Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 4, No. 3, 2022

First Light and Reionisation Epoch Simulation Prediction by Euclid Spacecraft

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Abstract: Astronomers and observers are never satisfied to stop exploring the Universe. With the development of space observing technology, more and more advanced telescopes were launched into space. It can be obviously seen that the space observing technique is closely related to humans' understanding about the early universe and galaxies. This project aims to study the goals of the Euclid program and learn how the First Light and Reionisation Epoch Simulation (FLARES) works, by determining the prediction range of the Euclid Spacecraft on galaxies in the Reionisation Epoch, based on the simulated data from the FLARES. Some brief introduction about the early universe, galaxies and stars will be mentioned for better comprehending, along with the principles of FLARES. Several diagrams are made for analysis and the results show that the detecting range approximately matches our realistic circumstances on space observing.

Keywords: Euclid spacecraft, Early universe, FLARES; Redshift, Observation prediction.

1. Introduction

As we are exploring the universe, it has been becoming quite obvious that understanding the early universe is necessary. Scientists are enthusiastic to know what the early universe was like and how the first star formed. According to the most advanced and reliable theory, the universe was emerged 13.8 billion years ago, with an uncertainty around 21 million years, from a extremely high density and temperature state [1]. The modern chronology of the universe divides our universe into several parts. For convenience, these stages are named as "The very early universe", "The early universe", "The Dark Ages and large- scale structure emergence", "The universe as it appears today" and "The universe in the future".

1.1. The Early Universe

We begin with the one of the first epoch after the recombination and decoupling of the universe, which is called The Dark Ages. Then I will explain the formation the first stars and proceed to the accumulation of the first galaxies. The formation of the first super-massive black holes will also be discussed. Next we are entering the early enrichment of the universe with heavy elements. At last the reionisation of the universe, the first period after stars and galaxies formation, will be explained as well.

1.1.1. The Dark Ages

The Dark Ages epoch was so named because lights and stars we see today had not formed yet. It is believed that in this epoch, as the structure of dark matter grew, the universe changed from a plain and dense state to a complicated and hierarchical system [2]. The entire universe was filled with neutral hydrogen clouds, which emitted the only photon from decoupling and 21 cm radio emissions. The decoupled photons glowed a bright and blanched light at the first place, then it slightly red-shifted to the invisible infrared after about 3 million years [3], eventually no visible light was left. Before recombination of electrons and protons, the universe was fully opaque due to the scattering of photons and free hadrons. At around redshift 1090, as the universe cooled to a critical point, electrons and protons recombined to form neutral hydrogen faster than the ionization rate, and neutral hydrogen began to recombine, and the universe became increasingly transparent as more electrons and protons combined. That was when the Dark ages started [4].

1.1.2. First Star formation

In modern cosmology, the formation of the first stars and galaxies at the end of the dark ages is one of the most significant problems [5]. Compared to dark-matter halos, which can arise only from gravity, the formation of such luminous objects is a more complicated process. For star formation, there must be a sufficient amount of cold and dense gas gathered in a dark halo. However, the primitive gas in early universe was not able to cool radiactively in an efficacious way because the excitation energies of atoms were too high and there were barely any molecule which has accessible rotational energies. The molecular hydrogen H_2 can be constituted via following reactions:

$$H + e^- \longrightarrow H^- + \gamma \tag{1}$$

$$H^- + H \longrightarrow H_2 + e^- \tag{2}$$

Here H is hydrogen atom, e^- is electron, H^- is hydride, γ is photon and H_2 is hydrogen molecule. Gas will therefore cool following process above and finally condense to form stars [2]. It is widely agreed that the first star formed 100 million years after the Big Bang and at that time the primordial gas was capable of cooling and collapsing into dark matter mini halos with a mass of the order of 10^6 $M_\odot$ [6]. The formed stars were presumed very massive, which had masses of the order of 100 $M_\odot$, due to the limited cooling capability primordial gas in mini halos via the radiation from H_2 molecules [7].

