DARK MATTER HALOS: SHAPES, THE SUBSTRUCTURE CRISIS, AND INDIRECT DETECTION

A. R. ZENTNER\textsuperscript{1}, S. M. KOUSHIAPPAS\textsuperscript{2}, AND S. KAZANTZIDIS\textsuperscript{1,3}

\textsuperscript{1}Kavli Institute for Cosmological Physics \& Department of Astronomy and Astrophysics, The University of Chicago, Chicago, IL 60637 USA
\textsuperscript{2}Department of Physics, Swiss Federal Institute of Technology, ETH Hönggerberg, Zürich, Switzerland
\textsuperscript{3}Institute for Theoretical Physics, University of Zürich, Zürich, Switzerland

In this proceeding, we review three recent results. First, we show that halos formed in simulations with gas cooling are significantly rounder than halos formed in dissipationless $N$-body simulations. The increase in principle axis ratios is $\sim 0.2 - 0.4$ in the inner halo and remains significant at large radii. Second, we discuss the CDM substructure crisis and demonstrate the sensitivity of the crisis to the spectrum of primordial density fluctuations on small scales. Third, we assess the ability of experiments like VERITAS and GLAST to detect $\gamma$-rays from neutralino dark matter annihilation in dark subhalos about the MW.

1. Introduction

A proponderance of evidence indicates that galaxies are embedded in massive, extended dark matter (DM) halos. Simulations of structure formation in the hierarchical cold dark matter (CDM) paradigm predict that CDM halos are generally triaxial\textsuperscript{1,2} that they teem with self-bound subhalos\textsuperscript{3}.

The structure of halos is an important ingredient in modeling the DM direct detection signals\textsuperscript{4} and halo shapes have recently received attention for testing the CDM paradigm as new and improved probes of halo shape have been applied\textsuperscript{5,6}. Dissipationless simulations predict that Milky Way (MW)-size halos have a mean minor-to-major axis ratio of $c/a \approx 0.6 - 0.7$ with a dispersion of $\sim 0.1$\textsuperscript{1}, while dynamical studies suggest that the observed coherence of the Sagittarius tidal stream constrains the inner MW halo to $c/a > 0.8$\textsuperscript{6}. In § 2, we present recent results on the effect of baryonic dissipation on halo shapes in high-resolution, cosmological simulations.

In § 3, we turn to halo substructure. In the MW and M31, there are more than an order of magnitude fewer observed satellites than the predicted number of subhalos of comparable size\textsuperscript{3}. Several explanations have
Figure 1. The effect of gas cooling on halo shapes. Left: Minor-to-major axis ratio $c/a$, as a function of major axis length for a cluster-size halo. The dashed line shows the shape profile of the DM in the adiabatic simulation. The thick, solid line shows the shape profile for DM and baryons in the cooling run. Right: Same as the left panel, but for a MW-size galaxy progenitor (see text).

been offered, including alternative DM properties\textsuperscript{7} and inefficient galaxy formation in the shallow potentials of small subhalos\textsuperscript{8}. We study the sensitivity of the dwarf satellite population to the primordial power spectrum (PPS) of density fluctuations on small, sub-galactic scales and demonstrate that our interpretation of the missing satellite problem is a function of the amount of small-scale power. If the lack of luminous MW satellites is due to inefficient galaxy formation, the MW halo should contain $> 10^2$ otherwise dark subhalos. Strong lensing will be one probe of dark subhalos\textsuperscript{9}. More speculatively, the annihilation of DM particles in these dense substructures may result in numerous $\gamma$-ray sources in the MW halo. We assess the potential for instruments like VERITAS\textsuperscript{11} and GLAST\textsuperscript{12} to detect such sources in favorable models of supersymmetric (SUSY) DM in § 4.

2. Halo Shapes

We studied the effect of gas cooling on the shapes of DM halos using high-resolution cosmological simulations of cluster and galaxy formation in a concordance $\Lambda$CDM cosmology. The simulations were performed with the ART $N$-body plus Eulerian gasdynamics code\textsuperscript{14}. We refer the reader to Kazantzidis et al.\textsuperscript{13} for further details.

Briefly, we analyzed simulations of 8 cluster-size objects of mass $10^{13} \, h^{-1}M_{\odot}$ to $3 \times 10^{14} \, h^{-1}M_{\odot}$. The cluster simulations had a peak
force resolution of $\simeq 2.4h^{-1}\text{kpc}$ and a DM particle mass of $m_p \simeq 2.7 \times 10^8 \ h^{-1}\text{M}_\odot$. We also analyzed a simulation of the early evolution ($z \gtrsim 4$) of a galaxy that becomes MW-size at $z = 0$ described by Kravtsov\textsuperscript{15}. This simulation had $m_p \simeq 9.2 \times 10^5 \ h^{-1}\text{M}_\odot$ and peak resolution $\simeq 183h^{-1}\text{kpc}$. The mass and force resolution are adequate to study the inner regions of halos reliably. For each object, we analyzed two sets of simulations started from the same set of initial conditions, but including different physical processes. In one set, the gas dynamics were treated adiabatically, without any radiative cooling and the results agreed well with those of $N$-body simulations with no baryonic component. The second set of simulations included radiative cooling, and star formation.

