BROKEN AND UNBROKEN: THE MILKY WAY AND M31 STELLAR HALOS

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ABSTRACT

We use the Bullock & Johnston suite of simulations to study the density profiles of L*-type galaxy stellar halos. Observations of the Milky Way and M31 stellar halos show contrasting results: the Milky Way has a “broken” profile, where the density falls off more rapidly beyond \( R \approx 25 \) kpc, while M31 has a smooth profile out to \( 100 \) kpc with no obvious break. Simulated stellar halos, built solely by the accretion of dwarf galaxies, also exhibit this behavior: some halos have breaks, while others do not. The presence or absence of a break in the stellar halo profile can be related to the accretion history of the galaxy. We find that a break radius is strongly related to the buildup of stars at apocenters. We relate these findings to observations, and find that the “break” in the Milky Way density profile is likely associated with a relatively early (\( 6-9 \) Gyr ago) and massive accretion event. In contrast, the absence of a break in the M31 stellar halo profile suggests that its accreted satellites have a wide range of apocenters. Hence, it is likely that M31 has had a much more prolonged accretion history than the Milky Way.

Key words: galaxies: halos – Galaxy: halo – galaxies: kinematics and dynamics – Local Group

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1. INTRODUCTION

A diffuse envelope of stars surrounds the Milky Way. This halo of stars only contributes a meager few percent to the total light, but comprises the oldest, and most metal-poor stars in the Galaxy. The dynamical timescales in the radial range of the halo stars (\( \sim 10-100 \) kpc) are long, so these stars can preserve their initial conditions. It is widely recognized that by studying the phase-space and chemical properties of the stellar halo we have the opportunity to unravel the accretion history of our Galaxy.

The density profile of the Milky Way stellar halo has been studied extensively over the past decade. Early work extending out to \( 25-30 \) kpc found that the halo follows an oblate, single power-law distribution with minor-to-major axis ratio \( q \sim 0.5-0.8 \), and power-law index \( \alpha \sim 2-4 \) (e.g., Yanny et al. 2000; Newberg & Yanny 2006; Jurič et al. 2008). More recent work probing further out in the stellar halo has found that the stellar density falls-off more rapidly beyond \( 25-30 \) kpc with a power-law index of \( \alpha_{\text{out}} \sim 4-5 \) beyond the break radius (e.g., Watkins et al. 2009; Deason et al. 2011b; Sesar et al. 2011). One could argue that the density distribution can just as easily be described by an Einasto profile (Einasto & Haud 1989), which allows for a steeper fall-off at larger radii, without resorting to a break. However, whether a broken power-law or Einasto profile are preferred, in both cases there exists a characteristic scale (break radius or effective radius) which deserves a physical justification. Is a break radius a ubiquitous feature of stellar halos? Unfortunately, the low surface brightness of stellar halos inhibits the study of individual galaxies beyond the local group. However, our nearest neighbor, M31, provides a useful comparison.

Early studies called into question whether a stellar halo even exists in M31: out to \( R \sim 30 \) kpc the stellar density profile seems to be a continuation of the M31 bulge (e.g., Pritchet & van den Bergh 1994; Durrell et al. 2004). However, more recent work extending to larger projected distances (out to \( R \sim 100-200 \) kpc) does indeed find evidence for a metal-poor halo component with a power-law index of \( \alpha \sim 3.3 \) (e.g., Guhathakurta et al. 2005; Irwin et al. 2005; Ibata et al. 2007; Courteau et al. 2011; Gilbert et al. 2012). However, there is no evidence for a break in the M31 stellar halo profile: the density profile follows a continuous single power-law all the way from \( R \sim 30 \) kpc to at least \( R \sim 90 \) kpc.

Of course, any measure of the smooth, underlying stellar halo density profile (if indeed it does exist), is hampered by the presence of substructure. A wealth of substructure has now been discovered in both the Milky Way (e.g., Ibata et al. 1995; Newberg et al. 2002; Belokurov et al. 2006, 2007; Jurić et al. 2008) and M31 (e.g., Ibata et al. 2001; Ferguson et al. 2002; Gilbert et al. 2007; McConnachie et al. 2009). These discoveries have strongly affirmed the theoretical predictions from numerical simulations that the majority of the stellar halo is built up from the accretion products of satellite galaxies.

