EXPECTED NUMBER OF MASSIVE GALAXY RELICS IN THE PRESENT DAY UNIVERSE

VICENT QUILIS\(^1\) AND IGNACIO TRUJILLO\(^2,3\)

\(^1\) Departament d’Astronomia i Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain; vicent.quilis@uv.es
\(^2\) Instituto de Astrofísica de Canarias, c/ Via Láctea s/n, E-38205 La Laguna, Tenerife, Spain

Received 2013 June 18; accepted 2013 July 6; published 2013 July 25

ABSTRACT

The number of present day massive galaxies that have survived untouched since their formation at high-z is an important observational constraint to the hierarchical galaxy formation models. Using three different semianalytical models based on the Millennium simulation, we quantify the expected fraction and number densities of the massive galaxies that form at \(z > 2\) and have evolved in stellar mass less than 10\% and 30\%. We find that only a small fraction of the massive galaxies that already formed at \(z \sim 2\) have remained almost unaltered since their formation (<2\% with \(\Delta M_*/M_* < 0.1\) and <8\% with \(\Delta M_*/M_* < 0.3\)). These fractions correspond to the following number densities of massive relics in the present day universe: \(\sim 1.2 \times 10^{-6}\) Mpc\(^{-3}\) for \(\Delta M_*/M_* < 0.1\) and \(\sim 5.7 \times 10^{-6}\) Mpc\(^{-3}\) for \(\Delta M_*/M_* < 0.3\). The observed number of relic candidates found in the nearby universe is rather uncertain today (with uncertainties up to a factor of \(\sim 100\)), preventing us from establishing firm conclusions about the ability of current theoretical expectations to predict such an important number.

Key words: dark matter – galaxies: evolution – galaxies: formation – galaxies: halos

Online-only material: color figures

1. INTRODUCTION

The merging of galaxies is an intrinsically stochastic process, which means that there should be a number of galaxies that formed in the early epochs of the universe that have remained untouched until today. Identifying and exploring these relics is of fundamental relevance for understanding the conditions and properties of the primordial phases of galaxy formation. How many of these objects are theoretically expected to survive without being significantly modified since high redshift? In this Letter, we address this issue, focusing our attention on the most compact at high redshift (Daddi et al. 2005; Trujillo et al. 2006). Observationally, massive galaxies have been found to be more compact at high redshift (Daddi et al. 2005; Trujillo et al. 2006). In particular, those with spheroid-like morphologies show sizes (measured using their effective radii) smaller by a factor of \(\sim 4\) at \(z \sim 2\) (see, e.g., Trujillo et al. 2007; Buitrago et al. 2008). These massive compact galaxies are expected to grow as cosmic time increases in both stellar mass and size by continuous accretion of minor satellites (e.g., Bezanson et al. 2009; Hopkins et al. 2009). This channel of evolution agrees very well with many observations and it has been theoretically proven to be able to produce the expected size evolution (e.g., Naab et al. 2009; Sommer-Larsen & Toft 2010; Feldmann et al. 2010; Oser et al. 2012). Merging being a stochastic process, it is expected that a number of these massive compact galaxies remain unaltered since their formation. Consequently, quantifying the number of these massive old compact objects in the present day universe is a proxy for exploring the number of massive relics of the early universe.

Contradictory claims in relation to the number of massive compact galaxies with old stellar populations present today have been reported. On one hand, Trujillo et al. (2009), using the Sloan Digital Sky Survey (SDSS), did not find any clear evidence for a single massive “old” galaxy that has survived untouched since high-z formation. In fact, they found that the number of massive (\(M_* > 8 \times 10^{10}\) M\(_\odot\)) and compact (\(r_e < 1.5\) kpc) galaxies in the nearby universe (\(z < 0.2\)) is less than 0.03\% (see also Taylor et al. 2010 for a confirmation of this result). Moreover, these galaxies are not old but relatively young (\(\sim 29\) Gyr; see also Ferré-Mateu et al. 2012). On the other hand, Poggianti et al. (2013), using a much more modest area, find evidence for up to four old massive compact galaxies satisfying the above selection criteria of stellar mass and size. The reason behind these two conflicting results remains a mystery and further studies are necessary to clarify this point.

