The cosmic evolution of halo pairs – I. Global trends

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ABSTRACT

Accumulating evidence suggests that galaxy interactions play an important role in shaping the properties of galaxies. For this reason, cosmological studies focused on the evolution of halo/subhalo pairs are vital. In this paper I describe a large catalogue of halo pairs extracted from the publicly available Millennium Simulation, the largest of its kind to date. (Throughout this work I use the term ‘halo’ to refer both to individual haloes in the field and to subhaloes embedded in larger structures.) Pairs are selected according to whether or not they come within a given critical (comoving) distance $d_{\text{crit}}$, without the prerequisite that they must merge. Moreover, a condition requiring haloes to surpass a critical mass $M_{\text{crit}}$ during their history is imposed. The primary catalogue, consisting of 502,705 pairs, is selected by setting $d_{\text{crit}} = 1\text{ Mpc} \, h^{-1}$ and $M_{\text{crit}} = 8.6 \times 10^{10} M_\odot \, h^{-1}$ (equivalent to 100 simulation particles). One of the central goals of this paper is to evaluate the effects of modifying these criteria. For this purpose, additional subcatalogues with more stringent proximity and mass conditions are constructed (i.e. $d_{\text{crit}} = 200\text{ kpc} \, h^{-1}$ or/and $M_{\text{crit}} = 8.6 \times 10^{11} M_\odot \, h^{-1} = 1000$ simulation particles – see Table 1 for a summary). I use a simple five-stage picture to perform statistical analyses of their separations, redshifts, masses, mass ratios and relevant lifetimes. The fraction of pairs that never merge (because one of the members in the pair is absorbed by a third halo or both members survive until the present time) is accounted for. These results provide a broad picture that captures the essential characteristics behind the evolution of these halo pairs. This is the first of a series of papers aimed to explore the huge wealth of information encoded in this catalogue. Such investigations will play a fundamental role in future cosmological studies of interacting galaxies and binary (and multiple) quasars.

Key words: galaxies: evolution – galaxies: formation – galaxies: interactions – galaxies: statistics – cosmology: theory – dark matter.

1 INTRODUCTION

Galaxy mergers and interactions are among the most spectacular events in the sky. But more importantly, they provide a bridge between worlds: linking the large-scale hierarchical universe to the internal properties of individual galaxies and their evolution. Such encounters have the ability to change the morphology of a galaxy (Toomre & Toomre 1972), and can cause a substantial migration of its gas towards the central regions (e.g. Barnes & Hernquist 1991, 1996). Ultimately, sudden bursts of star formation and the activation of the supermassive black hole at the nucleus can be attributed to this mechanism. This single idea has been, without a doubt, instrumental to all modern theories of galaxy formation (see e.g. the textbook by Mo, van den Bosch & White 2010, and references therein).

Admittedly, mergers have received more attention than the early stages of interaction preceding them. The last few years have witnessed the development of a whole industry of pre-prepared galaxy–galaxy merger simulations (e.g. Hopkins et al. 2005; Robertson et al. 2006). Unfortunately, the pre-merger stages are seldom the priority of these numerical studies (but see Di Matteo et al. 2007; Callegari et al. 2009, 2011, whose simulations are tailored to emphasize the role of early interactions on star formation and black hole growth, respectively). Likewise, huge efforts have also been reserved towards cosmological theoretical merger rates of galaxies, dark matter haloes and subhaloes (e.g. Lacey & Cole 1993, 1994; Governato et al. 1999; Cohn, Bagla & White 2001; Gottlöber, Klypin & Kravtsov 2001; Benson 2008; Fakhouri & Ma 2008; Guo & White 2008; Mateus 2008; Neistein & Dekel 2008; Genel et al. 2009; Wetzel, Cohn & White 2009; Hester & Tasitsiomi 2010; Hopkins et al. 2010; Moreno 2010).

Recently, however, a wide array of observations have provided hints that should persuade us as a community to redirect some of our attention to galaxy interactions. For example, a number of studies demonstrate that star formation is enhanced in pairs (typically within $\lesssim 50\text{ kpc}$), and this effect is anticorrelated with their...
separation (e.g. Barton, Geller & Kenyon 2000; Lambas et al. 2003; Nikolic, Cullen & Alexander 2004; Ellison et al. 2008; Darg et al. 2010; Wong et al. 2011, and subsequent works by these groups). Even at high redshifts, Ly$\alpha$ emission is heightened in pairs of Lyman-break galaxies with small separations (Cooke et al. 2010).

Galaxy interactions also play a role in active galactic nuclei (AGN). For example, Alonso et al. (2007) report enhanced nuclear activity in $\sim$10 per cent of their galaxy pair catalogue (with projected separations $<25\,kpc\,h^{-1}$). The intensity of nuclear activity may depend on various factors, including the budget of gas available and the strength of the torques that can drive this gas into the central regions (the latter effect is primarily determined by the orbit of the encounter and the mass ratio). Interestingly enough, they find that galaxies with bright/massive companions appear to be more active, suggesting that galaxies with shallower potentials are more susceptible to the gravitational torques produced during the interaction.

Lately, the search of binary quasars has gained impetus greatly in part because these systems are thought to be the precursors of coalescing black holes. While it is true that supermassive black hole growth is expected to be dominated by gas accretion during quasar phases, not by mergers of black hole pairs (Salucci et al. 1999; Marconi et al. 2004; Shankar et al. 2004; Shankar, Weinberg & Miralda-Escudé 2009); these unique events remain interesting, especially because their existence could be detected by future gravity-wave missions like the Laser Interferometer Space Antenna (LISA) (e.g. Sesana et al. 2005). From a theoretical perspective, pairs of quasars at galactic separations establish the initial conditions necessary to comprehend these peculiar duos as they find their way into the central regions and perhaps into each other.

In particular, building up on previous samples (Hennawi et al. 2006; Myers et al. 2007, 2008; Foreman, Volonteri & Dotti 2009) compiled a list of 85 quasar binary pairs. Their physical-separation distribution peaks at $\sim$30 kpc, with a long tail at larger separations ($\sim$100–200 kpc). Indeed, these authors find 14 pairs separated by distances $\gtrsim$300 kpc! The size of this census was recently increased by over an order of magnitude by Liu et al. (2011b), who report 1288 binary AGN (236 with tidal features), 39 triplets, two quadruplets and one quintuplet. For the binaries, their projected-separation distribution exhibits peaks at $\sim$5, 20 and 60 kpc $h^{-1}$. However, if only pairs displaying tidal features are considered, a sharper peak at $\sim$20 kpc $h^{-1}$ remains (at this stage, these are the only ones guaranteed to be truly interacting, and further investigations might be desirable for the rest). Additionally, these authors find evidence that the galaxies in the pairs with the smaller stellar mass manifest more nuclear activity than their companions, suggesting that either secondary galaxies have more available fuel or that they are more susceptible to tidal perturbations (Liu, Shen & Strauss 2011c). Lastly, supermassive black hole pairs have also been observed in dust-enshrouded merging galaxies. For instance, Dasyra et al. (2006) find 21 ultraluminous infrared galaxies with nuclear separations between 1.6 and 23.3 kpc, thought to be between the first and final passage prior to a merger.

All this emerging observational evidence highlights the immediate need to focus on the long-lived evolution of galaxy pairs (and their supermassive black holes) in the stages prior to mergers. With this ultimate goal in mind, I analyse a very large catalogue of halo pairs and their evolution, suitable for future statistical studies of galaxy and quasar binaries. This catalogue, consisting of over half a million pairs, is extracted from the publicly available Millennium Simulation Database (Springel et al. 2005), the largest of its kind published so far. In this work, pairs of haloes are selected by whether or not they are identified within a critical separation at some stage of their history. With this choice, pairs of haloes that never merge are not automatically rejected by construction. The effects of changing this critical condition are considered. I also explore the consequences of selecting pairs involving haloes that reach masses above a given threshold at some point of their evolution. The motivation here is to test whether close pairs of massive haloes are more or less susceptible to merging than pairs involving haloes with small masses.

This is the first of a series of papers that exploit this catalogue with the aim to understand the evolution of halo pairs in the universe. As in any exploratory paper, I only touch on the most basic general trends. These results will serve as a benchmark for future studies – with more specialized subcatalogues, refined recipes and astrophysical applications – to be presented in forthcoming papers.

Broadly speaking, I describe the evolution pairs in terms of five simple stages: initial, entry, closest, final and fate (see Section 2.3 for definitions). Quantities like the relative distance, redshift, total mass, mass ratio and lifetime are analysed statistically. Kinematic vector quantities like velocities and spins will be analysed in a companion paper (Moreno, in preparation). Relevant time intervals are also studied. Often throughout the paper I use the term ‘interacting’ to refer to pairs within a chosen critical separation. It is important to emphasize that I do not presume to know a priori the exact proximity criteria at which tidal disturbances are actually effective. Nevertheless, using this term facilitates the discussion of the trends in the halo pair catalogue.

The remainder of this paper is organized as follows. Section 2 describes the methods: the Millennium Simulation, halo pair identification, the catalogue and the stages of evolution. Statistical results are found in Section 3, which focuses on the stages and relevant lifetimes. In Section 4, I discuss the results, their interpretation and their relation to other works in the literature. A summary is provided in Section 5. Throughout this work, all distances are comoving, unless stated otherwise.

