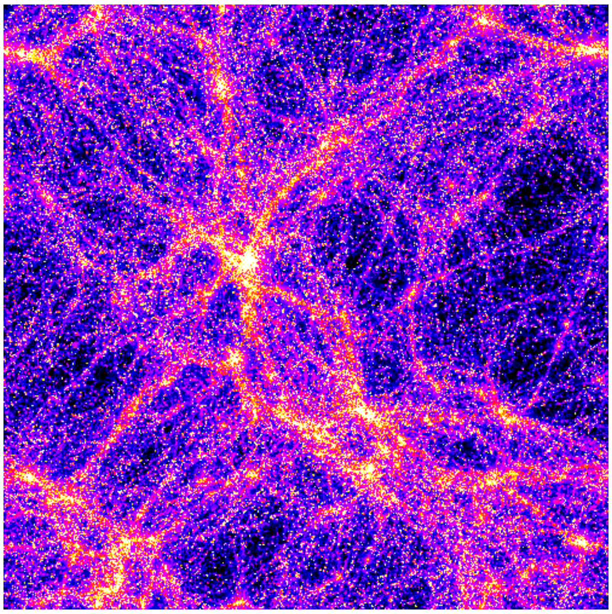

Fig. 4. Results from the KP-2008: The gas density map within a simulation box of 75 h^{-1}Mpc a side, resolved with 512^3 DM particles and as many gas particles. All the tiny white spots trace the highdensity gas where star formation takes place (Tornatore et al. 2008, in preparation).

completed or are now engaged in their PhD projects, and did the hard part of the work: Silvia Ameglio, Dunja Fabjan, Elena Rasia, Marco Roncarelli, Alex Saro and Edoardo Tescari. We are all very grateful to the HPC people in CINECA, and especially to Claudio Gheller, for their continuous and invaluable technical support.

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