Forming a large disc galaxy from a $z < 1$ major merger

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ABSTRACT

Using high-resolution SPH simulations in a fully cosmological Λ cold dark matter context, we study the formation of a bright disc-dominated galaxy that originates from a 'wet' major merger at $z = 0.8$. The progenitors of the disc galaxy are themselves disc galaxies that formed from early major mergers between galaxies with blue colours. A substantial thin stellar disc grows rapidly following the last major merger and the present-day properties of the final remnant are typical of early-type spiral galaxies, with an i-band bulge-to-disc ratio $\sim$0.65, a disc scalelength of 7.2 kpc, $g - r = 0.5$ mag, an H I linewidth ($W_{20}/2$) of 238 km s^{-1} and total magnitude $i = -22.4$. The key ingredients for the formation of a dominant stellar disc component after a major merger are (i) substantial and rapid accretion of gas through cold flows followed at late times by cooling of gas from the hot phase, (ii) supernova feedback that is able to partially suppress star formation during mergers and (iii) relative fading of the spheroidal component. The gas fraction of the progenitors' discs does not exceed 25 per cent at $z < 3$, emphasizing that the continuous supply of gas from the local environment plays a major role in the regrowth of discs and in keeping the galaxies blue. The results of this simulation alleviate the problem posed for the existence of disc galaxies by the high likelihood of interactions and mergers for galaxy-sized haloes at relatively low z.

Key words: methods: N-Body simulations – galaxies: evolution – galaxies: formation – galaxies: interactions.

1 INTRODUCTION

Within the Λ cold dark matter (ΛCDM) framework, the buildup of galaxies and their parent dark matter (DM) haloes occurs through a series of mergers and accretion of more diffuse matter (Frenk et al. 1985; Springe et al. 2005). The classic models of galaxy formation (White & Rees 1978; Fall 1983; White & Frenk 1991) and subsequent work (Dalcanton, Spergel & Summers 1997; Mo, Mao & White 1998; Silk 2001; Bower et al. 2006; Zheng et al. 2007; Somerville et al. 2008) assume that gas infalls inside the parent DM halo and subsequently cools to temperatures low enough to fragment and forms stars. The morphology of galaxies and the fraction of stars in their disc and spheroidal components are set by a combination of competing physical processes, as numerical simulations have shown that violent relaxation in mergers between similar-size galaxies can destroy or dynamically heat their stellar discs and turn them into spheroids (Barnes & Hernquist 1996). On the other hand, remaining and subsequently accreted gas can regrow a disc (Baugh, Cole & Frenk 1996; Steinmetz & Navarro 2002) if given enough time. It is then a prediction of hierarchical models that the morphology of a galaxy is not assigned '*ab initio*' but it might change often over cosmic times, as the spheroidal to disc light ratio changes back and forth. Observed merger remnants have discy isophotes (Rothberg & Joseph 2004) or evidence for young disc components (McDermid et al. 2006), hinting at disc regrowth and supporting the above scenario.

Observationally, major mergers are observed to be common in the redshift range 0–1. Their number density has been estimated to be of the order of $10^{-(3-4)} h^{-1}$ Mpc^{-3} Gyr^{-1} (Lin et al. 2008; Jogee et al. 2009), possibly increasing with redshift. As numerical work

suggests that a consistent supply of gas is important to regrow a disc component (Robertson et al. 2006), it is relevant that observational evidence for mergers between actively star-forming galaxies has also emerged showing that at redshift ∼1, 70 per cent of the merging pairs are between blue (or 'wet', defined as rest-frame $g - r < 0.65$) pairs; however, the fraction of blue and likely gas-rich mergers decreases by the present time (Lin et al. 2008).

Numerical work has also highlighted a possible problem for the existence of disc galaxies at low redshift, showing that interactions, mergers and accretion events are common at every redshift for L⋆ galaxy-sized haloes in ΛCDM models (Maller et al. 2006; Stewart et al. 2008) and potentially destructive for discs (Toth & Ostriker 1992; Kazantzidis et al. 2007; Bullock, Stewart & Purcell 2009; Purcell, Kazantzidis & Bullock 2009). This makes it potentially difficult to reconcile the observed present-day population of disc-dominated galaxies with ΛCDM, if a quiet merging history is essential for their existence. But, do disc galaxies really require a quiet merging history to be observed as such at the present time? What are the time-scales of disc growth and destruction? How quickly do disc galaxies regrow after a merger? Theoretical models also highlight the difficulties in predicting the outcomes of galaxy mergers and the subsequent regrowth of stellar discs. These difficulties arise from several factors. Given the decoupling of the baryonic cores from the parent haloes, it is difficult to predict robust merging rates of galaxies (as compared to their DM haloes) unless cosmological simulations with hydrodynamics are used (Maller et al. 2006). Also, numerical simulations have shown how the bulge-to-disc (B/D) ratio resulting from a major merger might depend on the orbital parameters, the internal spin of the progenitors, the gas fraction of the parent discs and the efficiency of supernova (SN) feedback (Barnes & Hernquist 1996; Cox et al. 2006; Scannapieco et al. 2008).

Recent observational and theoretical work has pointed out ways to alleviate the possible problem of a high merger rate for the survival of disc galaxies. Hopkins et al. (2009) showed that angular momentum loss of the gas component is not necessarily catastrophic even in 1:1 mergers. Discs can survive or rapidly regrow, provided that the gas fraction in the discs of the progenitors is high (Robertson et al. 2006; Robertson & Bullock 2008; Bullock et al. 2009). If feedback is able to suppress star formation (SF) during the merger event (Brook et al. 2004b; Robertson et al. 2006; Zavala, Okamoto & Frenk 2008; Governato et al. 2007), the existing cold gas can settle on a new disc plane and start regrowing a stellar disc.