2 METHODS

2.1 The Millennium Simulation

In a nutshell, the Millennium Simulation is a dark-matter-only simulation that adopts a flat $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology with the following parameters: $(\Omega_m, \Omega_b, \sigma_8, n_s, h) = (0.25, 0.045, 0.9, 1, 0.73)$. The simulation covers a periodic comoving box with $L_{\text{box}} = 500\,\text{Mpc}\,h^{-1}$ on a side. It follows the evolution of $2160^3 \approx 10^{10}$ dark matter particles with mass $m_p = 8.6 \times 10^9\,\text{M}_\odot\,h^{-1}$. Dark matter haloes are identified using a friends-of-friends (FOF) algorithm (Davis et al. 1985) with a linking length set equal to 0.2 times the mean interparticle separation. These structures are identified at 64 snapshots from $z = 127$ to the present, spaced nearly equally in log $(1+z)$. The Plummer-equivalent force softening scale is set to $5\,\text{kpc}\,h^{-1}$.

Self-bound structures with the FOF groups are identified with the SUBFIND algorithm (Springel et al. 2001). This method identifies the main background dark matter halo and its substructures (i.e. the subhaloes). Giocoli et al. (2010) compares SUBFIND against various other substructure-finding algorithms in their appendix A. Merger history trees are built from these self-bound objects by tracking their ‘descendants’ at the next snapshot with lower redshift (see the supplementary information in Springel et al. 2005 for more details). Once the trees are built, one can track the identity of each object in the hierarchy back in time by following its principal branch (see...
single merger history tree extracted from the Millennium Simulation in detail. In reality, the spatial evolution of a merger tree should be represented in (3 + 1) dimensions. However, for illustrative purposes, the (1 + 1)-dimensional representation in Fig. 1 suffices.

In this figure, the black open circles depict the redshifts and positions (schematically represented by the X-coordinates) of the haloes identified in the simulation. The radii are proportional to the logarithm of the mass. The solid grey lines flanking the branches enclose half of the mass of each halo, giving a rough sense of the ‘size’ of these objects. The solid red circles denote mergers and the black dotted rectangles (or parallelograms) represent close interactions. The branches are said to be ‘interacting’ if they are within some critical distance $d_{\text{crit}}$ of each other (in the figure, $d_{\text{crit}} = 200\, \text{kpc}\, h^{-1}$).

The merger history occurs as follows. First branch A (dark-green dot–dashed lines) merges with branch B (blue long-dashed lines). Of these two, only branch B continues on to later epochs after the merger. Another way to put this is that branch A ‘merges on to’ branch B because, right before the merger, the halo on branch B is more massive than the halo on branch A. Later on, branch C (magenta short-dashed lines) also merges on to branch B. This is followed by branch B merging on to branch D (dark-brown solid lines). Lastly, branch E (dotted long-dashed green lines) merges on to branch D. In this merger tree, branch D is the principal branch of the final halo rooted at $z = 0$.

Not all branches begin at the same redshift. For instance, branches A and B appear simultaneously. Later, branch D appears, followed by branch C. Branch E is born long after most of the other branches have already merged. Physically, the haloes might have been around from much earlier epochs. However, the simulation only identifies haloes with at least 20 particles.

The growth of haloes within larger haloes (i.e. subhaloes) is commonly thwarted by the rich environments surrounding them, which tidally strip them of their diffuse outer layers (e.g. Moore, Katz & Lake 1996; Moore et al. 1999; Tormen 1997; Ghigna et al. 1998; Tormen, Diaferio & Syer 1998; Klypin et al. 1999; Taffoni et al. 2003; Giocoli, Tormen & van den Bosch 2008). In many cases, haloes go below the resolution of the simulation, and are no longer identified. Such is the case of branch E, which disappears before merging on to branch D. Extra care must be taken when dealing with these situations. Namely, one must pay attention and make sure that both haloes are identified at every snapshot in the interaction. In this work I impose an extra condition on the mass which deletes many (but not all) of the small subhaloes that get stripped apart by their hosts (see Section 2.4.1). With this condition, much less than 1 per cent of the pairs have one member stripped apart by their hosts (see Section 2.4.1). With this condition, much less than 1 per cent of the pairs have one member below resolution (situations where both members go below resolution are non-existent under this condition). For the remainder of the paper, these effects will be ignored because they happen so infrequently.

A merger tree with $N$ branches has $N(N - 1)/2$ candidate pairs. However, not all of them qualify as interacting. For instance, the merger tree in Fig. 1 has five branches and $5(5 - 1)/2 = 10$ candidate pairs; but five of those 10 pairs are never counted as ‘close’ pairs. Namely, the distance between branch A and either branch C or D is always greater than $d_{\text{crit}}$. Moreover, branch E appears after branches A, B and C have already merged on to branch D. In other words, branch E never ‘coexists’ with branches A, B and C. Although there are five closely interacting pairs, only four end up as mergers. Pair C–D interacts briefly but eventually gets separated beyond $d_{\text{crit}}$. Branch C never has the opportunity to merge on to branch D, and instead merges on to branch B. It is often tempting to assume that
all close pairs merge eventually. One of the goals of this paper is to quantify the fraction of close pairs that never merge.

Fig. 1 only shows a single merger tree. However, many massive haloes often have plenty of substructures. The appropriate thing to do in such situations is to follow the merger histories of both the central dominant halo and the satellites. In this paper, I pair up all branches in a given group, even if they belong to different merger trees within that group. Often I will use the term ‘never-merging’ to refer to pairs that do not merge because either one of the members in the pair gets absorbed by a third halo or because both haloes survive as separate substructures of a larger background halo until the present time.

Lastly, one could also pair up branches belonging to different groups; i.e. pairs of haloes that never end up gravitationally bound to each other. These events could be important if one tries to use close pairs as a proxy of mergers (e.g. Wetzel et al. 2008), especially if large separations (of the order of 1 Mpc h$^{-1}$) are used. This contribution is more likely to be at the few per cent level if smaller separations (of the order of 200 kpc h$^{-1}$) are used (private communication with the reviewer). For the sake of simplicity, in this work I ignore those pairs whose haloes end up in different host haloes. The effects of this particular limitation will be addressed in future work in the context of close-pair counts.

2.3 The stages of evolution

In this paper, the evolution of a pair of closely interacting haloes is described in terms of the following five stages.

(i) Initial: when the two haloes both exist for the first time (above the resolution of the simulation), regardless of whether they are closely interacting or not.

(ii) Entry: when the two haloes are, for the first time, at a distance less than $d_{crit}$. This may occur either at the initial stage or later.

(iii) Closest: when the two haloes are both identified as separate entities by the simulation and are at their closest distance.

(iv) Final: the last time the two haloes are both identified by the simulation, regardless of whether they are closely interacting or not.

(v) Fate: what ultimately happens to the pair: either (1) they merge, (2) one or both haloes are absorbed by a third halo or (3) both haloes survive until today.

It is useful to clarify a few subtleties in these definitions with specific examples from Fig. 1. First of all, note that both haloes in the A–B pair appear simultaneously and are both very small (just above resolution, with mass ratio very close to 1) at the initial time. In other cases, however, one of the two haloes may have some time to grow before its partner shows up in the simulation (pairs B–C and C–D, and especially D–E – the latter with a mass ratio particularly different from unity).

When the initial distance of the pair is below $d_{crit}$, the entry and initial times coincide (pairs A–B, C–D and D–E). For pairs A–C and A–D, on the other hand, the initial distance is larger than $d_{crit}$; and the entry time occurs much later than the initial time. When the entry time does not correspond to one of the snapshots in the simulation (e.g. as in pairs B–C and B–D), a linear interpolation in log(1 + z) is performed.

The closest distance is often equal to the final distance, especially right before mergers (pairs B–C, B–D and D–E). In some cases, though, the closest distance does not match the final distance. Examples of these include pairs A–B and C–D; where the former results in a merger and the latter does not.

The final epoch refers to the last time both haloes are identified in the simulation as separate entities. They need not be within $d_{crit}$: for instance the final time for pair C–D takes place at $z \simeq 2.7$, with separation $\approx 2d_{crit}$. In this particular case, it is interesting to know when the pair is within $d_{crit}$ for the last time (i.e. $z \simeq 4$ for pair C–D). In Section 3.5, I use this information to estimate the typical ‘lifetime’ of interactions.

The ultimate fate stage is formally not considered part of the evolution of the pair. Failing to make this distinction may lead to overcounting the number of instances a halo participates in an interaction. For example, the halo resulting from the merger of branches A and B participates in both pairs B–C and B–D, but not in A–B itself. (Once the merger has happened, the single remnant halo cannot be counted as part of its own halo pair!) It is important to probe the interval between the final and the fate time. If this portion is not included towards the lifetime of the pair, one could conclude that pair D–E has zero duration, whereas in reality it lasts from $z \simeq 2.4$ to 1.8 (slightly less than three full snapshots). Nevertheless, as mentioned before, in this paper I impose a mass condition that deletes most pairs involving haloes going below resolution (see Section 2.4.1) – thus situations like the D–E pair are extremely uncommon with this condition. Lastly, if the final epoch takes place today, the fate epoch is set equal to the final epoch. This is the case for pairs involving different members of a group today.

2.4 Constructing the catalogue

In this section, I explain the construction of the halo pair catalogue used in this paper, which can be understood as a series of selection criteria. I defer discussions on the adopted choices and assumptions to Section 4.1.

