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# Testing the hierarchical assembly of massive galaxies using accurate merger rates out to $z \sim \mathbf{1 . 5}$ 

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#### Abstract

We established an accurate comparison between observationally and theoretically estimated major merger rates over a large range of mass $\left(\log M_{\mathrm{bar}} / \mathrm{M}_{\odot}=9.9-11.4\right)$ and redshift $(z=0.7-$ 1.6). For this, we combined a new estimate of the merger rate from an exhaustive count of pairs within the virial radius of massive galaxies at $z \sim 1.265$ and cross-validated with their morphology, with estimates from the morpho-kinematic analysis of two other samples. Theoretical predictions were estimated using semi-empirical models with inputs matching the properties of the observed samples, while specific visibility time-scales scaled to the observed samples were used. Both theory and observations are found to agree within 30 per cent of the observed value, which provides strong support to the hierarchical assembly of galaxies over the probed ranges of mass and redshift. Here, we find that $\sim 60$ per cent of population of local massive ( $M_{\text {stellar }}=10^{10.3-11.6} \mathrm{M}_{\odot}$ ) galaxies would have undergone a wet major merger since $z=1.5$, consistently with previous studies. Such recent mergers are expected to result in the (re-)formation of a significant fraction of local disc galaxies.


Key words: galaxies: evolution - galaxies: formation - galaxies: high-redshift-galaxies: interactions.

## 1 INTRODUCTION

A classical test of the prediction that galaxies assembled hierarchically (e.g. White \& Rees 1978; Blumenthal et al. 1984; White \& Frenk 1991) is to measure the rate at which galaxies merge at different epochs, which is expected to increase with redshift $z$ (e.g. Rodriguez-Gomez et al. 2016; Qu et al. 2017). Several methods to estimate the merger rate observationally were developed, including pair counts (e.g. Patton et al. 1997; Le Fèvre et al. 2000; Patton et al. 2000, 2002; Lin et al. 2004; Bell et al. 2006; Kartaltepe et al. 2007; Lin et al. 2008; Rawat et al. 2008; Bundy et al. 2009; de Ravel et al. 2009; Robaina et al. 2010; Ferreras et al. 2014; Keenan et al. 2014; Ferreras et al. 2014; López-Sanjuan et al. 2015), morphological disturbances (e.g. Conselice et al. 2003; Lotz et al. 2008b; Conselice, Yang \& Bluck 2009; Jogee et al. 2009; López-Sanjuan et al. 2009; Bridge, Carlberg \& Sullivan 2010; Lotz et al. 2011), or more recently, from spatially resolved kinematics (Puech et al. 2012, hereafter P12; López-Sanjuan et al. 2013). Each of them can identify galaxies at different phases of the merging. In particular, it has been realized that using only morphology or spatially resolved kinematics can lead to severally underestimate the merger rate (e.g. Hung et al. 2015), while combining both provides merger rates

[^0]that are consistent with both pair counts and $\Lambda$ CDM predictions (Rodrigues et al. 2017, hereafter R17). At $z \gtrsim 1$, cosmological brightness dimming starts affecting morphology estimates (and spatially resolved kinematics) dramatically (e.g. Barden, Jahnke \& Häußler 2008), which casts some doubt about the use of these methods at high redshift.

Estimating the merger rate accurately from pair counting requires a large photometric survey with redshift measurements, which is essential to build a representative sample of pairs. Deep surveys like CANDELS (Koekemoer et al. 2011) and 3D-HST (Momcheva et al. 2016) provide the necessary data at $z \gtrsim 1$, but so far these have been used only in combination with photometric redshifts (e.g. Man, Zirm \& Toft 2016). This introduces an $\sim 10$ times larger uncertainty in the velocity difference between the pair candidates, compared to the use of $z_{\text {spec }}$ (see below). This in turn implies to consider statistical corrections for projection false pairs, introducing a significant additional uncertainty on the results, with as much as $\sim 50$ per cent of false positive pairs at $z \sim 0.5$ (Snyder et al. 2017). Therefore, an important improvement is the use of large spectroscopic redshift surveys to avoid contaminations by on-sky projections and inherent statistical corrections (e.g. Tasca et al. 2014).

Another important difficulty lies in the conversion of the measured merging galaxy fraction into a merger rate, which requires an estimate of the visibility time-scale during which galaxies can be
identified as mergers using a particular method. Estimating these time-scales necessarily requires simulations (e.g. Lotz et al. 2008a, 2010a). However, when these are not specifically matched to the precise range of, e.g. mass or gas fraction of the observed sample, time-scales remain uncertain by as much as $\sim 50$ per cent and eventually dominate the (systematic) uncertainty on the derived merger rate (Hopkins et al. 2010b; Man et al. 2016). All these limitations have hampered reaching a clear consensus about the evolution of the merger rate, with comparison between theory and observations typically not better than an order of magnitude (Hopkins et al. 2010b; Rodriguez-Gomez et al. 2015).
The goal of this paper is to significantly improve on this situation by: (1) for the first time, combining the high-resolution CANDELS/GOODS-S imaging data with the most up-to-date $z_{\text {spec }}$ compilation, including grism spectroscopy from the 3D-HST survey. The constructed pair sample is then cross-validated using morphological classification; (2) using a visibility time-scale that is rescaled from an observed representative sample of galaxies (P12), and that is specifically tailored to a complete sample of spectroscopic pairs. Combined with previous estimates of the merger rate at different masses and $z$ (P12; R17), we are able to build an accurate comparison between observational and theoretical merger rates over a large range of mass and $z$ and provide a direct test of the hierarchical assembly of galaxies in the $\Lambda$ CDM model.
Throughout this paper, a Chabrier IMF and a $\Lambda$ CDM concordance cosmology were used; all magnitudes are quoted in the $A B$ system.

## 2 METHODOLOGY

### 2.1 Parent sample selection

We started from the 3D-HST Master catalogue (v4.0) (Brammer et al. 2012; Skelton et al. 2014; Momcheva et al. 2016) in GOODS-S ${ }^{1}$, which is the deepest of the 3D-HST field with a photometric completeness $\sim 90$ per cent down to $H_{A B}=25.1$. This field also provides the largest number of spectroscopic redshifts ( $z_{\text {spec }}$ ) measurements. Hereafter, we will refer to $z_{\text {spec }}$ as spectroscopic redshift measurements from ground-based spectroscopy at medium-spectral resolution, while $z_{\text {grism }}$ will refer to redshifts determinations from HST open-grism spectroscopy which has a much lower resolution. Section 2.1.1 describes how we cross-correlated the 3D-HST photometric and different spectroscopic catalogues, providing the most up-to-date redshift compilation in GOODS-S. Section 2.1.2 describes the selection of a representative parent sample of $1.16<z<1.37$ galaxies which are then used to identify major galaxy pairs. The properties of the parent sample are discussed in Section 2.1.3.