Hydrodynamical simulations indeed show that cold flows [cold gas that flows rapidly to the centre of galaxies from filamentary structures around haloes (Kereš et al. 2005; Dekel et al. 2009)] play a major role in the buildup of discs in galaxies (Brooks et al. 2009). Gas accreted through cold flows arrives to the central stellar disc on a time-scale a few Gyr shorter than gas that is first shocked to the virial temperature of the host halo and then cools on to the disc, leading not only to early disc SF, but the creation of a large reservoir of cold gas. No matter its origin, late infalling gas would likely have a higher angular momentum content than material accreted at earlier times (Quinn & Binney 1992), and gas in the merging discs would acquire a coherent spin set by the orbital parameters of the binary system and the internal spins of the parent galaxies. A feedback+cold flows model is particularly attractive as the mechanism for the survival/regrowth of gas (and then stellar) discs as it provides a natural explanation to the fact that more massive galaxies tend to have large B/D ratios (Benson et al. 2007; Graham & Worley 2008), while smaller galaxies are likely disc dominated. At large galaxy masses, energy feedback from SNe becomes in-

effective at suppressing SF while cold flows become inefficient at carrying a supply of fresh gas necessary to regrow a stellar disc (Dekel & Birnboim 2006). Combined with the relative higher frequency of major mergers for massive galaxies (Guo & White 2008), this framework leads to the buildup of a larger stellar spheroid and disfavours the quick rebuilding of stellar discs in massive systems.

Only recently have numerical simulations been able to directly compare the observable quantities of the outputs with real data (Jonsson 2006; Chakrabarti et al. 2007; Covington et al. 2008; Lotz et al. 2008; Rocha et al. 2008), rather than simply predicting the mass distribution of the simulated stellar systems. This is a crucial point as the stellar spheroids will fade drastically after a major merger, while reforming discs will contain a large fraction of younger and brighter stars. Different mass-to-light ratios for the two components will skew the observed photometric light ratios compared to the underlying stellar masses.

Despite all this progress, the effect of mergers on the existing disc components and of feedback and cold flows on the regrowth of stellar discs have not been studied in detail in fully cosmological simulations of major mergers. Here, we present results from a fully cosmological, smooth particle hydrodynamic (SPH) simulation where late gas accretion plays a major role in the rapid regrowth of a dominant stellar disc in an L⋆ galaxy after a $z = 0.8$ major merger. In this work, we focus on the physical processes that drive the regrowth of the disc as identified by its kinematical properties, but we also measure the structural properties of the simulated galaxy based on the light distribution, i.e. in a way closely comparable to observations. This result helps solve the apparent contradiction that strong interactions at relatively low redshifts are common even for DM haloes that are likely to host bright disc galaxies. This paper is organized as follows. Section 2 discusses the simulations; Section 3 describes the evolution of the system; Section 4 describes the observational properties of the merger remnant and Section 5 describes the assembly of the disc component. The results are then discussed in Section 6.

2 DESCRIPTION OF THE SIMULATION

The simulation described in this paper is part of a campaign of high-resolution simulations aimed at studying the formation of field galaxies in a *Wilkinson Microwave Anisotropy Probe* 3 cosmology ($\Omega_0 = 0.24$, $\Lambda = 0.76$, $h = 0.73$, $\sigma_8 = 0.77$, $\Omega_b = 0.042$). Our sample of haloes has been selected from low-resolution volumes of size 50 and 25 Mpc (the latter for dwarf size haloes) using the 'zoom-in' technique to ensure a proper treatment of tidal torques (Katz & White 1993). The sample covers 2 mag in total mass (from 2×10^{10} to 2×10^{12} M⊙) sampling a representative range in halo spins and epochs of last major merger. The galaxy described in this paper has a total mass of 7×10^{11} M⊙, spin $\lambda = 0.04$ [as defined in Bullock et al. (2001)] and a last major merger at $z = 0.8$. The environment density at $z = 0$ is typical of field haloes with an over density $\delta\rho/\rho = 0.1$ (0.2) measured over a sphere of radius 3 (8) h^{-1} Mpc. The final galaxy has 650 k, 320 k and 1.8 m DM, gas and star particles within the virial radius of the galaxy at the present time, with particle masses 1.01×10^6, 2.13×10^5 and 6.4×10^4 M⊙ for each DM, gas and star particle at the moment of formation. The force spline softening is 0.3 kpc. The minimum smoothing length for gas particles is 0.1 times the force softening. The simulations were performed with the *N*-body SPH code GASOLINE (Wadsley, Stadel & Quinn 2004) with a force accuracy criterion of $\theta = 0.725$, a time-step accuracy of $\eta = 0.195$

and a Courant condition of $\eta_C = 0.4$. The adopted SF and SN schemes have been described in detail in Stinson et al. (2006) and Governato et al. (2007). As in Governato et al. (2007) we set the SF efficiency parameter to $c = 0.05$ and the SN efficiency to eSN = 0.4. A Kroupa initial mass function is assumed. Our 'blast-wave' feedback scheme is implemented by releasing energy from SN into gas surrounding young star particles. The affected gas has its cooling shut off for a time-scale associated with the Sedov solution of the blastwave equation, which is set by the local density and temperature of the gas and the amount of energy involved. At the resolution of this study, this translates into regions of ~0.2–0.4 kpc in radius being heated by SN feedback and having their cooling shut off for 10–30 Myr. The effect is to regulate SF in the discs of massive galaxies and to lower the SF efficiency in galaxies with peak circular velocity in the $50 < V_c < 150$ km s^{-1} range (Brooks et al. 2007). At even smaller halo masses [$V_c < 20$–40 km s^{-1}, with $V_c = \sqrt{(GM/r)}$] the collapse of baryons is partially suppressed by the cosmic ultraviolet (UV) field (Hoeft et al. 2006; Governato et al. 2007), here modelled following Haardt & Madau (1996). The simulation applied a correction to the UV flux for self shielding of dense gas as introduced in Pontzen et al. (2008) and low-temperature metal cooling (Mashchenko, Wadsley & Couchman 2008). By $z = 0$, the total amount stars (excluding satellites) within the virial radius is 7.1×10^{10} M$_\odot$. Preliminary tests show that the implementation of metal cooling for gas temperatures higher than $T > 10^4$ would increase the amount of stars formed in an L_* sized galaxy by ~10 per cent, as also show in recent works (Choi & Nagamine 2009). It is important to note that the only two free parameters in the SN feedback scheme (the SF efficiency and the fraction of SN energy coupled to the interstellar medium) have been fixed to reproduce the properties of present-day galaxies (SF rates, Schmidt law, cold gas turbulence, disc thickness) over a range of masses (Governato et al. 2007). Without further adjustments, this scheme has been proven to reproduce the relation between metallicity and stellar mass (Brooks et al. 2007; Maiolino et al. 2008) and the abundance of damped Lyman α systems at $z = 3$ (Pontzen et al. 2008). However, even at this resolution the central regions ($r < 1$–2 kpc) of galaxies remain still partially unresolved and likely form bulges that are too concentrated (Governato, Mayer & Brook 2008;

Mayer, Governato & Kaufmann 2008). In this respect, the mass of the bulge component of our simulated galaxy has to be considered an upper limit imposed by current resolution limits, especially at high z, where the number of resolution elements per galaxy is less.