We measured halo shapes by diagonalizing the moment of inertia tensor\textsuperscript{3}. We used “differential” shape measurements because this makes the axis ratios measured at each radial bin nearly independent. Our main results are summarized in Figure 1. In the left panel, we show the profile $c/a$, as a function of major axis length for a representative cluster-size halo. On the right, we show results for the galaxy progenitor. The net effect of baryon dissipation is striking. At small radii, the axis ratios in the cooling simulations are greater by $\Delta(c/a) > 0.3$ and the systematic difference persists out to $\sim R_{\text{vir}}$, where $\Delta(c/a) \sim 0.1$. The baryons in the cluster are mostly in a massive, central, elliptical galaxy while in the galaxy formation simulation, $\sim 90\%$ of the baryons are in a flattened, gaseous disk. In both cases the effect of cooling is weakly dependent upon radius implying that the effect of baryonic dissipation on halo shapes is not critically sensitive to the detailed morphology of the baryonic component. In addition, the axis ratios change with radius in a manner that is not generally monotonic, indicating that different regions of a system may be flattened to different degrees.

3. Halo Substructure

The most accurate technique for studying halo substructure is numerical simulation; however, the computational expense of simulations limits their dynamic range and their applicability in explorations of cosmological parameter space. To overcome this, Zentner and Bullock (ZB)\textsuperscript{19} developed an approximate, analytic model for subhalo populations and an updated model has recently been successfully tested against a suite of $N$-body simulations\textsuperscript{20}. The model approximately accounts for the merger statistics of subhalos, dynamical friction, and mass loss and redistribution due to
We show the observed satellite velocity functions (squares) and the predicted satellite velocity functions (thick lines) for 6 different PS. Clockwise from the top left: standard $n = 1$, $\sigma_8 = 0.95$; $n = 0.94$, $\sigma_8 = 0.83$; WMAP best-fit $n = 1.03$, $dn/d\ln k = -0.03$, $\sigma_8 = 0.84$; BSI; $n = 0.84$, $\sigma_8 = 0.65$; and $n = 0.90$, $\sigma_8 = 0.75$. The models are labeled by $\sigma_8$. Lines are the means of 100 model realizations and errorbars represent the 1σ scatter. Observational data are from the review of Mateo.

In the standard paradigm, structure forms from primordial density fluctuations characterized by a nearly scale-invariant PPS, $P(k) \propto k^n$ with $n \approx 1$. This basic picture has significant observational support. However, cosmic microwave background anisotropy constrains the PPS on large scales, $k \sim 10^{-2} \, h\text{Mpc}^{-1}$, while halo substructure is sensitive to small scale power, $k \sim 10 - 100 \, h\text{Mpc}^{-1}$. ZB studied the effect of variant power spectra on the MW dwarf satellites. They took several PPS with various motivations, all normalized to COBE: (1) standard $n = 1$, $\sigma_8 = 0.95$; (2) $n = 0.94$, $\sigma_8 = 0.83$; (3) $n = 0.9$, $\sigma_8 = 0.75$; (4) running mass inflation $n = 0.84$, $\sigma_8 = 0.65$; (5) broken scale-invariance (BSI) with a power cut-off.
at \( k_c = 1 \, h\text{Mpc}^{-1} \); and (6) the best-fit running spectrum from WMAP
\( n = 1.03, \frac{dn}{d\ln k} = -0.03, \sigma_8 = 0.84 \). The steps in the calculation are
first to generate MW halo substructure realizations for each PPS and to
model the velocity dispersions of the embedded stellar components to deter-
mine the appropriate subhalo size (labelled by maximum circular velocity
\( V_{\text{max}} \)) in which the observed satellites may be embedded. In this way, one
constructs predicted and observed cumulative velocity functions.

Figure 2 summarizes the results. First, one sees that the degree to
which the dwarf satellite problem represents a challenge is greatly alleviated
in the WMAP best-fit cosmology. The level at which inefficient galaxy
formation or a critical mass scale for galaxy formation must be invoked to
solve the satellite scarcity problem is degenerate with the PPS on small
scales. Second, the MW satellite population by itself provides indepen-
dent evidence against extreme models, such as the low normalization, \( \sigma_8 = 0.65 \)
model which under-predict substructure.

4. \( \gamma \)-rays from Dark Substructure
One way of probing the distribution and properties of substructure as well
as the particle nature of the DM is through the detection of gamma-rays
from annihilations of the dark matter particle in the dense, inner regions of
subhalos. The currently favored DM particle is provided by supersymme-
try (SUSY) and it is the lightest of the neutralinos (\( \chi \)). The uncertainties
involved in trying to deduce information about the distribution and prop-
erties of substructure indirectly via the detection of \( \gamma \)-rays are twofold. First,
there are uncertainties that stem from the underlying cosmological model
and the details of formation of very small-scale structures\(^{18,19} \) and second,
uncertainties that arise from the lack of knowledge of the mass and cou-
plings of the dark matter particle. Using the analytic substructure model
of \( \S 3 \), we can assess the ability of experiments like VERITAS and GLAST
to detect \( \gamma \)-ray fluxes from DM annihilations.