### 2.1.1 GOODS-S redshift compilation

We collected all $z_{\text {spec }}$ measurements available in GOODS-S and constructed an updated catalogue of the most accurate redshift measurements for 3D-HST sources in this field. We used the GOODS-S master spectroscopic catalogue from $\mathrm{ESO}^{2}$ with 186 additional sources taken from Treister et al. (2009). The master catalogue collects

[^1]

Figure 1. Spectroscopic completeness of the redshift compilation in GOODS-S as a function of $J$-band magnitude. The dashed line represents the mean spectroscopic completeness (for $z_{\text {spec }}$ and $z_{\text {grism }}$ ) in the $18<J_{A B}<24$ range.
$z_{\text {spec }}$ from 17 surveys and contains multiple spectroscopic identifications of the same source from different surveys. We assigned a quality flag (QF) to each redshift measurement following Balestra et al. (2010) as follows: secure $z_{\text {spec }}$ with $Q F=3$ ( 99 per cent sure), likely $z_{\text {spec }}$ with $Q F=2$ ( 95 per cent sure, including spectrum with a single line), and insecure $z_{\text {spec }}$ with $Q F=1$ ( 70 per cent probability).
The 3D-HST photometric sources were cross-correlated with the $z_{\text {spec }}$ compilation by considering the nearest (on sky) spectroscopic match within a maximal radius of 0.5 arcsec. A QF was assigned to each photometric source as follows:
(i) Flag_type $=1$ : single $z_{\text {spec }}$ match;
(ii) Flag_type $=2$ : multiple $z_{\text {spec }}$ matches for a single photometric source. If all $z_{\text {spec }}$ measurements agreed within 0.001 , the $z_{\text {spec }}$ with higher spectroscopic $Q F$ was considered and we then set $Q F=3$. If the disagreement between the different $z_{\text {spec }}$ was larger than 0.001 , all spectra were checked visually to determine the final $z_{\text {spec }}$ and associated QF;
(iii) Flag_type $=3$ : multiple $z_{\text {spec }}$ matches for multiple photometric sources within the cross-correlation radius of 0.5 arcsec . All spectra and astrometry were checked to determine the final $z_{\text {spec }}$ and associated QF for all sources;
(iv) Flag_type $=4$ : no $z_{\text {spec }}$ match. The $z_{\text {grism }}$ estimate from Momcheva et al. (2016) was adopted;
(v) Flag_type $=-1$ : neither $z_{\text {spec }}$ nor $z_{\text {grism }}$ match. The $z_{\text {phot }}$ estimate from Momcheva et al. (2016) was adopted.

Fig. 1 shows the different types of redshift determinations per bin of $J_{A B}$ for the 13984 photometric 3D-HST sources in the GOODS-S field with $m_{H}<25.1$, i.e. within the 90 per cent photometric completeness of the 3D-HST catalogue. 2994 of them have $z_{\text {spec }}$ measurements with typical uncertainties $<120 \mathrm{~km} \mathrm{~s}^{-1}$ at $z \sim 1$ (Balestra et al. 2010), while 2396 have $z_{\text {grism }}$ measurements with lower precision $\sim 1500 \mathrm{~km} \mathrm{~s}^{-1}$ due to the much smaller spectral resolution of open-grism spectroscopy. The resulting catalogue provides the most up-to-date redshift compilation in GOODS-S. ${ }^{3}$ It supersedes the spectroscopic redshift compilation of Momcheva et al. (2016), doubling the number of $z_{\text {spec }}$ identifications in GOODS-S

[^2]field from 1426 sources to 2994 . For completeness, we also included in this catalogue $z_{\text {phot }}$ estimates from Momcheva et al. (2016) but we emphasize that these were not used in this work. The spectroscopic completeness of the compilation (including $z_{\text {grism }}$ ) in the $18<J_{A B}<24$ range is found to be 85 per cent.

### 2.1.2 Parent sample at $1.16<\mathrm{z}<1.37$

From the GOODS-S redshift compilation, we selected a highly complete and secure sample of galaxies as follows:
(i) $18<J_{A B}<24$, which corresponds to the 85 per cent spectroscopic completeness of the redshift catalogue (see Fig. 1);
(ii) $z_{\text {spec }}$ or $z_{\text {grism }}$ in the range $1.16<z<1.37$. This $z$ interval was chosen so that (1) the observed $J$ band samples the rest-frame $V$ band, i.e. redwards the 4000 Åbreak, hence closely sampling stellar mass, and (2) its width results in an overdensity contrast of galaxies representative of the field and not biased by denser environments (e.g. Lin et al. 2010; see further details in Section 3.3);
(iii) Objects which were not flagged as (or being close to) stars, with well-exposed F125W and F160W images.

This resulted in a sample of 354 galaxies satisfying the above selection criteria. Amongst them, 213 had $z_{\text {spec }}$ ( 29 galaxies with $Q F=1,64$ galaxies with $Q F=2$, and 120 with $Q F=3$ ), and the remaining 141 objects having $z_{\text {grism }}$.

For a number of objects having both $z_{\text {spec }}$ and $z_{\text {grism }}$, we found significant differences between the two measurements, which can be attributed to the less precise $z_{\text {grism }}$ (see Section 2.1.1). Since the absolute magnitudes provided in the 3D-HST photometric catalogue were derived based on $z_{\text {grism }}$, such errors can significantly impact the accuracy of the resulting absolute magnitudes. We recomputed absolute $J$-band magnitudes following the method detailed in Hammer et al. (2001), i.e. interpolating between the two closest photometric filters bracketing the rest-frame $J$ band, and using the 3 arcsec aperture photometry from the FIREWORKS catalogue (Wuyts et al. 2008). This catalogue contains $K s$-selected sources down to $K s=$ $24.3 \mathrm{mag}(5 \sigma)$ in the CDFS and provides ground-based and HST photometry from the $U$ to the MIPS $24 \mu \mathrm{~m}$ bands, which, at the considered $z$, samples rest-frame wavelengths between 0.16 and $10 \mu \mathrm{~m}$. The FIREWORKS photometrically is shallower than the 3D-HST one by $\sim 0.1-0.2 \mathrm{mag}$ in the IRAC bands, which sample the restframe $J$-band magnitude (Skelton et al. 2014). However, constant apertures were adopted in all photometric bands and total aperture corrections determined from the observed $K$ band, i.e. closer to the IRAC channels. 3D-HST adopted varying apertures as a function of wavelength and aperture corrections were determined from the observed $H$ band. This implies that the shape of the FIREWORKSbased Spectral Energy Distribution (SED) is more accurate than the SED based on 3D-HST photometry, although with a slightly more uncertain normalization (Skelton et al. 2014).