2.4.1 Mass selection

First, I only consider branches that reach a critical mass $M_{crit}$ at least once at some point throughout their lifetime. Isolated haloes typically reach their maximum mass at $z = 0$. However, recall that a halo immersed in a larger group (i.e. a subhalo) may be substantially dissolved by the gravitational tidal field of its host. In this case, it is possible that at some point a given halo had mass $> M_{crit}$, but ends up with mass $< M_{crit}$. In some extreme cases, it may even go below the resolution of the simulation. It must be mentioned that for general branches (i.e. those not obeying the above mass condition), this situation is not uncommon. Nevertheless, once the above mass condition is imposed, such situations become very infrequent (less than 1 per cent of the pairs have one member going below resolution at the late stages of interaction).

In this work, massive branches are kept even if they lose a substantial fraction of their mass at later epochs. To select these branches, the appropriate thing to do is to choose them by their maximum mass, not their final mass. Fig. 2 illustrates this situation by showing the mass history of two interacting haloes that are both accepted into the catalogue by this criterion. The horizontal dotted blue line denotes the mass selection threshold (in the figure, $M_{crit} = 8.6 \times 10^{10} M_\odot h^{-1} = 100 \times m_p$). The solid light-red line represents the more massive halo, while the secondary halo is shown as a dark-green dashed line. The first branch grows from $\approx 1.2 \times 10^{12}$ to $5 \times 10^{13} M_\odot h^{-1}$. For the most part, the mass of this halo increases monotonically (except for the brief dip near $z \approx 0.2$). At all times this branch is above the selection threshold. The second branch begins at $\approx 3 \times 10^{10} M_\odot h^{-1}$, below the selection threshold.

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relative distance can be calculated for all those snapshots for which both haloes are identified. With this, the next step is to find the minimum distance \(d_{\text{min}}\) (the closest stage, Section 2.3), and check if the \(d_{\text{min}} < d_{\text{crit}}\) criterion is met.

### 2.4.4 The halo pair sets

The following sets of halo pairs are considered: the Close Set (C), the Very Close Set (VC), the Massive Close Set (MC) and the Massive Very Close Set (MVC). These sets are defined by the following critical parameters:

(i) C: \((d_{\text{crit}}, M_{\text{crit}}) = (1 \text{ Mpc h}^{-1}, 8.6 \times 10^{10} \text{ M}_\odot \text{ h}^{-1})\);
(ii) VC: \((d_{\text{crit}}, M_{\text{crit}}) = (200 \text{ kpc h}^{-1}, 8.6 \times 10^{10} \text{ M}_\odot \text{ h}^{-1})\);
(iii) MC: \((d_{\text{crit}}, M_{\text{crit}}) = (1 \text{ Mpc h}^{-1}, 8.6 \times 10^{11} \text{ M}_\odot \text{ h}^{-1})\);
(iv) MVC: \((d_{\text{crit}}, M_{\text{crit}}) = (200 \text{ Mpc h}^{-1}, 8.6 \times 10^{11} \text{ M}_\odot \text{ h}^{-1})\).

Note that the latter three sets are simply subcatalogues of set C. Often in the text, and in all the remaining figures, I use the following terminology: C and MC are the Close Sets (with \(d_{\text{crit}} = 1 \text{ Mpc h}^{-1}\), upper panels); VC and MVC are the Very Close Sets (with \(d_{\text{crit}} = 200 \text{ kpc h}^{-1}\), lower panels); C and VC are the non-Massive Sets (with \(M_{\text{crit}} = 8.6 \times 10^{10} \text{ M}_\odot \text{ h}^{-1}\), left-hand panels); and MC and MVC are the Massive Sets (with \(M_{\text{crit}} = 8.6 \times 10^{11} \text{ M}_\odot \text{ h}^{-1}\), right-hand panels). For quick reference, Table 1 indicates the assigned values of \(d_{\text{crit}}\) and \(M_{\text{crit}}\), and the above terminology.

### 3 RESULTS

In this section, I present the distribution of several quantities as a function of what stage in their evolution the pairs happen to be. I also address relevant lifetimes and the effects of modifying \(d_{\text{crit}}\) and \(M_{\text{crit}}\). Only results are reported here. I postpone associated interpretations and discussions for Section 4. I do this for the sake of clarity because the forthcoming discussion requires having described all the figures in this section already.

#### 3.1 Relative distances

Each panel in Fig. 3 shows each of the four sets in Table 1. The vertical line is drawn at \(d_{\text{crit}}\) to indicate the separation at the entry stage. Relevant colours and line styles are indicated in all figures.

Typically, pairs have large initial distances, between a few up to 10 Mpc h\(^{-1}\), but never beyond 30 Mpc h\(^{-1}\). There is, however, a small fraction of pairs (~5 per cent) with \(d_{\text{initial}} < d_{\text{crit}}\). The most common closest separation is near \(d_{\text{crit}}\). Recall that close branches are selected so \(d_{\text{closest}} < d_{\text{crit}}\), which is why this distribution is truncated at \(d_{\text{crit}}\). At the final stage, a large fraction of pairs end

| Set   | \(d_{\text{crit}}\) | \(M_{\text{crit}}\) | Number |
|-------|---------------------|---------------------|--------|
| C     | 1 Mpc h\(^{-1}\)    | 8.6 \times 10^{10} M_\odot h\(^{-1}\) | 100    |
| VC    | 200 kpc h\(^{-1}\)  | 8.6 \times 10^{10} M_\odot h\(^{-1}\) | 100    |
| MC    | 1 Mpc h\(^{-1}\)    | 8.6 \times 10^{11} M_\odot h\(^{-1}\) | 1000   |
| MVC   | 200 Mpc h\(^{-1}\)  | 8.6 \times 10^{11} M_\odot h\(^{-1}\) | 1000   |

Table 1. Halo pair sets shown in the panels of all figures in Section 3. The abbreviations are as follows: C – Close, VC – Very Close, MC – Massive Close and MVC – Massive Very Close. Distances are in comoving coordinates. Recall that \(m_p = 8.6 \times 10^8\) M_\odot h\(^{-1}\). For reference, C and MC are the Close Sets, VC and MVC are the Very Close Sets, C and VC are the non-Massive Sets, and MC and MVC are the Massive Sets.
Figure 3. The relative-distance distribution of halo pairs. The set of halo pairs presented (see Table 1) is indicated in each panel: C (upper left), VC (lower left), MC (upper right) and MVC (lower right). The colours and line styles are indicated in the figure. The vertical line represents $d_{\text{crit}}$. Only pairs that never merge are presented for the fate stage (indicated by the ‘two haloes’ label). For reference, the text uses the following definitions to describe the set $s$: Close Sets ($d_{\text{crit}} = 1 \text{Mpc} h^{-1}$; upper panels), Very Close Sets ($d_{\text{crit}} = 200 \text{kpc} h^{-1}$; lower panels), non-Massive Sets ($M_{\text{crit}} = 8.6 \times 10^{10} \text{M}_\odot h^{-1}$; left-hand panels) and Massive Sets ($M_{\text{crit}} = 8.6 \times 10^{11} \text{M}_\odot h^{-1}$; right-hand panels). See Sections 2.3 and 2.4.4, respectively, for definitions and descriptions of the stages and sets.

3.1.1 Initial distances

The initial-distance distribution for the Close Sets peaks at $\simeq 10 \text{Mpc} h^{-1}$, is narrow, and drops sharply at low separations. For the Very Close Sets, the distribution peaks around 8 and 3 Mpc $h^{-1}$ (for the VC and MVC sets, respectively) and has a small secondary peak at $\simeq 100 \text{kpc} h^{-1}$ before dropping sharply at low separations (the secondary peak is more evident for the MVC set). Reducing $d_{\text{crit}}$ does not alter the distributions significantly, except for the appearance of a bump slightly below $d_{\text{crit}}$ and a trough slightly above this value. Increasing $M_{\text{crit}}$ also enhances the low-separation regime, but to a very small degree. I must emphasize that the initial stage depends strongly on the resolution of the simulation. Nevertheless, it is interesting to show the highest redshift status of the close pairs one can study with the Millennium Simulation.

3.1.2 Closest distances

For the most part, the closest-distance distribution increases monotonically with increasing distance and is truncated at $d_{\text{crit}}$. For up at distances beyond $d_{\text{crit}}$. For the rest, the final-distance distribution resembles the closest-distance distribution. In all cases, a non-negligible fraction of pairs never merge (labelled as ‘fate with two haloes’), and many of those even end up at distances greater than $d_{\text{crit}}$. Below, I describe these trends for each stage separately.
the Very Close Sets, the peak coincides with the location of the secondary peak in the initial-distance distribution. Reducing $d_{\text{cut}}$ strongly increases the contribution from pairs with small minimum separations (in particular, below 100 kpc $h^{-1}$). Increasing $M_{\text{cut}}$ leaves the distribution almost intact, except for a slight enhancement at small separations.

3.1.3 Final distances

The shape of final-distance distribution mimics that of the closest-distance distributions up to $d_{\text{cut}}$, and then decreases beyond that (with an extra small bump at $\approx 800$ kpc $h^{-1}$ for the Very Close Sets). The final distance never exceeds 5 Mpc $h^{-1}$. For the Close Sets, the final-distance distribution peaks at $\sim 800$ kpc $h^{-1}$, while the peak is at $\sim 200$ kpc $h^{-1}$ for the Very Close Sets.

Decreasing $d_{\text{cut}}$ shifts the distribution to smaller separations, enhancing the number of small-distance pairs (with $d_{\text{final}} < 200$ kpc $h^{-1}$) quite significantly. However, this change is not so strong for pairs with $d_{\text{final}} < d_{\text{cut}}$. On the other hand, the contribution to other regimes ($> 200$ kpc $h^{-1}$) is suppressed with decreasing $d_{\text{cut}}$. The effects of increasing $M_{\text{cut}}$ are similar to those of decreasing $d_{\text{cut}}$, but milder. However, while decreasing $d_{\text{cut}}$ enhances the secondary bump present in the Very Close Sets, increasing $M_{\text{cut}}$ actually suppresses the bump, but only slightly.