1.1.3. Reionisation Epoch

Reionisation Epoch is the process of reionisation of matter in the universe after the dark ages of Big Bang cosmology, and is the second of the two main phase transitions of gas in the universe. At this period the reionisation usually referred to hydrogen reionisation where most of the baryonic matter in the universe exists in the form of hydrogen and helium. After the universe became transparent, much electrospectrum was not possible to be observed. As the collapse of the structure progress continued, temperature gradually increased. Deliberately, neutral hydrogen was ionised due to the partial heating caused by the energetic radiation from heat sources, such as hot stars and super-massive black holes which can both supply huge amount energies. For instance, the earliest Population III stars were formed during this period. Thus, a chain reaction was activated and therefore such reaction was gradually spread into the entire universe. After around 400 million years evolution, the Reionisation Epoch ended and universe today had gradually formed [9].

1.1.4. The First Galaxies

Currently, there is no globally agreed definition on what a first galaxy mean. Theorists and observers conduct with various assumptions and these assumptions have altered with our developing understandings. It is very feasible that we will witness an iteration process continuously but making the right definition ought to be a part of the discovery [10]. The feedback supplied by smaller systems and stars formed inside the galaxies are the key component of how the first galaxies assembled [11]. A theory anticipates that dark matter halos in the centre of galaxies accommodate a mass of the order of 10^8 $M_\odot$ [7].

1.1.5. First Super-massive Black holes

The most famous SMBH (super-massive black hole) is the Sagittarius A* in the centre of the Milky Way. Normally a SMBH labours in the centre of a galaxy and has a mass of the order of hundreds of thousands to billions of times the $M_\odot$. One hypothesis proposes that small black holes that left behind by the supernova explosion of massive stars, which have masses of 10 to 100 $M_\odot$, grow with the accumulation of matter. Another hypothesis proposes that large gas clouds before first stars, might collapse into a "quasi-star", which would persist to collapse into a black hole of around 20 $M_\odot$ [13].