Koushiappas et al.\(^{22} \), adopted this approach and assumed the most opti-
mistic SUSY parameters consistent with constraints on \( \Omega_{\text{m}} \)\(^{16} \) to determine
the number of expected detections at a significance \( S > 3 \), as a function
of subhalo mass \( M \). In order to project counts of observed subhalos be-
ond the masses of the dwarf galaxies, several physically-motivated extrap-
olations are necessary; however, the recent simulation of “mini-halos” at
\( z \sim 26 \) are a first step toward justifying these extrapolations with explicit
numerical simulations\(^{23} \).
Our results are summarized in Figure 3. The figure shows that for \( \chi \) masses \( M_\chi \lesssim 100\,\text{GeV} \), the large field of view of GLAST and the energy sensitivity of VERITAS will allow them to detect substructure when operated in concert. For example, if \( M_\chi \sim 75\,\text{GeV} \), then in the case of optimal coupling to photons there will be on average \( \sim 1 \) detectable subhalo per GLAST field of view. In this case, subsequent direct observations with VERITAS should be able to confirm the line emission feature at an energy of \( \sim M_\chi \) after an exposure time of \( \sim 450 \) hours. For \( 100\,\text{GeV} \lesssim M_\chi \lesssim 500\,\text{GeV} \), detection requires an instrument with a large effective area, like VERITAS; however, such a detection must rely on serendipity due to the small number of potentially detectable objects in VERITAS’ comparably small field of view. For neutralino masses in excess of \( M_\chi \gtrsim 500\,\text{GeV} \), substructure detection via the \( \gamma \)-ray signal is unlikely with either GLAST or VERITAS.\textsuperscript{22}
Acknowledgments

These results are based on several collaborative works. We thank B. A. Allgood, J. S. Bullock, A. V. Kravtsov, B. Moore, D. Nagai, and T. P. Walker for their invaluable contributions and for allowing us to present our results here. We thank Von Freeman and Risa Wechsler for stimulating discussions. ARZ and SK are funded by the Kavli Institute for Cosmological Physics at The University of Chicago and The National Science Foundation through grant NSF PHY 0114422. SMK is funded by the Swiss National Science Foundation.

References

1. e.g. Y. P. Jing and Y. Suto, ApJ, 574, 538 (2002)
2. J. Dubinski and R. G. Carlberg, ApJ, 378, 496 (1991)
3. A. A. Klypin, ApJ, 522, 82 (1999); B. Moore et al., ApJL, 524, L19, (1999)
4. e.g. F. Stoehr et al., MNRAS, 345, 1313 (2003); S. Kazantzidis et al., ApJ, 608, 663 (2004); A. Green, This Proceeding, and references therein
5. e.g. Kolokotronis et al., MNRAS, 320, 49 (2001); D. A. Buote et al., ApJ, 577, 183 (2002); H. Hoekstra et al., ApJ, 606, 67 (2004)
6. R. Ibata et al., ApJ, 551, 294 (2001); S. Majewski et al., ApJ, 599, 1082 (2003); but see A. Helmi, MNRAS, 351, 643 (2004) and This Proceeding
7. e.g. D. N. Spergel and P. J. Steinhardt, PRL, 84, 3760 (2000); Colín et al., ApJ, 542 622 (2000); A. Knebe et al., MNRAS, 329, 813 (2002)
8. e.g. J. S. Bullock et al., ApJ, 539, 517 (2000); R. S. Somerville, 572, L23 (2002); A. V. Kravtsov et al., ApJ, 609, 482 (2004)
9. N. Dalal and C. S. Kochanek, ApJ, 572 25 (2001)
10. L. Bergström et al., PRD, 59, 043506 (1999); C. Calcáneo-Roldán and B. Moore, PRD, 62, 123005 (2000); A. Tassis and A. Olinto, PRD, 66, 083006 (2002); F. Stoehr et al., MNRAS, 345, 1313 (2003)
11. URL http://veritas.sao.arizona.edu
12. URL http://glast.gsfc.nasa.gov
13. S. Kazantzidis et al., ApJL, 611, L73 (2004)
14. A. V. Kravtsov, A. A. Klypin, and Y. Hoffman, ApJ, 571, 563 (2002)
15. A. V. Kravtsov, ApJL, 590, L1 (2003)
16. D. N. Spergel et al., ApJS, 148, 175 (2003)
17. M. Kamionkowski and A. R. Liddle, PRL, 84, 4525 (2000)
18. A. R. Zentner and J. S. Bullock, PRD, 66, 043003 (2002)
19. A. R. Zentner and J. S. Bullock, ApJ, 598, 49 (2003)
20. A. R. Zentner et al., ApJ, 624, in press (2005)
21. M. Mateo, ARAA, 36, 435 (1998)
22. S. M. Koushiappas et al., PRD, 69, 043501 (2004)
23. J. Diemand, B. Moore, and J. Stadel, Nature, 433, 389 (2005)