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LETTER TO THE EDITOR

# Mass downsizing and "top-down" assembly of early-type galaxies

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**ABSTRACT**

*Aims.* We present a new analysis of the rest-frame $B$-band COMBO-17 and DEEP2 luminosity functions (LFs) of early-type galaxies (ETGs) as a function of luminosity and mass. Our aim is to place new stringent constraints on the evolution of ETGs since $z \sim 1$.

*Methods.* We correct the LF($z$) data for the luminosity dimming assuming pure luminosity evolution. However, instead of relying on stellar population synthesis model-dependent assumptions, we adopt the empirical luminosity dimming rate derived from the evolution of the Fundamental Plane of field and cluster massive ETGs.

*Results.* Our results show that the amount of evolution for the ETG population depends critically on the range of luminosity and masses considered. While the number density of luminous (massive) ETGs with $M_B(z = 0) < -20.5$ ($\mathcal{M} > 10^{11}\ M_\odot$) is nearly constant since $z \sim 0.8$, less luminous galaxies display a deficit which grows with redshift and that can be explained with a gradual population of the ETG "red sequence" by the progressive quenching of star formation in galaxies less massive than $\sim 10^{11}\ M_\odot$. At each redshift there is a critical mass above which virtually all ETGs appear to be in place, and this fits well in the now popular "downsizing" scenario. However, "downsizing" does not appear to be limited to star formation, but the concept may have to be extended to the mass assembly itself as the build-up of the most massive galaxies preceeds that of the less massive ones. This evolutionary trend is not reproduced by the most recent theoretical simulations even when they successfully reproduce "downsizing" in star formation.

**Key words.** galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation

## 1. Introduction

Early-type galaxies (ETGs) dominate the top-end of the local ($z \sim 0$) galaxy mass function, and therefore are crucial probes to investigate the history of galaxy mass assembly. There is now convincing evidence that cluster ETGs formed the bulk of their stars very early in the evolution of the Universe, i.e., at $z \gtrsim 3$, while ETGs in low density ("field") environments did so 1 or 2 Gyr later, i.e., at $z \gtrsim 1.5$–2 (e.g., Thomas et al. 2005; Renzini 2006; and refs. therein). However, in the current hierarchical scenario star formation and mass assembly are not necessarily concomitant processes in galaxy formation: stars may well have formed at very high redshift in relatively small units, but only at lower redshift (e.g., $z \lesssim 1$) they may have merged together to build the massive ETGs that we see in the nearby universe. Only recently, with the advent of wide-field surveys (i.e. $\gtrsim$1 square degree) it became possible to reduce the strong cosmic variance which affects ETG studies, and place more stringent constraints on the ETG evolution. Yet, conclusions reached by different studies still appear quite discrepant with respect to each other. On the one hand, some results indicate little evolution. For instance, the VIMOS VLT Deep Survey (VVDS) shows that the rest-frame $B$-band LF of ETGs with $I < 24$ is consistent with passive evolution up to $z \sim 1.1$, and the number of bright ETGs decreases by only ~40% from $z \sim 0.3$ to $z \sim 1.1$ (Zucca et al. 2006). Similarly, the Subaru/XMM-Newton Deep Survey (SXDS) selected a large sample of ETGs at $z \sim 1$ down to $z' < 25$, finding their number density at $M_B^*$ to be up to 85% that of ETGs at $z = 0$ (Yamada et al. 2005). Moving ETG selection to even longer wavelengths, $K$-band selected surveys uncovered a substantial population of old (1–4 Gyr), massive ($\mathcal{M} > 10^{11}\ M_\odot$), passively evolving E/S0 galaxies at $1 < z < 2$ (e.g. Cimatti et al. 2002a, 2004; McCarthy et al. 2004; Glazebrook et al. 2004; Daddi et al. 2005; Saracco et al. 2005), and showed that the high-luminosity/high-mass tails of the total luminosity and stellar mass functions (which are dominated by old ETGs) evolve only weakly to $z \sim 0.8$–1 (e.g. Pozzetti et al. 2003; Fontana et al. 2004; Drory et al. 2005; Caputi et al. 2006; Bundy et al. 2006).

