Density Profiles of Dark Matter Halos

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DENSITY PROFILES OF DARK MATTER HALOS

A project work done by

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in partial fulfillment of the requirements for the award of the degree of

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Department of Physics
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May 2024

CERTIFICATE

This is to certify that the project report entitled **"Density Profiles of Dark Matter Halos"** is the bonafide work done by **Swaraj V** (Reg No: 35219054), in the Department of Physics, Cochin University of Science and Technology, under the guidance of **Dr.Charles Jose** for partial fulfillment of the requirements for the award of Degree of Integrated MSc in Physics.

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DECLARATION

I hereby declare that the project report entitled **"Density Profiles of Dark Matter Halos"**, submitted in partial fulfillment of the requirements for the award of the degree of Integrated MSc in Physics, is an authentic record of work done by me under the guidance of **Dr. Charles Jose**, Assistant Professor, Department of Physics, Cochin University of Science and Technology, has not been submitted to any institute for the award of any other degree.

Kochi
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ABSTRACT

This project focuses on the characteristics of dark matter halos using the AbacusSummit N-body simulations made upon the Planck2018 ΛCDM model framework. This study primarily investigates the distribution of matter within dark matter halos and its properties. It evaluates these features by examining the halo mass function, which studies the frequency of halos, and the radial density profile using the NFW model to understand the matter distribution within halos across different redshifts and mass ranges.

In the first part of this project, the Halo mass function is calculated utilizing Halo catalog data obtained from the AbacusSummit N-body simulations. The outcome shows a strong agreement between the data from the simulations and the predictions made analytically.

in the next half, the project investigates the radial density profile, which gives valuable information about the distribution of matter within the halos. The density profile estimated from the simulation data shows an excellent alignment with the NFW profile.

These investigations yield significant insights into how matter is distributed throughout the universe and within halos, enhancing our understanding of cosmic structure. Additionally, this project highlights the potential of N-body simulations in deciphering the enigmatic nature of dark matter halos.

Contents

Chapter 1

Introduction

Over the years, humanity gazed at the sky, marveling at its cosmic beauty and pondering its existence. Some worshipped it, some enjoyed it, and some tried to answer the question, "Why is it there?". Science enthusiasts, observers, astronomers, cosmologists, and many more paved the way for advancements in observations and analysis. Technological advancements improved the precision of observations and, later, the simulations of the observed phenomenon and predictions of probable events.

In this Thesis, I will focus on the N-body simulations of the dark matter halos since these simulations give a clear idea about the environments of dark matter halos

1.1 The Evolution of Cosmology

"Cosmology is the study of the formation and ultimate fate of galaxies and structures across the universe". It is an ancient subject, but the science of Cosmology is new. Recent theoretical and observational studies helped mature this "Precision Cosmology."

It all started with the Solutions to Einstein's theory of relativity (1915). He reintroduced the concept that the universe is governed by four-dimensional geometry in which *"time"* is the fourth dimension, and the general theory of relativity explains how mass[1] curves space-time. Therefore, in space-time, gravity is the geometric

[1] Mass and Energy are two manifestations of same thing

property of the space.

General Relativity is another milestone in the framework of modern cosmology. According to this theory, the universe can have three morphologies: Open, flat, or closed. An open universe implies the universe is infinite, which means if we draw a big triangle, the sum of the angles of the corners of those triangles is less than 180°. Furthermore, the opposite is valid for a closed universe. Friedmann equation (1922) was one of the formulations of the theory of general relativity. This equation showed that the universe cannot be static.

Edwin Hubble showed that the spectrum of a further away object shifts toward the red region in the spectrum, which indicates that they are moving away from us[2]. This observation suggests the uniform expansion of the universe, with galaxies moving from each other as the space between them expands, a key concept in the Big Bang theory (1931).

Cosmic Microwave Background Radiation, a constant radio signal from any direction of the universe, could find the spectrum of a perfect black body, then their temperature. Later, minute fluctuations in the temperature were observed.

After puzzling all these results together (in the 1970s), scientists have theorized how the Big Bang could lead to the rise of non-linear structures such as galaxies and galaxy groups. During this era, multiple computer simulation programs were created for the formation of cosmic structure clusters. Observations of COBE[3] satellite found the anisotropies of the CMBR[4] of the order $\frac{\Delta T}{T} \approx 10^{-5}$, which proved the existence of Cold Dark Matter[5].

After these discoveries and observations, the explanation for the evolution of the universe and its key parameters became more robust.

[2]Hubble's linear velocity-distance relation (1929).

[3]Cosmic Microwave Background Explorer

[4]Cosmic Microwave Background Radiation

[5]Even then, it was apparent that the rotation curves of galaxies and the velocity dispersion of galaxies in clusters could not be explained by looking at luminous matter. We needed some extra matter that only interacts through gravity to make sense of the gravitational effects we observed.

1.1.1 Friedmann Equations

Based on the assumptions of cosmological principle (Universe is homogeneous[6] and isotropic[7]), Alexander Friedmann derived his famous Friedmann equation[2] (in 1922) from Einstein's field equation of general relativity, which is a central equation describing the evolution of the Universe as a whole, is given by

$$\left(\frac{\dot{a}}{a}\right)^2 = \left(\frac{\dot{a}}{a}\right)_0^2 (\Omega_{r,0}a^{-4} + \Omega_{m,0}a^{-3} + \Omega_{k,0}a^{-2} + \Omega_{\Lambda,0}) \tag{1.1}$$

$$\ddot{a} = \frac{-4\pi G}{3} a\rho \tag{1.2}$$

where $\rho = \nu/a^3$ and ν is the amount of mass per unit volume. The solutions to a(t) give an idea about the Universe's expansion and contraction and the density parameters are:

$$\Omega_{r,0} = \frac{\rho_r}{\rho_{\text{crit}}} \tag{1.3}$$

$$\Omega_{m,0} = \frac{\rho_m}{\rho_{\text{crit}}} \tag{1.4}$$

$$\Omega_{k,0} = \frac{-k}{a_0^2 H_0^2} \tag{1.5}$$

$$\Omega_{\Lambda,0} = \frac{\rho_\Lambda}{\rho_{\text{crit}}} \tag{1.6}$$

$\Omega_{r,0}$, $\Omega_{m,0}$, $\Omega_{k,0}$ and $\Omega_{\Lambda,0}$ are the density parameters of radiation, matter (both baryonic and dark matter), curvature (spatial geometry) and dark energy (cosmological constant) at present (t_0) respectively.

Critical density is given by,

$$\rho_{\text{crit}} = \frac{3H_0^2}{8\pi G} \tag{1.7}$$

$3H_0$ is the current value of the Hubble parameter.

