Efficiency of IllustrisTNG in simulating galaxy properties

Comparing the output of the IllustrisTNG simulation to observational data.

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Abstract

1 Introduction

1.1 Motivation

The field of astrophysics is a relatively young field of study compared to most other disciplines of science, but in many ways it is also the most fundamental. From the tiniest quantum fluctuations at the beginning of time, to galaxy clusters, astrophysicists have to cover a range of magnitudes from the smallest particles discovered to the largest structures we know about.

In this project, galaxies are the focus of study. Theories for how galaxies formed and evolved since the Big Bang have been proposed since they were first discovered, and as new data and new physics emerge, new theories take over for old ones. The model that has been established as the one best able to explain our observations of the Universe is the Lambda cold dark matter (ΛCDM) model (Mo, Bosch, and S. White 2010). In this model, the energy in the universe is made up of about 75 percent dark energy (the so-called vacuum energy that is pushing the expansion of the Universe), 21 percent dark matter and about 4 percent baryonic matter.

There are many theories for what dark matter is (Boveia and Doglioni 2018), but what we do know is that cosmological models require the presence of dark matter to reproduce the structures seen today. Dark matter does not interact with baryonic matter in any noticeable way except through gravity. In the ΛCDM model of our Universe, galaxies are located in the center of dark matter halos (or just halos), which extend much further than the actual visible galaxy. Many of the properties of the galaxies are linked to its host halo. These, along with several other galaxy properties, are the main focus of this project report.

Hydrodynamical cosmological simulations have been around since the 1980s, starting as N-body simulations of only dark matter with a set of initial conditions (Frenk, S. D. M. White, and M. Davis 1983). As computers became more powerful, and physicists learned more about the complicated physics of galaxies, the simulations started to incorporate stars, gas and other baryonic components. The number of particles that can be resolved within a given space has increased tremendously, and newer projects such as the Illustris and EAGLE simulations have pushed the boundaries of modern astrophysics. IllustrisTNG is the new and improved version of the Illustris simulation, with the first result-papers being published in 2017, and more data being produced still. It increases the resolution, size and amounts of physics included, to produce the largest, most detailed simulated universe to this date.

In this report, the data from the IllustrisTNG simulations will be compared against observational data, to determine whether it manages to reproduce known galaxy properties. The data used is from the readily available data catalogues, and so this will also be a good way to check the usefulness of this resource which can easily be downloaded and studied by people without much programming experience.

1.2 The structure of this report

In this report .... The theory section explains the physics of the main galaxy property relations that are covered in this report. It also hopefully serves as a sort of glossary and explanation for many of the (sometimes confusing) astrophysical terms. In the method part of the report, it is explained how the simulation and observation data is filtered and edited to be comparable. The results and discussion section covers the comparison of the data, while the conclusions section sums up what was learned from the project and looks to the future for what should be studied next.

2 Theory

2.1 Galaxy formation

2.1.1 Dark matter halos

The ΛCDM model for our universe gives a bottom-up solution to galaxy formation. Essentially this means that larger galaxies have formed through mergers of smaller galaxies. In the early universe, dark matter is distributed isotropically on large scales, but with local perturbations. These perturbations in the density field grow with time, and the dark matter collapses into clumps known as halos. The halos provide the initial gravitational well needed for baryonic matter to collapse and create stars. This leads to galaxies forming at the center of their respective halos. Gravitationally bound halos are called subhalos, and are part of a larger host halo. Subhalos will fall towards the central subhalo, and accrete onto it, depending on variables like the subhalos size and orbit. There may be subhalos without an attached galaxy, but all galaxies have a dark matter subhalo.

2.1.2 Stellar-to-Halo mass relation

The stellar-to-halo mass relation (SHMR) gives us an idea about what size galaxy populates a dark matter halo of a certain size. One way of looking for this relation is through a method called abundance matching (Citations 2000). Abundance matching is a numerical method which employs a guess for the form of a relation to simulate how such a universe might look, and then compares it to observations. By tweaking the form of the equation, a better match can be achieved, and as such a better estimate for the right answer.

Using abundance matching, the SHMR has been found to be well described by a power law for low-mass galaxies, and a subpower law for the high-mass end of the spectrum (Behroozi, Wechsler, and Conroy 2013).

$$\log_{10}(M_*(M_h)) = \log_{10}(\epsilon M_1) + f(\log_{10}(M_h/M_1)) - f(0), \tag{1}$$
$$f(x) = -\log_{10}(10^{\alpha x} + 1) + \delta \frac{(\log_{10}(1 + \exp(x)))^\gamma}{1 + \exp(10^{-x})}$$

Here M_* is the stellar mass, M_h is the halo mass, M_1 is a characteristic halo mass, δ is the strength of the subpower law, α is the power law slope for $M_h << M_1$ and γ is the power law index for $M_h >> M_1$.

