The intriguing life of massive galaxies
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Modelling the formation of today's massive ellipticals

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Abstract. The discovery of a population of massive, compact and quiescent early-type galaxies has changed the view on plausible formation scenarios for the present day population of elliptical galaxies. Traditionally assumed formation histories dominated by 'single events' like early collapse or major mergers appear to be incomplete and have to be embedded in the context of hierarchical cosmological models with continuous gas accretion and the merging of small stellar systems (minor mergers). Once these processes are consistently taken into account the hierarchical models favor a two-phase assembly process and are in much better shape to capture the observed trends. We review some aspects of recent progress in the field.

Keywords. galaxies: elliptical and lenticular, galaxies: formation, galaxies: evolution

1. Introduction

During the formation and assembly of massive galaxies merging is a natural process in modern hierarchical cosmological models. It is expected to play a significant role for the structural and morphological evolution (e.g. Kauffmann *et al.* 1996; Kauffmann 1996; De Lucia *et al.* 2006; Khochfar & Silk 2006; De Lucia & Blaizot 2007; Guo & White 2008; Kormendy *et al.* 2009; Hopkins *et al.* 2010a). In the light of these theoretical expectations and direct observations of 'dry' mergers of gas poor elliptical galaxies up to high redshift (van Dokkum 2005; Tran *et al.* 2005; Bell *et al.* 2006a,b; Lotz 2008; Jogee 2009; Newman *et al.* 2012; Man *et al.* 2012) simulations of idealized collisionless mergers have again received attention and new studies were triggered. Merger simulations of already existing spheroidal galaxies have focused in detail on the evolution of abundance gradients, shapes and kinematics, scaling relations, sizes and dark matter fractions (White 1978, 1979; Makino & Hut 1997; Boylan-Kolchin *et al.* 2005; Naab *et al.* 2006b; Boylan-Kolchin *et al.* 2006, 2008; Di Matteo *et al.* 2009; Nipoti *et al.* 2009b, 2012a). If the progenitors were two disk galaxies (which then can include a gaseous component) the aim was to investigate the morphological transformation, i.e. the formation of new dynamically hot spheroidal elliptical galaxies from two dynamically cold progenitor spiral galaxies (Gerhard 1981; Farouki & Shapiro 1982; Negroponte & White 1983; Barnes 1988; Barnes & Hernquist 1992; Hernquist 1992). Apart from studies of the effect of the merger mass-ratio (Barnes 1998; Bekki 1998; Bendo & Barnes 2000; Naab & Burkert 2003; Bournaud *et al.* 2004, 2005; González-García & Balcells 2005) the tidal torquing of gas, its inflow to the central regions, the impact on the stellar orbits (Barnes & Hernquist 1996; Naab *et al.* 2006a; Hoffman *et al.* 2010), subsequent starbursts (Mihos & Hernquist 1994, 1996; Barnes 2004; Di Matteo *et al.* 2008) and the potential growth of black holes (Hernquist 1989; Springel *et al.* 2005; Di Matteo *et al.* 2005; Johansson *et al.* 2009a; Younger *et al.* 2009) was investigated in numerous studies together with influential studies on the origin of early-type galaxy scaling relations (Robertson *et al.* 2006; Dekel & Cox 2006; Cox *et al.* 2006; Hopkins *et al.* 2008, 2009c,b,d; Debuhr *et al.* 2010; Moster *et al.* 2011). However, despite the detailed insights on the stellar and gas dynamical processes in simulated galaxy mergers, the 'binary merger' approach is limited in scope and seems not to be able to naturally explain all properties of present day massive elliptical galaxies (Naab & Ostriker 2009).

