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Massive spheroids can form in single minor mergers

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ABSTRACT

Understanding how rotationally supported discs transform into dispersion-dominated spheroids is central to our comprehension of galaxy evolution. Morphological transformation is largely merger-driven. While major mergers can efficiently create spheroids, recent work has highlighted the significant role of other processes, like minor mergers, in driving morphological change. Given their rich merger histories, spheroids typically exhibit large fractions of ‘*ex situ*’ stellar mass, i.e. mass that is accreted, via mergers, from external objects. This is particularly true for the most massive galaxies, whose stellar masses typically cannot be attained without a large number of mergers. Here, we explore an unusual population of extremely massive ($M_* > 10^{11} M_\odot$) spheroids, in the Horizon-AGN simulation, which exhibit anomalously low *ex situ* mass fractions, indicating that they form without recourse to significant merging. These systems form in a single minor-merger event (with typical merger mass ratios of 0.11–0.33), with a specific orbital configuration, where the satellite orbit is virtually co-planar with the disc of the massive galaxy. The merger triggers a catastrophic change in morphology, over only a few hundred Myr, coupled with strong *in situ* star formation. While this channel produces a minority (~ 5 per cent) of such galaxies, our study demonstrates that the formation of at least some of the *most massive* spheroids need not involve major mergers – or any significant merging at all – contrary to what is classically believed.

Key words: methods: numerical – galaxies: evolution – galaxies: formation – galaxies: interactions.

1 INTRODUCTION

Understanding the processes that alter the morphological mix of the Universe and, in particular, drive the formation of spheroidal galaxies is a key topic in galaxy evolution studies. Observations indicate that, while the massive galaxy population in the early Universe was dominated by objects with discy morphologies (Wuyts et al. 2011; Buitrago et al. 2014; Conselice et al. 2014; Shibuya, Ouchi & Harikane 2015), their counterparts in the local Universe are dominated by systems that are spheroidal in nature (Bernardi et al. 2003; Kaviraj 2014a).

Morphological transformation, i.e. the conversion of rotationally supported discs into slowly rotating, dispersion-dominated spheroids, is believed to be triggered primarily by galaxy mergers (Toomre 1977; Negroponte & White 1983; Barnes 1992; Di Matteo et al. 2007; Conselice, Yang & Bluck 2009; Oser et al. 2010;

Naab et al. 2014; Dubois et al. 2016; Rodriguez-Gomez et al. 2017; Martin et al. 2018a; Welker et al. 2018). The past theoretical literature has often highlighted the important role of ‘major’ mergers (mass ratios greater than $\sim 1:3$), as potentially the primary driver of morphological transformation (Toomre 1977; Negroponte & White 1983; Solanes & Perea 2015; Willett et al. 2015; Solanes, Perea & Valentí-Rojas 2018). The strong gravitational torques generated by nearly equal mass-ratio mergers efficiently move material from rotational orbits into the random, chaotic ones that make up spheroidal systems. This appears to be generally true, except in cases where the progenitors are extremely gas rich, in which case residual gas from the merger can rebuild a disc, resulting in a remnant that still shows significant rotation (e.g. Springel & Hernquist 2005; Font et al. 2017; Martin et al. 2018b).

Observations lend general support to this picture. The evolution of the morphological mix of galaxies shows a gradual increase in the fraction of spheroids over cosmic time (e.g. Butcher & Oemler 1984; Dressler et al. 1997; Conselice et al. 2014). Many spheroids show signatures of rapid change in their stellar populations (e.g. Blake

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et al. 2004; Bundy, Ellis & Conselice 2005; Ferreras et al. 2009; Carpineti et al. 2012; Wong et al. 2012; Kaviraj 2014a; Wild et al. 2016), and internal structure (e.g. McIntosh et al. 2008; Tacconi et al. 2008; Kaviraj et al. 2012; Huertas-Company et al. 2015; Rodrigues et al. 2017), indicating a major merger in their recent history.

However, both theoretical and observational work in the recent literature (e.g. Fiacconi, Feldmann & Mayer 2015; Zolotov et al. 2015; Welker et al. 2017; Martin et al. 2017, 2018b) has highlighted the potentially important role of minor mergers (mass ratios less than $\sim 1:3$), which, by virtue of their higher frequency, may significantly influence the evolution of massive galaxies. For example, many massive spheroids that are in the process of forming at $z \sim 2$, the epoch at which the morphological mix of the Universe appears to change most rapidly (e.g. Conselice et al. 2014), do not show tidal features and extended haloes that should be visible if they were forming via major mergers (e.g. Williams et al. 2014; Lofthouse et al. 2017). Indeed, recent studies have shown that (multiple) minor mergers are capable of re-distributing stellar orbits in galaxies and creating spheroidal, slowly rotating remnants (e.g. Bournaud, Jog & Combes 2007; Qu et al. 2011; Taranu, Dubinski & Yee 2013, 2015; Moody et al. 2014).

Minor mergers are capable of enhancing both star formation (e.g. Knapen et al. 2004; Ellison et al. 2008; Carpineti et al. 2012; Kaviraj 2014a) and black hole accretion rates (e.g. Kaviraj 2014b; Pace & Salim 2014) and, at low redshift, may account for more than half of the star formation budget in the Universe (Kaviraj 2014b). Furthermore, the observed evolution in the sizes of massive (early-type) galaxies is also largely attributed to this process (e.g. Trujillo et al. 2006; Newman et al. 2012). A growing body of evidence therefore points towards minor merging being a significant driver of not only morphological transformation but also of the stellar mass buildup, black hole growth, and size evolution of massive galaxies.

Despite these examples, the impact of processes like minor mergers remains difficult to study observationally. This is because the surface brightness of merger-driven tidal features scales with the mass ratio of the merger (e.g. Kaviraj 2010; Peirani et al. 2010), and thus the efficient identification of minor mergers typically requires deeper imaging than that offered by current large-area surveys (e.g. van Dokkum 2005; Duc et al. 2011; Kaviraj 2014b; Kaviraj, Martin & Silk 2019). Given this lack of survey depth, the effect of minor mergers on galaxy evolution remains relatively unexplored, although forthcoming instruments like LSST, EUCLID and JWST (e.g. Tyson 2002; Gardner et al. 2006; Laureijs et al. 2011; Robertson et al. 2017) will enable the first truly statistical studies of minor-merger-driven galaxy evolution.

Much of our current understanding of the role of this process therefore continues to come from theoretical work e.g. from semi-analytical models (e.g. Somerville & Primack 1999; Cole et al. 2000; Benson et al. 2003; Bower et al. 2006; Croton et al. 2006) and, more recently, from cosmological hydrodynamical simulations (e.g. Dubois et al. 2014; Vogelsberger et al. 2014; Khandai et al. 2015; Schaye et al. 2015; Taylor & Kobayashi 2016; Kaviraj et al. 2017)

It is worth noting that exploring the role of various processes in driving morphological transformation ideally requires a simulation with a cosmological volume. While the past literature has often employed isolated and idealized simulations of galaxy mergers (e.g. Barnes 1988; Hernquist & Spiegel 1992; Bois et al. 2011), such simulations exclude the broader effects of environment and gas accretion from the cosmic web. Furthermore, since the parameter space (e.g. orbital configurations, mass ratios, etc.) explored by these studies is typically small, statistical conclusions about the

importance of various processes that drive morphological change are difficult to draw. This can be particularly important for channels, like the one studied here, that are relatively rare.