[6]Universe looks almost the same from all points in space, which implies that Universe has no spatial center

[7]Universe looks the same in all directions

Energy density associated with the cosmological constant,

$$\rho_\Lambda = \frac{\Lambda}{8\pi G} \tag{1.8}$$

and the Hubble parameter is given by,

$$H = \frac{\dot{a}}{a} \tag{1.9}$$

1.2 Structure Formation

Even though the cosmological principle states that the Universe is isotropic and homogeneous, observation of highly inhomogeneous structures negates this statement. Due to the quantum fluctuations produced in a phase shortly after the Big Bang, slight deviations from the homogeneity existed in the early stages of cosmic evolution (Inflation). These fluctuations are Gaussian in nature, and a power spectrum describes them. The amplitude of this power spectrum is an essential parameter to have a credible model of cosmological structure formation.

In a universe expanding under the influence of non-relativistic matter, disturbances increase over time. It is straightforward: if an area starts with a slightly higher density than average, it pulls in surrounding matter more strongly. As a result, dense regions attract more matter and become even denser over time.

Chapter 2

N-Body Simulation

2.1 N-Body simulation

Cosmological N-body simulation is one of the most essential tools for studying the large-scale structures in this universe. Although working with this huge database is computationally expensive, several efficient algorithms have been developed to run these simulations with better dynamic range and resolution. These are the steps involes:

1. Initialization of Conditions: Commence by establishing the initial state of the universe. This includes determining the distribution of matter and energy according to a selected model.

2. Grid Setup: Segment the simulated space into smaller units. Each unit represents a fraction of the universe, with grid resolution dependent on visualization requirements and computational capacity.

3. Dynamic Simulation: Evolve the universe over time using equations derived from the chosen model. These equations elucidate the interplay of matter, energy, and gravity.

4. Temporal Progression: Advance through discrete time intervals. Iteratively solve equations to determine spatial configurations or densities at each step,

ensuring simulation accuracy.

5. Incorporation of Additional Factors: Integrate supplementary phenomena, such as gas dynamics or stellar formation, for enhanced detail. These aspects necessitate their own equations and frameworks.

6. Result Analysis: Evaluate the outcomes post-simulation. Examine matters like matter distribution, galactic formation, and comparison with observational data for validation.

2.2 AbacusSummit

Abacus[3] is a high-accuracy, high-performance GPU-optimized large volume, moderately clustered cosmological N-body simulation code that runs in a dual-Xenon, dual-GPU computers, which clocks over 30 million particle updates per second and nearly 70 million particle updates on each node of Summit[1] supercomputer.
AbacusSummit[5] provides a comprehensive set of advanced simulations essential for cosmological N-body studies. These simulations are specifically designed to meet the requirements set by the Dark Energy Spectroscopic Instrument (DESI)[2] survey for cosmological simulations.

Majority of the simulations in AbacusSummit are $69123^3 = 330$ billion particles in 2 Gpc/h volume, which is a Planck2018 LCDM cosmology with 25 base simulations resulting in a particle mass of about $2 \times 10^9\ M_{\odot}/h$. Based on the Planck2018 LCDM model, the project establishes a primary cosmology consisting of 25 main simulations, each dispersing 330 billion particles across a volume of 2 Gpc/h. Additionally, it creates four secondary cosmologies, each comprising six simulations phase-matched with the initial six simulations of the primary set. Establishing a grid of 79 other cosmologies, each supported by one phase-matched simulation, facilitates interpolation

[1]Summit is the supercomputer in Oak Ridge National Laboratory.

[2]The DESI Survey, conducted at the Kitt Peak National Observatory using the Mayall 4-meter telescope, aims to explore the impact of dark energy on the universe's expansion. It gathers optical spectra from millions of galaxies and quasars to create a comprehensive 3D map spanning up to 11 billion light-years, providing insights into the structure and evolution of the nearby universe.

in an 8-dimensional parameter space, which includes ω_0, ω_a, N_{eff}. The project establishes a grid of 79 other cosmologies supported by one phase-matched simulation. Furthermore, the project maintains a suite of 1800 smaller simulations at the base mass resolution to assist in covariance estimation. It also conducts other simulations to align with the cosmology of external flagship simulations and explore the effects of neutrino approximations. For detailed investigations, the project conducts a simulation with six times higher mass resolution of the primary cosmology to study group formations. Conversely, a more extensive volume simulation with 27 times lower mass resolution provides a full-sky light cone up to z>2. Specialty simulations, including those with fixed-amplitude white noise and scale-free characteristics, are part of the project. The project generates extensive data products such as particle subsamples, catalogs of halos, merger trees, kernel density estimates, and light cones.

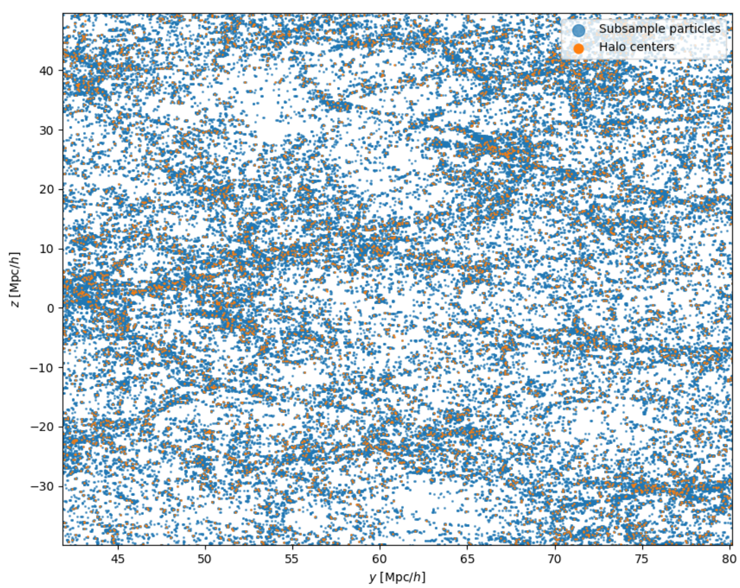


Figure 2.1: AbacusSummit_highase_c000_ph000 with boxsize 1000 $\mathrm{Mpc\,h^{-1}}$ visualization

2.2.1 Specifications

Simulation

The simulation name shows their characteristics. For instance, a typical name is "AbacusSummit_base_c000_ph000", where the segment "base" indicates the standard setup, which could instead be "high," "huge," or "hugebase." The segment "c000" serves as an identifier for the cosmology, corresponding to the ΛCDM cosmology aligned with the Planck 2018 findings. Lastly, the segment "ph000" denotes the seeding for the initial condition. The random seed, labeled as "ph000-ph4999," generates the distribution of matter in the simulated universe. In cosmological simulations, initial conditions are often established by creating a random field with a desired power spectrum, typically following a Gaussian distribution, and this simulation includes 10% of the subsample particles.

