Large Ultra-Faint Galaxies in the Firebox Simulation

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Abstract

Executive Summary

Acknowledgments

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Chapter 1

Introduction

Understanding the composition and structure of galaxies and the role that dark matter plays in their organization is one of the most pressing topics in modern intergalactic physics. A common method to explore these questions is using simulations. A simulation allows us to choose plausible initial conditions and plausible laws of physics and test how the universe would behave under those conditions. We can then compare those results to experimental data to examine the accuracy of those initial assumptions. For instance, if we wanted to test Newton's theory of gravity in our solar system, we could run a numerical simulation of Newton's equation, starting from a past known position of the planets, and test whether or not the simulated motion of the planets aligns with our real astronomical observations. Likewise, we can test our theories about dark matter and gravity by running galaxy simulations.

1.1 Physical Models

Our current leading theory for dark matter's role in galaxy evolution is the Dark Energy and Cold Dark Matter (ΛCDM) model (Sales et al. (2022)). This theory provides a framework for physical simulation that incorporates a non-interacting ("cold") model for dark matter and the cosmological constant model of dark energy. Dark matter is assumed to not interact with either itself or "normal" baryonic matter, except through gravity. Such a model leads to large dark matter halos around galaxies that do not collapse into disks, which is consistent with observational data (Feldmann et al. (2022)). Since not much else is known about dark matter, and we have yet to find a non-gravitational interaction between dark matter and baryonic matter, this assumption is widely accepted in practice. Likewise, Feldmann et al. (2022) assumes dark energy to be the cosmological constant Λ, which is a degree of freedom in in the Einstein Equation that adds a net offset to the energy density of a vacuum. While the cosmological constant model of dark energy is quite popular and consistent in most ways with observational data, it is not the only model of dark energy. Bassi et al. (2023) pose an alternative: the Bimetric gravity model. This theory hypothesizes that the graviton—the theoretical particle that causes gravitational interactions—has mass. Bassi et al. (2023) show that a graviton with a non-zero mass could cause a net pressure in the vacuum, negating the need for the cosmological constant. They argue that the Bimetric theory of gravity could also resolve the Hubble Tension. This is an inconsistency between the measurement of the Hubble Constant at large and small scales (Sen et al. (2022)), a calculation that relies on the cosmological constant being just that: a constant. If more evidence can be found in support of it, the Bimetric model may replace the ΛCDM model, but for now the latter is still the most widely used.

When creating a galaxy simulation, physicists must also incorporate baryonic processes, the physics of ordinary matter. Baryonic properties incorporated into galaxy simulations may include gas density, pressure, temperature, star formation rate. Our current computers limit us such that we cannot simulate the behaviors of individual stars within a galaxy (Feldmann et al. (2022)) because there are simply too many. Past simulations such as Bournaud et al. (2010) were forced to ignore stellar processes in favor of gaseous ones. They found that the simulated galaxies grew too massive and cooled too quickly compared to real galaxies. This tension was resolved by the creation of the Feedback in Realistic Environments (FIRE) physics model (Hopkins et al. (2018)). FIRE estimates the rate at which stars are forming within each gas particle without actually simulating their creation. It assumes an average amount of wind and thermal energy a star will produce. It then uses the estimated number of stars in each particle to simulate stellar feedback.

1.2 Dwarf Galaxies and their Tensions

Until recently, dwarf galaxies have not been closely studied due to them being difficult to detect with telescopes. For a period of time, the ΛCDM model was questioned because it predicted the existence of many more dwarf galaxies than had been observed in the region around the Milky Way (Sales et al. (2022)). According to Sales et al. (2022), enough dwarf galaxies have been discovered in recent years to resolve this tension. Unfortunately, the sudden influx of dwarf galaxy observations has provided theorists with more questions than answers.

As one would expect, the simulation results that predicted these galaxies' existence do not always line up with the observations. There are a number of new tensions between the two.

The diversity of the size-mass relation of dwarf galaxies is one such tension. Observational data of dwarf galaxies near the Milky Way suggests that the correlation between the mass and size of satellite dwarf galaxies is not as strong as simulations seem to predict (Sales et al. (2022)).

