

Reveal the Relationship between Density and Radius Base on Snapshot and Groupcat Data

Gilbert Yang

Sir Winston Churchill High School, 5220 Northland Dr NW, Calgary, AB T2L 2J6, Canada

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Abstract: Around 85% of the universe is believed to consist of dark matter, however, as there is still a large amount of unknowns revolving around dark matter, it is often difficult to collect physical data. In this paper, three different graphs using the simulation data will be created. First, using the groupcat data, a graph of the distribution of the subhalos through the region of space can be created. Next, using the dark matter particles, the intensity of dark matter particles throughout the examined region of space can be studied. Lastly, a density profile can be created by using both snapshot and groupcat data to reveal the relationship between density and radius.

1. Introduction

The most prominent model of cosmology at the moment supports the conclusion that the mass-energy density of the Universe is largely controlled by dark matter and energy. A lot regarding dark matter and dark energy are unknown. It is generally accepted that there has been an increase in dark energy while dark matter has decreased over the past 13.7 billion years within the universe. (NASA/WMAP Science Team, 2008). It is also accepted that this form of dark energy is what helps cause the rapid expansion of the universe, however, the specific mechanism of how this occurs remains veiled. As very little is known about dark energy and it is difficult to pinpoint such a theoretical concept, it is much easier to start with investigation with dark matter which still experiences forces such as gravitational forces[1].

Around 85% of the universe is believed to consist of dark matter, however, as there is still a large amount of unknowns revolving around dark matter, it is often difficult to collect physical data. An useful alternative towards the exploration of general patterns of dark matter is through the use of simulations. Especially in regard to dark matter, the use of simulations allow for the investigation of patterns that may be unnoticed in subhalos - the invisible collection of dark matter particles consisting of around 80% of a galaxy's mass. Through investigation of a simulated universe around time and more specifically, the subhalos it contains, patterns can be drawn and applied to the actual physical world, potentially leading to fundamental insights about our universe.

One of the newest simulations of the universe is the IllustrisTNG project which was conducted through taking a large strip of space in a mock Universe and then evolving it throughout the time frame of immediately after the Big Bang until present day. Through taking into account a wide variety of known physical phenomena regarding galaxy formation, the simulation is able to examine a wide range of topics ranging from the evolutionary process of the Universe to the study of the contained galaxies through time. (The TNG Collaboration, 2021) [2].

All together, the IllustrisTNG simulations have a total of 18 unique simulations and within those 18 simulations, there are further divisions into individual simulations that vary in terms of size, mass, and resolution. Each simulation is contained into a cube of one of three sizes: 50, 100, or 300 Mpc as side lengths. The shape of the cube was chosen as it allows the regions of space to be divided without skipping over any regions, unlike a spherical shape. The three different sizes of cubes are each intended to serve a different purpose. Specifically, the 300 Mpc cube enables the study of galaxy clustering as well as an analysis of rare objects like galaxy clusters. The 50 Mpc cube which limits the sampling of the rare objects allows for greater mass resolution which leads to a more detailed examination of concepts such as the structural properties of galaxies and the structure of gas revolving around galaxies. The 100 Mpc cube sacrifices some of the detailed views

of the 50 Mpc cube and the wide berth of the 300 Mpc cube for a balance between the two factors[3].

In this paper, the 100 Mpc cube will be used exclusively to achieve a balance between a detailed view and the wide berth view to create generalizations of patterns noticeable in the galaxies. The simulation that is used is the TNG100-1 simulation which considers both baryonic and dark matter, allowing for a full overview of the theoretical evolution of the given region of space[4].

The data through TNG-Illustris is split into 3 levels of resolution. For the purposes of this paper, TNG 100-2 will be predominantly utilized, the middle tier of resolution which strikes a balance between a reasonable data size while retaining a fairly high resolution. The data under each resolution is split into two main categories: groupcats and snapshots. Groupcats are smaller in size and take the center of the subhalos for their data. On the other hand, snapshots take every dark matter particle leading to larger file sizes[5].

The goal of doing these simulations, in general, is to reveal and model the physical processes that affect galaxy formation, the evolutions and factors within galaxy formation, and the properties of dark matter that control the development of phenomenons of the universe. To reach these goals, an extended investigation into the simulations needs to be done, with each investigation targeting a different aspect. Some of these aspects include the patterns in the colours of galaxies, stellar masses of galaxies, sizes of galaxies, the origin of heavy elements, and the distribution of galaxies[6].

