Does the Milky Way-M31 Remnant Violate ΛCDM Cosmology via the Cusp-Core Problem?

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Keywords: Elliptical Galaxy, N-body Simulations, Cold Dark Matter Theory, Hernquist Profile, NFW Profile, Dark Matter Halo, Rotation Curve, M200, ...

1. INTRODUCTION

Dark matter (DM) halos are the basic building blocks of the cosmos. DM particles within halos are collisionless, conserving their orbital energy, and are supported through dispersion A. R. Wetzel & D. Nagai (2015). In contrast, gas loses its orbital energy, gathering and clumping in the center of halos, triggering star and eventually galaxy formation C. S. Frenk & S. D. M. White (2012). Understanding DM halos is crucial for testing and improving **lambda cold dark matter (ΛCDM) theory**, the leading paradigm for cosmic structure and evolution.

ΛCDM inhabits the framework of general relativity and adopts a particle nature for dark matter to describe the cosmos J. S. Bullock & M. Boylan-Kolchin (2017). ΛCDM has been largely successful in describing the history, structure, and evolution cosmos, but can be improved by further investigating the nature of DM halos. Given their significance in the assembly of DM halos, *galaxy mergers* offer a unique perspective to peer into the nature of galaxy evolution and test ΛCDM cosmology.

Within ΛCDM theory, **the Navarro-Frenk-White (NFW) density profile** J. F. Navarro et al. (1997), Einsasto profile J. F. Navarro et al. (2004), and **Hernquist profile** L. Hernquist (1990) are commonly used to describe DM halos. These profiles are supported by ΛCDM theory and were formulated with the aid of **N-body simulations**. N-body simulations simplify complex systems with multiple components, such as DM halos, that would be impossible to study with absolute precision. C. S. Frenk & S. D. M. White (2012) used a number of N-body simulations, such as the Aquarius simulation seen in **Figure 1**, to determine that the mass in halos is concentrated toward the center, aspherical, and contains substructures especially in the outermost regions. It was also found from M. Davis et al. (1985) and the friends-of-friends algorithm that CDM halos are often triaxial and rotate slowly.

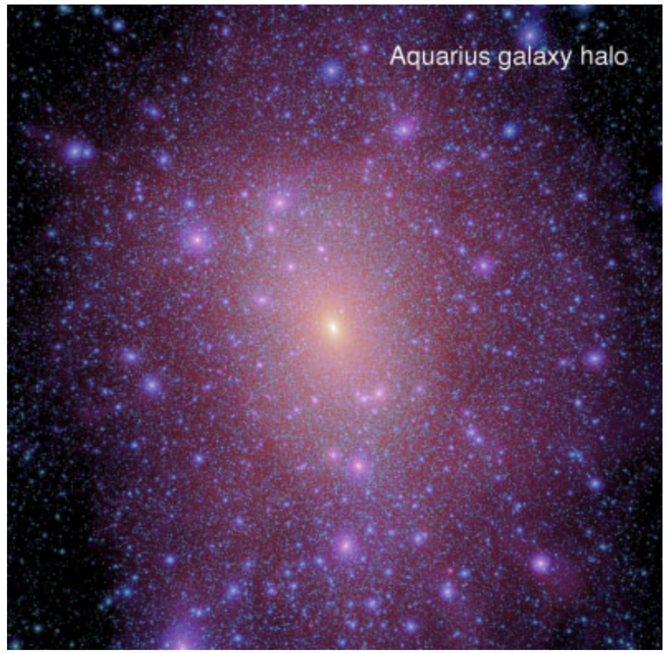

Figure 1. Simulated dark matter halo from C. S. Frenk & S. D. M. White (2012). Aquarius galaxy has similar mass to the Milky Way.

Observations have challenged ΛCDM theory on smaller scales. The cusp-core problem (first proposed by R. A. Flores & J. R. Primack (1994)) is the most testable challenge of ΛCDM when analyzing dark matter halos. ΛCDM theory suggests that the velocity profile of dark matter halos rises steeply at small radii akin to $\rho(r) \propto r^{-\gamma}$ where γ is dependent on the mass of the galaxy J. S. Bullock & M. Boylan-Kolchin (2017). Instead, some velocity profiles, especially from DM-dominant galaxies, are observed to exhibit flatter slopes than expected as seen in **Figure 2**. Addressing the cusp-core problem requires asking what role baryons have in the structure of dark matter halos J. S. Bullock & M. Boylan-Kolchin (2017). Additionally, at what galaxy

