

# The effects of gas on morphological transformation in mergers: implications for bulge and disc demographics

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## ABSTRACT

Transformation of discs into spheroids via mergers is a well-accepted element of galaxy formation models. However, recent simulations have shown that the bulge formation is suppressed in increasingly gas-rich mergers. We investigate the global implications of these results in a cosmological framework, using independent approaches: empirical halo-occupation models (where galaxies are populated in haloes according to observations) and semi-analytic models. In both, ignoring the effects of gas in mergers leads to the overproduction of spheroids: low- and intermediate-mass galaxies are predicted to be bulge-dominated ( $B/T \sim 0.5$  at  $<10^{10} M_{\odot}$ , with almost no ‘bulgeless’ systems), even if they have avoided major mergers. Including the different physical behaviour of gas in mergers immediately leads to a dramatic change: bulge formation is suppressed in low-mass galaxies, observed to be gas-rich (giving  $B/T \sim 0.1$  at  $<10^{10} M_{\odot}$ , with a number of bulgeless galaxies in good agreement with observations). Simulations and analytic models which neglect the similarity-breaking behaviour of gas have difficulty reproducing the strong observed morphology–mass relation. However, the observed dependence of gas fractions on mass, combined with suppression of bulge formation in gas-rich mergers, naturally leads to the observed trends. Discrepancies between observations and models that ignore the role of gas increase with redshift; in models that treat gas properly, galaxies are predicted to be less bulge-dominated at high redshifts, in agreement with the observations. We discuss implications for the global bulge mass density and future observational tests.

**Key words:** galaxies: active – galaxies: evolution – galaxies: formation – galaxies: spiral – cosmology: theory.

## 1 INTRODUCTION

In a  $\Lambda$  cold dark matter ( $\Lambda$ CDM) cosmology, structure grows hierarchically (e.g. White & Rees 1978), making mergers and interactions between galaxies an essential and inescapable process in

galaxy formation. Indeed, mergers are widely believed to be responsible for the morphologies of spheroids (Toomre 1977), and observations find recent merger remnants in considerable abundance in the local universe (Schweizer 1982; Lake & Dressler 1986; Doyon et al. 1994; Shier & Fischer 1998; James et al. 1999; Genzel et al. 2001; Tacconi et al. 2002; Rothberg & Joseph 2004; Dasyra et al. 2006) as well as, for example, faint shells and tidal features common around apparently ‘normal’ galaxies (Malin & Carter 1980; Schweizer 1980, 1996), which are thought to be signatures of galaxy collisions (e.g. Hernquist & Quinn 1988; Hernquist & Spiegel 1992).

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This has led to the concern that there may be too *many* mergers to explain the survival and abundance of galactic discs in the context of our present understanding of galaxy formation (see e.g. Stewart et al. 2008b; Purcell, Kazantzidis & Bullock 2009, and references therein). Indeed, the difficulty of forming very late type discs with low  $B/D$  is a well-known problem in cosmological simulations, which tend to consistently overpredict the bulge fractions of low-mass galaxies. There has been considerable effort to address the cause of these difficulties, with a great deal of focus on improving resolution (in order to properly resolve the bulge and disc components) and introducing feedback prescriptions to prevent artificial disc overcooling, clumping, fragmentation and angular momentum transport (Weil, Eke & Efstathiou 1998; Sommer-Larsen, Gelato & Vedel 1999; Thacker & Couchman 2000, 2001; Abadi et al. 2003; Sommer-Larsen, Götz & Portinari 2003; Governato et al. 2004, 2007; Robertson et al. 2004; Okamoto et al. 2005; Scannapieco et al. 2008). Similar problems are encountered in semi-empirical models that use observational constraints to populate a halo-occupation framework, and evolve this forward in time to follow mergers (see e.g. Stewart et al. 2009). A number of semi-analytic models, which predict galaxy properties from simple physical recipes and adopt simplified prescriptions for behaviour in mergers, allowing for the efficiency of merger-induced bulge formation to be adjusted, still find the same difficulty even with these degrees of freedom (Somerville, Primack & Faber 2001; Khochfar & Burkert 2003; Granato et al. 2004; Croton et al. 2006; Somerville et al. 2008a, hereafter S08).

More importantly, the problem can be seen empirically without reference to these models. Observations find that  $\sim 5$ – $10$  per cent of low- or intermediate-mass galaxies ( $M_* \lesssim 10^{10} M_\odot$  at redshifts  $z \sim 0.2$ – $1.2$ ) are in mergers – strongly morphologically disturbed or in ‘major’ similar-mass pairs about to merge (at small scales and small relative velocities) (Bridge et al. 2007, 2009; Kartaltepe et al. 2007; Conselice, Rajgor & Myers 2008; Lin et al. 2008; Lotz et al. 2008b; Conselice, Yang & Bluck 2009; Jogee et al. 2009). This is equal to or higher than the predicted rates from the models above – the problem does not seem to be that  $\Lambda$ CDM predicts ‘too many’ mergers. The problem is that, even without correcting for the short expected duty cycles/lifetimes of this merger phase, these fractions are *already* higher than the observed fraction of bulge-dominated galaxies at these masses (Allen et al. 2006; Balcells, Graham & Peletier 2007b; Domínguez-Palmero et al. 2008; Weinzirl et al. 2009). Invoking subsequent accretion to ‘rebuild’ discs will not eliminate massive bulges formed by these events, nor can it operate in a shorter time than the duration of the merger itself, and correcting for the expected duty cycles/lifetimes of these events, a large fraction of these low-mass galaxies should have experienced a violent event in the last  $\sim 10$  Gyr (Hopkins et al. 2007; Lotz et al. 2008a; Conselice et al. 2009). Moreover, although there may be some mass dependence in observed merger fractions, it is weak: a factor  $\sim 2$  increase with mass from  $\sim 10^9$ – $10^{11} M_\odot$  (Zheng, Coil & Zehavi 2007; Conselice, Rajgor & Myers 2008; Patton & Atfield 2008; Bridge et al. 2009; Bundy et al. 2009; Domingue et al. 2009; López-Sanjuan et al. 2009). Over the same range, there is an order of magnitude or more change in the fraction of bulge-dominated galaxies. As a result, uniformly increasing or decreasing the ‘efficiency’ of merger-induced bulge formation is insufficient to explain the observed trends (see e.g. Stewart et al. 2009). In short, the observed mergers at low and intermediate masses must somehow be inefficient at making bulges, whereas those at high masses must be efficient (Koda, Milosavljevic & Shapiro 2009). However, dissipationless systems with high or low stellar and/or virial masses

behave exactly the same in actual  $N$ -body simulations of mergers. They *must* do so – if gas is not allowed to change the dynamics of the merger, then the only force is gravity and the system is scale-free (a merger of two  $10^9 M_\odot$  systems is exactly equivalent to the merger of two  $10^{12} M_\odot$  systems). Because gravitational interactions of dissipationless systems are scale-free, it is not possible to design a physical prescription that does not treat gas differently from stars (or where the merger efficiency is just a function of mass ratio and orbital parameters) that can simultaneously match the observed merger fractions and  $B/T$  distributions at low and high galaxy masses. Some other controlling parameter or physics must work to suppress bulge formation in low-mass galaxies.

Springel & Hernquist (2005) and Robertson et al. (2006a) suggested that this parameter may be galaxy gas fraction:<sup>1</sup> they showed, in idealized merger simulations, that even major mergers of sufficiently gas-dominated discs could produce remnants with large discs. This has since been borne out in cosmological simulations (Governato et al. 2007, 2008), and may be seen in observations of high-redshift discs that are perhaps reforming after mergers (van Dokkum et al. 2004; Kassin et al. 2007; Genzel et al. 2008; Puech et al. 2008; Robertson & Bullock 2008a; Shapiro et al. 2008; van Starkenburg et al. 2008). The growing consensus that more realistic treatments of star formation and supernovae feedback – which suppress efficient early star formation – play a critical role in enabling disc formation in simulations (see references above) is connected with this insight into the link between gas fraction and disc survival. Because low-mass discs are observed to be more gas-rich, this may potentially provide the desired breaking of self-similarity in dissipationless merger histories.

In Hopkins et al. (2009b) (hereafter H09), we developed a physical model to explain this behaviour, and used a large suite of hydrodynamic simulations (see Robertson et al. 2006c,b; Cox et al. 2006b,a, 2008) to show that the suppression of bulge formation in mergers of more gas-rich discs can be predicted analytically, and is dynamically inevitable owing to fundamental properties of gravitational physics and collisional systems. Stars, being collisionless, violently relax in mergers, as they can mix and randomize their orbits by scattering off the fluctuating potential, even without net torques. Gas, being collisional, cannot violently relax, but must have its angular momentum torqued away in order to dissipate and build a bulge by forming stars in a central starburst. In a merger, this torque is primarily internal, from stars in the same disc: the passages and merger of the secondary induce a non-axisymmetric distortion in the primary stellar and gas disc. The stellar distortion (in a trailing resonance and close proximity to the gas response) efficiently removes angular momentum from the gas and allows it to fall to the centre and form a bulge (see also Barnes & Hernquist 1996). Other sources of torque (hydrodynamic shocks or the gravity of the secondary galaxy) represent less efficient, higher order effects (and often tend to spin up the disc).

