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Galaxy merger histories and the role of merging in driving star formation at $z > 1$

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ABSTRACT

We use Horizon-AGN, a hydrodynamical cosmological simulation, to explore the role of mergers in the evolution of massive ($M_* > 10^{10}$ M$_\odot$) galaxies around the epoch of peak cosmic star formation ($1 < z < 4$). The fraction of massive galaxies in major mergers (mass ratio $R < 4$: 1) is around 3 per cent, a factor of ∼2.5 lower than minor mergers (4: 1 $< R <$ 10: 1) at these epochs, with no trend with redshift. At $z \sim 1$, around a third of massive galaxies have undergone a major merger, while all remaining systems have undergone a minor merger. While almost all major mergers at $z > 3$ are 'blue' (i.e. have significant associated star formation), the proportion of 'red' mergers increases rapidly at $z < 2$, with most merging systems at $z \sim 1.5$ producing remnants that are red in rest-frame UV–optical colours. The star formation enhancement during major mergers is mild (∼20–40 per cent) which, together with the low incidence of such events, implies that this process is not a significant driver of early stellar mass growth. Mergers ($R <$ 10: 1) host around a quarter of the total star formation budget in this redshift range, with major mergers hosting around two-thirds of this contribution. Notwithstanding their central importance to the standard Λ cold dark matter paradigm, mergers are minority players in driving star formation at the epochs where the bulk of today's stellar mass was formed.

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

1 INTRODUCTION

The cosmic star formation history indicates that the bulk of the stars in today's massive galaxies formed at $z \sim 2$ (e.g. Madau, Pozzetti & Dickinson 1998; Hopkins & Beacom 2006). While the nearby Universe underpins much of our current understanding of galaxy evolution, a convergence of new multiwavelength surveys (e.g. WFC3/ERS2: Windhorst et al. 2011; and CANDELS: Grogin et al. 2011; Koekemoer et al. 2011) and high-resolution hydrodynamical simulations (e.g. Devriendt et al. 2010; Dubois et al. 2014; Vogelsberger et al. 2014; Khandai et al. 2015; Schaye et al. 2015) is revolutionizing our understanding of the $z > 1$ Universe. The processes that drive galaxy growth at these early epochs are still the subject of much debate. The role of mergers (major mergers in particular) at high redshift remains poorly understood. While mergers are capable of inducing strong star formation, black hole (BH) growth and morphological transformations (e.g. Springel, Di Matteo & Hernquist 2005), both theory (e.g. Dekel et al. 2009; Kereš et al. 2009) and observation (e.g. Genzel et al. 2011; Kaviraj et al. 2013b, hereafter K13b) have recently suggested a lesser (perhaps insignificant) role for this process in driving stellar mass growth in the early Universe.

Spectroscopic studies of star-forming galaxies around $z \sim 2$ have demonstrated high fractions of systems that are not in mergers but show kinematic morphologies indicative of turbulent discs (e.g. Förster Schreiber et al. 2006; Genzel et al. 2008; Shapiro et al. 2008; Law et al. 2009; Mancini et al. 2011). Since galaxy morphology carries an imprint of the mechanisms that drive star formation (e.g. Lintott et al. 2011), imaging studies, using e.g. high-resolution instruments like the *Hubble Space Telescope* (*HST*), have offered a complementary route to probing the processes that dominate stellar mass growth at $z > 1$. In broad agreement with the spectroscopic literature, a possible dominance of non-merging galaxies within

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the early star-forming population has been suggested by such work (e.g. Lotz et al. 2006; Förster Schreiber et al. 2011; Law et al. 2012; K13b). In particular, K13b have probed the overall significance of (major) merger-driven star formation in the early Universe, by estimating the fractional contribution of visually-classified mergers to the star formation budget at $z \sim 2$. Their work estimates that less than a third of the budget at this redshift is hosted by systems that are in major mergers.