1.3 Put this somewhere

It is a common myth that if we can simulate something, we must be able to fully understand it. Unfortunately, this is not generally true. The galaxy simulations we use are so complex and detailed that it is often very difficult to determine what physical assumptions or initial conditions cause certain behaviors. While it is much easier to make collect data from simulations—we do not need telescopes and we can view the galaxies in 3D with arbitrary resolution—we must still analyze that data using similar techniques used to study real galaxies.

If it is demonstrated that one of these tensions is caused by neither numerical approximations in the simulations nor simplifications of baryonic physics, then it could call the ΛCDM model into question.

1.4 Size-Mass Ratio

One such tension according to Sales et al. (2022) is the overall diversity of the diffusion of dwarf galaxies. The observed dwarf galaxies near the Milky Way (MW), have a wide variety of radii sizes compared to their masses. In other words, it is common for both diffuse and compact dwarf galaxies to form in real life. However, galaxy simulations including Fitts et al. (2017) tend to form dwarf galaxies with much tighter size-mass ratios (Sales et al. (2022)). Some may argue that these discrepancies are caused by numerical inaccuracy. However, even the simulations with the highest numerical resolution such as Wheeler et al. (2019) lack a deviation in size-mass ratios for dwarf galaxies.

The diversity of sizes of dwarf galaxies must therefore be caused by something else. Tidal disruption could be an answer. When a dwarf galaxy interacts with a larger galaxy, its dark matter halo can be removed by the gravitational tidal force exerted on it, according to Moreno et al. (2022). This can, in turn, lead to the creation of a compact or ultra-compact dwarf (Applebaum et al. (2021)), because only its core will remain gravitationally bound. According to Sales et al. (2022), the baseline for the size of dwarf galaxies is generally believed to be stellar feedback, which causes galaxies to grow. The true effect size of stellar feedback on dwarf galaxy size is not known within the range of sizes. Therefore, a large enough effect size from stellar feedback coupled with common enough tidal disruption could pose an explanation for diffuse galaxies.

1.5 FIREbox Galaxy Simulation

The FIREbox (Feldmann et al. (2022)) simulation is the most in-depth galaxy simulation ever performed as of the date of this thesis. It does not have the largest volume, nor is it the most detailed; sub-simulations such as FIRE in the Field (Fitts et al. (2017)) zoom in closer, to a particle size as low as 500 solar masses. FIREbox, however, has the total combined resolution and incorporates a balance of detail and scale.

Scale and resolution are an important component of galaxy simulations. Previous iterations of galaxy simulation needed to choose between larger volume and higher resolution. The large volume simulations allow scientists to closely study the interactions between galaxies and systems of galaxies, and to collect large amounts of statistical information about these galaxies (Feldmann et al. (2022)). However, the large resolution sacrificed physics accuracy and therefore realism; a higher resolution "zoom in" simulation allows us to better simulate the internal physics of the galaxies themselves (Feldmann et al. (2022))

Chapter 2

Methods

2.1 The Data

Over the course of the evolution of the FIREbox simulation, 1201 snapshots of the state of the universe were collected (Feldmann et al. (2022)). They were approximately evenly spaced out in time and included the positions of the particles, their densities, metalicities, star-formation rates, and other properties. The particle data was reduced by grouping the particles into their respective galaxies and dark matter halos. They used the AMIGA Halo Finder (AHF; Knollmann and Knebe (2009)) to sort the halos into categories of halos and sub-halos, which in turn allowed them to categorize the galaxies by host and satellite galaxies respectively. The reduced data, known as the galaxy and halo catalog, includes galaxy information such as position, radius, mass and star formation rate, as well as data about the dark matter halos around those galaxies. For the extent of this experiment, we will be using the snapshot 1201, the final state of the simulation. This snapshot depicts the simulated present day.

Each parameter for the galaxies is split between a few different definitions. For the purpose of this experiment, we will use the following definitions unless otherwise specified. The galaxy's radius R_{50} is defined to be the radius that contains 50% of its stars, as determined by AHF. The galaxy's mass M_* is defined to be the mass of the stars contained within R_{50}. We are not going to include dark matter in this definition. The reader should note that this is not the only way to define these parameters. Due to the fluid nature of matter on a galactic scale, it is often arbitrary as to whether a given particle belongs to a given galaxy. Alternate definitions include different thresholds for the radius, such as R_{80}, and different kinds of matter included in the mass, such as gas matter and dark matter.