To properly compare the outputs from the simulation to real galaxies and make accurate estimates of the *observable* properties of galaxies, we used the Monte Carlo radiation transfer code SUNRISE (Jonsson 2006) to generate artificial optical images (see Fig. 1) and spectral energy distributions (SEDs) of the outputs of our run. SUNRISE allows us to measure the dust-reprocessed SED of every resolution element of our simulated galaxies, from the far-UV to the far-infrared, with a fully three-dimensional treatment of radiative transfer. Filters mimicking those of the Sloan Digital Sky Survey (SDSS) survey (Adelman-McCarthy et al. 2006) are used to create mock observations.

To measure the rotational velocity of the remnant and other galaxies in the sample in a way comparable with observations, we used the spatial and kinematic distribution of cold gas in the disc of our simulated galaxy. Using the H I fraction calculated by GASOLINE, we determined the H I linewidth (W_{20}) by finding the width of the H I velocity distribution at 20 per cent of the peak. The value of $W_{20}/2$ is then used as a measure of the galaxy rotation velocity at different redshifts. This measurements reflects the mass-weighted position–velocity distribution of cold gas inside the central region of the galaxy, and in observed bright galaxies it is usually associated with the peak rotational velocity. Because the mass inside the central few kpc is likely overestimated owing to resolution effects (Mayer et al. 2008), $W_{20}/2$ provides a slightly larger measurement of the rotational velocity than that obtained from the rotational speed of young stars at 2.2 or 3.5 disc scalelengths (typically 10–20 kpc for bright galaxies), and thus is a useful upper limit for a comparison with real data.

3 DYNAMICAL AND PHOTOMETRIC EVOLUTION OF THE MERGING SYSTEM

The galaxy studied here was singled out for its particularly interesting assembly history, as the buildup of its stellar component involves numerous major mergers, seemingly a hostile environment to build
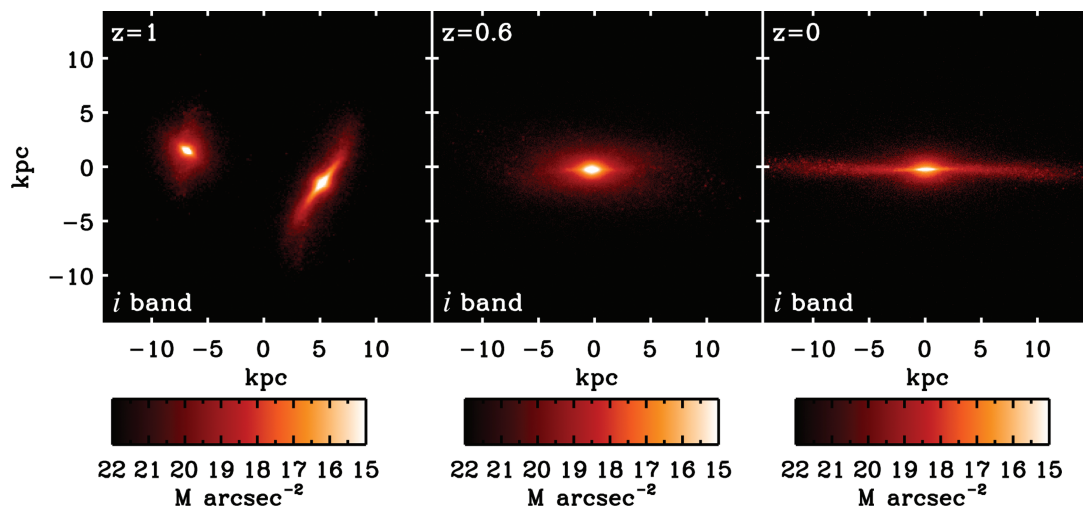

Figure 1. SDSS rest frame, unreddened *i*-band surface brightness images of the merging system at three different stages. Left (panel a): $z = 1.0$ close to the first pericentric passage. Centre (panel b): the merger remnant at $z = 0.6$, 1 Gyr after the stellar cores of the two galaxies have coalesced. Right (panel c): the system observed at the present day – the halo has faded considerably while the galaxy has grown an extended thin disc. The *i*-band disc scalelength R_d is 7.2 kpc and the light ratio of the kinematically identified bulge and disc components (B/D ratio) is 0.49, while a GALFIT two-dimensional decomposition gives a B/D ratio = 0.65.

a significant stellar disc. At $z = 3$, the four most massive progenitors form a hierarchy of two binary systems roughly aligned on the same large-scale filamentary structure. Each halo has a total mass $\sim 7 \times 10^{10}$ M$_\odot$ and has formed a rotationally supported stellar disc fed by strong cold flows, typical of galaxies at that redshift (Brooks et al. 2009). In this work, we define as 'cold flow' gas that has never been shocked to 3/8 the virial temperature of the parent halo (Kereš et al. 2005; Brooks et al. 2009). The average cold ($T < 4 \times 10^4$ K) gas fraction in the discs of the four galaxies is 25 per cent (defined as the fraction of total baryons in the disc). Both pairs merge by $z = 2$. Just before the mergers, the four progenitors have rest-frame B magnitudes in the range -21.1 to -20.2 (-21.5 to -20.6 in the r band) and rest-frame $g - r$ colours around 0.3–0.4 (unless specified all global magnitudes and colours in this work are in the rest-frame AB system and include the effects of dust reddening measured at a 45° inclination). These two early mergers are then 'wet', i.e. between galaxies with blue colours as defined in Lin et al. (2008).

Both merger remnants quickly reform extended gas discs from a combination of freshly accreted gas and gas already in the progenitors discs that was not turned into stars during the merger. For each merger, the SF history (SFH) peaked at 18 and 32 M$_\odot$ yr^{-1}, respectively (Fig. 2). At $z = 1.6$ (2 Gyr before the final merger), the two disc galaxies formed from the early mergers have again very similar magnitudes: -21.6 (-22.1) and -21.3 (-21.8) in the $B(r)$ band, respectively, close to the B-band L$\star$ at that z (Marchesini et al. 2007). Their $g - r$ colour $= 0.4$ makes them bluer than most galaxies of similar brightness at the present time (Lin et al. 2008).