This subsection details the specifications of various simulations:

1. **Base:** This configuration represents our standard setup, featuring 69123 particles within a volume of 2 Gpc/h.

2. **High:** With six times better mass resolution, this simulation comprises 63003 particles within a volume of 1 Gpc/h.

3. **Highbase:** Spanning 1 Gpc/h, this simulation maintains standard mass resolution.

4. **Huge:** These simulations utilize larger boxes and operate with 27 times lower mass resolution.

5. **Hugebase:** Re-runs of specific 2 Gpc/h simulations are conducted using the exact 27 times lower mass resolution.

6. **Fixedbase:** While maintaining standard mass resolution, these simulations incorporate fixed-amplitude initial conditions and consist of 40963 particles within a volume of 1.18 Gpc/h.

7. **Small:** Featuring standard mass resolution, these simulations contain only 17283 particles within a volume of 0.5 Gpc/h.

8. **Pngbase:** Investigating primordial non-Gaussianity within the standard volume at lower mass resolution, this simulation comprises 40963 particles within a volume of 2 Gpc/h.

Cosmology

The AbacusSummit simulation suite explores a variety of cosmologies for simulations. It utilizes the primary Planck 2018 ΛCDM model as the basis for high-precision simulations. Furthermore, it examines secondary cosmologies with differing parameter values while maintaining uniformity in base box size and mass resolution compared to the primary simulations. These secondary cosmologies provide insights into deviations from the ΛCDM model. Additionally, the suite contains simulations aligned with flagship counterparts and those focused on the impact of massive neutrinos. It also integrates additional cosmologies to facilitate interpolation in an eight-dimensional parameter space, allowing for comprehensive exploration. Overall, the suite presents a broad spectrum of cosmological models for thorough investigation.

Chapter 3

The AbacusSummit Data

For a proper understanding of the simulation, it is essential to have a clear idea about the storage and access methods for the vast amount of data generated by simulations, with information about the final positions, velocities, and other relevant quantities of dark matter particles in a 3-D grid at a particular time.

3.1 The Data Structure

The data set consists of several highly compressed ASDF[1] files, accessed through Globus, a research data management cloud. The statistics of this halo information are embedded inside "halo_info" files, which can be read using CompaSO Halo finder, which will be discussed in the section 3.2.

3.2 CompaSO Halo Finder

CompaSO[4] uses a hybrid of the FoF-SO algorithm. In the FoF algorithm, we consider particles part of the same group if they are closer to each other than a specific distance called the linking length, represented by l_{FoF}. Usually, this value is 0.2 times $0.2 l_{mean}$, where l_{mean} represents the average distance between particles. Then,

[1]The Advanced Scientific Data Format (ASDF) is a modern format for sharing scientific data. This package includes the Python implementation of the ASDF Standard.

the linked particles are called a virialized halo. Since this algorithm calculates distances, the FoF algorithm is co-ordinates free with one parameter. However, if groups identified by this method are two or more clumps, then this method is ineffective. On such occasions, in order to detect virialized halos, the spherical overdensity (SO) method adopts a mean overdensity threshold. In the SO method, the particle with the highest overdensity is selected and marked as the center of a halo, then the distance to each particle is computed, and the radius of the sphere around that center is increased until this density satisfies the virialization criteria.

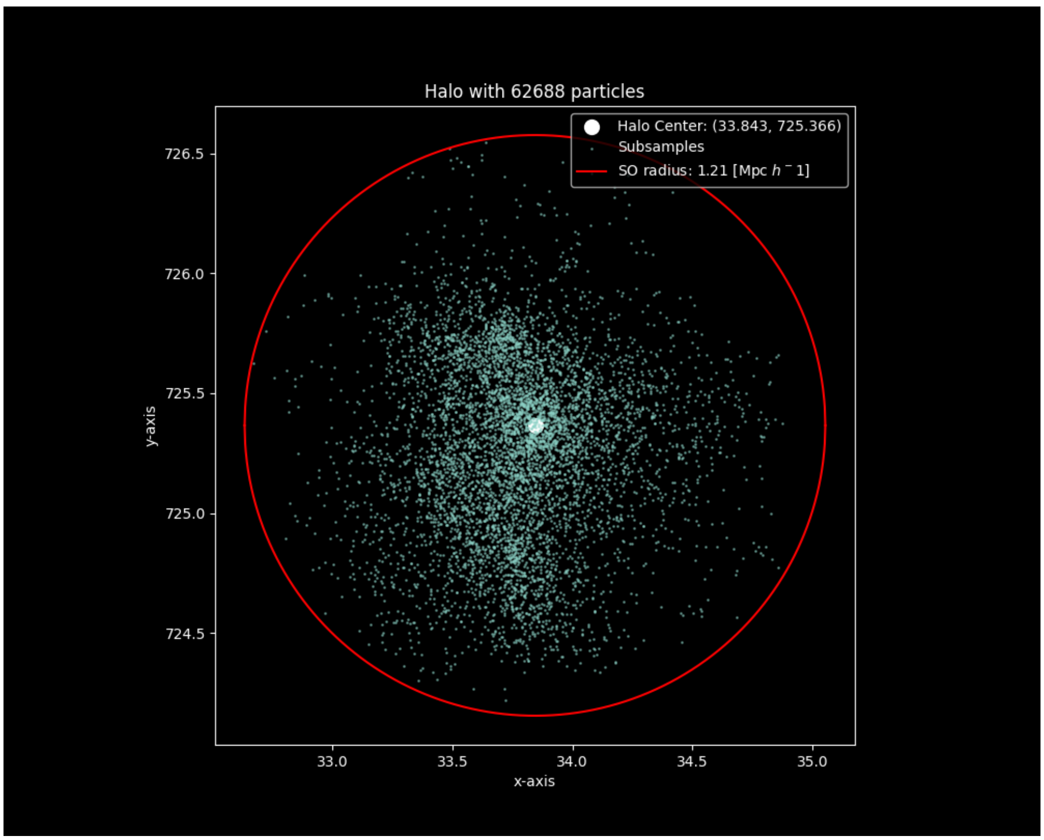


Figure 3.1: SO radius of a Halo

The Algorithm

- Kernel Density Estimation (finding L0): Computes particle density utilizing a weighted kernel. The volume corresponds to an 85 kpc/h comoving top hat. On average, weighted counts at an overdensity δ are roughly $\delta/10$, with a variance approximately 4/7 times the mean.

- L0 Halos: Divide the particle set using the FOF algorithm with a linking length of 0.25 times the interparticle spacing, but exclusively for particles with $\delta > 60$. The kernel density estimate determines the boundaries of L0 halos.

- L1 Halos: Within each L0 halo, establish L1 halos using a competitive spherical overdensity algorithm. Select the nucleus based on the highest kernel density. Identify the innermost radius with an enclosed density below 200. Assign eligible particles to the group. Initiate another nucleus based on the highest remaining kernel density meeting the density criteria, which leads to nucleus formation.

