

The formation and evolution of early-type galaxies : solid results and open questions

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Abstract. The most recent results and some of the open key questions on the evolution of early-type galaxies are reviewed in the general cosmological context of massive galaxy formation.

Keywords: galaxies: evolution; galaxies: formation; galaxies: elliptical and lenticular

PACS: 98.80.Es, 98.52.Eh, 98.62.Ai, 98.62.Ck, 98.62.Lv

INTRODUCTION

Early-type galaxies (ETGs) can be used to address several key questions of modern cosmology and astrophysics : **(1)** the cosmic history of galaxy mass assembly, **(2)** the evolution of large scale structure, **(3)** the evolution of galaxy clusters, **(4)** the link between supermassive black holes and host galaxies, **(5)** the role of feedback in galaxy formation, **(6)** the physical origin of the Hubble morphological classes, **(7)** the dark energy equation of state using the evolution of the relative stellar ages.

Although ETGs at $z \sim 0$ are rather simple and homogeneous systems in terms of morphology, colors, stellar population content and scaling relations [85], their formation and evolution is still a debated question. In the modern scenario of Λ CDM cosmology, it is expected that galaxies assembled their mass gradually through hierarchical merging, with most of the stellar mass in ETGs assembled at $0 < z < 1$, with a mass-dependent evolution which confines the assembly of the most massive ETGs at relatively low redshifts [32]. Two main approaches are possible to constrain the evolution of ETGs : observing directly how their properties change as a function of redshift, or deriving indirectly the evolutionary properties of "fossil" ETGs at $z \approx 0$ "backward" in cosmic time.

THE EVOLUTION AT $0 < z < 1$

Recent results based on imaging and/or spectroscopic surveys of ETGs at $0 < z < 1$ are converging on a scenario where the evolution of the distribution functions is strongly luminosity- and mass-dependent.

The luminosity and stellar mass functions show a very weak evolution from $z \approx 0.8$ to $z \sim 0$ for luminous, massive galaxies, but they evolve much faster for lower mass systems [45, 4, 37, 113, 17, 11, 93, 14, 82, 47, 40, 20, 12, 83, 15, 84, 3, 24]. In particular, 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 $z \approx 0.8$ (i.e. when the Universe had $\approx 50\%$ of its present age), less

luminous ETGs display a deficit which grows with redshift. This can be explained with a gradual population of the ETG "red sequence" [4] by the progressive suppression of star formation in galaxies less massive than $\sim 10^{11} M_{\odot}$. At each redshift there is a critical mass above which the majority of ETGs appear to be in place [20, 15]. Clearly, this scenario does not exclude some residual evolution in the assembly of massive ETGs, but the fractional contribution of this evolution is relatively small. For instance, a study of the colors of a sample of ETGs at $0.5 < z < 1$ showed that luminous ($-23 < M_V < -20.5$) and less luminous galaxies formed respectively ≈ 10 -15% and ≈ 30 -60% of their mass since $z \approx 1$ [59]. The above studies rely on the estimate of the so called "photometric" stellar masses. However, it is reassuring that stellar and dynamical masses of ETGs at $0 < z < 1$ show a rather good agreement [50, 16, 86, 34, 36].

The evolution of ETGs at $0 < z < 1$ fits well in the general "downsizing" scenario [25, 51] where galaxy evolution depends on the mass, with the most massive systems reaching the completion of star formation and assembly first, while less massive ones have a more prolonged star formation extended to later cosmic times.

Several other additional evidences support the downsizing scenario.

- The typical mass-to-light ratio of luminous ETGs is significantly larger than that of the fainter ones, implying short star-formation timescales and/or high formation redshifts for the massive population (e.g. [45, 116], see also [16]).
- The evolution of the Fundamental Plane indicates that the bulk of stellar populations formed at $z_f > 2$ and $z_f \sim 1$ for high- and low-mass ETGs respectively. The fraction of stellar mass formed at recent times ranges from $< 1\%$ for $M > 10^{11.5} M_{\odot}$ to 20%-40% below $M \sim 10^{11} M_{\odot}$ (with no major difference between the evolution of massive field and cluster ETGs) [108, 34, 115, 116].
- The differential evolution of the color-magnitude relation of field ETGs [103].
- Low mass galaxies show larger SSFR (i.e. SFR/\mathcal{M}) than higher mass galaxies at all redshifts, and the SSFR for massive galaxies increases by $\sim 10\times$ at $z > 2$ [42, 58].
- The evolution of spectral features in galaxy spectra and the rapid decrease of the number density of massive galaxies with strong $H\delta$ absorption since $z \approx 1$ [68, 118].