In the limit, then, of extremely gas-rich discs, there is no significant stellar feature available to torque the cold gas in the disc; gas will rapidly reform a cold disc in the background of the relaxing stellar potential. Because this is a purely gravitational process, the physics and consequences for fixed initial conditions are independent of uncertain physics associated with ‘feedback’ from

<sup>1</sup> In this paper, we use the term ‘gas fraction’ to refer specifically to the cooled gas fraction in the baryonic disc, i.e.  $(m_{\text{HI}} + m_{\text{H}_2})/(m_{\text{HI}} + m_{\text{H}_2} + m_*)$ , where  $m_{\text{HI}}$ ,  $m_{\text{H}_2}$  and  $m_*$  are the atomic, molecular and stellar masses, respectively.

either star formation and supernovae or accreting black holes (see H09). Feedback is important for *setting* these initial conditions – over cosmological time-scales, it can suppress star formation efficiencies and lead to retention of large gas reservoirs, and move that gas to larger radii; but for a given set of gas properties at the time of the merger, H09 outline a few simple equations motivated by well-understood gravitational physics that can robustly estimate how much of the gas will preserve its angular momentum content in a given merger.

We endeavour here to study the consequences of these detailed studies of disc survival as a function of merger gas content, for the global demographics of bulges and discs as a function of galaxy mass and redshift. To do so, we utilize both semi-analytic and semi-empirical cosmological models. Semi-analytic models predict galaxy properties from first principles via physical recipes; while the latest generation of models reproduce many observational quantities quite well, there remain significant discrepancies and uncertainties. We, therefore, compare to a semi-empirical model, where we assign galaxy properties to dark matter (sub)haloes in order to match observational constraints. We combine these with the detailed predictions from simulations presented in H09, to make predictions for bulge and disc populations. We contrast these predictions with the results from implementing the ‘traditional’ assumptions regarding bulge formation, which ignore the unique role of gas as outlined above.

In Section 2, we describe our empirical approach for tracking stellar and gas masses within the framework of our cosmological merger trees, and briefly summarize our semi-analytic approach. In Section 3, we outline the key predictions of our gas fraction-dependent bulge-formation recipe and the differences from those of the recipes generally adopted in the past. We summarize and discuss other implications in Section 4.

Throughout, we assume a flat cosmology with matter and dark energy densities  $\Omega_M = 0.3$  and  $\Omega_\Lambda = 0.7$ , respectively, and Hubble constant  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , but varying these parameters within the observationally constrained limits (Komatsu et al. 2009) makes little difference.

## 2 THE MODEL

In order to track merger histories with as few assumptions as possible, we construct the following semi-empirical model, motivated by the halo occupation framework. Essentially, we assume galaxies obey observational constraints on disc masses and gas fractions, and then predict the properties of merger remnants.

We follow a Monte Carlo population of haloes from cosmological simulations, with merger/growth trees from Fakhouri & Ma (2008). We populate every halo with a galaxy<sup>2</sup> on the empirically constrained stellar mass–halo mass relation from Conroy & Wechsler (2009). As the halo grows, the galaxy is assigned a star formation rate and net gas accretion rate (inflow minus outflow) corresponding to the track that would be obtained by strictly enforcing that galaxies at all times live on the same stellar mass–halo mass relation (Conroy & Wechsler 2009) and gas mass–stellar mass relation (fitted from observations as a function of mass and redshift in Stewart et al. 2009). In other words, using the empirical fits to  $M_{\text{gal}}(M_{\text{halo}})$  and  $f_{\text{gas}}(M_{\text{gal}})$ , we force galaxies to live on these relations at all times assuming gas is gained or lost, and stars are formed, exactly

as needed to stay on the empirically fitted correlations, but without a prior on how much of each is in a bulge or disc component. This amounts to the same prescription as assuming galaxies live on, for example, the observed stellar mass–star formation rate relation (Noeske et al. 2007) and tuning accretion rates to reproduce the observed dependence of gas fractions on stellar mass and redshift (Bell & de Jong 2000; McGaugh 2005; Shapley et al. 2005; Erb et al. 2006; Calura et al. 2008). Observational constraints are present up to redshifts  $z \sim 3$ , more than sufficient for our low-redshift predictions. Despite its simplicity, this effectively guarantees a match to various halo occupation statistics including stellar mass functions and the fraction of active/passive galaxies as a function of mass (Yang et al. 2005; Weinmann et al. 2006a,b; Gerke et al. 2007).

Together, these simple assumptions are sufficient to define a ‘background’ galaxy population. There are degeneracies in the model – however, we neither claim that this is unique nor that it contains any physics thus far. For our purposes, the precise construction of the empirical model is not important – our results are unchanged so long as the same gas fraction distributions are reproduced as a function of galaxy mass and redshift.

We illustrate this by comparison with a semi-analytic galaxy formation model (S08). A summary of the salient model features is presented in Appendix B. Unlike the semi-empirical model above, the semi-analytic model attempts to predict the relevant quantities (e.g. disc masses and gas content) from first principles, given physical prescriptions for cooling, star formation and feedback. Specifically, the model presented begins with similar halo merger trees, allowing for subhalo evolution and stripping, and distinguishes between accretion in the ‘cold mode’ in sub- $L_*$  galaxy haloes (where gas accreted into the halo reaches a galaxy on a dynamical time) and ‘hot mode’ in massive haloes [where the cooling occurs from a hot atmosphere, suppressed by active galactic nucleus (AGN) feedback]. The model adopts typical recipes for star formation and supernova feedback, motivated by observations.

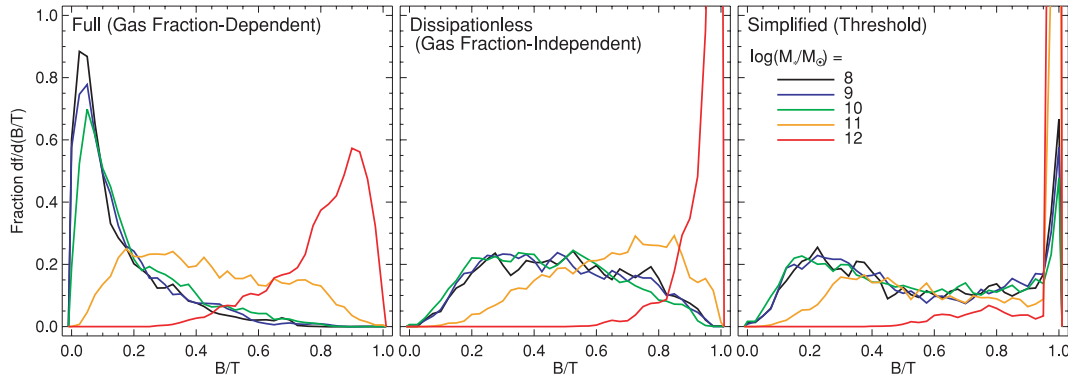
The relevant physics are entirely contained in the treatment of mergers. When a merger<sup>3</sup> occurs, we adopt a model for how much of the gas is drained of angular momentum and participates in a nuclear starburst, and how much of the stellar disc is violently relaxed – both components are removed from the disc component and added to the mass of the galaxy bulge. If orbital parameters – namely the relative inclination angles of the merging discs – are required, we simply draw them at random assuming an isotropic distribution of inclinations (allowing some moderate inclination bias makes no difference). We consider three models:

(i) *Gas fraction-dependent (‘full’) model*: the prescriptions from H09, based on a detailed physical model for how discs are destroyed in mergers and calibrated to the results of hydrodynamic merger simulations. In a merger of mass ratio  $\mu$ , a fraction  $\sim\mu$  of the primary stellar disc is violently relaxed, and a fraction  $\sim(1 - f_{\text{gas}})\mu$  of the gas loses its angular momentum. For the full details of these scalings as a function of mass ratio, orbital parameters and gas fraction, we refer to H09, but they are briefly listed in the Appendix A; the general sense is that the angular momentum loss is suppressed by a factor  $\sim(1 - f_{\text{gas}})$ .

(ii) *Gas fraction-independent (dissipationless) model*: the same, but without accounting for the different behaviour of gas and stars in the merger. We adopt the scaling from H09, but calculate the angular momentum loss in the gas as if the discs were entirely stellar

<sup>2</sup> Starting at some minimum  $M_{\text{halo}} \sim 10^{10} M_\odot$ , although this choice makes little difference.

<sup>3</sup> We include all mergers above a minimum mass ratio  $\mu \sim 0.01$ , although our results are not sensitive to this limit, so long as it is small.



**Figure 1.** Predicted distribution of bulge-to-total stellar mass ratios in galaxies of different stellar masses at  $z = 0$ , from our semi-empirical model, with different models for bulge formation in mergers (see text). Left: the full (gas fraction-dependent) model from H09: bulge formation is suppressed in gas-rich mergers. Centre: the ‘dissipationless’ model: bulge formation is gas fraction independent. Right: a simplified ‘threshold’ model, also gas fraction independent, with simplified treatment of the dependence on merger mass ratio. Accounting for the gas fraction-dependent physics of angular momentum loss in mergers, the predicted  $B/T$  is suppressed in low-mass, gas-rich galaxies.

