Asymmetric Drift of Andromeda Analogs in the Illustris Simulations

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ABSTRACT
We analyze the kinematics as a function of stellar age for Andromeda (M31) mass analogs from the Illustris and Illustris TNG cosmological simulations. We divide the star particles into four age groups: < 1 Gyr, 1 – 5 Gyr, 5 – 10 Gyr, and > 10 Gyr, and we compare the kinematics of these groups to that of the neutral gas cells. We calculate rotation curves for the stellar and gaseous components of each analog from 2 kpc to 20 kpc from the center of mass. We find that the lag, or asymmetric drift (AD), between the gas rotation curve and the stellar rotation curve on average increases with stellar age. This finding is consistent with observational measurements of AD in the disk of the Andromeda galaxy. When the M31 analogs are separated into groups based on merger history, we find that there is a difference in the AD of the analogs in the subgroup that corresponds to having had a 4:1 merger in a given time range compared to analogs that have not experienced a 4:1 merger in the same time frame. These differences are the most significant for recent 4:1 merger events (< 4 Gyr ago) and are therefore most visible in the 1-5 Gyr stellar age group where we find a difference in AD as large as \( \sim 55 \text{ km s}^{-1} \). This subset of analogs that have had a 4:1 merger within the last 4 Gyr are also very consistent with AD measurements of stars in M31’s disk, providing evidence that M31 may in fact have recently merged with a galaxy nearly 1/4 of its mass. Further work using high resolution zoom-in simulations is required to explore the contribution of internal heating to AD.

Key words: galaxies: kinematics and dynamics; galaxies: M31; galaxies: asymmetric drift; hydrodynamical simulations

1 INTRODUCTION
The kinematics of stars are influenced by dynamical heating events that occur in a galaxy. These events are common, and they are needed to explain the present-day properties of galaxies (e.g. Seth et al. 2005; Walker et al. 1996). Internal dynamical heating mechanisms include perturbations from spiral waves (e.g. Sellwood & Binney 2002; Sellwood 2013) or galactic bars (e.g. Dehnen & Binney 1998; Saha & Elmegreen 2018). Giant molecular clouds (GMCs) can also heat the disk of a galaxy (e.g. Jenkins & Binney 1990; Ting & Rix 2019). These sources influence the evolution of galactic disks and in turn perturb the stars in them.

While internal sources of heating affect a galaxy’s kinematics, they cannot alone explain the kinematics observed today. Instead, external sources of dynamical heating, such as mergers, are needed to recover these kinematics. For example, mergers are needed to explain the high velocity dispersion seen in some Local Group galaxies (Leaman et al. 2017). Furthermore, while stellar feedback can drastically affect the disk of galaxies less massive than the Milky Way (MW) (El-Badry et al. 2016), mergers are more important than stellar feedback for setting the present-day kinematics of massive galaxies. Mergers lead to the growth of galaxies via the accretion of gaseous material and stars from the inner to the outer regions of galaxies (Abadi et al. 2003); thus they can affect not only the galactic disks but also the halos. Consequently, mergers can perturb the orbits of stars throughout an entire galaxy (e.g. Quinn & Goodman 1986). These dynamically heated stars can lead to a kicked-up or puffed up disk (e.g. Purcell et al. 2010; Dorman et al. 2013). In summary, simulations show that mergers can heat and accrete stars with different kinematics than the stars formed in situ in the disk: as stars have a long dynamical time scale, they retain these differences (e.g. Abadi et al. 2003; Purcell et al. 2010). This contributes to higher velocity dispersion. Similarly, N-body simulations of galactic disks show that a minor merger can increase velocity dispersion permanently by up to 400% (Walker et al. 1996).

Effects of dynamical heating can be long lasting, and individual stars in galaxies can preserve the effects of heating. We see evidence for this in various observations, including the finding that velocity dispersion increases with stellar age in both the MW (Holmberg et al. 2009) and in M31 (Dorman et al. 2015; Bhattacharya et al. 2019). Furthermore, since the perturbations from dynamical heating can permanently alter the orbital paths of stars (e.g. Leaman et al.