Other parameters that we will use are a galaxy's position in space and its flyby distance—a satellite galaxy's minimum distance to its host galaxy. All distances (including radius) are measured in terms of the co-moving parameter h, a time-dependent scaling factor of the universe. In the final state of FIREbox, $h = 0.6774kpc$.

McConnachie (2012) compiled a number of data sets for dwarf galaxies in the local group of the Milky Way. One data set includes the galaxies' radii and another contains their mass. The radius is defined slightly differently in this case. It is the half-light radius, the radius from which half of the galaxy's light is emitted. The mass parameter is calculated by assuming a mass-light ratio of one, meaning that the brightness per unit mass is equal to the Sun. For the sake of this experiment, we will assume that the half-light radius is equal to R_{50} the presumed M_* is equal to M_*. To get this data in a usable form, I first dumped the text-based datasets into pandas spreadsheets. I removed invalid rows and then merged them by galaxy name. For galaxies whose names were reported differently on the different sheets, I merged them by hand. I then cast the mass and radius to float64 for use in the analysis.

2.2 The Diffusion Parameter

As diffusion will be main subject of this paper, let us define it. The dwarf galaxies in FIREbox loosely follow a power law size-mass relationship (see figure 2.3). The relationship can therefore be described using the following equation.

$$\frac{R_{50}}{1kpc} \approx a \left(\frac{M_*}{M_\odot}\right)^\gamma \tag{2.1}$$

Where γ and a are constants and $M_\odot$ is the mass of the sun. We are dividing by a kiloparsec unit to make the equation unitless. Taking the logarithm of this equation gives us

$$\ln\left(\frac{R_{50}}{1kpc}\right) \approx \ln(a) + \gamma \ln\left(\frac{M_*}{M_\odot}\right) \tag{2.2}$$

By taking the logarithm of a power law, we end up with an equation for a line. This linear relationship can be seen in figure 2.3. $ln(a)$ becomes the y-intercept of the line and γ becomes the slope. We have kept denoting this equation as *approximately* equal in order to emphasize that not every galaxy falls exactly into this relationship. However, we can replace that by introducing a galaxy-specific parameter β that is defined to be the galaxy's deviation from this linear relationship.

$$\ln\left(\frac{R_{50}}{1kpc}\right) = \ln(a) + \gamma \ln\left(\frac{M_*}{M_\odot}\right) + \beta \tag{2.3}$$

$$\beta \equiv \ln\left(\frac{R_{50}}{1kpc}\right) - \ln(a) - \gamma \ln\left(\frac{M_*}{M_\odot}\right) \tag{2.4}$$

We will call β the **diffusion parameter**, because it tells us how diffuse a galaxy is relative to its fellow galaxies. Positive values of β mean that the galaxy has a larger radius than other galaxies of the same mass, and negative values mean a smaller radius. β is especially useful for characterizing the diffuseness because the distribution of β remains consistent across all

