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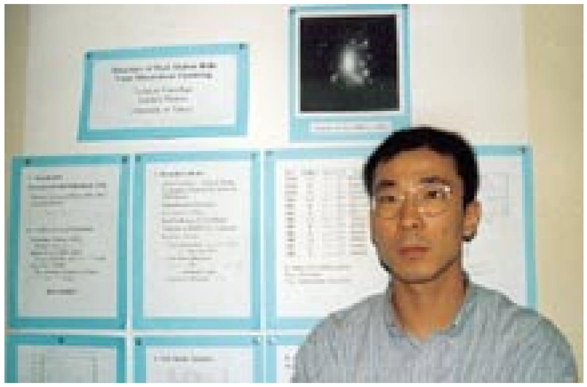
STRUCTURE OF DARK MATTER HALOS FROM HIERARCHICAL CLUSTERING



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We investigate the structure of the dark matter halo formed in the cold dark matter scenario using N-body simulations. We simulated 12 halos with the mass of $4.3 \times 10^{11} M_\odot$ to $7.9 \times 10^{14} M_\odot$. In almost all runs, the halos have density cusps proportional to $r^{-1.5}$ developed at the center, which is consistent with the results of recent high-resolution calculations. The density structure evolves in a self-similar way, and is universal in the sense that it is independent of the halo mass and initial random realization of density fluctuation as long as the halo mass is $M \gtrsim 3 \times 10^{12} M_\odot$. The density profile is in good agreement with the profile proposed by Moore et al. (1999), which has central slope proportional to $r^{-1.5}$ and outer slope proportional to r^{-3}.

1 Introduction

In standard cosmological pictures, such as the cold dark matter cosmology, dark matter halos are considered to be formed in a hierarchical way; smaller halos first formed from initial density fluctuations and they merged with each other to become larger halos. In reality, the formation process of dark matter halo is rather complicated, since a variety of processes, such as merging between halos of various sizes and tidal disruption of small halos (satellite) proceed simultaneously.

One of the most influential works on the dark matter halo is the "finding" of the universal profile by Navarro, Frenk, and White [13](hereafter NFW), though there were many analytical and numerical studies before NFW (see NFW or Bertschinger [1] for reviews). NFW performed N-body simulations of the halo formation and found that the profile of dark matter halo can be fitted by a simple formula

$$\rho = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2}, \tag{1}$$

where ρ_0 is a characteristic density and r_s is a scale radius. They also argued that the profile has the same shape, independent of the halo mass, the initial density fluctuation spectrum or the value of the cosmological parameters. It should be noted that, before NFW, Dubinski and Carlberg [3] also found in their high-resolution simulation the halo can be well fitted by Hernquist [8] profile .

Many studies on the NFW "universal profile", both numerical and analytical, were done after their proposal. Many N-body simulations whose resolution are similar to those of NFW were performed and results similar to NFW were obtained [2]. Analytical and semi-analytical studies to explain the NFW universal profile were also done [4]. The clear understanding for the NFW profile, however, has not yet been given. One of the reasons why a clear understanding has not been established might be that all these studies were trying to answer a wrong question.

Our previous study [5] (hereafter FM97) showed that density profile obtained by high-resolution N-body simulation is different from the NFW universal profile. We performed simulations with 768k particles, while previous studies employed $\sim$ 20k. We found that the galaxy-sized halo has a cusp steeper than $\rho \propto r^{-1}$.

This disagreement with the NFW universal profile was confirmed by other high-resolution simulations. Moore et al. [11] [12] and Ghigna et al. [7] performed simulations with up to 4M particles and obtained the results similar to ours. They found that cluster-sized halos also have cusps steeper than the NFW profile and they proposed the modified universal profile, $\rho = \rho_0/[(r/r_s)^{1.5}(1+(r/r_s)^{1.5})]$. On the other hand, Jing and Suto [9] found that the density profile of dark matter is not universal. They performed a series of N-body simulations and concluded that the power of the cusp depends on mass. It varies from -1.5 for galaxy mass halo to -1.1 for cluster mass halo.

In this paper, we again investigate the structure of dark matter halos using N-body simulation. We performed N-body simulations of formation of 12 dark matter halos with masses $4.3 \times 10^{11} M_\odot$ to $7.9 \times 10^{14} M_\odot$, using a special-purpose computer GRAPE-5 [10] and Barnes-Hut treecode. In the next section, we present the summary of simulation results. More details for the model, the results, and the interpretation of our simulations are in Fukushige and Makino [6].

2 Result

We performed in total 12 runs on 4 different mass scales. Initial conditions were constructed in a way similar to that in FM97. In Table 1, we summarized the radius r_{200}, the mass M_{200} and number of particles N_{200} within r_{200}, at the end of simulation. Figure 1 shows a final snapshot for Run 16M0.

