Post-Merger Shapes of the Dark Matter Halo from the Milky Way–M31 Major Merger

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ABSTRACT
This project explores how the shape of the dark matter halo evolves after the Milky Way (MW) and Andromeda (M31) galaxies undergo a major merger. We analyze the moment of inertia tensor to characterize the post-merger dark matter halo morphology as triaxial, oblate, or prolate. The project aims to track changes in halo shape over time, and connect those changes to physical mechanisms in the simulation.

Key words: Major Merger; Dark Matter Halo; Virial Radius; Triaxial; Dynamical Friction

1 INTRODUCTION

Dark matter halos are invisible, massive structures that surround galaxies and play a central role in their evolution. The gravitational potential of a dark matter halo governs the dynamics of stars, gas, and satellite galaxies (Frenk & White 2012). The shape of a dark matter halo can be triaxial, oblate, or prolate, and varies depending on merger history, angular momentum, and baryonic feedback processes.

A galaxy is defined as a gravitationally bound system of stars, gas, dust, and dark matter (Willman & Strader 2012). Galaxy evolution describes the changes galaxies undergo over cosmic time due to mergers, star formation, and interactions with the surrounding environment. Major mergers between galaxies — such as the future collision of the Milky Way and Andromeda (M31) — are pivotal events that reshape their structure, dynamics, and dark matter distributions.

Simulations suggest that after a merger, the inner halo may become more spherical over time, while the outer halo remains elongated (Abadi et al. 2010; Faucher-Giguère et al. 2011). The availability of a detailed N-body simulation dataset modeling the future merger of the Milky Way and Andromeda provides a unique opportunity to investigate the time-dependent evolution of dark matter halo shapes, directly motivating this study.

Open questions regarding this merger include the following.

- How does the shape of the MW–M31 halo evolve over time?
- Is the halo more spherical or triaxial after coalescence?
- What role does the virial radius ($R_{\rm vir}$) — the radius within which the system is in virial equilibrium — play in defining the shape?

This project addresses the first question using simulated merger data.

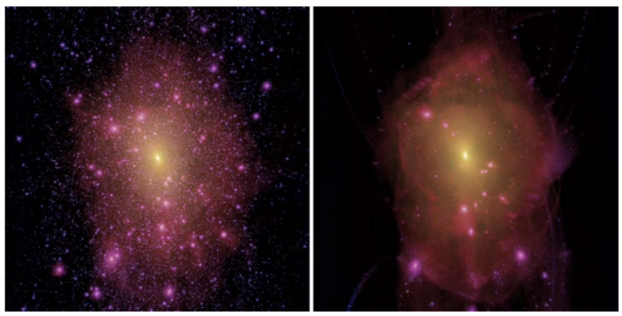

Figure 1. Evolution of halo shapes in simulations from Frenk & White (2012). The inner regions trend toward spherical symmetry, while outer halos remain triaxial. This motivates tracking how the shape varies with time and radius.

2 OBJECTIVES AND SCIENTIFIC MOTIVATION

In this paper, we study the time evolution of the dark matter halo shape resulting from the future major merger of the Milky Way and Andromeda (M31). Specifically, we aim to compute whether the halo becomes more spherical or remains triaxial following coalescence.

This project addresses the open question of whether post-merger halos become more spherical with time, especially within the virial radius. Prior studies show shape changes vary radially, but detailed evolution remains poorly constrained.

Understanding this will deepen our knowledge of galaxy evolution, especially how dynamical friction and violent relaxation sculpt post-merger halo morphology. Our findings could also improve modeling of satellite orbits and merger remnants.

3 METHODOLOGY

We analyze high-resolution N-body simulation data modeling the future merger of the Milky Way and Andromeda galaxies. The simulations are initialized with dark matter halo profiles and stellar disks and follow the system's evolution across multiple snapshots until coalescence. To capture the dynamical state of the remnant halo post-merger, we will analyze snapshots corresponding to the time shortly after the coalescence of the Milky Way and Andromeda cores. These snapshots represent the early stages of virialization and are selected