On the other hand, the COMBO-17 (Bell et al. 2004a) and DEEP2 (Faber et al. 2005) surveys indicate a stronger evolution of the ETG population characterized by a faster decrease of the number density with redshift. These two surveys rely on either high-quality photometric (COMBO-17) or spectroscopic redshifts (DEEP2), and ETGs were selected in the optical ($R < 24$) for lying on the "red sequence" in the rest-frame $U - V$ vs. $M_B$ color-magnitude relation, with as many as ~85% of them being also morphologically early-type (Bell et al. 2004b). The red sequence of ETGs in COMBO-17 becomes progressively bluer in the rest frame $U - V$ color, going from $z = 0$ to $z = 1$, consistent with pure passive evolution of stellar populations formed at high redshift ($2 < z_{\rm f} < 5$, Bell et al. 2004a). The rest-frame $B$-band luminosity function in the variousredshift bins was fitted (both in COMBO-17 and DEEP2) with a Schechterfunction, thus determining $M_B^*(z)$ and $\phi^*(z)$, havingassumed the faint-end slope of the LF to be independent of $z$, andfixed at its low-redshift value (−0.5 and −0.6, respectively for DEEP2 and COMBO-17). As such, this latter assumption virtuallyexcludes "downsizing" in galaxy formation, i.e. star formationending first in massive galaxies than in lower mass ones, a trend forwhich ample evidence is growing both at low and high redshift (Cowie et al. 1996; Thomas et al. 2005; Tanaka et al. 2005; Kodama et al. 2004; van der Wel et al. 2005; Treu et al. 2005; di Serego et al. 2005; Juneau et al. 2005; Feulner et al. 2005; Bundy et al. 2006). With theseassumptions, Faber et al. (2005) analyzed the DEEP2 data andre-analyzed the COMBO-17 data as well, finding $L^*_B$ toincrease by a factor ∼1.5 (∼2.4) between $z = 0.3$ and 1.1, while $\phi^*$ drops by a factor ∼2.5 (∼4), where values in parenthesis refer to COMBO-17 data. In the case of COMBO-17 data, also the brightening of $L^*_B$ is consistent with passive evolution. In both cases the $B$-band luminosity density provided by ETGs ($j_B \propto L^*_B\phi^*$) remains flat up to $z \sim 0.9$, while pure passiveevolution would have predicted an increase of the luminosity densityby a factor ∼2–3. Thus, while the ETG colors and $M^*_B(z)$ follow the passive evolution, the number density of ETGs does not, both Bell et al. (2004a) and Faber et al. (2005) concluded that the stellar mass in red sequence ETGs has nearly doubled since $z \sim 1$. Bell et al. further interpreted this result as strong evidence in supports of the semi-analytic model of galaxy formation by Cole et al. (2000), which indeed predicts $j_B$ to remain constant to $z \sim 1$. Both Bell et al. and Faber et al. then argue for a major role of ETG-ETG merging (now called "dry" merging) in the build up of the ETG population between $z \sim 1$ and $z \sim 0$, especially for the most massive ones given the shortage of massive star-forming precursors.

In this paper we attempt at offering a new and consistent interpretation of the COMBO-17 and DEEP2 data by exploring the dependence of ETG evolution on luminosity and mass, and where the passive evolution and number density decline with redshift are reconciled in a scenario that is also consistent with all other empirical evidences on ETGs, at low, as well as high redshift. We adopt $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ and give magnitudes in Vega photometric system.

