The unorthodox evolution of major merger remnants into star-forming spiral galaxies

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Abstract

Galaxy mergers are believed to play a key role in transforming star-forming disk galaxies into quenched ellipticals. Most of our theoretical knowledge about such morphological transformations does, however, rely on idealised simulations where processes such as cooling of hot halo gas into the disk and gas accretion in the post-merger phase are not treated in a self-consistent cosmological fashion. In this paper we study the morphological evolution of the stellar components of four major mergers occurring at $z = 0.5$ in cosmological hydrodynamical zoom-simulations. In all simulations the merger reduces the disk mass-fraction, but all galaxies simulated at our highest resolution regrow a significant disk by $z = 0$ (with a disk fraction larger than 24%). For runs with our default physics model, which includes galactic winds from star formation and black hole feedback, none of the merger remnants are quenched, but in a set of simulations with stronger black hole feedback we find that major mergers can indeed quench galaxies. We conclude that major merger remnants commonly evolve into star-forming disk galaxies, unless sufficiently strong AGN feedback assists in the quenching of the remnant.

Key words: cosmology: theory – methods: numerical – galaxies: evolution – galaxies: formation – galaxies: star formation – galaxies: starburst.

1 INTRODUCTION

Traditionally, the visual appearance of galaxies has motivated dividing them into irregulars, spirals and ellipticals (Hubble 1926). An important difference between spirals and ellipticals is that the former are star-forming, whereas the latter are more likely quenched (Kennicutt 1998). These classifications are also in line with the presence of the Tully-Fisher relation (Tully & Fisher 1977), which describes the relation between stellar luminosity and rotation velocity for spiral galaxies, and the Faber-Jackson relation (Faber & Jackson 1976), which encodes the scaling of luminosity with the velocity dispersion of ellipticals. In-between spirals and ellipticals are the lenticular galaxies, which are essentially quenched galaxies with a dominating spherical component and an old stellar disk. Lenticular and spiral galaxies have a different normalisation in their Tully–Fisher relations, with the amount of stellar rotation in the spirals being larger than for lenticulars.

In the modern view of galaxy evolution, the transformation from disks to ellipticals is discussed in terms of the so-called star formation main sequence, which is a relation between a galaxy’s star formation rate (SFR) and stellar mass ($M_\ast$). Numerous observational studies have established this relation (Noeske et al. 2007; Salim et al. 2007; Elbaz et al. 2011; Speagle et al. 2014; Lee et al. 2015; Tomczak et al. 2016; Kurczynski et al. 2016), which is a power-law with an observed scatter around 0.2–0.3 dex. The normalisation of the relation is declining with time, implying that galaxies in the early Universe were typically forming stars more rapidly than at the present day.

But only a subset of the galaxies follow this main sequence relation. Quenched galaxies, for example, have SFRs that are significantly lower than predicted by the main sequence. On the other hand, there are also starbursts that transform their interstellar gas into stars on unusually short timescales. These galaxies typically have much larger SFRs than predicted by the main sequence (Rodighiero et al. 2011; Sargent et al. 2012). Note, however, that the definition of a starburst is somehow ambiguous, since a relatively gas-poor galaxy can in principle consume its gas on a short timescale (if it is in a bursty mode), but it does not guarantee that the galaxy is more star-forming than a normal main sequence system of similar mass, simply because of the small absolute amount of gas available for star formation. The galaxies with a much larger SFR than predicted by the main sequence are therefore only a subset of all the galaxies consuming their gas in a bursty mode (for
In this paper we refer to galaxies with a SFR well above what is predicted by the main sequence as starbursts. In our companion paper, Sparre & Springel 2016, we studied the gas transformations of galaxies in large-scale cosmological simulations, such as Illustris (Vogelsberger et al. 2014), EAGLE (Schaye et al. 2015), Crain et al. 2015, MassiveBlack-II (Khandai et al. 2015) and Horizon-AGN (Volonteri et al. 2016; Kaviraj et al. 2017). Simulations of this kind have made it possible to study a diverse set of phenomena, for example the formation and evolution of massive compact galaxies at \( z = 2 \) (Wellons et al. 2015; Furlong et al. 2017; Wellons et al. 2016), the bimodal surface brightness distributions at \( z = 0 \) (Snyder et al. 2015), or the merger rate of galaxies (Rodriguez-Gomez et al. 2015). A limitation of these simulations is that they do not have the resolution to accurately capture starbursting gas that appears in galaxies (Sparre et al. 2015). For resolving such starbursting gas in merger-induced starbursts (for the galaxy formation model of Illustris) a \( \sim 10 \) or \( 40 \) times better mass resolution is necessary (Sparre & Springel 2016). Other numerical implementations of star formation may require an even higher resolution to fully resolve the star-bursting gas (Renaud et al. 2014).

