

Future Dynamics of the Local Group

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1. INTRODUCTION

The largest galaxies in our Local Group (LG) are the Milky Way (MW), Andromeda (M31) and Triangulum (M33). A simulation of MW–M31–M33 orbital evolution was described previously in Marel et al. (2012), hereafter vdM12. That paper included an extensive analysis of both N-body simulations and semi-analytic orbit integrations. The present study uses data from the same N-body simulation to carry out further computational analysis.

The simulation was based on data in vdM12 suggesting that M31 is approaching the MW directly with little proper motion detected by Hubble Space Telescope (HST) studies. Recent data from Gaia DR2 (Brown et al. 2018) suggest that infall is slightly less radial than previously thought (Marel et al. 2019), leading to a slightly later first approach with a larger pericenter distance. However, detailed simulations based on that new data have not yet been carried out.

This paper will review the initial conditions and time evolution for multiple physical parameters of the simulation. Particular attention will be paid to the first MW-M31 close approach around 4 Gyr, the second ap-

proach and merger around 6 Gyr, and the structure and dynamics of the post-merger remnant.

Time probably precludes much analysis of the fate of M33, which will need to be the subject of a future paper.

1.1. Data

Data from one N-body simulation in vdM12 was supplied in text-file format by one of the original authors. This included position and velocity data for each particle at the current epoch ($t = 0$) and 800 future time steps. For ease of analysis, this was all transferred to the open source database PostgreSQL¹ (approximately 1.35 billion records). The same database was used to store computed summary data during the analysis.

Table 1. Particle counts

Galaxy	DM Halo	Disk	Bulge	Total
MW	250,000	375,000	50,000	675,000
M31	250,000	600,000	95,000	945,000
M33	25,000	46,500	0	71,500
LG	525,000	1,021,500	145,000	1,691,500

Particle counts for each time point are shown in Table 1 and total masses in Table 2. We can see that total mass is the same for MW/M31 but our galaxy has more luminous stars (higher baryon fraction) and M31 has more dark matter (lower baryon fraction). M33 is about 10-fold lighter than either.

¹ <http://www.postgresql.org>

Table 2. Aggregate masses ($M_{\odot} \times 10^{12}$)

Galaxy	DM Halo	Disk	Bulge	Total
MW	1.975	0.075	0.010	2.060
M31	1.921	0.120	0.019	2.060
M33	0.187	0.009	0.000	0.196
LG	4.082	0.204	0.029	4.316

The coordinate system is approximately centered on the Milky Way at $t = 0$. The center of mass (CoM) of all particles in the system is not fixed over time, moving at an average of $\langle 35.9, -26.7, 27.5 \rangle$ km/s with some minor fluctuations due to numerical approximations. In contrast, the total angular momentum of the system is very small at all time points.

1.2. Software

The work in this report was carried out in Python using standard packages. Full details are available online²

2. RESULTS

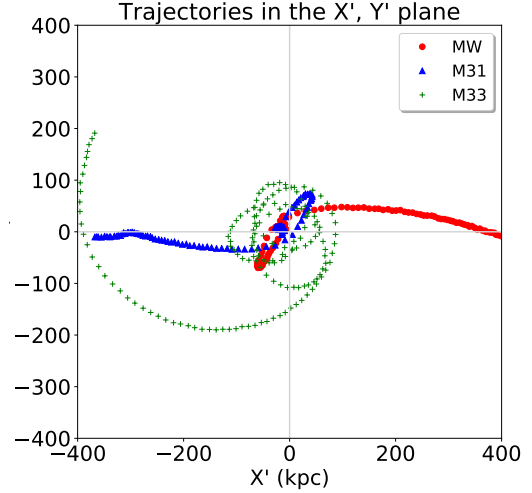
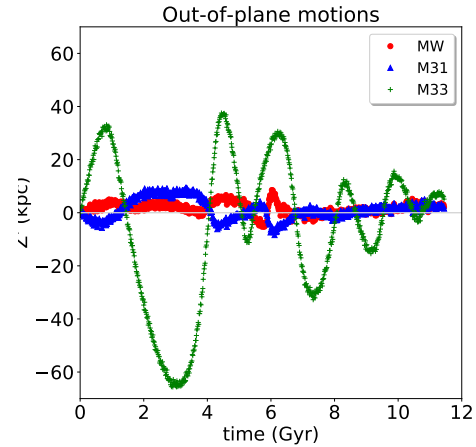
2.1. Trajectories

The simulation does not explicitly include a supermassive black hole (SMBH) at the center of each galaxy, but the galactic center was defined by calculating the center of mass (CoM) of the disk particles and iteratively constraining the radius of interest until convergence.