3.1.4 Fate distances (two haloes)

I only present the fraction of fate distances of pairs that never merge. (Recall that never-merging pairs are those that either get split by a third party or survive as two entities until today.) For the fate two-halo distribution, I will often speak of the ‘absolute’ and ‘relative’ contribution from a given regime. The former is normalized to the total population of pairs, while the latter is normalized to the subset of pairs that never merge. In other words, the sum of all relative contributions is 100 per cent, while the sum of all absolute contributions is (53, 42, 39, 27) per cent for the (C, VC, MC, MVC) set.

The shape of the fate-distance distribution is similar to that of the final-distance distributions for the Close Sets, and to the secondary bump in the final-distance distributions for the Very Close Sets. Reducing $d_{\text{cut}}$ decreases the absolute number of pairs that never merge. It shifts the distribution to lower distances (the peak moves from $\sim 800$ to $\sim 400$ kpc $h^{-1}$ for the non-Massive Sets, and from $\sim 800$ to $\sim 300$ kpc $h^{-1}$ for the Massive Sets). However, the relative fraction of pairs with $d_{\text{final}} > d_{\text{cut}}$ increases. In other words, there is a shift to smaller separations; but this shift is actually to larger separations in units of $d_{\text{cut}}$. Increasing $M_{\text{cut}}$ also suppresses the absolute contribution of pairs that never merge. This effect is more evident than that produced by reducing $d_{\text{cut}}$.

3.2 Redshifts

Fig. 4 shows the distributions of halo pair redshifts at various stages of their evolution. The initial-redshift distribution is dominated by pairs at very early epochs ($z > 4$), with some low-redshift contributions for the Massive Sets. The subsequent stages of interaction (i.e. entry $\rightarrow$ closest $\rightarrow$ final) happen at much lower redshifts (compared to the initial distribution), and are increasingly less frequent with high redshift. As the interaction progresses, the distribution shifts to lower redshifts (the final distribution exhibits a small upturn at very low redshifts). This trend continues at the fate stage for those pairs that never merge. More than $\sim 50$ per cent of the never-merging fate pairs occur at $z < 0.5$, while less than $\sim 10$ per cent take place at $z > 1$.

Reducing $d_{\text{cut}}$ only enhances the fraction of initial pairs below $z \sim 1$ slightly. This change makes the entry-redshift distribution shallower in the $z < 3$ regime, and introduces a sharp drop afterwards, bringing its shape more in line with the closest and final-redshift distributions. The same flattening and drop appear for the closest and final distributions. The fate distribution is suppressed more strongly as a function of redshift, increasing the discrepancy with the other three distributions described here. Increasing $M_{\text{cut}}$ also enhances the fraction of initial pairs below $z = 1$. Additionally the peak near $z \sim 6$ becomes narrower, and a trough at $z \sim 3$ appears. For the entry distribution, the high-redshift regime is slightly suppressed (but not completely erased) for the Close Sets, and completely cut off beyond $z > 4$ for the Very Close Sets. The closest and final distributions are also cut off completely beyond $z > 4$. The fate distributions are completely suppressed beyond $z > 3$, and enhanced in the $z < 0.5$ regime.

3.3 Total masses

Fig. 5 shows the distribution of the sum of the two masses (hereafter, the total mass) in a halo pair at various stages of their evolution. At the initial stage, the majority of the total masses are rather small (peaking below $10^{11} M_{\odot} h^{-1}$, with a negligible contribution from masses greater than a few $\times 10^{13} M_{\odot} h^{-1}$). The transition from the initial to the entry stage populates the large-mass regime, evacuating the small-mass regime as a result. This shift towards more massive pairs is more evident for the Massive Sets. As the interaction progresses (i.e. entry, closest and final stages), the very large mass regime ($\gtrsim$ a few $\times 10^{13} M_{\odot} h^{-1}$) continues to grow, while the rest shrinks. (This transition mass scale is not very evident for the MVC set.) These shifts are very small relative to the previous initial $\rightarrow$ entry shift, but not entirely insignificant. The fate-mass distribution of pairs that never merge does not resemble the others because it is controlled by third parties that absorb the pairs, not by the pairs themselves. Note that these pairs are incorporated preferentially into extremely massive haloes (ending up with masses typically greater than $10^{14} M_{\odot} h^{-1}$). These situations most likely involve two subhaloes interacting for a while until they are split apart by the central halo.

3.3.1 Initial total masses

Reducing $d_{\text{cut}}$ does not alter the initial-mass distribution by much, except for a small enhancement in the large-mass regime (with masses $\gtrsim$ a few $\times 10^{13} M_{\odot} h^{-1}$). A similar effect happens when $M_{\text{cut}}$ is increased. This distribution is strongly determined by the resolution of the simulation, and its features will not be addressed in much detail. Nevertheless, it serves as reference to see how much the branches grow during the interacting stages.

3.3.2 Entry, closest and final total masses

In this section, I describe the entry, closest and final stages together because they follow similar total-mass distributions. These distributions are broader than the initial-mass distribution, and peak at a higher values: slightly above $10^{11}$ and $10^{12} M_{\odot} h^{-1}$ for the non-Massive and Massive Sets, respectively. Relative to the initial stage, the typical total mass increases by a factor of $\sim$2 for the non-Massive
Sets, and by a factor of \(~20\) for the Massive Sets. Moreover, the large-mass contribution (with masses \(\gtrsim\) a few \(\times\) \(10^{13}\) \(\text{M}_{\odot}\) \(\text{h}^{-1}\)) is no longer negligible.

Reducing \(d_{\text{crit}}\) does not alter the distributions much, except that the high-mass drop becomes shallower, enhancing the contribution from that regime. This is particularly noticeable for the Massive Sets. Increasing \(M_{\text{crit}}\) shifts the peak of the distributions from \(\approx10^{11}\) to \(10^{12}\) \(\text{M}_{\odot}\) \(\text{h}^{-1}\). This suppresses the small-mass regime, and enhances the large-mass regime. The location of the new peak coincides with that of the small bump found in the initial total-mass distribution. The large-mass plateau is enhanced more significantly here than when \(d_{\text{crit}}\) is reduced.

### 3.3.3 Fate total masses (two haloes)

Fig. 5 shows the fate total-mass distribution, which is completely different from the distributions at other stages. This distribution increases monotonically with mass, except at the very high masses, where a small dip is present. Reducing \(d_{\text{crit}}\) and \(M_{\text{crit}}\) both have the same effect: to enhance the small-mass end and suppress the
Figure 5. The total mass distribution of halo pairs. The set of halo pairs presented (see Table 1) is indicated in each panel: C (upper left), VC (lower left), MC (upper right) and MVC (lower right). The colours and line styles are indicated in the figure. Only pairs that never merge are presented for the fate stage (indicated by the ‘two haloes’ label). For reference, the text uses the following definitions to describe the sets: Close Sets ($d_{\text{crit}} = 1\,\text{Mpc}\,h^{-1}$; upper panels), Very Close Sets ($d_{\text{crit}} = 200\,\text{kpc}\,h^{-1}$; lower panels), non-Massive Sets ($M_{\text{crit}} = 8.6 \times 10^{10}\,\text{M}_\odot\,h^{-1}$; left-hand panels) and Massive Sets ($M_{\text{crit}} = 8.6 \times 10^{11}\,\text{M}_\odot\,h^{-1}$; right-hand panels). See Sections 2.3 and 2.4.4, respectively, for definitions and descriptions of the stages and sets.

3.4 Mass ratios

Fig. 6 shows the distribution of the mass ratios of the haloes in the pairs at various stages of their evolution. In this work, the mass ratio is defined as the ratio of the small to the large mass in a given pair (i.e. this quantity is always $\leq 1$; small values correspond to disparate pairs while large values correspond to nearly equal pairs). In particular, the primary versus secondary ranking of the haloes in the pairs need not remain fixed at all times: at times the haloes may switch roles. For instance, a halo may begin more massive than its companion, but then the companion could grow quickly for some period and quickly surpass its partner. In these situations, the ranking of the mass ratios are adjusted accordingly.

The resolution of the simulation, and the criterion that branches must surpass a critical mass threshold, may affect the mass ratio distribution (especially for the initial stage, see Section 4 for a discussion). Nevertheless, these results are worth presenting because (1) they provide additional clues describing how the pairs in the

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The mass ratio distribution of halo pairs. The set of halo pairs presented (see Table 1) is indicated in each panel: C (upper left), VC (lower left), MC (upper right) and MVC (lower right). The colours and line styles are indicated in the figure. Only pairs that never merge are presented for the fate stage (indicated by the ‘two haloes’ label). For reference, the text uses the following definitions to describe the sets: Close Sets ($d_{\text{crit}} = 1 \text{Mpc} \, h^{-1}$; upper panels), Very Close Sets ($d_{\text{crit}} = 200 \text{kpc} \, h^{-1}$; lower panels), non-Massive Sets ($M_{\text{crit}} = 8.6 \times 10^{10} \text{M}_\odot \, h^{-1}$; left-hand panels) and Massive Sets ($M_{\text{crit}} = 8.6 \times 10^{11} \text{M}_\odot \, h^{-1}$; right-hand panels). See Sections 2.3 and 2.4.4, respectively, for definitions and descriptions of the stages and sets.