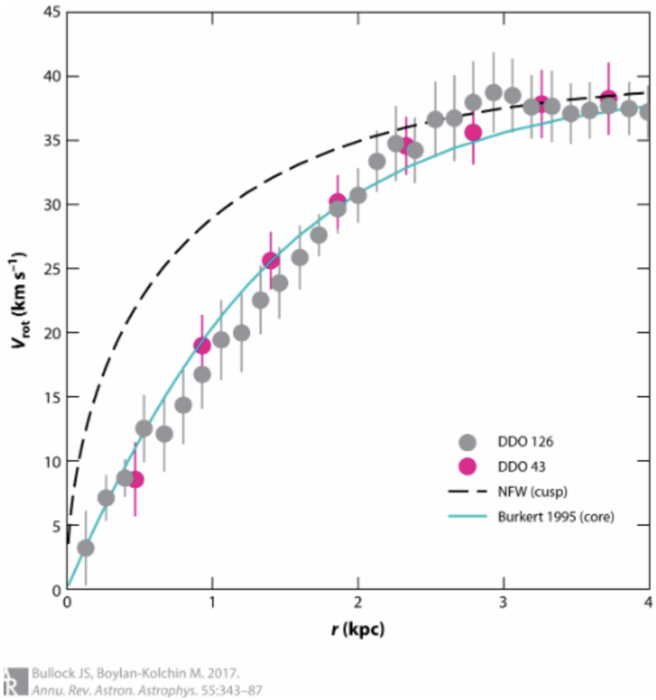

Figure 2. Example of cusp-core problem from J. S. Bullock & M. Boylan-Kolchin (2017). Dashed line is NFW expectation and points are two example galaxies. Galaxies are better fit with a constant-density core.

masses does the cusp-core problem become apparent and how are galaxy mergers related the problem, if at all?

2. PROPOSAL

2.1. *This Proposal*

Simulating the Milky Way and M31 merger event opens a unique opportunity to study galaxy formation. Because of the vast amount of information we can obtain from the galaxies, it is the most accurate simulation achievable for merger events, allowing incredibly in-depth analysis of the characteristics of elliptical galaxies, galaxy formation, and the evolution of the universe. In this project, I will test ΛCDM theory by comparing Hernquist, NFW, and Einasto halo density profiles with simulated results using the GADGET-3 N-body simulation of the Milky Way and M31 merger. After determining the profile with the best fit, I will compare the remnant's dark matter velocity curve with the model's expected velocity curve to determine if the Milky Way and M31 remnant suffers from the cusp-core problem of ΛCDM cosmology.

This paper will test which general profile fits the remnant's halo density profile, including which parameters best describe the merger remnant. Similarly, the velocity profile/rotation curve of the remnant will be able to answer if the remnant violates the cusp-core problem introduced in ΛCDM.

Galaxy evolution provides the groundwork...

[AB:] open questions [AB:] why is open question important for galaxy evolution

2.2. *Methods*

The Milky Way and M31 merger remnant is theorized to be a large elliptical galaxy R. P. van der Marel et al. (2012). The density profiles of large elliptical galaxy halos can be fit to an NFW profile (as described by J. F. Navarro et al. (1997)) outlined in Equation **1**. Here, ρ_{dm} is the characteristic density and r_{dm} is the characteristic radius. An example of a NFW density profile can be seen in **Figure 3**.

$$\rho(r) = \rho_{dm}\left(\frac{r}{r_{dm}}\right)^{-1}\left(1+\frac{r}{r_{dm}}\right)^{-2} \tag{1}$$

After small, systematic deviations in the NFW profiles became apparent, the Einasto profile provided extra pliability for improved fitting. The Einasto density profile, first used by J. Einasto (1965) to fit stars to the Milky Way, has been adopted by J. F. Navarro et al. (2004) to describe the density profile of dark matter halos. The Einasto profile is given by Equation **2**, where r_{-2} is the radius where $-\frac{d\log(\rho)}{d\log(r)} = -2$ and $\rho_{-2} = \rho(r_{-2})$. The parameter α has been found to increase with halo mass for redshifts of $z = 0$ C. S. Frenk & S. D. M. White (2012).

$$\rho(r) = \rho_{-2}\exp\left(\left(\frac{-2}{\alpha}\right)\left(\left(\frac{r}{r_{-2}}\right)^{\alpha}-1\right)\right) \tag{2}$$

