BACHELOR THESIS

Habitability in the Early Universe

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Abstract

The conditions for habitability and their distribution in the Universe is an exciting topic of research. It is interesting to study the habitability at high redshifts, specifically during the Epoch of Reionization, as this period is one of the least understood epochs of the Universe, and its study would help further our understanding of galaxy formation. In this thesis we look at the habitability of galaxies in and around the Epoch of Reionization ($5.5 \leq z \leq 20$). We include three key criteria for habitability: (i) the presence of a host star, (ii) sufficient metallicity to produce terrestrial planets, and (iii) an environment free of life extinguishing type II supernova radiation. These properties for each galaxy are calculated from their stellar masses and star formation rates. An extension to the model is also made wherein the effect of overlapping supernova bubbles on habitability is studied. We find that massive galaxies with low star formation rates have the most probable conditions for habitability.

Acknowledgements

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Contents

Chapter 1

Introduction

The question "How common are habitable conditions in the universe?" has driven the field of Astrobiology. Assuming Earth is not the only habitable place in the Universe, what are the requirements for habitability? And how common are they?

Through the years there has been a lot of progress made in our understanding of these requirements. However, our models are strongly dependant on the only life-hosting astronomical body that we know of: Earth.

Three basic requirements for habitability are generally considered (Lineweaver et al. 2004, Dayal et al. 2015): the presence of a host star, sufficient metallicity (i.e., the mass fraction of elements heavier than helium, see Sec. 1.3), and an environment free of deleterious radiation. To go even further, one could include the requirements for holding an atmosphere, and the presence of oxygen and water.

Taking the above requirements into account, theorists have defined 'habitable zones', around stars (Stellar Habitable Zone; Huang 1959), and in a galaxy (Galactic Habitable Zone; Gonzalez et al. 2001), where planets or natural satellites may develop and sustain conditions to host life. A habitable zone is usually thought of as a region where Earth-like conditions can exist and be maintained.

In this thesis, I have only considered habitable terrestrial planets and not habitable natural satellites. The aim of this thesis is to try to quantify the habitability of galaxies through cosmic time, specifically during and around the Epoch of Reionization.

1.1 Cosmic Timeline

About 378,000 years after the Big Bang, the Universe's density decreased and the temperature fell below 3000 K, allowing ions and electrons to combine into Hydrogen and Helium atoms. Photons decoupled from baryons and the Universe became transparent leading to the emission of the cosmic microwave background (CMB) radiation. After this period, the Universe became unobservable across much of the electromagnetic spectrum as any short wavelength radiation emitted was quickly absorbed by the atomic gas. This started the period known as the Dark Ages of the Universe (Loeb 2001).

The Dark Ages ended with the formation of the first stars in the first galaxies. These sources emitted ultraviolet radiation that caused the ionisation of the regions around them. The fraction of ionized gas in the Universe increased rapidly until the Hydrogen in the intergalactic medium became fully ionized (Fig. 1.1). This period, during which the cosmic gas went from neutral to ionized, is known as the Universe's Epoch of Reionization (EoR).

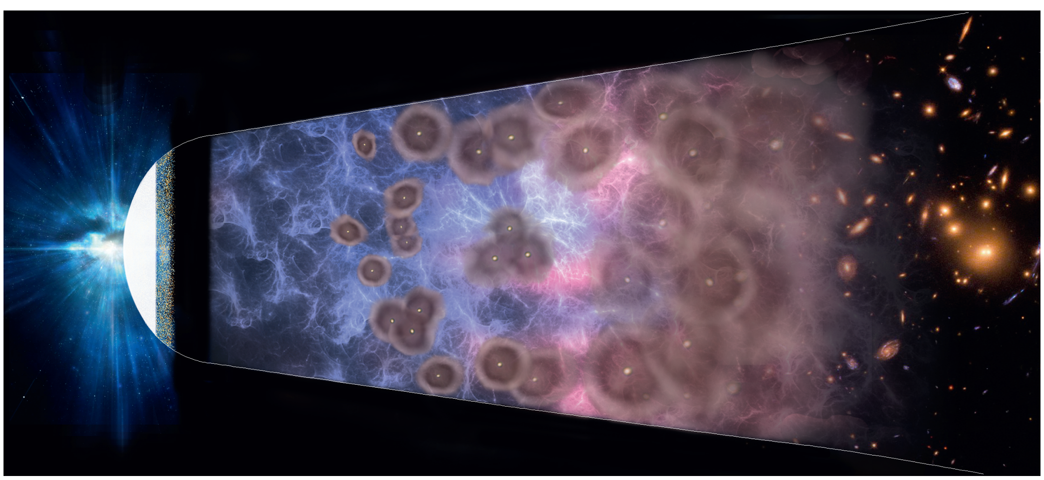

Figure 1.1: A schematic view of the major phases in the history of the Universe. Around 378,000 years after the Big Bang, ionized particles (re)combined to form neutral atoms and the Universe entered the Dark ages. Millions of years later, the first stars shone in the first galaxies, starting the Epoch of Reionization, a period during which the Hydrogen in the Intergalactic Medium transitioned from a mostly neutral, to a highly ionized state. Image credits: DELPHI project, ERC and EU Research SPR19/P53.

Studying the first galaxies that appeared at high redshifts, during the EoR, will greatly benefit our understanding of galaxy formation in the early Universe.

1.2 Theoretical Models for Galaxy Formation

There are different techniques for simulating and studying the formation and evolution of structures and galaxies in the Universe.

Two main techniques used are: numerical hydrodynamics and semi-analytical modelling. Numerical hydrodynamics simulations are detailed models that can provide high spatial resolutions and enable the treatment of complex interactions of the different baryonic components (gas, stars, black holes) at small scales of discretised mass and space. This technique is computationally expensive. Semi-analytic modelling reduces the computational requirements of the simulation significantly, by modeling baryonic physics at the scale of an entire galaxy, and using simplified equations and a reduced set of parameters.

Most modern simulations implement a 'hybrid' approach in order to achieve high efficiency. One such technique, called semi-numerical modeling, is the technique used to obtain the data used in this thesis.

In this thesis the ASTRAEUS framework (Hutter et al. 2020, Ucci et al. 2020) is used to simulate galaxy formation through cosmic time. This framework uses the semi-numerical approach and includes key processes of galaxy formation and evolution, such as accretion, mergers, supernova and radiative feedback. It also follows the evolution of ionized regions in the intergalactic medium. The framework is explained further in the next chapter.