To plot motions of the three galactic CoMs it is convenient to transform to a coordinate system in which at $t = 0$ they all lie in the x, y plane with MW and M31 on the x -axis. The overall CoM is moving, as noted above, so at each time point the coordinates are translated to center it at the origin.

In vdM12 this is referred to as the X', Y', Z' coordinate system and their figure 2 shows multiple views of how the galaxies move through time. In this paper, Figures 1 and 2 show some alternative views in essentially the same coordinates (up to a sign; the x and z axes are flipped). The left panel reproduces the top left panel of vdM12. The right panel shows that MW and M31 remain close to the starting plane while M33 has larger, irregular out-of-plane motions.

Relative motions of the CoMs are shown against time in Figures 3 and 4, equivalent to figures 3 and 4 in vdM12.

**Figure 1.** Trajectories of each galactic center of mass in the X', Y' plane. Points are at 71 Myr intervals.**Figure 2.** Trajectories of each galactic center of mass perpendicular to the X', Y' plane.

There is a MW-M31 close approach with first pericenter at 3.96 Gyr with a minimum separation of 35.1 kpc, then a separation to 173 kpc and finally a convergence to 7.8 kpc at second pericenter and merger between 5.9 - 6.5 Gyr. Relative velocities spike sharply during these approaches, as potential energy is converted to kinetic energy, before declining to essentially zero.

Meanwhile, in this simulation run M33 remains separate throughout, albeit on a decaying orbit. In vdM12 the authors investigate the effect of small changes in initial conditions and estimate a 9% chance of an M33-MW collision at first pericenter, before the M31-MW merger.

2.2. Mass profiles and rotation curves

² Code https://github.com/colinleach/400B_Leach_documentation <https://400b-leach.readthedocs.io>

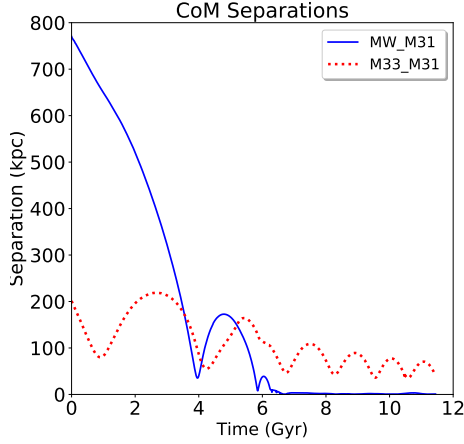


Figure 3. Separations of galactic CoMs.

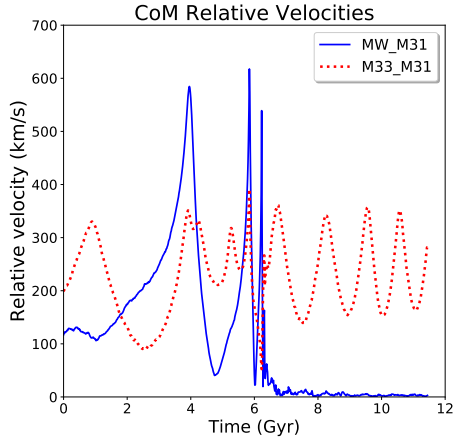


Figure 4. Relative velocities of galactic CoMs.

Figure 5 shows the cumulative mass profile, by particle type and in total, for each galaxy. The center of each galaxy is dominated by baryonic matter with the DM halo becoming dominant at larger radii.

