Tracing the Ancestry of Galaxies (on the land of our ancestors)
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Three-dimensional Visualization of Cosmological and Galaxy Formation Simulations

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Abstract. Our understanding of the structuring of the Universe from large-scale cosmological structures down to the formation of galaxies now largely benefits from numerical simulations. The RAMSES code, relying on the Adaptive Mesh Refinement technique, is used to perform massively parallel simulations at multiple scales. The interactive, immersive, three-dimensional visualization of such complex simulations is a challenge that is addressed using the SDvision software package. Several rendering techniques are available, including ray-casting and isosurface reconstruction, to explore the simulated volumes at various resolution levels and construct temporal sequences. These techniques are illustrated in the context of different classes of simulations. We first report on the visualization of the HORIZON Galaxy Formation Simulation at MareNostrum, a cosmological simulation with detailed physics at work in the galaxy formation process. We then carry on in the context of an intermediate zoom simulation leading to the formation of a Milky-Way like galaxy. Finally, we present a variety of simulations of interacting galaxies, including a case-study of the Antennae Galaxies interaction.

1. Introduction

Tracing the ancestry of galaxies involves high-resolution simulations at multiple scales, going from large-scale structures down to the interstellar medium. This simulation effort contributes significantly in the interpretation of the wealth of observational data and in making predictions relevant to the structure and composition of galaxies. The RAMSES simulation code (Teyssier 2002), based on an AMR "Adaptive Mesh Refinement" parallel algorithm, is used to perform massive simulations of how galaxies are born, evolve and interact in their environment. The size and complexity of the data produced in this context make it a challenge when it comes to visualization, analysis and interpretation. In this paper, we report on the results we obtain in the visualization of some of the most massive galaxy simulations performed using this code.

2. The SDvision Visualization software

The SDvision visualization interface (Pomarède *et al.* 2008a) is developed in the context of the COAST "Computational Astrophysics" Project that aims at high-performance simulations of astrophysical plamas (Audit *et al.* 2006). This software, deployed in the framework of IDL Object Graphics, benefits from both the large collection of scientific functions offered by IDL and the hardware acceleration of its OpenGL interface layer. It can handle 3D scalar and vector fields defined on Cartesian grids, and clouds of points. Scalar fields are visualized by either ray-casting, isosurface reconstruction, slicing, or stacking of textures. Vector fields are visualized with streamlines or hedgehog displays. Point clouds are visualized as 3D scatter plots. An example of utilization of the widget is

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displayed in Figure 1. The data handling methods and the visualization techniques used for the RAMSES outputs, including AMR hydrodynamical fields, dark matter particles, and the octree-based mesh structure, are presented in details in Pomarède *et al.* 2008b. The SDvision widget provides a high level of interactivity : the view can be rotated, translated and zoomed at will to explore the dataset. Full immersion within the data using wide angle projections is particularly useful for the inner investigation of intricated developing structures, turbulence patterns, clumps, tidal tails, ... Graphical outputs suitable for stereoscopic display systems are also available, providing a more comprehensive insight in the three-dimensional structuration of galaxies.