1.3 Metallicity

The metallicity of a star, nebula, or galaxy, is the mass fraction of elements heavier than Helium that make it up. It is generally denoted by Z. The solar metallicity (denoted $Z_{\odot}$) is around 0.02 (Vagnozzi 2019), meaning that chemical elements heavier than Helium make up two percent of the Sun's mass. In this thesis, all elements that are not Hydrogen (H) or Helium (He) are referred to as metals. I have adopted the notation for metallicity in terms of logarithmic abundances as described in Asplund et al. (2009), $log\epsilon_X = log(N_X/N_H) + 12$ where $log\epsilon_H = 12.00$ is the defined abundance for Hydrogen and N_X and N_H are the number densities of element X and hydrogen, respectively. It is also more simply denoted as $log\epsilon_X = log(X/H) + 12$.

With Earth as our template, metals are a fundamental requirement for habitability. Life as we know it would only form on rocky terrestrial planets (or moons) which are composed of heavy elements. Further still, oxygen and water are an important requirement for habitability.

From planet formation models (Bodenheimer et al. 2000, Lin et al. 1996, 1997) we know that there exists a certain range in metallicity where Earth-like planets are most likely to be harboured. With too little metallicity, Earth-mass planets would be unable to form; and with too much metallicity, giant planets destroy Earth-mass planets. These limits for metallicity have been defined in papers such as Lineweaver (2001).

1.4 Extinction of life

To have an idea of how many habitable planets (or moons) could exist, we also need to consider how easy it is to extinguish life in a galaxy. Nearby radiative activities like supernova (SN) explosion or gamma ray bursts (GRB) could affect many species directly by destroying the planet's ozone layer, and exposing the species to solar ultraviolet radiation. Dayal et al. (2016) paper concludes that type II supernovae dominate the total radiation among SNII, SNIa, GRBs and AGN (Active Galactic Nuclei), which is why only the effects of SNII radiation has been considered in this thesis. However, Stanway et al. (2018) comes to a different conclusion, with GRBs irradiating significantly larger volumes than SN. This consideration could be accounted for in further research.

Chapter 2

Theoretical Framework

2.1 The Cold Dark Matter Model

A cosmological model is a mathematical description of the Universe, that attempts to explain its current features and the reasons behind them, as well as describe its evolution over time.

The Lambda Cold Dark Matter Model (ΛCDM) is the current standard cosmological model that bases the origin of the Universe on a Big Bang and uses inflation to explain the evolution of the early Universe. The model assumes that in addition to ordinary matter made of protons, neutrons, and electrons (referred to as baryonic matter), there is also dark matter, which is composed of massive cold particles that have no interactions other than through gravity. This dark matter is assumed to be responsible for the structure formation in the Universe and makes up the dark matter halos surrounding galaxies and galaxy clusters.

In the first 10^{-34} seconds of the Universe's history, it underwent a brief period of extremely fast expansion, known as inflation. This period smoothed out irregularities in the Universe and left it with the homogeneity and isotropy we see today[1]. Fluctuations in density during this process remained and seeded the formation of structure in the Universe. (Eisenstein & Hu 1998)

As the Universe cooled, baryons began to condense and gas molecules formed within clumps of dark matter. The gas and dark matter were gravi-

[1] The cosmological principle states that the spatial distribution of galaxies is statistically homogeneous and isotropic when averaged on scales greater than $260h^{-1}$ Mpc (Ryden 2017)

tationally attracted to the areas of higher density and formed halos. Proto-galaxies formed from the collapse of these halos after they had become more massive. The hydrogen and helium gas within these proto-galaxies began to make the first stars and over time, the halos merged to form larger galaxies. This is known as the hierarchical structure formation scenario. (Blumenthal et al. 1986)

Following the ΛCDM model, the density of the Universe is given by $\Omega_0 = \Omega_M + \Omega_r + \Omega_\Lambda$, where Ω_M is the density of matter consisting of dark matter and baryonic matter, Ω_r is the radiation density, and Ω_Λ is the vacuum density. σ_8 describes the mass fluctuation in the Universe, i.e. the relative distribution of light to mass. A value of 1 would indicate that the Universe is unbiased in terms of the mass and light densities, whereas a value differing from 1 suggests a bias. The Hubble constant describes the expansion of the Universe and is defined as $H_0 = 100h$ km s^{-1} Mpc^{-1} where h is the reduced Hubble constant.

The initial mass function (IMF) is an empirical function that describes the distribution of mass in a newly formed stellar population.

In this paper we use a Salpeter IMF (Salpeter 1955) between 0.1 and 100 $M_\odot$ for our galaxies and the following set of cosmological parameters obtained from the Planck Collaboration et al.(2016): $\Omega_\Lambda = 0.69$, $\Omega_M = 0.31$, h = 0.6777, $n_s = 0.96$, $\sigma_8 = 0.82$.

2.2 ASTRAEUS framework

The ASTRAEUS (semi-numerical r**A**diative tran**S**fer coupling of galaxy forma**T**ion and **R**eionization in N-body d**A**rk matt**E**r sim**U**lation**S**) framework detailed in Hutter et al. (2020) is used to obtain the data used in this thesis.

ASTRAEUS integrates a high-resolution N-body simulation and a semi-analytical galaxy formation model. It supports multiple models for predicting the escape fraction of ionising photons, i.e, the fraction of HI ionising photons produced by star formation that can escape into the intergalactic medium. It models the accretion and mergers of dark matter halos and gas, along with star formation, SN feedback, and the time and spatial evolution of ionized regions. The framework accounts for recombinations, HI fractions and photoionization rates within ionized regions, and radiative feedback. It has a total of three free parameters: the threshold star formation efficiency (i.e the density over which star formation is most efficient), the fraction of

SNII energy that couples to gas, and the escape fraction of ionizing photons. The N-body simulation was run with a box size of 160h^{-1}c Mpc and 3840^3 dark matter particles resulting in a resolution mass of $6.2\times10^6 h^{-1}$ $M_\odot$.

A total of 150 different snapshots of the simulation, equally spaced in expansion factor, were stored from $z = 25$ till $z = 0$. In this thesis, 12 snapshots have between used with $5.5 \leq z \leq 20$.