The most massive elliptical galaxies (or their progenitors) are considered to start forming their stars at high redshift ($z \sim 6$, or higher) in a dissipative environment, rapidly become very massive ($\sim 10^{11} M_{\odot}$) by $z = 2$ (Keres *et al.* 2005; Khochfar & Silk 2006; De Lucia *et al.* 2006; Kriek *et al.* 2006; Naab *et al.* 2007, 2009; Joung *et al.* 2009; Dekel *et al.* 2009; Keres *et al.* 2009; Oser *et al.* 2010; Feldmann *et al.* 2010; Domínguez Sánchez 2011; Feldmann *et al.* 2011; Oser *et al.* 2012). A significant fraction of this high redshift population is observed to be already quiescent at $z \sim 2$, on average 4-5 times more compact (part of this apparent evolution might driven by selection effects, see e.g. Poggianti *et al.* 2012), and typically a factor of two less massive than their low redshift descendants (Daddi *et al.* 2005; van der Wel *et al.* 2005; di Serego Alighieri *et al.* 2005; Trujillo 2006; Longhetti *et al.* 2007; Toft *et al.* 2007; Buitrago *et al.* 2008; van Dokkum *et al.* 2008; van der Wel *et al.* 2008; Cimatti *et al.* 2008; Franx *et al.* 2008; Damjanov *et al.* 2009; Cenarro & Trujillo 2009; Bezanson *et al.* 2009; van Dokkum *et al.* 2010; van de Sande *et al.* 2011; Whitaker *et al.* 2012). It is reasonable to assume that the high-redshift population forms the cores of at least some, if not all, present day massive ellipticals. This rapid structural evolution is supposed to happen in an inside-out fashion, mainly by adding stellar mass to the outer parts of the galaxies over time, however, without the formation of a significant fraction of new stars (Hopkins *et al.* 2009a; van Dokkum *et al.* 2010; Szomoru *et al.* 2012; Saracco *et al.* 2012). In this respect the growth of massive quiescent high-redshift galaxies is markedly different to the star formation driven inside-out growth of disk galaxies

The implications of these observational findings for the formation and evolution of massive elliptical galaxies are many-fold. They are unlikely to have formed by an initial 'monolithic collapse' followed by passive evolution as their present day counterparts would be too small and too red (van Dokkum *et al.* 2008; Kriek *et al.* 2008; Bezanson *et al.* 2009; Ferré-Mateu *et al.* 2012). In addition the evolution of these systems cannot be explained by just a single 'binary merger of disk galaxies'. The compact high-redshift systems might have formed in such a process (Wuyts *et al.* 2010; Bournaud *et al.* 2011), if it were gas-rich, but the subsequent structural evolution requires additional processes which are not driven by the formation of new stars. Observational results that almost none of these massive compact galaxies were able to survive to the present day (Trujillo *et al.* 2009; Taylor *et al.* 2010) indicate that a general and common physical mechanism must be at work. Spectacular events alone, like major early-type galaxy mergers, might be too rare.

2. Minor mergers vs. major mergers

Minor merges, however, are expected to happen frequently in the lifetime of a massive galaxy and have received particular attention as they provide a natural way to increase the size of a galaxy. With only a few assumptions the virial theorem provides a simple estimate of how a one-component system evolves during major and minor mergers (Cole *et al.* 2000; Naab *et al.* 2009; Bezanson *et al.* 2009). Following Naab *et al.* (2009) we assume that a compact initial stellar system has formed (e.g. involving gas dissipation) with a total energy E_i, a mass M_i, a gravitational radius $r_{g,i}$, and the mean square speed of the stars is $\langle v_i^2 \rangle$. According to the virial theorem (Binney & Tremaine 2008) the total energy of the system is

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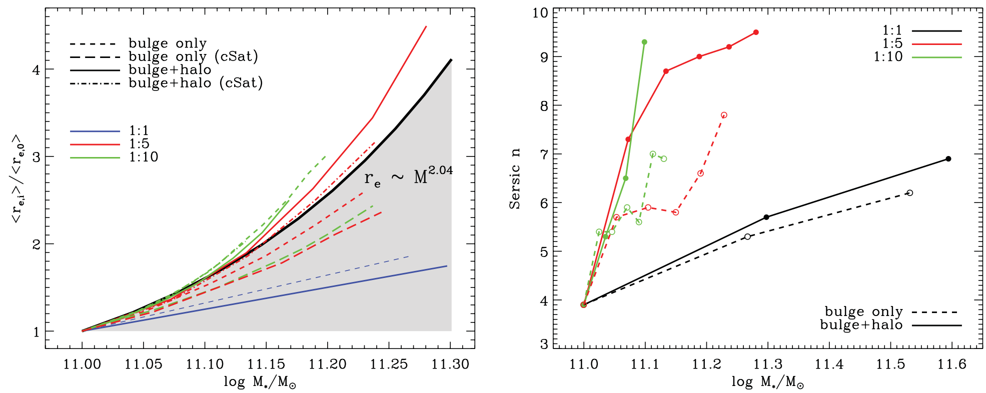

