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# Formation, evolution and properties of isolated field elliptical galaxies

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## ABSTRACT

We study the properties, evolution and formation mechanisms of isolated field elliptical (IfE) galaxies. We create a 'mock' catalogue of IfE galaxies from the Millennium Simulation Galaxy Catalogue, and trace their merging histories. The formation, identity and assembly redshifts of simulated isolated and non-isolated elliptical galaxies are studied and compared. Observational and numerical data are used to compare age, mass and the colour–magnitude relation. Our results, based on simulation data, show that almost 7 per cent of all elliptical galaxies brighter than −19 mag in *B* band can be classified as IfE galaxies. Results also show that isolated elliptical galaxies have a rather flat luminosity function; a number density of $\sim 3 \times 10^{-6}\,h^3\,\mathrm{Mpc^{-3}\,mag^{-1}}$, throughout their *B*-band magnitudes. IfE galaxies show bluer colours than non-isolated elliptical galaxies and they appear younger, in a statistical sense, according to their mass-weighted age. IfE galaxies also form and assemble at lower redshifts compared to non-isolated elliptical galaxies. About 46 per cent of IfE galaxies have undergone at least one major merging event in their formation history, while the same fraction is only ∼33 per cent for non-isolated ellipticals. Almost all (∼98 per cent) isolated elliptical galaxies show merging activity during their evolution, pointing towards the importance of mergers in the formation of IfE galaxies. The mean time of the last major merging is at $z \sim 0.6$ or 6 Gyr ago for isolated ellipticals, while non-isolated ellipticals experience their last major merging significantly earlier at $z \sim 1.1$ or 8 Gyr ago. After inspecting merger trees of simulated IfE galaxies, we conclude that three different, yet typical, formation mechanisms can be identified: solitude, coupling and cannibalism. Our results also predict a previously unobserved population of blue, dim and light galaxies that fulfil observational criteria to be classified as IfE galaxies. This separate population comprises ∼26 per cent of all IfEs.

**Key words:** methods: numerical – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – large-scale structure of Universe.

## 1 INTRODUCTION

Galaxies reside in three different environments: clusters, groups and voids. The majority, more than 50 per cent, of galaxies are found in groups and clusters (Humason, Mayall & Sandage 1956; Huchra & Geller 1982; Geller & Huchra 1983; Nolthenius & White 1987; Ramella et al. 2002). This is particularly true for elliptical galaxies, as the morphology–density relation has shown (Oemler 1974; Dressler 1980). The merger hypothesis (Toomre & Toomre 1972) suggests that the product of the merger of two spiral galaxies will be an elliptical galaxy. If this holds, then the probability to find an elliptical galaxy grows in environments with high densities and low velocity dispersions, e.g. groups of galaxies. Therefore, local environment is thought to play a crucial role in galaxy formation and evolution (e.g. Farouki & Shapiro 1981; Balogh et al. 1999; Kauffmann et al. 1999; Lemson & Kauffmann 1999; Moore et al. 1999).

In observations, it is relatively easy to study cluster and group galaxies. Because of this and the potential formation mechanism of elliptical galaxies, it is not surprising that most studied ellipticals are found in clusters and groups. Therefore, the detailed properties of isolated field elliptical (IfE) galaxies have not been extensively studied or very well understood; there are only a few observational studies and the surveys are small. Moreover, the formation mechanisms and evolutionary paths of these 'lonely' elliptical galaxies are not yet well understood.

In the past two decades, several observational projects have identified and studied the properties of IfE galaxies (e.g. Reda et al.

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2004; Smith, Martinez & Graham 2004; Hernández-Toledo et al. 2008; Norberg, Frenk & Cole 2008, and references therein). In many studies, based on observational data, different possible formation scenarios have been proposed (see e.g. Mulchaey & Zabludoff 1999; Reda et al. 2004, 2007), ranging from clumpy collapse at an early epoch to multiple merging events. Also equal-mass mergers of two massive galaxies or collapsed groups have been suggested. Theoretical studies predict that isolated ellipticals are formed in relatively recent mergers of spiral galaxy pairs, while large isolated ellipticals may be the result of merging of a small group of galaxies (e.g. Jones, Ponman & Forbes 2000; D'Onghia et al. 2005).

Observational studies have shown that several IfEs reveal a number of features such as tidal tails, dust, shells, discy and boxy isophotes and rapidly rotating discs (e.g. Reduzzi, Longhetti & Rampazzo 1996; Reda et al. 2004; Reda, Forbes & Hau 2005; Hau & Forbes 2006; Hernández-Toledo et al. 2008) indicating recent merger and/or accretion events. Hernández-Toledo et al. (2008) concluded that at least 78 per cent of their isolated elliptical galaxies show some kind of morphological distortion, and suggested that these galaxies suffered late dry mergers. Reda et al. (2004, 2005) compiled a sample of 36 candidates of isolated early-type galaxies and studied their properties, and concluded that a major merger of two massive galaxies could explain most observed features. They also concluded that a collapsed poor group of a few galaxies is a possible formation scenario. However, Marcum, Aars & Fanelli (2004) studied a similar sample of isolated early-type galaxies, and concluded that isolated systems are underluminous by at least a magnitude compared with objects identified as merged group remnants. Reda et al. (2007) concluded that mergers at different redshifts of progenitors of different mass ratios and gas fractions are needed to reproduce the observed properties of IfEs.

However, some IfEs have not shown any evidence of recent merging activity (e.g. Aars, Marcum & Fanelli 2001; Denicoló et al. 2005). Aars et al. (2001), who studied a sample of nine isolated elliptical galaxies, identified five galaxies that were located in environments similar to those of loose groups, while the environments of the remaining four galaxies were confirmed to be on low density. All galaxies showed smooth, azimuthally symmetric profiles, with no obvious indications of dust lanes, nascent spiral structure or star-forming regions. It is possible that the merging events have happened in distant past, and all signs of merging events have been wiped out. Mihos (1995) found out, by using a combination of numerical simulation and synthesized *Hubble Space Telescope* Wide Field Planetary Camera 2 images, that merger remnants appear morphologically indistinguishable from a 'typical' elliptical $\leq$1 Gyr after the galaxies merged, while Combes et al. (1995) estimated from numerical simulations that the time might be even less than 0.5 Gyr. Indeed, these times are very short in time-scales of galaxy evolution, making it difficult to find observational evidence to back up formation via merging events. On the other hand, it is equally possible that some or even all of these galaxies have initially formed in underdense regions and developed quietly without any major mergers.

Observational studies of IfE galaxies use similar isolation criteria as optical studies of fossil groups. Both classes show a large magnitude gap between the first- and the second-ranked galaxy. However, there is no criterion for IfEs that would require a presence of extended X-ray emission, as in case of fossil groups. Additionally, fossil groups are not necessarily found in low-density environments (von Benda-Beckmann et al. 2008) like IfEs. Despite the differences, it is possible that the formation mechanisms of the two systems are similar or related to each other. Therefore, it is interesting to compare IfE galaxies and fossil groups, and see if these systems share a common origin.

In this paper, we use the Millennium Simulation (MS; Springel et al. 2005) together with a semi-analytical model (Lucia & Blaizot 2007) of galaxy formation within dark matter haloes to identify IfE galaxies, to study their properties and formation history, and to compare them with observational data. This paper is organized as follows. In Section 2, we discuss the MS, the semi-analytical galaxy catalogue used and sample selection. In Section 3, we compare the properties of the Millennium IfEs with observations, while in Section 4 we show that the IfEs form a population that is different from the regular ellipticals. In Section 5, we concentrate on evolution of IfEs and possible formation mechanisms, while in Section 6 we discuss our results, the formation of field elliptical galaxies and their possible connection to fossil groups. Finally, in Section 7 we summarize our results and draw the conclusions. Throughout this paper, we adopt a parametrized Hubble constant: $H_0 = 100\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

## 2 SAMPLE SELECTION

### 2.1 The Millennium Simulation

We use a simulation that covers a big enough spatial volume and has a sufficient mass resolution – the dark matter only MS (Springel et al. 2005), a $2160^3$-particle model of a comoving cube of size $500\,h^{-1}$ Mpc, on top of which a publicly available semi-analytical galaxy model (Lucia & Blaizot 2007) has been constructed. The cosmological parameters used in the MS were: $\Omega_\mathrm{m} = \Omega_\mathrm{dm} + \Omega_\mathrm{b} = 0.25$, $\Omega_\mathrm{b} = 0.045$, $h = 0.73$, $\Omega_\Lambda = 0.75$, $n = 1$ and $\sigma_8 = 0.9$, where the Hubble constant is characterized as $100\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (for detailed description of the MS, see Springel et al. 2005). These values were inferred from the first-year *Wilkinson Microwave Anisotropy Probe* observations (Spergel et al. 2003).

The galaxy and dark matter halo formation modelling of the MS data is based on merger trees, built from 64 individual snapshots. From these time-slices, merger trees are built by combining the information of all dark matter haloes found at any given output time. This enables us to trace the formation history and growth of haloes and subhaloes through time. Properties of galaxies in the MS data are obtained by using semi-analytic galaxy formation models (SAMs), where star formation and its regulation by feedback processes is parametrized in terms of analytical physical models. The semi-analytical galaxy catalogue we use contains about nine million galaxies at $z = 0$ down to a limiting absolute magnitude of $M_R - 5\log h = -16.6$. A detailed description of the creation of the MS Galaxy Catalogue, used in this study, can be found in Lucia & Blaizot (2007).

Semi-analytical galaxy formation models are known to be less than perfect. There are several free parameters in each SAM that all have a different impact on the properties of galaxies. The free parameters usually control the feedback effects and cooling of hot gas. The SAM also controls how gas is stripped from a galaxy when it approaches another galaxy, and possible starburst events. The physics of these processes described is not well known. However, in general, SAMs can reproduce the observed galaxy luminosity function and other statistics well. As our study is statistical by nature, it is likely that the SAM used for the MS Galaxy Catalogue is accurate enough to predict the properties of IfEs and their evolution and formation history.

The MS Galaxy Catalogue does not predict galaxy morphologies. To assign a morphology for every galaxy, we use their bulge-to-disc ratios. Simien & de Vaucouleurs (1986) found a correlation between the $B$-band bulge-to-disc ratio and the Hubble type $T$ of galaxies from observations. The mean relation may be written:

$$\langle \Delta m(T) \rangle = 0.324x(T) - 0.054x(T)^2 + 0.0047x(T)^3, \quad (1)$$

where $\Delta m(T)$ is the difference between the bulge magnitude and the total magnitude and $x(T) = T + 5$. We classify galaxies with $T < -2.5$ as ellipticals, those with $-2.5 < T < 0.92$ as S0s, and those with $T > 0.92$ as spirals and irregulars. Galaxies without any bulge are classified as type $T = 9$.

### 2.2 Selection of IfEs

There are a few different selection criteria that are being used to define IfE galaxies in observations (see e.g. Colbert, Mulchaey & Zabludoff 2001; Marcum et al. 2004; Reda et al. 2004; Collobert et al. 2006). Despite the differences in selection criteria, all studies identifying IfEs share a common ideology. In general, IfEs are defined as elliptical galaxies that do not have nearby optically bright companion galaxies, usually in the $B$ band. This is tested by using an isolation sphere or a cone and choosing a minimum magnitude difference between the brightest and the second brightest galaxy $\Delta m_{12}$ inside the sphere or the cone. In observational studies, the isolation cone is often taken as a circle in the sky that expands in redshift space. Due to peculiar velocities, accurate line-of-sight distances of galaxies are unknown, complicating the identification. Thus, observational studies differ in the numerical values of the isolation criteria. Despite these differences, discussed next, we use all possible available observational data for comparison as the number of observed targets is small. For completeness, we show in Section 3.1 how the number of IfEs depends on the selection criteria.

Colbert et al. (2001) adopted rather strict rules for isolation, as they required that IfEs cannot have catalogued galaxies with known redshifts within a projected radius of $1.0\,h^{-1}$ Mpc and a velocity of $\pm 1000\,\mathrm{km\,s^{-1}}$, while for the morphology of the IfEs they required Hubble types $T \leq -3$. However, as their source of galaxies was the Third Reference Catalogue of Bright Galaxies (de Vaucouleurs et al. 1991), their sample IfEs might have faint companion galaxies due to the incompleteness of the source catalogue. Missing companions do not affect the study of bright isolated galaxies per se, but their environment is affected by the incompleteness and missing companions. Marcum et al. (2004) based their initial sample of IfEs on the same catalogue. They adopted an even stricter criterion in projected radius, a minimum projected physical distance of 2.5 Mpc to any nearest neighbour brighter than $M_V = -16.5$. Reda et al. (2004) used less strict criteria in their study and required only that an IfE candidate has no neighbours with brightness difference $\Delta m_{12} \leq 2.0$ mag, in the $B$ band, within 0.67 Mpc in the plane of sky and $700\,\mathrm{km\,s^{-1}}$ in recession velocity. Further, their elliptical galaxies are also of Hubble type $T \leq -3$.