2.3 Metallicity

The link between mass and metallicity is established in many papers (e.g. Tremonti et al. 2004, Maiolino & Mannucci 2019, Mannucci et al. 2010), and arises from the role of star formation in galaxy chemical evolution. The metallicity of a galaxy is affected by inflow of pristine gas and outflow of metal rich gas, the former being at the origin of star formation activity and the latter being caused by supernovae explosions.

Hunt et al. (2016) derived a relation between the gas-phase oxygen abundance (O/H), the star formation rate (ψ) and the stellar mass (M_*) of a galaxy. This relation, known as the Fundamental Plane of Metallicity relation (FPZ), is used in this thesis to obtain the metallicities for our galaxies.

$$12 + \log(O/H) = -0.14\log(\psi) + 0.37\log(M_*) + 4.82 \tag{2.1}$$

Here ψ is expressed in solar masses per year and M_* in solar masses.

At high masses, the gas metallicity goes to a constant for a given star formation rate, as the metal enrichment due to star formation is compensated by the inflow of pristine gas into the galaxy, whereas outflows are negligible due to the large potential wells of these massive galaxies. Less massive galaxies with smaller ψ produce less heavy elements that are easily ejected by their smaller potential wells, hence for a given mass, metallicity decreases with increasing ψ.

Hunt et al. (2016) compare two models for the FPZ, redshift dependant and independent, and conclude that the FPZ is approximately redshift invariant to within 0.15−0.16 dex. Therefore, the assumption that the FPZ is redshift invariant is maintained in this thesis.

Fig. 2.1 shows the gas phase oxygen abundance as a function of mass for our galaxies. There is a gradual but definite increase in metallicity with time for a particular stellar mass. At the high redshifts we have considered, the metal content of these galaxies is very low, and hence we do not apply an upper limit to the metallicity while calculating the habitability in the next section.

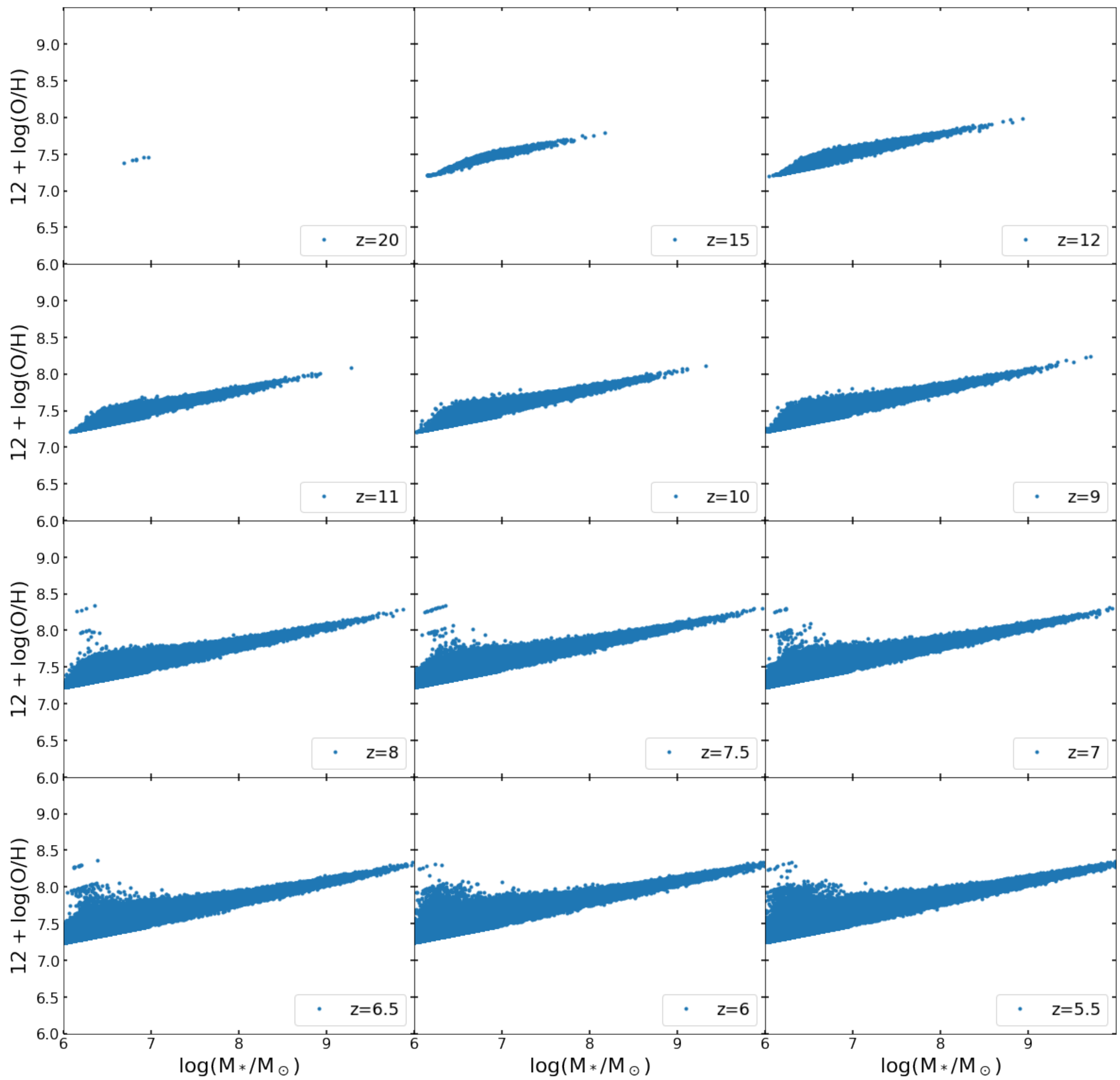

Figure 2.1: We show the metallicity of the galaxies as a function of their stellar mass, in units of 12+log(O/H), obtained from our simulation results for redshifts z∼20 to z∼5.5, as marked in each panel

Chapter 3

Modelling Habitability

This study is similar in spirit to the formalism in Dayal et al. (2015). As in that work, habitability of a galaxy is dependant on three key criteria:

1. the number of stars in the galaxy (N_{tot});
2. the probability of these stars hosting terrestrial planets (P_t)
3. the fraction of these planets that are unaffected by SN radiation and therefore are more likely to support complex life (P_{cl}).

