Galaxy growth through accretion and mergers

Author: Sergio-Yersi Villegas Pelegrín
*Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.**

Advisor: Alberto Manrique Oliva

Abstract: Galaxies have been the main protagonist in Cosmology and the study of the Universe for almost a century. Currently, they have become an independent and major field itself. Through the use of AMIGA, an analytic model that examines galaxy formation and evolution since the dark ages, we will study the roles of accretion and mergers as two different ways for galaxies to grow. The model will provide the ratio of mass coming from mergers for several ages. This ratio will be shown according to two different variables: the stellar mass of galaxies and the age of the Universe. We see that the role of mergers increased from $z \sim 10$ to $z \sim 4$, and had its peak at $z \approx 5$, with a value of 30%. This tendency is supported by recent studies on luminosity functions. Finally, even though mergers were the most significant process in the formation of the most massive galaxies, accretion has had the major role in galaxy growth.

I. INTRODUCTION

Galaxies, gathered in several types of clusters, are the shaping constituents of the Universe: a mixture of newborn, evolving and collapsing stars interacting with the interstellar medium. The super-massive black holes, located in the center of most galaxies, eventually swallow matter. Thus, they are able to release the largest amounts of energy known in the Universe, as powerful plasma jets. However, this active galactic nuclei (AGN) phenomenon was more frequent in the past. Altogether, this luminous matter is just a small percentage of the measured galaxies' mass; they develop within dark matter (DM) halos, one of the biggest mysteries of modern science [1].

In the last century, the knowledge about our cosmic world has been constantly changing and, in this process, galaxies have had the leading role. The studies in galaxy formation began with Hubble in 1929 [1],[2], when he established the self-bounded nature of galaxies, therefore confirming the existence of extra-galactic components. Back then, the main purpose in this field was aimed towards solving cosmological issues. Thus, with its kinematics, Hubble proved the current uniform expansion of the Universe. Over the years, even though the field is still important for cosmological reasons, it has been so strongly developed that it has become a major discipline itself. Since this field remains in a phase where new empirical discoveries, rather than accurate theoretical models, can end up in more significant improvements, the observational side is the main focus of the field. However, the secondary role of theoretical models is expected to be upgraded, so the transition to the theory-driven phase can arrive as soon as possible [2].

As stated before, one of the most important scientific enigmas at the moment is the nature of the DM. There are several hypothesis that try to explain it in different ways, and none of them have been 100% confirmed. The way to categorize the possible types of DM is based on the time its particles need to become non-relativistic [1]. Thus, taking into account that more massive particles favor the promptness of becoming non-relativistic, one of the models is the Cold Dark Matter (CDM), which assumes massive DM particles (therefore less-moving and colder) that do not self-interact. On the other hand, Warm Dark Matter (WDM) and Hot Dark Matter (HDM) are the other proposed models.

In modern astrophysics, the Λ Cold Dark Matter (ΛCDM) has become the archetype model due to its successful integration of cosmological theories (such as the Big Bang and the Inflation), astrophysical models in a large scale structure and the cosmic microwave background explanation [1],[2]. Knowing that CDM particles quickly become non-relativistic, DM perturbations cannot be stopped. With all those considerations in mind, galaxies, due to the gravitational evolution of collisionless CDM perturbations, would be formed in the centers of collapsed CDM structures, known as halos.

Finally, the empirical luminosity functions (LF) have been a relevant aspect in galaxy studies [3]. The LF provide the volume density of galaxies as a function of their luminosity. By comparing these LF with their halo mass function, we can gain information about the efficiency of star formation, gas cooling or the AGN phenomenon, and its dependency with the cosmic time [4]. They are also useful to track galaxy evolution through the change of its shape along time. In this way one can have a picture of how galaxies grow in mass. Furthermore, as we will see in section IV, comparing these observational results with theoretical models can be really interesting, either to better understand the obtained values or to question and improve the compared models.

