Do Halos that Form Early, Have High Concentration, Are Part of a Pair, or Contain a Central Galaxy Potential Host More Pronounced Planes of Satellite Galaxies?

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Abstract

The Milky Way, the Andromeda galaxy, and Centaurus A host flattened distributions of satellite galaxies that exhibit coherent velocity trends indicative of rotation. Comparably extreme satellite structures are very rare in cosmological \( \Lambda \)CDM simulations, giving rise to the “satellite plane problem.” As a possible explanation, it has been suggested that earlier-forming, higher-concentration host halos contain more flattened and kinematically coherent satellite planes. We have tested for such a proposed correlation between the satellite plane and host halo properties in the Exploring the Local Volume in Simulations suite of simulations. We find evidence for neither a correlation of plane flattening with halo concentration or formation time nor a correlation of kinematic coherence with concentration. The height of the thinnest subhalo planes does correlate with the host virial radius and the radial extent of the subhalo system. This can be understood as an effect of not accounting for differences in the radial distribution of subhalos and selecting them from different volumes than covered by the actual observations. Being part of a halo pair like the Local Group does not result in narrower or more correlated satellite planes either. Additionally, using the Phat ELVIS simulations, we show that the presence of a central galaxy potential does not favor narrower or more correlated satellite planes; rather, it leads to slightly wider planes. Such a central potential is a good approximation of the dominant effect baryonic physics in cosmological simulations has on a subhalo population. This suggests that, in contrast to other small-scale problems, the issue of planes of satellite galaxies is made worse by accounting for baryonic effects.

Key words: dark matter – galaxies: kinematics and dynamics – Galaxy: halo – Galaxy: structure – Local Group

1. Introduction

Galaxies such as the Milky Way (MW) or Andromeda (M31) are surrounded by numerous less-luminous dwarf satellite galaxies. Within the framework of the currently favored \( \Lambda \)CDM model of cosmology, which is based on the assumed existence of cold dark matter (CDM) and dark energy parameterized as a cosmological constant \( \Lambda \) and implies galaxy formation to proceed hierarchically, these satellites are hosted by dark matter subhalos and have a variety of accretion histories, origins, and infall times. Nevertheless, the structured nature of the cosmic web results in some coherences among subhalo satellites beyond a purely isotropic distribution, with accretion preferentially happening along the directions of sheets and filaments (Zentner et al. 2005; Libeskind et al. 2011, 2015). Similarly, some subhalos are expected to be accreted in groups, possibly resulting in coherences in the positions and orbital directions of the satellite galaxies hosted by them (Li & Helmi 2008; Wang et al. 2013; Wetzel et al. 2015; Shao et al. 2018). Finally, second-generation dwarf galaxies can form as highly correlated populations in the debris shed during galaxy collisions (Bournaud et al. 2008; Duc et al. 2011; Hammer et al. 2013; Yang et al. 2014). This effect, though, is purely baryonic in nature and therefore not included in dark-matter-only cosmological simulations, while cosmological hydrodynamical simulations still lack the resolution to fully model this mode of galaxy formation (though see Ploeckinger et al. 2018).

Satellite systems are thus not expected to be completely isotropic, but the observed degree of anisotropy is of importance. The strong flattening of the MW satellite system has been discussed for decades (Kunkel & Demers 1976; Lynden-Bell 1976; Haud 1988; Majewski 1994; Lynden-Bell & Lynden-Bell 1995), but it was not until Kroupa et al. (2005) that the discrepancy between this “plane of satellites” and the distribution of subhalo-based satellite galaxies in cosmological simulations was measured and pointed out as a severe challenge to \( \Lambda \)CDM. Since then, this intriguing distribution of satellites around the MW, now dubbed the Vast Polar Structure (VPOS; Pawlowski et al. 2012), has been studied in detail, revealing alignments of additional objects such as globular clusters (Forbes et al. 2009; Keller et al. 2012; Pawlowski et al. 2012) and of later discovered satellite galaxies (Pawlowski & Kroupa 2014; Pawlowski et al. 2015b; Pawlowski 2016).

Maybe more important than the purely spatial flattening is the strong kinematic coherence of this VPOS deduced from proper-motion measurements, with not only stellar and gaseous streams preferentially aligning with it (Pawlowski et al. 2012) but also a majority of the classical MW satellites co-orbiting within the plane (Metz et al. 2008; Pawlowski & Kroupa 2013). The Gaia DR2 (Gaia Collaboration et al. 2018) confirmed the previous finding that not all satellite galaxies share the same orbital plane (e.g., Pawlowski & Kroupa 2013), while a more detailed analysis concluded that only six out of 39 satellites can be claimed to have orbital poles that are conclusively misaligned with the VPOS given the current proper-motion uncertainties (Fritz et al. 2018).
When Conn et al. (2013) and Ibata et al. (2013) discovered a similar satellite galaxy plane around the Andromeda galaxy (M31) consisting of 15 out of the 27 satellites within the footprint of the PAndAS survey, this “satellite planes problem” was immediately regarded as much more pressing. Like the VPOS, this Great Plane of Andromeda (GPoA) is very uncommon among simulated subhalo systems (e.g., Ibata et al. 2014b; Pawlowski et al. 2014).

Similar satellite galaxy planes have been looked for in more distant host systems, and indications for planar structures have been obtained for the M81 group (Chiboucas et al. 2013) and the non-satellite galaxies in the Local Group (Pawlowski et al. 2013; Pawlowski & McGaugh 2014a). For Centaurus A, one or two planes of satellite galaxies have been proposed (Tully et al. 2015; Müller et al. 2016), and recently, a kinematic correlation reminiscent of that of the M31 satellite plane was discovered that places the Centaurus A satellite plane in tension with simulated satellites in both dark-matter-only and hydrodynamical cosmological simulations (Müller et al. 2018). There is even some evidence for a statistical overabundance of velocity-anticorrelated satellites in the SDSS that is consistent with a high abundance of satellites in co-orbiting planes (Ibata et al. 2014a, 2015, but see Cautun et al. 2015b; Phillips et al. 2015 for alternative views).