- L2 Halos: SO algorithm is applied on L1 halos, L2 halo with a radius of 800 is found out. Masses of the five largest subhalos are stored, and the center of mass of the largest L2 subhalo defines the statistics of L1.

Therefore, this algorithm keeps the kernel density scale unchanged by changing the density threshold.

3.3 Reading Catalog

The AbacusSummit data is read through CompaSOHaloCatalog, a module inside the abacusutils python package (Linux only).

```
cat = CompaSOHaloCatalog(file_path, cleaned=False, subsamples=dict(A
   =True, B=True),fields=colums)
```

This code will store all the data values in the header "colums" into "cat." Now, the cat contains some of the subsample information specified in the fields from subsample A (3%) and subsample B (7%). Together, the cat holds 10% of the information of the simulation.

The halo information and subsample data are stored in separate folders in the file directory. But they can be called using,

```
subsample = cat.subsamples['pos']
```

gives subsample position information, for example

```
halos=cat.halos[halo_index]
data_A = cat.subsamples['pos'][halos['npstartA']:halos['npstartA']
   halos['npoutA']]
```

Here, "halos" stores all the information about the halo with the index value halo_index and data_A stores the information about the samples sliced from npstartA with the count npoutA (for Ath subsample)

Chapter 4

Halo Mass Function

For the subsequent investigation of halo properties, we have taken a redshift slice and the halo mass function helps us understand the number of halos of a certain mass formed at a given redshift and in a specific cosmic environment. Since dark matter and dark matter halos play a vital role in modeling galaxies and clusters, this information is essential. Also, the halo mass function helps us study how matter is distributed in the early universe. It is also helpful in predicting how structures like galaxy clusters affect things we observe, such as the Sunyaev-Zeldovich effect[1] and lensing[2].

4.1 Theory

The halo mass function is a universal function that relates the Mass of halos to the variance of the mass fluctuations[7] when expressed as the multiplicity function $f(\sigma)$. This function represents the count of halos within each logarithmic mass interval as,

$$\frac{dn}{d\ln(M)} = f(\sigma)\frac{\rho_0 d\ln(\sigma^{-1})}{M d\ln(M)} \tag{4.1}$$

[1]As light from the cosmic microwave background (CMB) passes through a galaxy cluster, some of its photons get scattered by electrons in the hot gas within the cluster. This scattering changes the original Planck light spectrum, giving it a unique, distinctive signature[8].

[2]Gravitational lensing studies the effects of light deflection on the appearance of cosmic objects

where $\sigma(M)$ is the variance in lagrangian scale. Therefore, the multiplicity function is the fraction of Mass that has collapsed to form halos in a unit interval of $\ln(\sigma^{-1})$. ρ_0 is the mean density of the universe.
The sphere's Mass, with a radius of R and critical density, is

$$M = \frac{4\pi\rho_0 R^3}{3} \tag{4.2}$$

it is the fitting function that determines the fit of a halo mass function. Earlier analytical works[7][1] showed that

$$f(\sigma) = \sqrt{\frac{2}{\pi}}\frac{\delta_c}{\sigma}e^{-\frac{\delta_c^2}{2\sigma^2}} \tag{4.3}$$

where $\delta_c \approx 1.686$ (critical overdensity for spherical collapse).

Since different cosmological simulations give different fitting functions, the Halo mass function varies for different cosmological simulations as shown in Figure 4.1.

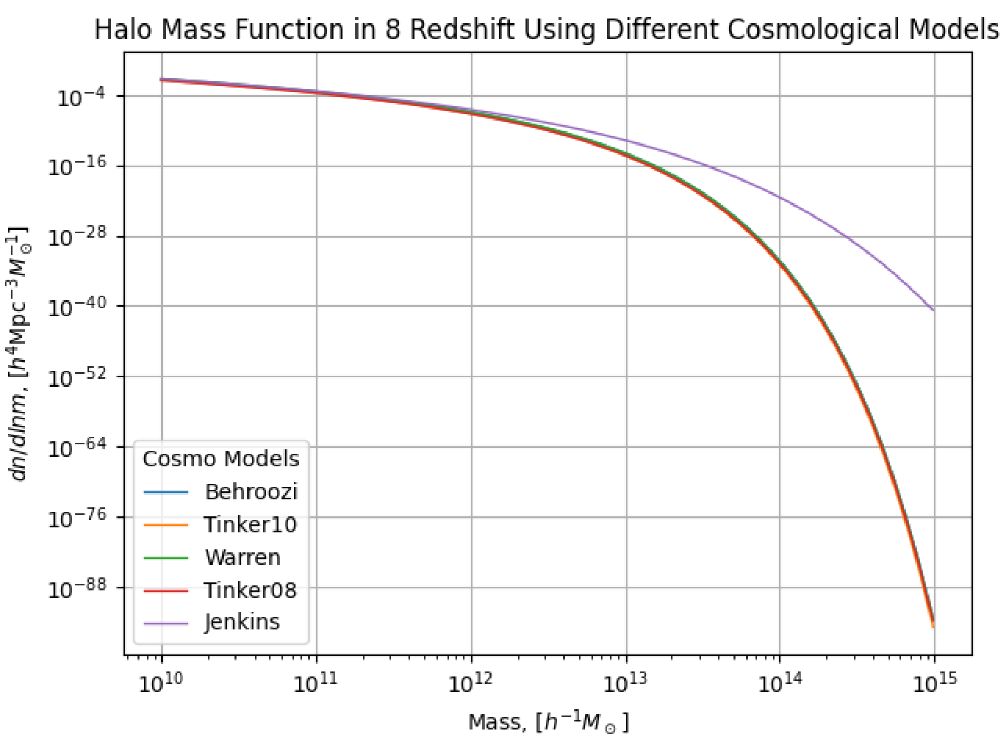


Figure 4.1: Halo Mass Function using different cosmological models

4.2 Data Analysis

Even though we have an equation that governs the density function of halos, it could be more computationally convenient. In fact, there are better statistical techniques available.

Since a large number of data points are available for calculation, it will be very computationally expensive. Making masses into bins and finding histograms corresponding to these bins is a more efficient and faster approach for calculating the halo number of particles in each bin. The header file gives us the information about the particle mass, and multiplying it with the total number of particles gives the total mass of the particles in each bin.