## 2. Lost and found progenitors to local ETGs

In this section, we analyze with a new approach the COMBO-17 and DEEP2 LFs in order to investigate the evolutionary link between the high-$z$ ETGs and their local descendants, as well as the metamorphosis of other kinds of galaxies to progressively turn passive and qualify as ETGs. In doing so, we assume that ETGs which are passive at high redshift will remain passive through $z = 0$ and will be subject to pure luminosity evolution. This is justified by the color evolution of the red sequence following the expectations for pure passive evolution (Bell et al. 2004a). Under this assumption, we *evolve* down to $z = 0$ the ETG LF($z$) in each redshift bin, and compare it with the corresponding LF of local ETGs. Instead of relying on stellar population synthesis models, we adopt the passive luminosity dimming derived empirically from the evolution of the Fundamental Plane for cluster ETGs, where $\Delta\log(\mathcal{M}/L_B) = (-0.46\pm0.04)z$ (van Dokkum & Stanford 2003; Treu et al. 2005; di Serego Alighieri et al. 2005). Massive field ETGs appear to follow the same relation, whereas less massive ones evolve faster in luminosity, indicative of younger ages (Treu et al. 2005; di Serego Alighieri et al. 2005). We first apply this relation to all ETGs, independent of their luminosity, and then we comment on the effect of a luminosity-dependent rate of evolution. In this way, the luminosity of high-$z$ ETGs is decreased by $\Delta\log L_B = 0.46\,z$ to obtain the luminosity to which

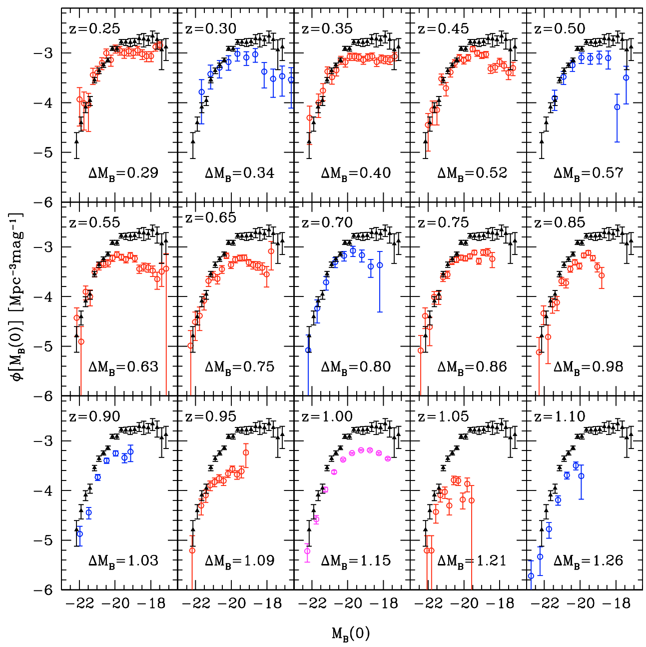


**Fig. 1.** The $B$-band LF of ETGs from COMBO-17 (Bell et al. 2004a, red), DEEP2 (Faber et al. 2005, blue), and SXDS (Yamada et al. 2005, magenta) "evolved" to $z = 0$ and compared to the local LF derived by Bell et al. (2004a) from SDSS data (black filled triangles). The amount of applied passive evolution ($\Delta M_B$) is also indicated.

they would fade by $z = 0$ due to their passive evolution, i.e., their $M_B$-band magnitude at $z = 0$ is obtained as:

$$M_B(0) = M_B(z) + (0.46\times2.5\times z) = M_B(z) + 1.15\,z.$$

This evolutionary rate is consistent with that predicted by stellar population synthesis models for stars formed at $z \gtrsim 1.5$ (Bell et al. 2004a). For each redshift bin in the range $0.25 < z < 1.10$, the resulting *evolved* LF to $z = 0$ is then compared to the data points of the local ($z = 0$) LF derived from Bell et al. (2004a) based on SDSS data. The result is shown in Fig. 1, where besides to COMBO-17 and DEEP2 galaxies, the same procedure has been applied also to the SXDS sample of ETGs (Yamada et al. 2005).

In each panel, the amount of luminosity evolution ($\Delta M_B$) is shown, and the error bars in the number density $\phi$ include also the cosmic variance contribution as estimated by Bell et al. (2004a) and C. Willmer (private communication) for COMBO-17 and DEEP2, respectively. It appears very clearly from Fig. 1 that the number density of the ETGs populating the bright-end of the LF shows basically no evolution with redshift up to $z \sim 0.8$, whereas less luminous ETGs display a deficit which grows with redshift.