While observational studies are transforming our understanding of the role of mergers at $z > 1$, the empirical literature unavoidably uses a heterogeneous set of methodologies and is often restricted to relatively small galaxy samples, with each study typically probing a relatively narrow range in redshift. A complementary approach to exploring the role of merging is to use a theoretical model that is well calibrated to the observed Universe at these epochs. In this study, we exploit Horizon-AGN, a hydrodynamical cosmological simulation that reproduces the mass functions and rest-frame UV–optical colours of massive galaxies at $z > 1$, to probe the impact of merging on massive ($M_* > 10^{10}$ M$_\odot$) galaxies at $1 < z < 4$. Our principal objectives are to perform a statistical study of major/minor merger histories, the enhancement of star formation in major mergers and the proportion of the star formation budget that is attributable to mergers around the epoch of peak star formation.

This paper is organized as follows. In Section 2, we describe the simulation that underpins our study. In Section 3, we study the fractions of galaxies in major and minor mergers at $1 < z < 4$, the cumulative merger histories of massive galaxies at $z \sim 1$ and the star formation activity in mergers across this epoch. In Section 4, we study the enhancement of star formation induced by the major-merger process and calculate the fraction of the star formation budget that is hosted by merging systems at these redshifts. We summarize our findings in Section 5.

2 THE HORIZON-AGN SIMULATION

We begin by summarizing the main properties of the Horizon-AGN simulation – we refer readers to Dubois et al. (2014) for further details. The simulation employs the adaptive mesh refinement Eulerian hydrodynamics code, RAMSES (Teyssier 2002). The size of the simulated volume is 100 h^{-1} Mpc comoving, containing 1024^3 dark matter particles, with initial conditions that correspond to a standard Λ cold dark matter (CDM) cosmology with *Planck*-like values: $H_0 = 67.11$ km s^{-1} Mpc^{-1}, $\Omega_{\rm b} = 0.049$, $\Omega_{\rm cdm} = 0.268$, $\Omega_\Lambda = 0.683$, $\sigma_8 = 0.834$, $n_{\rm s} = 0.962$ (Planck Collaboration XVI 2014). The initial 1024^3 uniform grid is refined with a quasi-Lagrangian criterion when eight times the initial total matter resolution is reached in a cell, down to a minimum cell size of 1 kpc in proper units.

Metal-dependent radiative cooling is implemented following Sutherland & Dopita (1993) and a uniform UV background is switched on at $z = 10$, following Haardt & Madau (1996). The standard Schmidt–Kennicutt law (e.g. Kennicutt 1998) is employed to produce star particles with a 2 per cent efficiency, when the gas density reaches a critical density of 0.1 H cm^{-3}. Based on Dubois & Teyssier (2008), mass-loss from massive stars occurs via stellar winds and Type II and Type Ia supernovae, which disperse gas and metals into the ambient medium (Kimm et al., in preparation). Seed BHs with a mass of 10^5 M$_\odot$ are assumed to form in regions of high gas density and the growth of the BH is tracked self consistently based on a modified Bondi accretion rate. When gas accretes on to BHs, we assume that a central BH impacts the ambient gas in two possible ways, depending on the accretion rate. For a high accretion rate (Eddington ratio >0.01), 1.5 per cent of the accretion energy is injected as thermal energy (a quasar-like feedback mode), while jets are employed for low accretion rates (Eddington ratios <0.01) with a 10 per cent efficiency (Dubois et al. 2012). Due to the presence of AGN feedback, the scaling relations between BH and galaxy mass (Dubois et al. 2014), the mass functions of massive galaxies ($M_* > 10^{10}$ M$_\odot$) and the rest-frame UV–optical colours of observed galaxies around the epoch of peak cosmic star formation (see Kimm et al. 2012) are well reproduced by our model. Given the high sensitivity of the rest-frame UV wavelengths to star formation (e.g. Martin et al. 2005; Kaviraj et al. 2007b), the agreement with galaxy UV–optical colours and mass functions (Kimm et al. 2012) implies a good reproduction of galaxy star formation histories in the simulation, making it a useful tool for exploring the processes that drive stellar mass growth at these epochs.