The consensus view from simulations is that morphological transformation and the creation of spheroids can proceed via various channels and shows a complicated dependence on factors such as mass ratios, gas fractions, environments, and orbital configurations [see the study by Martin et al. (2018a), which quantifies these dependencies in detail]. Here, we describe a channel for spheroid formation in which a *single* minor merger creates a massive ($M_* > 10^{11} M_\odot$) spheroidal system. In this process, the satellites approach the more massive merging progenitor on a trajectory that is close to being co-planar to the plane of the massive disc. Notwithstanding the low mass ratios of many of these mergers, these events are able to trigger a catastrophic change in morphology over just a few hundred Myr, coupled with an episode of strong *in situ* star formation, that creates a slowly rotating, massive spheroidal system from an otherwise typical disc galaxy.

This paper is organized as follows. In Section 2, we briefly describe the Horizon-AGN simulation and how galaxies, mergers, and morphologies are defined. In Section 3, we describe the properties of the spheroidal galaxies studied here and follow the evolution of their stellar and gas mass and morphology over cosmic time. In Section 4, we explore the properties of the progenitor systems (e.g. the gas fraction and clumpiness of the more massive galaxy and the orbital configuration of the merger) and investigate how such spheroids form via single minor-merger events. We summarize our findings in Section 5.

2 HORIZON-AGN SIMULATION

In this study, we use the Horizon-AGN cosmological hydrodynamical simulation (Dubois et al. 2014), which employs RAMSES (Teyssier 2002), an adaptive mesh refinement hydrodynamics code. Horizon-AGN simulates a $100 h^{-1} \text{coMpc}^3$ volume, with *WMAP7* Λ cold dark matter initial conditions (Komatsu et al. 2011). The simulation contains 1024^3 dark matter particles on an initial 1024^3 cell gas grid. This is refined according to a quasi-Lagrangian criterion, when eight times the initial total matter resolution is reached in a cell. This refinement can continue until 1 kpc in proper units. Horizon-AGN has dark matter and stellar mass resolutions of $8 \times 10^7 M_\odot$ and $4 \times 10^6 M_\odot$ respectively.

The simulation includes prescriptions for feedback from both stars and AGNs. Continuous stellar feedback is employed including momentum, mechanical energy and metals from stellar winds, Type Ia and Type II supernovae (SNe). Type Ia SNe are implemented following Matteucci & Greggio (1986), assuming a binary fraction of 5 per cent (Matteucci & Recchi 2001). Feedback from Type II SNe and stellar winds is implemented using STARBURST99 (Leitherer et al. 1999, 2010), which employs the Padova model (Girardi et al. 2000) with thermally pulsating asymptotic branch stars (Vassiliadis & Wood 1993).

Black holes (BHs) are implemented as ‘sink’ particles, with initial masses of $10^5 M_\odot$, and grow via gas accretion or coalescence with other BHs. When gas accretes on to a central BH it imparts feedback on ambient gas via two methods, depending on the accretion rate. When there is a high ratio of gas accretion to the Eddington rate (Eddington ratios of > 0.01), 1.5 per cent of the energy is injected into the gas as thermal energy (a ‘quasar’ mode). However, when Eddington ratios are less than 0.01, bipolar jets are employed with velocities of 10^4 km s^{-1} , which constitutes a ‘radio’ mode with an efficiency of 10 per cent. For more details of the baryonic recipes

used in the simulation, we refer readers to Dubois et al. (2014, 2016) and Kaviraj et al. (2017).

Horizon-AGN produces good agreement with an array of observational quantities that trace the aggregate growth of stars and BHs, particularly in massive galaxies. For example, in the stellar mass range $M_* > 10^{10.5} M_\odot$, it reproduces the morphological mix of the nearby Universe (Dubois et al. 2016; Martin et al. 2018b), the evolution of the stellar mass/luminosity functions, rest-frame UV–optical–near-infrared colours, the cosmic star formation history and the star formation main sequence (Kaviraj et al. 2017; Martin et al. 2017), galaxy merger rates at $z > 1$ (Kaviraj et al. 2015), and the evolving demographics of BHs over cosmic time (Volonteri et al. 2016). However, the simulation overproduces the number densities of very low mass galaxies at low and intermediate redshift (which is typical of all simulations in this class of models). The rest-frame UV colours of galaxies in the red sequence are also typically too blue, indicating that feedback processes employed in the model do not suppress star formation completely in ‘passive’ galaxies. Note, however, that since the star formation rate (SFR) density in the red sequence is negligible compared to that in the blue cloud this does not affect the overall reproduction of galaxy properties.

2.1 Identifying galaxies and mergers

In each snapshot of the simulation galaxy catalogues are produced using the ADAPTAHOP structure finder (Aubert, Pichon & Colombi 2004) applied to the star particles. Structures are selected when the local density, calculated for each particle using the nearest 20 neighbours, exceeds the average matter density by a factor of 178. A minimum of 50 particles is required for a structure to be identified, which imposes a minimum galaxy stellar mass of $\sim 2 \times 10^8 M_\odot$. Merger trees are produced for each galaxy from $z = 0.06$ to $z = 3$, with a typical spacing between time-steps of ~ 130 Myr, using the method described in Tweed et al. (2009).

2.2 Morphologies

Following Martin et al. (2018a), we define galaxy morphology using stellar kinematics, specifically $\frac{V}{\sigma}$, which is the ratio between the mean rotational velocity (V) and the mean velocity dispersion (σ). Galaxies with higher values of $\frac{V}{\sigma}$ are rotationally supported i.e. disc galaxies, while those with lower $\frac{V}{\sigma}$ values are pressure-supported spheroidal systems.

In order to obtain $\frac{V}{\sigma}$, the coordinate system is rotated so that the z -axis is oriented along the stellar angular momentum vector. V is then defined as V_θ , the mean tangential velocity component in cylindrical coordinates. The velocity dispersion (σ) is calculated by taking the standard deviations of the radial (σ_r), tangential (σ_θ), and vertical star-particle velocities (σ_z) and summing them in quadrature. $\frac{V}{\sigma}$ is then defined as

$$\frac{V}{\sigma} = \frac{\sqrt{3}V_\theta}{\sqrt{\sigma_r^2 + \sigma_z^2 + \sigma_\theta^2}}. \quad (1)$$

As described in Martin et al. (2018a), galaxies are separated morphologically by considering a range of values for $\frac{V}{\sigma}$ and comparing how the corresponding predicted early-type fractions compare to local observations (Conselice 2006). The value of $\frac{V}{\sigma}$ that produces the best agreement with the observed morphological mix of the Universe is then used to separate early- and late-type galaxies. This $\frac{V}{\sigma}$ threshold is 0.55 (see fig. 1 in Martin et al. 2018a), i.e. galaxies with $\frac{V}{\sigma} > 0.55$ are considered to be discs, while those

