Capstone Proposal: Investigating the M-Sigma Relation with Cosmological Hydrodynamical Simulations

Liam Meier[a]

[a] *NYU Abu Dhabi*

Abstract

The M-σ (M-Sigma) relation links the velocity dispersion of bulge stars in a galaxy to the mass of the black hole at its center. By adding code for black holes to their cosmological hydrodynamical simulations, the Galaxy Formation Group at NYUAD can now study the impact of black holes on galaxy formation and evolution. I propose a capstone where I analyze these simulations to understand how the M-σ comes about, how it changes over time, and how it holds at smaller black hole masses.

1. Introduction

Galaxy formation is a branch of astrophysics that studies how galaxies form and evolve. The sheer number of galaxies, 2^{12}, [3], gives ample material for astronomers to observe and collect statistics on. For example, the 2dF Galaxy Redshift Survey collected over 200,00 galaxy spectra[2]. Surveys like these give constraints on what sort of galaxies can exist.

Galaxies evolve at time-scales far longer than any that could be observed astronomically. Therefore astronomy can only give single snapshots of how particular galaxies are at a certain point in their life. To understand how individual galaxies change over time, a different technique is needed. A popular approach today employs large cosmological hydrodynamical simulations to study galaxy formation. Using simulations allows astrophysicists to fill in the gaps between observed galaxies.

To create accurate simulations, two components are needed: the correct starting conditions and correct algorithms to evolve with. The starting conditions come from the earliest observations we have of the universe, the cosmic microwave background. The cosmic microwave background is electromagnetic radiation left over from the Big Bang. Observations of the cosmic microwave background indicate that the universe just after the Big Bang, 400,000 years into the life of the universe (z=1089), was highly isotropic. Variations in density existed only at the scale of 10^{-6} [7]. That means that simulations start off as incredibly uniform distributions of matter. The correct physics must be implemented to arrive at galaxies that look familiar to astronomers.

The algorithms that advance the simulations are implementations of known physics. The two driving processes are those of gravity and hydrodynamics. Adding in the effects of star formation, early stellar and supernova feedback, gas cooling, UV heating, and more produces simulations that strongly match observed galaxies.

2. The Galaxy Formation Group at NYUAD

The Galaxy Formation Group at NYUAD studies galaxy formation under the influence of dark matter[7].The universe is comprised of 4.9% baryons (ordinary matter), 68.3% dark-energy, and 26.8% dark matter. The prevailing theory of dark matter is that it is composed of weakly interacting massive particles (WIMPs) that interact only through gravity and the weak force. A simple observation that supports the existence of dark matter is the radial velocity profiles of galaxies. Based on the visible matter, one would expect a rotation curve in which the orbital velocities decrease as distance from the center of mass increases, as occurs in solar and planet-moon systems. In fact, stars orbit galaxy centers at similar or increasing speeds as distance increases. This strongly suggests the presence of significant amounts of unseen matter.

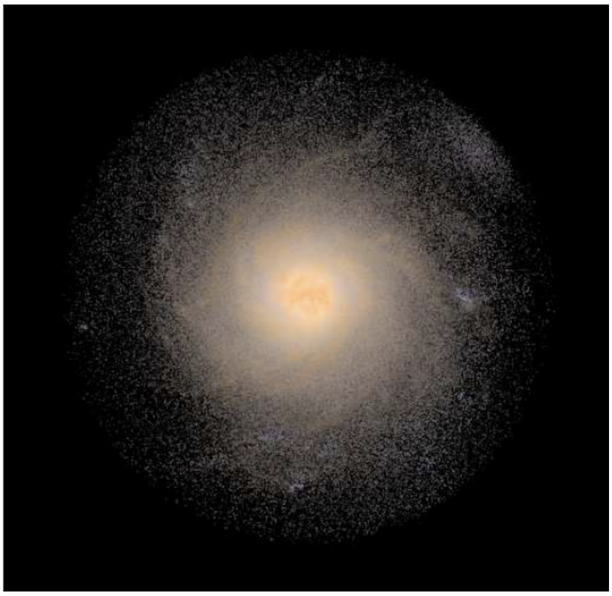

Figure 1: A spiral type galaxy. This image is representative of the galaxies produced by simulations today. Such visuals strongly resemble actual observed galaxies.