To reliably model the physical processes in major mergers it is therefore necessary to perform simulations with increased resolution compared to Illustris. In this paper we study the transformation of stellar morphology with a suite of major merger simulations in a zoom setup where the resolution is indeed much higher, allowing in particular a better representation of the starburst regions (and hence also of the black hole feedback). These simulations are fully cosmological, which means that the circumbulge gas and processes such as gas-fueling in the post-merger stage are included in a self-consistent way, as prescribed by the \( \Lambda \) CDM paradigm. Our suite of major mergers is therefore ideal to test whether the simulations are consistent with the observed galaxy evolution scenario, and to make new predictions for galaxies in the real universe.

The aim of the paper is to analyse the detailed stellar morphology of cosmological merger remnants, and to check whether these are indeed consistent with quenched ellipticals (which would be in line with simple interpretations of the main sequence evolution scenario), or whether some of them remain spiral galaxies, which would also not be too surprising given some previous simulations found this unexpected outcome (Springel & Hernquist 2005; Governato et al. 2009; Hopkins et al. 2009). We note that while semi-analytic models of galaxy formation have generally assumed that major merger remnants destroy disks and produce a spheroid, they have also allowed for a regrowth of a disk with time depending on the amount of gas left in the remnant (e.g., Kauffmann et al. 1993). Or study is structured as follows. We first introduce our simulations in Section 2. In Section 3 we study both the \( z = 0 \) morphology of the merger remnants, and the evolution of the stellar disks. We will among other things see how major mergers affect the stellar morphology by comparing merger simulations with galaxies of similar mass but with a more quiescent evolutionary history (from the Auriga simulation suite: Grand et al. 2017). In Section 5, we perform additional simulations with stronger AGN feedback to study how this affects the merger remnants. Finally, we give a discussion of our results in Section 4 and present our conclusions in Section 5.

1 In our companion paper, Sparre & Springel 2016 we studied the gas consumption timescales of major mergers, where we hence used a different starburst definition.
The width of each panel is 40 kpc. A disk is not clearly revealed in the image of 1526-3 (the off-center distribution of recently formed blue stars are caused by an accreted star-forming galaxy).

four different mergers occurring at $0.5 < z < 1$, with stellar mass ratios of the merging galaxies ranging from 1.00 to 1.51. The $z = 0$ stellar masses are in the range $10^{10.63} < M_\star / M_\odot < 10^{11.64}$, and the halos have virial masses $10^{12.00} < M_{200} / M_\odot < 10^{12.27}$.

These galaxies were selected by analysing the merger trees of Illustris (Rodriguez-Gomez et al. 2015). For an initial selection we picked out the $z = 0$ galaxies with merger trees obeying the following criteria:

- The main $z = 0$ galaxy has a stellar mass of $10^{10.5} < M_\star / M_\odot < 10^{11.0}$.
- At $z = 1$ exactly two galaxies with a stellar mass ratio in the range, $0.80 < \mu < 1.25$, are present in the merger tree.
- At $z = 0.2$ and $z = 0.5$ only one massive galaxy is present in the merger tree, i.e. if $M_1$ is the stellar mass of the main progenitor, then no other galaxy from the merger tree has $M_2 > M_1/3$ at any of these two redshifts. This criterion makes sure that the galaxy has time to relax until $z = 0$.
- The $z = 0$ dark matter mass bound to the central galaxy should be larger than half of the $M_{200}$-value of the halo in which the galaxy resides. This ensures that the $z = 0$ galaxy is dominating the halo, and that the galaxy is isolated.

With these selection criteria we obtain candidates that undergo a major merger between $z = 1$ and $z = 0.5$ and furthermore evolve relatively isolated between $z = 0.5$ and $z = 0$. Furthermore, the $z = 0$ stellar masses and halo masses are comparable to that of the Galaxy. These selection criteria yielded a total of 14 merger candidates from the Illustris simulation box. We randomly selected four of these 14 galaxies to arrive at our current sample of mergers.

