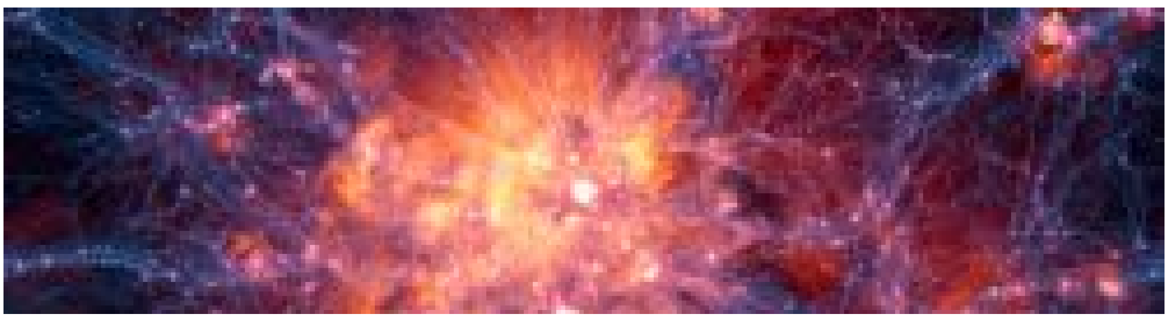
Research Proposal for a DAAD PhD scholarship
The Gaseous Cosmic Web with AREPO

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

Name	Sebastian Bustamante Jaramillo
Degree	B.Sc. in Physics, Universidad de Antioquia (2013)
Position	Adjunct Professor, Universidad de Antioquia
Birthday	20^{th} June, 1990
Nationality	Colombian
ID	C.C. 1128400433
Address 1	Avenida 21 # 57 AA 65, Bello - Colombia (personal)
Address 2	Calle 67 # 53 - 108, Off. 5-330, Medellin, Colombia (work)
Phone	+057 (4) 4820138
Mobile	+057 3108992409
E-mail 1	macsebas33 *at* gmail.com (personal)
E-mail 2	sebastian.bustamante *at* udea.edu.co (academic)

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	Professor Volker Springel. Heidelberg Institute for Theoretical Studies (HITS) & University of Heidelberg, Germany
Advisor 2	Professor Jaime Forero-Romero, PhD. Universidad de los Andes, Colombia
University	University of Heidelberg, IMPRS PhD program
Time Frame	3 years

2 Abstract

The cosmic web is one the most striking features of the Universe, being predicted by theory, widely tested by observations and studied through simulations. Currently, dark matter-only simulations is one of the best tools we have for understanding the cosmic web. Nevertheless, recent works about filamentary gas accretion, acquisition of angular momentum of galaxies and spin orientation have proven the need of using full hydrodynamic simulations. Incorporating gas dynamics in simulations is far from an easy task, and traditionally used hydro-solvers present important accuracy problems. Recently, a completely new paradigm was implemented in the `AREPO` code, which combines the strength of previous schemes and overcomes their weaknesses, making it a very attractive choice for simulating the large-scale Universe. Despite this, no much work has been done in studying the gaseous cosmic web and its impact on galaxy evolution using `AREPO` simulations, so that is the main objective of this PhD project.

3 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)), have revealed 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 with an exact Riemman solver 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.

Using a hydrodynamical simulation (HORIZON-AGN) computed through the RAMSES code, Dubois & et al. (2014) studied the alignment between the spin of galaxies and filaments above redshift one. They found a redshift-dependent stellar mass threshold above which high-mass galaxies are misaligned with filaments, while low-mass galaxies are aligned. On the other hand, Hahn et al. (2010) also studied this problem by mean of a RAMSES simulation, but finding a completely different result, high-mass galaxies are aligned while low-mass galaxies are misaligned with their embedding filaments. Related to highly efficient star forming galaxies at high-redfhits, Dekel et al. (2009) proposed a new scenario where the filamentary accretion of cold gas streams enhances the star formation rate. This is a very interesting alternative to the merger scenario, where star forming rates are propelled by violent collisions of galaxies. The new picture is consistent with the observed properties of those galaxies, where there can be found relatively intact rotating disks. All this shows the current interest in studying the impact of the gaseous cosmic web on galaxy evolution in the light of AREPO simulations, where it is necessary to conciliate and study deeper existing results and predict new ones.

