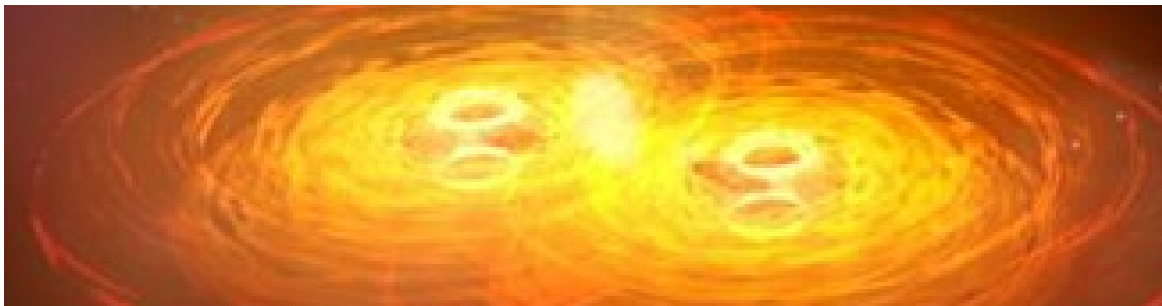


Research Proposal

Modeling supermassive Black Holes in hydrodynamical simulations of galaxy formation

Sebastian Bustamante Jaramillo



Artist representation binary black holes <https://astronomynow.com/2015/09/22/pairs-of-supermassive-black-holes-in-galaxies-may-be-rarer-than-previously-thought/>

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1 General Information

Information of the Applicant

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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 topic to be carried out as they play a central role in the current understanding of galaxy 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 objectives 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

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.

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 center. 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. (2011)). 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 important for current and future experiments such as LISA ¹, where constraints from theoretical and numerical models are needed.

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.

1. One can try to add a suitably modified version of Chandrasekhar's dynamical friction formula, similar to how this is attempted in Tremmel et al. (2015). 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 whether this method works sufficiently well in practice (e.g. for galaxy merger simulations, and for cosmological simulations of galaxy formation).

¹Laser Interferometer Space Antenna for observing gravitational waves <https://www.elisascience.org/>.

2. Because it is not really clear whether Chandrasekhar’s formula applies well when the BH is already close to the center of the galaxy (where 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 center, we can construct an ‘optimum’ friction force as follows: At the center, 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 center. 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 center than for a suitably smaller force). We can estimate the potential around the center as $g(x) \sim \phi_0 + (1/2)(d^2\phi/dx^2)x^2$, and the second derivative along one direction can be estimated from Poisson’s equation as $(d^2\phi/dx^2) \sim (1/3)(4\pi G\rho)$, where ρ is the local total mass density. The harmonic oscillator’s equation of motion will be $x'' = -\omega^2 x = -(dg/dx)x$, meaning that the oscillation frequency is $\omega = \sqrt{(4\pi G\rho)/3}$. For a critical damping we would then need to add a friction force as $x'' = -\omega^2 x - kx'$, where $k = 2\omega$. In this case, we expect the orbit to decay on the local free fall timescale.

7 Work Steps

First phase

The second idea presented in the methodology section is already implemented by us in the AREPO (Springel, 2010) code in a first version, through the switch `BH_FRICTION`. This implementation tries to determine a reference velocity of the potential minimum by measuring its position in the environment of the BH, and then taking finite differences to estimate this velocity (this is needed because for applying the friction force antiparallel to the velocity one needs to know the local reference frame). The oscillation frequency is estimated from the total matter density, and from this a friction force is estimated antiparallel to the velocity against the local frame of rest, with a tunable coefficient in front of order unity.

