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Abstract

Preface

Contents

1	Introduction	5
1.1	Motivation	5
1.2	The structure of this report	6
2	Theory	6
2.1	Galaxy formation	7
2.1.1	Dark matter halos	8
2.1.2	Galaxies	9
2.1.3	The Stellar-to-Halo mass relation	11
2.2	Galaxy evolution and classification	13
2.2.1	Elliptical (early type) galaxies	14
2.2.2	Spiral (late type) galaxies	15
2.2.3	Classifying galaxies	16
2.3	Galaxy properties	18
2.3.1	The Tully-Fisher relation	18
2.3.2	The Faber-Jackson relation and the Fundamental Plane	20
2.3.3	Color bimodality	21
3	Method	22
3.1	IllustrisTNG	22
3.1.1	The simulations	23
3.1.2	Data products	25
3.1.3	Sample reduction	25
3.2	Observational data	26
3.2.1	SAMI Galaxy Survey	26
3.2.2	Other data sets	26
3.3	Calculating properties	27
3.3.1	Cosmologies and h-dependence	27
3.3.2	Galaxy sizes	28
3.3.3	Magnitude and colors	29
3.3.4	Masses	29
3.3.5	Size	30
3.3.6	Velocities	31
3.4	Galaxy morphology classifications	32
4	Results and discussions	33

4.1	Stellar mass and half-mass radius	33
4.2	Kinematics	33
4.3	Color bimodality	34
5	Conclusions	35

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 the most fundamental. From the tiniest quantum fluctuations at the beginning of time, to the galaxy clusters found in our present day Universe, astrophysicists have to cover a range of magnitudes from the smallest particles discovered to the largest structures in the Universe.

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 understandings of physics emerge, new theories take over for old ones. The model that has been established as the one currently best able to explain observations of the Universe is the Lambda Cold Dark matter (Λ CDM) model. In this model, the energy in the Universe is made up of about 75 percent dark energy (one theory is that this is the so-called vacuum energy that is pushing the expansion of the Universe), 21 percent dark matter and about 4 percent baryonic (visible) matter (Planck Collaboration et al. 2016).

There are many theories for what dark matter actually is (see e.g., 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 any particles except through gravity. In the Λ CDM model of our Universe, galaxies are located in the center of dark matter halos (hereafter, halos), which extend much further than the actual visible galaxy. Many of the properties of galaxies are linked to its host halo.

Hydrodynamical cosmological simulations have been around since the 1980s, starting as N-body simulations of only dark matter particles with a set of initial conditions (Frenk et al. 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 resolution and size of simulations have increased tremendously. Now it is possible to have mass resolutions that show the inner structure of galaxies and at the same time have a simulation volume that is large enough to be relevant on cosmological scales. In this respect, 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. The first result-papers were published in 2017, and more data is still being produced. It increases the resolution, size and amounts of physics included, to produce the largest, most detailed simulated Universe to this date.

The use of the data from numerical simulations might seem straightforward, but comparisons against observational data or other numerical simulations require careful considerations. There are many existing practices for how the data is post-processed after the simulation is run, and the way that properties are defined and calculated are important factors to consider. In this thesis, the practice of using pre-calculated IllustrisTNG data from the SUBFIND group catalogues is compared against several other methods of treating the data during post-processing.

1.2 The structure of this report

Section 2 explains the physics of the main galaxy property relations that are covered in this report. It also contains a glossary with explanation of notation and some astrophysical terms used throughout the text. ... while section 5 sums up what was learned from the project and looks to the future for what should be studied next.

2 Theory

Some astrophysical notation, terms and constants:

- z - Redshift, a dimensionless measure of time where $z = 0$ denotes the current time and $z \rightarrow \infty$ as we move back in time towards the beginning of the Universe. The redshift also gives the actual physical frequency shift of light emitted from a source moving away from us in an expanding Universe.
- H_0 - The Hubble constant at present time $H(z = 0)$, a cosmological constant related to the expansion rate of the Universe. The best measurements of today sets the value of H_0 to 67.8 km/s/Mpc (Planck Collaboration et al. 2016). Specifically, this means that at $z = 0$ a galaxy located 1 Mpc away is receding from us at a velocity of 67.8 km/s because of the expansion of the Universe.

- h - The “little Hubble constant”, given by $H_0 = 100 h \text{ km/s/Mpc}$.
- G - The gravitational constant.
- M_* - The stellar mass of a given galaxy.
- M_{halo} - The dark matter halo mass of a given galaxy.
- M_\odot - Solar mass. In astrophysics, masses are always given in units of solar masses.
- L - Luminosity. The luminosity of a galaxy is a measure of its total radiated electromagnetic energy per unit time. The absolute magnitude (\mathcal{M}) is related to the luminosity as $\mathcal{M} = -2.5 \log(L/L_\odot) + \mathcal{M}_\odot$. With L_\odot and \mathcal{M}_\odot being the solar luminosity and solar magnitude respectively.
- r_e - Effective radius. The radius within which half the luminosity of a galaxy is emitted.

2.1 Galaxy formation

Our understanding of the formation and evolution of the Universe as a whole is based on the cosmological principle, which states that matter is distributed spatially isotropically and homogeneously across the Universe on large scales. Of course, we would not have any structure formation if the matter was actually perfectly uniformly distributed in the very beginning of the Universe. It is not completely clear how this initial deviation from homogeneity originated, but at very early times after the Big Bang, the Universe was so small that quantum effects would have played a significant role. These tiny quantum fluctuations may then have been responsible for the structure formation we can observe today. Given that these initial density fluctuations in matter were present, gravitational effects will then amplify the overdense regions of space as matter is pulled together. If the Universe did not expand, these instabilities in the density field would just keep growing. However, we know the Universe is expanding, and so the effect is damped significantly. As matter keeps being pulled in over time, the overdense region might reach a “turn-around size” where the gravitational pull is large enough to compensate for the expansion rate of space. Then the matter will collapse towards the center. The exact process for collapse is beyond the scope of this report, but it depends on the ratio of dark matter to baryonic matter, and the

properties of the dark matter itself.

2.1.1 Dark matter halos

Dark matter halos are the result of such initial overdense regions of dark matter particles. Halos cover a huge range in magnitude of mass from lower than $10^9 M_\odot$ up to sizes of at least $10^{15} M_\odot$. In general, halos are ellipsoid in shape. The spherically averaged density profile of halos, as predicted by N-body simulations of dark matter in a Λ CDM Universe, is well described by the Navarro-Frank-White profile (Navarro et al. 1996). This profile gives us a halo density (ρ) that is proportional to r^{-1} for smaller radii and r^{-2} for large radii,

$$\frac{\rho}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}, \quad (1)$$

where $\rho_{crit} = 3H_0^2/8\pi G$ is the critical density of the Universe, δ_c is the characteristic overdensity and r_s is the scale radius where the slope changes from r^{-1} to r^{-2} . Both δ_c and r_s may vary for each halo.

Halos grow hierarchically through mergers of smaller halos into larger halos. A smaller halo that merges with a larger halo may survive as a separate entity within the host halo and is then known as a subhalo.

One of the most interesting properties of a Λ CDM Universe is the halo mass function, which gives the number density of halos as a function of their mass. In 1974 the halo mass function was defined by William H. Press and Paul Schechter as:

$$\frac{dn}{dM_{halo}} = f(\sigma) \frac{\bar{\rho}}{M_{halo}^2} \frac{d\log(\sigma^{-1})}{d\log(M_{halo})}. \quad (2)$$

Where $\sigma = \sigma(R)$ is the variance of the field with a smoothing radius R , $\bar{\rho}$ is the mean density of the Universe and $f(\sigma)$ is the multiplicity function (Press and Schechter 1974).