For the selection of IfEs from the MS, we adopt the criteria used by Smith et al. (2004), similar to those adopted by Reda et al. (2004).We concentrate on galaxies that are incontrovertibly ellipticals and thus adopt a strict morphology limit $T \leq -4$. We further limit the brightness of the IfE candidates with the magnitude cut-off of $M_B \leq -19$. For the isolation criterion, we adopt two isolation spheres with the radii of $0.5\,h^{-1}$ and $1.0\,h^{-1}$ Mpc. Within these isolation spheres, we require that the $B$-band magnitude difference of the first- and second-ranked galaxies $\Delta m_{12}$ must be $\geq$2.2 and $\geq$0.7 mag, respectively. The application of the criteria is illustrated in Smith et al. (2004, fig.1).

Our adopted values of magnitude differences correspond to factors of about 8 and 2 in luminosity for the small and large sphere, respectively. This choice ensures that possible companions are small and light enough not to produce any major perturbations in the gravitational potential of the system. Note that in case of simulations our isolation criteria operate in real space rather than in redshift space. Therefore, we can use isolation spheres rather than cones and we are not plagued by interlopers due to inaccuracies in distance measurements.

### 2.3 Simulated IfEs and control samples

To identify IfE candidates in the MS, we chose five independent cubic volumes inside the simulation box. Initially, we chose each volume to have a side length of $\sim 200\,h^{-1}$ Mpc, while none of the cubes overlap. However, we later limited the volume from where the possible IfE candidates can be identified to have a side length of $195\,h^{-1}$ Mpc. This was done to enable the study of the surroundings of each IfE candidate in the same fashion. Moreover, without the limitation, we could have accidentally identified a field elliptical candidate $\leq 1.0\,h^{-1}$ Mpc from an edge of the box, leading to a possible false identification. The five volumes were chosen to overcome computational issues and for easier study of IfE environment. With five independent volumes it is also possible to make comparisons between the IfEs of each volume.

At first, all galaxies inside each volume are treated as possible IfE candidates. After identifying all candidates with $T \leq -4$ and $M_B \leq -19$, we apply the isolation criteria discussed in the previous section. This produces an initial list of 302 galaxies that fulfil the criteria for IfE galaxies. After compiling the initial list of IfEs, we inspected every galaxy individually, and found that nine candidates were not the main galaxy of the dark matter halo they reside in. Therefore, all galaxies that fulfil the observationally motivated IfE criteria are not the central galaxies of their friends-of-friends dark matter groups. In a strict sense these are not isolated galaxies, as they belong to a dark matter halo containing galaxies more massive and more luminous than the IfE candidate. Therefore, we omit them from the final list of IfEs, which contains 293 galaxies.

We also compile two control samples of elliptical galaxies for comparisons. The first control sample contains in total 4563 elliptical ($T \leq -4$) galaxies brighter than $-19$ in the $B$ band at the redshift $z = 0$ and it is named as Ellipticals (abridged as Es). For the second control sample, called Main Ellipticals (abridged as MEs), we only select galaxies of the first control sample that are the main galaxies of their dark matter haloes. This requirement further limits the Es sample, and we are left with 1209 galaxies in the MEs sample.

#### 2.3.1 Non-standard IfEs

The removed galaxies are interesting from another point of view than regular IfEs, as these nine non-standard IfEs are 'subhalo' galaxies (i.e. satellites of a larger galaxy) and have multiple nearby companions, from 30 to 80 inside the large isolation sphere. Thus, these galaxies are not isolated in galaxy number density, but reside in a cluster rather than in the field. Physically, it is obvious that a satellite galaxy is not the dominant galaxy in its dark matter halo. Since we find these non-standard IfEs, our observationally motivated isolation criteria are not strict enough and the radii of the isolation spheres should be slightly larger to avoid any false identifications. But as the number of non-standard IfEs is small, we can keep the criteria and remove the non-standard galaxies from our final sample, as described above.

The satellite non-standard 'isolated' elliptical galaxies can shed some light on the observational result (Smith et al. 2008) where an IfE galaxy (NGC 1600) was also found to be located off from the dynamical centre of the system. Sivakoff, Sarazin & Carlin (2004) found that the X-ray emission is centred slightly to the north-east of NGC 1600, suggesting that the galaxy is not at the centre of the gravitational potential. The dynamical study and the X-ray observations together suggest that NGC 1600 is surrounded by a massive halo extending out to several hundred kiloparsec. A subhalo galaxy, fulfilling the optical IfE criteria, could explain the observations of NGC 1600. All nine galaxies in our simulations reside inside a large dark matter halo, and in observations would be found to be off from the centre of the potential well, as in the case of NGC 1600. However, a massive and more luminous galaxy than NGC 1600 has not been detected at the centre of the potential well in observations, while this is often the case in simulations. Thus, a more straightforward explanation, where the IfE orbits around the centre of the potential well and therefore seems to be shifted from the centre, seen in X-ray observations, is more plausible. This is in agreement with an X-ray study of another isolated elliptical NGC 4555, which is assumed not to lie in the centre of a massive group-scale dark matter halo (O'Sullivan & Ponman 2004).

## 3 PROPERTIES OF OBSERVED AND SIMULATED FIELD ELLIPTICAL GALAXIES

Below we compare the properties of simulated IfEs with those of the observed IfEs. If these are close enough, it will justify the theoretical study of the formation, evolution and merger histories of IfEs, using the simulated IfE population. Due to the large number of simulated IfEs, we can actually make theoretical predictions for properties, formation mechanisms and evolution of IfEs that can be tested against observational data when the sample of observations is large enough.

In following sections, we use the Kolmogorov–Smirnov (KS) two-sample test to study the maximum deviation between the cumulative distributions of two samples. The null hypothesis of the KS test is that the two samples are from the same population. We give our results as probabilities (p-values) that the difference between the two samples could have arisen by change if they are drawn from the same parent population.

### 3.1 Number of IfEs

The fraction of IfE ($T \le -4$ and $M_B \le -19$ mag) galaxies among all galaxies of any brightness, morphology or dark matter halo status in the MS is merely $\sim 3.5 \times 10^{-3}$ per cent, corresponding to a number density of $\sim 8.0 \times 10^{-6}\, h^3\, \mathrm{Mpc}^{-3}$. This is a very low number density; however, such a straightforward calculation is not totally justified. More meaningful number to consider is the fraction of IfEs among elliptical galaxies. Moreover, our morphology limit ($T \le -4$) for a simulated IfE is very strict, biasing the fraction of elliptical galaxies to significantly lower fractions than observed in the real Universe. Thus, we also identified IfE galaxies with relaxed morphology limit $T < -2.5$ and quote the fractions below.

About 0.19 per cent of all simulated elliptical (now $T < -2.5$) galaxies of any brightness can be identified as IfEs when the criteria of Section 2.2 are adopted for IfEs. If we relax the strict morphology limit of the IfEs and require that IfEs also have $T < -2.5$, the fraction rises to $\sim$0.48 per cent as about 2.5 times more IfEs can be identified. Relaxing the morphology limit will therefore change the number density of IfEs to $\sim 1.9 \times 10^{-5}\, h^3\, \mathrm{Mpc}^{-3}$. When the brightness of the simulated elliptical galaxies and their morphologies are limited to $M_B \le -19$ at $z = 0$ and $T \le -4$, respectively, about 6.4 per cent of these galaxies are identified as IfEs at redshift zero. If we further limit our simulated elliptical galaxies to galaxies that are the main galaxies of their dark matter haloes (as in case of IfEs), $\sim$32 per cent of ellipticals are now identified as IfEs. Thus, IfEs are very rare objects among all galaxies, but at the same time, over 30 per cent of main elliptical galaxies brighter than $-19$ mag in $B$ band can be classified as IfEs.

Stocke et al. (2004) found from magnitude limited ($M_B \le 15.7$) observations that less than 3 per cent of all galaxies can be classified as isolated. This value should be interpreted as an upper limit for the number of IfEs, as it was based on all types of galaxies. Stocke et al. (2004) further found that early-type galaxies outnumber S0 galaxies 2 : 1 in very isolated areas. However, as spiral galaxies are the most dominant galaxy type in low densities (e.g. Dressler 1980), the observable estimate of the number of IfEs is significantly lower than 1 per cent. Hernández-Toledo et al. (2008) concluded that early-type galaxies amount to only 3.5 per cent among all isolated galaxies, lowering the observational estimate of IfEs to $\sim 1 \times 10^{-2}$ per cent. This fraction is in good agreement with our findings as about $\sim 9 \times 10^{-3}$ per cent of all simulated galaxies can be identified as IfEs when $T < -2.5$ morphology limit has been adopted.

As observational studies adopt different criteria for isolation, we illustrate their influence on the number of IfEs, with a stricter set of parameter values. For simplicity, we adopt only one isolation sphere with a radius of $2.5\, h^{-1}$ Mpc, and require that the magnitude difference between the brightest and the second brightest galaxy $\Delta m_{12}$ is $\ge$2.0 mag inside the isolation sphere. For the Hubble type, we adopt the same requirement as previously for our IfEs: $T \le -4$. Such values were used, e.g., by Marcum et al. (2004). With these values, we find that only $\sim 3 \times 10^{-4}$ per cent of all MS galaxies can be classified as IfEs, corresponding to an extremely low number density of $\sim 6 \times 10^{-7}\, h^3\, \mathrm{Mpc}^{-3}$. This is approximately 10 times less than before. It is obvious that changing the isolation criteria has a major impact on the number of IfEs and therefore their statistical properties, as stricter parameter values require a galaxy that is located in a true void. This result also shows that galaxies with comparable luminosities tend to reside in relatively close proximity rather than being truly isolated from any other reasonable sized companion.

The results of this section show that the fraction of IfE galaxies depends highly not only on the isolation criteria adopted, but also on the morphological type that is required. As the morphological type of simulated galaxies is less than precise, our number density for IfEs should not be taken as a strict limit, but as a guideline when observations are being planned. Thus, higher fractions of IfEs can be expected if isolation criteria or morphology limits are being relaxed.

### 3.2 Colour–magnitude diagrams

The easiest property of IfEs to observe must be the luminosity, and thus the colour–magnitude relation. This simple yet powerful relation is studied in Figs 1 and 2, which show the colour–magnitude diagrams (CMDs) of simulated and observed IfEs. Fig. 1 shows a comparison between the simulated IfEs and observed field elliptical galaxies presented in Reda et al. (2004), while Fig. 2 shows a comparison to the sample of IfEs presented in Marcum et al. (2004). We also plot the Es (our control sample) for completeness. Note, however, that in this section we limit the discussion of the CMDs

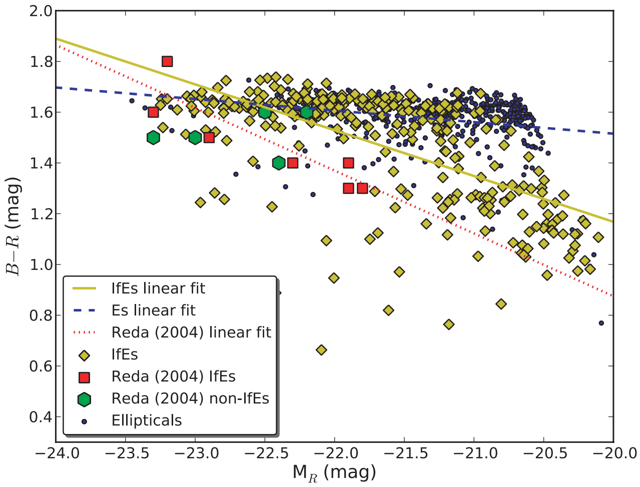


**Figure 1.** Colour ($B-R$) versus absolute $R$-band magnitude for the observed and simulated IfEs. The data for the Es control sample have been plotted for comparison. For IfEs and Es, a linear fit is shown. For clarity, only every 10th Es has been plotted. Note the separate population of faint and blue IfEs.

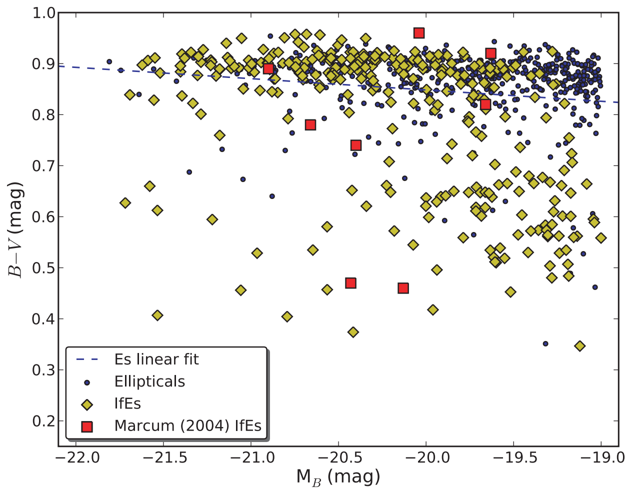


**Figure 2.** Colour ($B-V$) versus absolute $B$-band magnitude for the observed and simulated IfEs. The data for the Es control sample have been plotted for comparison. For Es, a linear fit is shown. For clarity, only every 10th Es has been plotted. Note the separate population of faint and blue IfEs.

to the comparison of simulated and observed IfEs, while the differences between simulated IfEs and Es are discussed in Section 4.2. Colours and associated errors and standard deviations of observed and simulated IfEs and simulated elliptical galaxies (Es) are listed in Table 1.