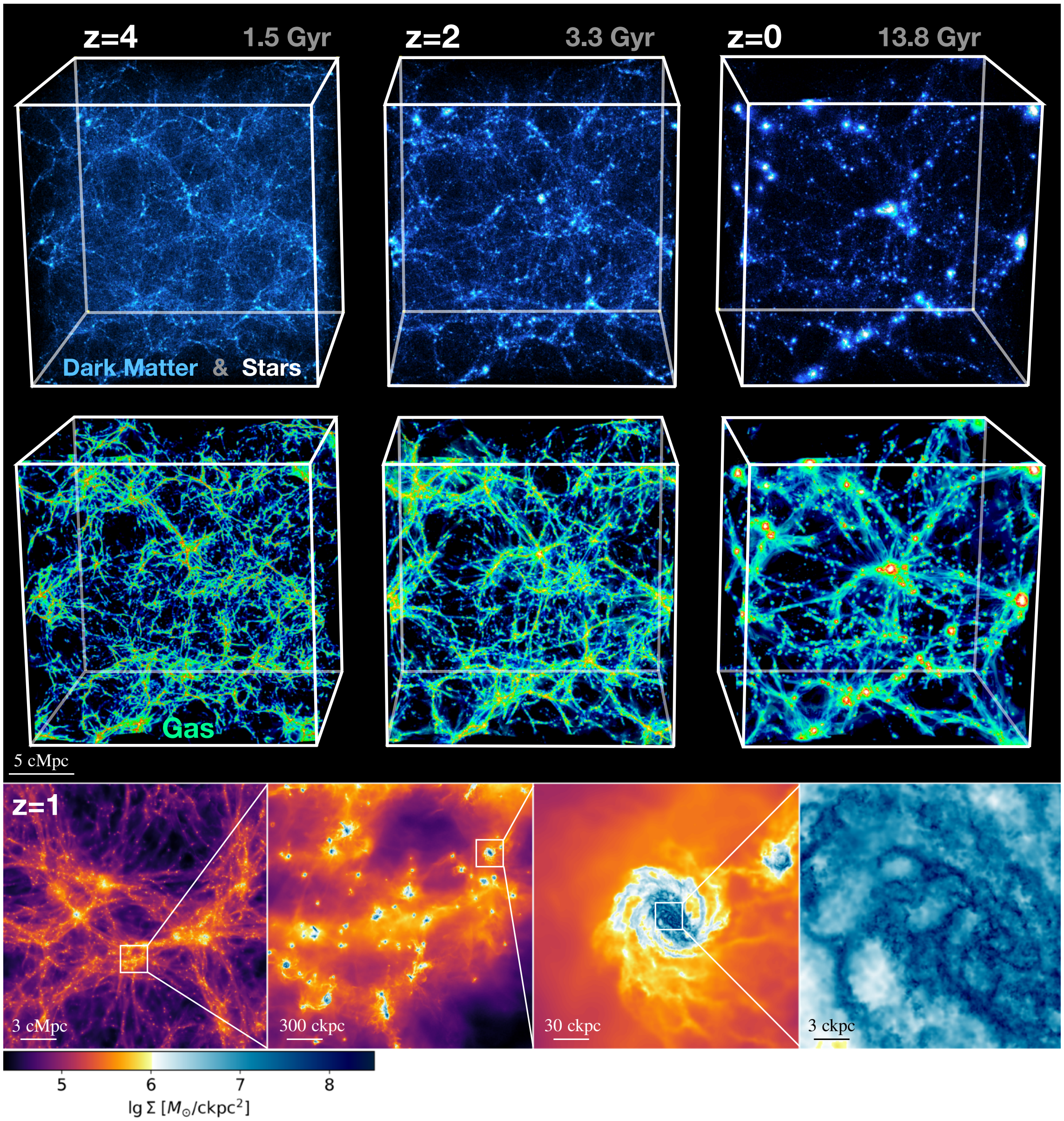

Figure 2.1: From: Feldmann et al. (2022). A representation of the FIREbox simulation. The first two rows depict the state of the simulation at three different time points; the rightmost images depict the simulation in the present time. The top row depicts dark matter in blue and stellar matter in white, while the middle row depicts gas. The bottom row shows a galaxy at different scales within a cluster. As we can see, matter collects into galaxies and systems of galaxies over the course of the simulated universe's evolution. These galaxies take on a variety of sizes, and they share threads of gas and are contained within hierarchical halos of dark matter.

