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Origin and fate of the most massive galaxies

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Abstract

In the last five years there has been cumulative evidence showing that massive galaxies have dramatically grown in size since $z \sim 3$. This result has remained very controversial as it seems at odd with our previous knowledge based on the detailed analysis of the stellar populations of nearby massive galaxies which shows that their stars were form very early on and over a short time interval. In this contribution, I will summarize what we have learned since the discovery of these compact objects, the mechanisms proposed to explain their size increase and the future research lines to explore.

1 Introduction

In the nearby Universe, the population of galaxies with stellar masses greater than 10^{11} $M_\odot$ is dominated by large early-type galaxies [2] with correspondingly large sizes [39]. These nearby systems contain old and metal-rich stellar populations that formed quickly in the early Universe [21, 20, 42]. In addition, the number density evolution of massive galaxies seems to have evolve little since $z \sim 1$ [37]. These observational evidences strongly point out to a scenario where massive galaxies are build in a fast and dissipative event: the so-called monolithic collapse model [16, 28, 1, 6] and evolve passively since then. For the above reasons, this has been traditionally considered as the most likely formation and evolutionary scenario for this type of galaxies.

The advent of large area near infrared surveys, and consequently the possibility of studying massive galaxies in large numbers at $z > 1$, has cast some doubts about the reliability of the above scenario. Massive galaxies at high-z are found to be significantly more compact than their local massive counterparts [14, 44]. We exemplified in Fig. 1 how massive galaxies look like at high-z. In that figure we can clearly appreciate that the full structure of a prototypical compact massive object at high-z is well contained within 5 kpc. This implies that a strong evolution in their structure (a factor or $\sim$5 since $z \sim 2$; [46, 7]) has taken place

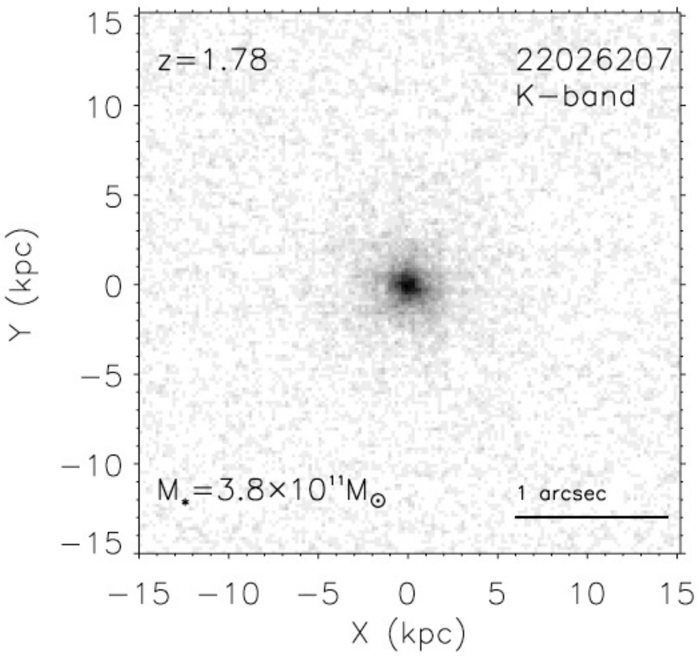

Figure 1: K-band high resolution Gemini imaging [9] of the massive galaxy POWIR22026207. Listed on the panel is the galaxy name, the stellar mass and the spectroscopic redshift. The image is so deep that the surface brightness profiles of these galaxies are detected up to ∼4 effective radii from the centre.

since that time. This is a significant result that was not expected from the study of lower mass galaxies at those redshifts. In fact, analysis of the evolution of the stellar mass–size relation of galaxies explored in the $10^{10} < M < 10^{11}$ $M_\odot$ range did not find a significant evolution of the stellar mass-size relation since $z \sim 1$ [3, 32] and only mildly since $z \sim 3$ [45].