The final major merger of these two progenitor galaxies begins at around $z = 1$ when their DM haloes, flowing along the same filamentary structure, first overlap. The galaxies plunge in on fairly radial orbits, with the internal spins of the two discs roughly aligned with the orbital angular momentum vector (Fig. 1a). Note that this is not necessarily a configuration favorable to the survival of gaseous discs, as noted by Hopkins et al. (2009). After two close passages, the two galaxies coalesce by $\sim z = 0.8$, i.e. 1 Gyr after the merger commenced. The mass ratio of the merging haloes is 1.2:1 while the i-band brightness ratio is 1.6:1. During the merger, the global SF rate of the system is enhanced and peaks at 11 M$_\odot$ with subsequent SF rates in the remnant dropping rapidly by almost a factor of 3 to ~ 4 M$_\odot$ yr^{-1} (Fig. 2). The moderate SF enhancement is consistent with estimates for interacting systems in the same redshift range

(Jogee et al. 2009). Given the galaxies' properties outlined above, even this final merger is then clearly identified as 'wet'. However, the discs of the two galaxies have gas fractions around 20 per cent, so they are only relatively gas rich compared to the present-day population of galaxies of similar brightness (Garcia-Appadoo et al. 2009) and have equal or lower gas abundance as $z \sim 2$ galaxies (Erb et al. 2006).

Once again, following the final major merger a gas disc rapidly regrows and SF is mainly concentrated in the reforming stellar disc. The galaxy remains relatively unperturbed after $z = 0.8$. Shortly after the merger, the spheroidal component of the newly formed galaxy dominates the light distribution (Fig. 1b), although a discy component is already visible. The $g - r$ colour is 0.5 and remains stable to the present time. We verified that the discy component at $z = 0.8$ is indeed associated with a thick stellar disc supported by rotation. By $z = 0$, the galaxy has regrown an extended thin disc and the spheroid has faded considerably. The galaxy retains the primordial baryon abundance, but more than 50 per cent of the baryons in the halo have been turned into stars. The amount of gas within the virial radius is about 5×10^{10} M$_\odot$. The halo has faded in the reddened B band by 0.8 mag to $B = -21$, due to the aging of the spheroidal component. The disc clearly dominates the light distribution in the SDSS i and bluer bands (Fig. 1c).

These results show that at all stages the progenitors of the final galaxy can be identified with a normal population of moderately gas-rich disc galaxies with colours and SF rates comparable with the galaxy population observed in the $3 > z > 1$ range. It is also important to emphasize that the cold gas fraction in all the disc progenitors suggests that idealized initial conditions with disc gas fraction as high as 50 per cent are not a necessary condition to have 'wet' mergers and rapid regrowth of stellar discs. As discussed in Section 5, the fundamental ingredient for disc regrowth and blue colours is the fast refuelling of gas from the hot haloes and the surrounding cosmic web, highlighting the necessity of a fully cosmological approach to the problem of the abundance of galaxy discs.[1]

4 PROPERTIES OF THE MERGER REMNANT FROM $z = 0.8$ TO THE PRESENT

In this section, we decompose our simulated galaxy into its kinematic components and 'observe' some of its properties at the present day (they are summarized and compared with those of the galaxy at $z = 0.8$ in Table 1). Does the galaxy have the photometric and kinematic properties of disc-dominated galaxies?

At the present time, the disc clearly dominates the light distribution even in the relatively red i band (Fig. 1c). The galaxy has a total magnitude $i = -22.3$ (-22.4 unreddened) mag and global reddened colour $g - r = 0.5$, consistent with those of luminous present-day disc galaxies (Lin et al. 2008).

To measure its morphology in a quantitative way, the different components of the galaxy were first identified using their kinematic and spatial information and classified as bulge, halo and disc. This is a crucial step to relate each galaxy component to its physical origin. First, the disc plane is defined using the cold gas in the central few kpc of the galaxy, then disc stars are defined as stars whose specific angular momentum perpendicular to the disc plane (j_z) is a significant fraction of the maximum angular momentum of a circular orbit with the same binding energy (j_c), i.e. $j_z/j_c > 0.8$.
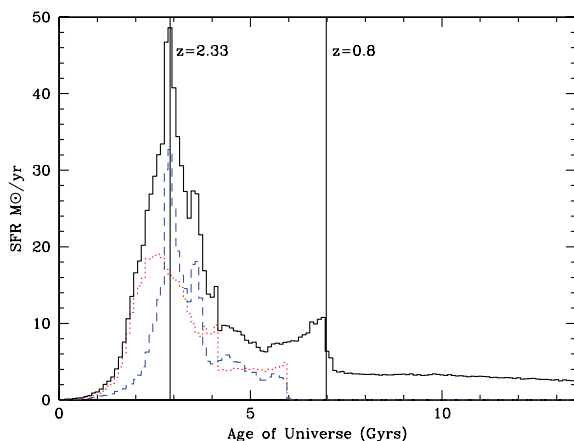

Figure 2. SFR versus time for the last major merger progenitors (red dotted and blue dashed) and for the whole galaxy (solid). The peaks of the dotted and dashed curves correspond to the two major mergers between the original four progenitors.

[1] Movie at http://www.astro.washington.edu/fabio/movies/Merger.mpg

Table 1. Merger remnant properties at $z = 0.8$ (shortly after the merger) and at the present time.

	$z = 0$	$z = 0.8$
Total mag i band	-22.3	-22.7
R_d i band (kpc)	7.2	4
B/D i band	0.49 (0.65)	1.1 (1.4)
B/D (stellar mass)	0.87	1.16
$g - r$	0.5	0.4
SFR	$2.2\,M_\odot\,yr^{-1}$	$6\,M_\odot\,yr^{-1}$
Disc stellar mass	3.24×10^{10}	2.07×10^{10}

Note. R_d is the disc scalelength and B/D is the B/D light ratio measured for the kinematically identified components. (B/D ratios in parentheses are measured using a two-dimensional photometric decomposition with GALFIT of the face-on projection of the light distribution). Total magnitudes and colours have been measured in SDSS filters, including the effects of dust (disc inclination $45°$), and in the AB system.