Figure 1. *Left:* Simulated size evolution as a function of bound stellar mass for mergers with mass-ratios 1:1 (blue), 5:1 (red), and 10:1 (green). The observationally expected relation is indicated by the black line (van Dokkum *et al.* 2010). The presence of dark matter significantly boosts the size evolution of 5:1 and 10:1 mergers. *Right:* This also leads to a significantly stronger evolution of the Sersic index (figures taken from Hilz *et al.* 2012a)

$$\begin{aligned} E_i &= K_i + W_i = -K_i = \frac{1}{2} W_i \\ &= -\frac{1}{2} M_i \langle v_i^2 \rangle = -\frac{1}{2} \frac{G M_i^2}{r_{g,i}}. \end{aligned}$$

This system then merges (on zero energy orbits) with other systems of a total energy E_a, total mass M_a, gravitational radii r_a and mean square speeds averaging $\langle v_a^2 \rangle$. The fractional mass increase from all the merged galaxies is $\eta = M_a/M_i$ and the total kinetic energy of the material is $K_a = (1/2) M_a \langle v_a^2 \rangle$, further defining $\epsilon = \langle v_a^2 \rangle / \langle v_i^2 \rangle$. Under the assumption of energy conservation (results from Khochfar & Burkert (2006) indicate that most halos merge on parabolic orbits) the ratio of initial to final mean square speeds, gravitational radii and densities can be then written as (Naab *et al.* 2009)

$$\frac{\langle v_f^2 \rangle}{\langle v_i^2 \rangle} = \frac{(1+\eta\epsilon)}{1+\eta}, \frac{r_{g,f}}{r_{g,i}} = \frac{(1+\eta)^2}{(1+\eta\epsilon)}, \frac{\rho_f}{\rho_i} = \frac{(1+\eta\epsilon)^3}{(1+\eta)^5}.$$

For mergers of two identical systems, $\eta = 1$, the mean square speed would remain unchanged, the size increases by a factor of two and the densities drop by a factor of four. In the limit that the mass is accreted in the form of very weakly bound stellar systems with $\langle v_a^2 \rangle << \langle v_i^2 \rangle$ or $\epsilon << 1$, the mean square speed is reduced by a factor two, the size increases by a factor four and the density drops by a factor of 32. These estimates are, however, idealized assuming one-component systems, no violent relaxation and zero-energy orbits with fixed angular momentum.

Hilz *et al.* (2012b) have recently re-investigated in detail the collisionless dynamics of major and minor mergers of systems including concentrated stellar spheroidal components embedded in extended dark matter halos. They present more accurate versions of the above equations including the effect of escapers and the interaction of the stellar baryonic with dark matter and describe in detail how the presence of a massive dark matter halos alter the evolution of the merging systems. One result of this study was that both minor and major mergers lead to size growth and an increase of the dark matter fraction. The physical processes are, however, different. Violent relaxation in major mergers mixes

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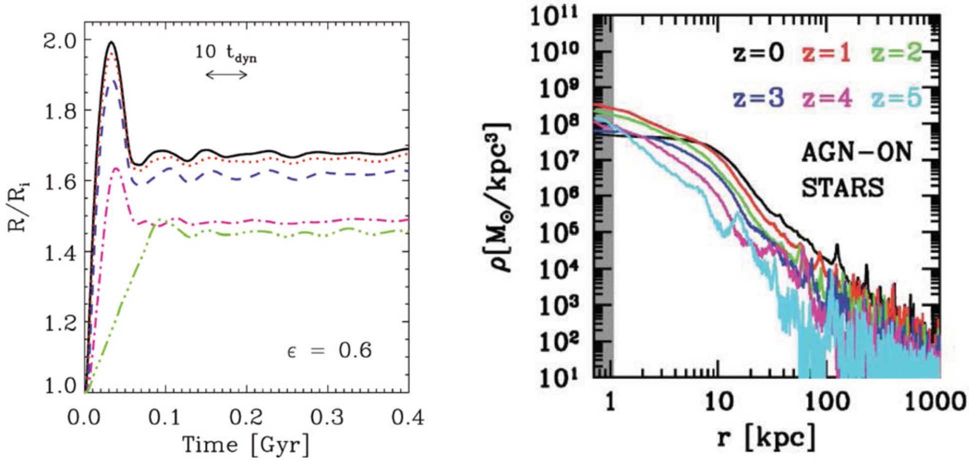