Each of the four merger systems was simulated at three different resolutions, with ‘zoom factors’ of 1, 2 and 3, corresponding to mass resolutions factors of 1.4, 11.4 and 38.5 times finer than in the Illustris simulation. The maximum physical softening is 0.64, 0.32 and 0.21 kpc, respectively. To carry out the simulations we used a zoom-in technique, where the spatial resolution is high in the vicinity of the galaxy of interest and progressively lower further away. This makes it possible to carry out fully self-consistent cosmological simulations of individual galaxies at a small fraction of the computational cost of the Illustris simulation.

The galaxy formation model, which is closely based on Marinacci et al. (2014) and Vogelsberger et al. (2013), is the same as used for the Auriga simulation project (Grand et al. 2017). The hydrodynamical equations are solved with the moving-mesh approach used by the AREPO code (Springel 2010), which ensures an accurate treatment of shocks and fluid instabilities in cosmological environments as well as low advection errors (Bauer & Springel 2012; Sijacki et al. 2012; Karen et al. 2012; Vogelsberger et al. 2012; Torrey et al. 2012; Bird et al. 2013; Nelson et al. 2013; Hayward et al. 2014). For details about the merger simulations and the galaxy formation model, we refer to Sparre & Springel (2016).

Merger trees were constructed by considering the stellar population particles contained in the two most massive halos at $z = 0.93$, which is before the major merger occurs in all simulations. At each snapshot, we determine the galaxies which have most stars in common with each of the selected galaxies at $z = 0.93$. With this method, we track two progenitor branches before the merger. After the merger, the two $z = 0.93$ progenitors have the same descendant galaxy.
2.1 Setup for runs with stronger AGN feedback

For each of our simulations with a ‘zoom factor’ of 2 we have performed additional simulations where the AGN feedback is gradually increased. In our AGN feedback model, which relies on the model of Nulsen & Fabian (2000), the black hole accretion rate is inversely proportional to the cooling function, \( \Lambda(Z,T) \), of the gas in a galaxy. The temperature \( T \) is here set to the virial temperature of a halo, and the metallicity, \( Z \), is a model parameter. Decreasing the metallicity will increase the strength of the black hole accretion rate and also make AGN feedback stronger. In our set of simulations with stronger AGN feedback we set the metallicity in the cooling function to 1.0, 0.4, 0.2 and 0.1 \( Z_\odot \). We refer to these runs as having normal, semi-strong, strong and very strong AGN feedback, respectively.

3 STELLAR MORPHOLOGY OF THE MERGER REMNANTS

Morphological classification of galaxies can be done in several ways. Traditionally, galaxy types have been distinguished based on their visual appearance (Hubble 1926). A more rigid morphological characterization method, which is especially well suited for observational applications, is based on surface brightness fitting (described in e.g. Peng et al. 2002, 2010). In galaxy simulations, where information for the coordinates and velocities are known, a disk–bulge decomposition can usually be done based on the angular momentum of each stellar population particle (Scannapieco et al. 2009). In the following, we classify the simulated galaxies according to each of these methods, and study how the disk evolution connects to the colours and quenching properties of the galaxies.

3.1 Visual inspection of the merger remnants

As a first step in studying the stellar morphology we create a composite \( U-, B- \) and \( K- \) band image of the stellar light distribution of the stars in our \( z = 0 \) merger remnants, see Figure [1]. This allows us to visually classify the morphology of the galaxies. We show the galaxies in a face-on (upper panels) and an edge-on projection (lower panels) for each of our high-resolution simulations with a ‘zoom factor’ equal to 3. The projections are determined based on the moment-of-inertia tensor of the stars in a galaxy. The figure reveals that two of our four major merger remnants (1349-3 and 1605-3) have a well-established disk containing young, recently formed stars. The edge-on projection of 1349-3 also reveals the presence of spiral arms, implying that spiral structure is not only present in galaxies with a quiescent merger history (as for the simulation studied in Governato et al. 2009). For the 1330-3 galaxy, the edge-on projection also reveals a thin disk, and the head-on projection furthermore reveals a bar. For 1526-3, the images show no signs of a star-forming disk, but rather a red spherical component surrounded by some recently formed (blue) stars with an irregular distribution. Based on the images we conclude that our major merger remnants fall into the category of either disk, bar or irregular galaxies.

3.2 Surface density profiles

The above considerations are made entirely based on images showing the stellar light distributions in different bands. An observationally motivated quantification of the morphology for the \( z = 0 \) merger remnants is presented in Figure [2], which shows the stellar mass surface density (black circles) in a face-on projection of the inner 25 kpc of the galaxies. Each profile is modeled with a contribution from a Sérsic profile (red dashed line) and an exponentially decaying profile (red dotted line). These components describe the contribution from the bulge and the disk, respectively. The sum of the two components is shown by the thick blue line. We have simultaneously fitted the parameters describing these profiles, and based on the stellar mass in each component we derive the mass fraction of stars in the disk (the ‘disk fraction’), or simply just \( D/T \), which is listed in each panel. Also listed is the disk scale length \( (R_d) \), where the surface density of the disk declines by a factor of e. When performing the fits we only include stars within 15% of \( R_{200} \).

