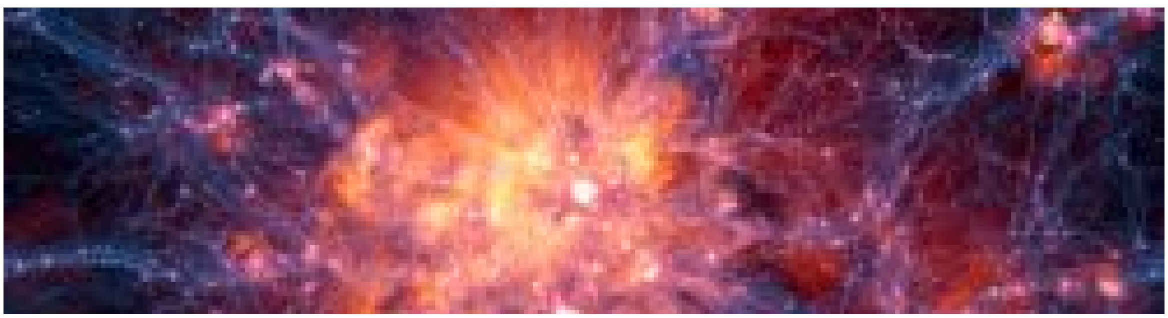
Research Proposal for DAAD PhD scholarship
The Gaseous Cosmic Web with AREPO

Sebastian Bustamante Jaramillo


A projection of the cosmic web in the ILLUSTRIS simulation, that was made with AREPO (http://www.illustris-project.org/)

Contents

1 General Information

Information of the Applicant

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More detailed information of the applicant can be found here `http://goo.gl/BPZGzK`

Information of the Project

Title	**The Gaseous Cosmic Web with AREPO**
Field	Cosmology, Astrophysics, Physical Sciences
Advisor 1	Volker Springel, PhD. Heidelberg Institute for Theoretical Studies (HITS) & University of Heidelberg, Germany
Advisor 2	Jaime Forero-Romero, PhD. Universidad de los Andes, Colombia
University	University of Heidelberg, IMPRS PhD program
Time Frame	3 years

2 Introduction

The filamentary nature of the large-scale matter distribution (the so-called cosmic web) is one of the most striking features of Universe (Bond et al., 1996), being an essential part of the current standard paradigm in cosmology. Last generation galaxy redshift surveys, such as the *two-degree-Field Galaxy Redshift Survey* (2dFGRS, see Colless et al. (2003)) and the *Sloan Digital Sky Survey* (SDSS, see Abazajian et al. (2009)), reveal the cosmic web at a level of detail never seen before. In addition, other observational probes like the Ly-α forest in distant quasars (Rauch, 1998; Cantalupo et al., 2014), fluorescence emissions (Cantalupo et al., 2012) and weak gravitational lensing (Massey & et al., 2007; Dietrich et al., 2012) have also validated this picture undoubtedly.

On the theoretical side, early descriptions of the evolution of the large-scale Universe, based on gravitational instabilities in primordial stages and leaded by the seminal work of Zel'dovich (1970), predict the cosmic web picture. Since then, our understanding of the structure and dynamics of the cosmic web has been dramatically improved as new and more powerful theoretical and computational tools and better observational data become available. In particular, N-body simulations, fuelled by last generation computing systems and ever more efficient numerical algorithms, have an increasingly important role in revealing the complexity of the large-scale Universe.

In the current cosmological paradigm, the ΛCDM model, there are two different types of matter, i.e. baryonic or luminous matter, corresponding to what we can see, and the poorly interacting (and of a still unknown nature) dark matter. The most actual measurements of their abundances indicate a proportion approximately of 1 to 6, respectively (Planck Collaboration, 2013). Accordingly, most of the related numerical research has been made based on dark matter-only N-body simulations, where the gas dynamics has been neglected (for a very detailed numerical analysis of the dark matter cosmic web, see Cautun et al. (2014)). Nevertheless, recent simulation studies in filamentary gas accretion in high redsfhit galaxies (Dekel et al., 2009), large-scale orientation and alignment of the spin of galaxies with they embedding cosmic web (Hahn et al., 2010), and filamentary-induced exchange of galaxy angular momentum (Dubois & et al., 2014), have proven the need of using fully hydrodynamical cosmological simulations due to the high level of coupling between dark and baryonic matter.

Incorporating gas dynamics into cosmological simulations is far from an easy task. The first reason is the highly complex *gastrophysical* processes involved in baryonic dynamics, i.e. shock heating, photoionization, supernova feedback, stellar wind, radiative cooling, star formation (Bond, 1993). The second reason is the complexity of the hydrodynamical equations followed by the gas. Traditionally, two different hydro-solvers have been used for this task, i.e. a Lagrangian *Smoothed Particle Hydrodynamics* (`SPH`) technique (Monaghan, 1992) (for an implementation, see e.g. the `GADGET` code by Springel (2005)) and an Eulerian solver on a mesh with *Adaptive Mesh Refinement* (`AMR`) (Berger & Colella, 1989) (for an implementation, see e.g. the `RAMSES` code by Teyssier (2002)).

