Pre-processing, group accretion and the orbital trajectories of associated subhaloes

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ABSTRACT
We use a high-resolution cosmological dark matter-only simulation to study the orbital trajectories of haloes and subhaloes in the environs of isolated hosts. We carefully tally all apsis points and use them to distinguish haloes that are infalling for the first time from those that occupy more evolved orbits. We find that roughly 21 per cent of subhaloes within a host’s virial radius are currently on first infall, and have not yet reached their first orbital pericentre; roughly 44 per cent are still approaching their first apocentre after infall. For the range of host masses studied, roughly half of all accreted systems were pre-processed prior to infall, and about 20 per cent were accreted in groups. We confirm that the entire population of accreted subhaloes – often referred to as “associated” subhaloes – extend far beyond the virial radii of their hosts, with roughly half currently residing at distances that exceed \( \approx 1.2 \times r_{200} \). Many of these backsplash haloes have gained orbital energy since infall, and occupy extreme orbits that carry them well past their initial turnaround radii. Such extreme orbits are created during the initial accretion and dissolution of loosely bound groups, but also through penetrating encounters between subhaloes on subsequent orbits. The same processes may also give rise to unexpectedly abrupt losses of orbital energy. These effects combine, giving rise to a large variation in the ratio of sequent apocentres for accreted systems. We find that, within 2 virial radii from host centres, the concentrations of first-infall halos are remarkably similar those of isolated field halos, whereas backsplash haloes, as well as systems that were pre-processed, are considerably more concentrated.

Key words: cosmology: dark matter – methods: numerical – galaxies: formation, evolution

1 INTRODUCTION

In the standard cosmological model the variance of linear matter density fluctuations increases systematically toward smaller scales. The dominant mass component is a cold and collisionless particle – referred to as cold dark matter (CDM hereafter) – and the energy density of the Universe is dominated by dark energy (denoted \( \Lambda \) in the simplest case of a cosmological constant). This is the \( \Lambda \)CDM model, which has few rivals in its ability to accurately describe the large-\(( \gtrsim 10 \text{ Mpc})\) and intermediate-scale \((1 \sim 10 \text{ Mpc})\) structure of the Universe (see [Frenk & White 2012] for a recent review). \( \Lambda \)CDM also makes a few unwavering predictions. One, a consequence of the shape of the density fluctuation power spectrum, is that structure formation proceeds hierarchically, from small to large scales. Dark matter accretes onto primordial overdensities, either smoothly or through mergers, which grow progressively more massive over time, forming gravitationally-bound dark matter haloes. The vestiges of a halo’s past accretion or merger events form a population of “substructure” haloes, or subhaloes for short. Haloes are the likely sites of galaxy formation (e.g. [White & Rees 1978]), and subhaloes the potential hosts of satellite galaxies, such as those observed around the Milky Way or other nearby galaxies, or of the individual galaxies in rich clusters. The dynamics, spatial distribution and structure of substructure haloes therefore hold valuable clues to the hierarchical nature of galaxy formation.

There is now a broad and comprehensive literature ad-
dressing a variety of issues related to the structure and substructure of dark matter haloes. For example, it is now known that substructure makes an important but sub-dominant contribution to the total mass of a halo, typically \( \lesssim 10 - 15 \) per cent \cite{Ghigna1998,Neto2007}, and that their mass function is well approximated by a single power-law, \( dN/d\log M \propto M^{-0.9} \) \cite{Springel2001,Gao2004,Springel2008,Giocoli2010,Garrison-Kimmel2014}. Subhaloes are spatially (e.g. De Lucia et al. 2004, Springel et al. 2008, Gao et al. 2012) and kinematically (e.g. Gill et al. 2004, Diemand et al. 2004, Sales et al. 2007b, Ludlow et al. 2009) biased with respect to the underlying distribution of dark matter, which likely indicates that different environmental processes shape orbital evolution of substructure and smoothly-accreted dark matter.

As with DM haloes, subhaloes can have substructure of their own, a hierarchy that can, in principle, extend to the free-streaming limit of the dark matter particle (indeed, four nested levels of subhaloes-in-subhaloes have been observed in highest-resolution simulation of the Aquarius Project; Springel et al. 2008). As a result, many subhaloes will have been accreted as part of a substructure group (e.g. Li & Helmi 2008), or will have been pre-processed in some manner prior to accretion \cite{Wetzel2015, Han2018, Bahé2019}.

In addition, when a halo or group of haloes is accreted by a more massive system, it will not necessarily remain a subhalo indefinitely. Instead, accreted haloes can pass through temporary phases of being nominal substructures – i.e. confined to the virial boundaries of their host haloes – and pass again into the field, reaching orbital radii that can, in principle, extend to many times the host’s virial radius (e.g. Gill et al. 2005, Bahé et al. 2013, Haggar et al. 2020). As a result, galaxies in the field may show tell-tale signs of having passed through the dense central regions of more massive systems. Indeed, simulations suggest that as many as half of all accreted systems currently lie at distances that exceed the traditional virial boundaries of their hosts \cite{Ludlow2009}. These are often referred to as "backsplash", or "associated" subhaloes, terms we adopt in this paper.

This can have important consequences. For example, at fixed luminosity, galaxies hosted by backsplash haloes have higher mass-to-light ratios \cite{Knebe2011} and higher quenched fractions \cite{Simpson2018} than field galaxies. The mass profiles of backsplash haloes are more concentrated than field haloes at comparable radial separations from their hosts, at least partially explaining a puzzling phenomenon known as assembly bias \cite{Wang2009a, Li2013, Sunayama2016, Mansfield2020}.

The accretion of groups of substructure expected in \( \Lambda \)CDM also has important consequences. One is that accreted groups, when interacting with their host haloes near orbital pericentre, can lead to multi-body interactions, a scenario favourable for the rapid exchange of orbital energy and angular momentum between group members. This can, in principle, result in the ejection of (typically low-mass) subhaloes on highly "unorthodox" orbits \cite{Sales2007a}, which often propel them to distances that exceed their nominal turnaround radius \cite{Ludlow2009}. As we will see in Section 4.5, the same interactions can also lead to an abrupt loss of orbital energy and angular momentum, confining subhaloes to the innermost regions of their host haloes.

One consequence of group accretion, mentioned above, is that many systems, apparently infalling for the first time, will have been "pre-processed" prior to accretion (i.e. will have been a satellite of a more massive halo prior infall). Simulation work suggests that as many as half of the Milky Way’s satellites (with \( M_\star \gtrsim 10^6 M_\odot \)) may have experienced such pre-processing \cite{Wetzel2015}. These numbers are likely higher in galaxy groups and clusters, \cite{Bahé2019}, for example, found that as many as 87 per cent of \( \gtrsim 10^{10} M_\odot \) haloes accreted by massive clusters were pre-processed, and 73 per cent of Milky Way-mass haloes were. In group environments, these numbers are \( \approx 70 \) per cent and 35 per cent, respectively.

There is also observational evidence for pre-processing. Group catalogues based on the Sloan Digital Sky Survey \cite{Yang2007} have been used to classify galaxies as infall or backsplash, central or satellite. In the radial range between 2 to 3 virial radii from hosts, satellite galaxies show a higher quenched fraction than centrals, even when controlling for backsplash galaxies \cite{Hou2014}. Results from the Local Cluster Substructure Survey \cite{LoCuSS} \cite{Bianconi2018} suggest that groups of galaxies infalling onto clusters possess lower star formation rates, on average, than the total infalling population. These are only a couple of examples of the rich literature exposing pre-processing as an important driver of galaxy evolution \cite{see also, Cortese2006, Wetzel2014, Just2019}.

