Simulating subhaloes at high redshift: merger rates, counts and types

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ABSTRACT
Galaxies are believed to be in one-to-one correspondence with simulated dark matter subhaloes. We use high-resolution N-body simulations of cosmological volumes to calculate the statistical properties of subhalo (galaxy) major mergers at high redshift \( (z = 0.6–5) \). We measure the evolution of the galaxy merger rate, finding that it is much shallower than the merger rate of dark matter host haloes at \( z > 2.5 \), but roughly parallels that of haloes at \( z < 1.6 \). We also track the detailed merger histories of individual galaxies and measure the likelihood of multiple mergers per halo or subhalo. We examine satellite merger statistics in detail: 15–35 per cent of all recently merged galaxies are satellites, and satellites are twice as likely as centrals to have had a recent major merger. Finally, we show how the differing evolution of the merger rates of haloes and galaxies leads to the evolution of the average satellite occupation per halo, noting that for a fixed halo mass, the satellite halo occupation peaks at \( z \sim 2.5 \).

Key words: methods: N-body simulations – galaxies: haloes – galaxies: interactions – cosmology: theory.

1 INTRODUCTION
Mergers are the key in the hierarchical growth of structure, and major galaxy mergers (referred to as mergers henceforth) are thought to play a crucial role in galaxy evolution. Specifically, they are expected to trigger quasar activity (e.g. Carlberg 1990), starbursts (e.g. Barnes & Hernquist 1991; Noguchi 1991) and morphological changes (e.g. Toomre & Toomre 1972), and are thought to be related to Lyman Break Galaxies (LBGs), submillimetre galaxies (SMGs) and ultra-luminous infrared galaxies (ULIRGs) (see reviews by Giavalisco 2002; Blain et al. 2002; Sanders & Mirabel 1996, respectively). Observational samples of such objects at \( z \gtrsim 1 \) are now becoming large enough to allow for statistical analyses of their counts (e.g. Steidel et al. 2003; Ouchi et al. 2004; Coppin et al. 2006; Yoshida et al. 2006; Gawiser et al. 2007; Genel et al. 2008; McLure et al. 2008; Patton & Atfield 2008; Tacconi et al. 2008; Yamauchi, Yagi & Goto 2008).

Understanding galaxy mergers and their connection to these observables requires comparison with theoretical predictions. In simulations, galaxies are identified with subhaloes, the substructures of dark matter haloes (e.g. Ghigna et al. 1998; Klypin et al. 1999; Moore et al. 1999; Ghigna et al. 2000). Simulations are now becoming sufficiently high in resolution and large in volume to provide statistically significant samples (e.g. De Lucia et al. 2004; Diemand, Moore & Stadel 2004; Gao et al. 2004b; Reed et al. 2005). This high mass and force resolution are necessary to track bound subhaloes throughout their orbit in the host halo and avoid artificial numerical disruption. This is particularly important for tracking the orbits of galaxies, which are expected to reside in the dense inner core of subhaloes and to be more stable to mass stripping than dark matter because of dissipative gas dynamics. The correspondence of galaxies with subhaloes has been successful in reproducing galaxy counts and clustering in a wide array of measurements (e.g. Springel et al. 2001, 2005b; Zentner et al. 2005; Bower et al. 2006; Conroy, Wechsler & Kravtsov 2006; Vale & Ostriker 2006; Wang et al. 2006). Henceforth, we will use the term galaxy and subhalo interchangeably.

A subhalo forms when two haloes collide and a remnant of the smaller halo persists within the larger final halo. Thus, subhalo merger rates are sometimes inferred from halo merger rates or subhalo distributions, using a dynamical friction model to estimate the infall time of satellite galaxies to their halo’s central galaxy (several of these methods are compared in Hopkins et al. 2008b). However, a detailed understanding of galaxy mergers requires a 

2 Halo merger counts and rates have been studied in a vast literature, both estimated analytically (e.g. Kauffmann & White 1993; Lacey & Cole 1993; Percival & Miller 1999; Benson, Kamionkowski & Hassani 2005; Zhang, Ma & Fakhouri 2008) and measured in simulations (e.g. Lacey & Cole 1994; Tormen 1998; Somerville et al. 2000; Cohn, Bagla & White 2001; Gottlöber, Klypin & Kravtsov 2001; Cohn & White 2005; Li et al. 2007; Cohn & White 2008; Fakhouri & Ma 2008; Stewart et al. 2008b).

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1 A subhalo can comprise an entire halo if there are no other subhaloes within the halo (see Section 2).
sufficiently high-resolution simulation that can track the evolution and coalescence of subhaloes directly.

Here, we use high-resolution dark matter simulations to examine subhalo merger rates, counts and types, their mass and redshift dependence, and their relation to their host haloes. Under the assumption that galaxies populate the centres of dark matter subhalo potential wells, our subhaloes are expected to harbour massive galaxies ($L \gtrsim L_\star$). Although our subhalo mass assignment is motivated by semi-analytic arguments, our results are independent of any specific semi-analytic modelling prescription.

Previous work on subhalo mergers includes both dark matter only simulations (Kolatt et al. 2000; Springel et al. 2001; De Lucia et al. 2004; Taylor & Babul 2005; Berrier et al. 2006; Wang & Kauffmann 2008; Mateus 2008) and hydrodynamic simulations (Murali et al. 2002; Tormen, Moscardini & Yoshida 2004; Maller et al. 2006; Thacker, Scannapieco & Couchman 2006; Simha et al. 2008). Many of these earlier studies concern subhalo mergers within a single object (such as the Milky Way or a galaxy cluster); others use lower resolution. We look at relatively large simulation volumes (100 and 250 $h^{-1}$ Mpc boxes) with high spatial and temporal resolution. In addition, many previous works focus on subhalo mass-loss and survival rate, while our main interest here is the population of resulting merged subhaloes itself (most similar to the works of Maller et al. 2006; Angulo et al. 2008; Guo & White 2008; Simha et al. 2008). We characterize subhalo merger properties in detail, including satellite mergers, at high redshift ($z = 0.6–5$), during the peak of merger activity. We also investigate the satellite halo occupation (number of satellites per halo), and its evolution as shaped by the relative merger rates of subhaloes and haloes. The satellite halo occupation is a key element in the halo model (Peacock & Smith 2000; Seljak 2000; Berlind & Weinberg 2002; Cooray & Sheth 2002), a framework which describes large-scale structure in terms of host dark matter haloes.

In Section 2, we describe the simulations, our definitions of haloes and subhaloes, their infall mass and the evolution of the satellite fraction. In Section 3, we define our merger criteria and examine subhalo merger rates and their relation to halo merger rates. In Section 4, we explore the relative contributions of satellites and centrals to the merger population, in terms of both parents and merged children. Section 5 gives the distribution of the number of mergers within a given look-back time and the fraction of haloes that host subhalo mergers. In Section 6, we show how the difference in halo and subhalo merger rates contributes to the evolution of the satellite halo occupation. We summarize and discuss in Section 7. The Appendices compare subhalo infall mass to infall maximum circular velocity and its evolution with redshift, and give our satellite subhalo mass function. The halo occupation and clustering of high-redshift galaxy mergers are treated in Wetzel, Cohn & White (2009).

2 NUMERICAL TECHNIQUES

2.1 Simulations

We use two dark matter only $N$-body simulations of $800^3$ and $1024^3$ particles in a periodic cube with side lengths 100 and $250 h^{-1}$ Mpc, respectively. For our A cold dark matter cosmology ($\Omega_m = 0.25$, $\Omega_b = 0.75$, $h = 0.72$, $n = 0.97$ and $\sigma_8 = 0.8$), in agreement with a wide array of observations (Smoak et al. 1992; Tegmark et al. 2006; Reichardt et al. 2008; Komatsu et al. 2008), this results in particle masses of $1.4 \times 10^9 h^{-1} M_\odot$ ($1.1 \times 10^9 h^{-1} M_\odot$) and a Plummer equivalent smoothing of $4 h^{-1}$ kpc ($9 h^{-1}$ kpc) for the smaller (larger) simulation. The initial conditions were generated at $z = 200$ using the Zel’dovich approximation applied to a regular Cartesian grid of particles and then evolved using the TreePM code described in White (2002) (for a comparison with other codes see Heitmann et al. 2007; Evrard et al. 2008). Outputs were spaced every 50 Myr ($\sim 100$ Myr) for the smaller (larger) simulation, from $z \sim 5$ to 2.5. Additional outputs from the smaller simulation were retained at lower redshift, spaced every ~200 Myr down to $z = 0.6$, below which we no longer fairly sample a cosmological volume.