3.5 Lifetimes

In this section, I estimate the typical duration of close interactions. The following relevant time intervals are considered.

(i) Total time: the interval from the initial to the fate time. Here, unlike in Section 4, fate here is not limited to the non-merging pairs.
(ii) Approach time: the interval from the initial to the entry time. This refers to the approach time from large distances down to the first time the pair is within $d_{\text{crit}}$. Note that those pairs with $d_{\text{initial}} < d_{\text{crit}}$ have zero approach time.

(iii) Interaction time: the interval from the first to the last time the pair is within $d_{\text{crit}}$. If $d_{\text{initial}} < d_{\text{crit}}$, the interaction begins at the initial time. If $d_{\text{initial}} > d_{\text{crit}}$, it begins at the entry time. If $d_{\text{initial}} < d_{\text{crit}}$ (i.e., mergers or subcritical non-merged pairs), the interaction ends at the fate time. If $d_{\text{initial}} > d_{\text{crit}}$, the last time at which the relative separation crosses the $d_{\text{crit}}$ threshold is sought. If this time does not coincide with one of the snapshots in the simulation, a linear interpolation in $\log (1+z)$ is performed.

It is important to mention that the approach time depends on the initial time, which itself is strongly determined by the resolution of the simulation. This issue also affects the estimate of the total time. Despite this limitation, it is interesting to study the typical time-scales experience by close pairs in the Millennium Simulation, and the effects of modifying $d_{\text{crit}}$ and $M_{\text{crit}}$. The interaction time is less susceptible to these resolution effects because the mass criterion adopted in this paper deletes most of the branches that are most prone to go below the mass resolution of the simulation more quickly due to tidal stripping. Nevertheless, additional improvements using dynamical-friction recipes can always be incorporated in future works (which will most likely increase the duration of the interaction times). The results presented here serve as a reference for such developments (see Section 4 for additional discussions on these issues).

The three lifetime distributions are shown in Fig. 7. The total-time distribution peaks sharply at long durations, with over 80 per cent with $t_{\text{fate}} > 5$ Gyr (and over 90 per cent with such long durations for the Massive Sets). The approach-time distribution resembles the total-time distribution, but with some contributions from shorter durations. Over 65 per cent of the pairs have $t_{\text{approach}} > 5$ Gyr (and over 80 per cent have such long durations for the Massive Sets). The interaction-time distribution is dominated by durations between approximately 0.2 and 4 Gyr. The distribution has a long tail at low durations (with $t_{\text{interaction}} < 0.1$ Gyr), especially for the Very Close Sets (~20 per cent for the VC set and ~12 per cent for the MVC).

Reducing either $d_{\text{crit}}$ or $M_{\text{crit}}$ does not affect the distributions significantly. There is a small enhancement in the intermediate-time regime (approximately 1–8 Gyr), but not for the longest time regimes. The effect of changing $d_{\text{crit}}$ is slightly stronger than that caused by changing $M_{\text{crit}}$. Increasing $M_{\text{crit}}$ shifts the lower end of both the total and the approach-time distributions to higher values. The most obvious change is that adopting a smaller $d_{\text{crit}}$ makes short interactions more common, while choosing a larger $M_{\text{crit}}$ makes the approach times longer. Lastly, when both modifications are applied, interactions lasting longer than ~8 Gyr are essentially absent.

4 DISCUSSION

This section discusses the assumptions and provides interpretations for results presented in this paper. A description of related work is included.

4.1 The assumptions in the catalogue

Before analysing and interpreting the results of Section 3, I devote this section to discuss the assumptions adopted in this paper.

The catalogue analysed in this work consists of halo pairs (1) that come within some comoving distance $d_{\text{crit}}$ and (2) in which both haloes reach a mass greater than some threshold value $M_{\text{crit}}$ at some point in their history.

The primary (largest) catalogue is dubbed the ‘Close Set’, and it has $d_{\text{crit}} = 1$ Mpc h$^{-1}$ and $M_{\text{crit}} = 8.6 \times 10^{10} M_{\odot}$ h$^{-1}$ (equivalent to 100 simulation particles). Subcatalogues are then selected from this set by either decreasing the critical distance to $d_{\text{crit}} = 200$ kpc h$^{-1}$ or/and by increasing the critical mass to $M_{\text{crit}} = 8.6 \times 10^{11} M_{\odot}$ h$^{-1}$ (equivalent to 1000 simulation particles). From these combinations, the following additional sets arise: the Very Close Set, the Massive Close Set and the Massive Very Close Set. See Table 1 for a summary. One of the goals of this work is to quantify the effects of modifying these selection criteria.

The larger critical distance adopted for the primary catalogue ($d_{\text{crit}} = 1$ Mpc h$^{-1}$) is not as large as it appears because it is in comoving coordinates. In these coordinates, this threshold is comparable to the large-separation tail of binary quasars found by Foreman, Volonteri & Dotti (2009). Indeed, these authors report 38 binaries (out of 85) with comoving separations larger than 200 kpc h$^{-1}$ and three binaries with separations larger than 1 Mpc h$^{-1}$. One could argue that such pairs are not truly associated. However, these authors found their measurements to be enhanced relative to simple extrapolations of the quasar correlation function, signalling that they may indeed be physically influencing each other.

The distance criterion used here is still larger than some of the popular thresholds found in the literature (≲50 physical kpc are commonly used to select pairs with enhanced star formation). Nevertheless, keeping this exaggerated choice is valuable for a variety of reasons. First, it facilitates future studies of halo triplets and N-tuplets. Such investigations can shed light on the evolution of close compact groups – e.g. like Stephan’s quintet (Stephan 1877; Renaud, Appleton & Xu 2010) – and multiple-quasar systems (Djorgovski et al. 2007; Alonso et al. 2008; Liu, Shen & Strauss 2011a; Liu et al. 2011b,c). Similarly, the effects of the local environment surrounding the pairs can be tracked (e.g. Barton et al. 2007; Ellison et al. 2010, and references therein). Lastly, this large proximity choice will be useful for future studies of sub-Mpc clustering studies of quasars (e.g. Myers et al. 2007; Bonoli et al. 2010; Shen et al. 2010) and/or luminous red galaxies (e.g. Bell et al. 2006; Masjedi et al. 2006; Wake et al. 2006, 2008; Brown et al. 2007; Conroy, Ho & White 2007; White et al. 2007; Almeida et al. 2008; Cool et al. 2008; Masjedi, Hogg & Blanton 2008; van Dokkum et al. 2010; Tojeiro et al. 2011).

Alternatively, one could select pairs by whether they come within a distance below a fixed multiple of the sum of the two virial radii (e.g. Sinha & Holley-Bockelmann 2011). However, the appropriate choice of separation for interaction-induced phenomena (e.g. star formation enhancement) may depend on environment (e.g. Ellison et al. 2008). For the sake of simplicity, a selection based on centre-to-centre distance is preferred at this point.

The mass criterion adopted in the primary catalogue ($M_{\text{crit}} = 100 m_p$) is introduced mainly for computational convenience. Including all possible branches without any mass constraint is extremely CPU-intensive. Obviously, the problem of interacting dwarf galaxies is very interesting. However, using the Millennium Simulation for this purpose is not entirely appropriate, since modelling such galaxies with less than 100 particles is a very crude approximation. For these systems, using something like the Millennium-II Simulation (with $d_{\text{box}} = 100$ Mpc h$^{-1}$ and $m_p = 6.9 \times 10^6 M_{\odot}$ h$^{-1}$; Boylan-Kolchin et al. 2009) is more suitable. I reserve an extension of this catalogue in that direction for a future project.
4.2 Interpretation of the results

The analysis of Section 3 provides a relatively simple picture that incorporates five basic stages: initial $\rightarrow$ entry $\rightarrow$ closest $\rightarrow$ final $\rightarrow$ fate. Below I use the wealth of statistical information gathered in Section 3 to make more sense of the details behind this process.

4.2.1 The initial stage

When both haloes are first identified (above the resolution of the simulation), they are typically found at distances of a few up to 10 $\text{Mpc} \, h^{-1}$, but never beyond 30 $\text{Mpc} \, h^{-1}$ (Fig. 3). Fig. 4 shows that the pairs usually begin at redshift $\geq 5-7$, with only about 5 per cent at $z < 1$ (except for the MVC set, which has a $\sim 20$ per cent contribution from this redshift regime – see the foregoing discussion for a plausible interpretation). The majority of the total masses in the pairs are initially small: about 60 per cent are in the $(5-10) \times 10^{10} \text{M}_\odot \, h^{-1}$ range, $\sim 35$ per cent are in the $(10^{11-12}) \times 10^{11} \text{M}_\odot \, h^{-1}$ range, and only $\sim 5$ per cent have masses greater than $10^{12} \text{M}_\odot \, h^{-1}$ (Fig. 5). About 90 per cent of the initial mass ratios are greater than 0.1 (Fig. 6).

The shape of the initial-distance distribution (Fig. 3) depends mainly on two competing factors. As the size of a region around a halo increases, more and more neighbours are within reach.