This gives us a relation that matches smaller halos to smaller galaxies, and vice versa, as well as a characteristic halo mass of about $10^{12} M_\odot$.

2.2 Galaxy evolution and classification

As soon as telescopes became good enough to clearly make out galaxies in the sky, it became apparent that galaxies come in many different shapes and sizes. The morphology of a galaxy is important, because it turns out that morphology is closely linked to other properties of the galaxy. Edwin Hubble

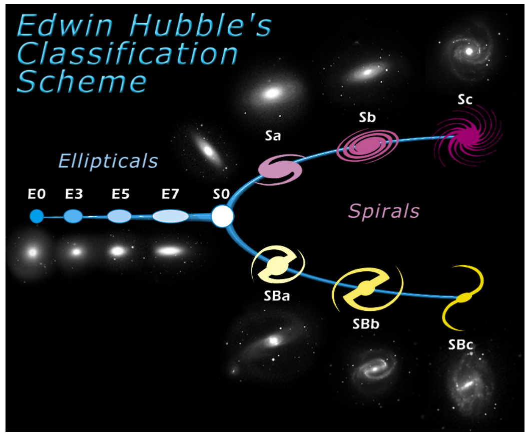

Figure 1: Chart from 1999 showing the original classifications of galaxy morphology. Credit: ESA/Hubble

classified galaxies on a spectra (Hubble 1926), with spiral galaxies (galaxies with a prominent disk component) on one end of the spectrum and elliptical galaxies (galaxies that have a dominant spheroidal component) on the other (see Figure 1). He thought that galaxies started off as ellipticals and evolved along the spectrum, becoming more disk-dominated as it aged. This is the reason that elliptical and spiral galaxies are known as early and late type galaxies. These terms can be confusing as it turns out that Hubble was probably wrong, and the evolution of galaxies probably moves in the other direction.

In the ΛCDM model, galaxies grow through mergers. Mergers are separated into two types, major and minor mergers. Major mergers are events where two galaxies of equal size collide and become one galaxy. Simulations have shown that a major merger between two disk galaxies produces an elliptical. The Milky Way, which is a large spiral galaxy ($M_* > 10^{10}$) has probably grown through many smaller minor mergers, and thus kept its disky part.

It is not always easy to distinguish between a disky elliptical and a spiral with a large spheroidal component (bulge). Some galaxies are in the middle of a merging process. These can have very irregular shapes, and so are hard to classify. Other galaxies are very small, so called dwarf galaxies. These galaxies tend to have very little stellar mass compared to dark matter, so they do not exhibit the properties of ellipticals, even though they may be more elliptical in shape. In this project, we mostly look at larger, central galaxies, so we will not have to consider most of these special galaxy types.

2.2.1 Elliptical (early type) galaxies

Elliptical galaxies are mainly pressure-dominated systems, meaning that the motion of the stars is predominantly radial. The largest galaxies in the universe tend to be ellipticals, but they come in all sizes. The star population of ellipticals is generally older than that of spirals, and there is usually little to no star formation. There is very little gas and dust in ellipticals, and they tend to emit more light in the redder end of the EM spectrum. Early type galaxies are less common than late type galaxies, and are more usually found in galaxy clusters.

2.2.2 Spiral (late type) galaxies

Late type galaxies have a prominent disky component, orbiting around the galaxy's center. The rotational velocity of the disk is typically much larger than the velocity dispersion of the galaxy's bulge. The stars in a spiral galaxy are usually much younger than those in early types. There is a lot of gas and dust present in spirals, giving rise to ongoing star formation. Late type galaxies are bluer in color than early types. Field galaxies, galaxies that are not part of a galaxy cluster, are predominantly spirals.

The large rotational velocities of the disky part of late-type galaxies perplexed early astrophysicists, as the mass inferred by the rotational motion was much greater than that which could be accounted for by the stars and gas in the galaxy. An effort to solve this problem led to the theory of dark matter, and later to the ΛCDM model.