For mergers, we restrict these later outputs to $z < 1.6$ based on convergence tests of the merger rates (we lack sufficient output time resolution in the intervening redshifts to properly catch all mergers; see end of Section 3.1 for more details). Our redshift range of $z = 0.6–5$ allows us to examine subhaloes across 7 Gyr of evolution.

To find the subhaloes from the phase-space data, we first generate a catalogue of haloes using the Friends-of-Friends (FoF) algorithm (Davis et al. 1985) with a linking length of $b = 0.168$ times the mean inter-particle spacing. This partitions the particles into equivalence classes by linking together all particles separated by less than $b$, with a density of roughly $\rho > 3/(2\pi b^3) \approx 100$ times the background density. The longer linking length of $b = 0.2$ is often used. However, this linking length is more susceptible to joining together distinct, unbound structures and assigning a halo that transiently passes by another as a subhalo. Thus, we use a more conservative linking length, which for a given halo at our mass and redshift regime yields a ~15 per cent lower mass than $b = 0.2$.\footnote{Many Millennium subhalo studies use Spherical Overdensity (SO) haloes based on an FoF(0.2) catalogue, in part to take out the extra structure joined by the larger linking length. Neto et al. (2007) compare the FoF(0.2) halo centres and those for the SO haloes used to define the corresponding subhalo populations. More generally, White (2001) compares different mass definitions in detail, and Cohn & White (2008) discuss the relation of FoF(0.2), FoF(0.168), SO(180) and Sheth–Tormen (Sheth & Tormen 1999, based on $b = 0.2$) masses at high redshift.}

We keep all FoF groups with more than 32 particles, we refer to these groups as ‘(host) haloes’. Halo masses quoted below are these FoF masses.

When two haloes merge, the smaller halo can retain its identity as a ‘subhalo’ inside the larger host halo. We identify subhaloes (and sometimes subhaloes within subhaloes) using a new implementation of the Subfind algorithm (Springel et al. 2001). We take subhaloes to be gravitationally self-bound aggregations of particles bounded by a density saddle point. After experimentation with different techniques, we find this method gives a good match to what would be selected ‘by eye’ as subhaloes. We use a spline kernel with 16 neighbours to estimate the density and keep all subhaloes with more than 20 particles. The subhalo that contains the most mass in the halo is defined as the central subhalo; all other subhaloes in the same halo are satellites.\footnote{In most cases, the central subhalo in Subfind is built around the most bound and most dense particle in the group. However, this is not always the case.}

The central subhalo is also assigned all matter within the halo not assigned to the satellite subhaloes. The position of a subhalo is given by the location of its most bound particle, and the centre of a host halo is defined by the centre of its central subhalo. For each subhalo, we store a number of additional properties including the bound mass, velocity dispersion, peak circular velocity, total potential energy and velocity.

Fig. 1 (top) shows the projected image of a sample halo of mass $2.2 \times 10^{12} h^{-1} M_\odot$, which hosts 12 satellite subhaloes, at $z = 2.6$ in the $100 h^{-1}$ Mpc simulation. [At this redshift, in our simulations...]

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times extend well beyond $r_{200c}$, which we will call the halo virial radius.\textsuperscript{5}

### 2.2 Subhalo tracking

We identify, for each subhalo, a unique ‘child’ at a later time, using subhalo tracking similar to Springel et al. (2005b), Faltenbacher et al. (2005), Allgood (2005) and Harker et al. (2006). We detail our method to illustrate the subtleties which arise and to allow comparison with other work.

We track histories over four consecutive simulation outputs at a time because nearby subhaloes can be difficult to distinguish and can ‘disappear’ for a few outputs until their orbits separate them again. For each subhalo with mass $M_1$ at scalefactor $a_1$, its child subhalo at a later time (scalefactor $a_2$ and mass $M_2$) is that which maximizes

$$\alpha = f(M_1, M_2) \ln^{-1} \left( \frac{\phi_{i_2}}{\phi_{i_1}} \right) \sum_{i_2 \in \phi} \phi_{i_2}$$

(1)

where

$$f(M_1, M_2) = \begin{cases} 1 - \frac{M_1 - M_2}{M_1 + M_2} & M_1 < M_2 \\ 1 & M_1 \geq M_2 \end{cases}$$

(2)

and where $\phi_{i_2}$ is the potential of particle $i$ computed using all of the particles in subhalo 1, and the sum is over those of the 20 most bound particles in the progenitor that also lie in the candidate child. We track using only the 20 most bound particles since our ultimate interest is in galaxies, which we expect to reside in the highly bound, central region of the subhalo (20 is the minimum particle count for our subhaloes). We do not use all the progenitor particles because summing over all of the particles in the progenitor that also lie in the child candidate leads to instances of parent–child assignment in which the child subhalo does not contain the most bound particles of its parent. Finally, we weight against large mass gains with a mass-weighting factor so that smaller subhaloes passing through larger ones and emerging later on the other side are correctly assigned as fly-bys and not mergers. We find $\sim$95 per cent of subhaloes have a child in the next time-step, with $\sim$4 per cent skipping one or more output times and $\sim$1 per cent having no identifiable child.

Fig. 1 (bottom) shows the tracking histories of the most massive subhaloes within the halo shown in Fig. 1 (top), for subhaloes that had a mass $>10^{11} h^{-1} M_\odot$ when they fell into the halo. The uppermost subhalo was a separate halo ($M = 1.3 \times 10^{11} h^{-1} M_\odot$) hosting its own massive satellite subhalo. It then fell into the main halo and then both (now satellite) subhaloes merged with each other. The right-most subhalo is an example of two separate haloes falling into the main halo, becoming satellites and subsequently merging with each other. Finally, the track through the centre shows a single subhalo falling towards the central subhalo. Instead of merging with the central, it passes through as a fly-by.

All of these tracks show instances where the parent–child assignment algorithm has skipped an output (dotted lines) as one subhalo passes through another and re-emerges on the other side. Note also that while the dot–dashed circle shows the halo virial radius, $r_{200c}$ (at the last output), based on its mass assuming a spherical NFW density profile, the locations of the transitions of central subhaloes

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Top: projected image of a halo of mass $2.2 \times 10^{12} h^{-1} M_\odot$ at $z = 2.6$ which hosts 12 satellite subhaloes. Particles assigned to the central subhalo are red, while those assigned to satellite subhaloes are blue. Dot–dashed circle shows the halo’s virial radius ($r_{200c}$), derived from its mass assuming a spherical NFW density profile, while the solid circles highlight the satellite subhaloes and scale in radius with their mass. The central subhalo has bound mass of $1.8 \times 10^{12} h^{-1} M_\odot$, so nearly 20 per cent of the halo’s mass lies in satellite subhaloes. Bottom: tracking histories of massive satellite subhaloes in the above halo. Large dots show the positions of satellite subhalo centres at $z = 2.6$ for subhaloes that had a mass $>10^{11} h^{-1} M_\odot$ when they fell into the halo. Small dots show their positions (relative to that of the halo centre) at each output (spaced 50 Myr) back 800 Myr. Thin blue curves show subhalo trajectories when they are satellites while thick red curves show when they are centrals (before falling into the halo). Dotted lines indicate when the parent–child assignment has skipped an output (during a fly-by near another subhalo).}
\end{figure}

\textsuperscript{5} The halo virial radius, $r_{200c}$, i.e. the radius within which the average density is 200 times the critical density, is calculated from the FoF ($b = 0.168$) mass by first converting to $M_{200c}$, assuming a spherical NFW (Navarro, Frenk & White 1996) density profile, and then taking $M_{200c} = 200 \rho_c r_{200c}^3$.\textsuperscript{2}
central and back to a satellite, the original satellite can be mistakenly assigned as a direct parent of the final satellite (and thus the central is assigned no parent) since our child assignment weights against large mass gains (which occurs when a satellite becomes a central). We fix these distinct cases by hand.

These switches highlight the fact that the distinction between a central and satellite subhalo is often not clear-cut: at this redshift and mass regime, massive haloes undergo rapid merger activity and thus are often highly disturbed and aspherical, with no well-defined single peak that represents the centre of the halo profile.

