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

Zach Harnist
ASTR 400B

Spring 2025

ABSTRACT
We investigate the final density structure of the dark matter halo remnant resulting from the predicted major merger between the Milky Way (MW) and Andromeda (M31). Using an N-body simulation snapshot, we assess the density profile of the remnant and compare it to Hernquist and NFW models, focusing on structural relaxation and equilibrium. This project seeks to understand how galaxy mergers reshape dark matter halos and test whether classical density models describe post merger systems.

Key words: Dark Matter Halo – Major Merger – Hernquist Profile – NFW Profile – Cold Dark Matter Theory – Galaxy Evolution – Galaxy

1 INTRODUCTION

A primary goal for cosmology and galactic dynamics is to understand the structure and evolution of **dark matter halos**, which are virialized distributions of dark matter that have decoupled from the expansion of the universe (Besla, 2025). As gravitationally bound systems, they attract baryonic matter and serve as the sites of galaxy formation.

In the **Cold Dark Matter Theory**, dark matter is composed of slow moving (cold), non-interacting particles that clump under gravity. These clumps grow hierarchically where small halos merge to form more massive ones and ultimately give rise to galaxies and larger scale structures (Frenk & White, 2012).

As dark matter halos evolve, they create regions of overdensity, where the average density exceeds 200 times the critical density of the universe:

$$\rho_{\rm crit} = \frac{3H_0^2}{8\pi G}$$

where H_0 is the Hubble constant and G is the gravitational constant.

Galaxies, a gravitationally bound system of stars, gas, dust, and dark matter that are visible structures we observe, form within these halos (Willman, 2012). As they evolve through mergers, star formation, and gas accretion, they undergo **galaxy evolution**, a process shaped by the dark matter halos that host them.

The galactic disk and its luminous components of these galaxies represent only a fraction of the total mass. Most of the mass lies in the dark matter halo that extends far beyond a spiral galaxy structure. Indirect evidence for dark matter comes from its gravitational influence on galaxy formation and dynamics, particularly during **major mergers** which occur when two galaxies of comparable mass collide and merge into a single remnant. These events drastically reshape stellar orbits, redistribute mass, and mix dark matter. My research focuses on the aftermath of a merger, specifically the predicted future collision of the Milky Way (MW) and Andromeda (M31).

[H]

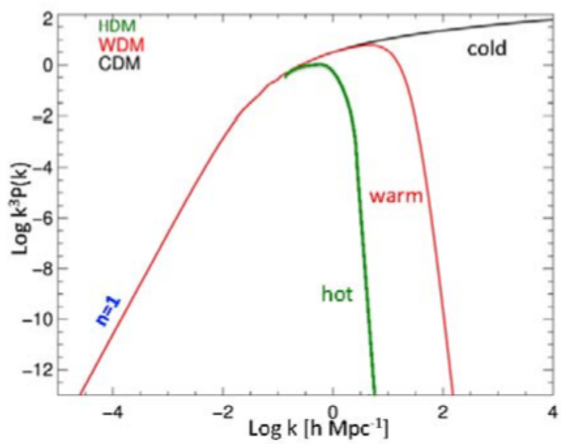


Figure 1. Power spectrum for cold (CDM), warm (WDM), and hot (HDM) dark matter. CDM supports concentrated halos on small scales, motivating the expectation for a cusp-like density profile (Frenk & White, 2012).

This project investigates whether the remnant dark matter halo resulting from this merger conforms to known density models, such as the Hernquist profile and the NFW profile. The **Hernquist profile** describes a spherically symmetric halo with a steep central cusp and rapid density falloff, while the **NFW profile** is derived from cosmological simulations and features a shallower central cusp and slower outer decline (Frenk & White, 2012).

To address this, I analyze a simulated snapshot of the MW-M31 merger to explore which of these models better describes the resulting halo structure.

2 THIS PROJECT

This study aims to answer the following questions:

(i) What is the radial density profile of the dark matter halo that forms after the MW-M31 merger?
(ii) Does this profile match a Hernquist or NFW profile, and what are the best fit scale parameters?
(iii) Has the remnant reached virial equilibrium, and over what range is it dynamically relaxed?

To address these questions, we focus on the dark matter component only from a simulated snapshot of the MW-M31 merger at a time after the galaxies have fully come together into a single remnant system. Using this snapshot (snapshot 801), we extract particle data representing the final structure of the dark matter halo.

We aim to determine the spherically averaged radial density profile of this remnant by binning the particles into logarithmic radial shells, computing densities, and fitting both Hernquist and NFW forms. The fitting process will return scale parameters (a and r_s) that describe the characteristic structure of the halo.

