DRAFT VERSION APRIL 30, 2025
Typeset using LaTeX **twocolumn** style in AASTeX631

Angular Momentum Alignment Between Stellar Remnants and Dark Matter Halos in Galaxy Mergers

BEN A PHAN

(Dated: April 29, 2025)

ABSTRACT

This project investigates the angular momentum alignment between stellar remnants and their dark matter halos during a major merger, focusing on the MW-M31 interaction. In particular, this work uses low resolution simulation of the MW-M31 system to track the angular momentum vectors of the stellar and halo components of both galaxies, evaluate how their directions evolve relative to their initial orientations, and one another. This will allow us to estimate how a major merger would distort the angular momentum alignment between galaxies' components and whether or not such alignment is re-established in the post-merger structure. The simulation data reveal that[a] the stellar and halo components begin moderately aligned, become significantly misaligned during the merger, and partially realign post-merger. This analysis provides insight into the dynamics of dark matter about stellar structure in galaxy evolution and whether their angular momentum alignment persists after major merger (violent dynamic interaction?).

Keywords: Galaxy — Galaxy Evolution — Stellar Disk — Dark Matter Halo — Major Merger — Angular Momentum — Hernquist Profile — Dynamical Friction — Tidal stripping/sharing — N-body Simulation

1. INTRODUCTION

1.1. *Angular Momentum Alignment in Galaxy Merger*

The angular momentum alignment between stellar structures and their surrounding dark matter halos significantly impacts galaxies' formation, structure, and dynamics. According to previous studies (e.g. Somerville et al. (2008); Chua et al. (2019); Baptista et al. (2023)), galaxy evolution involves complex interactions between baryonic matter and dark matter halos, especially during galaxy mergers when angular momentum is rearranged and realigned. In particular, during this event, angular momentum is redistributed through **tidal stripping/sharing**—the removal or exchange of weak gravitationally bounded material between interacting galaxies—and **dynamical friction**, a process where a massive object loses momentum through gravitational interactions with surrounding matter, generating "friction" or a drag force. These effects often lead to misalignment between the baryonic and dark matter components.

This study focuses on the Milky Way–Andromeda (MW–M31) system and investigates how the angular momentum vectors of their dark matter halos and stellar disks evolve before, during, and after their **major merger**, defined as the interaction between two galaxies of comparable mass (typically within a 3:1 mass ratio; Lotz et al. 2011). The goal is to determine whether these components realign after coalescence or retain signs of the misalignment due to the dynamical disturbance from the merging event.

1.2. *Significance to Galaxy Evolution*

Understanding the alignment between the **stellar disk** and **dark matter halo** angular momentum is essential for interpreting how galaxies form and evolve. A **galaxy** is a gravitationally bound system of stars whose properties cannot be explained by baryonic matter (i.e., gas, dust, and stars) and Newton's Law of Gravity alone. Instead, it requires the presence of dark matter to match observations (Willman & Strader 2012). The **stellar disk** forms the visible, rotationally supported component of many galaxies, while the **dark matter halo** is the extended, invisible structure that dominates the total mass and gravitational potential.

Galaxy evolution includes the full range of physical processes—such as mergers, gas accretion, and tidal interactions—that reshape the mass distribution, mor-

[a] Data summary of result goes here.

phology, and kinematics of a galaxy over cosmic time. These processes not only affect physical properties like stellar mass or gas content, but also play a key role in determining the dynamics between galaxies, such as their angular momentum realignment between components.

A central quantity in this study is the **angular momentum** vector:

$$\vec{L} = \sum_i m_i(\vec{r}_i - \vec{r}_{\rm COM}) \times (\vec{v}_i - \vec{v}_{\rm COM})$$

where m_i is the mass of a particle, and $\vec{r}_i$, $\vec{v}_i$ are its position and velocity relative to the component's center of mass.

Since dark matter cannot be directly observed, to characterize its structure, we apply the **Hernquist profile**, a radial density model defined as:

$$\rho(r) = \frac{M}{2\pi}\frac{a}{r(r+a)^3}$$

where M is the total mass and a is the scale radius. This profile ensures a finite total mass and helps define a stable core for angular momentum measurements (Hernquist 1990).

