# The Shape of the Dark Matter Halo After the Milky Way–M31 Major Merger

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## ABSTRACT

When the Milky Way and Andromeda (M31) merge, their dark matter halos combine into a single structure. The shape of this remnant halo—whether it is triaxial, oblate, or prolate—affects how the galaxy evolves over time. This project will analyze simulation data to determine the post-merger halo shape and how it changes over time.


## 1 INTRODUCTION

### 1.1 Dark Matter Halos and Galaxy Evolution

Dark matter halos are large structures made mostly of invisible mass, surrounding galaxies and influencing their movement. The shape of a dark matter halo—whether spherical, flattened (oblate), elongated (prolate), or irregular (triaxial)—determines how stars and gas behave inside a galaxy. In galaxy mergers, the halos interact, and their final structure depends on the physics of the collision.

### 1.2 Why This Matters

Understanding the final shape of a merged dark matter halo is important because it helps explain how galaxies settle into stable structures after a major event. If a remnant halo remains triaxial, it suggests the merger caused long-lasting distortions. If it becomes more spherical, it means interactions between dark matter and normal matter helped smooth out irregularities.

### 1.3 Current Understanding

Simulations show that halos usually start triaxial, but over time, they can become more spherical due to the way gravity redistributes the matter. However, the outer regions of the halo might take longer to settle, retaining a more elongated shape.

### 1.4 Open Questions

There are still many unknowns about how dark matter halos evolve after a major merger:

- What shape does the MW-M31 dark matter halo take after merging?
- Does the shape change over time?
- How do we define the boundary of the halo? Should we use the virial radius ($R_{\rm vir}$) or another measure?

Answering these questions will improve our understanding of galaxy formation and evolution.

## 2 PROPOSAL

### 2.1 Research Question

This study will determine the shape of the MW-M31 dark matter halo after their merger. We will classify the halo as triaxial, oblate, or prolate and examine whether its shape changes over time.

### 2.2 Methods

To determine the shape of the dark matter halo, we will analyze the simulation data step by step:

#### *2.2.1 Selecting the Right Simulation Snapshot*

The first step is to find the point in the simulation where MW and M31 have fully merged. We will check multiple time steps to see when the two galaxies have settled into a single structure.

#### *2.2.2 Extracting Dark Matter Particles*

Once we identify the correct snapshot, we will extract all the dark matter particles that belong to the remnant halo. These particles are stored in the simulation as separate data points with positions and velocities.

#### *2.2.3 Defining the Halo Boundary*

To analyze the shape, we need to define the "edge" of the halo. A common way to do this is by using the virial radius ($R_{\rm vir}$), which marks the region where the dark matter is still gravitationally bound to the system. We could also explore other definitions, such as the splashback radius (the boundary between the virialized (orbiting) and infalling regions of a dark matter halo, characterized by a sharp drop in the halo's density profile, and regarded as a physically motivated definition of the halo's edge.).

#### *2.2.4 Calculating the Shape of the Halo*

To determine whether the halo is triaxial, oblate, or prolate, we will compute its moment of inertia tensor, which describes how mass is distributed in different directions. The steps are:

(i) Compute the center of mass of the halo.
(ii) Shift all particle positions so the center is at (0,0,0).
(iii) Calculate the moment of inertia tensor:

$$I_{ij} = \sum_k m_k (r_k^2 \delta_{ij} - x_{k,i} x_{k,j})$$

where $m_k$ is the mass of particle $k$, $r_k$ is its distance from the center, and $x_{k,i}$ are its coordinates.

(iv) Find the eigenvalues of this matrix, which correspond to the squared lengths of the principal axes.

(v) Compute the axis ratios:

$$\frac{b}{a}, \quad \frac{c}{a}$$

where $a$, $b$, and $c$ are the largest, middle, and smallest axes. If all three are equal, the halo is spherical. If one is much smaller, it is oblate or prolate.