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While it is likely that all galaxies experience some sort of dynamical heating, the Andromeda Galaxy (Messier 31 or M31) is a particularly interesting candidate to study the effects of such heating because it is at a distance that allows us to observe its disk in detail. At a distance of only 785 kpc (McConnachie et al. 2005), we can study the entire disk and halo of M31 using individual, resolved stars. Furthermore, its disk has a higher velocity dispersion than our own solar neighborhood (Sysoiatiina et al. 2018; Dorman et al. 2015; Budanova et al. 2017) and a steeper velocity dispersion age gradient than the MW (Dorman et al. 2015). This gradient is two to three times steeper than that of the MW (Bhattacharya et al. 2019). Furthermore, the outer halo of M31 shows debris in the form of tidal streams and shelves, which are believed to be the relic of several mergers (e.g. Hernquist & Quinn 1988, 1989; Escala et al. 2019; McConnachie et al. 2018). The most prominent debris feature is the Giant Stellar Stream (GSS), whose progenitor is believed to have had a merger with M31 approximately 1 Gyr ago (Ibata et al. 2001, 2005; Ferguson et al. 2002).

The motions of globular clusters at high galactic radii suggest that M31 has had more than one major period of accretion (Mackey et al. 2019). New studies suggest that a major (4:1) merger could explain observed phenomenon (Hammer et al. 2018; D’Souza & Bell 2018) like the burst of star formation approximately 2 Gyr ago (Williams et al. 2017), a ring of star formation (Lewis et al. 2015), and the mass of the stellar halo (Bell et al. 2017). While it is believed that M31 has had a long and ongoing history of accretion (Ferguson & Mackey 2016), the exact merger history is of course unknown, and therefore leads to an ongoing debate as to whether or not a major merger alone could explain several observed properties better than a series of minor mergers.

To aid in our understanding of the dynamical heating history of M31 Quirk et al. (2019, from here on Q19) study the present day disk kinematics, specifically focusing on asymmetric drift (AD) in the disk as a function of stellar age. Q19 find that in M31, like velocity dispersion, AD increases with stellar age. Stars that lag the gas in M31 tend to do so by 20%–40% (Q19), compared to 11 ± 8% in the MW (Bovy et al. 2009, 2012) and other local galaxies (e.g. Ciardullo et al. 2004; Herrmann & Ciardullo 2009; Westfall et al. 2007, 2011). In our own galaxy, AD has been used to construct rotation curves beyond the solar neighborhood and to correct the local standard of rest (LSR) (Golubov 2014; Huang et al. 2016).

Since detailed AD measurements exist for M31, we aim to to better understand these measurements in the context of ≈ $10^{12} M_{\odot}$ halos. The goal of this study is to use simulated M31 mass analogs with a variety of merger histories to explore how AD as a function of stellar age changes with merger history and thereby determine how significant of a role external dynamical heating plays in the current kinematics of these analogs. This paper is organized as follows: in Section 2, we discuss the Illustris simulations and the selection criteria we use to choose our sample of analogs. Section 3 describes the methods used to calculate rotation velocities, construct rotation curves, and calculate AD. In Section 4, we discuss the AD as a function of stellar age changes with merger history and make comparisons to observational results in M31. In Section 5, we summarize our findings.
Figure 1. Histograms of virial mass (left) and stellar mass (right) for mass analogs of M31 that also host a massive satellite galaxy companion analogous to M33. In both panels, the black histogram represents the full sample of 249 analogs, and the black hatched histogram represents our primary sample of 150 analogs that are chosen based on visual inspection of their radially average rotation curves (see Section 3.3). Our primary sample is generally representative of the full sample of M31 analogs.

Figure 2 shows the distribution of the time of last major merger for the 150 M31 analogs in our primary sample. The median time of last major merger is 9.4 Gyr as denoted by the vertical dashed gray line, thus most analogs have had relatively quiet recent merger histories.

Figure 3 illustrates the total number of mergers (major and minor) for the primary sample in black. The distribution of total number of 4:1 mergers is indicated by the blue hatched histogram and the total number of 10:1 mergers is represented by the red histogram. On average, M31 analogs in our primary sample experience 5-6 mergers in total.