4 Objectives

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

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

✓ Deriving observable quantities from our theoretical studies.

5 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. This 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 carried out, 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 access to existing simulations and the private `AREPO` code (of which Prof. Volker Springel is the main author) is granted. Moreover, the renowned research trajectory and 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.*

Once analysed the gaseous cosmic web, we proceed to compute its impact on galaxy evolution, specially at high-redshifts due to the big amount of available observational constrains. This step involves computing new high resolution `AREPO` simulations in order to study specific processes like: star formation rate enhanced by filamentary gas accretion, angular momentum exchange between galaxies and the cosmic web, spin orientation of galaxies along filaments and walls.

✓ *Third, new observables will be derived based on the results of the simulations.*

At this point, we will compare our theoretical results with available observational data of the cosmic web, specially at high redshifts. This step will also involve deriving new observables based on our predictions.

6 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 the *ApJL* in which was studied the kinematics of the Local Group in a cosmological context, another paper (as co-author) published in the *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 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 also 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 about to be submitted. [2]. The second project involves a comparison of three simulation techniques, i.e. `SPH` vs `VPH` vs `AREPO`, with possible publishable results at the end of the present year [3].

7 Schedule

Year	Goals
First	• Identifying a set of existing `AREPO` simulations suitable for our succeeding studies. • Applying web finding schemes (T-web and V-web) to the simulations for quantifying structures in the gaseous cosmic web, i.e. voids, walls, filaments and clusters. • Evaluating properties of found structures at different redshifts.
Second	• Studying by mean of high resolution simulations the impact of the gaseous cosmic web specific galaxy evolution processes.
Third	• Comparing with available observational data of the cosmic web. • Deriving new observable from our theoretical studies.

[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`.
[3] Further information in `https://github.com/sbustamante/MethodsComparison`.

8 Bibliography

Abazajian K., et al. (the SDSS Collaboration) 2009, ApJS, 182, 543

Berger M. J., Colella P., 1989, Journal of Computational Physics, 82, 64

Bond J., 1993, in Shull J., Thronson HarleyA. J., eds, Astrophysics and Space Science Library, Vol. 188, The Environment and Evolution of Galaxies. Springer Netherlands, pp 3–26

Bond J. R., Kofman L., Pogosyan D., 1996, Nature, 380, 603

Cantalupo S., Arrigoni-Battaia F., Prochaska J. X., Hennawi J. F., Madau P., 2014, Nature, 506, 63

Cantalupo S., Lilly S. J., Haehnelt M. G., 2012, MNRAS, 425, 1992

Cautun M., van de Weygaert R., Jones B. J. T., Frenk C. S., 2014, MNRAS, 441, 2923

Colless M., et al. (the 2dFGRS Team), 2003, VizieR Online Data Catalog, 7226

Dekel A., Birnboim Y., Engel G., Freundlich J., Goerdt T., Mumcuoglu M., Neistein E., Pichon C., Teyssier R., Zinger E., 2009, Nature, 457, 451

Dietrich J. P., Werner N., Clowe D., Finoguenov A., Kitching T., Miller L., Simionescu A., 2012, Nature, 487, 202

Dubois Y., et al. 2014, ArXiv e-prints

Forero-Romero J. E., Hoffman Y., Gottlöber S., Klypin A., Yepes G., 2009, MNRAS, 396, 1815

Hahn O., Porciani C., Carollo C. M., Dekel A., 2007, MNRAS, 375, 489

Hahn O., Teyssier R., Carollo C. M., 2010, MNRAS, 405, 274

Hoffman Y., Metuki O., Yepes G., Gottlöber S., Forero-Romero J. E., Libeskind N. I., Knebe A., 2012, MNRAS, 425, 2049

Massey R., et al. 2007, Nature, 445, 286

Monaghan J. J., 1992, ARA&A, 30, 543

Planck Collaboration 2013, ArXiv e-prints

Plewa T., 2001, in Zinnecker H., Mathieu R., eds, The Formation of Binary Stars Vol. 200 of IAU Symposium, Numerical Hydrodynamics: SPH versus AMR. p. 563

Rauch M., 1998, ARA&A, 36, 267

Springel V., 2005, MNRAS, 364, 1105

Springel V., 2010, MNRAS, 401, 791

Teyssier R., 2002, A&A, 385, 337

Zel'dovich Y. B., 1970, A&A, 5, 84