Fig. 2 compares the $J$-band absolute magnitudes $M_{J}$ derived from the FIREWORKS catalogue to those extracted from the 3D-HST photometric catalogue. Sources for which the difference between $z_{\text {spec }}$ and $z_{\text {grism }}$ was $\Delta z>0.1$ are indicated using ' + ' signs. The correlation shows no significant systematics and a reasonable 0.2 mag $1 \sigma$ scatter, although the catastrophic $z_{\text {grism }}$ can lead to errors in $M_{J}$ reaching $\sim 4 \mathrm{mag}$ for the faintest sources (see bottom panel in Fig. 2). To avoid such errors, we adopted the FIREWORKS-based $M_{J}$ in this work.

Fig. 3 compares the resulting $M_{J}$ distribution with the expected luminosity function at these redshifts (Stefanon \& Marchesini 2013), which reveals that the sub-sample of 333 galaxies with $M_{J}<-20.3$ (see red line in Fig. 3) is a representative of the population of


Figure 2. Upper panel: comparison between the $M_{J}$ derived from FIREWORKS and the 3D-HST catalogues. The black line represents a $1: 1$ correlation. Lower panel: residuals between the two absolute magnitudes as a function of the FIREWORKS-determined $M_{J}$. The dashed and dotted lines show the $3 \sigma$ residuals for objects with $\Delta z \leq 0.1$ and catastrophic redshift ( $\Delta z>0.1$ ), respectively.


Figure 3. $J$-band absolute magnitude histogram of the sample of 354 massive galaxies with secured $z$. The green dashed line is the $J$-band luminosity function from Stefanon \& Marchesini (2013) at $z \sim 1.5$. The vertical red line shows the $M_{J}=-20.3$ completeness limit. To avoid being affected by a lack of representativity at low mass when searching for companions, the parent sample was restricted to objects 1.5 mag brighter than the completeness limit, i.e. $M_{J}<-21.8$. The final sample gathers 147 galaxies and is shown in blue.
massive galaxies at these $z$. Since the goal of this paper is to select major mergers using the pair technique, we further restricted our sample to galaxies that are 1.5 mag brighter in order to avoid the final pair sample being affected by a lack of representativity at the low luminosity end. This corresponds to stellar mass ratios $\lesssim 0.25$. We therefore selected the sample of primary galaxies so that $M_{J}<-21.8$ (see blue bins in Fig. 3), while secondary companions were selected down to the representativity limit of $M_{J}=-20.3$.


Figure 4. Estimated gas fractions as a function of stellar mass in the parent sample. Downward arrows indicate objects detected in X-rays. The dashed line represents the expected relation between gas fraction and stellar mass interpolated at $z \sim 1.265$ from Rodrigues et al. (2012).

Finally, we discarded a few objects that were too close (i.e. $<250 \mathrm{kpc}$; see Section 3.2) of any CANDELS image edges in order to avoid biasing the completeness of the search for secondary galaxies due to a lack of spatial coverage in the observations. The final sampling contains a secure and representative group of 147 primary massive galaxies with $M_{J}<-21.8$, which we refer to as the parent sample ${ }^{4}$.

### 2.1.3 Morphology and baryonic masses

Stellar masses $M_{\text {stellar }}$ for galaxies in the parent sample were extracted from the 3D-HST catalogue. As discussed in Section 2.1.2, $z_{\text {grism }}$ inaccuracies might result in slight biases of some of the 3DHST $M_{\text {stellar }}$ estimates. However, this effect does not exceed the scatter seen in Fig. 2 ( $\sim 0.07$ dex once translated in $M_{\text {stellar }}$, see cyan points), which is well within the typical uncertainty on usual estimates of the total baryonic mass $M_{\mathrm{bar}}$ of $\sim 0.3-0.35$ dex (e.g. Puech et al. 2010; Popping et al. 2012). We therefore did not attempt to explicitly correct for this relatively small effect.

Gas and then baryonic masses $M_{\text {bar }}$ were estimated by inverting the Schmidt-Kennicutt relation between the total Star Formation Rate (SFR) and gas mass surface densities (Kennicutt 1998). For this, the UV+IR photometric SFR estimates from Momcheva et al. (2016) were combined with the half-light radius derived from the CANDELS $H$-band curve of growth to derive gas mass estimates (see Fig. 4) with a typical resulting associated uncertainty on $\log M_{\mathrm{bar}} / \mathrm{M}_{\odot} \sim 0.35$ dex (Puech et al. 2010). Note that some of the most extreme outliers in Fig. 4 are found to be possible AGNs as identified using X-ray detections ${ }^{5}$ from Hsu et al. (2014).

[^3]

Figure 5. Examples of the different morphological types used to classify the primary galaxies in the parent sample. From top to bottom and left to right: Elliptical $(E)$, SO, Spiral $(S p)$, Peculiar (Pec), and close pairs with $r_{\text {proj }}<5 \mathrm{kpc}$. Each panel is a $40 \times 40 \mathrm{kpc}^{2} i-J-H$ image.

More accurate methods were developed to indirectly estimate the gas fraction in distant galaxies by, e.g. Popping et al. (2012). This method assumes that the stellar and gas masses are distributed within two superimposed exponential discs. However, the fraction of galaxies with Peculiar morphologies increases significantly as a function of $z$ (Delgado-Serrano et al. 2010), which prevents this method to be applied to the parent sample. To check this, we examined the morphology of the galaxies in the parent sample following R17 (see also Hammer et al. 2016), and classified them into $E / S O$, Spiral (Sp), and Peculiar (Pec) galaxies using a decision tree that incorporates quantitative information from colour maps and 2D bulge+disc profile fitting from galfit. Fig. 5 illustrates examples of each morphological class. Each galaxy was classified independently by three classifiers (HF, FH, MP) and the results compared until consensus was reached. The initial disagreement between classifiers was $\sim 11$ per cent, which is comparable to the uncertainty associated with the Poisson fluctuation in the sample ( $\sim 8$ per cent). The fraction of Pec galaxies in the parent sample is found to be 36 per cent, which confirms that the Popping et al. (2012) method cannot be applied to the parent sample. The resulting morphological split is shown in Fig. 4. As expected, $E / S O$ tend to fall below the gas fraction versus stellar mass relation followed by $S p$ and $P e c$ galaxies.


