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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.

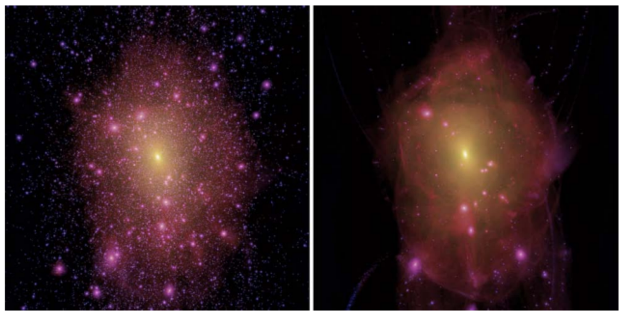

Figure 1. Evolution of halo shapes in simulations from Frenk & White (2012). The inner regions trend toward spherical symmetry, while outer halos remain triaxial. This motivates tracking how the shape varies with time and radius.

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

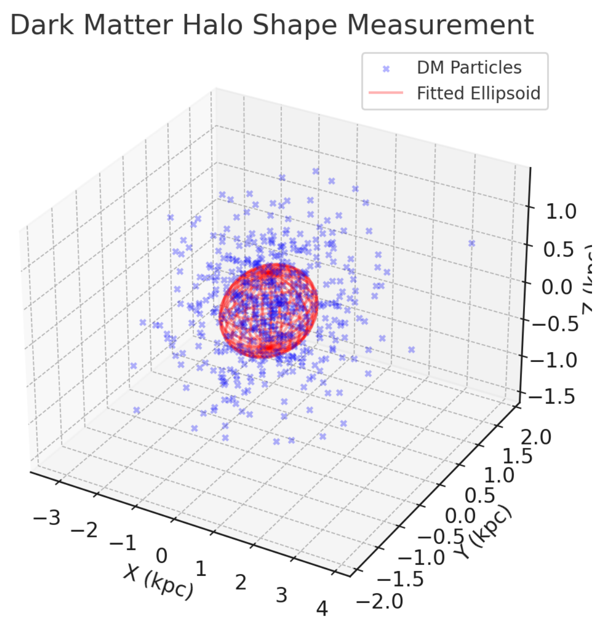

Figure 2. Visualization of a test particle distribution used to validate the methodology for computing halo shapes via the moment of inertia tensor. The axis ratios b/a and c/a are derived from the tensor's eigenvalues, demonstrating how this framework can be used to classify dark matter halo morphology 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.

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