3. NIHAO Project

NIHAO, Numerical Investigation of Hundred Astrophysical Objects, project is a collaboration between NYUAD, the Max-Planck-Institute for Astronomy and the Purple Mountain Observatory [7]. Utilizing the Gasoline code for simulations, the collaboration tries to build realistic galaxies through hydrodynamical simulations, comprised of stars, gas, and dark matter. A driving objective of this project is to better understand the formation of galaxies, especially spiral galaxies like the Milky Way we inhabit. Major improvements of NIHAO over previous simulations include higher resolution and improved models for stellar processes, both formation and feedback.

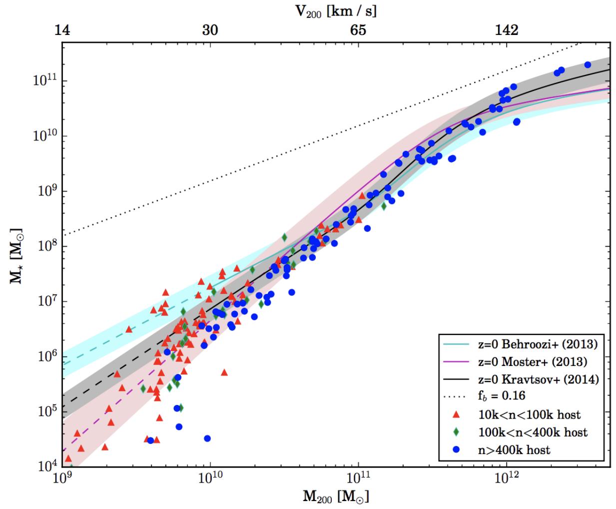

Figure 2: The M-star, M-halo relation, NIHAO galaxies plotted with blue points

Empirical scaling relations constrain models of galaxy formation. Key among these is the stellar mass, halo mass relation (M_{star}-M_{halo}). This relation, between the mass of the dark matter halo and the stars in a galaxy, relays information about how successful a galaxy is in turning gas into stars. The stellar mass, halo mass relation and related work have demonstrated to scientists that galaxies are inefficient at generating stars, converting at most 25% of gas into stars.

A key task of the NIHAO project is to replicate this relation across redshifts, producing stars at both the right times and halo masses. Several mechanisms help aid in this task. In the numerical simulations, star formation follows the Kennicut-Schmidt law. Gas must reach a certain temperature (e.g. below 15,000 Kelvin), and density before becoming star particles. As this star formation process occurs, two regulating mechanisms work. In supernovae feedback, the stars give energy to the surrounding particles. This feedback is sometimes observed in the simulations as a 'blast-wave', as rising gas temperatures force gas to expand out. Additionally, massive stars produce ionization that creates heavier elements and also regulates the formation of stars.

NIHAO has successfully replicated the M_{star}, M_{halo} relation, but only to halo masses of about $10^{12.3}$ solar masses (see figure 3). Beyond this, the NIHAO simulations demonstrate the lack of sufficient mechanisms for preventing star formation. In order to produce simulations of larger, elliptical-type galaxies, additionally physics must be modelled.

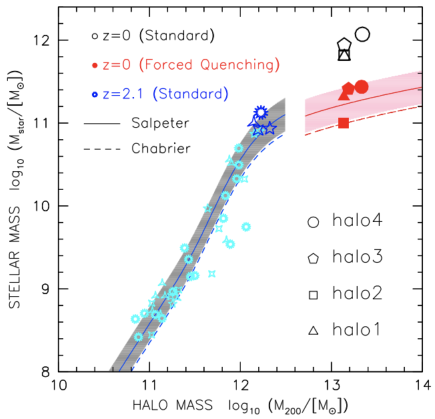

Figure 3: A halo mass, stellar mass plot showing that NIHAO simulations overproduce stars at large halo masses [4]

4. The Next Step: AGN Feedback

Active Galactic Nuclei (AGN) are a prime candidate for the missing physics apparent at large halo masses. Its thought that as a black hole accrete matter, the black hole emits large amounts of radiation. A supermassive black hole emitting radiation is active and hence deemed an AGN. Several observations suggest that AGN can be responsible for regulating star formation. It's been observed that there is gas at the center of galaxies that fails to condense and form stars, despite X-ray evidence suggesting the ability of this gas to do so [6]. Because black holes are thought to be at the center of every galaxy, they can explain this behavior. Semi-analytic models as well [1] suggest that AGN can serve this role and others (e.g. in explaining that massive galaxies tend to be bulge dominant).