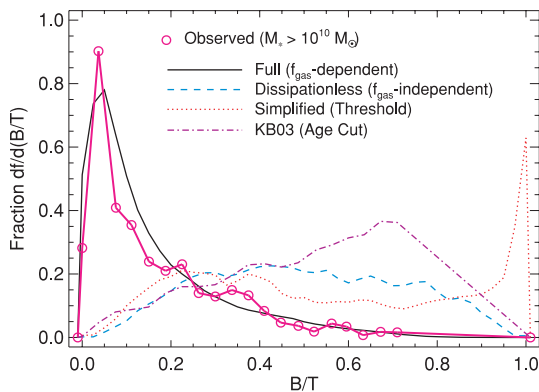
– equivalently, we ignore the fact that gas-richness changes the efficiency of bulge formation in mergers. In order for gas to behave in this manner, it would have to be dissipationless and collisionless; but nevertheless, this is a common (almost ubiquitous) assumption. The specific scalings are given in Appendix A.

(iii) *simplified (threshold) model*: a ‘threshold’ (‘major’ versus ‘minor’) assumption, common in many semi-analytic models. In major mergers ( $\mu > 0.3$ ), the model assumes that the entire stellar disc is violently relaxed and the entire cold gas content participates in a burst. In minor mergers, the primary is unperturbed, the stars of the secondary are added to the bulge, and the secondary gas content is added to the disc.

### 3 CONSEQUENCES

#### 3.1 Bulges and discs at $z = 0$

Fig. 1 shows the predicted distribution of bulge-to-total (bulge stellar mass divided by total galaxy stellar mass) ratios as a function of galaxy mass. Fig. 2 compares these predictions to observations



**Figure 2.** As Fig. 1, for galaxies with  $M_* > 10^{10} M_\odot$ . We compare the models from Fig. 1 with observations from Weinzirl et al. (2009). We also compare the semi-analytic model from Khochfar & Burkert (2003), which adopts different assumptions and does not allow mergers at  $z > 2$  to form bulges, but employs the simplified (threshold) model for bulge formation at  $z < 2$ . Only the gas fraction-dependent model matches the observations; suppressing high- $z$  bulges alone is insufficient to resolve the discrepancy in gas fraction-independent models.

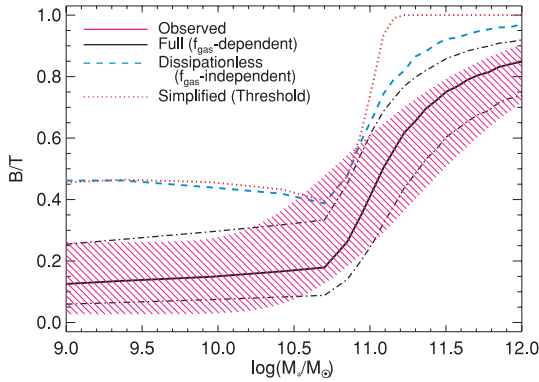
of field spirals from Weinzirl et al. (2009).<sup>4</sup> At high masses, all three models predict that most galaxies are bulge-dominated. At low ( $< 10^{10} M_\odot$ ) and intermediate ( $\sim 10^{10} - 10^{11} M_\odot$ ) masses, there is a dramatic difference: when the role of gas in suppressing disc destruction in mergers is accounted for, the model predicts the existence of considerably more disc-dominated systems.

The results are very similar when we adopt the semi-analytic approach from S08. We also compare the semi-analytic model of Khochfar & Burkert (2003), which relies on different cosmological assumptions and disc formation models, but still assumes the ‘threshold’-like (gas fraction-independent) model for bulge formation in mergers, leading to a too bulge-dominated population. The authors attempt to address this with an age cut: enforcing that all mergers at  $z > 2$  make no bulge. Fig. 2 shows this is insufficient: many of these systems have too many mergers at late times to invoke redshift-dependent dynamics or rapid subsequent cooling to ‘offset’ the bulge formed.

Fig. 3 compares the median  $B/T$  (and scatter) as a function of stellar mass for each model to that observed. The predicted scatter owes mostly to differences in merger history. We show the fits to observations in Balcells et al. (2007b), but others are similar (Kochanek et al. 2001; Allen et al. 2006; Driver et al. 2007; Noordermeer & van der Hulst 2007). All the models predict some mass dependence, as merger histories are not completely mass-independent. However, at low masses, the gas fraction-independent models predict  $B/T \sim 0.4 - 0.5$  (E/S0 galaxies), much larger than observed. Note that both gas fraction-independent models give similar results; tuning the relative importance of major/minor mergers does not resolve their problems.

Fig. 4 shows the results from the semi-analytic model for the same quantities considered in Figs 1 and 2. The differences between the predicted bulge-to-total distributions are dominated by the different treatment of the role of gas in mergers, rather than by the methodologies or different choices in the galaxy formation model.

<sup>4</sup> The observed  $B/T$  are determined in  $H$ -band; the models in Fig. 2 predict  $B/T$  in terms of stellar mass. In the semi-analytic model, the predicted star formation histories are used to predict the  $H$ -band  $B/T$ ; generally, we find this is slightly smaller than the stellar mass  $B/T$ , owing to the lower mass-to-light ratio in the younger stellar disc.



**Figure 3.** Mean  $B/T$  as a function of galaxy stellar mass in observations and our semi-empirical models. Dot–dashed black lines show the  $\pm 1\sigma$  scatter in the full (gas fraction-dependent) model. The shaded magenta range is the observed relation (with scatter) from Balcells et al. (2007b). The models are all similar at  $> L^*$  masses/luminosities, where discs are relatively gas-poor; at lower mass, the differences from Figs 1–2 are apparent.

Fig. 5 compares the predicted stellar mass functions in the semi-analytic model. Fig. 6 shows the corresponding early-type fraction as a function of stellar mass, compared with the results from the morphologically classified stellar mass functions of Bell et al. (2003) (see also Kochanek et al. 2001; Bundy, Ellis & Conselice 2005; Franceschini et al. 2006; Pannella et al. 2006, who obtain similar results). Although the gas fraction-independent models yield good agreement with the *total* stellar mass function, they predict an excess of bulge-dominated galaxies at low masses. This is robust to the exact morphology or  $B/T$  cut used to define bulge or disc-dominated systems; here, we adopt  $B/T \sim 0.4$  as a dividing line as this is a good proxy, in simulations, for the concentration cut in Bell et al. (2003).

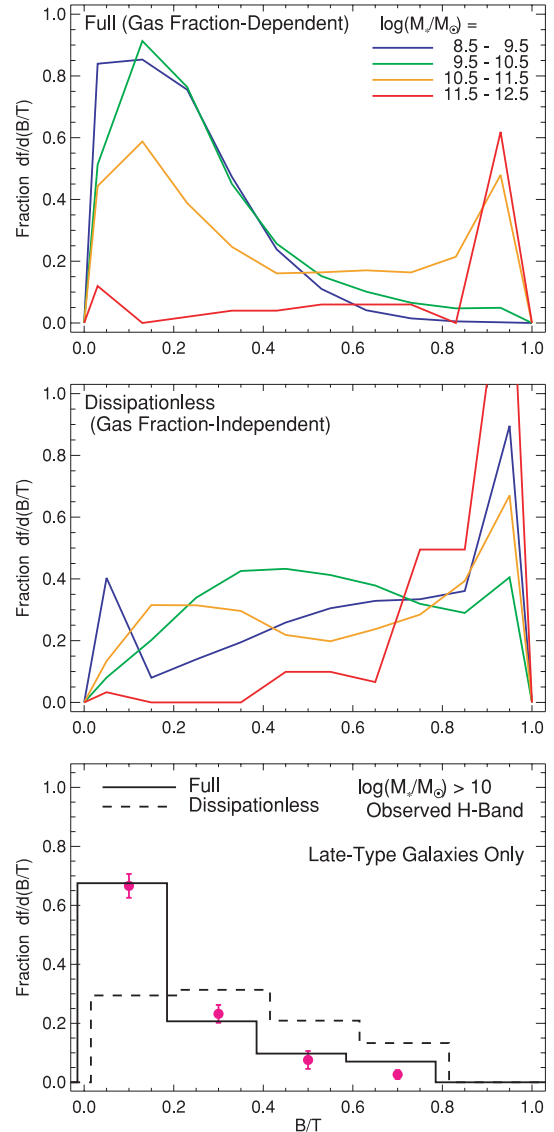
We emphasize that we have incorporated the bulge formation prescriptions directly from H09 with the values of all related parameters taken directly from the results of the hydrodynamic simulations. We have neither changed any of the other physical recipes in the semi-analytic model (SAM) nor have we retuned any of the baseline free parameters. We find it particularly convincing that the gas-fraction dependent bulge-formation prescription based on the simulations immediately produced excellent agreement with the observations at all mass scales, with no fine tuning.