The alignment between halo and stellar angular momentum affects many observable properties, including galaxy size, morphology, rotation curves, and stellar velocity dispersion. Recent studies, including Chua et al. (2019) and Baptista et al. (2023), have shown that angular momentum alignment is a valuable tracer of dynamical evolution during and after galaxy mergers.

1.3. *Current Understanding*

Recent studies have significantly improved our understanding on stellar-halo angular momentum alignment. Somerville et al. (2008) demonstrated the importance of realistic dark matter halo models (e.g., NFW profiles and adiabatic contraction) in accurately predicting the weaker observed evolution of galaxies compared to previous prediction model with simpler dark matter profile (see Fig. 1). Similarly, Chua et al. (2019) highlighted that stellar and dark matter angular momentum vectors tend to connect more strongly in massive halos at lower redshifts, suggesting this alignment depends on both mass and time. Furthermore, Baptista et al. (2023) showed that evolving stellar-to-halo mass ratios significantly impact the angular momentum distributions, influencing both galaxy formation and evolutionary trajectories.

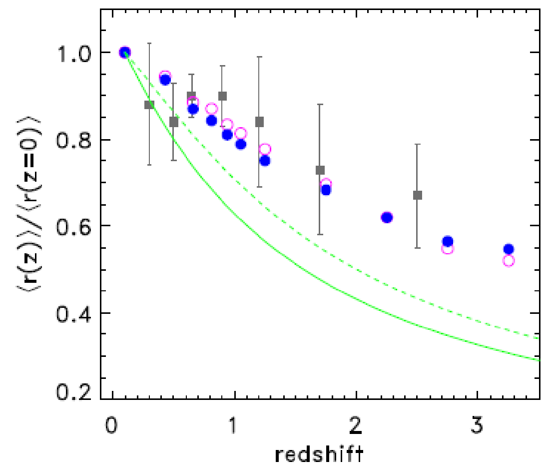

Figure 1. Evolution of average disk sizes normalized to present-day sizes as a function of redshift, with circles representing more detailed halo profiles. The circles show a more gradual size in evolution, which agrees more with observation. This emphasizes predictions from more realistic dark matter halo models. Adapted from Somerville et al. (2008).

1.4. *Open Questions*

Despite the significant progress on studying this topic, there are still many unknown questions:

- How does angular momentum alignment evolve throughout and after galaxy mergers?
- What factors govern the strength and persistence of this alignment throughout galaxy evolution?
- How does angular momentum realignment affect the structure and kinematics of stellar remnants post-merger?

2. THIS PROJECT

2.1. *Project Overview*

This project investigates the angular momentum alignment between the dark matter halo and stellar disk components of the Milky Way (MW) and Andromeda (M31) galaxies before, during, and after their merger. Using a VLowRes simulation of the Local Group, we track the evolution of angular momentum vectors from $t = 0$ Gyr to approximately $t = 12$ Gyr across 17 time snapshots (spaced at 0.5 Gyr intervals). For each galaxy, we compute the angular momentum of the halo and disk using inner regions—$r < 63$ kpc for the halo, based on the Hernquist scale length, and $r < 15$ kpc for the disk—to minimize biases from fast-moving particles in the loosely-bounded regions. After $t \sim 6.5$ Gyr, when MW and M31 fully coalesce, we calculate the alignment of the merger remnant. This approach allows us to quantitatively assess whether angular momentum realigns post-merger or remains disrupted.

2.2. *Research Question*

This project addresses the open question: *How does angular momentum alignment evolve through a major merger?* Specifically, we examine whether the dark matter halo and stellar disk components of a galaxy maintain, lose, or recover alignment during and after the MW–M31 merger. This question is significant to our understanding of **galaxy evolution** because the preservation or disruption of angular momentum coherence directly affects disk regrowth, remnant morphology, and kinematic stability. By following the complete timeline of mergers from $t = 0$ to $t \approx 12$ Gyr in the simulation, this study provides a picture of how mergers shape the structure of angular momentum over time.