Original claims that high-z massive galaxies were very compact in the past were received with skepticism, with claims that the compactness of those galaxies were likely to be a result of observational biases caused, for instance, by cosmological surface brightness dimming. However, many independent observations of different depth and at different wavelengths (see e.g. [29, 43, 56, 7, 13, 40, 50, 52, 15, 10, 31]) have confirmed the robustness of these observations and now it is well established that massive galaxies at high-z were substantially more compact than their local counterparts. This enormous size evolution has deep consequences on our understanding of the formation and evolution of these massive galaxies. They can not be form at high-z and just evolve passively since then. There should be a mechanism acting on these objects to make them grow in size as cosmic time evolves. Through this contribution I will scheme what is the present situation in this topic and what I think it could be the next steps forward to understand how this strong evolution has taken place.

2 Models for spheroid size evolution

Following the discovery of the strong size evolution of massive galaxies there was an intensive theoretical effort trying to understand which physical mechanisms are behind this significant growth (see e.g. [25, 51]). Among the different ideas that have been hypothesized we enumerate the following:

1. Removal of gas by AGN activity, also known as the "puffing up" model [18, 19]. This model argues that rapid expulsion of large amounts of gas by quasar winds destabilizes the galaxy structure in the inner, baryon dominated regions, and leads to a more expanded stellar distribution. This mechanism predicts a large change on the velocity dispersion of the massive galaxy with cosmic time that remains controversial observationally (see e.g. [12, 8, 53])

2. Major mergers. This scenario was one of the first that was considered [5]. The energy of the collision of these encounters transforms the compact progenitors into a larger remnant. This mechanism is not highly supported by the observations as not many major mergers are observed since $z \sim 2$ to favour a significant growth through this channel (see e.g. [30]).

3. Minor merging. In this scenario minor mergers on parabolic orbits mainly add stars in the outer parts of the galaxies from $z \sim 2$ down to the present epoch (see e.g. [35, 25, 33]). This mechanism is particularly efficient for making the galaxies to grow in size without adding a large amount of new mass to the system. This scenario seems to better fit with all the present observational evidence, although an observational quantification of the minor merging for these galaxies since $z \sim 3$ is still missing.

3 The velocity dispersion evolution of massive galaxies

Measuring the velocity dispersion of these massive high-z compact galaxies has been considered a top priority from the observational point of view. Having this measurement at hand would imply the possibility of: a) having an independent estimation of their mass through dynamics and consequently confirming the massive nature of these objects, and b) having the possibility of rejecting or, at the very least, strongly constrain the different evolutionary models enumerated above. For instance, in the puffing up model a strong evolution in the velocity dispersion of these objects is expected whereas in the minor merging scenario the degree of evolution is very mild.

Making use of public spectra from [13], we measured for the first time the velocity dispersion of spheroid-like massive ($M_\star \sim 10^{11}$ $M_\odot$) galaxies at $z \sim 1.6$ [12]. By comparing with galaxies of similar stellar mass at lower redshifts, we find evidence for a mild evolution in velocity dispersion, decreasing from ~ 240 km s^{-1} at $z \sim 1.6$ down to ~ 180 km s^{-1} at $z \sim 0$ (see Fig. 2). Such mild evolution contrasts with the strong change in size (a factor of ~ 4) found for these type of objects in the same cosmic time, and it is consistent with