### 3.2 Redshift evolution

Fig. 7 repeats the comparison from Fig. 1 at  $z = 1, 2, 3$ . Fig. 8 plots the median  $B/T$  and early-type fraction versus redshift and stellar mass. In the gas fraction-dependent model, higher gas fractions lead to more disc-dominated galaxies at high redshifts (see Section 3.3). The evolution in gas fractions that we adopt (fitted to the observations in Erb et al. 2006) is relatively weak; if real evolution in gas fractions is stronger, it will further suppress  $B/T$ .

Merger rates were higher in the past, so the gas fraction-independent models predict that galaxies should be *more* bulge-dominated. By  $z \sim 1-2$ , such models would predict that essentially all galaxies at all masses are bulge-dominated.

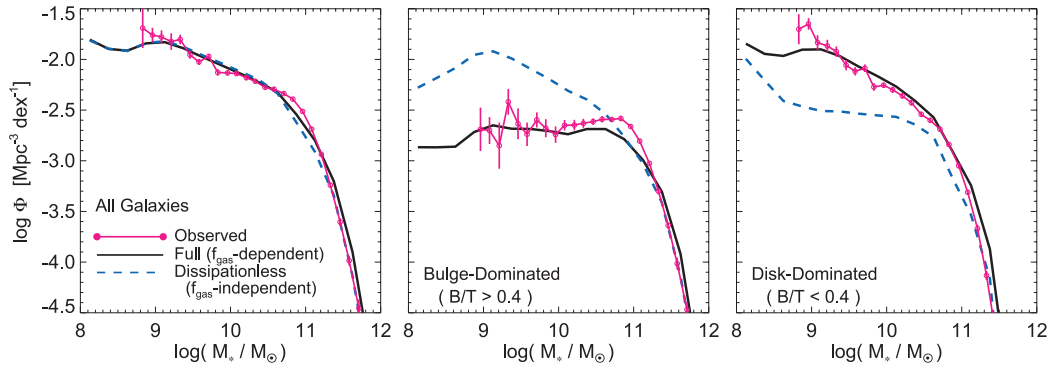
At the highest redshifts, morphological determinations are difficult; however, there are some measurements at  $z \sim 1$ . We compare to the results from Bundy et al. (2005) from the GOODS fields, Pannella et al. (2006) from the GOODS South and FORS Deep fields and Ilbert et al. (2009) from the COSMOS fields. Despite



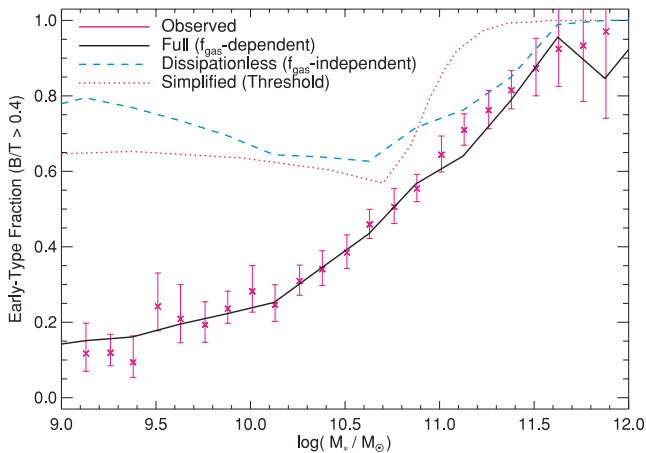
**Figure 4.** As in Figs 1 and 2; but showing the results of the semi-analytic model, with either the full (gas fraction-dependent) bulge formation model or threshold (gas fraction-independent) model. Bottom: the results for  $M_* > 10^{10} M_\odot$  galaxies with  $B/T$  computed in the  $H$  band, pre-selected to include *only* late-type galaxies ( $B/T < 0.75$ ), compared to the observations of Weinzirl et al. (2009). The semi-analytic and semi-empirical models yield similar conclusions.

large uncertainties, the trend in the fraction of bulge-dominated galaxies with mass is qualitatively very similar to that observed at  $z = 0$ , but with a systematically lower bulge-dominated (E/S0) fraction at all masses.

This agrees well with the expectations from the gas fraction-dependent model, and strongly conflicts with the gas fraction-independent model prediction. If anything, the data suggest that at high masses, bulges may be even more suppressed than the dissipational model prediction; as noted above, this could be explained if gas fractions at these masses evolve more rapidly. Theoretical models suggest, for example, that the efficient cooling (cold mode) regime may persist to high masses at high redshifts (Kereš et al. 2005, 2009; Dekel et al. 2009). However, cosmic variance (not included in the quoted errors) remains a significant source of uncertainty at high masses.



**Figure 5.** Comparison of the  $z = 0$  mass function of all (left), bulge-dominated (centre), and disc-dominated (right) galaxies. We compare the gas fraction-independent (threshold) and gas fraction-dependent (full) model, in the semi-analytic model, to the observed morphology-dependent mass functions from Bell et al. (2003). Despite freedom in the SAM to adjust prescriptions, gas fraction-independent models overpredict the low-mass bulge-dominated population. Including the physical dependence on gas fraction reconciles this discrepancy.

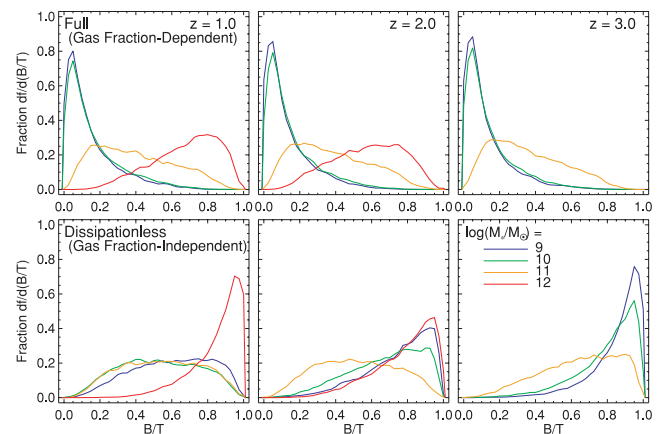


**Figure 6.** Early-type ( $B/T > 0.4$ ) fraction as a function of stellar mass. We compare with the  $z = 0$  observed trend from the morphologically classified mass functions in Bell et al. (2003).

Fig. 9 compares the redshift evolution of the predicted bulge mass density.<sup>5</sup> As expected from Fig. 8, in the gas fraction-independent models, the predicted bulge mass density approaches the global stellar mass density at high- $z$ . In gas fraction-dependent models, the trend is reversed: at high redshift, higher gas fractions suppress bulge formation. The latter trend agrees with the available observational results.

Though important for bulges, we find that these differences have little effect on the global star formation rate density. ‘Quiescent’ (non-merger-driven) star formation dominates at all redshifts (see also Wolf et al. 2005; Menanteau et al. 2006; Hopkins et al. 2006; Noeske et al. 2007; Jogee et al. 2009). Differences owing to, for example, systems ‘retaining’ more gas for later consumption are much smaller than the uncertainties from, for example, star formation rate and stellar wind prescriptions.

<sup>5</sup> Specifically, we plot the mass density in bulge-dominated galaxies, which is not the same as the absolute mass density in all bulges, but is closer to the observed quantity. At high redshifts  $z > 1.5$ , observed morphologies are ambiguous; we show the mass density in passively evolving red galaxies as a proxy. This may not be appropriate, but at  $z < 1$  the two correspond well, and the compactness, size, and kinematics of the ‘passive’ objects do appear distinct from star-forming objects (Kriek et al. 2006; Toft et al. 2007; Trujillo et al. 2007; Franx et al. 2008; Genzel et al. 2008).

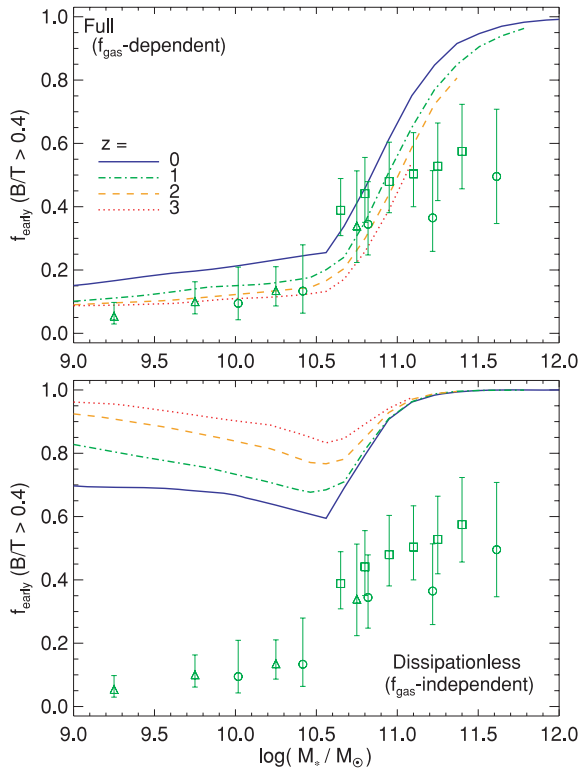


**Figure 7.** As Fig. 1, but evaluated at different redshifts  $z = 1, 2, 3$ , for our gas fraction-dependent model (top) and gas fraction-independent model (bottom), implemented within the semi-empirical framework. The gas fraction-independent model predicts that the population is *more* bulge-dominated at higher redshifts (because merger rates are higher). Including the gas dependence reverses this: bulges are less dominant at high redshifts, as gas fractions are systematically higher.