The Hernquist density profile was derived from the spherical galaxy density profile from W. Jaffe (1983). This was done to resemble the $R^{\frac{1}{4}}$ law at small radii L. Hernquist (1990). Hernquist density profile given by Equation **3**, where a is a scale length.

$$\rho(r) = \frac{M_{halo}}{2\pi}\frac{a}{r(r+a)^3} \tag{3}$$

2.3. *Finding the Remnant's Density Profile*

For proper analysis, I want to take the *equilibrium* density profiles of the remnant, so I will analyze the final high resolution snap number (801) of the *halo* component for the merged Milky Way and M31 galaxies. Considering the data from both galaxies is simple, as I can manually append the 801 snap numbers for the Milky Way and M31 together.

Using the merged data, I located the center of mass of the remnant using a recursive method that considers smaller and smaller spheres to lower error tolerance to 0.01. To find the dark matter density profile, I need to consider particles with respect from the center of mass. I defined a starting radius, maximum radius, and a sphere step-size. After each sequential step, I will check which dark matter particles fall within the radius and add their masses. I will also use the radius to define a spherical volume. After repeating for the required step-sizes, I will have an array of dark matter mass and an array of sphere volume. These can be easily divided to obtain the density at the corresponding radius, and a density plot with respect to radius can be made to show the halo's density profile.

[AB:] discuss the starting (0.1 to negate the sharp cusp at small radii)/stopping radius (r200) selection and step size selection

2.4. *Curve-fitting models*

SciPy curve-fit allows the user to fit a function to data via a non-linear least-squares-fit. Curve-fit returns the best-fit values and covariance of the function's parameters.

2.5.

After fitting each density profile to the remnant's DM halo density profile via scipy optimize curve fitting, I will perform a least squared test to determine which profile provides the best fit for the halo remnant. Each density profile has a corresponding spherically-averaged circular velocity profile as described by J. F. Navarro et al. (1997); however, I will determine the adequate velocity profile equation once a density profile has been established.

Lastly, I will overlay the expected and simulated velocity curves to identify if there is a significant difference between the two profiles. If the percent difference between the two profiles is $< 5\%$ on average, I will conclude that the Milky Way and M31 merger does not violate ΛCDM cosmology via the cusp-core problem.

2.6. *Hypothesis*

The GADGET-3 simulation is an N-body, smoothed, hydrodynamical simulation that represents the initial dark matter halo of each galaxy in a Hernquist profile R. P. van der Marel et al. (2012). It is uncertain if a Hernquist profile will be the most accurate fit for the halo remnant. However, due to the profile's vital role in initializing the simulation, I hypothesize that it will be the best fit after the merger has occurred and equilibrium is reached. Due to the size of the merged DM halo remnant, I also expect that the theoretical and simulated velocity profiles will have no significant difference and therefore will not violate ΛCDM theory.

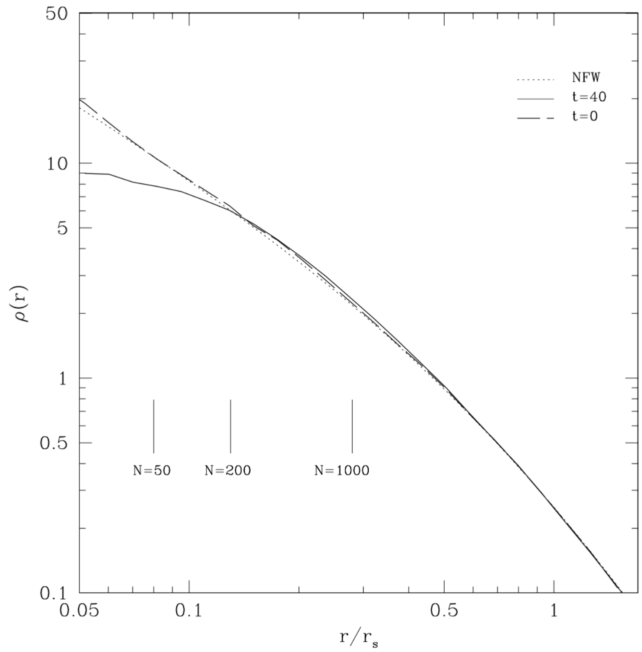

Figure 3. Example of NFW density profile from A. Klypin et al. (2013). Here, r_s is scale radius.

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