3 METHODS
AD is often defined as the difference between the circular velocity derived from the potential and the star rotation velocity (Strömberg 1946). For the purposes of comparing this work to Q19, we define AD slightly differently than Strömberg (1946) and Walker et al. (1996). Instead of relying on models of the potential to calculate circular velocity, we instead use the rotation velocity of the gas data to calculate AD as in Q19 since this gives a more empirical measurement.

The rotation velocity of the gas is used as a proxy for circular velocity because gas is collisional and therefore can easily dissipate energy and maintain a low energy orbit (Sellwood & Moore 1998). Stars, on the other hand, are not collisional and thus can maintain an eccentric orbit if they are gravitationally perturbed. When comparing the circular rotation speeds, stars can lag behind gas because they are following a different orbital path than the gas, not strictly because they are moving more slowly. In this sense, AD is a
measurement of the difference between a star’s orbit and a circular orbit and thus can also be treated as a longterm effect of dynamical heating.

Walker et al. (1996) find that minor mergers temporarily increase AD in a galaxy using idealized N-body simulations. In this work, we will focus specifically on the effect of 4:1 major mergers for a cosmological sample of M31 mass analogs. Where possible, we will make comparisons to existing AD measurements in M31 as this is the only external galaxy for which observational results of AD as a function of stellar age are available (Q19).

3.1 Rotating the Coordinates

To calculate rotation curves and subsequently AD, we first apply a center of mass (COM) shift and rotate the particles/cells in each simulated M31 analog to a face-on reference frame. Illustris-Dark particle/cell positions and velocities are reported relative to the simulation box edges, so we first shift the data to a (0,0,0) Cartesian reference frame by subtracting the COM of the dark matter halo from both the stellar and gaseous data. This COM position comes directly from the Illustris group catalogs (i.e. the position of each FoF group).

To rotate the particle/cell data to a face-on reference frame, we calculate the net specific angular momentum vector for all particles/cells belonging to a given halo. Then we apply a rotation matrix to the particle/cell data such that the unit vector of the net angular momentum is mapped to the z-axis in the face-on reference frame. In this new reference frame, the galaxy’s disk lies in the xy-plane.

Finally, particles with a z scale-height > 10 kpc are eliminated to ensure we only include data for the gas and stars roughly in the disks to construct rotation curves and subsequently AD.

3.2 Smoothing the Particles/Cells

Once the particles/cells are rotated to the face-on reference frame, we divide the stellar particles into four broad age groups: Group 1 with ages < 1 Gyr, Group 2 with ages 1 – 5 Gyr, Group 3 with ages 5 – 10 Gyr, and Group 4 with ages > 10 Gyr. These age bins differ from those used in the observational analysis of AD in M31 in Q19 so we can take advantage of the full range of stellar particle ages that exists in the Illustris simulation. The observational constraints on M31 in Q19 are limited to stellar ages of up to ~4 Gyr, as older stars are too faint to observe easily. Illustris, on the other hand, provides ages spanning approximately a Hubble time.

Q19 calculates AD of stars with respect to neutral H\textsubscript{I} gas. To follow this, we also calculate AD with respect to neutral gas data in this analysis. In Illustris-1 (and Illustris TNG100-1), we implement this by limiting our analysis to only include the gas data where the neutral hydrogen fraction, \( n_{H} \), is above some threshold. Since there is no exact boundary for what gas constitutes as neutral, we initially varied the neutral fraction cutoffs to find the highest fraction that still included enough gas cells for good statistics and to have a full spatial expanse across the inner 20 kpc of each analog. We find that \( n_{H} > 0.75 \) is a reasonable threshold.

After the stellar particles are divided into the four age groups and the neutral gas cells are isolated, we locally smooth the line-of-sight velocity (the vertical component or \( V_z \) in the face-on reference frame). This smoothing better mimics the resolution of HI observations described in Q19. For stellar age Groups 2 and 3, we use a circle of 200″ and a circle of 275″ for the less populated Groups 1 and 4 and for the neutral gas cells. Each circle is centered on a star particle or gas cell as in Dorman et al. (2015) and Q19. The size of the circle was optimized to probe local kinematics but also to include enough data points for good statistics. If there are at least 10 particles/cells in a circle, we assign the median of the velocity components to that particle/cell; otherwise, we skip that circle in our analysis.

