DARK MATTER DENSITY PROFILES OF HALOS IN THE ILLUSTRIS SIMULATION

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ABSTRACT

We conduct a detailed study of the evolution of dark matter density as a function of radius for the most massive galaxy halos in the Illustris Simulation. The dark matter density profiles of these clusters are fit using a generalized NFW function. With the tree structure of Illustris, each halo is traced back to its progenitor across many redshifts, gaining insights into the evolution of the profile parameters as a function of cosmic time and halo environment throughout the merger history. The power law value from the NFW function is plotted as a function of dark matter mass as well as dark matter percentage and compared to its progenitors, as is the total halo mass and dark matter percentage. We uncover correlations in the relationships among these parameters within individual halo tree histories. These correlations indicate that the process of hierarchical structure formation through mergers, while largely dependent on the initial conditions of each halo, does follow broader trends whose explanation we reserve for future work.

I. INTRODUCTION

BACKGROUND

Since the discovery of distant stars orbiting on the outskirts of galaxies at velocities much greater than the visible matter they encircled would suggest by Vera Rubin, Kent Ford and others, this strange gravitating mass that does not interact electromagnetically has been found to not only be a real component of the cosmos, but to also to be the primary matter component (Rubin et al 1970). Given that it is the largest gravitating mass energy source of the cosmos, we expect dark matter to play a dominant role in shaping the structure and formation of galaxies on the large scale of galaxy clusters. Galaxy Clusters are among the most massive objects that we observe, and are believed to have formed from a hierarchy of mergers where galaxies combine as a result of gravitational interactions to form groups. Our own local group is one such cluster. These processes make galaxy clusters some of the youngest gravitationally bound structures in the cosmos, given that they have undergone mergers since the beginning and in their present state represent the longest evolutionary progression (Poole et al 2006).

The composition of clusters, their components of stars, dark matter, and gas, provide a wealth of information about the underlying structure of our Universe. As the primary component of mass energy, composing approximately 85% of all known mass energy, dark matter is believed to be a dominant driver of the hierarchy of mergers. Its location, inferred from a variety of methods, in particular by detecting weak gravitational lensing shear, is found in halos that extend hundreds of kiloparsecs beyond the star rich centers, and on the large scale, dark matter is believed to be contained in web like structures connecting galaxies and pulling them together, serving as invisible yet dominant gravitational glue that plays a major role in the evolution of cluster formation (Kaiser et al 1986).

Of note, advancements in X-ray astronomy using the Chandra Space Telescope have greatly increased knowledge of galaxy clusters, from their scaling relations, their mass, to their physical structures and baryonic components, in particular, gas mass, which has been found to be a robust indicator for weak lensing (Mahdavi et al 2013). An example of the value in Chandra observations, is that it was successfully used along with

CFHT weak gravitational lensing data to obtain several measures of substructure, including central entropy, to determine the overall distribution of dark matter and gas in galaxy clusters under the assumption of hydrostatic equilibrium.

Finally, X-ray astronomy has also provided insights into the most energetic processes that occur at the centers of galaxies involving black holes. We know that black holes produce extraordinary amounts of energy. Combing this with simulations, it has been shown that these super massive black holes, which are the sources of power behind Active Galactic Nuclei, produce feedback mechanisms that rapidly heat gas and reduce the rate of star formation (Nelson et al 2015). Because the timescale of energy loss from radiative cooling determines the rate at which gas can cool into the halo center, these AGN processes control the rate at which stars can form, by reducing the ability for the gas to cool (White & Frenk 1991). The effect has been shown in simulations to result in galaxies that are darker and less baryon dominated than they would otherwise be, since the processes not only reduce star formation, but also displace gas. The effects are felt most dramatically in lower mass galaxies, such as dwarf spheroidal galaxies, which, have consequently been found to be consistently dark matter dominated.

Black holes have a profound influence over star formation and also gas heating, and therefore could affect the overall baryon fraction in clusters. Understanding the baryon fraction also depends on how dark matter is distributed in a cluster. In particular, the dark matter density profile serves as a critical tool in analyzing the structure of galaxy clusters. What I will examine in this paper is how the density of dark matter depends on the size of a cluster, its environment, (measured in terms of parameters such as its baryonic mass in the form of stars, gas and black holes), and on mergers it undergoes through cosmic time. I will then examine some other characteristics of the halo's components, such as its percent of dark matter (often called mass to light ratio) in order to determine if this has any correlation to the logarithmic density profile. Its dependence on time can be tracked through the evolution of its logarithmic density profile across mergers by tracking a cluster across a significant amount of time, and examining its density changes as it undergoes mergers with other halos and accumulates mass.

THE ILLUSTRIS PROJECT

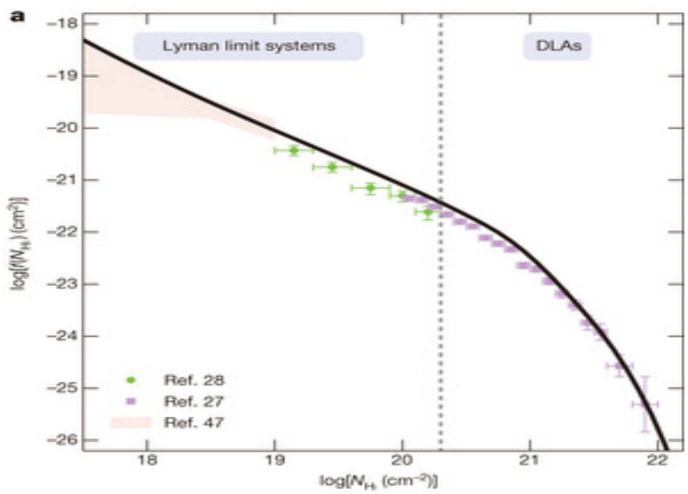
Since observations of galaxy clusters can only provide a snapshot of a galaxy cluster at one moment in time, in order to understand how galaxy clusters evolve across time, it is necessary to construct simulations incorporating as much physics as possible. In recent years, massive advancements have been made in computational capacity. This has enabled simulations to be greatly enhanced. For this paper, I have used the Illustris simulation, a highly advanced, hydrodynamical simulation that has produced significant results by successfully modeling internal velocity structures of disk galaxies which obey the stellar and gas Tully-Fisher relation while also producing the flat circular velocity curves that motivated the original papers on dark matter mentioned above (Vogelsberger et al 2014). The initial conditions assume a LCDM cosmology seeded with fluctuations consistent with WMAP-9 measurements, from which a linear power spectrum is used to create a random realization in a periodic box with side length 75 Mpc/h = 106.5 Mpc, at a starting redshift of 127. A series of simulations are run at different resolutions, and a second set is run with only dark matter. The main simulation initially has 1820^3 = 6,028,568,000 hydrodynamic cells, and the same number of DM particles and MC tracers (see table for more details, including mass resolutions and gravitational softening lengths). Evolving the main simulation to z=0 used 8,192 compute cores, a peak memory of 25 TB, and 19 million CPU hours (http://www.illustris-project.org/about/#astronomers).

The Ilustris Project, a Massive Cosmological Simulation, was created with the goals of surpassing the limitations of past simulations, reproducing observable properties of galaxies that other simulations had failed to create, specifically, simultaneously predicting galaxy statistics on large scales such as the distribution of neutral hydrogen and the galaxy population of massive galaxy clusters, together with galaxy properties on small scales, such as the morphology and detailed gas, dark matter, and stellar content of galaxies (Vogelsberger et al 2014). Illustris is a suite of cosmological simulations run with the moving mesh method called Arepo, including a comprehensive set of physical models critical for following the formation and evolution of galaxies across cosmic time. Each simulates a volume of 106MPC^3 (Nelson et al 2014). Whereas in the past large scale simulations employing n-body dynamics would focus on perhaps just a few dynamical components, in the Illustris Simulation, the dynamics of galaxies interacting in many complex ways was tackled. This is critical because it is well noted that these interactive processes play a major role in shaping the content and distribution of galaxies. Quoting from Genel 2013,

> “ Galaxies entering high density regions like clusters are prone to processes like ram pressure stripping, starvation, strangulation, and tidal stripping, which are captured self-consistently by hydrodynamical simulations, a major advantage over ad hoc treatments employed in semi-analytic models essentially evolving the equations of continuum hydrodynamics coupled with self-gravity”. The spatial discretization of the fluid is provided by an unstructured, moving, Voronoi tessellation. On the volumes defined by individual cells Godunov's method is employed, with a directionally unsplit MUSCL-Hancock scheme and an exact Riemann solver. The Voronoi mesh is generated from a set of control points which move with the local fluid velocity modulo mesh regularization corrections. Gravitational forces are computed using the Tree-PM approach, with long-range forces calculated with a Fourier particle-mesh method, and short-range forces with a hierarchical tree algorithm. The code is second order in space, and with hierarchical adaptive time-stepping, also second order in time. During the simulation we employ a Monte Carlo tracer particle scheme to follow the Lagrangian evolution of baryons.”

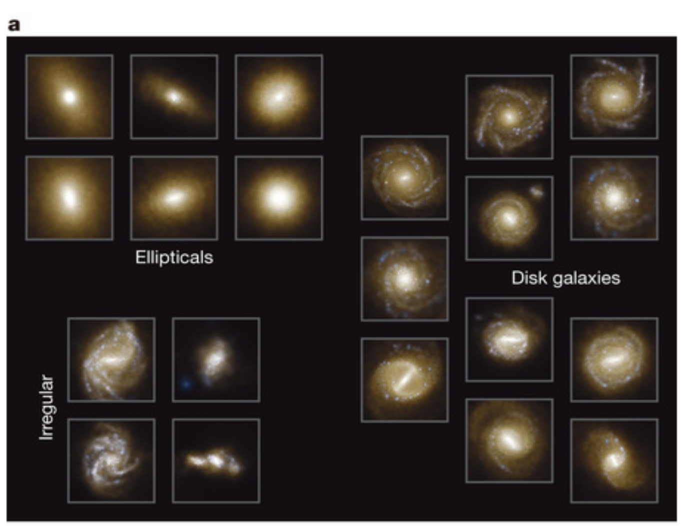
“These physical processes are significant because they influence, for example, the SF rates and colours of galaxies as a function of environment ” (Vogelsberger et al 2014). The stellar and gas mass buildup in the evolution of galaxies in Illustris has been well studied, and is detailed extensively. Illustris has succeeded in producing stellar populations that accurately model many observables, such as the range of metallicities seen in star populations, and the range and types of galaxies, such as spiral and ellipticals that are absent from other previous simulations.

FIGURE 1. NEUTRAL HYDROGEN - Column density distribution function (CDDF), $f(N_{HI})$, of neutral hydrogen at z = 3 compared to observations From M. Vogelsberger et al 2014



In the figure above, we see the successful prediction of neutral hydrogen abundance in the Illustris simulation, compared with observation. The success in replicated the hydrogen abundance is a phenomenal and critical success, given that neutral hydrogen is the most dominant element in the Universe and thus its abundance plays a significant role in the structure and formation of galaxies.

FIGURE 2. Visible luminosity profiles in Illustris (from Vogelsberger et al 2014)



II. ANALYSIS AND PROCEDURE

STATEMENT

Given the success of Illustris in simulating so many aspects of galactic astrophysics, we therefore pose the following questions in regards to galaxy clusters within Illustris: How well are the dark matter components of galaxy clusters in Illustris described by traditionally used cold dark matter density profiles, such as Navarro, Frenk, and White (1997 NFW) profile? How does the logarithmic density profile of a given halo vary with mass, and halo environment, such as dark matter percentage of a given halo? And is the slope of the logarithmic density profile sensitive to the dynamics within a cluster, such as mass redistributions occurring when clusters merge and gain mass?

DENSITY PROFILES: AN INTRODUCTION

First introduced by Navarro, Frenk and White (1997), NFW profiles are expressions of the density as a function of radius that are considered to be good models for the density distribution of dark matter on the large scale. Fitting these profiles to dark matter components of galaxies in Illustris would be a good test of whether this canonical dark matter profile, originally derived from pure cold dark matter simulations, is still relevant in full hydrodynamical simulations with black hole heating included. *In particular, we set out to test the evolution of the profile for individual halos undergoing mergers across cosmic time.*

To do this, we took dark matter density profiles of many galaxies in Illustris across many redshifts and compared them. The profile we chose is a modification of the NFW profile which contains several parameters, the most important being n, the power law associated with the density distribution.

NFW

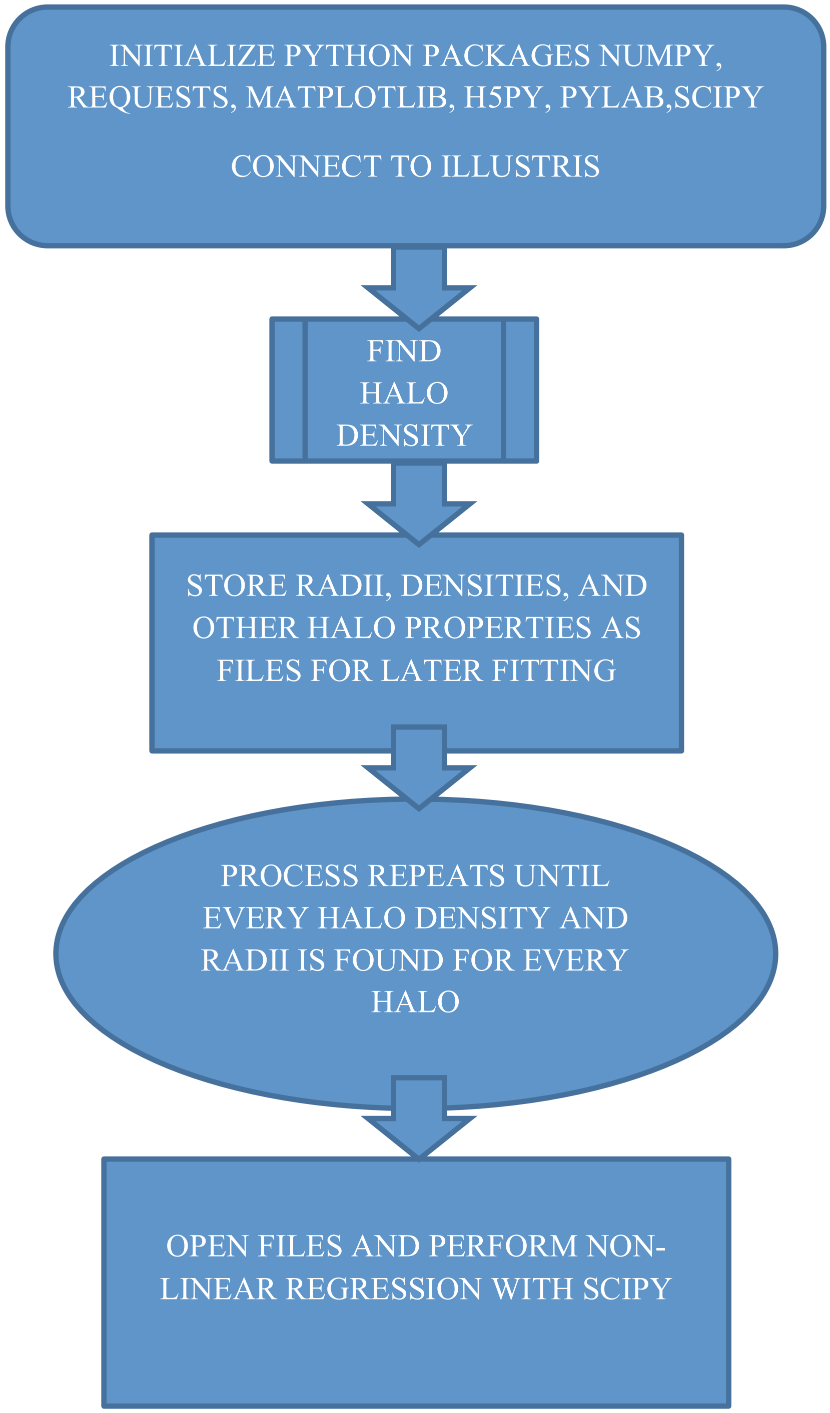
$$(1) \qquad Ar^{-n}\left(1+\frac{r}{r_0}\right)^{-3.0+n}$$

Here r represents the radius, r_0 is the scale radius and n is the power law. *n* determines the rate at which the logarithmic density of dark matter falls off at the center. Finding the NFW profiles of many galaxies in Illustris, particularly the most massive galaxies, would test the accuracy of Illustris' model for dark matter. Then, these profiles can be compared with each other. Examining the value of *n* for many halos could provide information about the impact of mergers on the dark matter density profiles of halos. The next natural question to ask is what effect baryonic components (gas and stars) might have on the structural components of a galaxy, impacting the overall distribution of dark matter. We could also ask whether black hole AGN outbursts have a significant effect. One quantitative measure of the baryonic component of a galaxy is the ratio of dark matter to total mass of a given halo. Once this is found, it can be examined to see if it is correlated to the power law value *n* of a given cluster. Another interesting aspect to examine, is the overall effect of the potential associated with the cluster itself, and if this potential alone affects the power law *n* in a significant way. Since the potential is directly proportional to the mass, we can examine the correlation of by comparing the total amount of dark matter mass vs. power law value *n.*

COMPUTATIONAL BACKGROUND

We set out to measure *n* for a large number of halos in Illustris at redshift zero, and to trace n back in cosmic time. In order to examine thousands of halos contained in the Illustris simulation, it was necessary to write programs where a majority of the work could be automated. For this task, the decision was made to work in the Linux Operating System, using Python version 2.7 and SQLite3. Python is a versatile language for scientific computing, offering a large number of novel packages that were used extensively in this project. For example, Scipy is an extensive machine learning module ideal for many applications. For the task of fitting density data, Scipy proved to be a valuable tool. The first step was finding the density profiles associated with a given Halo in Illustris. A chart of how this was accomplished is shown below in figure 3.