After having introduced the astronomical and cosmological background of this work, we will now focus on the several points we will go through. The main goal of this work is to study the roles of the two galaxy-growing

*Electronic address: sy.villegas@outlook.com

processes, accretion and mergers, and see which one of them is most common. In order to do that, starting in section II, we will go through the aforementioned ways in which galaxies can grow. Then, the basis of our experimental work will be established in section III, which consists in explaining the foundations of the Analytic Model of Intergalactic-medium and Galaxy evolution (AMIGA) we have used. This model will provide the ratio of galaxy mass gained through mergers in relation to the total gained mass. Then, in section IV we will show and discuss how the obtained merger ratio varies according to: firstly, the stellar mass (SM) of galaxies and secondly, the cosmic time, through the use of the redshift. Finally, after analyzing the aforementioned figures, we will provide some conclusions in section V.

II. GALAXY GROWTH

In order to understand how galaxies grow, it is necessary to study this evolution process focusing not only on galaxies themselves, but also in the DM halos containing them, since they have a major role on the evolution of ordinary matter.

A. Halo evolution

Halos grow in mass in a similar way as galaxies: by capturing other halos. Depending on the relative mass of the captured halo, the capture is considered a merger (the inner structure of the resulting halo is completely rearranged) or an accretion (the inner structure of the capturing halo keeps steady) [5]. In the first case, the most massive galaxy of both halos becomes the new central one, and all the remaining ones become its satellites. This leads to a decrease of the halo radius of these new satellites, which were originally central galaxies, while part of these galaxy's DM remain bound to it, maintaining its original mass distribution. The galaxies of halos captured through accretion become satellites located at the instantaneous radius of the accreting halo. In both cases satellites experience dynamical friction, a drag force caused by the sea of DM particles distributed within the halo, and, therefore, satellites lose orbital energy and fall towards the center.

B. Accretion vs Mergers

The main way to differentiate accretion from mergers, as stated before, is the relative mass between the interacting galaxies: when the ratio between the masses of the satellite and the central galaxy exceeds a certain value [5] (see section III), the capture is considered to be a merger, otherwise it is considered an accretion. Furthermore, both growing modes have different consequences in the evolving galaxy.

1. Accretion (or minor mergers). If the central galaxy has a disk, while stars are deposited in the spheroid without destroying it, the disk incorporates the gas of the satellite. In this case, the cold incorporated gas causes a continuous star-formation process, which results in a variety of galaxy morphologies. Otherwise, if the central galaxy is a spheroid, both the gas and stars of the satellite galaxy are accumulated in the spheroid, causing a starburst and feeding off the central MBH [5].

2. Major mergers. The central galaxy and satellite get destroyed and, as a result of it, spheroids are formed. This is the main way in which spheroids and hence, elliptical galaxies, are expected to be developed. However, depending on the redshift (z), the spheroid-formation process is considered to be different. At high z, with mainly gaseous disks, the process is close to the violent collapses of giant gas clouds in the early Universe (known as the Monolithic Collapse Model for galaxy formation). On the contrary, at low z, when a significant fraction of the galaxies' gas has already been transformed into stars, spheroids are set up as a dissipationless collision [1].

It has been shown [6] that, at a total given mass and irrespective of the morphological shape of the interacting galaxies, major mergers are the most efficient ones in new-star formation (up to a factor 2). Furthermore, it has also been pointed out that, regardless of the growing process that took place, interacting galaxies had a significantly higher total star formation rate than isolated galaxies.

III. MODEL AMIGA

For the past decades, with the help of hydrodynamic simulations and semi-analytic models (SAMs), there has been a great development in the gathering of information in order to understand the nature of galaxy evolution [5]. However, both techniques share the same weak points. First, the huge amount of analyzed data and therefore, the large CPU times required, which are restrictive enough even though studies focus on small regions or high z. Second, the simplicity and the multiple free parameters used to describe the baryon physics, providing non-realistic galaxy models. Moreover, the feedback of stars to the intergalactic medium (IGM) has a main purpose in the non-linear galaxy formation process. Without significant simplifying assumptions, the IGM is hard to accurately model. In this project we have worked with a reliable SAM that overcome the previous difficulties.