Fig. 1 shows that the observed IfEs lie in slightly bluer region in the CMD than simulated IfEs of the same brightness and that they seem to follow a tighter correlation than simulated IfEs. The $B-R$ colour scatter of simulated IfEs is slightly larger compared to observed IfEs: all simulated IfEs show a $1\sigma$ deviation of 0.23; however, as the observations of Reda et al. (2004) are limited to relatively bright ($M_R \leq -21.5$) galaxies, we calculate the colour scatter of bright simulated IfEs using magnitude cut-off of $M_R \leq -21.5$ and find it to be 0.17. The colour scatter of the bright simulated IfEs is close to the observed $B-R$ colour scatter (0.16), yet slightly higher. However, one should bear in mind that the number of observed IfEs is still small.

**Table 1.** Colours of simulated and observed IfEs and simulated non-isolated elliptical galaxies (Es).

| Sample | $\Delta$mag | Mean colour | Error | $\sigma$ |
|---|---|---|---|---|
| IfEs | $B-R$ | 1.47 | 0.01 | 0.23 |
| IfEs[1] | $B-R$ | 1.57 | 0.01 | 0.17 |
| IfEs | $B-V$ | 0.79 | 0.01 | 0.15 |
| IfEs[2] | $B-V$ | 0.82 | 0.01 | 0.14 |
| Es | $B-R$ | 1.58 | 0.002 | 0.10 |
| Es | $B-V$ | 0.86 | 0.01 | 0.07 |
| Reda et al. (2004) | $B-R$ | 1.49 | 0.06 | 0.16 |
| Marcum et al. (2004) | $B-V$ | 0.76 | 0.06 | 0.18 |

*Note.* the error refers to the standard error of the mean while $\sigma$ is the standard deviation. IfEs[1] and IfEs[2] refers to samples where faint simulated IfE galaxies have been removed and the IfE samples contain only galaxies with $M_R \leq -21.5$ and $M_B \leq -19.5$, respectively.

Reda et al. (2004) found a mean effective colour of $(B-R)_e = 1.49 \pm 0.06$ for their isolated elliptical galaxies, which is in good agreement with our mean value of $1.47 \pm 0.01$ (the errors are the standard error on the mean, see Table 1 for details). If we limit our sample of simulated IfEs to galaxies brighter than $M_R \leq -21.5$, as in the sample of Reda et al. (2004), the mean $B-R$ colour becomes $1.57 \pm 0.01$. This is redder than the mean colour in Reda et al. (2004) and shows that our mean colour is significantly affected by faint IfEs of the blue cloud. When the KS test is applied to the observed (Reda et al. 2004) and all simulated IfE colours, the p-value ($\sim$0.33) shows that we cannot reject the null hypothesis at 30 per cent level. However, if we consider only bright ($M_R \leq -21.5$) simulated IfEs, the p-value is only $\sim$0.01, implying that a difference between the observed and simulated IfE $B-R$ colours exists when faint simulated IfEs are excluded from the comparison.

A straight line fit to both observed and simulated IfEs differs in the slopes and intercepts (see Fig. 1). The linear fit of observed IfEs shows a steeper slope than the fit of the simulated IfEs. However, as the IfE sample of Reda et al. (2004) miss galaxies fainter than $M_R > -21.5$ it is not entirely clear what the order of magnitude of this difference might be, and due to the small number of observed IfEs in the sample of Reda et al. (2004) only a single new data point at the faint end of the CMD could change the fit significantly.

The $V$-band (Fig. 2) CMD differs from the $R$-band diagram as correlations seem significantly looser. Here, the colour scatter of the observed IfEs is larger than for the simulated IfEs ($1\sigma$ deviations are 0.18 and 0.15, respectively). The IfE sample of Marcum et al. (2004) extends to slightly fainter magnitudes than the sample of Reda et al. (2004), but their fainter IfEs are surprisingly red ($B-V \sim 0.9$). The simulated IfEs show slightly redder colours than observed IfEs; the mean $B-V$ colours are $0.79 \pm 0.01$ and $0.76 \pm 0.06$, for simulated and observed IfEs, respectively. The colours of simulated IfEs agree with observed colours within their standard errors of the mean, and the KS test approves the null hypothesis with high probability (p-value $\sim$0.63) when colours of the simulated IfEs are compared to the colours of the IfE sample of Marcum et al. (2004). The p-value would be only 0.04 if the observed IfEs of Marcum et al. (2004) were compared against the simulated Es. Thus, the simulated IfEs agree well with the observed IfEs of Marcum et al. (2004) when $B-V$ colour samples are compared.

Figs 1 and 2 show a separate population of simulated IfEs that belong to the blue cloud and populate the faint end of the CMD. Quantitatively, the colour and the brightness of this population is following: $B-R \leq 1.4$ or $B-V \leq 0.7$ and $M_R > -21.5$ or $M_B > -20.0$. The population of faint and blue IfEs comprise

∼26 per cent (76) of all simulated IfEs; thus, every fourth IfE belong to this population. We note that none of the IfEs of Reda et al. (2004) or Marcum et al. (2004) populates this faint and blue part of the CMDs. The sample of Marcum et al. (2004) shows two very blue IfEs that are part of the global blue cloud, but are not part of the population of faint and blue IfEs that is found from the simulation. However, this might be due to the magnitude limit of Marcum et al. (2004) sample, as they do not have IfEs fainter than $M_B > -19.5$.

Marcum et al. (2004) found preliminary evidence that 50 per cent of their sample of isolated early-type galaxies show blue global colours. However, because of the small sample size they could not conclude that the higher occurrence of blue E-type galaxies is related to the extremely low densities of the associated environments. As we are not limited by a small sample, we can confirm whether IfEs show bluer global colours than non-isolated early-type galaxies or not. The mean $B - V$ colour of simulated IfEs is $\sim 0.79 \pm 0.01$ in agreement with the findings of Marcum et al. (2004). However, this value is significantly affected by the population of faint IfEs; if we remove the faint IfEs and consider only IfEs with $M_B \leq -19.5$, the mean colour changes to $\sim 0.82 \pm 0.01$ (see Table 1 and also Fig. 6 of the next section). This is closer, yet slightly bluer, than the mean $B - V$ colour of simulated ellipticals ($0.86 \pm 0.01$). A similar result is seen when the $B - R$ colours are studied; bright ($M_R \leq -21.5$) simulated IfEs are almost as red as all simulated non-isolated ellipticals (Es) $B - R \sim 1.57 \pm 0.01$ and $1.58 \pm 0.002$, respectively. Thus, our results show that simulated IfEs do not show global blue colours if faint IfEs are removed, but the blue colours are due to the separate, faint and blue population of IfEs. Our theoretical findings predict that ∼26 per cent of IfEs show global blue colours and that these IfEs belong to the separate population of faint and blue IfEs.

Different trends in the CMDs, visible in Figs 1 and 2, may be interpreted as environment effects of galaxy formation. However, it is also possible that the bluest IfEs have had different formation mechanism and evolutionary path than redder IfEs. Different evolutionary paths and merging histories could explain different properties observed at redshift $z = 0$, as well as the influence of environment. Both possibilities will be explored in detail later.

### 3.3 Dark matter halo masses

We continue comparisons of simulated and observed IfEs by studying their dark matter haloes. Even if it is far from simple task to derive reliable dark matter halo masses from observations, the comparison is highly interesting, as the dark matter halo properties and galaxy properties are tightly linked.

IfE galaxies in the MS are mainly found residing inside dark matter haloes that are lighter than $7 \times 10^{12}\,h^{-1}\,\mathrm{M}_{\odot}$. The dark matter haloes of simulated IfEs are surprisingly light; the median mass is only $\sim 1.2 \times 10^{12}\,h^{-1}\,\mathrm{M}_{\odot}$. Even the most massive dark matter halo hosting an IfE is lighter than $2.2 \times 10^{13}\,h^{-1}\,\mathrm{M}_{\odot}$, which is comparable to a dark matter halo of a small group. Memola et al. (2009) calculated the total masses of two of their isolated ellipticals NGC 7052 and NGC 7785 from X-ray observations and quote values $\sim 5 \times 10^{11}$ and $\sim 1.9 \times 10^{12}\,\mathrm{M}_{\odot}$, respectively. These mass values agree well with our findings of dark matter halo mass. Norberg et al. (2008) did not find any isolated systems residing in haloes outside the range $\sim 5 \times 10^{11}$ to $10^{13}\,h^{-1}\,\mathrm{M}_{\odot}$ in their simulations; therefore, we can conclude that IfEs reside in lighter than $\sim 2 \times 10^{13}\,h^{-1}\,\mathrm{M}_{\odot}$ dark matter haloes.

The dark matter halo mass also sets constrains to the possible formation mechanisms; IfEs residing in light haloes cannot be merger remnants of groups or clusters. Only those IfEs that have a large and massive dark matter halo could have formed via merger of a group or multiple larger galaxies, but even then the group should have been poor with only few member galaxies. Evidently, this is true for fossil groups which are in many ways similar objects to IfEs. The dynamical masses of fossil groups range from $\sim 10^{13}$ to $10^{14}\,h^{-1}\,\mathrm{M}_{\odot}$ (see e.g. Díaz-Giménez, Muriel & Oliveira 2008).

### 3.4 Ages

The last property of IfEs we compare is their age. The median mass-weighted age of our model IfEs is 8.84 Gyr (see Table 3). We also note that the number density of young (mass-weighted age less than 5 Gyr) IfEs is extremely low (Fig. 10), giving a lower limit for the age of an IfE.

Reda et al. (2005) found a mean age of their IfEs to be $4.6 \pm 1.4$ Gyr, while Proctor et al. (2005) quote an age estimate of ∼4 Gyr. These age estimates are around the young end of our values. However, these estimates should not be compared directly to our values as the definitions are different: mass- versus luminosity-weighted age. Moreover, Collobert et al. (2006) found a broad range of stellar ages for their IfEs: ranging from ∼2 to 15 Gyr, in good agreement with our estimates, as the mass-weighted age of model IfEs ranges from 5 to 12 Gyr. The big scatter suggests that the formation and evolution of IfEs is not concentrated at a fixed epoch. This can also explain the large scatter we see in some properties of IfEs, as different formation times and evolutionary paths can lead to significantly different properties at $z = 0$.

### 3.5 Environments

To get a complete picture of the properties of IfE galaxies, we have to look at their environment. We define a companion as a galaxy that resides inside either of the two isolation spheres; the small $0.5\,h^{-1}$ Mpc or the large sphere $1.0\,h^{-1}$ Mpc. If not specifically mentioned, the number of companions refers to the total number of galaxies, $N_{\mathrm{COMP}}$, inside the large isolation sphere. Our definition of a companion does not guarantee that the galaxy belongs to the same dark matter halo as the IfE. Thus, it is possible that some of the companion galaxies are not gravitationally bound to the IfE. Truly isolated galaxies, without any companions in simulations, should be treated with caution. It may be that the mass resolution is not sufficient to form small subhaloes that could harbour a dwarf galaxy.

IfEs can have from 0 to ∼30 companion galaxies. We do not find a single IfE with more than 30 dwarf companions, indicating that our IfEs are in relatively low-density environments. The majority of IfEs have 0–20 companions, while the mean value of the number of companions, $N_{\mathrm{COMP}}$, is 10.7 in the MS. For IfEs with the total number of companion galaxies less than 17, most of the companions are found to reside inside the smaller ($0.5\,h^{-1}$ Mpc) isolation sphere. As the magnitude difference limit inside the small sphere is 2.2, we can be sure that our IfEs (excluding the nine subhalo galaxies discussed earlier) are well isolated from bright nearby galaxies. So, IfEs do not reside inside cluster-sized dark matter haloes, with virial radii $\sim 1.5\,h^{-1}$ Mpc, as most of their companion galaxies are within $0.5\,h^{-1}$ Mpc distance from the halo's main galaxy. If IfEs resided in cluster haloes, we should find companion galaxies also in the larger isolation sphere. We would also expect to find a larger number of dwarf companions.

Reda et al. (2004) found that only the very faint dwarf galaxies ($M_R \geq -15.5$) appear to be associated with isolated ellipticals. On the contrary, we find companion galaxies with a broad range of magnitudes from the MS. The mean $R$-band magnitude for these

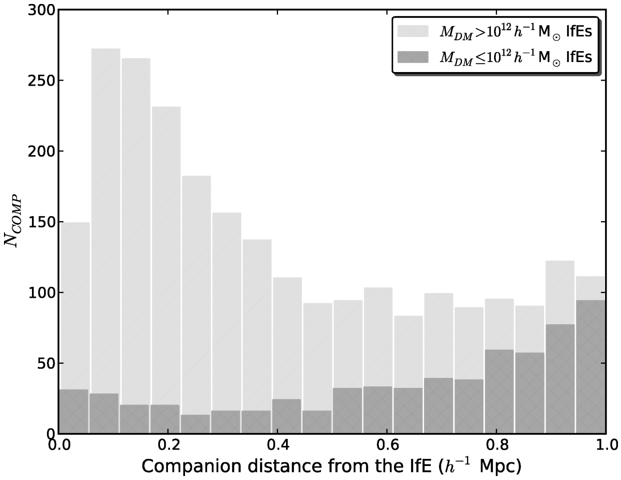


**Figure 3.** Total number of companion galaxies, $N_{\rm COMP}$, inside the large isolation sphere for light and massive IfEs.

companions is −17 mag. The quartile values for companion *R*-band magnitudes are −18.2 and −15.8 mag showing that model IfEs can have relatively bright companion galaxies. Thus, the magnitude gap between companion galaxies and an IfE seems to be larger in observations than in simulations. This may be due to the way how galaxy luminosities are treated in the SAM. Thus, this result is probably not without a bias due to the limiting mass resolution of the MS.