2.3. *Method Overview*

This analysis will use the provided MW-M31 simulation data, following these specific methods:

1. **Particle Classification and Mass Distribution** (code used from ReadFile, ParticleProperties, and GalaxyMass functions): Identify halo, disk, and bulge particles for each galaxy, then examine their mass and velocity distributions. This will define the evolving mass distribution and structure throughout the merger.

2. **Center of Mass Analysis** (code used from CenterOfMass and OrbitCOM functions): Calculate the COM positions and velocities for each galaxy at different simulation snapshots, establishing an accurate frame of reference for angular momentum analysis.

3. **Angular Momentum Calculation** (code used from Lab 3): Compute the angular momentum vectors of stellar and dark matter halo particles separately. This calculation will use each galaxy's COM frame, determined by subtracting the galaxy's COM position and velocity from particle positions and velocities. The angular momentum vectors' magnitudes and directions will be tracked across simulation snapshots, allowing analysis of alignment evolution throughout the merger process.

4. **Galaxy Morphology and Shape Evolution** (code used from Lab 6 and Lab 7): Apply contour plots to quantify changes in halo and stellar morphology, demonstrating the impact of mergers on the shape of the galaxy and its halo.

3. METHODOLOGY

3.1. *Simulation Overview*

We use the VLowRes Local Group simulation provided by the ASTR400B course[1], which models the gravitational evolution of the Milky Way (MW) and Andromeda (M31) galaxies through their eventual merger.

This is an example of an **N-body simulation** which follows the evolution of a system of collisionless particles under their mutual gravitational forces (Springel 2005). In this case, particles represent dark matter and stellar mass distributions in each galaxy.

Each galaxy is initially modeled as:

- Type 1: **Dark matter halo** particles, following a **Hernquist profile** (Hernquist 1990), with scale radius $a \approx 63$ kpc. This density profile provides total mass and replicates the inner structure of observed halos by modeling the radial mass distribution in three-dimensional space using spherical coordinates. .

- Type 2: **Stellar disk** particles, selected within a radial cutoff of $r < 15$ kpc to focus on the rotationally supported baryonic structure. This simulation also includes a similar data set to the dark matter halo particles.

The simulation provides outputs at 800 Myr intervals, including particle data snapshots and orbital tracking files. The initial halo masses are $M_{\rm MW} \sim 10^{12} M_\odot$ and $M_{\rm M31} \sim 1.6 \times 10^{12} M_\odot$, providing sufficient resolution to track angular momentum evolution throughout the merger.

3.2. *Step-by-Step Procedure*

1. **Read Data**: Load particle positions, velocities, and types for each snapshot using ‘ReadFile.py‘.

2. **Identify Components**: Select halo (type 1) and disk (type 2) particles.

3. **COM Calculation**: Use ‘CenterOfMass.py‘ to compute COM position and velocity for each component.

4. **Apply Radial Cutoffs**: Use $r < 63$ kpc for halos and $r < 15$ kpc for disks.

5. **Compute Angular Momentum**: Calculate $\vec{L}$ for each component using the COM frame.

[1] Citation for the simulation paper will be added here since I don't know what the paper is.

6. **Track Angular Momentum Evolution**: For each snapshot, calculate the angle between the component's angular momentum vector and its original direction at snapshot 0. This measures how much the halo and disk have reoriented over time.

7. **Compare Halo vs. Disk Alignment**: Measure misalignment angle between halo and disk components over time.

8. **Post-Merger Analysis**: After $t \sim 6$ Gyr, when MW and M31 have merged, combine the halo and disk particles from both galaxies to compute the angular momentum vectors of the merger remnant. This includes calculating a new center of mass for the combined system and tracking the evolution of halo–disk alignment in the post-merger structure.

3.3. *Figures*

To create a framework for our analysis method, we first generated preliminary figures without applying edge-on disk reorientation or inner boundary cutoffs. These draft figures (Figures 2 and 3) revealed large artificial misalignments between galaxy components, showing bias for outer-region components and mismeasurement of angular momentum alignments due to the inconsistent measuring frames across snapshots. This will help us correct the methodology adopted for the final results.