The total number of stars (N_{tot}) present in a galaxy should be proportional to its total stellar mass (M_*) such that $N_{tot} \propto M_*$.
In this thesis we assume that the formation of terrestrial planets in a galaxy is strongly dependant on its gas phase metallicity (Z), such that $P_t \propto Z$.

The gas phase oxygen abundance can be converted to the gas phase metallicity assuming that the gas comprises approximately 75% hydrogen by mass:

$$\log(Z) = \log(O/H) + 0.956 \tag{3.1}$$

Finally, assuming that the stars are homogeneously distributed throughout the galaxy, the the fraction of planets unaffected by SN radiation is inversely proportional to the fractional volume irradiated by recent SN in the galaxy

$$P_{cl} \propto \frac{1}{f_{\rm irr}} = \frac{V_{tot}}{V_{irr}} \tag{3.2}$$

where $V_{\rm irr}$ is total the irradiated volume and V_{tot} is the total volume of the galaxy, given by $V_{tot} = M_*/\rho$. The interstellar media of galaxies is assumed to have a density $\rho = 200\rho_{crit}$, where ρ_{crit} is the critical density of the Universe. Assuming that the radiation from a single SN can affect life on planets up to a radial distance Q, the total volume affected by a single SN then is $\frac{4}{3}\pi Q^3$. A redshift dependant relation for Q can be found as follows.

Observation has shown that star formation takes place in molecular clouds (Solomon & Vanden Bout 2005). We assume HI to make up the diffuse ISM, and the radius of this component is the radius of the galaxy. H_2 makes up giant molecular clouds where star formation takes place. Lagos et al. (2011) gives the following equation for the H_2/HI mass ratio as a function of the stellar mass:

$$\mathrm{H_2/HI} \approx 0.01 \left(\frac{M_*}{10^{10} h^{-1} M_\odot} \right)^{0.8} (1+z)^{3.3} \tag{3.3}$$

We then use

$$\begin{aligned} \mathrm{H_2/HI} &= \frac{\rho_{H_2} V_{H_2}}{\rho_{HI} V_{HI}} \\ &= \frac{200 n_{SN} \frac{4}{3}\pi Q^3}{200 \rho_{crit} \frac{4}{3}\pi R_{gal}^3} \end{aligned} \tag{3.4}$$

With n_{SN} being the SN rate in years^{-1}.

We have made the following assumptions:

1. The molecular density has an average value of $200 cm^{-3}$,
2. The entire volume of the molecular phase is irradiated by SN, and for this volume we have considered that no SN overlap in bubbles.

Using eqs. 3.3 and 3.4 we obtain an estimate for Q as a function of redshift

$$\frac{n_{SN} Q(cm)^3}{\rho_{crit} R_{gal}^3} = 0.01 \left(\frac{M_*}{10^{10} h^{-1} M_\odot} \right)^{0.8} (1+z)^{3.3}$$

$$Q(cm) = R_{gal} \left[\frac{0.01\rho_{crit}}{n_{SN}} \left(\frac{M_*}{10^{10}h^{-1}M_\odot} \right)^{0.8} (1+z)^{3.3} \right]^{1/3}$$

$$\begin{aligned} Q(pc) &= 3.2 \times 10^{-19} Q(cm) \\ &= 3.2 \times 10^{-19} R_{gal} \left[\frac{0.01\rho_{crit}}{n_{SN}} \left(\frac{M_*}{10^{10}h^{-1}M_\odot} \right)^{0.8} (1+z)^{3.3} \right]^{1/3} \end{aligned} \quad (3.5)$$

Continuing on the assumption that none of the Supernova bubbles overlap, the total volume affected is proportional to the volume irradiated per SN times the SN rate. The SN rate is linked to the ongoing star formation rate through the IMF. SN explode after roughly 28.6 million years (Padovani & Matteucci 1993). Using $[53.17 M_\odot]^{-1}$ as the SN rate for the chosen Salpeter IMF, $V_{\rm irr}$ is

$$V_{\rm irr} = \frac{\psi}{53.17} \frac{4}{3} \pi (Q \text{ pc})^3 (28.6 \text{ Myrs}) \quad (3.6)$$

Therefore, the number of habitable terrestrial planets can be expressed as

$$N_t \propto N_{tot} P_t P_{cl} \propto \frac{N_{tot} Z}{f_{irr}} \quad (3.7)$$

or

$$N_t \propto \frac{53.17 M_*^2 Z}{\rho \psi \frac{4}{3} \pi (Q \text{ pc})^3 (28.6 \text{ Myrs})} \quad (3.8)$$

Removing the various constants gives us,

$$N_t \propto \frac{M_*^2 Z}{\psi Q^3} \quad (3.9)$$

By re-normalizing this value with respect to the Milky Way, we are able to get rid of all constants of proportionality. Since stellar mass and star formation rates are the intrinsic galaxy properties that Z and Q depend on, we have plotted habitability as a function of M and ψ. Fig. 3.1 shows that habitability increases with increasing stellar mass and decreasing star formation rates. At these redshifts, habitability is seen to have a stronger dependence on ψ. This can be explained by noting that if we fill in eqn. 3.5 in eqn. 3.9, we have; $\mathrm{N}_t \propto \mathrm{M}_*^{1.2}$ and $\mathrm{N}_t \propto \psi^{-1}$, i.e, habitability is almost equally proportional to galaxy stellar mass and inverse star formation rate, however, star formation rate has a larger range in values for our data, hence the dependence of N_t on ψ is more easily seen.

In Chapter 4, we discuss an extension to this model, by considering overlapping SN bubbles and their impact on the number of habitable terrestrial planets.