The resulting debate about the existence of satellite planes in the universe and cosmological simulations and the degree of the tension they constitute with ΛCDM expectations has led to an extensive body of literature (e.g., Wang et al. 2013; Bahl & Baumgardt 2014; Ibata et al. 2014b, 2015; Buck et al. 2015, 2016; Cautun et al. 2015a, 2015b; Gillet et al. 2015; Pawlowski et al. 2014, 2015a). For a current review, see Pawlowski (2018). The sheer size of this body of literature, combined with the technical depth required to both discuss and explain biases and differences in the derived conclusions to untangle the controversy of the current debate, makes a detailed discussion prohibitively long for this contribution.5 In the following, we thus focus on one particularly enthralling proposition as the main emphasis of this contribution.

Satellite galaxy planes can be seen as a problem for ΛCDM cosmology due to their rarity in simulations. However, they can also be seen as a chance to potentially learn more about the Local Group host galaxies and their dark matter halos, if, for example, some host halo properties or special evolutionary histories strongly prefer the detection of correlated planes of satellite galaxies. Buck et al. (2015) proposed such a solution to the satellite plane problem. They reported the existence of thin, rotating planes of satellites that resemble the GPoA in a suite of 21 M31-like host halos. In particular, they found that the most narrow, kinematically coherent planes occur among the highest-concentration halos in their sample and interpreted this as a correlation between halo formation time and propensity for a halo to host a coherent plane of satellites.

As the physical cause of this effect, they envisioned the following scenario. Earlier-forming halos of similar mass have a higher chance of being situated at the nodes between filaments, whereas later-forming halos are preferentially situated within filaments. As a consequence, halos within a filament are fed in a pattern that is closer to spherical, whereas halos in nodes of filaments are fed from only a few directions. While this appears counterintuitive, given that being situated in a node implies that a halo is fed by more filaments and thus from more directions than if it were situated within a single filament, filaments were narrower at earlier times (Vera-Ciro et al. 2011). It is therefore worthwhile to test for such a correlation, though the question of whether an early-forming satellite plane would survive as a coherent and narrow structure until today remains of concern (Fernando et al. 2017).

If Buck et al. (2015) are correct, then this could provide an important clue to the puzzle of satellite planes; however, given that their sample included only 21 halos, there is the possibility that the result was a statistical anomaly. Another concern is that the effect could be caused by differences in the radial distribution of subhalo satellites. If the halos with higher concentration also contain more compact satellite systems, as seems to be the case for this sample (Buck et al. 2016), a comparison measuring only the absolute height of the satellite planes will be biased to find narrower planes in the higher-concentration cases.

We set out to address these concerns. In the following, we will test whether the concentration, formation time, virial radius (or mass) of a halo, or radial concentration of the subhalo population has an effect on the thickness and kinematic coherence of satellite galaxy planes. We do this using 48 MW and M31-like halos from the Exploring the Local Volume in Simulations (ELVIS) simulation suite, thereby alleviating the concern of low-number statistics in the host sample. We look for a correlation between host halo properties and the occurrence and properties of satellite galaxy planes and control for the effect of the radial distributions by exploring randomized samples with the same radial distributions drawn from isotropy. We further utilize the fact that the ELVIS suite consists of 24 isolated hosts and 24 in paired configurations as found in the Local Group to test for an effect of environment on the width or kinematic coherence of planes of satellites. In addition, we use the new Phat ELVIS suite of 12 hosts simulated both as dark-matter-only simulations and with an added analytical MW-like disk potential (Kelley et al. 2018) to investigate the influence that the additional tidal disruption by a central baryonic disk galaxy has on the width and kinematic coherence of satellite galaxy planes. Since such disruption is the main effect that the inclusion of baryonic physics has on the satellite galaxy system (Garrison-Kimmel et al. 2017), this comparison will provide hints to the feasibility of addressing the problem of planes of satellite galaxies with more realistic hydrodynamical cosmological simulations. We compare all planes with the observed GPoA, which consists of 15 satellite galaxies with an rms height of \( \Delta_{\text{rms}} = 12.6 \pm 0.6 \, \text{kpc} \) (with a 99% confidence upper limit of 14.1 kpc), out of which 13 show line-of-sight velocities consistent with co-orbiting around M31 (Ibata et al. 2013).

2. Method and Subhalo Selection

2.1. Top 30 Subhalos within \( r_{\text{vir}} \)

As a first step, we reproduce the earlier analysis, now using the 48 MW- and M31-like host halos of the ELVIS project by Garrison-Kimmel et al. (2014). We use the publicly available present-day (\( z = 0 \)) halo catalogs and rank all subhalos of a given host by the maximum mass \( M_{\text{peak}} \) they had over their history. This is consistent with the ranking used by Buck et al. (2015) and prevalent abundance matching schemes. The mass range covered by the ELVIS halos (\( M_{\text{vir}} = (1.0-2.8) \times 10^{12} M_\odot \)) is comparable...
with that of the halos analyzed by Buck et al. (2015; $M_{200} = (0.8\text{−}2.1) \times 10^{12} M_\odot$), especially when considering that $M_{200}$ is systematically smaller than $M_{\text{vir}}$ because the latter is calculated over a larger halo volume (encompassing an average density of 97 instead of 200 times the critical density of the universe). The resolutions of the two simulation suites are comparable, too. ELVIS uses a particle mass of $m_p = 1.9 \times 10^5 M_\odot$ and a force softening of $\epsilon = 141 \text{pc}$ for the highest-resolution regions, while the simulations of Buck et al. (2015) have a particle mass of $m_p \approx 1.5 \times 10^7 M_\odot$ and force softening of between $\epsilon = 370$ and 540 pc.

To investigate the effect of a central baryonic host galaxy, we additionally analyze the 12 hosts of the Phat ELVIS simulation suite by Kelley et al. (2018). This extension to the ELVIS project consists of 12 dark-matter-only zoom simulations, which were each rerun with an embedded galaxy potential grown to match the observed MW disk and bulge today. The host halos cover a mass range of $(M_{\text{vir}} = (0.7\text{−}2.0) \times 10^{12} M_\odot)$, while the central host disk galaxy is always $6.9 \times 10^{10} M_\odot$ at $z = 0$. The galaxy potential consists of a stellar and a gaseous disk, as well as a bulge component, and is grown starting from redshift $z = 3$. The resolution of Phat ELVIS is better than in the ELVIS suite, with a particle mass of $m_p = 3 \times 10^2 M_\odot$ and a force softening of $\epsilon = 37 \text{pc}$ for the highest-resolution regions. Due to the differences in resolution and assumed cosmological parameters—Planck 2015 results (Planck Collaboration et al. 2016) instead of WMAP7 (Larson et al. 2011) as in ELVIS—we refrain from combining the ELVIS and Phat ELVIS samples despite the temptation of a larger sample size. Instead, the Phat ELVIS simulations will be used in Section 5 to determine whether the changes to the orbital properties of a satellite system caused by the presence of a baryonic central galaxy potential can have a substantial effect on the properties of planes of satellite galaxies.