We build merger trees using TREEMAKER (Tweed et al. 2009), with a typical time difference between time steps of ~35 Myr (the range is between 20 and 60 Myr). Here, we explore the merger histories of the set of ~21 100 Horizon-AGN galaxies at $z \sim 1.2$ that have masses greater than 10^{10} M$_\odot$. The minimum galaxy mass probed is $\sim 10^{8.2}$ M$_\odot$ and the simulation is complete to mergers with mass ratios of ~10: 1 or less. Our subsequent analysis is restricted to this range of mass-ratio values. Note that the masses used here are total stellar masses within the galaxy's virial radius. The mass of individual star particles is $\sim 3.5 \times 10^6$ M$_\odot$. In what follows, mergers are defined as systems that merge within a time-scale of ~0.1 Gyr. These galaxies are at the final stages of a merger, with the centres of the merger progenitors typically less than 20 kpc from each other. Tidal features are more readily observable in images at such separations (e.g. Darg et al. 2010a,b), making our model results better aligned with observations of 'close pair' systems at similar relative distances.

3 MERGER HISTORIES OF MASSIVE GALAXIES

We begin by exploring the merger histories of massive galaxies ($M_* > 10^{10}$ M$_\odot$) around the epoch of peak cosmic star formation. In Fig. 1 , we show the mass distributions of galaxies that are merging at both ends of the redshift range probed in this study. In the top panel of Fig. 2, we present the fractions of galaxies in mergers of various mass ratios (R), where R is defined as the mass of the larger progenitor divided by the mass of its smaller counterpart. The fractions of merging systems with $R < 4$: 1 ('major' mergers), 4: 1 < R < 10: 1 ('minor' mergers) and $R < 10$: 1 (major + minor mergers) are around 3, 8 and 11 per cent, respectively, with no trend with redshift. In the redshift range $1 < z < 4$, the number of minor mergers is around a factor of 2.5 higher than their major counterparts (bottom panel of this figure). In Fig. 3, we present a cumulative view of the average merger history of massive galaxies at $z \sim 1$. We show the fraction of galaxies that have had a merger with a mass ratio less than the value on the x-axis. Thus, by $z \sim 1$, 30 per cent of galaxies have had a major merger, while all massive galaxies have had either a major or minor merger with $R < 10$: 1. Note that we do not consider mass ratios greater than 10: 1 because, as noted above, the simulation is incomplete beyond these mass ratios across our redshift range of interest.

The major-merger fractions in our model are consistent with both empirically-determined values (e.g. Man et al. 2012) and theoretical estimates in the context of the ΛCDM paradigm (see e.g. Bertone & Conselice 2009; Stewart et al. 2009). The cumulative merger history estimated by observational studies suggests that a massive galaxy ($M_* > 10^{10}$ M$_\odot$) experiences ~1.1 major mergers in the redshift

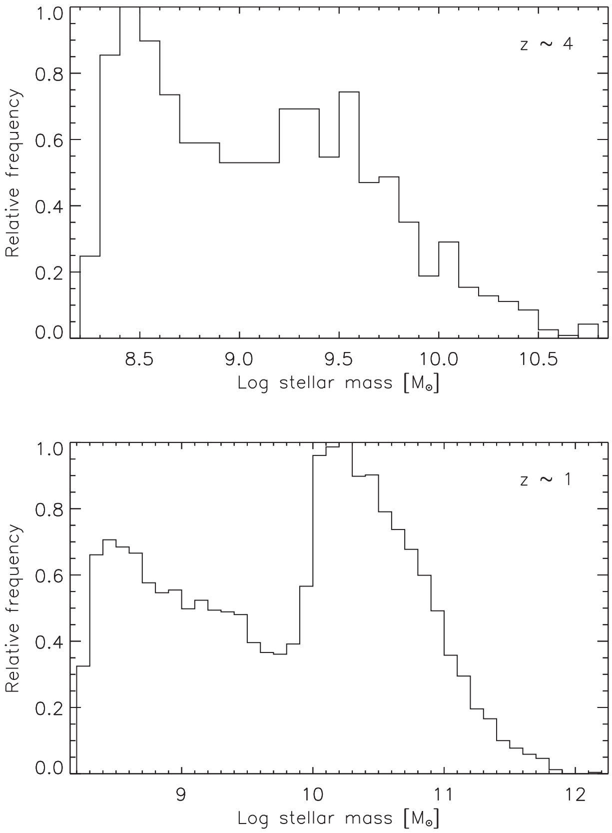

Figure 1. Mass distribution of merging galaxies at $z \sim 4$ (top) and $z \sim 1$ (bottom), which represent the opposite ends of the redshift range probed by our study.

