UNIVERSITY OF BIRMINGHAM

Extragalactic Astrophysics and Cosmology
Cosmic Re-ionization

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Abstract

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1 Introduction

The evolution of the Universe has been divided up by cosmologists into several epochs; each characterised by their unique physical properties. This project focuses on the Epoch of Re-ionization (EoR) whereby high energy photons produced during active star formation ionized the neutral hydrogen in the Inter-Galactic Medium (IGM). In order to probe this particular era and learn more about it, early (high redshift) galaxies are being studied as it is believed that they produced these first ionizing photons and hence their birth should understandably correlate directly to the beginning of the Epoch of Cosmic Re-ionization. (more detail in section 2).

There are many unanswered questions in cosmology; one of the most crucial is the nature of dark energy and matter which make up around 95% of the universe [9]. These mysterious substances are thought to be the key driving force behind the evolution and expansion of the universe. By studying and mapping the distribution of Hydrogen during the EoR and tracking the evolution of stars and galaxies we are able to infer more about the effects of dark energy and what it might consist of. There are many different theories about what dark matter consist of; the current most popular theories fall under the "Cold Dark Matter" model where dwarf galaxies are thought to be key building blocks in the hierarchical structure formation of the first galaxies [10].

The process of Cosmic Re-ionization is crucial to our understanding of the evolution of the Universe as it forms the bridge between our present and a distant, ill-understood past. It links our current familiar universe whereby stars and galaxies are more common than the grains of sand on Earth's beaches to its past; when the Universe was a barren soup of free particles devoid of structure and life as we know it. Understanding the mechanisms of structure formation and what drives the collapse and formation of structure is fundamental in refining the Concordance Cosmology Model. Completing the picture of what happened during the EoR will enable us to more accurately predict where the Universe is headed and how it may eventually end, will it be in a "big crunch" or a "big freeze"?

The light from this era is so far away, and hence dim, that technology is only just allowing astronomers to see these early galaxies using high-powered telescopes and sophisticated detection process. There are a number of different projects in progress investigating this particular period of the universe and there are many more in the pipeline, these will be discussed in more detail in part III.

1.1 Structure of Study

This study aims to develop an observing strategy based on original calculations for galaxy distributions and ultimately estimate the redshift range over which the EoR occurred. The group is split into two subgroups; a predictions group and an observational strategy group. The principal aim of the predictions group is to produce a set of calculations yielding the number of galaxies within the appropriate range of redshifts for re-ionization, with the inclusion of influences such as cosmic variance which skew the distribution. By considering the star formation rates and the ionization rate of neutral hydrogen the upper and lower bounds of this range respectively is determined. The final observing strategy explores which facilities to use; both current and planned and any adjustments required. The plan calculates the amount of observing time required to identify and confirm the properties of galaxies during the EoR. It also considers how to limit objects which will spoil our results; contaminants such as foreground stars and Supernovae

events. The strategy aims to see further than previously achieved in this field and help to drive the understanding of re-ionization to new heights.

Part I

General Theory

2 Cosmic Re-Ionisation

It is now universally accepted that the Universe began with the Big Bang whereby matter erupted from a singularity in an unexplained burst of energy. Following this the Universe was so hot (approximately 1012–1015 K) [11] that the photons had enough energy to suppress the binding of nucleons and so the Universe remained a soup of free baryons, leptons and energetic photons (amongst other things) until just a few minutes after the Big Bang during the Epoch of Nucleosynthesis when the protons and neutrons could begin to form atomic nuclei. Approximately 300,000 [11] years after the Big Bang came the Epoch of Decoupling when the majority of photons had lost a large proportion of their energy from frequent collisions within the plasma and hence most were left with less than the minimum hydrogen ionization energy of 13.6 eV. This allowed the electrons to finally bind to the hydrogen nuclei to form neutral hydrogen atoms, free from interfering photons. These newly retired photons were now able to travel across the Universe. With the photons having too little energy to interact with matter the Universe had become a transparent highway to our present and the photons set out on a journey which lasted almost as long as the age of the Universe, eventually arriving at Earth as a blanket of radiation known as the Cosmic Microwave Background.

Meanwhile, in the wake of Decoupling matter was able to interact without disturbance from photons; atomically and gravitationally. Small density fluctuations, seen from Earth as small temperature fluctuations in the Cosmic Microwave Background, began to grow to such an extent that their gravity became large enough to attract matter, as more and more matter was attracted the gravitation became stronger and hence attracted more matter. This was the beginning of structure formation and the era known as "Cosmic Re-ionization". As more and more matter accumulated, stars began to form with high enough core temperatures to create photons with enough energy to once again ionize the neutral hydrogen in the Inter Galactic Medium. As more stars formed, more of these high energy photons were being produced; gradually transforming the dark, neutral Universe to its current ionized state.

In order for these photons to ionize the IGM, they evidently must reach it and hence must escape from their resident galaxy. The rate at which these photons were produced and escaped determines the length of time over which re-ionization occurred if one defines the end of re-ionization as being the point at which all, or at least the vast majority, of neutral hydrogen has been ionized. This requires one to understand how these early galaxies formed and thus infer their characteristic temperatures to see how many photons may have had enough energy to fully ionize the neutral hydrogen. Then one must consider what fraction of these photons could escape from the galaxy having managed to avoid interactions with the dust and hydrogen within it. The specifics of this topic will be covered in more detail in section **??**.

3   Gravitational Lensing

3.1   Introduction

Contrary to a popularly held belief that Newton refers to gravitational lensing in his publication "Opticks" [12] (put into context, it is clear that he was discussing diffraction), the first person to allude directly to the bending of light due to gravitational attraction was Henry Cavendish. Around the turn of the 19th century Cavendish used Newton's corpuscular theory to correctly calculate the bending of light around a massive object. Around the same time, German astronomer Johann Soldner was independently addressing the same problem [13] and although his results were similar to those obtained by Cavendish, his method was fundamentally flawed due to incorrect assumptions [14].

The subject of gravitational lensing was then largely put to rest until 1915 when Einstein postulated his theory of general relativity, from which it is clear that massive objects will cause light to bend as a result of the curvature of spacetime. Despite having complete and correct calculations of the phenomenon of gravitational lensing, including the lens equation and the position of images, Einstein displayed very little interest in it. He mentions it only briefly in his notebooks and published a single, very short discussion in science magazine upon the request of a friend at the end of which he dismissively comments that there is "no great chance of this phenomenon being observed" [15].

During a solar eclipse in 1919, Eddington measured the positions of stars lying close to the sun and observed that their positions appeared at a greater distance from the sun than expected, thereby giving the first experimental evidence for the bending of light around the sun [16]. 5 years later, Chwolson published a paper on the idea that 'fake double stars' may be observed as a result of the gravitational lensing effect and postulated that if source, lens and observer are perfectly aligned then a 'Chwolson ring', later renamed 'Einstein ring', would form around the lens [14].

The true pioneer of the subject, however, is generally considered to be Czech astronomer [17] Frantisek Link. Through detailed calculations of image magnification and positions, Link concluded that in some cases gravitational lensing would make faint sources visible. Optimistic about the possibility of observing these sources, particularly for spiral nebulae, he published a detailed paper on his wide ranging calculations which included the deflection undergone by light rays passing massive objects, the resulting change in intensity of sources and the invariance of source surface brightness. Following this, there was again a period of lack of interest, during which only a few papers were published on the subject until the discovery of the first lens in 1979 by Walsh, Carswell and Weymann. From here onwards, it became a topic of intense interest to astronomers and many more lenses and faint sources have since been discovered [14].

3.2   Concept

The bending of light around a massive object is a direct result of Einstein's theory of relativity and the curvature of spacetime. This effect can cause massive objects to act as lenses for background sources by bending the light such that rays that otherwise would not have been detected converge at the observer, resulting in a brighter image being observed. The increase in flux reaching the observer can result in significant magnification of a source, for example, one of the most distant objects known was observed behind the cluster Abell 2218 with a magnification factor of 30,

equivalent to a decrease of 3.7 AB magnitudes [18]. Studying the magnification and properties of the images can yield information about both the lens and the source, making it an extremely useful tool [19]. Lensing in which multiple images are formed and the source is significantly
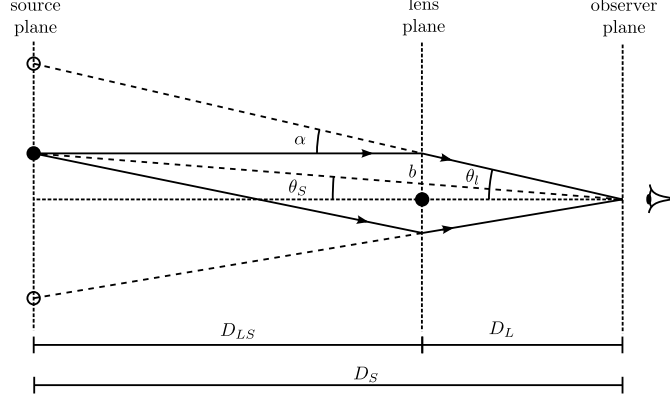
Figure 1: *In this schematic diagram of a gravitational lens, DL, DS and DLS represent the observer-lens, observer-source and lens-source distances respectively. θ_i is the image angle and θ_S the source angle, relative to the observer-lens axis. The light ray (solid line) passes by the lens at impact parameter b and as a result is deflected by angle α, converging with a second ray at the observer. The dotted lines indicate the position at which the images are observed [20].*

magnified is known as strong lensing. For this to occur, the lens must have a high mass and the source angle θ_S must be small. The schematic diagram in figure 1 shows a gravitational lens acting on light from a background source in such a way as to form two images. The distances between observer, lens and source are so large in comparison to the impact parameter b that to good approximation, the lens radius is negligible and it can be modelled as a thin lens. It is therefore reasonable to assume that the light travels in straight lines at all times except in the lens plane where the complete deflection occurs. Furthermore, it can be assumed that for all values of b, the deflection angle is given by

$$\alpha = \frac{4GM}{c^2 b} \tag{3.1}$$

where M is the mass of the lens, c the speed of light and G is the gravitational constant. In realistic lensing situations, all the angles shown in figure 1 are very small, hence the small angle approximation can be applied to yield the lens equation

$$\theta_i D_S = \theta_S D_S + \alpha D_{LS} \tag{3.2}$$

and also to approximate the impact parameter to $b \approx \theta_i DL$, it follows that

$$\theta_i = \theta_S + \frac{\theta_E^2}{\theta_i} \tag{3.3}$$

where θ_E corresponds to the Einstein angle (or Einstein radius), given by

$$\theta_E = \frac{4GM}{c^2} \frac{D_{LS}}{D_L D_S} \tag{3.4}$$

sets the characteristic angular scale for any lensing system [19].

In the rare case that the source, lens and observer in a lensing system are perfectly aligned, a ring of light is observed around the lens, known as an Einstein ring. This ring will be at a constant distance from the centre of the ring equal to the Einstein radius. More commonly, the source is offset from the observer lens axis, resulting in the formation of multiple images. The number of images formed by a lens is always odd, however, using the limit of a small but finite spherical lens, one image is formed directly behind the lens and is not observed since the lens will always be brighter.
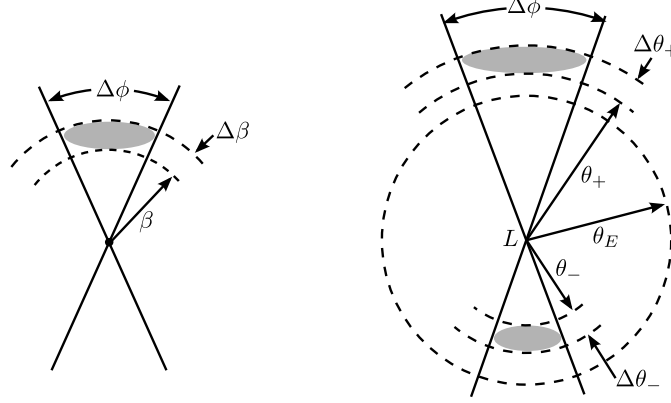
Figure 2: *Schematic diagram of location of images. The centre labelled L represents the observer-lens axis. The diagram on the left shows what would be observed if the lens was not present. The right hand diagram includes the effects of lensing [19].*

In the case shown in Figure lensing image positions where two visible images are observed, one image will form inside the Einstein radius (θ_{i+}) and the other outside (θ_{i+}). The positions of these two images are calculated by solving the equation 3.3 giving

$$\theta_{i\pm} = \frac{1}{2}\left(\theta_S \pm (\theta_S^2 + 4\theta_E^2)^{\frac{1}{2}}\right) \tag{3.5}$$

yielding the positions of the two images as shown in figure lensing image positions– one inside the Einstein radius, the other outside. Unlike optical lenses, gravitational lenses are achromatic, so the frequency of the light has no effect on the position of the images. As a result, images of the same object have exactly the same spectra and can easily be identified [19].