We then look for correlations of the properties of the thinnest and most corotating satellite planes among the subhalos and the following properties of their host halo.

1. $r_{\text{vir}}$, the virial radius measured as the radius of a sphere centered on the host halo that contains a density of 97 times the critical density $\rho_{\text{crit}}$ of the universe. Since this definition implies an unequivocal relation between $r_{\text{vir}}$ and the virial mass $M_{\text{vir}}$, we could also refer to the latter, which might be seen as more fundamental. However, we decided to refer to the virial radius in the following because it is more directly linked to the issue of spatial distributions.

2. $c_{\cdot\cdot2}$, the halo concentration determined as $c_{\cdot\cdot2} = r_{\text{vir}}/r_{\cdot\cdot2}$, where $r_{\cdot\cdot2}$ is the radius where $r^2$ peaks. This differs slightly from the concentration parameter in Buck et al. (2015), who instead of $r_{\text{vir}}$ used $r_{200}$, the radius at which the halo contains a density of 200 times the critical density. Since $r_{200} < r_{\text{vir}}$, this results in somewhat lower numerical values of concentration for a given halo.

3. $z_{\text{forms}}$, the formation redshift of the host halo, measured as that redshift at which the host’s main progenitor first acquires $50\%$ of the host halo’s $\rho = 0$ virial mass $M_{\text{vir}}$.

4. $\Delta_{\text{subhalos}}$, the rms of the radial distances from the center of their host of the selected subhalos (30, or 27 in the case of the PAndAS-like selection volume).

Figure 1 summarizes these host halo properties. Additionally, the lower panel compares the ELVIS halo concentrations $c_{\cdot\cdot2}$ to the average concentration relation of Prada et al. (2012), which uses the same cosmology (yellow line) plotted against virial radius $r_{\text{vir}}$ instead of virial mass $M_{\text{vir}}$. The dashed lines indicate a $1\sigma$ scatter of 0.11 dex (or a factor of 1.3) as reported by Dutton & Macciò (2014) and used in Buck et al. (2015). While the study of Dutton & Macciò (2014) is based on a slightly different cosmology, the typical scatter around the average mass–concentration relation is found to be virtually identical among different cosmologies (Macciò et al. 2008) and thus applicable to the ELVIS simulations, too. While the sample of host halos of Buck et al. (2015) was selected to especially sample the wings of the concentration distribution, Figure 1 shows that the ELVIS sample also contains nine hosts that are offset from the mean concentration relation by $\approx 2\sigma$ toward high concentrations.

Like Buck et al. (2015), we first select the top $N_{\text{sh}} = 30$ subhalos within the virial radius of each of our 48 host halos, excluding all subhalos within the innermost 30 kpc. This is our “simulated” sample. We also generate a “randomized” sample of subhalo systems. For this, we keep the radial distances and absolute velocities of all subhalos but draw random directions from an isotropic distribution for the position and velocity vectors. This constitutes a simple but necessary and important test: are potential differences in the properties of satellite planes due to an increase of subhalo coherence that is linked to host halo properties (such as concentration or formation redshift), or are such differences driven by the radial distribution of the subhalo system itself?

To find the thinnest planes for each number of subhalos between 3 and $N_{\text{sh}}$, we proceed as follows. We generate 10,000 normal directions that are approximately evenly distributed on a hemisphere. Each of these describes a possible satellite plane centered on the host halo. For each of these planes, we rank all $N_{\text{sh}}$ subhalos by their distance from the plane and measure the rms height of the $N_{\text{sh}}$ subhalos. Like Buck et al. (2015), we then use the relation between $r_{\text{vir}}$ and the virial mass $M_{\text{vir}}$ to determine the number of co-orbiting satellites by counting the number of satellites with a major in plane $\Delta_{\text{rms}}$. The number of co-orbiting satellites $N_{\text{Coorb}}$ is the larger of the two (and thus always $N_{\text{inPlane}}/2 \leq N_{\text{Coorb}} \leq N_{\text{inPlane}}$). For each combination of $N_{\text{inPlane}}$ and $N_{\text{Coorb}}$ that occurs in a subhalo system, we record the smallest plane height $\Delta_{\text{rms}}$.

2.2. PAndAS-like Selection of Subhalos

As already pointed out in Pawlowski et al. (2014), the satellite selection volume has a major effect on the distribution of subhalos selected from a simulation and thus on the deduced properties of satellite planes (see Figure 2). Volumes that differ in size and shape from the one actually observed can bias both toward and away from finding narrow satellite planes, depending on their shape. Furthermore, the number of satellites used to find satellite planes has a major influence on the resulting properties: the more satellites in the sample, the higher the chance to find more extreme properties among subsamples of a fixed number. This is why the selection of 30...
(instead of the observed 27) satellites from the virial radius (instead of the PAndAS footprint) but allowing for satellites close to the host in projection (in contrast to the observational study by Ibata et al. 2013, which excluded the inner 2°5 around M31) makes any comparison between the observed GPoA and satellite planes in the simulation futile.