From a theoretical perspective, there is not a single quantification about the expected number of massive galaxies that have not experienced any growth since formation. Quantitatively answering this question is crucial in order to settle the minor merging scenario (the present day favored channel of growth) under solid grounds. Intuitively, a moderate low number of massive compact galaxies in the nearby universe should favor the hypothesis that massive galaxies have evolved by satellite accretion. However, if the number of relics found today is very small or nil, then this will put the minor merging hypothesis into question. This is again due to the intrinsic stochastic nature of the merging model. It is then an urgent question to quantify what is the exact theoretical prediction of the number of massive relics in the present day universe. Fortunately, current cosmological simulations are large enough to permit the estimation of this fraction with accuracy.

In this Letter, we explore the model predictions on the fraction and number density of massive galaxies formed at \(z > 2\) that have not gained stellar mass since that epoch by more than 10\% and 30\%. To quantify these numbers, we used three different semi-analytical models (De Lucia et al. 2007; Guo et al. 2011, 2013) based on the Millennium simulation.

2. GALAXY CATALOGS

We use the public release of two very large N-body simulations, Millennium I (Springel et al. 2005: MI) and
Millennium I-WMAP7 (Guo et al. 2013: M17), a version of the original Millennium I simulation run using the seven-year WMAP data (Komatsu et al. 2011). The cosmological parameters for the MI (M17) simulation are: \(\Omega_m = 0.25\) (\(\Omega_m = 0.272\)), \(\Omega_b = 0.045\) (\(\Omega_b = 0.045\)), \(\Omega_{\Lambda} = 0.75\) (\(\Omega_{\Lambda} = 0.728\)), \(n = 1(n = 0.961)\), \(\sigma_8 = 0.9(\sigma_8 = 0.807)\), and \(H_0 = 73\) km s\(^{-1}\) Mpc\(^{-1}\) (\(H_0 = 70.4\) km s\(^{-1}\) Mpc\(^{-1}\)). The two simulations use the same number of particles, 2160\(^3\). Thus, the computational box has sides of 685 Mpc (710 Mpc), and particles masses of \(1.18 \times 10^6 M_{\odot}\) (\(1.32 \times 10^6 M_{\odot}\)). In order to facilitate comparison between the three different catalogues and the observational data (see Section 4), we present all the results assuming \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\).

A combination of two halo finders, a friends-of-friends (FoF) by Davis et al. (1985) and SUBFIND (Springel et al. 2001), is used in order to analyze the simulations and to build up the dark matter merger trees. The dark matter haloes found in the N-body simulations are transformed into galaxies according to different semi-analytical models. Depending on the particular implementation of each model, several phenomenological recipes are used to produce the gas and stellar components in the virtual galaxies. In this Letter, we use three semi-analytical models available in the Millennium database web (Lemson et al. 2006).

The first one is the model by De Lucia & Blaizot (2007) and the other two are Guo et al. (2011, 2013), which are, in fact, the same model but applied to different simulations. All of them are very similar considering that the models by Guo et al. (2011, 2013) are an improvement of the model by De Lucia & Blaizot (2007). Guo’s models implement several new features: the separate evolution of sizes and orientations of gaseous and stellar discs, the size evolution of spheroids, tidal and ram-pressure stripping of satellite galaxies, and the disruption of galaxies to produce intra-cluster light. All three models include the effects of AGN feedback. The stellar masses of the semi-analytical galaxies were estimated assuming a Chabrier (2003) initial mass function (IMF) for the three models. This is consistent with the IMF assumed in the observational works used to compare with the theoretical predictions.

### 3. RESULTS

We generate three galaxy catalogs using the Millennium database web (Lemson et al. 2006). Each catalogue corresponds to one different semi-analytical model as previously discussed. For each of the catalogues, we select all the massive galaxies at present day as those objects with stellar masses between \(8 \times 10^{10} M_{\odot}\) and \(10^{13} M_{\odot}\).