Figure 2. *Left:* Size evolution driven by rapid mass-loss from the idealized simulations of isolated galaxies. If 40 per cent of the mass is lost ($\epsilon = 0.6$) the sizes can rapidly increase by 60 per cent. From the black to the green line the ejection varies from immediate ejection to an ejection time of 80 Myrs (taken from Ragone-Figueroa & Granato 2011). *Right:* Evolution of the stellar surface density profiles of a cosmological zoom-simulation of a brightest cluster galaxy in a model with strong AGN feedback. Due to the gas explusion from the AGN the system is significantly more extended than in the no-AGN case and even develops a central core (taken from Martizzi *et al.* 2012).

dark matter to the central regions. Escaping, unbound, particles limit the expected size growth to values below the ones expected from the idealized equations above. In minor mergers (mass-ratios of 1:5 and 1:10), the stellar satellites are stripped at large radii where the host galaxies dominated by dark matter and the stellar effective radii and the dark matter fractions grow more rapidly than expected from the simple virial equations (see also Laporte *et al.* 2012). Due to the addition of stellar satellite material at large radii (Villumsen 1983), the stellar mass distribution changes significantly resulting in a significant increase of the Sersic index (see Fig. 1 and Hilz *et al.* 2012a). The general results on size evolution are in agreement with similar studies by e.g. Oogi & Habe (2012). However, there is an ongoing debate of whether the size growth by minor mergers is sufficient to explain the observed cosmological size evolution of elliptical galaxies. Whereas Oogi & Habe (2012) argue that the size growth by minor mergers alone might be sufficient, studies by Nipoti *et al.* (2012b), Cimatti *et al.* (2012), and Newman *et al.* (2012) have combined idealized numerical simulations embedded in a cosmological context and new observational constraints. They come to the conclusion that minor mergers might be able to explain the observed size growth from redshift $z \sim 1$ to the present. However, at higher redshift minor and major mergers might not be frequent enough to explain the rapid size evolution observed at $z \gtrsim 1$ and therefore an additional physical mechanism might be required.

A potential candidate for such an additional process is AGN driven outflow of gas from a massive high-redshift gas-rich and compact galaxy (Fan *et al.* 2008; Hopkins *et al.* 2010b; Fan *et al.* 2010). In general, stellar systems suffering from central mass-loss $\epsilon_{\rm loss} = M_{\rm final}/M_{\rm initial}$ will expand (Hills 1980) and for rapid and slow mass-loss simple relations for the ratio of the final to the initial radius can be derived:

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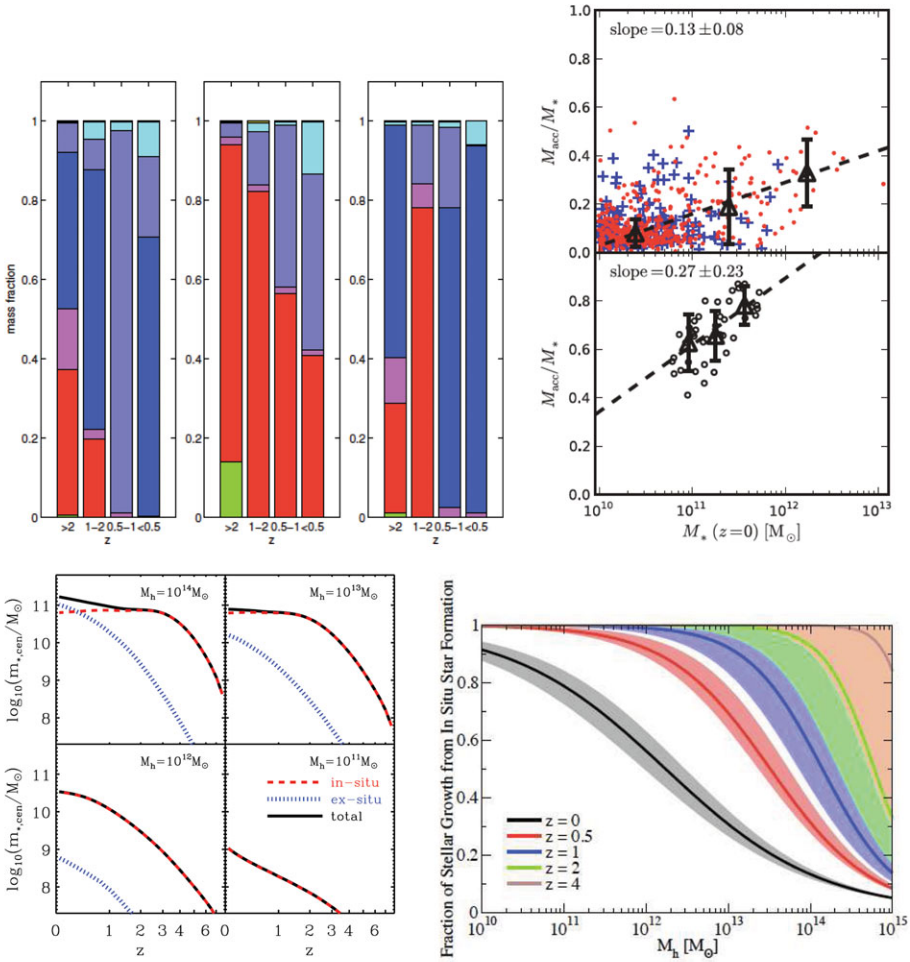