Then, by using this equation,

$$f_i = \frac{N_i}{w \times V} \tag{4.4}$$

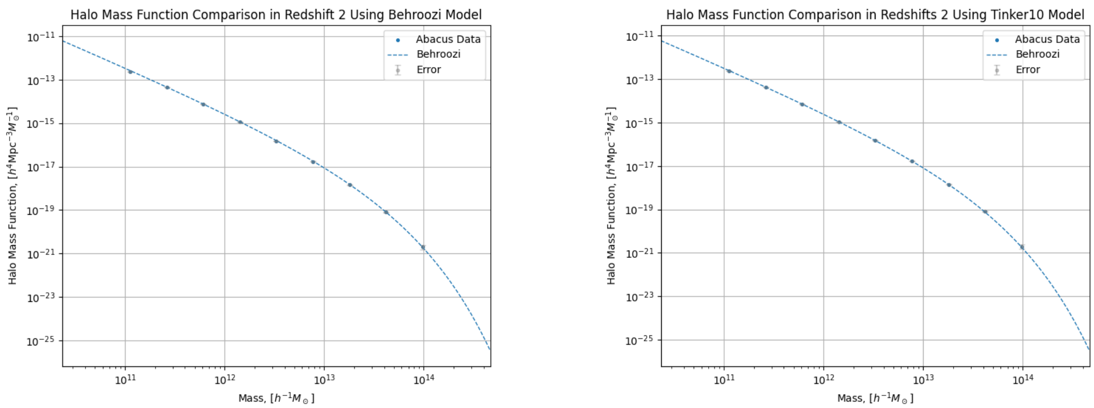
where N_i as the frequency of mass points in the i^{th} bin, w as the width of each bin, and, V as the total volume. We can compute the halo mass density function. And we can use Poisson error as

$$\sigma = \sqrt{N} \tag{4.5}$$

Where N is the number of particle in each bin.

upon plotting the halo mass function against the mass bins and comparing it with different halo finding algorithms available in hmf[3] in the redshift 2 with a boxsize of 500 $Mpch^{-1}$, we got the following graphs.

[3]hmf is a python module for finding halo mass function for different cosmologies and halo finding methods.



(a) Behroozi model

(b) Tinker 10 model

Figure 4.2: HMF comparison

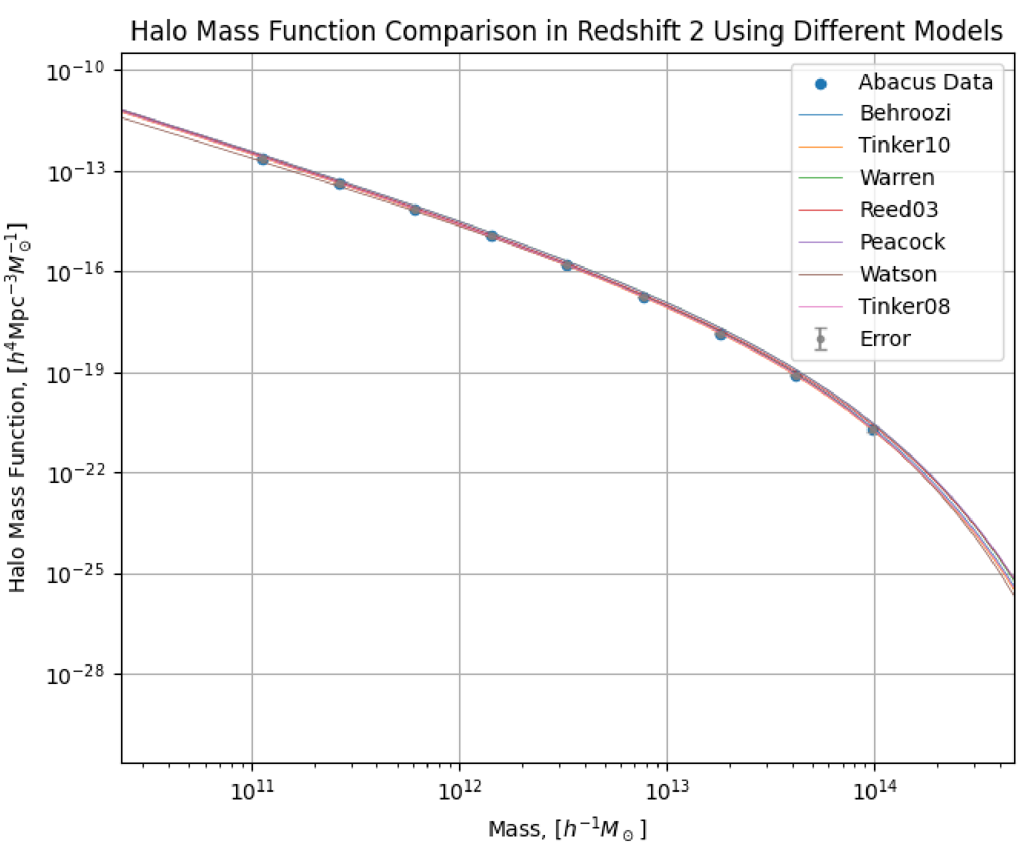
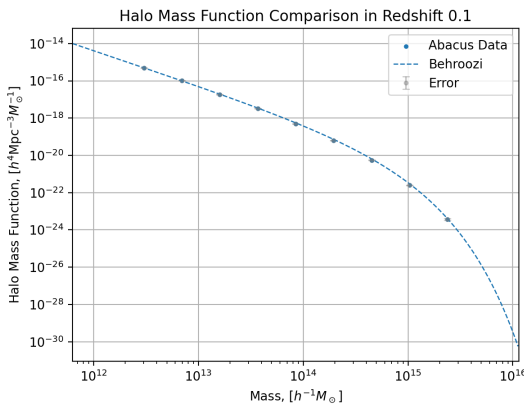
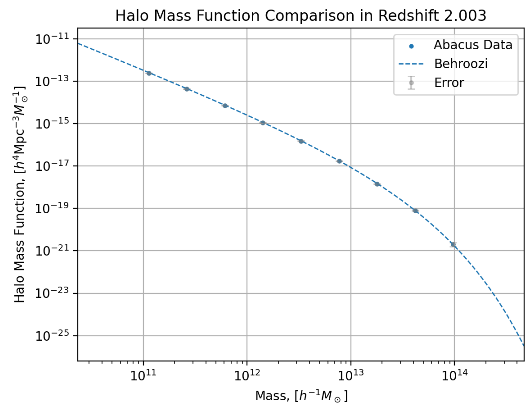


Figure 4.3: Comparison of HMFs

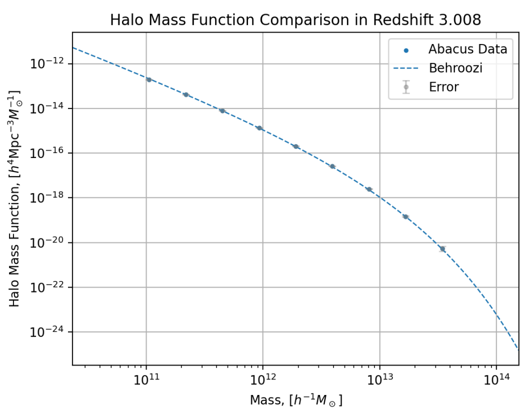
While comparing the *AbacusSummit_smallbase_c000_ph000* data with various group-finding algorithms, Behroozi's rockstar algorithm displays a closer alignment with the AbacusSummit dataset. Refer to Figure 4.4 for the comparison between the Behroozi model and the AbacusSummit data.