FIGURE 3. LOGICAL PROGRESSION OF THE MAIN PROGRAM



EXTRACTING THE DENSITIES OF DARK MATTER PARTICLES

Since the Illustris Project is hosted on a remote server exposing the simulation output to a novel API, we can define a Python function allowing a program to pull data directly from Illustris' API. First we can initialize empty arrays for quantities that will be extracted. Table 1 below shows some quantities that we extracted from a given halo for later analysis.

TABLE 1 Important Quantities of Interest for Halos in Illustris

Dark Matter Percentage	Total Halo Mass	Total Dark Mass	Halo ID	Progenitor ID	Descendant ID	Redshift	Star Half Mass Radius	DM Half Mass Radius

While we will need to write a program to get the specific density of dark matter at any radii, (which is needed to do the NFW Fits), Illustris already contains fields about every halo, so for instance, we can automatically compute the exact percentage of dark matter, simply divide the field dark matter mass by the total mass. Many other useful quantities such as redshift are also included. Thus, we will extract fixed number of dark matter particles, moving radially outward. The radius at which the last particle found is calculated, and the finishing radii minus the starting radius will form the radius of the sphere in which the dark matter particles are contained. Thus, we will have a fixed dark matter mass, but the radius will always be variable. From these quantities, we calculate the density of dark matter and the process resumes until every density has been found for the given halo in question.

After these initializations, we can define a while loop that will iterate by 1 and run as long as we have a halo id to pull from. For example, consider a search for halos between a mass range of 10^15 solar masses to 10^12.9, and our result pulls up 200 halos, we can store these halo ids in a list. The number of iterations will then be equal to the length of the list. Thus, while we are still on a shorter length than the end of the list, the while loop will continue looping through and grabbing the next halo. We can pull up the url associated with the given halo. This url will be a variable and will change depending on the halo in question.

```
url = "http://www.illustris-project.org/api/Illustris-
2/snapshots/135/subhalos/" + str(id)
```

The next step is where we begin to get our coordinates of the dark matter particles. Within the first While Loop pull out dark matter mass points for x, y and z, denoted as dx, dy, dz:

```
with h5py.File(saved_filename) as f:

        dx = f['PartType1']['Coordinates'][:,0] - sub['pos_x']

        dy = f['PartType1']['Coordinates'][:,1] - sub['pos_y']

        dz = f['PartType1']['Coordinates'][:,2] - sub['pos_z']

        rr2 = np.sqrt(dx**2 + dy**2 + dz**2)
```

What these lines of code accomplish is simple; they define which coordinates we want to describe as x coordinates, which ones as y, and which ones as z. The next line defines the transition to spherical coordinates. After this, we will deal with the radial distance away from the center of the halo. It is at this initial 0 distance the program counts outward from.

```
rr2 *= scale_factor/little_h # ckpc/h -> physical kpc
rrr2 = sorted(rr2)
darkmattermass_density = ([])
radial_distance2 = ([])
coun = 0
iter = len(rrr2) / (150)
remainder = len(rrr2) % (150)
dark_matters = ([])
outer_radius2 = ([])
```

Since Illustris contains an expansion of coordinates as consistent with results indicating that a big bang occurred, including the microwave background radiation measurements, we must multiply the radial coordinates by the appropriate scale factor from the appropriate Friedman-Robertson-Walker general relativistic metric. The scale factor is different for each redshift and is calculated from the redshift itself at the beginning of the program. The next line sorts the coordinates. Since each counted dark matter particle will have a specific coordinate, these are sorted in order. Then an iteration constant is defined where the number of particles can be chosen. In this case, the number chosen was 150. We generally need to choose a fairly reasonably sized iteration, to minimize count error. This is due to the fact that the fractional Poisson error is equal to

$$\frac{1}{\sqrt{N}}$$

Thus, the larger N is, the smaller the fractional error. However, we need to choose a smaller N as the halo size we look at decreases, so it is inevitable that there will simply be more error associated with the process if N is smaller. Most of the analysis presented here was done on massive halos with a quantify N per iteration, however, many smaller halos were also examined to shed light on certain aspects of the overall distribution of halos and their related properties.

In the code presented above the program will count the first 150 particles then count the last particles radial coordinate position. This will determine the radial position from which the density will be calculated. It is important to allow for the possibility of a remainder because without doing so the program will encounter errors, and in most cases a remainder will exist.

Now, in the next step the mass of the set of dark matter particles counted is calculated. Since each dm particle has the exact same mass, this is easy, and it simply involves multiplying the length of the number of dm particles counted by the mass of 1 dm particle.

```
while coun < iter:
        top5 = rrr2[:150]
        outer_radius2.insert(coun,top5[149])
        totaldm_mass = len(top5) * 0.0035271
        dark_matters.insert(coun,totaldm_mass)
        coun = coun + 1
outer_radius2.insert(0,0)
```

In this case, the count is every 150 particles, multiply by the mass of 1 dark matter particle, sum to get the mass, then divide by the volume, which is variable and found from the other loop, which counts the last value corresponding to the last particle counted. That value is the outer radius, (outer_radius[m + 1]) while the first particle counted has a coordinate that is the previous outer radius, i.e.

outer_radius[m].

```
m = 0

dark_mass_density = ([])

while m < iter :

        if remainder > 0 :

        volume2 = (4.0/3.0)*3.14*((outer_radius2[m + 1])**3) -
(4.0/3.0)*3.14*((outer_radius2[m])**3)

        elif remainder == 0:

                volume2 = (4.0/3.0)*3.14*((outer_radius2[m +
1])**3) - (4.0/3.0)*3.14*((outer_radius2[m])**3)

        density = (dark_matters[m]) / (volume2)

        dark_mass_density.insert(m,density)

        m = m + 1
```

A density value is computed for every set of 150 dark matter particles, in order. For smaller halos, one will need to lower the iteration to perhaps just 2 or 3 particles to get a suitable number of data points. These density values are stored in an array. It is important to make use of the concept of the scale radius. Because the NFW profile is only valid to the virial radius, we cut off profiles at this radius. An appropriate estimate of the virial radisu is R_{200}, the radius at which the cluster density is 200 times the density of the Universe. llustris contains the proper treatment of the overdensity in terms of vacuum density parameter Omega_lambda, the matter density parameter Omega_M0, redshift , and Hubble constant as part of its extensive physical model, so these can be used to calculate the critical density for the given halo, R_{200}. This value will determine the cutoff point at which we no longer consider the density points. For Illustris,

$$\Omega_\lambda \ = 0.7,\ \Omega_{M0} = 0.3,\ Ho = 2.2683 * 10^{-18}$$

$$(2) \qquad \rho_{critical} \ = \frac{3H_0\left[\Omega_\lambda + (1\ + redshift)^3\Omega_{M0}\right]}{8\pi G}$$

When R_{200} has been reached, the loop terminates and the remaining density points are ignored, allowing the profile to converge, and thus enabling the NFW fit to be performed.

```
for x in dark_mass_density:

        if x > P_200:

                dm_density.append(x)
```

AUTOMATION

The goal is to extract information from thousands of halos, so we must automate this process. One important step to accomplish this is to create filenames for all the different values extracted from the given Illustris halo. These text files will be stored in the same directory, and will be pulled out by the next program for fitting and analysis. The name of each text file is a variable and is associated with the given halo. Not only do we need to create text files for all the values found from a given halo, but we will also need to create files containing the actual names of the files we just created. This is so we can send a list of these file names to the next program in order for the program to know which files to open. Thus, several text files containing the names of all the text files just created are made. This object, essentially a list of all the text files, will be given to the next program. In this way, the program will automatically know which files to open up and perform non-linear regression on.

Once the lists of text files, which contain the names of given files, are created, they are closed and the program has concluded. The average run time for this program, with a reasonably sized iteration, is roughly 2 hours. If a smaller value of dark matter particles were counted (i.e.iteration) were chosen, more halos could be extracted, but the time required would be days/weeks to run without a super computer, given the large number of halos, and length of time required to iterate over the largest halos with a small iteration constant. This is because the number of computations would be greatly extended. Every time a fixed number of particles is found, a density is calculated, so the fewer number of fixed particles, the larger number of data points. However, particles may closely overlap, so if we choose to small of a number of particles to count before a density is calculated, this will introduce error. These are the disadvantages of a small iteration constant. The advantage of a smaller iteration constant is that smaller mass halos can then be fit simultaneously, and it would be possible to relate an even larger number of halos to their progenitors, across a larger mass scale. However, without an incredibly fast computer, this process is not easy. However, we did in fact do just this for 10,000 halos at redshift zero, in order to get a good overview of the halo properties at a mass scale from 10^15 to 10^10 solar masses.

FITTING

For the fitting, the process is fairly straightforward. All the files are opened based on the names and ids of the halos given, which were generated in order to make the process fully automated. Each halo has its density and radius fit to the NFW profile. For this, we used Scipy curvefit. In order to get a proper fit, it was necessary to restrict the value of powerlaw parameter between 0 and 2. Each profile fit was saved and stored in a PDF document, using PDF Pages, and so each fit can be referred back to when convenient. For each fit, both the density, and the total mass as a function of radius was plotted on a logarithmic plot. The profiles reveal a consistent fit with NFW model, with a steadily increasing mass for the halo as a function of radius. See figures 4,5, and 6.

THE ROLE OF SQLITE3

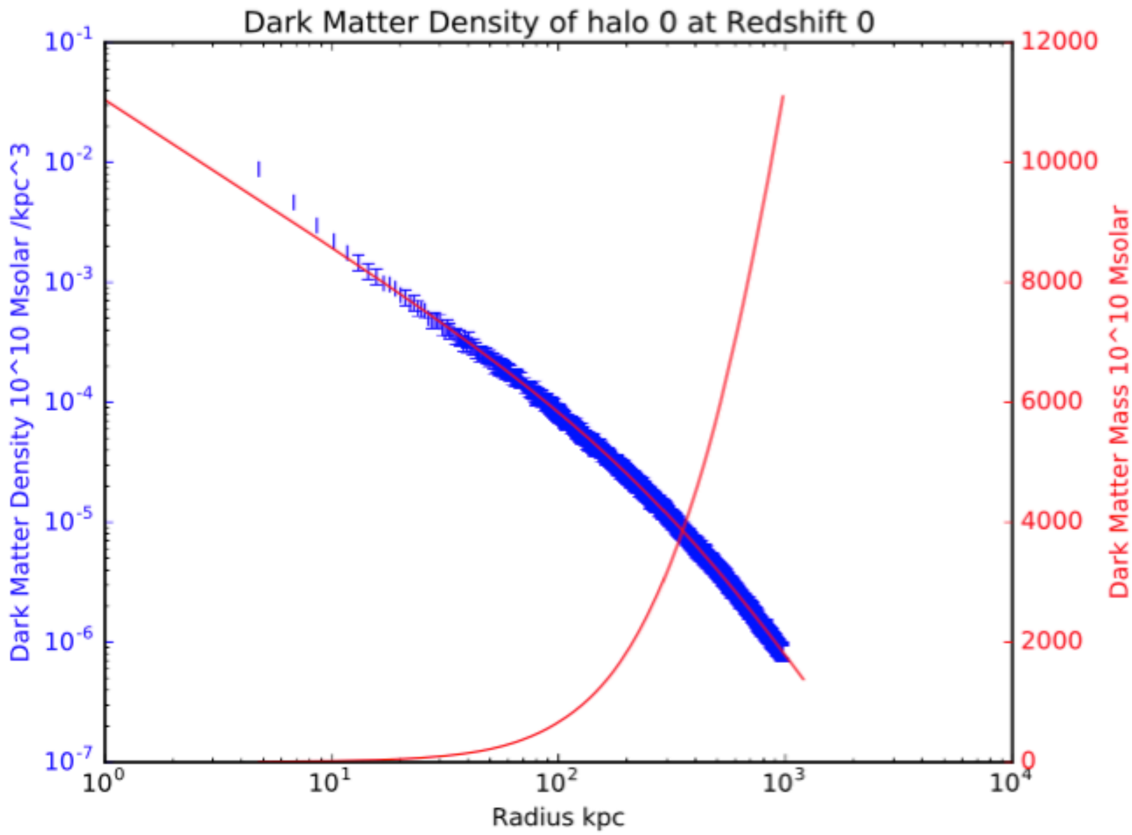
In addition to Python, a relational database was critical to connecting related halos. Because each halo has a parent and progenitor, given that Illustris has a tree structure, this was used to relate each halo to its progenitor. In this way, a collection of the most massive halos could be traced back across many redshifts. Starting with the latest redshift, the most massive halos (>= 10^13 M_solar) were examined and the features were stored in a relational database. Each database could then have entries matched based off of common progenitor. In this way, a new database was created where the lineage of related halos and all of their progenitors was generated. SQLITE3 was ideal for this purpose, because it has all the functionality of SQL databases, but does not require a server and other features that are time consuming to set up. SQLITE3 is fully supported by Python2.7, so a connection can simply be defined with the python program for the task of inputting the data needed into the corresponding database. This is precisely what was done for this project.

Once the family tree of a given cluster was found, it was possible to examine many structural relationships between a given cluster's gas mass, dark matter density, star mass, mass to light ratio (in terms of percentage of dark matter of a given halo) and other properties such as a given cluster's distribution of star, gas and dark matter in the central region and how these properties changed as the cluster grew and evolved through mergers across redshifts. The evolution of the power law fit was compared to many of these properties and plotted using linear fits, as were many other structural relationships of the halos. The linear coefficients were calculated and compared across redshifts. Doing so revealed the structural relationships: dark matter percentage vs. power law (n for NFW fits), dark matter percentage vs. gas mass and star mass, power law vs. average dark matter, gas, and star densities at half mass radius. NFW profiles were also obtained for low mass halos in Illustris, although these low mass profiles were not connected through their progenitors due to time constraints.

III). Massive Galaxy Profiles

The most massive galaxy clusters in Illustris are well described by NFW fits. A total of roughly 20,000 galaxies were examined. Of these, 1500 were traced through a large portion of their evolution.

Figure 4. A Density Profile of a Massive Halo in Illustris



Figures 4, 5, and 6 are examples of halos fit using the NFW profile. Tables 2 and 3 give values found for some of the halos that were examined in Illustris for this paper. These tables contain the parameters and errors associated with the NFW fits. Table 2 contains the values for the last redshift. Earlier redshifts produced similar results, the primary difference being that the halos were smaller in mass, having had less time to accumulate mass from mergers. Figure 2 on the previous page is of halo id = 0, the most massive halo at redshift 0. This halo has a mass of roughly 1.9 x 10 ^15 solar masses, and spreads out across 1 mega pc.

Looking at figure 4, the most massive halo in Illustris at redshift zero, we see that the fit is very good for much of the extent, except for the innermost regions. This result is common, and the cause is due to complex behavior of the dark matter density in the innermost regions. This is believed to be due to interactions with baryonic components of the halo in the innermost regions, particularly energetic feedback from black holes and stars.

