On the Evolution of Galactic Habitability

Master's Thesis in Astromundus

by

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Abstract

The Galactic Habitable Zone is a concept that was introduced for the Milky Way galaxy in order to complete the knowledge of the places in the Universe hospitable for complex life as we know it. In this work we will discuss the concept of Galactic habitability and explore how it behaves using a N-body/SPH simulation of the dynamics and evolution of a spiral galaxy using the GADGET-2 code. To our knowledge, it is the first time that this approach is taken.

We analyse how the different criteria chosen to develop complex life, such as enough metallicity and time to develop complexity, and how the presence of Supernova explosions, Gamma-ray bursts and high stellar density as life threatening phenomena affect the temporal and spatial distribution of habitable sites in the Galaxy, working separately and together.

The impact that the different life threatening phenomena considered have on Galactic habitability is also quantified. We find that this approach is in good accordance of previous calculations of boundaries of the Galactic Habitable Zone found in literature and is a viable platform to do astrobiological research.

Contents

1 Introduction

Guy de Maupassant was one of the many people who hated the Eiffel Tower when it was first built.
It is a famous fact that Guy regularly ate lunch in the restaurant of the Eiffel Tower. When asked why he visited the restaurant so frequently if he hated the Tower so much, he replied that 'Inside the restaurant was one of the few places where he could sit and not actually see the Tower!'

Astrobiology has nowadays the status of an emerging science. As all emerging sciences, it still suffers the skepticism of great part of the academic community, including experts from all research areas (even the style corrector of my computer considers the word "astrobiology" an orthographic error). It is because the very nature of astrobiology as an interdisciplinary field, somehow transcending the limits of a "natural" science, that it receives the attention, and therefore criticism, from the most diverse branches of knowledge. This should be not a matter for pessimism, as Ćirković (2012) points "when X is attacked from diametrically opposed sides, there must be something of worth in X!".

It is impossible to do research in astrobiology without entering in the domains of philosophy and speculation. And this is perhaps one of the most exciting features of astrobiology. From the most opposite sites, such as the Rare Earth hypothesis against the SETI enthusiasts, the astrobiological landscape is getting each time more and more rich, rigorous and complex.

We still don't know how common life is in the Universe. We still lack a complete panorama of what are the requisites for life to start and also what are, if any, the 'laws' that rule its evolution. We don't know if the technological achievements of the human species is the rule, as some SETI enthusiasts claim, or rather the exception. Moreover, we are not even sure if despite the grandness of the Universe, we are or not alone in it. But we do know also a lot of things either from the Universe or from life on Earth. And, as far as I can tell, if it is true that the motivation of the astrobiological research is the unknown, the methodological guide is based always in known facts. We DO know what are the conditions for life, perhaps not in general, but those the most important for life on Earth. We know, or at least we CAN know, how the Earth conditions can be spread in the Galaxy, and far beyond. This is a solid starting point. Astrobiology is not only the search for life in other places of the cosmos, but also to understand the life on Earth on its cosmic perspective. Denying this is geocentrism in its most pure form. Is as absurd as standing on the Eiffel tower and at the same time denying its presence and importance for drawing the landscape of Paris.

If we can locate the birth of modern astronomy with the Copernican Revolution, then we realize on the importance of a principle that has ruled great part of modern way of doing science, not only in astronomy, but as well as in biology, known as the Copernican Principle. This states that if the Universe has some kind of 'special' or 'privileged' places, humans are not on them. In order to describe the movement of planets in the Solar System, it was much more simpler to abandon the idea that Earth occupies its center. It is true that this methodological assumption can prevent us from committing some parochial mistakes, such as assuming that most galaxies in the Universe are receding from our planet just because from here we can see that. The Copernican Principle would say that, on that case, we will see the same recession of galaxies from any other point in the Universe. And we know that this is true not only because of the Copernican Principle, but from our most accepted cosmological models. In that sense, there is nothing special about Earth. However, with the development of modern cosmology, a different reasoning brought new light on our way of thinking. Brandon Carter (1974) made a limitation to the Copernican Principle stating that 'our location in the Universe is necessarily privileged to the extent of being compatible with our existence as observers'. This is know as the 'Anthropic Principle'.

We can see that in our immediate experience. The Cosmological Principle states that the Universe, on large scales, is homogeneous and isotropic. Moreover, the 'typical' place in the Universe is the cold, void and dark space. However, we see a very inhomogeneous immediate environment, full of stars, because we live in the disk of a spiral galaxy, around 8.5 Kpc from its center. Interstellar environment inside galaxies is not at all a 'typical' place in the Universe. But it is one which allows observers like us to exist. Given this background, we can outline the two methodological guides for the study of this thesis:

1) The Anthropic Guidance: We know that conditions of Earth are special, perhaps not in general, but for observers like us. We don't know weather it is possible for Nature to develop intelligence based in other kinds of life. We are aware that if that is at least in principle not impossible, we lack of a methodological guideline to research the habitable sites for those kind of observers. Moreover, they are not restricted to see an epoch or even kind of Universe like the one that we observe.

...and...

2) The Copernican Principle: We know that there is nothing particularly special about the conditions to produce such places like our planet. This same, very general conditions can be widespread in the Milky Way and in other galaxies as well.

It can look a little bit contradictory, given that the two principles guiding this research seem to point to opposite directions. On the one side, the Copernican Principle points the non specialness of our location, while the Anthropic Guidance reminds us on the selection effects we should expect in our observations given our own existence. As we will see in this work, there is another effect that usually takes place when speaking about Astrobiology, known as the Goldilocks' Principle[1]. This principle states that for some things to happen certain values must fall in certain margins, and not close to extreme values. There are, for example, the so-called Goldilocks' planets or Goldilocks' zones in Astrobiology (von Bloh et al., 2011; Ćirković, 2007). For instance, Earth is neither too massive, like the giant gaseous planets in the solar system, to have a very big atmosphere, nor too less massive to easily lose it. It is not too far from the Sun to be very cold, nor too close to be very hot, too less supernovae will lead to

[1]Term taken from the fairy tail Goldilocks and The Three Bears, where the protagonist always chooses the food temperature, bed size, etc. that is "just right" according to her.

a less metal rich Universe, while a supernova can also be considered dangerous for life on a planet, and so on... We can apply some kind of Glodilock's principle concerning two guiding principles. As Carter (1974) resumes "Although our situation is not necessarily *central*, it is inevitably privileged in some extent".

These are the main philosophical foundations for our modest research. We recognize our great ignorance, but make use of the well known facts of modern astrophysics and, as far as we can, also modern biology. This is not a new area in the rapidly evolving discipline of astrobiology, although we try to contribute with some original ideas. To decide whether our planet and form of life is rare or common in the Universe goes far beyond the scope of this work. We will try to remain, as much as possible, avoiding the most speculative part on the presence and behaviour of life in the Universe. I hope that this work can be usefull for future researchers, from either side on the astrobiology spectrum.

The Galactic Habitable Zone is a concept that was introduced for the Milky Way galaxy in order to complete the knowledge of the places in the Universe hospitable for life as we know it. In this work we will discuss the concept of Galactic habitability and explore how it behaves using a N-body/SPH simulation of the dynamics and evolution of a spiral galaxy. To our knowledge, it is the first time that this approach is taken. We analyse how the different criteria chosen to develop complex life and how life extinguishing phenomena affect the temporal and spatial distribution of habitable sites in the Galaxy, working separately and together. We find that our approach is in good accordance of previous calculations of boundaries of the Galactic Habitable Zone found in literature. We quantify the impact that the different life threatening phenomena considered have on Galactic habitability.

In the second chapter, we will talk about the main ingredients concerning habitability, including the most important concepts for the definition of the Galactic and Circumstellar Habitable Zones. The concept of Earth-like planets is also included. In Chapter 3 we describe the main parameters on Galactic habitability explored in this work. In Chapter 4 we introduce the GADGET-2 N-body simulation of a galaxy and how we include the astrobiological criteria to do the analysis. Finally in Chapter 5 the results of the simulations are presented and in Chapters 6 and 7 the discussion and conclusions of the research.

2 Habitability Concepts

Definitions are like belts, the shorter they are, the more elastic they need to be...
Stephen Toulmin

2.1 Galactic Habitable Zone

One of the main criticisms to astrobiology is that it is an inquiry without a definite subject. The case of the so called "Galactic Habitable Zone" (henceforth GHZ), the main topic of study of this thesis, is an archetypical example of this.

The history of the term GHZ has been controversial since it's very beginning. It was constructed in analogy to the Circumstellar Habitable Zone (CHZ), a previous concept defining the region surrounding a star where liquid water can exist in the surface of an Earth-like planet for an extended period of time (Hart, 1979; Shklovskii & Sagan, 1966) based on the fact that the only example of life we know in the Universe, ourselves, depend strongly on this condition (see discussion on this concept below). The GHZ was defined as the region favourable to the development and long-term maintenance of complex life comparable to terrestrial animals and complex plants (Gonzalez et al., 2001). Contrary to the case of the CHZ, the definition of the GHZ is much less clear, and there is not a universal consensus of which are these favourable conditions for complex life. It is also defined in more probabilistic terms. For instance, considering that supernova (SN) explosions are hazardous for the development of complex life, and that these events occur more frequently in the central regions of a spiral galaxy, it doesn't follow that there cannot be habitable planets in regions where complex life has enough time to evolve. Simply put, it is less probable that this will occur in such regions, but not impossible. For this reason the definition of inner or outer limits, if there are any, is quite more problematic. Gonzalez et al. (2001) made an attempt considering that the inner regions of the Galaxy contain a greater number of high energy events such as SN or Gamma-ray bursts (GRB). These authors also define an outer boundary given the metallicity gradient depending on the galactocentric distance, assuming that formation of Earth-like planets have dependence on metallicity. It is also important to take in account the migration of stars in the Galaxy. Some theoretical work has suggested that stars in the disk of spiral galaxies commonly migrate radially across significant distances in the disk, and this process can efficiently mix stars in all parts of the galactic disk (Roškar et al., 2011). These same authors conclude that radial mixing is crucial to understand the histories of stars in the Galactic history. This is a very important feature also for Galactic habitability.

The attempt to define a GHZ has been challenged in several occasions. It has been argued that it well can be that the entire galaxy is suitable for life (Prantzos, 2008), or that the formation of terrestrial planets has no special requirement of enhanced metallicity, and therefore can be widespread in the disk of the Galaxy (Buchhave et al., 2012). Or even that habitable zones are anthropocentrically defined and largely useless (for a review of these critics see Cirkovic, 2012). Nevertheless, the concept of GHZ can be of real practical use, leading research on habitability of exoplanets, or an important starting point for research of the search of Earth-like planets or for SETI targets.

There have been several approaches to study galactic habitability, being the Milky Way the main attraction. Lineweaver et al. (2004) present a simulation of formation and evolution of the Milky Way, constrained by observations, in order to obtain a space-time distribution for the prerequisites of life (Figure 1). Gowanlock et al. (2011) take a computational approach using Monte Carlo methods to model the Milky Way and explore its habitability, Vukotic & Cirkovic (2012) use probabilistic cellular automata to model Galactic habitability. However, the Galaxy is not the only one under research concerning habitability; Carigi et al. (2012) explore galactic habitability in M31 (Andromeda), while Suthar & McKay (2012) extend the concept of GHZ from spiral to elliptical galaxies. These several examples show the great variety on the approaches to explore galactic habitability. The basic assumptions included in the definition of GHZ are discussed in the following sections.