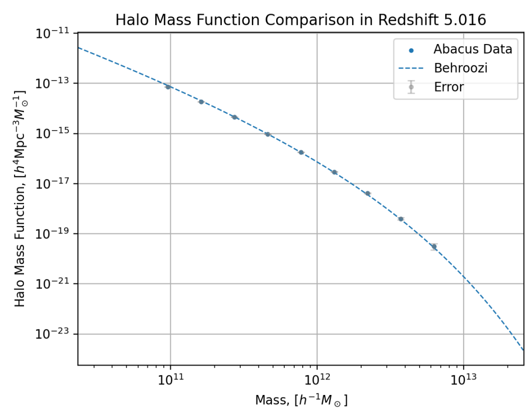
(a) redshift=0.1, box size=2000 $Mpch^{-1}$



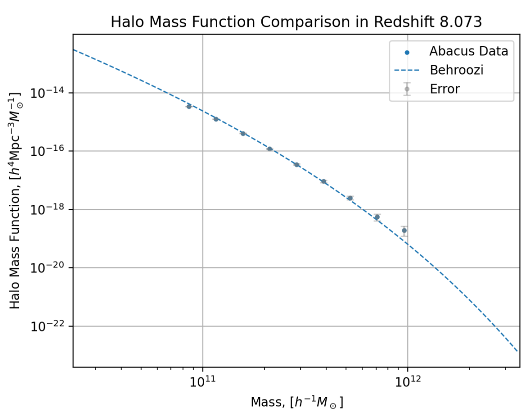
(b) redshift=2, box size=500 $Mpch^{-1}$



(c) redshift=3, box size=500 $Mpch^{-1}$



(d) redshift=5, box size=500 $Mpch^{-1}$



(e) redshift=8, box size=500 $Mpch^{-1}$

Figure 4.4: Halo Mass Function at different redshifts

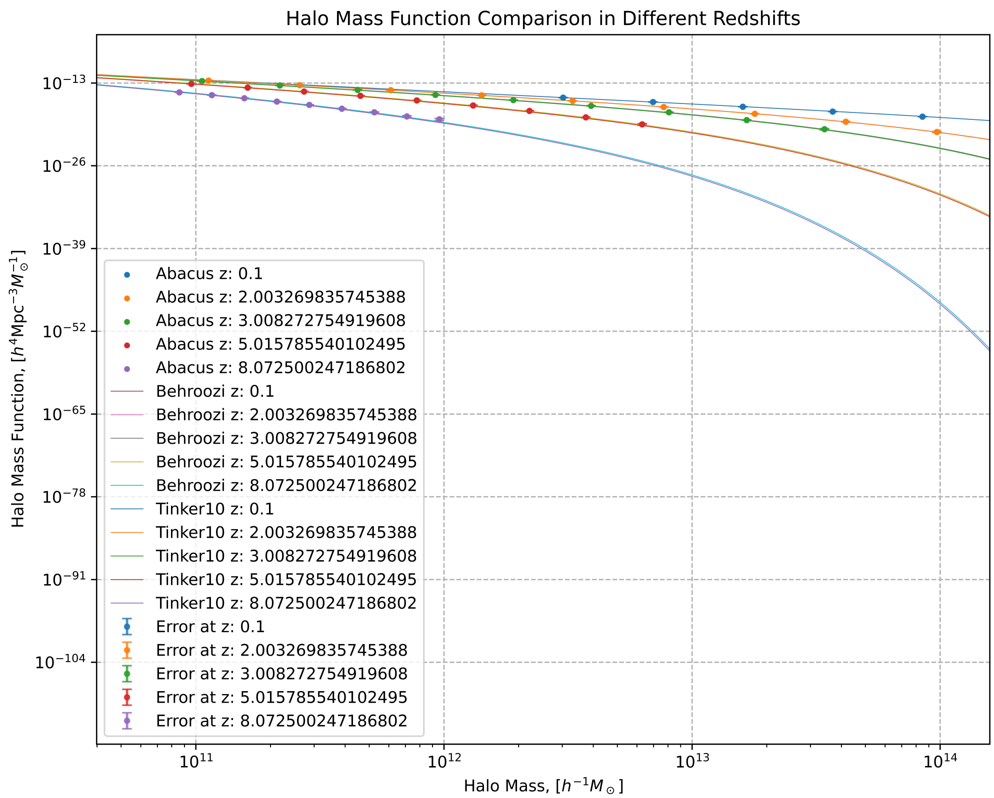


Figure 4.5: Halo mass function comparison in different redshifts

In the Figure 4.5 the data of redshift 0.1 has a box size of 2000 $Mpch^{-1}$, and all the other redshift had a box size of 500 $Mpch^{-1}$.

4.3 Inference

From the halo mass functions plotted in section 4.2, the number density decreases as the halo mass increases. Therefore, we can infer that the halos in consideration have fewer particles with higher mass; this is one of the shortcomings of the ΛCDM model.

In order to characterize the structure of halos, it is essential to have positional data on the subsample particles. Therefore, we examine the radial density profile to understand how the density of halos varies with the radial distance of the subsamples, which is discussed in chapter 5

Chapter 5

Radial Density Profile

5.1 The NFW Density Profile

The NFW (Navarro-Frenk-White) profile is a commonly applied mathematical framework describing the density distribution of dark matter halos in galaxies and clusters. Developed in 1995 by Julio F. Navarro, Carlos S. Frenk, and Simon D.M. White, this profile originated from extensive computer simulations aimed for finding the structure and characteristics of dark matter halos within the framework of the ΛCDM cosmological model. It offers a valuable basis for estimating dark matter halos mass, concentration, and structural attributes across different astrophysical scenarios.

NFW profile is highly applicable in the studies of the density distribution of dark matter, which gives the idea about the formation of large-scale structures like galaxies. The equation for the NFW profile is given by

$$\rho(r)/\rho_{crit} = \delta_c/(r/r_s)(1 + r/r_s)^2 \tag{5.1}$$

where $\rho_s = \rho_{cit}\delta_c$ is the characteristic density and r_s is the characteristic radius of the halo and the NFW profile is shown in Figure 5.1. Even though this NFW profile fits well with the observed data, it shows an infinite mass in large radii, which is rectified by the Einasto and Burkert profiles.