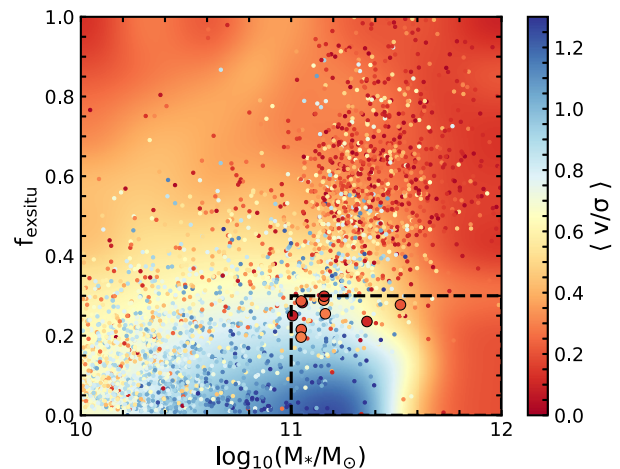


Figure 1. 2D histogram showing the fraction of *ex situ* mass versus stellar mass of galaxies in the Horizon-AGN simulation at $z = 0.06$. The individual points show a random selection of galaxies and the background colour is derived using a cubic spline interpolation over all galaxies. The colour coding indicates the value of $\frac{V}{\sigma}$ of both the background and the individual points. Massive spheroids typically exhibit large fractions of *ex situ* stellar mass. The spheroids in this study have $\frac{V}{\sigma} < 0.3$, $f_{ex\ situ} < 0.3$, and stellar mass $> 10^{11} M_\odot$, and are shown using the large outlined points in the bottom right-hand corner of the plot. Note that we do not consider objects that may have $\frac{V}{\sigma} < 0.3$ but are in ongoing mergers, as the $\frac{V}{\sigma}$ values of such objects are highly transient and the morphology of the remnant is uncertain.

with $\frac{V}{\sigma} < 0.55$ are spheroids. Note that the systems we study in this paper have $\frac{V}{\sigma}$ values that are significantly lower than 0.55 i.e. these galaxies are firmly in the spheroid regime. We note that the highest $\frac{V}{\sigma}$ in Horizon-AGN is 2.11, which is lower than observed values. This is because the spatial resolution results in the bulge components of discs being slightly too massive.

3 SPHEROIDAL GALAXIES WITH LOW EX SITU MASS FRACTIONS

3.1 Sample selection and properties of the galaxies

In a recent study, Martin et al. (2018b) have used Horizon-AGN to perform a detailed study of how mergers drive the change in the morphological mix of the Universe over cosmic time. Not unexpectedly, spheroidal galaxies, particularly those more massive than the knee of the galaxy mass function ($M_* > 10^{11} M_\odot$), typically have rich merger histories. As a result, they usually exhibit very high *ex situ* mass fractions, where *ex situ* mass is defined as that directly accreted from external objects, rather than having been formed *in situ* in the main (i.e. most massive) branch of the merger tree of the galaxy in question (Martin et al. 2018b). Fig. 1 shows a 2D histogram of galaxies in Horizon-AGN at the last snapshot ($z = 0.06$), with the *ex situ* stellar mass fraction plotted against stellar mass. Points indicate individual galaxies, while colours indicate their $\frac{V}{\sigma}$ ratios.

While most massive spheroids show high *ex situ* mass fractions, there exists a small, ‘anomalous’ population of spheroidal systems with unusually low *ex situ* mass fractions (< 0.3) that are more typical of discs. These objects are the focus of this study. We select galaxies that (1) have stellar masses greater than $10^{11} M_\odot$, which puts them beyond the knee of the galaxy mass function (see e.g. Kaviraj et al. 2017) where major mergers have classically been

thought to be essential for building up galaxy mass (e.g. Bell et al. 2004; Bundy et al. 2006; Faber et al. 2007), (2) exhibit $\frac{V}{\sigma} < 0.3$, i.e. are firmly in the spheroid regime, and (3) have very low *ex situ* mass fractions ($f_{ex\ situ} < 0.3$). The $f_{ex\ situ}$ threshold is not arbitrary but chosen at the approximate mass-ratio demarcation between major and minor mergers ($\sim 1:3$), making it unlikely that these galaxies have undergone major mergers. As we show below, while they have not undergone major interactions, these systems are the products of single minor mergers with a specific set of properties. Note that simulated galaxies in this mass regime have very complete merger histories. For example, the merger histories of galaxies with $M_* > 10^{11} M_{\odot}$ are close to 90 per cent complete for mass ratios greater than $\sim 1:10$ out to $z \sim 3$, and almost 100 per cent complete out to $z \sim 1$ (see fig. 1 in Martin et al. 2018b).

Our initial selection yields 20 galaxies, half of which exhibit, on visual inspection of their images, strong morphological disturbances (i.e. are in ongoing mergers). As the $\frac{V}{\sigma}$ of merging objects can be extremely spurious (Martin et al. 2018b), the final values of $\frac{V}{\sigma}$ for these systems are uncertain. Thus, we study only the 10 systems (indicated by the large black points in Fig. 1) that are morphologically settled spheroids. This represents ~ 5 per cent of spheroids ($\frac{V}{\sigma} < 0.55$) that have $M_* > 10^{11} M_{\odot}$.

Fig. 2 shows mock *gri* images of these galaxies (note the clearly spheroidal morphologies). To produce these images we use the Bruzual & Charlot (2003) stellar population synthesis models, with a Chabrier (2003) initial mass function, to calculate intrinsic spectral energy distributions (SEDs) of the constituent star particles within each galaxy. Dust-attenuated SEDs are then calculated using the SUNSET code, as described in Kaviraj et al. (2017), with line-of-sight optical depths calculated assuming a dust-to-metal ratio of 0.4 (e.g. Draine & Li 2007). The attenuated SEDs of star particles are then convolved with the SDSS *g*-, *r*-, and *i*-band filter response curves to produce mock images of each galaxy. The images include a Gaussian point spread function with 1.2 arcsec FWHM, but do not include a background or shot noise.

This population of galaxies consists of extremely massive, slowly rotating spheroids in the local Universe that have formed without recourse to a significant amount of merging, since only a small fraction of their stellar mass has been directly accreted from external sources. It is worth noting that the cuts in $\frac{V}{\sigma}$ and $f_{ex\ situ}$ made here are conservative i.e. we intentionally select very low values of $\frac{V}{\sigma}$ and $f_{ex\ situ}$ in order to cleanly isolate systems that have virtually no mergers in their assembly histories, yet are both massive and spheroidal. It could be reasonably expected, however, that the processes that drive the formation of these spheroids may also play some role in the creation of spheroids that have higher (i.e. more typical) values of $\frac{V}{\sigma}$ and $f_{ex\ situ}$.

In Table 1, we summarize key properties of these spheroids: the stellar mass today, the fractional increase in stellar mass after the merger that creates these systems, the $\frac{V}{\sigma}$, effective radius, effective surface brightnesses in the *r* band,¹ the local environment at the present day, key properties of the merger and the peak SFR as a fraction of the average SFR of a similar mass galaxy at the redshift of the merger ('Rel. ϕ_{max} ').

Following Martin et al. (2018a), we estimate local environment by ranking each galaxy by its local number density, which is calculated using an adaptive kernel density estimation method (Breiman, Meisel & Purcell 1977). Galaxies are then sorted into percentiles

¹The effective surface brightness is defined as the mean surface brightness within an effective radius.