Numerical simulations of stellar halos have developed substantially over the past few years. Bullock & Johnston (2005, hereafter BJ05) presented a suite of 11 stellar halos built entirely from the disrupted of accreted satellites. More recently, Cooper et al. (2010) used the Aquarius simulations and a dark matter particle “tagging” method to produce stellar halos in a fully cosmological context. Bell et al. (2008) studied the “lumpiness” of main-sequence turn-off (MSTO) stars in the Milky Way stellar halo and found consistency with the BJ05 simulations. This led the authors to suggest that the Milky Way stellar halo is consistent with being built up entirely by accretion. However, Xue et al. (2011) and Deason et al. (2011b) find a somewhat “smoother” stellar halo when traced by blue horizontal branch (BHB) stars. These observations perhaps suggest that accretion may not be the only formation mechanism of the stellar halo. Recent hydrodynamic cosmological simulations postulate that some fraction of the inner stellar halo is made up of stars formed in situ (e.g., Zolotov et al. 2009; Font et al. 2011). However, stars can diffuse relatively quickly in configuration.
space (as opposed to velocity space), so the spatial structure of the stellar halo can be smooth, even if it is built up from merging and accretion. Thus, a relatively smooth stellar halo could also signify an early accretion history.

In this paper, we study the density profiles of stellar halos drawn from the BJ05 suite of simulations. We investigate the origin of “broken” density profiles, and in particular, address why some halos have an obvious break (e.g., the Milky Way) and why some do not (e.g., M31). We know that accretion is at least an important (if not the sole) contributor to the stellar halo. By comparison with the BJ05 simulations we hope to link the observed stellar halo profiles of local galaxies to their accretion histories.

The paper is arranged as follows. In Section 2, we briefly describe the BJ05 simulations. In Section 3, we study the stellar halo density profiles of the 11 halos drawn from the BJ05 simulations. In Section 4, we investigate the origin of broken halo profiles and we discuss the implications for the Milky Way and M31 stellar halos in Section 5. Finally, we summarize our main findings in Section 6.

2. BULLOCK AND JOHNSTON SIMULATIONS

The Bullock & Johnston simulations (see BJ05 for full details), are a suite of 11 high resolution stellar halos built up from the accretion of dwarf galaxies onto a Milky-Way-like potential. The parent galaxy is represented by a time-dependent, analytical potential consisting of bulge, disk, and halo components. The accretion history of each halo is randomly drawn within the context of a ΛCDM universe; each accretion event was assigned a binding energy and orbital eccentricity drawn from the orbital distributions of satellites observed in cosmological simulations of structure formation. High-resolution N-body simulations were then run to track the evolution of dark matter particles in each accretion event. At the present day (z = 0), individual halos are built up from the disruption of N > 100 dwarf galaxies.

The baryonic component of each dwarf galaxy is followed by assuming that the cold gas inflow tracks the dark matter accretion rate. The gas mass is then used to determine the instantaneous star formation rate and to track the buildup of stars within each halo. The stellar matter in each dwarf galaxy is associated with the most tightly bound material in the halo. Variable mass-to-light (M/L) ratios for each particle are assigned in order to produce realistic dwarf galaxy stellar profiles; the M/L is chosen so that the luminous matter in the infalling satellites initially follows a King model embedded within a Navarro–Frenk–White (NFW) dark matter potential. The King profiles were chosen to specifically reproduce structure (e.g., sigma versus core relations) observed for dwarf satellites today. The time-dependent chemical content of the dwarf galaxies is also included in the models (see Robertson et al. 2005 and Font et al. 2006 for more details). The stellar population models include enrichment from Type Ia and Type II supernova, as well as stellar winds. A physically motivated supernova feedback prescription is used to reproduce the local dwarf galaxy stellar–mass–metallicity relation. The rate of chemical enrichment is calculated analytically, and the abundances of H, He, Fe, and the α-elements O and Mg are tracked in the simulations.

BJ05 verified that their models are able to reproduce a number of observational constraints, such as the number and distribution of structural parameters of the Milky Way’s satellite population. Furthermore, the resulting stellar halos have a similar luminosity (∼10^9 L⊙) and density profile to the Milky Way (α ∼ 3.5) and contain a similar amount of substructure (Bell et al. 2008). The scatter between the 11 simulated stellar halos is due to their different accretion histories; we will explore the effect of accretion history on the stellar halo density profiles in the following sections.