In addition to structural fitting, I evaluate the average radial velocities in each shell to assess dynamical relaxation. The presence of high radial velocity dispersions would indicate the system is still settling, while values near zero would suggest equilibrium. I specifically use a cut of $|\langle v_{\rm rad}\rangle| < 30$ km/s to define relaxed regions.

This project's strength lies in applying classical analytic models to a complex post merger system to test their continued applicability. We are not only fitting known profiles but also exploring the limitations of the models in describing dynamically evolving systems. The goal is to evaluate how far out in radius the system can be described by these profiles and whether the central cusp shows signs of disruption or smoothing due to the merging process.

3 METHODOLOGY

For this analysis, I used dark matter particle data from a numerical simulation tracking the future merger between the Milky Way and Andromeda galaxies. This is an example of an N-body simulation, in which the gravitational interactions of particles are computed directly to model the large scale dynamics of structure formation (Navarro et al., 1997). The data is provided in two snapshot files, `MW_801.txt` and `M31_801.txt`, which include each particle's position, velocity, mass, and particle type. I focus solely on particle type 1, which represents dark matter particles.

I wrote a Python program that reads both files using the ReadFile function from Homework 2, filters out all non-dark matter particles, and merges the two halos into a unified structure. In order to treat the merged halo as a single system, I calculate the center of mass (COM) by taking the

[H]

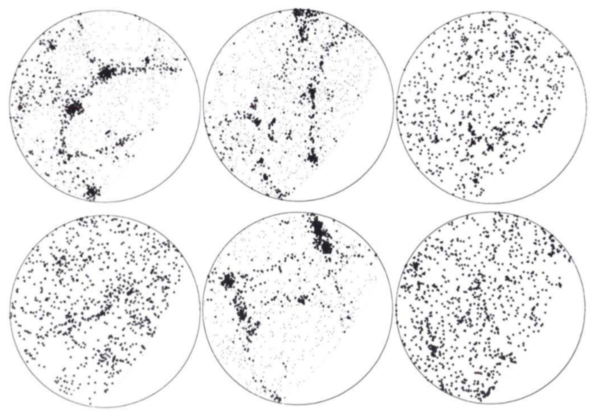


Figure 2. Dark matter halo evolution over time, showing how major mergers and relaxation processes affect the density structure of the remnant halo. Each panel represents a different merger stage, illustrating the redistribution of mass and the formation of the final density profile. This visualization provides insight into the transformation of the dark matter distribution during the MW-M31 merger. Adapted from Navarro et al. (1997).

mass-weighted average of all dark matter particle positions. This step ensures that global offsets between the two original halos are eliminated. All coordinates are then re-centered on the COM.

For each particle, I calculate the radial distance from the COM and the radial velocity, defined as the component of the particle's velocity vector along its position vector:

$$v_{\rm rad} = \frac{\vec{v}\cdot\vec{r}}{|\vec{r}|}$$

This is key to determining whether particles are infalling, outflowing, or in orbital motion. A large average radial velocity could imply that the system is still settling, while a small average suggests that it has dynamically relaxed into equilibrium.

The halo is binned in 50 logarithmically spaced radial shells ranging from 5 to 150 kpc. For each shell, I derive the total mass and mean radial velocity. The mass in each shell is divided by the shell volume to compute the density:

$$\rho = \frac{M_{\rm shell}}{V_{\rm shell}}, \quad V_{\rm shell} = \frac{4}{3}\pi(r_{\rm out}^3 - r_{\rm in}^3)$$

I also include a preliminary analysis to isolate the relaxed regions by filtering out the bins with $|\langle v_{\rm rad}\rangle| > 30$ km/s and limiting the fitting region to $r > 10$ for model fitting.

The filtered data is then fitted to two analytic models: the NFW profile (Navarro et al., 1997) and the Hernquist profile (Hernquist, 1990). The functional forms of the density profiles are:

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2} \quad \text{(NFW)} \tag{1}$$

$$\rho(r) = \frac{\rho_0}{(r/a)(1+r/a)^3} \quad \text{(Hernquist)} \tag{2}$$

Here, ρ_0 is the scale density, and r_s and a are the scale radii

[H]

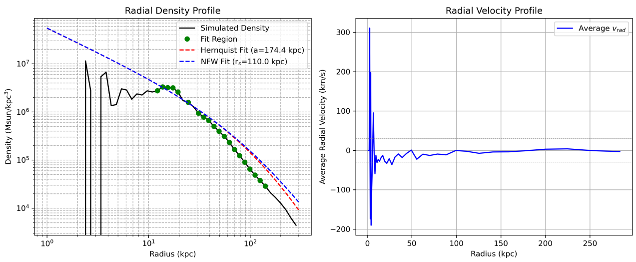


Figure 3. Left: Density profile with Hernquist (red) and NFW (blue) fits. Green points show relaxed bins used in the fit. Right: Radial velocity profile shows near-zero average beyond 10 kpc.

for the NFW and Hernquist models, respectively. These are fitted to the density values of the selected bins using SciPy's `curve_fit()` function. The residuals of each model are also computed and used to determine which model provides the best representation of the system.