Our goal is to reassess some of these issues, aided by high-resolution cosmological (dark matter-only) simulations. We focus our analysis on well-resolved and isolated primary haloes, and consider all secondary haloes (whether subhalo or field halo) that ever come with 4 virial radii of their host. We carefully classify the trajectories of secondary haloes using sensible diagnostics based on their orbital histories. Rather than drawing arbitrary distinctions between infalling and accreted systems, we instead separate them based on the number of periapsis points, \( N_{\text{peri}} \), measured along their trajectories: orbits for which \( N_{\text{peri}} = 0 \) are likely infalling for the first time; \( N_{\text{peri}} \geq 1 \) represent more evolved orbits. As discussed below, many infalling haloes have been pre-processed, a result that has important implications for not only their internal structure, but also for the ensuing evolution of their orbital trajectories.

Our paper is organized as follows. We describe our Numerical methods in Section 2; our simulations are described in Section 2.1; our halo-finding techniques in Section 2.2; our merger trees and orbit tracking methods in Sections 2.3 and 2.4 respectively. In Section 3 we describe our main findings: Section 3.1 focuses on the spatial distribution of associated and first-infall haloes and subhaloes; the distribution and evolution of their apsis points are described in Sections 3.2 and 3.3 respectively. The importance of pre-processing and group infall relative to the accretion of “pristine” haloes is discussed in Section 3.4 and the corresponding impact on subsequent dynamics in Section 3.5. Finally, in Section 3.6 we comment on the importance of pre-processing and group-infall for the structural scaling relations of dark matter haloes and subhaloes in the vicinity of massive systems. We summarize our results in Section 4.
2 SIMULATIONS AND ANALYSIS

2.1 Simulations

Our results are based on a high-resolution, cosmological dark-matter only simulation carried out with a lean version of {	extsc{gadget-2}} \citep{Springel2005}. The simulation is part of the {	extsc{Genesis}} simulations suite of cosmological N-body runs (cf. \cite{Poulton2019}), and follows the evolution of $N_{\text{DM}} = 2048^3$ collisionless DM particles in a cubic box of comoving side-length $L = 105\, h^{-1}\text{Mpc}$. The softening length, fixed in comoving units, is $\epsilon = 1.7\, h^{-1}\text{kpc}$ (roughly $1/30^\text{th}$ of the Lagrangian mean inter-particle spacing); the particle mass is $m_p = 1.17 \times 10^7\, h^{-1}\text{M}_\odot$. Particle data are saved as snapshots at 190 discrete intervals between $z = 20$ and 0, equally spaced in the natural logarithm of the expansion factor, which allows us to robustly track the orbits and assembly histories of haloes and subhaloes.

Initial conditions were created at $z = 99$ by perturbing an initially uniform particle lattice using second-order Lagrangian perturbation theory \citep{Scoccimarro98, Crocce2006} in accord with the linear power spectrum determined by the {	extsc{Planck}} Collaboration \citep{Planck2016}. The cosmological density of baryons, matter and dark energy are $\Omega_\text{b} = \Omega_\Lambda = (0.0491, 0.3121, 0.6879)$; $H_0 = 67.5\, \text{km/s/Mpc}$ is the Hubble-Lemaître constant; $\sigma_8 = 0.815$ is the rms density fluctuation in 8 Mpc spheres; $n_s = 0.965$ is the spectral index of primordial power-law density perturbations.

2.2 Halo identification and selection

Haloes and their substructures are identified using {	extsc{velociraptor}} \citep{Elahi2019}, which operates in two stages. First, distinct haloes are identified using a friends-of-friends (FOF) algorithm (e.g. \cite{Davis1985}) employing a linking length of $b = 0.2$ times the mean inter-particle spacing. Substructure haloes are then excised from each FOF group by searching for dynamically-distinct particle subsets in six-dimensional phase-space (i.e. using a 6DOF algo- rithm) whose velocity distributions differ substantially from that of the locally-averaged background halo.

One distinguishing feature of {	extsc{velociraptor}} is its ability to identify dynamically cold “substructure” that have only slight density contrasts with respect to the smooth background halo. A down side – at least for our purposes – is its tendency to identify subhalos with strong tidal features that also satisfy two isolation criteria: one ensures that each host is the most massive system within eight times its virial radius, and the other that the host is not within eight virial radii of a more massive system. We hereafter refer to these as primary haloes. The most massive primary in our sample has a virial mass of $M_{200} = 3.36 \times 10^{14}\, h^{-1}\text{M}_\odot$ ($N_{200} \approx 2.9 \times 10^7$).

Following custom, we refer to substructure haloes that lie within one virial radius $r_{200}$ of any primary host as “primary” satellites or subhaloes, terms that we use interchangeably. Isolated haloes that lie beyond $r_{200}$ of primary hosts and have never been substructures of a more massive system are referred to as field or secondary haloes; their satellites are secondary subhaloes.

2.3 Merger trees

Halo and subhalo merger trees are constructed using {	extsc{treefrog}} (see \cite{Elahi2018, Elahi2019} for details), which is part of the {	extsc{velociraptor}} software package. Moving forward through the list of halo catalogues, {	extsc{treefrog}} links haloes identified in snapshot $S_i$ to their most probable descendant in snapshot $S_{i+1}$ by maximising a figure-of-merit, defined

$$\psi^2 = \frac{N_{S_i}^2 S_{i+1}^{S_i \cap S_{i+1}}}{N_{S_i}^2 N_{S_{i+1}}^S},$$

(1)

Here $N_{S_k}^S$ is the number of particles in progenitor $k$ in snapshot $S_i$, $N_{S_i}^S \cap S_{i+1}$ are the numbers of particles in each unique descendant $l$ in snapshot $S_{i+1}$, and $N_{S_i}^S \cap S_{i+1}^k$ are the number of particles they have in common.

Rarely, idiosyncratic cases – such as multiple mergers of approximately equal-mass systems – lead to several equally-probable descendants being identified. These issues are dealt with following \cite{Poole2017}, by weighting each descendant’s figure-of-merit by the rank-ordered binding energy of particles $S_k \cap S_{i+1}$, where the rank ordering is carried out for particles in both the progenitor and descendant. This procedure maximizes the fraction of highly bound mass between progenitor and descendant. Other common failures of the algorithm arise when subhaloes temporarily disappear from the halo catalogues, either during a close passage through the centre of a more massive system, or by dropping below the 20-particle detection limit. We mend such occurrences by searching for descendants across a series of five consecutive snapshots until a suitable descendant is found; if one

\footnote{Note that secondary subhaloes differ from “second-order” subhaloes defined by \cite{vdBosch2017} which, in their case, refer to nested sub-subhaloes.}
is not, we assume the halo to have merged or to be tidally disrupted (details of the algorithm can be found in Poulton et al. 2019).

2.4 Subhalo orbits and their classification

We study the dynamical and structural evolution of surviving (i.e. \( z = 0 \)) haloes and subhaloes that have at some point in the past crossed within \( 4 \times r_{200} \) of any of the primary host haloes that meet the selection criteria described in Section 2.2. Orbits are calculated directly from the merger trees using ORBWEAVER (Poulton et al. 2019), which identifies any apsis points along a halo or subhalo’s trajectory about their primary host, as well as other quantities of interest (e.g. orbital eccentricities, angular momenta, etc.).

The orbital histories of these (sub)haloes can be quite complex, and depend strongly on their interaction history with the primary halo, or on interactions with secondary haloes or subhaloes in the primary’s vicinity. Many previous studies differentiate satellite \((r_{\text{sub}} \leq r_{200})\) and field \((r_{\text{sub}} > r_{200})\) haloes based on their instantaneous radial positions, \(r_{\text{sub}}\), or track satellite orbits to identify the full population of subhaloes to ever cross the primary’s virial radius (the so-called “associated” subhaloes). Instead, we divide subhaloes and secondary haloes into distinct categories based on whether or not they have crossed orbital pericentre, without appealing to arbitrary crossing radii, like \( r_{\text{peri}} \).