Defining the satellite selection volume by the virial radii of the individual host halos furthermore risks introducing the looked-for anticorrelation between host halo concentration and thickness of the narrowest satellite planes. If there is a relation...
between the overall extent of a satellite system and the height of the narrowest satellite planes (see Section 3.4), then linking the volume from which satellites are selected to \( r_{\text{vir}} \) introduces a correlation between \( r_{\text{vir}} \) and the minimum plane heights \( \Delta_{\text{min}} \). The definition of \( r_{\text{vir}} \) implies an unequivocal relation to the virial mass \( M_{\text{vir}} \) of the form

\[
    M_{\text{vir}} = 97 \times \rho_{\text{crit}} \times \frac{4}{3} r_{\text{vir}}^3,
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such that a correlation with \( r_{\text{vir}} \) also implies a correlation with \( M_{\text{vir}} \). In \( \Lambda \)CDM, it is well established that dark matter halos follow a halo mass–concentration relation, in the sense that halos with larger \( M_{\text{vir}} \) have lower \( c_{-2} \) (Bullock et al. 2001; Ludlow et al. 2014). Thus, a correlation with \( M_{\text{vir}} \) also implies an anticorrelation with the concentration parameter. Putting all this together, more concentrated host halos tend to be less massive and have smaller virial radii (see also lower panel of Figure 1); their satellite systems are thus selected from a smaller volume, which biases the satellite planes found in them to be more narrow. Thus, it is conceivable that the selection volume chosen by the previous study introduces the very correlation they reported. However, it is unclear whether this artificially introduced correlation is discernible given the low-number statistics, the substantial scatter in the mass–concentration relation, and the stochasticity of satellite plane heights.

Another distinction in our analysis that improves upon the initial exploration by Buck et al. (2015) is that we restrict the analysis to using only the 1D line-of-sight velocities, in contrast to the previously described analysis (Section 2.1), which uses the full 3D velocities of the subhalos to determine the kinematic coherence. The latter are not available observationally (proper motions at the distance of M31 are extremely difficult to measure; Sohn et al. 2012; van der Marel et al. 2012; Salomon et al. 2016).

Finally, we point out that, in principle, one should consider observational uncertainties, since these are an additional source of dispersion in the satellite coherence (they make planes appear thicker and velocities appear less coherent). We ignore this in the rest of this work for the sake of simplicity—and because the frequency of satellite planes comparable to the observed one turns out to be zero even without considering this effect—but we will revisit the point in a future publication (M. S. Pawlowski et al. 2019, in preparation).

To compare with the observed GPoA, we use the same ELVIS simulations as discussed before but select subhalos from a volume determined by the PAndAS footprint area. For this, we observe each of the isolated host halos from a random direction, while for the paired hosts, the direction of observation is from the partner host. To select only subhalos that fall into the survey area covered by PAndAS, we mock-observe the subhalos by projecting their positions into a spherical coordinate system with angles centered on the host halo. The mock observer is situated at a distance to the host halo of 780 kpc, consistent with the distance to M31. We then select the top 27 subhalos ranked by their mass at infall (\( m_{\text{max}} \)) that lie within the PAndAS survey polygon. This number is chosen to be identical to the number of satellites considered by Ibata et al. (2013) and Conn et al. (2013). The maximum allowed distance of a subhalo from the host halo center is 500 kpc, which makes the selection volume consistent with the most-distant M31 satellite in the observed sample (Andromeda XXVII at a most likely distance of \( \sim \)480 kpc from M31; Conn et al. 2012). Like Ibata et al. (2013), we also exclude the region within 2.5 of the host halo in projection and exclude all subhalos from that volume, because the high background this close to the host hampers the detection of satellite galaxies and

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9 In its simplest form, this can be thought of as if satellite systems of hosts with different \( r_{\text{vir}} \) can be assumed to be rescaled versions of the same underlying distribution, as can be expected from the self-similarity of \( \Lambda \)CDM halos over a large mass range.
negatively affects distance measurements. This selection results in a total volume of about 0.07 Mpc$^3$, or a volume corresponding to that of a sphere with radius 257 kpc. As before, we also generate a random sample by randomizing the subhalo positions and velocities before applying the PAndAS selection.

For the plane-fitting analysis, we consider the full 3D position vectors of the 27 selected subhalos for each host, as well as the line-of-sight velocity vectors as seen from the direction from which the PAndAS footprint was applied (within the host halo rest frame). The plane-finding routine itself is identical to the one described before.

3. Spatial Coherence

In Figure 3, the properties of the observed GPoA (black error bars) are compared to those of satellite planes identified in the simulations. The figure uses the PAndAS-like selection volume to mimic the selection biases present in the observed satellite sample. No planes with plane heights as narrow as observed are identified. While for some halos, planes of 15 satellites can be defined that contain 13 kinematically correlated satellites, analogous to the observed system, none of these simulated planes are simultaneously as narrow as the observed structure. The color-coding by each halo’s concentration highlights that no correlation with the concentration parameter of the host halo is present. Consequently, the presence of a narrow, kinematically highly correlated plane of satellite galaxies in the observed satellite system of M31 does not support the conclusion that M31 lives in a high-concentration halo.

3.1. Plane Thickness versus Halo Properties

Figure 4 presents the minimum plane height for each possible number of satellites in a plane $N_{inPlane}$, color-coded for host halo concentration. The figure shows the results for 30 subhalos in the virial radius (top left), 30 subhalos with randomized positions and velocities (top right), 27 subhalos selected from within the PAndAS volume (bottom left), and 27 subhalos selected from the PAndAS volume after randomizing their positions and velocities (bottom right). The thick dashed lines give the average plane heights for combinations of 12 subhalo systems ranging from the 12 most concentrated (red) to the 12 least concentrated (blue).
Figure 5. Radial distribution of subhalos in the samples color-coded by host halo concentration. The top four panels are for the same subhalo samples as those in Figure 4. The thick dashed lines again give the average radial profiles for different bins in halo concentration. The green lines correspond to those subhalo distributions that contain planes of 15 satellites that are narrower than the observed GPoA around M31. They are more radially concentrated than the average of the radial distributions, especially in the inner regions of the distribution. They are also considerably more radially concentrated in the inner regions than the 27 observed M31 satellites, illustrated by the black line in the lower left panel (assuming their most-likely positions from Conn et al. 2012). The fifth panel shows the radial distribution of the subhalos selected from a PAndAS footprint in the Phat ELVIS simulations that include a central disk potential. The subhalos tend to be found at larger radial distances from the host than in the DMO ELVIS simulations, and their radial distribution matches better with the observed one (black line), in particular in the inner regions.
minimum plane thickness is apparent. We would have expected to see a gradient of higher concentrations for lines at lower \( \Delta_{\text{rms}} \) at a given satellite number.