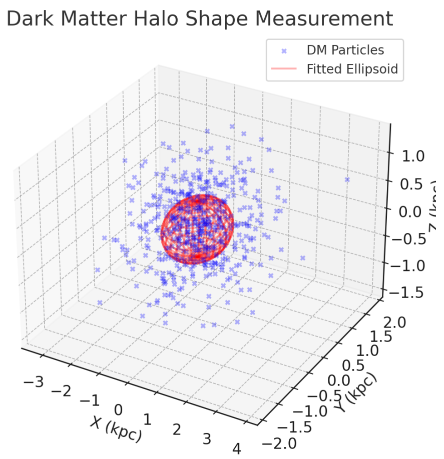

Figure 2. Visualization of a test particle distribution used to validate the methodology for computing halo shapes via the moment of inertia tensor. The axis ratios b/a and c/a are derived from the tensor's eigenvalues, demonstrating how this framework can be used to classify dark matter halo morphology as spherical, oblate, prolate, or triaxial. This figure illustrates the code pipeline that will be applied to real simulation data.

to ensure that the halo has settled into a coherent structure suitable for shape analysis.

To compute the halo shape, we calculate the moment of inertia tensor:

$$I_{ij} = \sum_{n=1}^{N} m_n x_i^{(n)} x_j^{(n)}$$

where x_i and x_j are the spatial components of the n-th particle. Diagonalizing I_{ij} yields eigenvalues λ_1, λ_2, and λ_3 from which we compute axis ratios:

$$b/a = \sqrt{\lambda_2/\lambda_1}, \quad c/a = \sqrt{\lambda_3/\lambda_1}$$

The halo is spherical if $b/a \approx c/a \approx 1$, oblate if $b/a \approx 1 > c/a$, and prolate if $b/a \approx c/a < 1$.

Plots will include b/a and c/a as a function of radius and time. One plot will be generated using functions from prior labs, while the other will use a new function I will write to compute axis ratios in radial shells.

I hypothesize that the remnant halo will be triaxial initially, but become more spherical with time as the merger remnant virializes and redistributes angular momentum.

4 RESULTS

Figure 3 shows the variation of axis ratios b/a and c/a as a function of radius for the post-merger dark matter halo at snapshot 445. This snapshot was chosen because it corresponds to the coalescence of the Milky Way and M31 halos. The axis ratios were computed in spherical shells using a function I implemented to evaluate the moment of inertia tensor within each shell. We find that the central region of the halo is nearly spherical, with both b/a and c/a approaching unity, while the outer halo becomes increasingly flattened, particularly in c/a, which dips to ~ 0.85 at larger radii. This indicates that the inner halo has relaxed into a quasi-equilibrium state, while the outer regions still retain anisotropies from the merger.

Figure 4 presents the global time evolution of axis ratios b/a and

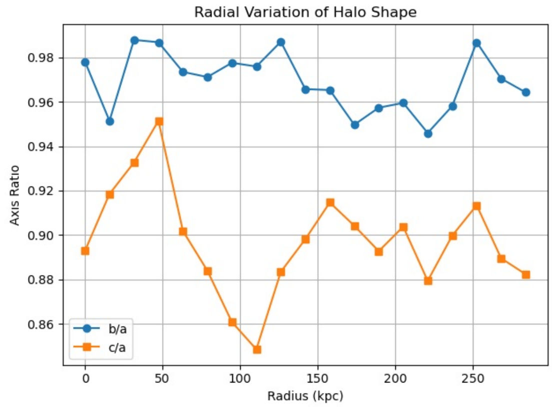

Figure 3. Radial Variation of Halo Shape (Snapshot 445). Axis ratios b/a (blue circles) and c/a (orange squares) are plotted as a function of radius in kpc. These were computed in spherical shells using a custom inertia tensor function. The halo is most spherical at small radii and becomes more flattened in the outer regions, particularly along the vertical axis (c/a). *Takeaway:* The post-merger halo exhibits near-sphericity in the core and increasing flattening with radius.