Figure 7. The interaction-duration distribution of halo pairs. The set of halo pairs presented (see Table 1) is indicated in each panel: C (upper left), VC (lower left), MC (upper right) and MVC (lower right). The colours and line styles are indicated in the figure. The total duration refers to the time from the initial until the fate stage. The approach time goes from the initial until the entry stage. The interaction lasts from the first until the last time the pair is identified within $d_{\text{crit}}$. For reference, the text uses the following definitions to describe the sets: Close Sets ($d_{\text{crit}} = 1 \text{Mpc} \, h^{-1}$; upper panels), Very Close Sets ($d_{\text{crit}} = 200 \text{kpc} \, h^{-1}$; lower panels), non-Massive Sets ($M_{\text{crit}} = 8.6 \times 10^{10} \text{M}_\odot \, h^{-1}$; left-hand panels) and Massive Sets ($M_{\text{crit}} = 8.6 \times 10^{11} \text{M}_\odot \, h^{-1}$; right-hand panels).
Eventually, this quantity drops precipitously because the number of branches that participate in the assembly of the final host halo is finite. One would expect that decreasing the adopted \( d_{\text{crit}} \) would preferentially select pairs with smaller \( d_{\text{initial}} \). Overall, this is not the case, except at small distances, the Very Close Sets (lower panels of Fig. 3) exhibit as a small secondary bump at 100 kpc \( h^{-1} \) and a trough at 300 kpc \( h^{-1} \).

A large fraction of initial halo pairs are ‘major’ (with mass ratio \( >1/10 \)), Fig. 6). This is not surprising. At early times, simulated haloes are expected to have masses slightly higher than the resolution limit \( (20 \times m_\odot = 1.72 \times 10^9 M_\odot h^{-1}) \), making the corresponding mass ratio of any two haloes \( \lesssim 1 \). In reality, one of the haloes often has to ‘wait’ for the other to be born (e.g. branches C and D in Fig. 1). During this wait period, the primary halo has some time to grow. However, this growth cannot be too strong, nor too frequent – otherwise the contribution from pairs with low mass ratios would be more significant.

The nature of the initial stage depends strongly on the capabilities of the simulation. A simulation with a smaller box would not generate massive enough pairs that begin at such early times, with such large separations. Likewise, it would not support enough massive final host haloes capable of hosting such massive branches in large numbers. A simulation with higher resolution, on the other hand, would in principle shift the initial mass distribution to even lower masses and higher redshifts. However, since the majority of pairs begin at levels not too different from the resolution threshold (which therefore consist, for the most part, of very similar haloes), the initial mass ratio distribution is not expected to be very susceptible to this.

4.2.2 The entry, closest and final stages

Recall that the great majority of pairs fall from rather large distances. Only \( \sim 5 \) per cent begin with \( d_{\text{initial}} < d_{\text{crit}} \). For the rest, it takes a few Gyr to go from \( d_{\text{initial}} \) to \( d_{\text{crit}} \). The entry, closest and final separations take place predominantly at low redshifts \( (\sim 70–90 \) per cent of these events happen at \( z < 1 \), while only \( \sim 0.5–5 \) per cent occur at \( z > 3 \); Fig. 4). The total masses at these stages are a few \( \times 10^{11} M_\odot h^{-1} \) for the non-Massive Sets, and a few \( \times 10^{12} M_\odot h^{-1} \) for the Massive Sets (Fig. 5). As expected in hierarchical scenarios of halo growth, increasing \( M_{\text{crit}} \) shifts the masses to higher values, and redshifts to lower values (left-hand versus right-hand panels of Figs 4 and 5, respectively).

Moreover, as in the initial stage, the mass ratio distribution at these subsequent stages is dominated by large mass ratios, but to a smaller degree (Fig. 6). This is because by the time two haloes come within a critical distance, one of them might have had time to grow (e.g. pair D–E in Fig. 1). In principle if a simulation with a much higher mass resolution were used – these distributions would include a less prominent contribution from low mass ratios simply because there would be more pairs involving two small haloes at all redshifts. Situations corresponding to massive haloes devouring miniscule ones would not be as important. This point highlights the fact that mass ratio statistics depends strongly on the resolution of the simulation. This limitation is not too problematic for the types of problems I intend to attack with this catalogue (e.g. interacting galaxies, binary quasars, etc.), where cuts in the type of haloes hosting gas-rich galaxies and supermassive black holes must be imposed.

As the evolution of the pair progresses (entry \( \rightarrow \) closest \( \rightarrow \) final), the corresponding redshift distributions shift towards more recent epochs. Moreover, the peak of the total mass distribution shifts slightly towards lower values. This behaviour is intriguing because one would expect mass to increase as the pairs (and the universe) evolve. However, this shift towards lower masses takes place in the small-mass regime. Above a few \( \times 10^{13} M_\odot h^{-1} \) this trend is reversed: pairs get more massive as their evolution advances. (Although this effect is minimal for the MVC set: only a small fraction of low-mass pairs dissolve, and the rest remain in place for the duration of the three stages – see lower-right panel of Fig. 5.) This evidence indicates that while massive pairs follow their expected hierarchical growth, smaller pairs are more susceptible to being stripped of their mass, since most of them inhabit massive environments like clusters. A detailed analysis splitting this catalogue as a function of environment will shed light on this effect. This will be the subject of a future paper.

Additional insight may be gained by looking at the behaviour of the mass ratio distribution as the evolution continues. Recall that initially \( \sim 90 \) per cent of pairs are identified in the simulation with mass ratios \( >1/10 \). By the entry time, this fraction drops to \( \sim 80 \) per cent for the C set, \( \sim 70 \) per cent for the MC and VC sets, and \( \sim 40 \) per cent for the MVC set. The low mass ratio regime, in turn, gets populated. In general, the masses of the haloes in pairs become more discrepant with time. In all cases this can be because, on average, either the primary halo grows faster than the secondary one or the secondary halo dissolves more quickly. This effect is not expected to be strong because, due to the resolution of the simulation, most pairs begin ‘major’ and remain more or less so.

From the point of view of redshift, total mass and mass ratio, the entry, closest and final stages behave rather similarly. The same cannot be said about the distance distribution, making it a very powerful tool to learn about the differences of these stages. As in the initial case, distributions are expected to increase with distance (as more neighbours are seen) and drop (because groups have a finite number of branches). For the most part, the closest-distance distribution only sees the rising portion. The exception is the MVC set (lower-right panel of Fig. 3), where the downturn is probed because groups have fewer massive branches satisfying the smaller critical-distance condition.

The distribution of final distances (along with the distribution of never-merging fate distances discussed below) has a couple of interesting peculiarities. For subcritical distances, this distribution approximately follows the shape of the closest-distance distribution. These are the pairs that may, in principle, have the largest chance of merging. However, there is also a large fraction of pairs ending up with \( d_{\text{final}} > d_{\text{crit}} \). This is expected because pairs are selected by whether or not they came within some critical separation, instead of by following imminent mergers back in time.

Surprisingly, the fraction of supercritical final distances increase when \( d_{\text{crit}} \) is reduced (from \( \sim 45 \) to \( 57 \) per cent for the non-Massive Sets and from \( \sim 39 \) to \( 45 \) per cent for the Massive Sets – see portions to the right of the vertical line in Fig. 3). A possible interpretation is as follows: as the adopted critical distance increases, the number of close neighbours a given halo can have also increases. While the number of massive neighbours increases, the number of less massive haloes increases more substantially. In other words, the importance of having massive haloes in the vicinity diminishes (relative to the less massive neighbours) with increasing \( d_{\text{crit}} \). Conversely, having a small \( d_{\text{crit}} \) means that the effects of third-party massive haloes in the neighbourhood (probably the main halo within the same group) become more dominant. One such effect is to split halo pairs: while two haloes may accompany each other for extended periods, one of them may be absorbed by a third massive halo before they have the opportunity to merge. Another effect is to
momentarily separate the pairs into very elongated orbits at the very last moments. Alternatively, these orbits might be elongated simply because when the distance between two haloes is comparable to their virial radii, their orbits tend to be rather eccentric (Zentner et al. 2005). In either case, at the final stage, a large fraction of halo pairs are observed with separations much larger than \( d_{\text{crit}} \). Indeed, it would be quite interesting to be able to track these last stages with more detail, using a simulation with much higher resolution.

On a side note, if the importance of massive neighbours increases with decreasing \( d_{\text{crit}} \), a larger contribution from low mass ratio pairs should be expected. Fig. 6 confirms this enhancement for all the stages mentioned here (upper versus lower panels). Nevertheless, this effect does not change the fact that the great majority of mass ratios remain more or less ‘major’ at all times.

Finally, I must emphasize that the notions of closest and final stages should not be taken too literally. If two haloes merge, the closest and final distances they attain are strictly zero. My motivation to introduce these stages is not in this strict sense. Instead, my intention is to give an approximate picture (albeit snapshot-limited) of how the pairs evolve in the simulation.

### 4.2.3 The fate stage

As expected, reducing \( d_{\text{crit}} \) promotes the contribution of mergers, consequently reducing the fraction of never-merging pairs (from \( \sim 53 \) to 42 per cent for the non-Massive Sets, and from \( \sim 39 \) to 27 per cent for the Massive Sets).

For non-merging pairs, the fate-redshift distribution is strongly shifted towards recent epochs (fate pairs with \( z < 0.5 \) amount to \( \sim 50 \) per cent for the non-Massive Sets, and \( \sim 60 \) per cent for the Massive Sets – see Fig. 4). At these late epochs, massive groups and clusters become more prominent. These dense environments may be responsible for preventing the mergers of otherwise close pairs of haloes.

Disruption of pairs can also be mitigated by adopting a larger \( M_{\text{crit}} \). This is because pairs of massive haloes are less prone to be disrupted by third-party haloes. In principle, only supermassive neighbours could actually achieve these splittings, but such extreme objects are not very common.