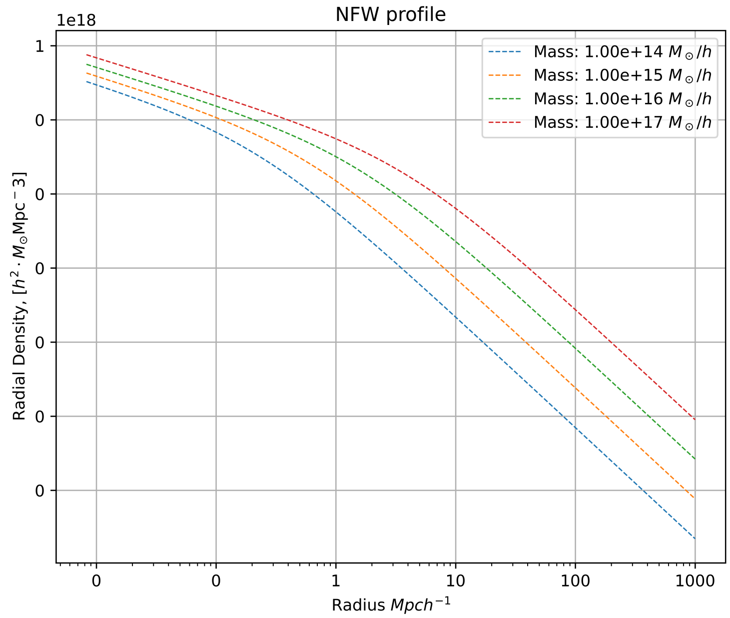


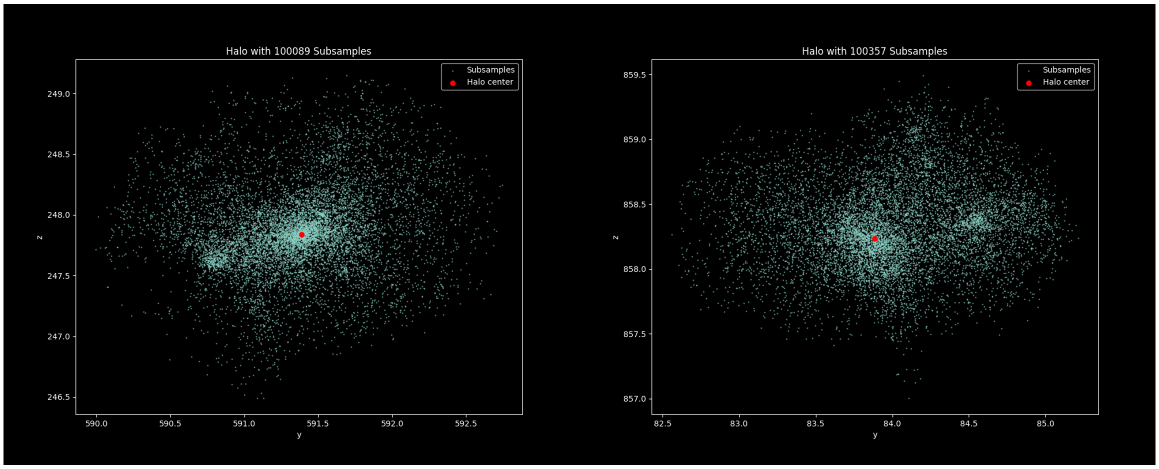
Figure 5.1: NFW profile

5.2 Data Analysis

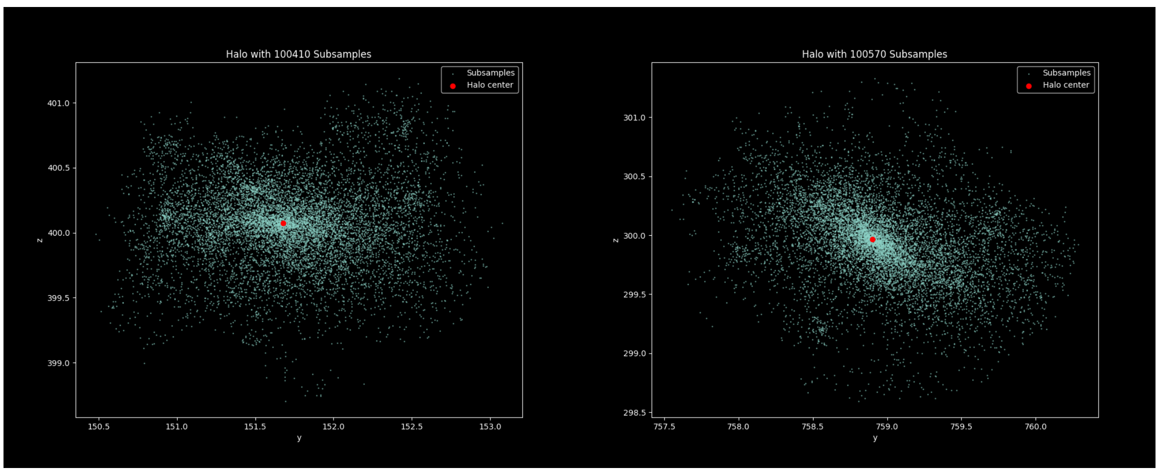
The file's data size containing radial information of the halos and their subsample particles is huge; roughly 4-5 million data points are available in the simulation file for a particular redshift. Similar to the HMF calculation, it is computationally very inefficient to calculate the radial density of each subsample. Even with particle numbers between 100000 and 101000, there are 11 halos, each containing more than 100,000 particles. Some of them are shown in Figure 5.2. Therefore, radial bins are created by taking the Euclidean distance between the subsample particle and the halo center[1] containing the radial data of subsamples in logspace, a histogram is plotted, and also the bin edges are taken as the bin radius. Radial density is calculated according to the equation.

$$\rho = \frac{M_{av}}{\frac{4}{3}\pi\left(r_{i+1}^3 - r_i^3\right)} \times \text{fraction} \tag{5.2}$$

[1]Here L2 is taken as the halo center



(a) (b)



(c) (d)

(a) 100089 subsamples (b) 100357 subsamples
(c) 100410 subsamples (d) 100570 subsamples

Figure 5.2: Halos with different subsamples

where M_{av}[2] is the average mass of particles in each bin, r_i and r_{i+1} is the radius of i$^{\text{th}}$ and i+1$^{\text{th}}$ bins respectively. finally, since the sample only contains 10% of data, a fraction is multiplied with the calculated radial density to make them 100% of the data.

The radial density profile of the abacus data in different redshifts and bases compared with the theoretical profile[3] are shown in Figure 5.3 and Figure 5.4

[2]since the data contains a large number of subsamples, average mass,M_{av} is taken.