To ensure that our smoothing does not obscure any substructures in the rotation curves and subsequent bias to AD, we illustrate...
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3.3 Calculation of Rotation Curve

For the rest of our analysis, we use the smoothed kinematic values, described in the previous section. We calculate a rotation velocity for every star particle and gas cell that passed the circle-membership requirement in the smoothing process. To calculate the rotation velocity, we find the tangential velocity of the particles/cells by first subtracting the radial velocity within that bin. Our radial bins go from 2 kpc to 20 kpc with a spacing of 0.1 kpc. We radially bin all of the particles/cells and calculate the median rotation velocity within the bin. As seen in the bottom panel of Figure 4, there is no clear azimuthal dependence of the rotation velocity, so we do not obscure any local substructure through this binning. In Appendix A, we address the line of sight velocity gradient seen in the first column of Figure 4 and its negligible effect on our rotation curve calculations.

3.3.1 Visual Inspection of Rotation Curves

Since both the gas cells and star particles of these M31 analogs are necessary to calculate AD, we perform an additional visual inspection of the rotation curves of each analog in the full sample to ensure they have enough overlapping stellar particles and gas cells across the inner 20 kpc of the analog. Those that do not have spatial overlap between the gas cells and star particles for at least five radial bins are removed. After this visual inspection, 150/249 host-massive satellite pairs from Illustris-1 remain and will be referred to as the primary sample. Of the 595 Illustris-1 M31 analogs that do not host a massive satellite companion, 549 pass this visual inspection.

In Illustris TNG100, only 63/244 host-massive satellite pairs pass the visual inspection. We find that this is due to a combination of fewer young stars (≤ 1 Gyr) and less neutral gas cells in the Illustris TNG100 analogs. For the sample of 836 M31 analogs in Illustris TNG100 that do not host a massive satellite companion, 257 analogs pass the visual inspection. Table 1 summarizes the number of analogs in each of the samples we have identified thus far, including those that pass the visual inspection.

3.4 Calculation of AD as a function of Stellar Age

AD, (also denoted by $v_{AD}$), is the difference between the rotation velocity of the gas and that of the stars.

$$v_{AD} = v_{rot, \text{gas}} - v_{rot, \star}$$

We calculate the AD at each radial bin for the four stellar age groups individually. Thus at each radial bin, we have an AD measurement for Group 1, 2, 3, and 4 with respect to the same neutral gas cell rotation velocities. An example of the velocity smoothing can be found in Figure 4, which shows the position and the individual line-of-sight velocity, the post-smoothing median line-of-sight velocity, and the rotation velocity of each star particle for the four age bins. The halo properties of this example analog are listed in Table 2. We continue to smooth the data since it mimics the resolution of taking observations of gas and individual stars in a local galaxy without loss of kinematic information.

| Sample                  | Total | Passed Visual Inspection |
|-------------------------|-------|--------------------------|
| Illustris-1 M31 Analog   | 844   | 699                      |
| with massive satellite  | 249   | 150                      |
| without massive satellite| 595   | 549                      |
| Illustris TNG100 M31 Analog | 1080 | 320                      |
| with massive satellite  | 244   | 63                       |
| without massive satellite| 836   | 257                      |