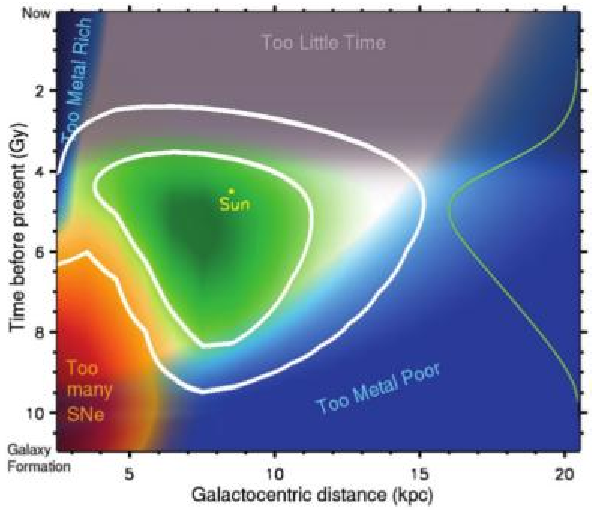


Figure 1: The GHZ of the Milky Way from Lineweaver et al. (2004). For this plot, the authors use almost the same ingredients like in our work. Such as SFR, Supernovae Events, Metallicity and sufficient time for biological evolution. The inner white contours encompass 68% of the origins of the stars with the highest potentials of being habitable by complex life today, while the outer encompass 95%. The green line is the age distribution of complex life.

2.2 Circumstellar Habitable Zone

The definitions of CHZ is strongly linked with Earth-like planets. It is defined as the region surrounding a star where an Earth-like planet can sustain liquid water on it's surface. Water needs a very definite range of temperature to remain liquid.[2] For the definition of the CHZ it is considered that the main source of energy for heating water comes from the central star. Now, the flux of energy varies with the distance to the star, so the energy received by the planet depends on this last variable. A distance too close to the star would lead to an increase of heating, raising the temperature of water beyond it's boiling point (Ward & Brownlee, 2000). On the other side, an increase of distance means a decrease of energy received by the planet from the host star. This would lead water to reach temperatures below its freezing point, transforming the planet in one covered by ice. Some calculations can be done in order to know with a certain degree of precision the inner and outer limits of the CHZ (Ward & Brownlee, 2000; Hanslmeier, 2009; Kasting et al., 1993). The position and wideness of CHZ depend on the type of star that holds a planet. Stars vary in temperature depending on their masses and chemical compositions. Fore example, Ward & Brownlee (2000) note that a star more luminous than the Sun will push their habitable zones farther, but can radiate more ultraviolet and live less time, while a star less massive will put the CHZ inside the tidal lock zone. This makes the topic of habitability of low mass stars quite controversial (Barnes et al., 2009; Tarter et al., 2007), even if they are far more numerous than more massive stars. The planet's albedo (Kasting et al., 1993), or even the kind of biosphere (McMahon et al., 2013) change the position of the CHZ. Earth is a very complex system and changing its position slightly nearer or slightly farther from the limits of the CHZ could lead rapidly to very hostile environments for our kind of life. For instance, an increase of temperature will increase the amount of water that converts in vapour. A hot atmosphere rich in water vapour limits the emission of thermal radiation to space, causing runaway warming (Goldblatt & Watson, 2012). This means, the limited emission of vapour increases more the temperature, evaporating more water, increasing more the temperature and

[2] Pressure is also a very important condition for having liquid water on the surface of a planet, see Vladilo et al. (2013).

so on. On the other side, a decrease of temperature transforms more water into ice. This can increase the planet's albedo, which decreases the absorption of energy, which lowers the temperature... and so on. For these reasons it is important also to take in consideration the eccentricity and stability of the orbit of the planet. A very eccentric orbit could lead the planet to enter and leave the CHZ several times in its orbit around the central star, leading to strong variations of planet's temperature. Also, the planet must remain in its orbit for the time enough to sustain life, so migrations can be potentially dangerous.

2.3 Earth-like planets

Earth has very special features on which life (as we know it) is strongly dependent. It is obviously in the CHZ around the Sun (a G2V star), but (perhaps) if necessary, this condition alone is not sufficient to make Earth habitable. The following list resumes features that are considered important, or even crucial, for the presence of life on Earth (Forget, 2012; Ward & Brownlee, 2000).

The importance of water

Without any exception known in the forms of life on planet Earth, two main ingredients are present. One of them are the carbon based molecules and the second is water, which in its liquid form is used as a solvent (Forget & Wordsworth, 2010). Water is made of two of the three most abundant elements in the universe, hydrogen being the most common element (75%) and oxygen the third one (almost 1%). Water is found on great abundance in interstellar space, in our Solar System, and on Earth.

The unique characteristics of liquid water, such as its large dipole moment, the capability to form hydrogen bonds, to stabilize macromolecules, to orient hydrophobic-hydrophilic molecules, to have its largest density in its liquid phase, etc., make difficult to think in an alternative solvent for supporting the chemistry of life (Barrow & Tipler, 1986; Henderson, 1914).

Rothschild & Mancinelli (2001) point that virtually regardless of the phyisical conditions in the environment, for the case of Earth, whenever there is liquid water, there is life. Liquid water is therefore generally considered as a prerequisite for the emergence of life on Earth. The case of water as a regulator of temperature is notable. It allows the presence of a great variety of ecosystems, habitats and climate conditions (Mottl et al., 2007).

Atmosphere

There would be no life on Earth without its atmosphere (Ward & Brownlee, 2000). Earth's atmosphere it's one of its main life-supporting properties. The Solar System shows a great variety of examples of atmospheres in rocky planets. For instance, Mercury has practically no atmosphere. Venus has a very dense CO_2 atmosphere, leading to a strong greenhouse effect. Mars, on the other hand, has also a CO_2 atmosphere with a very low density.

The relation between life in a planet and its atmosphere has been studied since a long time ago (Lovelock, 1980; Lovelock & Margulis, 1974). Life on Earth has an enormous influence on its atmosphere, and the evolution of atmosphere's chemical composition is so tightly related with the biological evolution to the point that today is highly controlled by biological processes. Otherwise it would be very hard to explain how the Earth's atmosphere has been out of thermodynamic and chemical equilibrium for the last millions of years (Lovelock & Margulis, 1974). With the advance on detection of extrasolar planets, the interest on atmospheres to search for biosignatures has increased on recent times (Seager, 2011; Kaltenegger et al., 2006). The protective role of atmosphere in shielding life from radiation and particles from space is also of great importance (Hanslmeier, 2009). Perhaps the most known example is the opacity of Earth's atmosphere to Gamma-rays and UV radiation.

However, not only life is important for the existence of maintenance of Earth's atmosphere. It is well known that Earth and other planets and celestial bodies, are susceptible to lose their atmospheres because of the action of different physical mechanisms. The existence of atmospheres and their chemical compositions (Table 1) are connected to the effect of integrated atmospheric escape. This means that the presence of the atmosphere is determined by the relationship between the stellar heating and the escape velocity of the planet (Catling & Zahnle, 2011). A planet must have the right mass in order to retain its atmosphere given the external conditions, such as distance to its host star, exposure to impacts or to high energetic astrophyiscal events. Also, the composition and maintenance of the atmosphere depends on the geological activity of the host planet via feed-back cycles as we will see in the the section below.

Geological activity

Several characteristics of Earth play important roles on its capacity for life maintenance. One of its planetary characteristics is a rich abundance of heavy elements (Table 2) in its core and sprinkled throughout its crust and mantle regions (Allègre et al., 1995), the other is amounts of carbon and other important life-forming elements. Earth has a very complicated structure. In previous sections we have pointed the importance of water and atmosphere on Earth. The third ingredient is the Earth's crust; the outermost layer of a rocky planet. One example of the interaction between the crust with the ocean is the sea water salinity, the result of millions of years of deposition of minerals from the crust into the ocean. Moreover, the distribution of continents plays an important role on the dynamics of ocean currents, regulating the temperature of the planet (Ward & Brownlee, 2000). The crust also provides the presence of highlands (where the only technologically intelligent species on Earth resides) and shallow water regions, ideal very complex habitat for photosynthetic species affecting the composition of Earth's atmosphere.

We have mentioned that the composition of the atmosphere is also affected by the interaction between the interior layers of Earth via volcanism and plate tectonics. Earth's interior is a potential source and sink for water and may interact with the surface and atmosphere reservoirs through volcanic activity and recycling via plate tectonics. A magnetic field also serves to protect an existing atmosphere against erosion by the solar wind and thus helps to stabilize the presence of water and habitability. Magnetic fields are generated in the cores of the terrestrial planets and thus habitability is linked to the evolution of the interior through magnetic field generation and volcanic activity. Moreover, volcanic activity has been thought as a possible scenario for the formation of life, if it was initially chemoautotrophic (Spohn et al., 2012).

Table 1: Earth's atmosphere chemical composition.

Element	Mole %
N_2	78.084%
O_2	20.948%
Ar	0.934%
H_2O	0.004-4%
CO_2	0.0385%
Ne	0.0018%
He	0.0005%
CH_4	0.0002%

Table 2: Earth's chemical composition (Morgan & Anders, 1980).

Element	Abundance
Fe	32.07%
O	30.12%
Si	15.82%
Mg	13.90%
S	2.92%
Ni	1.82%
Ca	1.54%
Al	1.41%

Dynamical stability

A very important role concerning habitability is played by the characteristics of Earth's orbit. It's long-term stability, small eccentricity, the stability of its rotation period and rotation axis inclination are fundamental to achieve a long term site for the maintenance of life. The presence of a large Moon at the correct distance controls not only the stability of the axis but also the climate of our planet (Laskar et al., 1993).

The presence of Jupiter as a shield against frequent asteroid or comet impacts (Ward & Brownlee, 2000; Horner et al., 2010) is also considered an important factor for the maintenance of life. It is not only important the amount of time that the central star remains in the main sequence, but also the long term stability of the planetary system (Laskar, 2012). We have seen the importance of water for life. The origin of Earth's water is still mysterious, but it has been thought that three possible sources of water are; water-containing rocky planetesimals like carbonaceous chondrites (CCs), icy planetesimals like comets, and the solar nebula (Genda & Ikoma, 2008). All these processes depend on the dynamics of the planetary system.

Finally, the origin of life itself can depend on the cosmic environment conditions. Some authors have proposed that life on Earth, can have an extraterrestrial origin (Crick & Orgel, 1973; Hoyle & Wickramasinghe, 1980). So, the presence of the elements needed for life or possible sites for interchanging material or even life forms, like the presence of Mars (Schulze-Makuch et al., 2008) are usually taken in consideration in the search for habitability.

Hazardous phenomena

The presence of water, plate tectonics, atmosphere characteristics, abundance of heavy elements, volcanic activity, dynamical stability, etc. are important prerequisites for habitability. However, this same factors also can play a hazardous role for living systems. If it is true that we require a minimum metallicity to build a planet, it has been argued that a very large metallicity can trigger the formation of more than one Jupiter-like planet in the planetary system, leading to planetary migrations (Gonzalez, 2005) and affecting the dynamical stability. Asteroid, comet and meteor impacts can bring the material necessary to form life but also intervene in life evolution. It is almost universally accepted that the extinction of dinosaurs was caused by one of this phenomena. We have pointed the importance of geological activity for sustaining life, but is also considered a threat to it. The global damage of atmosphere caused by volcanic activity will have major effects on planets climate (Bostrom & Cirkovic, 2008). A "volcanic-winter" scenario could have effects on photosynthetic organisms and affect agriculture. The problem with this kind of risks lies in its contingency. There are not accurately known timescales for the ocurrence of this catastrophic events (see Table 3). Finally, we must consider the threats to life caused by life itself. In recent years, anthropogenic climate change has become the poster child of global threats. Bostrom & Cirkovic (2008) offer an extensive monograph of global risks, including anthropogenic climate change, pandemics, wars or even "technology out of control" scenarios.

2.4 Biological and Astrophysical Timescales

The time factor is also an important one concerning the galactic habitability. The evolution of complex life requires time. So, it is important not just where in the Galaxy conditions are suitable to life, but also when do these conditions exist and how much time does they remain so that life can reach this complexity. This implies a relation between biological and astrophysical time scales. It is not known from first principles how much time is required for life to reach a significant level of complexity. Moreover, there is not yet a clear definition of complexity. However, as Ćirković (2012) points, the lack of a theory of complexity does not preclude our intuitive grasp of it.