range $0 < z < 3$ (Man et al. 2012, see also Bluck et al. 2012). Assuming the merger rate does not evolve strongly with redshift, as suggested by this study and others (e.g. Lotz et al. 2011; Man et al. 2012), this indicates that around a third of massive galaxies will have experienced a major merger by $z \sim 1$, in agreement with the cumulative merger histories presented in Fig. 3. The ratio of minor to major mergers ($\sim\times 2.5$) in our model is also consistent with recent observational work (Lotz et al. 2011; Bluck et al. 2012). We note that similar results (in terms of the cumulative merger history and the major-to-minor merger ratios) have been reported by theoretical work (e.g. Stewart et al. 2009; Oser et al. 2012). In particular, our results support the general consensus in the recent theoretical literature that major mergers play a weaker role than their minor counterparts in driving the evolution of galaxy properties such as masses, sizes and population gradients at early epochs (see e.g. Genel et al. 2008; Oser et al. 2012; Romano-Díaz et al. 2014; Hirschmann et al. 2015).

It is worth noting here that the observational literature on mergers is still developing at these epochs, and that the dispersion in current observational estimates of the merger fraction can be significant, with different studies reporting values that are discrepant by several factors (see e.g. the compilation of results in fig. 12 of Conselice 2014). The discrepancies are likely to be driven by different selection techniques, low number statistics in the high-redshift fields and cosmic variance (e.g. Lotz et al. 2011). The large current dispersion in the observational data makes a theoretical study such as this one useful, both for providing a quantitative picture of galaxy merging

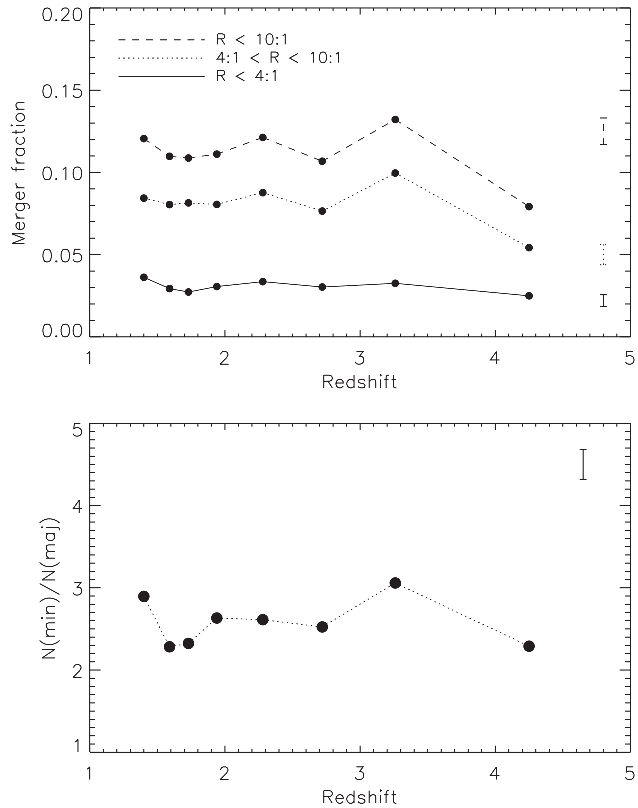

Figure 2. Top: fractions of massive galaxies ($M_* > 10^{10}$ M$_\odot$) that are in mergers of different mass ratios (R). The solid line indicates major mergers ($R < 4$: 1), the dotted line indicates minor mergers (4: $1 < R < 10$: 1), while the dashed line indicates all mergers with $R <$10: 1. Bottom: the ratio of minor to major mergers (i.e. the ratio of the solid and dotted curves in the panel above). The error bars indicate average standard deviations in values.