The fits yield disk fractions of 30% – 59%. The spherically symmetric bulge component dominates the inner 5 kpc of all the galaxies, and at larger radii the disk is dominant. These galaxies thus have more massive and more radially distributed bulges than the Milky Way. The disk scale radii \( (R_d) \) are 5–6 kpc, which is \( \sim 3 \) times larger than observed for the Milky Way (2.15 ± 0.14 kpc; Bovy & Rix 2013). Based on these characteristics the merger remnants differ from classical disk galaxies due to their dominating bulges. It is, however, interesting that these merger remnants still exhibit visible disks in the images (Figure [1]) and in the surface density profiles (Figure [2]).

Governato et al. (2009) also studied the evolution of the surface brightness profile of galaxies undergoing a cosmological merger. Their merger remnant ends up with a \( z = 0 \) disk dominating over the bulge\(^{3}\). We are therefore not the first to suggest that remnants of major mergers can have significant disks. Their disk fraction is as high as we find for 1330-3 (the bar galaxy). We regard our merger remnants to have disk fractions consistent with the galaxy from Governato et al. (2009). We note that the physical setup of our simulations is very different, however.

The best fit parameters from our surface brightness modeling of our \( z = 0 \) merger remnants are compared to the 30 galaxies of the Auriga simulation in Figure [3]. The Auriga simulation suite uses the exact same galaxy formation model as in our merger simulations, and the only physical difference is the initial conditions. The Auriga galaxies have \( z = 0 \) halo masses of around \( M_{200} \approx 10^{12} M_\odot \), and the halos are selected to be isolated at \( z = 0 \). No further constraints are enforced in their initial condition selection. The galaxies show a huge variety of mass accretion histories with some galaxies undergoing major mergers and other halos having a more quiescent evolution. The average properties of the galaxies from Auriga therefore represents what is expected for normal star-forming galaxies. In Grand et al. (2017) it was indeed also found that the galaxies from the Auriga simulation had stellar disk profiles and rotation curves consistent with observations.

The parameters we compare are the disk fraction, the bulge effective radius \( (R_{el}) \), which is the half-mass-radius of the bulge\(^{2}\) and \( R_d \). The disk fractions for the merger remnants are relatively similar to those from the Auriga sample. This supports the claim

2 Our standard choice in this paper is to analyse stars within 10% of \( R_{200} \) when we determine disk properties. When fitting surface brightness profiles we, however, allow for an exception and include stars within 15% of \( R_{200} \). This is done to better fit the scale radius of the disk, which is most easily determined in the radius-range of 8–15% \( R_{200} \). If we only included stars within 10% \( R_{200} \) we would get unreasonably steep disk profiles, and also too high disk fractions in our modelling.

3 For various definitions they find disk fractions in the range, 0.53–0.67.
3.3 The mass fraction of disk stars from a kinematical disc–bulge decomposition

To introduce a more physical estimator of a galaxy’s morphology we calculate the fraction of stars in the disk and bulge based on a kinematical disc–bulge decomposition procedure described in Marinacci et al. (2014). The idea behind this method is to compare the angular momentum of each star around the galaxy’s rotation axis to the angular momentum of a circular orbit. First, we diagonalise the moment of inertia tensor of the stellar distribution and determine the eigenvector with the largest absolute value of the angular momentum. The coordinate system is then rotated so the z-axis is along this eigenvector. We define a circularity parameter based on the angular momentum of a circular orbit (as in Scannapieco et al. 2009) at a given distance from the center of a galaxy.

\[ \epsilon \equiv \frac{j_z}{\sqrt{GM(<r)r}}. \]  

Here \( j_z \) is a stellar population particle’s specific angular momentum in the z-direction, \( G \) is the gravitational constant, \( r \) is the radius and \( M(<r) \) is the cumulative mass distribution. We then define all stars with \( \epsilon > 0.7 \) to be disk stars, and the remaining stars to be bulge stars. With this definition stars in a counter-rotating disk are not counted as disk stars. We refer to the fraction of stellar mass in the disk as the ‘disk fraction’. In our calculation we only study galaxies within 10% of \( R_{200} \) of the halo containing each galaxy.

