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# The emergence of galaxies in the epoch of reionization

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# SUMMARY FOR NON-EXPERTS

## Galaxy formation and evolution

Galaxies are one of the main sources of information we have at our disposal to understand how our Universe evolves. Simply put, galaxies are massive collections of stars, gas, and dust held together by the gravity generated by a dark matter halo. In addition, they can contain a supermassive black hole at their center. We estimate that there are at least a few trillion galaxies in the observable Universe and they come in various shapes and sizes. For instance, the largest galaxy to this date is estimated to be 123 kpc while the smallest one is a mere 35 pc, resulting in a difference in size by a factor of around 3514. Regarding their shape, galaxies can be classified as ellipticals, lenticulars, spirals, or irregulars based on a famous classification established by Edwin Hubble in 1926, which is shown in Fig. I. Besides these properties, galaxies present numerous attributes that we can measure such as the amount of matter they contain, the rate at which they form their stars or the amount of light they radiate. The field of galaxy formation and evolution is concerned with understanding what is the origin of the variety of galaxies we observed today.

The currently accepted paradigm regarding the formation of galaxies is a bottom-up scenario, in which the first structures to form are small dark matter halos. These halos contain gas, which condenses at its center, cools down and collapses to form the first stars. If they are massive enough, the stars end their life as a supernova explosion. This explosion expels the gas out of the galaxy, which prevents further stars from forming in a process called feedback. To continue forming stars, galaxies need to replenish their gas reservoir. They have two ways of growing. The first one is accretion in which the dark matter and gas surrounding the galaxy are attracted to it and fall onto it due to its gravity. The second way to grow is hierarchically through mergers.

Hence, internal feedback mechanisms such as supernovas are not the only determinant of galaxy evolution. The evolution of a galaxy is also dependent on external factors, such as the density of its environment. For example, galaxies that are isolated, called field galaxies, will have a lower number of interactions

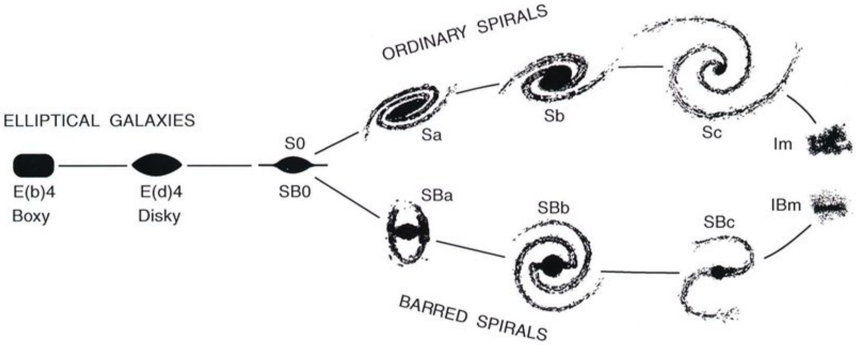

**Figure I:** The Hubble sequence is a classification of galaxies based on their morphologies. It contains four categories: ellipticals (Boxy and Disky), lenticulars (S0), spirals (ordinary and barred), and irregulars (Im and IBm). Image from Kormendy & Bender (1996).

with other galaxies than galaxies in a cluster. Taking into account the effect of the environment is not trivial due to many degeneracies. For example, galaxies in dense environments have more gas around them to accrete and grow but will also likely have neighbors that will compete for that gas. Hence, the effect of the environment on a galaxy is a complex thing to model. Beyond the gravitational effect of neighbors, galaxies are also affected by the radiative emission on their neighbors and the state of the surrounding IGM, which changes during the Epoch of Reionization.

## The Epoch of Reionization

To understand the importance of the Epoch of Reionization and its effect on galaxies, it is useful to put it in the context of the cosmic timeline, represented in Fig. II. The Universe starts as an infinitely dense and hot point known as the Big Bang. Almost immediately after, the Universe undergoes a period of tremendous growth, called cosmic inflation. At that stage, the Universe is too hot for any structure to form and for the light to escape. But it keeps expanding and cooling down until eventually, the light can disconnect itself from the particles and travel freely. We can still observe this radiation as the famous cosmic microwave background, shown in Fig. III. This map of the Universe teaches us that the Universe was extremely homogeneous and contained only small inhomogeneities. After further expanding and cooling of the Universe, these inhomogeneities grow through the gravitational force until the density is high enough for the first stars and