2.4.1 Carter's Argument

The so-called Carter's argument (Carter, 1983) developed also by Barrow & Tipler (1986) states that there is no (a priori) relation between astrophysical ($\tau_\star$) and biological time scales (τ_b). It follows that life, and in particular intelligent or complex life, can arise at random epochs with respect of the characteristic time scale of the cosmic environment where it occurs. For instance, the time that a star remains in the main sequence. We can have either one of the three following scenarios: 1)$\tau_b \gg \tau_\star$, 2) $\tau_b \ll \tau_\star$ or 3) $\tau_b \simeq \tau_\star$. The third scenario is disregarded given that, as there is no co-relation between τ_b and $\tau_\star$, the occurrence of this scenario is quite improbable. The second scenario is also disregarded, while it would be quite hard to explain why the only example of life we know shows that $\tau_\star \simeq \tau_b$. Then, Carter argues that the most probable scenario we should expect is the first one, and the case of life on Earth would be a observational or anthropic bias, and that complex life is indeed rare in the Galaxy. There are several ways of undermining Carter's argument (see for example Cirkovic & Vukotic, 2009; and references therein), but its force is due to the fact that it calls attention to the very important point that we must know, or at least estimate, biological as well as astrophysical time scales if we would like to speak about habitability from a cosmic perspective. Now, the problem of determining the time scales on astrophysics is more or less solved. It is possible to derive them from the laws of physics in combination with astronomical observations. However, the biological time scales are still a problem and this is because we still lack from a theory of life, and that the observations are biased by our own existence. The main ignorance of biological timescales arise from the still mysterious problems of biology: 1) The origin of life and 2) life's evolution. In recent times it has become more important to notice that these processes are strongly dependent on the changes on Earth's conditions, and as Earth is not a closed box, the astrophysical phenomena that affects it can lead to correlations between biological processes and its cosmic environment (Dragićević & Ćirković, 2003). We have seen previously the potential risks for life on Earth or on an earth-like planet. The risks have different chances of occurrence according to the position of Earth in space and time. Table 3 summarizes these potential risks and shows (when known) their time-scales.

Benefits or threats for evolution?

We have seen some of the most important ingredients taken in consideration when speaking of habitability from a cosmic perspective. However, we must notice that it is neither too much nor too less, of this phenomena to occur to have the kind of evolutionary history we have seen to occur in our planet. For example, we have seen that SNe are classically considered as hazardous for life. On the other hand, without some SNe happening in the past, our Universe will have never reach the metallicity we observe today, and therefore, we could not exist. Another example is that of asteroids or comets bombarding the planet. On one side they can cause extinctions, but the role of this extinctions can enhance evolution, opening previously occupied ecological niches to new species. This situation makes to wonder again how does the relation between astrophysical an biological timescales relate. Are, for example, asteroid bombardments or SN explosions making the rise of a technologically intelligent species to be slower or faster? (we don't claim that this event must happen, but given that we are such kind of a species, and therefore we know that this can occur, we have the right of doing such a question). As much of the questions raised in astrobiology we still are searching for the answer...

Table 3: Possible catastrophic occurrences of cosmic origin at various scales (Dragićević & Ćirković, 2003).

Type	**Catastrophic event**	**Time scale (yrs)**
Cosmological	Recollapse of closed universe	$> 10^{11}$
Cosmological	Vacuum phase transition	???
Cosmological	Horizon formation & heat death	10^{10-15}
Galactic	Recurrent nuclear activity	10^{7-8}
Galactic	Gamma-ray Busts	10^{7-8}
Galactic disk/local ISM	Supernovae	10^{8-9}
Galactic disk/local ISM	Encounters with stars or GMC's	10^{7-9}
Solar System	End of Sun's (Star's) life	6 x 10^9
Solar System	Cometary or asteroidal bombardment	3 x 10^7
Solar System	Secular changes in luminosity	1.1 x 10^9
Solar System	Long term changes of orbits	10^8 (?)
Planetary	Moon-related (tides, sea level)	???
Planetary	Atmosphere changes	10^9
Planetary	Geophysical effects (volcanism, tectonics, etc.)	???

3 Galactic Habitability

In previous sections, we have talked about the conditions for life that are usually taken in account in astrobiological research. In is important to notice that different concepts of habitability are taking in consideration different scales, of space and time, as shown in Table 3. In this section, we present the main features included in the definition of Galactic habitability for our study; Metallicity, transient energetic explosions and stellar density.

3.1 Metallicity

Metallicity plays a major role on assessing the habitability of particular locations of the galaxy. It gives a measure of the concentration of elements heavier than H and He, that we know are mostly formed on star interiors and supernovae. Therefore, it depends directly on the history of the material that forms stars. After formation, metals are then distributed and mixed in the interstellar medium by different means. Thus, metallicity increases with time, and if the habitability of galaxies have dependence on metallicity, the habitability must also change in time. We have seen in Tables 1 and 2 that the chemical compositions of the Earth and its atmosphere are mainly formed of metals.

From the definition of GHZ, we need that the maintenance of Earth-like planets is possible in such regions of the galaxies. So it is important to take in account also the migration of stars in the Galaxy from their birth place to understand the mixing of stars in stellar environments (Roškar et al., 2011). It has been suggested that there exist a correlation between the metallicity of a star and the presence of planets around it (Gonzalez, 1997; Ramírez et al., 2010; Schlaufman & Laughlin, 2011). As far as it is known, this relation holds for large planets, and to claim that this holds true also for Earth-like planets is an extrapolation. However, the formation of a rocky core in such large planets depend on the presence of refractory elements, and that may be needed for the formation of Earth-like planets as well (see Suthar & McKay (2012) and references therein). High metallicities can lead to greater formation of giant planets

(Gonzalez, 2005). Gravitational perturbations of comets can cause frequent impacts on habitable Earth-like planets.

3.2 Supernovae and Gamma-Ray Bursts

Gonzalez et al. (2001) consider that transient radiation events such as SN and GRB affect galactic habitability. These two are events that occur at the end of the stellar evolution of stars with high masses (more than 8 $M_{\odot}$). Supernova explosions can rival the luminosity of a whole galaxy for months, and it is estimated that in our galaxy they occur at rates of 1.98-2.40 x 10^{-2} yr^{-1} for the last Gyr (Gowanlock et al., 2011). When a supernova explodes, it emits radiation capable of wiping out the atmosphere of a nearby planet and sterilizing the life that may lie on its surface (Carigi et al., 2012). It can be assumed that they are potentially dangerous at a distance of 10 Ly. Moreover, 8 $M_{\odot}$ stars have very short lifetimes and it is more likely that they occur near star forming regions (Ulmschneider, 2003).

Much less frequent, but far more energetic events are GRBs. If still mysterious, there has been drawn a general picture of the nature of GRBs. Some general reviews are given by Dar & de Rújula (2004); Piran (2000); Gehrels et al. (2002); Mészáros (2013). GRBs are considered the most energetic explosions in the Universe (Mészáros, 2001; Bloom et al., 2009). It is believed that GRB have as progenitors the terminal collapse of super-massive objects, often called "hypernova", or mergers of compact objects such as neutron stars in binary systems. It is believed that they emit rapidly in form of jets with luminosities of around 10^{44} watts (Gehrels et al., 2002). They are relatively rare in the local Universe, being most of them of cosmological origin. Melott et al. (2004) argue that a GRB situated at a distance of 3 kpc from Earth constitutes a serious threat to it's atmosphere. These authors also calculate that such an event occurs at a rate of 6 x 10^{-9} yr^{-1}, in other words about 170 My between events within 3 kpc.

As GRBs are beamed phenomena, to be hazardous to a planet, it should lie within the angle of the jet. A GRB within a few parsecs that is directed at the Earth will impact one hemisphere of the planet with a short, but intense blast of high-energy photons. In the case of Earth, the atmosphere is opaque to this kind of radiation, and such an event would have not sudden, but long term effects (Bloom et al., 2009). It has been argued (Melott et al., 2004), that the late Ordovician mass extintion could have been caused by a GRB. As Annis (1999); Vukotic & Cirkovic (2007); Cirkovic & Vukotic (2009), have considered, and we will consider as well, GRB can play a role in the history of life in the Universe.

3.3 Stellar Density

Gonzalez (2005) argues that low stellar density seems to be the preferred formation environment of planets. There exist different processes that can perturb debris disks, such as interaction between planets (Batygin et al., 2011), secular perturbations by giant planets (Mustill & Wyatt, 2009), the presence of a stellar companion in a binary system (Paardekooper et al., 2012), or migrating planets (Walsh et al., 2011). All this processes affect the habitability of a planet by leading asteroidal or cometary bombardments, taking planets from the CHZ, or by planetary collisions. The most violent of these kind of processes is stellar interactions (Jiménez-Torres & Pichardo, 2008), which can rapidly change parameters of planets and minor bodies. This processes occur with more probability in regions where stellar density is high, and the number of interactions can partially or totally destroy planetary systems by breaking the gravitational link with the host star (Jiménez-Torres et al., 2013).

Galaxies present different environments concerning stellar density. Jiménez-Torres et al. (2013), present a study of habitabiliy for different galactic environments taking a dynamical approach of stellar interactions. These authors divide the environments in the nuclear cluster, globular clusters, young and old open clusters, the galactic center and the solar neighbourhood. Taking in account the densities and velocity dispersions, they estimate the number of encounters between stars, arguing that the stars that suffer less than one encounter are candidates for being habitable, from the stellar dynamics point of view. This includes both young and old open clusters and the solar neighbourhood, while excludes the rest of the studied environments to be considered habitable (Figure 2).

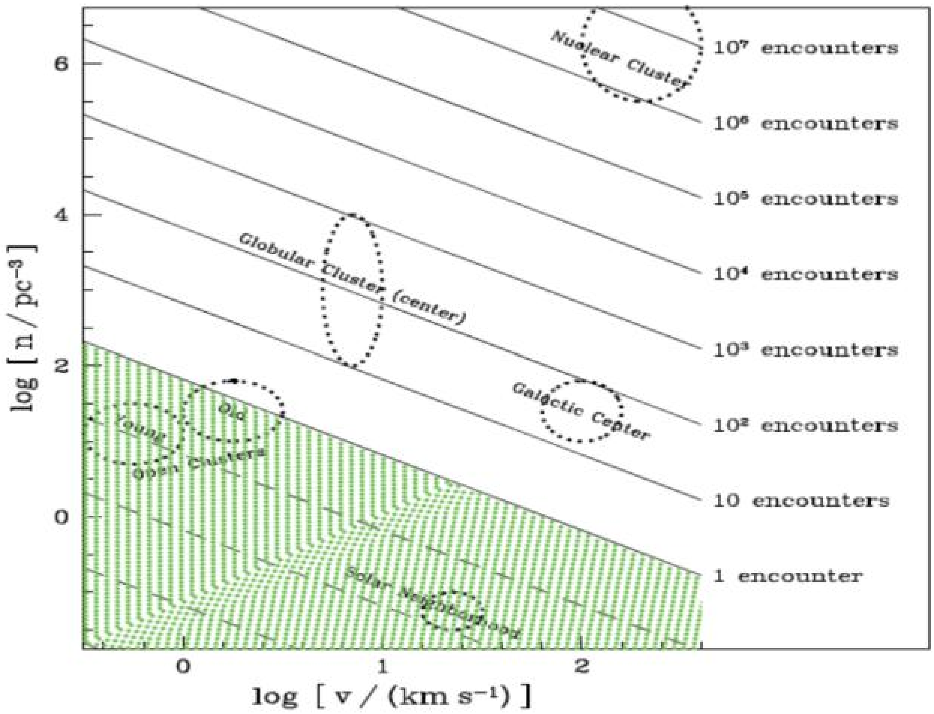


Figure 2: Log-log diagram of density vs. velocity dispersion in different Galactic environments from Jiménez-Torres et al. (2013), the green shadow covers the galactic regions where less than one stellar encounter occurred in its history; these regions are potentially habitable from the point of view of stellar dynamics of encounters.

4 Numerical Simulations

Numerical simulations play nowadays a very important role on astrophysical research (Springel, 2005; Steinhauser, 2010). In the case of astrobiology, it is now very difficult to obtain direct observations of the activity of life in the Universe beyond our own Solar System. As we have seen, in recent years the approach to astrobiological research has been mostly theoretical. However, works like those presented by Vukotic & Cirkovic (2008), Roškar et al. (2011), Vukotić & Ćirković (2012), Gowanlock et al. (2011), Forgan (2009), Cotta & Morales (2009), etc. use a computational approach on their studies.