AMIGA is an Analytic Model of Intergalactic-medium and Galaxy evolution, mainly developed by Drs. Manrique and Salvador-Solé [5], which presents an enhanced analysis of IGM and goes back in time to the dark ages. In order to deal with both weak points SAMs have, AMIGA has some particular traits, starting with its own way of dealing with DM halos' evolution: instead of constructing individual halo merger trees, it uses 3-dimensional grids to interpolate halo properties, which are initially started by well-known boundary conditions so they can progressively evolve. Thus, its memory and CPU time gets minimized. Moreover, AMIGA deals with all the apparently random and independent processes by creating the best-suited causal connections, either with analytic or accurate numerical probability distribution functions. By doing so, the amount of free parameters decreases and the its reliability rises. Finally, recalling what we stated in section II, the relative mass between the interacting galaxies (or halos) is the way we can tell which process is taking place: if it exceeds a certain reference value the capture is a merger, otherwise is considered as accretion. In this case, AMIGA sets this value in 0.3.

After having gone through the most noticeable features of AMIGA, and due to the high complexity that characterizes this model, we will now focus on the specific parts in which we have worked on during this project. The changes we have implemented are are all directed towards the extraction of the merger ratio. We have defined two new quantities (arrays), so one can accumulate the SM formed through mergers, while the other would do the same with the total SM formed through either mergers or accretion. These arrays store the SM formed in bins of (stellar) galaxy masses at different cosmic times. In particular, AMIGA is able to classify at each z the SM formed, and consequently the merger ratio, in 30 bins of galaxy masses, ranging from $\sim 10^2$ M$_\odot$ to 10^{13} M$_\odot$. These arrays are computed in 53 redshifts, from $z = 60$ to the present.

Following, we will analyze these results in section IV.

IV. ANALYSIS

Once we have collected all the data from AMIGA, we will study the behavior of the merger ratio according to two different variables: stellar galaxy mass and time. For the whole analysis, the maximum redshift value will be 15. Throughout the last decades, one of the main purposes of the galaxy-evolution field has been the obtention of LF for galaxies in the high-redshift region [3]. With the most recent studies in the subject, the maximum redshift for which it has been able to obtain a LF is $z \sim 10$. Therefore, there is no need to go beyond $z \sim 15$, because of the decreasing reliability of the results, since there would be a lack of observational values to compare with.

In the first place, we observe the dependence of the merger ratio with the SM of the galaxies involved and therefore, how it affects their own growing mode.

To begin with, there is a common pattern between the three panels of FIG. 1: the existence of a required