Figure 6 shows the rotation curves expected from these mass profiles. Without the DM halo the circular velocity would peak within a few kpc of the CoM then fall steadily at larger radii. With the more diffuse DM halo added, we see the relatively flat overall rotation curves which attracted the attention of astronomers including Zwicky (1933) and Rubin & Ford (1970)

TODO set xlim, make y axis log

2.3. Galactic Bulge

A bulge is present in the MW and M31 but not M33. This region of generally older stars extends further above and below the central plane than disk stars. Kinematics

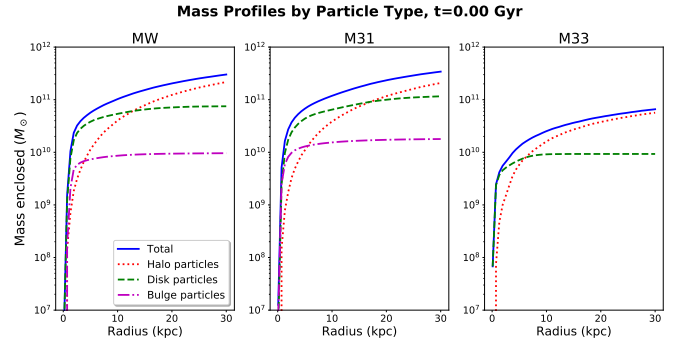


Figure 5. Mass profiles for each galaxy at the current epoch.

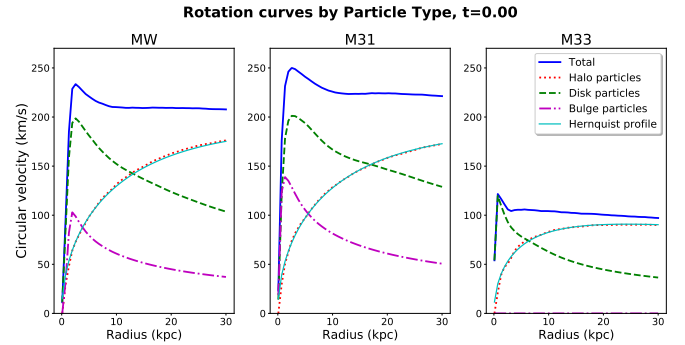


Figure 6. Rotation curves for each galaxy at the current epoch.

of the bulge are more typical of an elliptical galaxy than a spiral disk.

In a study of elliptical galaxies, de Vaucouleurs showed that surface brightness falls off exponential with radius and approximately as the one-fourth power of radius (de Vaucouleurs 1948). Later work found that this was too restrictive for a wider population of galaxies, so Sérsic generalized the formula to have the inverse exponential n as an additional free parameter (Sérsic 1963):

$$\log_{10} \left(\frac{I(r)}{I_e} \right) = -3.3307 \left[\left(\frac{r}{R_e} \right)^{1/n} - 1 \right]$$

Here R_e is the radius with which half the light is emitted, I_e is the surface brightness at R_e and n is the Sérsic parameter.

This formula is intended for analyzing photographic images and is in terms of light intensity. We have no brightness data in the current simulation, but for systems with few young blue stars we can assume the mass to light ratio $M/L \sim 1$. This is probably a reasonable approximation for undisturbed bulges and for an elliptical merger remnant long after the collision. R_e is then the radius enclosing half the mass.

We can see from Figure 7 that for each galaxy the bulge half-mass radius is fairly stable up to the collision

and merger of MW and M31. After a period of disturbance, they again become stable at a higher level. The M31 bulge is more diffuse than the MW bulge throughout, and the ex-bulge stars are clearly not randomized in the merger remnant: ex-M31 stars tend towards larger radii than ex-MW stars.

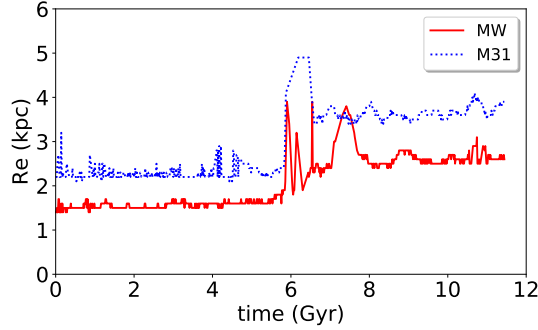


Figure 7. Half-mass radius for bulge particles.

The Sérsic parameter n was estimated by a nonlinear least squares fit to the bulge mass profile. As shown in Figure 8 it is fairly constant around 5.5 for any period with meaningful data. The spikes around 6 Gyr should probably be ignored: many values in this collision period are missing, as the least-squares fit failed, and the available data has substantially larger error bars than during stable epochs.