As an example, Figure 1 shows the halo mass function found by Tinker et al. (2008). In this work, they calculated the halo mass function at $z = 0$ based on a set of cosmological simulations (colored points). The solid black lines show the fit to the Schechter function for three different values of Δ , where Δ is the overdensity within a radius R_Δ with respect to ρ_{crit} .

We will not cover the mathematical details of this analytical solution to the mass function, but it is based on the assumption of spherical collapse and depends on both cosmology and redshift. Until the end of the century, numerical simulations tended to agree with the results presented by Press and Schechter. However, newer and more complex numerical solutions have shown that the Press-Schechter formalism tends to overestimate the amount of smaller halos, while under-predicting the abundance of larger halos.

2.1.2 Galaxies

Dark matter halos formed before baryonic matter could gather in densities even close to that needed to form stars, as there is 6-7 times more dark matter than baryonic matter. The dark matter halos created a gravitational potential well which gave room for the primordial baryonic matter (ionized hydrogen gas) to start collapsing.

As the density of the gas increases, temperature increases and halts the collapse, but through several radiation cooling processes the gas is able to collapse enough for fusion to start and stars to be born. Because of the halos role as initial potential wells, the baryonic matter collapses in such a way that the angular momentum of its initial components get transferred to the galaxy as a whole, and the result is a rotating disk galaxy at the center of the halo. This is the birth process of galaxies.

Galaxies are mainly composed of stars and hot gas, with a smaller contribution of stellar remnants, cold gas and dust. Hot gas is hydrogen gas that is fully ionized and does not collapse into stars, while cold gas has a much lower temperature and can contribute to star formation. There are at least two trillion galaxies in the observable Universe (Conselice et al. 2016), with stellar masses ranging from less than $10^6 M_\odot$ to $10^{12} M_\odot$ and larger.

It has been found that a large fraction of galaxies are gravitationally bound to each other in groups and clusters. Galaxy clusters are the largest gravitationally bound systems in the Universe, and can span a distance of several megaparsecs. They typically contain more than a hundred galaxies, as well as large amounts of intergalactic gas. Galaxies in clusters serve an important purpose to astrophysicists, as they essentially function as tracers of the largest halos in the Universe.

As galaxies reside in the center of halos, they too follow a hierarchical growth

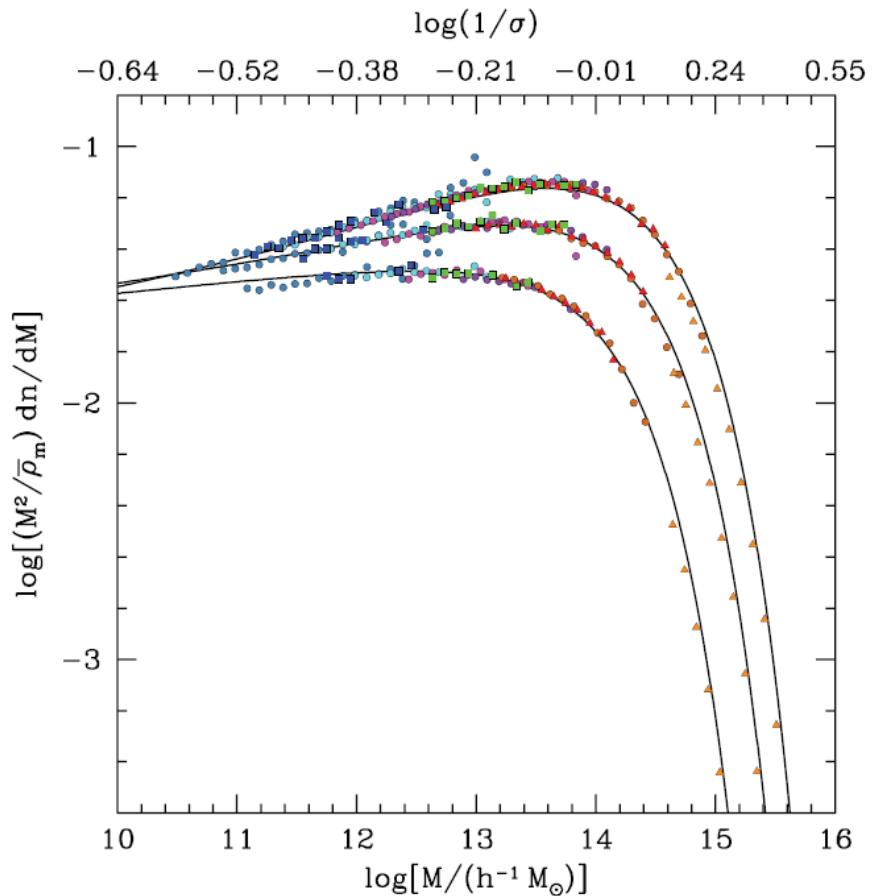


Figure 1: Halo mass function for three different overdensities, $\Delta = 200, 800, 3200$ from top to bottom (points). The different points represent the different simulations used. The solid black lines are best fits for each value of the overdensity Δ . They are all three Schechter functions, with varying multiplicity functions to get the best fit to their respective data points. Credit Tinker et al. (2008).

pattern where larger galaxies are created through the merger of smaller galaxies. All galaxies start off as disk galaxies, so galaxies that have an elliptical component of stars and gas with pressure dominated random motions and which extends in all directions from the center, are results of the merging of galaxies. In galaxy clusters the density of galaxies is much higher than the average of the Universe, so the likelihood of a galaxy merger is higher there. Therefore clusters contain a higher percentage of elliptical galaxies.

A very important property of the galaxy population is the galaxy luminosity function, which gives the number density of galaxies as a function of their luminosity. The luminosity of a galaxy is directly proportional to its stellar mass, so the luminosity function also gives us the mass distribution of galaxies. Mathematically, the luminosity function is defined as $\phi(L)dL$, where $\phi(L)dL$ is the number density of galaxies in the luminosity range $L \pm dL/2$. In 1976 Paul Schechter proposed a fit to the luminosity function of galaxies on the form

$$\phi(L)dL = \phi^*(L/L^*)^\alpha \exp(-L/L^*)dL/L^*, \quad (3)$$

where ϕ^* is a normalization, L^* is the characteristic luminosity for that sample of galaxies (it will differ for instance for galaxies within a cluster compared to isolated galaxies) and α is the slope of the power law where $L \ll L^*$ (P. Schechter 1976). Figure 2 shows the luminosity function (points) as well as the best fit for equation 3 (solid line). This Schechter function is still a good fit to this day, and is in excellent agreement for galaxies with $L \gg L^*$. For the low mass range of galaxies, the parameter α must be found, and this is one of the challenges of astrophysicists that study galaxy properties.

2.1.3 The Stellar-to-Halo mass relation

The Stellar-to-Halo mass relation (hereafter, SHM relation) gives the stellar mass of a galaxy as a function of its host halo mass. This is particularly difficult to determine empirically, as it is not possible to directly measure the dark matter halo mass.

