Research Proposal
Modeling supermassive Black Holes in hydrodynamical simulations of galaxy formation

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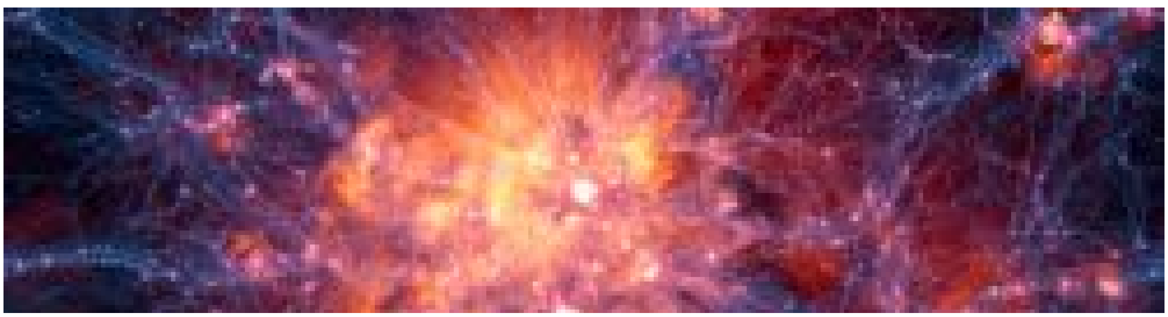

A projection of the cosmic web in the ILLUSTRIS simulation, that was made with AREPO (http://www.illustris-project.org/)

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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	**Modeling supermassive Black Holes in hydrodynamical simulations of galaxy formation**
Field	Cosmology, Astrophysics, Physical Sciences
Advisor	Professor Volker Springel. Heidelberg Institute for Theoretical Studies (HITS) & University of Heidelberg, Germany
University	University of Heidelberg, IMPRS PhD program
Time Frame	3 years

2 Abstract

The modelling of supermassive black holes in the center of galaxies is an important enterprise to be carried out as they play a central role in the current understanding of start formation theories. However, simulating such processes in a cosmological context is not an easy task due to the limited numerical resolution achieved by current state-of-art computing systems. One of our objective is to show that at typically employed numerical resolutions, the orbits of sink particles used to represent supermassive black holes in simulations can be quite unreliable, as a result of two-body effects, fluctuating gravitational potentials and noisy dynamical friction forces. We want to test several proposals from the literature to improve this treatment, and suggest a new one as well. We shall use the improved methods to investigate how black hole recoil kicks affect the growth of the black hole population when black holes return to the centers of halo potentials on realistic timescales.

3 Motivation

3.1 First phase

Supermassive black holes are ubiquitously observed in the centers of galaxies, and they play a critical role in current theories for galaxy formation, where they are supposed to suppress star formation in large galaxies by injecting energy into the gas. We hence want to simulate the growth of these black holes and the associated co-evolution with the galaxy when studying numerical models of galaxy formation. In reality, it is believed that the black holes experience dynamical friction against the background of dark matter and stars, and possibly also through gas-dynamical processes, making them spiral in to the centers of galaxies on a reasonably short timescale. Only when they are positioned there, they can efficiently influence the whole galaxy and grow rapidly.

After galaxy mergers, the remnant (merged) black hole will return to the center through these friction processes, after being kicked out through asymmetric emission of gravitational waves. To properly estimate how long the growth/feedback may be weak/interrupted after a merger (because the center is not yet found again), and how many free floating massive black holes there may be, the orbit of the black holes needs to be followed reasonably accurately.

3.2 Second phase

Whenever supermassive black holes merge during galaxy mergers, they emit a burst of gravitational wave radiation. This happens in an symmetric way such that there is a quite large recoil, kicking the BH out of the centre. It could even happen that the BH leaves the remnant halo entirely, but usually, it probably returns after some time. During this period, the galaxy may then grow unimpeded by the BH. We would like to find out how strongly predictions by galaxy formation are modified when the BH recoil kicks are accounted for. To this end, one can apply fitting functions produced by numerical relativity simulations to kick BH merger remnants depending on their mass ratio, whenever this happens in a cosmological simulation (see for example Sijacki et al., MNRAS, 2011, 414, 3656, arxiv:1008.3313). Combined with a treatment of BH friction, the BHs are then expected to return to the centers after a finite time, so that these effects can be studied in modern simulations of galaxy formation.