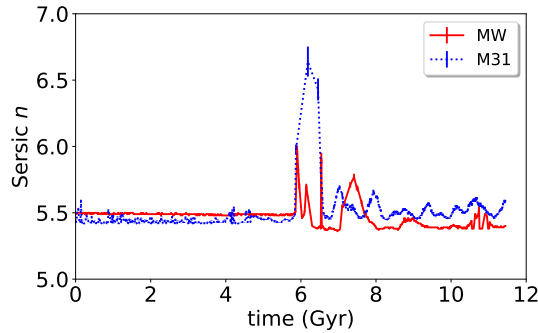


Figure 8. Sérsic n for bulge particles, with 1σ error bars.

The larger half-mass radius of M31 is reflected in the mass density profile, as shown in Figure 9. MW bulge stars have a higher central peak, M31 bulge stars are more numerous at larger radii. This is true both early in the simulation, and in the merger remnant at late times. For both galaxy bulge stars, the central peak is less pronounced post-merger.

The Sérsic fit for both galaxy bulges looks reasonable outside the central density peak, as shown for the MW in Figure 10. The plot for M31 is similar but is not included here.

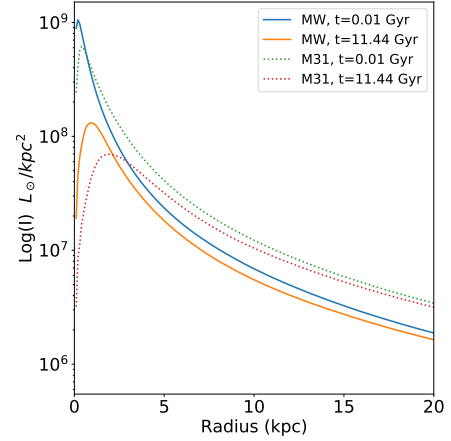


Figure 9. Bulge mass density profile for both galaxies at the beginning and end of the simulation.

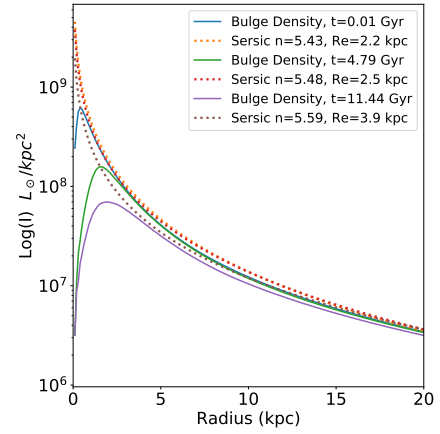


Figure 10. MW bulge mass density profiles and Sérsic best fits. Time points are the beginning, the pre-merger pericenter, and the end of the simulation

2.4. DM halo

Figure 6 also adds a theoretical curve in which the dark matter halo is fitted by a Hernquist profile (Hernquist 1990). The cumulative mass out to radius r is given by

$$M(r) = M_h \frac{r^2}{(a+r)^2}$$

where M_h is the total mass of halo particles (see Table 2) and a is a scale radius. Non-linear least squares fitting gave scale radii of 61.1 kpc for MW and M31, 24.3 kpc for M33 at $t = 0$.

Time evolution of the scale radius a is shown in Figure 11. The MW and M31 remain very similar through first pericenter, then start to diverge with MW particles tending to a larger radius than M31. This becomes most pronounced during and after merger. The dissimi-

lar distribution in the merger remnant will be discussed in a later section.

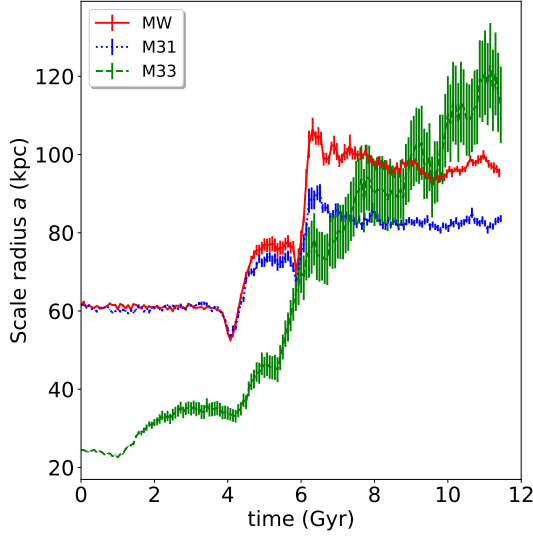


Figure 11. Hernquist scale radius a for DM halo particles originating from each galaxy, with 1σ error bars.