Figure 4 shows the mass fraction of stars belonging to the disc
as a function of the lookback time. Before the merger the most
massive progenitor (defined as the galaxy with the largest $M_*$ at
$z = 0.93$) is shown in thick blue and the other progenitor is shown
in thin blue. All our simulations show that a major merger has a de-
structive influence on the disk, but a disc fraction of around $\gtrsim 0.25$
again re-established after the merger for all the high-resolution
runs.

For the 1330-3 and 1526-3 galaxies, a disc is regrown within
1-2 Gyr. For the latter simulation the growth of the disc then stops,
and the disk fraction declines. The declining disk fraction at low
lookback time is consistent with Figure 1 where a visual disk is
absent. For the former simulation a dip in the disk fraction occur at
a lookback time of 3 Gyr, and the disk then slowly starts growing
again until $z = 0$. Based on these simulations we see that merger
remnants – with a weakened disc after a merger – can regrow a stel-
lar disk (with disk fractions up to 0.45) before $z = 0$. For 1605-3,
the $z = 0$ galaxy has a disk fraction comparable to the value at the
end of the merger (see time marked with a ⊿ symbol). This constant
disk fraction could either be a result of very little star formation
occurring in the galaxy, or it could be a result of a self-regulated
galaxy that forms stars at the same rate as stellar mass is removed
from the disk.

Only for the 1330-X simulations we see a similar evolution
of the disk fraction for the three resolution levels, implying that
the disk fraction is converged in this case. In the other simula-
tions (1349-X, 1526-X and 1605-X) increasing the resolution in-
creases the strength of the disk significantly, and we have thus not
established that the evolution of the disk fraction is converged in
the high-resolution runs. The resolution at which a simulation con-
verges depends on the details of the evolution history of the galaxy
(the same is seen in the Auriga simulation, see Fig. 23 in Grand
et al. 2017).
Figure 5. The age of the main progenitor’s disk as a function of lookback time. For each snapshot we identify the disk stars with $\epsilon > 0.7$, and measure their mean age at the given cosmic epoch. The two arrows show tracks of 1) a galaxy without ongoing star formation in the disk (SFR = 0) containing only old stars and 2) a constant SFR in the disk throughout the galaxy’s lifetime. One of our high-resolution simulations (1526-3) follows a track with no active star formation in the disk, and the three others show signs of recently formed disk stars.

Figure 6. The evolution of the $g - r$ SDSS colour for the simulated galaxies. In the time-interval where the mergers occur ($0.5 < z < 1$), the colour reaches a minimum in all the galaxies. This minimum is caused by the many young stars formed in the merger. In the post-merger evolution the galaxies become redder. The 1330-3 galaxy ends up with a $z = 0$ colour similar to the mean colour of galaxies in Illustris, implying that merger remnants are not necessarily redder than normal star-forming galaxies.
The disk properties of major merger remnants have also been studied in a set of idealised simulations based on semi-analytic merger models (the method is described in Moster et al. 2014). Fontanot et al. (2015) found this setup to reduce the bulge formation efficiency compared to semi-analytical galaxy formation models (De Lucia & Blaizot 2007; Somerville et al. 2008; Lo Faro et al. 2009; Porter et al. 2014), and this setup also makes it possible to examine the role of a transfer of hot gas to the cold disk in the merger process (Karman et al. 2015; Kannan et al. 2015). The disk fraction of two major merger remnants from this setup to be 0.22 and 0.33 (for galaxies 18989 and 215240 in their sample, respectively), which is in good agreement with our disc fractions. The results from Kannan et al. (2015) support the conclusion that merger remnants can have star-forming disks.

3.4 Age of the stellar disk and self-regulation

The merger simulations exhibit very different evolution-histories of the disk fraction. In the following we will see how these trends can be related to whether active star formation occurs in the disk. As an indicator of this, we first study the evolution of the mean age of the disk. At each snapshot we select the disk stars (with $\epsilon > 0.7$) of the galaxies having a stellar mass $M_\ast > 10^{9} M_\odot$ (dashed line; instead of lookback time the $x$-axis shows the probability density). The colour is calculated entirely based on synthesis modeling of the stellar populations in the galaxies. During the major merger, where the starburst occurs, all galaxies get bluer in terms of their $g-r$ colour. The typical minimum value is $g-r \approx 0.1$. After the merger-induced star formation peaks the galaxies settle into a more moderate star formation mode, and the galaxies become redder as time passes. At $z = 0$ there are merger remnants having both blue and red $g-r$ colours. The 1330-X simulations for example all end up near the blue $g-r$ peak of the Illustris galaxies. This reflects the fact that the merger remnants remain actively star forming after the merger.