So far I have suggested that some pairs of haloes never merge because one or both haloes participating in the interaction are absorbed by a third party. In practice, none of the fate pairs gets absorbed simultaneously by two distinct haloes. Instead, it is common to have only one of the two haloes in the pair be eaten by a third object, leaving the other one wandering alone. (Moreover, in many cases the leftover halo is also absorbed by the same third object, most likely the central halo, but at a much later time.) This picture is supported by the following pieces of evidence. First, \( \sim 80 \) per cent of the non-merging haloes end up with fate total masses \( > 10^{13} M_\odot \ h^{-1} \). Secondly, \( \sim 90 \) per cent of this subset have fate mass ratios \( < 1/100 \), supporting the interpretation that single, very massive third-party haloes are responsible for ripping the pairs apart.

The fate-distance distribution, just like the final-distance distribution discussed before, contains valuable spatial information. First of all, it is useful to compare the fraction of fate non-merging pairs with the fraction of supercritical final pairs. For the C, VC, MC and MVC sets, recall that the supercritical final fractions are \( \sim 45, 55, 40 \) and 45 per cent; while, on the other hand, the non-merging fate fractions (quoted above) are \( \sim 53, 42, 39 \) and 27 per cent. This demonstrates that the set of supercritical final pairs do not fully determine the set of never-merging fate pairs (read below for a possible interpretation).

Nevertheless, if I focus on the supercritical fate regime instead, the corresponding fractions (relative to the general halo pair population) are \( \sim 22, 35, 14 \) and 27 per cent. This demonstrates two things. First, the fraction of supercritical fate pairs are enhanced with reduced \( d_{\text{crit}} \), displaying the same behaviour as their supercritical final counterparts. Secondly, only a small fraction of the supercritical final pairs never merge. A significant fraction instead do return to subcritical separations and merge eventually. This restriction of the snapshot-limited final stage can be ameliorated by including velocity information across the last few snapshots.

Likewise, the selection of close pairs by their closest separation can be limited: pairs with separation \( > d_{\text{crit}} \) at two consecutive snapshots, but with separation \( < d_{\text{crit}} \) between these two snapshots, are automatically missed by the selection process. However, these instances are not expected to happen too frequently, and such pairs are not likely to penetrate close enough towards each other and have enough time to produce significant tidal damage. In any case, improvements like these can be incorporated in future, more detailed analyses.

It is interesting to concentrate also on the fraction of supercritical fate pairs relative to the sample of never-merging pairs (as opposed to the general population). The fractions are \( \sim 40, 80, 35 \) and 78 per cent. This finding, along with the behaviour of the total-mass and mass ratio distributions at the fate stage, support the idea that reducing \( d_{\text{crit}} \) augments the influence of massive neighbours on pairs that never merge. The importance of supercritical pairs with small \( d_{\text{crit}} \) is more considerable at the fate stage than at the final stage. This is because the latter cases are a special subset of the former: they are the ones that are split apart more powerfully.

This analysis suggest that single massive haloes (perhaps the main branch, but other massive secondary branches as well) enhance separations at the final stage and ultimately help split close pairs. The choice of adopted \( d_{\text{crit}} \) is very important in this regard: small values of critical distance give more weight to the influence of these third-party massive objects. At this point I speculate that further reducing \( d_{\text{crit}} \) will certainly mitigate the fraction of never-merging pairs, but those that never merge will be separated at even more violent levels. On the other hand, while it is true that increasing \( M_{\text{crit}} \) enhances mergers, the fraction of supercritical fate pairs are left largely untouched by this modification because there are not large number of supermassive neighbouring haloes to rip them apart at these impressive levels.

### 4.2.4 The lifetimes

The lifetime of a halo pair goes from \( t_{\text{finit}} \) to \( t_{\text{fin}} \). In general, the total duration of the pairs is very long, with over \( \sim 97 \) per cent of the pairs lasting more than 1 Gyr. Note that increasing \( M_{\text{crit}} \) increases the fraction of pairs that live more than 5 Gyr (from \( \sim 86 \) to 91 per cent for the Close Sets, and from \( \sim 78 \) to 89 per cent for the Very Close Sets – left-hand versus right-hand panels in Fig. 7). Reducing \( d_{\text{crit}} \), on the other hand, makes the total lifetimes shorter (upper versus lower panels in the figure). It is possible that long total times are mitigated because adopting smaller critical distances tends to pre-select pairs that have a higher probability of merging.

The approach period, which goes from \( t_{\text{fin}} \) to \( t_{\text{app}} \), takes up a dominant fraction of the total time. In many ways, \( t_{\text{app}} \), exhibits similar trends to \( t_{\text{total}} \). Over \( \sim 95 \) per cent of pairs have approach times greater than 1 Gyr. Increasing \( M_{\text{crit}} \) increases the fraction of pairs with approach time greater than 5 Gyr (from \( \sim 77 \) to 84 per cent...
for the Close Sets, and from ~66 to 80 per cent for the Very Close Sets). As is the case for the total time, reducing \(d_{\text{crit}}\) also shrinks the approach time. However, mergers do not happen at the end of the approach period. Nevertheless, adopting a small critical distance selects pairs of haloes that are more prone to merge eventually, even if this happens long after the end of the approaching phase.

As mentioned before, the total and approach times depend largely on the capabilities of the simulation. A simulation with either a larger box or higher resolution would in principle be capable of having even longer times (limited, of course, by the age of the universe). A larger box allows more massive haloes with massive branches that are born earlier. Despite these limitations, it is important to report the capabilities of the Millennium Simulation with regard to the evolution of close halo pairs. Higher resolution also allows all haloes to be born earlier, which can in turn be tracked down for longer periods, and more accurately. Even at late stages, small dissolving haloes in dense environments could be followed down for longer times (most likely making the interaction times longer) if a simulation with higher resolution were used (e.g. Boylan-Kolchin et al. 2009). Alternatively, one can also apply dynamical-time recipes to track these structures (Binney & Tremaine 1987).

Simulations also limit the short-time regime. In particular, given that \(t_{\text{total}}\) is defined as the difference of two epochs associated with two simulation snapshots (i.e. \(t_{\text{total}} \equiv t_{\text{fac}} - t_{\text{initial}}\)) results in an artificial lower bound governed by the largest time snapshot of the simulation (for the Millennium Run, this corresponds to \(\Delta t = 0.0122\) Gyr).

The interaction time goes from the entry time up until the last time the pair is within \(d_{\text{crit}}\). For merging and subcritical fate pairs, this ends at \(t_{\text{fac}}\); otherwise it ends before. Unlike the total and approach times, the distribution of interaction times has a noticeable short-time tail. This tail is more evident for the smaller choice of \(d_{\text{crit}}\), where the prevalence of mergers suppresses the duration of these phases. For instance, the fraction of pairs with interaction times shorter than 1 Gyr increases from ~40 to 60 per cent for the non-Massive Sets, and from ~30 to 50 per cent for the Massive Sets.

Using a large \(M_{\text{crit}}\) inhibits the fraction of pairs that interact for long periods because these pairs are more likely to spend most of their lives in the approach phase (see Section 3.5). In all cases, the contribution of pairs with durations longer than 8 Gyr is negligible.

Strictly speaking, the time spent within \(d_{\text{crit}}\) may be shorter than the \(t_{\text{interaction}}\) reported in this paper because, in many cases, the secondary halo may oscillate out and back inside the threshold on multiple occasions. Such instances are probably more important for subhaloes orbiting a primary massive (perhaps central) halo (e.g. Benson 2005; Khochfar & Burkert 2006; Angulo et al. 2009; Wetzel 2011). This level of detail is currently beyond the scope of this work, and can always be incorporated in more refined versions of the catalogue.

### 4.3 Relation to other theoretical work

The nature of the evolution of pairs of haloes (or galaxies) from a cosmologically point of view remains relatively unexplored. This section is devoted to discussing those few works that have attempted to rise beyond pre-prepared numerical experiments of a single nearly isolated pair of galaxies. Here I simply discuss how their methods and assumptions compare to mine. However, a direct comparison of results is not possible at this point because of the different set of goals of those papers and the present work.

Tissera et al. (2002) are among the first research groups to attempt to simulate interactions from a cosmological perspective. Smooth particle hydrodynamical simulations are employed to study starbursts in merging galaxies. Their results suggest a double-triggering scenario where the first starburst is provoked early on in the interaction. Unfortunately, to attain such detail, they use a very small volume, \(L_{\text{box}} = 5\,\text{Mpc}^{-1}\) (with \(h = 0.5\)) on a side, and only \(64^3\) particles. Follow-up work by Perez et al. (2006) uses a volume with \(L_{\text{box}} = 10\,\text{Mpc}^{-1}\) and \(~80^3\) particles. The scope of this approach can be thought to be ‘in between’ the single-pair simulations and the present work.

The approach of Sinha & Holley-Bockelmann (2011) is very similar to mine, in the sense that they also focus on dark-matter-only simulations (unlike Tissera et al. 2002; Perez et al. 2006, who include gas dynamics). These authors propose a notion called the ‘halo interaction network’, and suggest that fly-bys at high redshift \((z \gtrsim 10)\) are more frequent than mergers. However, their simulation has \(L_{\text{box}} = 50\,\text{Mpc}^{-1}\) on a side, only one thousandth of the volume in the Millennium Simulation. Their box size is comparable to the initial separations of pairs presented here (Fig. 3). It is not clear how representative their particular patch (or the merger histories within) actually is; or if they can produce enough massive background haloes where the majority of the halo pairs happen to exist. See appendix A of Wetzel & White (2010) for a discussion on the impact of using a small simulation box on the clustering of subhaloes.