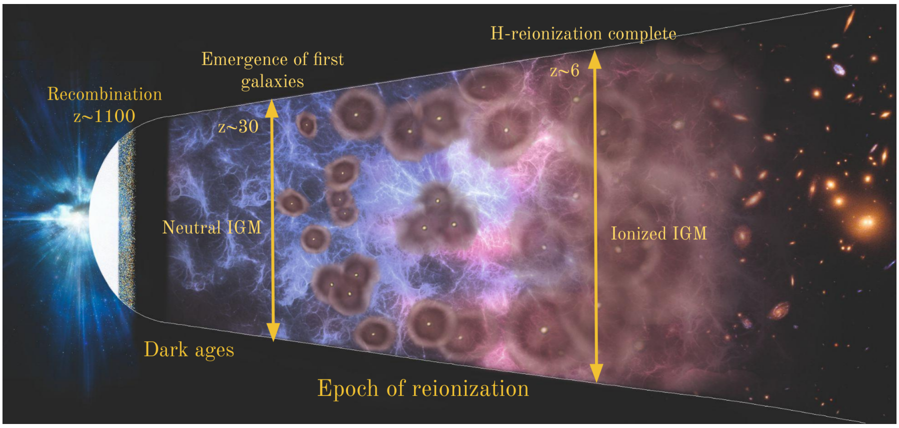

**Figure II:** The phases in the evolution of our Universe from its beginning on the left to our days on the right (credit: Pratika Dayal).

galaxies to appear. Up until that point, the gas in the Universe is neutral, meaning that it is at its lowest energy level. With the coming of the first stars, the Universe enters the Epoch of Reionization. During that period, some radiation emanating from the stars escapes their host galaxies and gives energy to the neutral gas, a process called ionization. This creates bubbles of ionized gas around individual galaxies, which expand with time and then merge with each other until the entire Universe becomes ionized, making it a patchy process. Today, the Universe is fully ionized and keeps expanding.

The Epoch of Reionization lasts from about 150 million years after the Big Bang to 1 billion years and is the last major phase change of the Universe. Galaxies during that Epoch formed in a Universe that was different from the one we are living in now. Galaxies that are located in ionized bubbles are affected by the high-energy background which can lead to the photo-evaporation of their gas or the suppression of gas infall. These feedback processes can reduce the cold gas content and quench subsequent star formation.

Due to their large distances, the observation of galaxies present at the beginning of the Universe is complicated. However, the field of high-redshift galaxies observation has seen incredible progress in the past decade. The recent deployment of the James Webb Space Telescope is expected to launch us into a new era and provide us with unprecedented data concerning these galaxies at the edge of the Universe. To understand and interpret these new data, we build models representing these galaxies to compare with the observations. The continual rise in the computational power of and the ever more ingenuous technique used

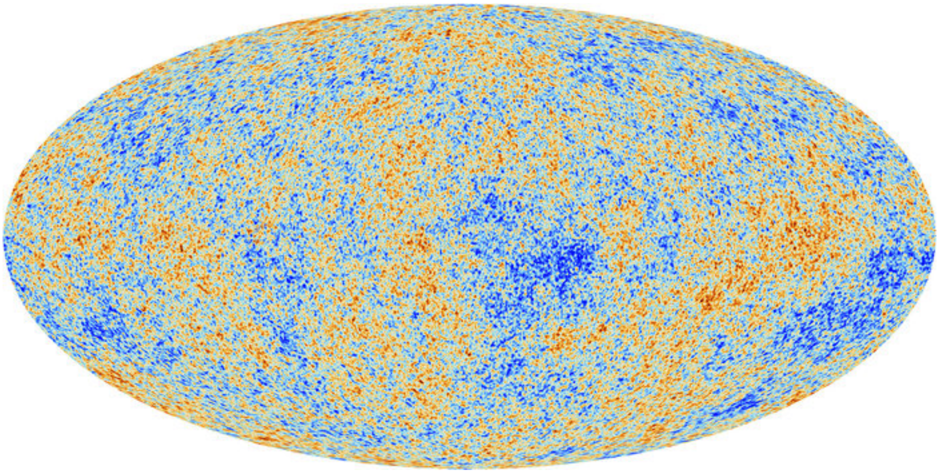

**Figure III:** The cosmic microwave background observed by Planck in 2013. The range of temperature variation shown on this map is of the order of 0.00001 K.

to simulate galaxies allows us to test many possible prescriptions regarding the evolution of galaxies but this topic remains a complicated challenge with many questions.