One way of looking for this relation is through a method called abundance matching. In abundance matching, the numerically found halo mass function and the observationally found luminosity function are combined. This is done using the simple assumption that the largest halo contains the largest

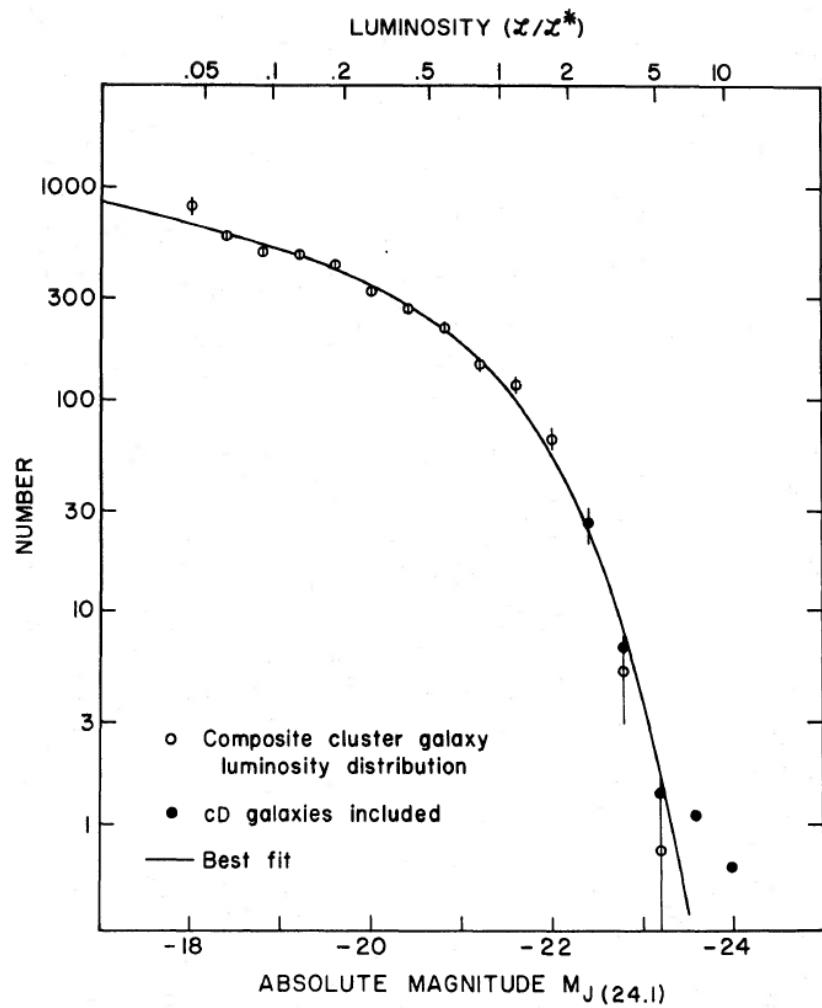


Figure 2: The luminosity function at redshift 0. The open circles correspond to observed galaxies in clusters, while the filled in circles denote cD galaxies (giant ellipticals). The solid line shows the best fit using equation 3. Credit: P. Schechter (1976).

galaxy, the second largest halo contains the second largest halo and so on. By mapping each galaxy to its corresponding halo in such a fashion, the shape of the SHM relation can be found directly.

Using abundance matching, the SHM relation has been found to be well described by a double power law with different slopes for the low-mass and high-mass end of the spectrum (Behroozi et al. 2013).

Other ways of studying the SHM relation could be through simulations which include halo and stellar mass like IllustrisTNG, or inferring the halo mass empirically by using the rotational curves of disk galaxies (see section 2.2.2).

2.2 Galaxy evolution and classification

As soon as telescopes became good enough to clearly make out galaxies in the sky, it became apparent to astronomers that galaxies come in many different shapes and sizes. The morphology of the galaxy is closely linked to other properties of the galaxy and is therefore important for the classification of galaxies. Edwin Hubble classified galaxies on a spectra (Hubble 1926), with elliptical galaxies (galaxies that have a dominant spheroidal component) on one end of the spectrum and spiral galaxies (galaxies with a prominent disk component) on the other (Figure 3). The galaxy types were presented as a sequence, so Hubble deemed it convenient to use the adjectives “early” and “late” to describe the two extreme ends of the spectrum. He did consider the fact that these words might be confusing because of their temporal connotations, but went ahead with using “early” and “late” as a proxy for “less complex” and “more complex”, respectively. Indeed this turned out to be confusing, as it is now established that galaxies actually evolve with time along the sequence, starting out as late type disk galaxies and often ending up as more massive early type ellipticals.

In the Λ CDM 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, while minor mergers happen when one of the galaxies is significantly smaller than the other. Simulations have shown that a major merger between two disk galaxies produces an elliptical. The Milky Way, which is a large ($M_* > 10^{10} M_\odot$) spiral galaxy has probably grown through many smaller minor mergers, and thus kept its disk shape.

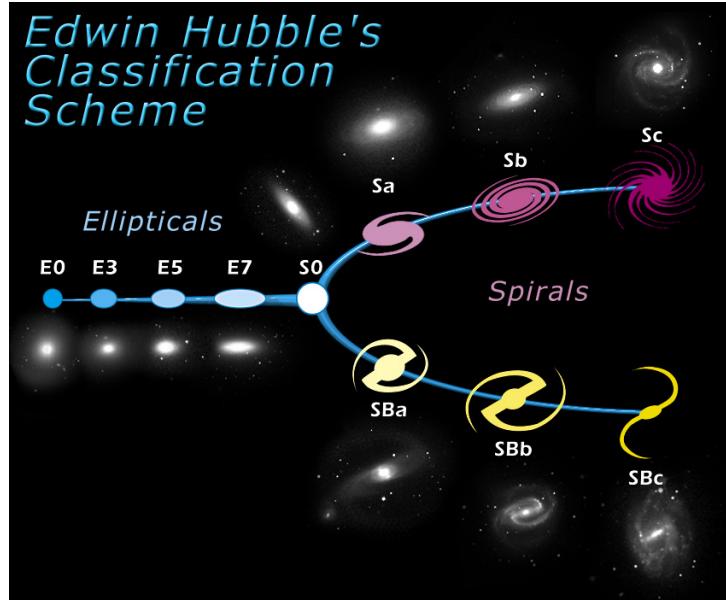


Figure 3: Chart from 1999 showing the original classifications of galaxy morphology. Credit: ESA/Hubble

It is not always easy to distinguish between a disk-like elliptical and a spiral with a large spheroidal component (bulge). Some galaxies are also 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.

Galaxies were initially separated into the two types (early and late) by their shape, but as astronomers have studied these different galaxy categories, it has become apparent that there are many other properties that also serve to distinguish the two types. Table 1 gives a quick overview of the main properties of early and late type galaxies, while the rest of this section explains them in more detail.

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

Table 1: Galaxy properties by morphology type.

	Early type	Late type
Shape	Spheroidal	Disk
Color	Red	Blue
Velocity direction	Radial	Circular
Stellar population	Older	Younger
Star formation rate	Low	High
Size	Smaller	Larger
Gas and dust	Little	More

Universes 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 electromagnetic 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 disk component which orbits around the galaxy's center. The rotational velocity of the disk is typically larger than the velocity dispersion of the galaxy's bulge. The stars in a spiral galaxy are usually 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, which are not part of any galaxy cluster, are predominantly spirals.