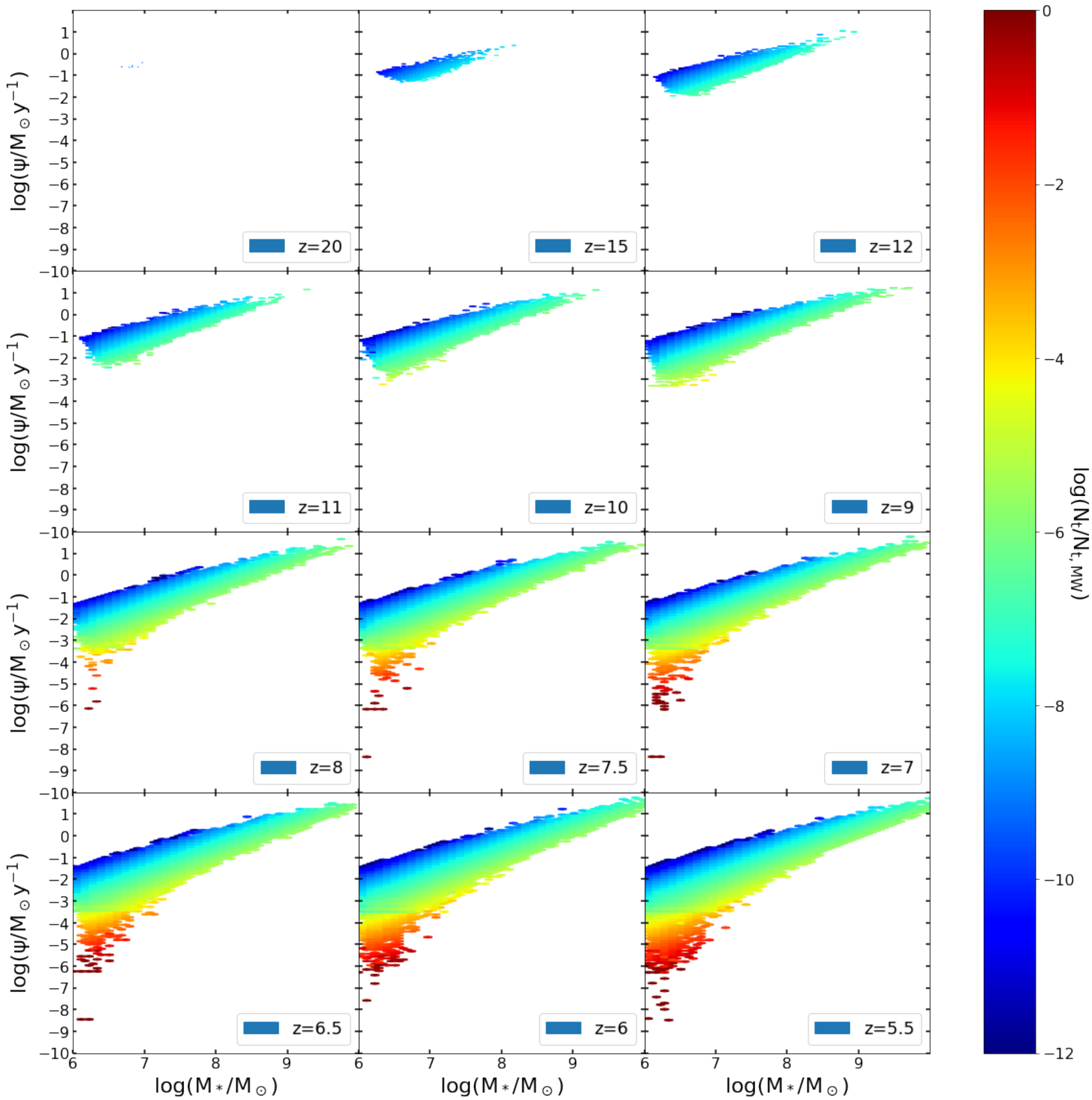

Figure 3.1: We show the number of earth-like habitable planets (N_t) in the galaxies as a function of their star formation rate and stellar mass, normalised to the number of earth-like habitable planets in the MW ($N_{t,MW}$), for redshifts z∼20 to z∼5.5, as marked in each panel. N_t values (in log) are shown by the colour bar.

Chapter 4

Overlapping volumes

Supernovae generally explode in high-density star-forming regions. This could create regions of influence that irradiate a fraction of volume that is common between two (or more) SN, giving rise to "overlapping bubbles".

In this Chapter, we extend the formalism used in the last chapter to account for these overlapping volumes. A very simple model has been made wherein only two SN may overlap in any given bubble. A derivation of the volume irradiated by SN in overlapping bubbles is given in the next section.

4.1 Volume irradiated by SN in Overlapping Bubbles

For this thesis, a simplistic model of overlapping SN bubbles has been constructed where only two SN overlap in any given bubble.

Assuming 'Q' to be the radius of influence of a given SN, the volume irradiated by an SN that is not in an overlapping bubble (NB) is:

$$V_{NB} = \frac{4}{3}\pi Q^3 \tag{4.1}$$

The total volume of two overlapping spheres of radii 'Q' with distance 'd' between their centres is found geometrically to be:

$$V = 2 * \frac{4}{3}\pi Q^3 - \frac{\pi}{12}(4Q + d)(2Q - d)^2 \tag{4.2}$$

where the second term in the RHS is the volume within the overlap.

Therefore, assuming 'd' to be the distance between two SN in an overlapping bubble (OB), the average volume irradiated by each SN in the bubble is half the total volume irradiated by the bubble:

$$V_{OB} = \frac{V}{2} = \frac{4}{3}\pi Q^3 - \frac{\pi}{24}(4Q + d)(2Q - d)^2 \tag{4.3}$$

If N is the fraction of total SN that overlap in a given galaxy, then the total volume irradiated by SN due to the on going star-formation is

$$\begin{aligned} V_{irr} &= \frac{\psi}{53.17}(28.6 \text{ Myrs}) \left[(1 - N)V_{NB} + NV_{OB}\right] \\ &= \frac{\psi}{53.17}(28.6 \text{ Myrs}) \left[\frac{4}{3}\pi Q^3 - \frac{N\pi}{24}(4Q + d)(2Q - d)^2\right] \end{aligned} \tag{4.4}$$

where $0 \leq N \leq 1$ and $0 \leq d \leq 2Q$. Simple limiting cases are:
for $N \to 0$ or $d \to 2Q$:

$$V_{\text{irr}} \to \frac{\psi}{53.17}(28.6 \text{ Myrs})V_{NB} \tag{4.5}$$

and for $N \to 1$ and $d \to 0$:

$$V_{\text{irr}} \to \frac{1}{2}\frac{\psi}{53.17}(28.6 \text{ Myrs})V_{NB} \tag{4.6}$$

The number of habitable planets in a galaxy is inversely proportional to the volume irradiated by SN:

$$N_t \propto \frac{1}{V_{\text{irr}}} \tag{4.7}$$

Therefore, the higher the fraction of SN in overlapping bubbles, the higher the number of habitable terrestrial planets. If all the SN overlap, the number of habitable terrestrial planets may be up to twice that when they don't overlap. Fig 4.1 outlines the effect of overlapping bubbles on the total irradiated volume for a few example values of N and d.