In Fig. 3, we show the distribution of companion galaxy distances from IfEs. We have divided the IfEs sample into two, to separate the population of blue, light and faint IfEs; the IfE sample is divided by dark matter halo mass. Fig. 3 clearly shows that more massive IfEs have close companions more often than light IfEs. The mean virial radius of the dark matter haloes of heavy IfEs ($M_{\rm DM} > 10^{12}\,{\rm M}_\odot$) is 225 $h^{-1}$ kpc, while it is 115 $h^{-1}$ kpc for light IfEs ($M_{\rm DM} \leq 10^{12}\,{\rm M}_\odot$). A significant number of companions of heavy IfEs are inside the mean virial radius and belong to the same dark matter halo as the IfE. However, for blue, light and faint IfEs the trend is opposite; we find most of the companions more than six times the mean virial distance away from the IfE. The median companion distances are 0.33 and 0.73 $h^{-1}$ Mpc for heavy and light IfEs, respectively.

Similar results are also found if the IfEs are divided by their colour. The blue, $B - R \leq 1.4$, IfEs have most of their companion galaxies more than five times away than the mean virial radius, while the red IfEs have the majority of their companions within the mean virial radius. These results show that the most isolated IfE galaxies are blue and relatively faint.

## 4 COMPARISON OF REGULAR AND FIELD ELLIPTICALS

Here, we compare the properties of the simulated IfE galaxies to the control sample of all elliptical galaxies in the simulation, to find out the differences between the two populations. For many properties the median values are relatively close to each other, but clear differences exist in the shapes of the distributions. Thus, throughout the following sections we use the KS two-sample test to assess whether two distributions are drawn from the same parent population. Results of the KS tests are given as probabilities (p-values) and presented in Table 2. For completeness, we also plot the histograms of studied properties (see Figs 5–10) and present the quartile values in Table 3.

**Table 2.** Mean values of the properties and results of the KS test: IfE versus control sample (Es) galaxies.

| Quantity | IfEs | Es | KS probability (p-value) |
|---|---|---|---|
| $\rm Mass_{DM}$ | 186.29 | 6751.93 | $<10^{-10}$ |
| $\rm Mass_{ST}$ | 5.46 | 3.92 | $<10^{-10}$ |
| $\rm Mass_{CG}$ | 0.32 | 0.10 | $<10^{-10}$ |
| Age | 8.58 | 9.32 | $<10^{-10}$ |
| Colour | 1.47 | 1.58 | $<10^{-10}$ |
| $M_B$ | −20.19 | −19.76 | $<10^{-10}$ |
| $T$ | −6.60 | −7.06 | 0.39 |

*Note.* quantity $\rm Mass_{DM}$ refers to virial dark matter mass of the background halo, $\rm Mass_{ST}$ refers to stellar mass, while $\rm Mass_{CG}$ refers to the mass in cold gas. All masses are in units of $10^{10}\,h^{-1}\,{\rm M}_\odot$. Age is the mass-weighted age of a galaxy in units of $10^9$ yr. Colour is $B - R$ in absolute rest-frame (Vega) magnitudes and $M_B$ is the absolute rest-frame (Vega) magnitude in the *B*-band (Buser B3 filter). $T$ is the morphology, and it is the only quantity for which the null hypothesis of the KS test is approved.

**Table 3.** Quartile values of the properties of isolated (IfE) and control sample (Es) galaxies.

| Sample | Quantity | First quartile | Median | Third quartile |
|---|---|---|---|---|
| IfEs | $\rm Mass_{DM}$ | 34.86 | 120.58 | 235.48 |
| Es | $\rm Mass_{DM}$ | 311.95 | 1069.28 | 4998.61 |
| IfEs | $\rm Mass_{ST}$ | 1.69 | 4.34 | 7.94 |
| Es | $\rm Mass_{ST}$ | 1.97 | 2.84 | 4.73 |
| IfEs | $\rm Mass_{CG}$ | 0.10 | 0.22 | 0.44 |
| Es | $\rm Mass_{CG}$ | 0.04 | 0.05 | 0.09 |
| IfEs | Age | 7.21 | 8.84 | 10.03 |
| Es | Age | 8.44 | 9.39 | 10.41 |
| IfEs | Colour | 1.28 | 1.59 | 1.64 |
| Es | Colour | 1.56 | 1.60 | 1.63 |
| IfEs | $M_B$ | −20.70 | −20.18 | −19.64 |
| Es | $M_B$ | −20.14 | −19.65 | −19.28 |
| IfEs | $N_{\rm COMP}$ | 3.00 | 7.00 | 15.00 |

*Note.* $\rm Mass_{DM}$ is the virial dark matter mass of the background halo, $\rm Mass_{ST}$ – the stellar mass, $\rm Mass_{CG}$ – the mass in cold gas. All masses are in units of $10^{10}\,h^{-1}\,{\rm M}_\odot$. Age is the mass-weighted age of a galaxy in units of $10^9$ yr. Colour is $B - R$ in absolute rest-frame (Vega) magnitudes and $M_B$ is the absolute rest-frame (Vega) magnitude in the *B*-band (Buser B3 filter). $N_{\rm COMP}$ is the number of companion galaxies within the large (1.0 $h^{-1}$ Mpc) avoidance sphere around the IfE galaxy.

### 4.1 Morphology

The distributions of morphologies ($T$ values) of IfE galaxies and Es are very similar, with median values −5.62 and −5.80, respectively. The KS test approves the null hypothesis with high probability (p-value ∼0.39); thus, it is likely that the differences in morphology distributions have arisen by change. This is no surprise as our definition of IfEs and Es requires that the morphology value is smaller than 4.

### 4.2 Galaxy colour–magnitude diagrams

The galaxy CMDs show three main features: the red sequence, the green valley and the blue cloud. In general, elliptical galaxies populate the area known as the red sequence. This is certainly true for most elliptical galaxies of the MS; however, is this true for IfEs as well?

Figs 1 and 2 show that the red sequence of IfEs starts at $M_R \sim -21$ (or $M_B \sim -19.5$), while it extends to fainter magnitudes for Es. A trend of redder colours with increasing luminosity is noted for both simulated IfEs and Es. However, the slope of the trend is steeper and the scatter is higher for IfEs. Simulated IfEs show a broader distribution in colours (Figs 1 and 2) than simulated Es. The $1\sigma$ scatter of $B - R$ colours is $\sim$0.23 and $\sim$0.10 for IfEs and Es, respectively. For $B - V$ colours, the $1\sigma$ values are $\sim$0.15 and $\sim$0.07 for IfEs and Es, respectively. Spearman rank order correlation test shows a very strong (correlation coefficient $cc \sim -0.65$) correlation for IfEs (in Fig. 1) and significant ($cc \sim -0.33$) correlation for Es. The trends in Fig. 2 are not as strong according to the Spearman test: $cc \sim -0.60$ and $\sim -0.27$ for IfEs and Es, respectively. However, all correlations are highly significant, as the probability to have as large correlation coefficients for uncorrelated data is $<10^{-20}$ in all cases.

The colour correlations in Figs 1 and 2 suggest that IfEs follow a different colour–magnitude trend than Es. The KS tests show large differences (D-values) when the colours of IfEs are compared to Es. The KS test rejects the null hypothesis in case of IfEs and Es $B - R$ and $B - V$ colours with high probability (p-values $<10^{-15}$ in both cases). If we exclude the separate population of faint and blue IfEs, the previous statement does not change, only the probabilities (p-value now $<10^{-6}$). Thus, the CMDs of IfEs and Es differ significantly even when the separate population of faint and blue IfEs is removed.

### 4.3 Colour–mass diagrams

Fig. 4 shows the $B - R$ colour of a galaxy as a function of the mass of the underlying dark matter halo. We note from Fig. 4 that the Es show a rather constant relation with a few outliers; in general, Es have the $B - R$ colour $\sim 1.6 \pm 0.15$ independent of the mass of the dark matter halo they reside in. However, a completely different trend is seen for IfEs, as they tend to get redder when the dark matter halo mass grows, while light ($M_{\rm DM} < 10^{12}\,h^{-1}\,{\rm M}_{\odot}$) dark matter haloes host blue IfEs. The $B - R$ colours of IfEs grow steeply as a function of dark matter halo mass below $10^{12}\,h^{-1}\,{\rm M}_{\odot}$ indicating the influence of dark matter halo properties to the IfE galaxy they host.

All IfEs are the main galaxies of their dark matter haloes. If instead of the Es sample we used the MEs for comparison, Fig. 4 would change. There would still be a significant number of red, $B - R \sim 1.6$, non-isolated elliptical galaxies residing in dark matter haloes lighter than $M_{\rm DM} < 10^{12}\,h^{-1}\,{\rm M}_{\odot}$, but their total number would be significantly smaller. MEs that reside in light ($M_{\rm DM} < 10^{12}\,h^{-1}\,{\rm M}_{\odot}$) dark matter haloes show a big scatter in colours, indicating that not only the dark matter halo, but also the environment and the formation history of the halo affects the galaxy it hosts.

Fig. 4 further shows that the population of faint and blue IfEs noted in the CMDs resides in the lightest dark matter haloes with $M_{\rm DM} < 10^{12}\,h^{-1}\,{\rm M}_{\odot}$. Below this mass scale, we see a strong correlation between the dark matter halo mass and the evolution of the galaxy. Thus, simulations predict an unobserved population of IfEs that are blue and faint and that reside in light dark matter haloes.

### 4.4 Colour and luminosity distributions

Fig. 5 shows the number density of absolute $B$-band rest-frame magnitudes for IfEs and Es. The distributions look very different and the KS test (Table 2) rejects the null hypothesis with high probability. The differences in the luminosity functions are likely due to the isolation criteria of IfEs. The most interesting result, seen in the figure, is that IfE galaxies have an almost constant, $\sim 8 \times 10^{-6}$, number density throughout their $B$-band magnitudes. Surprisingly, when only brighter ($-21.7 < M_B < -21.0$) elliptical galaxies are considered, it is almost as probable to find an IfE as it is to find a non-isolated elliptical. It is also noteworthy that we have not identified a single IfE galaxy brighter than $-21.7$ mag (in $B$ band), while the brightest Es are almost 1 mag brighter ($\sim -22.5$). This result is natural, since the brightest elliptical galaxies are normally found to reside in centres of large clusters. The brightest cluster galaxies have $M_V \sim -23.5$ mag and they have usually experienced many merging events during their evolution (e.g. Lucia & Blaizot 2007). Multiple merging events have brought more mass and gas to the central galaxy and have caused massive star formation and greater luminosity. It is unlikely that IfEs have followed the same evolutionary path (see Figs 7 and 8).

Since the $B$-band luminosity function of IfEs is almost constant, it leads to another question, namely if IfEs have a constant number

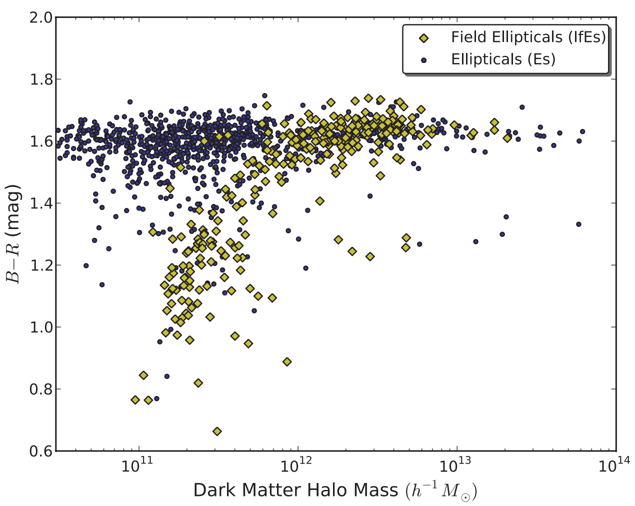


**Figure 4.** Dark matter halo mass versus colour ($B - R$) of the galaxy. For clarity, only every fifth Es has been plotted.