Figure 3. Lower panel: time evolution of the cold disc gas ($T < 4 \times 10^4$ K) scalelength and the stellar disc scalelength (measured in the unreddened i band) of the final merger remnant. Upper panel: the B/D ratio for the final remnant as a function of redshift. Dashed line: stellar masses. Dotted line: B/D light ratio (unreddened i band) with a GALFIT decomposition based on the two-dimensional, face-on light profile. Continuous line: B/D light ratio (unreddened i band) of the kinematically defined disc and bulge components.

Particles on circular but inclined orbits (more than $30°$) are excluded. To determine the angular momentum of a circular orbit, we used the fully consistent potential of the total matter distribution. We then determined the total energy for each particle, and measured a corresponding angular momentum from that mapping.

Bulge and halo stars were then identified based on their radial orbits and their binding energy (bulge stars being more bound). The energy separation criteria between halo and bulge stars corresponds to the radius at which the spheroid mass profile changes slope (halo stars having a shallower profile than bulge stars) and in our simulated galaxy sample separates an older and metal poor population (the halo) from bulge stars that are more metal rich. Halo stars contribute a fraction ($\sim$15 per cent) of the total stellar mass within the virial radius of the galaxy, but the halo central density is two orders of magnitude lower than that of the bulge. Hence, the details of the bulge/halo decomposition do not change our conclusions. At $z = 0$, the kinematically identified disc, bulge and halo stellar masses are, respectively, 3.4, 2.7 and 1. $\times 10^{10}\,M_\odot$. We then imaged each separate component using SUNRISE and measured their structural parameters using the unreddened images. We focused on a structural analysis of the unreddened components, avoiding the additional layer of complexity given by the details of the dust distribution, which will be explored in future papers with a larger number of galaxies. However, we have verified that our findings do not change if the reddened images are used instead.

How and when did the disc reform after the last major merger at $z = 0.8$? The stellar disc and bulge components were identified at different redshifts after the last major merger event. To better understand the B/D ratio evolution of the merger remnant, we measured B/D ratio in three different ways. We used the kinematic decomposition to find (i) the stellar mass ratio of the bulge and disc components and (ii) their relative flux ratio in the i unreddened band. Then, we analysed the unreddened, face-on two-dimensional light distribution created by SUNRISE using all the galaxy star particles (including halo particles) with GALFIT (Peng et al. 2002) to find (iii) the B/D ratio as determined by a fit to the surface brightness profile. Fig. 3 shows how the i-band disc scalelength and the B/D ratio evolve with time. Shortly after the merger event, the disc component is already visible edge-on, then the bulge component fades relative to the disc and the disc becomes more extended. At $z < 0.4$, or about 3.5 Gyr after the merger, the disc dominates both in terms of the light contribution and the B/D ratio decreases further by $z = 0$. All measurements agree on the same trend of B/D ratio
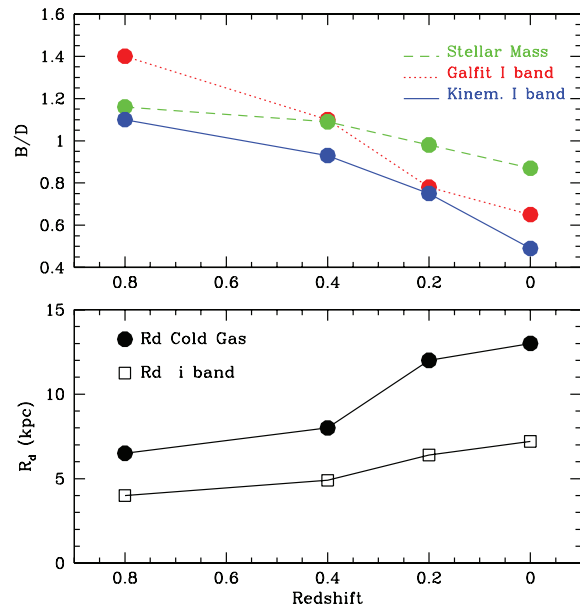
decreasing with time. At the present time, the disc extends almost far as 20 kpc in radius from the galaxy centre and the stellar disc scalelength R_d is 7.8 and 7.2 kpc in the B and i bands, respectively (Fig. 3), consistent with observations of real galaxies that show larger R_d in bluer bands. Smaller B/D ratios are obtained using the light distribution, more sensitive to the younger ages of disc stars. At $z = 0$, the B/D ratio stellar mass ratio of the kinematically defined components is 0.87, but the unreddened i-band light ratio is only 0.49. GALFIT shows the steepest trend with age, and shortly after the merger it underestimates the disc component, if by less than 20 per cent. GALFIT gives a fairly precise estimate of the light-weighted B/D ratio when the stellar disc becomes dominant.

Soon after the merger, the cold gas disc increases its size by nearly a factor of 2 as the new infalling gas settles on high angular momentum orbits. The angular momentum of the present-day disc baryons is mostly acquired at high z (Fig. 4) as predicted in analytical models (Quinn & Binney 1992) with a fraction of it transferred to the DM halo during the last major merger. As this gas is gradually converted into stars, the stellar disc also grows in size; however, the cold gas disc remains significantly more extended than the stellar one. Shortly after the merger, the (unreddened i band) disc scalelength is 4 kpc, at the present time it is almost twice as large, with only minor warping (Fig. 7). Most likely due to the late assembly of its younger component, this is a fairly extended disc for galaxies of this mass, more extended than many discs formed in cosmological simulations where the assembly history of the galaxy was more 'quiet'. Encouragingly, we verified that the structural properties of the bulge and disc do not change much if they are measured using GALFIT on the global unreddened two-dimensional light distribution, i.e. without a prior knowledge of the kinematic decomposition. With GALFIT, the i-band R_d is 6.8 kpc, a 5 per cent difference. GALFIT finds systematically larger B/D ratios, but only by 20 per cent or less. However, B/D ratios decrease if the GALFIT fitting is done on
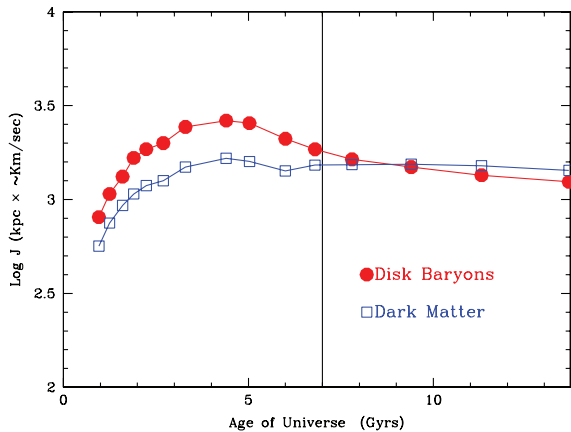
Figure 4. The time evolution of the angular momentum content per unit mass of the kinematically identified $z = 0$ baryonic disc (gas and stars) and the DM of the merger remnant. The reference frame is defined by the centre of mass of the selected particles. Disc material conserved most of the angular momentum gained by $z = 1.5$. The vertical line marks the epoch when the haloes and the baryonic cores merge during the last major merger.

dust-reddened images. These B/D ratio and R_d are quite typical of bright Sa and Sb galaxies that typically have dust-corrected B/D ratio ~0.5 and red $R_d \sim 3$–7kpc (Benson et al. 2007; Driver et al. 2007; Graham & Worley 2008).