Table 1: Halo properties at the end of simulation

Run name	M_{200} ($M_\odot$)	r_{200} (Mpc)	N_{200}
16M0	3.8×10^{14}	1.8	1042582
16M1	7.9×10^{14}	2.4	1086045
16M2	7.4×10^{14}	2.2	1021500
8M0	4.2×10^{13}	0.57	912650
8M1	9.5×10^{13}	0.72	1041264
8M2	9.2×10^{13}	0.86	1012213
4M0	3.0×10^{12}	0.15	526924
4M1	1.0×10^{13}	0.21	907988
4M2	1.1×10^{13}	0.30	980998
2M0	4.3×10^{11}	0.064	608638
2M1	1.3×10^{12}	0.090	944962
2M2	1.5×10^{12}	0.12	1063328

Figure 2 show the final density profiles for all Runs. In this study, we plot the density only for the radii free from numerical artifact. We used the following three criteria: (1) $[r/\varepsilon] > 3$, (2) $[t_{\rm dy}(r)/\Delta t] > 20$ and (3) $[t/t_{\rm rel}(r)] > 0.007$, which we obtained experimentally. Details will

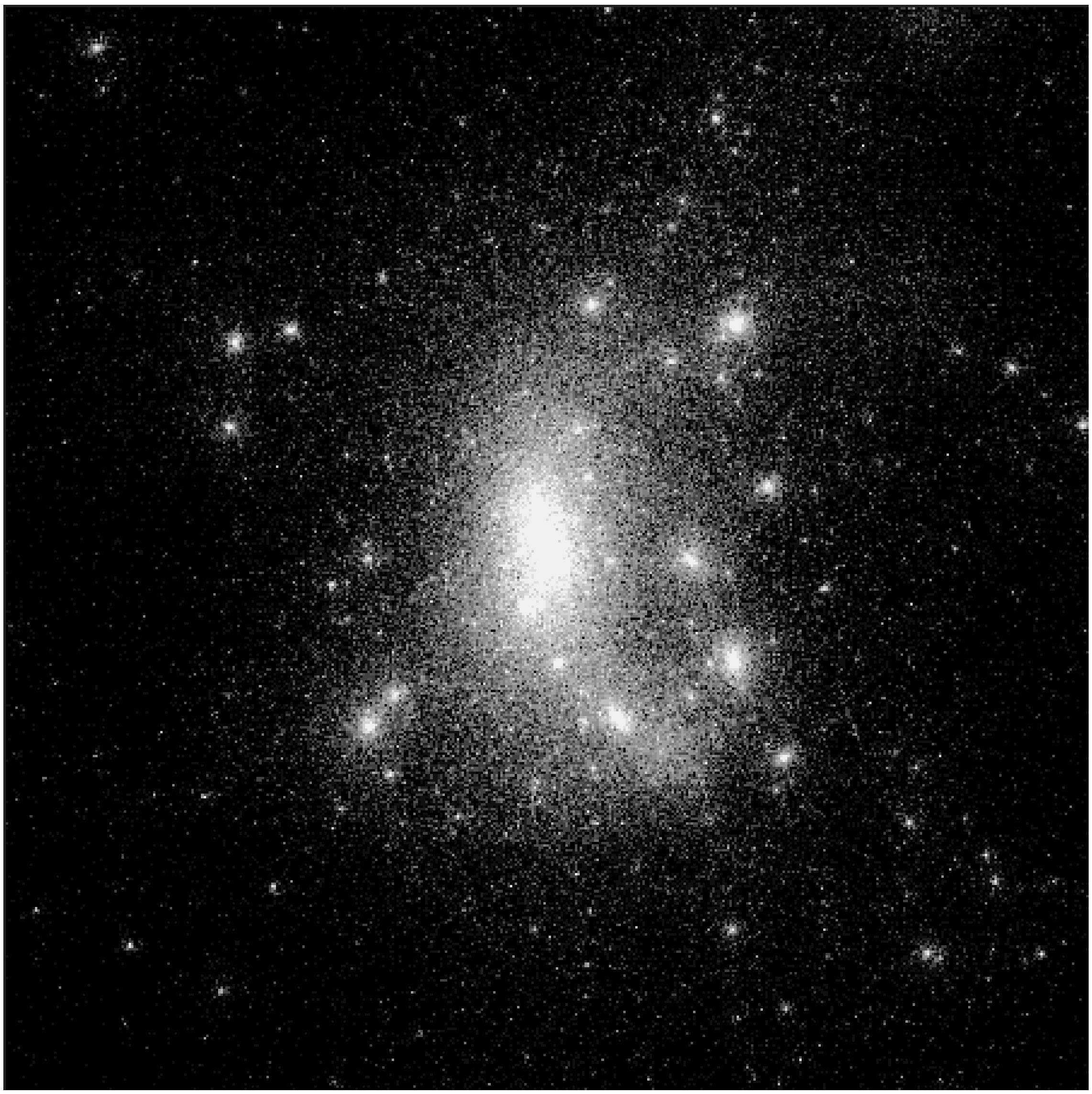

Figure 1: Snapshot at the end of simulation for Run 16M0. The length of the side is 4Mpc.