Figure 5. Massive Dark Matter Halo Fits at the final redshift (snap 135)

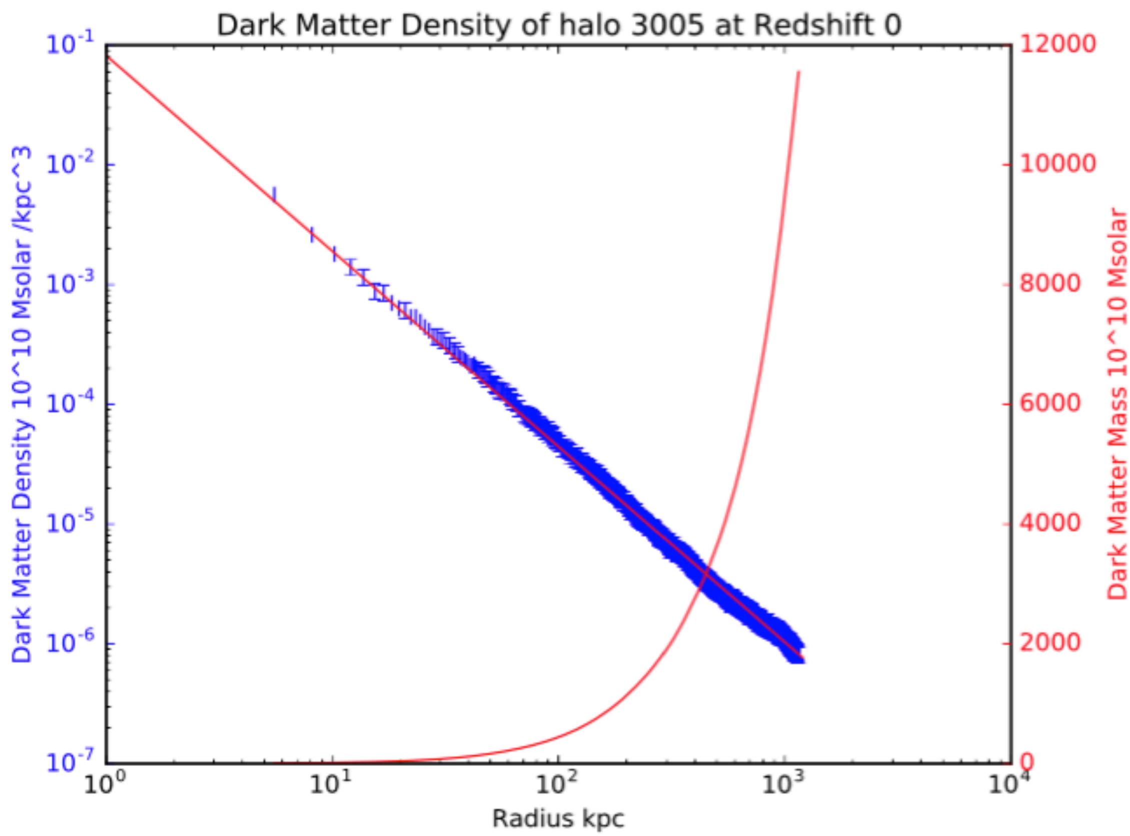


Figure 5 above is another massive halo. The increase in mass with radius matches well with the density profile.

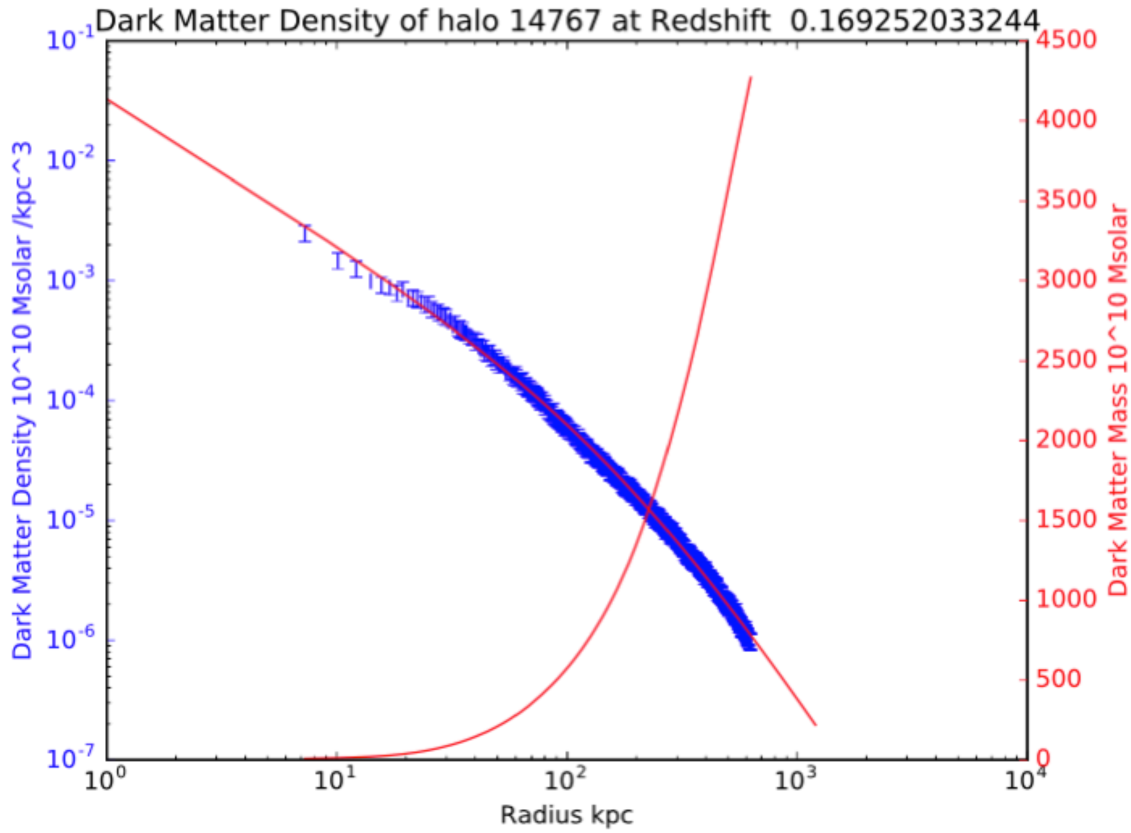
TABLE 2: Values for NFW fits (Massive Halos at Snap 135)

id	n	ner	a	aer	r0	r0er
0.0	1.20201121797	0.00390157069892	0.031573372356	0.00047597667948	382.573300575	2.33584688507
3005.0	1.62617533889	0.00119721733761	0.0782914419346	0.000596431776035	4439471400.95	0.0
5317.0	1.44794595859	0.00370941016944	0.0766288376961	0.00115770838307	651.50736037	5.96798428792
7077.0	1.40407554381	0.00474231995813	0.0632163040565	0.00109906316287	352.186985463	3.27468054164
10299.0	1.45484788	0.00405065844147	0.0720236809705	0.00110364096587	439.51117081	3.99764011577
8952.0	1.18534474467	0.0120302401476	0.0200213001084	0.000886836653874	320.310150934	6.00495767485
15066.0	1.43785581877	0.00563791791526	0.0609868460046	0.00131867540636	479.502115051	6.23928293067
12430.0	1.34492949366	0.00582637491184	0.0388331611543	0.000849289296261	394.5579203	4.45190777884
11426.0	1.39818811062	0.00472350862259	0.054357928785	0.000967102174965	410.064264904	3.99305747276
16352.0	1.17480785107	0.00842910702789	0.0272206299833	0.000792760591316	234.618447435	2.85917858032
17407.0	1.40805644145	0.00670165710229	0.0539976482811	0.00124451198205	269.200925611	3.39556876849
13786.0	1.21725527137	0.0132468876941	0.0393615145918	0.00146145643699	107.373761432	1.83471268857
21301.0	1.68112752277	0.00463603563986	0.150952250252	0.00257300656093	505.154599638	7.78877173718
20805.0	1.63190996574	0.00470949385236	0.105537082279	0.00180693262247	457.415503272	6.45212399617
21896.0	1.43958250307	0.00733941939704	0.0491199147346	0.00129494641801	359.660127405	5.82566004566
20191.0	1.26450518298	0.0137559169291	0.0175919064214	0.000886618505728	357.636490472	9.00496006818
22338.0	1.70988702093	0.00229829228766	0.0640048333835	0.000856721561547	4597081708.14	0.0
25355.0	1.59782037143	0.00508140588158	0.0547508685837	0.00111626991067	1027.54220036	23.396314696
24569.0	0.97340178091	0.0205831666123	0.0204498940164	0.00115740351767	91.091546168	1.91942220513
23556.0	1.61167034084	0.00918536092157	0.043764103488	0.00156842023582	985.699678649	43.725852641
18448.0	1.46981903164	0.0139439653575	0.0186242122104	0.000996262725143	755.569489049	38.0150202923
22968.0	1.33190134333	0.00938359297318	0.0285596887707	0.000887150906178	231.586050608	3.84454568893
26957.0	1.47013908	0.00886343257335	0.0576916238416	0.00166394385094	233.371236786	4.22319146674
26166.0	1.63101947423	0.00640713845684	0.0949547156897	0.00208966263894	356.0551122	6.55904134484
28110.0	1.52763804893	0.00762414863966	0.0857514152899	0.00200408739054	183.866494228	2.83929517376
28784.0	1.25372602117	0.0107913012017	0.02467575371	0.000857833012216	194.615046488	3.27269268718
26538.0	1.70714269845	0.00638215815683	0.0994543368006	0.00229639553063	575.104051417	14.8125445874

TABLE 2 continued.

id	n	ner	a	aer	r0	r0er
25783.0	1.39880569204	0.0105461243086	0.0306360408759	0.00106419659893	247.478679467	5.18490206429
30601.0	1.20598116518	0.0138980625866	0.0185416084284	0.000836826766638	193.849276162	3.96307167246
24162.0	1.46216674462	0.00827331198066	0.0471458800186	0.00127288129023	236.956761654	4.01022785913
30279.0	1.29581915492	0.0117845282388	0.0347700124389	0.00124683082839	156.106691292	2.81289334301
27709.0	1.67523633008	0.00750500062268	0.0779354267625	0.00208984141033	522.476637089	14.7537880561
28421.0	1.61467790692	0.00763408672736	0.0698134153005	0.00179520127103	327.646199674	6.97529691646
34096.0	1.37512459413	0.0110575215456	0.045646333843	0.00151383858712	155.254327605	2.84805816516
31619.0	1.36551771699	0.0127394328952	0.0191633550926	0.000916819757626	514.628511609	16.5882556771
29926.0	1.562002263	0.00820475112881	0.0522481658039	0.00144347476343	317.709281168	6.80649513039
34343.0	1.49584178506	0.00811839668395	0.0551940377001	0.00143656182395	225.336335835	3.8424966004
33763.0	1.46293858917	0.0102315531818	0.0480702031045	0.00150214763384	179.505134096	3.51348277273
19510.0	1.59511413046	0.00904426419268	0.0635227431873	0.00192133520461	317.044281894	7.81517184115
32831.0	1.7060400561	0.00730183127846	0.0775254632891	0.00203953298117	617.260194034	19.8050098891
29527.0	1.49174855226	0.00931525966117	0.0599568097595	0.001696729483	179.10361998	3.2993635743
35205.0	1.34017444089	0.0157718394473	0.0472432482251	0.00205721428468	110.189851222	2.56425586121
34763.0	1.31405342309	0.0129544137229	0.0181716918867	0.000807689390745	284.972328923	7.03330747879
27324.0	1.15883125694	0.0177337604439	0.0194562360741	0.00098412042307	118.238848626	2.74648514987
31916.0	1.82016122909	0.00798834758701	0.098055302918	0.00279498877502	788.01619239	39.4286983906
29148.0	1.64479693059	0.00857600657255	0.0726103679368	0.00196258357164	254.258084596	5.97914228659
1.0	1.58793273635	0.0144810139144	0.0494743465184	0.00229430331823	270.4434956	10.4991016435
13787.0	1.32342739594	0.0166822010556	0.0243638374519	0.00134610576406	240.721107446	7.32158722162
31297.0	1.61687808838	0.00928591463052	0.0532480192961	0.00172859930565	443.8088848	13.6672450311
35944.0	1.67775407301	0.0114880648847	0.0693742046911	0.00274084119688	438.573469344	18.2286907954
34984.0	1.6155924697	0.00863460259038	0.0565440430052	0.00162748956016	330.67470528	8.32655103689
34577.0	1.81027967958	0.00989175446162	0.114542880855	0.00379548754084	442.250541703	19.1621465626
30923.0	1.8951388116	0.00624144587128	0.0941417063476	0.00228636298095	27472.8005637	28190.6083702
37938.0	1.51689489562	0.012418286307	0.0640326944143	0.00235294721045	167.246912196	4.210838121
36905.0	1.65547974132	0.00832254238101	0.0395620314398	0.00123892821176	972.389946954	45.5084540524
39240.0	1.49221493304	0.0118381779035	0.0572527868726	0.00198113597326	156.606402932	3.60152035108

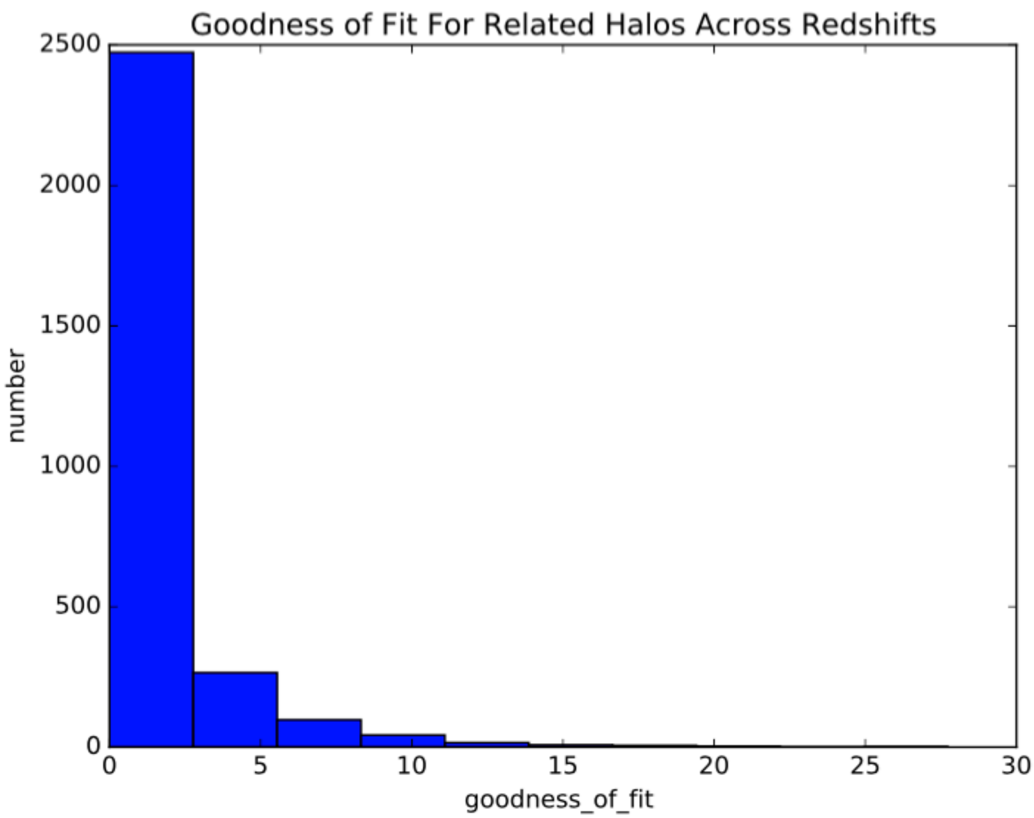
FIGURE 6. A less massive halo at earlier redshift (0.169).



In figure 6, we see another massive halo at slightly earlier redshift (0.16). The results of the fit are successful for the majority of the radial extent, but again, in the innermost regions, the fit is less successful. Because of complicated factors related to the interactions of baryons, many fits had more trouble in the innermost regions. This has motivated an extensive statistical overview of the quality of fits, in order to ensure that the fitting of halos falls within an acceptable range.

Figure 7 below shows the goodness of fit for all the halos fit. The histogram reveals that the overall quality of fits is very good, despite the complications resulting from baryons in the central regions of halos.