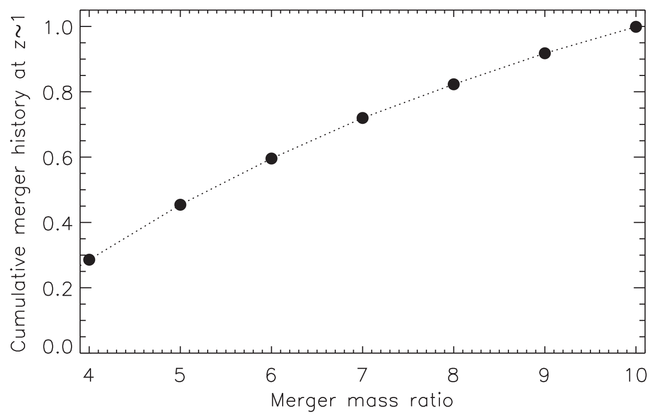

Figure 3. The fraction of massive galaxies ($M_* > 10^{10}$ M$_\odot$) at $z \sim 1$ (y-axis) that have had at least one merger with a mass ratio (R) less than the value on the x-axis. For example, at $z \sim 1$, 30 per cent of galaxies have had a major merger ($R < 4$: 1), while all massive galaxies have had either a major or minor merger with $R < 10$: 1.

at $z > 1$, and for offering theoretical estimates that can be better tested as the observational literature matures.

In Fig. 4, we study the star formation activity in major mergers. Since the literature often invokes red mergers (i.e. those where the fraction of new stars formed is close to zero) to explain massive-galaxy evolution (e.g. Naab, Johansson & Ostriker 2009; Oser et al.

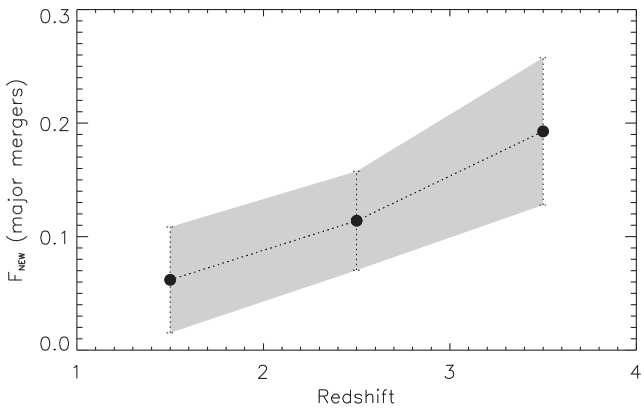

Figure 4. The mass fraction (F_{new}) of young (age <0.1 Gyr) stars in major-merger remnants. The points indicate median values, while the width of the shaded region indicates the standard deviation in the values of F_{new} at that redshift.

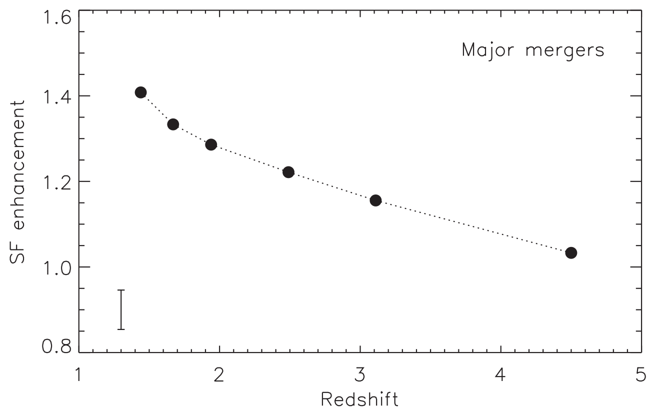

Figure 5. The star formation enhancement in systems that are in major mergers. The enhancement is defined as the ratio of the total star formation activity in mergers to that in non-merging systems at a given redshift. The error bar indicates an average standard deviation in values.

2010; Johansson, Naab & Ostriker 2012; Lackner et al. 2012; Feldmann & Mayer 2015), it is useful to explore the star formation that is associated with mergers at these epochs. We define the fraction of 'new' stars as the fraction of stellar mass formed within the last 0.1 Gyr (F_{new}), which is close to typical dynamical timescales at these epochs (e.g. Ceverino, Dekel & Bournaud 2010). The points in this figure indicate median values, while the width of the shaded region indicates the standard deviation in the distribution of F_{new} values at a given redshift.