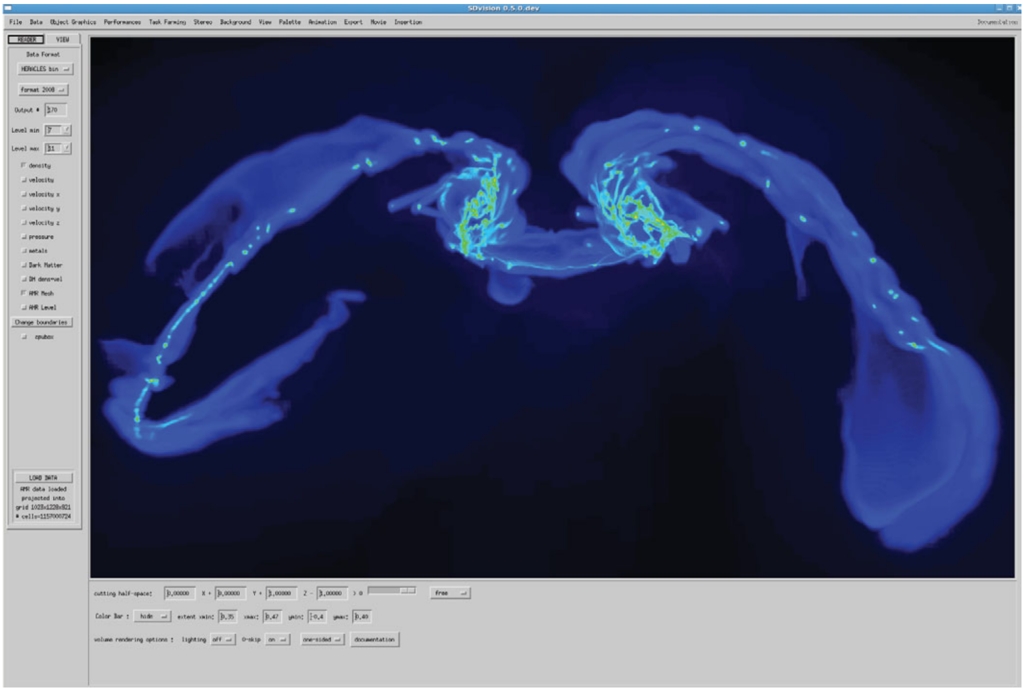

Figure 1. The SDvision graphical interface used here to visualize a 256-processor parallel simulation of the Antennae galaxies interaction.

3. Visualization of a large scale galaxy formation simulation

The HORIZON "Galaxy Formation" Simulation was performed in 2006 to adress the multi-scale problem of galaxy formation in a cosmological framework. This simulation engaged 2048 processors of the MareNostrum mainframe at the Barcelona Supercomputing Center during three weeks. With a total of 4 billion AMR cells and one billion particles, a resolution of 2 kpc/h is obtained within a simulated volume of 50 Mpc/h. This simulation is characterized by the implementation of a number of physical processes, including star formation, supernovae feedback, metal enrichment, metal dependent cooling, and background UV heating. For each of the 128 output step, 100 to 200 GB are stored, resulting in a grand total of 20 TB of data. The visualization of such data is a challenge that has been adressed using SDvision, as reported in Pomarède *et al.* 2009. A volume rendering of the baryon gas distribution is presented in Figure 2 where the color is associated to the

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gas temperature (hot=red,cold=blue) and the intensity is associated to the gas density, using a mixing algorithm proposed by S. Colombi (private communication).

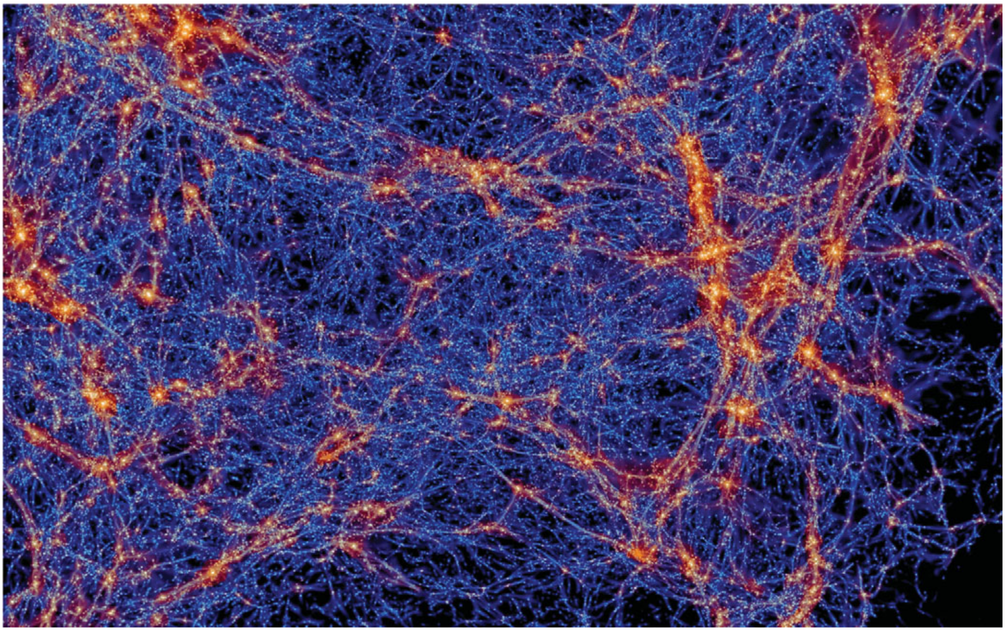

Figure 2. Visualization of the baryon gas distribution in the HORIZON Galaxy Formation Simulation. obtained with SDvision. The color is associated to the gas temperature (hot=red,cold=blue) and the intensity is associated to the gas density.