FIGURE 7. Goodness of Fit For Massive Halos



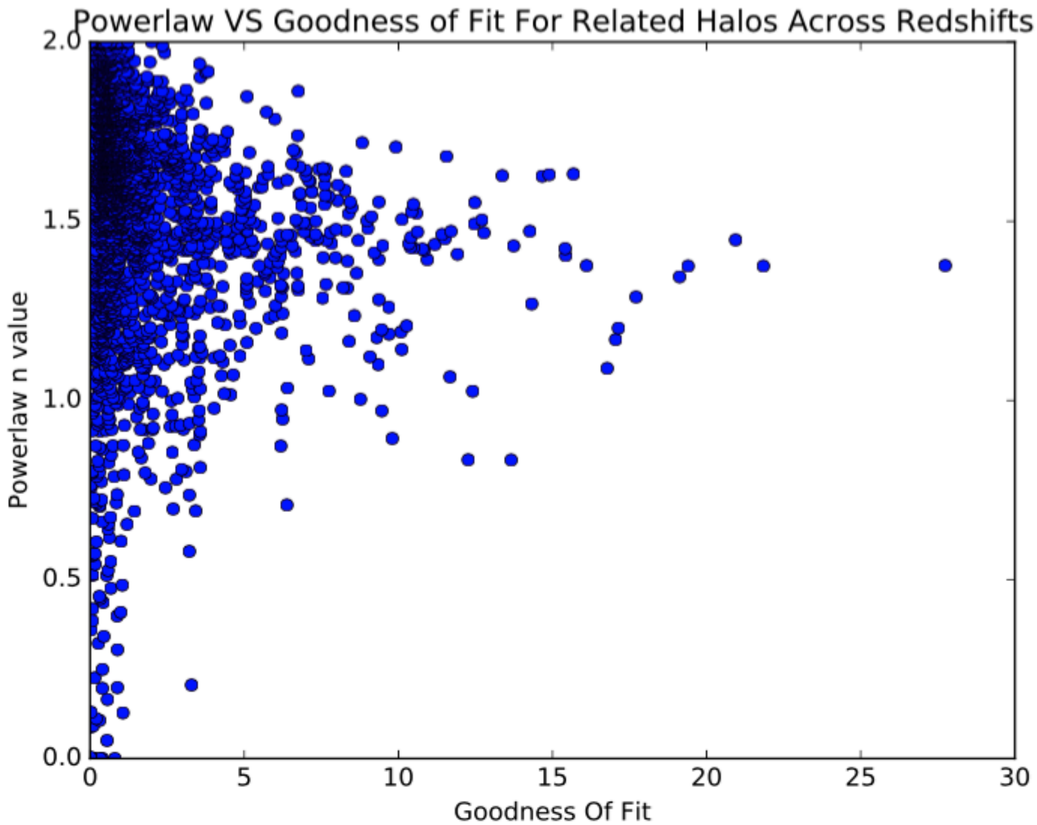
Approximately 3,000 of the most massive halos in Illustris were examined across 23 redshifts. The goodness of fit for the n value of the NFW profile fits are shown above.

The consistency of the fit is measured by the goodness of fit, which is defined as

$$Goodness\ of\ Fit\ =\ \frac{\chi^2}{N}$$

The majority of halos fit had profiles with a goodness of fit that was less than 2.5.

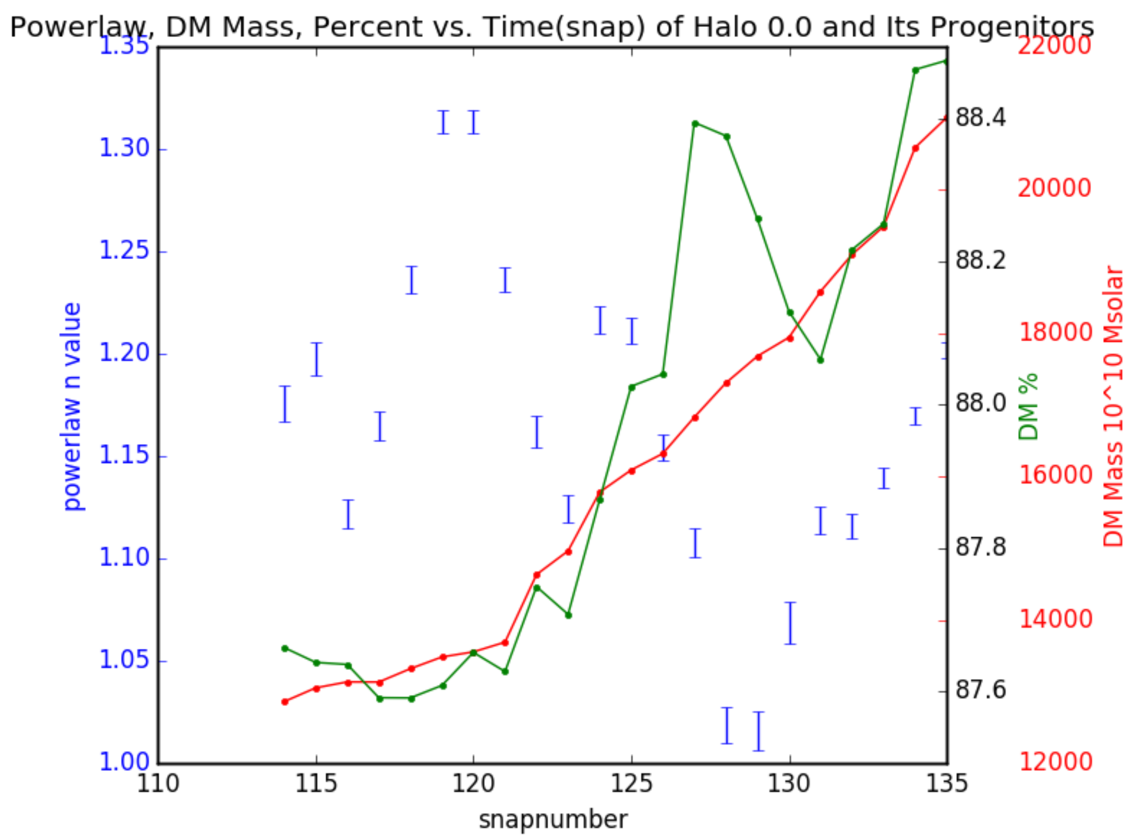
FIGURE 8. Power – Law Vs. Goodness of Fit



Another important measure of error was the Powerlaw as a function of goodness of fit. If the majority of bad fits were clustered around a specific power law value, this would indicate that errors were occurring with the fitting. Examining this plot however, reveals a small goodness of fit across the full range of power law values, revealing that the fits were good across many halos.

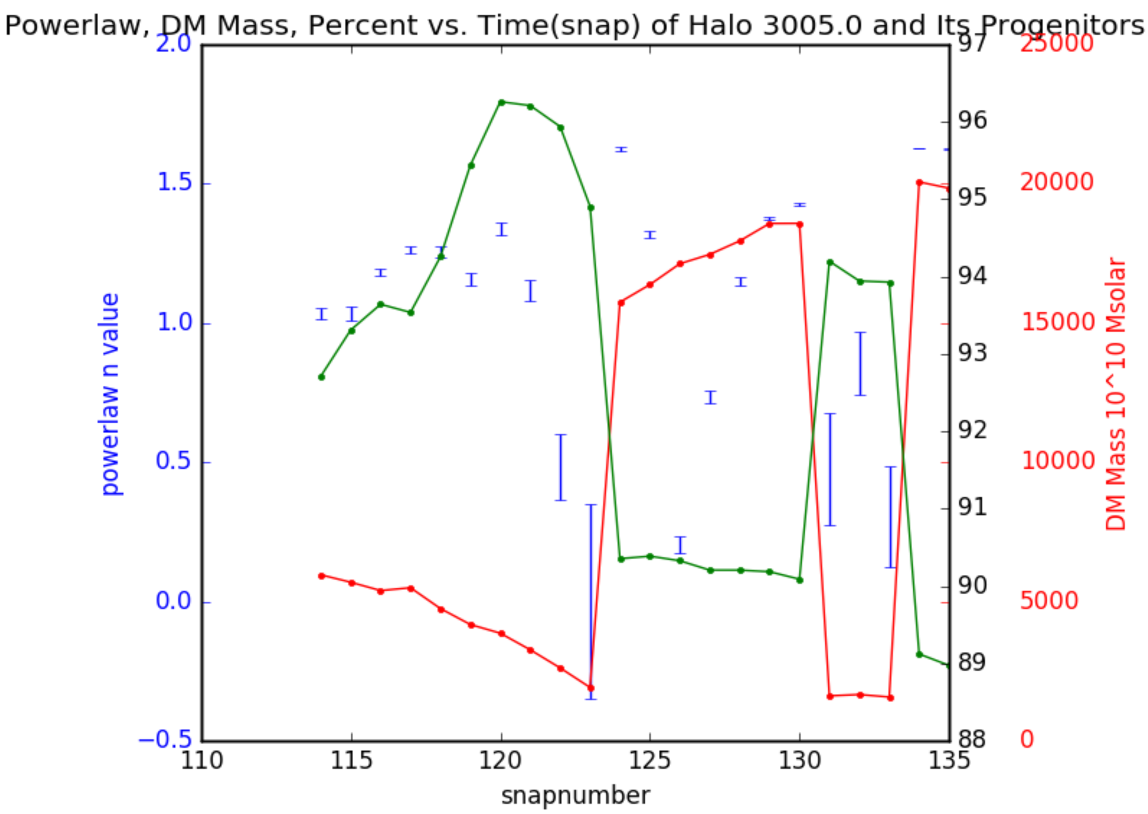
IV). TIME EVOLUTION OF HALOS

FIGURE 9. The change in Power law value n and mass for halo 0 and Progenitors reveals that the power law is variable across redshifts. In this case, dark matter percentage is positively correlated with total dark matter mass for this evolutionary group of halos.



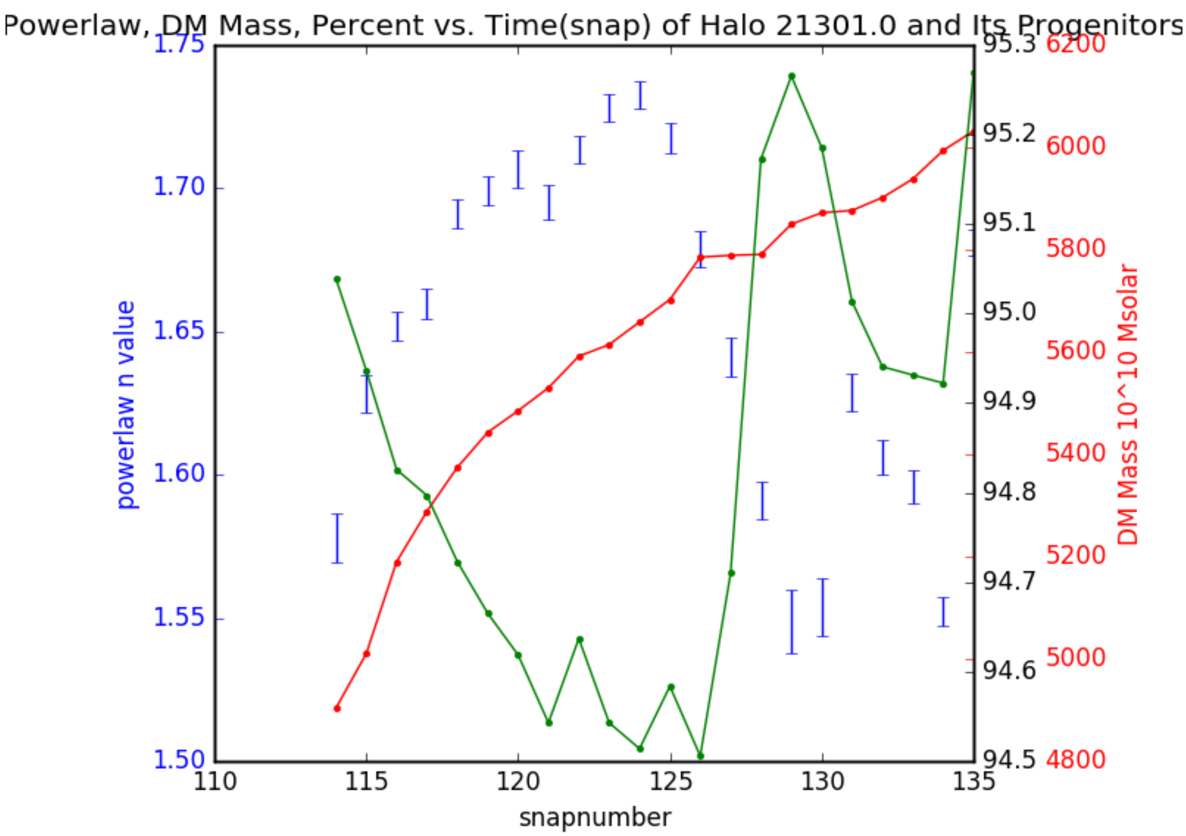
Once the dark matter density profiles of thousands of halos and their related progenitors were fit, the next step was to examine how the power law value changed in response to mergers. Since each of the most massive halos at redshift 0 could be traced back through generations through relational database SQLITE3, we were able to trace back the change of each halo in response to mergers and then plot these changes as a function of time. Figure 7 is one example, for a group of related galaxy clusters. Snapshot 135 is the final halo, which has evolved from the first halo at snapshot 113 in the series. This plot is interesting, because for this group of halos, there is consistent (though not quite linear) increase in dark matter fraction as a function of time and mass increase.

FIGURE 10. For id = 3005, the 2nd most massive halo at redshift 0, dark matter mass and dark matter percentage were strongly inversely correlated. On the other hand, power law value n, which determines the density fall off as a function of radius, appears to be strongly correlated to dark matter percentage.



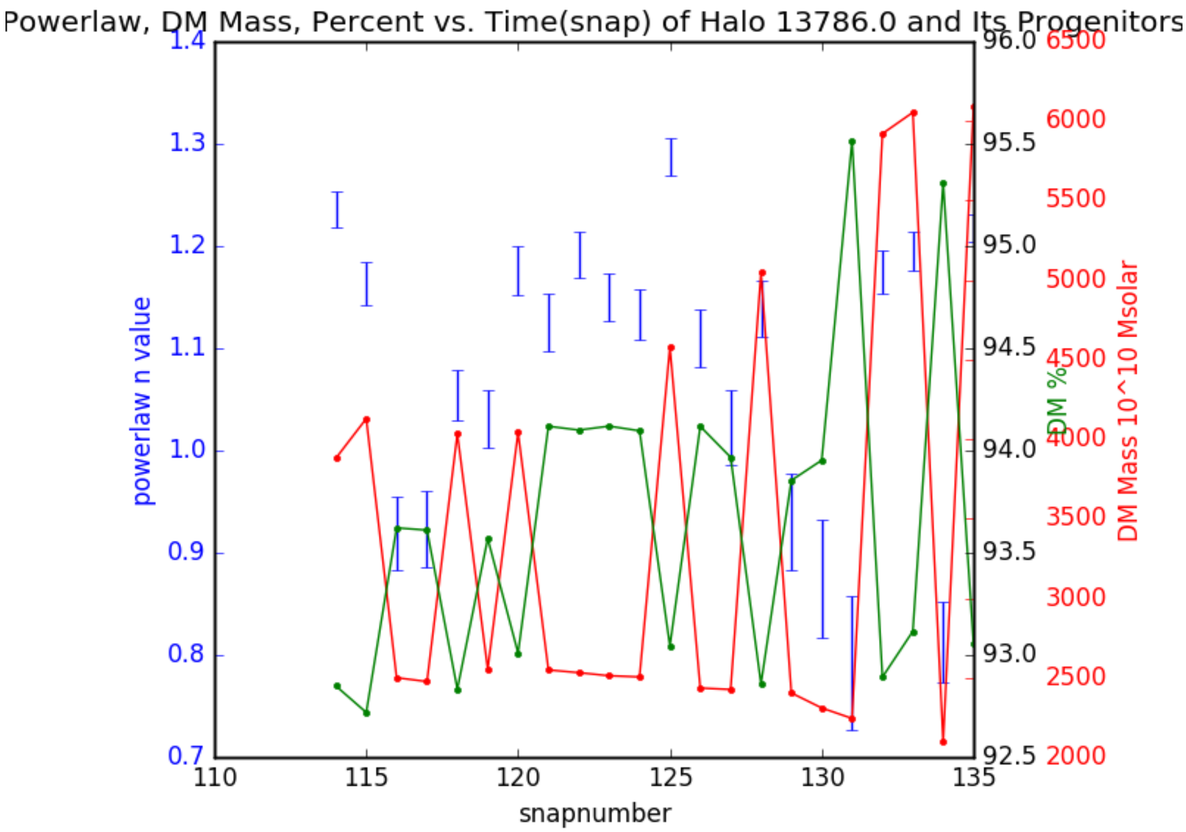
The time evolution of halos represents an important stage in the analysis for halos in Illustris. Here for the first time we get a glimpse into how a halo changes as it undergoes mergers across cosmic time. Interestingly, the density distribution, which is described by power law value n, changes dramatically across mergers and redshifts.