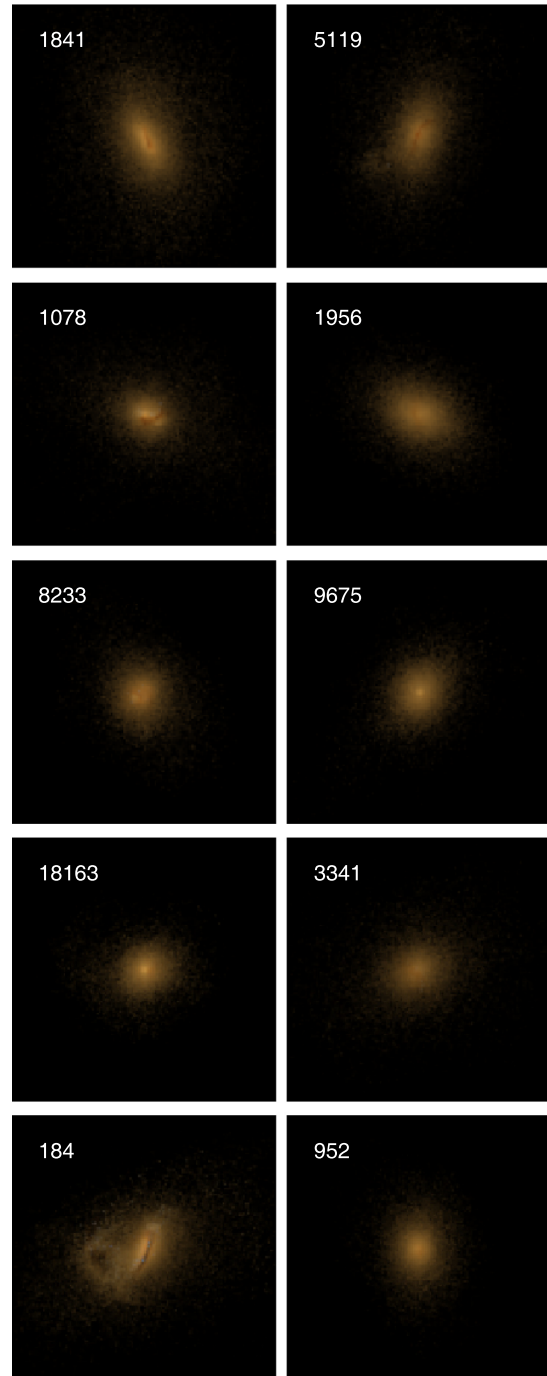


Figure 2. Mock *gri* images of the spheroids studied in this paper. The ID of each galaxy (same as in the tables) is shown in the panels. The procedure for constructing the images is described in Section 3.1. The angular resolution of the images is $1.05 \text{ arcsec pixel}^{-1}$.

of density, so that galaxies in the 0–40th percentile range inhabit environments that roughly correspond to the ‘field’, those in the 40–90th percentile range inhabit ‘groups’ and those in the 90–100th percentile range inhabit environments typical of ‘clusters’. We refer readers to Martin et al. (2018a) for more details of this procedure. Rel. ϕ_{max} is calculated by dividing the maximum spheroid SFR by the average value of the observational star formation main sequence for $M_* = 10^{11} M_{\odot}$ at the redshift of the merger that creates these spheroids. The star formation main sequences are taken from Lee

Table 1. Properties of the spheroids studied in this paper (cols 1–8) and properties of the mergers that create them (cols 9–11). Columns are as follows: (1) Galaxy ID, (2) stellar mass in units of $10^{11}M_{\odot}$, (3) ratio of stellar mass of the spheroid to the mass of the progenitors before the merger, (4) $\frac{V}{\sigma}$ (recall that the boundary between discs and spheroids is $\frac{V}{\sigma} \sim 0.55$), (5) effective radius (R_e) in kpc, (6) effective surface brightness (i.e. the average r -band surface brightness within R_e), (7) local environment, expressed in terms of the percentile in local density (values greater than 0.9 indicate cluster environments, values in the range 0.4–0.9 indicate groups and values below 0.4 indicate the field), (8) the fraction of *ex situ* stellar mass, (9) redshift of the merger, (10) stellar mass ratio of the merger, and (11) ratio of the maximum SFR in the merger remnant during the phase where the morphological transformation is fastest (shown by the grey regions in Fig. 3) and the average value of the observational star formation main sequence, for $M_* = 10^{11}M_{\odot}$, at the redshift of the merger that creates these spheroids.

1 ID	2 M_* ($10^{11} M_{\odot}$)	3 M_*/M_i	4 $\frac{V}{\sigma}$	5 R_e (kpc)	6 μ_e^r (mag arcsec $^{-2}$)	7 Density perc.	8 $f_{ex\ situ}$	9 Merger z	10 Merger mass ratio	11 Rel. ϕ_{max}
1841	2.28	1.97	0.12	10.39	21.08	0.30	0.24	0.4	0.15	63.7
5119	1.42	1.51	0.28	12.28	22.43	0.26	0.29	0.95	0.11	20.52
1078	1.33	6.33	0.10	10.87	21.55	0.82	0.29	2.45	0.33	27.22
1956	1.45	3.63	0.27	12.43	22.22	0.75	0.25	1.3	0.17	37.02
8233	1.11	1.54	0.24	7.66	21.57	0.53	0.21	0.3	0.24	18.51
9675	1.01	1.77	0.07	9.26	21.69	0.10	0.25	0.6	0.17	9.75
18163	1.11	1.71	0.30	7.34	20.60	0.17	0.20	0.25	0.20	8.16
3341	1.13	3.55	0.03	11.53	22.83	0.77	0.28	2.1	0.15	9.12
184	3.36	2.85	0.16	10.07	19.75	0.92	0.28	0.9	0.27	31.38
952	1.13	2.69	0.23	8.98	21.95	0.04	0.29	0.4	0.20	32.82

et al. (2015) ($0.3 < z < 1.2$), Karim et al. (2011) ($0.3 < z < 2.5$), Whitaker et al. (2012) ($0.3 < z < 2.5$), and Tasca et al. (2015) ($2.5 < z < 5.0$).

Table 1 shows that the current mass of the spheroids is several factors ($\times 1.5$ – 6.3) larger than the mass of their progenitor systems. The effective radii (R_e) are typically larger than the typical value of R_e for spheroids of such masses in the present-day Universe (~ 4 kpc; Bernardi et al. 2010) and the effective surface brightnesses of these objects are somewhat fainter than that of typical massive spheroids (~ 18 mag arcsec $^{-2}$, e.g. Blanton et al. 2005; Driver et al. 2005). Indeed, the effective surface brightness of some of these systems is close to the surface brightness limit of current large surveys like the SDSS (~ 23 mag arcsec $^{-2}$, e.g. Kniazev et al. 2004). The local environments of our spheroids span the full range of density percentiles, from systems that are in the field to one object that is in a cluster. These events are therefore not strongly correlated with a particular type of local environment. Finally, the SFRs of these spheroids show significant enhancements above the average SFR of similar-mass galaxies at the redshifts of their mergers.

3.2 Creation in single minor mergers

Table 1 also summarizes the properties of the mergers that create the spheroids in this study. The redshifts of these events do not show a preference for a particular epoch. The mass ratios indicate that the events are minor mergers, albeit with a wide range of values, ranging from events that are close to being major mergers (mass ratios close to $\sim 1:3$) to those where the mass ratios are as low as $\sim 1:10$. It is worth noting that many of these spheroids exhibit prominent dust lanes (see Fig. 2) that are considered to be signposts of recent minor mergers (see e.g. Kaviraj et al. 2012).