4. Visualization of cosmological zoom simulations

Zoom simulations of the formation of massive disc galaxies in a cosmological context are used to study how baryon acquisition is achieved, see e.g. Agertz *et al.* 2009. Examples of the visualization of such a simulation are shown in Figure 3. This simulation, which includes gas, stars and dark matter, was performed on the Platine Supercomputer at CEA/CCRT using 128 processors, producing 724 output steps.

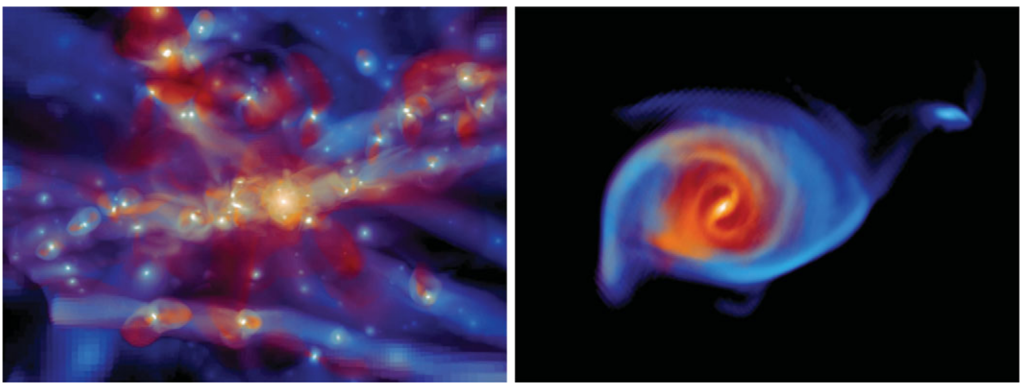

Figure 3. Visualization of a cosmological zoom simulation of the formation of a Milky Way-like galaxy. Left : viewed from outside. Right : zooming in on the spiral disc at the center.

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5. Visualization of high-resolution disk simulations

High-resolution simulations of isolated galaxies are used to study the properties of the ISM substructures and turbulences (see e.g. Bournaud *et al.* 2010). An example of a 700-processor simulation performed at the CEA/CCRT Supercomputing Centre on the Titane mainframe is shown in Figure 4.

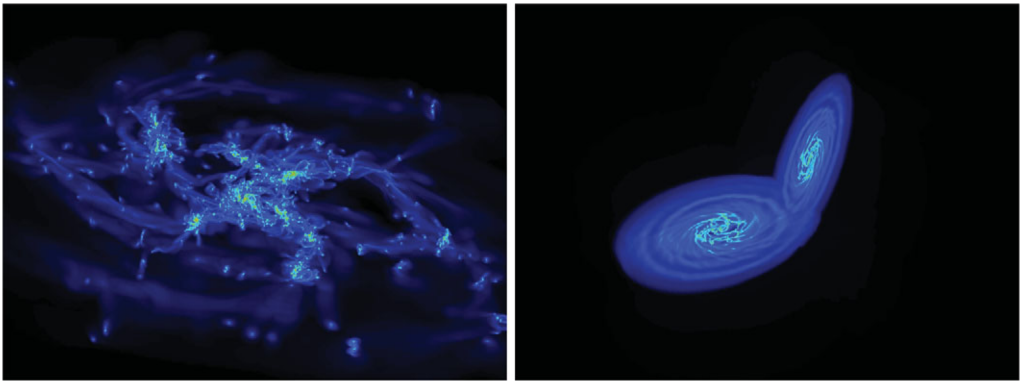

Figure 4. Visualization of the baryon gas density in a high-resolution simulation of a clumpy disk (left) and in colliding galaxies (right).

6. Visualization of galaxy interaction simulations

The outcome of galaxy interactions is investigated using simulations of disk mergers, see e.g. Bournaud *et al.* 2011. A snapshot of such a simulation is presented in Figure 4. It was performed using 256 processors of the Jade mainframe at the CINES Supercomputing Center as part of a series of simulations where the impact parameter of the colliding disks is varied. Finally, a snapshot of a merger of two galaxies with the interaction orbit of the Antennae galaxies (Teyssier *et al.* 2010) is also displayed in Figure 1.

7. Conclusion and perspectives

The SDvision visualization software is used to provide useful insights over a large spectrum of simulations involved in understanding the ancestry of galaxies. This tool will be maintained and evolved to face the challenges of the forthcoming more massive, more refined and more complex simulations performed on the new generations of supercomputers, to trace the origins of galaxies beyond what we have learned on the Land of our Ancestors...

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