I present an analysis of the density shapes of dark matter halos in ΛCDM and ΛWDM cosmologies. The main results are derived from a statistical sample of galaxy-mass halos drawn from a high resolution ΛCDM N-body simulation. Halo shapes show significant trends with mass and redshift: low-mass halos are rounder than high mass halos, and, for a fixed mass, halos are rounder at low $z$. Contrary to previous expectations, which were based on cluster-mass halos and non-COBE normalized simulations, ΛCDM galaxy-mass halos at $z = 0$ are not strongly flattened, with short to long axis ratios of $s \approx 0.70 \pm 0.17$. I go on to study how the shapes of individual halos change when going from a ΛCDM simulation to a simulation with a warm dark matter power spectrum (ΛWDM). Four halos were compared, and, on average, the WDM halos are more spherical than their CDM counterparts ($s \approx 0.77$ compared to $s \approx 0.71$). A larger sample of objects will be needed to test whether the trend is significant.

1 Introduction

A variety of observational indicators suggest that galaxies are embedded within massive, extended dark matter halos, lending support to the idea that a hierarchical, cold dark matter (CDM) based cosmology may provide a real description of the universe, especially on large scales (see, e.g., the review by Primack and references therein). A useful small-scale test of CDM and variant theories may come from observations aimed at inferring the density structure of dark halos. Specifically, the quest to measure dark halo shapes has developed into a rich and complex subfield of its own.

Predictions for shapes of dark matter halos formed by dissipationless gravitational collapse are most reliably derived using numerical studies. These past investigations focused on galaxy-sized halos formed from power-law or pre-COBE CDM power spectra, and found that halos were typically flattened triaxial structures, with short-to-long axis ratios of $s \approx 0.5 \pm 0.15$. Examinations based on currently favored cosmologies have been done, but they studied only cluster mass halos, and also found significantly flattened objects, $s \sim 0.4 - 0.5$. Interestingly, Thomas and collaborators saw an indication that low matter density models (with early structure formation) tended to produce more spherical clusters than high density models. This result was qualitatively consistent with indications from Warren et al. that high-mass halos are more flattened than (early-forming) low-mass halos. In light of these
hints that formation history plays a role in setting halo shapes, it is important to reexamine the question for a currently standard cosmological model. Specifically, this work aims at characterizing halo flattening as a function of mass and redshift for the popular flat ΛCDM cosmology. I also explore how shapes of halos are affected when going to a ΛWDM model, in which the power spectrum is damped on small scales.

2 Simulations and shape measurement

The simulations were performed using the Adaptive Refinement Tree (ART) code. The main results are derived from a ΛCDM simulation with $\Omega_m = 0.3, \Omega_\Lambda = 0.7, h = 0.7$, and $\sigma_8 = 1.0$, which followed $256^3$ particles of mass $1.1 \times 10^9 h^{-1} M_\odot$ within a periodic box of comoving length $60 h^{-1}$Mpc, obtaining a formal force resolution of $1.8 h^{-1}$kpc. A second simulation was run until $z = 1.8$ with the same particle number, half the box size, and thus eight times the mass resolution; it was used to check resolution issues. Dark halos were identified using a (spherical) bound density maxima method, and masses were determined by counting particles within the spherical virial radius $R_v$, inside which the mean overdensity has dropped to a value $\Delta_v \simeq (18\pi^2 + 82p - 39p^2)/(1 + p)$, where $p \equiv \Omega_m(z) - 1$. This sample contains $\sim 800$ halos that span the mass range $3 \times 10^{11} - 5 \times 10^{14}$.

A second pair of simulations were used to explore how shapes of halos are affected by damping the power spectrum. We compare four halos, each simulated from the same initial conditions, for a ΛCDM and ΛWDM model with the multiple-mass ART code and the same cosmological parameters and effective mass per particle discussed above. The filter mass scale for the ΛWDM run was $1.7 \times 10^{14} h^{-1} M_\odot$, and the four halos we compare have masses $(2 - 8) \times 10^{13} h^{-1} M_\odot$. Simulation results were kindly supplied by P. Colin.

Halo axis ratios are determined using the moments of the particle distributions within the virial radius $R_v$. The short-to-long axis ratio, $s$, and intermediate-to-long axis ratio $q$ are calculated by iteratively diagonalizing the tensor

$$M_{ij} = \sum \frac{x_i x_j}{a^2}, \quad a \equiv \sqrt{x^2 + \frac{y^2}{q^2} + \frac{z^2}{s^2}},$$

where $q^2 \equiv M_{yy}/M_{xx}$ and $s^2 \equiv M_{zz}/M_{xx}$.

Although the filtering mass is much too large to be consistent with with Ly-α forest measurements, the simulation provides a useful comparison to test the effect of an imposed filtering scale, since the halo masses considered are well within the affected regime. Since
3 Results

The left panel in Figure 1 shows the average value of $s$ as a function of halo mass for three redshifts, $z = 0, 1,$ and 3. Low mass halos, on average, are rounder than high mass halos, as are halos of fixed mass at low $z$. The relation is well-approximated by $s \approx 0.7 \left( \frac{M}{10^{12} h^{-1} M_\odot} \right)^{-0.05} (1 + z)^{-0.2}$ over the mass and redshift ranges explored. The right panel of Figure 1 shows the distribution of $s$ parameters for galaxy-mass halos as a function of $z$. The average and rms dispersion in these distributions are $s = 0.70 \pm 0.17, 0.61 \pm 0.17,$ and $0.55 \pm 0.15$, for $z = 0, 1,$ and 3, respectively. Note that the distributions are quite non-Gaussian, with a significant tail of highly flattened halos.