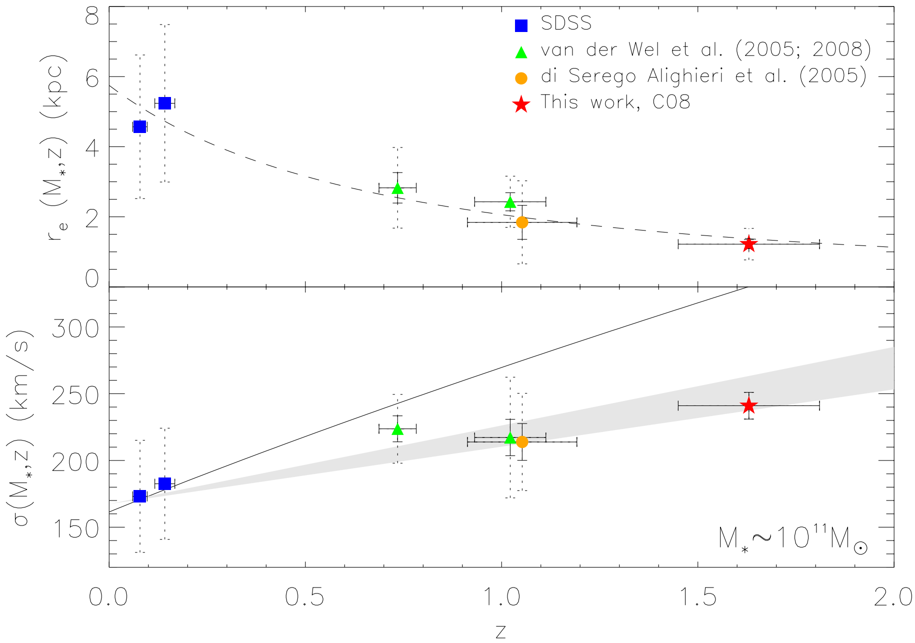

Figure 2: *Top panel*: Size evolution of $M_\star \sim 10^{11}$ $M_\odot$ spheroid-like galaxies as a function of redshift. Different symbols show the median values of the effective radii for the different galaxy sets considered in [12], as indicated in the labels. Dashed error bars, if available, show the dispersion of the sample, whereas the solid error bars indicate the uncertainty of the median value. The dashed line represents the observed evolution of sizes $r_e(z) \propto (1+z)^{-1.48}$ found in [7] for galaxies of similar stellar mass. *Bottom panel*: Velocity dispersion evolution of the spheroid-like galaxies as a function of redshift, with symbols as given above. Assuming the [7] size evolution, the solid line represents the prediction from the "puffing up" scenario [18], whereas the grey area illustrates the velocity dispersion evolution within the merger scenario of [23] for $1 < z < 2$.

a progressive larger role, at lower redshift, of the dark matter halo in setting the velocity dispersion of these galaxies.

Other works confirmed our results [8, 36] or even measured larger velocity dispersions than our estimates [53]. Summarizing, present data confirm that compact massive galaxies are really massive and put into questions the puffing up model scenario as the observed velocity dispersion evolution is moderate. Still, however, is pending a measurement of the velocity dispersion of a single object with an spectra of significant signal-to-noise to have a reliable measurement of this quantity.

4 Is there any compact massive galaxy at z∼0?

Within some hierarchical merging scenarios [23], a non-negligible fraction (1–10%) of massive compact galaxies is expected to survive since their formation epoch retaining their compact-