Complementary studies of ETGs at $0 < z < 1$ based on gravitational lensing and stellar dynamics show a remarkable homogeneity of the internal structures and mass density profiles and, together with the stellar population constraints, support the scenario with most of the massive systems being already in place at $z \approx 1$ [90, 64].

Constraints from ETGs at $z \approx 0$

Several studies derived "indirectly" the evolution by reconstructing the past history of "fossil" ETGs at $z \approx 0$ based on spectral analysis, Lick indices, $[\alpha/\text{Fe}]$ and SED fitting (see [85] for a review). It is remarkable that the majority of the results obtained with this approach are now in broad agreement with those obtained for ETGs at $0 < z < 1$ and support the "downsizing" scenario (e.g. [104, 49, 50, 89, 57]). For instance, the analysis of a large sample of ETGs selected from the SDSS showed that the objects with larger masses have older stellar populations, and the most massive ones formed more than 90% of their current stellar mass at redshift $z > 2.5$ [57].

However, not all the results on ETG evolution at $0 < z < 1$ fully agree with each other (e.g. [94]). Part of the discrepancies can be due to the biases which may affect the selection of ETG samples (e.g. [110]) and/or the use of "stacked" data which may include heterogeneous objects. Typical examples are represented by the contamination of "red sequence" ETGs by dust-reddened galaxies and/or by systems with low residual star formation activity which may strongly affect the colors and the spectra. It is well known that a few percent of young stars can change dramatically the colors and spectra of ETGs even if the bulk of the mass is made by old stars (e.g. [107]).

The influence of the environment

Several studies investigated the dependence of the ETG evolution on the environment. In general, the scaling relations of ETGs persist in low density environments, but show a larger scatter than in dense regions and clusters, and ETGs in clusters are ≈ 1 -2 Gyr older than in the field (e.g. [6, 104, 50, 23]). This is interpreted as the consequence of a more complex and prolonged star formation and assembly history of field ETGs. However, the environment seems to have a weaker influence on evolution than ETG mass [50, 15].

THE EVOLUTION AT $1 < z < 3$

The results outlined in the previous sections indicate that the critical redshift range where the strongest evolution and assembly of massive ETGs took place is at $1 < z < 3$ (see also [1]). At these redshifts, ETGs are usually identified in pure flux-limited samples (e.g. K20, GDDS, GMASS), or using color selections such as the "passive"- BzK ($pBzK$) ($1.4 < z < 2.5$; [27]) or the Distant Red Galaxy (DRG) criterion ($z > 2$; [48]). However, the information available at these redshifts is much more fragmentary than at $z < 1$. This is mostly due to the difficulty to identify spectroscopically large samples of ETGs as they become rapidly very faint, and the most prominent spectral features are redshifted to the near-infrared, where spectroscopy is usually prohibitive with the current telescopes.

The ETGs identified spectroscopically so far up to $z \approx 2.5$ are characterized by very red colors ($R - K > 5 - 6$), passively evolving old stellar populations with ages of 1-4 Gyr, e -folding timescales $\tau \sim 0.1$ -0.3 Gyr (where $SFR(t) \propto \exp(-t/\tau)$), very low dust extinction, stellar masses $\mathcal{M} \geq 10^{11} M_\odot$ and strong clustering with $r_0 \approx 8$ -10 Mpc [38, 99, 19, 54, 75, 28, 91, 69, 63, 65, 72, 21, 26, 44, 63, 41]. Preliminary estimates indicate that the number density of massive ETG photometric ($pBzK$) candidates at $1.4 < z < 2.5$ is $\approx 20\%$ of that at $z = 0$ [63]. However, due to the strong clustering and the consequent high cosmic variance, more wide-field surveys are needed to constrain stringently the luminosity and mass functions of ETGs at $z > 1$.