Figure 6. $\Delta \mathrm{V}, r_{\text {proj }}$, magnitude difference in $J$ band, and stellar mass of the principal companion for the 77 pairs with $r_{\text {proj }}>5 \mathrm{kpc}$ (blue). Primaries with more than one companion were counted more than once. The pairs with $r_{\text {proj }}<r_{\text {vir }}$ are shown in red. In the case of pairs having both their primaries and secondaries in the parent sample, only the most massive companion was considered.

### 2.2 Selecting merging pairs

### 2.2.1 Identifying galaxy companions

We first looked for companions around the 147 primary galaxies in the parent sample that were within a conservative projected separation of $5 \mathrm{kpc}<r_{\text {proj }}<250 \mathrm{kpc}$, and with $z_{\text {spec }}$ such that the relative rest-frame velocities $\Delta V$ between the primaries and companions $<500 \mathrm{~km} \mathrm{~s}^{-1}$ (Patton et al. 2013). To estimate whether additional pairs could be identified using the less precise $z_{\text {grism }}$, we cross-correlated the independent $z_{\text {spec }}$ and $z_{\text {grism }}$ measurements within the parent sample. We found that 78 per cent of the galaxies have $\left(z_{\text {spec }}-z_{\text {grism }}\right) /\left(1+z_{\text {spec }}\right)<1500 \mathrm{~km} \mathrm{~s}^{-1}$ (see also R17), with only a few cases well above this value that are due to the much less precise $z_{\text {grism }}$ measurements. We therefore added to the pair candidate sample those having $z_{\text {grism }}$ so that $\Delta V_{\text {grism }}<1500 \mathrm{~km} \mathrm{~s}^{-1}$, and with $r_{\text {proj }}<250 \mathrm{kpc}$. Pair candidates were further restricted to $\Delta J_{A B}<1.5 \mathrm{mag}$ (i.e. mass ratios $\lesssim 0.25$ ) to select those involved in major mergers. ${ }^{6}$

We found 77 such pairs, in which 25 had their primary and secondary galaxies both in the parent sample. A significant fraction of them (45/77) were found to belong to galaxy groups, as also found in analyses of cosmological simulations (Moreno et al. 2013). The distributions in $\Delta V, r_{\text {proj }}, \Delta J_{A B}$, and stellar mass $M_{\text {stellar }}$ of the primaries are shown in Fig. 6. The uncertainty associated with the use of less accurate $z_{\text {grism }}$ in the pair selection was quantified using the sub-sample of 20 pure $z_{\text {spec }}$ pairs with $5<r_{\text {proj }}<100 \mathrm{kpc}$ and $\Delta \mathrm{V}<$ $500 \mathrm{~km} \mathrm{~s}^{-1}$. We counted the fraction of pairs that would no longer have $\Delta V_{\text {grism }}<1500 \mathrm{~km} \mathrm{~s}^{-1}$ if $z_{\text {grism }}$ were used instead of $z_{\text {spec }}$ (see Table 1). As expected, the uncertainty increases when both galaxies in a pair have $z_{\text {grism }}$ instead of $z_{\text {spec }}$. The resulting uncertainty on the merging pair fraction was estimated by weighting each merging pair

[^4]Table 1. Uncertainties associated with the use of $z_{\text {grism }}$ on the fraction of pairs.

| Principal | Companion | Uncertainty |
| :--- | :---: | :---: |
| $z_{\text {spec }}$ | $z_{\text {spec }}$ | 0 |
| $z_{\text {grism }}$ | $z_{\text {spec }}$ | 16 per cent |
| $z_{\text {spec }}$ | $z_{\text {grism }}$ | 28 per cent |
| $z_{\text {grism }}$ | $z_{\text {grism }}$ | 37 per cent |

by the uncertainty factors listed in Table 1, depending on whether $z_{\text {grism }}$ was used for the primary and/or secondary galaxy.

Very close pairs with $r_{\text {proj }}<5 \mathrm{kpc}$ are superimposed in the CANDELS images so it was not possible to identify them as two distinct objects using the 3D-HST photometric catalogue (see example in the last panel of Fig. 5). The images of the galaxies in the parent sample were visually inspected to identify such cases. 10 pair candidates were found. Six of them had $z_{\text {spec }}$, so we visually inspected the associated slit data. For three of them, both nuclei were included into the slit width (see Appendix A) so we considered them as real pairs, which brings the total number of pairs in the parent sample to 80 . The seven remaining ones correspond to a possible systematic underestimation of the number of pairs.

Correcting factors to the number of pairs related to, e.g. projection effects are discussed in Section 2.2.4.

### 2.2.2 Comparing observational and theoretical merger rates

The goal of this paper is to compare observational estimates of the (major) merger rate to the predictions of the $\Lambda \mathrm{CDM}$ model. To avoid introducing systematics in the comparison, one therefore needs to adopt consistent definitions and assumptions.

Merger rates in simulations can be defined in several ways. One of them consists in defining the merger rate as the rate at which a secondary halo is accreted on to a primary halo and becomes a sub-halo. This halo-halo merger rate then needs to be corrected by an estimate of the extra time needed for the secondary galaxy entering the primary halo to actually merge with the primary galaxy. Estimates based on semi-analytical or semi-empirical models need to explicitly account for such a correction, which can rely on several methods (e.g. based on the dynamical friction time). This can introduce a systematic uncertainty of a factor of $\sim 2$ on the expected merger rate (see extensive discussion on these aspects in, e.g. section 2.4 of Hopkins et al. 2010a). Using cosmological simulations, one can directly estimate the resulting galaxy-galaxy merger rate by intrinsically accounting for this delay. However, they are not immune to other uncertainties such as how and when the mass ratio and infall time are defined (Rodriguez-Gomez et al. 2016).

In this paper, we choose to rely on the semi-empirical approach in which dark matter haloes are populated with realistic galaxies using the halo occupation distribution and empirical scaling relations that are relatively well constrained in the redshift and mass ranges considered in this study.