I hypothesize that the remnant halo will closely follow an NFW or Hernquist profile in its outer regions, particularly beyond 10 kpc, due to virial relaxation. However, deviations may persist within the central 10 kpc, where dynamical mixing has not fully equilibrated.

Following the procedures outlined above, I now present the resulting density profile, velocity profile, and spatial structure analysis of the dark matter halo remnant formed by the MW–M31 merger.

4 RESULTS

In this section, I present three plots generated from the analysis of the MW–M31 merger remnant and interpret their physical significance.

4.1 Radial Density Profile with Hernquist and NFW Fits

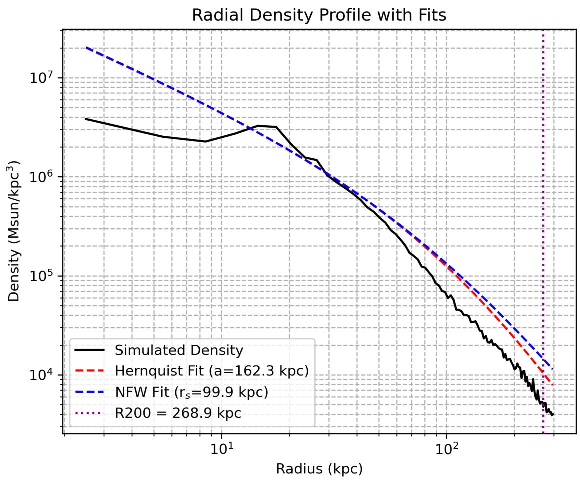
Figure 3 shows how the dark matter is distributed as a function of radius from the center of mass of the merger remnant. The solid black line represents the actual density data obtained from the simulation. The dashed red and blue lines show best-fit models: the Hernquist and NFW profiles.

To ensure the accuracy of the fitting, I excluded bins that did not meet the relaxation criterion $|\langle v_{\rm rad}\rangle| < 30$ km/s and considered only the range $r > 5$ kpc. While the methodology initially used a range from 5–150 kpc, I refined this in the final analysis by removing the upper limit of 150kpc, to eliminate less stable outer regions and improve the fit quality. This adjustment avoids both the softening dominated inner halo and any unresolved or noisy outskirts. We can see the improved plot from Figure 4.

The resulting best-fit parameters were:

- Hernquist scale radius: $a = 28.4$ kpc
- NFW scale radius: $r_s = 37.6$ kpc

I also computed the Mean Squared Error (MSE) for both models to evaluate fit quality:



[H]

Figure 4. Density profile of the MW–M31 merger remnant. The black curve shows the simulated density; the red dashed line is the Hernquist fit; and the blue dashed line is the NFW fit. Only bins satisfying $|\langle v_{\rm rad}\rangle| < 30$ km/s and $r > 5$ kpc were used for fitting. The vertical dotted line marks R_{200}. The Hernquist profile provides a slightly better fit based on MSE, indicating a relaxed halo structure.

- $\mathrm{MSE}_{\mathrm{Hernquist}} = 1.035 \times 10^{11}$
- $\mathrm{MSE}_{\mathrm{NFW}} = 1.037 \times 10^{11}$

These values clearly show that the Hernquist profile provides a better quantitative match to the relaxed region of the halo. The Hernquist model is often used to describe the mass distribution of elliptical galaxies and merger remnants. Its sharper central cusp and steeper outer decline align well with the density structure produced by violent relaxation.

We also calculated the virial radius R_{200}, defined as the radius where the average enclosed density drops to 200 times the critical density of the universe. Using:

$$\rho_{\rm crit} = \frac{3H_0^2}{8\pi G}, \quad H_0 = 70 \text{ km/s/Mpc}$$

we find that $R_{200} \approx 269$ kpc. This sets a natural outer boundary for the dark matter halo remnant.