2.3 Galaxy properties

2.3.1 The Tully-Fisher relation

In 1977, R.B. Tully and J.R. Fisher (Tully and Fisher 1977) published a paper where they found a surprisingly good correlation between the luminosity of a spiral galaxy and the rotational speed of its disk on the form of a simple power law with index 4.

$$L \propto v_{rot}^4 \tag{2}$$

As stellar mass is directly proportional to the luminosity, this gives us the ability to estimate stellar mass from a simple measurement of the rotational velocity.

$$M_* \propto v_{rot}^4 \tag{3}$$

This relation is a great tool for estimating the distance (and hence age) to a galaxy, as the calculated luminosity can be compared to the observed luminosity at Earth. For numerical simulations, being able to reproduce the Tully-Fisher relation is an essential way to check if the model used is reliable.

2.3.2 The Faber-Jackson relation and the Fundamental Plane

At around the same time that Tully and Fisher published their paper, Sandra M. Faber and Robert Earl Jackson published a paper that linked the velocity dispersion and luminosity of early-type galaxies. The proposed relation was on the form of a power law as well, with an index of approximately 4 (Faber and Jackson 1976).

$$L \propto \sigma^\gamma \tag{4}$$

This is known as the Faber-Jackson (FJ) relation. The correlation was not as tight as the Tully-Fisher relation however, and it was later found that the velocity dispersion also was dependent on the size of the galaxy.

$$\sigma \propto L^a R^b \tag{5}$$

With the radius added into the equation, the deviations from observations became much less significant. Most ellipticals are found on the same plane in σ, R, L space. This plane became known as the Fundamental Plane (FP), through a paper published in 1987 (Djorgovski and Marc Davis 1987), and is also something which successfull numerical simulations must reproduce.

2.3.3 Color bimodality

Color, in astrophysics, is defined as the difference in magnitudes measured for a galaxy by two different optical filters. A galaxy that is "blue" has a larger amount of blue light than red. In general, galaxies are found to inhabit one of two groups on a color-mass diagram, blue and red. The blue galaxies are most often late type galaxies, while the red ones are mainly ellipticals. There are many factors that contribute to the color of a galaxy, like stellar age and metallicity as well as the amount of gas the light has passed through and its metallicity.

2.3.4 Supermassive Black Holes

Almost every large galaxy with a spheroidal component has a supermassive black hole (SMBH) in its center. These are black holes with masses over $10^6 M_\odot$ and even above $10^9 M_\odot$. The mass of the SMBH correlates surprisingly well with other properties of the galaxy, such as the velocity dispersion and luminosity. This is surprising because the SMBH only has a gravitational influence within a pretty small radius compared to the entire galaxy, which suggests that the SMBH evolves along with the galaxy and that their formation is linked. In fact, it seems very likely that these gigantic black holes play a vital role in galaxy evolution, and are a central component of the galaxy as a whole.

3 Method

3.1 IllustrisTNG and the Data Catalogues

IllustrisTNG is the follow-up project after the success of the Illustris simulations. It is a huge project, built upon a magneto-hydrodynamical cosmological simulation code with added physical processes on a subgrid level (Weinberger et al. 2016). The IllustrisTNG project includes 18 different simulations, with varying resolutions, spatial size and included physics. In this project, the TNG100-1 simulation data has been used. It has a volume of 110.7^3 Mpc, and a baryonic particle resolution of $1.1 \cdot 10^7 M_\odot$. The TNG-300 simulations have a volume of 302.6^3 Mpc which is great for studying galaxy clusters, but they have a significantly lower mass resolution. In this project, the effects of galaxy environments are not studied, so the TNG-100 simulation was the ideal middle ground with respect to size and resolution.

All the Illustris-TNG data is available online at the TNG webpage **insert link**. The data products that are available for each simulation are snapshots, group catalogs and merger trees. The snapshots are taken at specific redshifts and include all the particles in the whole volume of the simulation, with a handful including all the particle fields for each particle as well. Group catalogs are a smart way to access the different halos/galaxies instead of looking at each particle. There are two different group catalogs, FoF and Subfind. The FoF catalog contains all the DM halos, and the Subfind catalog contains all the subhalos. Each subhalo has a parent halo, and the largest subhalo in each halo is the central subhalo. The merger trees data product contain the merger history of each subhalo.

This project makes use of the group catalogs, as they require much less computational power to work with. (...)

3.2 Finding central galaxies

For most of the relations covered in this project, it is desirable to only use the central galaxies in each halo. The FoF catalog contains the index for the largest subhalo in each halo, so combining this information with the Subfind catalog allows one to create a subset of the data that contains only the central galaxies.

3.3 Separating out early and late type galaxies

As several of the relations studied in this project relate to the morphological type of the galaxies, it is interesting to filter out early and late type galaxies to study separately. This can be done in many different ways, and in many studies several criteria for classification have been chosen. In this case, the fraction of gas inside the effective radius of each galaxy has been chosen as the criteria for classification.

$$M_{gas}/M = f \tag{6}$$

For $f > 0.1$, the galaxy is classified as late type, while for $f < 0.1$, the galaxy is classified as early type.