2.3 Subhalo mass assignment

Since we use subhaloes as proxies for galaxies, we track subhalo mass that is expected to correlate with galaxy stellar mass. Galaxies form at halo centres as baryons cool and adiabatically contract towards the minimum of the halo’s potential well, which leads to a correlation between halo mass and galaxy stellar mass (White & Rees 1978; Blumenthal et al. 1986; Dubinski 1994; Mo, Mao & White 1998). When a halo falls into a larger halo and becomes a satellite subhalo, its outskirts are severely stripped as discussed above, but its galaxy’s stellar mass would be little influenced as the radial radius is typically ~10 per cent that of the subhalo radius. This motivates assigning to subhaloes their mass at infall, $M_{\text{inf}}$, which is expected to correlate with galaxy stellar mass throughout the subhalo’s lifetime. The subhalo mass gain function has been successful at reproducing the observed galaxy luminosity function and clustering at low redshifts (Vale & Ostriker 2006; Wang et al. 2006; Yang, Mo & van den Bosch 2009). Maximum circular velocity at infall, $V_{c, \text{inf}}$, has also been successfully matched to some observations (Berrier et al. 2006; Conroy et al. 2006). In Appendix A, we show the relation between $M_{\text{inf}}$ and $V_{c, \text{inf}}$ and its redshift evolution.

Our prescription for assigning $M_{\text{inf}}$ to subhaloes is as follows. When a halo falls into another and its central subhalo becomes a satellite subhalo, the satellite is assigned $M_{\text{inf}}$ as the subhalo mass of its (central) parent. If a satellite merges with another satellite, the resultant child subhalo is assigned the sum of its parents’ $M_{\text{inf}}$. Since the central subhalo contains the densest region of a halo, inter-halo gas is expected to accrete on to it, so we define $M_{\text{inf}}$ for a central subhalo as its current self-bound subhalo mass, which is typically ~90 per cent of its host halo’s mass. However, since a central subhalo can switch to being a satellite, while a satellite switches to being a central (all within a single host halo), we require an additional rule because using the above simple assignment of $M_{\text{inf}}$ to centrals would lead to a central and satellite in a halo each having the halo’s current bound mass. Thus, we assign a central to have $M_{\text{inf}}$ as its current self-bound subhalo mass only if it was the central in the same halo in the previous output. Thus, if a satellite switches to a central and remains the central for multiple outputs, it has robustly established itself as the central subhalo, so it is assigned its current self-bound mass. However, if a central was a satellite (or a central in another smaller halo) in the previous output, it is assigned

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6 A fly-by, i.e. when a subhalo passes through and is temporarily indistinguishable from a larger subhalo, is an extreme case of this.

7 In more detail, a switch occurs when the density peak of a satellite (above the background) contains more mass than is within the central subhalo’s radius at the position of the satellite.

---

**Figure 2.** Top: evolution of mass (solid curve) and circular velocity (dashed curve) as a function of time since infall for a satellite that fell into a halo of mass $8 \times 10^{12} h^{-1} M_{\odot}$ at $z = 3.7$. Bottom: radial distance of satellite from centre of host halo. Mass and circular velocity exhibit correlations with radial distance, such as mass gain as the satellite recedes from the centre of its host halo. This satellite experienced no major merger activity throughout its history.

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**Table 1.** Properties of simulated haloes at high redshift.

<table>
<thead>
<tr>
<th>Halo Mass [M_\odot]</th>
<th>Satellites</th>
<th>M_{\text{inf}} [M_\odot]</th>
<th>V_{c, \text{inf}} [\text{km/s}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$8 \times 10^{12}$</td>
<td>2</td>
<td>7.3e11</td>
<td>258</td>
</tr>
</tbody>
</table>

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the sum of its parents’ \( M_{\text{inf}} \), with the additional requirement that its \( M_{\text{inf}} \) cannot exceed its current self-bound mass.

A small fraction (~1 per cent) of satellites composed of at least 50 particles are not easily identifiable with any progenitor subhaloes and thus cannot be tracked to infall. On inspection, we find that these ‘orphaned’ satellites are loosely self-bound portions of a central subhalo, remnants from a collision between a satellite and its central subhalo that soon re-merge with the central. Given their origins and fates, these orphans are not expected to host galaxies and are ignored.

Although we track subhaloes down to 20 particles, we impose a much larger minimum infall mass to our sample to avoid selecting subhaloes that artificially dissolve and merge with the central too early. This requires sufficient resolution of the radial density profile of a satellite subhalo at infall: if the satellite’s core is smaller than a few times the force softening length, its profile will be artificially shallow and it will be stripped and disrupted prematurely (see Appendices for details). For calibration, we use the regime of overlap in mass between our two simulations of different mass resolution, requiring consistent subhalo mass functions, halo occupation distributions and merger statistics for a minimum infall mass. For example, going too low in mass for the larger simulation resulted in more mergers and fewer subhaloes than for the same mass range in the smaller simulation. In the larger simulation, our consistency requirements led us to impose \( M_{\text{inf}} > 10^{12} \, h^{-1} M_\odot \).

For a fixed number of particles per subhalo, this scales down to \( M_{\text{inf}} > 10^{11} \, h^{-1} M_\odot \) in the smaller simulation. In the larger simulation, our characteristic mass of collapse, at \( z = 1.5 \) \((z = 0.8)\), so we probe massive subhaloes across most of our redshift range.

At \( z = 2.6 \), there are \( \sim 16 \, 000 \) subhaloes with \( M_{\text{inf}} > 10^{11} \, h^{-1} M_\odot \) in our 100 \( h^{-1} \) Mpc simulation and 9400 subhaloes with \( M_{\text{inf}} > 10^{12} h^{-1} M_\odot \) in our 250 \( h^{-1} \) Mpc simulation. At \( z = 1 \), there are \( \sim 29 \, 400 \) (2500) subhaloes with \( M_{\text{inf}} > 10^{11} (10^{12}) h^{-1} M_\odot \) in our 100 \( h^{-1} \) Mpc simulation.

### 2.4 A note on stellar mass and gas content of subhalo galaxies

A galaxy’s stellar mass is expected to be a non-linear, redshift-dependent function of its subhalo mass. An approximate relation based on abundance matching is given in Conroy & Wechsler (2008). At \( z = 1 \), they find that subhaloes of infall mass \( 10^{11} \, 10^{12} h^{-1} M_\odot \) host galaxies of stellar mass \( \sim 10^9 \, 10^{10.5} M_\odot \). At \( z = 2.5 \), subhaloes at the above masses are expected to host lower mass galaxies, though quantitative relations at this redshift are less certain, and our subhalo and halo finders differ in detail from theirs.

Our sample of \( M_{\text{inf}} > 10^{12} h^{-1} M_\odot \) subhaloes approximately corresponds to \( L \geq L_* \) galaxies at the redshifts we examine.

Although our simulations do not track the baryonic content of subhaloes, most massive galaxies are gas-rich at high redshift. That is, at \( z \approx 1 \), 70 to 90 per cent of \( L \sim L_* \) galaxies are observed to be blue (Cooper et al. 2007; Gerke et al. 2007), possessing enough gas to be actively star forming. The fraction of gas-rich galaxies at higher redshift is more poorly constrained but is thought to be higher (Hopkins et al. 2008a). Thus, we anticipate that most, if not all, mergers we track have the capacity to drive galaxy activity such as starbursts and quasars.

### 2.5 Satellite fraction

To frame our ensuing discussion of mergers, and the relative importance of satellite and central subhaloes, Fig. 3 shows the evolution of the satellite fraction, \( n_{\text{satellite}} / n_{\text{subhalo}} \), for subhaloes of a fixed mass,\(^{10}\) which grows monotonically with time from \( z = 5 \) to 0.6, as

\[
\frac{n_{\text{satellite}}}{n_{\text{subhalo}}} = C - e^{-\frac{\beta}{z}}
\]

with \( \beta = 9.7 \) valid across all subhalo masses and \( C = 0.26 (0.24) \) for lower (higher) mass. The satellite fraction decreases with increasing subhalo mass since more massive subhaloes are more likely to be centrals, and for a fixed subhalo mass the satellite fraction increases with time as the number of high-mass haloes hosting massive satellites increases. The increase in the satellite fraction is slowed at late times because the number of massive satellites in haloes of a fixed mass decreases with time as the satellites coalesce with the central subhalo (see Section 6).

Note that equation (3) predicts a much higher satellite fraction than that of Conroy & Wechsler (2008), who found

\[
\frac{n_{\text{satellite}}}{n_{\text{subhalo}}} = 0.2 - \frac{0.1}{3} z.
\]

It is unlikely that the difference is driven by numerical effects, since both their and our simulations are of similar mass resolution and volume, and both analyses are based on similar subhalo infall mass cuts (we see similar satellite fractions selecting instead on fixed \( V_{\text{c,inf}} \)). One likely factor is that, as noted above, our smaller output spacing yields higher infall mass for satellite subhaloes, since we catch haloes closer to infall when their mass is higher. In addition, they use a different halo and subhalo finding algorithm (Klypin et al. 1999; Kravtsov et al. 2004), and their higher \( \sigma_8 \) (0.9 rather than our 0.8) would give a lower merger rate and thus fewer satellites (one expects satellite survival time-scales not to change). If normalized to the same satellite fraction at a given epoch, the redshift evolution of equations (3) and (4) is in rough agreement.