### 2.2.3 Identifying merging pairs

Since the halo-halo merger rate is the most direct predictions of semi-empirical models, we designed a method for estimating the observational merger rate that matches as closely as possible the halo-halo merger rate definition and thus avoids introducing the uncontrolled systematic uncertainty discussed in Section 2.2.2.

For this, we further selected merging pairs amongst the pair candidates that have $r_{\text {proj }}<r_{\mathrm{vir}}$, where $r_{\mathrm{vir}}$ is the virial radius of the primary halo. We used the $r_{\text {vir }}\left(M_{\text {bar }}\right)$ relation from Mo, Mao \& White (1998), which is, in principle, valid for isothermal haloes and (approximately) for Navarro-Frenk-White haloes. This relation depends only (at fixed cosmology) on the baryon fraction within the haloes, which was assumed to be ranging between $f_{\text {bar }}=5$ and 10 per cent, i.e. following current assumptions in hydrodynamical simulations of distant galaxies with similar masses
Abundance matching models have been used to compare the estimated ratio between galaxy and halo sizes in high-redshift galaxies to $\Lambda$ CDM models of disc formation (Kravtsov 2013; Huang et al. 2017; Somerville et al. 2018). In the simplest models, this ratio depends only on the halo spin parameter, but more advanced models also introduce dependences to the ratio of the specific angular momentum of the disc and of the halo, the fraction of baryonic mass in the disc, the structure of the halo, or the amplitude of the halo adiabatic contraction in response to baryons (e.g. Somerville et al. 2018). These parameters can be estimated statistically from large surveys of distant galaxies, and results (see above-cited papers) are generally found to be in good agreement with the simpler Mo et al (1998) relation, which was therefore preferred to avoid introducing possible additional uncertainties associated with the larger number of parameters.
Fig. 7 shows the $r_{\text {proj }}$ versus $M_{\text {bar }}$ distribution for the pair candidates, with the expected $r_{\mathrm{vir}}\left(M_{\text {bar }}\right)$ relation from Mo et al. (1998) with $f_{\text {bar }}=5$ and 10 per cent, shown as a black and dashed line, respectively. In the rest of this paper, we average the merging pair fractions estimated using these two limits and use their (half) difference to account for the uncertainty associated with $f_{\text {bar }}$.

### 2.2.4 Correcting factors

Even when using spectroscopic redshifts, a number of corrections must be considered to estimate the fraction of merging pairs from the fraction of galaxies in pairs (Patton et al. 2000). Compared to photometric redshifts, the use of accurate $z_{\text {spec }}$ (and $z_{\text {grism }}$ ) removes the need for correcting for false pairs due to projection effects. However, spectroscopically selected pairs can still be contaminated by unbound pairs that are not necessarily merger (due to, e.g. unknown but large tangential velocities), or by pairs that appear close in projection but are actually beyond the adopted radius threshold in real 3D space (Patton et al. 2000). Several methods (based on the observed morphology or semi-analytic models) suggest that as much as $50 \pm 15$ per cent of local close pairs (i.e. $r_{\text {proj }}<30-50 h^{-1} \mathrm{kpc}$ and $\Delta \mathrm{V}<300-500 \mathrm{~km} \mathrm{~s}^{-1}$ ) might actually be interlopers (Patton et al. 2000; Kitzbichler \& White 2008; Lin et al. 2008; Patton \& Atfield 2008). This factor has been shown to vary as a function of luminosity, $r_{\text {proj }}, z$, and environment, with a smaller fraction of interlopers at higher $z$ and luminosity, but a larger fraction at larger $r_{\text {proj }}$ (Patton \& Atfield 2008; de Ravel et al. 2011; Kampczyk et al. 2013). However, there is yet no systematic study of how the fraction of interlopers varies as a function of all these parameters so that it remains difficult to correct quantitatively for it. We therefore followed the approach of Man et al. (2016), and the merger rates derived in this paper are formally upper limits. Of note, Snyder et al. (2017) found, using cosmological simulations, a fraction of interlopers of 30 per cent in similar ranges of $z$ and masses. In principle, this fraction should be considered as a strict upper limit since it was derived adopting $\Delta \mathrm{V}<18000 \mathrm{~km} \mathrm{~s}^{-1}$ (typical of photometric redshifts), while this paper is based on the $\sim 10$ times more accurate $z_{\text {spec }}$ and $z_{\text {grism }}$. We

Table 2. Sources of uncertainty associated with the number ( $\sigma_{N_{\text {pair }}}$ ) and fraction ( $\sigma_{f_{\text {pair }}}$ ) of merging pairs. All numbers are corrected for spectroscopic incompleteness (see the text).

| Random <br> uncertainty | $\sigma_{N_{\text {pair }}}$$\sigma_{f_{\text {pair }}}$ <br> [per cent] | Comment |  |  |
| :--- | :---: | :---: | :---: | :---: |
| $f_{\text {bar }}$ | 6.2 | 3.6 | $f_{\text {bar }}=5-10$ per cent, see Section 2.2.3 |  |
| $z_{\text {grism }}$ | 2.2 | 1.3 | See Section 2.2.1 and Table 1 |  |
| $M_{\text {bar }}$ | 2.2 | 1.3 | $\sigma_{M_{\text {bar }}}=0.35$ dex, see Section 3.1 |  |
| Poisson fluctuations | 5.9 | 3.4 | From the parent sample |  |
| Total | $\pm 9.2$ | $\pm 5.3$ | Quadratic combination |  |
| Systematic | $\sigma_{N_{\text {pair }}}$ | $\sigma_{f_{\text {pair }}}$ | Comment |  |
| [per cent] |  |  |  |  |
| Uncertainty | $\quad$ |  |  |  |
| Proj. interlopers | -10.6 | -6.1 | 30 per cent of $N_{\text {pair }}$, see Section 2.2.4 |  |
| Very close pairs | +9.7 | +5.6 | $r_{\text {p }}<5$ kpc, see Section 2.2.1 |  |
| AGN interlopers | -0.7 | -0.4 | See Fig. 7 |  |
| Total | ${ }_{-10.7}^{+9.7}$ | ${ }_{-6.1}^{+5.6}$ | Quadratic combination |  |

nevertheless adopted a conservative 30 per cent systematic effect in overestimating the number of merging pairs.