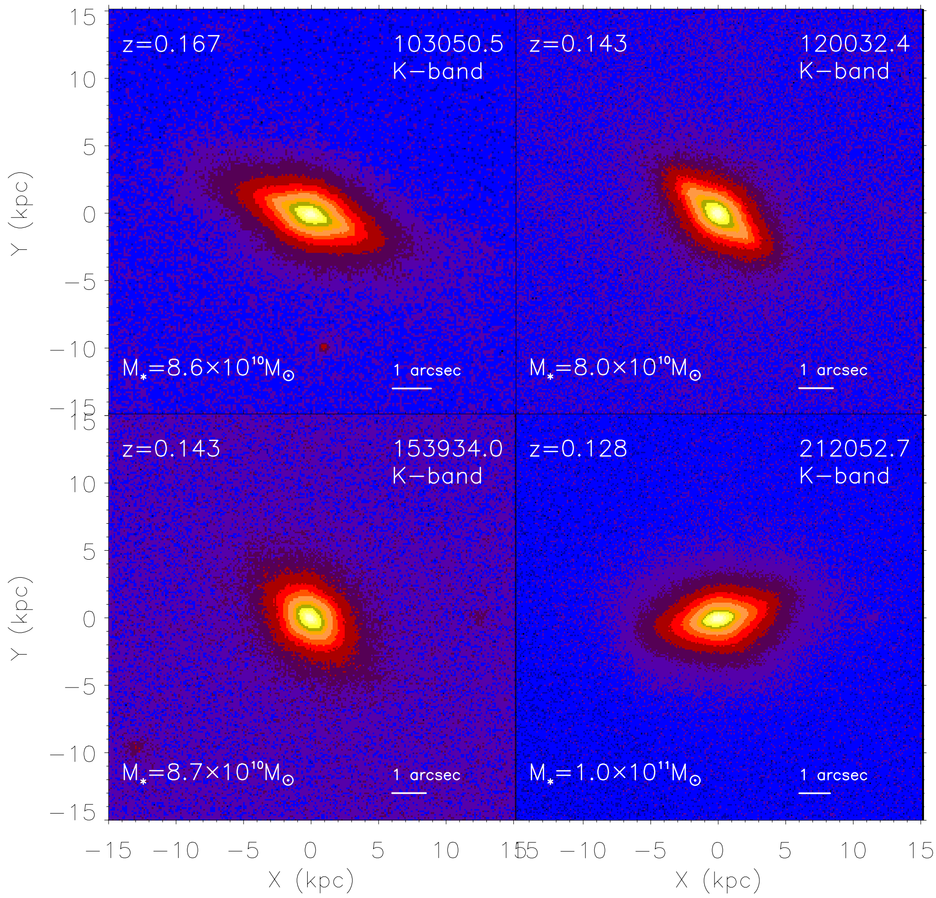

Figure 3: *K*-band high resolution Gemini observations of our sample of nearby massive compact galaxies [48]. Listed on each is the galaxy's name, the stellar mass and the redshift. The solid line indicates 1 arcsec angular size.

ness and presenting old stellar populations in the present universe. We conducted a pilot program for finding these objects in the local Universe [47]. We used the NYU Value-Added Galaxy Catalog from the SDSS Data Release 6. We found only a tiny fraction of galaxies (∼0.03%) with $r_e < 1.5$ kpc and $M_\star > 8 \times 10^{10}$ $M_\odot$ in the local Universe ($z < 0.2$). Surprisingly, they were relatively young ($\sim$ 2 Gyr) and metal rich ([Z/H]$\sim$ 0.2). The conclusions from this analysis was that basically no single massive compact relic from the early Universe is present in the local Universe (see also [49, 41]). We have now undertaken a project to image the massive compact galaxy population in the local Universe with unprecedented resolution. Fig. 3 illustrates some examples of the morphology of the galaxies we have found so far [48]. We can see that in some cases nearby massive compact galaxies present disk-like features, whereas in other cases some hints of interactions are visible and other galaxies are fairly roundish.

The nearly absence of massive compact galaxies in the local universe and, moreover, their young ages, implies that the massive compact galaxies observed in the high-z universe have all suffered a significant transformation since that epoch. We will address where the descendants of these galaxies could be hidden in the next section.

At the moment, I think the lesson we learn from the existence of young compact massive galaxies in the local Universe is that they likely represent the last events of the formation of massive galaxies that reached their maximum efficiency at z ∼2–3.

4.1 Where are the compact massive galaxies today?

If there are not old nearby massive compact galaxies, where are descendants of the high-z compact galaxy population? A significant step forward on answering this question was provided by the works from [4] and [24]. In these studies they explored the stellar mass density profiles in comparison with nearby massive elliptical galaxies. They found that the inner regions of these profiles is just slightly above the local values but with significant lack of stars in the outer regions. This has been also nicely illustrated by [54] and [9]. These results point out to an evolution of the structure of massive compact galaxies basically in their outskirts and a more modest (although no negligible) change in their centres. This fit well into an scenario whether the outer region of the local massive galaxies have been incorporated into the system by a continuous accretion process of minor merging. Consequently, the descendants of the high-z population are likely to be the most massive galaxies we can find today in the richest environments. A definitive prove of this scenario will require an analysis of the stellar populations in the outer part of the nearby massive ellipticals. It will be also interesting to check whether there are any hints for massive compact kinematically decouple cores in the central part of the nearby massive system that could be considered as the dense remnants of these compact massive galaxies in the early universe.