Doing so results in two distinct groups, which we now define:

**Orbital haloes and subhaloes:** The full population of haloes and subhaloes that have crossed pericentre at least once on an orbit defined relative to the centre-of-mass motion of their primary. These include current satellites of the host halo (providing they have crossed pericentre), the entire population of “backsplash” haloes that were once within \( r_{200} \) but have since left, as well as a small fraction of haloes whose pericentres exceed the virial radius of their hosts. Orbital haloes and subhaloes are divided into three distinct subcategories:

(i) **Orbital subhaloes** are currently within \( r_{200} \) and have passed orbital pericentre at least once. Note that we do not restrict pericentres to radii \( r_{\text{peri}} < r_{200} \) and therefore a small fraction of orbital subhaloes, \( \approx 2 \) per cent, are infalling for the first time (their orbital pericentres occurred at \( r > r_{200} \), but their current separation is \( r_{\text{sub}} \leq r_{200} \)).

(ii) **Orbital haloes** have periapses that exceed \( r_{200} \) and have never crossed the virial radius of their host. At \( z = 0 \) they are typically receding from the primary, or on second approach. These systems are not infalling for the first time, but have never crossed the primary’s virial radius and were therefore never classified as subhaloes.

(iii) **Ex-satellites**, or “splashback” haloes, are seemingly isolated haloes that have crossed within the virial radius of their primary host at least once in the past, but have since left \( (r_{\text{sub}} \geq r_{200}) \) at \( z = 0 \).

**First-infall haloes and subhaloes:** Any halo or subhalo, regardless of its radial separation from the primary, that has not yet crossed periapsis on its orbit about the primary. These include all secondary haloes (and their subhaloes) at \( r \geq r_{200} \) that cannot be classified as ex-satellites or orbital subhaloes, as well as primary subhaloes \((r_{\text{sub}} \leq r_{200})\) on their first approach (i.e. \( N_{\text{peri}} = 0 \)). We define the following distinct categories of first-infall systems:

(iv) **Pristine haloes**, or secondary haloes, are systems that have never been identified as a satellite of a more-massive halo and have not crossed pericentre.

(v) **Secondary subhaloes** are the current substructures of pristine, secondary haloes.

(vi) **Secondary ex-satellites** were once secondary subhaloes, but have since veered beyond the virial boundary of their secondary host.

Note that secondary haloes (iv) and subhaloes (v) only exist beyond \( r_{200} \) of their primary halo; after crossing \( r_{200} \) we refer to them as first-infall satellites in order to distinguish them from orbital subhaloes (i). Secondary ex-satellites (vi) and subhaloes (v) form a population of “pre-processed” systems that have encountered dense environments beyond the virial boundary of the primary host. Of course, associated subhaloes (a term we will often use for the combined population of orbital subhaloes (i), ex-satellites (iii) and first-infall subhaloes) may have been pre-processed as well and we will draw explicit distinctions between the two samples when necessary.

Figure 4 plots the phase-space diagram of radial velocity versus distance for orbital and first-infall haloes and subhaloes relative to their primary hosts. Data are shown for primaries in the mass range \( 10^{13} \leq M_{\odot}/[h^{-1} M_{\odot}] \leq 10^{14} \), and use different colours to highlight several examples of the possible orbital histories outlined above. Red and dark blue points, for example, show \((r_{\text{sub}} \leq r_{200})\) subhaloes of primary hosts that are on first-infall or have crossed first pericentre within \( r_{200} \) of the primary, respectively. Light blue points correspond to primary ex-satellites, or backsplash subhaloes. First-infall haloes and subhaloes that have not yet crossed \( r_{200} \) of the primary are plotted as orange points. A minority \((\approx 5 \) per cent of all systems within \( 4 \times r_{200} \)) are orbital haloes, coloured green, the majority of which \((\approx 94 \) per cent) are beyond \( r_{200} \) at \( z = 0 \).

The lower panel shows the fraction of haloes/subhaloes of each type as a function of distance from the primary. Not surprisingly, orbital subhaloes dominate at radii \( r_{\text{sub}} \leq r_{200} \), making up roughly 78 per cent of classically-defined “substructures” (i.e. of all subhaloes with \( r_{\text{sub}} \leq r_{200} \)). First-infall subhaloes are nevertheless quite common, accounting for \( \approx 24 \) per cent of satellites systems at \( r_{\text{sub}} \approx r_{200} \), and of order 11 per cent in the halo inner regions \((r_{\text{sub}} \lesssim 0.1 \times r_{200})\) where a central galaxy is expected to dominate; approximately 22 per cent of all subhaloes at \( r_{200} \) are on first infall. As previously noted (Gill et al. 2004 Ludlow et al. 2009), the population of backsplash haloes extends well beyond \( r_{200} \) of the primary: roughly half populate regions that exceed \( 1.5 \times r_{200} \), and as many as \( \approx 2 \) per cent exceed \( 3 \times r_{200} \).

Another important point to note is that ex-satellites and orbital (sub)haloes tend to have a slight positive radial velocity bias relative to their host, at least for the host mass range studied here. The mean radial velocity of all (primary) ex-satellites, for example, is \( \approx 0.28 \times V_{200} \), which increases to \( \approx 0.35 \times V_{200} \) for those at radii \( r \gtrsim 2 \times r_{200} \). This suggests that many of these systems are still approaching first their apocentre (after turnaround), and do not have “backsplash”
3 RESULTS

3.1 Spatial distribution of associated subhaloes and secondary haloes

The number density profiles of orbital (blue curves) and first-infall haloes and subhaloes (red) are plotted in Figure 2 for three different bins of primary halo mass (the full populations are shown using black lines). The median spherically-averaged density profiles of dark matter (normalized arbitrarily for comparison) are shown using grey lines. As hinted at in previous work (e.g. Diemand et al. 2004; Reed et al. 2005; Gao et al. 2004; Han et al. 2016), the spatial distributions of the orbital haloes deviates significantly from the dark matter, but can be approximated by an Einasto profile (Einasto 1965; thick green line). This density profile is given by

\[
n(r) = \frac{2}{\alpha} \exp \left( \frac{r}{r_2} - 1 \right),
\]

where \(n_2\) and \(r_2\) are characteristic values of density and radius where the logarithmic slope, \(d \ln n / d \ln r\), is equal to \(-2\). The third parameter, \(\alpha\), controls the shape of the profile: \(\alpha \approx 0.18\) yields one similar to the typical structure of dark matter haloes over the radial range resolved by cosmological simulations (e.g. Navarro et al. 2010); larger and smaller values correspond to profiles that are more or less curved than that of the dark matter, respectively.

Regardless of the mass of the primary, the spatial distribution of orbital haloes is well-approximated by eq. (2) with \(\alpha \approx 1.2\) (shown as a thick green line in Figure 2), suggesting that they are significantly less concentrated than the dark matter. Nevertheless, their number density profiles do not show evidence of converging to a constant density core, but rather continue to rise all the way to the centre. The spatial bias between satellites and DM is a well-known result but is worth re-emphasizing, particularly since many semi-analytic galaxy formation models assume that the “orphan” galaxies – the past residents of now disrupted satellites – trace the distribution of dark matter (e.g. Lagos et al. 2018). This seems unlikely given the results shown in Figure 2.

3.2 Distribution of subhalo accretion times and apsis points

In Figure 3 we plot the relative fraction of the number of apsis crossings for orbital haloes (green), orbital subhaloes (blue) and ex-satellites (red), showing separately pericentres (left) and apocentres (right; note that only apocentres occurring after the initial turnaround radius are included). Shaded bars show results after combining all primary halos, but there is little variation across the mass range covered by our sample. Solid and dotted open bars, for example, correspond to the lowest and highest host mass bins used in Figure 2.