There are, however, a few minor indications that can be interpreted to be consistent with the findings of Buck et al. (2015). Three of the halos do in fact contain satellite planes of \( N_{\text{inPlane}} = 15 \) that are at least as narrow as the 99% upper limit of the GPoA around M31 (\( \Delta_{\text{rms}} \leq 14.1 \) kpc). Two of these three halos seem to be of higher-than-average concentration, too, while the two halos with the largest min \( \Delta_{\text{rms}} \) at \( N_{\text{inPlane}} = 15 \) are of lower concentration. In addition, the average of the minimum plane heights for the 12 most-concentrated hosts (thick dashed red line) tends to be slightly below that of the 12 least-concentrated hosts (thick dashed blue line).

However, before we jump to this conclusion, we need to take a step back and compare the findings with our randomized control sample (top right panel in Figure 4). Interestingly, the randomized sample also has a high-concentration halo at the lowest \( \Delta_{\text{rms}} \). Like in the simulated sample, the two most-pronounced high-min \( \Delta_{\text{rms}} \) halos up to \( N_{\text{inPlane}} = 20 \) have low concentration, too. Furthermore, even the average min \( \Delta_{\text{rms}} \) for the 12 most- and least-concentrated hosts show the same behavior as in the simulated sample, with the more concentrated ones having slightly lower min \( \Delta_{\text{rms}} \). All indications for a possible correlation between host halo concentration and the height of satellite planes previously discussed for the simulated sample are therefore also present in a sample of satellites drawn from isotropy. This randomized sample does not have any formation history that could be responsible for this. The similarities, therefore, are hints that indeed the radial distributions of the subhalos might be most responsible for driving min \( \Delta_{\text{rms}} \), since this is the only property that the simulated and randomized samples have in common.

More support for this interpretation can be found in the radial profiles of the subhalo systems (Figure 5). The systems belonging to the lowest-concentration hosts tend to be slightly less radially concentrated, especially in the inner parts (compare the dashed red and blue lines, which show the average radial profiles for the high- and low-concentration halos, respectively). More importantly, those systems that contain planes of 15 satellites that are at least as narrow as the GPoA (underlaid with a thick green line) are more radially concentrated than the average subhalo distributions in high-concentration halos. This confirms that the radial concentration is the factor driving the tendency to lower minimum plane heights, but this is only due to an overall more compact scaling of the satellite system that is not accounted for when measuring plane heights in absolute distance.

The PAndAS samples do not even show a weak indication of a correlation between min \( \Delta_{\text{rms}} \) and \( c_{-2} \) in Figure 4, which demonstrated that the selection volume is an important aspect of any comparison between simulations and observations. None of the 48 ELVIS halos contains a subhalo plane that is as

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Figure 6. Same as Figure 4, but the lines are now color-coded for host halo formation redshift \( z_{f, h} \), virial radius \( r_{\text{vir}} \), and rms radius of the subhalo system \( \Delta_{\text{rms}}^{\text{inPlane}} \). The top row gives the results for the 30 top-ranked subhalos selected from within the respective virial radii; the bottom row gives the sample of randomized positions (but identical radial distances). The formation redshift does not correlate with the height of the thinnest satellite planes, but there is a clear correlation with the virial radius and the radial distribution of the subhalo system. These are also present for the samples with randomized positions, indicating that the radial distribution drives the differences in plane heights and not an additional positional or kinematic coherence within the simulated subhalo systems of these hosts.

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8 We would like to stress again that due to the very different selection volume, this does not intend to claim consistency between the simulations and the observed M31 satellite system. Furthermore, to resemble the GPoA, these satellite planes would simultaneously need to show the same degree of kinematic coherence, which they do not (see Section 4 below).
narrow as the observed GPoA. Figure 5 reveals that the PAndAS volume affects the typical radial distribution of selected subhalos compared to the spherical volumes of radius $r_{\text{vir}}$. It results in a somewhat steeper inner slope within $d_{\text{host}} \lesssim 150$ kpc and then a more extended tail to larger distances, the latter because the selection function allows subhalos to be found up to 500 kpc from the host if they lie within the PAndAS footprint instead of cutting off at the virial radius. Note that the radial profile of the 27 observed M31 satellites among which Ibata et al. (2013) discovered the GPoA (black line in Figure 5) is less radially concentrated than the vast majority of subhalo systems, especially in the inner regions of the halos. This is another indication that it is the radial subhalo distribution that drives $\Delta_{\text{rms}}$ to lower values, not the presence of actual satellite planes. In this regard, it is important to note that the analyzed simulations are
Table 1

| $N_{\text{inPlane}}$ | $\min \Delta_{\text{rms}} \text{ vs. } c_{-2}$ | $\min \Delta_{\text{rms}} \text{ vs. } z_{0.5}$ | $\min \Delta_{\text{rms}} \text{ vs. } r_{\text{vir}}$ | $\min \Delta_{\text{rms}} \text{ vs. } \Delta_{\text{subhalos}}^{\text{rms}}$ |
|---------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|
|                     | Pearson $\rho$ | Spearman $\log p$ | Pearson $\rho$ | Spearman $\log p$ | Pearson $\rho$ | Spearman $\log p$ | Pearson $\rho$ | Spearman $\log p$ |
| 3                   | 0.17          | 0.37          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 4                   | 0.24          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 5                   | 0.03          | 0.57          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 6                   | 0.10          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 7                   | 0.14          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 8                   | 0.15          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 9                   | 0.10          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 10                  | 0.11          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 11                  | 0.11          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 12                  | 0.12          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 13                  | 0.08          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 14                  | 0.06          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 15                  | 0.05          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 16                  | 0.03          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 17                  | 0.03          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 18                  | 0.00          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 19                  | 0.01          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 20                  | 0.00          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 21                  | 0.00          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 22                  | 0.00          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 23                  | 0.00          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 24                  | 0.00          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 25                  | 0.00          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 26                  | 0.00          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 27                  | 0.00          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 28                  | 0.00          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 29                  | 0.00          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |
| 30                  | 0.00          | 0.47          | 0.03          | 0.57          | 0.15          | 0.37          | 0.03          | 0.57          |

**Note.** Correlation coefficients and logarithms of the corresponding $p$-values for Pearson ($\rho$) and Spearman ($r_s$) tests of correlations between the minimum plane heights $\min \Delta_{\text{rms}}$ for different numbers of satellites in a plane $N_{\text{inPlane}}$ vs. various halo parameters: halo concentration $c_{-2}$, formation redshift $z_{0.5}$, virial radius $r_{\text{vir}}$, and rms radius of the subhalo distribution $\Delta_{\text{subhalos}}^{\text{rms}}$.

collisionless, and that the host halos do not contain central galaxy disks, whose tidal effects can result in a depletion of subhalos in the innermost regions, resulting in more radially extended subhalo systems (Garrison-Kimmel et al. 2017; Sawala et al. 2017). This effect on the distribution of satellite subhalos is present in the Phat ELVIS sample that includes a central galaxy potential. As a consequence, for this set of simulations, we find a better match with the observed radial distribution of M31 satellite galaxies, provided that the subhalos are selected from the PAndAS footprint (see Section 5).