The aim of this thesis is to use the outputs of a N-body simulation of the dynamics and evolution of a galaxy in order to analyse its habitability under different scenarios. For that it is necessary to get a simulation of the evolution of a disk galaxy and use the same simulation to check how the habitability changes just due to the different criteria of habitability and not to the dynamics of the galaxy itself.

4.1 The GADGET-2 simulation

GADGET-2 (GAlaxies with Dark matter and Gas intEracT) is a freely available code for cosmological N-body/Smoothed particle hydrodynamics (SPH) simulations on massively parallel computers with distributed memory. It was developed by Volker Springel in 1998, being the 2.0 version released to public in 2005 (Springel, 2005). The code computes gravitational forces with a hierarchical three algorithm and represents fluids by means of SPH. It has the virtue of being used either for studies of isolated systems or simulations that include cosmological expansion, both with or without periodic boundary conditions. In the code, the evolution of a self-gravitating collisionless N-body system is followed, and can include also gas dynamics.

Following the model presented in Springel & Hernquist (2003), a small-scale simulation of an individual star-forming disk galaxy was performed. The halo was set up in isolation following the approach taken by Navarro et al.

(1997), with the gas and dark matter initially in virial equilibrium, known as the Navarro, Frenk & White (NFW) halo. The conventional parameter in this kind of model (Binney & Tremaine, 2008) is known as r_{200}, which is the distance from the center of the halo at which the mean density is 200 times the cosmological critical density ρ_c. The mass interior $M_{200} = 200\frac{4}{3}\pi r_{200}^3 \rho_c$ was chosen to be $M_{200} = 10^{12} M_\odot$, being baryonic 10% of the mass. The concentration of the halo $c \equiv r_{200}/a$, being a the core radius where the surface brightness has fallen to half its central value, was chosen to be c = 9.0. To describe the initial angular momentum J of the halo, the spin parameter $\lambda = \frac{J|E|^{1/2}}{GM_{vir}^{5/2}}$ is usually used. To produce a large disk, a value of the spin parameter $\lambda = 0.1$ was chosen. Initially 10^6 gas particles were set, with a mass resolution of $10^5 M_\odot$. After a 10 billion years simulation, we have 1055078 stellar particles, and 488158 gas particles. We took 100 snapshots of the simulation, for which time steps are 100 million years. The simulation took ∼1.3 days on a computer cluster on 128 cores. The following characteristics of the particles were used in our analysis:

- Position.
- Velocity.
- Particle Type (gas or stellar).
- Particle identity.
- Star formation rate (only for gas particles).
- Metallicity.

4.2 Defining habitability in our simulation

We have seen in previous sections the potential risk factors and the requirements for the habitability of an earth-like planet. It is important to notice that the original GADGET-2 simulation of the galaxy was not intended to give relevant information concerning the habitability of the galaxy. It doesn't contain, for instance, the presence of supernovae or GRB. It also gives no information about the presence or absence of planets around the stellar particles or if these planets are in the CHZ and so on. The mass resolution is not in the stellar level and the galaxy is simulated in isolation, which results in smooth star formation rate that is unrealistic. However, we think that the mass resolution is sufficient to track global trends in population mixing (Roškar et al., 2011) that are of concern on assessing boundaries of the GHZ. Using the values of the outputs of the simulation, we can adjust our habitability criteria according to multiple scenarios taken by different authors in the scientific literature. To our knowledge, this kind of analysis, using galactic dynamics to explore habitability, has been never done before. In the following parts we will present the criteria selected for defining habitability.

4.2.1 Metallicity criteria

The first basic requirement for our habitability criteria is the presence of stars. From all the possible kinds of particles present in our N-body simulations just stellar particles will be considered candidates for habitability. Not enough, just stellar particles above a threshold metallicity are called "candidate particles". The simulation provides the information of when and where this kind of particles are born and how they move through the galaxy. All this factors will influence their destiny in terms of habitability.

4.2.2 The astrobiological clock criteria

Once we have in the simulation the presence of such candidates, we set on what we will call the "astrobiological clock". Then, we can count the age of the candidate, measured on the number of snapshots passed since its birth. Whenever one of the reset events explained below affect our candidate particle, we reset its astrobiological clock, and start counting its age again. We define an "evolutionary time" required to achieve a certain level of complexity. We will call a "habitable particle" to all those candidate particles who have reached the evolutionary time without being affected by any of the habitability hazardous events, described in the following parts. Once a particle has reached the status of habitable particle, its astrobiological clock cannot be reset. For each snapshot of the simulation our analysis provide the number of habitable particles obtained under the different scenarios, as well as their positions in the galaxy.

4.2.3 Reset events

Energetic explosions criteria

To keep track of our particles, we define a grid in our simulation consisting on boxes of definite sizes covering the whole volume of our simulated galaxy and stays at rest during the whole simulation. Each cell of the grid is defined by the coordinates of its center (x,y,z). The cells have the following dimensions:

Resolution X = 1 kpc, resolution Y = 1 kpc, resolution Z = 0.32 kpc.

We have seen that supernovae events occur nearby places of high SFR. This is a parameter that just can be obtained from gas particles. We will set a minimum value of SFR above which we will consider that significant amount of SN explosions occur to affect habitability. This means that we will assume that SN explosions occur in gas particles with certain SFR. We will count the number of SNe for each snapshot of the simulation, that are in each of the cells of our grid. We will do this by calculating the corresponding cell coordinates using the position information of the stellar and gas particles. We will then reset the astrobiological clock of each of our candidate particles whenever they are in a grid with a high number of gas particles with high SFR, where we assume that SNe occur.

We have mentioned that our simulation is a discrete one, and the time between snapshots is 10^8 years. In this time our particles change position, and they can cross cells that can reset the astrobiological clock. We track the positions of the particle between two consecutive snapshots, and assume that the particle follows a straight line when it changes position between snapshots. We then calculate which grid cells have been crossed by this line and check whether the cells crossed reset or not the astrobiological clock.

As said, the origin of GRB is still under debate, but it is mostly accepted that the progenitors of this high energetic astrophysical phenomena are high mass stellar objects on advanced stages of their evolution. This means that the trend of GRB must follow the trend of SFR. We obtained from the simulation a SFR history (Figure 3) and adjust the time distribution of GRB to this history. We do this by obtaining a cumulative function for the SFR and normalize it to the numerical value of 100 (Figure 4). Following this function, we distribute a definite number n of GRB to occur during the evolution time of the galaxy, generating n random numbers between 0 and 100 and finding to which value of the horizontal axis our cumulative function corresponds. We consider the location of the GRB to occur randomly across the whole disk of the galaxy wherever we have gas particles. The direction of the jets of the GRB occur also in a random direction. We consider that any stellar particle that is located within the cone of the jet to be affected by the GRB (within a certain distance, with the possibility of changing this value, as well as the opening angle of the cone). Once we have generated the coordinates of the GRB, we generate its direction by choosing randomly from a full spatial angle. For each candidate particle we test whether or not its distance from the GRB origin is smaller that the predefined GRB radius of influence. If it is smaller, we define a vector $\vec{b}$ joining the GRB origin with the coordinates of the stellar particle. Whe then calculate the angle θ formed by this vector and the direction of the jet of the GRB with the formula:

$$\theta = acos\frac{\vec{a}\cdot\vec{b}}{|\vec{a}||\vec{b}|}, \tag{1}$$

where $\vec{a}$ is the vector defined by the direction of the GRB jet, and θ is the angle between vectors $\vec{b}$ and $\vec{a}$. We then compare θ with the opening angle of the jet, which we have previously defined. Whenever a candidate particle is inside the cone, the astrobiological clock will be reset.

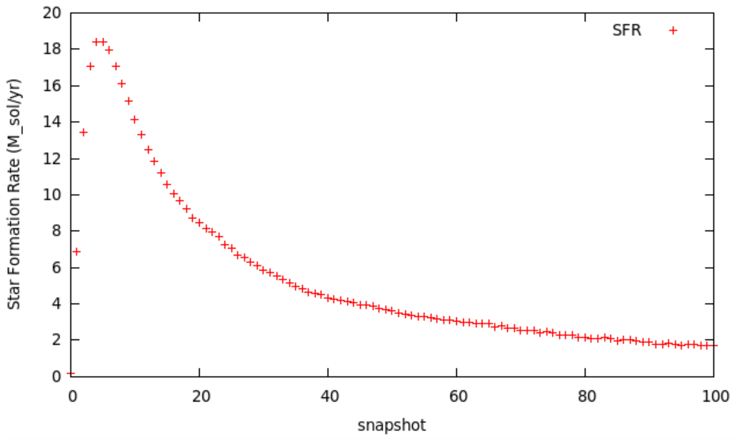


Figure 3: Star formation history of our simulated galaxy used to obtain the distribution of GRB in the simulation.

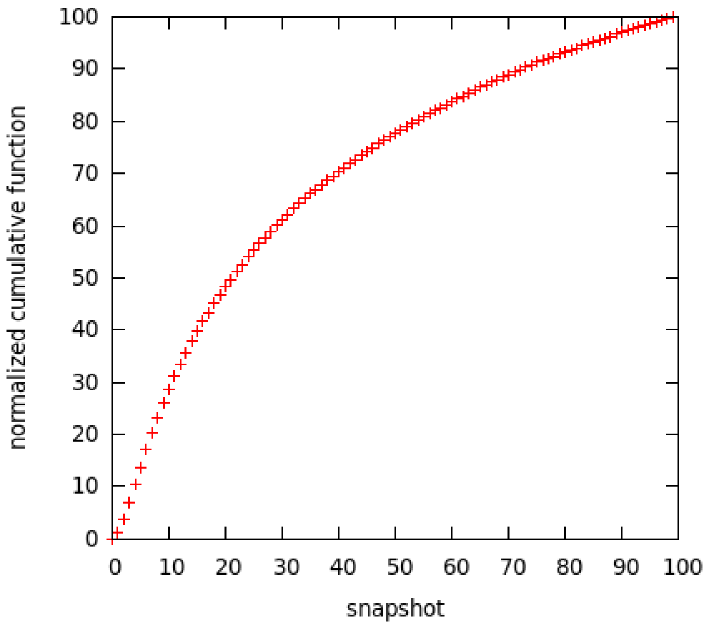


Figure 4: Cumulative function of the SFR history of our simulated galaxy.

Stellar density criteria

Regarding that a high density of stars can be considered a threat to the development of complex life in an Earth-like planet, we will use again the grid defined in the previous section. In this case, we count the number of stellar particles inside each of the cells forming the grid for each snapshot of the simulation and set a number of stellar particles per cell to be considered as dangerous for life. So, the astrobiological clock will be reset when a candidate particle is in a cell too crowded of stars in the correspondent snapshot, testing different values in different scenarios. We also track the particle positions between snapshots, in the same way explained in the previous section and reset the astrobiological clock when the conditions of habitability are violated.

5 Results

The following subsections show the different scenarios of habitability taken in consideration. Scenarios 1–4 model each of the habitability factors separately, while in Scenario 5 all factors are modelled in a synergistic manner. The first one considers just the basic requirements for building complex life (metallicity and time) and represent an ideal scenario, the most life friendly galaxy without any reset event, while the last one considers the case when all the risk factors play a role and can represent the most realistic one. The percentage of habitable particles is taken considering as 100% the total number of stellar particles at the end of the simulation. In scenarios 1-4 a large range of free parameters of our model are explored, while in scenario 5 we show a more realistic model (scenario 5.2). However, we also modelled different values of free parameters to test the resulting behaviour of galactic habitability when all risk factors are working together. With the exception of the first scenario, the time for achieving the status of habitable particle and the minimum metallicity required, remain constant at 40 snapshots and solar metallicity, respectively, unless a change in these values is specified.