As anticipated in Figure 1, a large fraction of ex-satellites, of order 63 per cent, are still approaching their first orbital apocentre, and the vast majority, \(\approx 86\) per cent, have crossed pericentre only once. Only \(\approx 5\) per cent have completed two or more apocentres. These numbers are even higher for orbital haloes: 76 per cent are still approaching first apocentre and \(\gtrsim 95\) per cent have only one measured periapsis. This suggests that ex-satellites and orbital haloes are either relatively recent arrivals, or occupy long-period orbits about their primary halos. Intriguingly, many orbital subhalo\es must have also been accreted relatively recently: at \(z = 0\) as many as 30 per cent have yet to reach first apocentre, and about half have crossed pericentre only once. Less than \(\approx 21\) per cent of orbital subhaloes have crossed peri-centre three or more times; less than \(\approx 13\) per cent have three or more measured apocentres. A significant fraction of orbital haloes, subhaloes and ex-satellites are therefore unlikely to be well-mixed with the potential of their primary host haloes.

We explore this further in Figure 4, where we plot the distribution of subhalo accretion times for two separate bins of host mass. As expected, essentially all first-infall subhaloes (red line) were accreted recently. The dis-
distribution peaks at $z = 0$, and is largely confined to infall times that do not exceed a half-crossing time $t_{\text{cross}}$, defined $t_{\text{cross}}/2 = r_{200}/V_{200}$ (shown as the right-most vertical grey line in Figure 1). Interestingly, orbital subhaloes (dark blue lines) have a strongly bimodal accretion time distribution: one peak clearly confined to infall times spanning $t_{\text{cross}}/2 \leq t_{\text{acc}} \leq t_{\text{cross}}$ (these are primarily subhaloes with $N_{\text{apo}} = 0$) and another peaking at $t_{\text{acc}} \approx 3.5 \times t_{\text{cross}}$; the minimum between the two is reached at roughly $t_{\text{acc}} \approx 1.5 \times t_{\text{cross}}$. Not surprisingly, the minimum in the accretion time distribution of orbital subhaloes coincides with a maximum for ex-satellites (light blue lines), since accreted material will typically require at least $t_{\text{cross}} \approx 1.8$ Gyr to exit the virial boundary of a halo once accreted. Indeed, the vast majority of ex-satellites were accreted by their hosts at lookback times exceeding this timescale (second vertical grey line from the right).

For comparison, we also plot the distribution of infall times for “merged” satellites, i.e. those that have merged with their host, were tidally disrupted or fell below the 50-particle limit. The majority of these systems were accreted well before those that survive to the present day. For example, the peak accretion rate of merged subhalos occurred around $z \approx 2.3$. Averaged over all hosts, we find that 95 per cent of subhalos that survive to $z = 0$ were accreted since $z \approx 1.37$, whereas 95 per cent of those that do not, have accretion redshifts $z_{\text{acc}} \gtrsim 1.95$.

Overall, these results suggest that robustly measuring the distribution of orbital apocentres directly from the orbital tracks of accreted subhaloes may be challenging, since many have not yet had one. We demonstrate this in Figure C where we compare the current radial distribution of all associated subhaloes (black curves) to the distribution of their last measured apocentres ($r_{\text{apo}}$; green lines). As noted above, only $\approx 46$ per cent of associated subhaloes have at least one measured apocentre, and the majority of those that do not are either orbital haloes or ex-satellites that currently reside at radii $r \gtrsim r_{200}$. This is why the radial distribution of associated subhaloes is broader than the distribution of their last-measured apocentres: haloes at very small radii are unlikely near apocentre, and so $r_{\text{apo}} \gtrsim r_{\text{apo}}$, whereas many of those at large radii have not yet reached apocentre, and are not included in the plot. As we discuss below, this may have important implications for measuring the so-called “backsplash” radius of primary haloes by appealing to measurements of the apocentres of recently accreted material. This is an important caveat to consider, particularly if backsplash radii are to be used as observational probes of cosmology (e.g. Adhikari et al. 2018).

Nevertheless, it is possible to improve matters by estimating the orbital apocentres for associated subhaloes when one cannot be directly measured. Knowing the spherically-averaged potential of the host halo, $r_{\text{apo}}$ (occurring at $z \leq 0$ in these cases) can be estimated directly from the subhalo’s orbital kinetic energy and angular momentum (see eq. 3.14 of Binney & Tremaine 2008). Adding these predicted apocentres to the last-measured ones yields an apocentre distribution (blue lines) that peaks at $\approx 1.6 \times r_{200}$ (downward arrow), which coincides with the value for periodic orbits anticipated by the self-similar infall model of Bertschinger (1985). This is roughly 23 per cent larger than the peak of last-measured apocentres, occurring at $\approx 1.3 \times r_{200}$. Note also the extended tail of $r_{\text{apo}}$; depending on primary mass, between roughly 10 to 13 per cent of associated subhaloes have $r_{\text{apo}} \gtrsim 3 \times r_{200}$, with between 1 to 4 per cent exceeding $5 \times r_{200}$. As discussed by Ludlow et al. (2009), many of these halos ($\approx 37$ per cent in their study) occupy orbits that carry them beyond their initial turnaround radius, a scenario difficult to reconcile with simple analytic infall models.

We characterize the mass-dependence of the spatial distribution and apocentres of associated subhaloes quantitatively in Figure C. From left to right, different panels correspond to the ($z = 0$) radii enclosing 50, 75 and 95 per cent of all associated subhaloes (dashed purple lines), and their apocentres (solid orange line). For comparison,

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2 A half-crossing time is roughly the time required for recently accreted material to reach orbital pericentre.

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3 We have verified the robustness of this procedure by comparing the last-measured apocentre to the predicted one for a sample of associated subhaloes with $N_{\text{apo}} \geq 1$; the errors on the predicted $r_{\text{apo}}$ are typically random, and $\lesssim 10$ per cent.
the solid black lines indicate $r_{200}$ and thick solid grey lines $r_{\text{edge}} = 1.96 \times r_{200,\text{mean}}$, determined by [Aung et al. (2020)] to enclose roughly 99 per cent of associated subhaloes (note that these authors used the radial velocity distributions of haloes and subhaloes to distinguish infalling from accreted systems rather than explicitly tracking the orbits of individual objects). Thick dot-dashed grey lines enclose the equivalent fraction of splashback radii for DM particles (defined as the first apocentre after infall) determined from the fitting formulae of [Diemer et al. (2017)].

Each of these measures of the spatial distribution of associated subhaloes differ in the details, but all paint a consistent picture: the spatial distribution extends far beyond $r_{200}$, and many associated subhaloes occupy orbits with unexpectedly large apocentres. For example, we find that only about half have apocentres that confine them to within $1.6 \times r_{200}$, and roughly 5 per cent have apocentres that exceed $3.4 \times r_{200}$. The radius enclosing a fraction $f_{\text{apo}}$ of all associated apocentres can be accurately described by the following fitting formula:

$$\log r(\text{apo}) = \log r_{200} \times (a \log f_{\text{apo}} + (1 - f_{\text{apo}})^b - c),$$  \hspace{1cm} (3)$$

where $a = 0.321$, $b = -0.089$ and $c = 0.767$. Equation 3 is shown as a dotted green line in each panel of Figure 6 and is valid for $0.05 \lesssim f_{\text{apo}} \lesssim 0.98$, and for host masses between $10^{12} M_\odot$ and $10^{14} M_\odot$.

Such extreme apocentres are not reached on their own, but require a considerable injection of orbital energy, likely through 3-body encounters with other associated subhaloes, or as a result of a group accretion event. We will return to this discussion in Section 3.5, but first turn our attention to the evolution of successive orbital apocentres.

