# Structure of the Dark Matter Halo Remnant After the MW–M31 Merger

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## 2.1 Project Overview

A primary goal for cosmology and galactic dynamics is to understand the structure and evolution of **dark matter halos**. The galactic disk and its bright components are only a small part of the total mass of a galaxy, most of which is, in fact, devoid of light but still proffers gravity, and is thereby classified as a "dark matter halo," the huge gravitationally bound halo that extends far beyond the spiral-disk galaxy structure. This is the indirect evidence for dark matter due to the fact that they affect the formation, interactions and mergers of galaxies. My research focuses on the **major merger**, the structural result of one of the most dramatic gravitational phenomena.

A major merger occurs when two galaxies of comparable mass collide and are left as one remnant system. These events significantly shape the structure and kinematics of the newly formed galaxy since they disturb stellar orbits and mix dark matter. Through this project, I investigate the remnant halo of the future predicted merger of the Milky Way (MW) and Andromeda (M31). My aim is to determine whether the profile of the post-merger dark matter halo conforms to established theoretical profiles such as the **Hernquist profile** or the **NFW profile**.

Both models show how density decreases with distance from the center of a system. The **Hernquist profile** describes a spherically symmetric system with a central cusp, and steeper fall-off at large radii. The **NFW profile** is based on cosmological simulations and describes dark matter halos in ΛCDM (Frenk & White, 2012). My analysis uses a simulated snapshot of the MW-M31 merger to explore whether the resulting halo follows either of these profiles.

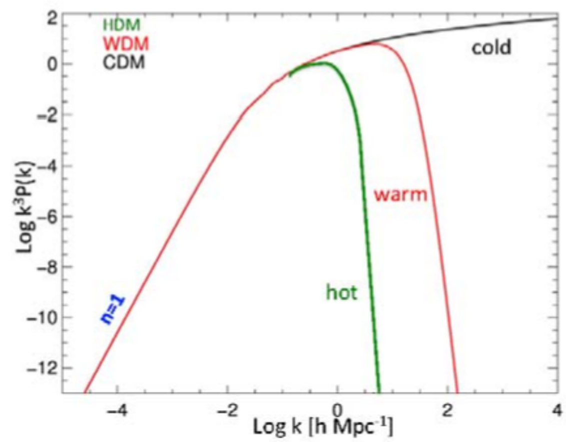


Figure 1: Power spectrum for cold (CDM), warm (WDM), and hot (HDM) dark matter. CDM supports concentrated halos on small scales, motivating the expectation for a cusp-like density profile (Frenk & White, 2012).

## 2.2 Research Questions

This study aims to answer the following questions:

1. What is the radial **density profile** of the dark matter halo that forms after the MW–M31 merger?

2. Does this profile match a Hernquist or NFW profile, and what are the best-fit scale parameters?

3. Has the remnant reached **virial equilibrium**, and over what range is it dynamically relaxed?

These questions stem from the assumption that, by whatever means they form, dark matter halos will eventually settle down into a quasi-equilibrium state. If this is true, the remnants of a big merger should look like halos that formed in isolation. Under the cold dark matter paradigm, such a model would enhance the universality of halo formation models.

These questions also help with relaxation timescales and the inner versus outer halo structure. However, dynamical models are more of an average description of the overall structure of the halo, and simulations give high precision data to test these models throughout all scales; from the very central regions to the halo outskirts. Previous simulations suggest that mergers may lead to mass redistribution, a flattened cusp, and relaxation through violent mixing (Abadi et al., 2010; Prada, 2019). Some studies suggest the inner slope may be altered or that deviations may arise compared to classical profiles (Drakos et al., 2019a,b). How well theory and simulation reproduce reality in non-idealized systems is defined by the fitting process and the limitations.

## 2.3 Methods and Data

For this I used dark matter particle data from snapshot 801 of a simulation tracking the merger between Milky Way and Andromeda. This image depicts the one system of merged galaxies. The data is provided in two text files, `MW_801.txt` and `M31_801.txt`, as well as containing position, velocity, mass, and particle type information. I will only use particle type 1, which represents dark matter particles.

I also wrote a Python program that reads both files using a custom `ReadFile` function, filters the dark matter particles out, and merges them into a unified data structure. In order to analyze the halo as a single system, we compute a mass-weighted center of mass (COM) by averaging the positions of all of the dark matter particles. Then I recenter all coordinates on the COM for that to eliminate any global offsets between the galaxies.

I calculate the radial distance of each particle from the COM, and its **radial velocity**. **Radial velocity** is the velocity vector projecting along the direction from center to particle. This is key to determining whether particles are inflowing, outflowing or stably orbiting. A large average radial velocity could imply that the system is still settling, while a small average suggests that it has dynamically relaxed.

The halo is binned in 50 logarithmic radial shells ranging from 1 to 300 kpc. For each shell, I derive total mass and mean radial velocity. Mass in each shell is divided by volume to calculate density. I have included some preliminary analysis to isolate the relaxed regions by filtering out the bins at $|\langle v_{\rm rad}\rangle| > 30$ km/s and setting the fit region to be between 10 and 150 kpc. These limits are chosen according to physical expectations, and preliminary diagnostics.