\( ^{10}\) We show the satellite fraction for two mass bins, but since the mass function falls exponentially at these masses and redshifts, almost all objects are at the low end of the mass bin. Using instead a minimum mass cut changes our results by only a few per cent.
3 MERGER CRITERIA AND RATES

3.1 Merger criteria

For two parents with $M_{\text{inf},1} \leq M_{\text{inf},2}$ sharing the same child subhalo at the next output they appear, a child is flagged as a (major) merger if $M_{\text{inf}1} > \frac{1}{2} M_{\text{inf}2}$. If a child has more than two parents, we count multiple mergers if any other parents also exceed the above mass ratio with respect to the most massive parent.

Our mass ratio represents a trade-off between strong mergers (to maximize signal) and frequent merging (for statistical power). Galaxy mergers with stellar mass ratios closer than 3:1 are expected to drive interesting activity, e.g. quasars and starbursts, as mentioned above.\(^\text{11}\)

For generality, the distribution of merger (infall) mass ratios, $R:1$, for both haloes and subhaloes in the mass and redshift regimes we consider can be approximated by

$$f(R) \propto R^{-1.1}$$

in reasonable agreement with the $R^{-1.2}$ distribution of galaxy mass ratios at $z < 0.5$ found in hydrodynamic simulations by Maller et al. (2006).\(^\text{12}\) Thus, the counts/ rates of mergers with (infall) mass ratio closer than $R:1$ can be approximately scaled from our results through the relation

$$N(< R) = 8.6 (R^{0.1} - 1) N(< 3).$$

Sometimes, merger criteria are based on instantaneous subhalo mass gain (e.g. Thacker et al. 2006). However, as exemplified in Fig. 2, subhaloes can gain significant mass without coalescence. We find that most cases of significant subhalo mass gain are not a two-body coalescence, and so we do not use this to select mergers [see Wetzel et al. (2009) for more detail, also see related results in Maulbetsch et al. (2007)].

\(^{11}\) Since galaxy stellar mass is a non-linear function of subhalo mass, a subhalo mass ratio of 3:1 may correspond to a galaxy merger of a more or less discrepant mass ratio. However, since the $M_{\text{stellar}}-M_{\text{subhalo}}$ relation is expected to peak for $M_{\text{subhalo}} \sim 10^{12} h^{-1} M_\odot$ (Conroy & Wechsler 2008), we do not expect this effect to strongly bias our results.

\(^{12}\) The distribution of merger mass ratios also agrees well with the fit for haloes at $z = 0$ provided by Wetzel et al. (2008).
The former is simply the latter divided by the number density of objects of the same mass, but the merger rate per volume has qualitatively different behaviour because the (comoving) number density of objects at a fixed mass increases with time in a redshift-dependent manner. Specifically, at high redshift where the mass function rapidly increases, the merger rate per volume for both haloes and subhaloes increases with time, reaching a peak at \( z \sim 2.5 \). Below this redshift, it decreases with time in a power-law manner as in Fig. 4, though with a shallower slope of \( \alpha \approx 1.5 \).

Table 1. The amplitude, \( A \), and power-law index, \( \alpha \), for halo and subhalo merger rates fit to equation (7).

<table>
<thead>
<tr>
<th>Redshift</th>
<th>( z = 5 - 2.5 )</th>
<th>( z = 1.6 - 0.6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass ([h^{-1} \text{M}_\odot])</td>
<td>(10^{11} - 10^{12})</td>
<td>(10^{12} - 10^{13})</td>
</tr>
<tr>
<td>Haloes</td>
<td>(A)</td>
<td>0.29</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Subhaloes</td>
<td>(A)</td>
<td>0.093</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>1.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

as

\[
\frac{n_{\text{merge}}}{n_{\text{obj}}} = A(1 + z)^\alpha, \tag{7}
\]

where \( n_{\text{merge}} \) is the number of (sub)haloes whose parents match our mass ratio selection, \( n_{\text{obj}} \) is the total number of (sub)haloes within the same mass range at the same output and \( d \) \( t \) is the time interval between consecutive outputs. The best-fitting values in each redshift regime are shown in Table 1. Note that the merger rate we examine is the number of mergers per time per object, different from another common definition, the number of mergers per time per volume.

The relation of subhalo mergers to halo mergers is non-trivial. Although subhalo mergers are the eventual result of halo mergers, the former are governed by dynamics within a halo and the latter by large-scale gravitational fields. For haloes, both the slope and the amplitude of the merger rate exhibit little dependence on mass or redshift. Similarly, for example, Fakhouri & Ma (2008) found \( \alpha = 2 - 2.3 \) for all halo masses at \( z < 6 \), and weak halo mass dependence of the amplitude. In contrast, the subhalo merger rate amplitude has strong dependence on mass, and its slope depends strongly on redshift. Relative to the halo merger rate, the subhalo merger rate is lower in amplitude than that of haloes of the same (infall) mass, and, most notably at \( z > 2.5 \), the rate of subhalo mergers falls off significantly more slowly than that of haloes. This is consistent with earlier work: De Lucia et al. (2004) found a higher merger fraction for haloes than subhaloes, and Guo & White (2008) found strong mass dependence of the galaxy merger rate amplitude and that the slope becomes much shallower at \( z > 2 \) (see also Mateus 2008). [Note that as our haloes are FoF(0.168) haloes and so our merger rates can differ from those for FoF(0.2) haloes; merging occurs sooner for a finder with a larger linking length.]

We now focus on the relation between halo and subhalo merger rates to understand these trends with time.

### 3.3 Subhalo versus halo merger rates

A simple analytic argument based on dynamical infall time, i.e. subhalo mergers are simply a delayed version halo mergers, leads one to expect that subhalo merger rates simply track those of haloes: they have the same time evolution, with the subhalo merger rate having a higher amplitude. In this argument, when two haloes merge, the new satellite galaxy collides with the other central galaxy within a dynamical friction time-scale, approximated by

\[
t_{\text{merge}} = \frac{C_v M_{\text{halo}}/M_{\text{sat}}}{\ln(1 + M_{\text{halo}}/M_{\text{sat}})} t_{\text{dyn}}, \tag{8}
\]

where \( t_{\text{dyn}} = 0.1 t_{\text{Hubble}} \), \( t_{\text{Hubble}} = \frac{1}{H(z)} \) and \( C_v \approx 1 \) accounts for the ensemble averaged satellite orbital parameters (Conroy, Ho & White 2007; Binney & Tremaine 2008; Boylan-Kolchin, Ma & Quataert 2008; Jiang et al. 2008). Thus, for a fixed mass ratio, letting \( m_o = M_{\text{halo}}/M_{\text{sat}}/\ln(1 + M_{\text{halo}}/M_{\text{sat}}) \),

\[
t_{\text{sat,merge}} = 0.1 C_v m_o t_{\text{Hubble}} \approx 0.1 C_v m_o t. \tag{9}
\]

The evolution of the halo merger rate per object during matter-domination (valid at the high redshifts we examine), where \( \alpha \propto t^{2/3} \), is approximately

\[
\frac{n_{\text{merge}}}{n_{\text{halo}}/d\text{\text{t}}} = A(1 + z)^\alpha = \left( \frac{1}{t_e} \right)^{\frac{1}{\alpha}} \tag{10}
\]

with \( t_e \) some proportionality constant. Assuming all halo mergers lead to satellite–central subhalo mergers on a dynamical friction time-scale, the subhalo merger rate per object would evolve with time as

\[
\frac{n_{\text{merge}}}{n_{\text{subhalo}}/d\text{\text{t}}} = \left( t - t_{\text{sat,merge}} \right)^{-\frac{2}{\alpha}} \frac{1}{t_e} \tag{11}
\]

\[
= \left( 1 - 0.1 C_v m_o \right)^{-\frac{2}{\alpha}} \left( \frac{1}{t_e} \right)^{\frac{1}{\alpha}} \tag{12}
\]

and so the subhalo merger rate would simply track that of haloes of the same mass, but with higher amplitude.