## Simulations

Modeling galaxy formation is a complex task due to the wide range of scales involved. As we have seen, accurately modeling the evolution of a galaxy requires taking into account effects from the large-scale structure of the Universe at a size of dozens of Mpc ($\sim 3 \times 10^{19}$ km) down to the star formation process at a scale of at most $\sim 1 \times 10^{9}$ km. For comparison, it is like modeling Earth down to the size of ants.

We use a hybrid method: we first run an N-body simulation. Then we extract the merger history from galaxies, represented as merger trees. This is shown in Fig. IV. From an almost perfectly homogeneously placed set of particles, the code computes the gravitational force applied to each element and moves it accordingly. At regular intervals, the algorithm outputs an "image" of the Universe containing the position of every particle, called a snapshot. Another code then identifies every group of particles within these snapshots, called halos, and computes their properties. Finally, a third code links these halos between snapshots, allowing us to follow the path of halos through time. The outputs are called merger trees, shown in the fourth panel of Fig. IV, which represent the entire history of a given galaxy. This allows us to have a manageable and organized amount of data. We then use a set of prescriptions to simulate the growth of galaxies within the halos.

Simulating the Universe requires a trade-off between the size of the box and the mass resolution. Using a bigger box allows us to take into account the large-scale effect while a higher mass resolution allows us to study lower-mass galaxies. Many techniques have been developed to decrease the run time of N-body simulations, with for example the parallelization of the codes or the gathering of particles when computing the gravitational pull. However, these methods have their limits and the mass resolution and box size required to study the coming flood of data from next-generation facilities leads to a runtime of millions of CPU hours, even using the most recent optimization techniques. A recent wave of methods focuses on improving the resolution of the N-body simulations after it has run, by adding halos below the mass resolution. This approach could theoretically increase the mass resolution as high as we want but is a complicated task as many critical properties need to be estimated for the result to be trusted. The most important aspects to match are the masses and positions of the added halos. On top of that, it is useful to maintain consistency between subsequent snapshots, meaning that we can follow the time evolution of halos.

## This thesis

The main goal of this thesis is to study the formation and evolution of galaxies during the Epoch of Reionization using simulations. We focus more specifically on the mass assembly of galaxies, both in terms of dark matter and stellar mass and its dependence on the environment. Throughout this work, we use the Astraeus framework which combines a large state-of-the-art N-body simulation, a galaxy formation model, and a reionization scheme. Our simulation has multiple strengths. First, the use of a simple galaxy formation model based on only three free parameters allows for the possibility to explore a wide range of physically plausible radiative feedback models, all the while reproducing the key observables from the EoR. Second, the large simulation box we use contains a wide variety of environments which is ideal to study the effect of the environment. Finally, our mass resolution is high enough to accurately capture the evolution of the reionization of the Universe.

In chapter 2, we focus on the star formation history of galaxies with special attention on stochasticity. The rate at which a galaxy forms its stars depends on multiple factors: the gas it contains and the rate at which it can convert this gas into stars. In addition, the gas reservoir of a galaxy evolves continuously throughout its life. For example, it increases when the galaxy accretes matter from