The rotational velocities of the stars at different radii in the disk of spiral galaxies can be measured observationally, and plotting the velocity as a function of radius gives us the velocity curve of the galaxy. If the mass in the galaxy was solely made up of the gas and stars that we are able to detect optically, we would expect the velocity curve to drop off as we get to the outer parts of the galaxy. Assuming the particles move in circular orbits around the center of mass, the circular velocity at a given radius is given by the formula

$$v_{circ} = \sqrt{GM(< R)/R}, \quad (4)$$

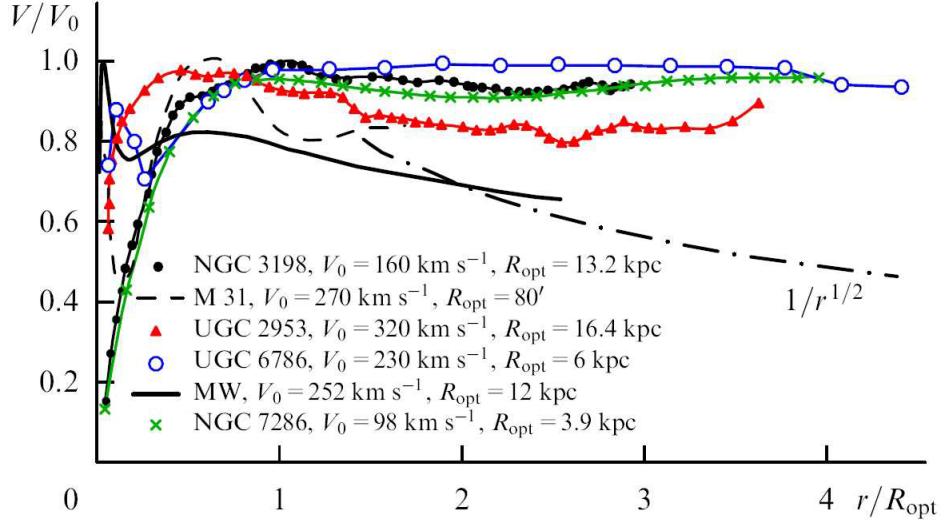


Figure 4: Rotation curves for several spiral galaxies (points). The velocities are normalized with respect to each of the galaxies maximum velocity. Radial distances are in units of the optical radius R_{opt} (the radius within 83% of the light is enclosed). The long-dashed line shows the expected Keplerian curve if there was no dark matter. Credit: Zasov et al. (2017).

where $M(< R)$ is the total mass within radius R . However, the observational data shows that the velocity curve does not fall off towards the outer parts of the galaxy, but actually flattens out. An example of this can be seen in Figure 4. There the rotation curves of several spiral galaxies are shown, along with the curve showing the expected fall off of velocity if there was no dark matter (long-dashed line). This perplexed early astrophysicists, as the mass inside the outer radius must be 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 Λ CDM model.

2.2.3 Classifying galaxies

An important factor in many studies of galaxy formation and evolution is looking at the properties of the two morphological types of galaxies. As a visual classification method is intensively time-consuming, other methods have been devised for identifying early and late-type galaxies in simulations. In many studies, several of these classification criteria are used in conjunction.

As early-type galaxies have much less cold gas than late-type galaxies, a simple cut in the galaxy population based on the gas fraction will be effective at roughly separating the two types. TNG doesn't differentiate between cold and hot gas, so it is important to consider the physical volume where the gas fraction is calculated. A large volume will inevitably contain more hot gas and potentially allow for early-type galaxies to be considered as late types. Late-type galaxies also have a wide range of gas fractions. The most massive spiral galaxies can contain as little as 5% gas, while low-mass disks can contain up to 80% (Mo et al. 2010). In Ferrero et al. (2020) galaxies with less than 10% gas were considered for early types, while those with more were potential candidates for late-type classifications.

Another way of separating galaxies into the early and late-type categories is by using the specific star formation rate (sSFR). The sSFR of a galaxy is the galaxy's star formation rate divided by the stellar mass content of the galaxy. In this case, the galaxies are tagged as “quenched” or “main-sequence”, where quenched galaxies have little to no star formation, while main-sequence galaxies have a significant amount of star formation. More formally, they are separated by how far from the ridge of the star-formation main-sequence they are found (//cite). In Genel et al. (2017) the ridge of the main-sequence is defined as the mean of the sSFR for galaxies with mass $10^9 M_\odot < M_* < 10^{10.5} M_\odot$, and takes a value of $\log(sSFR[Gyr^{-1}]) = -0.94$ for $z = 0$. Galaxies are then considered ‘main-sequence’ if their sSFR are within 0.5 dex of this value. “Quenched” galaxies are defined as those with sSFR at least 1 dex below the ridge.

A common way of estimating a galaxy's “diskyness” is to use the rotational-to-total-kinetic-energy parameter κ_{rot} .

$$\kappa_{rot} = \frac{K_{rot}}{K} = \frac{\sum_{i=1}^N m_i (j_{z,i}/R_i)^2}{\sum_{i=1}^N m_i v_i^2}, \quad (5)$$

where $j_{z,i}$ is the z-component of the specific angular momentum ($\vec{j} = \vec{r} \times \vec{v}$), m_i is the mass, and R_i is the projected radius of stellar particle i in the xy-plane. This value indicates how much of the kinetic energy of the galaxy is invested in the ordered rotation about its axis. To calculate κ_{rot} , the axis of rotation must first be found. The galaxy is then rotated such that the z-axis of the galaxy's coordinate system is pointed in the direction of the axis of rotation, and κ_{rot} is calculated. For a perfect disk galaxy

that is totally rotationally supported $\kappa_{rot} = 1$, while for a totally pressure supported system, κ_{rot} would approach zero. In Sales et al. (2012), galaxies were classified as early type if they had $\kappa_{rot} < 0.5$ and late type for $\kappa_{rot} > 0.7$. This leads to a significant amount of “intermediate types”, but other works have simply made use of a single cut at $\kappa_{rot} = 0.6$.

2.3 Galaxy properties

In this report I will be looking at many of the main galaxy properties that have been explored throughout the years. We will only be looking at the relations in the present time, $z = 0$, but the relations have been studied across redshifts and many are redshift-dependent.

2.3.1 The Tully-Fisher relation

Tully and Fisher (1977) found a surprisingly good correlation between the luminosity of a spiral galaxy and the characteristic rotational speed of its disk on the form of a simple power law with index α ,

$$L \propto V_{rot}^\alpha. \quad (6)$$

This is known as the Tully-Fisher relation (TFR) (Figure 5). 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.

$$M_* \propto V_{rot}^\alpha \quad (7)$$

α was found to be 3.7 (Tully and Fisher 1977). Later work has found α to lie between 3 and 4 (Lelli et al. 2019; Bloom et al. 2017).

This relation is a great tool for estimating the distance to a galaxy, as the predicted total luminosity can be compared to the apparent magnitude at Earth. For numerical simulations, being able to reproduce the TFR is an essential way to check if the model is reliable.