3. STELLAR HALO DENSITY PROFILE

We investigate the density profile of halo stars belonging to the 11 parent halos discussed in BJ05. Table 1 in BJ05 shows that the majority (80%–90%) of the stellar halo is built up from the 15 most massive accreted satellites. For this reason, we only consider the contribution to the stellar halo from the 15 largest satellites. We fit single power-law (SPL) and broken power-law (BPL) density profiles to stellar halos between 10 and 100 kpc. To fit the density profiles, we compute the density in radial bins and use the MPFIT IDL routine (Markwardt 2009) to find the minimum χ^2 SPL or BPL density profile. The best-fit parameters for the density profiles are given in Table 1. In addition, we also fit profiles for stars belonging to individual accretion events. Provided the accretion event is not too recent (less than 4.5 Gyr ago; cf. Figure 3 in Johnston et al. 2008), a BPL is a good description of the density profile (see, e.g., Figure 3).

The density profile for each stellar halo is shown by the thick black lines in Figure 1. The dashed blue line shows the best-fit BPL profile for the stellar halo, and the break radius for this fit is shown by the vertical dotted line. The thinner lines show the profiles for the five most massive accreted satellites. The fraction (by mass) contributed to the stellar halo (between 10 and 100 kpc) decreases from thicker black lines to thinner red lines.

Figure 1 shows that a broken power-law profile is generally a good description of the stellar halo density profiles, where the stellar density falls off more rapidly beyond the break radius. Such “broken” stellar halos are also seen in the stellar halos of Cooper et al. (2010; see also BJ05). However, it is worth noting that some stellar halos can just as easily be described by a single power law.
4. ORIGIN OF BROKEN PROFILES

The stellar halo in the BJ05 models is a superposition of stars stripped from several satellite galaxies. Thus, to understand the origin of the global stellar halo profile, we must first investigate the profiles of stars belonging to individual accretion events. The density profile of stars stripped from an individual satellite galaxy is well described by a BPL (see e.g., Figure 3). What causes this BPL profile?

For each star particle, we find the apocenter and pericenter of its orbit. Assuming a spherically symmetric, stationary potential, we can estimate the apocenter and pericenter from the following equation (see Binney & Tremaine 1987, Chapter 3):

\[ u^2 + \frac{2(\Phi(1/u) - E)}{L^2} = 0. \]

Here, \( u = 1/r \) and the roots of this equation give the apocenter and pericenter. This equation can be solved for each star particle given the potential and particle properties defined at redshift \( z = 0 \). This is a good approximation to the orbital properties of the stars at the time of stripping. However, the orbital properties
may have evolved since the time of accretion onto the parent halo. In the Appendix, we verify some of our deductions made from the halo star properties at redshift $z = 0$ by tracing back the orbital histories of the accreted satellites.

From the inferred orbital properties of the stars, we can find the average apocenter and pericenter of the stars belonging to an individual satellite accretion event. As the star particles can have different masses (see BJ05 for details), we compute the spread in apocenter at the time of stripping for each accreted satellite against the apocenter of the orbits. Satellites accreted at early times have smaller apocenters even if they are accreted when the parent galaxy is smaller. Therefore, breaks give an indication of when a satellite was accreted and/or disrupted. However, a further complication is dynamical friction, as more massive satellites can sink to the center of the parent halo relatively quickly. The colors in the bottom panel of Figure 2 indicate the satellite (stellar) mass. More massive satellites tend to have smaller apocenters (at stripping) even if they are accreted relatively recently.

In Figure 3, we show the radial velocity structure of three accreted satellites in Halo05. The stripped material from the satellite in the left-hand panel shows an obvious break in the density profile which coincides with the apocenter of its star particles. The middle panel shows a (massive) satellite accreted a long time ago ($\sim 9$ Gyr ago) which is now well mixed in phase space and can be described by a single power-law density profile (cf. Johnston et al. 2008). Finally, the right-hand panel illustrates a relatively recent accretion remnant for which the density profile is poorly defined. In general, satellites accreted between 4.5 and 9 Gyr ago follow a BPL density profile. Satellites accreted a long time ago ($T_{ub} \gtrsim 9$ Gyr) can be well mixed in phase space, and recent accretion events ($T_{ub} \lesssim 4.5$ Gyr ago) are unrelaxed and their density profiles are poorly defined.