In this paper, three different graphs using the simulation data will be created. First, using the groupcat data, a graph of the distribution of the subhalos through the region of space can be created. Next, using the dark matter particles, the intensity of dark matter particles throughout the examined region of space can be studied. Lastly, a density profile can be created by using both snapshot and groupcat data to reveal the relationship between density and radius.

2. Methods

2.1 Subhalo Distribution

The data held in the groupcats contains the centers of the subhalos. One of the first investigations that can be undertaken is the portrayal of the subhalo distribution through the region of space. Data of the simulation can be found on the IllustrisTNG website. There are a total of 100 different snapshots, each with a different redshift varying from 0 (present-day in the simulation) to a redshift of 20.05. As such, each groupcat of data takes a moment in time from the simulation.

For the following graphs created, the data set TNG100-1 at groupcat 98 was used, with a redshift of 0.01. This will also be the subhalo used for the final density profile, except at a lower tier of resolution of 100-2. The data within this groupcat consists of 3 variables for the three different coordinate planes in space. By using the `illustris_python` library, the positions for each coordinate of the subhalos can be assigned to the arrays `x`, `y`, and `z`.

To visualize this data, the `matplotlib` library paired with the `numpy` library for Python can be used to create a 3D graphic of the data. The colour of each point can be tied to the logarithm of the total mass of each subhalo. The logarithm is taken so that there is so colour distinction as otherwise, the colour would be impossible to differentiate between each point of the graph. The full code for the graph can be found on the right and the resulting graph of the rendered visual with all the data points can be seen below fig.1.

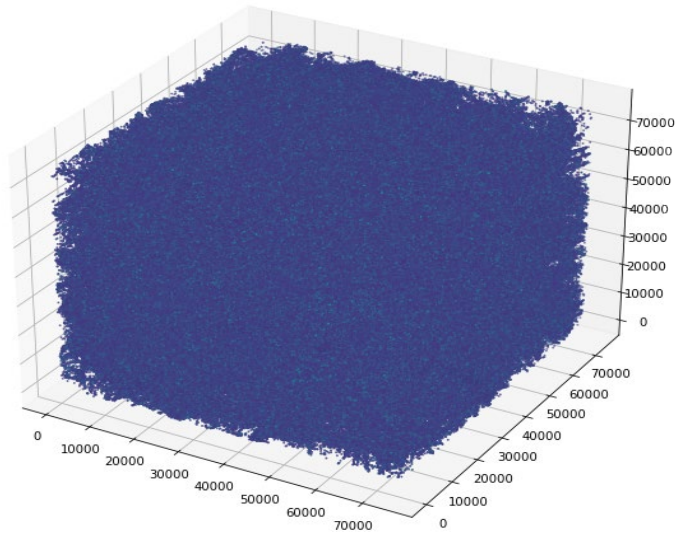


Fig.1 Resulting graph of rendered visuals for all data points.

Due to Many Subhalos Present, However, the Graph for the Large Part Seems Like One Large Blue Cube with Minimal Space between Each Subhalo as show in fig.2 to Remedy This, the Graphic Can Be Converted into a 2d Graphic by Removing the Z Coordinate. However, Putting All the Points on One 2d Visual Would Just Result in a Very Dense Blue Square. Thus, to Isolate the Points into a More Reasonable 2d Graph, an Index Can Be Used. the Index Can Be Controlled by the Z Coordinate. by Splitting the Cube into thin Slices Controlled by the Z-Axis, the Graphs Can Be Limited to a Much More Reasonable Number of Points. by Creating a While Loop, the Graph of Each Slice of the Cube Can Be Created Where the Center of the Slice is Entered by 5000 Each Time. in the End, a Sequence of Graphs Can Be Generated of the Positions of Subhalos Throughout the 100 Mpc Cube Investigated. the Following Graph is an Example of a Slice of Groupcat 98 and Illustrates How Much More Reasonable the Number of Points is.