FIGURE 11. Non-chaotic: Note the interesting relationship between dark matter percentage and power law value, which jumps sharply, while mass grows steadily through non chaotic mergers. This particular evolutionary group of halos shows a particularly strong inverse correlation between dark matter percent and power law density.



When looking at the same group of related halos and their change of power law value *n* versus time, and then comparing this to the change in dark matter percentage, an interesting correlation appears. For this particular group of halos, the dark matter percentage is inversely correlated to the power law value *n* of the density profile.

FIGURE 12. Chaotic Mergers, where mass loss and gain are periodic. Interestingly, there again appears to be an inverse correlation between mass and dark matter percent for this family of evolving halos.



At many points in the evolution of the halos, there appeared to be correlations between the dark matter percentage and both the overall mass of the halo, as well as the power law value *n*. Examining the time evolution of halos thus motivated further investigations into possible correlations between the quantities. These results are very interesting, and they motivated the investigations that follow. In every series of evolving halos, there are dynamical correlations between various quantities, particularly dark matter percent vs. powerlaw value n , and dark matter percent versus total dark matter mass of a given halo. However, the correlations are uneven and difficult to pinpoint in this form. Therefore, the next natural step was to more closely examine the correlations between each of these halos and their related progenitors properties to understand more fully the statistical significance across thousands of halos. This is done now in the next section.

V). Correlations between Dark Matter Density, Percent Dark Matter, and Overall Mass of Halos

After examining the evolution of halos across cosmic time, it became evident that interesting relationships between mass, power law value n, and dark matter percent existed. However, to get a better estimate for the overall correlation between these quantities, it was necessary to do linear correlation tests using Pearson's Correlation Coefficients.

$$\rho_{X,Y} = \frac{cov(X,Y)}{\sigma x \sigma y}$$

Where the cov is the covariance of the independent and dependent variables and sigma's are the standard deviations. This ratio is a measure between -1 and 1 of the linearity of the relationship between the two variables. A value of -1 signifies absolute negative correlation whereas positive 1 is absolute positive correlation. A value of 0 means there is no correlation (Pearson 1895).

Scipy contains the Pearson Correlation Test, and thus this was used to test the correlation. Three correlations were examined: The correlation between Power Law value *n* Vs. Total Dark Matter Mass, Power Law value *n* Vs. and dark matter percent, and dark matter percent vs. Total Mass of Halo. Recall from the previous discussion that power law value n is a measure of how rapidly the dark matter density declines with radial distance from the center of the galaxy cluster. Here we use the term halo and galaxy cluster interchangeably.

Each related family of halos was examined for these 3 correlations, and the correlation coefficients were calculated and compared. The results for 71 groups of related Halos are displayed in the histograms below.

Finally, we performed a Student's T-Test, to measure how the correlations differed from 0.

$$t = \frac{\widehat{x} - \mu_0}{\frac{s}{\sqrt{n}}}$$

Here $\widehat{x}$ is the mean of the samples, and μ_0 is the population mean, which we set to 0, s is the standard deviation of the samples, and n is the number of data points (71 total evolutionary tracks). The results of this statistical analysis are discussed below.

POWERLAW VALUE *n* VERSUS DARK MATTER MASS

The first thing we tested for was a correlation between powerlaw value *n* and dark matter mass of the halos. Since the gravitational potential of a cluster of galaxies would be change depending on the overall mass of the halo, the total energy available of the system would also change for this form of potential energy. Thus, examining how the mass affected the power law value n amounts to testing how the total gravitational potential energy could affect the density distribution of dark matter. Since the potential is also a function of the density of the matter itself, this question is more complicated than at first glance, since the density could also influence how the potential energy of the system evolves in time.

The process of estimating the dependence of the density on the total mass of the system consisted of fitting thousands of individual halos across redshifts. These halos were then related by progenitor through the relational database SQLITE3, and then plots of these values of n vs the total dark matter mass of the halo were then generated through python. Several of these plots are shown below. The Pearson Correlation Coefficient was computed for each group of halos, to see if there was a correlation. Then, these correlation coefficients were tested against a null hypothesis.

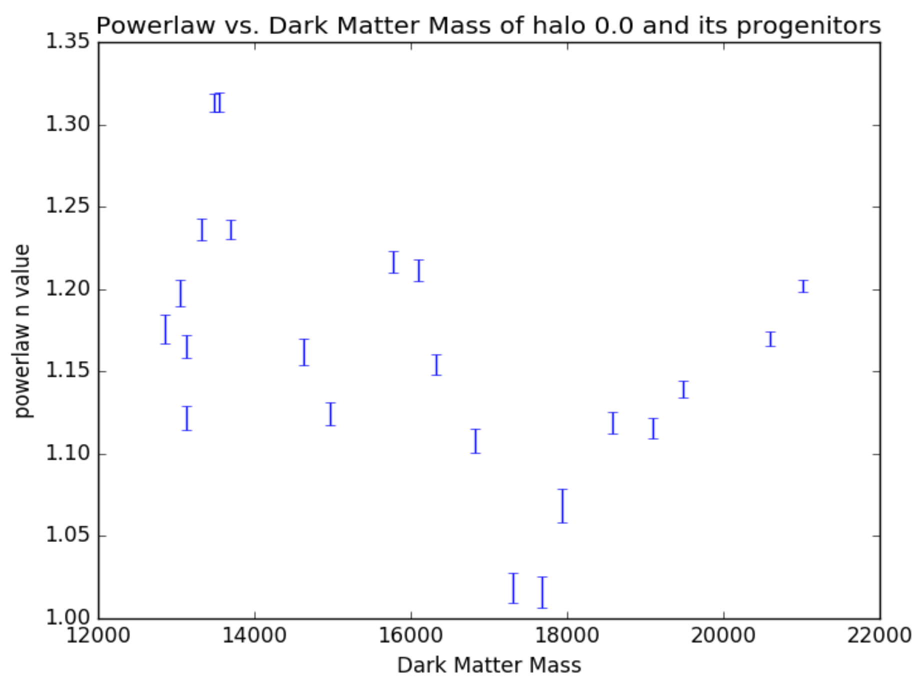
Results For Powerlaw Vs. Dark Matter Mass of Halos

The P value and statistical significance for the correlation between dark matter mass and power law revealed that the two-tailed P value equals 0.7540. By conventional criteria, this difference is considered to be not statistically significant.

Confidence interval:
The hypothetical mean is 0
The actual mean is -0.014850709458200
The difference between these two values is -0.014850709458200
The 95% confidence interval of this difference:
From -0.108990758037054 to 0.079289339120654

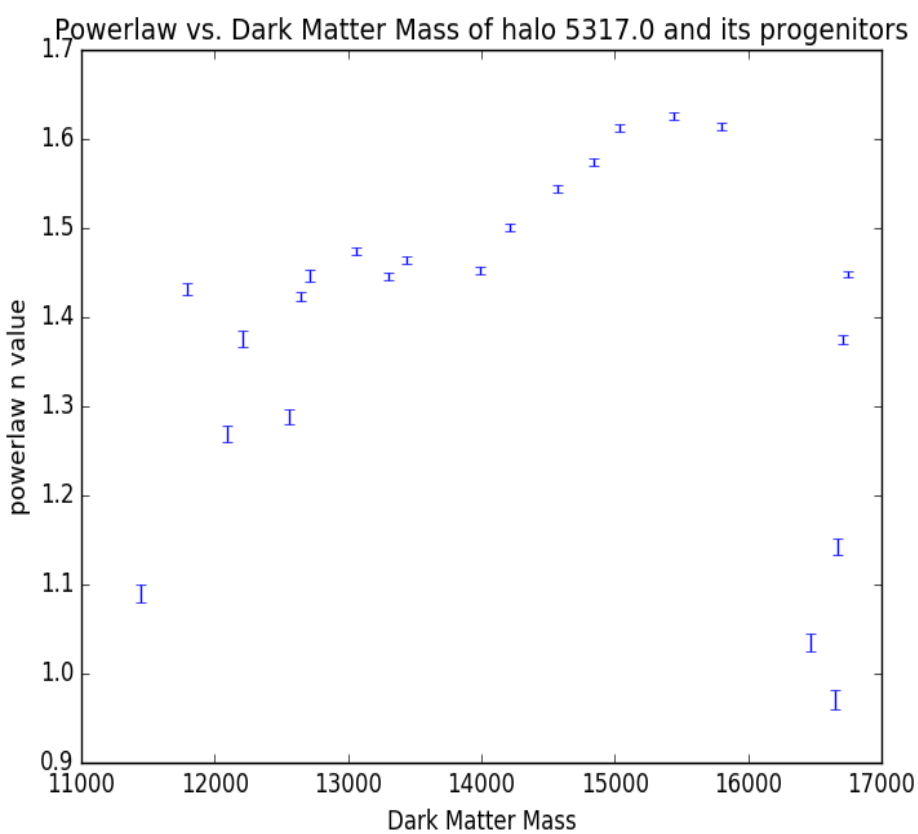
Intermediate values used in calculations:
t = 0.3146

FIGURE 13. LINEAR CORRELATION BETWEEN POWER LAW VALUE N and DARK MATTER MASS



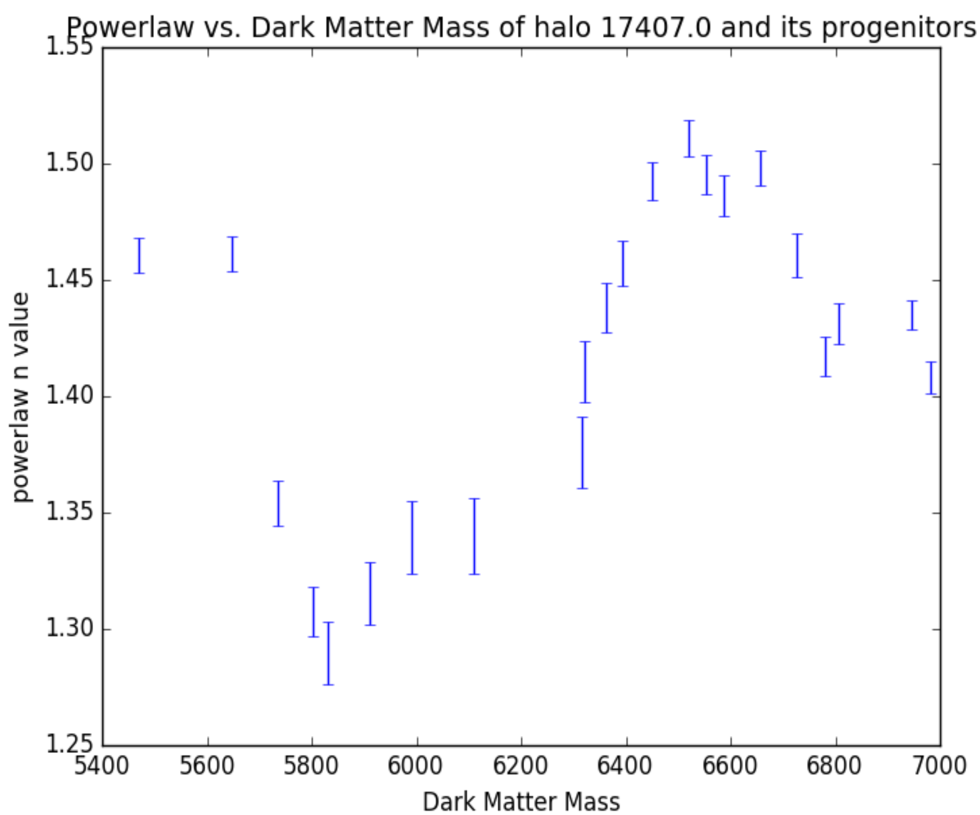
These results are somewhat surprising, given that this was the first hypothesis we wanted to test. When looking at the power law value as it is related to mass, it is revealed that the power law value jumps around significantly as mergers occur. There are clearly other factors involved that are impacting the power law density other than the total dark matter mass of the halo. These results motivated my further investigations into other properties of the halos in Illustris, and possible correlations between them.

FIGURE 14



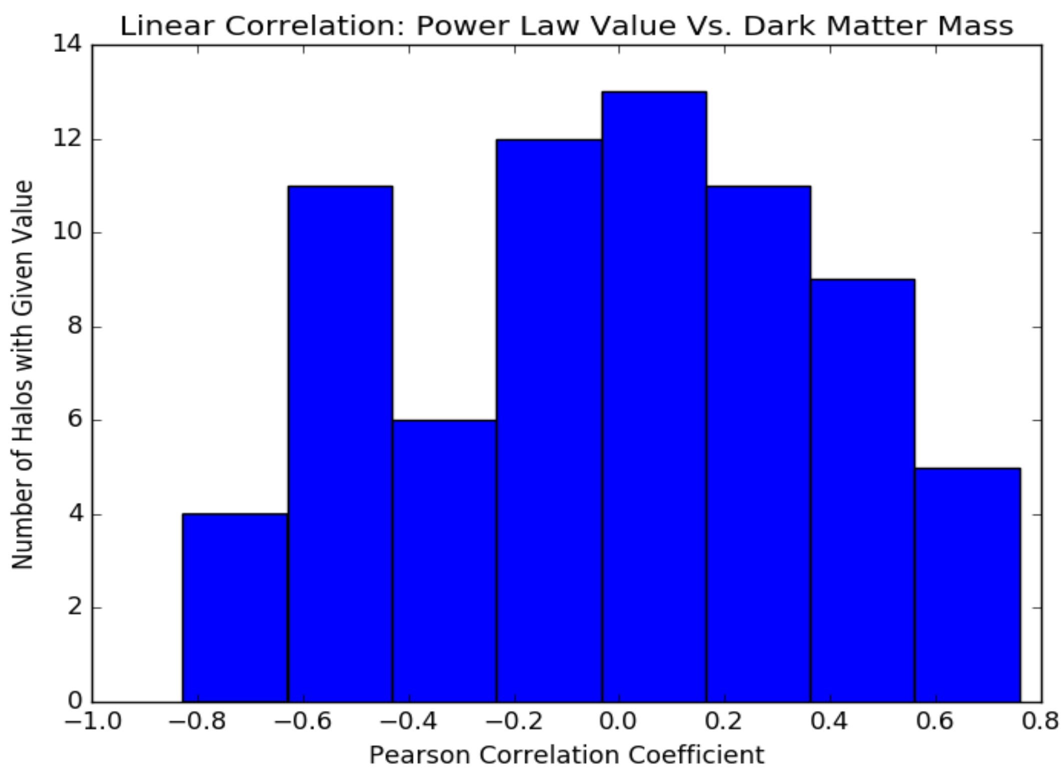
As noted, the tree structure of Illusris allows one to select the progenitor field when extracting data. The progenitor contained in this field is the most massive progenitor halo that the present halo evolved to, so if multiple halos merge into a new halo, when tracing backwards the most massive progenitor is the one that is selected.

FIGURE 15. Several groups of related halos showed significant correlations, such as 17407 with a coefficient of 0.87



Despite the overall lack of statistical significance in the total mass being correlated with power law density, a number of halos did show significant positive and negative correlations. Thus, mass cannot be ruled out as an insignificant contributor to power law density for massive halos in the Illustris Simulation, although they would likely not be the only or most significant factor.