### 3.3 The evolution of orbital apocentres

Figure 7 plots the ratio of successive apocentres, $r_{\text{apo},i+1}/r_{\text{apo},i}$, versus the subhalo-to-primary mass ratio at the initial one, $i$. Dots correspond to individual (associated) subhaloes; different lines mark the median relations for the entire sample of primaries (solid line), and for the highest (dotted; $\gtrsim 5 \times 10^{13} h^{-1} M_\odot$) and lowest mass ones (dashed; $\lesssim (1 - 3) \times 10^{12} h^{-1} M_\odot$). The shaded regions show the 25th and 75th percentile scatter for the entire sample. Different panels correspond to more or less evolved orbits: the ratio of first apocentre to turnaround radius is shown in the top left panel, for example, and fourth-to-third apocentre ratio in the bottom-right. Dotted horizontal lines correspond to successive equal-amplitude apocentres. Subhaloes lying above or below these lines must have either gained or lost orbital energy, respectively.

A few results are worth emphasizing. First, note that the majority of orbital energy loss occurs after first pericentric passage, i.e. between turn around and first orbital apocentre (top-left panel). On average, the ratio of first apocentre to the turnaround radius is $\approx 0.8$. Subsequent apocentres, at least for low mass subhaloes, tend to have comparable amplitudes, on average. This is indeed the trend expected from self-similar infall models, in which accreted material gradually loses energy, eventually reaching a stable orbit whose successive apocentres have equal amplitude. The arrows in each panel of Figure 7, for example, show the ratios antic-
The effect, however, is mass dependent: subhaloes with masses exceeding \( \gtrsim 0.01 \times M_{200} \), for example, tend to experience an increased drain of orbital energy due to the increasing importance of dynamical friction; lower mass subhaloes behave as test particles in the potential of the host, and the mass-dependence of apocentre ratios weakens substantially. This effect ultimately leads to a spatial segregation of subhaloes according to their mass at infall, with more massive systems congregating toward the centres of halos (see, e.g. Nagai & Kravtsov 2005; Ludlow et al. 2009).

Note also the considerable scatter along the ordinate axes of Figure 7 (the rms variance, \( \sigma_{\text{apo}} \), is quoted in each panel). Indeed, as many as 11 (5.3) per cent of associated subhaloes have first apocentres that exceed their turnaround radius by as much as 25 (50) per cent, indicating a significant gain in orbital energy after infall. Subhaloes may also lose energy after infall, and not always gradually, as would be expected from, e.g., dynamical friction or self-similar infall models. Roughly 42 (13) per cent have first apocentres that, by \( z = 0 \), have either merged with their host halos, were tidally disrupted, or fell below our 50-particle limit. The black dashed lines correspond to the entire subhalo population. Thin vertical lines mark integer multiples of half-crossing times, defined as \( t_{\text{cross}} = r_{200}/V_{200} \).

Figure 4. Distribution of subhalo accretion times for hosts in two separate mass bins (upper and lower panels). The red lines correspond to first-infall subhalos (i.e. \( N_{\text{peri}} = 0 \) and \( r_{\text{sub}} \leq r_{200} \)); dark blue lines to orbital subhalos (\( N_{\text{peri}} \gtrsim 1 \) and \( r_{\text{sub}} \leq r_{200} \)); light blue lines to ex-satellites (i.e. back splash halos; \( N_{\text{peri}} > 1 \) and \( r_{\text{sub}} > r_{200} \)). Dot-dashed grey lines show the distribution of accretion times for subhalos that, by \( z = 0 \), have either merged with their host halos, were tidally disrupted, or fell below our 50-particle limit. The black dashed lines correspond to the entire subhalo population. Thin vertical lines mark integer multiples of half-crossing times, defined as \( t_{\text{cross}} = r_{200}/V_{200} \).

Figure 5. Distribution of associated subhalo radii, \( r_{\text{sub}}(z = 0) \) (black curves), their last-measured orbital apocentric distance, \( r_{\text{apo}}^{\text{last}} \) (green lines), and the combined distribution of \( r_{\text{apo}}^{\text{last}} \) and \( r_{\text{apo}}^{\text{pred}} \) (blue lines), where the latter are the predicted apocentres for systems that have not yet had one (the predictions are based on the radial energy equation; see text for details). Results are shown for the same three mass bins used in previous figures: \( (1 - 3) \times 10^{12} \ M_\odot \) (solid), \( (1 - 3) \times 10^{13} \ M_\odot \) (dot-dashed) and \( \gtrsim 5 \times 10^{13} \ M_\odot \) (dotted). Note that the distribution of last-measured apocentres is a poor indicator of the true distribution of apocentres; this is primarily a result of the large fraction of associated subhaloes, around 54 per cent, that are (at \( z = 0 \)) still approaching their first apocentre after turnaround.

Figure 7 shows a classic example of an “ejected” subhalo. Such extreme orbits are generated when accreted groups are tidally-dissolved by the main halo near their orbital pericentre, redistributing their orbital energy and often propelling low-mass members onto highly eccentric orbits. The remaining thin yellow lines show the orbits of other group members, which exhibit a broad range of first apocentres, from \( r_{\text{apo}} \approx 0.6 \times r_{\text{ta}} \) to \( r_{\text{apo}} \approx 2.6 \times r_{\text{ta}} \). At least two members of this group are placed on orbits so extreme that they are effectively removed from the system as a whole.

Of course, the opposite is also possible and energy can be abruptly lost during the tidal disruption of groups, and one such example is evident in the upper-left panel of Figure 4.
Another, more extreme case is shown in the lower-left panel (green square in Figure 7). This subhalo is also a member of an accreted group (symbols along the orbital trajectories mark snapshots where each infalling halo was identified as a secondary satellite of a more massive secondary halo), whose tidal disruption led to a rapid reduction in orbital energy; indeed, its first apocentre after infall is only of order 0.3\(r_{\text{e}}\), and remains comparable thereafter.

While the types of interactions leading to abrupt changes in subhalo orbits are most common among members of infalling groups, the high number densities of subhaloes within \(r_{200}\) means that penetrating encounters\(^6\) between them, which may also perturb their orbits, should be relatively common (see e.g. Tormen et al. 1998; van den Bosch 2017). This, in principle, allows for less likely scenarios, such as the one plotted in upper-right panel of Figure 8. Here, the accreted halo loses orbital energy on first pericentre (\(r_{\text{apo},1}/r_{\text{e}} \approx 0.7\)) but regains even more on the second and is pushed to a third apocentre that exceeds its original turnaround radius (\(r_{\text{apo},2}/r_{\text{e}} \approx 1.2\)). Interestingly, this subhalo experienced a penetrating encounter with another close to its second orbital pericentre (triangles along the orbital trajectory indicate when this encounter occurred), leading to a 3-body encounter (the primary is the third body) favourable to the exchange of orbital energy and angular momentum.

It is also worth mentioning that instances of group accretion and penetrating encounters are not the only means of provoking unorthodox orbits such as these. In fact, any rapid change in the gravitational potential of the host – which may be brought about by a merger, or any other large-scale fluctuation in the gravitational potential – can also lead to unexpected changes in the orbits of subhaloes as violent relaxation drives the system towards a new equilibrium.

While such unorthodox orbits are not difficult to identify, they are aberrant. Indeed, many accreted subhaloes follow well-defined orbits that are not too dissimilar from those anticipated by simple spherical infall models. The purple curve in the lower-right panel (purple stars in Figure 8) shows a typical example of how subhalo orbits evolve. We will see below that the outliers in the distributions of apocentre ratios are mainly associated with systems that have been “pre-processed” by groups prior to infalling onto the primary halo.

### 3.4 Pre-processing and the importance of group accretion

A number of previous studies have identified pre-processing as an important regulator of galaxy evolution in dense environments. It may therefore have a significant impact on the evolution of the orbital trajectories of many satellite systems. As discussed in the Introduction, pre-processing is naturally expected in the ΛCDM cosmology – or in any hierarchical model – due to the bottom-up assembly of dark matter haloes. This motivates robustly quantifying the effect.