Additional correcting factors can be considered to account for different selection effects in the underlying photometric and spectroscopic surveys. Since we built a volume-selected representative parent sample, no correction for luminosity incompleteness had to be considered. We accounted for the modest spectroscopic incompleteness discussed in Section 2.1.1 following de Ravel et al (2011): each galaxy in the merging pair counting was weighted by the inverse of the spectroscopic completeness rate (see Fig. 1). Since the completeness rate is quite constant with luminosity, we did not apply individual weights but considered a constant average 85 per cent completeness independent of luminosity.

## 3 RESULTS

### 3.1 Fraction of merging pairs

Following Section 2.2, the number of pairs $N_{\text {pair }}$ was found to be $30(21)$ for $f_{\text {bar }}=5$ per cent ( 10 per cent), hence we adopted a raw value of $25.5 \pm 4.5$, which translates into $N_{\text {pair }}=35.3 \pm 6.2$ once corrected for spectroscopic incompleteness (i.e. $0.85 \times 0.85$, see Section 2.2.4). For two pair candidates, gas masses could not be estimated (because SFR measurements were not available), so its $M_{\text {stellar }}$ was used as lower limits on $M_{\text {bar }}$, but considering the typical uncertainty on $M_{\text {bar }}$, this did not change whether or not they were selected as pairs (see Fig. 7). For four merging pairs, both the principal object and the companion were in the parent sample Excluding the closest (i.e. $<5 \mathrm{kpc}$ ) pairs, the average $M_{\text {stellar }}$ in the principal objects is found to be 10.54 , while the average mass ratio is 3.1.

The different sources of random and systematic uncertainty on $N_{\text {pair }}$ and the resulting fraction of major merging pairs $f_{\mathrm{p}}$ are summarized in Table 2. In addition to the uncertainties detailed above, we used Monte Carlo simulations to estimate the impact on $N_{\text {pair }}$ of the 0.35 dex uncertainties on $M_{\text {bar }}$ (see Table 2). All uncertainties were quadratically combined. The resulting fraction of major merging pairs is found to be $f_{\mathrm{p}}=20.4$ per cent $\pm 5.3$ (rand.) ${ }_{-6.1}^{+5.6}$ (syst.). The fraction of pairs and the associated uncertainties were corrected for spectroscopic incompleteness by a factor of 0.85 (see Section 2.2.4).


Figure 7. Projected distance in kpc in the pair candidates as a function of $M_{\mathrm{bar}}$. The solid curve represents the virial radius of haloes assuming $f_{\text {bar }}=5$ per cent, while the dashed line corresponds to $f_{\text {bar }}=10$ per cent. The objects for which no gas masses could be estimated are plotted using their $M_{\text {stellar }}$ as lower limits on $M_{\text {bar }}$, which is illustrated by horizontal arrows pointing right with sizes equal to the typical uncertainty. Possible AGNs detected in X-rays have $M_{\text {bar }}$ possibly overestimated and are represented by arrows pointing left. The selected pairs are plotted with symbols coding their morphological classifications, for which typical examples are shown in Fig. 5. Symbols are as in Fig. 4.

### 3.2 Morphology of the merging pairs

Fig. 7 reveals that the fraction of Pec galaxies increases as $r_{\text {proj }}$ decreases, with almost all galaxies with $5<r_{\text {proj }}<50 \mathrm{kpc}$ classified as Pec. This is consistent with expectations from major mergers simulations (e.g. Lotz et al. 2010a), which predict that morphological disturbances increase near first passage and fusion. R17 investigated the morpho-kinematics of pairs and found that their identified pairs have peculiar morphologies and/or kinematics. Here, the lack of spatially resolved kinematics prevents us to further check whether the most separated pairs show the kinematic signatures of ongoing interaction. Indeed, combining both highresolution spatial imaging and spatially resolved kinematics allows identifying all of the galaxies involved in mergers regardless of the merging phase (i.e. pre-fusion, fusion, and relaxation phase; see Hammer et al. 2009 and P12). To this respect, the earliest stages of the pre-fusion and the latest post-fusion relaxation phases are the most difficult to identify solely based on morphology or kinematics, and only their combination can provide a robust identification (Hung et al. 2015). Morpho-kinematic data at high redshifts therefore remain highly valuable (R17).

### 3.3 Environment of the merging pairs

Fig. 8 shows a reconstruction of the projected (over)density contrast of galaxies at $z=1.16-1.37$. For each object in the 3D-HST catalogue, Fossati et al. (2017) identified all neighbours within $\Delta \mathrm{V}=1500 \mathrm{~km} \mathrm{~s}^{-1}$ in apertures of radius $=0.75 \mathrm{Mpc}$ to estimate the density contrast $\log \left(1+\delta r_{0.75}\right)$ in the neighbourhood of each object. This aperture is large enough to sample the galaxy density beyond the virial radius of galaxies in the parent sample (see Fig. 7),


Figure 8. Galaxy overdensity contrast at $z=1.16-1.37$ in the GOODS-S field. The dots represent the galaxies from the parent sample ( 147 objects), colour-coded as a function of the overdensity contrast $\log \left(1+\delta r_{0.75}\right)$ as estimated by Fossati et al. (2017). The contours illustrate the iso-densities of these sources. Galaxies in pairs are indicated as black diamonds.
and is therefore of interest to examine whether the parent sample is a representative of the underlying density contrast and to compare it with the sample of merging pairs. In this metric, $\log \left(1+\delta r_{0.75}\right)>5$ corresponds to clusters, while $\log \left(1+\delta r_{0.75}\right)>0.5$ corresponds
to mild overdensities (Salimbeni et al. 2009). Most galaxies in the parent sample (see coloured dots) are found amongst the densest regions, and in particular along a filament (traced by the red dots in the top of Fig. 8) identified by Fossati et al. (2017). The median projected density contrast in the parent sample is found to be $\log \left(1+\delta r_{0.75}\right)=0.15 \pm 0.05$, while merging pairs have a median $\log \left(1+\delta r_{0.75}\right)=0.21 \pm 0.09$. Both can be considered as a representative of the field environment and are significantly less dense than cluster regions or even mild overdensities (see above).