FIGURE 16. Power Law Value vs. Dark Matter Mass

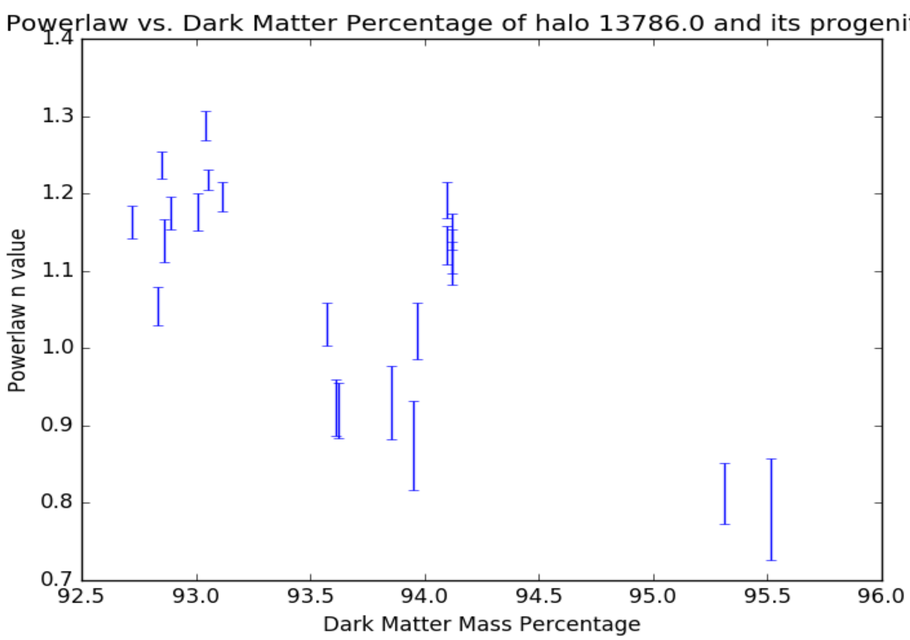


These results have also motivated future analysis, since it would be worthwhile to look at how the density of dark matter was influenced by baryonic components (i.e. stars and gas).

POWERLAW VALUE *n* VS. DARK MATTER PERCENT

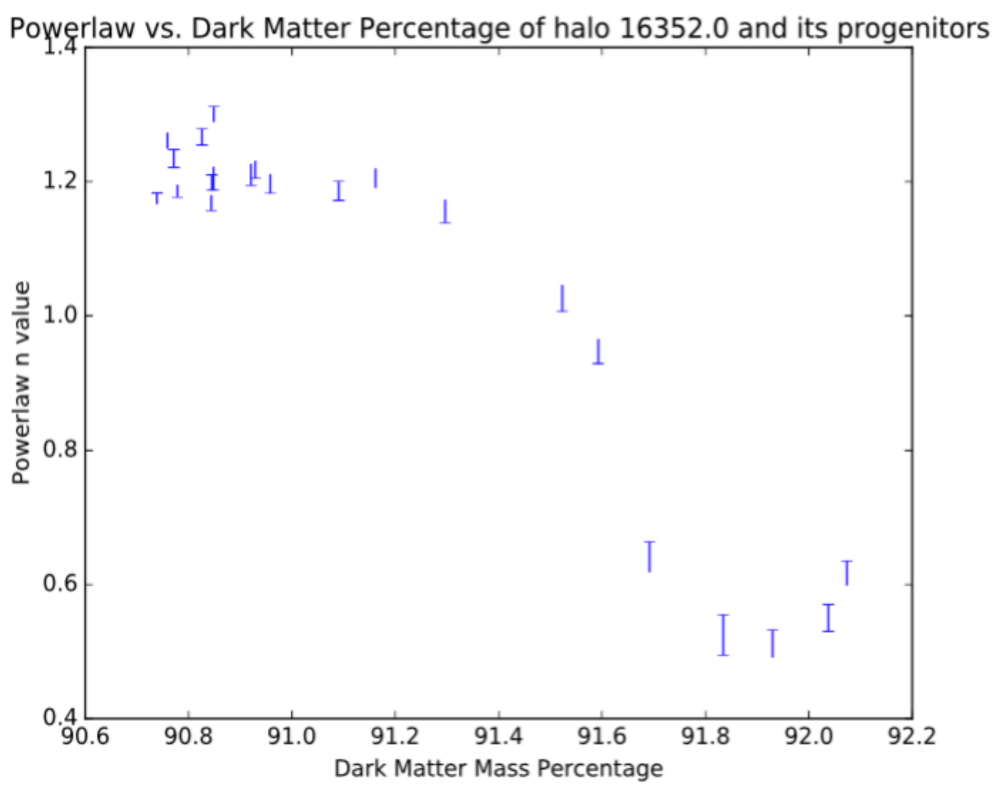
Following the result discussed above, the next thing to examine was if dark matter percent of the halo played any role in the density fall off of a given halo. Mass to light ratios are commonly used to measure the amount of dark matter a galaxy or other large body (such as a globular cluster) contains. Because the mass of the body we are observing can only be inferred, assumptions are made to simplify the analysis, such as the light output of the galaxy, cluster, or other object being caused by a roughly equal mass number of stars. In reality the light output for stars based on mass is nonlinear, but does scale approximately with mass, with larger more massive stars being the most luminous. Thus, the light output provides a rough measure of baryonic content, and the dark matter content must then be measured by examining the rotational velocities of orbiting stars or globular clusters or by using techniques involving weak lensing.

FIGURE 17.



In Illustris the precise percent of dark matter is known for every halo, simply by taking the ratio of the dark matter mass field over the total mass field for each halo. This was one property that was computed as each halo's profile was analyzed. The next step was to plot this dark matter percent of each halo as a function of power law value *n*, to see if there was any significant correlation. There is great diversity in Mass to Light ratio among astronomical bodies. Dwarf Spheroidal Galaxies are often rich in Dark Matter, while Globular Clusters are believed to contain very little dark matter, given that their output from luminous matter closely matches their gravitational potential that is observed. There are of course many exceptions to these general examples (with some dwarf spheroidals having much larger mass to light ratios than others for example), and many other objects such as Giant Ellipticals and Spiral Galaxies fall somewhere in between these ranges.

FIGURE 18. An example of power law n vs. DM Percent. For this evolutionary group of halos there is a strong inverse correlation with dark matter percent



Black holes lie at the center of nearly every galaxy, from large to small. An analysis of galaxies in Illustris at redshift 0 has shown that low mass galaxies are significantly greater in dark matter percent than middle range or high mass galaxies and clusters. The reason is due to feedback from energetic black holes, warming and displacing gas from the centers and preventing star formation at the same time. The effect is greater in low mass galaxies since these galaxies simply have a smaller spatial extent, so it is easier for them to totally lose gas in this process, lowering their star forming potential further still. This effect may also play a role in the power law density fall off from central radius, although further investigation is required. For now, the correlations are noted.

The process for examining correlations between dark matter percent and power law value n proceeded as follows: Each galaxy cluster was traced to its progenitor, redshift by redshift, yielding a lineage across many redshifts.

FIGURE 19.

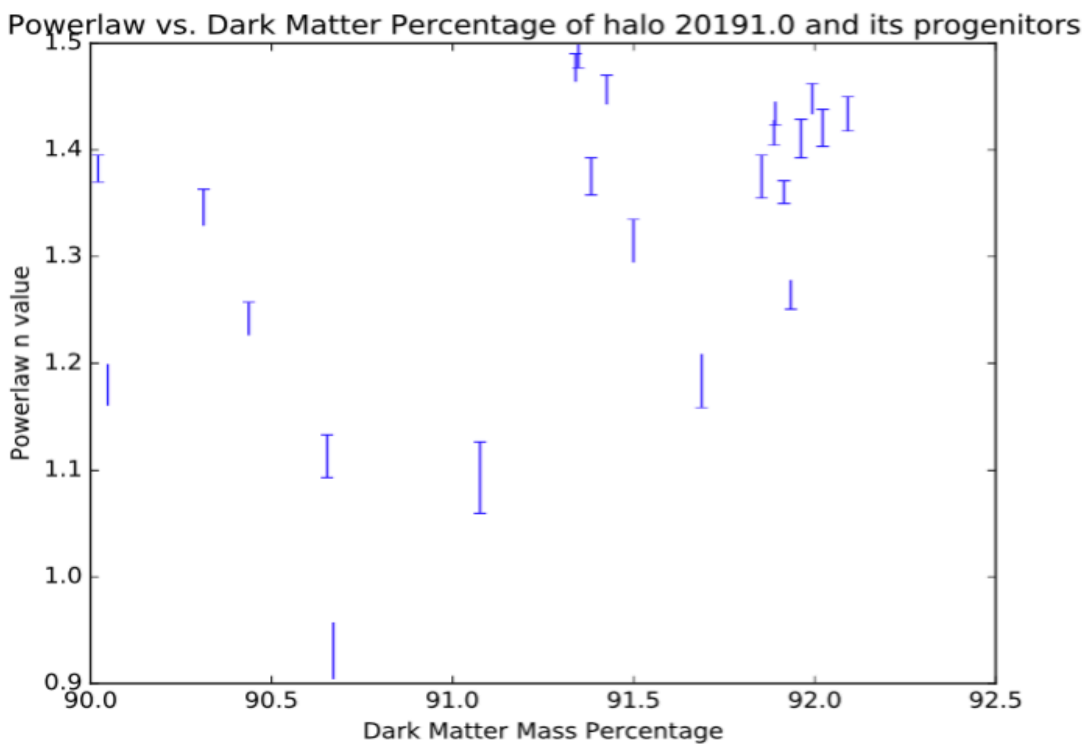
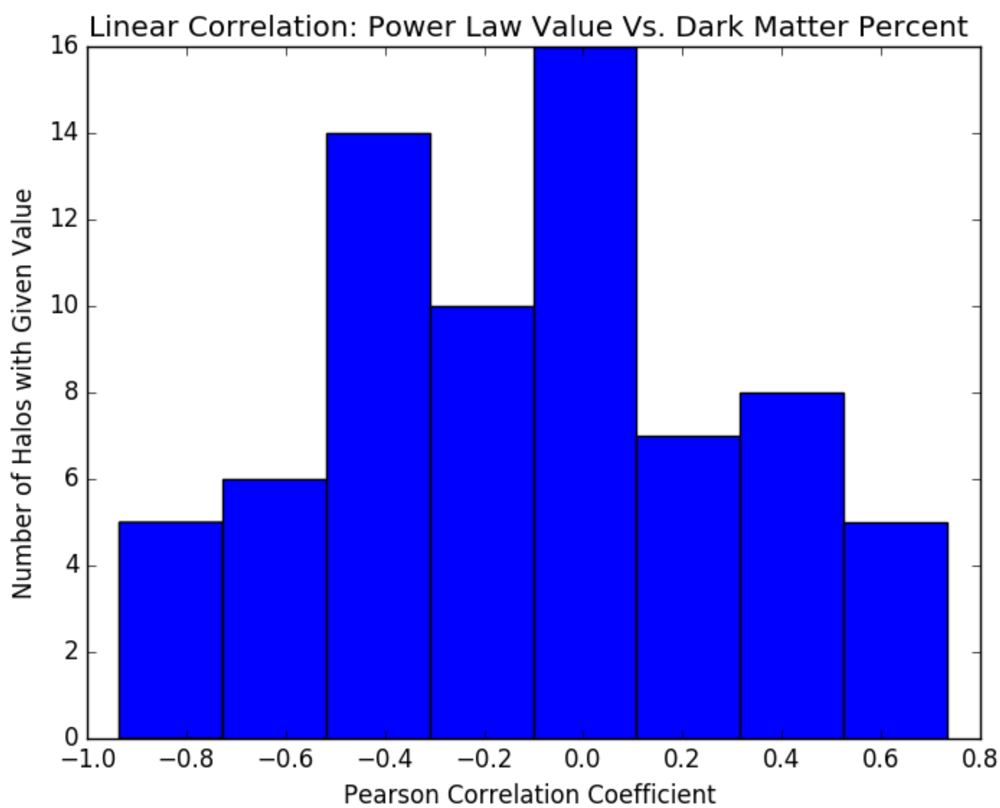


FIGURE 20. Histogram showing the range of correlation coefficients for Power Law vs. Dark Matter Percent



RESULTS

P value and statistical significance:
The two-tailed P value equals 0.0297
By conventional criteria, this difference is considered to be statistically significant.

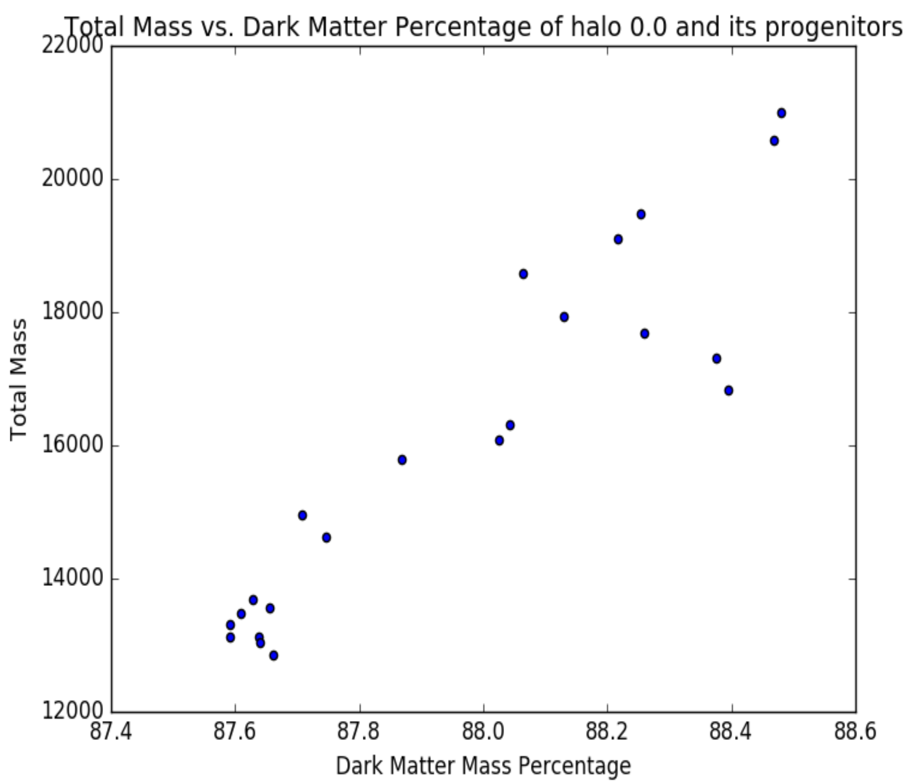
Confidence interval:
The hypothetical mean is 0
The actual mean is -0.10874267419000
The difference between these two values is -0.10874267419000
The 95% confidence interval of this difference:
From -0.20648208306153 to -0.01100326531847

Intermediate values used in calculations:
t = 2.2190
df = 70
standard error of difference = 0.049

DARK MATTER PERCENTAGE VS. HALO MASS

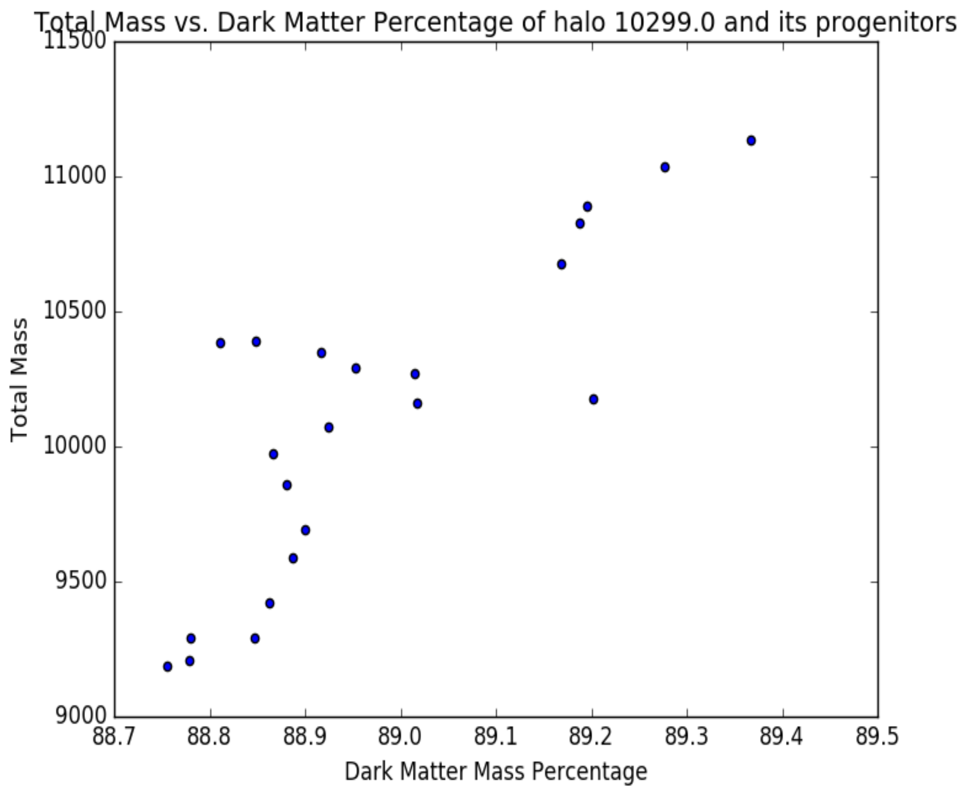
After finding a statistically significant correlation between dark matter percent and the power law density fall off of dark matter as a function of radius, the next step was to examine the correlation between dark matter percentage and mass of a halo.