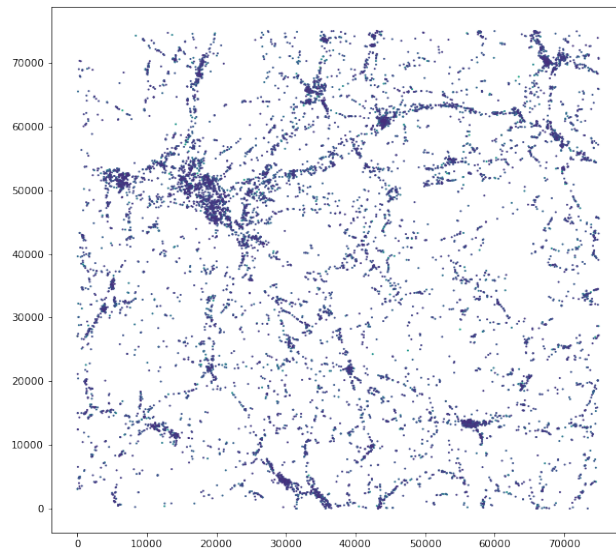


Fig.2 Two-dimensional graphics

As These Graphs Show the Position of the Points Throughout Space, These Positions Can Be Used to Find the Radius of the Subhalos to Generate the Final Density Profile. These Graphs Can Be Further Evolved into a Sequence of Photos to Show the Evolution of the Subhalo Positions Throughout Space. This Can Be Done by Taking a Single Slice of the Cube and Changing the Groupcat Used. by Using a Different Groupcat, the Resulting Image Will Be One of a Different Redshift. Then Each Visual Representation of the Data At Every Groupcat Number Can Be Combined to Create a Video of the Evolution in the Position of the Subhalos in the Given Slice. However, It Should Be Noted That the Change in Position of the Subhalos is Minimal Given the

Vast Units of Up to 100 Mpc for the X and y-Axis, Rendering Smaller Changes in Position to Be Nearly Impossible to Detect on the Graph.

2.2 2D Histograms

The IllustrisTNG data is split into two different files - groupcats and snapshots. The snapshot data for simulation 98 can be used as well to create a 2D histogram of the intensity of all the individual dark matter particles present in the region of space studied. The histogram is made 2D with 3D data points through a similar process done for the visualization subhalos distribution by using an index with the z component. By splitting the 100 Mpc cube into slices, the data becomes more manageable. This time to create a more precise evolution of the subhalo intensity in a given region, the slices are made smaller with a z-length of 1000 and where the center of each region is increased by 25 each time. For this 2D histogram, the subhalo 98 was used at a resolution of 100-2 due to the large file size of the snapshot for 100-1 as the data contains every dark matter particle that exists in the region of space.

Next, to construct the actual histogram, as show in fig.3 the spatial coordinates of all the contained dark matter particles within the snapshot of data can be set to distinct variables. This data can then be used to generate a 2D histogram by using the matplotlib library for Python where the data is projected out of the z-axis. The code for such a histogram can be seen on the right. The resolution was initially set to 64 bins. However, the generated image was vague in shape, so the resolution was adjusted to 512 bins. Through increasing the number of bins, the division of the data is increased allowing for a higher resolution. In addition, to automate the process of getting all 3000 graphs, a while loop can be used and the printing of a number can be used to ensure the code is continuously working. The line of `plt.clf()` should be noted for its importance in clearing the figure out of previous data. Without the line, the graph would be quickly overloaded with data from previous graphs leading to a completely covered graph. An example of one of the obtained 2D histograms can be seen below.

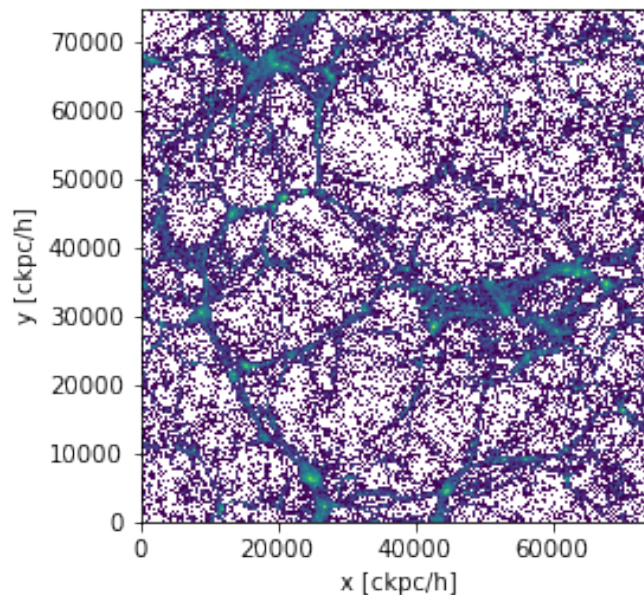


Fig.3 Histogram

By ordering all the slices into one smooth transition in the format of a video, the evolution of the intensity of subhalos across the simulated universe can be seen.