5.1 Scenario 1. Metallicity and time

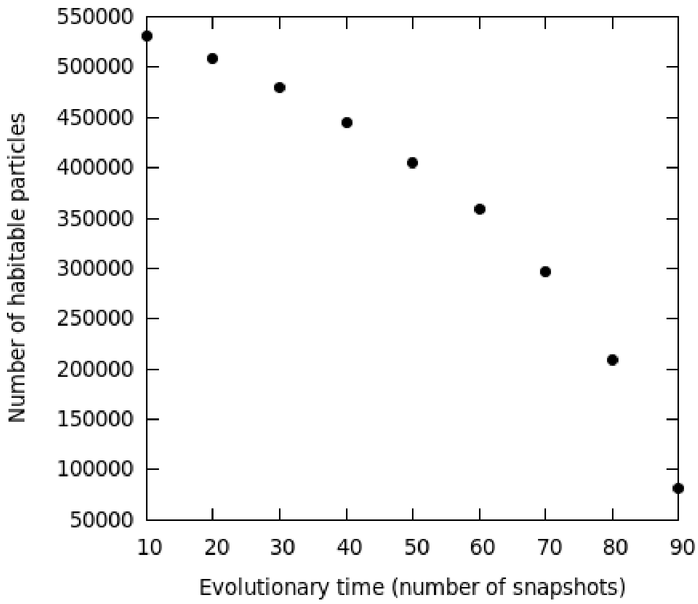
This scenario will play a very important role in our analysis, given that it will provide us with the greatest number of habitable particles that can be obtained taking in consideration just the two more basic requirements for the development of complex life; enough time and enough metallicity. In scenarios 1.6, 1.7 and 1.8 we discard as candidate particles those that have metallicity values greater than the one indicated as "Max" in column 2 of Table 4. In general terms, we can say that the habitability of this scenarios just follows the evolution of metallicity in the galaxy. Therefore the most habitable particles are found in the central regions of the galaxy, even when we take an upper metallicity criteria for disregarding habitable particles, as shown in Figure 9.

If it is true that the spatial distribution remain on the central regions of the galaxy. The number of habitable particles at the end of the simulation (Figure 5-a. To plot this, we use more values than those shown in Table 4) and the time extension of the distribution of habitable particles (Figure 7) are affected by the change on the evolutionary time to achieve complexity. Being the greater numbers for small metallicity values and short time for achieve complexity.

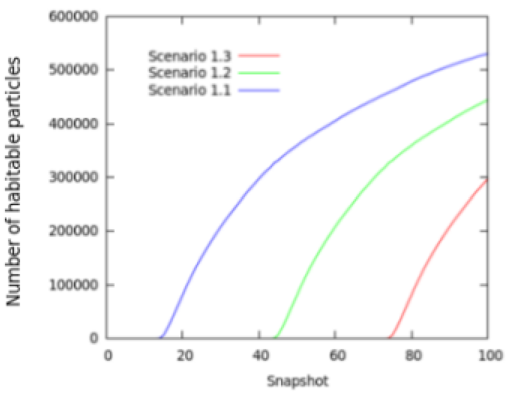
As a general trend, the change of minimum metallicity required to start the astrobiological clock affects mainly the number of habitable particles at the end of the simulation (Figure 6-a), but not much the spatial and time distribution of the habitable particles (Figures 8 and 9).

Table 4: The different scenarios used to test different outputs depending on the change of the values of minimum metallicity and time required to develop complex life.

Scenario	**Metallicity [Fe/H] (dex) Min — Max**	Time-scale (Number of snapshots)	Percentage of habitable particles
1.1	0.0 — NO	10	50%
1.2	0.0 — NO	40	42%
1.3	0.0 — NO	70	28%
1.4	-0.5 — NO	40	67%
1.5	-1.0 — NO	40	77%
1.6	0.0 — 0.5	40	32%
1.7	0.0 — 1.0	40	42%
1.8	0.0 — 0.7	40	39%

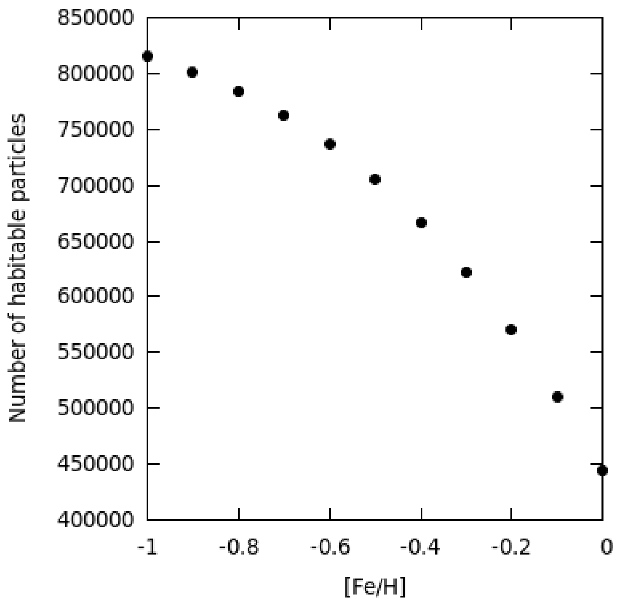


(a) Number of habitable particles (with solar metallicity) for snapshot 100 vs. evolutionary time chosen to achieve habitability

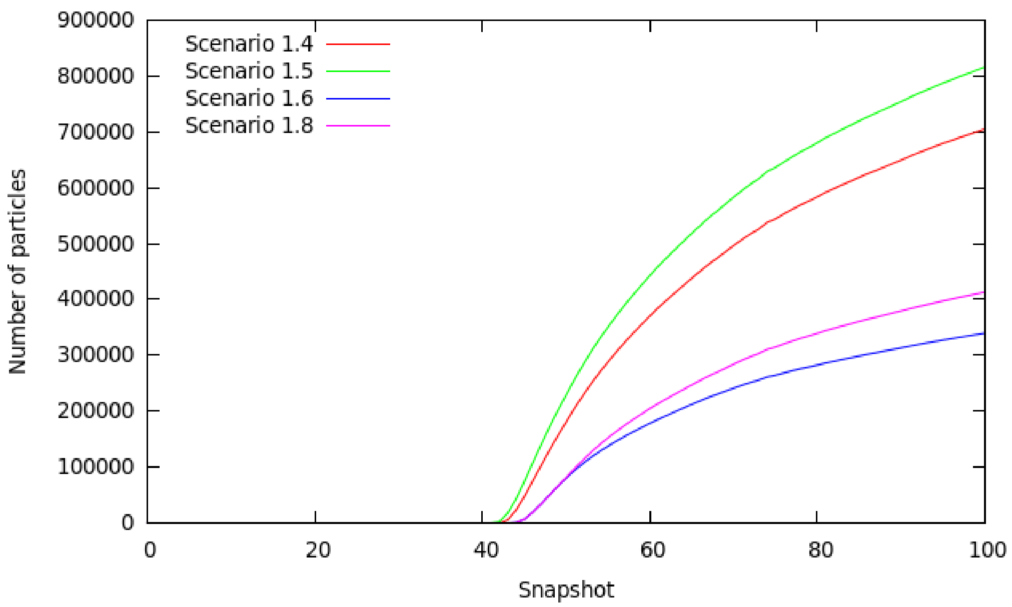


(b) Cumulative plot of habitable partilcles vs. time for scenarios 1.1, 1.2 and 1.3

Figure 5: Number of habitable particles: time-scale criteria.



(a) Dependence of number of habitable particles for snapshot 100 on minimum metallicity required to be considered a candidate particle in our model.



(b) Number of habitable particles (cumulative plot) for each snapshot for the given values of time and metallicity to achieve habitability.

Figure 6: Number of habitable particles: metallicity criteria.

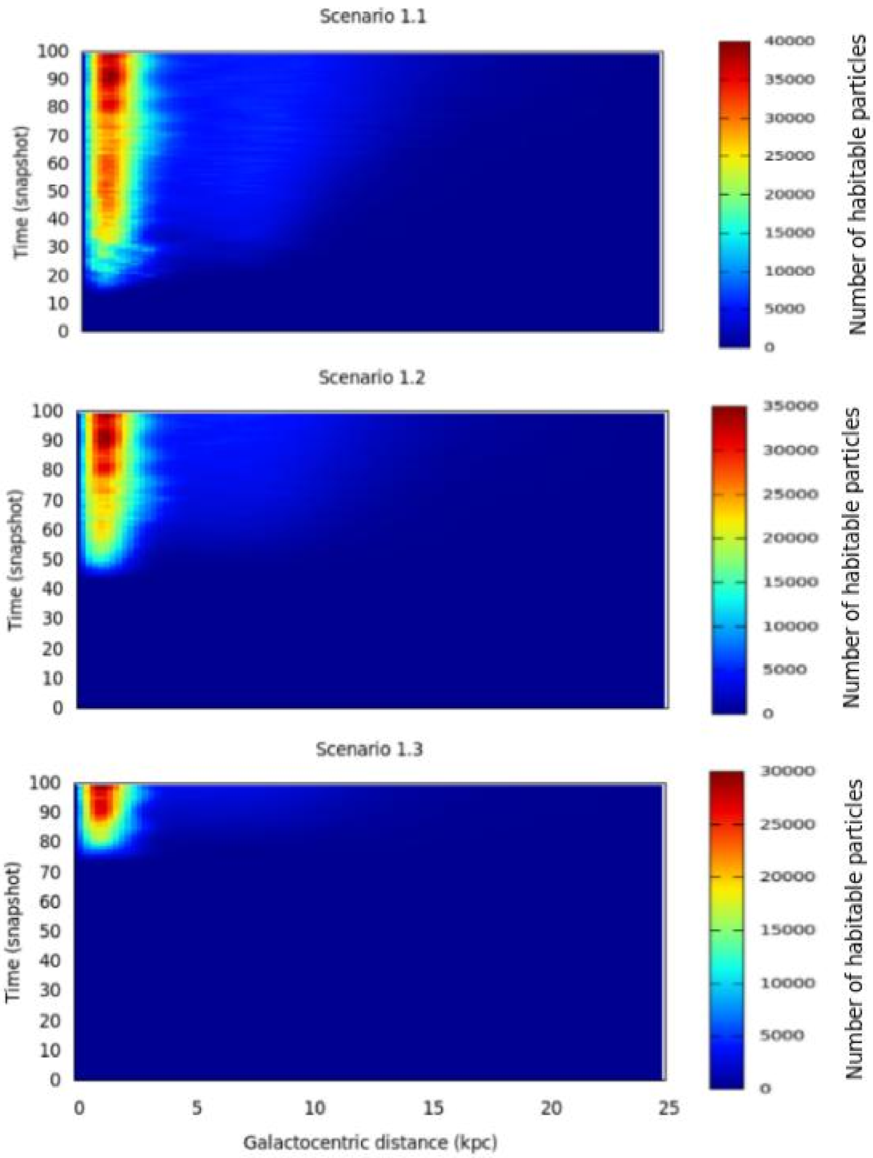


Figure 7: Distribution if habitable particles for scenarios 1.1, 1.2 and 1.3.