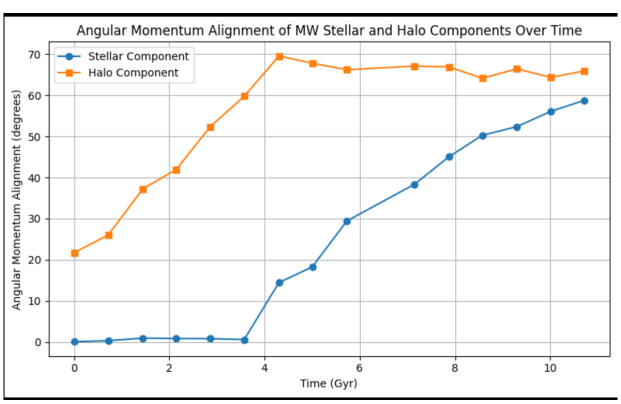

Figure 2. Draft figure: MW halo and stellar disk angular momentum vectors tracked over time relative to their directions at snapshot 0, without applying edge-on reorientation or inner boundary cutoffs. Without these corrections, the halo and disk angular momentum directions separate significantly, preventing meaningful alignment analysis.

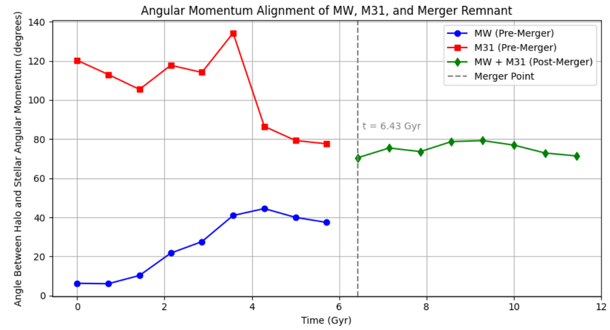

Figure 3. Draft figure: Instantaneous angle θ between halo and stellar angular momentum vectors for MW, M31, and the merger remnant over time, without applying edge-on reorientation or inner boundary cutoffs. The absence of corrections leads to large discrepancies between galaxy components, emphasizing the importance of proper measuring frame alignment and particle selection.

3.4. *Calculations and Plot Interpretation*

The main calculation performed in this project is the angular momentum vector of a group of particles (either halo or disk), defined by:

$$\vec{L} = \sum_i m_i(\vec{r}_i - \vec{r}_{\text{COM}}) \times (\vec{v}_i - \vec{v}_{\text{COM}})$$

where m_i is the mass of particle i, and $\vec{r}_i$ and $\vec{v}_i$ are the position and velocity vectors relative to the system's center of mass (COM). This equation computes the total angular momentum of each component in a COM frame. COM values are calculated iteratively via the shrinking sphere method.

To measure angular momentum evolution, we compare the current vector $\vec{L}_t$ at each snapshot t to the initial direction $\vec{L}_0$ from snapshot 0 using the dot product property:

$$\theta_t = \cos^{-1}\left(\frac{\vec{L}_t \cdot \vec{L}_0}{|\vec{L}_t||\vec{L}_0|}\right)$$

This angle θ_t shows how much the vector has rotated over time.

Similarly, to evaluate halo–disk coupling at each snapshot, we compute:

$$\phi_t = \cos^{-1}\left(\frac{\vec{L}_{\text{halo}\cdot\vec{L}_{\text{disk}}}}{|\vec{L}_{\text{halo}||\vec{L}_{\text{disk}|}}}\right)$$

where ϕ_t is the misalignment between halo and stellar angular momentum directions. If ϕ_t remains low, halo–disk alignment is preserved. Large ϕ_t indicates kinematic decoupling during the merger.

The two diagnostic plots generated from these calculations are:

- **Figure 1:** Angular momentum angle θ_t relative to the initial vector ($\vec{L}_0$) for MW's halo and stellar disk. This plot reveals how much the orientation of each component changes over time.

- **Figure 2:** Instantaneous halo–disk angle ϕ_t for MW, M31, and the post-merger remnant. This allows us to see when halo–disk coupling weakens, and whether it recovers.

Together, these (incompleted) calculations and plots quantify the timing and extent of angular momentum misalignment during a major merger, providing direct insight into post-merger dynamics and structure.