Figure 1 also shows that at any redshift there is a characteristic luminosity above which the bright end of the passively evolved ETG LF is consistent with the local LF, and the luminosity at which it departs from it depends on redshift, becoming more luminous for increasing redshifts. Figure 2 displays this trend by showing the absolute magnitude, $M_B(0)(60\%)$, at which in each redshift bin of Fig. 1 the evolved LF is 0.6 times less than the local LF, corresponding to the luminosity below which less than 60% of the ETGs are already in place. Figure 2 clearly shows a trend of $M_B(0)(60\%)$ becoming brighter for increasing redshifts, indicating once more that the most massive galaxies are the first to reach the ETG sequence, while less massive ones join it later, i.e., at lower redshifts. The trend shown in

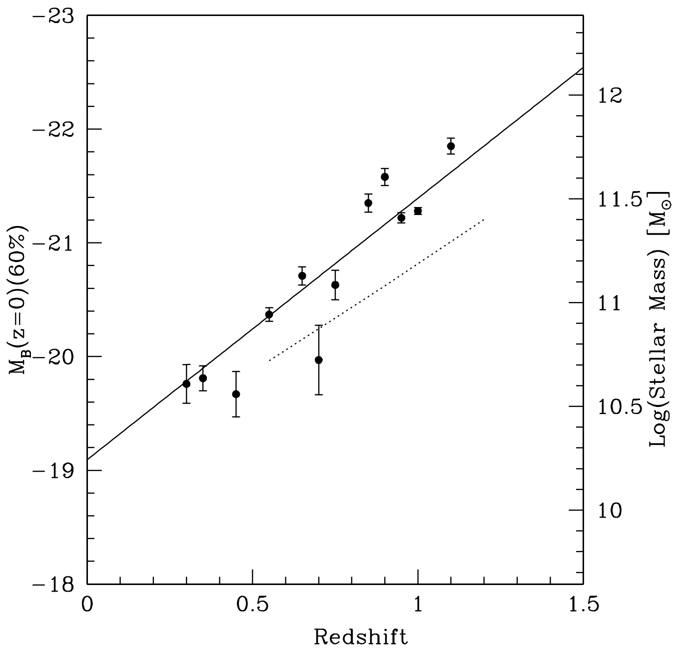


**Fig. 2.** The luminosity (or equivalent mass) at which about 60% of the ETGs are already in place. The dashed line represent the evolution of the "quenching" mass of Bundy et al. (2006).

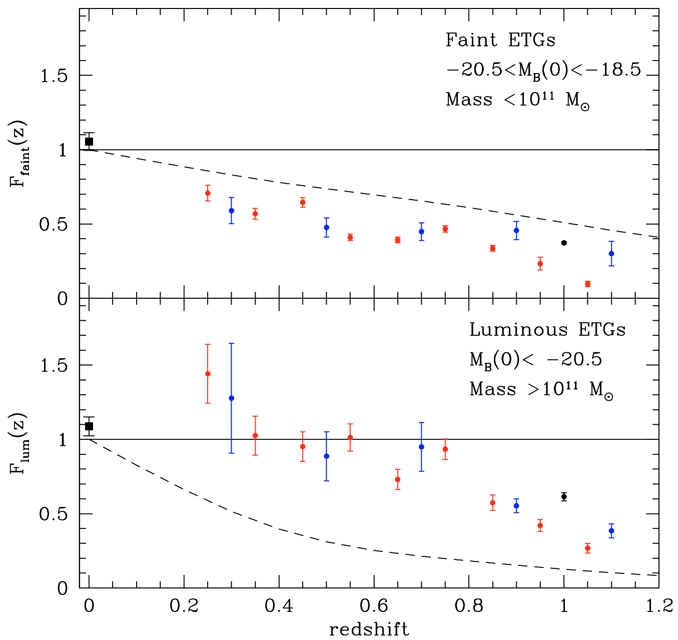


**Fig. 3.** The evolution of the fractional number density of low- (*top*) and high-luminosity (*bottom*) ETGs compared with the $z = 0$ best-fit Schechter function of Bell et al. (2004a). The points at $z = 0$ are not exactly equal to 1 due to the slight mismatch between the Schechter fit ($\Phi$) and the actual SDSS data points ($\phi$). Red, blue, black symbols at $z > 0$ refer to COMBO-17, DEEP2 and Yamada et al. (2005) respectively. The dashed lines correspond to the evolving fraction of the $z = 0$ ETGs which have assembled 80% of their stellar mass (from Fig. 5, bottom panel, of De Lucia et al. 2006).