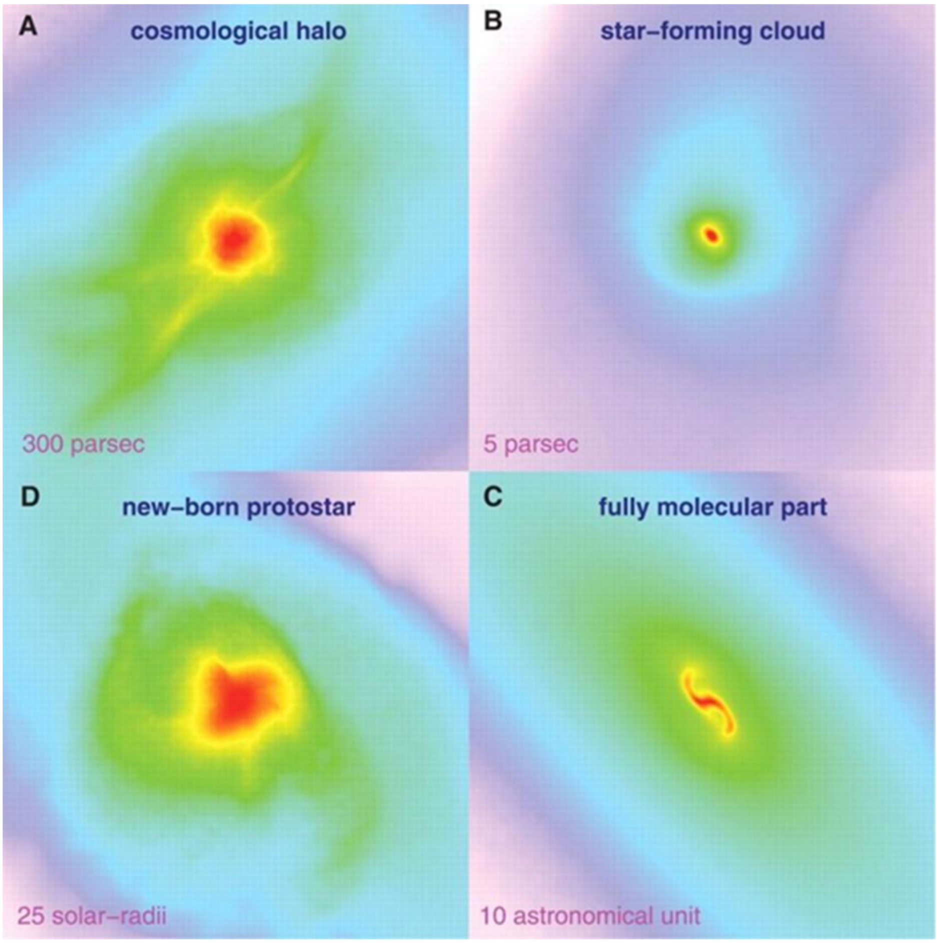

Figure 1. Predicted gas distribution around primitive protostars. Colours represent the densities of gases and red stands for higher density. **A.** Large-scale view of gas distribution around a small halo; **B.** A self-gravitating, star-forming cloud; **C.** The central part of a fully molecular core; and **D.** A protostar [8].

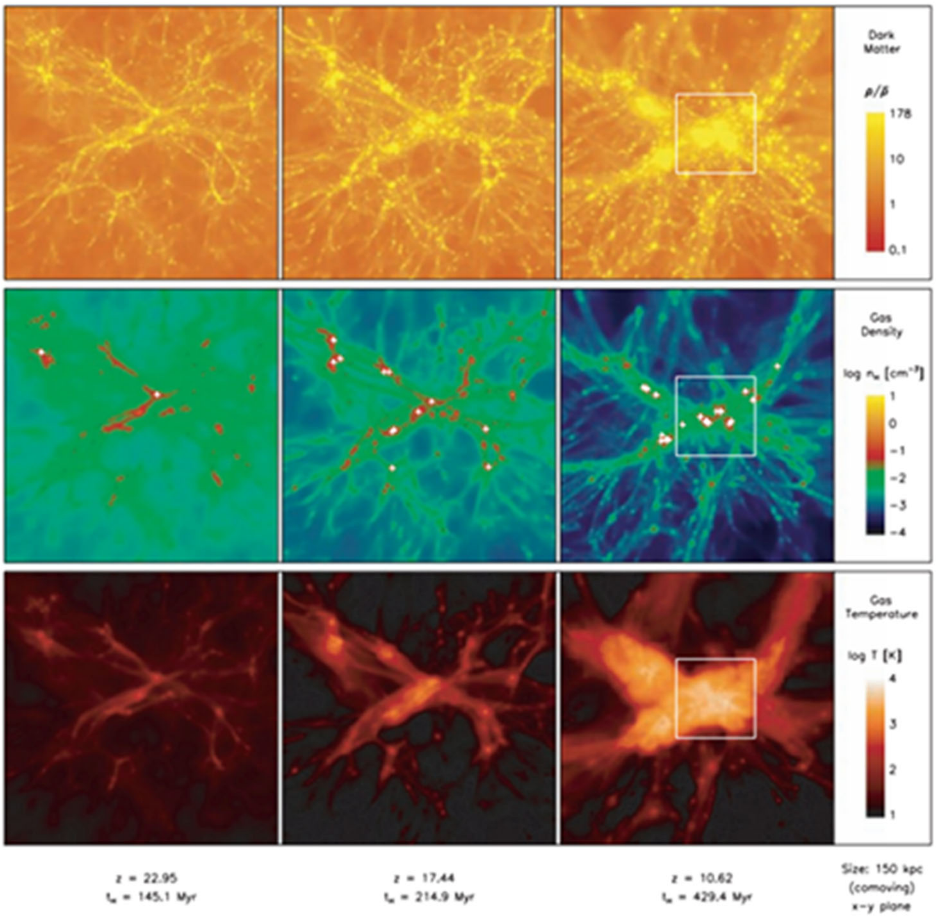

Figure 2. The first galaxies assembly simulation [12]. Top row: dark matter is assembled due to gravity. Middle row: primordial gas is gathering into the centre. Bottom row: powerful virialization shock waves that incites the temperature of the gas. (Columns from left to right indicates three different stages.)