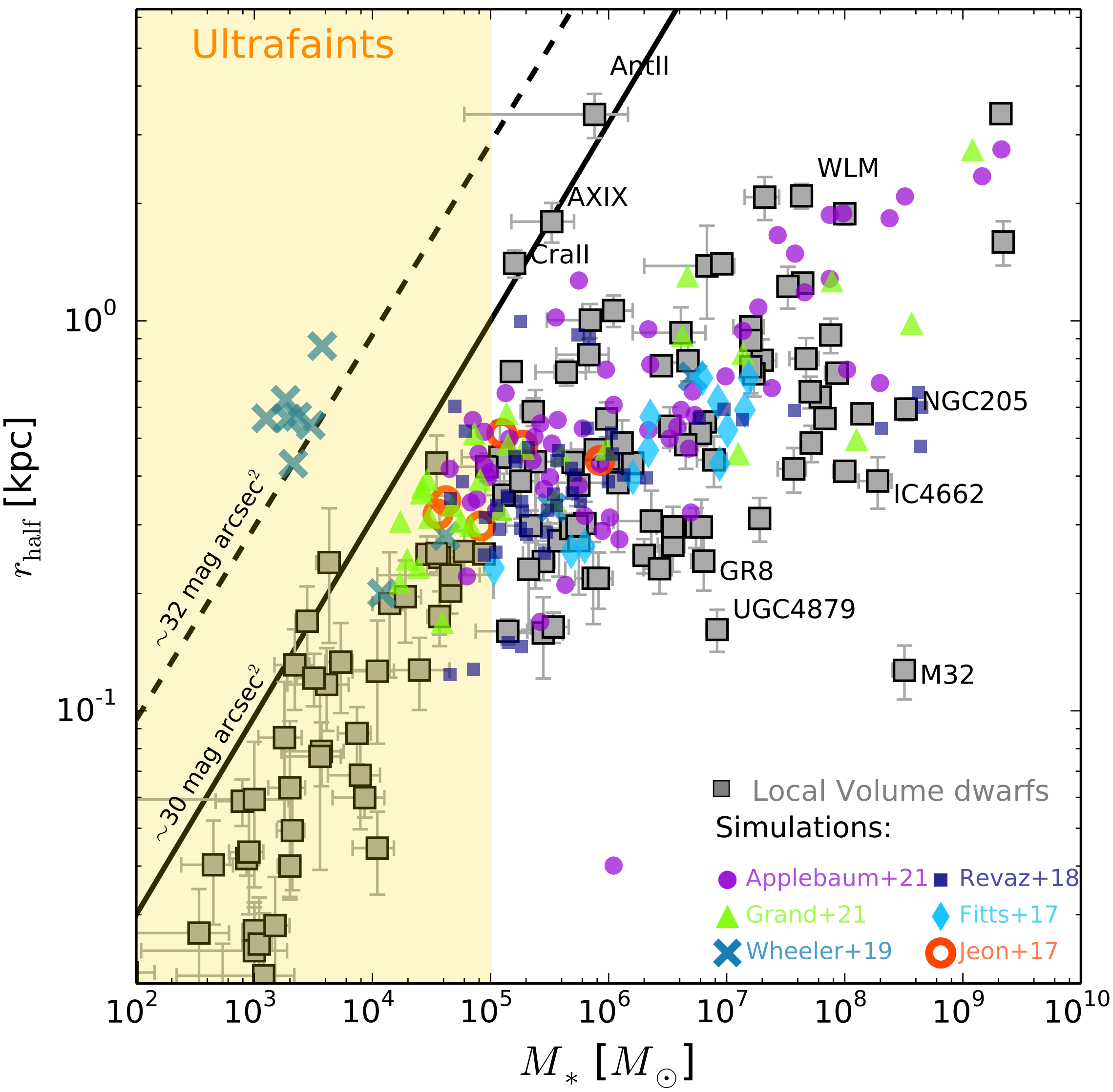

Figure 2.2: From: Sales et al. (2022). A comparison of the sizes and masses of dwarf galaxies from simulations and reality. The y axis plots r_{50} and the x axis plots M_{50}. The gray squares depict real galaxies from the Milky Way's local group, whose data was compiled by McConnachie (2012). The other colors depict data from various simulations other than FIREbox. As we can see, the dwarfs from the local group show much diversity in their size-mass ratios. The simulated galaxies, however, show more consistency, especially when compared to others from their own simulation (for example, notice that the orange circles are all clustered together).