### 3.4 Resolving the discrepancy

As Fig. 4 shows, however, this tracking does not occur, particularly at high redshift where the slope of the subhalo merger rates is much shallower than that of haloes. One reason for this is that we compute the merger rate per object, in which we divide by the number of objects at the given mass, \( n_{\text{obj}}(m) \). Since halo masses are added instantaneously during halo mergers, a recently merged halo will instantly jump to a higher mass regime (with smaller dynamical friction time-scale, approximated by \( t_{\text{dyn}} \approx t_{\text{Hubble}}/(\ln(1 + M_{\text{halo}}/M_{\text{sat}})) \)). For haloes, both the slope and the slope is also shallower (\( \alpha \approx 1.6 \)) than for haloes selected on full halo mass, showing that the above effect is stronger at earlier times. By the above argument, the ratio of amplitudes of the merger rate per object of haloes to subhaloes is \( n_{\text{halo}}/n_{\text{cen}} \). A fixed (sub)halo mass cut probes lower \( M/M_{\text{cen}} \) at later times, and the mass function drops exponentially with increasing \( M/M_{\text{cen}} \) at these masses. Thus, a fixed \( M_{\text{halo}}/M_{\text{cen}} \) after a halo merger means \( n_{\text{halo}}/n_{\text{cen}} \) becomes closer to unity at later times, leading to the shallower slope.

The measured subhalo mergers have an even lower amplitude and shallower slope than the dotted line in Fig. 4, driven by two additional effects. First, a halo major merger might not lead to a
subhalo major merger since the satellite–central merger mass ratio can be smaller than the mass ratios of their source haloes. This is because $M_{\text{inf}}$ naturally grows for a central but only grows for a satellite if it has a merger before coalescing with the central (see Wang & Kauffmann 2008, for a detailed analysis of this effect in terms of assigning baryons to subhaloes). Since haloes grow in mass more quickly at higher redshift, this effect is stronger at earlier times, further flattening the subhalo merger rate slope. Secondly, there is a significant contribution of recently merged satellites to the merger population. We find that satellites are twice as likely to merge as centrals of the same mass, regardless of mass cut and redshift (see Section 4 for more detail). This enhances the merger rate, with a stronger enhancement at later times since the satellite fraction grows with time as in Fig. 3.

At lower redshift, Fig. 4 (right-hand panel) shows that the amplitude of the subhalo merger rate remains lower than that of haloes, but the slopes become similar, indicating the effects examined above become less time-dependent. Since the masses we probe are crossing $M_{\text{c}}(t)$ as these redshifts, the reduced amplitude from subhalo versus halo mass cut becomes less sensitive to time. Similarly, our mass range crossing $M_{\text{c}}(t)$ means that halo mass growth slows, so the fraction of halo major mergers that leads to subhalo major mergers remains roughly constant with time. Finally, as shown in Fig. 3, the satellite fraction growth asymptotes at lower redshift, which means that the enhancement from recently merged satellites remains roughly constant.

4 Satellite versus central mergers

The stereotypical galaxy merger is a satellite coalescing with the central in its halo and producing a central merger remnant. These mergers do dominate the merger population, both in parent types (central–satellite) and in child type (central). However, while satellites form the minority of the subhalo population at all epochs (see Fig. 3), satellites are twice as likely to have had a recent merger as centrals of the same mass, regardless of mass and redshift.

Since the identities of satellite versus central subhaloes at this mass and redshift regime are not clear-cut (from switches), we characterize mergers in terms of both their parent types (central/satellite) and resulting child types. For mergers resulting in centrals, this ambiguity is not important: 97 per cent arise from satellite–central parents, while the other 3 per cent arise from satellite–satellite parents during switches.15

Recently merged satellites are a more varied population. Fig. 5 shows the contributions of satellite mergers to the overall merger populations as a function of the scalefactor.16 The fraction of all subhalo mergers that result in a satellite is $\sim 30$ per cent for $M_{\text{inf}} = 10^{11} - 10^{12} M_{\odot}$, with little dependence on redshift. For $M_{\text{inf}} = 10^{12} - 10^{13} M_{\odot}$, it is 15–20 per cent at $z < 2.5$ and rises to $\sim 35$ per cent at $z < 1.6$. Thus, at lower redshift ($z < 1.6$) where the satellite fraction asymptotes to $\sim 25$ per cent, the fraction of mergers that result in a satellite roughly reflects the satellite fraction as a whole.

Of these recently merged satellites, 20–35 per cent come from satellite–satellite parents within a single halo, while $\sim 7$ per cent arise when a central–satellite merger occurs in a halo as it falls into a larger halo, becoming a satellite. The rest arise from switches, i.e. a satellite merges with a central, and the resulting subhalo no longer is the most massive subhalo, thus becoming a satellite. These switches occur primarily in haloes only a few times more massive than the satellite, typically for satellites in close proximity to their central. At higher halo masses, recently merged satellites are dominated by satellite–satellite parents. These satellite–satellite mergers preferentially occur in the outer regions of a halo and are comparatively less common in the central regions. We examine in more detail the environmental dependence of subhalo mergers in Wetzel et al. (2009).

Considering instead only parent types, Fig. 5 shows that 5–10 per cent of all mergers come from satellite–satellite parents at $z < 2.5$, a fraction which increases to 10–15 per cent at $z = 1.6$ and remains flat thereafter. Approximately 80 per cent of all satellite–satellite mergers lead to a satellite child, while the rest lead to a central during a switch.

15 A few per cent arise from central–central parents, when the central regions of two haloes coalesce so quickly that they are not seen as satellite–central subhaloes given finite time resolution. We include these as satellite–central parents.

16 Satellite merger fractions are boxcar-averaged across three consecutive outputs to reduce noise from small number statistics.
5 GALAXY AND HALO MERGER COUNTS

5.1 Counts of recent mergers

The distribution of the number of mergers per object within a fixed time interval gives the fraction of objects at a given epoch that might exhibit merger-related activity or morphological disturbance. Multiple mergers as well might contribute to specific properties, e.g. the formation and mass growth of elliptical galaxies (e.g. Boylan-Kolchin, Ma & Quataert 2005; Robertson et al. 2006; Naab, Khochfar & Burkert 2006; Conroy, Ho & White 2007).

Fig. 6 shows the fraction of subhaloes at $z = 2.6$ and 1 with a given number of mergers in the last 1 Gyr. At $z = 2.6$, 30 per cent of subhaloes have suffered at least one major merger. Interestingly, this fraction is nearly constant across the mass regimes we probe. In contrast, the fraction of haloes with at least one major merger within 1 Gyr is about twice as large, with stronger mass dependence: higher mass haloes experience more mergers. At high redshift, haloes are also significantly more likely to have undergone multiple mergers than subhaloes, which builds up the satellite population.

At $z = 1$, recent mergers of subhaloes and haloes become less common, with only 8 per cent of subhaloes having suffered at least one major merger in the last 1 Gyr. Objects which have had one or two mergers are still more common for haloes than subhaloes, though high-mass subhaloes exhibit a much higher fraction of three or more mergers than haloes of the same (infall) mass. (Subhaloes that have undergone one merger can be either satellites or centrals, those that have undergone two or more mergers are almost entirely centrals.) The build-up of the satellite population at higher redshift has allowed massive centrals to experience multiple mergers at lower redshift. This effect is stronger for more massive subhaloes since they are more likely to be centrals, and they reside in higher mass haloes with more massive satellites.

5.2 Fraction ‘on’

The fraction of haloes that host recent mergers, $f_{\text{on}}$, is of particular interest for quasar or starburst evolution models, and quasar/starburst feedback effects such as heating of the Intracluster Medium (ICM). We select mergers up to 200 Myr after coalescence, motivated by the expected time interval during which quasars or starbursts remain observable (e.g. Hopkins et al. 2005). This time interval is only illustrative, though, as one expects relevant lifetimes to depend strongly upon galaxy mass and merger ratio. Observables might depend upon dynamical time as well, although many quasar triggering effects might be related to microphysics – small scale interactions close to the merger – that do not evolve with time.

Fig. 7 shows the evolution of $f_{\text{on}}$ for haloes hosting subhalo mergers within the last 200 Myr. The same quantity is shown for haloes with recent mergers themselves. At high redshift, $f_{\text{on}}$ for halo mergers shows a steep decline from the decreasing halo merger rate. However, $f_{\text{on}}$ for subhalo–subhalo mergers is flat from $z = 2.5$ to 5, because the subhalo merger rate per object decreases while the number of massive satellites in a given mass halo rises, causing the number of massive subhalo mergers within the halo to remain constant. At low redshift, where the satellite population grows more slowly, the evolution of this fraction for subhalo mergers more closely parallels that of halo mergers.