3.5. *Hypothesis*

We hypothesize that:

- MW and M31 start with moderate halo–disk alignment.

- Dynamical friction and tidal interactions during the merger disrupt this alignment.

- After coalescence, partial realignment occurs, but full restoration of coherence is unlikely.

- Stellar components are more affected by the merger compared to dark matter components, and thus they contribute more significantly to shifts in angular momentum alignment during and after the merger.

4. RESULTS

We present two figures that illustrate the evolution of angular momentum alignment between the stellar and dark matter halo components of the Milky Way (MW), Andromeda (M31), and the resulting merger remnant. The first shows how the halo–disk angular momentum angle evolves during the merger process, while the second tracks the orientation of each component (halo and disk) relative to its initial angular momentum direction. Together, these figures investigate how the merger event alters angular momentum alignment and identify which components contribute most to the misalignment during and after the interaction.

4.1. *Halo-Disk Alignment Over Time*

Figure 4 shows the angle between the halo and stellar angular momentum vectors for MW, M31, and the merger remnant as a function of time. Initially, MW and M31 show significant misalignment (around 70° and 120°, respectively). A sharp disruption occurs during 2–4 Gyr, especially for M31. We define the merger to occur

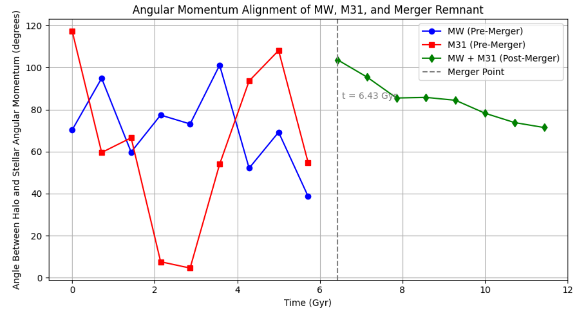

Figure 4. Angular momentum misalignment angle between halo and disk components for MW (blue), M31 (red), and the merger remnant (green) as a function of time. The merger occurs near 6.43 Gyr. Both MW and M31 experience significant disruption during 2–4 Gyr. After the merger, the remnant shows improved alignment stability.

when the separation between the two galaxies falls below 30 kpc, which happens at approximately 6.43 Gyr. After the merger, the remnant shows gradual stabilization, with halo–disk alignment fluctuations decreasing over time.

4.2. *Component Alignment Relative to Initial Directions*

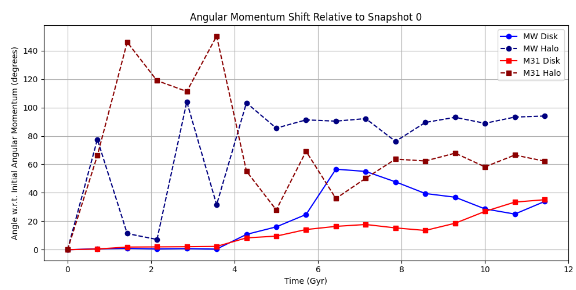

Figure 5. Evolution of the angular momentum vectors of MW and M31 halos and disks relative to their initial directions. During the merger phase (2–4 Gyr), halos experience greater reorientation than disks. After coalescence ($t \sim 6.43$ Gyr), components partially realign but do not fully recover their original orientations.

Figure 5 tracks the evolution of the halo and disk angular momentum vectors for MW and M31 relative to their initial directions at $t = 0$ Gyr. Both halos and disks experience significant reorientation during the merger phase (2–4 Gyr), consistent with the period during which Figure 4 shows greatest alignment disturbance. Notably, the halos reveal larger fluctuations in alignment compared to the disks, suggesting that the dark matter components contribute more to the misalignment of both galaxies in Figure 4 and are more sensitive to gravitational perturbations. After the merger, the remnant components show partial realignment toward their original angular momentum directions, but full recovery is not achieved during the 12 Gyr timeframe of this simulation.

5. DISCUSSION

5.1. *Halo-Disk Alignment and Merger Disruption*

The result in Figure 4 confirms the hypothesis that a major merger disrupts angular momentum alignment between galaxy components. However, the initial misalignment was greater than expected, with MW and M31 starting at $\sim 70^\circ$ and $\sim 120^\circ$, respectively. This suggests that even before the merger, the halo and disk were not naturally well-aligned, possibly due to differences in their properties or formation histories.