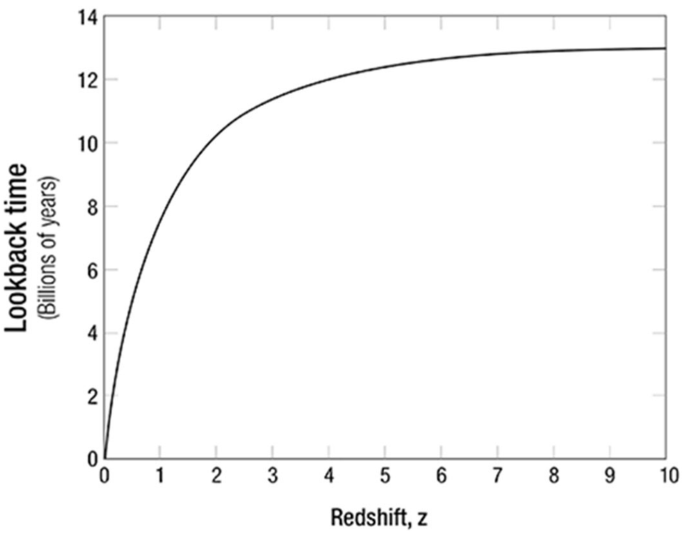

Figure 3. The age of the universe is in logarithmic relationship with the redshift [14].

1.1.6. Ways To Observe The Early Universe

Today we are able to observe lights after around 300 thousand years after the Big Bang, which is called the Microwave Background Radiation. We are capable to acquire properties of the early universe by observing these radiations from early epochs. One of the most important parameters is the redshift, which is a remarkable constant that contains several information of the host object. By studying the redshift, we are able to know about the distance and thus position in the Universe's history of the object. In Einstein-DeSitter Model, the universe is matter dominated and the curvature of the universe is zero (k=0). In this case, $\Omega_m = 1$, $\Omega_{rad} = 0$, $\Omega_k = 0$ and $\Omega_\lambda = 0$, the universe will expand, with just the right amount of energy, to infinitely. Therefore, the redshift versus the age of the universe becomes:

$$t_L(z) = \frac{2}{3H_0}\left[1 - \frac{1}{(1+z)^{\frac{3}{2}}}\right] \quad (3)$$

and from the Figure 1, Figure 2 and Figure 3 above, we can get that objects with z>6 are present in the first billion years of the Universe's history. The redshift can be measured in various ways. The most common way is to compare the spectrum absorption line in the lab frame with that from observed and the redshift can be determined by:

$$z = \frac{\lambda_0 - \lambda_l}{\lambda_l} \quad (4)$$

here λ_o is the observes wavelength and λ_l is the wavelength in the lab frame.

1.2. The Euclid Telescope

1.2.1. What is Euclid?

Euclid is a telescope (detecting range from visible to near infrared) currently being developed by the European Space Agency (ESA) and the Euclid Consortium. The purpose of the Euclid mission is by measuring the acceleration of expansion of the universe to understand dark matter and dark energy better. To accomplish the goal, the Euclid telescope will be measuring the assembly of galaxies at different altitudes from the earth and examine the relation among redshifts, age of the universe, luminosity distance of galaxies and other data. This mission is named after Euclid, the archaic Greek mathematician Alexander and this mission accelerates and completes the blank of the Planck Telescope mission from ESA.

1.2.2. What Does The Telescope Do?

The primary scientific purpose of the telescope is to perceive the reason of universe expansion and research on the nature of dark matter and dark energy. Following questions will be solved by Euclid:

What is the property of the dark matter?

What are the original circumstances that trigger the formation of the universe structure?

Is the dark energy a cosmological constant included in Einstein's theory or is it a new parameter dynamically emerges with universe' expansion?