3.3.2 Demonstrating the Effects of Smoothing Particle/Cell Data

In this section, we randomly choose a single M31 analog from our primary sample to demonstrate the difference between smoothing the particle/cell data prior to calculating rotation curves. Since the rotation curves are radially binned, we find that the choice of whether or not to locally smooth the velocities did not affect the rotation curves. An example of the velocity smoothing can be found in Figure 4, which shows the position and the individual line-of-sight velocity, the post-smoothing median line-of-sight velocity, and the rotation velocity of each star particle for the four age bins. The halo properties of this example analog are listed in Table 2. We continue to smooth the data since it mimics the resolution of taking observations of gas and individual stars in a local galaxy without loss of kinematic information.
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Figure 4. Individual line-of-sight velocity (top row), local medians of the line-of-sight velocity (middle row), and rotation velocity (bottom row) as a function of location and age for star particles in analog 419510. From left to right: age $< 1$ Gyr, age $1 - 5$ Gyr, age $5 - 10$ Gyr, and age $> 10$ Gyr. Smoothing circles are used to calculate the median of the individual line-of-sight velocities. We use a circle of $200''$ for Groups 2 and 3 and $275''$ for the less populated Groups 1 and 4. The circles in each panel of the middle row show the respective sizes of the smoothing circles. The blue cross marks the center of the analog.

Figure 5. Normalized histograms (probability distribution function) of AD values for the neutral gas cells and star particles in analog 419510. The blue dashed histogram represents stars that are $< 1$ Gyr, the one with the purple hatch marks represents stars between $1 - 5$ Gyr, the green solid histogram represents stars between $5 - 10$ Gyr, and histogram denoted by the red line represents the stars $> 10$ Gyr. AD increases with stellar age.

4 RESULTS

As discussed in the previous section, we calculate AD for the four stellar age groups along radial bins in every analog. To compare the AD values across all of the analogs, we find the median of AD for each of the four age bins for every analog. Thus, for our primary sample, we have 150 median AD values for each of the four age bins.

We show the distribution of these median AD measurements along with the cumulative rotation curves across the primary sample of analogs in Figure 6. To construct the rotation curve for the primary sample, we first calculate the rotation curve for each individual analog. As in Figure A3, the rotation velocities are radially binned. To create this cumulative rotation curve for the whole primary sample, we look at every radial bin for all of the analogs and take the median rotation velocity for each age group. We find there is a progression to higher AD as stellar age increases. This trend and the amplitude of median AD values are aligned with expectations from theory and from an observational study of AD as a function of stellar age (Q19). The width of the distribution also increases with stellar age. The peak and the width of the distributions for each age bin are listed in Table 4.

We aim to explore possible drivers of AD in this work. With the

| Stellar Age Group | Median AD (km s$^{-1}$) |
|------------------|-------------------------|
| Group 1: $< 1$ Gyr | $-17.66^{+5.27}_{-9.45}$ |
| Group 2: $1 - 5$ Gyr | $+7.16^{+4.05}_{-12.27}$ |
| Group 3: $5 - 10$ Gyr | $+68.30^{+10.47}_{-27.21}$ |
| Group 4: $> 10$ Gyr | $+93.18^{+13.19}_{-28.72}$ |
stellar assembly catalogues described in Section 2.4, we know the detailed merger history of the analogs in our sample. We therefore divide our primary sample into two subgroups: those that have had a recent 4:1 merger and those that have not. We vary our definition of “recent” to mean those with a 4:1 merger in the past 4 Gyr, the past 9.4 Gyr (the median time of last 4:1 merger across the analogs), and the past 12 Gyr. We create rotation curves (Figure B1) and histograms of the median AD (Figure 7 and Table 4) for the subgroups for each specified time frames. In all cases but two in the 12 Gyr subgroup, AD is higher in the merger group than it is in the no merger group.

In both sets of rotation curves (Figure B1) and AD distributions (Figure 7), the left panels show the merger subgroup, and the right panels show the no merger subgroup. The division in the top panels is a 4:1 merger in the past 4 Gyr. In this scenario, star particles from Group 3 and 4 were present during the merger. Group 1 and 2 contain a mix of star particles that may or may not have been present. We see the greatest difference (roughly 55 km s$^{-1}$) in AD is between the Group 2 merger vs no merger subgroup. Group 2, ages between 1 and 5 Gyr, is likely to have been formed during the merger and therefore their birth kinematics would be greatly influenced by the merger. The smallest difference in AD between the merger vs no merger subgroups is in Group 4 (roughly 9 km s$^{-1}$); the star particles in this age group and in the merger subgroup would have been present for the merger. If we just examine the merger subgroup, we see the largest offset in AD distribution between Group 1 and Group 2, suggesting that stars likely to have been born during the merger event were pushed to a higher AD.