We cast our results in terms of an empirical boundary between 'red' and 'blue' systems, estimated via recent observational work at these epochs. Using star formation histories constructed via spectral energy distribution (SED) fitting, Kaviraj et al. (2013a, hereafter K13a) have recently studied the rest-frame UV–optical colours of massive galaxies at $1 < z < 3$. The high sensitivity of the UV wavelengths to star formation means that even small mass fractions of young stars (of the order of a per cent or less) will drive galaxies into the UV–optical blue cloud (e.g. Yi et al. 2005; Kaviraj et al. 2007a), making the UV–optical colour space particularly effective at separating star-forming and quiescent systems. Taking the boundary between red and blue galaxies to be $(NUV - V) \sim 3$ (see fig. 4 in K13a), the SED-fitted star formation histories in K13a indicate that galaxies that are blue in UV–optical colours typically have $F_{new} \gtrsim 0.1$. We therefore take $F_{new} = 0.1$ as the boundary between red and blue systems in our subsequent analysis. Based on the blue versus red threshold assumed above, we find that, while almost all major mergers at $z > 3$ are blue, the proportion of red mergers increases rapidly at $z < 2$. At $z \sim 1.5$, most (but not all) major mergers are red in UV–optical colours (i.e. produce very little star formation).

4 ARE MAJOR MERGERS SIGNIFICANT DRIVERS OF STAR FORMATION?

The overall role of the major-merger process in driving stellar mass growth has been an important question in the recent literature (e.g. Rodighiero et al. 2011; K13b). The overall significance of major-merger-driven star formation depends both on the frequency of such mergers and on the enhancement of star formation that is induced when a major-merger event takes place. Thus, if the enhancement of star formation is high during the merger, then major-merger-driven star formation can be a significant contributor to the star formation budget, even if the merger fraction itself is relatively low (as has been shown to be the case in the previous section).

In Fig. 5, we present the enhancement of star formation during major mergers. The enhancement is defined as the average F_{new} in merging systems divided by the average F_{new} in the population of galaxies that are not undergoing a major merger. We find that the enhancement is relatively mild – around 20–40 per cent in the redshift range $1 < z < 3$. This is smaller than that suggested by K13b who estimated an enhancement of a factor of 2, but consistent with a forthcoming study that has repeated this analysis on a much larger sample of galaxies (Lofthouse et al., in preparation). Interestingly, the star formation enhancement in major mergers shows a gradual increase with decreasing redshift. This is likely driven by the gradual decrease in the 'background' level of star formation in normal (non-merging) galaxies, as has been noted in recent observational work (e.g. K13b). In other words, as star formation activity in galaxies becomes progressively more quiescent, the impact of a major merger becomes proportionately higher. Indeed in the local Universe, where star formation driven by secular processes is significantly weaker than at high redshift (e.g. Pannella et al. 2015), gas-rich major mergers can enhance star formation by orders of magnitude (e.g. Mihos & Hernquist 1996), in contrast to the situation at $z > 1$.

Taken together with the relatively low frequency of major mergers (recall that only ∼30 per cent of massive galaxies at $z \sim 1$ have had such a merger), this indicates that, overall, the major-merger process is not a significant driver of stellar mass growth at these redshifts. In Fig. 6, we quantify this further by calculating the fraction of the star formation budget that is hosted by major and minor mergers ($R < 10$: 1). This fraction is around 25 per cent across our redshift range of interest. Around two-thirds of this value (17 per cent) is in systems with $R < 4$: 1 (i.e. major mergers), again slightly lower than the observational estimate of K13b but consistent within the observational uncertainties.

It is worth noting here that the quantities explored in this study – such as the fraction of blue and red mergers and the star formation enhancement during the merger process – depend on the baryonic physics prescriptions employed in the model, in particular the implementation of AGN feedback. As mentioned before, the model we have employed produces agreement with basic observables e.g. mass functions, colours and the BH–galaxy mass scaling relation, making it a useful tool for exploring galaxy evolution in our redshift range of interest. However, deeper exploration of how

