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'10kpc collar' – probing the evolution of early-type galaxies by focusing its inner mass density profile

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ABSTRACT
Early-type galaxies (ETGs) today is believed to have experienced more dramatic growth in their evolution history, comparing with their star-forming counterpart. The underlying mechanism of the evolution of ETGs,which is still not been well-understood yet, could be inferred by tracing its impact on various properties of galaxies, among which the mass density profile is one that has not drawn much attention in literature. In this work, we aim to investigate the evolution of ETGs by focusing on the mass density profile inside a fixed aperture, 10kpc. We use a new parameterization, namely $M_{*,10}$ and $\Gamma_{*,10}$ which is the mass and the mass-weighted density slope enclosed in circularised aperture 10kpc respectively, to capture the feature of mass density profile in such inner region and then probe its evolution trend. We first explore the $\Gamma_{*,10} - M_{*,10}$ relation for a sample of quiescent galaxies from GAMA survey combining with the KiDs image, and find a steeper slope of the $\Gamma_{*,10} - M_{*,10}$ relation for galaxies with lower redshift. We then analyzed a collection of binary-merger simulations which contains mergers with different merger mass ratio. From the simualtion result we could directly observe that mergers would always induce a decrease in $\Gamma_{*,10}$, but might induce a counter-intuitive increase in $M_{*,10}$ for larger galaxies and smaller merger mass ratio. We then built a toy model to predict the evolution in $\Gamma_**, 10 - M_{*,10}$ relation, and found that for every merger mass ratio, the slope would always increase and the normalization would always decrease, while the change would become more intensive for smaller merger mass ratio. Comparing with the observation result, we believe galaxies do grow during redshift range $0.15 \le z \le 0.40$, and the growth should be driven by mergers with merger mass ratio lower than 1:5.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: structure

1 INTRODUCTION

Early type galaxies (ETGs), which are, by definition, typically elliptical in shape, are believed to be the end product of galaxy formation and evolution process and have completed most of their star-forming activities by the time that being observed. The passive evolution process of ETGs is a key problem in astrophysics. Obtaining a better understanding on this process could help us better understand the hierarchical structure formation theory, which is fundamental in ΛCDM cosmology.

Over the past few decades, observations have suggested that ETGs at higher redshift (i.e. $z \approx 2$) have significant differences from their $z \approx 0$ counterpart in many aspects. For instance, ETGs at higher redshift are more compact in size (e.g. Daddi et al. 2005; Toft et al. 2007; Trujillo et al. 2006, 2007; van Dokkum et al. 2008) and more homogeneous in color gradient, i.e. the contrast in color between the outskirt and the center is less significant than their low-redshift counterparts (e.g. Suess et al. 2019a,b, 2020). In particular, the size growth of such quiescent, ultra compact objects induced by the passive evolution process is believed to be a factor of about 3 between $z = 2$ and $z = 0$ (e.g. Fan et al. 2008; van Dokkum et al. 2010; van der Wel et al. 2014; Damjanov et al. 2019; Hamadouche et al. 2022). Combining with the fact that the star formation rate of ETGs are relatively low, it is suggested that the these galaxies should have experienced a built-up process of their outer envelope since $z \approx 1.5$ via some form of merging and accretion (e.g. Hopkins et al. 2009, 2010; van Dokkum et al. 2010) . Numerous works in literature that based on both observations and hydrodynamic simulations have suggested that among various possible mechanisms, the major one should be the dissipationless dry mergers, especially for mergers with a relatively small mass ratio between the accreted galaxy and the progenitor galaxy (hereafter minor merger).The rationale is that the minor merger is more promising in qualitatively reproducing the evolution trend in size, central densities and orbital structures of these quiescent galaxies. (e.g. Naab et al. 2009; van Dokkum & Brammer 2010; Oser et al. 2011; Newman et al. 2012; Hilz et al. 2013; Dekel & Burkert 2014; D'Eugenio et al. 2023). Recently, taking the advantage of the depth and resolution of JWST Advanced Deep Extragalatic Survey (Gardner et al. 2023; Eisenstein et al. 2023), it is suggested that minor merger also have the potential to contribute the color gradient evolution of ETGs (Suess et al. 2023).

However, if we investigate the evolution process quantitatively, we would find one of the problems in this field is that the minor merger scenario is not sufficient to explain the entire growth of ETGs at redshift $z > 1$. Works in literature that based on HST images could be an example.They identified satellite galaxies around massive ETGs and found that the merging event of ETGs with their surrounding satellites could only account for at most a half of the entire size growth (Newman et al. 2012; Belli et al. 2015). Moreover, works based on theoretical model also implies that if we aiming at explaining the size growth of ETGs by solely invoking minor mergers, the scatter in the scaling relation ($M_* - R_e$ relation) of ETGs would become larger and thus inconsistent with observation (Nipoti et al. 2009; Nipoti et al. 2012). Fortunately, some possible solutions to this problem have already been proposed. Given the fact that the observed size of star-forming galaxies are on average larger than quiescent ones (e.g. Newman et al. 2012; van der Wel et al. 2014; Belli et al. 2015; Roy et al. 2018), the joining of newly quenched ex-star-forming galaxies to the population of ETGs could be a possible supplement to the size growth of ETGs (e.g. Dokkum & Franx 1996; van Dokkum & Franx 2001; Carollo et al. 2013; Fagioli et al. 2016). In addition, the existence of color gradient could also mimic the observed size growth of ETGs, thus mislead to a conclusion that the minor merger scenario is insufficient (Suess et al. 2019a,b). Nevertheless, detailed theoretical models that could take various possible scenarios into account and explain the entire growth of ETGs is still missing.