The division in the middle panels in Figure 7 is a 4:1 merger in the past 9.4 Gyr. Star particles in Group 1, 2, and 3 might not have formed prior to the merger. The greatest AD difference between the merger vs no merger subgroup is in Group 3 (ages 5-10 Gyr) and is about 18 km s$^{-1}$. Star particles from this age group in the merger subgroup are likely to have been born during the merger event.

In the bottom panels, the subgroup division is based on a merger in the past 12 Gyr. Thus, star particles from all of the age groups might not have formed before the merger but star particles from Group 4 could have been forming during the merger event. The largest difference in AD between the merger vs no merger subgroup is in this age group and is approximately 20 km s$^{-1}$. However, the no merger group still has AD increase with stellar age. Since this group did not experience a 4:1 merger in the past 12 Gyr, AD must be influenced by other dynamical heating sources as well. We also explored dividing the analogs based on other stellar assembly parameters: number of 4:1 mergers, number of 10:1 mergers, and time since last 10:1 merger, but we found similar trends with these parameters. Thus, AD must also be influenced by internal sources of dynamical heating, such as GMCs and galactic bars. Understanding the specifics of internal heating events and their separate contributions to AD requires further work with a set of higher resolution simulations and is beyond the scope of this analysis.

We further examine the AD of analogs that have had a 4:1 merger in the past 4 Gyr and those that have not (top panels in Figures 7 and B1), since recent studies suggest that M31 might have had a major merger in the past several billion years. Figure 8 shows the comparison of AD in the simulated analogs to the AD measured in M31 as in Q19. The blue shaded regions represent AD for the analogs that have experienced a 4:1 merger in the past 4 Gyr, and the pink represents the AD for analogs that have not. The vertical dotted line marks 4 Gyr. Stars to the right of this line existed during the merger event, while stars to the left might have. Like in Figure 7, there is the least difference in AD between the merger and no merger group for star particles in Group 4: in the merger subgroup, these stars would have already been formed before the merger event. The larger differences in AD occur when an age bin in the merger subgroup contains a mix of stars that had and had not formed before the merger event. The largest difference in AD occurs when stars in the merger subgroup were likely to have been forming during the merger. In all cases, AD is higher for the merger group, showing that recent 4:1 mergers can perturb stars even in the inner 20 kpc of a galaxy.

The black points show the observations, and each point repre-
Figure 7. Histograms of median AD values for the primary sample of analogs subdivided into two subgroups: those that have had a recent 4:1 merger (left panels) and those that have not (right panels). In the top two panels, we define “recent” as having occurred in the last 4 Gyr. In the middle panels, “recent” is 9.4 Gyr, and in the bottom panels “recent” is 12 Gyr. In every panel, the blue histogram stars that are < 1 Gyr, the one with the purple hatch marks represents stars between 1 - 5 Gyr, the green solid histogram represents stars between 5 - 10 Gyr, and histogram denoted by the red line represents the stars > 10 Gyr. The number of analogs in each subgroup is written in the top left of each panel. On average, the median AD is higher for the merger subgroups.

sents an average stellar age for a broad stellar evolution classification: massive main sequence (MS), intermediate mass asymptotic branch (AGB), older AGB, and less massive red giant branch (RGB). The range of each age bin varies on the exact star formation history of M31, which is unknown. To emphasize that each point represents a range of stellar age, we have arbitrarily added horizontal bars on each point to show +/- 50% of the mean age. The observational AD measurements from M31 fall nicely within the blue shaded region, suggesting the observations are consistent with a 4:1 merger in the past 4 Gyr. This is a potential piece of evidence that M31 did in fact have a recent major merger. For example, the GSS could have been formed by a major merger event that could have led to
We have analyzed the AD of M31 mass analogs in the Illustris and Illustris TNG simulations to look for trends with stellar age. For the 150 analogs in our primary sample, we also examined merger histories to look for any correlations with AD. Our main conclusions are summarized below:

1. We find that AD for M31 mass analogs in the Illustris simulations increases with stellar age. Our stellar age bins are defined as Group 1: < 1 Gyr, Group 2: 1-5 Gyr, Group 3: 5-10 Gyr, and Group 4: > 10 Gyr. Each stellar age bin is compared to the properties of neutral gas, defined as gas cells with neutral hydrogen fractions > 0.75.