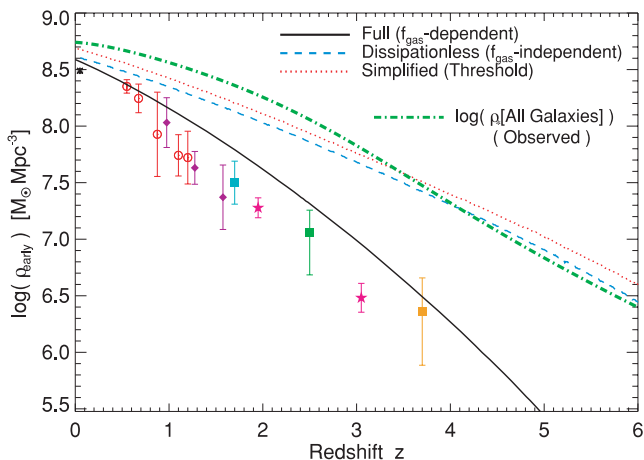
### 3.3 Why does it work?

Why does the revised bulge formation model produce the observed trends? Fig. 10 illustrates the relevant physics. Consider the observed gas fractions of discs as a function of stellar mass, shown in the figure to be a strong decreasing function of mass.<sup>6</sup> Now assume that every such galaxy doubles its mass in a merger or

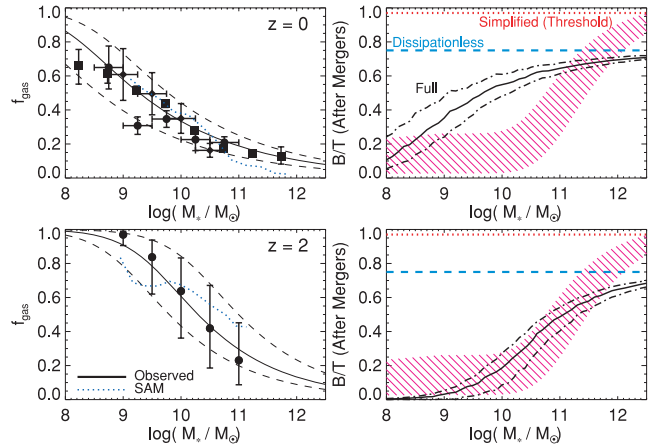
<sup>6</sup> At  $z = 0$ , the gas fractions shown are based on measured atomic H I gas fractions; Bell & de Jong (2001) correct this to include both He and molecular H<sub>2</sub>; McGaugh (2005) correct for He but not H<sub>2</sub>; Kannappan (2004) gives just the atomic H I gas fractions (this leads to slightly lower estimates, but still within the range of uncertainty plotted; H<sub>2</sub> may account for ~20–30 per cent of the dynamical mass, as per the measurements in Jogee, Scoville & Kenney 2005). We emphasize that these gas fractions are lower limits (based on observed H I flux in some annulus). At  $z = 2$ , direct measurements are not available; the gas masses from Erb et al. (2006) are estimated indirectly based on the observed surface densities of star formation and assuming that the  $z = 0$  Kennicutt law holds; other indirect estimates yield similar results (Cresci et al. 2009).



**Figure 8.** Early-type fraction at different redshifts, in the semi-empirical model. Green points show the observations from Bundy et al. (2005, circles), Ilbert et al. (2009, squares) and Pannella et al. (2006, triangles) from the COSMOS, DEEP and GOODS fields at  $z \approx 1$  (compare the green dot-dashed line). Ignoring the gas-fraction dependence predicts that even low-mass populations are  $\gtrsim 80$  per cent elliptical at  $z > 1$ .



**Figure 9.** Integrated mass density in bulge-dominated galaxies in the semi-empirical models as a function of redshift, compared to observations (points). Contrast the observed total stellar mass density (Hopkins & Beacom 2006, dot-dashed line). Observations are compiled from the morphologically-selected samples of Bell et al. (2003, black  $\times$ ), Bundy et al. (2005, 2006, red circles), Abraham et al. (2007, violet diamonds) and Daddi et al. (2005, cyan square), and colour-selected samples of Labbé et al. (2005, green square), van Dokkum et al. (2006, orange square) and Grazian et al. (2007, magenta stars).



**Figure 10.** Top left: observed median gas fraction as a function of stellar mass in  $z = 0$  discs, from Bell & de Jong (2001, diamonds), Kannappan (2004, squares) and McGaugh (2005, circles), with an analytic fit (solid line) and  $\pm 1 \sigma$  scatter (dashed). Dotted (blue) line compares median gas fractions in the semi-analytic model. Top right: predicted bulge-to-total ratio in the remnants if every such galaxy immediately underwent a series of mergers that doubled its stellar mass (style as Fig. 3). Lines correspond to the different models: full/gas fraction-dependent (solid black), dissipationless/gas fraction-independent (dashed blue) and simplified/threshold (dotted red). Compare the observed trend (shaded). Bottom: same, but based on the gas fractions at  $z \sim 2$  (Erb et al. 2006). Accounting for the full model results from simulations, high gas fractions in low-mass systems suppress bulge formation.

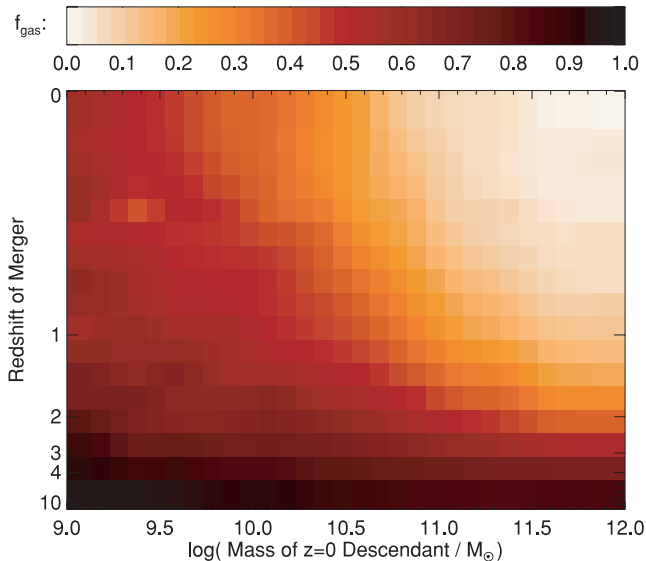
sequence of mergers<sup>7</sup>, and consider the resulting  $B/T$  at each mass. This represents a major perturbation, and in any of the gas fraction-independent models would uniformly transform every galaxy into nearly 100 per cent bulge, independent of mass.

As discussed in Section 1, however, gas loses angular momentum to internal torques from the stellar disc. If the disc is mostly gas, then the stellar bar/perturbation that does the majority of the work torquing the gas is relatively less massive and so less gas falls to the centre and starbursts. In a collision of two pure gas discs, there is no stellar feature to torque the gas (in fact, accounting for typical orbital angular momenta, such a collision typically increases the disc specific angular momentum).

Given these physics and the observed trend of gas fraction with mass, we expect low-mass galaxies ( $M_* \lesssim 10^9 M_\odot$ ) to have just  $\sim 20$  per cent bulge even after a recent 1:1 merger. If mergers occur at higher redshift, when gas fractions are higher, the suppression is more efficient. It is possible for every galaxy to double its mass at  $z \sim 1-3$  in major mergers and still lie below the local  $B/T$ -mass correlation (allowing some later mergers). In practice, many of these bulges are made by minor mergers, but the relative suppression is similar (Hopkins et al. 2009e; Weinzirl et al. 2009).

This accounts for most of the observed trend in bulge fraction versus stellar mass. However, it is supplemented by two other trends

<sup>7</sup> This could be a single 1:1 merger, three 1:3 mergers, or even ten 1:10 mergers; because the efficiency of bulge formation as calibrated in simulations is nearly linear in mass ratio, they give indistinguishable results for our purposes here, so long as they all occur within a short time-scale (see e.g. Naab & Burkert 2003; Bournaud, Jog & Combes 2005; Cox et al. 2008; H09). In practice, this is unlikely at smaller mass ratios; cosmological calculations show that, for example, ten 1:10 mergers are a less likely channel for growth of spheroids than three 1:3 mergers (Gottlöber, Klypin & Kravtsov 2001; Maller et al. 2006; Zheng, Coil & Zehavi 2007; Stewart et al. 2008b).