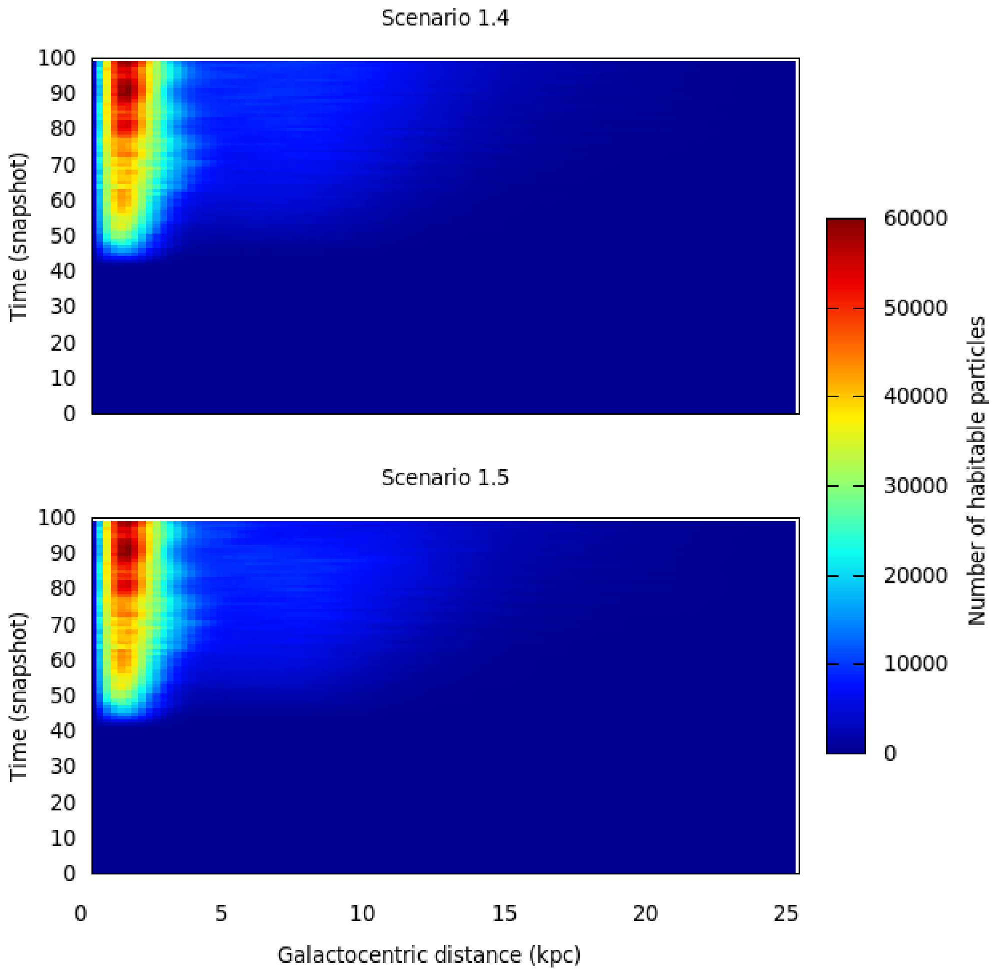


Figure 8: Distribution of habitable particles for scenarios 1.4 and 1.5.

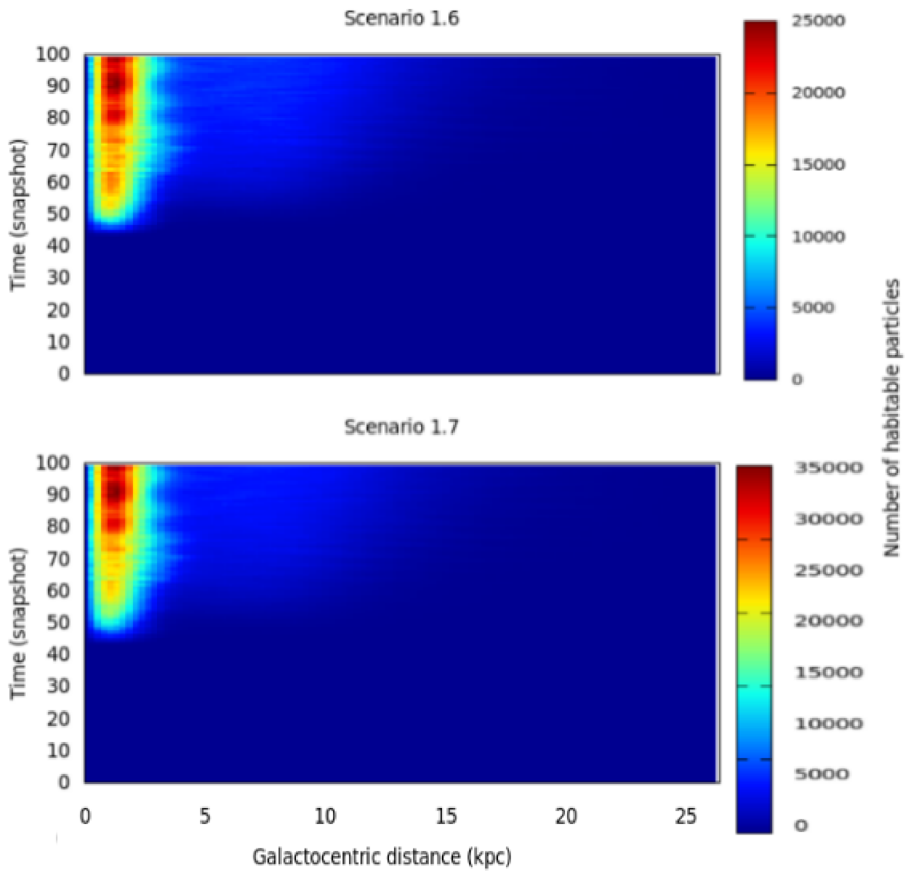


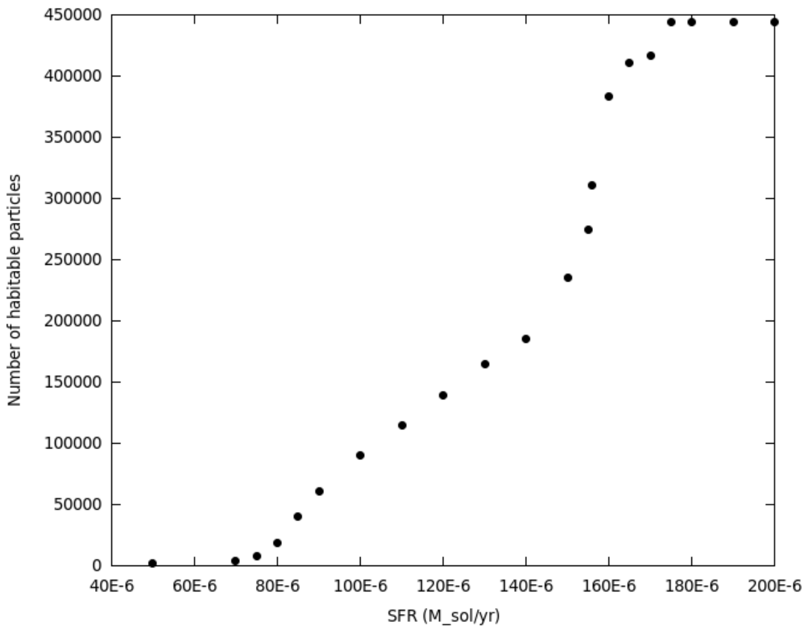
Figure 9: Habitable zones for scenarios 1.6 and 1.7.

5.2 Scenario 2. Supernovae

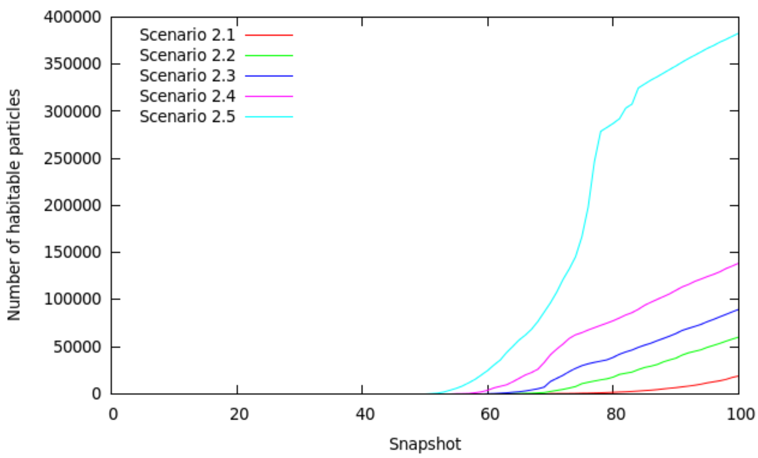
We have argued in previous sections that SNe might be very important phenomena controlling the behaviour of galactic habitability. It is a notable feature from this scenarios that when we plug in the SNe explosions in our simulation the distribution of habitable particles is shifted outwards, has a significantly smaller number of habitable stars and becomes much wider. We can see a general trend for scenarios 2.1 to 2.4, where habitable particles *avoid* the central regions of the galaxy (Figure 11 and upper panel Fig. 12). This induces the presence of an *inner bound* of the galactic habitable zone. The case of scenario 2.5 (Fig 12, lower panel) is a bit different and resembles more the case of the scenarios of previous section. This is because the chosen supernovae threshold is so high, that the galaxy is out of significant number of SNe explosions very soon, and then the habitability follows just the growth of metallicity. In figure 10 the number of habitable particles at end of simulation for different values of SFR are shown, including values that do not appear in Table 5.

Table 5: Different Star formation rates of gas particles were chosen to consider that a SN explosion occurs.

Scenario	**SFR** ($M_{\odot}$/yr)	**Habitable particles**
2.1	0.00008	1.79%
2.2	0.00009	5.70%
2.3	0.00010	8.49%
2.4	0.00012	13.14%
2.5	0.00016	36.31%



(a) Dependence on the number of habitable particles at snapshot 100 for different values of SFR for SNe to occur in a gas particle of the simulation.



(b) Cumulative plots for number of habitable particles on different scenarios of the SN risk.

Figure 10: Habitability dependence on star formation rate for supernovae scenarios.

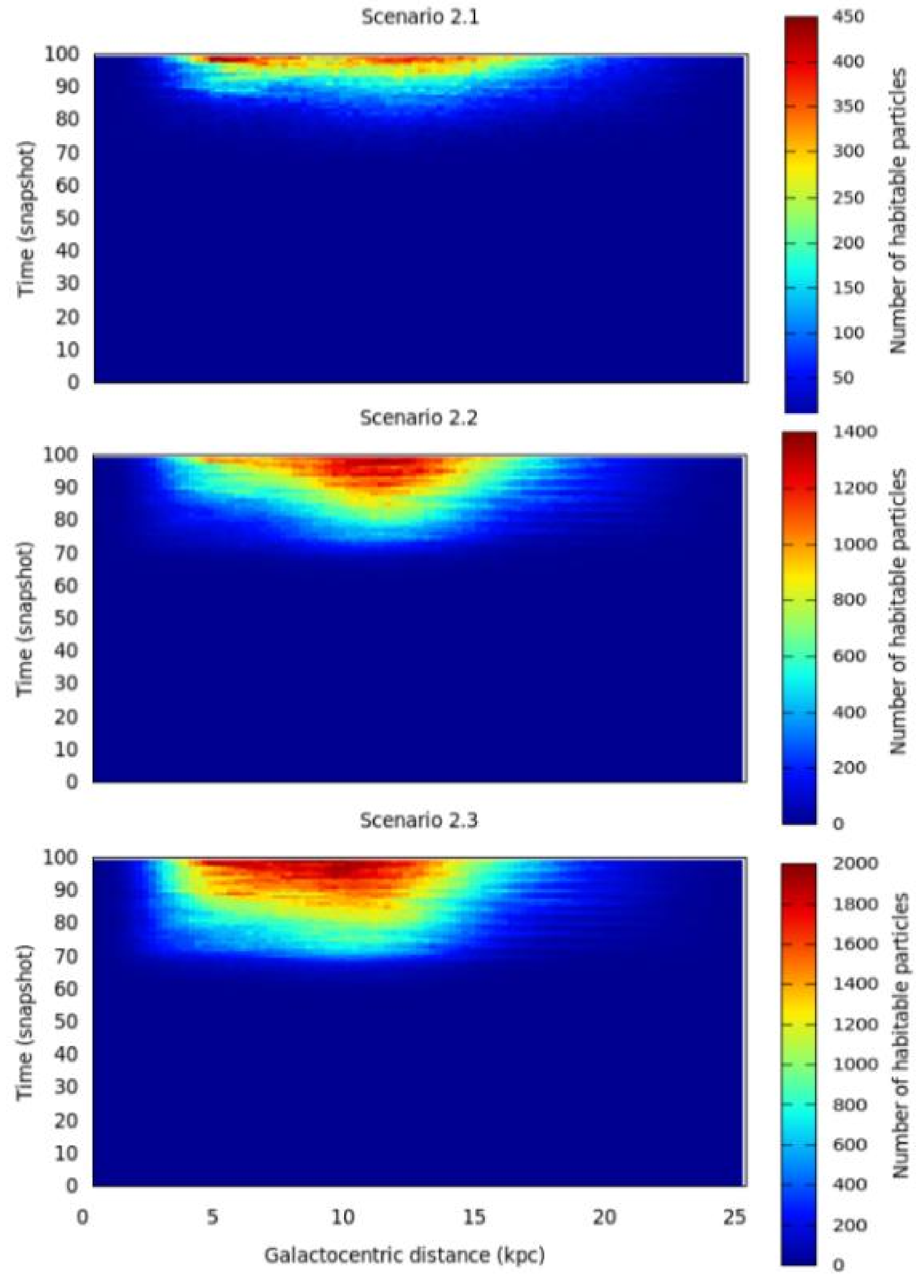


Figure 11: Distribution of habitable particles for scenarios 2.1, 2.2 and 2.3. The presence of Supernovae induces an *inner bound* for the GHZ.