2. The M31 mass analogs are selected independently from their merger histories. However, upon examining their merger trees, we find that major mergers do affect the value of AD but they are not the sole agent giving rise to observed trends in AD. For example, we find that AD increases as a function of stellar age even without a major merger event. Thus, AD is also influenced by internal dynamical heating and minor mergers. However, understanding the specific internal processes by which AD is affected requires higher resolution zoom-in simulations such as Auriga or IllustrisTNG50.

3. On average, analogs that have experienced a recent merger have higher AD than those that have not (up to a 55 km s⁻¹ difference). The effect is greater for stars that were formed approximately during the merger event rather than stars that had already formed or had not yet formed.

4. The AD measurements observed in the disk of M31 from Q19 are very consistent with the subgroup of the primary sample that experienced a 4:1 merger within the past 4 Gyr. This is a piece of evidence that M31 may have experienced a major merger event in the past several billion years.

| Time Since Last 4:1 Merger | Stellar Age Group | Median AD (Merger) [km s⁻¹] | Median AD (No Merger) [km s⁻¹] |
|---------------------------|------------------|-----------------------------|--------------------------------|
| 4 Gyr                     | Group 1          | −2.25 ± 8.31 –10.70         | −20.56 ± 9.12 –9.22            |
|                           | Group 2          | +57.28 ± 13.23 –23.23       | +2.64 ± 3.71 –12.19            |
|                           | Group 3          | +87.30 ± 11.68 −27.75       | +63.90 ± 9.75 –25.94           |
|                           | Group 4          | +100.28 ± 13.84 −22.67      | +91.69 ± 14.72 −30.07          |
| 9.4 Gyr                   | Group 1          | −15.66 ± 16.12 –9.50        | −19.26 ± 9.01 –13.45           |
|                           | Group 2          | +15.16 ± 6.03 –13.34        | +0.77 ± 7.84 –13.15            |
|                           | Group 3          | +74.71 ± 9.13 −26.31        | +57.16 ± 8.44 −27.18           |
|                           | Group 4          | +90.22 ± 9.01 −21.94        | +96.83 ± 17.44 −36.29          |
| 12 Gyr                    | Group 1          | −19.82 ± 4.77 −7.02         | −12.55 ± 10.02 −15.66          |
|                           | Group 2          | +6.33 ± 5.86 −11.30         | +7.06 ± 8.32 −14.75            |
|                           | Group 3          | +68.49 ± 10.71 −24.21       | +64.77 ± 11.58 −25.26          |
|                           | Group 4          | +88.95 ± 12.77 −27.00       | +108.59 ± 12.15 −41.78         |

Figure 8. AD as a function of stellar age for the primary sample of analogs and observations of M31’s disk. The observations from Q19 are the black points. The shaded regions represent the median AD of stellar Groups 1, 2, 3, and 4 from the primary sample of analogs. The dotted lines in each region show the median AD value, and the shading shows the 1σ confidence levels. The blue represents analogs that have experienced a 4:1 merger within the past 4 Gyr, and the pink represents those that have not. The vertical line marks 4 Gyr. The observations are consistent with the AD from the analogs that have experienced a 4:1 merger within the past 4 Gyr.

prominent features that have been observed in M31’s halo such as the various stellar streams, shelves, and tidal features identified in McConnachie et al. (2018).

