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 virialized distributions of dark matter that are decoupled from the expansion of the Universe. These halos are overdensities, where the average density exceeds the mean cosmic density by a fixed factor. They gravitationally attract baryons and are therefore the sites of galaxy formation (Besla 2025) . Their gravitational potential governs the dynamics of stars, gas, and satellite galaxies, making them central to the structure and evolution of galaxies.

A **galaxy** is a gravitationally bound system composed 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 their environment. A **major merger** occurs when two galaxies of comparable mass (typically with a mass ratio of less than 3:1) collide and coalesce, transforming their structural and dynamical properties.

The shape of a dark matter halo may be **triaxial** (three unequal axes), **oblate** (flattened at the poles), or **prolate** (elongated along one axis), and evolves depending on the system's merger history, angular momentum, and baryonic processes. Simulations show that inner halo regions tend to become more spherical post-merger, while outer halos often remain elongated for extended periods (Abadi et al. 2010; Faucher-Giguère et al. 2011).

In this project, we investigate the shape evolution of the MW–M31 post-merger dark matter halo using a high-resolution N-body simulation. These simulations track the gravitational interactions of massive particle ensembles, modeling stars and dark matter over time. This dataset offers a unique opportunity to explore how halo shape evolves with radius and time in the aftermath of a major cosmological merger.

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?

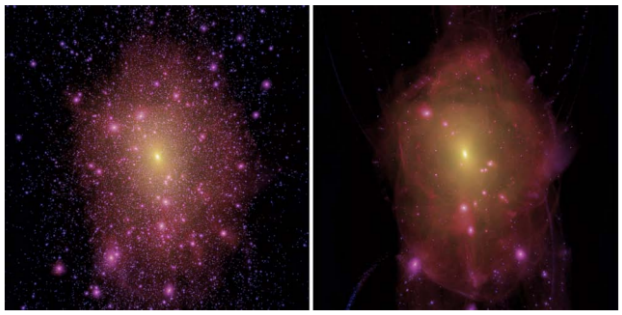

Figure 1. Evolution of halo shapes in simulations from Frenk & White (2012). The inner regions trend toward spherical symmetry, while outer halos remain triaxial. This motivates tracking how the shape varies with time and radius.

This project addresses the first two questions using simulated merger data.

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. Prior studies show shape changes vary radially, but detailed evolution (especially temporal progression) appears to be not well characterized within established literature.

Understanding this evolution deepens our knowledge of galaxy formation and hierarchical structure growth, particularly how **dynamical friction**—the gravitational drag acting on massive bodies moving through a sea of lighter particles—and **violent relaxation**—a rapid energy redistribution caused by time-varying gravitational potentials—contribute to the emergence of post-merger halo

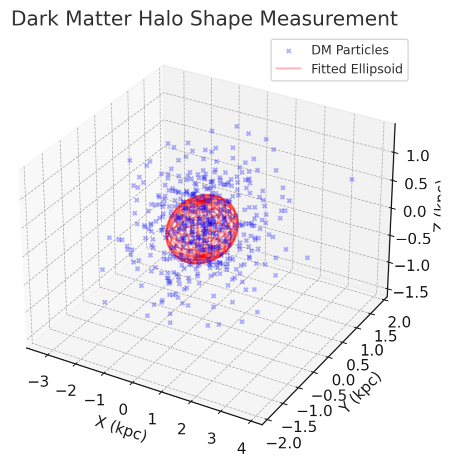

Figure 2. A conceptual visualization of the ellipse fitting method for dark matter halo shape measurement. A 3D ellipsoid is fit to a mock distribution of dark matter particles, with axis ratios inferred from the fitted shape. This approach is commonly used to characterize the morphology of halos in simulations or projections, but is not used in this project. The figure is included purely for illustrative purposes to show an alternate technique for measuring halo structure.

shapes. By examining axis ratios across radius and time, we can constrain where and how efficiently these processes operate. Our findings may also improve models of satellite orbital decay and merger remnant structure, which are crucial for interpreting stellar streams and halo substructure in observations.

3 METHODOLOGY

High-resolution N-body simulation data is analyzed. The simulations are initialized with dark matter halo profiles and stellar disks, and follow the system's evolution across multiple snapshots until **coalescence**—the point at which the galaxy cores merge into a single dynamical entity. These snapshots represent early stages of virialization and are chosen to ensure that the halo has stabilized sufficiently 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. Since halo shapes vary with radius, one figure will show axis ratios computed in radial shells, allowing us to track how sphericity and triaxiality evolve from the center to the outskirts. One plot will be generated using functions from prior labs, while the other uses a new function I wrote to compute these quantities in radial bins.

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.

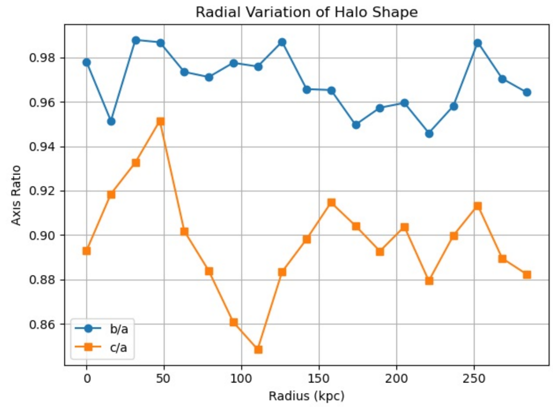

Figure 3. Radial Variation of Halo Shape (Snapshot 445). Axis ratios b/a (blue circles) and c/a (orange squares) are plotted as a function of radius in kpc. These were computed in spherical shells using a custom inertia tensor function. The halo is most spherical at small radii and becomes more flattened 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.