Another property which characterizes ETGs at $z > 1$ is their compact structure [28], with sizes ($R_e \leq 1$ kpc) much smaller than in present-day ETGs. Several studies have confirmed this property and showed that R_e is typically smaller by a factor of ≈ 2 -3 than at $z \approx 0$, implying that the stellar mass surface and volume internal densities are up to ≈ 10 and ≈ 30 times larger respectively [109, 121, 70, 105, 112, 21, 13, 117]. The rest-frame B -band Kormendy relation shows a large offset (2-3 mag) in effective

surface brightness with respect to the local relation. This is difficult to explain with simple passive luminosity evolution models and requires that these "superdense" ETGs should somehow increase their size in order to match the local Kormendy relation at $z \approx 0$ (e.g. [70, 21, 92]). Surprisingly, the majority of ETGs at slightly lower redshifts ($0.7 < z < 1.2$) does not show such compact sizes. It is unclear how to explain these size properties in the context of ETG evolution, and subtle observational biases (e.g. surface brightness dimming and S/N ratio effects) should not be completely excluded yet.

The comparison between field and cluster ETGs at $z > 1$ [55, 87] shows that cluster ETGs at $z \sim 1.2$ formed the bulk of their stars ≈ 0.5 Gyr earlier than ETGs in the field at the same redshift, whereas field ETGs terminated to form their stellar content on a longer time scale. Such a difference is particularly evident at masses $\mathcal{M} < 10^{11} M_{\odot}$, whereas it becomes negligible for the most massive ones. However, cluster and field ETGs at $z \sim 1.2$ follow comparable size–mass relation and have analogous surface stellar mass densities and lie on the same Kormendy relation. A proposed interpretation is that while the formation epoch of ETGs depends mostly on their mass, the environment does regulate the timescales of their star formation histories, implying that the last episode of star formation must have happened more recently in the field than in the cluster [87].

ETGs at $z > 1$ have been found also in high density regions up to $z \approx 1.5 - 1.6$ [66, 76]. These overdensities might represent protoclusters observed before virialization.

The existence of a substantial population of old, massive, passively evolving ETGs up to $z \approx 2.5$ was not expected in the galaxy formation models available in 2004 [19, 54]. This raised the critical question on how it was possible to assemble such systems when the Universe was so young. A promising mechanism is the AGN feedback which, in addition to that of SNe, would allow the rapid suppression ("quenching") of the star formation during the formation of massive ETGs at high redshifts (e.g. [56, 77, 98, 31]).

EARLY-TYPE GALAXIES AT $z > 3$?

Following the claim of an "old" galaxy at $z=6.5$ [78], ETG-like candidates at $z > 3$ have been searched in deep near- and mid-infrared surveys. However, at these redshifts, the current studies have to rely only on photometric redshifts and SED fitting analysis because spectroscopy is unfeasible. Due to the degeneracies in the SED fitting analysis, most of the ETG candidates at $z > 3$ can be either heavily dust-enshrouded starbursts or old/passive galaxies [39, 88, 119, 71].

However, a small fraction does not show degeneracies and is formally consistent with being massive galaxies ($\mathcal{M} \approx 10^{11} M_{\odot}$) at $z \approx 4 - 5$ with low dust extinction and the oldest ages allowed for these redshifts (i.e. up to ≈ 1 Gyr). If confirmed by future studies (e.g. JWST, ELTs), this population of massive, evolved galaxies would contribute significantly to the total stellar mass density at $z \approx 4 - 5$ [88, 71].

HOW DID MASSIVE EARLY-TYPE GALAXIES FORM ?

The properties of ETGs illustrated in previous sections indicate that the massive systems formed at $z > 2$ with very short timescales. Examples of precursor candidates have been

found amongst starburst galaxies selected at $z > 2$ with a variety of techniques: *sBzK* [27], submm/mm [18], DRG [48], optically-selected systems with high luminosity [97], IRAC Extremely Red Objects, IEROs [114], HyperEROs [106] and ULIRGs at $z \sim 1 - 3$ selected with *Spitzer Space Telescope* [7].

Deep integral-field near-IR spectroscopy (sometimes assisted by Adaptive Optics) is being used by observing redshifted $H\alpha$ emission as a kinematic tracer and to perform detailed studies of these precursor candidates (e.g. [100, 46, 120, 67]). The most detailed studies of massive star-forming galaxies at $z \approx 2$ show sometimes the existence of massive rotating disks with high velocity dispersion. These systems may become unstable and lead to the rapid formation of massive spheroids. Although the samples of $z \approx 2$ galaxies observed with this approach are still rather small, the analysis of the kinematic criteria ("kinemetry") suggests that $>50\%$ have kinematics consistent with a single rotating disk, while the remaining systems are more likely undergoing major mergers. The emerging scenario indicates that, in addition to merging, also secular evolution and smooth accretion of gas play a role in building up disks and massive spheroids at high redshifts, even without major mergers [52, 96, 53].