The scale radius for M33 grows inexorably as the original halo is scattered by tidal forces. Figure 11 also shows the increasingly wide error bars for M33: halo particles for this galaxy are no longer well fitted by a Hernquist profile.

TODO identify the bar?

TODO more on spiral arms

2.5. MW-M31 Close approach

2.5.1. Inclinations

The MW and M31 disks have angular momentum vectors inclined at an angle of 52° to each other, making this a prograde approach.

2.5.2. Tidal tails and bridges

The presence of long, symmetrical tails giving some galaxies a distinct ‘S’-shape has been described at least as far back as Zwicky (1955). Some astronomers postulated that these were the result of tidal forces during close, glancing encounters, but this was often contested until a detailed computational study by Toomre & Toomre (1972).

In our simulation, both MW and M31 disks remain near-circular during much of the close approach, but conspicuous tails develop as the centers then move further apart. We also see a more sparsely-populated bridge forming between the galaxies.

To determine the nature and origin of stars in this region, a manual selection was performed as in Figure

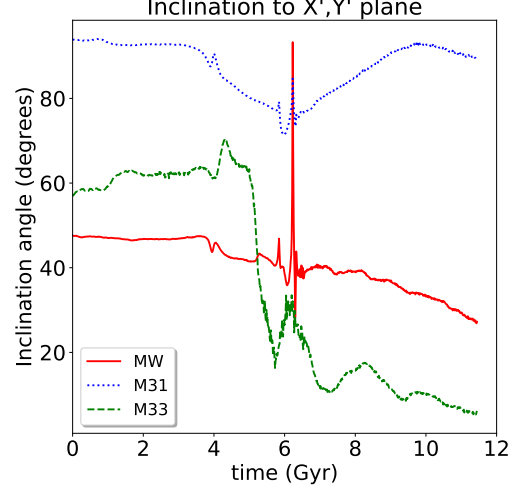


Figure 12. Angular momentum inclination angle to the X',Y' plane for each set of galactic disk particles.

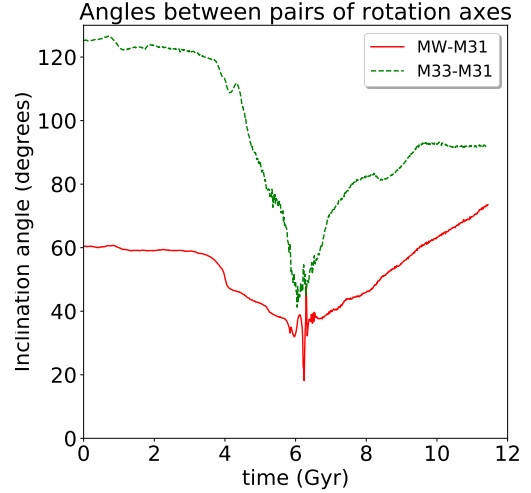


Figure 13. Angular momentum angles between pairs of galaxies.

14. Stars within the yellow rectangle (left panel) are shown with velocity vectors (center panel) and origin (right panel). Velocities are mostly moderate (mean 195 km/s, range 19-586 km/s), with relatively few stars having high kinetic energy.

It appears from the right panel that stars in the tail regions originate in the corresponding disk. The bridge region is more mixed and appears to have a high proportion of former bulge stars. To study this further the coordinate system was transformed to place the large galaxy CoMs on the x -axis at ± 64 kpc, as in Figure