FIGURE 21. Below: evolution of the most massive halo id = 0 in Illustris



When looking at the relationship between dark matter percentage and total halo mass, a definite pattern emerged. In general, as massive halos in Illustris grow larger, they increase in dark matter percent as well.

FIGURE 22. For the most massive halos in Illustris, a significant positive correlation was found between the increase in mass and the increase in dark matter percent



The majority of the massive halos examined had histories that produced this trend. As the halo underwent mergers, the dark matter percent of the total halo tended to increase.

FIGURE 23. Dark Matter % Vs. Mass for Chaotic Mergers

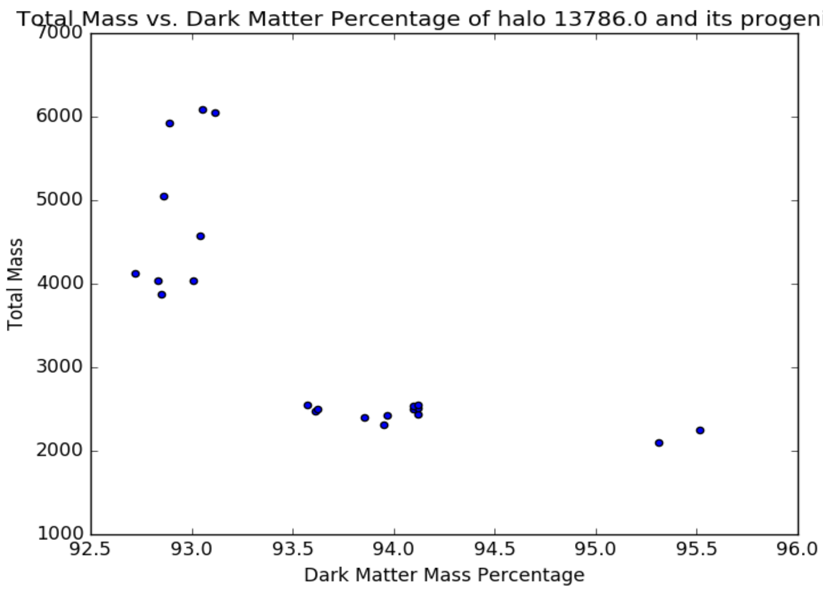
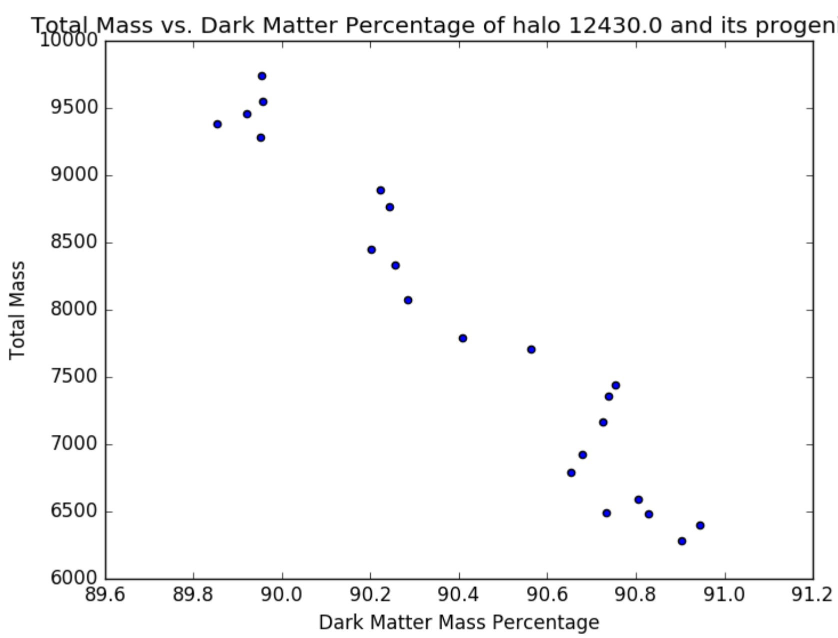
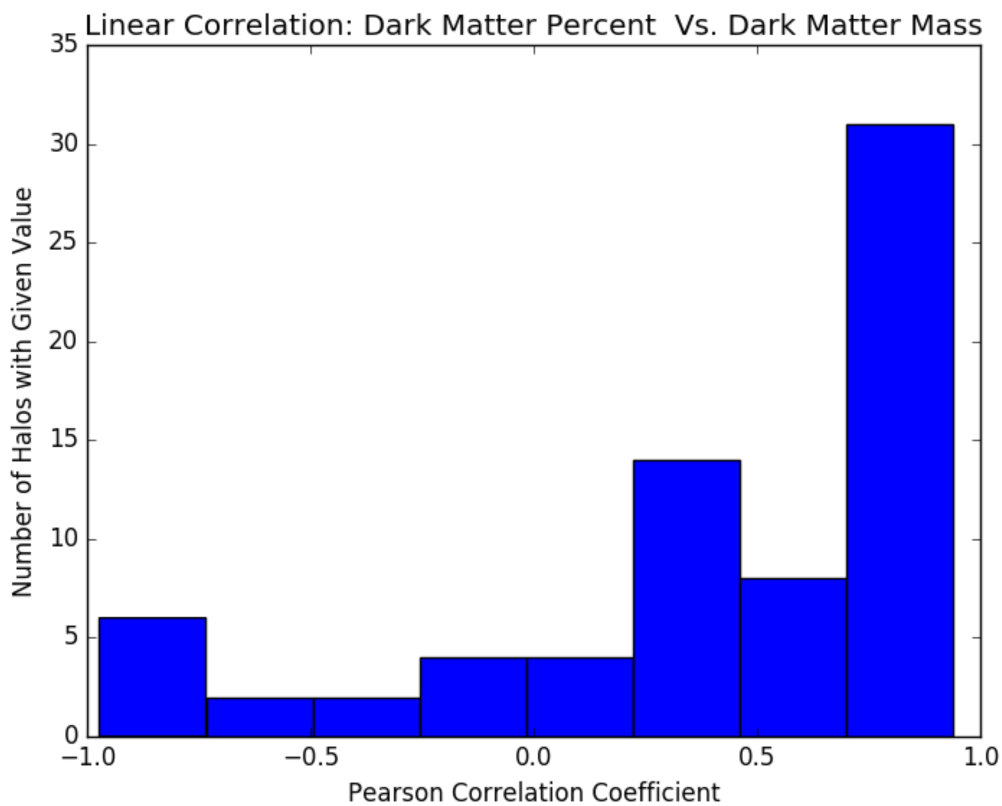


FIGURE 24. Several evolutionary tracks showed significant negative correlations. The result below is one such example.



The steady decrease in dark matter precent with total halo mass is an interesting result that stands in stark contrast to the majority of evolutionary halo tracks. For most evolutionary tracks, the dark matter percent increased as a given halo gained mass under mergers. However, for 12430 and its progenitors, the opposite has occurred.

FIGURE 25. Linear correlation for Dark Matter Mass Vs. Dark Matter Percent Reveals Strong Positive Correlations



RESULTS For Dark Matter Percent Vs. Total Halo Mass:

The P value and statistical significance:
The two-tailed P value is less than 0.0001
By conventional criteria, this difference is considered to be extremely statistically significant.

Confidence interval:
The hypothetical mean is 0.00000000000000
The actual mean is 0.37965978303600
The difference between these two values is 0.37965978303600
The 95% confidence interval of this difference:
From 0.25041901483354 to 0.50890055123846

Intermediate values used in calculations:
t = 5.8589
df = 70
standard error of difference = 0.065

VI). INTERPRETATION OF RESULTS AND MOTIVATIONS FOR FUTURE INVESTIGATION

The results that there was an extremely statistically significant correlation between the increase in halo mass and an increase and dark matter percent is a very interesting result that motivates more in depth future investigations into the structure of halos and their formation. One possible hypothesis to investigate, is whether the increase in dark matter percent is more dramatic for massive halos, because they represent an overall more massive gravitational potential. As the halo grows larger, it tends to increase in star, gas, and black hole mass. However, it will also have the ability to trap small satellite galaxies.

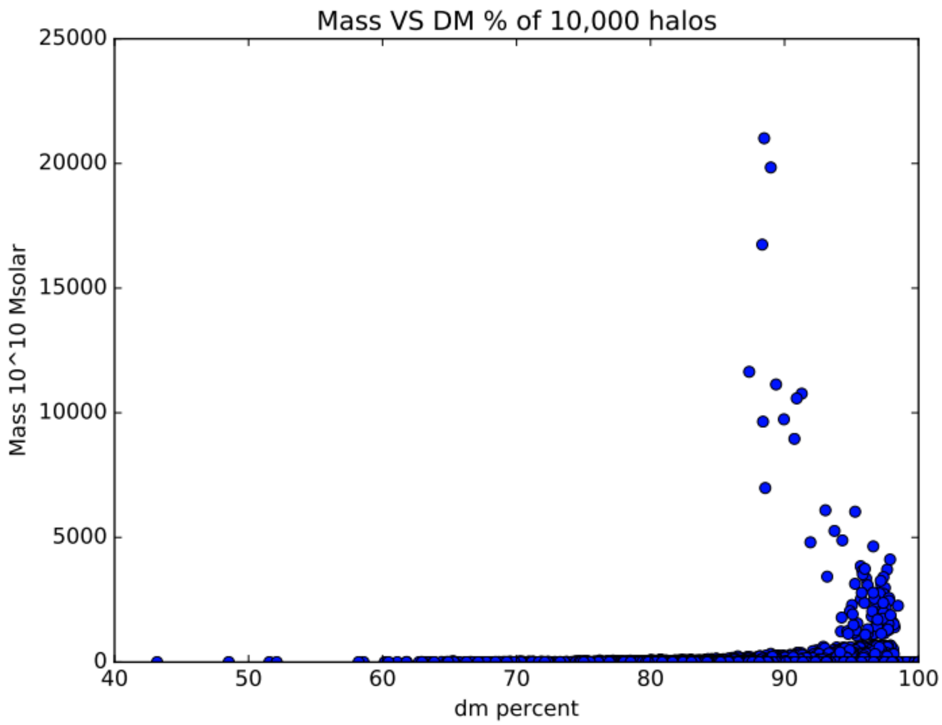
A preliminary analysis of low mass galaxies in Illustris has shown that roughly 1/5 of these galaxies are almost entirely dark. Thus, it is possible that these massive halos are trapping purely or nearly pure dark matter halos that are much smaller on the outside, producing an overall larger dark matter halo composed of newly trapped low mass dark matter rich galaxies. On the interior of these massive clusters, the increased star mass and black holes would contribute to an increase in baryonic mass, but the spatial extent would be significantly less, and may not be able to keep up with the gravitational appetite of these massive halos for low mass dark matter halos. Indeed, when looking at the inner most densities of these massive clusters, it is often seen that the interiors of galaxies become much more concentrated with the densest baryonic objects, black holes, followed by stars, and at the same time, dark matter and certainly gas particles would be displaced from the interiors by energetic events. In the follow sections I present evidence for the assertion that low mass galaxies in Illustris are dark matter dominated, and that they are accumulating on the outskirts of clusters, while the interiors of these massive clusters become more star and black hole dominated, while less dense in gas and dark matter.

LOW MASS GALAXIES IN ILLUSTRIS

Roughly 10,000 Halos were analyzed for dark matter percent, mass, and power law value n. These less massive halos were not linked to their progenitors, as the massive halos were, due to temporary time constraints. This will be a good task to attempt in future analysis. For the meantime however, a statistical distribution of halos across many mass ranges (10^15 Msolar – 10^11 Msolar) were analyzed.

Very low mass halos in Illustris tend to be dark matter dominated (>= 90 percent). Since massive halos represent an enormous gravitational potential, it is quite plausible that these massive halos are better at trapping low mass dark matter rich galaxies, and thus they become enriched with these low mass galaxies, trapping them on their exteriors and incorporating dark matter at a rate greater than the increase in star birth, gas accretion, or black hole creation.

FIGURE 26). Mass Vs. DM Percent for 10,000 Halos. The vast majority of low mass halos are clustered around a value above 90 percent dark matter (bottom right corner).



From the figure above, it is evident that most low mass halos in Illustris are significantly dark matter dominated. Thus, they are a possible source of enrichment for massive halos, since massive halos are more likely to gravitationally trap them, given their enormous potentials. It is possible that the rate at which massive clusters are trapping these small low mass dark matter dominated halos exceeds the rate of star formation and baryonic matter generation in these massive clusters, and that this results in a positive correlation.

The accumulation of dark matter rich galaxies on the outskirts of massive clusters would also affect the power law *n* value from the NFW profile associated with a given halo. Recall from previous sections, that a statistically significant correlation was found between dark matter percent and power law *n* value for the evolutionary groups of halos related by progenitors. It is possible that as these halos accumulate dark matter and their overall percentage of dark matter increases, that this is affecting the rate of power law density decrease with radius, which is what the *n* value measures. Thus, for massive galaxies in Illustris, it is probable that the increase in dark matter percentage across mergers is due to the gravitational effects of the attractive potential of the massive cluster, allowing the rate of dark matter enrichment through mergers to exceed the rate of increase in mass from star birth, gas accretion, and black hole creation.

THE CUSPY HALO PROBLEM

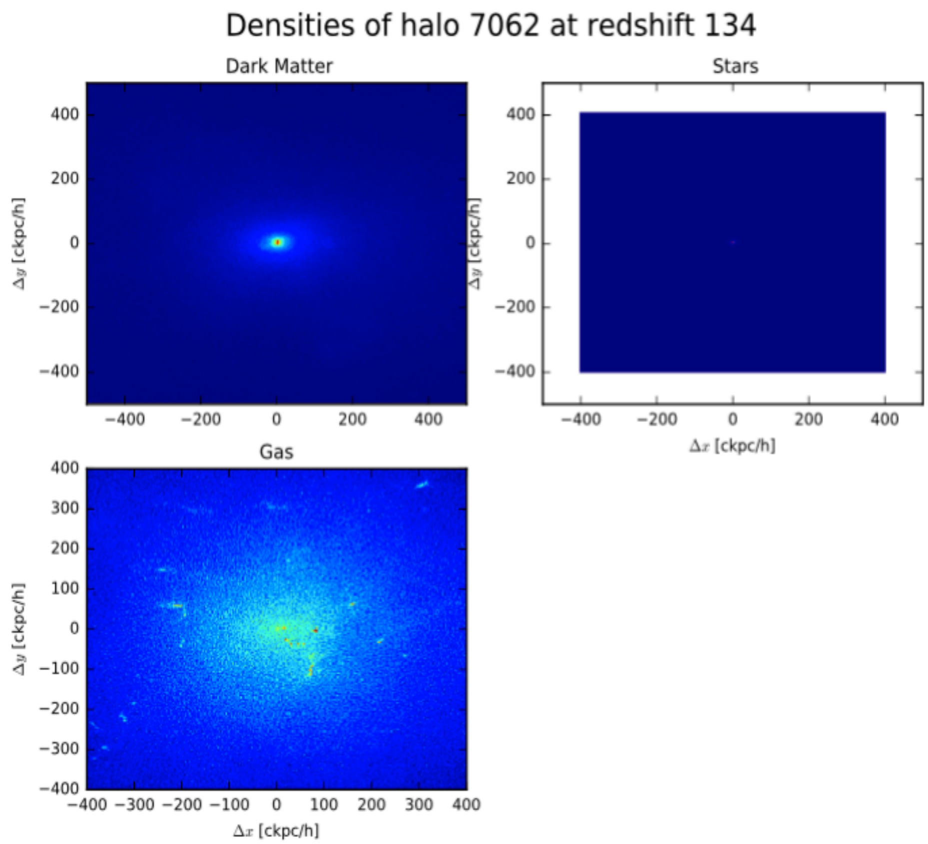
Illustris has an extensive physical model that incorporates high energy feedback mechanisms from the internal black hole and stellar components[1]. The result is that Illustris impressively reproduces the result that gas densities are reduced as a result of these mechanisms. For example, Massive Halos have an average density over their half mass radii that is several orders of magnitude less than for smaller halos. For dark matter components of halos, the central regions (found from the average half mass radius density) for both massive and low mass halos are of the same order of magnitude. In both instances, the central density is greater and falls off with increasing radius. This result has been found in virtually every other n-body simulation, and is in disagreement with observations of low mass galaxies (Moore et al 1994). However, it is still strongly debated whether a significant core that deviates from the NFW profile is present in low mass galaxies at all. It has been suggested that energetic feedback processes are also responsible for this discrepancy(Navarro 1996).