The azimuthal angle ϕ remains unchanged with and without the lens but as shown in figure lensing image positions, the polar angle and the width of the images are changed. The observed images are, therefore, stretched out into arcs and at any given radius will have the same curvature of a circle with origin at the centre of the lens [21]. The change in the polar angle θ can be calculated by differentiating equation 3.5, giving

$$\Delta\theta_{i\pm} = \frac{1}{2}\left(1 \pm \frac{\theta_S}{(\theta_S^2 + 4\theta_E^2)^{\frac{1}{2}}}\right)\Delta\theta_S \tag{3.6}$$

This shape distortion results from the fact that the sources are not point objects but in fact have light coming from a large area of the sky. The light from each end of the object will take different paths through the sky and will pass the lens at a different distance. The light will therefore be bent differently for different parts of the galaxy and the shape is distorted [22].

The magnification of the source is given by the ratio of the image brightness to the source brightness. The surface brightness of any given source remains constant [19] but the effective solid angle Ω subtended by the detector is increased by the lens, hence the flux received by the detector, given by

$$F = (\text{surface brightness}) \times \Omega \qquad (3.7)$$

is also increased. Since the observed brightness of the source depends on the flux, the magnification is given by

$$\mu = \frac{F_{i\pm}}{F_S} = \frac{\Omega_{i\pm}}{\Omega_S} \qquad (3.8)$$

Since in the small angle approximation, $\sin\theta \approx \theta$, the solid angles for the image and source are given by $\theta_{i\pm}\Delta\theta_{i\pm}\Delta\phi$ and $\theta_S\Delta_S\phi$ respectively. Given that $\Delta\phi$ is the same for both images, the magnification can be expressed as

$$\mu_\pm = \left| \left(\frac{\theta_{i\pm}}{\theta_S} \frac{\mathrm{d}\theta_{i\pm}}{\mathrm{d}\theta_S} \right) \right| \qquad (3.9)$$

$$= \frac{1}{4} \left(\frac{\theta_S}{(\theta_S^2 + 4\theta_E^2)^{\frac{1}{2}}} + \frac{(\theta_S^2 + 4\theta_E^2)^{\frac{1}{2}}}{\theta_S} \pm 2 \right) \qquad (3.10)$$

The change in AB magnitude is then found using equation 3.11 [23],

$$\Delta m = -2.5\log(\mu) \qquad (3.11)$$

The smaller the angle between the observer-lens axis and the source θ_S, the greater the magnification of the source.

Part II

Predictions

4   Predictions Group

In order for those attempting to observe high redshift galaxies to propose a detailed experimental plan, it is important to know how many galaxies one is expecting to observe within a certain volume of the sky. This is the fundamental purpose of the predictions sub-group; to be able to compute this quantity with the depth of the surveyed volume corresponding directly to redshift. In order to do this, a computer program is required to efficiently calculate this number as a function of redshift, field of view and luminosity enabling those observing to make an informed prediction of the telescope one would need and the observing time required to make definitive observation of such elusive galaxies.

This section of the project will be structured as follows:

- Research how early galaxies are professionally predicted.

- Find a general Schechter function in terms of luminosity and/or magnitude.

- Mathematically process this function to ensure it is consistent with the units used by those carrying out the observations.

- Build a computer program to automate the process of calculating the number of galaxies from the Schechter function.

- Find plausible starting parameters to use in primary program.

- Collate parameter data from published papers.

- Determine parameter evolution with time.

- Plot these results to produce a visual description of how these parameters affect the outcome.

- Give expected number of galaxies to the observers.

- Refine technique with the inclusion of more advanced adaptations

In addition to running a program to calculate the total number of galaxies, there will also be a separate program to determine the star formation rate of galaxies. This can then be used to determine an estimate of when the epoch of re-ionization occurred and hence would limit the range of redshifts which it would be necessary to include in the calculation of total number of galaxies.

5   Cosmological Distances

This section introduces some of the important distances used in our prediction calculations. First of all is the comoving distance between two observers at different redshifts this is calculated

via [24],

$$D_C(z) = \frac{c}{H_0} \int_{z_1}^{z_2} \frac{\mathrm{d}z'}{E(z')} \tag{5.1}$$

where $E(z)$ is the dimensionless hubble parameter which general form is,

$$E(z) = \sqrt{\Omega_M(1+z)^3 + \Omega_R(1+z)^4 + \Omega_\Lambda} \tag{5.2}$$

Where the omegas are the different density parameters for mass, radiation and dark enery respectively. Therefore to calculate the comoving distance to a object at a particular redshift we use the integral above but use for $z_1 = 0$. Comoving distance is a distance between two comoving observers, i.e. factoring out the expansion of the unviverse. The luminosity distance is the distance a photon travels from that source. This is essentially a redshifted transverse comoving distance [24], which for a flat universe is the comoving distance therefore,

$$D_L(z) = (1+z)D_C(z) \tag{5.3}$$

This is used when converting between magnitudes, luminosity and flux.

6   Schechter Function

One important part of our project is to determine the luminosity function at high redshift, which is a plot of the number density of galaxies agaisnt their respective luminosity. A Schechter function is used to fit this luminosity function. A Schechter function is a form that has a power law which at a ceartian cut-off at which it becomes an exponential curve. The Schechter function in terms of luminosity, i.e. the luminosity function is shown below [25].

$$\phi(L) = \phi^* \left(\frac{L}{L^*} \right)^\alpha e^{-L/L^*} \tag{6.1}$$

The three parameters, ϕ^*, L^* and α, in our project, are cited from various sources at different redshifts. ϕ^* is the normalisation factor in units of Mpc^{-3}, α is the gradient of the faint end slope of the luminosity function and L^* is the characteristic luminosity at which the function changes from a power law to an expoenential cut off.

There are two basic methods to determine the best fit parameters of the Schechter function [26]. The first one is to take cluster samples and bin them by apparent magnitude then fit a Schechter function trying to minimise the error. The other way is to use the "maximum likelyhood method". This method takes a flux limited sample and finds the probability that a galaxy actually has a particular luminiostity at respective distances and then define a likelyhood function which is the joint probability of finding all luminosities at their respective distances. These are then the most likely parameters consistent with the data and a Schechter form. Although we simply used Schechter parameters from articles in our project.

The luminosity function can then be integrated to find the number density in Mpc^{-3},

$$\rho_N = \int_L^\infty \phi(L)\,\mathrm{d}L \tag{6.2}$$

Where L is the lower limit luminosity that can be seen in the universe, this is needed as the luminosity function tends to infinity at the faint end.
or luminosity density of galaxies in $\mathrm{erg\,s^{-1}\,Mpc^{-3}\,Hz^{-1}}$.

$$\rho_L = \int_L^\infty L\phi(L)\,\mathrm{d}L \tag{6.3}$$

A Schechter function is also used for the mass function of dark matter halos, this suggests a relation between the dark matter halo mass and luminosity of their galaxies. However it turns out that this is not an exact relation due to feedback and baryonic cooling.

6.1   Number of Galaxies

To get a lower limit luminosity for the integral of the number density integral, we can use the jeans mass at a particular redshift and for a given mass to light ratio. However this will be very much a lower limit as we are unlikely to actually see galaxies at jeans mass, or they may not actually form due to supernovae and AGN feedback. It is easier to plot the luminosity function on the log scale and therefore most of the papers we cite state the absolute magnitude Schechter function instead which is,

$$\phi(M) = \phi^*(\ln 10)\Big(10^{0.4(M^*-M)}\Big)^{\alpha+1}\exp\Big(-10^{0.4(M^*-M)}\Big), \tag{6.4}$$

where M^* is the characterstic absolute magnitude where the cut off happens. However the observing team will be looking at a range of apparent magnitudes rather than absoulte magnitudes and so we can change the absolute magnitude equation above to apparent using the simple relationship below,

$$m = M + 5((\log_{10} D_L) - 1), \tag{6.5}$$

where D_L is the luminosity distance.

6.2   Star Formation Rate

Star formation rate is directly related to luminosity via the relationship in equation 6.6 [27],

$$\mathrm{SFR}(M_\odot\mathrm{yr}^{-1}) = 1.4\times10^{-28}L_\nu(\mathrm{erg\,s^{-1}\,Hz^{-1}}) \tag{6.6}$$

Therefore we can get a star formation rate density from the luminosity density calculated from our Schechter function. This is useful to us as it will let us calculate the rate of ionizing photons in the high redshift universe via the equation,

$$\frac{\mathrm{d}n_\mathrm{ion}}{\mathrm{d}t} = f_\mathrm{esc}\zeta\rho_\mathrm{SFR} \tag{6.7}$$

7   Assumptions Made

The mathematical model that will be used in our program is limited by certain assumptions about the universe that we are working in. Some of these are generally held to be true and

are accepted widely in the scientific community, others are due to the constraints of what we can mathematically program and the observational data available from previous studies. A major assumption that we are making throughout our work on re-ionisation concerns the type of universe that we exist in. A related pair of assumptions which have firm mathematical basis are the "Cosmological Principle" and the "Isotropic Universe Theorem". These state that our observations, as made from the Earth, are not subject to any influence from our location within it, in other words, we are not in a privileged position in the universe. This is assumed for almost all cosmological studies and shall not be considered.

An important assumption that we are forced to make is that the Schechter function that we use describes our universe sufficiently to make predictions from. This is not as trivial as it sounds since the function is derived from data collected from much lower redshifts than some that we are considering. Further data will allow the accuracy of these functions to be improved. We have collected data and mathematical contributions from a number of high redshift studies to attempt to reduce the possibility of error and increase the accuracy of our function to as high a redshift as possible.

For the early stages of our investigation, we will assume that both parameter evolution and cosmic variance do not influence the results. Clearly, these are big assumptions to make and so will be integrated into the calculations at later stages. This will be discussed further later.

7.0.1   AB Magnitude

In order to keep consistency between the parts of this project, we have used the AB magnitude system throughout. This is a system for measuring the magnitude of an object in the sky. It is defined as

$$M(AB) = -2.5 \log(f_\nu) - 48.60 \tag{7.1}$$

where f_ν is the monochromatic flux measured in $\mathrm{erg\, s^{-1}\, cm^{-2}\, Hz^{-1}}$.

7.0.2   Cosmological Parameters

In addition to the parameters of the Schechter function, there are a number of cosmological parameters that govern the relative fractions of matter, radiation and dark energy in the universe for any given redshift. These are defined as functions of redshift in equation 7.3.

At the current redshift, $z = 0$, the universe is flat and so the total density parameter is defined as

$$\Omega = \frac{\rho}{\rho_{\mathrm{crit}}} \tag{7.2}$$

where ρ_{crit} is the density required for a flat universe, meaning that the total density is required to be unity. Thus, the sum of the separate density parameters must be 1.

$$\Omega = \Omega_{\mathrm{M}} + \Omega_{\mathrm{R}} + \Omega_{\Lambda} \tag{7.3}$$

The values of each of these parameters is varies with redshift. These relations account for the changes in the geometry of the universe. The values that have been used are shown in

equations 7.4 to 7.6, along with the relations that govern their evolution with time, in accordance
with the ΛCDM model. [28].

$$\text{Matter Density,} \qquad \Omega_{M,0} = 0.27 \pm 0.04, \qquad \Omega_M = \Omega_{M,0}(1+z)^3 \qquad (7.4)$$

$$\text{Radiation Density,} \qquad \Omega_{R,0} = 8.24 \times 10^{-5}, \qquad \Omega_\Lambda = \Omega_{\Lambda,0} \qquad (7.5)$$

$$\text{Dark energy Density,} \qquad \Omega_{\Lambda,0} = 0.73 \pm 0.04, \qquad \Omega_R = \Omega_{R,0}(1+z)^4 \qquad (7.6)$$

Together, these values set the Hubble parameter, and so this parameter can be written in terms
of the current values of the parameters, and redshift, as shown in equation 7.7 [29].

$$H^2(z) = H_0^2 \left(\Omega_M(1+z)^3 + \Omega_R(1+z)^4 + \Omega_\Lambda \right) \qquad (7.7)$$

It will be assumed that the universe has a curvature of, or very close to, zero [30], in other words,
that the universe is flat. This has been shown before and is generally held to be true, "we now
know that the universe is flat with only a 0.4% margin of error" [31]. This means that we do
not need to take into account any of the effects of observing objects near the beginning of the
universe when it might have had different properties.

8   Parameter Values

There are also a number of parameters in the Schechter function that must be specified. In
order to find suitable values to use, we collected data from a number of different sources covering
several studies. All of the studies that have been performed in the past concern galaxies at lower
redshifts than we are expecting to examine. To get an estimate for the value of each of the
parameters at higher redshift, the values found were plotted and the fit extrapolated to cover the
era necessary. Since some of the fits demonstrate that these parameters are not constant with
time, their evolution shall be incorporated into the calculations.

The values in the Schechter function that we have determined fits for are α, M^* and ϕ^*. The
data collected for each of these fits is shown in appendix B.

8.1   Parameter Evolution

The early stages of the models we used assumed that the parameters of the Schechter function
were static with respect to time. This means that, when iterating over the redshift, the only
property that changed was the co-moving volume. This is unphysical since it does not allow for
changes in the characteristic mass and characteristic luminosity for different conditions in the
universe. In order to improve the model, we collected data from a number of previous studies
for three values, the characteristic mass, M^*, the Schechter normalisation, ϕ^* and the linear
parameter, α.