How will our universe develop in the next ten billion years? [15]

1.2.3. Basic Parameters of The Euclid Telescope

The telescope is able to observe through both visible light channel and a simultaneous field for near-infrared spectroscopy and photometry. The Euclid telescope is built up with a three-mirror Korsch configuration with a 0.45 deg off-axis field and an aperture stop at the primary mirror. The pupil at the entrance has a diametre of 1.2 metres. 0.79*1.16 deg^2 is the field of view corrected optically and the focal length is 24.5m [16].

The visible instrument (VIS) consists of a matrix of 6×6 4096×4132 12-micron pixel CCDs (Charge Coupled Devices) provided by e2V, which is specially amended for the Euclid mission. VIS will be equipped with a very broad band filter covering a wavelength range from 550 nm to 900 nm with an average image resolution of about 0.23 arcsecond. The Near Infrared Spectrometer and Photometer (NISP) instrument consists of a matrix of 4×4 2040×2040 18-micron pixel TIS detectors from Teledyne, covering a 0.53 deg^2 field of view shared with VIS, with a pixel width of 0.3 arcsecond. The photometric channel of NISP will be equipped with 3 broad band filters (Y, J and H) covering the wavelength ranges from 900 nm to 1192 nm, 1192nm to 1544 nm and 1544 nm to 2000 nm, correspondingly. The spectroscopic channel of NISP will be equipped with 4 different low resolution near-infrared gratings (spectral resolution of R=380 for a 0.5 arcsecond diameter source), 3 'red' gratings (1250 nm to 1850 nm) and 1 'blue' gratings (920 nm to 1250 nm), but without slits (for 'slitless' spectroscopy) [16].

1.2.4. Euclid Surveys

There are two surveys Euclid is managed to execute:

Euclid Wide Survey: the survey covers our sky at 15000 deg2. Euclid will be able to observe lights without contamination from the sun and the Milky Way, to investigate on the dark energy of which weak lensing, redshift space distortion signal and baryon acoustic oscillation will be measured.

Table 1. Designated performance of the Euclid Telescope on specified survey area [17]

	Area	Description
Wide Survey	15000 deg^2(24*mag*)	Step and gazing with 4 dither points per step.
Deep Survey	40 deg^2(26 *mag*)	In at least 2 patches of > 10 deg^2 2 magnitudes deeper than wide survey

Table 2 Designated performance of the Euclid Telescope on specified wavelength range [17]

Wavelength Range	500 - 900 nm	Y (920-1146 nm)	**J** (1146-1372 nm)	H (1372-2000nm)	1100 - 2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	3×10^{-16}erg $cm^{-2}s^{-1}$ 3.5σ unresolved line flux

Euclid Deep Fields: the survey covers about 40 deg2 of the sky and is 2 magnitudes deeper than the wide survey. It includes calibrations of a wide range of survey data and the expansion of the mission's science to faint high redshift galaxies, quasars and AGNs [16].

1.3. FLARES introduction

In researches of the Universe developments, cosmological simulations of galaxy formation have contributed to advancing our understandings on formation of the early universes and galaxies. Such simulations follow the nonlinear evolution track of the Universe and establish good models of processes of physics over a great amount of time [18]. The First Light And Reionisation Epoch Simulations (FLARES) is a set of zoom simulations that uses the Eagle model to simulate a series of excess densities during the Reionisation Epoch to build composite distribution functions. In the meanwhile, it is also a goal of FLARES to explore the environmental dependence of galaxy formation and the evolution during this critical period of galaxy assembly [19].