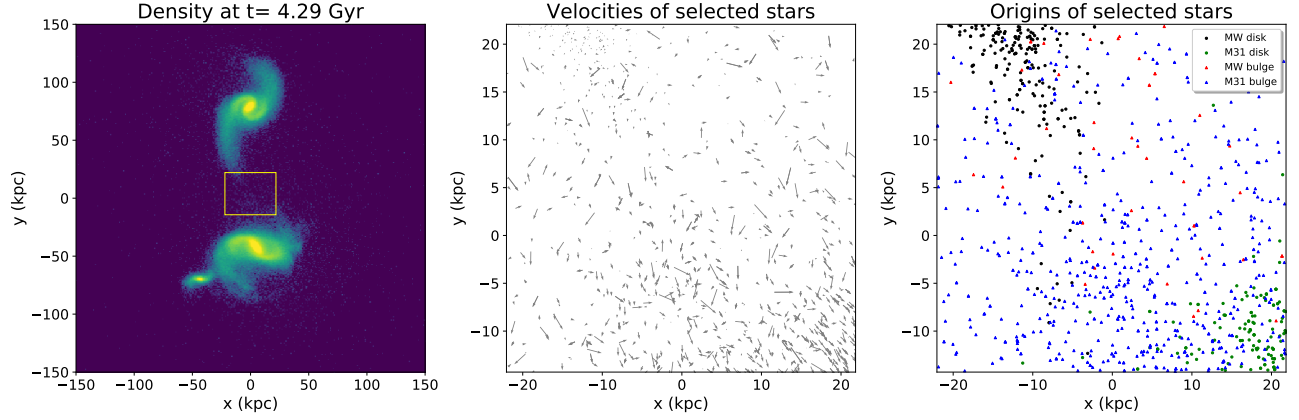


Figure 14. Manual selection of bridge particles at 0.33 Gyr after the first MW-M31 pericenter. The left panel shows stellar surface density and the selected region. The center panel shows velocity vectors for these stars and the right panel shows origin by galaxy and particle type. Orientation is with MW top, M31 bottom and M33 lower left.

15. It is clear in this view that one MW tail is oriented approximately towards the center of M31.

TODO identify, trace history, trace fate
 TODO Jacobi radius

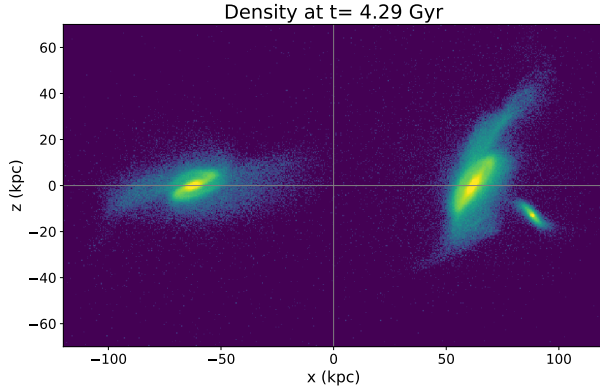


Figure 15. View along the midplane between the galactic centers, MW on the left.

Table 3. Particle counts close to the midplane

	Bulge	Disk	Total
MW	305	1317	1622
M31	1137	4	1141
Total	1442	1321	2763

The different orientations mean that symmetry about the midplane is imperfect, so the “bridge” region was taken as $-20 < x < 30$ kpc. A count of stars in this region is shown in Table 3. This confirms that the largest populations are MW disk stars (mostly in a relatively dense tail) and M31 bulge stars (more widely dispersed).

2.5.3. Mass transfer

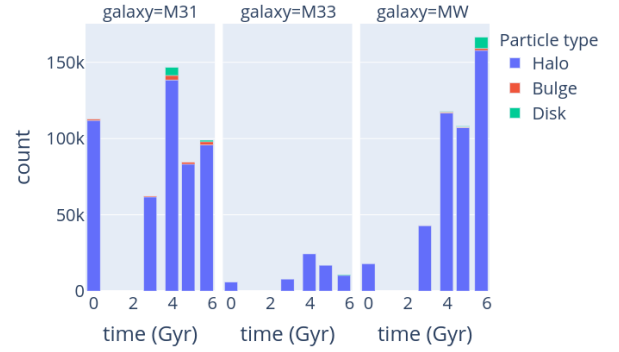


Figure 16. Particles closer to a different CoM.

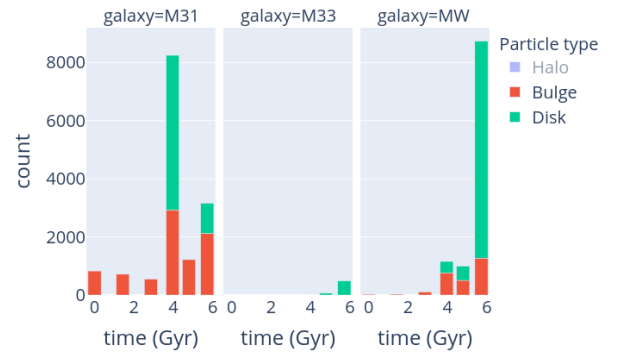


Figure 17. Luminous particles closer to a different CoM (DM halo hidden).