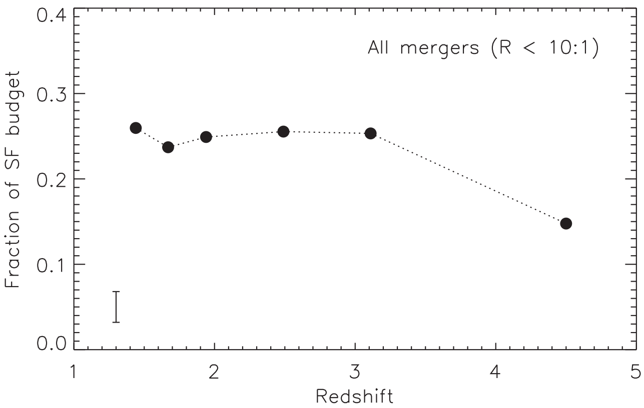

Figure 6. The fraction of the total star formation budget that is hosted by systems that are in mergers with $R < 10{:}\ 1$. Major mergers host around two-thirds of the contribution, without much trend with redshift. The error bar indicates an average standard deviation in values.

individual parameters in the model affect various galaxy properties is desirable. In forthcoming work, we will explore the impact of parameters (particularly the prescriptions for AGN feedback) more fully, by comparing Horizon-AGN with a twin simulation without AGN feedback (Horizon-NoAGN), in the context of new observational data sets like the *HST* Frontier Fields.[1]

5 SUMMARY

We have used Horizon-AGN, a hydrodynamical cosmological simulation that reproduces the mass functions and rest-frame UV–optical colours of massive galaxies ($M_* > 10^{10}\ \mathrm{M_{\odot}}$) at $z > 1$, to probe the merger histories of such objects and the impact of merging (major mergers in particular) in triggering stellar mass growth at $1 < z < 4$. Our main conclusions are as follows.

(i) The fraction of massive galaxies in major mergers ($R < 4{:}\ 1$) is around 3 per cent, while the fraction of systems in major or minor ($R < 10{:}\ 1$) mergers is around 11 per cent. The merger fractions show no trend with redshift in the range $1 < z < 4$.

(ii) Minor mergers ($4{:}\ 1 < R < 10{:}\ 1$) are around a factor of 2.5 more frequent than their major counterparts at $1 < z < 4$.

(iii) At $z \sim 1$, ~30 per cent of massive galaxies have undergone a major merger, while all massive galaxies have undergone either a major or minor merger, i.e. a merger with $R < 10{:}\ 1$.

(iv) While almost all major mergers at $z > 3$ are blue and result in significant star formation (i.e. greater than 10 per cent of the stellar mass in the remnant is less than 0.1 Gyr old), the proportion of red mergers increases at $z < 2$, with most major mergers at $z \sim 1.5$, producing remnants that are red in rest-frame UV–optical colours.

(v) The enhancement of star formation in major mergers at these epochs is relatively mild (~20–40 per cent). Together with the low frequency of these events, this indicates that major mergers are not significant drivers of stellar mass growth at these redshifts.

(vi) (Only) a quarter of the total star formation budget is hosted by mergers with $R < 10{:}\ 1$. While they are a key feature of the standard hierarchical paradigm, mergers with $R < 10{:}\ 1$ play a relatively insignificant role in driving stellar mass growth in the early Universe.