Buck et al. (2015) concluded that the narrowness of satellite planes correlates with halo formation time, in the sense that earlier-forming halos contain narrower planes. They based this conclusion on using halo concentration as a proxy for formation time and argued to have found an anticorrelation between plane height and halo concentration. We cannot reproduce the reported correlation between host concentration and the width of the satellite planes, which appears to invalidate this line of argument. Thus, in Figure 6, we more directly check for a possible correlation with halo formation time by comparing to the halo formation redshift $z_{0.5}$ (left panels). Maybe unsurprisingly, no correlation is apparent between $z_{0.5}$ and the minimum plane heights either. However, color-coding by the virial radius $r_{\text{vir}}$ of the host (middle panels) or the rms radius of the subhalo sample $\Delta_{\text{subhalos}}^{\text{rms}}$ (right panels) reveals a clear gradient (and thus correlation) that confirms our preceding discussion: systems with a smaller total radial extent result in apparently narrower satellite planes if measured by absolute rms height.

3.2. Average Halo Properties

As another test, we now invert our approach. Instead of testing whether a halo property results in narrower satellite planes, we now test whether the narrowest satellite planes live in halos that, on average, have different properties. For each number $N_{\text{inPlane}}$ of satellites in a plane, we separate the halos into four bins by the value of $\min \Delta_{\text{rms}}$ for these satellite planes. In other words, we split them into groups of 12 halos that range from containing the 12 thinnest satellite planes (thick red line in Figure 7) to the 12 widest (thin blue line). This is done for each number of satellites in the plane $N_{\text{inPlane}}$ such that the composition of the bins changes for different satellite numbers. We then calculate the average halo concentration, formation redshift, virial radius, and subhalo rms distance for each bin and number of satellites. The results are shown in Figure 7. The averages of the mean properties over all numbers of satellites in the plane (i.e., flattening the $x$-axis), as well as the scatter...
around this average, are given at the top of each panel for each bin in the corresponding color.

It is clear from the highly fluctuating and crossing curves that the higher concentrations (first row) and formation redshifts (second row) of the host halos do not result in those halos having the thinnest satellite planes. The scatter in the averages over all numbers of satellites in the planes is as large or larger than the difference between them, too. If anything, the halos resulting in the narrowest planes seem to be forming slightly later (smaller $z_{0,S}$) than the others for $N_{\text{in Plane}} \geq 15$, which is the opposite of the trend suggested by Buck et al. (2015). However, the differences in the averages between the four bins are consistent with the scatter in each bin and therefore not significant, and the same trend is seen for the randomized satellite positions.

There is a tendency that halos that contain narrower satellite planes (for a given number of satellites in the plane) have smaller virial radii if the satellites are selected from within the whole virial radius (third row). Averaged over all satellite numbers, the mean virial radii in the four bins are consistent between the simulated sample and the one with randomized angular positions. This again evidences that the driving variable is the radial extent to which the subhalo system is considered. Consequently, in the case of the fixed-volume PAndAS-like selection, this dependency on $r_{\text{vir}}$ is not as pronounced anymore. The averages are consistent with being identical.

There is a strong tendency that subhalo systems that are more radially concentrated result in narrower planes (fourth row) if selected from the whole virial volume. This is again less clear in the PAndAS samples. However, this effect is again also present for the samples with random subhalo positions (columns 2), which demonstrates that it is merely an effect of considering only the absolute thickness of the subhalo systems. It does not stem from an increase in the spatial and kinematic coherence of subhalo systems in these types of halos, which is completely eradicated by choosing random angular positions of the subhalos.

### 3.3. Tests of Correlation

In addition to these qualitative comparisons, we now apply more formal, quantitative tests of correlation, searching for dependencies between the various halo properties, as well as between these and the satellite plane heights. We use both the Pearson correlation coefficient $\rho$ and the Spearman rank correlation coefficient $r_s$ and report the corresponding $p$-values, which give the probability of obtaining a more extreme correlation coefficient by chance. We assume that we can reject
the hypothesis of no correlation if the p-value is below 0.05 (or log $p < -1.3$).

For the top 30 subhalo sample selected from the whole virial volume, we find no evidence for a correlation between the halo concentration $c_{-2}$ and $\Delta_{\text{subhalos}}$ ($\rho = 0.01, p = 0.93$; $r_s = -0.01, p = 0.95$) or the virial radius $r_{\text{vir}}$ and halo formation redshift $z_{\text{f}}$ ($\rho = 0.09, p = 0.52$; $r_s = 0.09, p = 0.55$). There are hints of a weak correlation between the formation redshift $z_{\text{f}}$ and $\Delta_{\text{subhalos}}$, but the two tests are not quite significant ($\rho = 0.28, p = 0.06$; $r_s = 0.20, p = 0.16$). We do find a weak, marginally significant correlation between the halo concentration $c_{-2}$ and the halo formation redshift as measured via $z_{\text{f}}$ ($\rho = 0.39, p = 0.011$; $r_s = 0.30, p = 0.04$), as well as a strong and highly significant correlation between $r_{\text{vir}}$ and $\Delta_{\text{subhalos}}$ ($\rho = 0.77, p = 1.1 \times 10^{-10}$; $r_s = 0.74, p = 1.4 \times 10^{-9}$).