### 3.4 Major merger rate

The major merger rate was estimated as $r_{\text {merger }}\left[\mathrm{Gyr}^{-1}\right]=f_{\mathrm{p}} /<$ $T_{\mathrm{p}}>$, in which $f_{\mathrm{p}}$ is the above-estimated major merging pair fraction and $<T_{\mathrm{p}}>$ is the average time-scale during which the two progenitors can still be separated as distinct objects. Hammer et al. (2009) and P12 studied the different phases of an averaged merging sequence at $z \sim 0.6$ from the morpho-kinematics of a representative sample of $\log M_{\text {stellar }} / \mathrm{M}_{\odot} \sim 10.5$ galaxies. The average stellar mass ratio and stellar mass in this sequence were found to be $\sim 3$ and 10.5 , respectively, which is a very good match to the values found in the present pair sample ( $\sim 3.1$ and 10.54 , respectively; see Section 3.1). P12 studied in detail the different merging phases and found that the observed pre-fusion/pair phase lasts on average 1.8 Gyr. This time-scale is by definition inclusive of all pairs since it was derived from a statistical study of a complete average merging sequence. It is moreover found to be in good agreement with expectations from hydrodynamical simulations including large pairs (see discussion in P12; Lotz et al. 2008a, 2010a,b). Adopting $T_{\mathrm{p}}=1.8 \mathrm{Gyr}$, the major merger rate is found to be $r_{\text {merger }}=0.11 \mathrm{Gyr}^{-1} \pm 0.03$ (rand.) $\pm 0.03$ (syst.).

López-Sanjuan et al. (2013) compiled and homogenized a number of merger rate estimates from gas-rich close pairs in the literature with samples of average stellar masses in the range 10 $0^{9.76-10.26}$ (once converted to a Chabrier IMF). While gas-rich mergers dominate the global merger rate in this range of mass and $z$ (e.g. Lin et al. 2008), the merger rate (per galaxy) increases as a function of stellar mass (Hopkins et al. 2010a) so that the López-Sanjuan et al. (2013) compilation provides a lower limit to the value derived in this study. From their least-square regression as a function of $z$, we indeed found $r_{\text {merger }} \sim 0.12 \mathrm{Gyr}^{-1}$. Other studies using close pairs but in samples with larger stellar masses (i.e. $\log M_{\text {stellar }} / \mathrm{M}_{\odot}$ larger than 10.5-11; Bluck et al. 2009; Man et al. 2012; Newman et al. 2012; Man et al. 2016) found a fraction of close pairs $\sim 9-11$ percent, which translates in a merger rate $\sim 0.18-0.22 \mathrm{Gyr}^{-1}$ using a fiducial time-scale $T_{\mathrm{p}}=0.5 \mathrm{Gyr}$ suitable for $r_{\mathrm{proj}}=20-30 \mathrm{kpc}^{7}$ (Lotz et al. 2010a). This is, as expected, higher that the present estimate. The most directly comparable estimates are those of Williams, Quadri \& Franx (2011), who found for $\log M_{\text {stellar }} / \mathrm{M}_{\odot}>10.25$ close pairs a merger rate $r_{\text {merger }} \sim 0.12 \mathrm{Gyr}^{-1}$ at $z=1.2-1.6$, and Bundy et al. (2009), who also found for $\log M_{\text {stellar }} / \mathrm{M}_{\odot}>10$ close pairs, a merger rate $r_{\text {merger }} \sim 0.12 \mathrm{Gyr}^{-1}$ (uncorrected for unbound pairs), which are both consistent the present estimate, but used less accurate photometric $z$.

### 3.5 Comparison with theory

We used the semi-empirical model of Hopkins et al. (2010a) as used in P12 and R17 to which we refer for details. ${ }^{8}$ As detailed in Section 2.2.2, we considered the $r_{\text {merger }}$ provided by this model at the time when haloes start merging, i.e. when galaxies that inhabit these haloes are still in pairs. As such, the observed point has to be plotted at the median $z$ of the observed sample plus $0.5 \times<T_{\mathrm{p}}$ $>$, which is the average epoch at which the observed pairs were starting to interact (see Fig. 9). This shifts the observed point from $z \sim 1.265$ to $z \sim 1.607$, i.e. 0.9 Gyr earlier.
The semi-empirical model was used to calculate predictions of the merger rate in a given range of baryonic mass $\left[M_{\text {bar }}{ }^{\min }(z), M_{\text {bar }}{ }^{\text {max }}(z)\right]$, gas fraction $\left[f_{\text {gas }}^{\min }(z), f_{\text {gas }}^{\text {max }}(z)\right]$, and baryonic mass ratio between the two progenitors $\left[\mu_{b}^{\min }(z), \mu_{b}^{\max }(z)\right]$ as a function of $z$. The merger rate was parametrized as a function of baryonic mass (rather than stellar mass) because it traces more accurately bound material that can strongly perturb the primary (Hopkins et al. 2010a). Most studies usually consider merger rates estimated within a fixed range of mass as a function of $z$. We rather considered an evolving range of mass as a function of $z$ in order to sample the progenitors and descendants of the merging pairs (see P12 for details). We set $\left[\mu_{b}^{\min }(z), \mu_{b}^{\max }(z)\right]=[0.25-1]$ adopting the stellar mass ratios found in Fig. 6. In this intermediate range of mass, baryonic and stellar mass ratios should roughly be equivalent (Hopkins et al. 2010b). Rescaling the baryonic mass ratios as proposed by Hopkins et al. (2010b) moves the predicted merger rate within the typical range of uncertainty of a factor of $\sim 2$ shown in Fig. 9. We determine the expected range of gas fractions in the descendants and progenitors as a function of $z$ using their predicted ranges of stellar mass derived by the model and interpolating the relation between gas fraction of stellar mass from Rodrigues et al. (2012).

The observational estimate and the theoretical prediction are found to be in very good agreement ( $\sim 20$ per cent relative difference). Fig. 9 also shows observational estimates and corresponding predictions from the IMAGES sample (in black), which probed $\log M_{\mathrm{bar}} / \mathrm{M}_{\odot}=10.1-10.9$ galaxies using spatially resolved morpho-kinematic data (P12), and from the KMOS data as analysed by R17, which sampled more massive (and gas-rich) galaxies with $\log M_{\text {bar }} / \mathrm{M}_{\odot}=10.4-11.5$ using both spatially resolved morphokinematic data and pair statistics (in blue). This study extends these samples towards smaller masses. All predictions for these samples were specifically tailored to the sampled range of mass and gas fraction. All these estimates match the corresponding theoretical predictions within 30 percent. This remaining difference is fully accounted for by the level of random and systematic uncertainties on the observational estimate, which represent $\sim 39$ per cent of the measured value (quadratic combination). We conclude that the hierarchical assembly of galaxies predicted by the $\Lambda$ CDM model is found to be in very good agreement with observational estimates (see Fig. 9) over almost two decades in mass $\left(\log M_{\text {bar }} / \mathrm{M}_{\odot}=\right.$ $9.8-11.5$ ) and over a large redshift range ( $z=0.7-1.6$ ).