be discussed elsewhere. We plot the densities only if all three criteria are satisfied. Here, $t_{\rm dy}(r)$ is the local dynamical time defined by $t_{\rm dy} = (G\bar{\rho})^{-1/2}$ where $\bar{\rho}$ is the average density within radius r, and $t_{\rm rel}(r)$ is the local two-body relaxation time defined by $t_{\rm rel} = v^3/(\rho m)$. Using these criteria we judge whether the density profile is free from numerical artifacts due to the potential softening (1), the step size for the time integration (2), and the two-body relaxation (3).

In almost all runs we can see the central density cusps approximately proportional to $r^{-1.5}$. The exception is Run 2M1, which has slightly shallower cusp proportional to $r^{-1.3}$. In other words, as long as the mass of halos is $M \gtrsim 3 \times 10^{12} M_\odot$, the power of the cusp is -1.5 and is independent of halo mass, which is consistent with the result of Moore et al. [12]. There is a small run-to-run variation in galaxy-sized halo ($M \lesssim 3 \times 10^{12} M_\odot$). In the outer region, the density profiles are very similar for all runs. The dependence of the power-law index of the inner cusp on the halo mass observed by Jing and Suto [9] was not reproduced in our simulations. Even if we take into account the run-to-run variation, the dependence on mass in our results is in the opposite direction compared to that of Jing and Suto [9].

Figure 3 shows the final density profile of all Runs except for Run 2M{0,1,2} using non-dimensional variables, ρ_{**} and r_{**}, defined as

$$\rho_{**} = \rho/\rho_0 \tag{2}$$

$$\rho_0 = 7 \times 10^{-4} \cdot \delta \left(\frac{M}{10^{14} M_\odot} \right)^{-1} \quad (M_\odot/{\rm pc}^3) \tag{3}$$

$$r_{**} = r/r_0 \tag{4}$$

$$r_0 = 0.2 \cdot \delta^{-\frac{1}{3}} \left(\frac{M}{10^{14} M_\odot} \right)^{\frac{2}{3}} \quad ({\rm Mpc}) \tag{5}$$

where M is the total mass of halos, δ is a non-dimensional free parameter. The free parameter δ is constant during evolution of a halo. We can see that the 9 density structures agree very nicely, which means they are universal. We attempted to fit the density structure to several profiles proposed by Moore et al. [12]. The function form is given by $\rho_{**} = r_{**}^{-1.5}(1 + r_{**}^{1.5})^{-1}$. Our simulation results agree with the profile proposed by Moore et al. [12] very well.

3 Conclusion

We performed N-body simulations of dark matter halo formation in the standard CDM model. We simulates 12 halos whose mass range is $4.3 \times 10^{11} M_\odot$ to $7.9 \times 10^{14} M_\odot$. We introduced the accuracy criteria to guarantee that numerical artifact due to the potential softening, time integration, and two-body relaxation do not affect the result, and obtained the density profile which free from numerical artifact down to the radii $(0.007 - 0.01) r_{200}$.

Our main conclusions are:

(1) In almost all runs, the final halos have density cusps proportional to $r^{-1.5}$.

(2) The density profile evolves self-similarly. As long as the halo mass is $M \gtrsim 3 \times 10^{12} M_\odot$, the density profile is universal, independent of the halo mass, initial random realization of density fluctuation and the redshift. The density structure is in good agreement with the profile proposed by Moore et al. [12].