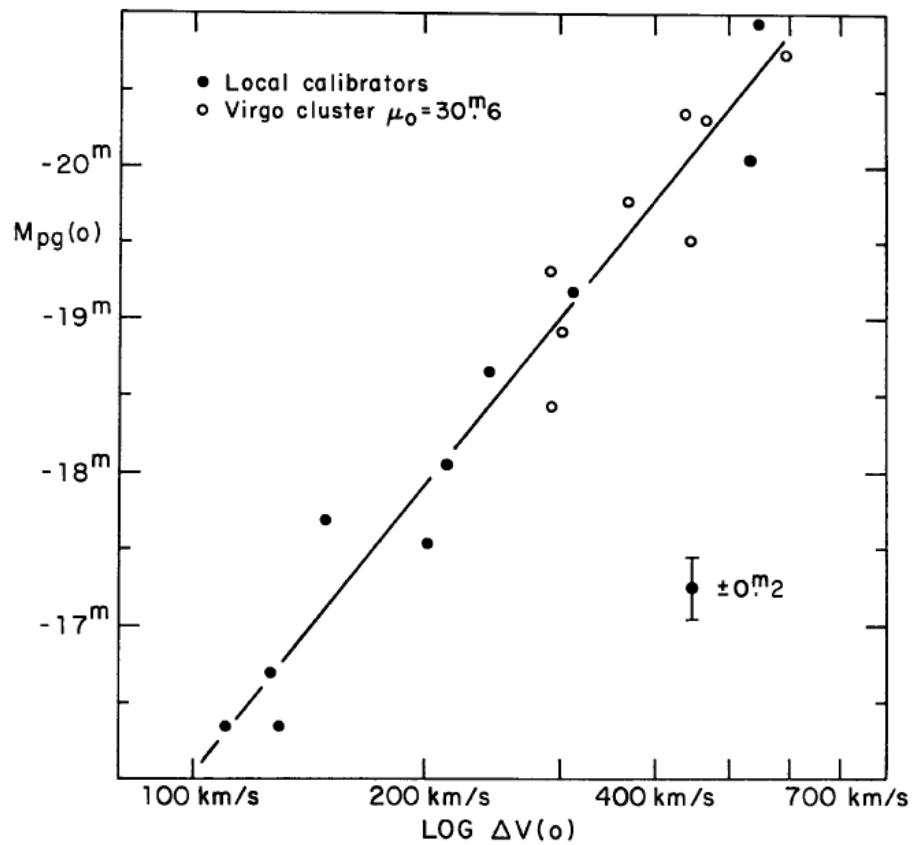


Figure 5: The original figure from the 1977 paper by R.B. Tully and J.R. Fisher, showing the linear fit for the luminosity - velocity values in the log-log plane. Credit: Tully and Fisher (1977)

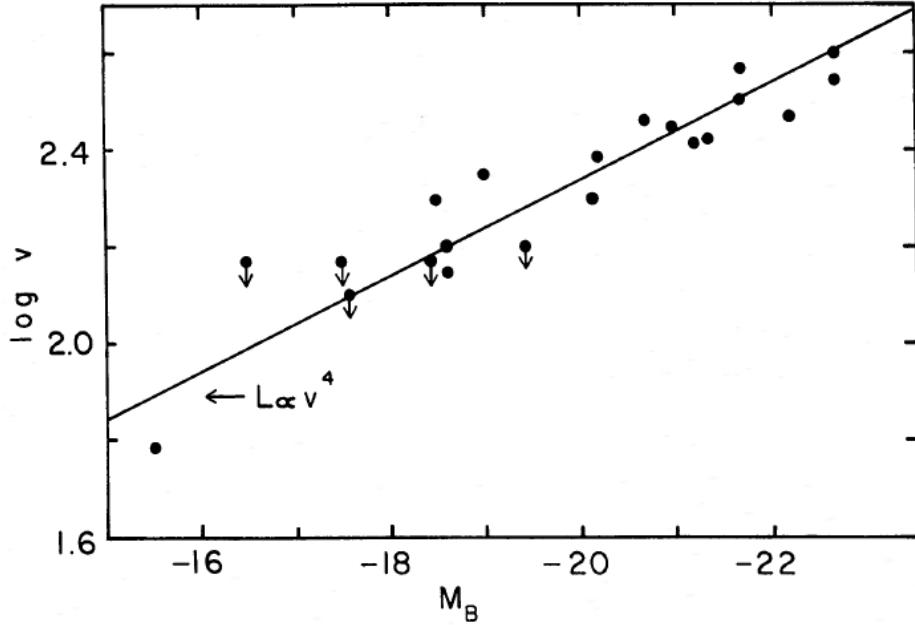


Figure 6: The original fit for the Faber-Jackson relation as presented in the 1976 paper. It shows the velocity dispersion as function of the luminosity in the log-log plane (dots), along with a power law with index 4 (solid black line). Credit: (Tully and Fisher 1977)

2.3.2 The Faber-Jackson relation and the Fundamental Plane

At around the same time Tully and Fisher (1977) linked the velocity dispersion and luminosity of early type galaxies. The proposed relation was on the form of a power law as well,

$$L \propto \sigma^\gamma, \quad (8)$$

with a power law index γ of approximately 4 (Figure 6).

This is known as the Faber-Jackson (FJ) relation. The scatter in the FJ relation was larger than that found for the TFR however, and it was later found that the velocity dispersion was dependent on the size of the galaxy. This dependency also took the form of a power law, and so the velocity dispersion is more accurately described by the function

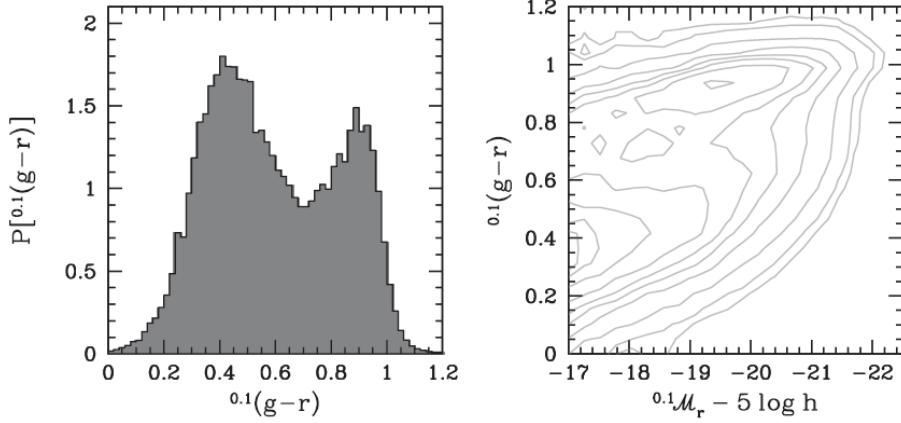


Figure 7: To the left: The probability density of the colors for over 350 000 galaxies in the Sloan Digital Sky Survey. To the right: The color-magnitude contour map for the same galaxies, clearly showing two distinct populations. Credit: Mo et al. (2010)

$$\sigma \propto L^a R^b. \quad (9)$$

With the radius added into the equation, the scatter became much less significant. Most ellipticals are found on the same plane in σ, R, L space. This became known as the Fundamental Plane (FP) (Djorgovski and Davis 1987), and is also something which successful 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 or red (see Figure 7). The blue galaxies are most often late type galaxies, while the red ones are mainly early types. 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.

3 Method

3.1 IllustrisTNG

IllustrisTNG ¹ is the follow-up project after the success of the Illustris simulations (Springel et al. 2017; Pillepich et al. 2017; Naiman et al. 2018; Nelson et al. 2017; Marinacci et al. 2018). 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). Adding physical processes like gas radiation, star formation, stellar feedback through supernova explosions, supermassive black hole accretion and magnetic fields is essential to model galaxy formation and evolution and allows for a much better comparison to reality compared to dark matter-only simulations. The data output from the simulations is extensive, and is not meant to be analyzed all in one go, but rather through a series of analyzes, each targeting a specific scientific question.

Hydrodynamical cosmological simulations are used to predict the movements and interactions between different types of particles in a cosmological box, and follow these through time steps as the simulation progresses. In the end, the simulation gives information about the final particle positions and properties. The simulation does not know about halos, so the raw data must be processed to extract information about separate halos and galaxies. To identify which particles belong together as one halo, their closeness has to be examined, as well as their velocities to see if their kinetic energy is enough to make them gravitationally unbound.

SUBFIND is an algorithm developed by (...Springel et al 2001) for identifying halos and subhalos. It first defines parent halos with a Friends-Of-Friends algorithm, which determines halos by the proximity of the particles only. It then looks at the halo's density fields and separates out subhalos. Finally physically unbound particles (those with positive total energy) are removed. Subhalos identified to reside inside a larger subhalo are counted as a separate subhalo, and thus its particles are not part of the parent subhalo. The relative mass of a parent subhalo and any subhalos contained within it is usually such that the impact of removing the latter is minimal with respect to any properties of the former.