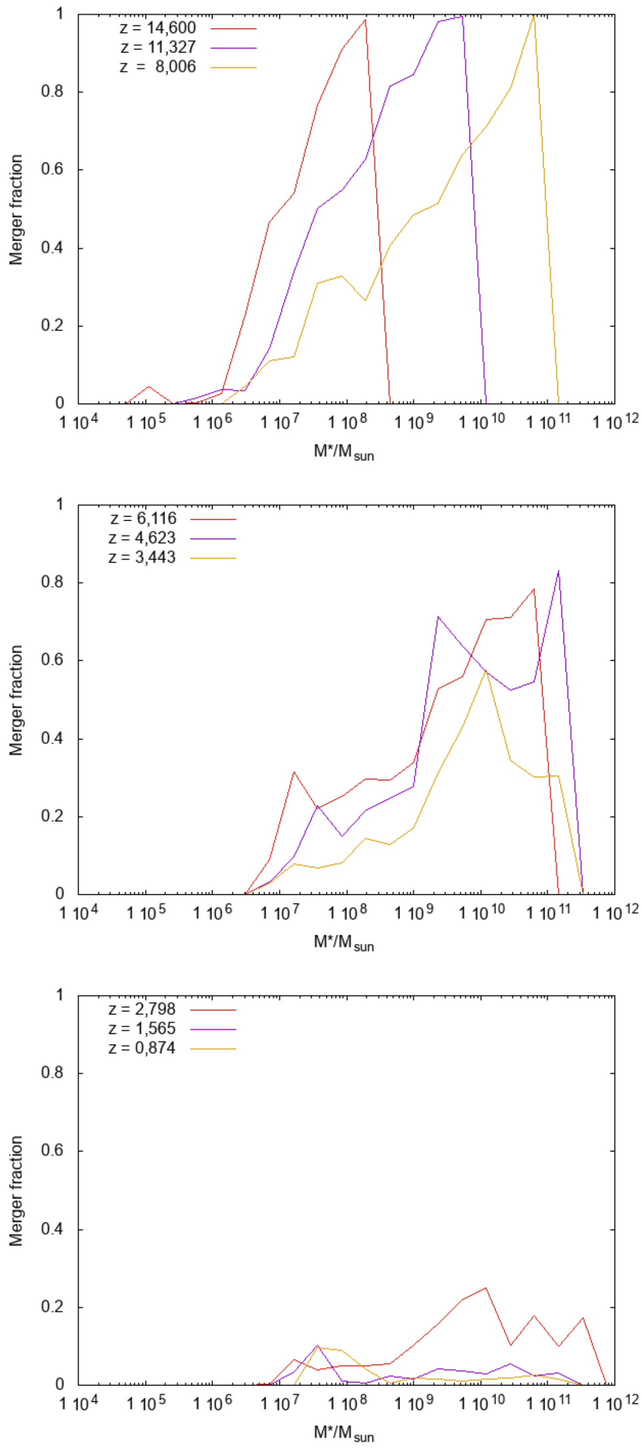

FIG. 1: Evolution of the merger fraction with the SM of galaxies for different redshift ranges: upper panel for high z, medium panel for moderate z and lower panel for low z.

minimum SM of galaxies for mergers to be possible (less massive galaxies grow through accretion). This is the reason the galaxy mass range has been delimited and thus, we focus on the massive galaxies at each z. We can see that this minimum discreetly increases with decreasing z. Moreover, similarly to the aforementioned, we can also observe a maximum mass value, from which the merger ratio immediately goes to 0. This represents the maximum mass galaxies have at each z; therefore, it is expected to slightly increase with time, since galaxies keep becoming more massive. These two limits create a range in which the merger ratio curves vary at each z: averagely, this curve has an increasing tendency until it reaches a maximum value. Thus, the importance of mergers increases with the galaxy mass. More particularly, in the high-z range, we can clearly see the hierarchical scenario firstly introduced in two seminal papers [7],[8] that, in time, would have established the basis of the ΛCDM model [1]. This process is called *hierarchical clustering* [1], where the first large structures were formed by the merging of smaller systems that were added into a larger cluster. Taking into account the relative mass of galaxies [5] as the way to differentiate mergers from accretion, since the biggest galaxies at this early age of the Universe had similar SMs, they mainly evolved through mergers. Now, the reason these curves change with z also relies in the relative galaxies' mass. Mergers are the main evolution process of galaxies similarly massive. At high z, as we have seen, there could not be more massive galaxies; therefore, for these first large galaxies the merger ratio values are the highest ones. Then, as time went by, the galaxies in the Universe kept growing and thus, some of them began to be much more massive than the rest. In consequence, since the relative mass between galaxies kept decreasing, accretion began to gain significance as we can see in the medium z range, where the several maximum merger ratios are between 0.8 and 0.6. Finally, the curves for low values of z clearly show mergers have become the minority growing process. All things considered, we can observe a change of the growing behavior with time: for low z values, galaxies that would have formerly grew through mergers in the high z range, would now grow through accretion.

Secondly, in FIG. 2, we will now study the fraction of SM coming from mergers according to the age of the Universe. In order to be able to show this dependency, since AMIGA provided values for each SM of galaxies, we have calculated the total merger fraction at each z by adding up the contributions for all galaxy masses.