We have found that the satellite apocenter sets the scale of the break radius, but what sets the “strength” of the break? In the top panel of Figure 4, we show the break strength (defined by a two-sided K-S test between SPL and BPL profiles) against the spread of apocenters for stars belonging to an individual satellite. We find that stronger breaks have a smaller spread in particle apocenters. The spread in apocenters is related to the energy distribution of the star particles; the bottom left-hand panel of Figure 4 shows that the dispersion in energy of an accreted remnant is strongly correlated with the spread in particle apocenters. Note that these relations also hold for the global stellar halo properties (shown by the blue star symbols). Here, the spread in apocenter is calculated from all 15 satellite accretion remnants.

The bottom right-hand panel of Figure 4 shows that more massive satellites have a larger spread in energy (as expected analytically; see, e.g., Johnston 1998). The colors indicate the average time of stripping for each satellite. Satellites accreted a long time ago ($T_{ub} \gtrsim 9$ Gyr) can have a large spread in energy, regardless of the satellite mass (cf. phase-mixed example in the middle panel of Figure 3).

5. IMPLICATIONS FOR GLOBAL STELLAR HALO PROPERTIES

In the previous section, we found that the density profile of stars stripped from an individual satellite is strongly related to the orbital structure of the stars. The average apocenter of the star particle orbits corresponds to the break radius of the best-fit BPL density profile. Furthermore, the strength of the break radius and break strength are related to the spread in apocenters for stars belonging to an individual satellite. We find that stronger breaks have a smaller spread in particle apocenters. The spread in apocenters is related to the energy distribution of the star particles; the bottom left-hand panel of Figure 4 shows that the dispersion in energy of an accreted remnant is strongly correlated with the spread in particle apocenters. Note that these relations also hold for the global stellar halo properties (shown by the blue star symbols). Here, the spread in apocenter is calculated from all 15 satellite accretion remnants.
Figure 3. Examples of individual satellite contributions to the global stellar halo. Three satellites accreted/disrupted at different times in Halo05 are shown. The top panels show their radial velocities as a function of radius and the bottom panels show their density profiles. The dashed line is the best-fit broken power-law model. In the left-hand panel, there is an obvious “break” in the stellar density that coincides with the average apocenter of the star particle orbits. Satellites disrupted a long time ago ($T_{ub} \gtrsim 9$ Gyr) are often well phase mixed and follow a single power-law profile. Recent accretion events ($T_{ub} \lesssim 4.5$ Gyr) are often unrelaxed and have poorly defined (i.e., non-smooth) density profiles.

(A color version of this figure is available in the online journal.)

Figure 4. Top panel: the “strength” of the broken power-law density model against the dispersion of star particle apocenters. The strength of the break is characterized by a K-S test between single and broken power-law density models. A high probability that the best-fit single power-law model is drawn from the same distribution as the best-fit broken power-law model indicates a weak, if not non-existent, break in the stellar density profile. The black circles are individual satellites and the blue stars indicate the global stellar halo properties. Bottom-left panel: the dispersion in energy of star particles against the dispersion in star particle apocenters. A large range of star particle energies leads to a large dispersion in their apocenters, and hence a weaker break in the stellar density profile. Bottom-right panel: the dispersion in energy of star particles against satellite mass. Higher mass satellites have a larger range of particle energies. The colors indicate the time of stripping.

(A color version of this figure is available in the online journal.)
break depends on the spread in energy (and hence apocenters) of the stars. In general, more massive satellites have a larger energy spread. However, very early accretion events ($T_{ab} \geq 9$ Gyr ago) which are well mixed in phase space can also have a large spread in energy, regardless of the initial satellite mass.

We now relate these findings to the global stellar halo properties. The global stellar halo is a superposition of individual satellite contributions. Therefore, the overall stellar density break radius reflects the individual satellite contributions. For example, a strong break ensues when the accreted satellites all have similar apocenters (e.g., Halo07, middle panel of Figure 5). The halo can also be dominated by one massive satellite (e.g., Halo14, top panel of Figure 5), and the overall break radius reflects the apocenter of this massive satellite. In Figure 5, we show the best-fitting break radius for individual satellite contributions versus average time of stripping (left-hand column) and strength of break (right-hand column). The size of the black squares illustrates the satellite mass (larger symbols for more massive satellites). The blue triangles indicate the global parent stellar halo properties and the blue dotted line indicates the parent stellar halo break radius. We also show the “mass-weighted” global break radius by the black-dashed line. This is computed from the individual satellite radii weighted by their mass. The top two rows illustrate the two different scenarios mentioned above. In Halo14, the overall stellar halo density profile is dominated by one massive satellite, while in Halo07 several satellites (of comparable) mass have very similar break radii.