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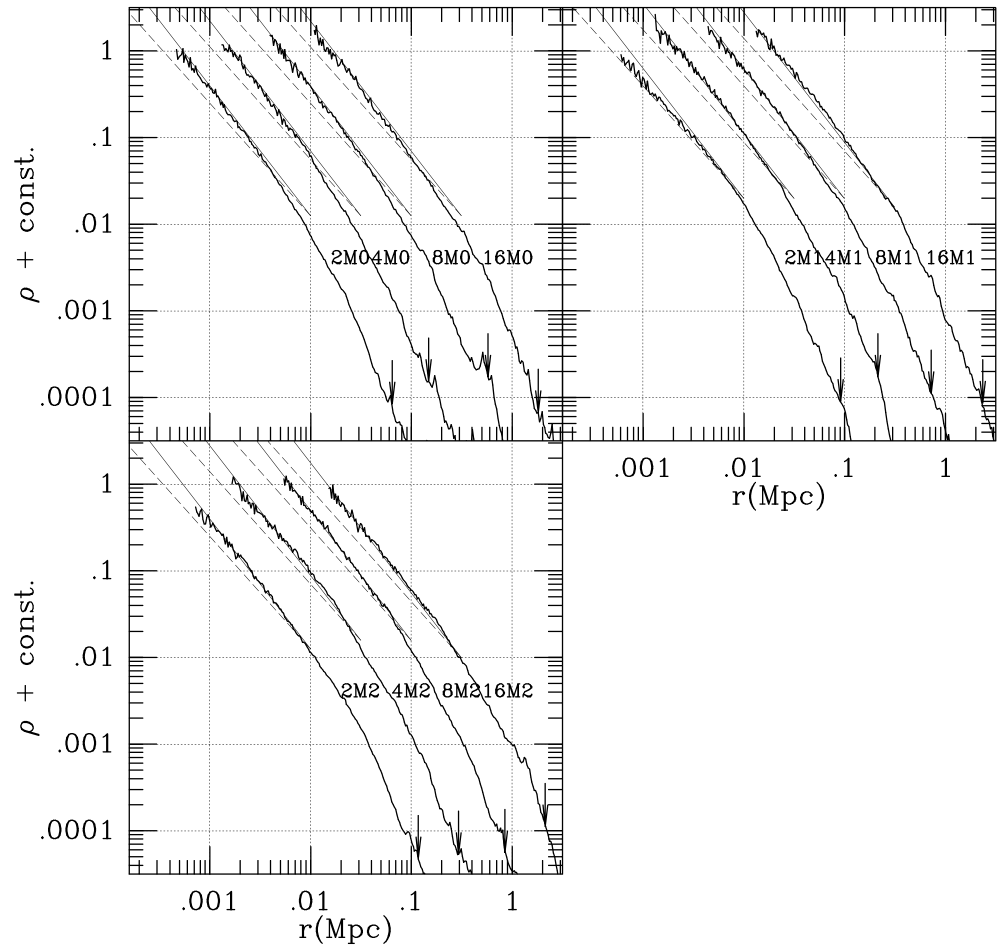

Figure 2: Density profile of the halo for all Runs at the end of simulation. The unit of density is $M_{\odot}/\mathrm{pc}^3$. The profile for Run 16M{0,1,2}, 8M{0,1,2}, and 4M{0,1,2} are vertically shifted upward by 1.5, 1, 0.5 dex, respectively. The arrows indicate r_{200}. The thin solid and dashed lines indicate the densities proportional to $r^{-1.5}$ and $r^{-1.3}$.

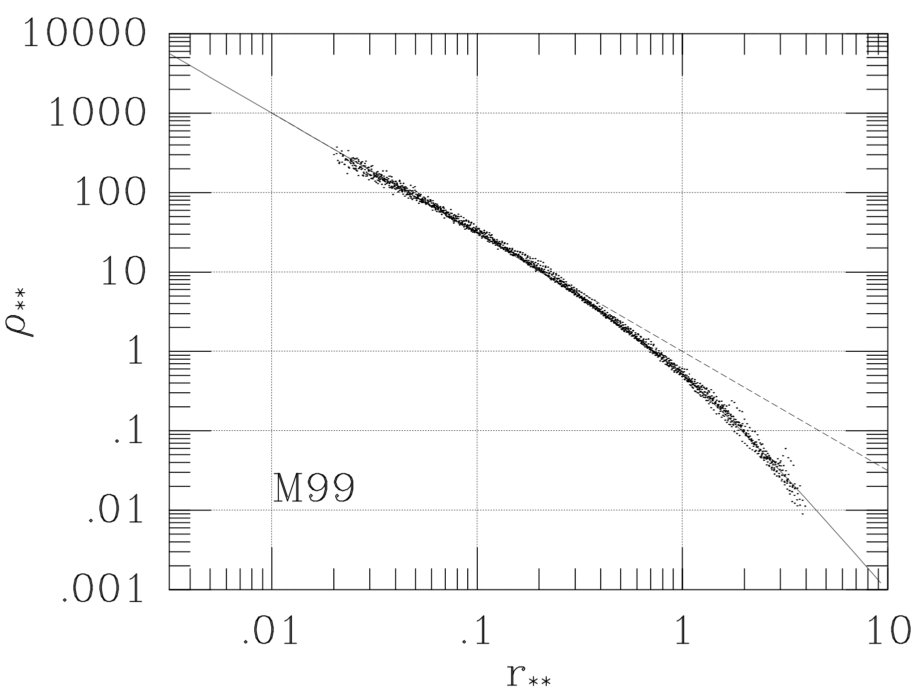

Figure 3: Universality in the density strucuture. The scaled densities ρ_{**} within r_{200} are ploted as a funtion of the scaled radius r_{**}. Fitting of the density structure by the profile proposed by Moore et al. (1999)

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