6 EVOLUTION OF THE SATELLITE HALO OCCUPATION

The redshift evolution of the satellite galaxy populations of dark matter haloes is shaped by halo versus galaxy mergers: halo mergers create satellites while galaxy mergers remove them. If the infall rate of satellites on to a halo is different than the satellite destruction rate, the satellite halo occupation will evolve with time.

As shown in Fig. 4, at $z > 2.5$, the merger rate of subhaloes is significantly lower and shallower in slope than that of haloes, implying that subhaloes are being created faster than they are destroyed (at a rate decreasing with time). Conversely, at $z < 1.6$ the merger rates of haloes and subhaloes exhibit approximately the same redshift dependence, and their amplitudes are similar (also

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17 This differs from the merger rates of Section 3, since we are tracking the histories of individual objects selected at a given redshift.
18 If we scale our $f_{\text{on}}$ time interval by the dynamical time, the slope of $f_{\text{on}}$ becomes slightly shallower, but the qualitative results do not change.
19 Though if one applies a mass threshold to a population, this is not strictly true since mergers also scatter lower mass objects into the population.
recall from Section 3 that not all halo major merger lead to subhalo major mergers). Thus, for haloes of a fixed mass, we expect a rapid rise in the satellite halo occupation prior to \( z \sim 2 \) and a levelling-off with more gradual evolution at lower redshift.

### 6.1 Satellite halo occupation in simulation

The above trends are seen in Fig. 8, which shows the evolution of the satellite occupation per halo, for satellites with \( M_{\text{inf}} > 10^{11} h^{-1} M_{\odot} \) in the 100\( h^{-1} \) Mpc simulation. Satellite occupation counts are normalized using the last output at \( z = 0.6 \). More massive satellites \((M_{\text{inf}} > 10^{12} h^{-1} M_{\odot})\) have similar evolution, with a peak in the satellite halo occupation at \( z \approx 2.5 \). For a fixed satellite infall mass, less massive haloes exhibit stronger satellite occupation evolution with redshift, leading to a more prominent peak.

### 6.2 Analytic estimate of satellite halo occupation

The rate of change of the satellite subhalo population per halo, for a fixed satellite \( M_{\text{inf}} \), is given by the rate at which satellites fall into a halo (the halo merger rate) minus the rate at which satellites coalesce with the central subhalo

\[
\frac{dN_{\text{sat}}}{dt} = \frac{dN_{\text{halo, merge}}}{dt} - \frac{dN_{\text{sat, cen, merge}}}{dt}.
\]

The halo merger rate at all epochs is given by (Section 3)

\[
\frac{dN_{\text{halo, merge}}}{dt} = A(1+z)^\alpha = Aa^{-\alpha}.
\]

The time-scale for the satellite to coalesce with its central subhalo after infall is given to good approximation by

\[
t_{\text{sat, cen, merge}} \approx \frac{C_0}{10 \ln(1 + M_{\text{halo}}/M_{\text{sat}})} t_{\text{infall}}.
\]

where \( C_0 \) is a constant of the order of unity that accounts for the ensemble averaged satellite orbital parameters, and we leave it as our sole free parameter. The rate of satellite destruction/coalescence is thus

\[
\frac{dN_{\text{sat, cen, merge}}}{dt} = \frac{10 \ln(1 + M_{\text{halo}}/M_{\text{sat}})}{C_0 M_{\text{halo}}/M_{\text{sat}}} H(z).
\]

Combining equations (14) and (16) into equation (13) one gets

\[
\frac{dN_{\text{sat}}}{dt} = Aa^{-\alpha} - \frac{10 \ln(1 + M_{\text{halo}}/M_{\text{sat}})}{C_0 M_{\text{halo}}/M_{\text{sat}}} H(z).
\]

At high redshift, \( H(z) \approx H_0 (\Omega_m a^{-3})^{1/2} \), where \( H_0 \approx 0.1 h \) Gyr\(^{-1} \), which implies

\[
\frac{dN_{\text{sat}}}{dt} \approx Aa^{-\alpha} - \frac{10 \ln(1 + M_{\text{halo}}/M_{\text{sat}})}{C_0 M_{\text{halo}}/M_{\text{sat}}} \Omega_m^{1/2} a^{-3/2}.
\]

Across all mass and redshift regimes, the power-law index for halo mergers is \( \alpha = 2–2.3 \) (Section 3), and we find no additional dependence on merger mass ratio, suggesting a universal power-law index.\(^{20}\) Thus, the creation and destruction terms in equation (18) have differing dependencies on the scalefactor, which implies they become equal at some redshift, where the satellite occupation per halo reaches a maximum.

\(^{20}\) Though merger rates for more discrepant mass ratios have higher amplitudes, as given by equation (5).
Using the exact evolution of the Hubble parameter (in our cosmology) of \( H(z) = H_0 \Omega_m a^{-3} + \Omega_k a^{-1/2} \) in equation (17), and integrating over \( a \), the full evolution of the satellite occupation per halo is

\[
N_{sat}(a) = \frac{A}{H_0} \int da \frac{a^{\alpha (a+1)}}{H(z)} \left( 1 - \frac{M_{ satellite}}{M_{halo}} \right) \ln(a) + K, \tag{19}
\]

where the constant \( K \) accounts for initial/final conditions. Fig. 8 shows the resultant \( N_{sat}(a) \), normalized to the satellite occupation per halo at final output, using typical values for the halo merger rate from Table 1 (\( A = 0.032 \) and \( \alpha = 2.3 \)). These values correspond to 3:1 mass ratio mergers, for satellites with \( M_{sat} = 10^{11} h^{-1} M_\odot \) this gives \( M_{halo} = 3 \times 10^{13} h^{-1} M_\odot \). While the fit of this model to the simulation results is not exact, it nicely reproduces the general trends, especially given the simplicity of the model, which ignores halo/central mass growth, satellite–satellite mergers and switches. For instance, it correctly produces a lower peak in satellite occupation for haloes with satellites of more discrepant mass ratios (more massive haloes for a fixed satellite mass, or less massive satellites for a fixed halo mass), relative to the amplitude at low redshift. This is because the decreased infall times for smaller satellite-halo mass ratios cause a more dramatic fall (after the peak) in the satellite population for lower mass haloes.

Agreement of this model with our simulations also requires \( C_\alpha \approx 2 \), which can be compared with other work. Zentner et al. (2005) and Jiang et al. (2008) find that the ensemble-averaged satellite orbital circularity distribution is given by \( \epsilon = 0.5 \pm 0.2 \), with no strong dependence on redshift or satellite-halo mass ratio. When applied to detailed dynamical friction time-scale fits from simulation, this yields \( C_\epsilon \approx 0.6 \) (Boylan-Kolchin et al. 2008) and \( C_\epsilon \approx 1.4 \) (Jiang et al. 2008).\(^{21}\) Taken at face value, our even higher value of \( C_\epsilon \) means that our satellites are taking longer to merge, suggesting that the discrepancy does not arise from artificial over-merging in our simulations. However, exact comparisons are difficult given the simple nature of our analytic model, and because both of these groups use different halo and subhalo finding algorithms. Jiang et al. (2008), who used a simulation of roughly similar volume and mass resolution to ours, also incorporated hydrodynamics, which is likely to shorten the merger time-scale since it introduces further dissipational effects to the subhalo orbits and reduces mass loss. Compared with Boylan-Kolchin et al. (2008), who performed much higher resolution simulations of isolated halo mergers, it is possible that our satellite subhaloes experience more severe mass stripping upon infall, decreasing their mass and thus extending their subsequent infall time (see equation 8). A more detailed investigation of satellite infall time-scales in a cosmological setting is needed; studies now in progress are targeting in particular the role of hydrodynamic effects (Dolag et al. 2008; Saro et al. 2008; Simha et al. 2008).

6.3 Comparison to other work on satellite occupation evolution

Fig. 8 shows a peak in the number of satellites per halo at \( z \sim 2.5 \). Fundamentally, the reason for this peak is that we select subhaloes of fixed minimum infall mass in haloes of fixed mass across time. If instead we examine the satellite occupation for haloes above a minimum mass cut, the growth of massive haloes (hosting more satellites) at late time would overwhelm the drop in the satellite population at a fixed halo mass, so the satellite halo occupation would grow monotonically and appear much like the satellite fraction in Fig. 3, which ignores halo mass.\(^{22}\)

These results agree with the interpretation that more massive haloes have later formation times and longer satellite infall times, and thus host more substructure at a given epoch (van den Bosch, Tormen & Giocoli 2005; Zentner et al. 2005). Similarly, for a fixed satellite infall mass, the satellite halo occupation evolves more rapidly for less massive haloes, as Zentner et al. (2005) and Diemand et al. (2007) found, though their results were based upon subhalo instantaneous mass and maximum circular velocity (we compare these to \( M_{inf} \) in the Appendices).