8.1.1   Linear Parameter Evolution with Redshift

In order to provide useful errors on the fits of the parameters, a technique called the pivot fit
method is used to decouple the errors on y-intercept and gradient. This involved fitting the data

after it has been normalised around the mean value. This normalisation simply involves taking the mean x- and y-value from each data point so that the graph is centered about the origin. This means that the y-intercept is fixed to zero and thus the fitting error applies only to the gradient. Subsequent linear fits shall be treated in this manner, so that errors quoted corespond to the gradient. For clarity of presentation, the data shall be plotted in its original form.

The graph in figure 3 shows the data collected, with the corresponding uncertainties, for the linear parameter, α. From this data, a linear fit is taken.
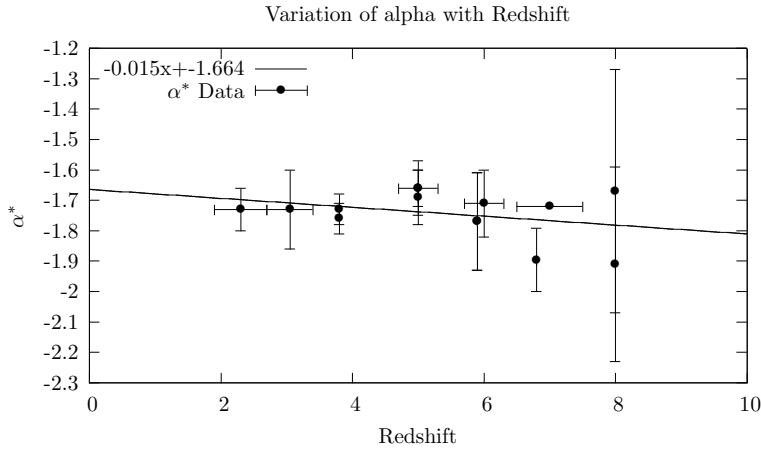
Figure 3: *The evolution of α as a function of redshift according to past observational studies.*

Figure 4 shows the data for the evolution of the normalisation parameter ϕ^*.
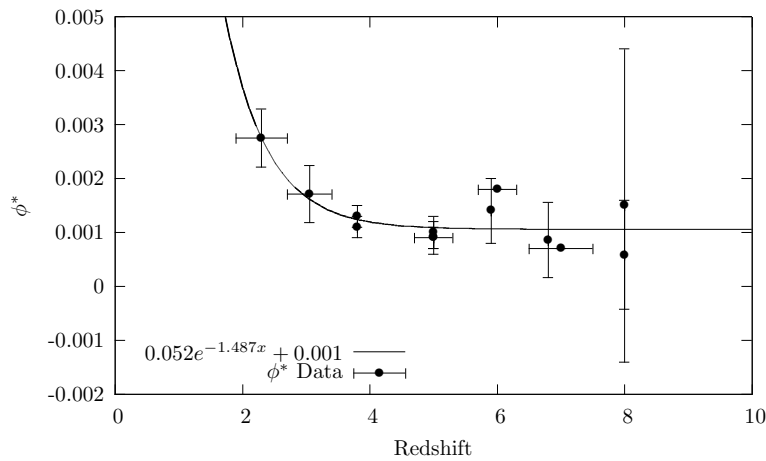
Figure 4: *The evolution of ϕ^* as a function of redshift according to past observational studies.*

9   Rate of Reionizing photons

With a knowledge of the luminosity density, it is possible to calculate the star formation rate density, using the following formula.

$$\rho_{SFR} = 1 \times 10^{-28} \rho_L \tag{9.1}$$

Using estimates of the fractional escape and zeta, we can use the formula above (7.7) to calculate the rate of re-ionization. From this, and the number of neutral hydrogen particles in the universe, it is possible to calculate the timescale of re-ionization.

$$t = \frac{dNion}{d}t \times \frac{1}{N_H} \tag{9.2}$$

Where t is the time between the start of re-ionization and the end, in seconds, Nion is the number of ionizing photons produced and N_H is the number of Hydrogen atoms in the universe.

As the number of photons produced roughly equalls the number of neutral hydrogen in the universe, it is possible to calculate a limit on the redshift accosiated with the end of re-ionization, given the corresponding opposite limit.

A simulation of this was undergone using the equation above, and the resultant timescale was found to be...

9.1   Techniques for Finding an Upper Limit on Redshift

We know that when ρ_{SFR} and $\rho_{SFR}*$ are equal, re-ionization will begin. Knowing the Clumping factor (See Section X) it is possible to calculate the critical Star formation rate density, using the following equation,

$$\rho_{SFR}* = 2 \times 10^3 \frac{C}{f_{esc}} \left(\frac{1+z}{10} \right)^3 \tag{9.3}$$

Where f_{esc} is the fractional escape of photons from reionizing spheres, and C is the clumping factor. Combining with equation X it is possible to calculate the conditions for which re-ionization began as follows:

$$1 \times 10^{-28} \int_L^\infty L\phi(L)dL = 2 \times 10^3 \frac{C}{f_{esc}} \left(\frac{1+z}{10} \right)^3 \tag{9.4}$$

Solving this equation, will give an upper z limit to re-ionization, and usign the timescale IN THE PREVIOUS SECTION it is possible to calculate both limits.

The resultant values for redshift were z+/-z

9.2   Jeans Mass for Collapse and Galaxy Formation

The Jeans Mass defines the cirtical mass of a cloud before it can collapse to form a galaxy, thereby limiting the minimum mass of a star foming galaxy. It is defined as the equation below:

$$M_J = 5.73 \times 10^3 \left(\frac{\Omega_m h}{0.15} \right)^{-1/2} \left(\frac{\Omega_b h^2}{0.022} \right)^{-3/5} \left(\frac{1+z}{10} \right)^{3/2} M_\odot \tag{9.5}$$

Assuming an appropriate Mass-Luminosity ratio, this corresponds to an upper limit on both the Luminosity and the Absolute Magnitude (i.e. the dimmest ionizing galaxy.) This therefore provides a lower limit of magnitude to the schechter function, the L specified in the equation in the previous section

9.3 Mass-Luminosity Ratios

An appropriate Mass-Luminosity Formula is:

$$L(M) = L_0 \times \frac{(M/M_s)^a}{q + (M/M_s)^{cd}}^{1/d}$$
(9.6)

where d=0.23, a=40 q=0.57 c=3.57

Or you can get the star formation rate of a galaxy from the mass (0911.1356v4) and from this you can obtain the Magnitude Kennicutt 1998 conversion from UV luminosity to AB magnitude and thereby to luminosity.

9.4 Press Schechter Formalism

PSF is a method of obtaining the number of objects with a specific mass within a certain volume. It assumes that the universe linearly "clumped" at the beginning of the universe, until a point where the density of the clumps break away from the rest of the universal expansion, and is treated as a massive body which collapses rapidly. (this occurs at around $\delta_c \tilde{1}.68$- Gunn and Gott). Press and Schechter suggest a probability distribution function of =:

$$p(M, z) = -2p_0 \frac{\Delta P[\delta_v > \delta_c(z)]}{\Delta M} dM$$
(9.7)

Where p_0 is the mean density of the universe, and $\delta_c(z)$ is the overdensity threshold per redshift. P is the cumulative probability distribution of δ_v (volume)

It is from this that Schechter functions of luminosity and magnitude could arise. . .

Part III

Observations

10   Observing Strategy Group

This primary aim of this subgroup is to formulate an observing strategy capable of probing the depths of the Epoch of Re-ionization. Our strategy is going to be based upon using optical techniques to detect candidate Lyman Break Galaxies (LBG) and confirming their properties using spectroscopy.

The study of this era in the universe's history has come a long way in the past 30 years and with the selection of new telescopes and radio arrays being designed currently it is only set to accelerate over the coming decades. It is a massive understatement to say such distant redshifts are very difficult to see and it is a testament to scientific and engineering achievement that we are able to take the detailed images we can. The light from these galaxies is so faint that it can take a very long time to see anything. Due to this lengthy nature of the projects, time on telescopes is highly sought after and very competitive.

This strategy must therefore be as complete as possible with as many influencing factors included. This strategy will have two main focuses:

- Using the most efficient methods available in order to limit the observing time required.

- To probe the beginning of re-ionization; there have been few observations above $z = 10$ and future telescopes will have the ability to break new frontiers and observe what happened at these earliest moments of structure formation.

Our strategy will look to utilise the capabilities of the new technology to further the scientific understanding of the EoR.

The observing strategy will be established as follows:

- Research possible telescopes capable of observing high-redshift objects.

- Explore the advantages and disadvantages of ground and space-based telescopes.

- Identify the most efficient telescope for a wide survey of the sky to locate candidates; this will be determined using exposure time calculations.

- Research gravitational lensing, its possible application in assisting our wide surveys and how we might locate more lenses.

- Identify the telescope which will produce the highest resolution imaging of in a narrower deep survey; this will be established using exposure time calculations and observational limits of the system.

- Identify a telescope capable of spectroscopically confirming the nature and redshift of the candidates.

- Investigate the application of methods such as colour-colour diagrams for selecting candidates and removing contaminants from the sample.

- Compile a 'Final Observing Strategy' capable of observing the EoR using numerical predictions from the predictions subgroup.

This 'Final Observing Strategy' will give calculations of the observation time required (inc. photometry, overheads, spectroscopy), the timescale on which the project can be actioned, the limitations of our strategy, possible areas for optimisation/refinement and areas for further research.

11   Determining Redshift

Need a section on candidates and how the contaminants are eliminated. (COMBINE WITH JOE'S COLOUR STUFF?)

Section 18 described how contaminants could be eliminated from the large number of potential high redshift galaxies. Taking the remaining objects, the following methods are used to check whether they are in fact LBGs.

11.1   Filters and the Dropout Technique

Using photometry, the redshift of a LBG can be estimated using the dropout technique: The flux from the galaxy can be measured in three different bands, ideally two above and one below the Lyman break. If the galaxy is a high redshift Lyman break galaxy, it would be expected that, so long as the filters were correct for the redshift expected, one image would not see the galaxy whereas the other two would observe flux. Below in figure 5, the dropout technique is shown for a model galaxy of redshift seven.
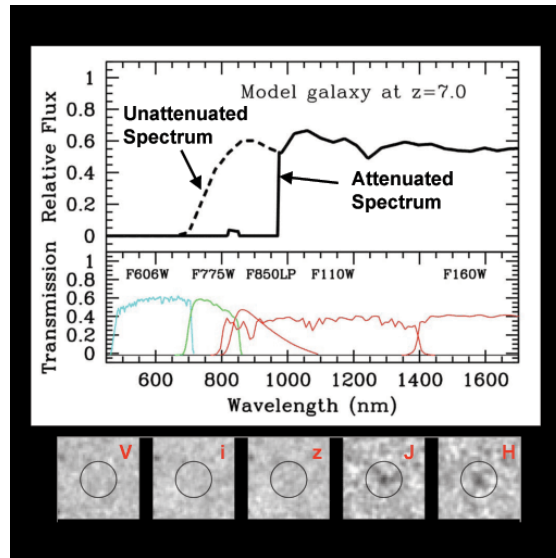
Figure 5: *Dropout technique for model redshift 7 galaxy [1].*

The neutral hydrogen has attenuated almost all flux at wavelengths shorter than approximately

1 micrometre. The galaxy has been imaged in several different bands, and the longer wavelength filters show flux, whereas those at wavelengths corresponding to blue-ward of Lyman alpha do not. The galaxies that the group look to study have been shifted such that the drop happens in the infrared. The wavelength of the drop can be worked out using the known rest wavelength of Lyman alpha, as well as the factor by which the wavelength shifts due to the expansion of the universe, as shown in equation 11.1.

$$\text{Rest wavelength of Lyman alpha} \times (1 + z) = \text{observed wavelength of drop} \tag{11.1}$$

Since the rest wavelength of Lyman alpha is known and the observed wavelength of the drop can be measured, the redshift of the galaxy can be determined. This is only a rough estimate when doing photometry since the flux is simply a number in each of the bands. For example, if the bands do not overlap, and the drop happens between two bands, it will not be known at what point the drop occurred, only the range in which it occurred. This motivates the use of bands which are close together or potentially even overlapping. Figure 6 shows some different bands and their bandwidth, for different filter systems. Johnson-Cousins- Glass is one of the oldest and still the most commonly used system [32].
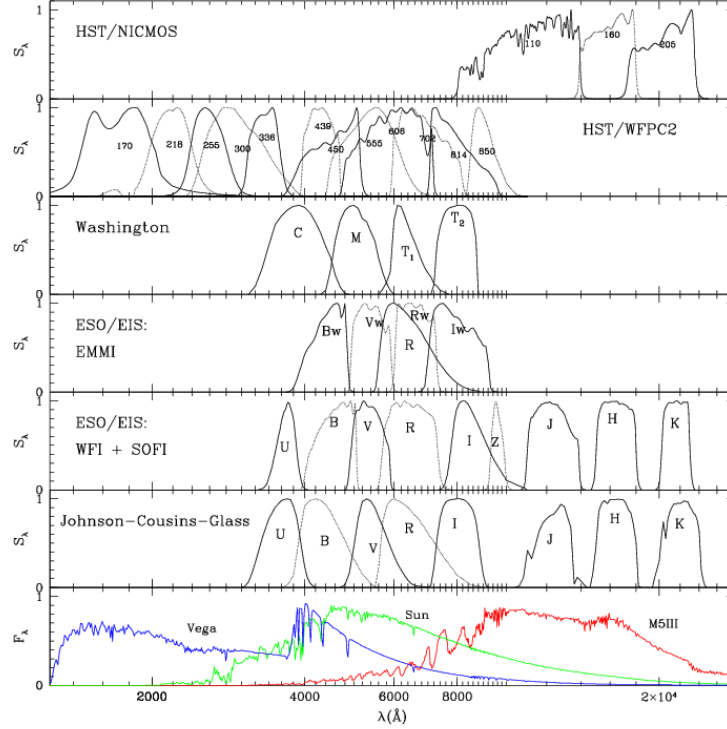
Figure 6: *Various filtering systems [2].*