The SPH scheme is easily implemented on a computer due to its Lagrangian character. Furthermore, as the mesh follows the evolution of each single particle and has a continuously auto-adjusting resolution, its usage is very suitable for problems like turbulent flows. However, its same Lagrangian nature originates an inhomogeneous and distorted spatial resolution, what makes difficult to account for low density regions in simulations and causes suppressions in fluid instabilities, making it poor suitable for capturing shock dynamics. An artificial viscosity term is usually introduced for improving the accuracy in these situations. On the other hand, AMR is more efficient for capturing shock dynamics. However, due to the conservative nature of the hydrodynamical equations, a fixed mesh causes a lack of Galilean invariance, making the computer implementation considerable harder. Furthermore, the unsmooth sampling of physical properties introduces spurious vorticity to the fluid, making the scheme unsuitable for studying turbulent flows (for a further discussion and comparison of both schemes, see Plewa (2001)).

Recently, a completely new paradigm was introduced by Springel (2010) and implemented in the AREPO code. It combines the strengths of AMR and SPH but overcoming their weaknesses. This code uses a moving mesh based on a Voronoi tessellation defined over a set of particles that represents the fluid. The geometry of the mesh resembles very closely that of the point distribution, avoiding a distorted spatial resolution and retaining the auto-adaptivity inherent of SPH. Unlike AMR, the hydro-solver of AREPO is based on a Gudonov's scheme that guarantees the Galilean invariance and the conservative nature of the solutions. All of these features makes AREPO highly efficient and accurate for simulating a plethora of hydrodynamical problems, even including those where AMR and SPH fail separately. Hence AREPO is a very attractive approach for computing fully hydrodynamical simulations of the large-scale Universe.

3 Objectives

✓ Study gaseous filamentary accretion of the cosmic web using `AREPO` simulations.

✓ Quantify the impact of gaseous filamentary accretion on galaxy evolution.

✓ Deriving observable quantities from our theoretical studies.

4 Methodology

The proposed project is subject to a PhD study and will cover the following aspects:

✓ *First, an analysis and characterization of existing hydrodynamical simulations based on the* `AREPO` *code will be done.*

As this project will be entirely based on numerical results, an analysis and characterization of existing `AREPO` hydrodynamical simulations is one of the key steps; the achieved unprecedented accuracy will guarantee a proper description of the simulated Universe.
This step includes a quantification of the dark matter and the gaseous cosmic web through two different web finding schemes (i.e. the T-web based on the tidal tensor (Hahn et al., 2007; Forero-Romero et al., 2009), and the V-web based on the velocity shear tensor (Hoffman et al., 2012), schemes in which prof. Jaime Forero-Romero has a wide research trajectory); thus voids, walls, filaments and clusters will be identified. Then, a statistical analysis of the found structures will be done, i.e. volume and mass filling fractions at different redshifts, morphology, halo populations and filamentary accretion of gas.
In Heidelberg, the required computer facilities and the access to existing `AREPO` simulations and the private code (of which Prof. Volker Springel is the main author) is granted. Moreover, the renowned research trajectory and the expertise of Prof. Springel in numerical cosmology is certainly another appealing for pursuing this specific PhD project.

✓ *Second, detailed simulations of specific process at high redshifts will be computed.*

✓ *Third, once established the underlying dark matter cosmic web, it is necessary to quantify the through gas dynamics. To this aim, inward and outward gas flows through potential wells (set by non-linear structures such as clusters and filaments) and accretion rates of the gas component residing within dark matter halos at different redshifts should be computed. At this point, it should be possible to evaluate environmental influences on different astrophysical phenomena.*

In order to exploit the new accuracy provided by the `AREPO` code, a correct quantification of the gas dynamics should be done. The current cosmological paradigm predicts a complex pipeline set by the potential well of non-linear structures, generally corresponding to clusters and filaments, through which the gas is transported toward over-dense regions like dark matter haloes. This process yields to different environmental phenomena of great current interest. We list here the most relevant for this project: influence of filament-induced flows on star forming galaxies at high redshifts, acquisition of the spin of galaxies through exchanging of angular momentum with the gaseous cosmic web, and kinematical and dynamical effects of the host environment on Local Group-like systems.

5 Current State

At present the applicant has already the fundamental basis in Astrophysics and Cosmology required for this investigation. This can be confirmed by his research trajectory, including a paper (as co-author) published in *ApJL* in which was studied the kinematics of the Local Group in a cosmological context, another paper (as co-author) published in *ApJ* where was studied the influence of thermal evolution in the magnetic habitability of rocky planets, and some participations in academic congresses. Furthermore, a Bachelor's thesis [1] where was studied the preferred place of simulated Local Group-like systems regarding the host environment in the cosmic web, also proves the ability of the applicant for handling simulations and massive data, a skill that is necessary for carrying out this project.

Currently, the applicant is involved in two research projects: first, a new method for finding voids in simulations based on the local fractional anisotropy. An ongoing publication (as first author) related to this is close to be submitted. [2]. The second project is about a comparison of three simulation techniques, i.e. `SPH` vs `VPH` vs `AREPO`, with possible publishable results at the end of the present year.

6 Timetable

8 Bibliography

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[1]Further information and an electronic version of this thesis can be found here `https://github.com/sbustamante/Thesis`.

[2]Information of this paper can be found here `https://github.com/sbustamante/CosmicVoidsPaper`.

Year	Goals
First	• First goal • Second goal
Second	• First goal • Second goal
Third	• First goal • Second goal

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