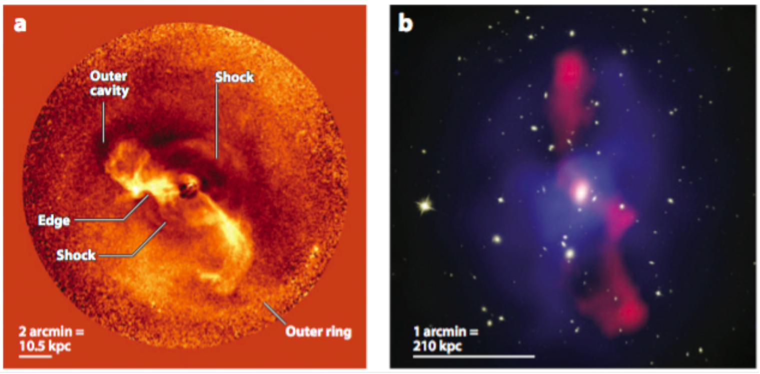

Figure 4: Observations of AGN feedback: the jet producing a shockwave in the gas is present in panel A, and B shows X-ray, a quantitative measure of the AGN's affect on star formation [5]

There's also another strong empirical scaling relation that suggests an intimate connection between black holes and galaxy formation. M-σ, the mass of a galaxy's black hole and the stellar velocity dispersion of the galaxy, are highly correlated (with especially low scatter at the higher masses). In log-log, their relation is linear with low scatter. In essence, this relation connects the dynamics of a galaxy with its black hole. It's not obvious that the two would be connected. The gravitational radius of a black hole is several orders of magnitude smaller than the radii at which the stars in the velocity dispersion are measured. It seems that non-gravitational effects of the black hole somehow work their way into the evolution of the galaxy.

NIHAO is now wrapping up as the next major changes are being made to the simulation code. Postdoc Marvin Blank has implemented the code for Active Galactic Nucle in GASOLINE. This is major improvement and is to be marked by moving to the project (tentatively) named SALAM. By placing black holes in the centers of galaxies, giving them the proper accretion rates, energy output, and gas coupling, the M-σ relation can be matched. The M-σ relation, shown in Figure 5, shows the relationship between the the stellar velocity dispersion and mass of the black hole at the center of the galaxy.

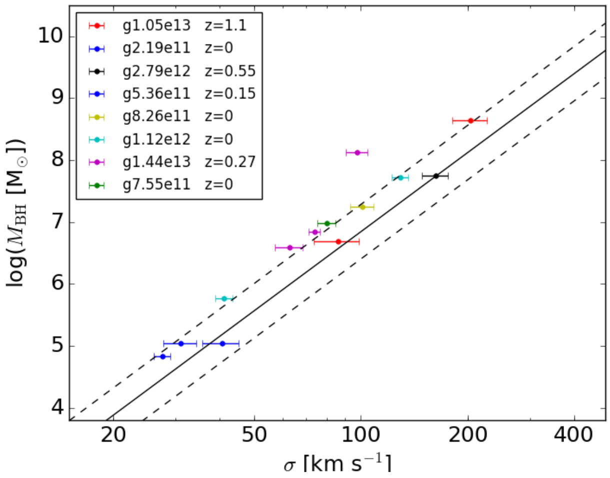

Figure 5: M-σ Relation. Several NIHAO galaxies with AGN are shown. The solid line shows the observed relation from Gueltekin et al. 2009, the dashed line is the 1-sigma scatter of this relation. This plot indicates the current implementation is reproducing the effects of galaxy formation by the AGN.

5. Research Project

The project that I propose involve studying the M-σ relation. There are several questions regarding M-σ I want to answer. It's unclear the mechanisms in which the black hole and the galaxy interact. How exactly does the black hole affect the evolution of the galaxy? Is this effect present at all halo mass and black hole mass sizes? Do patterns of galaxy formation in simulations verify that the presence of a black hole in the center of every galaxy? Do the outliers of the M-σ have some unique morphology or formation history?