## 4 CONCLUDING REMARKS

This paper provides the first estimate of the major merger rate from a complete and representative sample of galaxies with spectroscopic (and grism) redshift measurements at $z \sim 1.265$. The major merger

[^5][^6]Lookback time [Gyrs]


Figure 9. Merger rate $r_{\text {merger }}$ as a function of $z$ for different ranges of mass and $z$. The orange box shows the 3D-HST observational estimate derived in this study, in which the width corresponds to the redshift range probed by the pair sample, while the height represents the associated random uncertainty. The systematic uncertainties are represented by the vertical black lines. The orange solid line shows the prediction from a $\Lambda$ CDM semi-empirical model (with typical uncertainties $\sim 2$, see P12). The blue symbol represents the KMOS data as analysed by R17, while the black symbols show the results obtained by Puech et al. (2012) from a sub-sample of the IMAGES survey of $z \sim 0.6$ emission line galaxies. The blue and black lines represent predictions from the same semi-empirical model but specifically tuned to the ranges of $z, M_{\mathrm{bar}}$, and gas fractions of these samples.
rate is found to be $r_{\text {merger }}=0.12 \mathrm{Gyr}^{-1} \pm 0.03$ (rand.) $\pm 0.03$ (syst.), consistent with previous but less accurate estimates. This observational estimate was compared with the theoretical prediction from a semi-empirical model, both of which are found to agree well within their respective uncertainties.

Considering other similar comparisons between observational and theoretical merger rates from previous works, both are found to agree within 30 per cent over a large range of $z$ and mass, providing strong evidence for the predicted hierarchical assembly of galaxies. This level of accuracy can be reached by the combination of two essential ingredients. First, pair identification, morphology, and spatially resolved kinematics are combined to get exhaustive counts of all merger candidates at different $z$. Secondly, observations and simulations are combined to derive visibility time-scales purposely tailored to the observed sample. Usually, the visibility time-scale is directly taken from the literature without special considerations to tune it to the considered sample, which eventually dominates the uncertainty budget on the merger rate (Hopkins et al. 2010b). In this work, the (random + systematic) uncertainty is instead dominated by observational factors which are only of the order of $\sim 39$ per cent. This is consistent with the small differences between the theoretical predictions. Different merger identification methods can provide consistent estimates when (1) exhaustive pair counting is combined to a visibility time-scale specifically tailored to the observed sample and (2) morphological and kinematic data are combined to properly distinguish and deconvolve the different merger phases (see also P12 and R17).

Major mergers have been suggested to have important consequences on the structural formation of local galaxies, possibly lead-
ing to the formation of ellipticals (Toomre \& Toomre 1972; Mihos \& Hernquist 1996) but also of local discs, depending on gas fractions at fusion time (Hammer et al. 2005; Robertson et al. 2006; Hopkins et al. 2009; Athanassoula et al. 2016; Sparre \& Springel 2016). Gas-rich major mergers between intermediate-mass galaxies ( $\log M_{\text {bar }} \sim 10.1-10.9$ at $z \sim 0.6$ ) were found to be probably driving the formation of a large fraction of local $\log M_{\text {stellar }} / \mathrm{M}_{\odot} \sim 10.3-11.1$ discs (Hammer et al. 2009; P12). The semi-empirical model used in this paper predicts that the major mergers probed here $\left(\log M_{\text {bar }} \sim\right.$ 9.8-11.4) should end up in the range $\log M_{\text {stellar }} / \mathrm{M}_{\odot}=10.3-11.6$ at $z=0$. By integrating the red curve in Fig. 9, we estimate that $\sim 60$ per cent of these galaxies should have undergone a gas-rich major merger since $z \sim 1.5$. These are expecting to lead to the rebuilding of rotating discs in a large fraction of local spirals (Hammer et al. 2009; P12). The role of gas-rich major mergers as an important channel for local disc (re-)formation has also been confirmed by a number of recent cosmological simulations (e.g. Aumer, White \& Naab 2014; Rodriguez-Gomez et al. 2017).

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## SUPPORTING INFORMATION

Supplementary data are available at MNRAS online.

## 3DHST_CANDELS_redshift_compilation.csv

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## APPENDIX A: SPECTROSCOPIC SLIT DATA FOR CLOSE PAIRS

We retrieved spectroscopic slit data for six of the close pair candidates (i.e. with $r_{\text {proj }}<5 \mathrm{kpc}$ ). Amongst them, three revealed two sub-components within the slit, while a single [ $\mathrm{O}_{\text {II }}$ ] emission line was detected, which is consistent with these three candidates being real pairs. These were therefore considered as real pairs (see Section 2.2.1). Fig. A1 shows the slit data for these three close pairs.


Figure A1. Spectroscopic data for the three very close pairs added to the sample. First line: $i$-band HST stamps with the 1.2 arcsec VIMOS or FORS2 spectroscopic slit superimposed. Second line: [OII] emission line flux extracted from the slit (not corrected for aperture) in units of $10^{-17} \mathrm{erg} \mathrm{s}^{-1} \mathrm{~cm}^{-2} \AA \AA^{-1}$.

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[^1]:    ${ }^{1}$ http://3dhst.research.yale.edu/
    ${ }^{2}$ http://www.eso.org/sci/activities/garching/projects/goods/spectroscopy. html

[^2]:    ${ }^{3}$ An electronic version can be found at TBD.

[^3]:    ${ }^{4}$ Restricting further to the sub-sample of 109 galaxies with $z_{\text {spec }}$ measurements would result in slightly biasing the sample at low luminosities. The 38 objects with $z_{\text {grism }}$ have on average reddest colour and faintest magnitudes than the rest of the 109 galaxies in the parent sample, which also explains why $z_{\text {spec }}$ were not measured for these sources.
    ${ }^{5}$ Only objects with a secure counterpart (xflag=1 indicating that the source is the only possible counterpart to an X-ray source) were considered.

[^4]:    ${ }^{6}$ We also tested selecting major pairs using $\Delta H_{A B}<1.5 \mathrm{mag}$, which is a better proxy for stellar mass, with no significant impact on the results.

[^5]:    ${ }^{8}$ Available at https://www.cfa.harvard.edu/~phopkins/Site/mergercalc. html as an IDL code.

[^6]:    ${ }^{7}$ We used this fiducial time-scale to convert the different reported close pair fractions into merger rates in all the comparisons of this section.