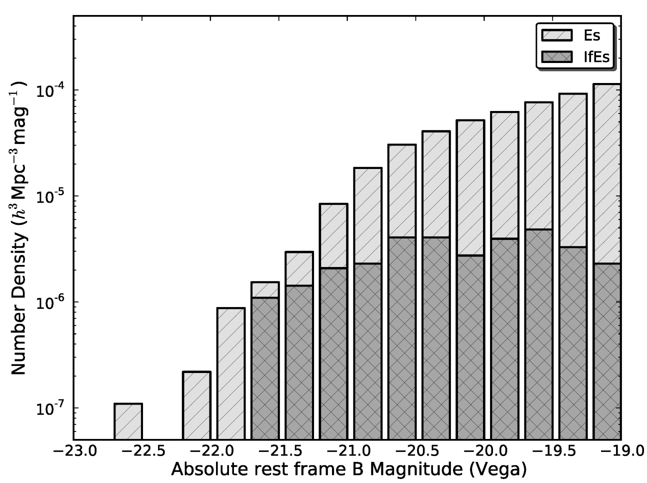


**Figure 5.** Number density of $B$-band rest-frame magnitude for IfEs and Es.

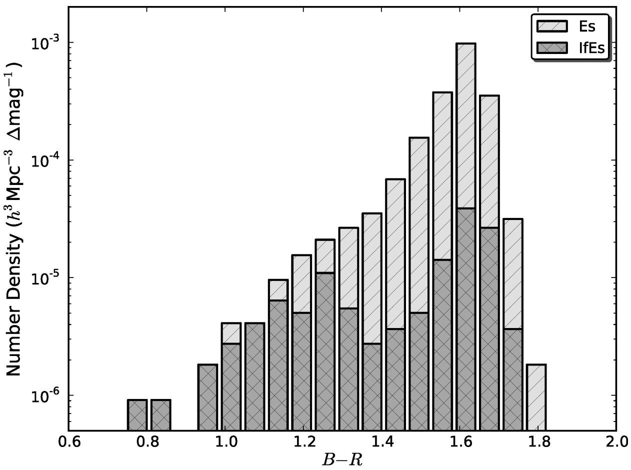


**Figure 6.** Number density of colour distribution ($B - R$ magnitudes) for IfEs and Es.

density in colour as well. Fig. 6 replies to this question and presents the number density for the $B - R$ colour. The distributions for Es and IfEs look very different and the KS test (Table 2) quantifies that these distributions are not drawn from the same parent population. The IfE galaxies show a bimodal distribution while Es show clearly only one peak. This result is also seen when the values of first quartiles of both distributions (Table 3) are compared. The value of the first quartile of our IfEs is almost 0.3 mag bluer than for the Es in agreement with Marcum et al. (2004) who found evidence that 50 per cent of their sample of isolated early-type galaxies show blue global colours.

The number density of isolated and non-isolated elliptical galaxies is quite similar for blue, $B - R < 1.3$, galaxies. The bimodality of the IfE distribution and the blue peak present in Fig. 6 is caused by the population of blue, faint and light IfEs. The colour distribution of IfEs suggests that some IfEs have either formed later or had merger activity at lower redshifts than non-isolated ellipticals. We confirm whether this is the case in Section 5 where formation and merging times of IfEs are compared to non-isolated ellipticals.

### 4.5 Dark matter and stellar masses

We continue our comparisons between IfEs and Es by studying their masses and composition. Both samples show very little cold gas: $<1.0 \times 10^{10}\, h^{-1}\, \mathrm{M}_{\odot}$, with no ongoing star formation (the median star formation rate is $\sim 0\, \mathrm{M}_{\odot}\, \mathrm{yr}^{-1}$). This is typical for elliptical galaxies that are usually considered as 'red and dead' at $z = 0$.

When dark matter halo masses are studied in detail, an interesting result is found. IfE galaxies reside mainly inside dark matter haloes that are lighter than $7 \times 10^{12}\, h^{-1}\, \mathrm{M}_{\odot}$, while Es are found to reside more often in more massive haloes. The differences between the dark matter haloes of Es and IfE galaxies are striking, which is clearly visible in Fig. 7 where we plot the dark matter halo mass distribution as a function of number density. It is no surprise that the KS test (Table 2) does not approve the null hypothesis, especially as the distribution of IfEs shows weak bimodality. The great difference in dark matter halo mass is interesting as the properties of galaxies are tightly related not only to the environment, but also to the dark matter halo mass within the galaxy resides in (Croton & Farrar 2008).

While the dark matter haloes of IfEs are, in general, significantly lighter than haloes of Es, we see a different trend when stellar masses are compared. Even though the distributions in Fig. 8 may look somewhat similar, the KS test (Table 2) disproves the null hypothesis with high probability. The differences in stellar mass distributions become very clear if we consider the quartile values of both samples. IfE galaxies have, in general, more stellar mass than Es (Table 3). This is especially intriguing as IfEs reside inside rather light dark matter haloes (see Fig. 7). To emphasize this difference, we plot the dark matter halo mass versus the stellar mass for both samples in Fig. 9. IfEs are found to contain more stellar matter with respect to dark matter than Es. The stellar mass of IfEs grows almost linearly with the dark matter mass with a mass (dark/stellar) ratio of $\sim 4 \times 10^{-2}$. It is possible that the difference is related to the formation and evolutionary paths of IfEs. This possibility is studied in detail in Section 5.

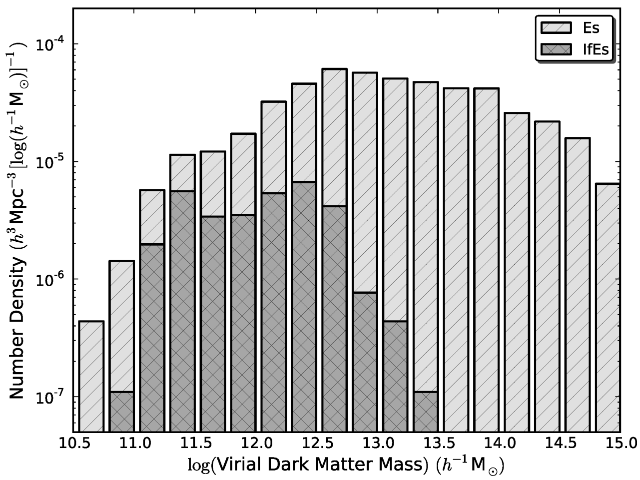


**Figure 7.** Number density of dark matter halo mass for IfEs and Es.

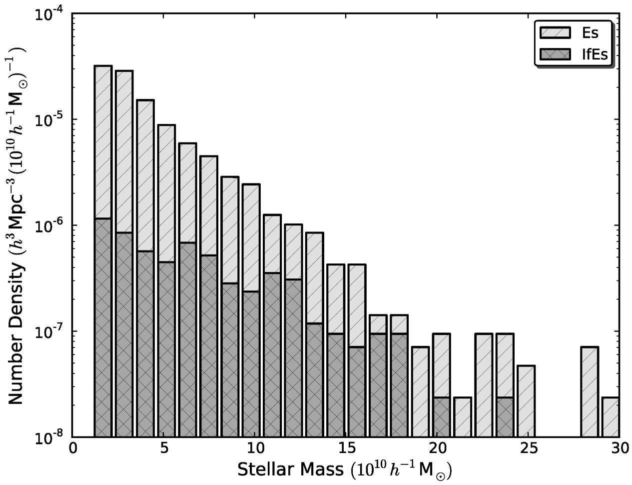


**Figure 8.** Number density of stellar mass for IfEs and Es.

### 4.6 Age distributions

Distributions of mass-weighted age (Fig. 10) look rather similar; however, the KS test (Table 2) does not approve the null hypothesis. When quartile values (see Table 3) are studied, it is obvious that IfEs have lower mass-weighted age than Es, suggesting that IfEs are younger. Even IfEs seem to be slightly younger than Es in statistical sense, they cover roughly the same age range, only the extremes are missing.

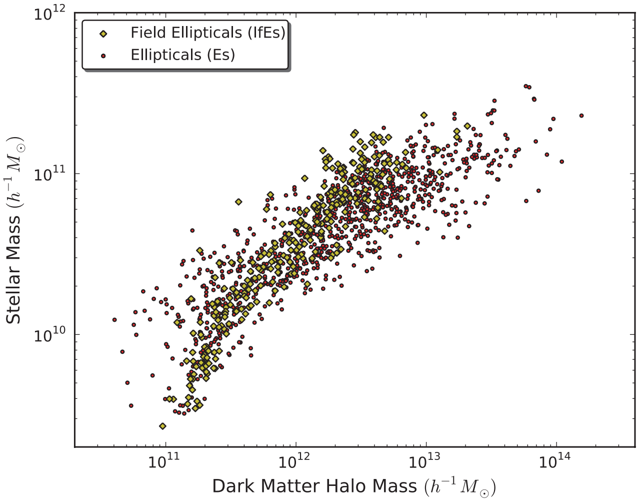


**Figure 9.** A scatter plot of stellar and dark matter halo mass. Yellow diamonds correspond to the sample of IfE galaxies, while red circles correspond to Es. For clarity, only every second galaxy has been plotted.

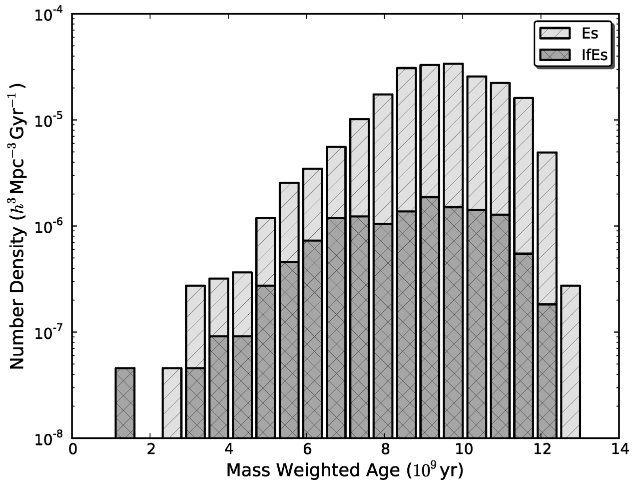


**Figure 10.** Number density of the mass-weighted age for IfEs and Es.

## 5 FORMATION AND EVOLUTION OF IFES

The analysis of simulated IfEs in the previous sections shows similarities in CMDs and comparable ages, colours and dark matter halo masses with observational data. In general, we do not find big discrepancies between simulations and observations for the properties of IfEs we can compare. The KS tests between the IfEs and Es do not approve the null hypothesis, except for morphology. Therefore, IfEs selected with the criteria of Section 2.2 form a distinct class of objects and are significantly different from regular elliptical galaxies. As a next step in our analysis, we use simulation data to study evolutionary paths and formation mechanisms of IfEs. Note that in this section, unless otherwise stated, we use the MEs sample as the control sample, which contains only those non-isolated elliptical galaxies that are the main galaxies of their dark matter haloes.

### 5.1 Formation and evolution times

Lucia & Blaizot (2007) defined a set of times related to formation and evolution of dark matter haloes and galaxies that they reside in. We adopt the same definitions for convenient and easy comparison, but we add one more quantity named last merging time, $z_l$. Briefly, the different times are defined as follows.

(i) Assembly time ($z_a$) is the redshift when 50 per cent of the final stellar mass is already present in a single galaxy of the merger tree.

(ii) Identity time ($z_i$) is the redshift when the last major (the two progenitors both contain at least 20 per cent of the stellar mass of the descendant galaxy) merger occurred.

(iii) Formation time ($z_f$) is the redshift when 50 per cent of the mass of the stars in the final galaxy at $z = 0$ have already formed.

(iv) Last merging time ($z_l$) is the redshift when the last merger occurred.

We compute all four times, measured in redshifts, related to the formation and evolution of galaxies, and present numerical results in Table 4. Fig. 11 shows cumulative distributions of the assembly ($z_a$), identity ($z_i$), formation ($z_f$) and last merging ($z_l$) times. In Table 5, we show probabilities that the distributions of formation and evolution times of IfEs and MEs are drawn from the same parent distribution. The KS tests indicate great differences in all cases, implying that the formation and evolution of IfEs is different from MEs.

Fig. 11 (top panel) shows that IfE galaxies have assembled at lower redshifts than galaxies of MEs. Thus, in general, stars of IfEs form later than stars of MEs and thus IfEs are younger. This result is natural for hierarchical cold dark matter models. If the conventional theory, that higher density areas collapse earlier, holds, this implies that IfEs have formed originally in less dense regions than MEs. Fig. 11 (second panel) also shows that IfEs undergo their major merging events at significantly lower redshifts than the ellipticals of MEs. The difference in redshift is significant (see Table 4) and implies that a different formation mechanism is behind the evolution of IfEs and MEs.

Fig. 11 (third panel) shows that stars that will eventually form an IfE galaxy are present already at higher redshifts than for MEs, in agreement with observational findings (e.g. Reda et al. 2005). These results indicate that IfEs can form stars more efficiently than MEs (see also Fig. 12). Note, however, that we find the formation time ($z_f$) to be highly dependent on the mass of the dark matter halo, as noted in (Lucia et al. 2006). If we limit MEs to galaxies with dark matter halo mass greater than $5 \times 10^{12}\,h^{-1}\,\mathrm{M}_\odot$, we find the median formation time to be at very high redshift ($z \sim 3.3$). This shows that galaxies in massive dark matter haloes form the bulk of their stars already at very early cosmic epochs, in agreement with the general hierarchical halo mass growth scenario.

We define a major merger as an event where the two progenitors both contain at least 20 per cent of the stellar mass of the descendant galaxy. Almost half (∼46.3 per cent) of IfE galaxies have experienced a major merger at some point of their formation history. The percentage of major merging events for IfEs is higher than for MEs, where only one-third (∼33.3 per cent) of galaxies have experienced a major merging event. If all non-isolated E-type galaxies, independent of their luminosity or status in their dark matter haloes, are considered, only about 4 per cent experience a major merger. The difference is significant and shows that it is possible to form elliptical galaxies, isolated or not, without a major merger via disc instabilities.