The results in FIG. 2 show that, firstly, at the highest z, the mass of galaxies coming from mergers was almost 0. Then, for $14 > z > 4$, this ratio began to grow and the role of mergers in galaxy evolution became significant, having its peak at $z \approx 5$, with a value of a 30%. Then, from that point, we can observe a rapid decrease in the value of this fraction, going all the way down to almost 0 again. Hence, irrespective of the SM of galaxies, we can see the greater role of the accretion process, since it has clearly been the dominant way for galaxy growth throughout time. However, FIG. 1 showed that mergers actually had a major role in the first massive galaxies, reaching high merger fraction values. The reason these

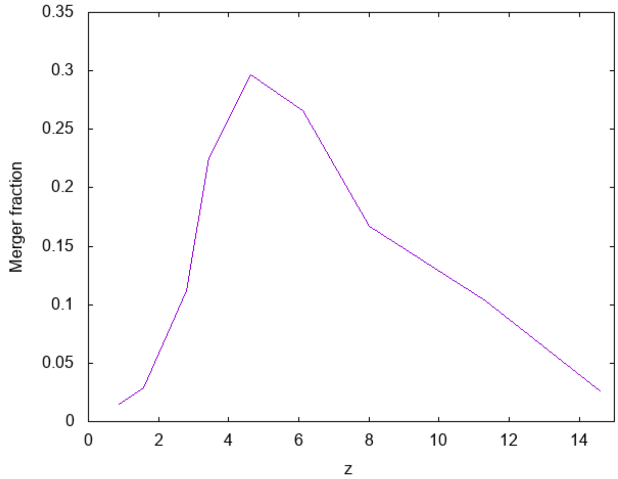

FIG. 2: Evolution of the merger fraction with z.

results do not have a greater weight when adding all of the values together is the small number of SMs that had this high merger ratio values. Even though there were massive galaxies that did not grew through accretion, as we stated, AMIGA considers 30 bins of galaxy masses for each z. Therefore, in the sum of this results, the high merger fraction values would not be reflected, as the vast majority of the other cases evolved through accretion. Moreover, as we can see in FIG. 2, there is a build-up in the role of mergers as a way for galaxies to grow in the $10 > z > 4$ range. Currently, in the most recent LF research, special emphasis has been placed in the aforementioned redshift range in order to understand the LF evolution more accurately [3]. By comparing our results with the recent work of Bouwens et al. (2015) displayed in FIG. 3 [3], we can see a correspondence with this verified study.

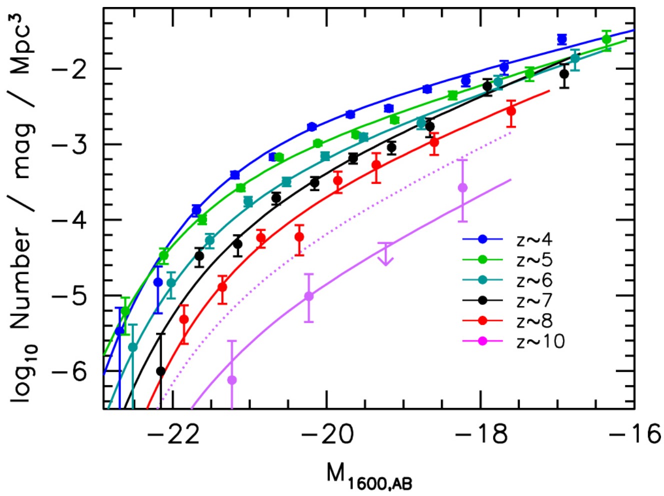

FIG. 3: Evolution of the LF at $z \sim 10$, compared to the ones at lower redshifts, according to the absolute magnitude of galaxies. This figure corresponds to FIG. 15 in [3].