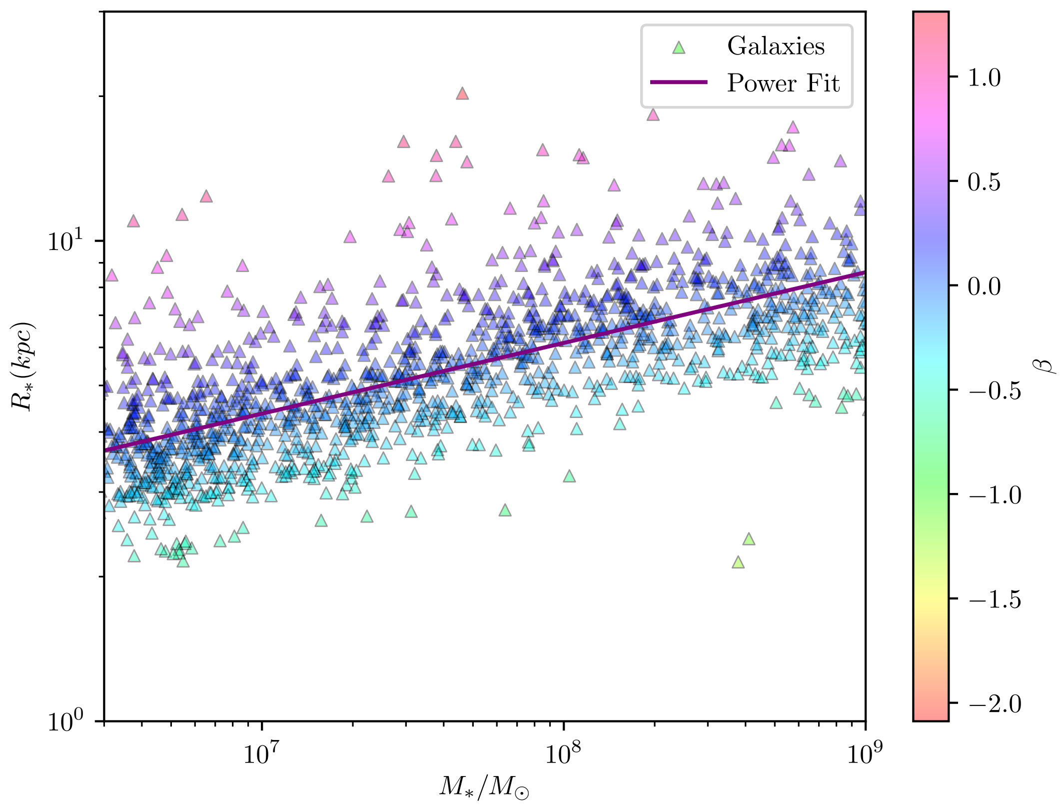

Figure 2.3: This shows the size-mass relationship for the FIREbox dwarf galaxies. It covers the range $3 \cdot 10^3$ - 10^9. Galaxies larger than this are no longer dwarfs and do not follow the power law, and galaxies smaller than this approach FIREbox's resolution limit. The line of best fit is described by equation 2.2 and β represents the deviation from that line. β is chosen to characterize the diffusion of a galaxy because the distribution of β is essentially independent of mass.

masses of dwarf galaxies (see figure 2.3). Note that this does not apply for galaxies larger than $10^9 M_\odot$, as they stop following the power law.

We can calculate γ and $\ln(a)$ using equation 2.2 and fitting the dataset to a line. We can then use those values in equation 2.2 to find each galaxy's value of β. We can also characterize the **diversity of the diffusion** of galaxies using the the standard deviation σ_β (the mean is zero by design). We will use these values to compare FIREbox with the galaxies of the Local Group.

2.3 Proximity

To determine what may cause differences in the diffusion of galaxies, one thing that we may look at is its interactions with its neighbors. Specifically, we will examine a galaxy's distance to its nearest neighbor as well as a satellite galaxy's distance to its host galaxy (as defined by AHF).

Calculating the distance between two galaxies is not as trivial as it may seem because of the shape of FIREbox. The simulation volume is defined as a cube that repeats itself (Feldmann et al. (2022)). In other words, if you travel across one border of the universe you appear on the opposite side. This is done to avoid any strange boundary conditions from affecting the simulation, but also without having to simulate an infinite region. In order to measure the X component of the distance between two objects one must first determine whether they are across the X border. If they are, then we find the sum of the distances to the border. Otherwise, we find the difference of their positions like normal. The same logic is used to find the Y and Z components. Only then do we calculate magnitude of the distance.

2.3.1 Minimum Proximity

To determine whether tidal interactions affect the diffusion of galaxies, it is better to look at the *minimum* distance between a satellite and its host, as opposed to the current distance. The minimum distance is the point at which the tidal forces are strongest, and therefore could cause the most extreme effects. We must therefore also compare β to d_{min}.

Appendix A

An appendix

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