Figure 3. *Upper left:* Examples for the assembly history (stellar origin) of three massive galaxies in high-resolution cosmological zoom simulations. At high redshift the formation is dominated by in-situ star formation (red colors). The low redshift assembly is dominated by merging of stellar systems (blue colors, taken from Feldmann *et al.* 2010). *Upper right:* Ratio of the accreted over final stellar mass versus final stellar mass for galaxies in a cosmological simulation box (void: blue, cluster: red) including strong supernova feedback (upper panel). The fraction of accreted stars is about a factor 2 -3 lower than in the high-resolution zoom simulations of Oser *et al.* (2010) without strong supernova feedback (lower panel); the trend with mass is similar but less strong (taken from Lackner *et al.* 2012). *Lower left:* Independent estimate of the ratio of accreted to in-situ formed stars as a function of halo mass from abundance matching studies (Moster *et al.* 2012). *Lower right:* Similar estimates from a study by Behroozi *et al.* (2012). Both studies find a strong trend that the assembly of galaxies in more massive halos is more dominated by the accretion of stars rather than in-situ star formation.

$$\frac{R_{final,rapid}}{R_{initial}} = \frac{\epsilon_{loss}}{2\epsilon_{loss} - 1},$$
$$\frac{R_{final,slow}}{R_{initial}} = \frac{1}{\epsilon_{loss}}.$$

It is worth noting that rapid mass-loss of more than half the total mass can unbind the whole system. This process is well known and has been studied for star clusters (Hills

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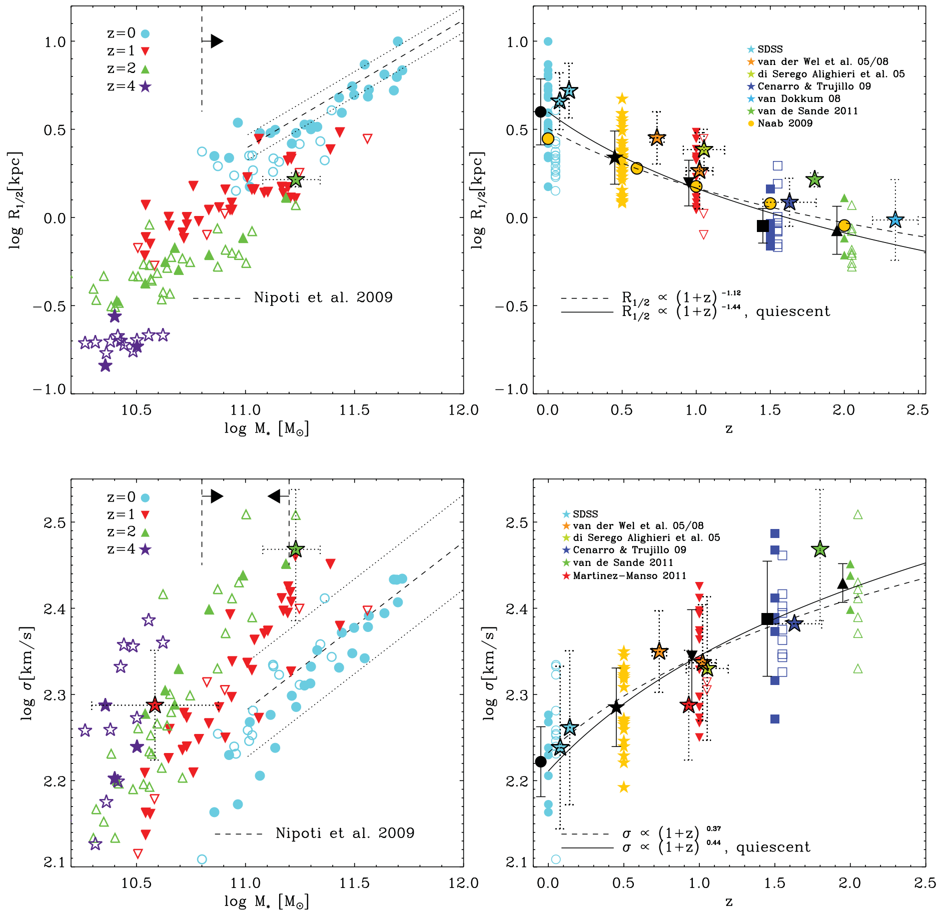