- Simulations of Milky Way sized galaxies. Here, an important diagnostic would be to develop a plot script that shows the distance of BHs relative to the potential minima of the corresponding halos, which can be done based on the group catalogs. First, we plan to look at the current state of affairs in some of the finished production simulations of the group. Next, one can repeat one or two of these runs by disabling the BH centering that had been used (to see how bad the displacements get if one does not try to correct them). Finally, we plan to try one or several variants of the friction treatments above, starting with method (2) and later also with method (1).
- Toy simulations of an isolated halo where one injects a BH with some velocity and impact parameter to study the decay of the orbit. Again, one should compare differ-

ent friction treatments (ideally also at different resolution) with the results where no treatment is applied.

- Finally, we plan to repeat the test of the first step for a cosmological simulation, where one can compile statistical results, e.g. about the distribution function of the average distances of BHs to their halo centers.

Second phase

Once the first phase is done, where a method for following BH orbits in simulations is developed, we will proceed to estimate the effects of gravitational kicks produced right after a merger event.

- One first needs to compile recent results from numerical relativity simulations to get the most up-to-date fitting function for the strength of the recoil kicks as a function of BH mass ratio.
- We then need to implement an option in AREPO that adds a kick with the corresponding strength after the merger of two black holes.
- Then, we repeat a cosmological simulation of galaxy formation with the kicks enabled, and compare to the equivalent one without kicks.
- The quantities to focus on are, in particular, the galaxy luminosity function at the bright end, the BH mass function, and the color distribution of galaxies. Also interesting would be histograms that quantify the distance of BHs from the center, the time of return to the center, the number of free floating BHs, etc.
- Implications for the merger rate of BHs, and the distribution of the mass ratios, would also be particularly interesting as this is directly related to the statistics of gravitational wave emission events.

8 Bibliography

Sijacki D., Springel V., Haehnelt M. G., 2011, MNRAS, 414, 3656

Springel V., 2010, MNRAS, 401, 791

Tremmel M., Governato F., Volonteri M., Quinn T. R., 2015, MNRAS, 451, 1868

Schedule

Semester	Goals	Status
First (WS15/16)	<ul style="list-style-type: none"> • Pass the lecture of Theoretical Astrophysics. • Pass the literature seminar (IMPRS seminar). • Read and compile literature related to the project. • Run some basic AREPO simulations with the aim to get familiar with the code. • Study analytical models of dynamical friction, e.g. the Chandrasekhar's formula and comparing them with simple simulations of isolated halos. 	Done Done Done Done Done
Second (SoS16)	<ul style="list-style-type: none"> • Get the admission from the University as a PhD student. • Take the lecture of Observational techniques. • Take the second semester seminar (IMPRS seminar). • Implement an improved scheme in AREPO to find potential minima of galaxies based on a multidimensional fitting. • Test different dynamical friction models in AREPO for isolated galaxies. • Run a cosmological simulation with an improved DF model. • Make statistical analysis of the BH population in simulations. • Participate in a Summer school. 	Done Ongoing Ongoing Ongoing Ongoing To be done To be done To be done
Third (WS16/17)	<ul style="list-style-type: none"> • Take the lecture of Stellar Astrophysics. • Write and (ideally) publish a first paper with the previous results. • Read and compile literature of the second phase of the project. • Compile recent results of numerical relativity simulations to get fitting functions of recoil kicks of BHs. • Participate/Attend in a Conference. 	
Fourth (SoS17)	<ul style="list-style-type: none"> • Take a lecture of Advance Topics. • Implement in AREPO an option that adds a kick after a merger event. • Run cosmological simulations where the kick option is fully implemented. • Make statistical analysis of the effects of gravitational recoils. 	
Fifth (WS17/18)	<ul style="list-style-type: none"> • Study the implications of the previous results on galaxy properties. • Compile observational evidence in order to contrast with our findings. • Write a paper with these results. 	
Sixth (SoS18)	<ul style="list-style-type: none"> • Teaching duty. • Start writing the dissertation. 	
Seventh (WS18/19)	<ul style="list-style-type: none"> • Continuing with the dissertation writing. • Prepare thesis defense. 	