4 Problem

Following the orbit of supermassive black holes in cosmological simulations is not readily possible, as the masses of dark matter and star particles in N-body simulation are very much larger than in reality and similar to the mass of the black hole. As a result, two-body scattering effects will try to 'heat-up' the central black hole particle and prevent it from experiencing proper dynamical friction, or in other words, the black hole will not return to the center of the potential by itself under these conditions. Current simulation models therefore usually employ non-physical tricks to 'glue' the black hole particle to the potential minimum, for example by searching for the smallest black hole potential value among neighbors around the black hole, and then simply positioning the black hole particle to this minimum. This is for example done by the Illustris and Gigagalaxy projects. While this prevents that the central black hole particle is lost, it also prevents that the above questions can be studied, and potentially one also introduces severe inaccuracies in the efficiency with which black holes can grow.

5 Objectives

The objectives of the project are:

- ✓ Improving and proposing semi-analytical methods to follow accurately the orbit of supermassive black holes in cosmological simulations, where dynamical friction is accounted for.
- ✓ Studying the effect of dynamical friction on the properties of merging galaxies, e.g. how the growth and feedback of the black hole is strengthened, weakened or even interrupted during merging processes.
- ✓ Making statistical predictions, in a cosmological context, of gravitational wave emissions produced by coalescing black hole pairs. This is very much important for current and future experiments such as LISA. [1]

6 Methodology

One approach for improving the modelling would be to augment the equation of motion for the black hole particle by an explicit dynamical friction force. This can be done in different ways.

- One can try to add a suitably modified version of Chandrasekhars dynamical friction formula, similar to how this is attempted in Tremmel et al. (2015, MNRAS, 451, 1868, arxiv:1501.07609). This involves some assumptions and technical approximations. In the formulation of Tremmel, they arranged it such that the force becomes ever weaker in the limit of infinite resolution, so that one argue it is a correction for the finite resolution of real- work simulations. However, the tests presented in the paper are not fully convincing and it is still unclear (certainly to me), whether this method works sufficiently well in practice (e.g. for galaxy merger simulations, and for cosmological simulations of galaxy formation). (2) Because it not really clear whether Chandrasekhars formula applies well when the BH is already close to the centre of the galaxy (where

[1] Laser Interferometer Space Antenna for observing gravitational waves `https://www.elisascience.org/`.

stars need to be ejected from the loss- cone and interactions with gas play a very important role), one may instead also conjecture different models. For example, if we assume that the BH is brought back efficiently to the potential minimum if it is displaced from the centre, we can construct an optimum friction force as follows: At the centre, the gradient of the potential is zero by definition, so that it can be approximated as quadratic to first order. The BH is hence expected to carry out harmonic oscillations around the centre. We can now try to define an optimum damping force that eliminates the oscillation on the shortest possible timescale (if the friction is too large, the motion will be overdamped, and one takes longer to the centre than for a suitably smaller force). We can estimate the potential around the centre as g(x) phi$_0 + 1/2 * (d^2 phi/dx^2) *$
$x^2, andtheseconderivativealongonedirectioncanbeestimatedfromPoissonsequationas(d^2phi/dx^2$
$-om^2*x = -dg/dx*x, meaningthattheoscillationfrequencyisom = sqrt[(1/3)(4PiGrho)].Foracr$
$-om^2*x-k*x, wherek = 2*om.Inthiscase, weexpecttheorbittodecayonthelocalfreefalltimescale.$

7 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.

8 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 [2] 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[3]. 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 [4].

9 Schedule

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

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

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

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.

References

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