We proceed by exploring the evolution of the properties of the more massive galaxy (stellar mass, *ex situ* stellar mass, gas mass, effective radius, and $\frac{V}{\sigma}$) in the minor mergers that create these spheroids. We follow these properties between $z = 0.06$ and $z = 3$ and focus on changes in these characteristics before and after the minor-merger event in question. Note that, in all cases, the massive galaxy in these mergers is firmly in the disc regime *before* the merger takes place.

In Fig. 3, we show the evolution of these properties for two galaxies, in order to illustrate the process (the evolution is similar for other spheroids in our sample). In each panel, we highlight in grey the redshift at which the merger occurs. The left-hand panels show the evolution in $\frac{V}{\sigma}$. After the event the galaxies undergo a catastrophic decrease in $\frac{V}{\sigma}$ that can drop from the disc regime $\frac{V}{\sigma} > 0.55$ well into the spheroid regime within only a few hundred Myr (which represents only a few dynamical time-scales). The $\frac{V}{\sigma}$ ratio does not recover after the merger, indicating that a disc does not reform after the event. We note that, while some of these spheroids do undergo further mergers (typically events with very low mass ratios), the creation of the dispersion-dominated system takes place in a *single* minor-merger event. An analysis of the angular momentum budget indicates that the angular momentum lost by the stars during these mergers is largely transferred to the dark matter halo.

The rapid formation of these spheroids is in contrast to the average morphological change of the general massive spheroid population (fig. 11 in Martin et al. 2018b), in which the mean $\frac{V}{\sigma}$ changes from the disc regime to values close to 0.3 over Hubble time (note, however, that this is not the same as the average change in $\frac{V}{\sigma}$ in individual typical spheroids where the morphological change can be bursty and changes fastest during merger events). For the spheroids in this study, a similar change in $\frac{V}{\sigma}$ is achieved within only a few hundred Myr.

The middle panels show the change in the stellar mass of the galaxy (solid line), the *ex situ* i.e. accreted stellar mass (dashed line) and the gas mass of the system (dotted line). The step change in the *ex situ* mass (dashed line) around the time of the merger indicates the stellar mass brought in by the accreted satellite. The galaxies undergo strong stellar mass growth during the merger, with high SFRs (demonstrated by the steep gradient of the solid line), a corresponding decrease in the gas mass as it is consumed as the merger progresses, and an increase in the effective radius (right-hand panels). In many cases the gas mass increases prior to the star formation event, due to gas brought into the system by the satellite. It is worth noting that these merger remnants do not undergo compaction, akin to minor-merger-driven disc instabilities that are expected to take place in the gas-rich high-redshift Universe

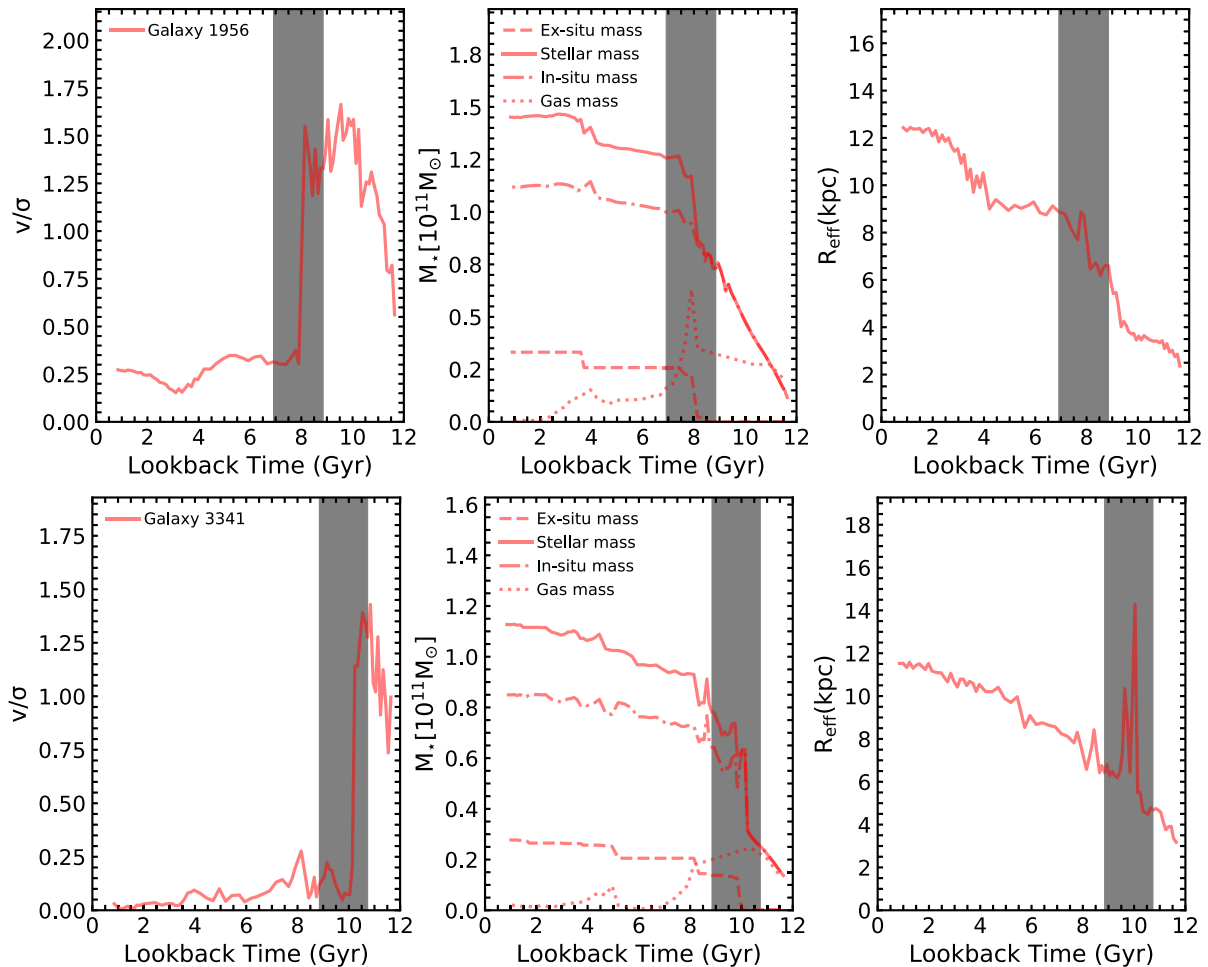


Figure 3. The evolution of the properties of the progenitor system of the spheroids in this study. The top and bottom rows show the evolution of two typical galaxies in our sample. The grey region indicates the epoch at which the merger event takes place. Left: Evolution in $\frac{v}{\sigma}$ of the more massive galaxy. Middle: Change in the stellar mass (solid), *ex situ* (i.e. accreted) mass (dashed), *in situ* mass (dash-dotted), and gas mass (dotted) of the more massive galaxy. The near-step change in the *ex situ* mass around the time of the merger indicates the stellar mass brought in by the accreted satellite. Right: Change in the effective radius of the more massive galaxy. In all cases, the merger results in a catastrophic (and permanent) decrease in $\frac{v}{\sigma}$, followed by a period of significant star formation and an increase in the effective radius of the galaxy.