¹<https://www.tng-project.org/>

Table 2: The simulation details for the three main TNG simulations. N_{DM} is the amount of dark matter particles. m_{DM} and m_{baryon} is the mass of the dark matter and baryonic particles, respectively.

	Volume [Mpc^3]	N_{DM}	$m_{DM} [M_\odot]$	$m_{baryon} [M_\odot]$
TNG50	51.7^3	2163^3	4.5×10^5	8.5×10^4
TNG100	110.7^3	1820^3	7.5×10^6	1.4×10^6
TNG300	302.6^3	2500^3	5.9×10^7	1.1×10^7

3.1.1 The simulations

The IllustrisTNG project includes 18 different simulations with varying resolutions, spatial size, and included physics. There are three main simulations, TNG300, TNG100, and TNG50, that differ in volume and resolution. The details of these are summed up in Table 2. Each of the main simulations has been run at three different resolution levels, which makes it possible to study how the outcome is affected by changing only the resolution in a given simulation. TNG100 has a physical box volume of $110.7^3 Mpc^3$, and a baryonic particle resolution of $1.4 \times 10^6 M_\odot$, while the TNG300 simulation has a volume of $302.6^3 Mpc^3$ and a baryonic particle resolution of $1.1 \times 10^7 M_\odot$. The newly released third simulation, TNG50, has a smaller volume of $51.7^3 Mpc^3$, but with a much higher baryonic particle resolution of $8.5 \times 10^4 M_\odot$.

In this project, a large statistical sample of galaxies was needed, as well as a resolved structure of the inner part of the galaxies to calculate the different properties, so the TNG100 simulation was the best choice with respect to size and resolution. The TNG100-1 simulation data, which is the highest available resolution for TNG100, has been used throughout the project and will from now on be referred to as TNG only. A visual representation of parts of the simulations can be seen in Figure 8. For its cosmology parameters TNG uses the results from the Planck Collaboration, which are given by $\Omega_{\Lambda,0} = 0.6911$, $\Omega_{m,0} = 0.3089$, $\Omega_{b,0} = 0.0486$, $\sigma_8 = 0.8159$, $n_s = 0.9667$ and $h = 0.6774$ (Planck Collaboration et al. 2016).

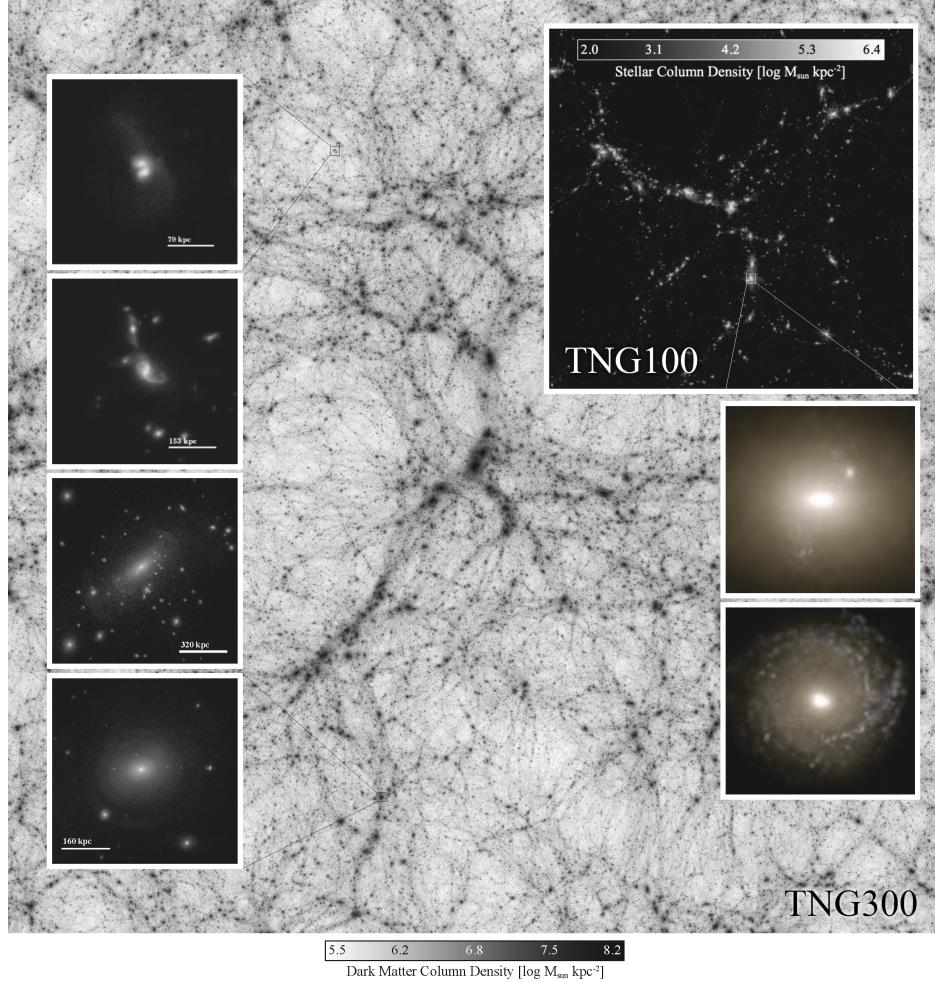


Figure 8: A composite image that illustrates the two simulations TNG100 and TNG300. In the background is the dark matter distribution for the whole TNG300 volume. In the upper right is the stellar mass distribution across the entire TNG100 volume. The panels on the left show galaxy-galaxy interactions, while the panels on the right show the stellar light projections of two $z = 0$ galaxies. Credit: TNG Collaboration

3.1.2 Data products

All the Illustris-TNG data is publically available online at the TNG web-page². The data products that are available for each simulation are snapshots, group catalogs, and merger trees as well as some supplementary data sets. There are five different particle types in the simulations, and each has its properties stored as particle fields. These fields include information like position, kinematic data, and chemical composition. For each different run of the simulation, 100 snapshots are created, which are taken at specific redshifts. They include all the particles in the whole volume of the simulation, with 20 of them including all the fields for each particle as well.

The group catalogs provide a convenient way to quickly access already calculated properties of the different halos and subhalos instead of dealing with all the particles in a snapshot. This saves a lot of time and effort but gives the user less control over what can be analyzed. There is one group catalog for each snapshot, and this includes two types of objects, Friends-of-Friends (FoF) and SUBFIND. The FoF catalog contains all the halos, and the SUBFIND catalog contains all the subhalos and their associated galaxy (if there is any) for each halo. Each subhalo has a parent halo, and the largest subhalo in each halo is the central subhalo. The merger trees data products contain the merger history of each subhalo.

This project makes use of the group catalogs and particles for the $z = 0$ snapshot.

3.1.3 Sample reduction

The TNG documentation recommends filtering out all subhalos that are flagged with the *SubhaloFlag* field, and so these were cut from the data. They are most probably subhalos of non-cosmological origin, and so should not be considered real galaxies.

For this project, only the central galaxies in each halo are selected. 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.

²<https://www.tng-project.org/data/>

Only galaxies with stellar mass greater than $10^{9.5} M_{\odot}$ are used, which corresponds to about 4500 stellar particles.