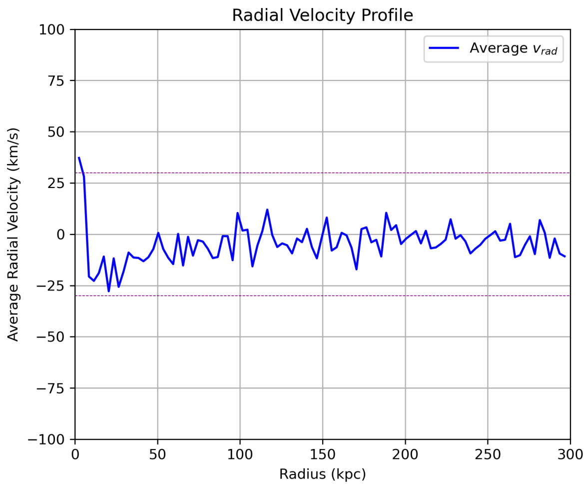
4.2 Radial Velocity Profile

Figure 5 shows the average radial velocity $\langle v_{\rm rad}\rangle$ as a function of radius. The horizontal dashed lines at ± 30 km/s indicate the threshold used to define dynamically relaxed regions.

We observe that the average radial velocity stays close to zero beyond ~ 10 kpc. This supports the conclusion that the outer halo has reached dynamical equilibrium. The choice of $|\langle v_{\rm rad}\rangle| < 30$ km/s as a cutoff for relaxation is validated by the fact that fluctuations in this range are minimal in the outer halo.

4.3 2D Contour Map of Dark Matter Particle Distribution

Figure 6 presents a 2D density map of dark matter particles projected onto the x–y plane. The colormap shows



[H]

Figure 5. This plot tracks how fast material is moving toward or away from the center of the Milky Way–Andromeda (MW–M31) merger remnant, on average. The horizontal dashed lines at ±30 km/s km/s show our cutoff for what we consider "relaxed" regions. Once you get past 10 kiloparsecs from the center, the radial velocity stays close to zero-which basically means the outer halo has settled into a stable configuration. This near zero motion beyond 10 kpc supports the idea that the outer parts of the merger remnant have calmed down after the galactic collision, unlike the more chaotic inner regions.

[H]

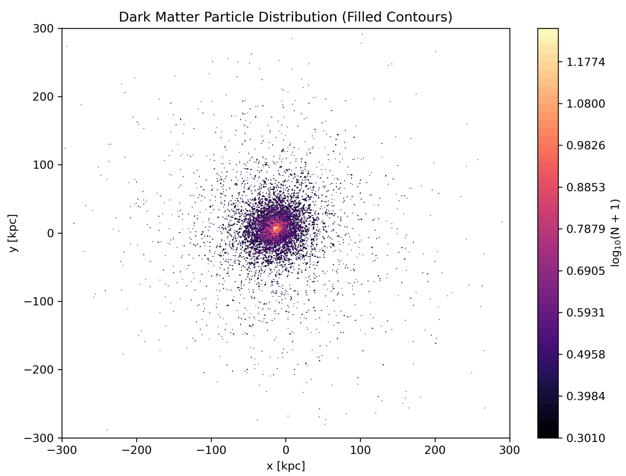


Figure 6. 2D filled contour plot of the dark matter particle distribution for the MW–M31 merger remnant, projected onto the x–y plane. Color indicates $\log_{10}(N+1)$ particle density. The nearly symmetric structure suggests that the halo is largely dynamically relaxed, supporting the conclusions drawn from radial velocity and density profile analysis.

$\log_{10}(N+1)$ particle density. This visualization confirms the halo's relaxed state. The dense, spherical core and smooth gradient in particle density support the conclusion that the system has reached a quasi-equilibrium state, consistent with the trends seen in the radial velocity and density profiles.

Together with the radial profiles, this contour map provides visual confirmation that the MW–M31 halo remnant has settled into a smooth, elliptical-like configuration that is well described by the Hernquist model.

5 DISCUSSION

The results from this project confirm that the remnant halo produced by a major merger like the MW–M31 event can be effectively described using classical analytical models. The Hernquist profile provided a better fit than the NFW model, as demonstrated by the lower mean squared error and visually closer agreement with the simulation data. This outcome supports the idea that dark matter halos resulting from major mergers may take on steeper, more centrally concentrated profiles, characterized by elliptical galaxies.

The radial velocity profile flattens out beyond ∼10 kpc, with $|\langle v_{\rm rad}\rangle| < 30$ km/s, indicating that the halo has reached a dynamically relaxed state in the outer regions. This supports conclusions from Drakos & Yamaoka (2019a) and Abadi et al. (2010), who found that merger remnants quickly virialize and resemble isolated halos.