The bandwidth (or passband) is the wavelength range that can pass through the filter. Filters in different parts of the spectrum are given a common name, for example I band at 806 nm. When observing LBGs, it is beneficial to have three filters in a row so that the position of the drop can be more accurately measured. As can be seen, there are gaps between the J H and K filters, meaning if the drop occurs between J and H, full flux should be observed in H and K

and virtually no flux should be seen in J. (the panels beneath figure 6 show an image (or lack thereof) of the $z = 7$ galaxy in each of the V, I, z, J and H bands)

Table 9 below shows a list of filter names, the central wavelength of that filter, the bandwidth the filter covers, and range of redshifts for which the Lyman alpha drop would be covered. (This range assumes the bandwidth covers 50% either side of the central wavelength)

Filter	Central wavelength	Bandwidth	Redshift coverage
V	551 nm	88 nm	3.17–3.90
i	806 nm	149 nm	5.01–7.25
Y	1020 nm	120 nm	6.90–7.88
J	1220 nm	213 nm	9.16–9.91
H	1630 nm	307 nm	11.14–13.67
K	2190 nm	390 nm	15.41–18.61

Table 1: *Data highlighting which filters would be useful for observing particular redshift galaxies [5]*

Table 9 must be taken into consideration that two filters should be red-ward of the drop and one blue-ward. One the fluxes have been measured in all three bands, if the object is indeed a LBG, there should be a sharp drop in flux in one of the bands. However this does not totally rule out other possibilities: Some other objects could also exhibit a drop in flux, posing as LBGs, so usually a follow up method is used, and this is spectroscopy. Spectroscopy The drop out technique provides a good indication that a galaxy is a high redshift Lyman break galaxy, however the best way to confirm this is with spectroscopy. Spectroscopy involves...

At loads of different wavelengths, measure the spectra. Look for the drop

Use ground based such as KECK or space based, JWST will have one.

12 Other methods for detecting Re-ionization (21cm)

12.1 Hydrogen 21cm line

The method of using the hyperfine transition of neutral Hydrogen from the ground state to study re-ionization could provide much more detail about the process of re-ionization than the Lyman break dropout method.

12.1.1 Hyperfine transition of Hydrogen

The Hyperfine transition corresponds to the change in the two hyperfine levels of the hydrogen 1s ground state with an energy difference of $5.874\,33\,\mu eV$.

FURTHER RESEARCH FROM BOOK AND DIAGRAM

12.1.2 Method of Measuring $21\,cm$

To observe the hydrogen 21 cm absorption spectrum, radio sources are needed. If the radio source is located before or during the epoch of re-ionization, it's possible to see the structure of neutral

hydrogen gas along the line of sight using the absorption of the 21 cm line in the radio spectrum. Several features should be apparent blueward of the redshifted 21 cm line: a decrement of flux due to the optical depth of the IGM along the line of sight at a particular redshift, which will vary along the line of sight due to changes in density and the ionization of the IGM and there will be areas of transmission and absorption due to 'bubbles' of photoionized hydrogen and dense areas or clouds of hydrogen. MORE NEEDED HERE

12.1.3 Advantages/disadvantages

The major advantage of observing the 21 cm forest over the Lyman break technique is that it is possible to study the history of the re-ionization far more accurately, this is because the Gunn Peterson trough reaches zero flux for the lyman break technique with only a small fraction of hydrogen in the line of sight needed.

The main reason this study did not use the 21 cm absorption spectrum is that it requires far more careful consideration of the IGM. This is quite a different setup from the broad assumptions that can be made for the lyman break technique, and therefore it was thought that with the time constraint of the project. MORE NEEDED HERE

12.2 Other methods (tbc)

12.3 CMB Secondary Anisotropies

Over large angular scales, the CMB polarization contains key information concerning the evolution of ionization during the EoR. The CMB photons released during recombination experienced considerable Thomson scattering off free electrons. This scattering is imprinted onto the CMB anisotropy map, it introduces secondary anisotropies. This has the effect of removing anisotropies on smaller scales and introducing polarization anisotropies. By comparing the anisotropies observed with models of what the CMB would have looked like without re-ionization having taken place we can determine the electron column density during EoR.

Using this data it is possible to calculate the period over which re-ionization took place. It is also possible to make measurements of the metal enrichment history of the IGM at the EoR. On-resonance scattering off metals, and the influence of inverse Compton scattering (the Sunyaev-Zel'dovich effect) introduced additional signals into the CMB [33]. Studies in this field are expected to get a new impetus in the coming years with the results from the Planck telescope giving greater insight into the CMB anisotropies.

13   Observational Gravitational Lensing

The phenomenon of gravitational lensing has the potential to be very useful for the chosen observing strategy. Lensing will allow distant objects that could not otherwise have been seen to be observed and identified. This could be a very important part of the observing strategy as we look to push boundaries to observe objects at as yet unexplored redshifts. There is a trade-off when using gravitational lenses between the ability to see to much higher redshifts using the magnification and the fact that the viewing area is decreased due to obscuration by the lens and the increased size of the images. As a result, the most useful way to integrate gravitational

lensing into the strategy will be to use it as a supplement to the deep survey, to attempt to observe a few objects at very high redshift, rather than to magnify and better resolve sources that can be detected otherwise.

There are two routes that can be taken to select a lens: either known lenses from surveys that have already been carried out can be used, or a new set of lenses can be located as part of the observing strategy. Examples of surveys that have been carried out previously include Cluster Lens And Supernova survey with Hubble (CLASH) [34] and the MAssive Cluster Survey (MACS) [35]. There are only a limited number of massive clusters known, and a disadvantage of selecting those from other surveys is that they may already have been studied, for example, CLASH has already located a candidate $z \approx 11$ galaxy behind cluster MACSJ0647.7+7015 [36]. The chances of located strongly lensed high redshift galaxies will be greater if new lenses are selected. There are several advantages to using clusters that have already been found, for example, many of them will have masses and velocity dispersions that have been well determined, allowing an accurate calculation of the magnification to be made. It may also reduce the observing time for the strategy if an extra survey must be made to find the lenses.

The second option, to locate new clusters, is appealing because the lenses chosen can be carefully selected with optimum properties for the observing strategy. Both CLASH and MACS used x-ray emission selection criteria in order to find a range of cluster masses, however for the purposes of this strategy, selection using the strong lensing properties of the cluster would be the best option. The stronger the lensing exhibited by a cluster, the more useful it is likely to be for observing very faint objects. The region of sky in which the lenses lie can be chosen such that it is compatible with all the telescopes chosen for the observing strategy. By selecting based on lensing properties, it is likely that the lenses chosen will be very massive since the lensing strength depends directly on lens mass, as shown in figure 7 [37].
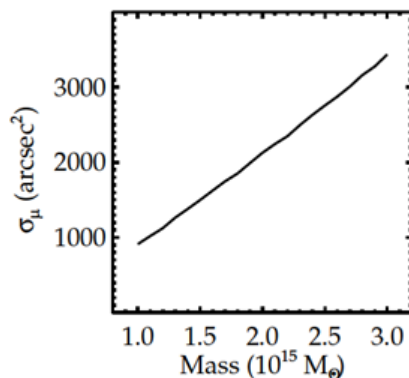
Figure 7: *[37]Plot of the lensing cross section as a function of mass for a spherical halo at z=0.5. The dependence of cross section on mass can be clearly seen, indicating that the more massive a cluster, the better a lens it will be.*

The lens redshift also has a significant effect on the magnification of the source. As a result, it is important to choose a range of redshifts within which the lenses found must lie. The shear caused by a lens at a given redshift is given by

$$\gamma(r) = \frac{4\pi G}{c^2} \frac{D_{LS} D_L}{D_S} \left(\overline{\Sigma}(< r) - \Sigma(r) \right) \tag{13.1}$$

where $\overline{\Sigma}(< r)$ is the mean projected surface mass density within r and $\Sigma(r)$ the projected surface mass density at r. Keeping the radius (and therefore surface mass density) constant, figure 8 shows the dependence of shear on source redshift at fixed lens redshifts. The point at which each curve crosses the x-axis is the lens redshift, since the magnification is equal to 0 at the lens. It can be seen from the plot, that at low source redshifts, the shear distortion is immeasurably small. As the redshift increases to around 0.5, the lower redshift clusters will distort the source images. Once the source redshift is greater than 1, shear distortion is seen around all the lenses [38].
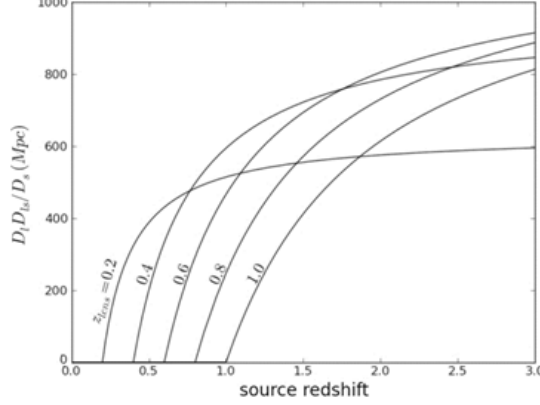
Figure 8: *[38]A plot of shear against source redshift, with each line representing a different lens redshift. The point at which the lines cross the x-axis is the lens redshift, since at the lens, the magnification of the source is equal to 0.*

A similar plot is shown in figure [Einstein angle as a function of source redshift], but in this case, the relation between source redshift and Einstein angle is seen. From this plot, the Einstein angle and hence the strength of the lens decreases as the lens redshift increases, with the Einstein angle increasing rapidly for source redshifts just past that of the lens, and then rapidly saturating.

Combining these two results, the optimum lens redshift is found to be around 0.6. A range of lens redshifts within which the lenses chosen must lie will be defined.

The magnification of the source can be roughly calculated using the arcs formed by the images. The Einstein radius can be approximated by taking the mean distance from the centre of the lens to the two images. For strong lensing to occur, it is a mathematical requirement for the projected surface density to be greater than the critical surface density which is given by [39]

$$\Sigma_c = \frac{c^2}{4\pi G} \frac{D_L}{D_L D_{LS}} \tag{13.2}$$

Assuming that Einstein radius encloses the significant mass, an estimate of the mass can be made from

$$M = \Sigma_c \pi \theta_E^2 \tag{13.3}$$

since the thin lens approximation is being used. Similarly, an order of magnitude calculation of
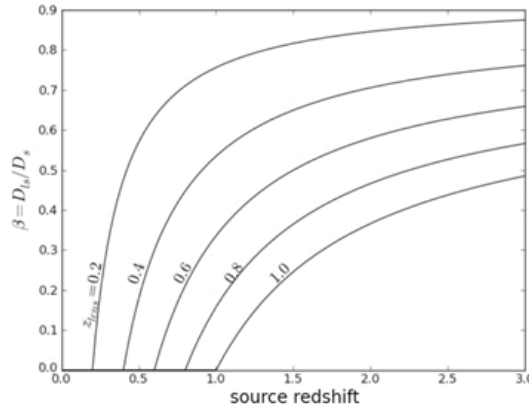
Figure 9: *[38] Plot of Einstein angle against source redshift. Again, each line corresponds to a different lens redshift. The point at which each line crosses the x-axis is the lens redshift, since at the lens, the magnification of the source is equal to 0.*

the magnification can be made using

$$\mu = \frac{x_E}{x_E - 1} \tag{13.4}$$

where x_E is the radial co-ordinate in units of the Einstein radius [40].

14 Photometry and Colour

Photometry is one of the principle methods that astronomers use to detect objects in the universe. In principle, Photometry is the measurement of flux from objects through filters with a certain wavelength range (bandpass). Using a filter does not disperse the light as in spectroscopy, so if you use a filter with a large bandpass, more light is obtained in the image than if the observation was done using spectroscopy or narrow band filters. This means much fainter objects can be observed quicker using broad band photometry. [Romanishin]. To detect Lyman break galaxies the dropout method is used, which uses at least three filters to get enough spectral information to identify the object as a candidate for being a Lyman break galaxy (see dropout method section). However, using the dropout method is not enough to confirm the identities of these candidates, other observational methods need to be used to be certain the object is a Lyman break galaxy and not a contaminant. One of the most effective ways of eliminating these contaminants is to use the colour information of the object, obtained from the photometric measurements.