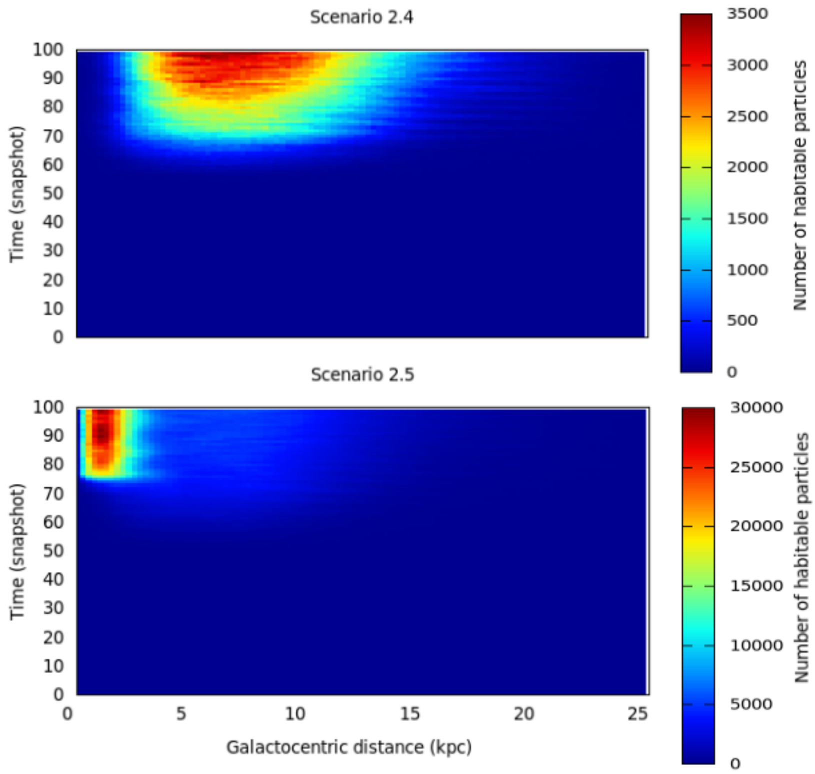


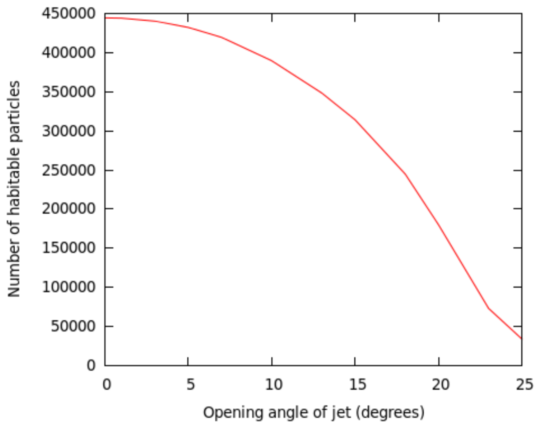
Figure 12: Distribution of habitable particles for scenarios 2.4 and 2.5. In the plot below (scenario 2.5) the SFR threshold criteria was so high that the galaxy runs out of SNe after some time. Therefore, habitability follows just the evolution of metallicity.

5.3 Scenario 3. Gamma-Ray Bursts

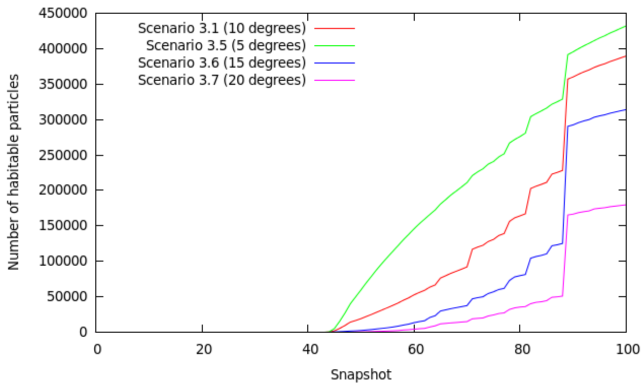
The exploration of the parameters on GRB was a very interesting one. Actually, it offers the most possibilities to test different parameters on the model, such as the radius of influence, opening angle and number of GRB happening during the evolution of the simulated galaxy. Looking on Figure 16 we see that most of the habitable particles on these scenarios are in central regions of the galaxy. It should also be noticed the 'rugged' form of the cumulative plots of particles achieving habitability (Figures 13, 14 and 15 lower panels). Gamma-Ray Bursts are the only phenomena that strongly induces this kind of behaviour. This is reflected on the plots of the distribution of habitable particles (Figure 16) where there are some 'phase transition' features, instead of smooth changes. Table 6, shows the parameters chosen for different scenarios.

Table 6: Gamma-Ray Bursts

Scenario	Number of Gamma-Ray Bursts	Opening Angle (degrees)	Radius of influence (kpc)	Percentage of habitable particles
3.1	200	10	10	36.93%
3.2	500	10	10	32.45%
3.3	800	10	10	22.53%
3.4	1000	10	10	15.17%
3.5	200	5	10	40.97%
3.6	200	15	10	29.76%
3.7	200	20	10	17.03%
3.8	200	10	3	41.48%
3.9	200	10	7	39.24%
3.10	200	10	15	34.14%

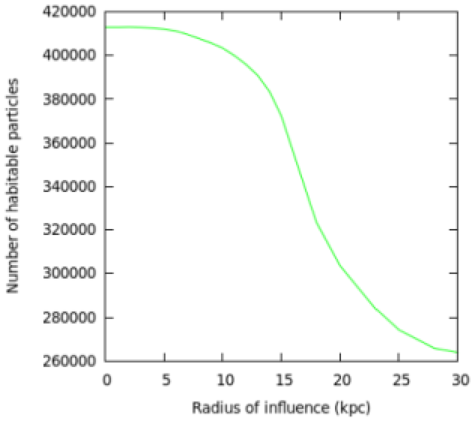


(a) Dependence of number of habitable particles on snapshot 100 for different values of opening angle of GRB jet in our simulation.

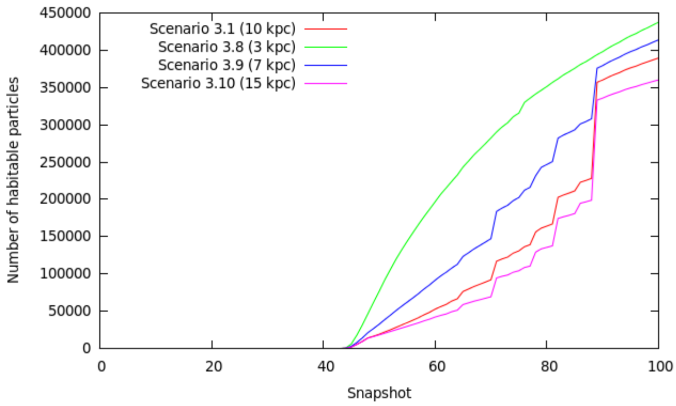


(b) Cumulative plots for number of habitable particles for different opening angles of GRB jet.

Figure 13: Angular dependence for GRB scenarios

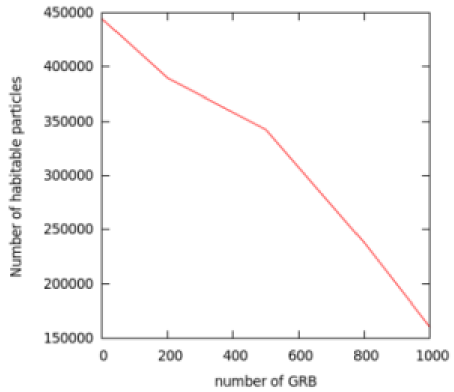


(a) Dependence of number of habitable particles on snapshot 100 on the radius of influence of GRB.

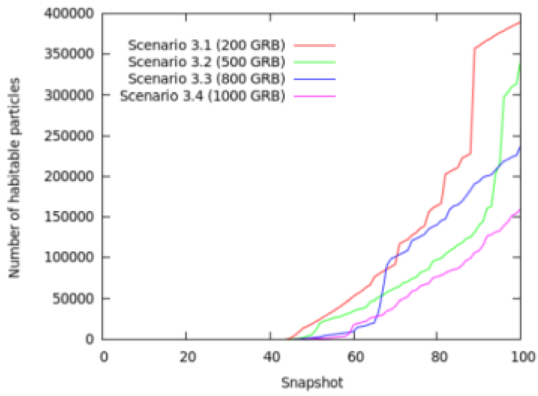


(b) Cumulative number of habitable particles for different radii of influence.

Figure 14: Radius of influence of GRB



(a) Number of habitable particles on snapshot 100 as a function of the number of GRB occurring during the simulation.



(b) Cumulative number of habitable particles for different number of GRB.

Figure 15: Dependence on number of GRB occurring in the simulation.

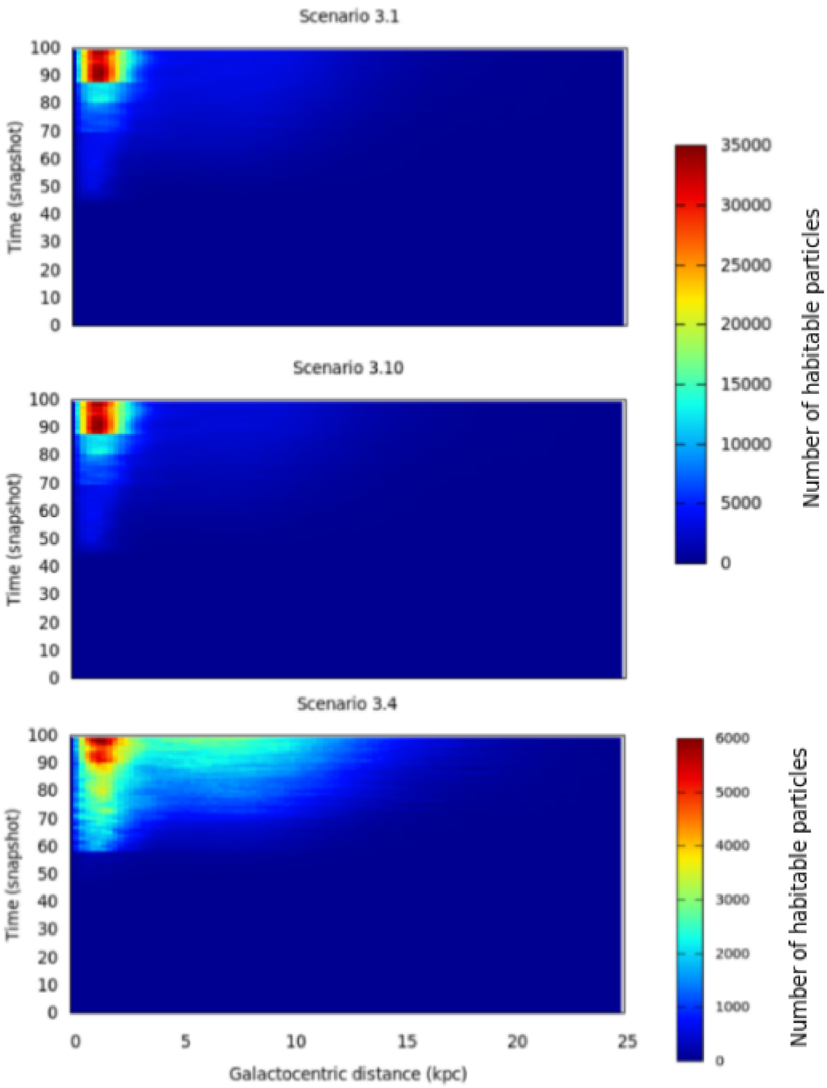


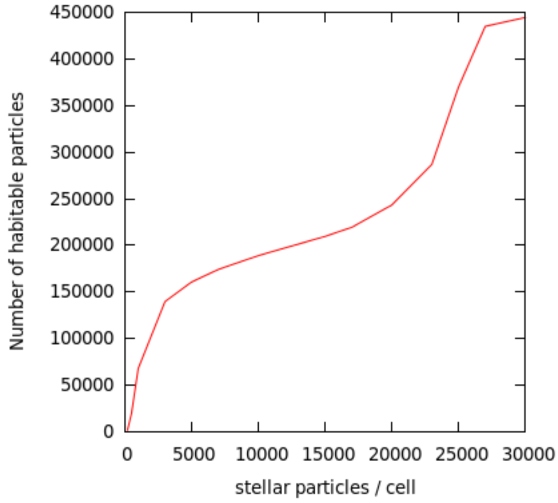
Figure 16: Distribution of habitable particles for scenarios 3.1, 3.4 and 3.10