Figure 4. *Upper panels:* The present day mass-size relation (left) for a sample of high-resolution zoom simulations (blue points, full symbols are quiescent galaxies) compared to observations. The evolution of the relation is driven by accretion of stars and is indicated by the location of the most massive progenitor galaxies at different redshifts. For all galaxies more massive than the mass limit indicated on the left plot ($\log(M_*) = 10.8$) the average size evolution agrees well with observations. *Lower panels:* Similar plot for the evolution of the mass-dispersion relation (left). In a fixed mass range galaxies have higher dispersions at higher redshifts (right). Again, the simulated evolution is very similar to the observed one (figures are taken from Oser *et al.* 2012).

1980), galaxies (Hills 1980; Hopkins *et al.* 2010b; Ragone-Figueroa & Granato 2011; Pontzen & Governato 2012), as well as cores of galaxy clusters (see Fig. 2 and Martizzi *et al.* 2012).

3. The cosmological two-phase assembly

The assembly histories of massive galaxies in currently favored hierarchical cosmological models are significantly more complex than a single binary merger. They grow - in particular at high redshift - by smooth accretion of gas, major mergers but also numerous minor mergers covering a large range of mass-ratios which can dominate the amount of assembled stars. The picture that is emerging from semi-analytical models and high-resolution cosmological simulations of massive galaxies bears a two-phase characteristic

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(De Lucia & Blaizot 2007; Guo & White 2008; Genel *et al.* 2008; Feldmann *et al.* 2010; Oser *et al.* 2010; Feldmann *et al.* 2011; Hirschmann *et al.* 2012).

At high redshifts the formation is dominated by dissipative processes (i.e. significant radiative energy losses) and in-situ star formation leading to compact progenitors with high phase space densities. In a second phase massive galaxies are growing by the addition of stars at large radii that have formed early outside the main galaxies in other galaxies that were accreted later-on. This assembly phase is dominated by collisionless dynamics and radiative energy losses are of minor importance (see e.g. Johansson *et al.* 2009b; Lackner & Ostriker 2010; Laporte *et al.* 2012).

Independent studies using cosmological simulations based on different numerical methods come to similar conclusions that - on average - the mass assembly of massive galaxies is dominated by minor mergers with mass-ratios $\sim 1:5$ (Oser *et al.* 2012; Lackner *et al.* 2012; Gabor & Davé 2012). The relative importance of accreted versus in-situ formed stars increases with galaxy mass, a result that was already predicted by semi-analytical models (De Lucia *et al.* 2006; De Lucia & Blaizot 2007; Guo & White 2008) and has been confirmed by independent estimates from abundance matching techniques (Moster *et al.* 2012; Behroozi *et al.* 2012). The absolute fractions are model dependent and can vary e.g. by $\sim 50\%$ for different feedback models (see Fig. 3). Studies based on cosmological zoom simulations make a plausible point that the present day scaling relations might be set by the stellar accretion history of massive galaxies, i.e. the above mentioned fraction of in-situ to accreted stars (Oser *et al.* 2012). In addition, based on still small samples, in high-resolution cosmological simulations the evolution of the scaling relations appears to be in accordance with observations (Feldmann *et al.* 2011; Oser *et al.* 2012; Johansson *et al.* 2012). However, in general the cosmological simulations of massive galaxies still fail to reproduce all observational constraints at the same time and are still limited with respect to either resolution and statistics as well as the algorithmic implementation of relevant feedback processes. In particular feedback from super-massive black holes might help to finally meet observational constraints for massive ellipticals (McCarthy *et al.* 2010, 2011; Puchwein & Springel 2012).

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