Contrary to these 1330-X galaxies are runs 1349-3, 1526-3 and 1605-3, which are redder with $g-r > 0.5$ at $z = 0$. This shows that a major merger at $0.5 < z < 1$ most often leaves a $z = 0$ merger remnant with a colour redder than the mean of the galaxy population.

3.6 Starburst and quenching phases diagnosed by the specific SFR

An essential characterisation of a galaxy is whether it is quenched, normal or a starburst. We will here quantify this by examining the specific SFR, SSFR $\equiv SFR/M_\ast$, of the galaxies, see Figure 4. This quantity has been computed based on the star formation rate and stellar mass at each outputted simulation snapshot. We compare the galaxies with the SSFR of main sequence galaxies with $M_\ast = 10^{10} M_\odot$ at $z = 0$ from Illustris (taken from Fig. 2 in Sparre et al. 2015). This corresponds to the normalisation of the star formation main sequence, because the simulated main sequence relation has a slope of $\log(\text{SFR})/\log M_\ast \approx 1$. Also shown is the threshold above which galaxies are characterized as starbursts, and the threshold below which a galaxy is considered quenched. The thresholds are selected to be 0.75 dex away from the mean of the main sequence (i.e. $3\sigma$ away from the main sequence, given that the scatter in Illustris is around 0.25 dex).

First, it is seen that all the galaxies experience a merger-induced SSFR peak at a lookback time between 5 and 7 Gyr. Only one of the high-resolution galaxies (1349-3) gets a SSFR larger than the starburst threshold. Note, however, that we have a snapshot-spacing of 54 Myr during the merger. If we instead of calculating the instantaneous SFR in each snapshot estimate the averaged SFR in 28 Myr intervals (this can be done based on the formation times and initial stellar masses of the stellar population particles in the merger remnant, as done in Fig. 1 in Sparre & Springel 2016 we find that the peak SSFR is increased above the starburst threshold for both 1349-3 and 1605-3. The 1330-3 and 1526-3 simulations never get a SSFR larger than the starburst-threshold, which is not surprising, since dense starbursting gas with short gas consumption timescales never arises in these simulations (unlike for the 1349-3 and 1605-3 simulations), as pointed out in Sparre & Springel 2016).

The merger remnants are not necessarily quenched. The 1330-X and 1526-X runs are for example characterised as main sequence...
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Figure 7. The specific star formation rate, SFR/$M_*$, as a function of time. We compare our galaxies to the star formation main sequence from the Illustris simulation (Sparre et al. 2015), and based on this we define a starburst and quenching threshold as being 0.75 dex above and below, respectively. At $z = 0$ the 1605-3 galaxy is close to being quenched. The same is the case for 1349-3 in the first couple of Gyr after the merger, but at $z = 0$ the specific SFR indicates that it is a normal star-forming galaxy. The two other high-resolution simulations have a specific SFR indicating that they are normal galaxies belonging to the star formation main sequence. The behaviour challenges the simple galaxy evolution picture, where the feedback followed by a merger-induced starburst automatically quenches galaxies.

Figure 8. The evolution of the specific star formation rate for the various runs with gradually increased strength of the AGN feedback (as described in Section 2.1). Common for all runs is that the pre-merger stage ($z > 1$) is not strongly affected by the strength of the AGN feedback, and furthermore, the pre-merger galaxies are classified as star-forming galaxies. In the post-merger galaxies at $z < 0.5$ the situation is very different. Here the galaxies with very strong AGN feedback in some cases have a 10 times lower SSFR than for the runs with normal AGN feedback. We also see that the runs with very strong AGN feedback in all the simulations are able to quench a galaxy a fraction of the time after the merger. 1330-2 and 1526-2 are for example quenched at $z = 0$, and 1605-2 and 1349-2 go through a quenched phase (at lookback times of 2.5 Gyr)