There are at least three ways in which a dark matter halo (or galaxy) may be pre-processed before being accreted by a primary halo. It may be an ex-satellite (or backsplash halo) of the primary itself, and is again infalling. Having been previously accreted, these seemingly isolated systems have already passed through the much denser environment...
Figure 7. Ratio of successive apocentres, $r_{apo,i+1}/r_{apo,i}$, for orbital haloes, orbital subhaloes, ex-satellites, and first-infall subhaloes (i.e. associated subhaloes) plotted as a function of subhalo mass (expressed in units of the mass of the primary at apocentre $i$). From top-to-bottom, left-to-right panels correspond to the ratio of the first apocentre to the turnaround radius, $r_{ta}$, then to the ratios of second-to-first, third-to-second, and fourth-to-third apocentres. In all panels, the mass of the subhalo and primary are measured at the first relevant apocentre (e.g. at the turnaround radius for those plotted in the upper-left panel). Note that only a small fraction, $\lesssim 1$ per cent, of all accreted haloes have $>4$ measurable apocentres and have been left out of the plot for clarity. Individual (sub)haloes are shown using grey points, regardless of the mass of the primary; the thick black line and grey shaded region highlight the corresponding median and 25/75 percentile scatter. Medians for two separate primary mass bins, $(1-3) \times 10^{12} M_\odot$ (dot-dashed lines) and $\geq 5 \times 10^{13} M_\odot$ (dotted lines), are also shown. The distributions are shown to the right ($\sigma_{apo}$ in each side panel indicates the linear variance): the black arrows mark the values of $r_{apo,i+1}/r_{apo,i}$ anticipated by Bertschinger’s (1985) spherically-symmetric self-similar infall model. Note that orbital energy loss is most pronounced between turnaround and first apocentre after accretion, and exhibits a relatively strong mass dependence for $M_{sub}/M_{200} \approx 0.01$. Outsized coloured points mark specific subhaloes whose trajectories are plotted in Figure 8.

As discussed above, roughly 59 per cent of associated subhaloes are currently beyond the virial radius of their host despite being bound to it. This adds a level of ambiguity to what is meant by “group accretion” as any infalling halo may also have its own population of secondary subhaloes and ex-satellites. Because of this ambiguity, we define the satellites of accreted groups in two ways: First, as the full population of (sub)haloes that were at any point prior to accretion by the primary identified as a secondary subhalo of a more massive infalling system (these systems have been “pre-processed” by secondary haloes but are not necessarily secondary subhaloes at the present time). And second, as the population of infalling systems that were identified as secondary subhaloes within a narrow radial window – which we initially take to be $(1 - 1.2) \times r_{200}$ – prior to their accretion by the host. The latter definition of group accretion is stricter, and demands that members of accreted groups be secondary subhalos near the point of infall.

Figure 9 summarises the relative fraction (thick lines) of pre-processed haloes and subhaloes as a function of distance from their primary, showing separately those on first-infall (i.e. $N_{peri} = 0$, left) and the combination of orbital subhaloes and ex-satellites ($N_{peri} \geq 1$, right). As in several previous figures, results are shown for three separate primary mass bins, with mass increasing from top to bottom.

A large fraction of first-infall subhaloes ($r_{sub} \leq r_{200}$, left panels) were satellites of more massive systems prior to their accretion by the primary – typically 40 to 55 per cent, depending on the primary’s mass. Of these pre-processed haloes, roughly 31 to 38 per cent (depending on primary mass) were satellites at the time of accretion (i.e. were identified as secondary subhaloes at their point of entry into the primary; light shaded bars for $r \leq r_{200}$); $\approx 29$ to 32 per cent are current secondary subhaloes of infalling haloes (dark shaded bars for $r > r_{200}$).

The right-hand panels of Figure 9 show the fraction of all orbital subhaloes and ex-satellites at a given radial sepa-
Subhalo orbital trajectories

Figure 8. Example orbital trajectories for the individual haloes and subhaloes highlighted in Figure 7. Identifying symbols, shown in the upper-right corner of each panel, are chosen to match those used in Figure 7. The upper-left panel shows an example of an extreme orbit. This particular subhalo was accreted as part of a group (thin yellow lines correspond to orbits of other group members identified at the time of accretion) and was propelled onto a highly unorthodox orbit during the group’s tidal dissociation at first pericentric passage. The dissociation of accreted groups not only ejects subhaloes along highly eccentric orbits, but can also lead to a rapid loss of orbital energy and angular momentum, resulting in some subhaloes becoming trapped on highly bound orbits, an example of which is shown in the lower-left panel (note that snapshots in which these infalling haloes were identified as secondary subhaloes – i.e. subhaloes of an infalling secondary halo – are marked using symbols). Penetrating encounters between subhaloes, particularly near orbital pericentre, can also lead to energy exchange (upper-right panel). For comparison, we plot a “typical” orbital trajectory in the lower-right panel. The virial radius $r_{200}(z)$ of the primary halo is shown using a black line in all panels.

ration that were pre-processed by a secondary halo prior to first infall (thick lines), or were accreted as part of a group (shaded regions). Pre-processing and group accretion are approximately equally important for systems already accreted (right panels), and for those currently infalling for the first time (left panels). These results depend only weakly on the mass of the primary, and on present-day radial separation.

In the upper panel of Figure 10 we plot the fraction of (sub)haloes of various orbital types as a function of their mass at accretion time, normalized by the present-day mass of their host halo. We use different line styles for different primary mass bins, as in previous figures. Note the strong mass-dependence of the orbital subhalo and ex-satellite fractions, a result already hinted at in Figure 7. The mass dependence arises because the most massive accreted subhaloes ($M_{\text{acc}} \gtrsim 0.01 \times M_{200}$) tend to rapidly lose orbital energy due to dynamical friction after infall, and often remain orbital subhaloes until the present day.

As discussed in Ludlow et al. (2009), and as evident in Figure 10, low-mass members of accreted groups tend to be the ones “ejected” to higher energy orbits. This is because low-mass systems are more likely to be loosely bound to the group, and therefore to occupy large-amplitude orbits that are able to capture orbital energy when in phase with the orbit of the group within the primary. As a result, ex-satellites tend to dominate the population of associated subhaloes below a characteristic mass that depends on the mass of the host.

Low-mass haloes are also more likely to be pre-processed than massive ones, as shown in the lower panel of Figure 10. For example, roughly half of all present-day satellites whose accretion mass is of order $M_{\text{acc}} \approx 10^{-3} M_{200}$ were previously satellites of another (secondary) halo; as many as 60 per cent were for $M_{\text{acc}} \approx 10^{-4} M_{200}$. Even the most massive of accreted systems are not entirely immune to the effects of pre-processing; for example, roughly 15 per cent of those with $M_{\text{acc}}/M_{200} \approx 0.1$ had been satellites of other haloes prior to infall, and of order 5 per cent were satellites at the time of accretion.

3.5 Impact of pre-processing and subhalo-subhalo encounters on the evolution of orbital trajectories

We showed above (Figure 7) that successive apocentres of associated subhaloes evolve roughly as expected from simple spherical infall models, albeit with considerable variation among individual systems. The orbital trajectories of a few
carefully-selected subhaloes, show in Figure 8 suggest that the accretion of dynamically-associated groups of haloes, or close encounters between subhaloes on subsequent orbits, can lead to an exchange of orbital energy resulting in rather abrupt changes to their orbital apocentres. Do these particular examples encompass the majority of scenarios that may lead to deviant evolution of orbital apocentres? We explore this possibility in Figure 11.