However, the peak in satellite halo occupation in Fig. 8 does not appear in Halo Occupation Distribution (HOD) evolution studies by Zentner et al. (2005) because they use a fixed cut on instantaneous maximum circular velocity across time. As shown in Appendix A, fixed \( V_c,\text{max} \) probes lower mass at higher redshift, and this evolution in satellite occupation over time overwhelms the satellite evolution of Fig. 8, leading to a monotonic rise in the satellite halo occupation with redshift. Similarly, Conroy et al. (2006) noted that the HOD shoulder (the halo mass where a halo hosts only a central galaxy) becomes shorter at higher redshift as an increasing fraction of low-mass haloes host more than one galaxy, finding a monotonically increasing satellite population with redshift. However, they compare fixed satellite number density (not mass) across redshift, which corresponds to a lower subhalo mass at higher redshift. Again, this overwhelms the evolution of Fig. 8, leading to a monotonic rise in the satellite population per halo with redshift.

In their semi-analytic model matched to simulation, van den Bosch et al. (2005) find that the average subhalo mass fraction of a halo always decreases with time, and they claim that, as a result, the time-scale for subhalo mass loss (approximately the dynamical/infall time) is always smaller than the time-scale of halo mass accretion (mergers). This implies that the satellite infall rate is always higher than the halo merger rate, and so the satellite HOD always decreases with time. However, this result refers to the total subhalo instantaneous mass per halo, not galaxy counts based on infall mass. If instead we examine the evolution of the satellite occupation per halo as in Fig. 8 selecting the satellites based on instantaneous subhalo mass instead of infall mass, we find a monotonic increase in the satellite occupation with no peak, in agreement with other authors above.

These examples all illustrate how the evolution of the HOD is dependent both on satellite mass assignment and on the selection of fixed mass versus circular velocity versus number density across time.

7 SUMMARY AND DISCUSSION

Using high-resolution dark matter simulations in cosmological volumes, we have measured the rates, counts and types of subhalo (galaxy) major mergers at redshift \( z = 0.6–5 \), describing their populations in terms of centrals/satellites and contrasting their merger
properties with those of haloes of the same (infall) mass. We assign subhaloes their mass at infall (with the capacity for mass growth during satellite mergers), motivated by an expected correlation with galaxy stellar mass, but include no further semi-analytic galaxy modelling. We select mergers requiring 3:1 or closer infall mass ratios, motivated by the expectation that these can trigger activity such as quasars, starbursts and related objects such as LBGs, sub-millimetre galaxies and ULIRGs. We highlight our main results as follows.

(i) The merger rate per object of subhaloes is always lower than that of haloes of the same (infall) mass. Galaxies exhibit stronger mass dependence on the amplitude of their merger rate than haloes, with more massive galaxies undergoing more mergers. While the slope of the halo merger rate per object is essentially redshift independent, the slope of the galaxy merger rate is much shallower than that of haloes at $z > 2.5$ and parallels that of haloes at $z < 1.6$.

(ii) These differences in haloes and subhalo merger rates arise because (1) halo mergers add mass to haloes instantly, while central subhalo mass grows more gradually after a halo merger; (2) halo major mergers do not necessarily lead to subhalo major mergers, since central subhaloes experience mass growth while a satellite subhalo’s infall mass typically remains constant as it orbits and (3) the satellite subhalo fraction grows with time, and satellites are twice as likely to be recent mergers as centrals of the same infall mass.

(iii) 15–35 per cent of all recently merged subhaloes are satellites, though a significant fraction of these arise from satellite–central parents during switches. 5–15 per cent of galaxy mergers arise from satellite–satellite parents, with a higher fraction at lower redshift.

(iv) At $z = 2.6$ ($z = 1$), 30 per cent (8 per cent) of galaxies have experience at least one major merger in the last 1 Gyr, regardless of mass. Haloes are more likely to have experience multiple mergers in their recent history.

(v) The likelihood of a halo to host a recently merged galaxy, $f_{\text{merg}}$, does not evolve with time at $z > 2.5$ and falls with time at $z < 1.6$.

(vi) Comparing galaxy and halo merger rates allows one to understand the evolution of the satellite halo occupation, and we approximated this behaviour analytically including fits to our simulations. Selecting subhaloes on fixed infall mass, the satellite halo occupation for haloes of a fixed mass increases with time at high redshift, peaks at $z \sim 2.5$ and falls with time after that. This implies similar evolution for the satellite galaxy component of the Halo Occupation Distribution.

Our results, based entirely on the dynamics of dark matter, represent an important but preliminary step towards quantifying the nature of galaxy mergers in hierarchical structure formation. To compare to many observables we would need to include baryonic effects, and indeed such effects can provide corrections to the merger rates themselves (Dolag et al. 2008; Jiang et al. 2008; Saro et al. 2008). The merger rates here also do not include whether the subhaloes are gas-rich (required for some observables) or not, though at the high redshifts we examine, we expect almost all galaxies to be gas-rich. While satellites can be stripped of much of their gas before merging with their central (e.g. Dolag et al. 2008; Saro et al. 2008), we have considered primarily massive satellites (relative to their host haloes), which have short infall times and thus experience less gas stripping.

Time-scales between observables and our measured merger event also play a role. In simulations, a quasar can appear up to $\sim 1$ Gyr after galaxy coalescence, though starbursts may occur more quickly (e.g. Hopkins et al. 2005; Springel, Di Matteo & Hernquist 2005a; Cox et al. 2008). However, morphological disturbance is clearest during first passage and final coalescence (Lotz et al. 2008b). The time-scales for each signature to commence and/or persist also have a large scatter, ranging from 0.2 to 1.2 Gyr after the merger. Finally, specific observations will also have specific selection functions. The quantitative measurements provided here provide starting points for these analyses in addition to helping to understand the properties of galaxies and their mergers in general.

Unfortunately, our predictions are not easily compared to observations which estimate merger rates at $z \lesssim 1$ using close galaxy pairs or disturbed morphologies (most recently, Bell et al. 2006; Kampczyk et al. 2007; Kartaltepe et al. 2007; Lin et al. 2008; Lotz et al. 2008a; McIntosh et al. 2008; Patton & Atfield 2008) since they have found that the close pair fraction evolves as $(1 + z)^{m}$ with a diverse range of exponents from $\alpha = 0$ to 4. Furthermore, translating these observations into galaxy or halo merger rates requires including more physical effects, e.g. time-dependent galaxy coalescence time-scales (Kitzbichler & White 2008; Mateus 2008) or inclusion of changes in numbers of host haloes with redshift (Berrier et al. 2006).

While we were preparing this work, Simha et al. (2008) appeared which consider detailed merger properties of satellite subhaloes in a hydrodynamic simulation, and Angulo et al. (2008) appeared which consider satellite mergers in the Millennium simulation. After this paper was submitted, Stewart et al. (2008a) appeared, which also considers merger rates as a function of mass, redshift and mass ratio.

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APPENDIX A: SUBHALO MASS AND CIRCULAR VELOCITY

Here, we further elaborate on the details of subhaloes in our simulations, including their radial density and circular velocity profiles and the relation between mass and maximal circular velocity, including its evolution with time.

Fig. A1 shows the radial density and circular velocity profiles for eight satellite and eight central subhaloes with $V_{c,\text{max}} \simeq 250 \text{ km s}^{-1}$ ($M \sim 10^{12} h^{-1} M_\odot$) at $z = 2.6$ in the $100 h^{-1}$ Mpc simulation. Circular velocity is defined as $V_c \equiv \sqrt{GM(<r)/r}$, and since subhaloes follow NFW density profiles, with a break in the power-law density profile at the scale radius, $r_s$, they have a maximum value in their circular velocity profiles, $V_{c,\text{max}}$, at $r_{\text{max}} = 2.2 r_s$. The left-hand panels show the radial profiles of all matter surrounding the subhaloes, while the right-hand panels show only that of matter assigned to the subhaloes. Satellites and centrals have similar profiles at small radii, though the right-top panel shows that satellites exhibit signs of tidal truncation at $\sim 50 h^{-1}$ kpc. This is also visible in the circular velocity profile in the bottom-left panel, where $V_c$ for satellites rises sharply, exhibiting a transition to their host haloes. For the centrals, the rise in $V_c$ beyond $\sim 1 h^{-1}$ Mpc arises from neighbouring structures.