To show how the simulated galaxy of this study relates to the general population of real disc galaxies on the Tully–Fisher (TF) relation, we compared its H I velocity width $W_{20}/2$ (238 km s^{-1}) and total rest-frame unreddened i-band relation with the disc-dominated galaxies in our simulated sample and with the sample of disc galaxies described in Geha et al. (2006) and references therein (Fig. 5). We find that the agreement between the observed TF and our set of simulations is quite good, as the combination of high resolution and the feedback adopted in our simulations yields a good match to real galaxies over a wide range of magnitudes and circular velocities. The merger remnant object of this study lies well within the observed scatter of both the observed and simulated samples, confirming that its structural properties are similar to those of typical bright spiral galaxies. We will present the scaling properties of the full data set of simulated galaxies in a forthcoming paper. An interesting feature of the TF plot is the evolution of the remnant on the TF plane: the very limited growth of the bulge stellar mass (only a few per cent) and the inside out growth of the disc ensures that the amount of mass within the central region of the galaxy does not change, hence $W_{20}/2$ does not evolve strongly, while the overall fading of the stellar components makes the galaxy dimmer by less than half a magnitude between redshift 0.8 and 0 (see Table 1). Even if the assembly history of our galaxy is not typical of galaxies of similar total mass, this result is consistent with observations that find a small evolution in the observed galaxy TF relation up to $z = 1$ (Conselice et al. 2005) along with strong size evolution (Trujillo et al. 2007). This result is not trivial and we plan to extend this analysis to our full sample of simulations in a future work.

We also verified that the metallicity of the cold gas is consistent with the observed stellar mass–metallicity relation [$8.5 < 12 + \log$ (O/H) < 8.9, depending on the aperture used; Tremonti et al. 2004; Brooks et al. 2007]. An average metallicity consistent with real galaxies is an important test of the realism of this simulation and makes the estimates of the galaxy colours of the final remnant and its progenitors more robust. Finally, the satellite system of the remnant includes 11 resolved luminous satellites within the virial radius
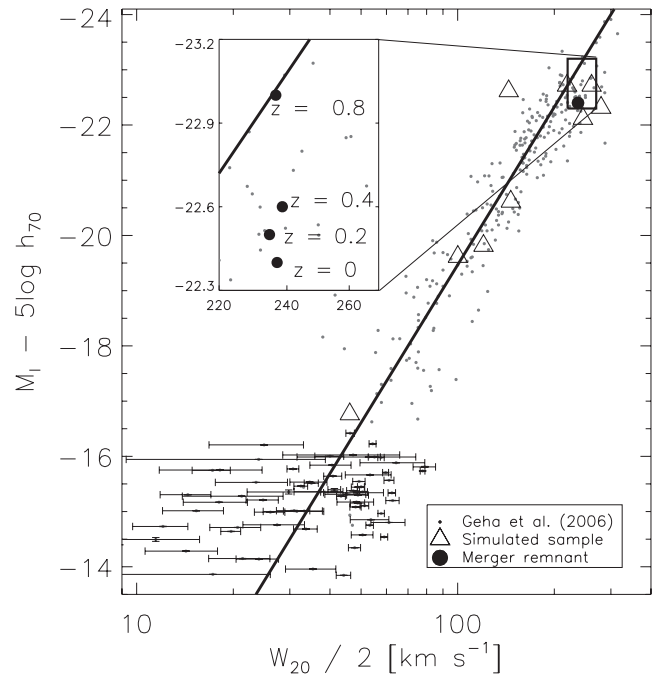

Figure 5. The location of the simulated galaxy in this work on the present-day 'TF' relation, i.e. the unreddened i band versus $W_{20}/2$. Grey dots: Galaxies from a compilation of observational data (Geha et al. 2006). Triangles: other disc galaxies from our simulated sample at similar resolution. Filled dot in main panel: the galaxy of this study at $z = 0$. Filled dots in upper-left inset: different snapshots of the merger remnant from $z = 0.8$ to the present. Circular velocities are the $W_{20}/2$ velocity widths from the H I distribution of the simulated galaxies. The inset shows the weak-redshift evolution of the merger remnant on the TF plot.

of 230 kpc. The faintest has AB B magnitude $= -8.7$, the brightest -17.9. By tracking the satellites through different outputs after the merger event, we verified that the galaxy disc undergoes several fly-bys by small dark satellites, but no significant accretion of luminous satellites after the final merger. Many faint satellites have undergone severe tidal stripping of both their DM haloes and of their stellar component. This analysis quantifies the dramatic regrowth of the disc component and how, coupled with the fading of the bulge and halo components, it leads to the formation of a galaxy dominated by an extended disc. It also highlights the difference between evaluating a galaxy morphological type using the mass distribution compared to the light distribution. It is encouraging, however, that similar trends (growing disc size and decreasing B/D ratios) are recovered using complementary techniques, as GALFIT provides a decomposition into bulge and disc components quite similar to that obtained using the full spatial and kinematic information. These results support the notion that the observed B/D ratios in bright galaxies are indeed representative of the underlying dynamical disc and spheroidal components.

5 THE ASSEMBLY OF THE GALAXY DISC

A detailed analysis of the gas accretion history was performed by tracking backwards every gas particle that was ever within the virial radius of the simulated galaxy and its progenitors. Every star particle comes from a gas progenitor which is uniquely identified at the moment of the star particle formation. The thermodynamical history of each gas particle progenitor was then studied. This temperature history was done for each of the original four progenitor galaxies,

then again for the resulting two binary galaxies, and finally for the merger remnant. Gas particles were then classified as (i) 'cold flows' if it never belonged to a progenitor halo before being accreted on to one of the progenitor galaxies or the merger remnant, and if it never shocked to 3/8 the virial temperature of the galaxy, (ii) 'shocked' if the gas was first shocked to >3/8 the virial temperature of the main halo and then cooled on to the disc and (iii) 'clumpy' if the gas particle was assigned to a subhalo before becoming part of the disc (i.e. a halo other than one of the four main progenitors and their subsequent merger remnants).