MORE DETAIL ON BANDS AND PHOTOMETRY

14.1 Eliminating Contaminants

The "colour" of an object in photometry is defined as the difference in magnitude between two filters. If there are two filters, for example called A and B, where A has a lower central wavelength, the colour for an object in these two filters would be $m(a) - m(b)$. The larger the value is, it is said that the "redder" the object is, and equally as the value gets smaller, it gets

"bluer". To eliminate candidates from observations, a colour-colour diagram is made using three filters, with two colour values for each object. For instance if the observations were done in the J, H and K filters, the colour colour diagram would be (H-K) plotted against (J-H).

14.2 Hyperz

To eliminate contaminates and predict colour windows for observations the program Hyperz and its sub-program "make_catalog" can be used to produce a catalogue of synthetic galaxies and their magnitudes in different bands at different redshifts.

DESCRIPTION OF OPERATION AND PARAMTERS FOR HYPERZ

14.3 Results for Colour

GRAPHS FOR RANGE OF REDSHIFTS. APPROXIMATE MAXIMUM NUMBER OF GRAPHS: 10

COLOUR WINDOW SELECTION FOR TELESCOPES

15   Ground Based versus Space Based Telescopes

Ground based telescopes are seeing limited which is a resolving limitation due to distortion caused by the atmosphere. Light is scattered by the atmosphere and so detecting a source by these telescopes can be difficult. There is also the limitation of considerably more background light, compared to what is measured by space telescopes. To minimise these limitations, ground based telescopes are usually located at high altitude at locations such as Mauna Kea, Hawaii. The main advantage of ground based telescopes is that they can be built to very large sizes with telescopes with a primary diameter of around 30 metres on the periphery. This cannot be achieved by space telescopes as the cost of transport to space would be very large and the telescope may well be damaged during this transportation.

Space based telescopes are diffraction limited, i.e. the only limitation is whether they can resolve the object being observed. Taking the source as a point spread function, the light from the source will spread out and so the telescope must determine the source. This is important as light from other sources in the sky may almost overlap and so the diffraction gives the angle in the sky which can be resolved. Thus if the diffraction angle, the smallest angle between two objects can be resolved, is small, the better the telescope. Should two sources fall within this diffraction angle when looking into the sky, the telescope will not be able to resolve the two objects and so one cannot be distinguished from another. The diffraction angle can be calculated using the formula below:

$$\Delta\theta = \frac{(1.22\lambda)}{D} \tag{15.1}$$

This also shows that the larger the diameter, the smaller the diffraction angle will be and so the better the telescope will be at resolving sources.

The main disadvantage of space based telescope is that they must be transported into space. This is usually done with the aid of a rocket and so the cost of achieving this can be considerable.

The telescope may also be damaged during this transportation and so this limits the size of the telescope as a smaller size will mean a smaller chance of being damaged. The James Webb Space Telescope scheduled for launch in 2018 consists of a 6.5 metre primary mirror made up of multiple mirrors that will unfold once it is in space. Despite this folding up of the telescope, the primary mirror size is still small relative to some ground based ones currently in use such as the VLT (primary mirror of 8.2 metres) and is considerably smaller than some proposed for the future such as the EELT (primary mirror 39.3 metres).

15.1 Astronomical Seeing

Plane waves from a source being observed are distorted by the Earth's atmosphere and so upon reaching a telescope within the atmosphere are slightly perturbed and so the image formed is blurred. This effect is contributed to by numerous layers where different temperatures or the interaction of different wind speed causes this effect with "Seeing" the term used to describe the total distortion of the wavefront [41, p. 188]. This effect is shown below in figure 10 where a turbulent layer of the atmosphere causes a change in the shape of the wavefront.
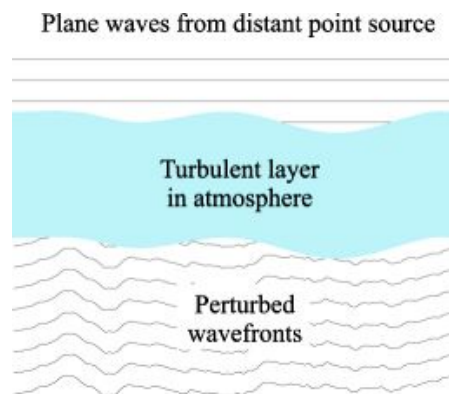
Figure 10: *The perturbation of a wavefront due to the atmosphere*

Whilst the resolving power of a telescope is generally largely dependent on its diameter, this seeing limitation becomes the major source of error when resolving a point source from within the Earth's atmosphere. This is consequently the main limitation for ground based telescopes which are therefore known as being seeing limited. A point spread function (PSF) imaged in these circumstances produces what is known as a seeing disc due to the atmospheric turbulence and the most common measurement used to describe this effect is the full width at half maximum, hereafter the FWHM, shown below in figure 11 where a peak shape is produced by this overall blurring of the source. When measuring the flux arriving at the CCD from a particular source, an area of radius four times the FWHM is recorded over and so a larger value of FWHM also increases the integration time required to observe the source.

15.2 The Future of Ground Based Telescopes

The main disadvantage of ground based telescopes compared to space based telescopes is the poorer resolution due to the distortion caused by the atmosphere or astronomical seeing. The
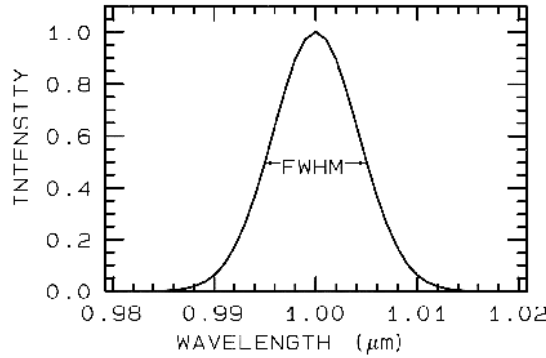
Figure 11: *A peak produced by the blurring of a point source*

introduction of adaptive optics however, should help resolve this issue and allow ground based telescopes to be only diffraction limited similar to space based ones. This, combined with the large diameter mirrors currently in the pipeline such as for the European Extremely Large Telescope (E-ELT), a primary mirror of 39.3 metres, and the Giant Magellan Telescope (GMT), a primary mirror of 25 metres, ensure ground based telescopes hold a place in the future of space observation, even if just to compliment space based ones. The larger mirrors ensure a greater light collecting power, receiving more photons for the source being observed and so significantly reducing the observing time required. These large diameter mirrors are currently only possible for ground based telescopes and so provide them with a distinct advantage over space based ones.

15.2.1   Adaptive Optics

As described earlier in astronomical seeing, light passing through the atmosphere from a source, such as a distant galaxy, is perturbed due to atmospheric turbulence and so the images produced by ground based telescopes are blurred. Adaptive optics works by first sensing the wavefront perturbations and then counteracting this blurring in real time thus enabling the telescopes to hold a much larger resolving power. This system will be used on future ground based telescopes ensuring they are no longer limited by the ability to resolve a source. An example of how this is set up, as on the Subaru Telescope, is shown below in figure 12.

The wavefront sensor (WFS) measures the distortions in the incoming wavefront of light. This then provides the measured information to an actuator control computer identified in figure 12 as the control system. This then adjusts the shape of the adjustable mirror to effectively correct the wavefront reaching the telescope [41]. The wavefront sensor can measure the distortions introduced into the wavefront on the timescale of a few milliseconds with the information then computed and the shape of the mirror adjusted accordingly. The correction process should therefore be completed in a time similar to the time between the changes of the wavefront thus ensuring the distortion is compensated for.
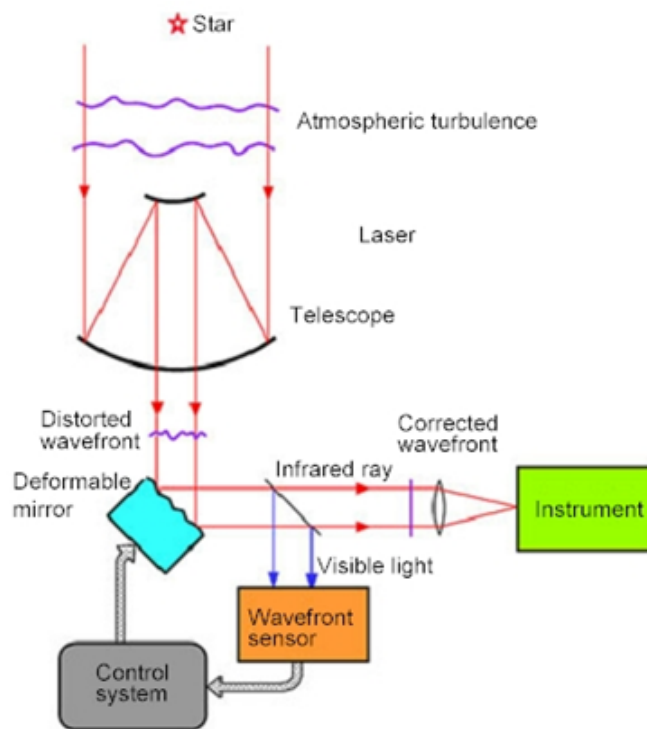
Figure 12: *A schematic of an adaptive optics system*

16 Observation Times

The main aim of this project is to produce an observing strategy to view some of the earliest galaxies in the universe. An important aspect of this is therefore the viewing of the galaxies themselves and the time it will take to do so. The time required to view these galaxies depends not only on the telescope being used, but also the devices used. A charged coupled device (CCD) will be used to measure the light from these sources and so to calculate the times required to view these galaxies, these must be understood in more detail. The telescope or telescopes used during the observation of these galaxies will have different properties which will affect the time required to view the source. Some of these are mentioned below.

16.1 Telescope Properties

16.1.1 Mirror Reflectivity

One such factor that will increase the time required to view a source is the reflectivity of the mirrors used on the telescope. The mirror reflectivity, given as a percentage, is the amount of light reflected by the mirror. Some of the light is absorbed as the mirror is not one hundred per cent efficient meaning not all photons striking the mirror reach the CCD. The reflectivity differs depending on the material used on the surface of the mirrors. Various optical coatings are produced and used depending on the wavelengths being observed, for example, the James Webb

Space Telescope uses a gold coating which is particularly useful in the infrared region and also very durable due to the inert nature of Gold. The reflectivity of this gold coated mirror is in the region of 98–99% [42]. Other coatings regularly used include aluminium, which has a reflectivity in the region of 80–90% and is utilised in the UV and IR range, as well as silver, which has a reflectivity in the range of 95–99% and is utilised in the visible and IR range.

16.1.2 Telescope Throughput

The definition of throughput is the ratio of the flux detected by a particular instrument in a given filter and the incoming flux measured over an area equal to the area of the telescope primary mirror [43]. The throughput is therefore the percentage of photons striking the primary mirror that reach the CCD and are recorded. This contributes to the time required to observe a source as not all the photons striking the primary mirror, originated from the source, will reach the CCD. As the number of photons reaching the CCD is fewer, a larger portion of time is required to obtain the sought after signal-to-noise ratio and so the overall observation lasts a longer period of time.

16.1.3 Filters

### 16.1.4 Field of View

16.2   Charged Coupled Devices

Describe CCD and how it works here.

The CCD does however have numerous errors known as noise, which contribute to the integration time required to view these early galaxies and so must be taken into account. The conversion of light to pixel values in a CCD leads to an inevitable noise being introduced into the image. This noise is the unwanted variations in pixel values and causes the image produced to differ from the one being observed. The noise incurred will make it more difficult to distinguish the source being observed hence increasing the integration time. For an electrical measuring system such as a CCD, a signal to noise ratio characterises the quality of the measurement taken where the signal to noise ratio (SNR) is the ratio of signal from the source being observed and signal produced by background radiation and other sources of noise. This is generally used to quantify the quality of a CCD measurement. The main sources of noise for a CCD are the dark current, sky background and read noise, which are all described below.

16.2.1 Dark Current

Atoms in the silicon substrate of the CCD used are thermally excited and thus electrons are freed. This occurs even when the CCD is not exposed to light, hence there is a steady creation of electrons, and this is called the dark or thermal current. As this is caused by thermal excitation, it strongly depends on the temperature at which the device is operating. At any given temperature, the rate at which electrons are freed is constant, however for every rise in temperature of 6 degrees Celsius, the dark current produced approximately doubles [44, p. 124–125]. This relationship is shown in figure 13 below [45].
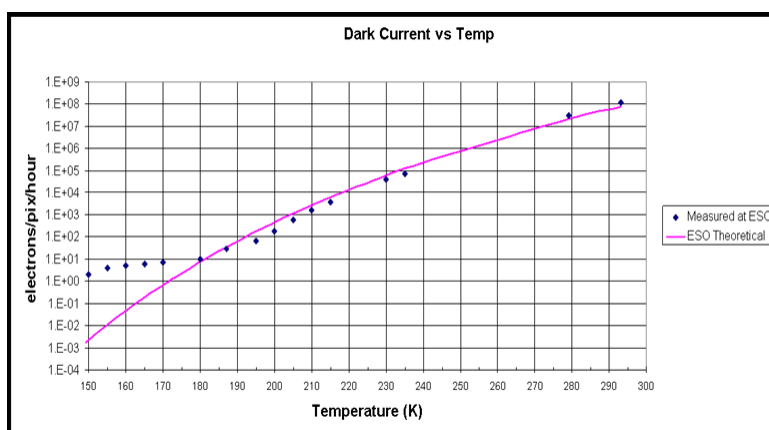
Figure 13: *A graph showing the relationship between dark current and temperature*

Figure 1 shows that relationship between temperature and dark current for a custom designed CCD provided to the European Southern Observatory and shows clearly the increase in dark current at higher temperatures. CCD's are therefore cooled, often with the use of liquid nitrogen, to minimise this effect. The dark current itself is a relatively small electric current that flows through numerous photosensitive devices, and is one of the main sources of noise for a CCD.