3.7 Simulations with strong AGN feedback

A remarkable result of Section 3.6 is that merger remnants in our simulations rarely quench. In this section we will study how robust this result is to changes in the strength of the AGN feedback. In Figure 8 we show the evolution of the specific star formation rate for the various runs with gradually increased strength of the AGN feedback (as described in Section 2.1). Common for all runs is that the pre-merger stage ($z > 1$) is not strongly affected by the strength of the AGN feedback, and furthermore, the pre-merger galaxies are classified as star-forming galaxies. In the post-merger galaxies at $z < 0.5$ the situation is very different. Here the galaxies with very strong AGN feedback in some cases have a 10 times lower SSFR than for the runs with normal AGN feedback. We also see that the runs with very strong AGN feedback in all the simulations are able to quench a galaxy a fraction of the time after the merger. 1330-2 and 1526-2 are for example quenched at $z = 0$, and 1605-2 and 1349-2 go through a quenched phase (at lookback times of 2.5 Gyr).
4 DISCUSSION

The $z = 0$ properties of our high-resolution (with normal AGN feedback) major merger remnants are summarised in Table 1. The different simulations of major mergers at $z = 0.5 - 1$ give very diverse $z = 0$ galaxies. At one end of the spectrum is the blue star-forming barred galaxy (1330-3) with a disk that accounts for 43% of the stellar mass in the galaxy. The other extreme is 1605-3 which is close to being quenched and has a galaxy colour characterising it as a green-valley galaxy. It furthermore has a low disk fraction of 24%, but despite of this low value, the disk is still clearly visible in the mock-image of the galaxy. In-between these two extreme galaxies are the other galaxies (1349-3 and 1526-3), which have blue-green colours, and are slightly less star-forming than the mean of the star formation main sequence. Their morphologies, as revealed by the optical images, show an ordered disk and a bulge surrounded by an irregular star-forming structure, respectively. For the runs with very strong blackhole feedback, quenching occurred in all galaxies, but two of the galaxies were also rejuvenated before $z = 0$. Within the framework of our galaxy formation model, quenching of merger remnants is therefore a possibility, even though our model tends to prefer the formation of a star-forming disk.

The idea that major mergers might evolve into star-forming galaxies is very different to the standard picture based on idealised simulations, where the AGN feedback associated with the merger quenches the remnant (Di Matteo et al. 2005; Springel et al. 2005; Hopkins et al. 2006). The reason for this fundamentally different behaviour is that our cosmological simulation setup allows gas accretion in the post-merger stage, unlike previous idealised merger simulations.

4.1 The role of the AGN feedback model

In this paper we have only studied the role of black hole feedback by varying the parameters of our particular model. Of course, as the physics of blackhole feedback is poorly understood, other models might lead to different results. For example, Pontzen et al. (2017).
dark matter halo masses are not massive enough for halo quenching to occur, even though strong feedback processes are responsible for decreasing the SFR.

A result from our analysis is that a quenched galaxy can transition into a star-forming phase lasting for a few hundreds of Myr (as we saw for 1349-3 in Figure 7), and then either remain star-forming for the rest of its lifetime or quench again. Such a scenario is consistent with the evolutionary path outlined by Zolotov et al. (2015) and Tacchella et al. (2016), where cosmic streams can ignite star formation in galaxies. In the FIRE simulation suite (Hopkins et al. 2014) a similar re-ignition is also seen as a result of stellar feedback (Sparre et al. 2017), and analytical considerations support the same process (Hayward & Hopkins 2017). It is thus well motivated by theoretical considerations that a quenched galaxies can evolve back into the star-forming population. Various groups have studied whether filamentary accretion streams can potentially lead to re-ignition-events (Birnboim & Dekel 2003; Kereš et al. 2005; Nelson et al. 2015), and even though past hydrodynamical methods likely overstated the importance of such streams (Nelson et al. 2015), it remains likely that at least a fraction of galaxies get fed through such events.

4.3 Disk fractions of galaxies from Illustris

A natural extension of this project would be to see how merger remnants behave in a larger set of simulations. One possibility to study this would be to simply run more simulations of major mergers with a similar setup as presented in this paper. Another possibility is to study the behaviour of galaxies in a large-scale simulation. This would provide much larger samples, but as we have shown a coarser resolution leads to slightly lower disk fractions than in our high-resolution zoom-setup. Despite of this the lessons learned from such large-scale simulations should be quite still useful.

Rodriguez-Gomez et al. (2017) did such an analysis, where they used galaxies from the Illustris simulation to study how the disk fraction depends on the mass fraction of stars formed ex-situ. Here the ex-situ fraction is a proxy for the importance of mergers in the assembly history of a galaxy. For $10^{11} \lesssim M_*/M_\odot \lesssim 10^{12}$, the two quantities are anti-correlated implying that mergers destroy disks. Their findings suggest that this anti-correlation is caused by a decreased gas fraction of the merging galaxies. For galaxies with lower stellar masses of $10^{10} \lesssim M_*/M_\odot \lesssim 10^{11}$, the anti-correlation between disk fraction and ex-situ fraction is less pronounced, implying that mergers do not play a significant role in destroying stellar disks; for example several galaxies with ex-situ fractions of $\approx 0.5$ have significant disk components with mass fractions of $\approx 0.5$. This is consistent with our finding that merger remnants in this mass-range might evolve into star-forming disk galaxies.