Are we able to discern between these two scenarios? Figure 6 shows the radial velocity dispersion profiles for these two halos. The black line is the overall profile, and the red and blue colors illustrate the profiles for metal-rich(er) and metal-poor(er) stars (arbitrarily split at the average metallicity of the stellar halos). The profile for the most massive satellite contributing to the stellar halo (between 10 and 100 kpc) is shown by the black dashed line. In both Halo07 and Halo14 there are “dips” in the velocity dispersion profile near the break radius (indicated by the vertical dotted line). This is a result of the low radial velocities of the star particles at the apocenters of their orbits. However, in Halo14 this dip is much more pronounced in the higher-metallicity stars. This is because a massive satellite, which is therefore relatively metal-rich, dominates the break in Halo14. One can see that the profile for this massive satellite (dashed black line) closely follows the profile for the most metal-rich stars in the halo. There is little difference between the metal-rich and metal-poor material in Halo07. This is because all of the satellites in Halo07 (low and high mass) have very similar apocenters, and there is no massive, dominating accretion remnant.

Finally, we consider the case where there is no obvious break in the stellar density profile. In this case, the accretion events may have a wide range of apocenters (e.g., Halo08,
The stellar halo of Halo14 is dominated by one massive satellite while Halo07 is built up from several similar mass satellites with similar apocenters. The metal-rich(er) velocity dispersion profile for Halo14 shows a more pronounced “dip” near the break radius. There is little difference between the metal-rich(er) and metal-poor(er) profiles for Halo07, indicating that the break is not dominated by a single, massive accretion event.

(A color version of this figure is available in the online journal.)

Figure 6. Radial velocity dispersion profile for two example halos. The black lines show the overall profiles, the red/blue lines show the profiles for star particles with metallicity greater than/less than [Fe/H] ∼ −0.9. The dashed lines show the profiles for the stars belonging to the most massive satellite accreted by the galaxy. The dotted lines indicate the break radii of each halo. The stellar halo of Halo14 is dominated by one massive satellite while Halo07 is built up from several similar mass satellites with similar apocenters. The metal-rich(er) velocity dispersion profile for Halo14 shows a more pronounced “dip” near the break radius. There is little difference between the metal-rich(er) and metal-poor(er) profiles for Halo07, indicating that the break is not dominated by a single, massive accretion event.

6 In the radial range of the Deason et al. (2011a) study, 10–50 kpc, the line-of-sight velocity is a good approximation for the radial velocity.

6. CONCLUSIONS

The stellar halos of the Milky Way and M31 have conflicting density profiles: the Milky Way has a broken profile, whereby the stellar density falls off more rapidly beyond a break radius (r_b ∼ 25 kpc), whereas, the stellar halo of M31 shows no obvious break and can be described by a single power law. In light of these recent observations, we have studied the density profiles of stellar halos—built solely by the accretion of dwarf galaxies—drawn from the BJ05 suite of simulations, with the aim of understanding the contrasting stellar halos of our local galaxies.

We summarize our conclusions as follows.

1. The simulated halos often have “broken” stellar halo profiles, where the density falls off more quickly beyond the break radius. However, some halos do not have an obvious break, and their density distribution can be described by a single power law (e.g., the Milky Way versus M31).

2. In the BJ05 simulations, the global stellar halo is a superposition of accretion products from the ~15 massive accretion events. The density profiles of the stars that once belonged
to an individual satellite follow a broken profile, where the break radius corresponds to the average apocenter of the stars. However, material belonging to recently stripped satellites ($T_{	ext{ub}} \leq 4.5$ Gyr) have ill-defined density profiles, and very ancient accretion events ($T_{	ext{ub}} \gtrsim 9$ Gyr) are often well-mixed in phase space.

3. The location of the break in the stellar density is linked to the time of accretion/stripping and the mass of the satellite. Satellites accreted at early times have smaller apocenters as the physical size of the parent halo is smaller. More massive satellites can have smaller apocenters (and hence break radii) at the time of stripping, as the satellite can spiral into the center of the galaxy via dynamical friction.