Consider first the upper-left panel, where we plot the relative fraction of associated subhaloes in bins of \( r_{\text{apo,1}}/r_{\text{ta}} \) that were either a) pre-processed prior to accretion (grey line), b) accreted as part of a group of haloes (coloured lines), or c) as “pristine” secondary haloes that were never identified as substructures of any other halo (solid black line). The differences are striking. For pristine haloes the ratio of first apocentre to turnaround radius peaks at around \( r_{\text{apo,1}}/r_{\text{ta}} \approx 0.81 \), comparable to analytic expectations. Very few of the outlier subhaloes can be accounted for. Instead, the outliers are primarily pre-processed haloes, i.e. haloes and subhaloes that are (or were) satellites of more massive systems prior to being accreted by their host. Indeed, pre-processed haloes account for more than two-thirds of systems with \( r_{\text{apo,1}}/r_{\text{ta}} \gtrsim 3 \), and more than 80 per cent of those with \( r_{\text{apo,1}}/r_{\text{ta}} \lesssim 0.25 \).

Many of these pre-processed halos are members of loosely-bound groups that are tidally disrupted near first pericentre, giving rise to the unorthodox orbits seen in Figure 8 (this includes systems that both gain and lose orbital energy). This effect is portrayed more clearly by the coloured lines, which correspond to sub-samples of associated subhalos that were pre-processed (i.e. identified as secondary subhaloes) within increasing radial apertures from the host’s centre prior to infall. The blue curve, for example, corresponds to systems that were formally accreted in a group (according to the definition of group accretion in section 3.4, i.e. were pre-processed within a spherical aperture between \( 1 \) and \( 2 \times r_{200} \) prior to infall); these systems account for the majority of the most extreme cases (both large and small). Orange and green curves, respectively, correspond to systems that were pre-processed within \( 1.5 \) and \( 2 \times r_{200} \) when on first approach. Increasing the aperture within which dynamically-associated infalling groups are identified clearly accounts for an increasing number of unexpectedly large and small first apocentres.

But what about subsequent orbits? The fact that accreted groups are likely disrupted on first pericentric passage suggests that whether a halo was pre-processed or not is unlikely to determine whether energy is lost or gained thereafter. This expectation is borne out by our simulations. The dashed grey lines in the remaining three panels, for example, show the ratio of subsequent apocentres (first-to-second to third-to-fourth) for systems that were pre-processed prior to first infall. In all cases this distribution remains approximately flat; evidently, pre-processing greatly affects the extrema of first apocentres, but not subsequent ones.

As discussed in Section 3.3 (see also Tormen et al. 1998), penetrating encounters between subhaloes (i.e. between two or more satellites with \( r_{\text{sub}} \lesssim r_{200} \)) are common, typically affecting 60 per cent of all associated subhaloes at some point along their orbital paths. The majority of these encounters occur near pericentre – i.e. as close to the potential minimum of the host halo as their orbit allows – where subhalo number densities are highest, and therefore may constitute \( \geq 3 \)-body interactions. Such 3-body interactions allow for a rapid redistribution of orbital energy between the interacting bodies and, as with infalling groups of haloes, can readily perturb orbits to higher or lower energies.

The remaining panels in Figure 11 show that penetrating encounters indeed affect the evolution of subsequent orbital apocentres. Each panel plots the relative fraction of haloes, in bins of \( r_{\text{apo,i+1}}/r_{\text{apo,i}} \) that either experienced a penetrating encounter along that particular segment of their orbit (grey lines) or did not (black lines). In all cases, the extrema tend to be associated with those subhaloes that have experienced a penetrating encounter between \( r_{\text{apo,i}} \) and \( r_{\text{apo,i+1}} \); those that have not tend to follow more closely the evolution expected from simple spherical infall models (the arrows in each panel mark the expectations from Bertschinger’s model).
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3.6 The structure of first-infall and associated haloes and subhaloes

It is well-established that the structure of dark matter haloes — quantified by the concentration parameter — is largely determined by their collapse time (e.g. Bullock et al. 2001, Neto et al. 2007, Ludlow et al. 2013, 2014, Correa et al. 2015), as well as on their interaction history with nearby haloes (Li et al. 2013, Wang et al. 2020). Due to their non-linear nature, correlations between the structure of haloes and their varied assembly histories are difficult to disentangle, but give rise to important secondary phenomena. One, known as assembly bias, quantifies the clustering strength of haloes of a given mass as a function of their concentration or formation time (e.g. Gao et al. 2005): older haloes cluster more strongly than younger ones, highly concentrated haloes more than less concentrated ones. A variety of interpretations have been put forth for the origin of the age-dependence of halo clustering, although it appears that no single process can explain it entirely (see, e.g., Mansfield & Kravtsov 2020, for a recent discussion). For example, backsplash haloes have undergone tidal stripping by their hosts and appear older than field haloes of similar mass; they are also, by selection, more clustered than field haloes due to their proximity to more massive hosts. Nevertheless, the assembly bias remains even after backsplash haloes have been accounted for (Wang et al. 2009b), suggesting that other dynamical processes are at work. Possibilities include the suppression of halo growth in dense environments due to tidal forces from large-scale structure (e.g. Hahn et al. 2009, Hearin et al. 2016), or large-scale tidal anisotropies (Paranjape et al. 2018).

In Figure 12 we quantify how the orbital histories of haloes and subhaloes affect their concentrations — a use-
ful proxy for formation time – which we characterize using the magnitude and location of the maximum circular velocity, $V_{\text{max}}$ and $R_{\text{max}}$ respectively. This is a robust proxy for concentration for a couple of reasons: first, it can be estimated non-parametrically, and is therefore free from subtle biases that may be introduced when fitting to some suitably-smooth profile, such as NFW; second, while tidal stripping may substantially reduce the DM mass of a halo, its impact on $V_{\text{max}}$ and $R_{\text{max}}$ is much less dramatic (e.g. Gao et al. 2012).

The different panels of Figure 12 compare the $V_{\text{max}}$ – $R_{\text{max}}$ relations for the various samples of (sub)haloes used in previous figures to that of the entire population of field haloes in the simulation (shown as a solid black line and repeated in all panels for comparison). Not surprisingly, the full population of (sub)haloes that lie within 2 virial radii of their hosts (dotted purple line, upper-left panel) are, on average, more concentrated than field halos, typically by about $\approx15$ per cent (recall that roughly half of these are “associated” subhaloes and half are on first infall).

The upper-right and lower-left panels distinguish orbital haloes and subhaloes from those on first infall, respectively, and in each case the two samples have been subdivided into those inside and outside of $r_{200}$. Orbital subhaloes and ex-satellites (solid and dashed blue lines in the upper-right panel) typically have concentrations that are of order 22 per cent higher than field halos, except possibly for the highest $V_{\text{max}}$. Interestingly, infalling (sub)haloes have similar concentrations to field haloes – smaller by only a few per cent – regardless of their radial separation from the host (the dashed orange line, for example, corresponds to subhaloes that are on first infall, whereas the solid red line corresponds to infalling haloes at $r > r_{200}$).

The lower-right panel divides infalling haloes further, into a pristine sample comprised of haloes that have never been satellites of more massive systems (solid orange line), and a pre-processed sample that have (dashed green line; these are secondary ex-satellites). Pristine infalling haloes have concentrations that are indistinguishable from those of field haloes, even when the former are restricted to radial separations $r \leq 2 \times r_{200}$: pre-processed haloes are, on average, $\approx10$ per cent more concentrated. These results agree with the conclusions of Li et al. (2013), who claim that tidal interactions between ex-satellites and their former hosts are primarily responsible for modifying the concentrations of haloes in the environs of more massive systems.