We define a relic as a galaxy in the present day universe that has barely increased its stellar mass since \(z \sim 2\). In order to identify the possible candidates of relic galaxies, we use the merger tree structures to trace the massive galaxies identified at \(z \sim 0\) backward in time, together with two conditions: (1) the galaxy must have been already formed at \(z \sim 2\), and (2) the galaxy mass at \(z \sim 2\) has to be larger than 90% or 70%, depending on the considered case, of the limit mass at the present day \(8 \times 10^{10} M_{\odot}\). Once all the candidate relics are selected, it is possible to obtain their stellar mass increment at several redshift since \(z \sim 2\). To estimate the number of massive relics in the present day universe, we quantify the number of almost pure massive relics as the number of galaxies, among all the candidates, with an increase in their stellar mass less than 10% since \(z = 2\). Additionally, we also explore the number of massive galaxies in the \(z = 0\) universe with an increase in stellar mass less than 30% since \(z = 2\). This last limit is selected to avoid a galaxy that has suffered a major (i.e., 1:3 or lower ratio) merger since \(z = 2\) that could have altered its structure.

In Figure 1, we show the fraction of massive galaxies at \(z \sim 0\) already present at \(z \sim 2\) as a function of the relative increment of their stellar mass. All three models considered show that roughly half of the massive galaxies already built at \(z \sim 2\) have increased in mass at \(z \sim 0\) more than a factor of two. Only a small fraction of the massive galaxies in the present epoch corresponds to massive galaxies at \(z \sim 2\) that remain untouched or that have a minor increase in mass. In fact, less than a 2% (8%) of the massive galaxies already formed at \(z \sim 2\) gained less than 10% (30%) of their stellar mass since that epoch.

In Figure 2, we represent the redshift evolution of the ratio of the number of relic galaxies to the total number of massive galaxies (left panel) and the number density of relics for the three models considered (right panel). The total number of massive galaxies at each redshift accounts for all massive galaxies that are progressively being incorporated into the family of massive galaxies as cosmic time increases. No substantial differences appear between the three models. At redshifts, the De Lucia & Blaizot (2007) model produces ratios of relic galaxies slightly higher than the other two models. As in Figure 1, we distinguish between two samples, those massive galaxies that have increased their relative stellar masses less than 10% and those with a relative mass increment less than 30%. For the sake of completeness, we include the observational upper limits from Trujillo et al. (2009) and Taylor et al. (2010), and the observational data from Poggianti et al. (2013).4

The current ratios of relic galaxies to the total number of galaxies and the present day number densities for the three different considered catalogues are summarized in Table 1.

### 4. DISCUSSION

As was mentioned in the Introduction, having an accurate estimation of the expected number density of massive relics in the present day universe is crucial for probing the minor

---

4 The number densities from Trujillo et al. (2009), Taylor et al. (2010), and Poggianti et al. (2013) are computed assuming a standard cosmology: \(\Omega_m = 0.3\), \(\Omega_{\Lambda} = 0.7\), and \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\).
merging channel of galaxy growth. Since the massive galaxies at high-$z$ are much more compact compared to current massive counterparts, a good proxy to identify massive galaxy relics in the nearby universe is to search for massive compact galaxies with old stellar populations. The observed fraction of compact ($r_e < 1.5$ kpc) massive ($M_\star > 8 \times 10^{10}$ $M_\odot$) galaxies with $z < 0.2$ in the present day universe (i.e., a good set of candidates to be relics of the early universe) is $\sim 0.0003$ (Trujillo et al. 2009). At first glance, this number is similar to the fractions estimated in this Letter (particularly with those values obtained using the Guo et al. 2013 model). However, the number estimated by Trujillo et al. (2009) is uncertain for several reasons. First, the ages of the compact galaxies found in that work are relatively young ($\sim 2$ Gyr), which means that they cannot be relics of the early universe. In that sense, the Trujillo et al. results should be understood as an upper limit of the true value (i.e., $< 0.0003$; $< 1.3 \times 10^{-7}$ Mpc$^{-3}$). Using a slightly different selection ($M_\star > 8 \times 10^{10}$ $M_\odot$ and $\Delta \log r_e < -0.4$ dex with respect to the SDSS stellar mass–size relation from Shen et al. 2003) and focusing only on red objects (i.e., more likely to be relics from the early universe), Taylor et al. (2010) found only one dubious candidate at $0.066 < z < 0.12$. This is 5000 times less than the expected number density of compact massive galaxies in the present day universe if the high-$z$ massive objects did not evolve either in size or mass (i.e., $\sim 1.5 \times 10^{-4}$ Mpc$^{-3}$ versus the number found in Taylor et al. 2010, $< 3 \times 10^{-8}$ Mpc$^{-3}$).