TOWARDS AN OVERALL PICTURE ?

If all the current observational constraints are taken into account, a possible picture for the formation and evolution of massive ETGs could be outlined as follows (Fig. 1).

(1) A large fraction of massive star-forming galaxies selected in the optical/near-IR are gas-rich disk systems characterized by a "quiet" evolution with long-lived star formation (e.g. $\approx 0.5-1$ Gyr, [29, 30]) supported in some cases by "smooth accretion" of cold gas streams [60, 33]. These massive systems may later evolve into spheroids through disk instabilities and/or merging processes [52, 53].

(2) The submillimeter galaxy (SMG) [8, 100] phase corresponds to the cases of rapid, highly dissipative, gas-rich major mergers [80, 61] characterized by short-lived (≈ 0.1 Gyr) starbursts [101, 102]. It is intriguing to notice that SMGs are the only star-forming systems at $z > 2$ having the same small sizes and high (gas) mass surface density of ETGs at $1 < z < 2$ [101, 102]. If the compact superdense ETGs at $1 < z < 2$ are the descendants of SMGs, the duty cycle timescale of the SMG phase can be estimated as the ratio of the comoving number densities of the SMGs ($\approx 10^{-5} \text{ Mpc}^{-3}$; [95, 18]) and ETGs ($\approx 10^{-4} \text{ Mpc}^{-3}$) and the amount of cosmic time available from $z \approx 2.5$ to $z \approx 1.5$ (≈ 1.5 Gyr), i.e. ≈ 0.15 Gyr. This is broadly consistent with the e -folding timescale derived independently from the SED fitting and from the SMG molecular gas [101, 102]. AGN feedback would then be required to "quench" the star formation (e.g. [31, 43, 2]). This could also explain the origin of the relation between super-massive black hole and galaxy masses. Although the involved physical processes are different, this scenario is somehow reminiscent of the "old-fashioned" monolithic collapse.

(3) The compact, superdense ETGs at $1 < z < 2$ evolve by increasing gradually their sizes. A possible mechanism is major dissipationless ("dry") merging [81, 35, 111, 5, 61, 62, 22, 9]. However, it is unclear how the "dry" merging scenario can be reconciled with the properties of the small-scale clustering of low- z ETGs [73, 74] and with the weak evolution of the high-mass end of their stellar mass function at $0 < z < 0.7$. Other

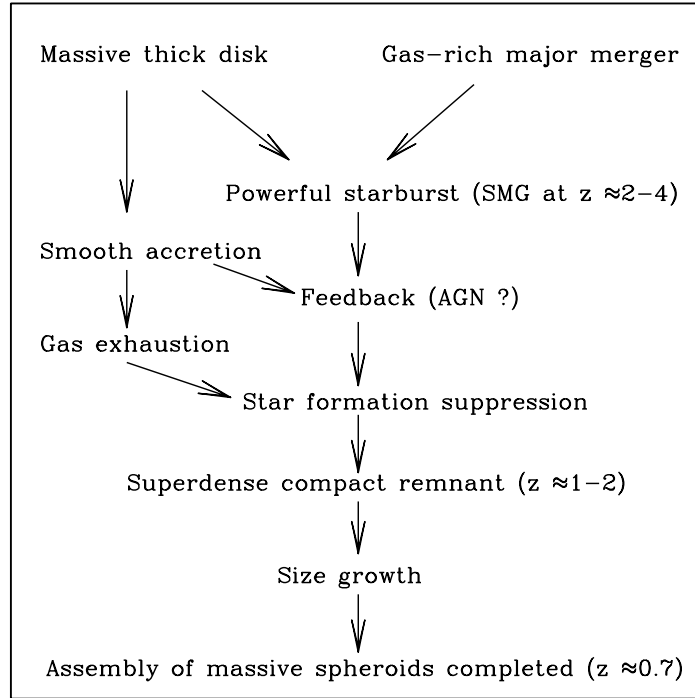


FIGURE 1. The variety of possible evolutionary paths for the formation of massive spheroidal galaxies.

processes which may increase the sizes at $z < 1$ are the smooth envelope accretion [79] and multiple frequent minor mergers [10].

(4) The majority of most massive ETGs reaches the assembly completion around $z \approx 0.7-0.8$, while lower mass ETGs continue to assemble down to lower redshifts (downsizing).

Future studies of galaxies at $1 < z < 3$ will allow a better understanding of the global processes which lead to formation and evolution of ETGs.

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