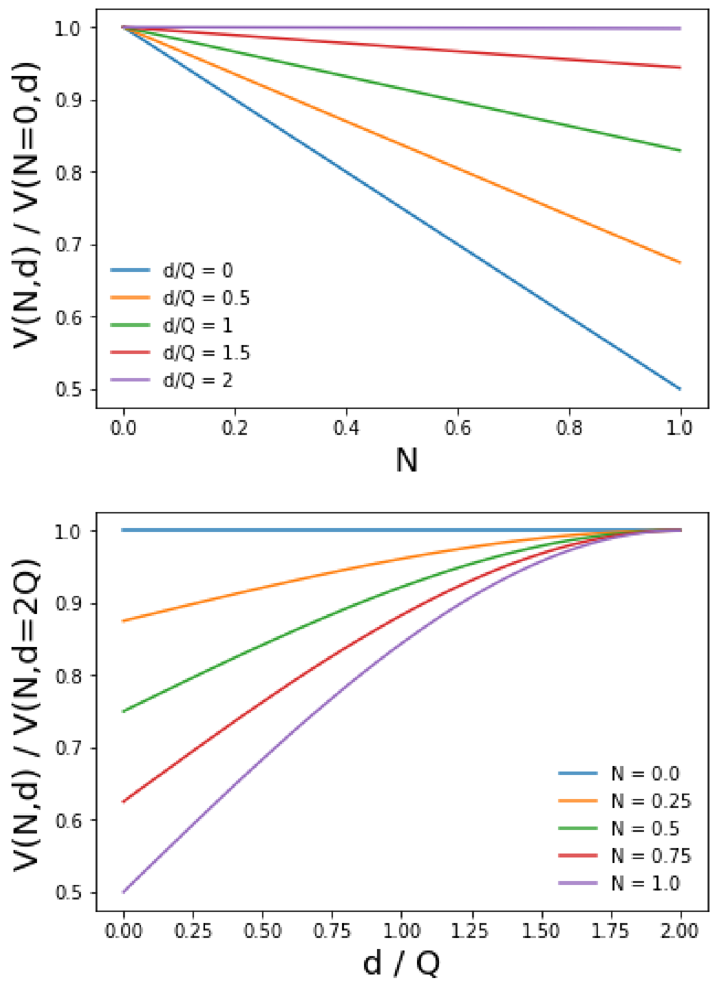

Figure 4.1: We show the effect of overlapping bubbles on the total irradiated volume, in terms of the ratio of the irradiated volume with overlap to the irradiated volume without overlap, for different values of distance d between the supernova and fraction N of total supernova that overlap in a given galaxy. The upper panel gives the ratio of V(N)/V(N=0) for different values of d/Q, where Q is the radius of influence of one supernova. The lower panel gives the ratio V(d)/V(d=2Q) for different values of N.

4.2 Extension of formalism

The total volume irradiated by SN in a galaxy where N fraction of them overlap in bubbles as described in the previous section is given by

$$V_{irr} = \frac{\psi}{53.17}(28.6Myrs)\left[\frac{4}{3}\pi Q^3 - \frac{N\pi}{24}(4Q+d)(2Q-d)^2\right] \tag{4.8}$$

where Q is the radius of influence of a SN and d is the distance between two overlapping SN.

If we assume the distance between overlapping SN to be given by the 'mean inter-star distance', we can approximate N$\approx$ 1 and proceed with the calculations for V_{irr}.

$$d(pc) = 3.2\times10^{-19}\left[\frac{0.01}{\rho_{crit}n_{SN}}\left(\frac{M_*}{10^{10}h^{-1}M_\odot}\right)^{0.8}(1+z)^{3.3}\frac{4\pi R_{gal}^3}{3}\right]^{1/3} \tag{4.9}$$

Using eqs 3.7, number of habitable terrestrial planets is then given by

$$N_t \propto \frac{M_*^2 Z_g}{V_{irr}} \tag{4.10}$$

Fig. 4.2 gives the habitability of the galaxies, normalized to the Milky Way, accounting for overlapping bubbles. The ratio of values from fig. 4.2 and fig. 3.1 have been plotted in fig. 4.3. From our derivations for Q and d, we have a ratio $d/Q \approx 1.5$. From fig. 4.1, we see that for $N = 1$ and $d/Q = 1.5$, the ratio of volumes is between 0.9 and 1.0, resulting in the value for the ratio ($\mathrm{N}_{t,OB}/\mathrm{N}_{t,NB}$) to be between 1.0 and 1.1. This is reflected in fig. 4.3.

Physically this means that from our assumptions for a homogeneous distribution of stars in the galaxy, most SN are placed with sufficient distance to one another so as to not overlap significantly, hence, overlapping SN bubbles do not contribute significantly to habitability. However, stars (and hence SN) are usually localised to high star forming regions within the galaxy, hence the distribution of planets on a galaxy would also be more localised than homogeneous. SN radiation in these regions would then irradiate a larger fraction of planets than our method accounts for. However, SN overlap would also then be significant in these regions.