Let us study the redshifts of the last merging event $z_l$ (see Fig. 11, bottom panel, and Tables 4 and 5) and the total number of merging events. IfEs have their last merging event at lower redshifts than MEs. The median redshift of the last merging event is 0.21 and 0.28 for IfEs and MEs, respectively. This shows that IfEs have merging

**Table 4.** Statistics of formation and evolutionary times.

| Sample | Time | Mean | Median | First quartile | Third quartile | Mode | Min | Max | Stdev |
|---|---|---|---|---|---|---|---|---|---|
| IfEs | $z_i$ | 0.644 | 0.408 | 0.183 | 0.687 | 0.242 | 0.064 | 6.200 | 0.836 |
| MEs | $z_i$ | 1.062 | 0.624 | 0.242 | 1.386 | 0.116 | 0.020 | 5.724 | 1.089 |
| IfEs | $z_a$ | 1.079 | 0.989 | 0.564 | 1.504 | 1.173 | 0.020 | 5.289 | 0.710 |
| MEs | $z_a$ | 1.303 | 1.276 | 0.755 | 1.766 | 1.276 | 0.041 | 4.520 | 0.737 |
| IfEs | $z_f$ | 1.520 | 1.386 | 0.828 | 1.912 | 1.386 | 0.012 | 5.289 | 0.831 |
| MEs | $z_f$ | 1.055 | 0.687 | 0.457 | 1.386 | 0.564 | 0.041 | 6.197 | 0.893 |
| MEs* | $z_f$ | 3.214 | 3.308 | 2.831 | 3.576 | 3.576 | 1.276 | 6.197 | 0.790 |
| IfEs | $z_l$ | 0.310 | 0.208 | 0.116 | 0.408 | 0.116 | 0.020 | 2.070 | 0.325 |
| MEs | $z_l$ | 0.427 | 0.230 | 0.144 | 0.509 | 0.242 | 0.020 | 3.866 | 0.483 |

*Note.* quantities $z_i$, $z_a$, $z_f$ and $z_l$ are the identity, assembly, formation and last merging times, respectively. MEs* refers to a sample where only haloes more massive than $5 \times 10^{12}\, h^{-1}\, M_\odot$ have been considered.

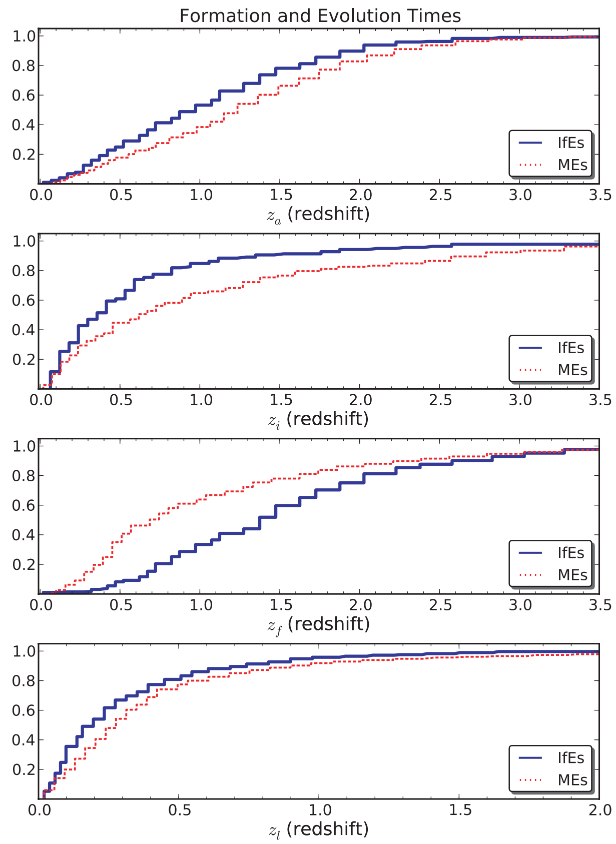


**Figure 11.** Cumulative distributions of assembly ($z_a$), identity ($z_i$), formation ($z_f$) and last merging ($z_l$) times measured in redshifts. The blue solid lines correspond to IfEs, while the red dashed lines mark the MEs.

**Table 5.** Results of the KS test: IfEs versus the control sample (MEs) galaxies.

| Time | D-value | KS probability (p-value) |
|---|---|---|
| $z_a$ | 0.190 | $5.7 \times 10^{-8}$ |
| $z_i$ | 0.239 | $1.1 \times 10^{-5}$ |
| $z_f$ | 0.353 | $<10^{-10}$ |
| $z_l$ | 0.179 | $6.5 \times 10^{-8}$ |

*Note.* quantities $z_i$, $z_a$, $z_f$ and $z_l$ are the identity, assembly, formation and last merging times, respectively.

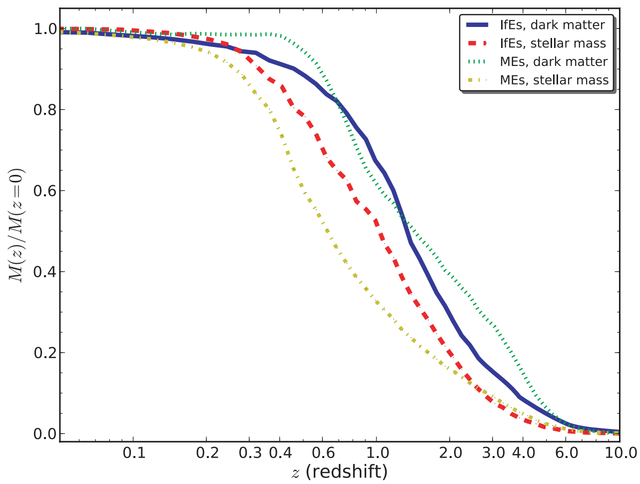


**Figure 12.** Mass assembly of IfEs and MEs as a function of redshift $z$. Lines show the median value at given redshift.

activity also at very late stages of their evolution in agreement with Hernández-Toledo et al. (2008). Hau, Carter & Balcells (1999) quoted an age estimate of ~1.1 Gyr for isolated elliptical galaxies since the last merger. This age estimate from observational data seems to disagree with our median time of the last merging, which is more than twice as high: ~2.5 Gyr. However, we do find IfEs that have experienced their last merging event only ~0.3 Gyr ago. Thus, the discrepancy can arise from the small number of observed IfEs in Hau et al. (1999).

It is possible that evolution of IfEs is suppressed by the low-density environment they reside in; thus, the major merging events happen at later stage in their evolution if at all. The larger fraction of IfEs having major mergers than MEs can also be due to the requirement of the magnitude gap, not only the region they formed in. IfEs of denser areas with comparable sized galaxies must clean their environment effectively, leading to a larger fraction of major merging events.

While studying the redshifts of the last merging events, we noticed that six IfEs did not experience a single merging event during their evolution. These galaxies have developed in truly isolated areas; although, maybe, a greater mass resolution in simulations would reveal one or more minor merging events. Despite the resolution limitations, the result is in agreement with observations where some IfEs do not show any signs of merging activity. Typically, simulated IfEs experience one to 10 merging events (above the mass limit of $10^8\, h^{-1}\, M_\odot$) during their lifetime, the average being 7.6 and the median six mergers. These numbers are significantly higher than for MEs, for which we find the average and median of 4.6 and one merging event, respectively. This suggests that IfEs accrete multiple smaller haloes (and galaxies) during their formation, cleaning their neighbourhood from dwarf galaxies effectively. This leads to a question how effectively IfEs accrete mass as a function of time compared to MEs.

## 5.2 Mass assembly

Fig. 12 shows the dark and stellar matter mass assembly as a function of redshift for both IfEs and MEs. The figure shows that IfEs start to form around the same epoch as MEs; however, IfEs accumulate stellar matter much faster. According to our findings, IfEs can form stars more efficiently than MEs, while MEs seem to accrete dark matter slightly faster than IfEs. We confirm that IfEs form the bulk of their stars at $z > 2$, as suggested in Reda et al. (2005). We also note that at $z = 1$, IfEs have formed over half of their stars (stellar mass) and have gathered as much as 80 per cent of their final dark matter. The galaxies of MEs have accreted roughly the same fraction of dark matter as IfEs at $z \sim 1$; however, they have formed as little as 30 per cent of their stars compared to the final stellar matter at $z = 0$. This difference is significant and shows that IfEs form their stars quickly and are rather dark-matter poor compared to other elliptical galaxies (see also Fig. 9 for stellar versus dark matter). It is also noteworthy that IfEs continue to accrete dark matter till $z = 0$ while MEs have gathered ~99 per cent of their final dark matter already at $z \sim 0.5$. All this points towards a different formation mechanism for these two galaxy classes and suggests that late merging events can be a significant part of the evolution of an IfE.

To further illustrate the mass assembly of IfEs, we plot the sample of blue, light and faint IfEs separately in Fig. 13. We have divided the IfEs sample into two: light ($M_{\rm DM} \leq 10^{12}\,h^{-1}\,{\rm M}_{\odot}$) and heavy ($M_{\rm DM} > 10^{12}\,h^{-1}\,{\rm M}_{\odot}$) IfEs. Fig 13 shows that there is a significant difference in mass accretion of light and heavy IfEs. The stellar mass of heavy IfEs follows closely the dark matter mass accretion, while light IfEs evolve differently. The heavy IfEs have created half of their stellar matter already at $z \sim 1.6$, while the light IfEs have created barely 10 per cent of their stellar matter, in agreement with the findings of Treu et al. (2005). We note that the light IfEs create half of their stellar matter by $z \sim 0.7$. The heavy IfEs also form stars extremely efficiently compared to the light IfEs, as the stellar mass follows dark matter accretion closely. Fig. 13 also shows that heavy IfEs host older stellar populations than light IfEs, as ~99 per cent of their stellar mass has been accumulated already by $z \sim 0.3$. Thus, more massive (and luminous) IfEs have old stellar populations, while the lighter ones have formed a signification fraction of their stellar mass relatively recently.

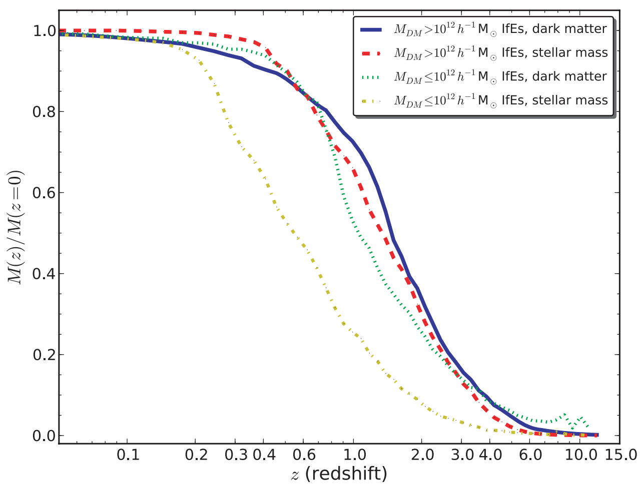


**Figure 13.** Mass assembly of IfEs as a function of redshift $z$ when the sample of IfEs has been divided by dark matter halo mass. Lines show the median value at a given redshift.

## 5.3 Merger histories of IfEs

So far, we have shown that minor and major merging events take place during the formation of an IfE. Thus, in the following sections, we try to identify general formation mechanisms based on different types of merger trees and merging events. We study merger trees of all IfEs individually and identify three typical formation scenarios.

We illustrate merger histories in merger plots. The IfE itself lies at the bottom of the plot at $z = 0$, and all its progenitors (more massive than $10^8\,h^{-1}\,{\rm M}_{\odot}$) are plotted upwards going back in time. Galaxies with stellar mass larger than $10^9\,h^{-1}\,{\rm M}_{\odot}$ are shown as symbols, and are colour-coded as a function of their rest-frame $B - R$ colour.

### 5.3.1 Solitude

Fig. 14 shows an example of an IfE galaxy that has developed undisturbed, alone, and has not undergone even a single merging event. We group IfEs that form in this fashion to a single group that we call solitude formation class.