How do the shapes of halos change with radius? The axial ratios presented in Figure 1 were obtained using particles within $R_v$. The left panel of Figure 2 shows this average “virial” flattening measurement as a function of halo mass (at $z = 0$) compared with the average $s$ measured within a sphere of radius $30 \ h^{-1}\text{kpc}$ for each halo. Although the difference is quite small for the low mass halos (since $30 \ h^{-1}\text{kpc}$ contains much of the halo mass), generally halos

---

\[ \text{Figure 1: (Left) The average short-to-long axis ratio, } s, \text{ as a function of halo mass at } z = 0, 1, \text{ and } 3. \text{ Error bars reflect the Poisson uncertainty associated with the number of halos in each mass bin and not the scatter about the relation. (Right) Distribution of measured } s \text{ values for } \sim 10^{12} h^{-1} M_\odot \text{ halos as a function of } z. \]

---

$^b$ In order to check resolution effects, the $z = 3$ distribution was compared to the corresponding one obtained in the high resolution simulation and found to be statistically equivalent.
Figure 2: (Left) $s$ as a function of mass measured within halo virial radii $R_v$ (solid) and within $30 h^{-1}$kpc spheres from halo centers. (Right) $q$ and $s$ parameters for halos simulated using ΛCDM (solid symbols) and ΛWDM (open symbols) cosmologies. Individual halos, identified by mass and location between the two runs maintain the same symbol shape.

are rounder at small radii. Interestingly, within this fixed central radius, halos typically have the same flattening, $s \sim 0.7$, independent of the halo mass.

Finally in the right panel of Figure 2, we compare the measured $s$ and $q$ values of four halos, simulated in ΛCDM and ΛWDM. There is a tendency for the halos to be rounder (approaching the upper right corner) in WDM, although one halo (designated by the triangles) does become slightly flatter in WDM. The average flattening shifts from $s \simeq 0.71$ for CDM to 0.77 for WDM, but it is difficult to make strong conclusions based on four halos. Indeed, Moore has simulated a single halo using CDM and WDM power spectra and finds a very similar shape for each. A larger sample of objects will be needed to test for systematic trends.

4 Conclusions

We find that ΛCDM galaxy-mass halos at $z = 0$ are more spherical than previously believed, with $s = 0.70 \pm 0.17$. High mass halos show more substantial flattening, as do halos of fixed mass at high redshift: $s \propto (1 + z)^{-0.2} M^{-0.05}$. Halos are also more spherical in their centers, and tend to become more flattened near the virial radius. These trends suggest collapsed structures become more spherical with time, perhaps because they have had more time to phase mix and to obtain isotropic orbit distributions. It is also possible that the
accretion history itself plays a role. Halos formed within a ΛWDM simulation show a slight indication of being less flattened than their ΛCDM counterparts. This may be a reflection of substructure differences between the two models, but a larger number of halos will be needed to decisively test this conclusion. A more complete description of these results, and some discussion of shape correlation with other halo parameters is presented in a forthcoming paper.

Acknowledgments

I thank my collaborators Pedro Colín, Ricardo Flores, Andrey Kravtsov, Anatoly Klypin, Ariyeh Maller, Joel Primack and Risa Wechsler for allowing me to present our results here. Thanks to Tsafrir Kolatt, Ben Moore, and David Weinberg for insightful discussions, and to Priya Natarajan for organizing this stimulating meeting. This work was supported by NASA LTSA grant NAG 5-3525 and NSF grant AST-9802568.

References

1. V. Avila-Reese et al., 2001, astro-ph/0010525
2. J.S. Bullock et al. 2001, MNRAS, 321, 559
3. J.S. Bullock, R. Flores, A.V. Kravtsov, A.A. Klypin, J.R. Primack, A. Maller, and R.H. Wechsler, in preparation
4. D. Buote 2001; M.R. Merrifield 2001; L.S. Sparke 2001 (these proceedings)
5. J. Dubinski and R.G. Carlberg 1991, ApJ, 378, 496
6. C.S. Frenk et al., 1988 ApJ, 372, 507
7. A.V. Kravtsov et al., 1997 ApJS, 111, 73
8. J.J. Mohr et al., 1995 ApJ, 447, 8
9. B. Moore, 2001 (these proceedings)
10. V.K. Narayanan et al. 2000, ApJ, 543, L103; R. Barkana et al., 2001, ApJ, in press, astro-ph/0102001; S.H. Hansen et al., 2001, astro-ph/0106108
11. J.R. Primack, ASP Conf. Ser. 201: Cosmic Flows Workshop, 2000, Eds. S. Courteau and J. Willick, 389, astro-ph/0007187
12. P.D. Sackett, ASP Conf. Ser. 182: Galaxy Dynamics - A Rutgers Symposium, August 1999, eds. D.R. Merritt et al., 393, astro-ph/9903420; K.V. Johnston et al. 1999, ApJL, 512, 109; Ibata et al., 2001, ApJ, 551, 294
13. P.A. Thomas et al. 1998, MNRAS, 296, 1061
14. M.S. Warren et al. 1992, ApJ 399, 405