(Dekel & Burkert 2014; van Dokkum et al. 2015; Zolotov et al. 2015) Instead, they continue to grow in stellar mass and size after the merger.

4 PROPERTIES OF THE PROGENITOR SYSTEM

We proceed by exploring why these minor mergers have such a profound and unusual impact on the morphology of the remnant, by studying properties of the progenitor system that are likely to contribute to the observed evolution of the morphology, stellar mass, and effective radius of the remnant. We focus on three characteristics: the gas fraction and clumpiness of the more massive progenitor and the orbital configuration of the merging galaxies.

Discs in the early Universe ($z > 2$) can be gas-rich and clumpy and more susceptible to gravitational instabilities that can be triggered by events such as minor mergers (e.g. Swinbank et al. 2012; Zolotov et al. 2015; Saha & Cortesi 2018). Even though the redshifts of the mergers that create our spheroids are typically much lower than the epoch of such gas-rich discs, it is worth considering whether the more massive progenitors may be anomalously gas-rich and/or

clumpy, compared to control samples at similar redshifts. Note that we have also examined whether the merging satellites have properties that diverge from other galaxies of similar stellar masses at the merger redshifts in question, but find that they are not anomalous. In any case, given the typically low mass ratios of these events, the properties of the spheroidal remnants are driven more by those of the more massive progenitors, which are therefore more pertinent to our analysis.

In a similar vein, the outcome of a merger can be dependent on the orbital configuration of the progenitor system (e.g. Naab & Burkert 2003; Chilingarian et al. 2010; Solanes & Perea 2015; Martin et al. 2018b). It is therefore worth exploring whether the progenitors of these spheroids show a pattern in their relative trajectories that may explain the properties of their remnants.

4.1 Gas fraction and clumpiness of the more massive progenitor

We begin by comparing the gas fraction and clumpiness of the more massive progenitor, at the time-step before the merger, to a control sample of 200 randomly selected disc galaxies at the same redshift

Table 2. Properties of the more massive progenitor of the spheroids studied in this paper. Columns: (1) Galaxy ID, (2) stellar mass in units of $10^{11} M_{\odot}$, (3) and (4) gas fraction and stellar clumpiness, respectively, relative to the mean of a control sample at the merger redshift.

1 ID	2 M_{\star} ($10^{11} M_{\odot}$)	3 Rel. f_{gas}	4 Rel. clumpiness
1841	1.16	1.15 ± 0.13	0.79 ± 0.05
5119	0.94	0.99 ± 0.15	1.17 ± 0.08
1078	0.21	0.89 ± 0.36	0.84 ± 0.06
1956	0.40	1.19 ± 0.27	1.55 ± 0.11
8233	0.72	1.23 ± 0.17	1.61 ± 0.11
9675	0.57	1.53 ± 0.26	1.65 ± 0.12
18163	0.63	1.20 ± 0.16	2.06 ± 0.15
3341	0.23	1.08 ± 0.39	1.22 ± 0.23
184	1.01	1.42 ± 0.20	0.74 ± 0.05
952	0.42	1.47 ± 0.31	0.62 ± 0.04

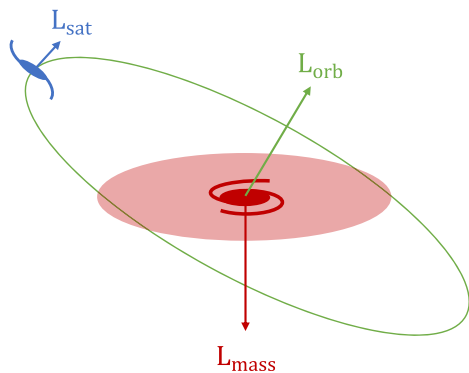


Figure 4. Diagram indicating the vectors used to describe the orbital configuration of the mergers. The angles between vectors are defined in the standard way, in the common plane containing both vectors.

that have stellar masses within 10 per cent of the galaxy in question. The gas fraction is defined as

$$f_{\text{gas}} = \frac{M_{\text{gas}}}{M_{\star} + M_{\text{gas}}}, \quad (2)$$

where M_{gas} and M_{\star} are the total gas and stellar masses in the progenitor system, respectively. Column 3 in Table 2 shows the ratio of the gas fractions in the more massive progenitors just before the merger to those in the control samples. For many systems these ratios are actually lower than the median values for similar disc galaxies at the same redshift, while for the others the ratios are less than ~ 1.5 . Compared to galaxies at intermediate redshift (where most of our spheroids form), gas fractions in the gas-rich early Universe are expected to be almost an order of magnitude larger (see fig. 4 in Martin et al. 2018b), indicating that, on the whole, the more massive progenitors in these mergers are not anomalously gas-rich.

We proceed by comparing the clumpiness of the more massive progenitor to the control samples.² Since we are interested in the *relative* clumpiness, compared to that of other galaxies at the same redshift, we simply use the star-particle distributions for this exercise. To measure the clumpiness in the stars we follow

²Note that, given the spatial resolution of the simulation, we are largely exploring kpc-scale clumps (Elmegreen et al. 2013; Cava et al. 2018) in this exercise.

Conselice (2003) and Hambleton et al. (2011). We first apply a Gaussian filter with a standard deviation of $0.3 \times r_{20}$, where r_{20} is the radius that contains 20 per cent of the galaxy’s stellar mass surface density (Conselice 2003), and then subtract the original image from the smoothed one, which leaves the high-frequency structure as a residual. The absolute signal in this residual image is then summed and divided by the sum of that in the original image to yield a value for the clumpiness.

We study the ratio of the clumpiness of the more massive progenitors to control samples at the redshift of the merger. Column 4 in Table 2 shows that many of the progenitor systems are substantially *less* clumpy than their control samples and that the clumpiness of the more massive progenitors is within 46 per cent of the mean values of the control samples in all cases. On the whole, the ratios do not indicate that the more massive progenitors of our spheroids have anomalously high values of clumpiness.

Hence, the progenitor systems do not appear to be atypical, either in terms of their gas fractions or their clumpiness. These properties are therefore unlikely to be the key factors behind the rapid morphological transformation observed in these mergers.

4.2 Orbital configurations

We proceed by investigating whether the merger progenitors may have a specific orbital configuration that plays a role in the observed properties of the remnant. The orbital configurations are calculated at the closest time-step before coalescence. Fig. 4 describes the vectors used to quantify the orbital configuration of the mergers. We study two key aspects of the orbital configuration: the angle between the spin (i.e. angular momentum) vectors of the two merging galaxies (i.e. whether the merger is prograde or retrograde) and the angle between the angular momentum vector of the satellite orbit and the spin of the more massive galaxy.

The top panel of Fig. 5 shows the alignment of the spin vectors, defined using the star particles, of the two galaxies. Positive values of $\cos(\theta)$ indicate prograde mergers, where the spin vectors of the discs of the two galaxies point in the same direction. Negative values of $\cos(\theta)$ indicate retrograde mergers, where the spin vectors of the discs of the two galaxies do not point in the same direction. The red dotted line indicates the distribution from a control sample (constructed as described in Section 4.1 above). As might be expected, neither the control sample nor the progenitors of our spheroids show any preference for prograde or retrograde mergers. The relative spins of the two merging galaxies are therefore not the principal cause of the properties of the remnant.