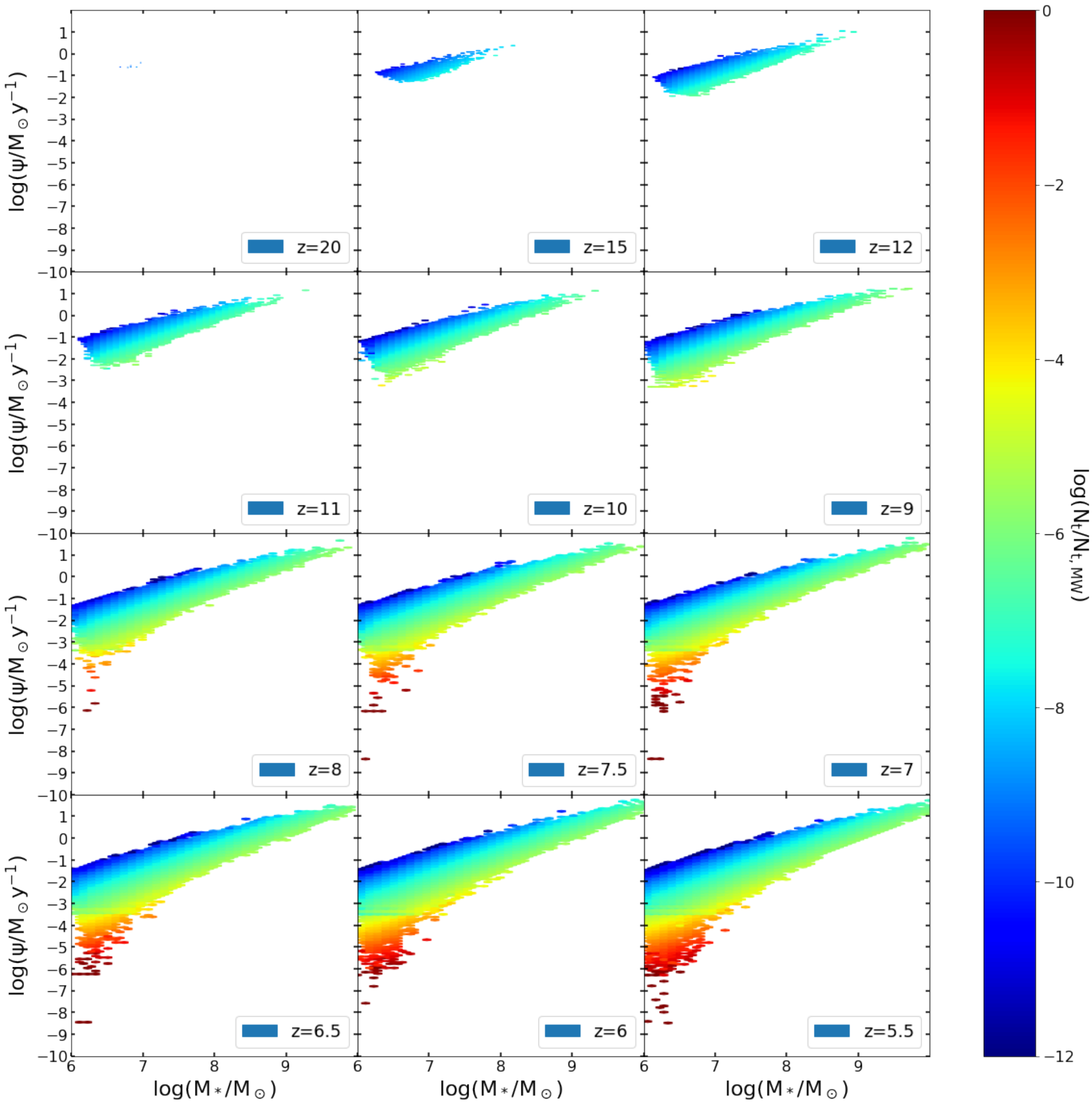

Figure 4.2: We show the number of earth-like habitable planets (N_t) in galaxies, accounting for the effect of overlapping SN bubbles, as a function of their star formation rate and stellar mass, normalized to the number of earth-like habitable planets in the MW ($N_{t,MW}$) for redshifts z∼20 to z∼5.5, as marked in each panel. N_t values (in log) are shown by the colour bar.