5 Are the massive galaxies evolving passively?

There has been a long debate about whether the evolution of the stellar populations of the massive compact galaxies at high-z is passive or active. As we mentioned in the Introduction the information provided by the local stellar population analysis suggest that the bulk of the stellar population of these galaxies was formed very early on and has passively evolved since then. The natural expectation is, consequently, that the stellar population of massive galaxies in the high-z universe evolve passively after an intense burst of star formation. However, as we will see studies of the star formation history of massive galaxies at all redshifts are controversial.

Some groups [27] claim based on rest-frame optical spectra analysis that the massive compact galaxies at high-z have old and passive stellar populations. Other groups [37] claim, on the contrary, that a fraction as large as 50% of these compact objects present significant emission at 24μm based on Spitzer very deep data. If this emission is considered to be caused by dust heated by star formation the implied star formation rate at $z \sim 2$ is as high as

~ 100 $M_\odot$/year. Very recent work with galaxies at $2 < z < 3$ obtained using either Herschel 250μm infrared data [11] as well as a stacking analysis [55] of known objects taken from the GOODS NICMOS Survey (GNS) catalog, on maps at 870μm (LABOCA); 250, 350, 500 μm (BLAST); and 24 μm (Spitzer) agree on the following result: a significant fraction of compact massive galaxies is emitting considerably in the IR. On average the compact, spheroid-like population appear to be red but not dead, and that localized, dust obscured star formation is a likely mechanism for size evolution in this population, consistent with several models of galaxy growth.

If these results are finally confirm, this points out to an scenario where massive compact galaxies are growing inside-out with new stars created potentially in the outer region by accretion of fresh material. A detailed analysis of stellar population gradients in local galaxies is required to confirm or reject this view.

6 How do the massive compact galaxies form?

In just two or three years we have learned a significant amount of information about how the massive compact galaxies evolve with time. However, it is still not clear how these objects have been originally formed. An emerging picture (e.g. [22, 13, 25]) for the formation of these compact systems predicts that massive, gas-rich galaxies at very high redshift become unstable following a major merger event, triggering a short lived starburst within $\sim$0.1 Gyr. Theoretical models [26, 22] have shown that the size of the remnant strongly depends upon the degree of dissipation involved, being very small in the case of strongly dissipative mergers. Since at high redshift ($z > 2$) galaxies are more gas-rich than they are today [17], the degree of dissipation is expected to be high and the resulting remnant extremely compact, with sizes < 1 kpc. Given the great amount of gas involved in these star formation processes, we expect the progenitors of massive compact galaxies to be undergoing a high amount of star formation, and hence should be detectable in the submillimetre (sub-mm; [34]).

To probe the above scenario, we analysed in. [38] a sample of 12 gas-rich and active star-forming submillimetre galaxies (SMGs) at $1.8 < z < 3$. We presented a structural and size measurement analysis for all of these objects using very deep Advanced Camera for Surveys (ACS) and Near Infrared Camera and Multi-Object Spectrometer (NICMOS) imaging in the Great Observatories Origins Deep Survey (GOODS) North field. Our analysis reveals a heterogeneous mix of morphologies and sizes. We find that four galaxies (33 ± 17 %) show clear signs of mergers or interactions, which we classify as early-stage mergers. The remaining galaxies are divided into two categories: five of them (42 ± 18 %) are diffuse and regular disc-like objects, while three (25 ± 14 %) are very compact, spheroidal systems. We argue that these three categories can be accommodated into an evolutionary sequence, showing the transformation from isolated, gas-rich discs with typical sizes of 2–3 kpc, into compact ($<$ 1kpc) galaxies through violent major merger events, compatible with the scenario depicted by theoretical models (see Fig. 4). Our findings that some SMGs are already dense and compact provide strong support to the idea that SMGs are the precursors of the compact, massive galaxies found at slightly lower redshift. Although this work is suggestive that compact massive galaxies can form in such a way, further work with a much larger