Is it possible that both the Trujillo et al. (2009) and Taylor et al. (2010) results can be biased against the detection of massive relics in the present day universe? Taylor et al. (2010) performed an extensive study of the potential biases that affect the SDSS spectroscopic sample and found that their results cannot be explained as a consequence of incompleteness. In a recent work, Poggianti et al. (2013), applying the same selection as in Trujillo et al. (2009), found four old compact massive galaxies in 30.88 deg$^2$ within $0.03 < z < 0.11$ using the PM2GC (Calvi et al. 2011) sample. This is equivalent to a number density of $1.3 \times 10^{-5}$ Mpc$^{-3}$. This number is significantly larger than the numbers quoted in the Trujillo et al. (2009) and Taylor et al. (2010) studies. The Poggianti et al. (2013) results are based on a sample with a larger spectroscopic completeness. However, the different spectroscopic completeness of the SDSS survey.

---

**Figure 2.** Left panel: redshift evolution of the ratio of the relic galaxies to the total number of massive galaxies. The three different lines represent the three models considered. Orange (orange-red) shows galaxies that have increased in mass by less than 10% (30%) since $z \sim 2$. Right panel: redshift evolution of the comoving number density of relic galaxies. The lines and color shaded areas have the same meanings as in the right panel. The red and blue arrows show the observational upper limits from Trujillo et al. (2009) and Taylor et al. (2010), respectively. The green point displays the observational data from Poggianti et al. (2013).

(A color version of this figure is available in the online journal.)

**Table 1**

| $\Delta M_\star/M_\star$ (Since $z = 2$) | De Lucia et al. (2007) | Guo et al. (2011) | Guo et al. (2013) | Average |
|----------------------------------------|------------------------|-------------------|-------------------|---------|
|                                        | $n_{\text{relics}}/n_{\text{total}} ~ z ~ 0$ |                   |                   |         |
| <10%                                   | 0.0038                 | 0.001             | 0.0006            | 0.0018  |
| <30%                                   | 0.016                  | 0.006             | 0.005             | 0.009   |
| Number density (Mpc$^{-3}$)            |                        |                   |                   |         |
| <10%                                   | $2.7 \times 10^{-6}$   | $5.8 \times 10^{-7}$ | $2.6 \times 10^{-7}$ | $1.2 \times 10^{-6}$ |
| <30%                                   | $1.2 \times 10^{-5}$   | $3.2 \times 10^{-6}$ | $2.0 \times 10^{-6}$ | $5.7 \times 10^{-6}$ |
compared to the PM2GC cannot explain a factor of at least 100 in the discrepancy among these works. Poggianti et al. (2013) indicates that only 25% of their compact galaxies are not spectroscopically identified in the SDSS. It is clear that a more detailed analysis is necessary to solve this enormous discrepancy.