3.2 Observational data

When possible, it is good practice to use the same observational data for comparisons with the simulation data. Trying to accomplish this, in the the SAMI Galaxy Survey (Bryant et al. 2015) has been used throughout this work. For the SHM relation however, it was not possible to use the SAMI data set, so other works have been chosen to use for that comparison. All the data sets and best fits used in comparing the results from TNG to observations are described in this section.

3.2.1 SAMI Galaxy Survey

The Sydney–Australian Astronomical Observatory Multi-Object Integral Field Spectrograph (SAMI) is mounted on the Anglo-Saxon telescope in Australia. The SAMI Galaxy Survey ³ is a spectroscopic survey of a large sample of galaxies in the nearby Universe ($z < 0.113$). The survey was started in 2013, and ended in 2018. There have been two major data releases, with the newest being Data Release Two (DR2) (Scott et al. 2018). DR2 includes data for 1559 galaxies, which is about 50 % of the full galaxy survey. The data products available are IFS data cubes and 2D maps, as well as catalogue data. As the same galaxies have been catalogued in several other studies, data products from those studies are added to SAMI data. Analysing data cubes and 2D maps falls outside the scope of this work, so catalogue data is used where possible.

3.2.2 Other data sets

For the SHM relation, best fit models from two different abundance method papers were used in the comparison to TNG.

The first one found a fit to the data by using a power law for the high mass end, and a subpower law for the low mass end (Behroozi et al. 2013).

$$\log(M_*(M_{halo})) = \log(\epsilon M_1) + f(\log(M_{halo}/M_1)) - f(0), \quad (10)$$

³<https://sami-survey.org/>

$$f(x) = -\log(10^{\alpha x} + 1) + \delta \frac{(\log(1 + \exp(x)))^\gamma}{1 + \exp(10^{-x})}.$$

Here M_1 is a characteristic halo mass, δ is the strength of the subpower law, α is the power law slope for $M_{halo} << M_1$ and γ is the power law index for $M_{halo} >> M_1$. The best fit values for the parameters are $M_1 = 11.514 \pm (0.053, 0.009)$, $\delta = 3.508 \pm (0.087, -0.369)$, $\alpha = -1.412 \pm (0.020, -0.105)$, $\epsilon = -1.777 \pm (0.133, 0.146)$ and $\gamma = 0.316 \pm (0.076, -0.012)$.

The second one employed the same function for the fit as Behroozi et al. (2013), but with different data. The best fit parameters were found to be $M_1 = 11.632 \pm (0.008, 0.009)$, $\delta = 3.797 \pm (0.026, 0.021)$, $\alpha = -2.352 \pm (0.026, -0.021)$, $\epsilon = -1.785 \pm (0.010, 0.008)$ and $\gamma = 0.600 \pm (0.10, 0.013)$ (Zanisi et al. 2019).

3.3 Calculating properties

3.3.1 Cosmologies and h-dependence

When making measurements of galaxy properties, some assumptions about the underlying cosmology of the Universe must be made. One of these assumptions is the value of the Hubble constant H_0 , more commonly represented by h , where $H_0 = 100 h$ km/s/Mpc. In addition to several other cosmological parameters, this constant is used when running a cosmological simulation. Astrophysical properties, both numerical and observational, are presented in publications with an h -dependence (leaving the user to specify the cosmology) or without an h -dependence (by assuming a value for h).

For IllustrisTNG, $h = 0.6774$ and the explicit h -dependence of each property value is stated clearly in the documentation. For the SAMI data catalogue, no h -dependence is explicitly stated in the documentation or data release papers, but the Hubble constant used is given as $h = 0.7$.

Best practice dictates that to compare works with different assumed Hubble constants, the h used in those specific works should be replaced with the most recent value for h (Croton 2013). The values for galaxy properties will then be comparable. In Table 3 the h -dependency of the galaxy properties of TNG as well as the common h -dependencies for observational data is shown along with their corresponding units. In this work, all data results are converted

Table 3: The h -dependence and units for the galaxy properties used in this work. For TNG, the dependency is given in the data documentation. The dependencies for SAMI are the standard dependencies for observational data, as found in Table 2 in Croton (2013).

	TNG	SAMI
Stellar mass	$M_{\odot}h^{-1}$	$M_{\odot}h^{-2}$
Halo mass	$M_{\odot}h^{-1}$	-
Size	$\text{kpc } h^{-1}$	$\text{kpc } h^{-1}$
Luminosity	mag	mag +5 log(h)
Velocity	km/s	km/s

to the TNG cosmology, which uses the newest values for the cosmological parameters.

3.3.2 Galaxy sizes

When observing galaxies with telescopes, there is always the problem of contamination of the measurements by surrounding sources as well as background radiation. As such, when the images are processed, aperture sizes have to be chosen with care for each identified galaxy. A larger aperture will be sure to contain most of the light from the galaxy but might overshoot by including surrounding light as well. However, choosing a too small aperture will result in lost data, and as such a smaller apparent galaxy. Usually a circular or elliptical aperture with a calculated radius to balance these two issues is chosen.

In simulations, we are not limited by hardware, attenuation, and background light. A cut-off point still needs to be determined. `SUBFIND` does this for the dark matter part of the simulation, separating out subhalos from larger halos. The galaxy properties of that subhalo are then calculated using all the stellar and gas particles in the subhalo and saved in the group catalog.

When comparing simulation data to observational data, there are many ways to emulate the finite size of observed galaxies. Calculating luminosities and selecting a cut-off point at the faint end, using a spherical volume with a radius that is a multiple of their particular effective radius, or a fraction of the virial radius of the parent subhalo are some of the most commonly employed methods. For this work, the galaxy size is chosen to be a spherical

volume with a radius (R_{gal}) equal to 15 % of the subhalo’s virial radius (R_{200}).

3.3.3 Magnitude and colors

The absolute magnitude (\mathcal{M}) is a measure of the total luminosity (L) of the galaxy such that $\mathcal{M} = -2.5 \log(L/L_\odot) + \mathcal{M}_\odot$, where L_\odot is the solar luminosity and \mathcal{M}_\odot is the solar magnitude.

For the SUBFIND group catalog, the `SubhaloStellarPhotometrics` field gives the magnitudes based on the summed up luminosities of all the stellar particles in the Subhalo. The particle luminosities are determined by summing the luminosities within R_{gal} . Eight bands are available, but here only the g- and i-band are used.

The g-i colors for the particles are calculated by simply subtracting the i-band magnitude from the g-band magnitude.

In SAMI, g-i color values are adopted from the GAMA Sérsic catalogue (Driver et al. 2011).

3.3.4 Masses

Stellar mass estimates depend on the stellar initial mass function (IMF), which describe the spectral evolution of a population of stars, and as such the relationship between luminosity and mass in a given spectral band. SAMI and TNG both adopt a Chabrier (2003) IMF.

In SUBFIND, masses for each particle type are calculated by summing up all the masses of that particle type belonging to the subhalo. Values for the mass within the stellar half-mass radius, two times the stellar half-mass radius and the radius at which the maximum rotational velocity is found are also available.

The stellar masses of the galaxies studied using the particles are the summed up masses of all stellar particles within R_{gal} .

For SAMI DR2, the stellar mass values are taken from the GAMA Sérsic catalogue (Driver et al. 2011). They calculate the stellar masses by using the i-band magnitude and g-i color of each galaxy through the formula $\log(M_*/M_\odot) = 1.15 + 0.70(g - i) - 0.4\mathcal{M}_i$, where \mathcal{M}_i is the rest-frame i-band absolute magnitude (Taylor et al. 2011).