**Figure 11.** Galaxy gas fractions as a function of the  $z = 0$  stellar mass of the descendant and the time at which the merger occurred (in the semi-analytic model). Specifically, considering galaxies which have the given  $z = 0$  stellar mass, and whose main branch progenitor experienced a merger at the given redshift (scaled here in equal cosmic time units), we plot the median gas fraction of the progenitors just before the merger(s). All galaxies were more gas-rich at high redshift, but low-mass galaxies are more gas-rich than high-mass galaxies (on average) at all epochs.

(the origin of the weak scaling in even the gas fraction-independent models): more massive galaxies tend to have had more violent merger histories, and to have lower cooling rates (leading to less disc regrowth and lower gas fractions).

Fig. 11 illustrates this in another way – we show the distribution of gas fractions in mergers as a function of merger redshift and stellar mass of the  $z = 0$  descendant galaxy (*not* instantaneous mass at the time of the merger). Gas fractions decrease with time overall, but low-mass galaxies are always more gas-rich than high-mass galaxies. This is for two reasons: (i) the Kennicutt law predicts that star formation, and therefore gas consumption, is more efficient in high mass, higher surface density galaxies; (ii) cooling and accretion are quenched in high-mass haloes (in semi-analytic models, this is typically attributed to heating of ‘hot’ quasi-static haloes by AGN feedback).

Figs 10 and 11 illustrate that the dividing line between gas-rich and gas-poor galaxies moves to higher masses at higher redshifts, suppressing bulge formation even in massive galaxies at high redshifts. In semi-analytic models, this evolution occurs for three reasons: (i) cooling rates increase uniformly with redshift, (ii) the critical halo mass dividing the ‘cold’ and ‘hot’ accretion modes (below which accretion is efficient) likewise increases with increasing cosmic gas densities at higher redshifts, and (iii) AGN feedback becomes less efficient at high redshifts. For most of the  $z = 0$  population, there is a relatively narrow ‘window’ of efficient bulge formation, where cooling slows down, galaxies consume most of their gas and mergers become efficient at forming bulges.

Disc survival and bulge formation are at some level zero-sum. However, because various processes contribute to disc growth at different times, it is useful to ask whether disc ‘survival’ or the suppression of bulge growth is more important. In order to answer this, we consider the following simple experiment: in each merger, we destroy as much of the disc gas and stellar mass as

predicted by the dissipationless (gas fraction-independent) model; however, we only add to the bulge the mass that the dissipational (gas fraction-dependent) model says should be violently relaxed or lose angular momentum. The remaining mass is thrown away. This is not physical, but it allows us to see whether our conclusions would change if bulge formation was suppressed as per our full gas fraction-dependent model but discs were still relatively efficiently destroyed in mergers (as per our gas fraction-independent model).

We find that the results are almost unchanged from the full gas fraction-dependent model. The overprediction in gas fraction-independent models of  $B/T$  is a problem of too much bulge formation, rather than too little disc survival from early times. This should not be surprising; various constraints suggest that low-mass galaxies are growing rapidly, and so disc masses are usually dominated by recent accretion and star formation (see e.g. Bell & de Jong 2000; Gallazzi et al. 2005; Noeske et al. 2007, and references therein).

#### 4 DISCUSSION

A realistic model for how gas loses angular momentum and builds bulges in mergers qualitatively changes the expectations for the global distribution of bulge to disc ratios in the local Universe and the efficiency of bulge formation as a function of mass and redshift. As demonstrated in simulations in H09, gas in mergers loses its angular momentum to *internal* torques from the induced non-axisymmetry in the stellar distribution in the same disc as the gas. Therefore, in the limit of very gas-rich mergers (with little or no stellar mass in the discs to do such torquing), angular momentum loss and destruction of the gas disc is inefficient [to lowest order, the efficiency scales  $\propto (1 - f_{\text{gas}})$ ].

We incorporate this idea into a cosmological framework using two different approaches: a simple semi-empirical model and a full semi-analytic model. The conclusions appear robust to this choice; we have also experimented with a number of variations to the semi-empirical model (detailed comparison of the resulting differences for merger rates will be the subject of future work; we briefly summarize the variations in Appendix C), and find similar results in each case. Stewart et al. (2009) also consider an independent semi-empirical model, using different halo merger trees, observational constraints and more qualitative prescriptions for behaviour in mergers (rather than the detailed simulation results here), and reach the same conclusions. It appears that, regardless of the methodology, this picture of morphological transformation in mergers makes qualitatively different predictions from the ‘traditional’ picture which ignores the dependence on gas fraction. Because, in the local Universe, lower mass discs have large gas fractions ( $f_{\text{gas}} \gtrsim 0.5$  at  $M_* < 10^{10} M_\odot$ ), this in particular implies stronger suppression of bulge formation at low masses. Even if the dissipationless (halo) merger histories were self-similar across different mass scales, this trend of gas fraction with mass breaks this self-similarity and largely explains the observed trend of bulge fraction with mass.

Other factors are expected to weakly break this self-similarity (the non-linear dependence of galaxy baryonic mass on halo mass, and weak scale dependence in the dark matter merger histories), but simulations and empirical constraints have found that accounting for these factors alone predicts too weak a trend. On the other hand, allowing for the role of gas-richness (implicitly related to the nature of cooling and star formation efficiency) provides a natural and predictive explanation for the observed mass–morphology relation.



Moreover, whereas simulations without large gas supplies, or gas fraction-independent models have difficulty reproducing the abundance of ‘bulge-less’ or low  $B/T$  discs ( $B/T \lesssim 0.1\text{--}0.2$ ), this problem is largely solved by incorporating the gas fraction-dependent bulge formation prescription. In practice, if galaxies have sufficiently low star formation efficiencies in order to retain very large gas fractions, as implied by observations of these systems, and especially if the gas distribution is very extended (as in, for example, low surface brightness systems), then it is possible to produce systems with such low  $B/T$  even in the immediate aftermath of a major merger, let alone in systems which have gone  $\sim 10$  Gyr since the last such merger with significant subsequent accretion. In practice, many bulges of low (and, to a lesser extent, intermediate) mass systems are predominantly made by minor mergers, making the required gas-richness even more moderate.

At low redshifts, this is primarily relevant for small-mass galaxies, where gas fractions are high. However, observations indicate that gas fractions should be larger at high redshifts, such that even some  $\sim L_*$  galaxies appear to have  $f_{\text{gas}} \gtrsim 0.5$  at redshifts  $z > 2\text{--}3$ . At increasing redshift, therefore, the effects described above propagate to higher and higher masses, and become important for an increasingly large proportion of the galaxy population.

This is seen as well in recent cosmological simulations (Governato et al. 2007, 2008): the presence of gas leads to non-destructive mergers and rapid disc re-assembly. The role of stellar feedback is to preserve gas, preventing it from all turning into stars at early times or in very small galaxies, and to remove low angular momentum gas from the disc (keeping the gas at relatively large radii, comparable to observed disc sizes). Even at  $z \sim 0.5$ , discs experience major mergers in these simulations and rapidly rebuild. These processes, it appears, are now being seen in a growing number of observations (Hammer et al. 2005; Trujillo & Pohlen 2005; Zheng et al. 2005; Flores et al. 2006; Puech et al. 2007a,b; Atkinson, Conselice & Fox 2007; Puech et al. 2008). The suppression of bulge formation in the merger owing to its gas-richness, combined with rapid large-scale gas inflows concurrent with and subsequent to the merger, both contribute to the rapid rebuilding of a disc-dominated galaxy following the event (Springel & Hernquist 2005; Robertson et al. 2006a). The inclusion of this continuous accretion means that a very large gas fraction  $f_{\text{gas}} > 0.5$  is not needed to build a disc-dominated galaxy (as would be the case if the system received no new gas after the merger); the more moderate bulge suppression that would result from intermediate gas fractions is sufficient.

At higher redshifts, merger rates increase, but in gas fraction-dependent models this is more than offset by the increase in disc gas content and cooling efficiencies, and thus low  $B/T$  ratios are maintained. However, because the rates of these processes (mergers and cooling/accretion) scale with the Hubble time while the internal relaxation times of discs are relatively constant, discs should be more turbulent and the relaxation from the building/merger/reformation process should be evident in more systems, as thicker, more dispersion-dominated discs with enhanced incidence of structure and clumpiness. In fact, this is widely observed (Weiner et al. 2006; Atkinson et al. 2007; Puech et al. 2007b; Neichel et al. 2008; Yang et al. 2008) especially approaching  $z \sim 2$  (Bouché et al. 2007; Shapiro et al. 2008; van Starckenburg et al. 2008), and agrees well with the structure of simulated discs undergoing rapid simultaneous accretion and post-merger reformation (Governato et al. 2008; Robertson & Bullock 2008b).