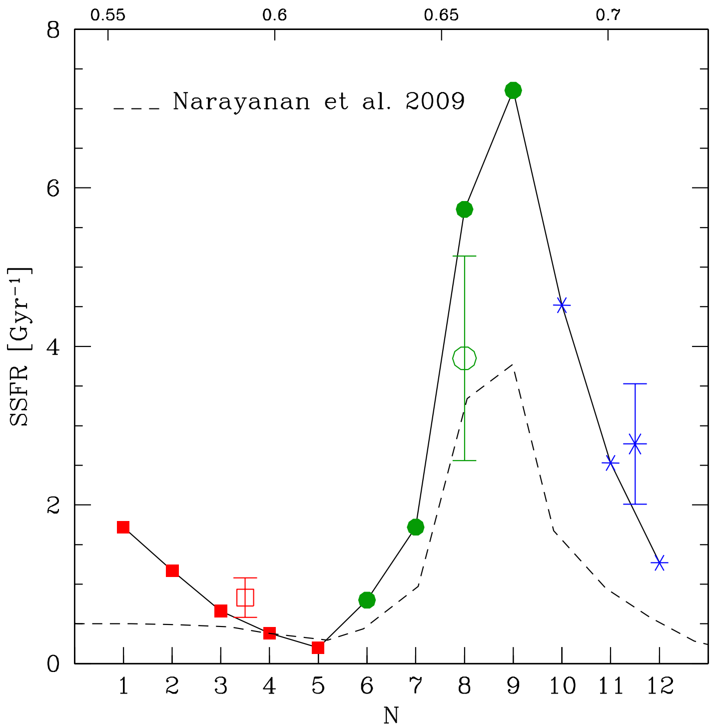

Figure 4: Specific star formation rate for 12 SMGs (points, solid line) from [38]. Different symbols refer to different morphological classes (red squares: disc-like galaxies, green circles: mergers, blue asterisks: compact galaxies). The open symbols with errorbars indicate the average specific star formation rate (SSFR) for a given class. Average and standard deviation have been computed with a bootstrap resampling. The x-axis refers to the position of the galaxy following a potential evolutionary sequence as suggested in [38]. The dashed line shows the predictions of [34] from a merger model for SMGs, with the time-scale shown in the upper axis in units of Gyrs.

sample is necessary to explore other alternative modes of formation like cooling flows.

7 Open issues from the observational point of view

A compilation of the observational evidence collected in the last years suggests that the most likely evolutionary scenario to explain the dramatic growth in size of massive galaxies since $z \sim 3$ is the late accretion of minor satellites. However, there is a still a lot of important work to conduct before we can assure the above path is rooted on solid grounds. What follows is a list of tasks I consider will imply significant advances in our knowledge of the evolution of these singular galaxies:

- An estimation of the velocity dispersion of compact massive galaxies at high-z based on single object spectra with S/N > 10. As mentioned earlier, the present estimations of this important parameter are either based on stacking of several spectra or in individual spectra but with poor S/N. A reliable measurement of this quantity is key to robustly establish the mass of the compact massive galaxies at high-z and to strongly constrain the evolutionary path followed by these objects.

- An estimation of the evolution of the number of 1:10 satellites of the most massive galaxies since $z < 2$. We have already suggested that the most likely evolutionary mechanism for the growing in size of the massive compact galaxies is the continuous bombardment of smaller units into the main system. A direct test to check this hypothesis would be the analysis of the satellite population of the massive galaxies in the last ∼11 Gyr (both their number as well as their photometric properties).

- A determination of the age and stellar metallicity gradients of the present-day most massive galaxies to explore their wings properties. If the decay of satellite galaxies is the main reason for the formation of the outer envelopes of the massive galaxies we see today, it is reasonable to expect that their stellar population properties change from the inner to the outer region.

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