2.3 Density Profile

All subhalos share a similar distribution of mass. To examine this relationship of the distribution of mass, a density profile can be created which graphs density (y-axis) with radius (x-axis).

First, to find the radius, the Euclidean distance formula can be used. Taking the center of a subhalo in the groupcat data and the distance to each localized particle of dark matter found in the

snapshot data, the radius can be calculated. For this investigation, the subhalo of 0 was chosen within the data set of 98 for the initial investigation. It should be noted, however, the difference in x-coordinates of the center of the subhalo and the dark matter particles in the subhalo 0 are polarized to either around 0 or 75000. This is due to how the subhalo is near the edge of the cube leading to some of the points being moved to the opposite side of the cube. To amend this, the points that are near 75000 can be subtracted by 75000. Next, after having the radius values, the radius values can be taken to the log and then binned to produce 11 groups to be used in the final density profile.

Now, the density can be found. To do this, the assumption of a perfect sphere needs to be made. Following this, the subhalo can be divided into regions of hollow spheres of a given thickness based on the radius bins. Through this, the volumes of each region can be found. To get density, the number of dark matter particles can be taken in each region and divided by that region's volume since each dark matter particle can be assumed to have the same mass. Through this, there will be a total of 11 densities, each of them attributed to a unique radius value. In the end, the density can be graphed against the radius with a logarithmic scale to produce the following graph.

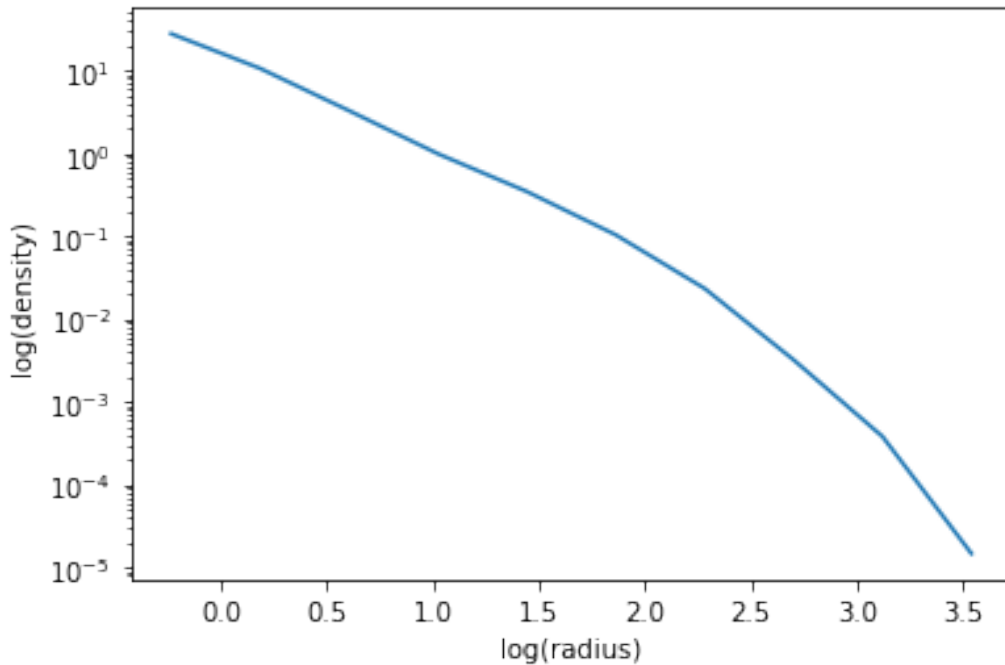


Fig.4 The correct density curve for Subhalo

Fig.4 Now, the Obtained Graph is the Correct Density Profile for Subhalo, However, to Analyze This Graph, a Relationship Needs to Be Established between Density and Radius. This Relationship is Already Well Established through the Navarro–Frenk–White Profile with the Equation:

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s} \left(1 + \frac{r}{R_s}\right)^2} \quad (1)$$

Here, ρ is density, ρ_0 and R_s (scale radius) are parameters that vary from halo to halo, and r is radius. Through curve fitting the found relationship, such a relationship would be obtained. However, around using brute force to try values for these parameters, a very close curve that nearly perfectly fits the established graph can be obtained.