3.3.5 Size

In observational data, galaxy sizes are always projected sizes, as they are derived from 2D images. A common measure of the size of a galaxy is the effective radius, which is the radius within which half the light of the galaxy is contained. This quantity depends on the analysis and quality of the 2D profiles, and may not be able to include all the light in a galaxy in the way that we can ensure for computer simulated data. The radius also depends on which optical filter the measurements are made in, as different filters will be receptive to light from different parts of the galaxy.

For TNG data, the `SubhaloHalfmassRadStellar` field has been used. The half-mass radius is the radius of a spherical volume within which half the stellar mass is found. It is the 3D half-mass radius (R_{hm}), as it is not a projected quantity. This value is generally higher than the 2D half-light radius (r_{hl}) for a given mass up to $M_* < 10^{10.5}$, as seen in Genel et al. (2017).

The half-mass radii of the galaxies calculated using the particles are derived using the same method, but using only the total stellar mass calculated within R_{gal} .

To be consistent with observed data, the 3D radius from the simulation is projected by using the relation $R_{hm} = \frac{4}{3}r_{hm}$ which generally holds for pressure supported systems like elliptical galaxies (Wolf et al. 2010).

The SAMI catalog data takes the values for the effective radius from the GAMA Sérsic catalogue (Driver et al. 2011). The effective radius is defined as the semi-major axis half-light radius, measured in the r-band. The values are given in units of arcsec which were then converted to a physical radius in kpc.

Then these semi-major axis radii are converted to circular radii using the formula

$$r_{circ} = r_{sm} \sqrt{(1 - \epsilon)}, \quad (11)$$

where r_{circ} is the circular radius, r_{sm} is the semi-major axis effective radius and ϵ is the eccentricity.

3.3.6 Velocities

Galaxy velocities are usually given by the velocity dispersion and rotational velocity for early and late-type galaxies, respectively. This is because of the difference in the shape of the two galaxy types. It makes more sense to talk about velocity dispersion in a spheroidal pressure-dominated system and rotational velocity in a rotating disk.

In SUBFIND, the field `SubhaloVMax` gives the maximum value for the spherically averaged rotation curve of a given galaxy. As the rotational curves are nearly flat for large enough radii, it should not be very important at which specific radius the observational rotational velocity is measured, as long as it is in the flat part of the curve. For observational data, a common practice is to look at the rotational velocities of stars in the outer part of the galaxy.

Rotational velocities were not available as SAMI catalogue data, but an extensive analysis of the 2D velocity maps in DR2 is found in Bloom et al. (2017). They defined the rotational velocity as the velocity at $2.2 r_e$, which should be in the flat regime of the velocity curve, and coincide well with the maximum velocity. Their best fit for the TFR was used in our comparison,

$$\log(V_{rot}) = 0.31 \pm 0.0092 \times \log(M_*) - 0.93 \pm 0.1. \quad (12)$$

//To compare with SUBFIND's `SubhaloVMax`, the rotational velocity at a radius of $2.2 \times R_e$ was calculated for all galaxies.

In observations, the only velocities of the components of a galaxy we can measure are the line-of-sight velocities. These are calculated using the observed Doppler shift in the galactic spectrum. The velocity dispersion of a galaxy is then defined as the standard deviation of the line-of sight velocities.

$$\sigma^2 = \frac{1}{N} \sum_{n=1}^N (V_i - \bar{V})^2 \quad (13)$$

If the velocity dispersion tends to fall off at larger radii, and the galaxy has an ellipsoid shape, the angle at which the galaxy is viewed will affect the observed velocity dispersion. To compensate for this when comparing simulations to observations, velocity dispersions in simulations may be calculated in three different projections of the galaxy and averaged over these.

Table 4: Gas fraction.

	SUBFIND		Particles	
	Early-type	Late-type	Early-type	Late-type
Half-mass radius	2024	3409	2065	3368
2 × half-mass radius	1446	3987	1532	3901
15% R_{200}	-	-	619	4814
$R_{subhalo}$	40	5393	-	-

$$\sigma^2 = \frac{1}{3}(\sigma_x^2 + \sigma_y^2 + \sigma_z^2) \quad (14)$$

In SUBFIND, the velocity dispersion is simply calculated as the velocity dispersion of all the particles over the entire subhalo.

In SAMI catalog data, the given velocity dispersion is averaged within an aperture with radius equal to the effective radius of each galaxy.

With the particles the velocity dispersion was calculated within the projected half-mass radius in three orthogonal projections.

3.4 Galaxy morphology classifications

Starting off with the same subset of 5433 galaxies for both the SUBFIND group catalogue and the particles, we get different results for which galaxies are early- and late-type galaxies, based on the volume in which the gas mass is measured. Table 4 show the number of early and late type galaxies for different volumes.

The selection is here very similar whether SUBFIND or particles are used. For SUBFIND we get 1028 early-types, 3874 late-types and 531 intermediate types, while for the particles we find 1040 early-types and 3858 late-type galaxies with 535 intermediate types.

By using the simple cut at $\kappa_{rot} = 0.6$ the 5433 galaxies are then separated into 3970 early type galaxies and 1463 late types. This is a completely different result from the two methods above, where there was a majority of late-type galaxies. In real life we know that smaller late-type galaxies dominate, so using only the rotational energy does not yield the expected ratio. However,

combining this result with one of the two above should result in a subset of galaxies which exhibit both the right amount of cold gas and the star formation that goes with it, as well as the right kinematic structure.

In the rest of this paper, early-type galaxies are those which, calculated using the particles, have a sSFR of $\log(sSFR[Gyr^{-1}]) < -1.94$ as well as $\kappa_{rot} < 0.6$. Late-types have a sSFR of $-1.44 < \log(sSFR[Gyr^{-1}]) < -0.44$ as well as $\kappa_{rot} > 0.6$. This results in 925 early-type galaxies, 1227 late-types and 3281 intermediate-type galaxies. For the SUBFIND sample, the same galaxies in each group are chosen by matching the subhalo-id from the previously mentioned selection.

4 Results and discussions

4.1 Stellar mass and half-mass radius

Using the cut in galaxy size described in section 3.3.2 with $R_{gal} = 0.15 \times R_{200}$ the stellar mass in galaxies are found to be similar to those of SUBFIND up to about $M_* = 10^{10.5} M_\odot$. For more massive galaxies, the stellar mass becomes rapidly smaller compared to those of SUBFIND, reaching a fractional difference of almost 15% at $M_* > 10^{11} M_\odot$. This of course translates into a difference in half-mass radii as well, although this trend is even steeper. For stellar masses larger than $10^{11} M_\odot$ the stellar half-mass radius is over 20% smaller. Plotting the stellar mass as a function of the half-mass radius for both SUBFIND and the particles, it is clear that in the high-mass end of the spectrum the latter has a higher slope. As these galaxies are expected to be mostly early types, we might then experience a change in the slope of the fundamental plane.

4.2 Kinematics

Looking at the velocity dispersion for early type galaxies, there is a significant scatter about the one-to-one line. For the stellar mass range of $10^{10} M_\odot < M_* < 10^{11} M_\odot$, the velocity dispersions calculated using the particles are both smaller and larger than those found by SUBFIND. At larger masses, the velocity dispersion is smaller. Now there are several variables which might affect this result. Firstly the galaxy size compared to using the entire subhalo, and secondly the method of simulating the projected velocity dispersion.

We have therefore calculated the velocity dispersion for the entire subhalo using the projection method and also calculated it within the galactic radius without projection.

The rotational velocities at a radius of $2.2 \times R_e$ for late-type galaxies is behaving entirely as expected. It is similar to that of SUBFIND, just slightly smaller.

4.3 Color bimodality

Completely similar.

5 Conclusions

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