Fig. 2 is consistent with that of the "quenching" mass with redshift $\mathcal{M}_Q \propto (1+z)^{4.5}$ (Bundy et al. 2006), where most galaxies more massive than $\mathcal{M}_Q(z)$ have already turned passive.

This luminosity-/mass-dependent evolution of ETGs is further highlighted in Fig. 3 which shows the evolution of the ratio[1] between the $z > 0$ and $z \sim 0$ ETG number density, splitted into the bright ($M_B(0) < -20.5$) and the faint sample ($-20.5 < M_B(0) < -18.5$). The luminosity cut of $M_B(0) = -20.5$ corresponds to $\mathcal{M} \sim 10^{11}$ $M_\odot$ (di Serego Alighieri et al. 2005, see their Fig. 13, from which we derive $M_B(0) \simeq -1.825 \times \log[\mathcal{M}/M_\odot] - 0.4$). In order to avoid the mismatch between the data points of the LF($z \sim 0$) and LF($z$), we use here the Schechter function derived by Bell et al. (2004a, Appendix) for the LF($z \sim 0$). $F_{\rm lum}(z)$ and $F_{\rm faint}(z)$ can be seen as the fractions of assembled ETGs in the two luminosity (mass) intervals as a function of redshift. Figure 3 shows that (within the error bars) the number density of ETGs with $\mathcal{M} > 10^{11} M_\odot$ is nearly constant within the range $0 < z < 0.8$, and starts to decline signficanlty for $z > 0.8$. The values of $F_{\rm lum}(z)$ at $z = 0.25$ and $z = 0.3$ are higher than the local one by 1–2$\sigma$, presumably as a result of a fluctuation due to the small volumes sampled at low-$z$. Instead, the number density of ETGs in the fainter sample (or lower masses) shows a smooth decrease from $z \sim 0$ to $z \sim 0.8$ and beyond. Note that beyond $z \sim 0.9$ the COMBO-17 and DEEP2 LFs do not reach $M_B(0) = -18.5$ (see Fig. 1), and therefore $F_{\rm faint}$ is relative to the integration of the LF($z$) down to the faintest $M_B(0)$ available in the data points. Thus, most of the number density evolution of ETGs is confined to the galaxies fainter than $M_B(0) < -20.5$ ($\mathcal{M} \lesssim 10^{11}$ $M_\odot$). In other words, up to $z \sim 0.8$ there is a sufficient number of massive ETGs that will passively evolve to the local massive ETG and will match their number density. We tested if all the above results (Figs. 1–3) are solid with respect to the adopted ingredients of our analysis. First, we verified that the ~10% uncertainty in the adopted relation $\Delta \log(\mathcal{M}/L_B) = (-0.46 \pm 0.04)z$ results in tiny shifts of the LFs, i.e., ±0.025 mag at $z = 0.25$ and ±0.1 mag at $z = 1$, and do not affect the results. Second, our choice to dim the luminosity functions with a rate independent of luminosity is a *conservative* one: adopting a luminosity-dependent rate of evolution consistent with the results of Treu et al. (2005) and di Serego Alighieri et al. (2005) would have made the number density deficit of faint ETGs even more marked. Third, we also tested that the results do not change significantly if instead of the Bell et al. (2004a) best fit, we use an interpolation which provides a closer match to the local LF.