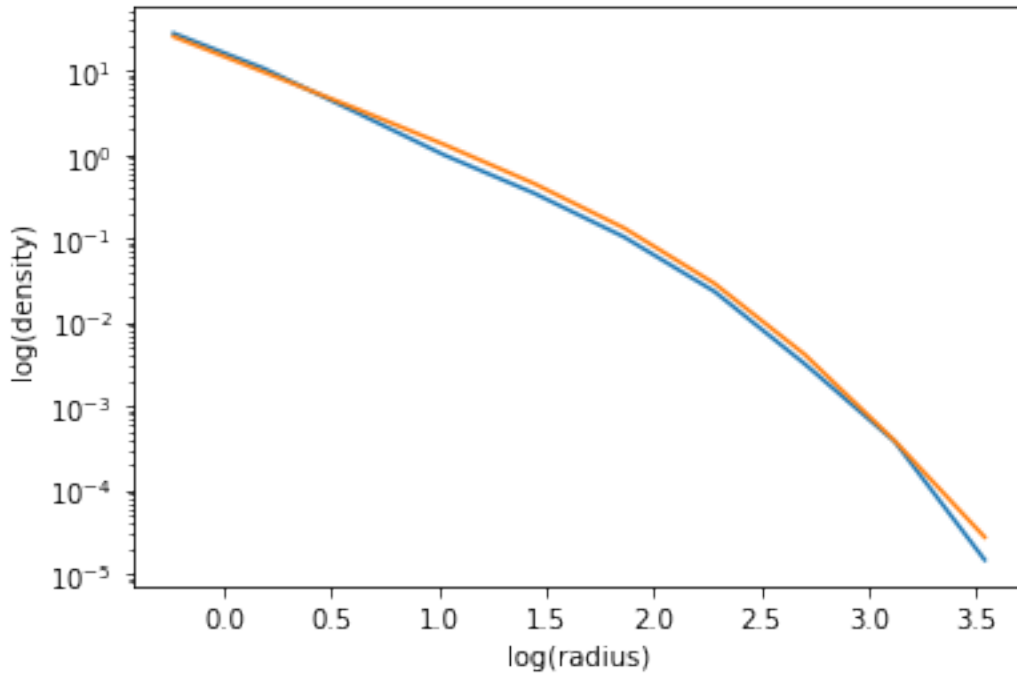


Fig.5 Such a Curve Was Created through Setting the Scale Radius as 300 and ρ_0 as 0.05. This Can Be Seen through the Used Code as Follows.

As such, it can be seen that this NFW equation can be seen from these simulations. However, this relationship being true is not just a coincidence and can be seen in other halos as well.

3. Discussion

The density profile, the NFW profile, in general illustrates the equilibrium configuration of dark matter halos found in different simulations. In general, the NFW profile allows for the estimation of the equilibrium configuration of subhalos found in the simulations of dark matter particles. The NFW profile, however, is not the only theory as the Einasto profile, which considers a third parameter, is considered by some to be the better model. However, the limited resolution of the current simulations prevents a conclusive conclusion to this issue. In addition, the NFW profile changes depending on the initial parameters of the simulation such as the assumption of the density of the universe. As more observational evidence is collected from the actual universe, the range of data is constrained more and more, allowing for better study into the NFW profiles.

The subhalo density profiles can be measured directly for massive galaxy clusters through the use of gravitational lensing. Currently, the collected data from these experiments have proven to fit well with the predicted NFW profiles where the scale factor and ρ_0 were estimated from other data collected from researchers. However, this accuracy has only been experienced from large massive galaxy clusters as with smaller mass halos, the gravitational lensing done has far too much noise to provide useful information regarding individual objects. Still, fairly accurate measurements can be made through the averaging of the data across similar systems. Currently, the inner regions of bright galaxies such as the Milky Way and M31 are believed to be compatible with the NFW profile. However, the NFW profile does not seem compatible with the observations made regarding the inner regions of low surface brightness galaxies with a lower central mass than from what is predicted. This conflict is known as the cuspy halo problem. With debate currently revolving around whether this conflict arises from a flaw in the modelling or is a consequence of dark matter's properties, the future of dark matter continues to remain an ongoing mystery. However, the answers to that mystery become ever more bright through the investigation of NFW profiles into the very nature of dark matter and how it interacts with the universe.

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