As expected from the discussions in Section 3, our tests reveal no highly significant correlation between the formation redshift or the halo concentration and the satellite plane heights for the different numbers of satellites per plane (or averaged over them). The corresponding p-values of these tests mostly remain well above 0.1 or log $p > -1$ (see Tables 1–4).7 For the sample of 30 subhalos selected from the whole virial volume, we find a correlation with $r_{\text{vir}}$, which is present and of similar strength for both the simulated and the randomized sample. Unsurprisingly, such a correlation with $r_{\text{vir}}$ is not found for the PAndAS-like selection volume. While the top 30 subhalo samples show a strong correlation between the satellite plane heights and the rms radius of the subhalo samples $\Delta_{\text{subhalos}}$, a weak correlation like this exists in the PAndAS-like samples. This quantitatively demonstrates the importance of accurately accounting for the selection volume of the observed M31 satellite galaxies when comparing to subhalos in simulations.

### 3.4. Satellite System Extent versus Plane Height

Figure 8 shows the correlation between the satellite plane height for planes consisting of 15 satellites and the rms radius of the subhalo samples, $\Delta_{\text{subhalos}}$. The latter is a good predictor of the height of the narrowest plane if the satellites are selected from the whole virial volume. This is independent of whether the actual subhalo positions of the simulations or randomized positions are used. A linear fit of the form

$$\min \Delta_{\text{rms}} = a \times \Delta_{\text{subhalos}} + b$$

demonstrates the similarity. The fit parameters are $a = 0.163 \pm 0.001$ and $b = -9.95 \pm 20.93$ kpc for the simulated sample and $a = 0.145 \pm 0.001$ and $b = -5.73 \pm 19.21$ kpc for the randomized one. Even the residuals around these best-fit lines have almost identical scatter (3.48 and 3.34 kpc, respectively). This shows how little additional structure is present in the simulated subhalo systems compared to subhalo
positions randomly chosen from an isotropic distribution. Knowing the radial distribution of a subhalo system thus allows one to predict the height of its narrowest satellite plane. However, this is not as pronounced if the subhalo positions are constrained by the PAndAS-like selection volume, either for the simulated subhalo positions \((a = 0.0393 \pm 0.0002, b = 12.61 \pm 8.57 \text{ kpc}, \text{scatter of 3.37 kpc})\) or for the randomized ones \((a = 0.0339 \pm 0.0003, b = 14.81 \pm 10.45 \text{ kpc}, \text{scatter of 3.18 kpc})\).

### 4. Kinematic Analysis

While we find that there is no correlation between the concentration of a host halo and the minimum heights of subhalo planes, there remains the possibility that a stronger kinetic coherence is present for subhalos in hosts of higher concentration. We investigate this possibility for planes consisting of a total of 15 subhalos in Figure 9. It shows the minimum of the height of satellite planes that contain a given number of co-orbiting satellites. For example, if a system contains a plane of 15 subhalos of height 20 kpc of which 10 co-orbit and another of height 25 kpc of which 12 co-orbit, then the line for a given ELVIS halo remains at min \(\Delta_{\text{rms}} = 20\text{ kpc}\) for \(N_{\text{Coorb}} = 10\) and then goes up to min \(\Delta_{\text{rms}} = 25\text{ kpc}\) for \(N_{\text{Coorb}} = 11\) and 12. Once no plane of any height is found for a given number of co-orbiting subhalos, the corresponding line for this halo stops.

Figure 9 suggests that, as is to be expected, the randomized samples (right panels) are a bit less kinematically coherent: the lines tend to end at lower \(N_{\text{Coorb}}\). Similarly, the planes in the PAndAS-like samples are less kinematically coherent than those selecting the top 30 subhalos within the full virial radius. A larger number of subhalos to choose planes from increases the number of possible combinations for a given number of subhalos per plane, which therefore increases the chance to find planes with a higher degree of velocity coherence. This demonstrates again that closely modeling observational selection effects is indispensable for a meaningful comparison of simulations with the observed situation. None of the subhalo systems can reproduce the height and number of co-orbiting satellites of the observed GPOA. This allows us to put a lower limit on the frequency of such planes in cosmological simulations of \(\lesssim 2\%\), which is consistent with the low frequencies of 0.04%-0.17% found in earlier studies using larger samples of host halos (Ibata et al. 2014; Pawlowski et al. 2014).

If there is an increase in the kinematic coherence for subhalo systems of more concentrated hosts, the corresponding lines in this plot should turn upward later than those of the less-concentrated halos. This is not the case, as can be seen from the thicker dashed lines indicating the average plane heights for

\[\Delta_{\text{rms}}\]
four bins of host halo concentration ranging from the 12 highest-concentration hosts (red) to the 12 lowest-concentration hosts (blue). The lines follow a common trend and overlap within the scatter of their respective host satellite system populations.

5. Testing for Effects of Environment and Central Host Galaxy

5.1. Isolated versus Paired Hosts

We now split up the ELVIS sample into a subsample containing the 24 isolated hosts (ELVIS isolated) and a subsample containing 24 hosts that are part of 12 pairs of host galaxies (ELVIS paired). The distributions of plane heights for these two sets are shown in the top panels of Figure 10, similar to Figure 4 but now color-coded according to subsample membership. Comparing the subhalo systems of the ELVIS isolated (red) and ELVIS paired (blue) hosts, we find no significant difference in both the average (thick lines) and the scatter (shaded regions) of the plane height. The bottom panels of Figure 10 show the kinematic coherence (as in Figure 9).

As is the case for the whole sample, neither of the two subsamples shows a correlation between the plane heights and...
halo concentration or formation redshift. There is thus no indication that being part of a paired host halo configuration or an isolated host results in a correlation with these halo properties. As expected from the full sample, if subhalos are selected from the virial volume, a weak correlation with the virial radius and strong correlation with the extent of the subhalo distribution is again present. However, owing to the reduced sample sizes, the respective significances are lower than for the full sample.