### 2.1. Incompleteness effects

The drop in the space density of ETGs with increasing redshift being stronger at faint luminosities suggested that it may at least in part be due to sample incompleteness, thus exaggerating an apparent downsizing effect. Indeed, incompleteness may especially affect optically selected samples, due to the large $k$ corrections of ETGs. Instead, $K$-band selected samples are less affected by this problem having much smaller $k$-correction. In order to assess the relevance of this effect, we performed a simple test with the highly complete K20 sample (Cimatti et al. 2002b; Mignoli et al. 2005) by deriving the fraction of the K20 spectroscopically-classified ETGs fainter than the nominal limiting magnitude of the COMBO-17 and DEEP2 surveys (i.e., $R_{\rm lim} \simeq 24$). This fraction is ~16–21% and ~50% at $0.8 < z < 1.0$ and $1.0 < z < 1.2$, respectively, showing that in the redshift range $0.8 < z < 1.2$ these surveys are affected by non-negligible incompleteness effects, which become very important at $z \geq 1$. The K20 ETGs with $R > R_{\rm lim}$ have absolute magnitudes at $z = 0$

[1] $F(z) = \int_{M_1}^{M_2} \phi[M_B(0), z] dM_B(0) / \int_{M_1}^{M_2} \Phi[M_B(0)] dM_B(0)$, where $M_1$ and $M_2$ are the integration extremes, $\phi$ are the LF data points, and $\Phi$ is the best-fit Schechter function of the LF($z = 0$) (Bell et al. 2004a).

in the range of $-19.5 < M_B(0) < -18.5$ and stellar masses in the range of $10^{10} \lesssim \mathcal{M} < 3 \times 10^{10}\ M_\odot$. This test indicates that the highest redshift bins of the COMBO-17 and DEEP2 surveys are affected by non-negligible incompleteness, with up to ~50% of the $-19.5 < M_B(0) < -18.5$ ETGs being missed at $z \sim 1$. However, for objects with $M_B(0) < -19.5$ the COMBO-17 and DEEP2 samples should be fairly complete up to $z \sim 1$, hence genuine evolution appears to be responsible for the observed drop of the LF for $-20.5 < M_B(0) < -19.5$ at $z > 0.8$.

## 3. Main implications on ETG evolution

The present new analysis of the COMBO-17/DEEP2 LFs shows that the evolution of ETGs, as inferred only in terms of the Schechter function best fit parameters $\phi^*(z)$ and $M^*(z)$ does not fully exploit all the available information because the evolution is a strong function of luminosity and mass. Thus, the redshift evolution of the ETG number density must depend on the luminosity (mass) range of each specific sample under consideration. The main implications of our analysis on the ETG evolution can be summarized as follows.

• When the empirical passive evolution dimming is used to project the passive evolution of high redshift ETGs down to $z = 0$, then the high-luminosity end ($M_B(0) < -20.5$) of the resulting LF comes to a perfect match to the $z \sim 0$ LF of local red-sequence ETGs (Fig. 1). This implies that the number density of massive ETGs ($\mathcal{M} > 10^{11}\ M_\odot$) is nearly constant from $z = 0.8$ to ~0 (Fig. 3). This near-constant number density of massive ETGs cannot be the result of a sizable fraction of them leaving the red sequence (because e.g., of re-activated SF), while being compensated by a near equal number joining the top end of the LF by SF quenching. Indeed, as emphasized by Bell et al. (2004a) at every redshift in the COMBO-17 sample the top end of the LF is dominated by ETGs on the red sequence, with a comparatively insignificant number of blue galaxies. Therefore, there is no room for an appreciable fraction of red sequence galaxies to turn blue. Moreover, one could imagine a scenario in which dry merging operates in such a way to keep constant the number of massive ETGs (e.g., $\mathcal{M} > 10^{11}\ M_\odot$). However, as dry merging would inevitably increase the total stellar mass in ETGs above any given mass, the LF($z$) would have to change, either in shape or in normalization (to keep constant the number of galaxies). This possibility is unlikely because Fig. 1 shows that the shape and normalization remain the same. One can then safely conclude that the majority of the $\mathcal{M} > 10^{11}\ M_\odot$ ETGs were already in place at $z \sim 0.8$, have evolved passively since then, and that virtually no new massive ETGs are formed within this redshift interval. This result is not affected by incompleteness effects (Sect. 2.1) or by the "progenitor bias" (van Dokkum & Franx 2001), as the constant number density of luminous ETGs implies that the progenitors up to $z \sim 0.8$ are all included in the ETG sample. Near-infrared surveys unveiled galaxies at $z > 1.5$–2 with properties (star formation rates, masses, metallicity, clustering) which qualify them as the progenitors of the massive ETGs at $0 < z < 0.8$, and showed that the star formation activity in massive galaxies at $1.4 < z < 2.5$ is enough to account for all $\mathcal{M} > 10^{11}\ M_\odot$ red galaxies by $z \sim 1$ (Daddi et al. 2005b).