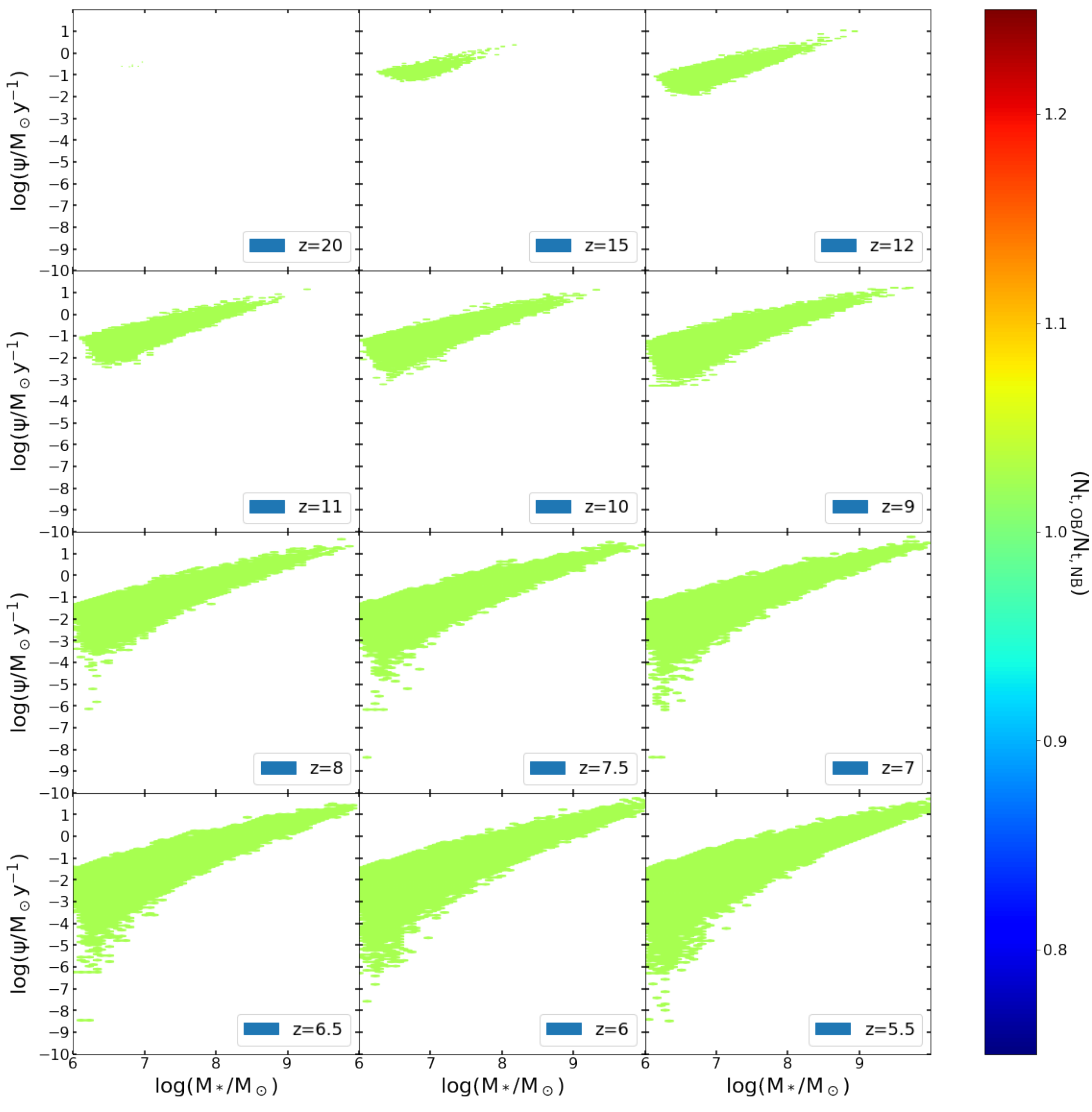

Figure 4.3: We show the ratio of the number of earth-like habitable planets in galaxies with overlapping SN bubbles ($N_{t,OB}$), to those in galaxies without ($N_{t,NB}$),for redshifts z∼20 to z∼5.5, as marked in each panel. The values of the ratio are shown by the colour bar.

Chapter 5

Discussion

We have made many simplifying assumptions in this thesis which we expect to have affected the resulting calculated habitability of the Universe. Below we discuss these assumption and their effects on our calculations.

Firstly, we have neglected the effects of SNIa, AGN, and GRB radiation while accounting for the extinction of life. From dayal et al. (2016) [fig 5.1 below], we see that the contribution of SNIa is only a factor $10^{0.5} \approx 3$ less than SNII on the irradiated volume. While star formation starts around z$\sim$20, due to the 370Myr delay between star formation and the first SNIa explosions, the first SNIa appear around z$\sim$10.5. Therefore, after z$\sim$10.5, the contribution of SNIa on the deleterious radiation would be significant, lowering the net habitability of the galaxies from then on. For a complete picture, contributions of all these sources (SNII,SNIa, GRB, and AGN) should be considered. As Stanway et al. (2018) has differing results on the contributions of these sources on the total radiation density, with GRBs dominating the deleterious energy budget, a comparison could further be made between the habitabilities calculated with the Dayal et al. (2016) results and those calculated with the Stanway et al. (2018) results.

Secondly, we have assumed stars to be homogeneously distributed across the galaxy. Since SN generally go off in more localised high star forming regions in galaxies, they would cause more damage to potentially habitable planets than we have accounted for. However, in these regions, the effect of overlapping SN bubbles would also be significant.

Finally, the derivation for radius of influence Q makes the simplifying assumption that the entire volume of the molecular phase is irradiated by SN. This assumption results in a larger value for Q, and hence lower values for habitability, than if only a fraction of the molecular phase volume is irradiated.

Most of these assumptions cause an increase in the calculated value habitability of the Universe. Hence by changing these assumptions, the Universe, at any given redshift, would be found to be less habitable than we have calculated.

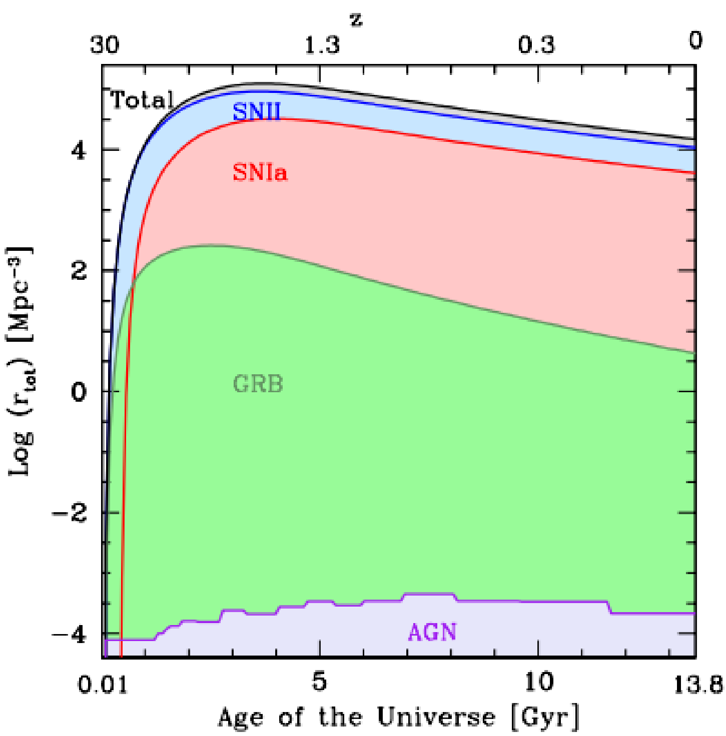

Figure 5.1: The plot shows r_{tot}, a proxy for the total volume hosting stars that is irradiated, as a function of the age of the Universe. As seen, SNII dominates r_{tot} throughout the age of the Universe, closely followed by SNIa, whereas the contribution of GRB and AGN are a factor 3 and 8 orders of magnitude lower, respectively. Plot from Dayal et al.(2016)

Chapter 6

Conclusion

In this thesis, the habitability of the Universe through cosmic time was researched, using 12 snapshots of the ASTRAEUS framework between redshifts z = 20 and z = 5.5.

We have found that the Universe gradually becomes more habitable over cosmic time. Habitability at the higher redshifts is up to 10^{12} times lower than that of the current Milky Way, however, at redshifts ≈ 5.5 a significant portion of the galaxies have comparable habitability to the current Milky Way. Of the three key criteria for habitability explored, the probability of stars hosting terrestrial planets does not vary much with time at these redshifts, due to the low metal content in these galaxies and the slow rate at which it increases. The effect of SN radiation is more noteworthy, and can be seen in the dramatic rise of habitability for low star formation rates. Hence galaxies with low star formation rates are the most habitable at high redshifts.

With the assumption of homogeneous distribution of stars (and hence SN) in galaxies, SN overlap does not factor much in habitability. However, in more realistic assumptions with denser and rarer populated regions in galaxies, SN overlap would factor significantly.

With better understanding of the dependence of planet formation on mass and metallicity of the galaxy, the model and the assumptions therein can be improved. Future work can also implement the contribution of SNI, AGN and GRBs in the deleterious radiation.

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