2. Scientific Analysis

2.1. What galaxies are accessible to Euclid in the early Universe

First, we need to convert the deep field magnitude sensitivity limit (H<26) into a flux sensitivity limit (in units of nJy (nano Jansky)). The equation between AB magnitude and flux density in nJy is:

$$F[nJy] = 10^{-0.4\times(AB+48.6)} \tag{5}$$

for magnitude < 26, the detection limit for Euclid is the flux density > 1.4454×10^{-30} erg s^{-1} cm^{-2} Hz^{-1}. From astropy.cosmology module in Python, luminosity distance D_L can be directly converted from redshift. So the flux can also be determined by:

$$F[ergs^{-1}cm^{-2}Hz^{-1}] = \frac{(1+z)L}{(4\pi D_L^2)} \tag{6}$$

For Better comparison, in Figure 4, three different luminosities L = 10^{28}, 10^{29}, 10^{30} erg s^{-1} Hz^{-1}, are added. It is noticeable that the object with higher luminosity can be observed more straightforward at higher redshifts by Euclid. At L = 10^{28}, only a small fraction of galaxies is observable to Euclid, under the range z 1. However at L = 10^{30}, almost all galaxies with such luminosity can be observed. Objects which have luminosity lower than 10^{28} are impossible to be detected at high redshifts (i.e. z > 5). Therefore, it is appropriate to acquire galaxy data from FLARES of which luminosity lie within range from 10^{28} to 10^{30}.

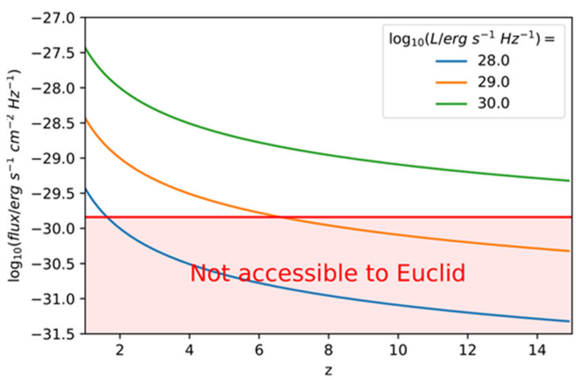

Figure 4. Diagram above indicates the accessible detecting area for Euclid.

2.2. Galaxies in FLARES

In Figure 5, the scatter plot partially shows how mass of galaxies is related to their fluxes. Theoretically, fluxes should be proportional to masses. However, dots after value of 9.0 on x-axis appear to deviate from the linear regression line and start to distribute more discretely. This is because galaxies with higher masses are more possible to have dust, gas and small asteroids within themselves. Part of light emitted from these galaxies is obscured by such interstellar medium and thus fluxes of galaxies are lower than expected. The histogram indicates that galaxies in the intermediate part (medium SFR) are more likely to radiate high fluxes than those active or dormant galaxies.

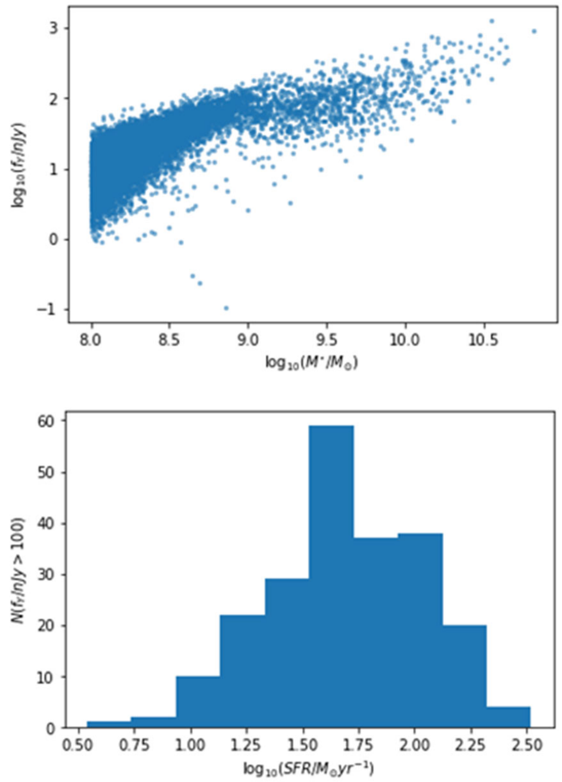

Figure 5. Top: A scatter plot of mass ratio compared to the sun versus flux. Both in logarithm of 10. Bottom: A histogram of flux versus Star Formation Rate.

