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

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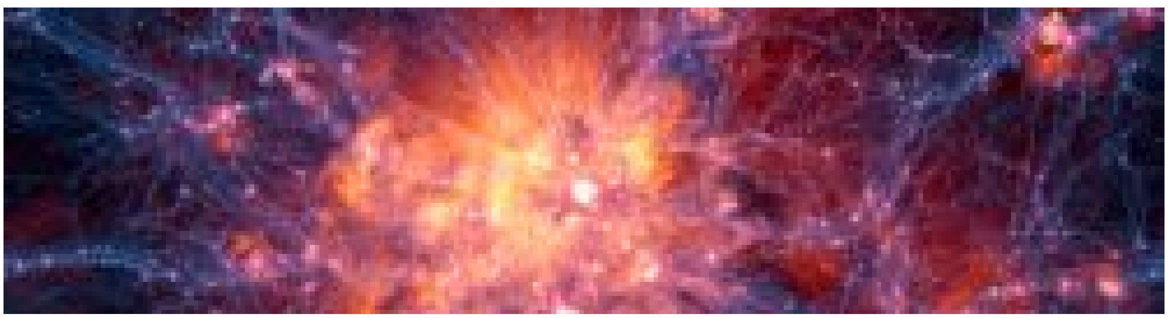

A projection of the cosmic web in the ILLUSTRIS simulation, that was made with AREPO (http://www.illustris-project.org/)

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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	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. It has been widely tested by observations and studies through theory and simulations. This web pattern has been studied in detail for the dark matter distribution. Nevertheless, recent numerical work on filamentary gas accretion demonstrated the need of hydrodynamical simulations to understand galaxy evolution in the cosmic web. However, modelling gas dynamics is a complex task. Common hydro solvers present accuracy problems that can bias the results of a cosmic web study. However, recently a completely new simulation technique was implemented in the `AREPO` code, which combines the strength of previous schemes and overcomes their weaknesses. The main aim of this PhD project is to perform a novel analysis of the gaseous cosmic web using this new generation of hydrodynamical cosmological simulations.

3 Introduction

The filamentary nature of the large-scale matter distribution (the so-called cosmic web) is one of the most striking features of the Universe (Bond et al., 1996), The most recent generation of 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 with a great level of detail. In addition, other observational probes like the Ly-α forest in distant quasar spectra (Rauch, 1998; Cantalupo et al., 2014) and weak gravitational lensing (Massey & et al., 2007; Dietrich et al., 2012) have also validated this picture.

On the theoretical side, Ya. B. Zeldovich (Zel'dovich, 1970) provided the founding insights into the physical mechanism driving the cosmic web formation. Since then, our understanding of the structure and dynamics of the cosmic web has improved dramatically thanks to powerful computational tools that became available. In particular, N-body simulations have played a key role in understanding the origin and evolution of the Universe on its largest scales.

To obtain quantitative predictions from this paradigm it is necessary to specify the matter components of the Universe. In the current cosmological paradigm there are two different types of matter. The baryonic or luminous matter and the non-relativistic (i.e. cold) dark matter (DM). In our Universe the DM dominates the matter content as many different cosmological probes indicate (Planck Collaboration, 2013).

Accordingly, numerical research focuses on simulating dark matter dominated universes, providing us with a detailed understanding of the Universe on its largest scales. However, on small (galactic) scales the effects of baryons become important. For instance, recent simulations show that filamentary gas accretion in early stages of galaxy evolution is a key physical process (Dekel et al., 2009); there is evidence that it plays a central role in the formation of discs (Dubois & et al., 2014), determining the alignment of galaxies with respect to the web (Hahn et al., 2010) and fueling high star formation rates (Dekel et al., 2009).

Modelling baryons by incorporating gas dynamics into cosmological simulations is a complex task. The main reason is that gas is affected by a great variety of physical processes absent in dark matter dynamics, mainly shocks and radiative cooling (Bond, 1993). Besides, there is the inherent complexity in solving numerically the relevant equations. Traditionally, two different hydro-solvers have been used by the astrophysical community for this task. The first is a Lagrangian scheme on moving point masses named *Smoothed Particle Hydrodynamics* (`SPH`) (Monaghan, 1992) (for an implementation, see e.g. the `GADGET` code by Springel (2005)); the second is an Eulerian solver on a fixed mesh known as *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 physical systems evolves, the mass particles naturally move into higher density regions providing a self-adjusting spatial resolution. However, this scheme has been shown to produce spurios supression of fluid instabilities making it unsuitable to model some of the dynamics accurately. On the other hand, AMR is more efficient for capturing shock dynamics. However, due to the conservative nature of the hydrodynamical equations, the fixed mesh causes a lack of Galilean invariance. Furthermore, the sampling of physical properties over the grid introduces spurious vorticity to the fluid, making the scheme unsuitable for studying turbulent flows. For a detailed discussion and comparison of SPH and AMR see Plewa (2001)).

Recently, a completely new approach to solve hydrodynamical problems was introduced by Springel (2010) and implemented into the AREPO code. It combines the strengths of AMR and SPH but overcomes many of their weaknesses. AREPO 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 retaining the auto-adaptivity inherent of SPH and also keeping a grid to capture shocks like AMR does. These features make AREPO highly efficient and accurate for simulating a wide range of hydrodynamical problems, making it the best available approach for computing the effects of the gaseous cosmic web in the 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-redshifts, 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 appears consistent with the observed properties of those galaxies, which exhibit 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, which make to possible to 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 broad research experience); 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 extensive research expertise of Prof. Springel in numerical cosmology is certainly another interest for pursuing this specific PhD project.

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

Once the gaseous cosmic web is analysed, we proceed by computing its impact on galaxy evolution, especially at high-redshifts due to the large amount of available observational constraints. 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, specifically 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 knowledge in Astrophysics and Cosmology required for this investigation. This can be confirmed by his research experience, including a paper (as co-author) published in the *ApJL* in which the kinematics of the Local Group in a cosmological context was studied, another paper (as co-author) published in the *ApJ* where the influence of thermal evolution on the magnetic habitability of rocky planets was studied, and some participations in academic congresses. Furthermore, a Bachelor's thesis [1] where the preferred place of simulated Local Group-like systems in the cosmic web was studied, also demonstrates 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 is investigated. 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 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 means of high resolution simulations the impact of the gaseous cosmic web on 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`.

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