Fig. 6 shows (top panel) the total gas accretion rates to progenitor galaxies and merger remnant, and (bottom panel) the SFH of the resulting disc (as identified at $z = 0$ based on the stellar kinematics), separated by the different histories of each gas particle progenitor. It is remarkable that a large fraction of the disc formed at redshift one or earlier, when the galaxy had not undergone its last major merger yet. This result supports the suggestion that major mergers do not always completely destroy the pre-existing discs (Hopkins et al. 2009), although they heat them quite substantially, making them thicker. Cold flows build the largest fraction of the disc up to low redshift. This analysis shows how the buildup of the disc of bright galaxies differs from the simple picture of gas cooling from the hot halo and assembling into a disc; only at later times does gas cooling from the hot halo phase plays a role. From Fig. 6, it is clear that cold flows dominate the early gas accretion history of the progenitor galaxies, and is the dominant source of SF in the galaxy disc. Because SN feedback regulates SF in the disc, a cold gas reservoir is able to develop that sustains SF until the present time. The SF rate drops significantly when the two progenitor disc galaxies merge at $z \sim 1$. After this time, gas cooling from the hot halo becomes more important, resulting in 30 per cent of the disc stars formed in the last 2 Gyr from gas labelled as shocked. However, only 10 per cent of the total amount of stars in the disc at the present
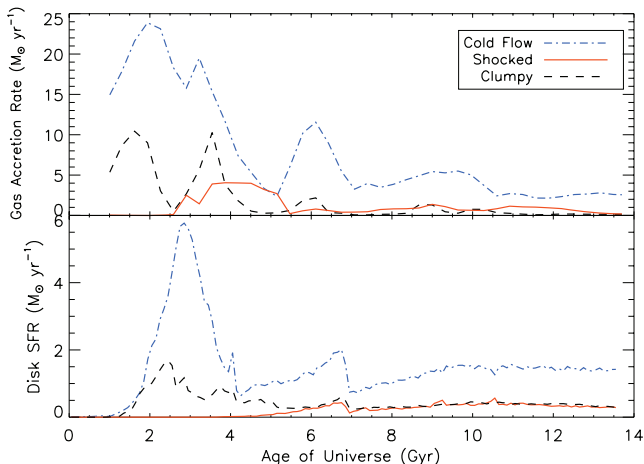
time have formed from gas that was previously heated to the virial temperature of the main progenitor, and almost 40 per cent of the disc stars after $z = 0.8$ formed from cold flows accreted after the last major merger. We find that this result is quite typical for disc galaxies of total mass $<10^{12}$ M$_\odot$ (Brooks et al. 2009) stressing the role of cold flows in building early discs and of 'shocked' gas in rebuilding some of the young, and hence bluer, more metal rich and brighter part of the disc. These effects will have to be carefully modelled in semi-analytical models of galaxy formation. Fig. 1 shows that as the disc grows in mass most of the stars are added to a thin and dynamically cold part of it. To quantitatively evaluate this process, we separated the stars previously dynamically identified as disc into two populations: those that formed before the $z = 0.8$ merger and those formed after, i.e. in the last ~6 Gyr. Fig. 7 shows the edge-on *i*-band surface brightness image (unreddened) of the two populations. Their properties are strikingly different: the younger stars form a thin exponential disc with *i*-band scalelength of 8.4 kpc (measured using stars in the 2–13 kpc range) and scaleheight of just 0.5 kpc (measured as a Gaussian distribution at a radius of 8.5 kpc). This scaleheight is likely as small as allowed by the force softening of 0.3 kpc. The older component, while being comparable in mass, is 1.3 mag fainter in the *i* band and 2.2 mag in the *B* band. It also has a much shorter disc scalelength, 3.1 kpc, and is considerably thicker, 2.7 kpc, again at an 8.5 kpc radius. The flaring in the old disc is due to the kinematic selection criteria, that exclude particles on circular orbits that are highly inclined from the disc plane.

While beyond the scope of this paper, we speculate that the mix of the two components could easily be identified as a thick- and thin-disc components if observed using typical observational techniques (Yoachim & Dalcanton 2006). Results from this simulation support the notion that thick discs are formed during major mergers and the early assembly of galaxy discs (Brook et al. 2004b). Furthermore, the last major merger should leave a clear signature in the age distribution of thick disc (which will be older than the merger) and thin-disc stars (mostly formed after the merger).
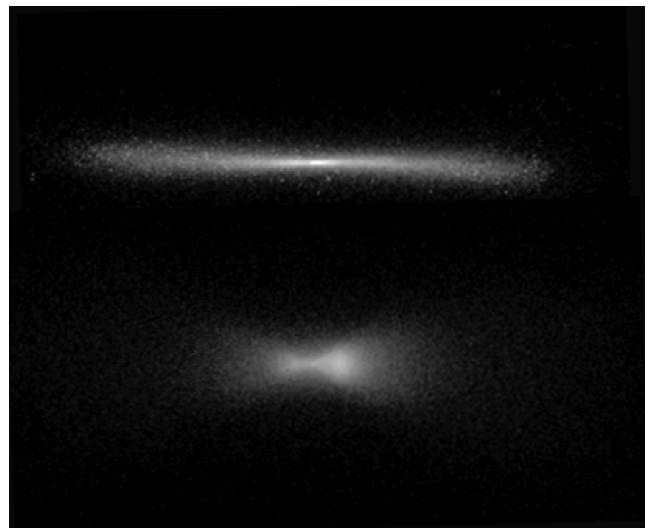

Figure 6. Top panel: the total gas accretion history of the merger remnant, divided by the thermodynamical history of the gas (at high z, the lines are the sum of the contributions from individual progenitors). Bottom panel: the SFH of disc star particles separated by the history of their parent gas particles. The disc stars are kinematically identified at $z = 0$. Dashed: from clumpy gas accretion, dot–dashed: from unshocked gas (or 'cold flows'), solid: shocked gas. A significant fraction of stars formed at high z and were identified as part of the disc even after two major mergers. At the present time, they form the thick disc component (see also Fig. 7). SF in the disc is partially disrupted during the last major merger, and stars formed from gas cooled from the hot halo form a significant fraction of the younger disc component.