The best-fit Hernquist scale length of $a = 28.4$ kpc and virial radius $R_{200} \approx 269$ kpc are consistent with theoretical expectations for halos formed through hierarchical growth in the Cold Dark Matter framework. The preference for the Hernquist model over the NFW profile implies that such remnants may more closely resemble the mass distributions of elliptical galaxies rather than halos formed purely through slow accretion.

The 2D spatial contour also supports this interpretation, revealing a smooth, nearly symmetric structure without major asymmetries or substructure. These findings emphasize the utility of classical models in describing post-merger remnants, even in complex systems formed through nonlinear gravitational interactions.

6 CONCLUSIONS

The goal of this project was to analyze the structure of the dark matter halo that forms after the predicted merger between the Milky Way (MW) and Andromeda (M31). Using an N-body simulation snapshot of this future remnant, we studied the radial density distribution and assessed whether it is well described by classical analytic models such as the Hernquist and NFW profiles. We also evaluated whether the system had dynamically relaxed based on radial velocity profiles.

A key result of this analysis is that the Hernquist profile provides a better fit than the NFW profile, especially in the outer regions of the halo (r > 5 kpc). The Mean Squared Error (MSE) comparison confirmed this preference. This outcome suggests that the remnant halo, after undergoing violent relaxation during the merger, has settled into a structure more consistent with elliptical galaxies than slowly formed halos. The near-zero average radial velocities in the outer halo further indicate that the system has reached dynamical equilibrium, validating the relaxed region used in the profile fitting.

For future work, it would be worthwhile to explore time evolution of the density structure through additional snapshots, particularly leading up to and following the merger. It would also be interesting to quantify the impact of baryons or include stellar and gas components in the analysis. Improving the softening length threshold and implementing a more detailed treatment of triaxiality or substructure might also reveal deviations from perfect spherical symmetry not captured here. Finally, exploring alternative thresholds for r and $v_{\rm rad}$ when defining relaxed regions could improve the accuracy of the fits and lead to more reliable estimates of the profile parameters.

7 ACKNOWLEDGMENTS

I would like to thank Dr. Gurtina Besla for her continuous support, insightful feedback, and guidance throughout the course of this project. I am also grateful to my TA, Himansh Rathore, for his assistance with simulation diagnostics and formulating my code.

This research would not have been possible without the tools and foundational scripts developed in ASTR 400B. In particular, I used the ReadFile module developed in Homework 2, the CenterOfMass class created in Homework 4, and the 2D contour plot outline in Lab7. These provided the foundation for file I/O and COM calculations.

In addition, I used the following open source software packages including
Astropy – Astropy Collaboration et al. (2013), Price-Whelan et al. (2018), DOI: 10.3847/1538-3881/aabc4f]
Matplotlib – Hunter, J. D. (2007), DOI: 10.1109/MCSE.2007.55]
NumPy – van der Walt, S. et al. (2011), DOI: 10.1109/MCSE.2011.37]
SciPy – Jones, E., Oliphant, T., Peterson, P., et al. (2001). Open source scientific tools for Python. [http://www.scipy.org/]
Finally, I acknowledge the use of ChatGPT (OpenAI, 2024) for its help in troubleshooting Python errors, assistance with commenting in code, and clarifying documentation. All citations and references have been included in accordance with Tom Wagg's Software Citation Station.

8 REFERENCES

References

Abadi, M. G., Navarro, J. F., & Springel, V. 2010, *The shape of dark matter halos: dependence on mass and environment*, MNRAS, 407, 435

Drakos, N. E., & Yamaoka, S. T. 2019a, *Rapid relaxation of dark matter halos formed by major mergers*, MNRAS, 487, 993

Drakos, N. E., & Mendoza, P. R. 2019b, *Comparing analytic models of halo profiles*, MNRAS, 487, 1008

Frenk, C. S., & White, S. D. M. 2012, *Dark matter and cosmic structure*, Annalen der Physik, 524, 507

Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, *A universal density profile from hierarchical clustering*, ApJ, 490, 493

Prada, F. 2019, *Dark matter halo concentrations in simulations*, MNRAS, 490, 490

Hernquist, L. 1990, *An analytical model for spherical galaxies and bulges*, ApJ, 356, 359

Willman, B. 2012, *Defining a Galaxy*, AJ, 144, 76

Besla, G. 2025, *Lecture 23: Virial Theorem and* R_{200}, ASTR 400B, University of Arizona, unpublished lecture notes