16.2.2 Sky Background

The sky background is the incoming light from the sky measured on the telescope that is not from the source being observed. The amount of sky background can vary at different wavelengths and is mainly due to light diffusion by the atmosphere. There are numerous sources that contribute towards the sky background such as airglow and zodiacal light. Airglow is the atmospheric emission of photons at wavelengths from the near-UV to the near-IR range due to chemical reactions in the upper atmosphere [46, p. 9]. These chemical reactions lead to light emission due to the decay of electrons from an excited state in one of the reaction products. One such example is the emission in the near infrared region by OH radicals created from a reaction between ozone and hydrogen in the upper atmosphere [47]. Other processes contributing to airglow are the recombination of ions originally ionised by the sun, and the luminescence of cosmic rays striking the upper atmosphere. Thermal radiation in the atmosphere by greenhouse gases also contributes to the sky background and is due to the absorption and emission of radiation from the Sun into the atmosphere in the mid-IR region. In this case, observations in the mid- and far-IR region must be carried out from outside the atmosphere [48, p. 22–23]. The sky background is therefore primarily an issue for ground based telescopes as they can incur a large background number of photons compared to the number of photons arriving from the source being observed. As space based telescopes are situated outside of the atmosphere, they avoid almost all of this background.

17   Telescopes chosen for investigation

17.1   Hubble Space Telescope

17.1.1   Mission Launch

On April 24th 1990 NASA's Space Shuttle Discovery launched the world's first space-based optical telescope; The Hubble Space Telescope (HST), named in honour of American astronomer Edwin P. Hubble. Edwin Hubble's greatest contribution to astronomy was the Hubble Law which states that galaxies are receding from us at a speed directly proportional to their distance from us. This showed that our universe is expanding, a notion which underpins modern cosmological thinking. The telescope sits in a low-Earth orbit, as shown in figure 14, at an altitude of 569 kilometres completing one orbit of the Earth every 97 minutes [49].

Figure 14: *Photograph of HST orbiting the Earth.*

The HST was designed to provide clear and deep views of distant galaxies and stars and most of the planets in our solar system. Hubble's domain extends from the ultraviolet through the visible and into the near-infrared [50].

17.1.2   Achievements to Date

The HST has provided unprecedented detail in images of star formation allowing astronomers to see the jets and disks present during the birth of new stars. It has also been able to study the atmospheric composition of extra-solar planets and take the first visible light picture of a planet outside our solar system; Fomalhaut b [51].

Many EoR galaxies and candidate galaxies have been identified using HST data. In December 1995 the HST was pointed at what was believed to be a fairly empty and uninteresting patch of sky; 342 separate exposures were taken over 10 consecutive days and formed an image called the Hubble Deep Field (HDF) [52]. The image contains around 3,000 objects of which the vast majority are galaxies, with a few local stars in the foreground. The HDF is one of the most iconic images of the 20th century, and it has since been cited in over 800 scientific papers.

In 2004 its successor was revealed, the Hubble Ultra Deep Field (UDF); a million-second exposure in a $200'' \times 200''$ area of sky containing 10 000 galaxies stretching back 13 billion years [53]. This exposure utilised the recently installed Advanced Camera for Surveys (ACS), seen in figure 15. This survey was further refined in September 2012 in the Hubble eXtreme Deep Field (XDF) which utilised the recently installed WFC3 camera as well as combining over 2000 separate exposures from different sources [52].
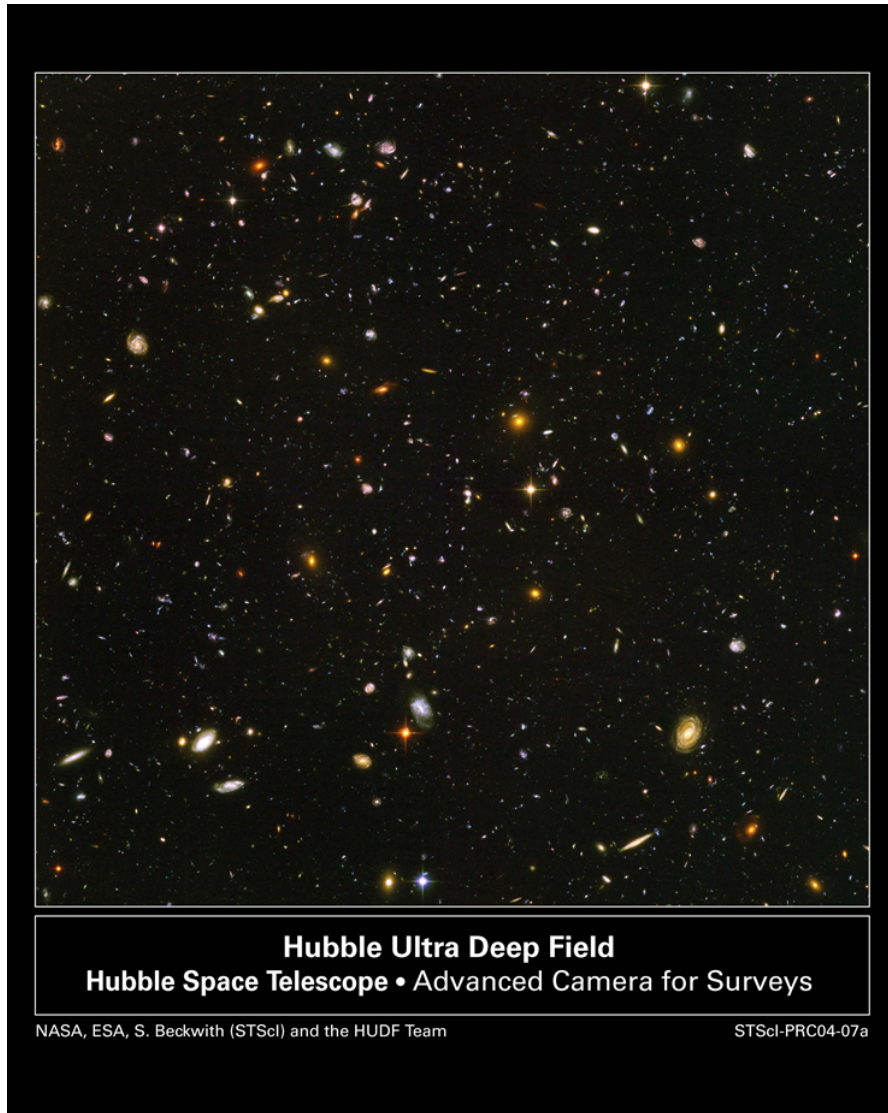
Figure 15: *The HUbble Ultra Deep Field.*

Using data from the HUDF, object UDFj-39546284 was identified. In a paper by Bouwens et al, published in 2012, their best fit places it at a redshift of 11.8 ± 0.3 [54]. This would classify it as the oldest object ever observed. The exact nature of the object is not known but it is believed to be a mini-galaxy. Confirmation will require spectroscopic analysis, which is likely to be carried

out by the James Webb Space Telescope. This observation demonstrates both the achievements and limits of the current technology.

17.1.3   Operation

The HST is operated remotely from the earth, it has 4 antennae which can send and receive signals from the Flight Operations Team at Goddard Space Flight Centre in Greenbelt, Maryland via the Tracking and Data Relay Satellite system. For communication to be possible HST must have a direct line of sight to at least one of these 5 satellites.

The HST is powered using 2 arrays of solar panels each capable of converting the Sun's rays into 2800 watts of electricity. The arrays are able to store the electricity in batteries allowing the HST to remain active while in the Earth's shadow (approximately 36 minutes out of every 97 minute orbit).

Orbiting the Earth subjects the HST to extreme conditions due to the effect of zero gravity and the variation in temperature (up to around 40 K) during each orbit. The optical system is held together using a skeleton (truss) constructed from Graphite epoxy. Graphite epoxy, commonly found in racquets and golf clubs is a stiff and lightweight material able to resist expansion and contraction due to temperature changes [55].

17.1.4   Performance and Optical Telescope Array

The HST is constructed using a Ritchey-Chretien Cassegrain design; this allows high-performance over a wide field of view. The incoming light enters a tube with baffles removing any unwanted stray light, as shown in figure 16 below. The light is then collected by the concave Primary mirror and reflected towards the smaller convex Secondary mirror. This light is then reflected back through a hole in the centre of the Primary mirror where it is focused onto a small area to be picked up by the instruments [56].
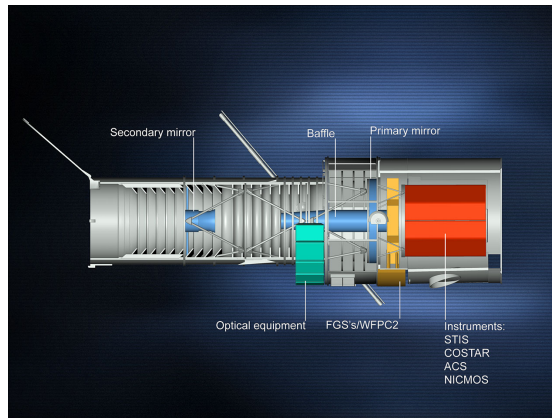
Figure 16: *Diagram showing basic systems of HST, note that WFC2 has since been replaced by WFC3.*

The mirrors have been polished to an accuracy of better than the wavelength of visible light. When the HST was first launched the scientists soon realised that the curve to which the mirrors

had been ground was not correct resulting in an error known as spherical aberration which blurred the images. A servicing mission in December 1993 deployed 5 pairs of mirrors which were able to successfully correct the error and allow Hubble to take the images it was intended to [57].

There have been 4 servicing missions sent to the HST with the final mission taking place in May 2009. Over its lifetime the cameras and instruments have undergone many improvements and replacements. The camera currently operating that is of interest to this project is the WFC3/IR camera, installed in 2009. This camera is able to observe in the near-infrared where we expect to see the Lyman-break galaxies. Table 2 shows the key technical data for the HST, amazingly the HST is so precise it is able to lock onto a target at a distance of 1 mile without deviating more than the width of a human hair.

Component	Details
Primary Mirror Diameter	$2.4\,\mathrm{m}$
Secondary Mirror Diameter	$0.3\,\mathrm{m}$
Wavelength range	800–1700nm
Total Field of View	$123'' \times 136''$ $(16\,728''^2)$
Pixel Size	$18 \times 18\,\mathrm{\mu m}$
Plate Scale	$0.13''\,\mathrm{pix}^{-1}$
Quantum Efficiency	77% at $1000\,\mathrm{nm}$ 79% at $1400\,\mathrm{nm}$ 79% at $1650\,\mathrm{nm}$
Dark count	$0.048\,\mathrm{e^-\,s^{-1}\,pix^{-1}}$
Readout noise	$12.0\,\mathrm{e^-\,s^{-1}\,pix^{-1}}$
Full Well	$77\,900\,\mathrm{e^-}$
Gain	$2.28\text{--}2.47\mathrm{e^-\,ADU^{-1}}$
Operating Temperature	$145\,\mathrm{K}$
FWHM	$0.151'$ at $1600\,\mathrm{nm}$

Table 2: *Technical data for HST WFC3/IR camera system [6]*

17.2 Spitzer Space Telescope

Spitzer Space telescope was launched by NASA on 25th August 2003 [58] and is designed for use in the infrared. It was the last of NASA's "Great Observatories", working alongside HST in the optical, Compton Gamma Ray Observatory and Chandra X-ray Observatory. The telescope is 85 cm in diameter, and sits in an Earth-trailing orbit around the Sun, shown in figure 17. It is a Cassegrain telescope, meaning it has primary and secondary hyperbolic mirrors to focus the light and reduce spherical aberration, in a similar manner to Hubble. The majority of Spitzer's instrumentation is now non-operational due to a lack of cryogen, but some photometry remains possible.

17.2.1 Capabilities

Spitzer had the capabilities detailed in table 3:
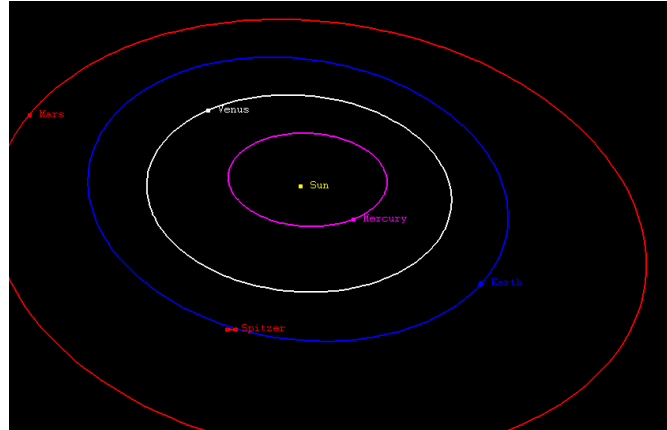
Figure 17: *The Spitzer Space Telescope's Orbit [3].*

Component	Details
Imaging/Photometry	3–180µm
Spectroscopy	5–40µm
Spectrophotometry	50–100µm

Table 3: *Technical data for the Spitzer orbiting telescope [6].*

It employed three scientific instruments which helped it do the above:

- Infrared Array Camera (IRAC): an imaging camera working in the near IR at wavelengths of 3.6, 4.5, 5.8 and 8 micrometres.