5 Conclusion

In this work, we have continued our study of fully self-consistent cosmological high-resolution hydrodynamical simulations of major mergers. A companion paper showed how starbursting gas appears when the mass resolution is made 10-40 times finer than in the Illustris simulation. This suggests a solution to the problem of too few starburst galaxies in the Illustris simulation.

In the present paper, we study how morphological transformations and quenching occur in mergers. Our findings challenge the orthodox idea that a major merger automatically leads to a
quenched elliptical. Our main results can be summarised as follows:

- Visual inspection, surface-density modeling and a kinematical disk-bulge decomposition reveal that the $z = 0$ remnant of a major merger (simulated at our highest resolution) that happened at $z = 0.5-1$ can easily have a star-forming disk. Also, the colours of our galaxies classify them as blue–green galaxies. This challenges the conventional idea that the black hole feedback associated with a merger-induced starburst quenches galaxies. Idealised simulations have previously shown that a major merger remnant is not necessarily a quenched elliptical, but we here show the same result in a set of cosmological self-consistent galaxy formation simulations.
- In a set of runs with stronger AGN feedback we show that merger-induced quenching occurs if the feedback is made sufficiently strong. For our runs with the strongest feedback, all galaxies go through a quenched phase, but only two of the four merger remnants have a quenched elliptical, but we here show the same result in a set of cosmological self-consistent galaxy formation simulations.
- In the majority of our simulations with normal strength of the AGN feedback, major mergers have a destructive effect on the disk, since the pre-merger galaxies have larger disk fractions than the merger remnant. It does, however, not prevent merger remnants from regrowing a new disk before $z = 0$.
- The bulges of the $z = 0$ merger remnants have effective radii which are on average significantly larger than galaxies with a more quiescent accretion history (from the Auriga galaxy simulation suite). The distribution of disk fractions and disk scale lengths are similar between the two simulation samples, again implying that major mergers do not necessarily need to be the main mechanism for driving galaxy transformations.

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APPENDIX A: EVOLUTION HISTORY OF THE MERGERS

The time-evolution of the high-resolution mergers is shown in Figure 1. At $z = 0.71$, seven galaxies are visible in the image of 1349-3. This explains why the two most-massive progenitors of this merger remnant approach each other faster than an $E = 0$ orbit (see Sparre & Springel 2016). In the other mergers only two massive progenitors are present in the pre-merger snapshots.

1330-3 undergoes several minor mergers at low redshift; at $z = 0.41$, $z = 0.27$ and $z = 0.04$ accreted satellites are revealed in the figure. This is accompanied by active star formation in the merger remnant. Figure 6, for example, reveals that this galaxy maintains a blue colour after the merger, and Figure 7 shows that it is slightly above the mean of the star formation main sequence. The gas accretion and tidal disruptions caused by such minor mergers is likely what drives the formation of the bar revealed in the $z = 0$ image of the galaxy (see Figure 1).
| $z = 0.81$ | $z = 0.76$ | $z = 0.71$ | $z = 0.66$ | $z = 0.56$ | $z = 0.41$ | $z = 0.27$ | $z = 0.04$ |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| ![1330-3](image1) | ![1330-3](image2) | ![1330-3](image3) | ![1330-3](image4) | ![1330-3](image5) | ![1330-3](image6) | ![1330-3](image7) |
| ![1349-3](image1) | ![1349-3](image2) | ![1349-3](image3) | ![1349-3](image4) | ![1349-3](image5) | ![1349-3](image6) | ![1349-3](image7) |
| ![1526-3](image1) | ![1526-3](image2) | ![1526-3](image3) | ![1526-3](image4) | ![1526-3](image5) | ![1526-3](image6) | ![1526-3](image7) |
| ![1605-3](image1) | ![1605-3](image2) | ![1605-3](image3) | ![1605-3](image4) | ![1605-3](image5) | ![1605-3](image6) | ![1605-3](image7) |

**Figure 1.** The time-evolution of the stellar components of the four high-resolution galaxies. The colour coding is the same as in Figure 1. Each panel has a width of 80 kpc.