Although the expected fraction of massive relics galaxies change by a factor of 5 among the different semi-analytical models, the change in the number density can be as high as a factor of 10. For the discussion and the comparison with the observations, we take the average values of the different models for the fraction and the number density of massive relics. The results based on the SDSS survey (Trujillo et al. 2009; Taylor et al. 2010) found significantly fewer (by more than a factor of 10) relics than predicted by the models. If these observations are confirmed in the future, then this will be hardly understood within the merging scenario. Due to its stochastic nature, there should be a number (small, but measurable) of relics in the nearby universe that remains undetected. Again, if confirmed, the absence of compact massive relic galaxies in the nearby universe will be a strong indication that the growth mechanisms of the massive galaxies require more than merging to produce the observed massive population or that the number of mergers is much larger than theoretically predicted. This is odd, as we know that the number of satellites among massive galaxies at all redshifts is overpredicted by those simulations (see e.g., Quilis & Trujillo 2012). On the contrary, if the number density of massive relics galaxies is closer to the values quoted by Poggianti et al. (2013), then the number of merging seems to be lower than theoretically expected. Once more, it is urgent to understand the discrepancy between the observational results to put a stringent constraint to the question.

The authors thank Bianca Poggianti for clarifying some aspects of her work and the anonymous referee for useful comments and criticism. This work was supported by the Spanish Ministerio de Economía y Competitividad (MINECO: grants AYA2010-21322-C03-01 and AYA2010-21322-C03-02) and the Generalitat Valenciana (grant PROMETEO-2009-103). The Millennium Simulation databases used in this paper and the web application providing online access to them were constructed as part of the activities of the German Astrophysical Virtual Observatory.

REFERENCES

Bezanson, R., van Dokkum, P. G., Tal, T., et al. 2009, ApJ, 697, 1290
Buitrago, F., Trujillo, I., Conselice, C. J., et al. 2008, ApJL, 687, L61
Calvi, R., Poggianti, B. M., & Vulcani, B. 2011, MNRAS, 416, 727
Chabrier, G. 2003, PASP, 115, 763
Daddi, E., Renzini, A., Pirzkal, N., et al. 2005, ApJ, 626, 680
Davis, M., Efstathiou, G., Frenk, C. S., & White, S. D. M. 1985, ApJ, 292, 371
De Lucia, G., & Blaizot, J. 2007, MNRAS, 375, 2
Feldmann, R., Carollo, C. M., Mayer, L., et al. 2010, ApJ, 709, 218
Ferré-Mateu, A., Vazdekis, A., Trujillo, I., et al. 2012, MNRAS, 423, 632
Guo, Q., White, S., Angulo, R. E., et al. 2013, MNRAS, 428, 1351
Guo, Q., White, S., Boylan-Kolchin, M., et al. 2011, MNRAS, 413, 101
Hopkins, P. F., Bundy, K., Murray, N., et al. 2009, MNRAS, 398, 898
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18
Lemson, G., & the Virgo Consortium, 2006, arXiv:astro-ph/0608019
Naab, T., Johansson, P. H., & Ostriker, J. P. 2009, ApJ, 699, L178
Oser, L., Naab, T., Ostriker, J. P., & Johansson, P. H. 2012, ApJ, 744, 63
Poggianti, B. M., Calvi, R., Binodoni, D., et al. 2013, ApJ, 762, 77
Quilis, V., & Trujillo, I. 2012, ApJL, 752, L19
Shen, S., Mo, H. J., White, S. D. M., et al. 2003, MNRAS, 343, 978
Sommer-Larsen, J., & Toft, S. 2010, ApJ, 721, 1755
Springel, V., White, S. D. M., Jenkins, A., et al. 2005, Natur, 435, 629
Springel, V., White, S. D. M., Tormen, G., & Kauffmann, G. 2001, MNRAS, 328, 726
Taylor, E. N., Franx, M., Glazebrook, K., et al. 2010, ApJ, 720, 723
Trujillo, I., Cenarro, A. J., de Lorenzo-Cáceres, A., et al. 2009, ApJL, 692, L118
Trujillo, I., Conselice, C. J., Bundy, K., et al. 2007, MNRAS, 382, 109
Trujillo, I., Feulner, G., Goranova, Y., et al. 2006, MNRAS, 373, L36