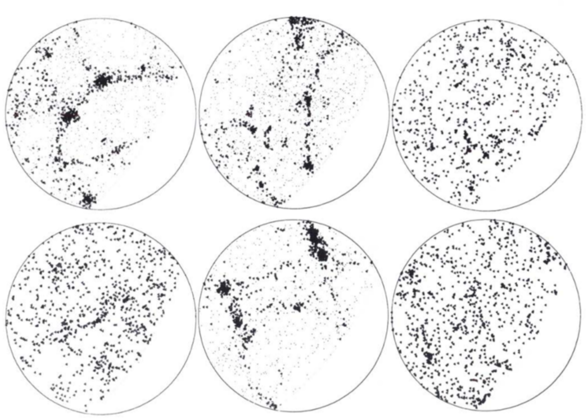

Figure 2: Dark matter halo evolution over time, showing how major mergers and relaxation processes affect the density structure of the remnant halo. Each panel represents a different merger stage, illustrating the redistribution of mass and the formation of the final density profile. This visualization provides insight into the transformation of the dark matter distribution during the MWM31 merger. Adapted from Navarro et al. (1997).

The filtered data was fitted with both Hernquist and NFW models using SciPy's `curve_fit()`. Various forms of the density profile $\rho(r)$ exist, such as the NFW profile: $\rho(r) \propto \frac{1}{(r/r_s)(1+r/r_s)^2}$, or the Hernquist profile: $\rho(r) \propto \frac{1}{(r/a)(1+r/a)^3}$, with $r_s$ and $a$ the characteristic scale parameters. These are fitted to the density values of the selected bins to give the best scale lengths. Residuals from the fitting process are also output, which can be used to judge how good the fit is.

## 2.4 Preliminary Results

Figure 3 shows the density and velocity profiles of the merged halo. The left panel displays the binned density profile (black), with green dots marking the relaxed region used in fitting. Overlaid are the best-fit Hernquist (red dashed) and NFW (blue dashed) curves. The fits match the simulation data well in the filtered range, confirming that the system is structurally consistent with both models.

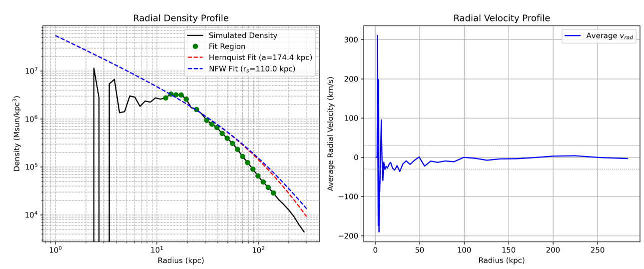


Figure 3: Left: Density profile with Hernquist (red) and NFW (blue) fits. Green points show relaxed bins used in the fit. Right: Radial velocity profile shows near-zero average beyond 10 kpc.

The best-fit scale parameters are:

- Hernquist scale length: $a \approx 174.4$ kpc
- NFW scale radius: $r_s \approx 110.0$ kpc

The right panel of Figure 3 shows that the average radial velocity is nearly zero beyond 10 kpc. This indicates that the outer halo has reached **virial equilibrium**, meaning it is gravitationally stable with balanced kinetic and potential energy. The central 10 kpc show some deviations, likely due to residual motion from the merger event. These results support prior findings that the outer halo reaches equilibrium faster than the central core (Prada, 2019).

The alignment between the simulation and both profiles is a strong result. It shows that even a complex, violent process like a **major merger** can result in a halo that fits simple, well-known analytic models. This supports the universality of these profiles and reinforces the CDM assumption that halos are self-similar, regardless of their assembly history.

## 2.5 Next Steps

There are several directions I plan to explore to extend this work. First, I plan to study snapshots before and after 801 to track the evolution of the density profile and determine how long the system takes to relax. This can reveal when the outer halo settles and whether the core ever reaches full equilibrium.

Second, I will compute the cumulative mass profile $M(< r)$ and compare it to the analytic integrals of Hernquist and NFW profiles. These comparisons test whether the total enclosed mass behaves as expected, which is especially important for understanding gravitational lensing and satellite motion predictions.

Third, I could even plan to test alternate profile models. For example the Einasto profile, which introduces an additional shape parameter and may provide a better fit at large radii. Comparing model accuracy across multiple frameworks can improve our understanding of structural diversity in merger remnants.

Finally, I will compare the MW–M31 halo to real galaxies observed with dark matter constraints. Many elliptical galaxies are believed to be merger remnants, so if their halos also fit Hernquist or NFW profiles, it supports the simulation as a physical analog. This bridges theory, simulation, and observation in a meaningful way.

Ultimately, this project shows how analytic modeling, code-based analysis, and simulation data come together to answer real cosmological questions. A deeper understanding of how halos form and settle can inform everything from galaxy morphology to dark matter properties, making this a powerful study of cosmic structure.

## References

## References

Frenk, C. S., & White, S. D. M. 2012, *Annalen der Physik*, 524, 507

Abadi, M. G., Navarro, J. F., & Springel, V. 2010, *MNRAS*, 407, 407

Drakos, N. E., Yamaoka, S. T. 2019a, *MNRAS*, 487, 993

Drakos, N. E., Mendoza, P. R. 2019b, *MNRAS*, 487, 1008

Prada, F. 2019, *MNRAS*, 490, 490