We also perform the same AD calculation analysis with our sample of TNG100 analogs to check for possible effects in the AD measurement caused by the difference in the galaxy formation models implemented in Illustris-1 versus Illustris TNG100. We find comparable results to those shown in Figure 6 for the AD distribution across the sample of TNG100 analogs. The median and width of the AD distributions and the trend between increasing AD and stellar age are comparable. Because the stellar assembly catalogues for IllustrisTNG are not yet published, we cannot provide a direct comparison to the divisions based on merger history. Similarly, we repeat the AD calculation with the sample of Illustris-1 and also Illustris TNG100 analogs that do and do not have a massive satellite companion (referred to the control sample earlier). We find no significant differences from the results for our primary sample.
the opportunity to use data collected from this site for this analysis.

Software: This research made use of astropy (Astropy Collaboration et al. 2013, 2018), Illustris Python (Nelson et al. 2015), matplotlib (Hunter 2007), numpy (van der Walt et al. 2011), and scipy (Virtanen et al. 2019).

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APPENDIX A: LINE OF SIGHT VELOCITY GRADIENTS

In many of the analogs, we see a gradient in the line-of-sight velocity (the vertical velocity component, Vz) mostly in the youngest age group. We believe this gradient is caused by asymmetries in the star particles and gas cells and find that the presence of this gradient is not dependent on merger history. In Figure A1, we show a mock image (Torrey et al. 2015) for an analog where this effect is evident. Figure A2 shows a more detailed view of this analog’s geometry. The left panel shows the gas cell density in the inner 100 kpc of the simulated galaxy. The right panel shows the stellar particle density across the same extent. The gray circle illustrates the 20 kpc region encompassing the data that is used to compute rotation curves. This region is generally equivalent to the contour encompassing 68 per cent of all particle/cell data respectively, which is denoted with a white contour.

The corresponding kinematic spatial maps for this analog were
already shown in Figure 4. As described before, the top panel shows the line of sight velocity and the middle panel shows the smoothed line of sight velocity. The velocity gradient is evident in both. However, there is no evidence this LOS gradient affects the calculation of rotation velocity, as the spatial maps show no gradient or azimuthal dependence for the rotation velocity (bottom panel). The rotation curve for this analog can be see in Figure A3. Like in the spatial map, we see no evidence that the LOS gradient has affected the calculation of the rotation curve.

Appendix B: Rotation Curves

In this section, we show the rotation curves from the merger and no merger subgroups (Figure B1). These rotation curves are used to make the histograms of AD shown in Figure 7. The vertical gap between the stellar particle rotation curves and the gas data rotation curve is a visual representation of AD.
Figure A2. Density maps for one random M31 analog exhibiting a line-of-sight velocity gradient. The data has been rotated to the face-on reference frame and only includes particles within 10 kpc of the disk plane. The left panel shows the gas density and the right panel shows the stellar density. In both panels, the gray circle denotes a radius of 20 kpc. All rotation curves are calculated using particle/cell data within 20 kpc of the COM. The white contour illustrates where 68 percent of the data is contained for each panel respectively. The 20 kpc region generally encompasses the 68 percent contour, so the rotation curves used to calculate AD are representative of the most prominent inner regions of the M31 analogs with little contamination from nonspherical substructures.

Figure A3. Rotation curve for analog 419510. Each point represents the median rotation velocity in a radial bin with a width of 0.1 kpc. The grey points represent the neutral gas cells, the blue triangles represent star particles with ages < 1 Gyr, the purple diamonds represent star particles with ages 1-5 Gyr, the green squares represent star particles with ages 5-10 Gyr, and the red dashes represent star particles with ages > 10 Gyr.
Figure B1. Rotation curves for the primary sample of analogs subdivided into two groups: those that have had a recent 4:1 merger (left panels) and those that have not (right panels). In the top two panels, we define “recent” as having occurred in the last 4 Gyr. In the middle panels, “recent” is 9.4 Gyr, and in the bottom panels “recent” is 12 Gyr. In every panel, the grey line shows the rotation curve of the neutral gas, the blue dashed line represents stars that are \(< 1\) Gyr, the purple represents stars between \(1 – 5\) Gyr, the green represents stars between \(5 – 10\) Gyr, and the red dotted line represents the stars \(> 10\) Gyr. The error bars show the width of distribution of median rotation values across all of the analogs at a given radial bin. The oscillations in the individual rotation curves shows the radial variations in rotation velocity.