Kitzbichler & White (2008) also employ the Millennium Simulation, along with the semi-analytic galaxy formation model of Croton et al. (2006) and De Lucia & Blaizot (2007). Their mock catalogue is extracted from a narrow light cone with a field of view of \(10 \times 1.4\) deg$^2$. Their goal is very specific: to calibrate the timescales connecting close galaxy pairs and their subsequent mergers. Given the nature of their objective, they are required to refine the stages immediately prior to the mergers. To do this, they include additional dynamical friction times in their estimates (Binney & Tremaine 1987; Boylan-Kolchin, Ma & Quataert 2008). Improvements like this can certainly be implemented in the estimates shown in Fig. 7.

On a similar vein, Berrier et al. (2006) use a simulation with \(L_{\text{box}} = 120\,\text{Mpc}^{-1}\) on a side. Following halo mergers, these authors employ the analytic substructure model of Zentner et al. (2005) to track down subhaloes as they sink in their host groups. Their goal is also very concrete: to evaluate the number of close companions per galaxy. They argue that instead of using close halo pairs to predict the halo merger rate, the number of companions is a more suitable quantity to test various galaxy formation scenarios. This research group then takes advantage of that approach to search simulated galaxy pairs in isolation (Barton et al. 2007) and investigate star formation enhancements provoked by interactions. The types of selection criteria applied in these papers will be very valuable in future studies of halo pairs in different environments, and in more realistic applications of my catalogue.

Wetzel et al. (2008) also investigate how reliable close halo pairs are as proxies of mergers. However, they only concentrate on mergers of cluster-sized haloes (with masses \(>5 \times 10^{13}\) M$_\odot$) at low redshifts \((z < 1)\). To do this, they track pairs of ‘halo objects’ (i.e. the equivalent of an isolated halo in this paper), at the expense of ignoring subhaloes altogether. In a way, that work is complementary to mine: they manage to relate pairs that end up in different final groups but dismiss pairs of subhaloes within a given group. Pairing up all possible haloes and subhaloes at a given distance in a simulation, and tracking their evolution to test whether they merge or not, is a very computationally cumbersome problem. A possible way to extend my approach in that direction is to compare branches that end up within a small bundle of groups in the local
universe. However, at this point it is not clear how large the volume containing these groups should be. These difficulties illustrate how challenging the general study of close pairs as proxies of mergers can actually be.

On a slightly different subject, Wetzel et al. (2008) also find that while rich environments have more halo pairs, mergers of such pairs are more likely to take place in less dense environment. With the analyses presented in this work I argue that mergers are inhibited when the pairs involved happen to live in crowded environments. While it is true that this is reassuring, a direct comparison between the two works is impossible at the moment because their environmental scale is $\lesssim 17\,\text{Mpc}\,h^{-1}$, while mine is restricted to regions that end up as single host haloes.

5 SUMMARY

This paper describes a statistical analysis of a very large catalogue of co-evolving halo pairs I constructed from the merger history trees in the publicly available Millennium Simulation Database (Springel et al. 2005).

The catalogue itself is comprised of over half a million pairs, selected by whether they come within a given critical separation $d_{\text{crit}}$ (Fig. 1). Only haloes that attain a mass larger than $M_{\text{crit}}$ at some point in their history are chosen (Fig. 2). Subcatalogues are constructed to study the effects of modifying these criteria. The adopted values are $d_{\text{crit}} = 1$ and $0.2\,\text{Mpc}\,h^{-1}$; and $M_{\text{crit}} = 8.6 \times 10^{10}$ and $10^{11}\,\text{M}_{\odot}\,h^{-1}$ (corresponding to 100 and $1000$ simulation particles, respectively). See Table 1 for a summary of four sets arising from these combinations.

In order to shed light on the evolution of these pairs, I establish a simple picture consisting of five basic stages: \textit{initial} $\rightarrow$ \textit{entry} $\rightarrow$ \textit{closest} $\rightarrow$ \textit{final} $\rightarrow$ \textit{fate} (see Section 2.3). Moreover, the following relevant time-scales are considered: the \textit{total}, \textit{approach} and \textit{interaction} times (see Section 3.5).

Below I highlight some of the most interesting points we learn from this picture.

(i) The majority of pairs begin at $z \gtrsim 4$, with separations $\lesssim 10\,\text{Mpc}\,h^{-1}$. The initial-distance distribution is largely insensitive to $d_{\text{crit}}$, except for the subcritical pairs (with $d_{\text{initial}} < d_{\text{crit}}$, only $\sim 5\%$ of them).

(ii) The distribution of the sum of the initial masses peaks at a few $\times 10^{10}\,\text{M}_{\odot}\,h^{-1}$, regardless of $M_{\text{crit}}$. Initially, the two haloes in a given pair tend to be similar, with mass ratios typically greater than $1/10$.

(iii) The small portion of subcritical initial pairs is likely to correspond to the surviving substructures in cluster-sized host haloes. This is supported by the end-of-the-tail effects at low redshifts, high total masses and low mass ratios.

(iv) As the evolution advances (entry $\rightarrow$ closest $\rightarrow$ final), total masses increase steadily if they are $\gtrsim 10^{11}\,\text{M}_{\odot}\,h^{-1}$, otherwise, they tend to decrease. This particular mass scale marks the range where tidal stripping becomes relevant. Mass ratios tend to decrease, making the discrepancy between the two haloes in the pair more evident.

(v) Adopting a larger $M_{\text{crit}}$ shifts the mass distribution in the interacting stages to higher values: from $10^{11}$ to $10^{12}\,\text{M}_{\odot}\,h^{-1}$. This also suppresses the high-redshift regime (with $z \gtrsim 4$) significantly (for the stages after the entry time).

(vi) The final-distance distribution peaks at $d_{\text{crit}}$. Around 40–50 per cent of the pairs end up with supercritical separations (with $d_{\text{final}} > d_{\text{crit}}$). Some of these pairs may be on their way to becoming permanently separated, while others may be temporarily on elongated orbits, bound to return together and merge eventually.

(vii) Around 53 per cent of the pairs in the primary catalogue never merge (these include pairs in which one of the haloes is absorbed by a third halo or pairs that do not merge by $z = 0$, but may merge in the future). Reducing $d_{\text{crit}}$ turns this number into $\sim 42$ per cent; while enhancing $M_{\text{crit}}$ turns it into $\sim 39$ per cent. With both effects, one gets $\sim 27\%$ per cent. Over half of these non-merging pairs take place at $z < 0.5$.

In general, merging pairs are more likely to be selected when the critical distance threshold is reduced. However, the relative fraction of never-merging pairs with supercritical fate separations is enhanced with this reduction. The same happens with the supercritical final separations. Squeezing the proximity criterion facilitates the selection of mergers, but also selects never-merging pairs that get ripped apart more violently. This hypothesis is supported by the fate total masses and mass ratios, which suggest a picture in which massive third haloes in the vicinity are responsible for preventing mergers. Indeed, it would be interesting to see if this effect remains with a simulation capable of following subhaloes with much higher mass resolution. Overall, a higher $M_{\text{crit}}$ also induces mergers. This is because supermassive third-party haloes in the vicinity capable of splitting the pairs are less common. However, the violent supercritical effects are less important with this choice.

The second aim of this paper is to provide rough estimates on the typical lifetimes of the pairs, and the duration of their interactions. Some of the main findings are as follows.

(i) On average, halo pairs last a few Gyr, spending most of this time in their approach phase. Interactions (from the first to the last time the haloes are within $d_{\text{crit}}$) last from a few hundred Myr to a few Gyr. Interactions are never longer than $\sim 8$ Gyr.

(ii) Adopting a smaller $d_{\text{crit}}$ promotes the fraction of mergers, shortening the typical interaction time as a consequence. Approach and total times are also reduced, but this effect is less noticeable.

(iii) Adopting a larger $M_{\text{crit}}$ produces longer lifetimes. This is because massive haloes are usually born earlier. However, this increase in duration happens mostly in the approaching stages (between the initial and entry times).

In the discussion I mention that the nature of the initial stage depends strongly on the resolution of the simulation (which in turn affects the statistics of the approach and total times). Nevertheless, it is useful to have an idea of the capabilities of the Millennium Simulation in regards to close pairs at the highest possible redshifts. The mass ratio distribution is also susceptible to the low-mass cut in the simulation. However, the types of applications the catalogue in this paper is ultimately intended for will also include necessary cuts in the types of haloes used. Lastly, resolution also affects subhaloes in the late stages of interaction. Higher resolution or the adoption of dynamical-friction recipes should, in principle, provide better estimates in this regime. In particular, interaction times are expected to be longer than those reported here.

This paper marks the foundation of a series of papers dedicated to the analysis of this huge halo pair catalogue. For the sake of space, several studies must be postponed for forthcoming papers. For instance, the basic quantities discussed here (separation, redshift, total mass and mass ratio) constitute a four-dimensional parameter space, whose exploration is prohibitively unmanageable to be addressed in this exploratory paper. The same is true for the environment or kinematic quantities like relative velocities and spins. These studies are reserved for forthcoming papers.
Ultimately, this catalogue will be the basis of future investigations of galactic interactions and double (and multiple) quasar systems from a cosmological perspective. Such studies will require more detailed analyses, including the incorporation of semi-analytic recipes and the handling of selection effects. For this reason, preliminary studies like the present work are a vital step. The results in this introductory paper will be essential pieces to guide this effort.

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Halo pairs 427
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