Finally, we study the orientation of the orbit of the satellite relative to the disc of the more massive galaxy. We first measure the angular momentum vector of the satellite orbit, defined as $L_{\text{orbit}} = M_{\text{sat}}(r \times v)$, where v and r are the velocity and position vectors of the satellite with respect to the massive galaxy respectively, and then calculate the angle between L_{orbit} and the spin vector of the massive progenitor. Thus, a value of 0 for $\cos \theta$ represents a satellite whose orbit is exactly perpendicular to the disc of the more massive progenitor. A value of 1 indicates that the satellite orbit is exactly co-planar with the plane of the disc of the more massive progenitor and prograde with its spin, while a value of -1 indicates that the satellite orbit is co-planar with the plane of the disc of the more massive progenitor, but retrograde with its spin.

We find that, unlike the control sample that exhibits a flat distribution in orbital configurations (although it shows a slight, expected tendency towards prograde co-planar orbits, as satellites in the inner parts of haloes tend to align with the central galactic

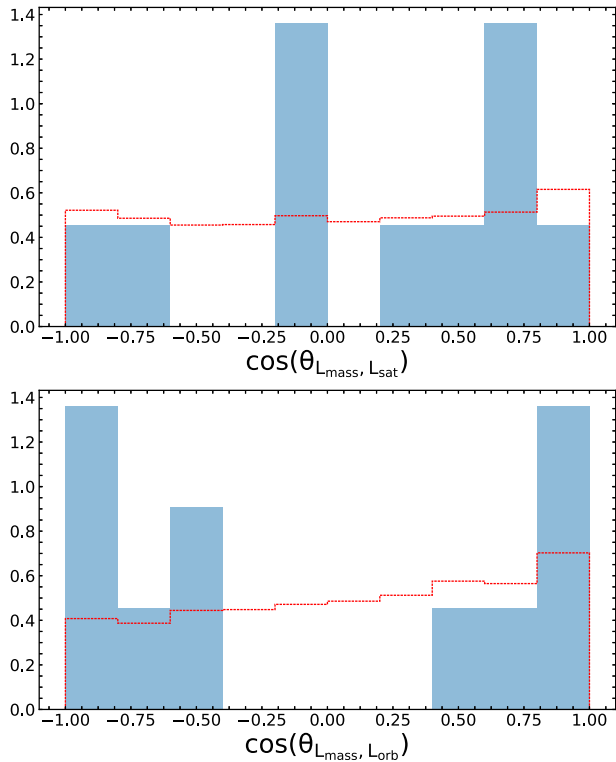


Figure 5. Top: The cosine of the angle between the spin vectors, defined using the star particles, of the massive galaxy (L_{mass}) and the satellite (L_{sat}). The corresponding distribution from a control sample is shown in red (the normalization is arbitrary and chosen for clarity). There is no preference for the spins of the two galaxies to be either prograde or retrograde. Bottom: The cosine of the angle between L_{orb} (see Fig. 4) and the spin vector of the massive galaxy (L_{mass}). The merger events cluster around a specific orbital configuration, where the satellite’s orbit tends to be close to coplanar with the disc of the massive galaxy i.e. $\cos \theta$ tends to be close to either -1 or $+1$.

plane, see Welker et al. 2018), the progenitors of our spheroids strongly favour satellite trajectories that are close to coplanar with the disc of the more massive progenitor (regardless of whether the mergers are prograde or retrograde). Such trajectories are likely to be those that are able to deliver the orbital energy of the satellite into the disc of the more massive progenitor in the most efficient manner (e.g. Cox et al. 2008), which likely enables even a small satellite (recall that the lowest mass ratio in the progenitors of our spheroids is 0.11) to quickly destroy the disc of the massive progenitor and create a dispersion-dominated system.

In Fig. 6, we combine the information in the two histograms from Fig. 5 by plotting the angles between the spin vectors of the two galaxies against the angle between the satellite orbit and the spin of the massive galaxy. Our systems show no preference for either the relative spins of the two galaxies or the satellite orbit to be prograde or retrograde. In addition, there appears to be no correlation between these two quantities. These mergers therefore occur in all combinations of spin and orbit alignment, with the only common feature being that they are coplanar.

Since our galaxy sample is relatively small, we briefly check whether a broad similar trend remains if we relax the mass threshold of the analysis. As we show in the Appendix, studying the orbital configurations of similar (i.e. low $f_{\text{ex situ}}$) spheroids with a mass cut

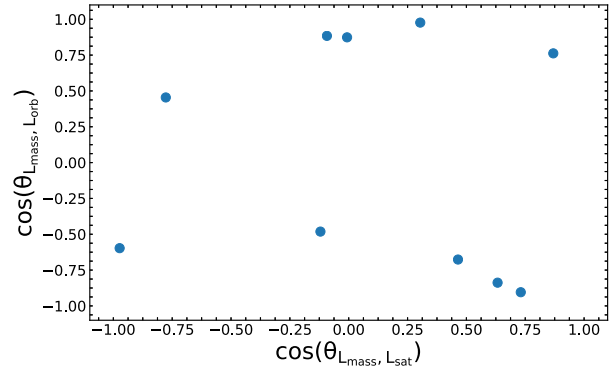


Figure 6. The cosine of the angle between the (stellar) spin vectors of the massive galaxy (L_{mass}) and the satellite (L_{sat}) plotted against the cosine of the angle between L_{orb} (see Fig. 4) and the spin vector of the massive galaxy (L_{mass}).

of $10^{10.5} M_{\odot}$ shows the same general tendency towards coplanar orbits, indicating that the result for our $M_{*} > 10^{11} M_{\odot}$ does not occur by chance. Note, however, that we perform this exercise only as a sanity check on our results; lower mass galaxies can naturally end up with a large *in situ* stellar mass fraction via early gas accretion and not due to a peculiarity in their merger histories (Martin et al. 2018b), as a result of which the deficit of non-planar orbits in Fig. A1 is not as severe for lower masses, even though they have low $f_{\text{ex situ}}$. Our focus therefore remains on the most massive galaxies ($M_{*} > 10^{11} M_{\odot}$), beyond the knee of the mass function, where low $f_{\text{ex situ}}$ is particularly anomalous.

Finally, it is also interesting to consider whether a disc could survive a coplanar orbital configuration similar to the ones that produce our population of spheroids. We find that there are some discs that have similar stellar masses as the spheroids in our study that undergo coplanar mergers but maintain their disc morphology. These systems overwhelmingly prefer *prograde* minor mergers. In addition, the mergers have higher gas fractions ($\times 1.7$ the control sample compared to $\times 1.1$ for the spheroids) and lower mass ratios (median mass ratio of 0.12 compared to 0.2 for the spheroids). The survival of the disc is therefore due to a combination of a low mass-ratio merger that is relatively gas-rich and has a prograde configuration. This disc population will be studied in detail in a forthcoming paper (Jackson et al. in preparation).