The difficulty lies in establishing a dark matter map at a scale small enough to capture the cores. While with gas this is certainly possible (see for example Mahdavi et al 2013) given its interactions electromagnetically, dark matter remains a difficult object to pinpoint on small enough distance scales, such as the centers of small galaxy halos. Nonetheless, many strong efforts have been made to develop techniques to infer the existence of dark matter at scales that could help solve this problem, but much work remains and it is not conclusively demonstrated whether the cores of low mass halos are less dense in dark matter than predicted in simulations, including Illustris.

1.The author gratefully thanks Dr. Dylan Nelson for his explanation of the hydrodynamics of gas in feedback processes.

Figures 27,28,29 Below : 2-D Density plots of halo 7062. Zooming in on the interior regions of the halo reveals that in the very centers gas and dark matter densities are much less than stars. In the very most central regions, gas has been depleted by energetic processes in the core of the halo due to black holes and stars.

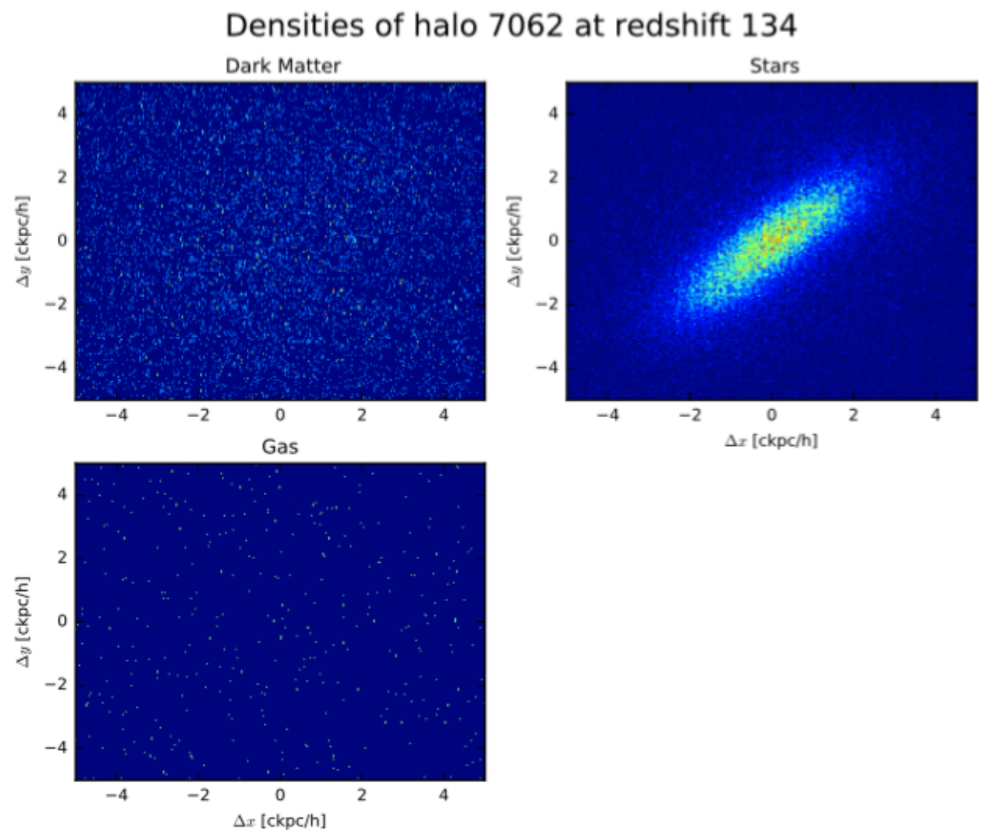
FIGURE 27



Massive clusters such as 7062 feature gas that is extensively distributed. It is a common result for halos in Illustris to have gas densities that decrease as the halo size increases, particularly in the center most regions.

Gas densities commonly have a more diffuse extent. As the halos become larger, their gas becomes more diffuse, driven outward by energetic processes of stars and black holes. Stars become more concentrated within the cores.

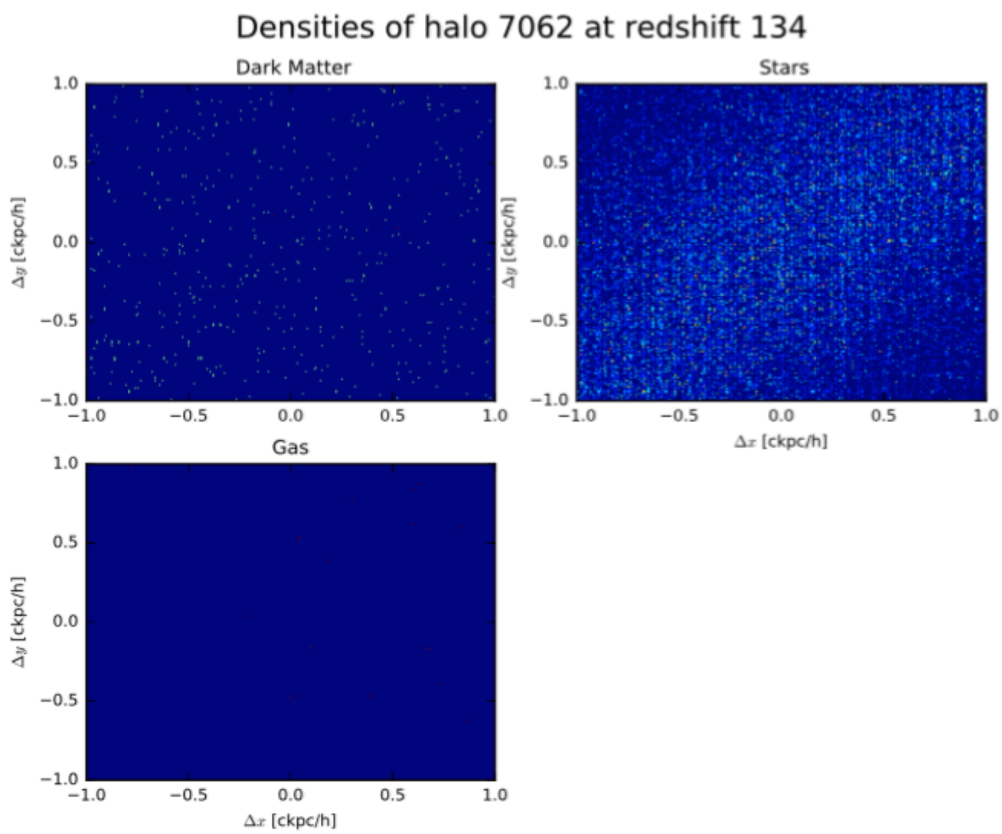
Figure 28. A zoomed in picture of the same halo. Note the reduced density of gas in relation to dark matter and particularly stars.



The same massive halo as before, on a much smaller distance scale reveals the tight core of stars that was almost impossible to see on the larger scale. Where before the gas was the most visibly dominant component, at the center it is far reduced.

In the innermost regions, the gas is the most depleted component of massive halos in Illustris. The dark matter is also significantly less dense than the stars. An important question that remains is whether the same feedback processes that drive gas out of the centers of halos would significantly affect dark matter as well. Since gas outflow due to energetic processes would create a time varying potential, this should gravitationally impact dark matter density distributions as well.

Figure 29. The same halo zoomed in to the most inner regions (1kpc). Here stars dominate over dark matter and gas.



VII). CONCLUSION

We set out to quantify the evolution of dark matter halos in the Illustris simulation and analyzed the density of these halos on a scale of 10^10 to 10^15 Msolar, representing some of the smallest halos as well as the most massive. These halos were well described by NFW profiles. Smaller halos were more likely to have a smaller value for power law. Roughly 20 percent of low mass halos had a power law value that was nearly 0. The most massive halos tended to have power law values ranging from 1.0 to 2.0 and none of them were less than 1.0. In addition, for the most massive halos, we traced back their evolution of components across cosmic time. In this way, for massive halos we were able to measure the change in power law as a function of parameters and internal properties of the halo. For massive halos and their progenitors with their power law versus dark matter halo mass, a significant correlation was not found, meaning that there was no direct relationship between the evolution of the halo and its mass, and a change in the density decrease in radius.

For massive halos and their progenitors, a statistically significant correlation was found for power law *n* value and dark matter percent. When performing the student's t test for the correlation coefficients, the two-tailed P value equaled 0.0297. By conventional criteria, this difference is considered to be statistically significant. This result has motivated future investigations, which will be required to examine this result in more detail. Topics to investigate include the possibility that this result is due to mergers and their intrinsic gravitational disruptions, or perhaps even due to energetic processes in the central regions, which we would expect to affect halos of different mass scales to different extents.

When comparing the dark matter mass of the most massive halos in Illustris and their change in dark matter percentage across mergers, a very statistically significant correlation was found. The P value and statistical significance: The two-tailed P value is less than 0.0001. By conventional criteria, this difference is considered to be extremely statistically significant. The majority of high mass halos increased in dark matter percentage across mergers, so that as they gained in mass, they also increased in dark matter percent.

Our explanation for this result is as follows: Massive halos appear to be enriching themselves gravitationally with more dark matter mass because as they grow, they capture small galaxies with very high (<90%) percentages of dark matter, and this rate of capture exceeds their increase in baryonic matter. Massive halos represent massive gravitational potentials. These potentials would allow them to capture low mass halos more efficiently. Thus, it is probable that the increase in dark matter percentage seen for so many massive halos in Illustris is caused by the gravitational capture of low mass halos on the outskirts of the cluster, while the increase in baryonic matter, due to star formation, gas accretion, and black hole formation might not be able to keep up with the increasing ability for these halos to capture small dark matter dominated halos. Halo id=0 for example, the most massive halo in Illustris, featured a strongly linear increase in dark matter percentage with mass increase for example. Thus, the massive (and increasing) gravitational potential of massive clusters is a possible reason for the increase in dark matter percentage, via enrichment from very low mass halos drawn to the massive potential represented by these clusters.

REFERENCES

1). Rubin, Vera C.; Ford, W. Kent Jr. "Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions". *The Astrophysical Journal*. (February 1970). **159**: 379–403.

2) The impact of mergers on relaxed X-ray clusters – I. Dynamical evolution and emergent transient structures. Gregory B. Poole, Mark A. Fardal, Arif Babul, Ian G. McCarthy, Thomas Quinn and James Wadsley Mon. Not. R. Astron. Soc. 373, 881–905 (2006)

3). "Joint Analysis of Cluster Observations: II X-ray and Weak Gravitational Lensing Scaling Relations for a Sample of 50 Rich Clusters of Galaxies," Andisheh Mahdavi, Henk Hoekstra, Arif Babul, Chris Bildfell, Tesla Jeltema, and J. Patrick Henry*, ApJ, 767, 116*

4). Kaiser, N.; Squires, G. (February 1993). "Mapping the dark matter with weak gravitational lensing". Astrophysical Journal. 404 (2): 441–450.

5).JOINT ANALYSIS OF CLUSTER OBSERVATIONS. II. CHANDRA/XMM-NEWTON X-RAY AND WEAK LENSING SCALING RELATIONS FOR A SAMPLE OF 50 RICH CLUSTERS OF GALAXIES
Andisheh Mahdavi, Henk Hoekstra, Arif Babul, Chris Bildfell, Tesla Jeltema, and J. Patrick HenryThe Astrophysical Journal, 767:116 (18pp), 2013 April 20

6). The impact of feedback on cosmological gas accretion
Dylan Nelson, Shy Genel, Mark Vogelsberger, Volker Springel, Debora Sijacki, Paul Torrey, Lars Hernquist MNRAS (2015) [ads] [arXiv:1410.5425] (Oct. 20, 2014)

7**)** White S. D. M., Frenk C. S., 1991, ApJ, 379, 52

8). Properties of galaxies reproduced by a hydrodynamic simulation Mark Vogelsberger, Shy Genel, Volker Springel, Paul Torrey, Debora Sijacki, Dandan Xu, Gregory F. Snyder, Simeon Bird, Dylan Nelson, Lars Hernquist NATURE
(2014) [ads] [arXiv:1405.1418] (May 6, 2014) [nature]

9). The impact of feedback on cosmological gas accretion
Dylan Nelson, Shy Genel, Mark Vogelsberger, Volker Springel, Debora Sijacki, Paul Torrey, Lars Hernquist
MNRAS (2015) [ads] [arXiv:1410.5425] (Oct. 20, 2014)

10). Following the flow: tracer particles in astrophysical fluid simulations
Genel, Shy; Vogelsberger, Mark; Nelson, Dylan; Sijacki, Debora; Springel, Volker; Hernquist, Lars

11). Introducing the Illustris Project: Simulating the coevolution of dark and visible matter in the Universe
Mark Vogelsberger, Shy Genel, Volker Springel, Paul Torrey, Debora Sijacki, Dandan Xu, Gregory F. Snyder, Dylan Nelson, Lars Hernquist
MNRAS (2014) [ads] [arXiv:1405.2921] (May 12, 2014)

12).Introducing the Illustris Project: the evolution of galaxy populations across cosmic time
Shy Genel, Mark Vogelsberger, Volker Springel, Debora Sijacki, Dylan Nelson, Greg Snyder, Vicente Rodriguez-Gomez, Paul Torrey, Lars Hernquist
MNRAS (2014) [ads] [arXiv:1405.3749] (May 15, 2014)

13). Halo Mass and Assembly History Exposed in the Faint Outskirts: the Stellar and Dark Matter Haloes of Illustris Galaxies
Annalisa Pillepich, Mark Vogelsberger, Alis Deason, Vicente Rodriguez-Gomez, Shy Genel, Dylan Nelson, Paul Torrey, Laura V. Sales, Federico Marinacci, Volker Springel, Debora Sijacki, Lars Hernquist
MNRAS (2014) [ads] [arXiv:1406.1174] (June 4, 2014)

14). Large-Scale Mass Distribution in the Illustris-Simulation.
Markus Haider, Dominik Steinhauser, Mark Vogelsberger, Shy Genel, Volker Springel, Paul Torrey, Lars Hernquist
MNRAS (2016) [ads] [arXiv:1508.01525] (Aug. 6, 2015)

15). The Illustris Simulation: Public Data Release.Dylan Nelson, Annalisa Pillepich, Shy Genel, Mark Vogelsberger, Volker Springel, Paul Torrey, Vicente

Rodriguez-Gomez, Debora Sijacki, Gregory F. Snyder, Brendan Griffen, Federico Marinacci, Laura Blecha, Laura Sales, Dandan Xu, Lars Hernquist

16). Navarro, Julio F.; Frenk, Carlos S.; White, Simon D. M. (May 10, 1996). "The Structure of Cold Dark Matter Halos". The Astrophysical Journal. **462**: 563. *arXiv*:*astro-ph/9508025*. *Bibcode*:*1996ApJ...462..563N*. *doi*:*10.1086/177173*.

17). Christoph T. Lee, Joel R. Primack, Peter Behroozi , Aldo Rodrıguez-Puebla , Doug Hellinger , Avishai Dekel "Properties of Dark Matter Halos as a Function of Local Environment Density" Mon. Not. R. Astron. Soc. 000, 1–20 (2016) January 2017.

18). Galactic Dynamics James Binney, Scott Tremaine Princeton University Press, 1987

19). Moore, Ben; et al. (August 1994). "Evidence against dissipation-less dark matter from observations of galaxy haloes". *Nature*. **370** (6491): 629–631.

20)Mahdavi, Andisheh; Hoekstra, Henk; Babul, Arif; Balam, David D.; Capak, Peter L." A DARK CORE IN ABELL 520" The Astrophysical Journal, Volume 668, Issue 2, pp. 806-814

21). Karl Pearson (20 June 1895) "Notes on regression and inheritance in the case of two parents," *Proceedings of the Royal Society of London*, **58** : 240–242.

22). Moore, Ben; et al. (August 1994). "Evidence against dissipation-less dark matter from observations of galaxy haloes". *Nature*. **370** (6491): 629–631.

23).Navarro, Julio; et al. (December 1996). "The cores of dwarf galaxy haloes". MNRAS. **283** (3): L72–L78. arXiv:astro-ph/9610187.