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

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## 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 have been widely used to uncover the nature of DM halos. For example, C. S. Frenk & S. D. M. White (2012) used a number of 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.

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

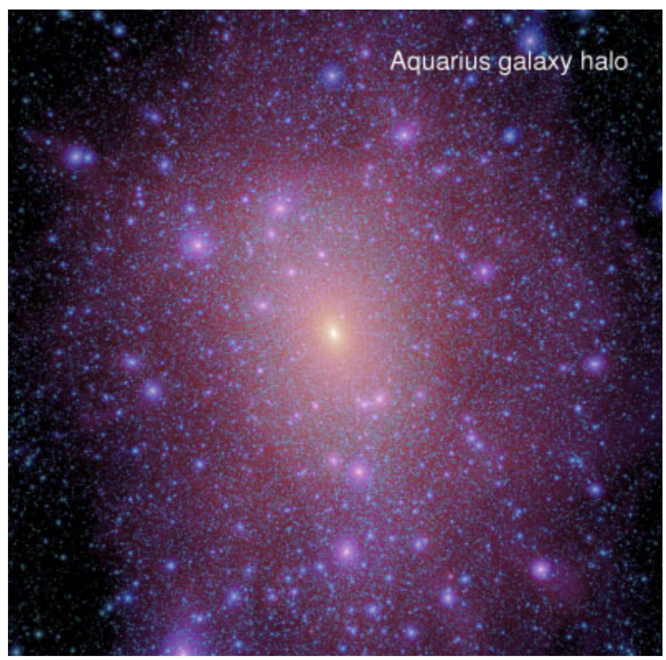


**Figure 1.** Simulated dark matter halo from C. S. Frenk & S. D. M. White (2012). Aquarius galaxy has similar mass to the Milky Way.

## 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.

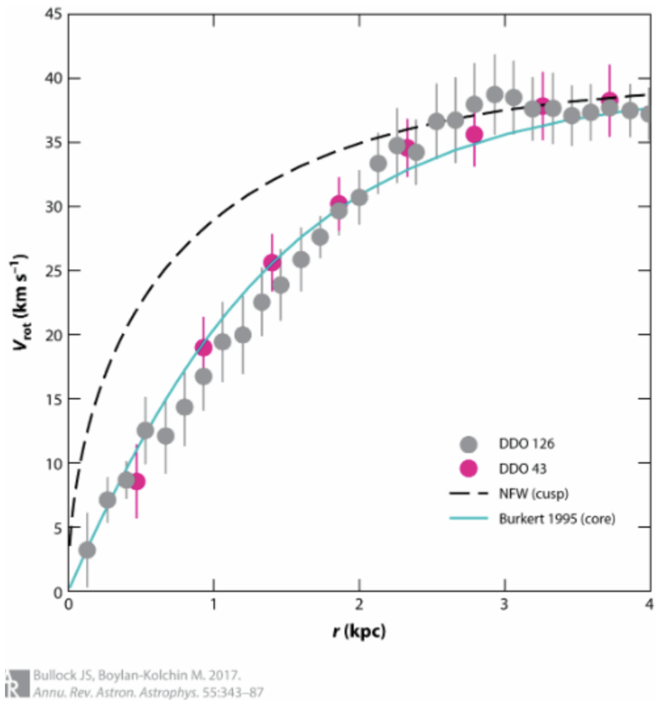


**Figure 2.** Example of cusp-core problem from J. S. Bullock & M. Boylan-Kolchin (2017). Dashed line is NFW expectation and points are two example galaxies. Galaxies are better fit with a constant-density core.

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.

### 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, $\rho_{dm}$ 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 $\alpha$ 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.

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

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.

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.

### 2.3. *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.

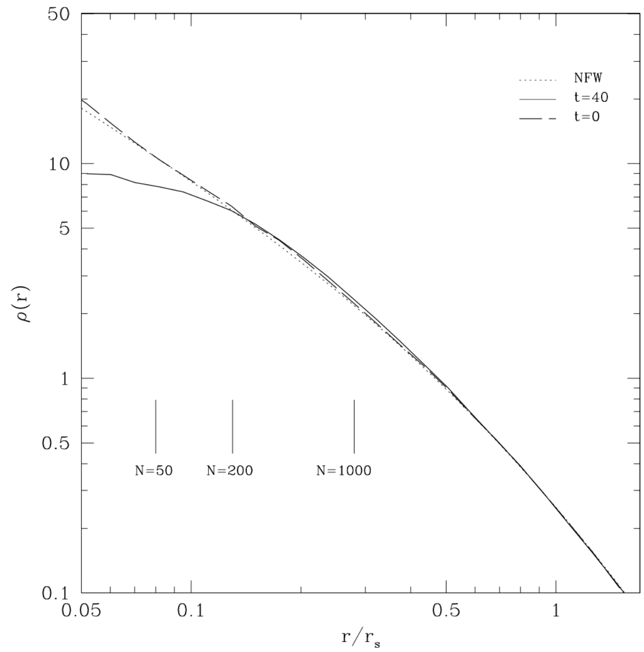


**Figure 3.** Example of NFW density profile from A. Klypin et al. (2013). Here, $r_s$ is scale radius.

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