5.2. DMO versus Central Galaxy Potential

It has been found that the addition of a central galaxy potential to a cosmological simulation, whether self-consistently via a hydrodynamical simulation or using an analytic potential, results in enhanced tidal disruption of subhalos compared to a dark-matter-only simulation. This, in turn, changes the radial distribution and orbital properties of the subhalo system (Garrison-Kimmel et al. 2017; Sawala et al. 2017). The inner regions of host halos become depleted in subhalos, and the orbits of surviving subhalo satellites are less radial, on average, than in equivalent dark-matter-only runs. To investigate whether the presence of a central galaxy potential and its effect on the subhalo distribution influence the properties and coherence of planes of satellite galaxies, we now compare the resulting plane heights and kinematic coherence of the two Phat ELVIS simulation samples by Kelley et al. (2018): the 12 dark-matter-only runs that are equivalent to the ELVIS simulations (Phat ELVIS DMO) and the 12 runs started from the same initial conditions but

Figure 9. Plane height vs. number of co-orbiting satellites for planes consisting of 15 satellites, color-coded for host halo concentration. The four panels are for the same subhalo samples as in Figure 4. The lines stop once no plane with a given number of co-orbiting satellites \( N_{\text{Coorb}} \) is present in the sample. The thick dashed lines give the average plane heights for combinations of 12 subhalo systems ranging from the 12 most concentrated (red) to the 12 least concentrated (blue). As expected, the randomized satellite systems result in less narrow and less kinematically coherent satellite planes. None of the 48 ELVIS halos can reproduce the observed flattening and kinematic coherence. Furthermore, there is no indication that the more concentrated halos result in narrower and more kinematically coherent satellite planes. Rather, the subhalo systems of the most concentrated host halos appear to be less thin and coherent (the average of the 12 most-concentrated halos is above that of the less-concentrated halos). Plots with color-coding by other halo properties than \( c^{-2} \) (\( z_0.5, r_{\text{vir}}, \text{and } \Delta r_{\text{subhalos}} \), for a total of four figures with four panels each) are available as a figure set in the online journal.

(The complete figure set (4 images) is available.)
with an added central galaxy potential (*Phat ELVIS disk*). In the bottom panel of Figure 5, the expected change in the radial distribution of subhalos is apparent: satellite subhalos in the *Phat ELVIS disk* runs selected from the PAndAS footprint have a radial distribution that is in better agreement with the observed distribution of satellite galaxies in M31 than the original ELVIS runs that did not include a central galaxy potential.

Figure 11 compiles the results of this comparison. The average plane heights (thick lines) are comparable for the dark-matter-only (DMO; red) and disk (blue) runs, though the former are slightly more narrow. The typical scatters (shaded regions) overlap well and show similar width, though there appears to be more scatter in the DMO runs if subhalos are selected from the PAndAS footprint (right panels). For subhalos selected from the PAndAS footprint (right panels), we find \( \min \Delta_{rms} \) to be, on average, 7% larger for the simulations that contain a disk potential compared to their disk-free analogs (compared to 11% if selected from \( r_{vir} \)). This is in line with the general trend of a correlation between the \( \min \Delta_{rms} \) and the radial extent of a subhalo system measured by \( \Delta_{\text{subhalos}} \), discussed in Section 3.4. The median \( \Delta_{\text{subhalos}} \) is 188 kpc for the DMO and 214 kpc for the disk runs (or 184 and 191 kpc, respectively, if the subhalos are selected from \( r_{vir} \)). Using the corresponding linear fits in Section 3.4, this translates to an expected increase in the width of the subhalo distributions of 5% (6%), which largely accounts for the found increase in plane widths. This further supports the notion that the major driver behind the width of the narrowest planes of satellites found in a given distribution is the distribution’s radial extent. The lower panels of Figure 11 further show that the inclusion of a central galaxy potential does not result in a more pronounced kinematic correlation in the narrowest satellite planes.
simulations does not appear to offer a solution to the problem of planes of satellite galaxies. Using the concentration parameters of the Phat ELVIS host halos, we have also confirmed that no significant correlations with host halo concentration or formation time are present, either for the DMO or for the disk samples. This is in line with our previously discussed findings for the ELVIS simulations.

6. Conclusion

We have used the 48 host halos of the ELVIS simulations to test whether the host halo concentration, formation time, or status as an isolated or paired halo has an effect on the existence of narrow, kinematically coherent planes of satellites. We are unable to reproduce the result of Buck et al. (2015) that the flattening of subhalo systems correlates with the host halo formation time. Similarly, we do not find evidence of a correlation between the host halo concentration and the height of the thinnest subhalo planes. Only the overall radial extent of the considered subhalo distribution, as constrained by $r_{\text{vir}}$ or measured by $\Delta_n^{\text{subhalos}}$, shows signs of a correlation. However, this correlation is present to a similar degree if the subhalo positions are randomized, indicating that it is mainly an effect of a smaller total radial extent of lower-mass halos and not of a stronger spatial or kinematic coherence among the subhalos in certain host dark matter halos.

We showed that it is important to select halos in a similar way as the observed satellite distribution in order to avoid biases by constructing subhalo selections that follow the PAndAS survey volume and number of satellites. These reveal that none of the 48 ELVIS halos hosts a plane of satellites that is as narrow and kinematically coherent as the observed GPoA, in line with earlier findings indicating that such structures are elusive in current ΛCDM simulations (Ibata et al. 2014b; Pawlowski et al. 2014). In line with the results of Pawlowski & McGaugh (2014b) for the VPOS of the MW, we also do not find a difference between the satellite plane properties of isolated versus paired host halos.

The main effect of baryonic physics that is relevant for the spatial and orbital properties of a satellite galaxy system is the...
formation of a central host galaxy. Using the Phat ELVIS simulation suite (Kelley et al. 2018), we have investigated whether the presence of such a central galaxy potential results in narrower or more kinematically coherent planes of satellite galaxies compared to dark-matter-only analogs. We found this not to be the case. On the contrary, since the added potential of a central host galaxy results in enhanced tidal disruption, which in turn depletes the inner regions of the host halo of satellite galaxies, it results in a more extended satellite distribution. We find that more radially extended systems tend to contain less narrow planes of satellite galaxies. Consequently, while other small-scale issues of cosmology can potentially be addressed by adding baryonic physics to cosmological simulations, it appears that the dominant baryonic effect makes the problem of planes of satellite galaxies worse.

We are thus left with the unsettling realization that the incidence of satellite planes as extreme as those observed remains an unsolved problem for the $\Lambda$CDM model of cosmology, and that this problem is not easily addressed by invoking baryonic effects, an exceptionally high concentration or early formation time of the host halo, or the host-pair environment of the MW and M31 halos.

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