2.6. Velocity dispersion

The changes in velocity dispersion of disk particles originating from each galaxy are shown in 18. The small periodic oscillation seen from the start, especially in M31, appears to be caused by deviations from radial symmetry in the disk: spiral arms and an increasingly prominent bar. Small MW spikes at initial pericenter (around 4 Gyr) and much larger ones at merger (around 6 Gyr) are clearly visible.

TODO comment on M33

2.7. MW-M31 merger

After second pericenter, the MW and M31 never fully separate and eventually merge. Their mass ratio is 1:1.6 for stellar matter and 1:1 when the DM halo is included. This is thus a ‘major merger’ in the terminology of **TODO** ref?. A 1:1 mass ratio has been reported (Boylan-Kolchin et al. 2008; Ji et al. 2014) to lead to the shortest coalescence time.

2.7.1. Inclinations

TODO Relative rotation axes of disks – prograde?
TODO expanded 3D trajectories
TODO changes in velocity dispersion
TODO changes in mass profile

2.8. MW-M31 merger remnant

TODO shape - how to get principal axes? boxiness?
Refer to Figure 19

2.8.1. Rotation

TODO phase diagram
Refer to Figure 20
TODO alignment between particles of different origin?

2.9. Dark Matter halo

May need to be split up among previous sections
TODO what happens during close approach?
merger? remnant?

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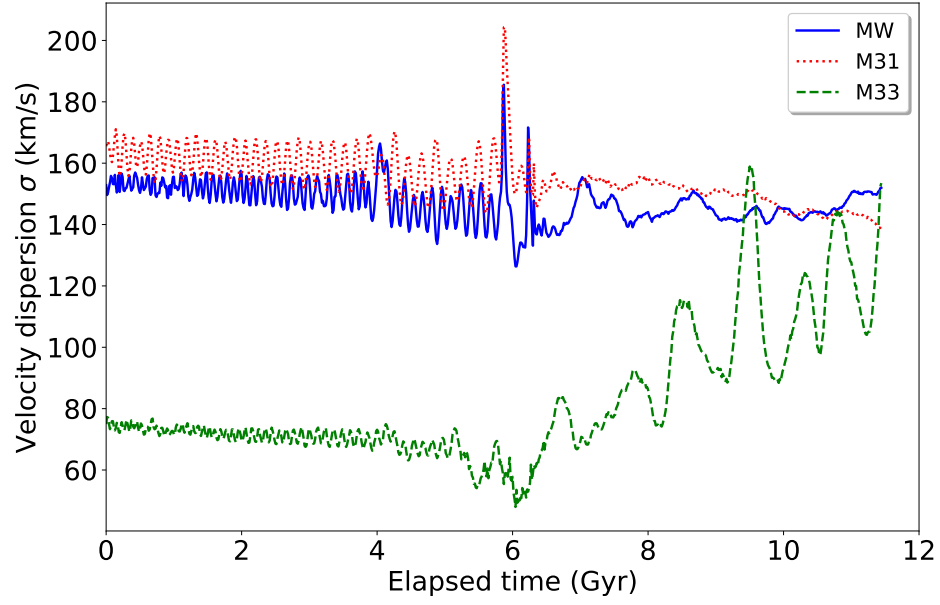


Figure 18. Velocity dispersion of disk particles from each galaxy over time.

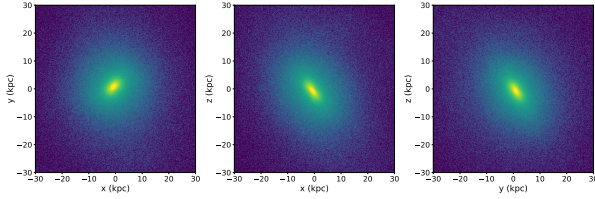


Figure 19. Luminous star density of the MW-M31 remnant in three orthogonal projections.

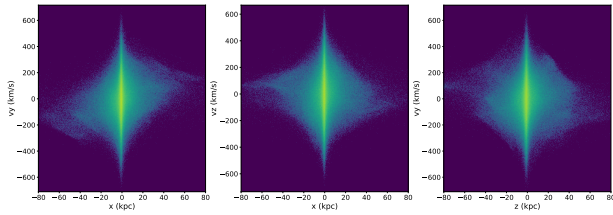


Figure 20. Phase diagrams of the MW-M31 remnant.