4. The strength of the break in the stellar density depends on the spread of apocenters of the stars. For the global stellar halo, the break strength depends on the range of apocenters of its accreted components. Individual satellite accretion remnants can also have varying break strengths. More massive satellites have a larger spread in energy (and hence apocenters). Also, stars belonging to satellites accreted a long time ago can have a wide spread in energy as they are well mixed in phase-space today.

5. The global stellar halo density profile depends on the accretion history of the galaxy. An obvious break in the overall density profile suggests that (1) the accreted satellites have similar apocenters, or (2) one massive satellite dominates the stellar density in the applicable radial range. These two scenarios could be distinguished observationally. The radial velocities of stars near apocenter are very low, thus the radial velocity dispersion is also low (i.e., shell-type structures). In case (2) above, the apocenters of stars that once belonged to a massive, and hence metal-rich, satellite dominate the break. Thus, a “dip” in the velocity dispersion profile, the signature of a buildup of apocenters, will be more pronounced in the metal-rich(er) material. Conversely, if the accreted satellites all have similar masses (and similar apocenters), then we would expect no metallicity bias.

6. The profiles of some halos show no obvious break in the stellar density. Often, these halos have a prolonged accretion history whereby satellites are accreted over a wide range of timescales ($\sim 0$–10 Gyr ago). Thus, the average apocenters of the accreted satellites, whose material now makes up the stellar halo, also have a wide range of values.

Our investigation into the simulated BJ05 stellar halos has provided some important insights into the accretion histories of the Milky Way and M31. The absence of a break in the M31 stellar halo suggests that this galaxy has had a prolonged accretion history, where the accreted satellites had a wide range of apocenters. However, the strong break in the Milky Way stellar halo (at $r_h = 20–30$ kpc), in addition to the presence of a shell-type feature in the relatively metal-rich BHB stars, suggests that the stellar halo break is dominated by the apocenter of a (relatively) massive satellite.

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APPENDIX

RELATING SATELLITE PROPERTIES AT ACCREPTION TO $z = 0$ HALO STARS

In this section, we verify some of our deductions from the star particle properties at $z = 0$, by tracing back the accreted satellites whose stripped stellar material make up the stellar halos today.

We follow the orbits of satellites from Halo02 and Halo07. In the left-hand panels of Figure 7 we show three examples of satellites from Halo07. These are the three most massive contributors to the stellar halo within 100 kpc of this galaxy. In the left columns we show the evolution of radius with time for the satellites, and the right columns show the evolution of total satellite mass with time. The red dashed line indicates the average time when stars become unbound ($<T_{ub}>$) for the satellites, and the right columns show the evolution of radius with time. The dotted black line indicates the average apocenter of the stripped stellar material. This figure shows that the break radius we measure at $z = 0$ from the stars is indeed coincident with the apocenter of the host satellite galaxy near the time of stripping. In Section 4, we deduced this by estimating the apocenter of star particle orbits using Equation (1).

In the right-hand panels of Figure 7 we relate some of the initial satellite properties to those we infer from their stripped stars at $z = 0$. The top-left panel of this figure shows the relation between accretion time (of the satellite) and the average time at which the star particles become unbound. The stars are stripped a few Gyr after satellite accretion, but there remains a positive correlation between these two timescales. The bottom-left panel shows that the difference between these timescales is related to the mass of the stellar galaxy. Due to dynamical friction effects, more massive satellites spend a shorter amount of time orbiting the galaxy before the stellar material is stripped. In the top-right panel we show satellite accretion time against initial satellite apocenter (red asterisks) and average star particle apocenters at $z = 0$ (filled black circles). In Section 4, we noted that larger apocenters correspond to more recent accretion events as the physical size, and mass of the parent galaxy is larger, and hence more distant satellites can be captured. The strong trend between initial apocenter and accretion time reinforces this statement. Although the trend is slightly weaker, we see that the apocenters of the stripped stars at $z = 0$ are still an indication of when their host satellite was accreted. The final apocenter of the satellite (and hence stripped stars) is generally reduced from the initial apocenter via dynamical friction effects.

In the bottom-right panel of the figure we show that the difference in apocenter radius is strongly related to the satellite mass.

In summary, we find that our deductions made from the $z = 0$ halo stars in the main section of the text, are verified when we trace the accreted satellite properties back in time.

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