FIG. 3 shows an increase in the number density of galaxies with the cosmic time, which can be linked to our obtained results in FIG. 2. Firstly, for the least massive galaxies corresponding to the least negative absolute magnitudes (right side of FIG. 3), we can see a common value of the LF for $z \sim 4{-}7$. These galaxies show their slow development with time in this redshift range and thus, they manifest the steady behavior of the accretion processes. Then, for the most massive galaxies (left side of FIG. 3), we can see a strong increasing tendency of the LF curves, for a given mass, with z. Hence, these massive galaxies are growing faster in this redshift range, showing the intense development caused by mergers. Furthermore, this tendency stops at $z \sim 4{-}5$, where both curves intersect and therefore reflect a ceasing of this merger behavior. The previous analysis of FIG. 3 is in correspondence with the results of FIG. 2, where the increasing role of mergers in this redshift range stops around the same value of $z \sim 4{-}5$. Finally, as we can see in FIG. 3, they found a remarkable difference between the observational values for $z \sim 10$ and the extrapolated values, from the $8 > z > 4$ results, for $z \sim 10$ (see the magenta doted line). Thus, we can verify our earlier assumption of not focusing in $z > 15$, since the results would probably not be accurate.

V. CONCLUSIONS

After having analyzed our data, we can provide the most relevant conclusions of this work.

- Mergers are the main growing process of similarly and highly massive galaxies. Thus, at the high z range of FIG. 1, the first most massive galaxies had to grow through mergers. In time, the former most massive galaxies were not the largest ones anymore. Therefore, for medium z, accretion started becoming relevant for galaxies with a mass that used to grow through mergers. Finally, at low z, accretion had already become the main galaxy growing method of these galaxies.
- The results for the high z range reflect the hierarchical evolution scenario in which the ΛCDM model is based. For the moment, this model has been successfully tested in situations with much larger scales than the ones concerning the galaxy evolution field [2] in which he have worked. Therefore, it is satisfactory that the results are not in disagreement with the archetype cosmological model.
- In the $4 > z > 0$ range of FIG. 2, there is a complete decrease in the merger ratio value. Thus, the most recent times seem to be quiet and steady when talking about galaxy evolution. The most massive galaxies do not interact with each other anymore, and they just lightly grow by the capture of small galaxies.
- The results obtained in FIG. 2 are in concordance with the most recent LF studies for the $10 > z > 4$ range, as we have seen in FIG. 3. Both figures manifest a time of significant galaxy evolution and therefore, a noticeable increase in the role of mergers. Furthermore, they both show the ending of this tendency at $z \sim 4{-}5$. Thus, taking into account the relaxed recent epoch, the currently most massive galaxies of the Universe seemed to had formed in the $z \sim 4{-}8$ range.
- Finally, FIG. 2 leaves no doubt in which growing process has been the dominating one when taking into consideration all galaxies. From the highest zs until the present time, the maximum peak for the merger ratio barely reached the 30%. Recalling the relative mass of the interacting galaxies, we can affirm that central galaxies have mostly been much more massive than the satellite galaxies they captured. Thus, galaxies have mainly tended to grow through accretion. Nevertheless, mergers had the major role in the formation of the current most massive galaxies. Altogether with mergers being more efficient in new-star formation (see section II), they obviously cannot be underestimated.

Acknowledgments

Special thanks to my advisor, Dr. Alberto Manrique, for his time and great counsel in this work. It has been a real pleasure to learn from you. To my family and closest friends for their support. And finally to the Astrophysics community, for always trying to unravel the biggest mysteries of our Universe.

[1] Avila-Reese, V. 2007, Astrophysics and Space Science Proceedings, 2, 115. (astro-ph/0605212)
[2] Benson, A. 2010, Physics Reports, 495, 33-86
[3] Bouwens, R.J., Illingworth, G. D., Oesch, P. A. et al. 2015, ApJL, 803, 34
[4] Carmeli, M., Hartnett, J. G., & Oliveira, F. J. 2006, Found.Phys., 277, 283
[5] Manrique, A., Salvador-Solé, E., Juan, E. et al. 2015, ApJSS, 216, 13
[6] Lambas, D. G., Alonso, S., Mesa, V., & O'Mill, A. L. 2012, A&A, 539, A45
[7] Press, W. H., & Schechter, P. 1974, ApJ, 187, 425
[8] White, S.D.M. & Rees, M. J. 1978, MNRAS, 183, 341