Fig. A2 shows the relation between subhalo infall mass, $M_{\text{inf}}$, and infall maximum circular velocity, $V_{c,\text{inf}}$, for subhaloes at $z = 2.6$. We fit this relation to

$$V_{c,\text{inf}}^\gamma = B(z) M_{\text{inf}}$$

(A1)

for all subhaloes above $10^{11} h^{-1} M_\odot$, finding $\gamma = 3$ holds to good approximation at all redshifts we examine, in agreement with the virial relation $V_{c,\text{max}}^2 \sim M/R \propto M / M^{1/3} \propto M^{2/3}$. The outliers with large $M_{\text{inf}}$ relative to $V_{c,\text{inf}}$ are satellites that experienced a major merger; under our prescription, a satellite child’s $M_{\text{inf}}$ is the sum of its parents’ $M_{\text{inf}}$, but a child’s $V_{c,\text{inf}}$ is that of its highest $V_{c,\text{inf}}$ parent.

Fixing $\gamma = 3$, Fig. A3 shows the evolution of the amplitude $B(z) = V_{c,\text{inf}}^\gamma / M_{\text{inf}}$. A subhalo of a given mass has a higher maximum circular velocity at higher redshift, reflective of the increased density of the universe when the subhalo formed. As a subhalo subsequently accretes mass, its $V_{c,\text{max}}^3$ grows more slowly than its mass (in cases of slow mass growth, we find $V_{c,\text{max}}^3$ can remain constant).

Figure A1. Left: radial density profiles (top) and circular velocity profiles (bottom) of all matter around eight satellite (dotted) and eight central (dashed) subhaloes with $V_{c,\text{max}} \simeq 250 \text{ km s}^{-1}$ at $z = 2.6$. Right-hand panel: same, but only for matter assigned to the subhaloes.

Figure A2. Relation between subhalo infall maximum circular velocity, $V_{c,\text{inf}}$, and subhalo infall mass, $M_{\text{inf}}$, at $z = 2.6$. Black points show a 25 per cent sub-sample of all subhaloes as a measure of scatter, the solid red line shows the least-squares fit to equation (A1) and the dashed red lines show the 1σ scatter, for subhaloes with $M_{\text{inf}} > 10^{11} h^{-1} M_\odot$.

Figure A3. Evolution of the ratio of subhalo infall maximum circular velocity to infall mass, $B(z) = V_{c,\text{inf}}^3 / M_{\text{inf}}$ (solid), and 1σ scatter (dashed) for subhaloes with $M_{\text{inf}} > 10^{11} h^{-1} M_\odot$. Dotted line shows fit to $B(z)$ of equation (A2).
This is in agreement with Diemand et al. (2007), who found that haloes undergoing mild mass growth (no major mergers) had less than 10 per cent change in $V_{\text{c,max}}$ and $r_{\text{max}}$. We find that the evolution of $B(z)$ (within the redshifts we probe) can be well-approximated by

$$B(z) = 6.56 \times 10^{-6} e^{0.056 (\text{km s}^{-1})^2 h \text{M}_\odot^{-1}}.$$  

(A2)

Thus, $M_{\text{inf}} = 10^{11} (10^{17}) h^{-1} \text{M}_\odot$ subhaloes correspond to $V_{\text{c,inf}} \simeq 120 (250) \text{km s}^{-1}$ at $z = 2.6$ and $V_{\text{c,inf}} \simeq 100 (200) \text{km s}^{-1}$ at $z = 1$. Conversely, for fixed $V_{\text{c,inf}}$, a subhalo is about half as massive at $z = 2.6$ than at $z = 1$.

Since we fit relations of satellite subhalo properties at infall, our results above are applicable equally to satellite and central subhaloes. In addition, our results change by only a few per cent if we instead consider host haloes.

**APPENDIX B: SATELLITE SUBHALO MASS FUNCTION**

Fig. B1 shows the satellite subhalo (scaled) mass function versus the ratio of satellite mass to halo mass, for various host halo mass bins at $z = 1$. Thick curves show satellite masses selected on $M_{\text{inf}}$, while thin curves show satellite masses selected on instantaneous bound mass. The rollover in the $M_{\text{inf}}$ curves at low satellite mass indicates where satellites become numerically disrupted by resolution effects. Numerical disruption occurs at higher satellite $M_{\text{inf}}$ for more massive haloes, indicating that satellites of a fixed $M_{\text{inf}}$ experience more pronounced tidal stripping in higher mass haloes, where dynamical friction time-scales and central densities are higher. The rollover in the highest halo mass bin occurs at $M_{\text{sat,inf}} \approx 10^{11} h^{-1} \text{M}_\odot$, which sets our minimum subhalo mass for robust tracking.

We find that the scaled instantaneous bound mass function exhibits little-to-no systematic dependence on halo mass, in agreement

with Angulo et al. (2008). This is in contrast to the scaled infall mass function, which shows more satellites at a given mass ratio for more massive haloes. This difference is driven by subhalo mass stripping. Averaged over the entire satellite population at this redshift, the instantaneous bound mass function is $\sim 30$ per cent that of $M_{\text{inf}}$, as can be seen by the $x$-axis offset of the solid and dashed curves. However, satellites exhibit less average mass loss in low-mass haloes than high-mass haloes, the instantaneous to infall mass ratios being 40 and 25 per cent, respectively. This is considerably higher than the 5–10 per cent at $z = 1$ found in the semi-analytic model of van den Bosch et al. (2005). Additionally, van den Bosch et al. (2005) and Giocoli, Tormen & van den Bosch (2008) found the opposite trend with halo mass, i.e. that the average mass loss of satellites is higher for lower mass haloes. They find that this arises because lower mass haloes form (and accrete their subhaloes) earlier, when the dynamical/stripping time-scale is shorter. Thus, the satellites of lower mass halo are stripped both more rapidly and over a longer time period (see also Zentner et al. 2005). Finally, Giocoli et al. (2008) find that the scaled mass functions of subhaloes at infall does not depend on halo mass, in seeming contrast with Fig. B1.

These discrepancies likely arises because we examine the masses of extant subhaloes in our simulation, while van den Bosch et al. (2005) and Giocoli et al. (2008) track subhalo mass loss much longer than our simulation does. Their semi-analytical model of subhalo mass loss has no prescription for central–satellite mergers, which preferentially serve to reduce highly stripped satellites from our sample. Since satellites of a given infall mass to halo mass ratio have lower mass in lower mass haloes, they are closer to our minimum subhalo finding mass threshold. Thus, a fixed amount of stripping will cause lower mass haloes to have a reduced population of satellites of a given infall mass to halo mass ratio. It is unclear at what level of subhalo mass stripping we should expect the galaxies to become disrupted as well.

Various studies using high-resolution simulations have explored in detail the slope of the subhalo mass function (De Lucia et al. 2004; Gao et al. 2004a; Diemand, Kuhlen & Madau 2007; Angulo et al. 2008; Madau, Diemand & Kuhlen 2008), finding that the instantaneous mass function of subhaloes goes as $N_{\text{sat}}(>M_{\text{sat}}) \propto (M_{\text{halo}}/M_{\text{sat}})^\alpha$, with $\alpha = 0.9–1$. We note, though, that these fits are based on cuts on instantaneous subhalo mass or circular velocity, not those at infall. However, we find that, between the rollover in $M_{\text{inf}}$ at low and high satellite mass, the slopes of the mass functions selected on infall and instantaneous bound mass are the same within error, and $\alpha = 0.9$ fits our mass function selected on either mass. The similarity of the two slopes also implies that the mass-loss rate of satellites does not depend strongly on satellite mass, in agreement with Giocoli et al. (2008).

![Figure B1. Satellite subhalo (scaled) mass function, for various host halo mass bins, at $z = 1$. Thick curves show satellite mass selected on $M_{\text{inf}}$, while thin curves show satellite mass selected on instantaneous bound mass. While the instantaneous bound mass function exhibits no dependence on halo mass, the infall mass function has a higher amplitude for more massive haloes. An appreciable number of satellites exists at $M_{\text{inf}}/M_{\text{halo}} \approx 1$ because of switches. Below the rollover at high satellite mass, both mass functions scale as $\Delta N_{\text{sat}}/\Delta M_{\text{sat}} \propto M_{\text{inf}}^{-0.9}$, in agreement with instantaneous satellite subhalo bound mass functions found by numerous authors (see text).](https://academic.oup.com/mnras/article-abstract/395/3/1376/998022/0.9531.3769/2222/199456751015802)

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