Another problem occurs at relatively lower redshift $z \leq 1$, the observed evolution of ETGs at that epoch do not converge in some degree. The growth rate of ETGs at that time seems to be mass-dependent. van der Wel et al. (2014); Roy et al. (2018) suggested a more rapid size growth rate for more massive ETGs ($M_* \geq 10^{11} M_\odot$), while is not in consistent with Damjanov et al. (2019), which found that less massive ETGs tends to grow faster. Moreover, effort on exploring the number density growth of ETGs implies a lack of growth in the stellar mass function in the same redshift interval (e.g. Bundy et al. 2017; Kawinwanichakij et al. 2020), which is in general in agreement with Damjanov et al. (2019) as they both imply that massive ETGs do not grow significantly, and thus in contrast with van der Wel et al. (2014) and Roy et al. (2018). Such complexity limit our ability to make precise conclusion on the evolution of ETGs in this redshift range. Whether the ETGs grow in this redshift range is still not determined, let alone the detailed growth mechanism.

Besides the traditional size and mass, which is often represented by effective radius R_e and M_*, another quantity that might could also reflect the evolution of ETGs is the mass distribution, or in another word, the density profile, as the evolution process would indeed leave impact on it. For instance, Sonnenfeld et al. (2014) has measured this quantity using lensing data, and this work is proved to be a success in providing a new evidence on the insufficiency of minor merger scenario. In fact, switching to a new perspective is sometimes essential, as some new information may be difficult to be obtained by traditional methods. To provide an additional perspective, we choose to focus on the inner region of ETGs, in supplement to some previous effort on measuring the outer properties of galaxies and their evolution (e.g. Huang et al. 2020).

Following Sonnenfeld (2020), we define the 'inner region' as the region that inside a circularized radius, $10kpc$, and focus on the mass profile using the mass ($M_{*,10}$) and mass-weighted density slope ($\Gamma_{*,10}$) that enclosed in the inner region. The later is defined as

$$\Gamma_{*,10} = \frac{2\pi \int_0^{10} R \frac{dlog\Sigma_*}{dlogR} \Sigma_*(R) dR}{2\pi \int_0^{10} R\Sigma_*(R) dR} = 2 - \frac{2\pi \times 10^2 \times \Sigma_*(10)}{M_{*,10}} \quad (1)$$

Setting a certain value to these two parameters, the mass profile inside 10kpc could be described precisely (see Fig.8 in Sonnenfeld 2020), we hence believe this parameterization is reliable to be used in probing the evolution of inner mass profile. In fact, a benefit of using this parameterization is that it could avoid the potential bias introduced by "extrapolation problem", which might arise when one try to obtain some quantities, such a the total light of one galaxy, by extrapolating the surface brightness model to outer region as the model itself is not well constrained by reliable data there. Traditional parameters, such as R_e and M_*, however, are both sensitive to this problem, thus we believe that they are not as robust as $M_{*,10}$ and $\Gamma_{*,10}$. With the help of our new robust parameterization, our main goal in this paper is to probe the evolution of the inner density profile of ETGs in the redshift range $0.15 \leq z \leq 0.40$. Given the literature uncertainty in that redshift range, we would first try to answer whether the inner mass profile of ETGs would evolve, and then try to infer the growth mechanism in details.

To achieve this goal, it's necessary to understand the impact of various growth mechanism, in particular, mergers with diferent merger ratio. We thus utilize the simulation result from Nipoti et al. (2009) which contains a number of binary mergers with different mass ratio. We measure the $M_{*,10}$ and $\Gamma_{*,10}$ of both progenitor and merger remnant and calculate the growth in these two quantities. In addition to finding that different merger ratio behaves differently, we discovered that the scale of galaxy also make diferences. With the knowledge on how mergers will evolve galaxies in $M_{*,10}, \Gamma_{*,10}$ space, we thus proposed a simple toy model on how different merger scenarios would affect the relation between $\Gamma_{*,10}$ and $M_{*,10}$. We then turn to the observation data in order to make comparison between with our toy model and thus build a intuitive understanding on what could be the possible growth mechanism of ETGs. . We select ETGs from GAMA DR4 main survey (Galaxy and Mass Assembly, Driver et al. (2022);Bellstedt et al. (2020) ; Baldry et al. (2010); Hopkins et al. (2013)) and obtained precise spectroscopic redshift and other quantities that related to spectrum measurement, e.g. stellar mass. In addition, the structural parameter are measured from KiDs photometry (Kile Degree survey , Kuijken et al. (2019), Roy et al. (2018), Amaro et al. (2021)) using GalNet (Li et al. (2022)). Based on these observation datas, we then calculated their $M_{*,10}$ and $\Gamma_{*,10}$ and further analyse the , $M_{*,10} - \Gamma_{*,10}$ relation and their evolution from $z = 0.4$ to $z = 0.15$. We then compared the observation result with the predicted one from our toy model and thus infer the growth mechanism of ETGs in this redshift range.

The structure of this paper is as follows. We present the selection of our observational sample and the observed $\Gamma_{*,10} - M_{*,10}$ relation in Sect.**??**. In Sect.**??**, we present the details of the simulation and the toy model that we built upon the simulation, as well as the comparison between observations. Then we discussed the result in Sect.**??** and give a brief conclusion in Sect.**??**.

In this paper, we assume a flat ΛCDM cosmology with $\Omega_M = 0.3$ and $H_0 = 70km\ s^{-1}\ Mpc^{-1}$. Magnitude are in AB units and stellar mass are in solar units.

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