4 SUMMARY

We used high-resolution, cosmological dark matter-only simulations to classify the orbital histories of haloes and subhaloes surrounding isolated hosts. Our analysis targets hosts that span the mass range $10^{12} \leq M_{200}/[h^{-1}M_\odot] \leq 3.4 \times 10^{14}$ ($8.6 \times 10^{4} \leq N_{200} \leq 2.9 \times 10^{7}$; 2309 in total). As in previous work, we characterized the full population of haloes that ever crossed the virial radius of their host (so-called “associated” subhaloes) but considered, in addition, the remaining population that lie within four virial radii of the host’s centre-of-potential. We carefully tracked the orbital trajectories for each of these haloes and subhaloes, tallying all apsis points in order to identify an unambiguous sample of “first-infall” haloes and subhaloes – i.e. those that have not yet crossed pericentre on their orbit about the host – as well as “orbital” haloes and subhaloes – i.e. those that have completed at least one pericentric passage. By doing so, we were able to easily distinguish both haloes and subhaloes that are infalling for the first time from those that occupy more evolved orbits. Orbital systems are either “typical” substructure (i.e. have $r_{\text{sub}} \leq r_{200}$ at $z = 0$), ex-satellites (often referred to as backsplash haloes; $r_{\text{sub}} > r_{200}$ at $z = 0$ but $r_{\text{sub}} < r_{200}$ in the past), or, less often, haloes whose pericentres occur outside their host’s virial radius (referred to as “orbital” haloes). The variety of possible orbital trajectories considered in this paper are defined in Section 2.3 their distribution in radial velocity-distance phase-space is shown in Figure 1.

In agreement with previous work (e.g. Diemand et al. 2004 Reed et al. 2005 Gao et al. 2004 Han et al. 2016), associated subhaloes are substantially less concentrated towards the halo centre than the dark matter. The radial number density of accreted subhaloes, for example, can be well approximated by an Einasto profile with shape parameter $\alpha \approx 1.2$, also implying a substantially shallower “cusp” than the traditional NFW profile. However, the number density of subhaloes does not approach a constant-density core, but rather increases (slowly) all the way to the halo centre (Figure 2). We find that half of all associated subhaloes are located within $\approx 1.24 \times r_{200}$ from the centre of their hosts, and 95 per cent are located within $2.6 \times r_{200}$; associated systems make up 77 and 63 percent of all (sub)haloes within these radii, respectively.

We find that a large fraction of classically-defined (surviving) substructures (i.e. those with $r_{\text{sub}} \leq r_{200}$) were accreted very recently: roughly 15 per cent in the past half-crossing time, $t_{\text{cross}}/2 = r_{200}/V_{200} = 1.72$ Gyr (90 per cent of which are first-infall subhaloes), and 21 per cent in the interval $t_{\text{cross}}/2 \leq t_{\text{acc}} \leq t_{\text{cross}}$ (primarily orbital subhaloes still approaching their first apocentre). Ex-satellites (or backsplash haloes) were primarily accreted at lookback times exceeding $t_{\text{cross}}$, which is the typical timescale required for recently-accreted material to first exit the virial boundary of its host halo. This suggests that many orbital subhaloes are recent arrivals: roughly half have crossed pericentre only once, and roughly one-third have yet to reach their first apocentre (after turnaround). Only $\approx 56$ per cent of all subhaloes within $r_{200}$ have completed at least one apocentric passage since infall (Figure 1).

Apoapses are therefore not directly measurable from orbital tracks for many associated subhaloes, but may nevertheless be estimated provided their orbital energy and angular momentum is known. The ratio of consecutive (measured plus predicted) apocentres for associated subhaloes with masses $M_{\text{sub}}/M_{200} \approx 0.01$ approximately follow the pattern expected from simple self-similar infall models (e.g. Bertschinger 1985), although with slightly greater loss of orbital energy after first pericentre. Bertschinger’s model, for example, predicts that the first apocentre of a typical orbit should be of order 90 per cent of its turn around radius; our simulations suggest a median value of $r_{\text{apo,1}}/r_{\text{tG}} \approx 0.8$ (or a mean value of 0.87) for the lowest-mass subhaloes. Nevertheless, as expected from analytic models the loss of orbital energy is most pronounced after first pericentric passage, after which the orbits of low-mass subhaloes typically reach
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Figure 12. The $R_{\text{max}} - V_{\text{max}}$ relations for the various categories of haloes and subhaloes studied in this paper. The upper-left panel compiles results for all haloes and subhaloes that lie within 2 virial radii from their respective hosts (purple dotted line); the upper-right panel shows separately the median relations for all orbital subhaloes (i.e. $N_{\text{peri}} \geq 1$ and $r_{\text{sub}} \leq r_{\text{200}}$; solid blue lines) and ex-satellites (i.e. $N_{\text{peri}} \geq 1$ and $r_{\text{sub}} > r_{\text{200}}$; dashed blue lines); the lower-left panel distinguishes secondary infalling haloes (solid red line) and secondary ex-satellites (dashed orange line); the lower-right panel distinguishes pre-processed haloes (green dashed line) from pristine ones (solid orange). Note that, in all cases, we restrict the subhalo samples to those that lie within $2 \times r_{\text{200}}$ from the primary. The black solid line, repeated in all panels for comparison, shows the $R_{\text{max}} - V_{\text{max}}$ relation for all field haloes in the simulation volume (no isolation criteria are imposed). The dashed grey lines show the $R_{\text{max}} - V_{\text{max}}$ relation predicted by the analytic model of Ludlow et al. (2016). The solid grey line (delineating the open and shaded regions of the plot) shows the $R_{\text{max}} - V_{\text{max}}$ relation for a halo whose mass is determined by the constraint $R_{\text{max}} = 2 \times r_{\text{conv}}$, where $r_{\text{conv}}$ is the convergence radius defined by Ludlow et al. (2019).

a stationary state, and the ratio of successive apocentres approaches unity. These results do not apply to the orbits of the most massive subhaloes ($M_{\text{sub}}/M_{\text{200}} \gtrsim 0.01$), which are repeatedly degraded due to dynamical friction (See Figure 4).

Although these trends apply on average, the orbits of individual subhaloes exhibit a large variation between successive apocentres. For example, for hosts with $M_{\text{200}} \approx 10^{12} h^{-1} M_{\odot}$ ($5 \times 10^{13} h^{-1} M_{\odot}$), roughly 26 (25) per cent of associated subhaloes have first apocentres that exceed their nominal turnaround radius, whereas $\approx 10$ (15) per cent have $r_{\text{apo}}/r_{\text{ta}} \lesssim 0.5$. These outliers – common in cosmological haloes – deviate significantly from simple, analytic predictions. The discrepancy between orbits in simulations and
those expected from analytic models appear to arise due to high-order interactions between subhaloes and the hosts in which they orbit. On first approach, the accretion of loosely-bound groups of haloes (i.e. the secondary-subhaloes and ex-satellites of first-infall haloes) can account for the vast majority of outlier first apocentres (roughly two-thirds of those with \( r_{\text{apo},1} / r_{\text{ta}} \gtrsim 3.3 \), and 80 per cent of those with \( r_{\text{apo},1} / r_{\text{ta}} \gtrsim 0.25 \) were pre-processed prior to accretion). For subsequent apocentres, extremau are mainly a results of penetrating encounters between two or more orbital subhaloes at radii \( r_{\text{sub}} < r_{200} \) (see Figure 11).

The orbital histories of haloes and subhaloes also affects their internal structure, results which we summarize in Figure 12 for haloes and subhaloes within \( 2r_{200} \) from their host’s centre. Pristine, infalling haloes (i.e. those that have never been substructures of more massive haloes) follow a \( V_{\text{max}} - R_{\text{max}} \) relation that is similar to the entire population of field haloes. Those that have been pre-processed, but not yet accreted by the host, are systematically more concentrated. Orbital subhaloes and ex-satellites – which, by definition, have completed at least one pericentric passage about their host haloes – exhibit, relative to isolated field haloes, the most discrepant concentrations. These results imply that, within \( 2 \times r_{200} \), tidal encounters between associated subhaloes and their hosts are the primary mechanism by which the structural scaling relations of DM haloes are modified in dense environments.

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