2.3. FLARES galaxies accessible to Euclid

2.3.1. Euclid Detecting Range In FLARES

We now focus on identifying FLARES galaxies that are accessible to Euclid and investigate their properties. By rearranging equation 6:

$$L[ergs^{-1}Hz^{-1}] = \frac{F(4\pi D_L^2)}{1+z} \tag{7}$$

the luminosity detecting range by Euclid in FLARES is shown in Figure 6.

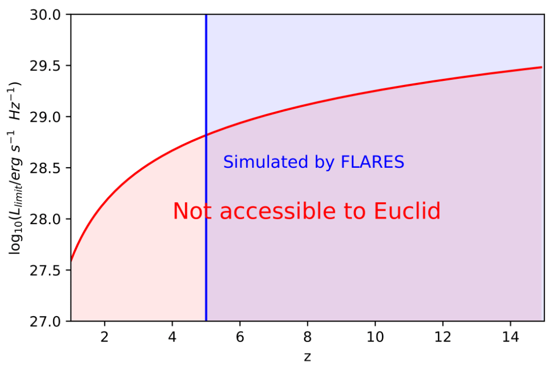

Figure 6. Detecting range by Euclid in FLARES.

Since FLARES only simulates galaxies at z > 5, the top-right area divided by the red curve and the blue vertical line is which Euclid is able to observe in FLARES.

2.3.2. Galaxies At Different Redshifts

For more accurate classification of galaxies that Euclid is able to detect at high redshifts, we divide all galaxies simulated which are at z in 5, 6, 7, 8, 9 and 10. What needs to be noted is that from equation 5 there is a flux limit. Therefore, all galaxies observable to Euclid are filtered out for comparison with all galaxies at high redshifts in FLARES (Figure 7).