5 SUMMARY

The most massive galaxies ($M_{*} > 10^{11} M_{\odot}$), regardless of morphology, typically exhibit rich merger histories, which results in high fractions of ‘*ex situ*’ stellar mass i.e. mass accreted directly from external objects rather than having been formed *in situ*. This is particularly true for the most massive spheroids at the present day, whose stellar masses have classically been considered unattainable without significant numbers of both major and minor mergers.

In this paper, we have studied the formation of a sample of massive ($M_{*} > 10^{11} M_{\odot}$) spheroidal systems, in the Horizon-AGN simulation, which have anomalously low (< 0.3) *ex situ* mass fractions. These systems are unusual, in the sense that they are extremely massive and spheroidal, yet do not exhibit significant fractions of *ex situ* stellar mass – the opposite to what is usually the case for such galaxies.

We have shown that these objects are created in a single minor merger, which triggers a catastrophic (and permanent) morphological change, with $\frac{V}{\sigma}$ declining rapidly from the disc to spheroid regime in only a few hundred Myr. The merger event triggers strong star formation, driven by the native gas reservoir of the more massive progenitor, and an increase in the effective radius of the system. The remnant is a massive, relatively diffuse, slowly rotating spheroidal galaxy.

We have studied the properties of the progenitor system to explore why the minor merger has such a profound effect on the remnant. Since minor mergers are thought to be able to influence the production of spheroidal systems by triggering gravitational instabilities in clumpy, gas-rich disc galaxies at high redshift, and since orbital configurations can have an impact on the properties of the remnant, we have focused on the evolution of these properties in the progenitor systems of our spheroids.

We have shown that the properties of the individual progenitors are not anomalous. The more massive progenitors in these mergers have gas fractions and clumpiness values that are consistent with the mean values in control samples at the same redshifts. However, the relative trajectories of the merging progenitors exhibit a specific orbital configuration that likely drives the observed behaviour. The satellites approach the more massive galaxies in close to co-planar orbits, which are likely to maximize the tidal forces and therefore the transfer of orbital energy, enabling the satellite to destroy the disc in only a few hundred Myr and drive the creation of a massive spheroidal galaxy.

The principal distinguishing feature of the spheroids described in this paper is the high SFR of these systems for a time after the spheroid has formed. Recent ultraviolet studies have led to the discovery of widespread star formation activity in spheroidal galaxies across cosmic time (see e.g. Yi et al. 2005; Kaviraj et al. 2007). However, this star formation is typically at a low level (e.g. Kaviraj et al. 2008), with spheroidal galaxies lying well below the star formation main sequence (e.g. Salim et al. 2007; Kaviraj et al. 2013), even if they have had recent mergers. This is particularly true for spheroids in the low- and intermediate-redshift Universe.

Our spheroids on the other hand lie significantly above the star formation main sequence (column 11 in Table 1) that offers a route to potentially identifying such systems in observations. Indeed, some (rare) cases of spheroids with SFRs well above the star formation main sequence are known (e.g. Fukugita et al. 2004; Schawinski et al. 2010), with number fractions of a few per cent (similar to our findings here). While such spheroids are difficult to explain via traditional channels, it is plausible that at least some of these massive spheroids with anomalously high SFRs are formed via the co-planar minor-merger channel described here.

Our study adds to the burgeoning literature that is highlighting the significant role of processes other than major mergers in driving the change in the morphological mix of massive galaxies. It demonstrates that, for close to co-planar orbital configurations, a single minor merger (with a mass ratio as low as $\sim 1:10$) is able to completely destroy a disc and create a spheroid, even at the high-mass end of the galaxy mass function. While this channel produces a minority (~ 5 per cent) of such galaxies, our study indicates that the formation of some of the *most* massive spheroids in the local Universe need not involve any major mergers – or indeed any significant merging at all – contrary to our classical assumptions.

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APPENDIX A: ORBITAL CONFIGURATIONS WITH A RELAXED MASS CUT

Section 4.2 indicates that the principal difference in the formation mechanism of our massive, low $f_{ex\ situ}$ spheroids compared to typical (i.e. high $f_{ex\ situ}$) spheroids of similar mass is that they form via minor mergers where the satellite orbit is close to being co-planar with the disc of the massive galaxy. As noted in Section 4.2, since our sample

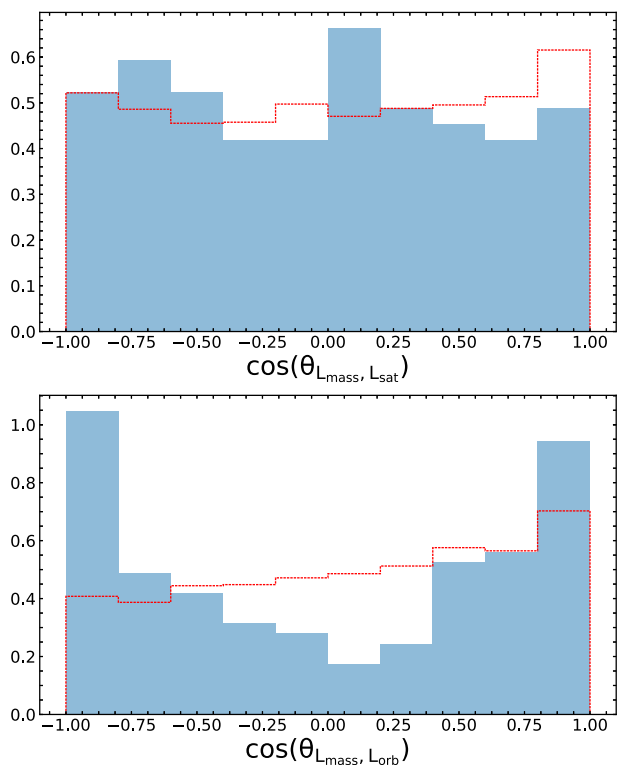


Figure A1. Same as Fig. 5 but for a sample where the mass threshold is $M_* > 10^{10.5} M_\odot$, with other parameters unchanged (i.e. $\frac{V}{\sigma} < 0.3$ and $f_{ex\ situ} < 0.3$). As is the case for the $M_* > 10^{11} M_\odot$, low $f_{ex\ situ}$ spheroids continue to show a tendency towards mergers that have close to co-planar orbits.

size is relatively small, we check whether this result could have originated by chance, by exploring whether this tendency towards co-planar orbits persists with more relaxed selection criteria.

For this exercise, we reduce the mass threshold of our sample to $M_* > 10^{10.5} M_\odot$ but leave constraints on the other variables (i.e. $\frac{V}{\sigma} < 0.3$ and $f_{ex\ situ} < 0.3$) the same. We perform an identical orbital configuration analysis on this sample as that described in Section 4.2. As Fig. A1 indicates this analysis shows the same tendency towards close-to-co-planar orbits creating low $f_{ex\ situ}$ spheroids, indicating that the result for the more massive spheroids does not occur by chance.

Note, however, that, as described in Section 4.2, we use this only as a sanity check of our results. Lower mass galaxies naturally produce larger *in situ* mass fractions because they produce more mass via gas accretion, as opposed to mergers (Martin et al. 2018b). As a result, the deficit of non-co-planar orbits in Fig. A1 is not as severe in this lower mass regime as it is for their more massive counterparts that are the subject of this paper. Our focus therefore remains on the most massive galaxies ($M_* > 10^{11} M_\odot$) in which low $f_{ex\ situ}$ is particularly anomalous.

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