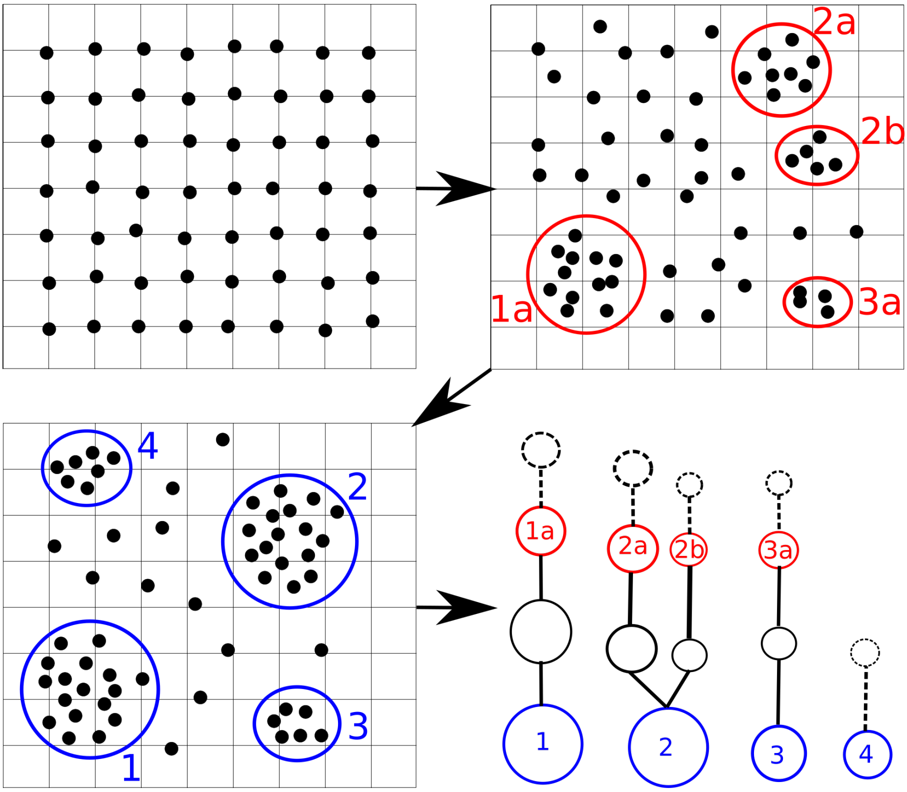

**Figure IV:** Representation of N-body simulation. The first panel shows the beginning of the simulation where particles (represented by black dots) are almost homogeneously positioned. The second and third panels show different snapshots of the simulation. Using a halo finder, we see that the halos 2a and 2b merged into halo 2 while halos 3a and 1 grew through accretion. Halo 4 only formed after the second time step. The fourth panel shows the resulting merger trees, with the black solid halos in the intermediate snapshot and the black dotted halos present between the beginning and the second shown snapshot.

its surroundings or when the galaxy merges with another and it decreases when it gets converted into stars, when stars explode at the end of their lives and expel the gas out of the galaxy, and when the radiative feedback from the UV background heats up which evaporates out of the galaxy. This results in the rapid increase and decrease of star formation rate which we call stochasticity. In this chapter, we start by fitting the star formation rate history of galaxies with a simple line whose slope and normalization depend on their stellar mass and their redshift. We find that the slope increases with increasing stellar mass until reaching a plateau and the normalization increases with stellar mass. Using that fit, we then quantify the amount of stellar mass that is formed stochastically and find that the more massive a galaxy, the less fraction of stellar mass it formed stochastically and that it does not depends strongly on the reionization model. We validate our fit by predicting the luminosity of galaxies, which shows that our model can be used to interpret future observations.

In chapter 3, we investigate the effect of the environment on the mass assembly of galaxies. Galaxies grow through mergers and accretion and their properties depend on which channel is dominant. The density of the environment in which a galaxy is located influences the number of neighbors and the amount of matter available for accretion. We found a redshift- and mass-dependent environment in which galaxies are the most efficient at accreting dark matter. We then quantify the relative contribution of minor mergers(ratio between progenitors lower than 1:4) and major mergers (ratio between progenitors higher than 1:4). We found that they contribute similar amounts of dark matter but due to the quenching of star formation in the low-mass galaxies, major mergers are dominant in terms of stellar mass assembly. We also show that low-mass galaxies in over-dense environments tend to be older than in under-dense due to star formation quenching.

Chapter 4 focuses on the development of a cost-efficient method to increase the mass resolution of simulations. Instead of running a simulation with a higher mass resolution, I outline a three-step method to improve the merger trees produced by N-body simulations. First, using two similar simulations with different resolutions, a machine learning algorithm corrects the mass of halos that are near the mass resolution limit. Second, we evaluate the number of halos that are missing in the low-resolution simulation. Finally, we derive their properties using analytical merger trees. We show that this method improves the number density of halos as a function of halo mass, called the halo mass function, but that the stellar masses are not greatly improved. As this chapter is a proof of concept, we also outline the future steps needed to further improve this method.