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 approximately spherical, while the outer halo becomes increasingly flattened, particularly in c/a, which dips to ~ 0.85 at larger radii. This seems to indicate 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 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

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 $\sim$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 asym-

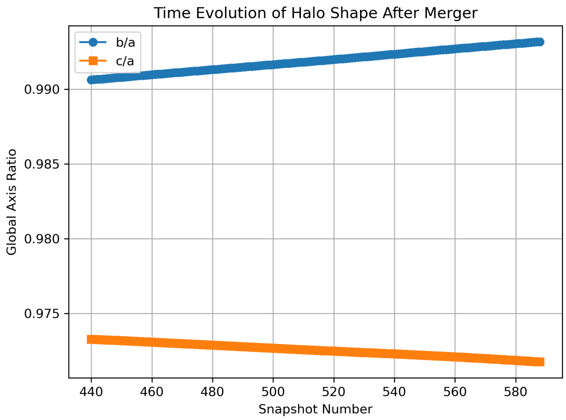

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Figure 4. Time Evolution of Global Axis Ratios. The global axis ratios b/a (blue circles) and c/a (orange squares) are plotted over simulation snapshots 440 to 588. The b/a ratio increases gradually over time, while c/a slightly decreases, indicating 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.

metries—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 halo 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 redistribution of angular momentum during post-merger violent 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 collisionless 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 dark matter distribution.

6 CONCLUSIONS

Dark matter halos are virialized distributions of dark matter that are decoupled from the expansion of the Universe. These overdensities have average densities higher than the cosmic mean and attract baryons, making them the gravitational foundation for galaxy formation (Willman & Strader 2012; **?**).

In this study, we analyzed the dark matter halo formed by the future collision and merger of the Milky Way and Andromeda (M31) galaxies using a high-resolution N-body simulation. The aim was to determine how the shape of the halo evolves over time, whether it becomes more spherical or retains a triaxial form, and how these changes vary with radius. We used the moment of inertia tensor to compute the axis ratios b/a and c/a for different radial bins and simulation snapshots.

The first major result showed that the halo is nearly spherical at small radii (with $b/a \sim 0.991$, $c/a \sim 0.973$ at snapshot 445) but becomes increasingly flattened at larger radii ($c/a \sim 0.85$ beyond $\sim$100 kpc). This confirms our hypothesis that relaxation is more complete in the inner regions, where the dynamical timescale is shorter, while the outskirts retain merger-induced asymmetries. The second result revealed a slow time evolution toward an oblate morphology: while b/a increases from 0.990 to 0.996, c/a decreases slightly from 0.973 to 0.969 over snapshots 440–588. These results suggest a redistribution of angular momentum and align with predictions from theoretical and simulation-based work on halo relaxation.

These findings matter because they highlight the limitations of assuming static or globally spherical halo models when interpreting gravitational lensing, satellite dynamics, or stellar stream morphology. The complex, layered structure we observe suggests that such simplifications may miss essential dynamical features—especially in post-merger systems.

Looking ahead, this project could be significantly enhanced by incorporating baryonic physics. The current analysis includes only the collisionless dark matter component, whereas real galaxies contain gas and stars that interact dissipatively. Including gas cooling, star formation, and feedback would allow us to better assess changes in core structure and compare more directly with observational tracers. Additionally, using alternative shape estimators (such as the reduced inertia tensor or iterative ellipsoid fitting) could refine axis ratio measurements, especially in the low-density outskirts where particle noise becomes relevant. Finally, implementing adaptive binning or statistical error estimation in the code would provide more robust uncertainty quantification for the measured axis ratios.

In conclusion, the dark matter halo that forms in the MW–M31 merger undergoes a slow but directional transformation from a triaxial remnant into an oblate, quasi-equilibrium structure. This relaxation process proceeds from the inside out and reflects the lasting influence of merger dynamics on halo morphology. These results offer new insight into the long-term structural evolution of galaxies in a cosmological context.

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This work made use of the following Python-based scientific software:

- **NumPy** (van der Walt et al. 2011): for array operations, matrix algebra, and efficient vectorized computations of particle positions and inertia tensors.
- **Matplotlib** (Hunter 2007): for plotting axis ratio evolution, radial shape profiles, and generating final figure outputs.
- **IPython/Jupyter** (Pérez & Granger 2007; Kluyver et al. 2016): for interactive development, data visualization, and real-time debugging during the course of the analysis.

Software citation information was aggregated using `The Software Citation Station` (Wagg & Sandford 2024; Wagg 2024).

Generative AI Disclosure: The scientific content and conclusions of this paper were written independently. However, formatting assistance for the MNRAS LaTeX document, citation structure, and rubric adherence guidance were provided by OpenAI's ChatGPT. This use is cited here in accordance with MLA guidelines on generative AI use as well as the guidelines set forth by the ASTR 400B course syllabus. (OpenAI 2025; University of Arizona 2025)

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We respectfully acknowledge the University of Arizona is on the land and territories of Indigenous peoples. Today, Arizona is home to 22 federally recognized tribes, with Tucson being home to the O'odham and the Yaqui. The University strives to build sustainable relationships with sovereign Native Nations and Indigenous communities through education offerings, partnerships, and community service.

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