- Infrared Spectrograph (IRS): performing spectroscopy from 5 to 40 micrometres.

- Multiband Imaging Photometer (MIPS): detected wavelengths in the far IR, at 24, 70 and 160 micrometres.

The telescope was cryogenically cooled to around 1.4 K, allowing all the instruments to function without excessive thermal interference from the telescope itself. The mission, labelled the 'Cold Mission', was estimated to last between 2 and 5 years, depending on when the cryogen ran out. During this time, Spitzer imaged in all four NIR filters simultaneously, as well as doing spectroscopy, and some imaging in the far infrared. In 2009, when the cryogen ran out, the longer wavelength filters became non-operational, and the Spitzer 'Warm Mission' continued imaging with the nearest IR filters (3.6 and 4.5 micrometres). This was made possible because Spitzer's orbit keeps it substantially cooler than an Earth-centred orbit would, due to the lack of IR radiation received from Earth. Furthermore it is made mostly of beryllium which has a low heat capacity at low temperatures, helping to keep it cool.

In order to keep enough sunlight on the solar panels, Spitzer cannot point further than 120 degrees away from the Sun. However, it also cannot get closer than 80 degrees towards the Sun in case damage is done to the scientific instruments. This is a limitation on the area of sky which can be observed, meaning that some regions can only be seen for 40 days semi-annually, whilst other areas can be observed all year round.

The spectrograph (IRS) operated at wavelengths too long to be of use to study the EoR, as did

the far IR photometry (MIPS), however the near IR photometry capabilities of both the Spitzer warm and cold missions have been used to study high redshift galaxies, and in conjunction with HST have confirmed galaxies at redshifts as far back as $z \approx 10$. Particularly the 3.6 and 4.5 micrometre filters observe significant flux from such galaxies, and so these have been used in a number of studies looking for high redshift galaxies.

17.2.2 Studies involving Spitzer

Coe et al (2012) [59] reports a $z \approx 11$ candidate which had been observed using HST (WFC3, ACS) and Spitzer (IRAC) for longer wavelengths. This is one of the highest redshift candidates to date. The Spitzer data was taken over a total integration time of 5 hours.

An earlier study in 2008 by Richard et al also used Hubble to detect galaxies greater than redshift seven (making use of gravitational lenses). Spitzer imaged these galaxies to help confirm that they were not foreground objects of a different nature, by looking at the flux in longer wavelength filters [60].

In 2005, during the cold mission, a study was made by Spitzer on a confirmed $z = 6.56$ galaxy (HCM 6A) lensed by a cluster (Abell 370). The study was used to detect the rest frame optical emission of this galaxy in order to better understand the physical properties of objects at such high redshifts [61]. Several other papers have also used Spitzer data in the study of high redshift galaxies.

The data in table 4 shows some of the key technical data availible for the telescope.

Component	Details
Primary mirror	$0.85\,\mathrm{m}$
FoV	$5.2' \times 5.2'$
Pixel size	$1.2'' \times 1.2''$
Detector Array	$256 \times 256\,\mathrm{pix}$
Full well	145,000 at $3.6\,\mathrm{\mu m}$ 140,000 at $4.5\,\mathrm{\mu m}$

Table 4: *Technical data for the Spitzer orbiting telescope [7].*

17.3 Euclid

17.3.1 Mission Overview

The Euclid mission is planned for launch in 2018 [8, p. 8] at an estimated total cost of 800 million Euros, and will work in the optical and near infrared [62]. Its primary goal is to conduct a wide survey, some 15000 degrees of sky is planned to be covered, in order to map the geometry of the dark universe. It will look at galaxies and galaxy clusters to work out their redshifts and shapes, back to $z = 2$. There is also to be a deep survey which is expected to cover around 40 degrees of sky to a depth 2 magnitudes deeper than the wide survey. This deep survey will allow astronomers to see even further back in time, up to redshifts of 8 and potentially even higher. The primary mission objectives are expected to be completed within 7 years.

One of Euclid's main scientific objectives with the deep survey is to study high redshift galaxies at $z \geq 6$ over a very wide survey area. This will give astronomers the opportunity to spectroscopically confirm hundreds of galaxies for use in the study of the EoR. It will help constrain the bright end of the luminosity function at high z. Euclid will "detect hundreds of $z = 7$ galaxies brighter than an apparent magnitude $J = 26$ and tens at z greater than 8" [8].

Another is to study clusters of galaxies in the near IR as well as the visible; a weak gravitational lensing survey (as discussed in section 3) will be carried out, looking for disturbances and distortions in the light from galaxies as a result of large amounts of mass perturbing the path of the photons emitted from them. "Euclid measures the shapes of 30 resolved galaxies per $arcmin^2$ in one broad visible R+I+Z band (550–920 nm) down to AB mag 24.5" [8, p. 9].

17.3.2   Capabilities

- Visual Imaging/ Photometry, 550–900nm

- Spectroscopy, 1100–2000nm

- NIR Imaging/ Photometry, 920–2000nm (Y, J,H bands)

Euclid will have two instruments in order to do the above; a wide-band imaging system in the visible (VIS), and an instrument capable of both slit-less spectroscopy as well as NIR imaging (NISP). These instruments will be able to operate simultaneously when required.

### 17.3.3   Method of Conducting Deep Survey

The Euclid deep survey will be carried out by re-visiting particular areas in the wide survey over an extended period of time. Over this time, the depth will be built up by combining a series of images taken of the same piece of sky (known as stacking). The wide survey will reach the required magnitude depth with one exposure, but to reach 2 magnitudes deeper (26th magnitude AB at 5 sigma) considerably more exposures will be needed. Figure 18 shows the number of visits to increase the depth to 26th magnitude. The current estimate is that this will take around 36 exposures, and it has been decided to do 40 to make sure [63]. The telescope operates a 4 step dithering mode so that if there are faulty pixels or systematic errors, the image is still usable.

17.3.4   Uses and Limitations For Euclid's Use In Studying High Redshift Galaxies

The main limitation of using Euclid for this study is its filter range: Since the drop out technique requires two filters above the drop and one below, the redshift of the galaxy must be such that the filters available are able to achieve this. Euclid's longest wavelength filter is centred at 1.63 µm (J-band filter). If the drop is at too long a wavelength, only one band will observe flux. Without two bands observing flux, no colour-colour diagrams can be plotted, and one measurement of flux and another of no flux is not enough to have confidence that the object is a Lyman break galaxy. Table 5 shows the IR filters of Euclid, along with each filter's central wavelength and it's bandwidth.

From this, it can be concluded that the survey will be unhelpful in determining galaxies past a redshift of 10.5 (corresponding to the drop being observed at 1.40 µm): The object would be
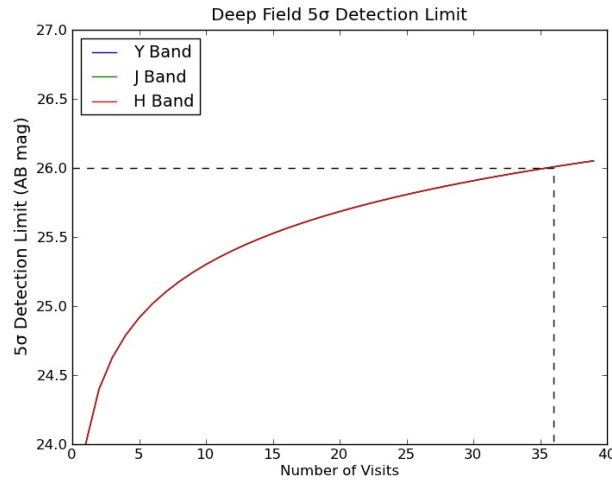
Figure 18: *Number of visits required to meet the Euclid's goal of a depth of 26th magnitude.*

Filter	Central Wavelength	Bandwidth
Y (920–1146)	1020	226
H (1146–1372)	1220	226
J (1372–2000)	1630	628

Table 5: *Euclid space telescope IR filters.*

detected in the J band, but not in either H or Y. The end of the H filter and start of the J filter is at $1.37\,\mu m$. To get significant flux in the Y band, ideally the galaxy would need to be at a redshift of 10 or lower, such that a noticeable amount of flux was detected in H.

A weak lensing survey is planned with Euclid. This will help find gravitational lenses which could be used to magnify very faint Lyman break galaxies at high redshift. From this weak lensing survey, the strongest lenses could be selected and used as targets for other telescopes such as JWST or ELT to study more closely to see if any high redshift LBGs lay behind.

The spectroscopic mode can be used (grism spectroscopy) to determine the redshift of LBGs as outlined in section **??**. The advantage of grism spectroscopy is that multiple objects can be studied simultaneously, meaning if there are multiple likely candidates in the field of view, their spectra can all be gathered at once, reducing the overall time taken to study a large number of redshift galaxies. This is particularly useful to Euclid, which has a wide field of view of just over 0.5 square degrees, increasing the chance of multiple candidates.

17.3.5 Key Technical Data

The data in table 6 is quoted for the deep survey NIR photometry. Some data is subject to slight change as the planning stages progress.

Component	Details
Primary mirror	1.2 m
FoV	$0.763 \times 0.763°^2$
Pixel size	$0.3'' \times 0.3''$
Detector Array	2000×2000 pix
Resolution	0.3 to $0.6''$ (in J band)
Plate Scale (infrared)	$0.3''\,\mathrm{pix}^{-1}$

Table 6: *Technical data for the deep survey NIR photometry [8].*

17.4   European Extremely Large Telescope

One of a new generation of ground based telescopes, the European Extremely Large Telescope (E-ELT), shown in figure 19, is scheduled for first light in 2022 and has a projected lifetime of 30 years, although major upgrades are expected during this period [64, p. 163], and an estimated cost of around 1083 million Euros. The Telescope will be constructed on Cerro Armazones in Chile at an altitude of approximately 3060 m and will be part of the La Silla Paranal observatory. With a primary mirror diameter of 39.9 m, the E-ELT will be the largest optical/near-infrared telescope in the world. The telescope will also incorporate adaptive optics, discussed in section 15.2.1, which will result in it being able to correct for atmospheric perturbations and therefore be diffraction limited.
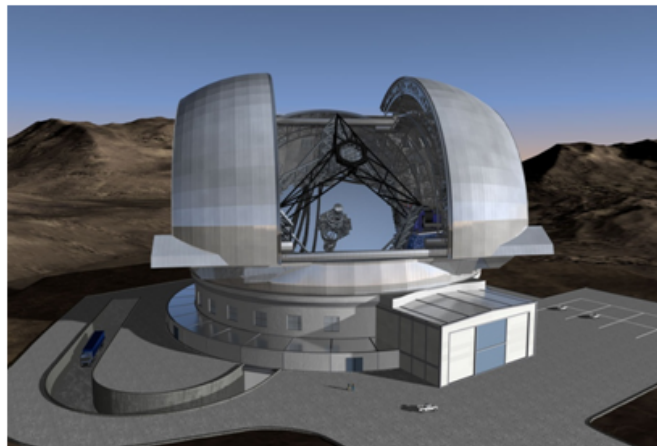
Figure 19: *An artist's impression of the E-ELT [4]*

One of the most important components of the E-ELT is the dome within which the telescope is enclosed. This primarily provides protection to the telescope against unfavourable weather conditions and during the day. The dome is designed to allow complete freedom to the telescope, allowing it to position itself, permitting observations between a 20° angle to the horizon and zenith and also incorporates a windscreen protecting the mirrors. As well as being watertight, the dome is also air-tight to minimise the air-conditioning load. The E-ELT will use an air-conditioning system to cool the mirror and instrumentation to ensure optimum operating conditions in preparation for the upcoming night.

The E-ELT utilises a three mirror anastigmat system with two further mirrors providing the

adaptive optics, shown below in figure 20, with the fifth mirror directing the beam towards the Nasmyth focus [64, p. 16]. The primary mirror, measuring 39.3 m in diameter, will be comprised of 798 hexagonal segments eventually producing a collecting area of 978 m^2. The E-ELT will therefore have a light collecting power approximately 13 times larger than any existing telescope and is predicted to produce images 16 times sharper than those of the Hubble Space Telescope. Other new generation extremely large telescopes include the Giant Magellan Telescope with a primary mirror of diameter 25 m and the Thirty Metre Telescope with a primary mirror of diameter 30 m. The E-ELT however remains the largest of these planned telescopes.
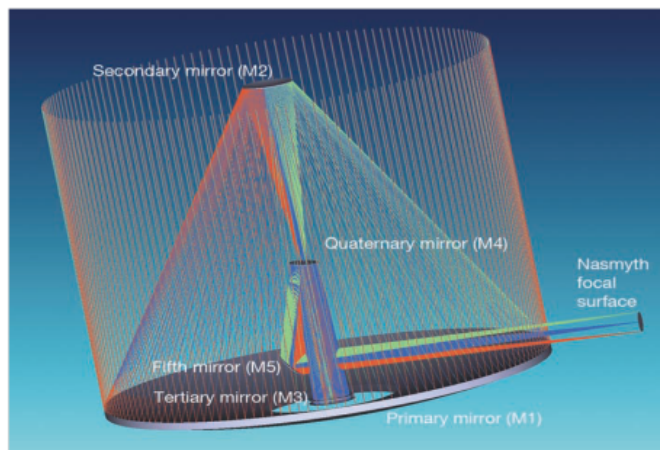
Figure 20: *The 5 mirror design to be utilised on the E-ELT*

17.4.1   Main Aims

One of the main aims of the E-ELT will be the search for extra-solar planets. This will include the detection of extra-solar planets using the radial velocity technique, the detection of variations of the radial velocity of a star with respect to the Earth in response to the gravity of an orbiting planet, as well as possible direct imaging of larger planets. The E-ELT may also be used to characterise the atmosphere of these larger planets using low resolution spectroscopy. The observation of giant planets in star forming regions and young stellar clusters will also provide an insight into their evolution.