Even though Fig. 14 does not show a single merging event during the formation history, this may not be the whole story; the plot does not show mergers smaller than the resolution limit (~$10^8\,h^{-1}\,{\rm M}_{\odot}$) of the MS. Therefore, it is possible or even likely that IfEs belonging to this class have had one or even several minor merging events during their evolution. Even so, the merging events would have involved very light dark matter clumps, and it is likely that no significant observational evidence would exist. In this context,

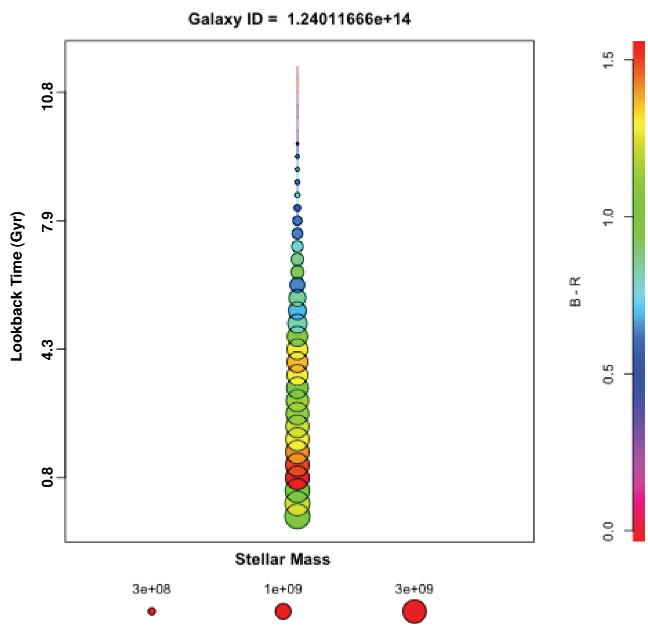


**Figure 14.** Example of a merger tree of an IfE galaxy that has developed alone without any significant merging events. Symbols are colour-coded as a function of the $B - R$ colour and their area scales with the stellar mass. Only progenitors more massive than $10^8\,h^{-1}\,{\rm M}_{\odot}$ are shown.

small merging events can be interpreted as accretion of dark matter, making solitude a proper formation mechanism.

We identify six IfEs, corresponding to mere 2 per cent of all IfEs, that belong to the solitude class. This implies that either IfEs that develop truly alone in underdense regions are extremely rare or some of the IfEs have been misclassified. It is possible that some IfEs with one or more small mergers could belong to this formation class, especially if the motivation of classification is based on observability of each class. It is not obvious how massive a merging event is required to find observational evidence of a merger, complicating the classification.

The six IfEs identified all show unsteady evolution in their colour as a function of redshift. This is somewhat surprising as one would assume that a passively evolving galaxy should show a steady colour evolution from blue to red while the stellar population ages. The bulge formation of solitude class is assumed to happen via disc instabilities. Solitude IfEs reside inside lighter dark matter haloes than IfEs of other class, with typical dark matter halo mass of $\sim 2 \times 10^{11}\, h^{-1}\, \mathrm{M}_{\odot}$ or even less. This makes IfEs that belong to the solitude class the lightest IfEs in the MS. The formation, when the dark matter mass grows larger than $10^{8}\, h^{-1}\, \mathrm{M}_{\odot}$, epoch of solitary IfEs is in the redshift range $3.6 < z < 5.3$. However, we find one solitude IfE that formed as late as $z \sim 2.5$, making it a very late bloomer, showing that, IfEs can have formed very recently. Solitude IfEs are in agreement with observations of, e.g., (Aars et al. 2001) and (Denicoló et al. 2005), who did not find any evidence of merging activity while studying their samples of IfEs.

### 5.3.2 *Coupling*

Fig. 15 shows an example of an IfE that has undergone at least one ‘equal’ size merger during its evolution. IfEs that have experienced at least one equal-sized merger comprise a formation class named coupling.

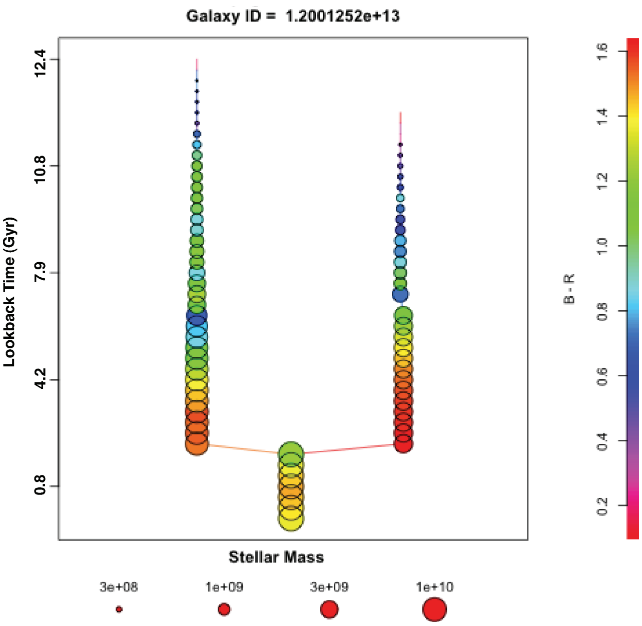


**Figure 15.** Example of a merger tree of an IfE galaxy that has undergone an equal-sized merger. Symbols are colour-coded as a function of the $B - R$ colour and their area scales with the stellar mass. Only progenitors more massive than $10^{8}\, h^{-1}\, \mathrm{M}_{\odot}$ are shown.

Our definition for an equal size merging is the following: the lighter of the merged galaxies had at least 50 per cent of the stellar mass of the more massive one. This is far larger than in our definition of a major merger (20 per cent) that was applied when calculating the identity time $z_{\mathrm{i}}$. Thus, an equal-sized merger guarantees that the merging event has had a great impact not only on the morphology, but also on the evolution and other properties of the IfE.

The motivation for this formation class resides in observations; a major merging event should be visible in observational data. Thus, an equal-sized merging should leave distinct marks to the descendant galaxy, which should be observable for at least a few Gyr, if not longer. It has been suggested that IfEs have formed in relatively recent mergers of spiral galaxy pairs, i.e. in merging of two comparable sized galaxies. Marcum et al. (2004), Reda et al. (2007) and Kautsch et al. (2008) have found several isolated galaxies that show signs of recent morphological disturbances, while Hau et al. (1999) (see also Hau & Forbes 2006) have found that ∼40 per cent of isolated galaxies show kinematically distinct cores (KDC). KDCs are generally believed to be the result of a major or an equal-sized merger (Hernquist & Barnes 1991). Thus, it is possible that these observations have already identified galaxies that belong to this formation class. However, it is also possible that KDCs can form in an early collapse without subsequent mergers (Harsoula & Voglis 1998), complicating the identification of the formation mechanism.

We identify in total 93 IfEs, corresponding to ∼32 per cent of all IfEs, that belong to the coupling class of formation scenarios. IfEs that belong to the coupling formation class show colour evolution that is in agreement with conventional theory. The time from the last equal-sized merging correlates well with the colour of the galaxy at $z = 0$; galaxies with late merging are bluer than galaxies that experienced their equal-sized merging a long time ago. The mean redshift of the last equal-sized merger is 1.09 while the median is 0.62. IfEs that belong to this formation class start to form usually in the redshift range $3.6 < z < 5.3$. We also identify a few IfEs that have started to form as early as $z \sim 8$, making IfEs that belong to the coupling class older, in a statistical sense, than IfEs that belong to the solitude formation class.

The coupling formation mechanism can explain several observed IfEs. The CMDs of Reda et al. (2004) show a slope and scatter that is in agreement with equal-mass mergers. They find 11 per cent of their IfEs to show boxy isophotes that can form when equal-sized galaxies merge. Marcum et al. (2004) argue that all except one of their IfE have luminosities that would, at most, be consistent with a single equal-mass merger event. Note that all these observations are best explained by the IfEs of the coupling class.

### 5.3.3 *Cannibalism*

Fig. 16 shows a typical IfE galaxy that has developed and accreted dark matter and stellar mass through multiple, small and larger merging events, but has not experienced any equal-sized mergers. All IfEs that form via multiple mergers form a formation class called cannibalism.

The merger trees of cannibal IfEs show a large number of mergers, with also a relatively large ones. It is obvious from the merger trees that the colour of the IfE does not change due to a minor merger. This is due to the fact that many small merging events are likely to be dry and, therefore, do not induce significant star formation that would make the global colour of the IfE bluer. However, the largest merging events can have a significant impact on the IfE’s morphology and colour (see Fig. 16 and the merging event around 0.8 Gyr ago). Some merging events, visible in the merger trees of

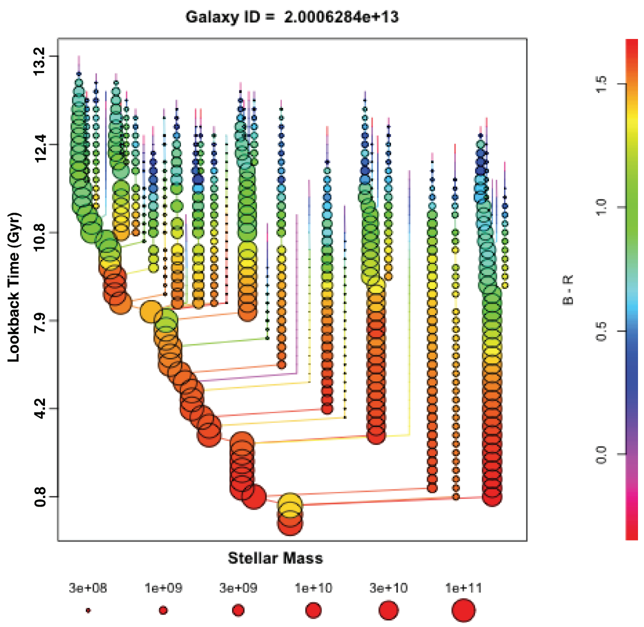


**Figure 16.** Example of a merger tree of an IfE galaxy that has undergone multiple merging events, but not any equal-sized ones. Symbols are colour-coded as a function of the $B - R$ colour and their area scales with the stellar mass. Only progenitors more massive than $10^8\,h^{-1}\,\mathrm{M}_{\odot}$ are shown.

cannibal IfEs, can be classified as major mergers, and these could be visible in observational data.

Most (194) of the IfEs in the MS belong to the cannibal class, corresponding to ∼66 per cent of all IfEs. The large number of IfEs belonging to this class shows that merging events are important for the formation and evolution of IfE galaxies. Cannibals often show a large number of merging events, more than 20, while the number of major merging events ranges from one to three. The possibility of major mergers can complicate the identification of IfEs of this class, especially as we cannot identify any preferred time for the last major merger. In general, IfEs of the cannibal class form early, in the redshift range $5 < z < 12$. However, we identify a few cannibal IfEs that form as late as $z \sim 2.4$. The cannibal IfEs that form late could also be classified as solitudes, especially as these IfEs do not, in general, show a single major merging event, only few minor ones.

This formation class can explain a few observed IfEs. Reda et al. (2004) found low-luminosity dwarfs close to an isolated galaxy that avoid accretion. Three of their IfEs show high central space density, but they also found quite strong morphological disturbances requiring an accretion of a fairly large galaxy. This is in agreement with cannibal IfEs that have had a major merging event that would explain the morphological disturbances, while a large number of smaller satellite dwarfs could have survived due to the large dark matter halo and long dynamical friction times.

## 6 DISCUSSION

### 6.1 Population of blue and faint IfEs

Figs 1 and 2 show a separate population of blue and faint IfEs. This population was also confirmed to comprise IfE galaxies that reside in light, $M_{\mathrm{DM}} < 10^{12}\,h^{-1}\,\mathrm{M}_{\odot}$, dark matter haloes. Moreover, the IfE samples of Reda et al. (2004) and Marcum et al. (2004) do not reveal a single observed IfE that would belong to this predicted population of IfEs.

Hernández-Toledo et al. (2008) studied isolated galaxies and used modern observations of Sloan Digital Sky Survey (SDSS) Data Release 6. The base sample of their galaxies were the Catalogue of Isolated Galaxies (CIG) in the Northern hemisphere compiled by Karachentseva (1973). Although the isolation criteria in the study of Karachentseva (1973) and in our study are not the same, it is still interesting to compare if any of the elliptical galaxies could belong to the population of faint and blue IfEs that our results predict. Hernández-Toledo et al. (2008) noted that four early-type galaxies of the CIG sample showed blue ($g - i < 1.0$) colours. Three of their blue galaxies were found to be discy while the other one was found to be boxy. From the morphological inspections, they concluded that three of the blue galaxies were ellipticals while one was S0-type. Thus, below we will inspect if any of the three blue elliptical galaxies noted in Hernández-Toledo et al. (2008) could belong to the faint and blue population of IfEs that simulations predict.

As the magnitudes of Hernández-Toledo et al. (2008) are in the SDSS system, we need a method to transform their magnitudes for a comparison. For a crude comparison, we can use galaxy colours of Fukugita, Shimasaku & Ichikawa (1995) and derive a transformations

$$M_R \approx M_r - 0.35 \quad (2)$$

for $R$-band magnitudes for a typical elliptical. Since our IfEs show bluer colours than typical ellipticals, this transformation is not very accurate; however, for our purposes it should be adequate. To transform the SDSS colours, we use the following equation:

$$B - R \approx (g - i) + 0.44, \quad (3)$$

which has been derived from the works of Fukugita et al. (1996) and Jester et al. (2005). Again, we note that this may not provide exact colour transformation, but should provide satisfactory conversion for our crude comparisons.

The three isolated ellipticals of Hernández-Toledo et al. (2008) show $g - i$ colours of 0.91, 0.98 and 1.02. With equation (3), we can approximate that these colours correspond to $B - R$ colours of 1.35, 1.42, and 1.46. Clearly, at least one of their galaxy is blue enough ($B - R \leq 1.4$) to belong to the separate population of faint and blue IfEs. Given the inaccuracy of equation (3), it is possible that all three of their galaxies would belong to the blue population of IfEs. The blue galaxies of Hernández-Toledo et al. (2008) have absolute $r$-band magnitudes −20.84, −21.24 and −16.73, respectively. With the help of equation (2), we can approximate their $R$-band magnitudes to be −21.19, −21.59 and −17.08, respectively. Thus, at least two of their galaxies are faint enough ($M_R > -21.5$) to be part of the population.