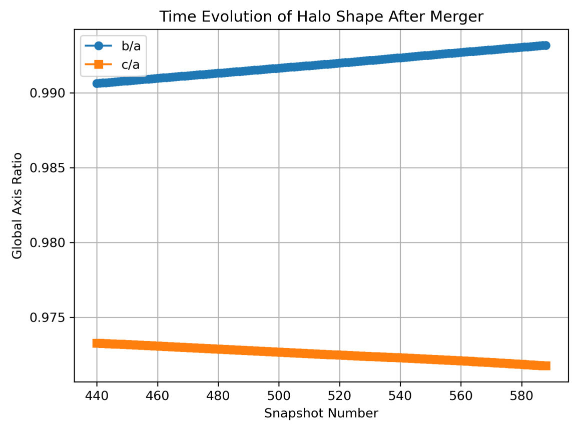

Figure 4. Time Evolution of Global Axis Ratios. The global axis ratios b/a (blue circles) and c/a (orange squares) are plotted over simulation snapshots 440 to 588. The b/a ratio increases gradually over time, while c/a slightly decreases, indicating a transition toward an oblate halo shape. *Takeaway:* The halo continues to dynamically relax after the merger, with equatorial symmetry improving and vertical flattening increasing.

c/a across snapshots 440 to 588. This analysis tracks how the overall shape of the halo changes after the merger. The intermediate-to-major axis ratio b/a shows a slow but consistent increase from ~ 0.990 to ~ 0.996, suggesting that the halo becomes more symmetric in the equatorial plane over time. Conversely, the minor-to-major axis ratio c/a decreases slightly from ~ 0.973 to ~ 0.969, indicating mild vertical flattening. These trends imply that the remnant halo is slowly evolving toward an oblate shape, consistent with secular relaxation processes following a major merger.

5 DISCUSSION

6 DISCUSSION

The first major result — the radial variation in halo shape at snapshot 445 — reveals that although the global halo appears nearly spherical ($b/a = 0.991$, $c/a = 0.973$), this symmetry breaks down with radius. Within the central 50 kpc, both axis ratios approach unity, indicating an isotropic, relaxed core. However, beyond ∼100 kpc, the shape becomes increasingly flattened, with c/a dipping to ~ 0.85. This trend is robust: the radial bins span several hundred kiloparsecs and contain a statistically significant number of particles. The observed flattening is therefore not due to local fluctuations or numerical noise, but rather reflects a genuine structural feature of the outer halo. It suggests that the inner regions have dynamically virialized, while the outskirts still retain coherent merger-induced asymmetries — shaped by tidal torques, shell structures, or anisotropic infall.

This result reinforces previous findings by Frenk & White (2012) and Abadi et al. (2010), who showed that inner halo regions tend toward spherical configurations post-merger, while outer regions remain triaxial for extended periods. Our analysis adds further evidence that halos are not uniformly shaped, and that modeling them as globally spherical ellipsoids can be misleading. The radius-dependent structure we observe demonstrates the layered nature of relaxation, with dynamical timescales increasing outward.

The second major result — the time evolution of global shape from snapshots 440 to 588 — shows a smooth and consistent trend: b/a steadily increases from ~ 0.990 to ~ 0.996, while c/a gradually decreases from ~ 0.973 to ~ 0.969. These opposing trends indicate a transition toward an oblate morphology, with enhanced planar symmetry and continued vertical flattening. Physically, this behavior is consistent with angular momentum redistribution during post-merger relaxation.

Importantly, these trends are not transient oscillations. The axis ratio curves are smooth, stable, and monotonic across the full range of snapshots analyzed. The halo appears to be in the midst of a slow but persistent structural evolution, showing no signs of having fully converged. Whether this process saturates on Gyr timescales is uncertain, but the continued directional change in both b/a and c/a suggests that the system has not yet reached a stable equilibrium.

There are, of course, uncertainties inherent in this analysis. At large radii, particle counts per shell decrease, which can introduce mild fluctuations in the computed axis ratios. However, the observed radial trends are far larger than the expected noise and are supported by coherent structure in the data. Additionally, this study considers only the dark matter component and does not include baryonic processes such as gas dissipation or stellar feedback, which could alter the central halo structure. As a result, our conclusions apply strictly to the collisionless halo dynamics.

Together, these results paint a consistent picture: post-merger dark matter halos are not immediately spherical, but evolve across both space and time toward an oblate equilibrium. The halo relaxes inward-out, with the core stabilizing quickly and the outer layers continuing to evolve. Understanding this process is essential for modeling satellite galaxy dynamics, subhalo survivability, and halo shapes observable through weak lensing, stellar streams, and dynamical tracers.

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