[1] http://www.stsci.edu/hst/campaigns/frontier-fields/

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REFERENCES

Bertone S., Conselice C. J., 2009, MNRAS, 396, 2345
Bluck A. F. L., Conselice C. J., Buitrago F., Grützbauch R., Hoyos C., Mortlock A., Bauer A. E., 2012, ApJ, 747, 34
Ceverino D., Dekel A., Bournaud F., 2010, MNRAS, 404, 2151
Conselice C. J., 2014, ARA&A, 52, 291
Darg D. W. et al., 2010a, MNRAS, 401, 1043
Darg D. W. et al., 2010b, MNRAS, 401, 1552
Dekel A. et al., 2009, Nature, 457, 451
Devriendt J. et al., 2010, MNRAS, 403, L84
Dubois Y., Teyssier R., 2008, A&A, 477, 79
Dubois Y., Devriendt J., Slyz A., Teyssier R., 2012, MNRAS, 420, 2662
Dubois Y. et al., 2014, MNRAS, 444, 1453
Feldmann R., Mayer L., 2015, MNRAS, 446, 1939
Förster Schreiber N. M. et al., 2006, ApJ, 645, 1062
Förster Schreiber N. M., Shapley A. E., Erb D. K., Genzel R., Steidel C. C., Bouché N., Cresci G., Davies R., 2011, ApJ, 731, 65
Genel S. et al., 2008, ApJ, 688, 789
Genzel R. et al., 2008, ApJ, 687, 59
Genzel R. et al., 2011, ApJ, 733, 101
Grogin N. A. et al., 2011, ApJS, 197, 35
Haardt F., Madau P., 1996, ApJ, 461, 20
Hirschmann M., Naab T., Ostriker J. P., Forbes D. A., Duc P.-A., Davé R., Oser L., Karabal E., 2015, MNRAS, 449, 528
Hopkins A. M., Beacom J. F., 2006, ApJ, 651, 142
Johansson P. H., Naab T., Ostriker J. P., 2012, ApJ, 754, 115
Kaviraj S. et al., 2007a, ApJS, 173, 619
Kaviraj S., Kirkby L. A., Silk J., Sarzi M., 2007b, MNRAS, 382, 960
Kaviraj S. et al., 2013a, MNRAS, 428, 925 (K13a)
Kaviraj S. et al., 2013b, MNRAS, 429, L40 (K13b)
Kennicutt R. C., Jr, 1998, ApJ, 498, 541
Kereš D., Katz N., Fardal M., Davé R., Weinberg D. H., 2009, MNRAS, 395, 160
Khandai N., Di Matteo T., Croft R., Wilkins S., Feng Y., Tucker E., DeGraf C., Liu M.-S., 2015, MNRAS, 450, 1349
Kimm T. et al., 2012, MNRAS, 425, L96
Koekemoer A. M. et al., 2011, ApJS, 197, 36
Lackner C. N., Cen R., Ostriker J. P., Joung M. R., 2012, MNRAS, 425, 641
Law D. R., Steidel C. C., Erb D. K., Larkin J. E., Pettini M., Shapley A. E., Wright S. A., 2009, ApJ, 697, 2057
Law D. R., Steidel C. C., Shapley A. E., Nagy S. R., Reddy N. A., Erb D. K., 2012, ApJ, 745, 85
Lintott C. et al., 2011, MNRAS, 410, 166
Lotz J. M., Madau P., Giavalisco M., Primack J., Ferguson H. C., 2006, ApJ, 636, 592
Lotz J. M., Jonsson P., Cox T. J., Croton D., Primack J. R., Somerville R. S., Stewart K., 2011, ApJ, 742, 103
Madau P., Pozzetti L., Dickinson M., 1998, ApJ, 498, 106

Man A. W. S., Toft S., Zirm A. W., Wuyts S., van der Wel A., 2012, ApJ, 744, 85
Mancini C. et al., 2011, ApJ, 743, 86
Martin D. C. et al., 2005, ApJ, 619, L1
Mihos J. C., Hernquist L., 1996, ApJ, 464, 641
Naab T., Johansson P. H., Ostriker J. P., 2009, ApJ, 699, L178
Oser L., Ostriker J. P., Naab T., Johansson P. H., Burkert A., 2010, ApJ, 725, 2312
Oser L., Naab T., Ostriker J. P., Johansson P. H., 2012, ApJ, 744, 63
Pannella M. et al., 2015, ApJ, 807, 141
Planck Collaboration XVI, 2014, A&A, 571, A16
Rodighiero G. et al., 2011, ApJ, 739, L40
Romano-Díaz E., Shlosman I., Choi J.-H., Sadoun R., 2014, ApJ, 790, L32
Schaye J. et al., 2015, MNRAS, 446, 521
Shapiro K. L. et al., 2008, ApJ, 682, 231
Springel V., Di Matteo T., Hernquist L., 2005, MNRAS, 361, 776
Stewart K. R., Bullock J. S., Barton E. J., Wechsler R. H., 2009, ApJ, 702, 1005
Sutherland R. S., Dopita M. A., 1993, ApJS, 88, 253
Teyssier R., 2002, A&A, 385, 337
Tweed D., Devriendt J., Blaizot J., Colombi S., Slyz A., 2009, A&A, 506, 647
Vogelsberger M. et al., 2014, Nature, 509, 177
Windhorst R. A. et al., 2011, ApJS, 193, 27
Yi S. K. et al., 2005, ApJ, 619, L111

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