Above magnitudes and colours show that possibly at least one or up to three IfE galaxies that belong to the predicted population of faint and blue IfEs has already been observed. One of the isolated ellipticals of Hernández-Toledo et al. (2008) is significantly fainter than any of our IfEs, and would not qualify as an IfE in our study. Moreover, as the isolation criteria of CIG galaxies are different than ours, we cannot conclude without a doubt that any of the blue and faint population IfEs have been observed. Thus, more observations of blue and faint isolated elliptical galaxies are required to confirm our prediction.

### 6.2 Observing a formation class

Section 5.3 introduced three typical formation classes of IfE galaxies: solitude, coupling and cannibalism. Our results show that the majority of IfEs experience numerous merging events during their evolution and belong to the cannibalism class. A smaller, yet a significant fraction of IfEs belong to the coupling class, whose members have experienced an equal-sized merging, while only a small fraction of IfEs show insignificant merging activity and belong to the solitude class. If merging events are so important for the evolution of IfEs, an obvious question remains: is it possible to identify the formation scenario based on observational data? Therefore, in this section we briefly discuss the properties of IfEs that can be observed and that at the same time would readily indicate the formation mechanism of the IfE.

IfEs that belong to the coupling class form later than cannibal IfEs and are found to reside in lighter dark matter haloes than cannibal IfEs: the median masses are 54 and 200 $\times\ 10^{10}\,h^{-1}\,\mathrm{M}_{\odot}$, respectively. The coupling class IfEs can therefore be merger remnants of nearby galaxy pairs having a modest sized dark matter halo at redshift zero. Unfortunately, dark matter haloes cannot be observed directly. IfEs of equal-sized mergings can show a weak X-ray emission; however, it is not clear how well this could be detected, if at all. Moreover, differentiating coupled IfEs from cannibals might be difficult from X-ray data only.

The mean number of companion galaxies of IfEs that have formed through coupling is lower than for the cannibal IfEs, but larger than for the solitary IfEs. Unfortunately, the distribution of stellar mass, *B*-band magnitude and colour of IfEs of the coupling class is indistinguishable from the cannibal IfEs. The redshifts of equal-sized merging events suggest that to be able to identify galaxies belonging to the coupling class, observations should concentrate on intermediate redshifts in the range $0.25 < z < 1.4$. However, to find evidence of equal-sized merging may not be simple; it is not clear how different are the traces an equal size merger leaves, compared to a major merger. Study of stellar populations could provide a way to identify IfEs that have experienced an equal-sized merging, but this may not be applicable for high redshifts.

A cannibal IfE can be a merger remnant of a small or compact group. We find cannibal IfEs to reside in more massive and larger dark matter haloes than other types of IfEs. However, their dark matter haloes are less massive than haloes of typical groups, leaving only small or compact groups to consider. Multiple merging events of cannibal IfEs could also be visible in their stellar populations, especially if merging events were gas-rich, so-called wet mergers. Observational evidence shows that it is possible to detect IfEs in X-ray observations (e.g. Mulchaey & Zabludoff 1999; O'Sullivan & Ponman 2004; Sivakoff et al. 2004; Memola et al. 2009). Due to their more massive dark matter haloes, X-ray bright IfEs are the best candidates for the cannibal formation class.

### 6.3 Comparison to fossil groups

Have fossil groups formed in a similar way as IfE galaxies? Are IfEs an intermediate product while they develop to become fossil groups, or vice versa? These questions are justified as the selection criteria of IfEs are very similar to those used for the identification of fossil groups, especially if only optical data are available. Objects of both classes are required to show a large magnitude gap between the brightest and the second brightest galaxy in optical. In general, fossil groups are also required to show extended X-ray emission while it is not demanded for IfEs. However, several IfEs have shown some amount of extended X-ray emission even if it is not required. Due to similar selection criteria, objects of both classes might have similar evolution and assembly histories and a similar formation mechanism, being actually the same class seen only at different phases of evolution.

The majority of fossil groups seem to have experienced the last major merging event longer than 3 Gyr ago and they have assembled half of their final mass by $z \geq 0.8$ (von Benda-Beckmann et al. 2008). Moreover, von Benda-Beckmann et al. (2008) found from simulations that only 15 per cent of fossil groups experience the last major merger less than 2 Gyr ago, and at least 50 per cent had the last major merger longer than 6 Gyr ago. These time-scales are in modest agreement with our findings. Our results show that IfEs have experienced their last major merging, on average, ∼6 Gyr ago, while IfEs have half of their final mass assembled by $z \sim 1$. For fossil groups, this number is ∼0.6 (Díaz-Giménez et al. 2008).

Díaz-Giménez et al. (2008) study the evolution of the brightest galaxies of fossil groups. They identified fossil groups from the MS and adopted the same galaxy catalogue (Lucia & Blaizot 2007) as in this study, making it interesting to compare their findings to ours. When comparing the medians of assembly, formation and identity times, we find that IfE galaxies have assembled their stars earlier than the brightest galaxies of fossil groups $z_{\mathrm{a}} \sim 1.1$ and ∼0.6, respectively. However, fossil groups form significantly earlier than IfEs $z_{\mathrm{f}} \sim 3.6$ and ∼1.5, respectively. The median time of the last major merging of the IfEs is almost twice ($z_{\mathrm{i}} \sim 0.6$) the identity time of the brightest galaxies of fossil groups ($z_{\mathrm{i}} \sim 0.3$). These discrepancies in formation and evolutionary times cast a serious doubt over the idea of similar formation mechanisms.

von Benda-Beckmann et al. (2008) argue that the primary driver for the large magnitude gap is the early infall of massive satellites that is related to the early formation time of fossil groups. We do not find infall of massive satellites at early time in our sample of simulated IfE galaxies. The early evolution of an IfE includes relatively minor mergers, except for some IfEs that experience an equal-sized merging. However, the time of the equal-sized mergers is usually in a later stage of the development of the IfE, not early as argued for fossil groups. Our study shows that the primary driver for the large magnitude gap of IfEs is either a merging of a comparable sized galaxy pair or effective mass accretion and sweeping up of surrounding galaxies (coupling and cannibalism, respectively).

Dariush et al. (2007) argue that fossil groups can be identified from dark matter only simulations if one selects dark matter haloes more massive than $5 \times 10^{13}\,h^{-1}\,\mathrm{M}_{\odot}$. They argue that above that limit, all optical fossil groups in the MS have enough hot gas to show X-ray emission, therefore qualifying as X-ray fossils. Our Table 3 shows that the median mass of the dark matter haloes of IfEs is only $\sim 1.2 \times 10^{12}\,h^{-1}\,\mathrm{M}_{\odot}$, while even the third quartile is just $\sim 2.4 \times 10^{12}\,h^{-1}\,\mathrm{M}_{\odot}$. This comparison shows that IfEs reside in significantly lighter dark matter haloes than the brightest galaxies of fossil groups. Dariush et al. (2007) argued that fossil groups have formed early and that more than ∼80 per cent of their mass accumulated as early as 4 Gyr ago. Moreover, they suggest that X-ray fossil groups are not a distinct class of objects but rather that they are extreme examples of groups which collapse early and experience little recent growth. This formation scenario does not apply for IfEs, as cannibal IfEs can have merging activity till the redshift $z \sim 0$, and IfEs start to form later than fossil groups.

Although a large magnitude gap seen in both fossils and IfEs could imply a similar formation mechanism, the above comparison does not support this idea. Considering the assembly and formation times, it seems unlikely that fossil groups, and especially their brightest galaxies, could share the same formation mechanism as IfE galaxies. The large differences in dark matter halo masses of fossil groups and the most massive IfEs makes it improbable that fossil groups and IfEs are the same class of objects seen at different phases of their evolution. We therefore conclude that fossil groups and IfEs form two distinct classes.

## 7 SUMMARY AND CONCLUSIONS

The aim of this paper is twofold: (1) to compare simulated field elliptical galaxies with observed ones and to make predictions on their properties and (2) to define the formation mechanism and history of IfE galaxies. We also discuss if IfE galaxies are related to fossil groups and if they can share a common formation mechanism.

Our results show that it is possible to identify IfE galaxies from cosmological *N*-body simulations with semi-analytical models of galaxy formation, that have similar properties to observed IfEs. We show that simulated IfEs are in good agreement with observations when similar identification criteria are adopted. The CMD of simulated IfEs agree with observations, and the average colour of simulated and observed IfEs are within their error limits when all simulated IfEs are considered. Unfortunately, observational data sets are still small complicating more detailed comparison. An agreement in age and mass estimates of IfEs between observations and simulations is found. However, the age comparisons are less robust due to different age definitions.

Our results show that IfEs are very rare objects; we find their total number density to be as low as $\sim 8.0 \times 10^{-6}\,h^3\,\mathrm{Mpc}^{-3}$. Our result agrees with observational estimates of number of IfEs, which however, are inaccurate at best. Our IfEs have a small number of companion galaxies, ranging from only a few dwarf companions to as much as about 20. Thus, IfEs are not completely isolated, although they are found to be located in underdense regions. Our results show that IfEs reside in relatively light dark matter haloes. However, at the same time, the baryonic to dark matter ratio is higher in IfEs than in Es generally. The stellar mass of IfEs grows almost linearly with the dark matter mass with a mass ratio (dark/stellar) of $\sim 4 \times 10^{-2}$, whereas our comparison ellipticals have a lower stellar to dark matter ratio. Therefore, IfEs are good candidates for galaxies with low dark matter mass to stellar light ratio. We also find a flat *B*-band luminosity function for our simulated IfEs.

When studying the basic properties of IfEs, we find that IfEs populate different regions in CMDs than regular elliptical galaxies, which are found mostly in the red sequence. This is due to the bimodality of the distribution of colours, as IfEs populate not only the red sequence, but also the blue cloud. From simulation data, we find a separate population of blue and faint IfEs. On average, IfEs are found to be bluer than our control sample ellipticals; however, this result is biased because of the separate population of IfEs. The bluest IfEs are found to reside in light dark matter haloes, while red IfEs are usually found inside more massive ($M_{\mathrm{DM}} \geq 10^{12}\,h^{-1}\,\mathrm{M}_{\odot}$) dark matter haloes. We note that simulations predict a previously unobserved population of blue, dim and light galaxies that fulfil observational criteria to be classified as IfE galaxies. These galaxies have only a few companions, which are usually located many times further away than the virial radius of their dark matter halo. These blue, dim and light IfEs have formed their stars only lately and have continued to accrete dark matter mass till redshift zero. This population of IfEs is very interesting as it has not been detected yet in observations.

Our results also show that IfEs start to form around the same epoch as the galaxies of the control sample (MEs); however, IfEs seem to accumulate stellar mass much faster. IfEs form stars more efficiently than MEs, while MEs accrete dark matter slightly faster than IfEs. We confirm that IfEs form the bulk of their stars at $z > 2$, as suggested in Reda et al. (2005). By $z = 1$, IfEs have formed over half of their stars (stellar mass) and have gathered as much as 80 per cent of their final dark matter. The galaxies of MEs sample have accreted roughly the same fraction of dark matter as IfEs by $z \sim 1$. However, they have formed as little as 30 per cent of their stars compared to the final stellar matter at $z = 0$. This difference shows that IfEs form their stars quickly and are rather dark-matter poor compared to other elliptical galaxies. Moreover, IfEs continue to accrete dark matter till $z = 0$ while MEs have gathered ∼99 per cent of their final dark matter already by $z \sim 0.5$. We note that more massive (and luminous) IfEs have older stellar populations, while the lighter ones have formed a signification fraction of their stellar mass relatively recently.

While studying the evolution of IfEs, we note that almost half (∼46 per cent) of IfEs have experienced at least one major merger during their formation history, while only about 4 per cent (Es) up to one-third (MEs) of control sample ellipticals experience a major merger. Major merging events happen later in IfEs evolution than for control sample galaxies, the average of the latest major merging being $z \sim 0.6$ for IfEs while it is $z \sim 1.1$ for MEs. We also find IfEs that have not experienced a single merger event above the mass resolution limit of the MS during their evolution. Therefore, it is possible to form elliptical galaxies without major mergers.

When inspecting the merger trees of simulated IfEs, we identify three typical formation scenarios: solitude, coupling and cannibalism, which can all lead to a formation of an IfE. The scenarios range from a solitary growth (solitude class) with quiet mass accretion and star formation to more violent evolution with multiple mergers (cannibalism class). We also identify a formation scenario where two comparable sized galaxies merge to form an IfE (coupling class). Our merger trees show that merging events are important for IfEs that form through cannibalism or coupling. All three formation classes are in agreement with observational findings.

Comparison between IfE galaxies and fossil groups show that these two classes are distinct. Galaxies of both classes show some similarities, but many properties and evolution times are significantly different. IfEs reside in significantly lighter dark matter haloes and we do not find an infall of massive galaxies at early times for IfEs as argued for fossil groups (von Benda-Beckmann et al. 2008). However, we cannot exclude that some fossil groups could not share the formation mechanism of the most massive IfEs, namely cannibalism.

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