#### *2.2.5 Tracking Shape Evolution Over Time*

We will repeat these calculations for multiple time steps after the merger to see how the halo shape changes. If the shape remains triaxial, it suggests the system has not fully relaxed. If it becomes more spherical, it means the halo has settled.

For this proposal, we have created a conceptual methodology diagram to illustrate our approach. The dark matter particle distribution in the figure is an abstract representation rather than real simulation output. In the actual analysis, we would extract dark matter particle positions from the dataset and generate a true distribution plot.

### 2.3 Hypothesis

Based on previous studies, we expect the post-merger halo to be triaxial at first due to the violent relaxation process. Over time, we predict that the inner regions of the halo will become more spherical, while the outer halo will stay triaxial for longer. If the halo remains highly triaxial for a long time, it could indicate that mergers cause persistent distortions in dark matter structures.

## 3 CONCLUSION

This project will use simulation data to study the MW-M31 merger remnant and determine its dark matter halo shape. By tracking how the shape changes over time, we can gain insight into how dark matter structures evolve after galaxy mergers.

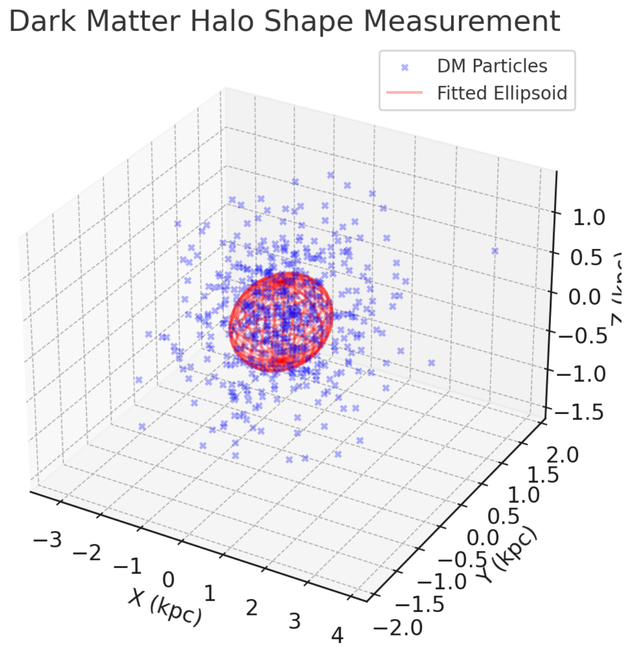


**Figure 1.** Methodology for measuring the dark matter halo shape. Blue points represent dark matter particles, while the red ellipsoid is a fitted shape. The principal axes are calculated using the moment of inertia tensor to determine whether the halo is triaxial, oblate, or prolate.

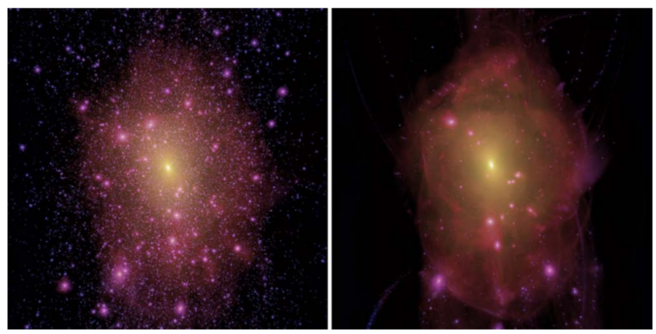

**Figure 2.** Images of a CDM (left) and a WDM (right) galactic halo at $z = 0$ from Frenk & White (2012). The CDM halo is one of the Aquarius simulations (Aq-A), and the WDM halo is its warm dark matter counterpart. The image intensity indicates the line-of-sight projected density squared, and hue the projected density-weighted velocity dispersion. Each box is 1.5 Mpc on a side. Note the sharp caustics visible at large radii in the WDM image.