• In contrast, at fainter magnitudes the LF is progressively depopulated with increasing redshift (Figs. 1 and 3), an effect that cannot be explained solely in terms on incompleteness (Sect. 2.1). The progenitor bias appears to be at work here, with an increasing fraction of the progenitors to local ETGs which do not already qualify as such at higher redshift. A possibility is that these progenitors are still star-forming galaxies which are too blue for fulfilling the selection and which would gradually populate the low-luminosity part of ETG red sequence since $z \sim 1$ by the progressive quenching of star formation in galaxies with masses $<10^{11}\ M_\odot$.

• The relative contribution of this residual star formation to the build up of the final mass of local ETGs remains to be assessed. However, the homogeneity of local cluster and field ETGs (Bernardi et al. 2003; Thomas et al. 2005) argues for the bulk of the stellar mass having formed at $z > 1$ even in low mass ETGs. Indeed, even a low level of star formation (e.g. the "frosting" scenario of Trager et al. 2000) is sufficient to make the color of galaxies too blue for qualifying them as color-selected ETGs, whereas quenching such residual SF should ensure that the galaxies will quickly join the red sequence.

• With the vast majority of ETGs more massive than $\sim 10^{11}\ M_\odot$ being already in place by $z \sim 0.8$, there appears to be no much room left for any major contribution of dry merging events in increasing the number of the most massive ETGs. This appears to be in a agreement with the very low rate of dry merging events estimated from SDSS data (Masjedi et al. 2005) and from the most recent results on the stellar mass function evolution (Caputi et al. 2006; Bundy et al. 2006), but at variance with other estimates (e.g., van Dokkum 2005; Bell et al. 2006). On the other hand, dry merging does not change the ETG contribution to the $B$-band luminosity density $j_B$, hence the constancy of $j_B$ since $z \sim 0.8$ (Bell et al. 2004a; Faber et al. 2005) in spite of the passive dimming of ETGs, requires the transformation of blue to red galaxies to take place, indeed by the progressive quenching of residual star formation.

• At each redshift there is a critical mass above which virtually all ETGs appear to be in place, and the trend of this critical mass with $z$ parallels that of the "quenching" mass introduced by Bundy et al. (2006), as the mass at which the number density of star forming and passive ETGs is the same (see Fig. 2).

• All these findings bring new evidence in favor of the "downsizing" scenario in galaxy formation which is apparent at low as well as higher redshifts (see Sect. 1). However, our findings extend the concept from the mere *star formation* (stars in more massive galaxies are older) to the *mass assembly itself*, i.e., with massive galaxies being the first to be assembled (see also Bundy et al. 2006). Downsizing in star formation may be a natural expectation in a hierarchical galaxy formation scenario, provided that a suitable mechanism is found to quench star formation at earlier times in more massive galaxies (e.g., Granato et al. 2004; De Lucia et al. 2006; Rasera & Teyssier 2006; Bower et al. 2005). However, downsizing in mass assembly seems to be harder to achieve in current renditions of the $\Lambda$CDM paradigm, where stars in more massive ETGs are indeed older and formed at fairly high redshift, but the most massive galaxies are the last (not the first) to be fully assembled, and are so mostly by dry merging at $z < 1$. This is shown by Fig. 3, where the predictions of De Lucia et al. (2006) (dashed line) based on the *Millennium Simulation* (Springel et al. 2005) show that the brightest, most massive ETGs are those which space density most rapidly drops with increasing redshift, contrary to the observed evolution of their LF.

• Being more directly connected to the evolution of dark matter halos, the apparent "top-down" *mass* assembly of galaxies should provide a more fundamental test of the $\Lambda$CDM scenario and its renditions than the mere downsizing in star formation. As pointed out by Hogg (2005), the empirical dry merging rate appears to be "lower, much lower than the rate at which ETG-hosting dark matter halos merge with one another".

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