Other observational signatures of this process include ‘in situ’ bulge formation: rather than the conventional wisdom, in which most classical (merger-induced) bulges are formed by mergers that

destroyed the progenitor disc at some early time, with a later accreted disc around them, the dissipational models predict that it is much more likely, especially in gas-rich (low-mass) systems, that such bulges were formed by more recent mergers (many of them minor) that formed a small bulge out of a large disc, without destroying most of the disc. As such, the properties of the stellar populations in the bulge should be reasonably continuous with those in the disc. Note that, in an integrated sense, the bulge may have older or more metal-rich stars, but this is true even in a pure disc system if one compares the central regions to the outer regions; moreover, star formation may continue in the disc after the merger, whereas it may not in the bulge. But, in terms of, for example, the full stellar population gradients and even resolved colour gradients, there should be continuity between disc and bulge, with properties such as their metallicities correlated. Indeed, high resolution resolved spectroscopic observations of disc + bulge systems have begun to show that such continuity is the norm, in metallicity and  $\alpha$ -enrichment, stellar population ages and colours (Moorthy & Holtzman 2006; Peletier et al. 2007; Domínguez-Palmero & Balcells 2008; MacArthur et al. 2008; Morelli et al. 2008).

Observations and simulations have shown that the two-component (gas + stellar) nature of mergers leads to a two-component structure of bulges, with a low-density outer component reflecting disc stars that are violently relaxed in the merger and dense inner component built by the gas that loses angular momentum (Mihos & Hernquist 1994). In a series of papers, Hopkins et al. (2008b,a,d), Hopkins, Cox & Hernquist (2008a) and Hopkins et al. (2009c) demonstrated that with sufficiently high-dynamic range observations of spheroid structure and/or stellar populations, these can be decomposed, yielding empirical constraints on the efficiency of angular momentum loss in gas. Considering a large sample of ellipticals and recent merger remnants (Rothberg & Joseph 2004; Lauer et al. 2007; Kormendy et al. 2009), the mass fraction of spheroids in the dissipational component appears, to lowest order, to trace typical disc gas fractions as a function of mass; however, Hopkins et al. (2009a,c) note that at low masses, this appears to asymptote to a maximum dissipational/starburst fraction  $\sim 0.3\text{--}0.4$ . Independent tests (Balcells, Graham & Peletier 2007a; Hopkins et al. 2008b; Kormendy et al. 2009) and constraints from stellar populations (McDermid et al. 2006; Reda et al. 2007; Sánchez-Blázquez et al. 2007) yield similar conclusions. If angular momentum loss in mergers were always efficient, the natural expectation would be that this should rise at low galaxy masses as the progenitor disc gas fractions, i.e.  $\sim f_{\text{gas}} \rightarrow 1$ . If, however, angular momentum loss becomes less efficient in these extremely gas-rich systems, the observed trend is the natural prediction: if the fraction of gas losing angular momentum scales as adopted here, then the dissipational fraction of the bulge formed from discs with gas fraction  $f_{\text{gas}}$  is not  $\sim f_{\text{gas}}$ , but  $\sim f_{\text{gas}}/(1 + f_{\text{gas}})$ , i.e. asymptoting to the values observed for all  $f_{\text{gas}} \sim 0.5\text{--}0.9$ . Expanded samples with high-resolution photometry, kinematics and stellar population constraints would provide powerful constraints to extend these comparisons.

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## APPENDIX A: DETAILS OF THE HOPKINS ET AL. 2009 (H09) MODEL

The full gas fraction-dependent ('new') model for the efficiency of bulge formation as a function of gas fraction and merger properties, discussed in the text, is derived in detail and compared to a large suite of hydrodynamic merger simulations spanning the relevant parameter space in H09. We refer the reader to that paper for a detailed discussion of the physical motivation for the model and numerical tests. Here, we briefly present the key physically-motivated prescriptions which are shown therein to provide a good fit to the simulation behaviour and provide our implementation of the hydrodynamic results in analytic or semi-analytic cosmological models.

Define:  $m_{*, \text{disc}}$  the mass of stars in the disc component and  $m_{*, \text{bulge}}$  the mass of stars in the bulge component, with  $m_* = m_{*, \text{disc}} + m_{*, \text{bulge}}$  the total stellar mass;  $m_{\text{cold}}$  the mass of cold gas in the galaxy (assumed to all reside in the disc). Here,  $m_{\text{bar}} = m_* + m_{\text{cold}}$  is the baryonic mass of the galaxy and  $r_d$  is the effective radius of the disc. The disc gas fraction is then  $f_{\text{gas}} = m_{\text{cold}} / (m_{\text{cold}} + m_{*, \text{disc}})$  and the disc mass fraction is  $f_{\text{disc}} = (m_{\text{cold}} + m_{*, \text{disc}}) / m_{\text{bar}}$ .<sup>8</sup>

The model outlined in Section 4.3 of H09 then gives a simple set of formulae to compute the fraction of cold gas in both merger progenitors that will participate in a central starburst (as a consequence of losing its angular momentum), and as a result be removed from the disc and added to the bulge component of the remnant. The mass of gas that participates in the starburst is

$$m_{\text{burst}} \equiv m_{\text{cold}}(< r_{\text{crit}}), \quad (\text{A1})$$

or the mass of cold gas within a critical radius  $r_{\text{crit}}$  where angular momentum loss from the gas disc in the merger is efficient.

<sup>8</sup> In simulations, the following descriptions are most robust if these quantities are defined just before the final coalescence/merger where the gas will lose angular momentum and stars will violently relax. Defining them at earlier times means that other quantities such as the star formation efficiency will be important for determining how much gas is actually present at the time of interest (the merger).

H09 derive the following relation for  $r_{\text{crit}}$  (their equation (7)):

$$\frac{r_{\text{crit}}}{r_d} = \alpha (1 - f_{\text{gas}}) f_{\text{disc}} F(\theta, b) G(\mu), \quad (\text{A2})$$

where

$$F(\theta, b) \equiv \left( \frac{1}{1 + [b/r_d]^2} \right)^{3/2} \frac{1}{1 - \Omega_o/\Omega_d} \quad (\text{A3})$$

contains the dependence on the merger orbit, and

$$G(\mu) \equiv \frac{2\mu}{1 + \mu} \quad (\text{A4})$$

contains the dependence on the merger mass ratio  $\mu \equiv m_2/m_1$ . There is some ambiguity in the most relevant definition of ‘mass ratio’ (e.g. Stewart 2009); because we are interested in the gravitational dynamics induced by passage/merger, we find the best match to behaviour in simulations by defining the masses of interest ( $m_1$  and  $m_2$ ) as the baryonic plus tightly bound (central) dark matter (specifically, dark matter mass within a core radius of  $r_s$ , the NFW scalelength  $\equiv r_{\text{vir}}/c$ , roughly  $\sim 10$  per cent of  $r_{\text{vir}}$  or  $\sim$  a few disc scalelengths; the results are not strongly sensitive to the choice within a factor of  $\sim 2$ – $3$  in  $r$ ). This is important, in particular for low-mass galaxies which are observed to be dark-matter dominated (and have high  $f_{\text{gas}}$ ); simply considering the stellar or baryonic mass ratio significantly underestimates the ‘damage’ done to the disc relative to the results of high-resolution simulations.

In equation (A3) above,  $b$  is the distance of pericentric passage on the relevant final passage before coalescence ( $\lesssim$  a couple  $r_d$  for typical cosmological mergers), but H09 show that for systems which will actually merge, as opposed to fly-by encounters, identical results are obtained in the limit  $b \rightarrow 0$ , since the final coalescence – regardless of initial impact parameter – will be largely radial. The quantity  $\Omega_o$  is the orbital frequency at pericentric passage and  $\Omega_d$  is that of the disc;

$$\frac{\Omega_o}{\Omega_d} = \frac{v_{\text{peri}}}{v_c} \frac{r_d}{b} \cos(\theta) \approx \sqrt{2(1 + \mu)} [1 + (b/r_d)^2]^{-3/4} \cos(\theta), \quad (\text{A5})$$

where  $\theta$  is the inclination of the orbit relative to the disc ( $v_{\text{peri}}$  is the velocity at pericentric passage,  $v_c$  the circular velocity at the impact parameter  $b$ ). We draw  $\theta$  randomly for each merger assuming discs are isotropically oriented (although this affects primarily the scatter, not the mean relations predicted).

Adopting  $b = 2r_d$ , typical of cosmological mergers, or taking the limit  $b \rightarrow 0$  for final radial infall gives a similar scaling:

$$\alpha F(\theta, b) = \frac{0.5}{1 - 0.42 \sqrt{1 + \mu} \cos(\theta)}. \quad (\text{A6})$$

The parameter  $\alpha$  in equation (A2) subsumes details of the stellar profile shape and bar/driven distortion dynamics in a merger. The precise value above is obtained from the numerical simulation results in H09, but is also derived analytically therein.

The discs are assumed to follow an exponential profile, so the fraction of the cold gas mass within  $r_{\text{crit}}$  is given by

$$f_{\text{burst}} = \frac{m_{\text{burst}}}{m_{\text{cold}}} = 1 - (1 + r_{\text{crit}}/r_d) \exp(-r_{\text{crit}}/r_d). \quad (\text{A7})$$

Generally, evaluating these quantities with the cold gas and stellar content being the sum of the two merging galaxies is a reasonable approximation to the numerical results (representing the fact that the burst takes place near or shortly after the time of coalescence); it is also straightforward to independently apply the equations above both primary and secondary at the time of the merger. In practice,

it makes little difference (even assuming that the entire gas mass of the secondary is part of the burst is a good approximation for all but the most rare very major mergers with mass ratios close to 1:1).