Another of the main aims is the study of the universe at high redshift. The E-ELT will look back at the earliest galaxies formed after the "dark ages", the galaxies therefore responsible for the re-ionisation of the universe. Properties of these early galaxies including their star formation rates, ages, metallicities and stellar masses will be determined contributing to a better understanding of galaxy formation and evolution.

The E-ELT will also help to understand the nature of dark energy through the discovery and identification of type 1a supernovae. As these are excellent distance indicators, they can be used to map space and its expansion history thus providing information on what is believed to be the source of this expansion. The E-ELT will also attempt to measure small time-drifts in the redshifts of distant objects in the intergalactic medium, a consequence of the evolution the universal expansion rate. The E-ELT will also attempt to discover variations of physical constants

over time which, if found to be the case, will have great consequences on our understanding of the general laws of physics.

17.4.2   Instrumentation

At first light, the E-ELT will have just two instruments [65], a diffraction-limited near-infrared imager (MICADO) as well as a single-field near-infrared wide-band integral field spectrograph (HARMONI). Three further objects, a mid-infrared imager and spectrometer (METIS), a high-resolution spectrometer (SIMPLE) and multi-object spectrometer (OPTIMOS) will be added soon after first light [65]. There are also some other concepts being studied for use on the E-ELT including a planet imager with extreme adaptive optics (EPICS). Importantly, the instrumentation available will mean that the E-ELT can be used for both photometry and spectroscopy and is also said to be able to switch between these instruments in a matter of minutes.

18   Contaminants

18.1   Low Mass Stars

These can easily be identified due to the high resolution imaging provided by . . . . The Point-spread function (PSF) obtained will allow us to determine which sources are point-like and which are extended. We should be able to avoid significant contamination by removing any point-like sources from the results as all galaxies should have a great enough diameter.

18.2   Spurious Sources

By stipulating that we will be requiring detections in two bands the influence of spurious sources will be negligible. Finding detections in 2 bands at reasonable confidence interval (?3sig?) is very improbable. By inspecting the negative with the same requirements for detection we are able to identify any such sources easily [66].

18.3   Supernovae and other transient sources

Events such as Supernovae happen incredibly quickly releasing a vast amount of energy, as seen in figure 21. These events can spoil images due to their short duration by introducing new data in only a portion of the sample. These effects are usually only considered when taking exposures years apart or when combining multiple sources over a long time scale. Such events are very unlikely to contaminate our results as we propose to take our images close in time.

18.4   Lower Redshift Sources and photometric scattering

This category is likely to provide the greatest source of contamination for the surveyed area. It will do so increasingly at high redshifts where its affect on the faintest magnitudes is most greatly felt. Its affect is most influential with a small S/N ratio for the observations, by fixing this at a level of S/N = . . . we can be confident that the contamination will be low. Detecting a source in
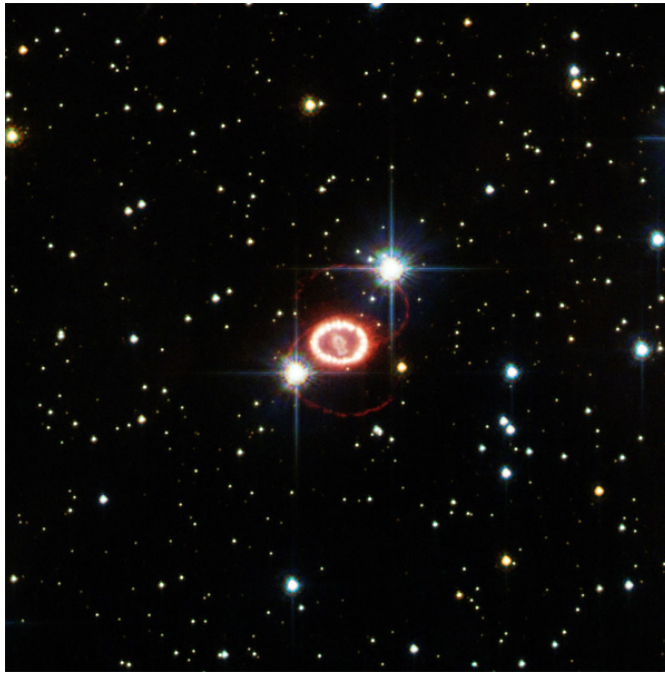
Figure 21: *The shock wave from Supernova 1987a imaged by HST in 2006.*

another band such as b435, v606, i775 for YJH photometry would class it as a contaminant and then should be removed from sample.

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nosity Functions from 132 z ˜ 7 and z ˜ 8 Lyman-break Galaxies in the Ultra-deep HUDF09 and Wide-area Early Release Science WFC3/IR Observations. , 737:90, August 2011.

A   Derivation of Thermal Background

Number of incident photons, N_γ, is

$$N_\gamma = \int_{\nu_1}^{\nu_2} \frac{\epsilon B_\nu(T)}{h_\nu} \, \mathrm{d}\nu \tag{A.1}$$

This integral spans the filter from the red to the blue end.

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\mathrm{e}^{\frac{h\nu}{kT}} - 1} \tag{A.2}$$

where $\mathrm{e}^{\frac{h\nu}{kT}} \ll 1$. Using the substitution

$$x = \frac{h\nu}{kT}, \qquad \nu = \frac{kTx}{h} \tag{A.3}$$

$$\Rightarrow \mathrm{d}\nu = \frac{kT}{h} \, \mathrm{d}x \tag{A.4}$$

$B_\nu(T)$, then, is

$$B_\nu(T) = \frac{2k^3 T^3 x^3}{h^2 c^2} \frac{1}{\mathrm{e}^x} \tag{A.5}$$

Thus, the number of photons is given by

$$N_\gamma = \frac{2k^3 T^3 \epsilon}{h^2 c^2} \int_{x_1}^{x_2} x^2 \mathrm{e}^{-x} \, \mathrm{d}x \tag{A.6}$$

$$= \frac{2k^3 T^3 \epsilon}{h^2 c^2} \left[-x^2 \mathrm{e}^{-x} + \int \mathrm{e}^{-x} \cdot 2x \, \mathrm{d}x \right]_{x_1}^{x_2} \tag{A.7}$$

$$= \frac{2k^3 T^3 \epsilon}{h^2 c^2} \left[-x^2 \mathrm{e}^{-x} - 2x\mathrm{e}^{-x} + \int 2\mathrm{e}^{-x} \, \mathrm{d}x \right]_{x_1}^{x_2} \tag{A.8}$$

$$= \frac{2k^3 T^3 \epsilon}{h^2 c^2} \left[-\mathrm{e}^{-x} \left(x^2 + 2x + 2 \right) \right]_{x_1}^{x_2} \tag{A.9}$$

By integrating from the blue end of the filter to the red, we can remove the negative sign to give

$$N_\gamma = \frac{2k^3 T^3 \epsilon}{h^2 c^2} \left[\mathrm{e}^{-x} \left(x^2 + 2x + 2 \right) \right]_{x_1}^{x_2} \tag{A.10}$$

B   Parameter Fit Data

B.1   Faint End Slope (α) Data

B.2   Normalisation (ϕ^*) Data

B.3   Characteristic Magnitude (M^*) Data

Rest λ (Å)	z	error z	α	pos error ϕ^*	neg error ϕ^*	upper z	lower z	upper	lower	Citation
1750	8		-1.91	0.32	0.09	8	8	-2	-1.59	[]
1750	8		-1.67	0.4	0.4	8	8	-2.07	-1.27	[]
1700	2.3	0.4	-1.73	0.07	0.07	2.7	1.9	-1.8	-1.66	[]
1700	3.05	0.35	-1.73	0.13	0.13	3.4	2.7	-1.86	-1.6	[]
1500	7	0.5	-1.72	0	0	7.5	6.5	-1.72	-1.72	[]
1500	5	0.3	-1.66	0.06	0.06	5.3	4.7	-1.72	-1.6	[]
1500	6	0.3	-1.71	0.11	0.11	6.3	5.7	-1.82	-1.6	[]
1600	3.8		-1.76	0.05	0.05	3.8	3.8	-1.81	-1.71	[]
1600	5		-1.69	0.09	0.09	5	5	-1.78	-1.6	[]
1600	6.8		-1.895	0.1045	0	6.8	6.8	-1.895	-1.791	[]
1600	3.8		-1.73	0.05	0.05	3.8	3.8	-1.78	-1.68	[]
1600	5		-1.66	0.09	0.09	5	5	-1.75	-1.57	[]
1350	5.9		-1.74	0.16	0.16	5.9	5.9	-1.9	-1.58	[]
1350	5.9		-1.77	0.16	0.16	5.9	5.9	-1.93	-1.61	[]

Table 7: *Data highlighting which filters would be useful for observing particular redshift galaxies [5]*

Rest λ (Å)	z	error z	ϕ^*	pos error ϕ^*	neg error ϕ^*	upper z	lower z	upper	lower	Citation
1750	8		5.90E-04	1.01E-03	3.70E-04	8	8	1.60E-03	2.20E-04	[]
1750	8		1.50E-03	2.90E-03	1.00E-03	8	8	4.40E-03	5.00E-04	[]
1700	2.3	0.4	2.75E-03	5.40E-04	5.40E-04	2.7	1.9	3.29E-03	2.21E-03	[]
1700	3.0	0.35	1.71E-03	5.30E-04	5.30E-04	3.4	2.7	2.24E-03	1.18E-03	[]
1500	7	0.5	7.00E-04	0	0	7.5	6.5	7.00E-04	7.00E-04	[]
1500	5	0.3	9.00E-04	2.00E-04	2.00E-04	5.3	4.7	1.10E-03	7.00E-04	[]
1500	6	0.3	1.80E-03	0	0	6.3	5.7	1.80E-03	1.80E-03	[]
1600	3.8		1.10E-03	2.00E-04	2.00E-04	3.8	3.8	1.30E-03	9.00E-04	[]
1600	5		9.00E-04	3.00E-04	2.00E-04	5	5	1.20E-03	7.00E-04	[]
1600	6.8		8.60E-04	7.00E-04	3.90E-04	6.8	6.8	1.56E-03	4.70E-04	[]
1600	3.8		1.30E-03	2.00E-04	3.00E-04	3.8	3.8	1.50E-03	1.00E-03	[]
1600	5		1.00E-03	3.00E-04	3.00E-04	5	5	1.30E-03	7.00E-04	[]
1350	5.9		1.50E-03	2.90E-03	1.00E-03	5.9	5.9	4.40E-03	5.00E-04	[]
1350	5.9		1.40E-03	6.00E-04	4.00E-04	5.9	5.9	2.00E-03	1.00E-03	[]

Table 8: *Data highlighting which filters would be useful for observing particular redshift galaxies [5]*

Rest λ (Å)	z	error z	M^*	error M^*	upper z	lower z	upper	lower	Citation
1750	8		-20.1	0.52	8	8	-20.62	-20.1	[67]
1750	8		-19.54	0.56	8	8	-20.1	-19.54	[67]
1700	2.3	0.4	-20.7	0.11	2.7	1.9	-20.81	-20.7	[67]
1700	3.05	0.35	-20.97	0.14	3.4	2.7	-21.11	-20.97	[67]
1500	7	0.5	-20.11		7.5	6.5	-20.11	-20.11	[68]
1500	5	0.3	-20.73	0.11	5.3	4.7	-20.84	-20.73	[68]
1500	6	0.3	-20.04	0.12	6.3	5.7	-20.16	-20.04	[68]
1600	3.8		-21.06	0.1	3.8	3.8	-21.16	-21.06	[69]
1600	5		-20.69	0.13	5	5	-20.82	-20.69	[69]
1600	6.8		-20.14	0.26	6.8	6.8	-20.4	-20.14	[70]
1600	3.8		-20.98	0.1	3.8	3.8	-21.08	-20.98	[70]
1600	5		-20.64	0.13	5	5	-20.77	-20.64	[70]
1350	5.9		-20.24	0.19	5.9	5.9	-20.43	-20.24	[70]
1350	5.9		-20.29	0.19	5.9	5.9	-20.48	-20.29	[69]

Table 9: *Data highlighting which filters would be useful for observing particular redshift galaxies [5]*