Compared to existing work (Chua et al. 2019), our result agrees that major mergers introduce significant angular momentum misalignment. These findings emphasize that angular momentum structure is fragile and easily perturbed, complicating the ability of merger remnants to maintain their dynamics post-merging.

This has important implications for galaxy evolution: galaxies undergoing major mergers can only partially recover their disk structures, even after billions of years. Merging events alter long-term kinematic and morphological properties of galaxies.

5.2. *Dominance of Halo Realignment*

Figure 5 challenges the hypothesis that the stellar component would be more affected than the halo. In fact, halos show stronger angular momentum fluctuations during and even after the merging process. This result demonstrates that halos are dynamically less tightly bound than stellar disks, and thus react more strongly to external gravitational influences. This can be attributed to the more spread-out and lower-density properties of dark matter halos, making them more susceptible to tidal torques and dynamical friction.

Our finding is consistent with simulation results from Zavala et al. (2008), who showed that dark matter halos lose a significant fraction of their angular momentum during mergers, while baryonic components (especially in disc-dominated galaxies) tend to preserve theirs.

The partial stabilization after 6 Gyr suggests that remnants can eventually re-establish coherent structures, but not necessarily recover their previous angular momentum alignments. This result provides a more complete view of galaxy mergers, which are critical and frequent events that drive the evolution of galaxies.

5.3. *Uncertainties and Limitations*

The primary uncertainty in this analysis is the definition of merger time. Here, merger completion was defined as the moment when the MW and M31 reached a physical separation of 30 kpc. While this threshold provides a convenient marker for merger analysis, its accuracy is debatable and may vary from case to case. For example, Lotz et al. (2011) defines close galaxy pairs observationally using projected separations in the range of 10–30 h^{-1} kpc (approximately 14–43 kpc for $h = 0.7$), which aligns with the merger point adopted in this work. This suggests that a 30 kpc cutoff is a reasonable approximation for merger completion. However, since this is a convenient assumption without a physically derived calculation, its precision remains open to question.

Additional uncertainties include:

- The absence of M33, whose gravitational influence could alter the MW-M31 orbital history.
- Limitations of the VLowRes simulation, which does not include gas dynamics, feedback processes, or star formation physics.
- The choice of radial cutoffs (63 kpc for halo, 15 kpc for disk), which might exclude loosely bound materials that have meaningful contributions to angular momentum. The disk radial cutoff is also a convenient assumption without calculation, which may negatively affect the accuracy of this work.

Despite these uncertainties, the major conclusion of this work remains clear: major mergers experience significant angular momentum misalignment, which cannot be fully recovered post-merger.

REFERENCES

Baptista, L., Conselice, C. J., Mundy, C., & Duncan, K. J. 2023, The Astrophysical Journal, 958, doi: 10.3847/1538-4357/ab148a

Chua, K. T. E., Pillepich, A., Rodriguez-Gomez, V., Vogelsberger, M., & Hernquist, L. 2019, Monthly Notices of the Royal Astronomical Society, 484, 476, doi: 10.1093/mnras/sty3531

Hernquist, L. 1990, The Astrophysical Journal, 356, 359, doi: 10.1086/168845

Lotz, J. M., Jonsson, P., Cox, T. J., et al. 2011, The Astrophysical Journal, 742, 103, doi: 10.1088/0004-637X/742/2/103

Somerville, R. S., Barden, M., Rix, H.-W., et al. 2008, The Astrophysical Journal, 672, 776, doi: 10.1086/523649

Springel, V. 2005, Monthly Notices of the Royal Astronomical Society, 364, 1105, doi: 10.1111/j.1365-2966.2005.09655.x

Willman, B., & Strader, J. 2012, The Astronomical Journal, 144, 76, doi: 10.1088/0004-6256/144/3/76

Zavala, J., Okamoto, T., & Frenk, C. S. 2008, Mon. Not. R. Astron. Soc., 387, 364–370, doi: 10.1111/j.1365-2966.2008.13243.x