Figure 7. The *i*-band (unreddened) edge on image of the galaxy disc at $z = 0$. Upper panel: light distribution from stars formed after the last major merger. Lower panel: the light distribution from stars formed before the last major merger, but still identified as disc based on their angular momentum. The image is 40 kpc across The relative brightness of the two components is not to scale.

In this realization, no significant component of the stellar disc is formed by accretion of stars in smaller satellites through minor mergers. While a substantial galaxy to galaxy scatter is expected, this is consistent with results from our larger sample of simulated disc galaxies (Brooks et al. 2009) and, compared with the existing literature, a consequence of the smaller stellar masses of the galaxy satellites resulting from the realistic feedback implementation (Governato et al. 2007). We verified that the bulge grows only modestly in mass from $z = 0.8$ to 0 and that no strong bar instabilities form after the last major merger. Similarly, the halo component shows minimal mass growth during the same time period. A close examination of the time evolution of the system shows several passages and disruption of small dark satellites, but they do not prevent the system from reforming a thin stellar disc.

6 CONCLUSIONS

We have analysed an SPH, fully cosmological simulation of the evolution of a galaxy that grows an extended thin stellar disc after a major (1.6:1) merger at $z = 0.8$. The disc dominates the light distribution 3.5 Gyr after the merger. By the present time, the galaxy shares several properties with the observed population of disc-dominated $L*$ galaxies.

This result is particularly relevant as the assembly history of the galaxy's parent DM halo is different from many previously published studies of cosmological simulations of disc galaxies, as it undergoes a late major merger, whereas previous works tended to select galaxies with a relatively quiet merger history. The two progenitors underwent major mergers themselves, at $z \sim 2$. The end result of this simulation strongly contradicts the notion that disc formation requires a 'quiet' halo merging history. In fact, the merging history of the halo picked for this study has often been considered hostile to the formation of extended discs at the present time. Our study provides strong support to the notion that galaxy discs can reform in a few Gyr after a gas-rich major merger, while a fraction of the pre-existing stellar disc can survive, even if faded by age and thickened by the strong interaction.

The results of our analysis are made particularly robust by measuring the properties of the remnant light distribution rather than just that of the stellar mass. This approach is crucial, as it highlights the effects of fading of the light from older stellar populations and plays a major role in quantifying the predominance of the newly formed (and hence bluer and brighter) stellar disc. The main structural parameters of the galaxy at $z = 0$ suggest that it has an Sa or Sb morphology: reddened i-band B/D ratio ~ 0.65; Rd = 7.2 kpc; $g - r = 0.5$; a $W_{20}/2$ H I velocity width of 238 km s^{-1}. Moreover, being able to measure the reddened colours and brightness evolution of the progenitors allows us a comparison with high-z galaxies, showing that they are representative of the population of blue, gas rich and moderately star-forming galaxies observed at $z > 1$. Verifying that the progenitors have some of the observed properties of high-redshift galaxies is important, as it makes the present-day properties of the merger remnant more relevant, having been built from realistic progenitors.

As our simulation includes a full treatment of the cosmological environment it includes a realistic treatment of a number of hydrodynamical processes that are necessary for the regrowth of stellar discs and that have to be simultaneously included: continuous inflow of gas from the cosmic web; stellar feedback and cooling from hot halo gas. This explains the difference between our results and those of the collisionless simulations of Purcell et al. (2009), which showed significant disc heating due to interactions and accretion

events. Lack of gas infall prevented the discs in their simulations to regenerate a new thin component (gas resupply was in fact advocated as a possible solution). In our simulation, the effect of interactions with infalling satellites, both luminous and dark, is naturally included. However, interactions and minor mergers are not strong enough to significantly disrupt or thicken the disc as it reforms from new gaseous material.

Idealized hydrodynamic simulations of binary galaxy mergers (Robertson et al. 2006; Hopkins et al. 2009) did not include the continued infall of gas from cold flows and the hot halo. These works pointed out that without any subsequent accretion/growth on to the disc after the merger, a cold gas fraction in excess of 50 per cent would be required in the discs of the progenitors in order to rebuild a disc-dominated galaxy after the merger. Here, we have shown that such high disc gas fractions are not necessary, as cold flows and cooling from a hot halo make disc regrowth possible even at low redshifts, when the gas fraction in the progenitors' discs and the remnant is only $\sim$20 per cent at any given time. The analysis of the buildup of the disc in our simulated galaxy highlights the dominant role of cold flows at high redshift. Cold flows funnel gas to the central disc on a time-scale a few Gyr shorter than gas that is first shocked to the virial temperature of the host halo and then cools on to the disc, leading not only to early disc SF but the creation of a large reservoir of cold gas. Thus, if a substantial fraction of this cold gas reservoir survives a merging event, it can provide a faster accretion rate on to the reforming disc than that available from cooling the hot gas in galaxy haloes alone. Rapid disc reformation will also be aided if cold gas accretion on to the galaxy halo is still occurring, while gas cooling from the hot phase forms just 30 per cent of the post merger stellar disc. However, this young component is more evident when the system is observed in bluer bands. It is important that these processes of disc formation and destruction be carefully implemented in analytical models that study the properties of large sample of galaxies.

More work is also needed to make detailed quantitative predictions about the morphology of galaxies formed in cosmological simulations and to make the results of our study more general. The maximum halo mass and lowest redshift at which mergers can regrow discs are obviously a function of the feedback efficiency (Brook et al. 2004a; Scannapieco et al. 2008) and could therefore provide useful qualitative tests of models of SF and feedback. In dense environments, such as groups or clusters, the gas reservoir associated with cold flows and cooling halo gas will likely be disrupted by tidal forces and ram pressure stripping. Hence, the disc regrowth process should be much less efficient, as expected by the observed correlation between galaxy morphology and environment density. Also, higher resolution cosmological simulations will have to address the role of secular processes on the detailed structure of the bulge and thin-disc components and their role in setting the B/D ratio of galaxies (Debattista et al. 2004; Genzel et al. 2008; Weinzirl et al. 2009). Still, results of the work presented here greatly alleviate the problem posed for the existence of disc galaxies by the high likelihood of interactions and mergers for galaxy-sized haloes at relatively low z.

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