I'm also interested in how the M-σ changes over time. Figure 6 shows tracks (individual points of the same galaxies from different times) of six different galaxies with black holes. In aggregate, the M-σ relation is strongly linear, but these tracks show that at different points in a galaxy's lifetime, the relationship changes. Are these the result of mergers, or other large scale unique events, or do they occur as a galaxy evolves a specific way? If we plot the M-σ at different redshifts, does the relation move?

I'm also interested in building the M-σ at smaller black hole masses. Observational techniques limit the range of the empirical correlation, but simulations should be able to extend the study to include smaller black holes. It's possible that this work would suggest an selection bias of some sort in the observations.

Finally, I would consider the impact of our choice of model on the results produced by adding AGN feedback. In adding a new feature to the code, Dr. Blank chooses to match certain relations. For example, if the velocity dispersions were above the empirical relation, he may choose to increase the accretion rate of the black hole, or vice-versa if the opposite were true. Some relations of the galaxies will be true because the code was adjusted to make them so. An important task will be to separate these model-dependent relations and relations which inform true physics.

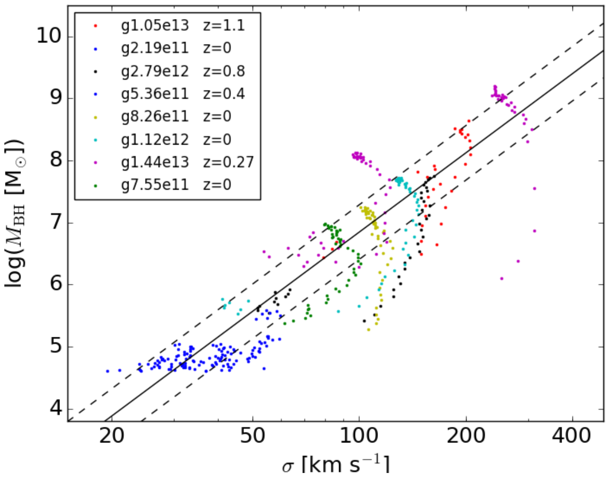

Figure 6: M-σ Tracks of NIHAO Galaxies

This will be an ideal capstone project, because Professor Macciò's group is entering a new stage of work almost exactly as I begin my project. The implementation of AGN feedback stands to create lots of new results. I look forward to learning more about galaxy formation and I hope that I am able to use this opportunity to make contributions to astrophysical understanding.

6. References

[1] L. Ciotti et al. "AGN feedback and star formation in ETGs: negative and positive feedback". In: *IAU General Assembly* 22, 2256683 (Aug. 2015), p. 2256683. arXiv: `1511.00510`.

[2] M. Colless et al. “The 2dF Galaxy Redshift Survey: spectra and redshifts”. In: 328 (Dec. 2001), pp. 1039–1063. doi: 10.1046/j.1365-8711.2001.04902.x. eprint: astro-ph/0106498.

[3] C. J. Conselice et al. “The Evolution of Galaxy Number Density at z 8 and Its Implications”. In: 830, 83 (Oct. 2016), p. 83. doi: 10.3847/0004-637X/830/2/83. arXiv: 1607.03909.

[4] A. A. Dutton et al. “The response of dark matter haloes to elliptical galaxy formation: a new test for quenching scenarios”. In: 453 (Nov. 2015), pp. 2447–2464. doi: 10.1093/mnras/stv1755. arXiv: 1506.06760.

[5] A. C. Fabian. “Observational Evidence of Active Galactic Nuclei Feedback”. In: 50 (Sept. 2012), pp. 455–489. doi: 10.1146/annurev-astro-081811-125521. arXiv: 1204.4114.

[6] J. Silk and M. J. Rees. “Quasars and galaxy formation”. In: 331 (Mar. 1998), pp. L1–L4. eprint: astro-ph/9801013.

[7] L. Wang et al. “NIHAO project - I. Reproducing the inefficiency of galaxy formation across cosmic time with a large sample of cosmological hydrodynamical simulations”. In: 454 (Nov. 2015), pp. 83–94. doi: 10.1093/mnras/stv1937. arXiv: 1503.04818.