Following H09 (section 4.3.3), we further assume that the mass of the stellar disc in the primary (more massive) galaxy that is transferred to the bulge/spheroidal component from the disc and violently relaxed is

$$m_{\text{disc, destroyed}} = \mu m_{*, \text{disc}}. \quad (\text{A8})$$

Furthermore, the whole stellar mass of the secondary,  $m_2$ , is also added to the spheroidal remnant. A more detailed accounting of, for example, the efficiency of violent relaxation as a function of radius (see H09; Hopkins et al. 2008c) in the stellar disc suggests that one should further multiply the right-hand side of equation (A8) by a factor of  $(1 + \mu^{-0.3})^{-1}$ ; in practice, including this weak dependence on  $\mu$  makes no difference.

As described in the text, the gas fraction-independent or ‘dissipationless’ model treats gas in the same way as stars in terms of the efficiency of merger-induced bulge formation. Gas which is assumed to be transferred to the spheroid in the merger is still allowed to lose angular momentum and participate in a central starburst as opposed to being violently relaxed (so the system is not, formally speaking, dissipationless), but the gas mass fraction that does so scales with merger properties in the same manner as the dissipationless violently relaxed stellar fraction. This amounts to replacing our more physical model for the gas behaviour with the analogue of equation (A8): the gas mass which goes into a starburst in the merger is simply  $m_{\text{burst}} = \mu m_{\text{cold}}$ , independent of gas fraction. Since the behaviour of interest is the dependence of bulge formation efficiency on gas fraction, we can instead still choose to adopt equation (A2) for the behaviour of the gas, but omit the dependence on disc gas fraction [the  $(1 - f_{\text{gas}})$  term], equivalent to assuming that the gas always loses angular momentum as efficiently as in a relatively gas-poor merger [formally computing equation (A2) with  $f_{\text{gas}} \rightarrow 0$ , regardless of the actual disc gas fraction]. This choice makes no difference in our calculations and comparisons throughout the paper: the dependence on, for example, orbital parameters in equation (A2) only affects the scatter in  $B/T$ , not the mean trends, and the scaling with mass ratio is very similar. The important difference between the models is entirely contained in the  $(1 - f_{\text{gas}})$  scaling.

We emphasize that there are no free or ‘tuned’ parameters in this model. All of the parameters and values given above are determined in H09 based on physical models and hydrodynamic merger simulations, and are adopted without adjustment in both the empirical and the semi-analytic model.

## APPENDIX B: DETAILS OF THE S08 SEMI-ANALYTIC MODEL

Here, we give further details of the semi-analytic model in which we embed the above models for bulge formation. This model has been described in detail in Somerville & Primack (1999), Somerville et al. (2001) and a version with major updates has recently been described in Somerville et al. (2008a, S08). We refer the reader to those papers for details, but briefly summarize the main ingredients of the models here. The models are based on Monte Carlo realizations of dark matter halo merger histories, constructed using a slightly modified version of the method of Somerville & Kolatt (1999), as described in S08. The merging of subhaloes within virialized dark matter haloes is modelled by computing the time required for the subhalo to lose its angular momentum via dynamical friction and fall to the centre

of the parent halo. The S08 model takes into account the mass loss of the orbiting dark matter haloes owing to tidal stripping, as well as tidal destruction of satellite galaxies.

The model discriminates between cooling and accretion in two different regimes: ‘cold mode’, in which the gas cooling time is less than the free-fall time, and ‘hot mode’, in which the opposite condition holds. In the cold mode, gas accretion on to the disc is limited only by the rate at which gas is incorporated into the virialized halo. In the hot mode, the rate at which gas can lose its energy and cool via atomic cooling is estimated. This cooling gas is assumed to initially settle into a thin exponential disc, supported by its angular momentum. Given the halo’s concentration parameter, spin parameter and the fraction of baryons in the disc, angular momentum conservation arguments are used to compute the scale radius of the exponential disc after collapse (Somerville et al. 2008b). The models make use of fairly standard recipes for the suppression of gas infall owing to a photo-ionizing background, star formation and supernova feedback, as described in S08. Quiescent star formation, in isolated discs, is modelled using the empirical Kennicutt star-formation law (Kennicutt 1998). A critical surface density threshold is adopted, and only gas lying at surface densities above this value is available for star formation. Cold gas may be reheated and ejected from the galaxy, and possibly from the halo, by supernova feedback. Heavy elements are produced with each generation of stars, and enrich both the cold and hot gas.

Galaxy mergers trigger the accretion of gas on to supermassive black holes in galactic nuclei. Energy radiated by black holes during this ‘bright’, quasar-like mode can drive galactic-scale winds, clearing cold gas from the post-merger remnants. In addition to the rapid growth of black holes (BHs) in the merger-fuelled, radiatively efficient ‘bright mode’ BHs also experience a low-Eddington-ratio, radiatively inefficient mode of growth associated with efficient production of radio jets that can heat gas in a quasi-hydrostatic hot halo. Thus, once the black hole has grown sufficiently massive, this ‘radio mode’ feedback can completely switch off further cooling, eventually quenching star formation in massive galaxies. Note that the radio mode feedback is assumed only to be effective in heating gas that is being accreted in the ‘hot mode’ described above. The semi-analytic models contain a number of free parameters, which are summarized in Table 1 of S08. These parameters were chosen in order to reproduce certain observations of nearby galaxies, as described in detail in S08 (most importantly, the stellar mass function, cold gas fraction of spirals as a function of stellar mass, and the metallicity-mass relation zero-point). In this work, we use the fiducial values of all parameters, as given in S08.

### APPENDIX C: VARIATIONS OF THE SEMI-EMPIRICAL MODEL

An advantage of the semi-empirical model approach is that it is trivial to alter various assumptions, provided that the key observational constraints (e.g. galaxy masses and gas fractions, in this case) remain satisfied. We have experimented with a number of such variations, and find that the conclusions in this paper are robust. A

detailed discussion of these variations and their consequences for merger rates and galaxy merger histories will be presented in future work (Hopkins et al. 2009e). Here, we briefly outline some of these choices.

Changing the adopted dark matter merger rates makes little difference. We have recalculated our model adopting the halo merger trees from Stewart et al. (2008a), using the subhalo-based merger trees from Wetzel, Cohn & White (2009), and implementing various approximations for a ‘merger time-scale’ (delay between halo–halo and galaxy–galaxy merger, given, for example, by some approximation to the dynamical friction time) from Boylan-Kolchin, Ma & Quataert (2008) and Jiang et al. (2008). We have also recalculated the model using different observational constraints to determine the galaxy masses populated in haloes or subhaloes of a given mass; using the monotonic-ranking method of Conroy, Wechsler & Kravtsov (2006) applied to the redshift-dependent galaxy mass functions from Fontana et al. (2006) or Pérez-González et al. (2008), or using the  $z = 0$  constraints determined directly from clustering of Sloan Digital Sky Survey (SDSS) galaxies in Wang et al. (2006) and ignoring redshift evolution in this quantity. We find in each case a similar result.

We can also change the methodology, to essentially a toy model (between our strict semi-empirical approach and a semi-analytic model) fitted to observations. We assume at each time-step that all galaxies in haloes below  $10^{12} M_{\odot}$  simply accrete cold gas proportional to their halo growth (this corresponding to what is seen in simulations and observations; low-mass galaxies accrete efficiently in the ‘cold mode’ with gas coming directly into discs on a dynamical time, high-mass galaxies are ‘quenched’; see e.g. Kereš et al. 2005, 2008). We can then determine a star formation rate either by forcing the galaxies to move along the empirically constrained  $M_{\text{gal}}(M_{\text{halo}})$  track (our default method, based on the observational constraints described above), or by assuming the galaxies lie on a fixed size–mass relation and using the Kennicutt (1998) relation (both appear to evolve only weakly with redshift; see Bouché et al. 2007; Genzel et al. 2008; Puech et al. 2008; van Starckenburg et al. 2008), or by assuming they live on the fitted SFR-galaxy mass relation in Noeske et al. (2007). We can further allow some ‘outflow’, with an efficiency  $\dot{M}_{\text{outflow}} \propto \dot{M}_{*}$  fitted so as to yield a good match to the  $f_{\text{gas}}$ -galaxy mass relation observed at different redshifts (e.g. Bell & de Jong 2000; McGaugh 2005; Shapley et al. 2005; Erb et al. 2006; Calura et al. 2008). Recall, in our ‘default’ semi-empirical model, we simply assume whatever inflow/outflow necessary such that the galaxies always live on the  $f_{\text{gas}}$ -galaxy mass relation fitted to these observations; but appropriately tuned, this simple toy model can yield a similar result.

Ultimately, we find that these choices make little difference, so long as they yield the same distribution of galaxy masses and galaxy gas fractions. Those are the parameters that effect the model conclusions; to the extent that the variations above provide a means to interpolate between the empirical constraints on these quantities, they yield similar conclusions.

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