(... hopefully do more here)

3.4 Comparing data

SAMI...Behroozi etc

4 Results and discussions

4.1 FJ relation and the FP

The velocity dispersion as function of stellar mass can be seen in Figure 2. The trend for the TNG-100 data is a clear power law as expected from the FJ relation. Compared to the observational data, the simulation data shows lower σ values, by about 0.1-0.2 dex. This could be explained by the fact that the σ in the TNG galaxies is averaged across all particles, across the whole size of the subhalo. In general, gas has a lower σ than stars and dark matter, so this could push the total σ down. However, in early-type galaxies there is little gas so the impact would be expected to be small. The fact that σ is found by averaging across the entire subhalo would include particles further out than for the SAMI data in which the velocity dispersion is averaged inside the effective radius (σ_e) is used. Other studies have also found that simulations tend to get lower values for σ (Sande et al. 2018), so this might also just be a limitation of the simulations.

5 Conclusions

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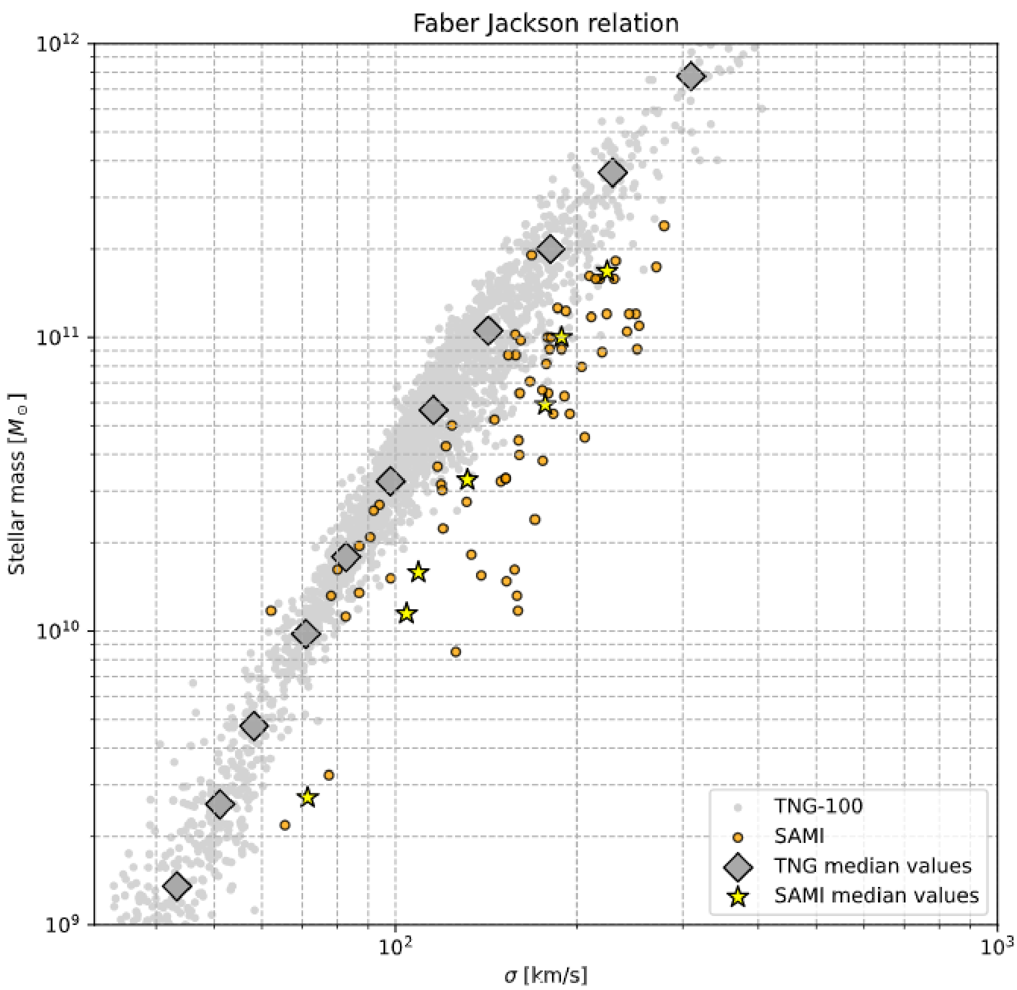

Figure 2: Early type galaxies for both TNG and SAMI.

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