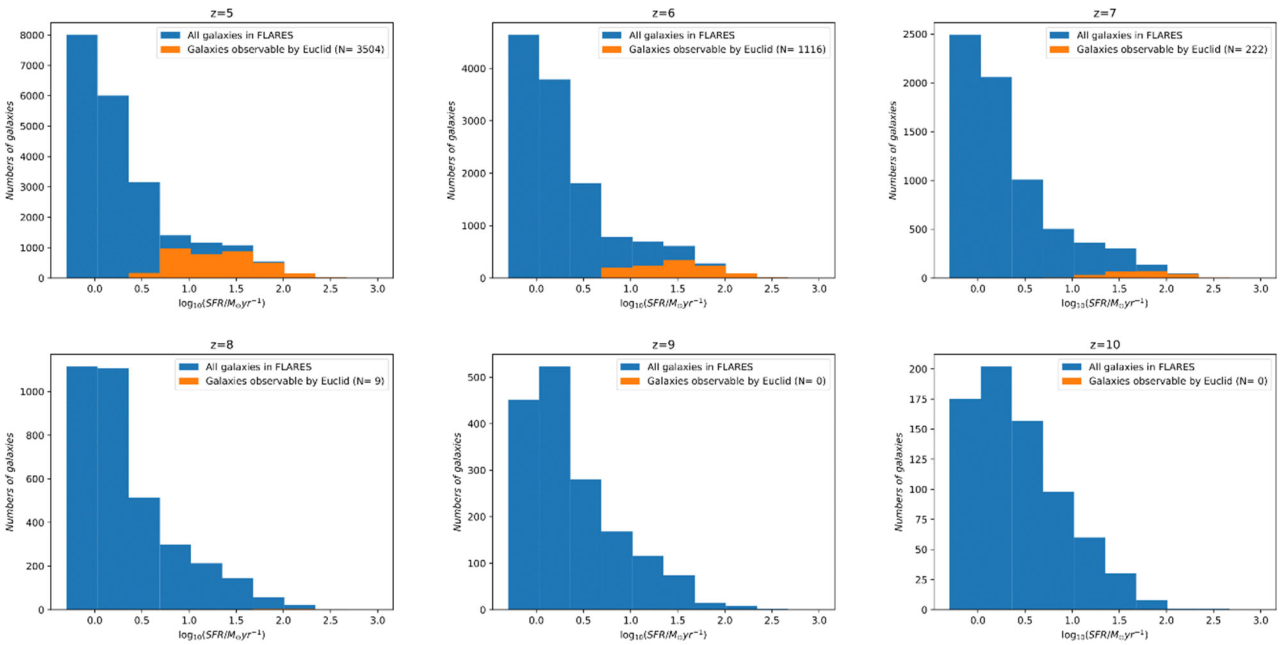

Figure 7. Fraction and number of galaxies that is observable to Euclid from z = 5 to 10.

In this chapter only the histogram galaxies in redshift=5 is listed. It is intriguing to see that the observable galaxies are all gathering at the most intensely star forming galaxies. By summing the 5 histograms, we can list the total number of galaxies observable to Euclid together in one histogram, and the fraction of the number can also be obtained (Figure 8).

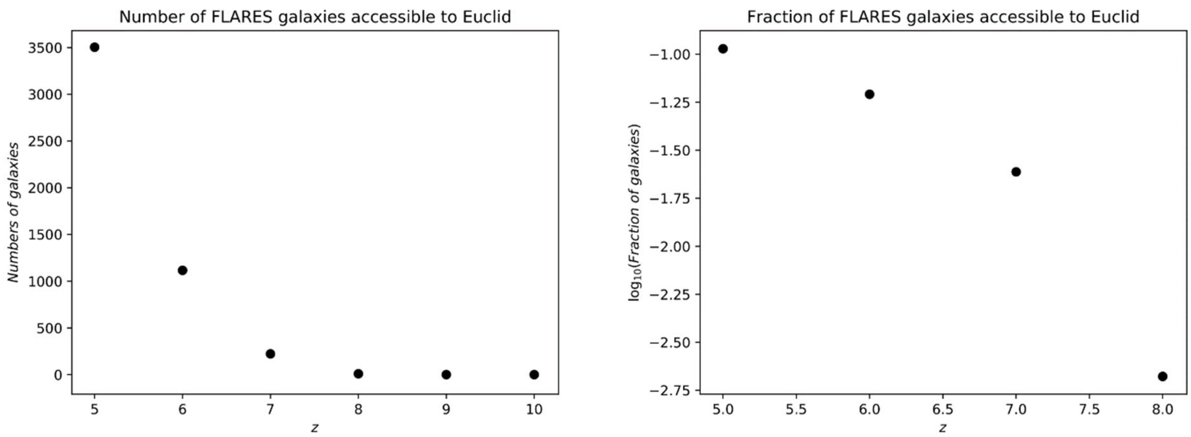

Figure 8. Number of galaxies that is observable to Euclid in multiple redshifts

3. Conclusion

We reviewed the early history of the Universe which includes The Dark ages and Reionisa- tion Epoch. Conditions of the formation of the first star and galaxies are discussed. Two hypothesises of the formation of a super-massive black hole are proposed. Moreover, the relationship between the redshift and age of the universe is mentioned. We briefly intro- duce what the Euclid project is and the basic parameters of the Euclid telescope. The aim of the project and the observational goal of the telescope are acknowledged. The key goal of this project is to use the First Light and Reionisation Epoch Simulations (FLARES) data to anticipate the observation range of the Euclid telescope to verify the advantage of the Euclid, in comparison to other previous telescopes. In the analysis chapter, the minimum flux and luminosity of an object that can be observed are determined among all simulated data. Then all galaxies simulated in FLARES are compared with that can be observed by Euclid from several perspectives, such as the star formation rate, the stellar masses of galaxies and the Euclid H-band flux. In this project, many parts are still worth improving. For instance, with more time spent on studying the FLARES, a more detailed explanation about FLARES is possible to be provided. In the comparison part of the fraction of galaxies observable, more diagrams can be drawn with different data supplied by FLARES, for instance, specific star formation rate and fluxes on other bands.

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