[3]Theoretical radial density is plotted using halomod[6], a python package dealing with the Halo Model of Dark Matter Halos

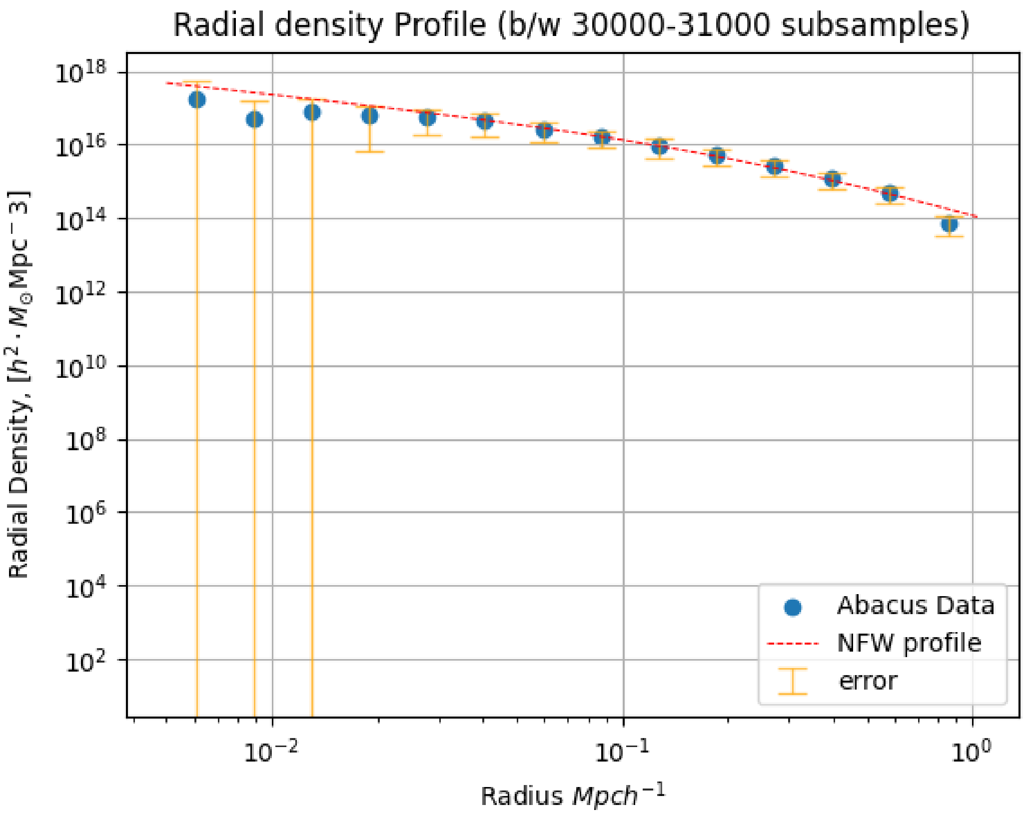


Figure 5.3: Radial Density profile of halos between 30000-31000 subsamples at redshift 2

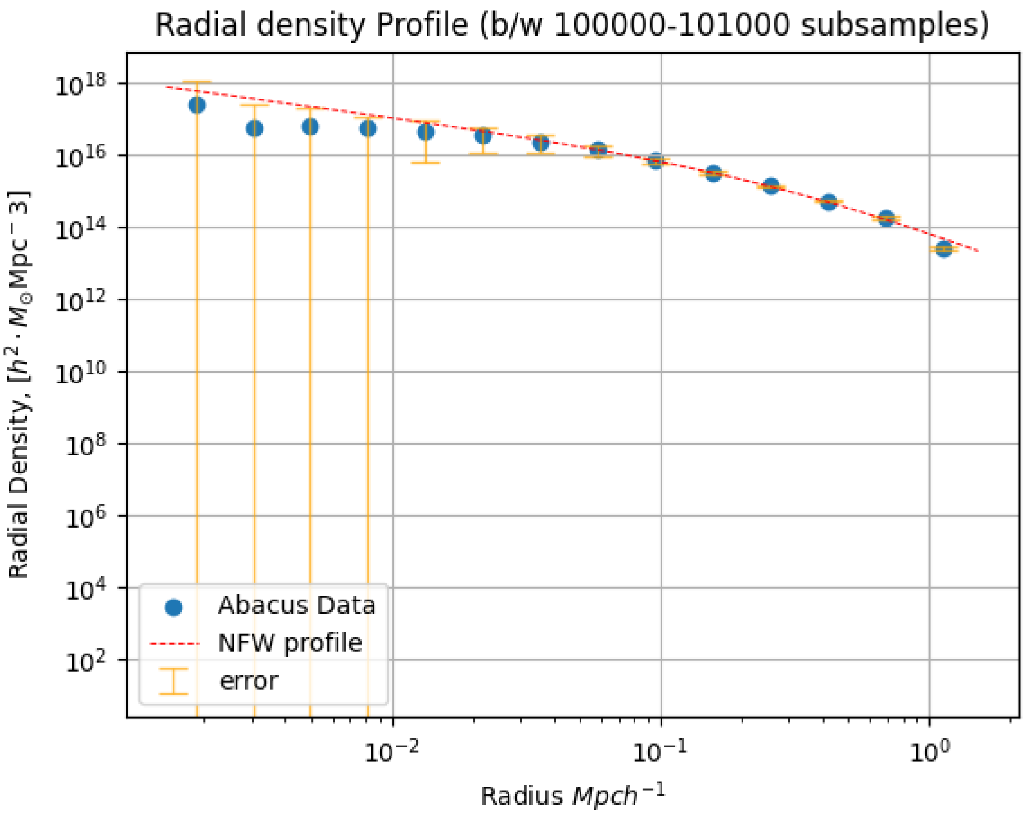


Figure 5.4: Radial Density profile of halos between 100000-101000 at redshift 0.8

5.3 Inference

The radial density profiles of the theory and simulation data indicate that the density profile of all the dark matter halos matches. This suggests that in the model under consideration, as the radius of halos increases, the number density decreases. This implies that all the halos are clumped together, demonstrating the formation of halo structures in ΛCDM model.

Chapter 6

Conclusion

6.1 HMF

From the halo mass function observation of abacus data in different overdensities, verified with the theoretical density profile and the cosmological parameters used in the simulation data in ΛCDM model, we could find that the density decreases as the mass increases for a halo. From this, we can conclude that every halo in the ΛCDM model is made up of particles with smaller masses, and the probability of occurrence of higher masses is very low compared to the probability of occurrence of particles with smaller masses, which is the key concept of hierarchical structure formation where halos with smaller masses are formed by the gravitational instability due to the collapse of dark matter under gravity.

6.2 Radial Density Profile

From the radial density profile, we can observe that the density decreases as the radius increases. This occurs because denser cores form within halos resulting from the gravitational collapse of matter in areas where the initial density exceeds that of the surrounding regions.

Therefore this project shows the structure of dark matter halos, using radial density profile and mass function.

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