5.4 Scenario 4. Stellar Density Criteria

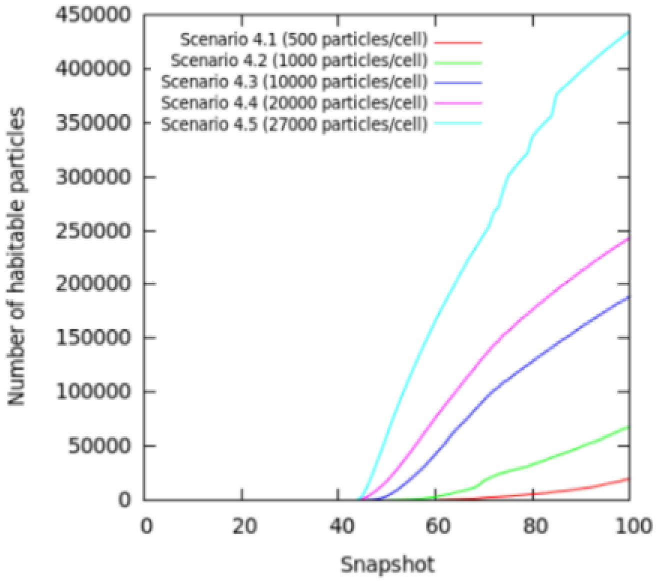
The consideration of a high stellar density as a risk factor concerning habitability, leads to habitable zone morphologies similar to those on the Supernova scenarios (Figure 18). We have again in this case the appearance of inner boundaries, given that the more crowded cells of the grid are located near the central regions of the galaxy. When we relax this condition, the number of habitable particles increase (Figure 17) and again the central regions of the galaxy become habitable (Figure 19). So, the habitable zone moves to outer regions and shrinks in size in the time axis as we decrease the number of stellar particles per cell to reset the astrobiological clock.

Table 7: Parameters of density criteria related scenarios

Scenario	Stellar particles per cell	Percentage of habitable particles
4.1	500	1.86%
4.2	1000	6.41%
4.3	10000	17.19%
4.4	20000	23.05%
4.5	27000	41.23%



(a) Number of habitable particles on snapshot 100 as a function of number density of stellar particles in the simulation.



(b) Cumulative plots for number of habitable particles vs. time for different risk values of stellar number density.

Figure 17: Density of stars scenarios

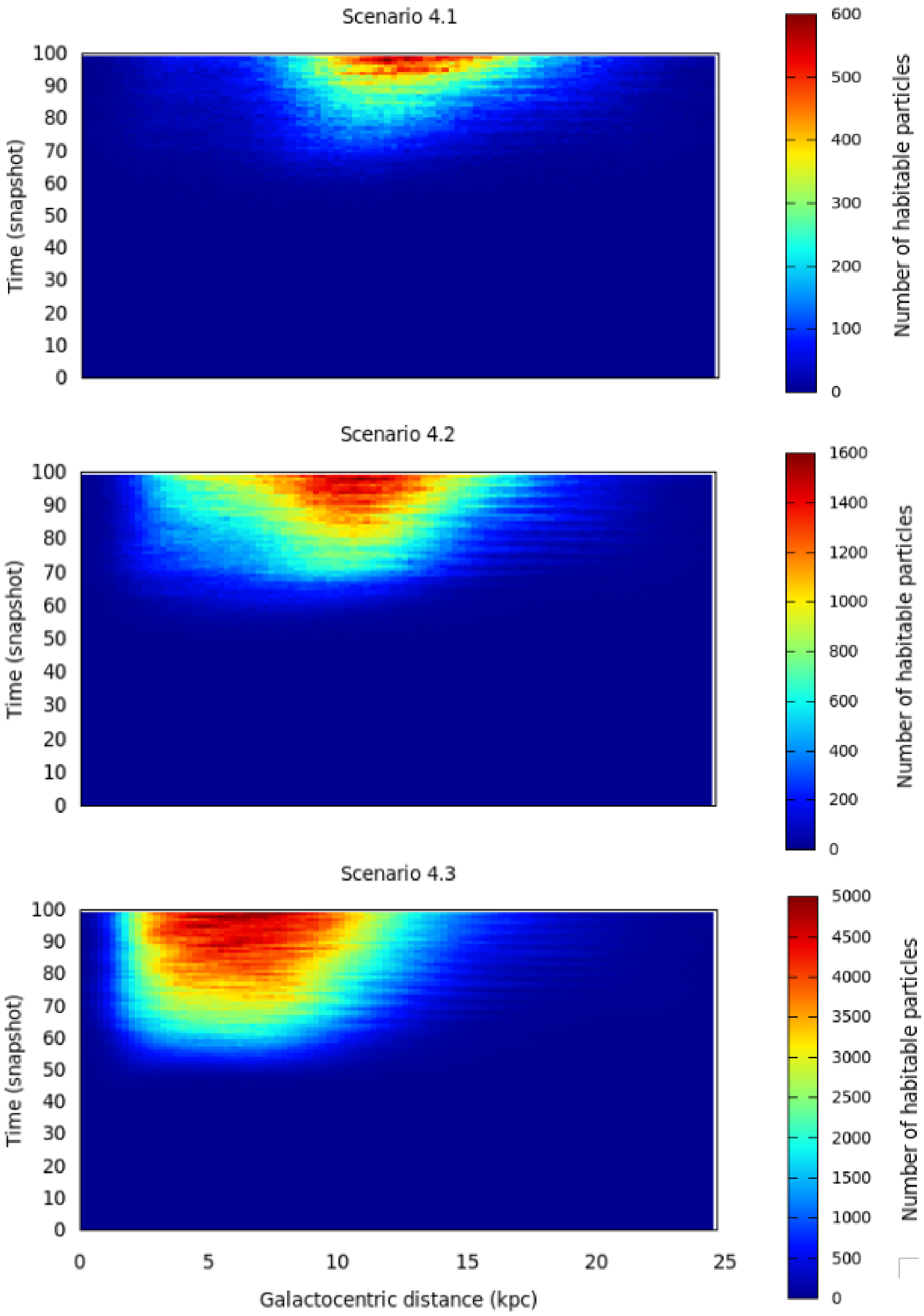


Figure 18: Distribution of habitable particles for scenarios 4.1, 4.2 and 4.3.

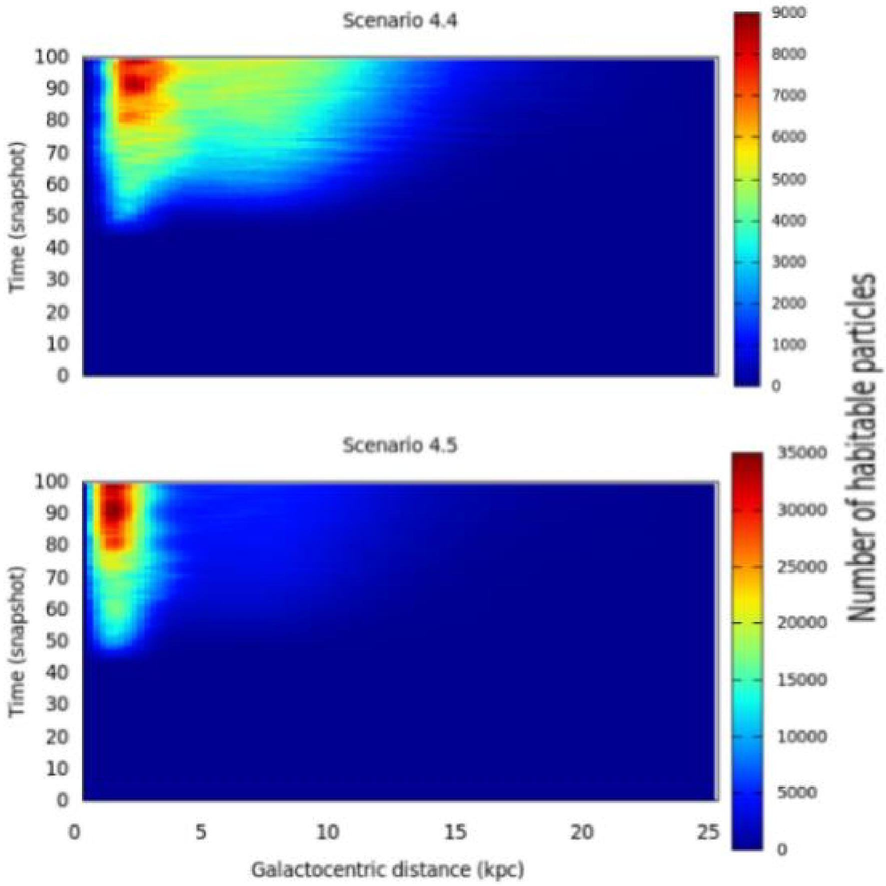


Figure 19: Distribution of habitable particles for scenarios 4.4 and 4.5.

5.5 Scenario 5. All risks

We have explored in the previous sections the role that different values of habitability relevant parameters have on the behaviour of galactic habitability. We have examined each of the parameters separately. However, none of the past scenarios represent a realistic one, while all the different risk factors are working in galaxies together during its evolution. This is why this last set of scenarios shown in Table 8 is the more realistic one. Figures 21 and 22 show the distribution of habitable particles for these set of scenarios. It is notable the avoidance of central regions, following mainly the trends either of supernovae or high stellar density scenarios. Figure 20 shows how the number of habitable particles after the different life threatening phenomena acting alone compare with each other and with the correspondent all risk scenario. In this section we present the models considered for all risk factors working together, while we discuss the validity of the values chosen in the next section.

Table 8: Habitability parameters for scenarios that include all risk factors.

Scenario	**Risk**	**Description**	**Percentage of habitable particles**
5.1	Metallicity	0.0 dex	**7.60%**
	Time	40 snapshots	
	Supernovae	0.00012 $M_{\odot}$/yr	
	Gamma Ray Bursts	1000 GRB	
	Stellar density	20000 stars/cell	
5.2	Metallicity	0.0 dex	**9.26%**
	Time	40 snapshots	
	Supernovae	0.00012 $M_{\odot}$/yr	
	Gamma Ray Bursts	200 GRB	
	Stellar density	10000 stars/cell	
5.3	Metallicity	0.0 dex	**12.94%**
	Time	40 snapshots	
	Supernovae	0.00016 $M_{\odot}$/yr	
	Gamma Ray Bursts	200 GRB	
	Stellar density	10000 stars/cell	
5.4	Metallicity	0.0 dex	**27.23%**
	Time	10 snapshots	
	Supernovae	0.00012 $M_{\odot}$/yr	
	Gamma Ray Bursts	200 GRB	
	Stellar density	10000 stars/cell	
5.5	Metallicity	-1.0 dex	**20.60%**
	Time	40 snapshots	
	Supernovae	0.00012 $M_{\odot}$/yr	
	Gamma Ray Bursts	200 GRB	
	Stellar density	10000 stars/cell	

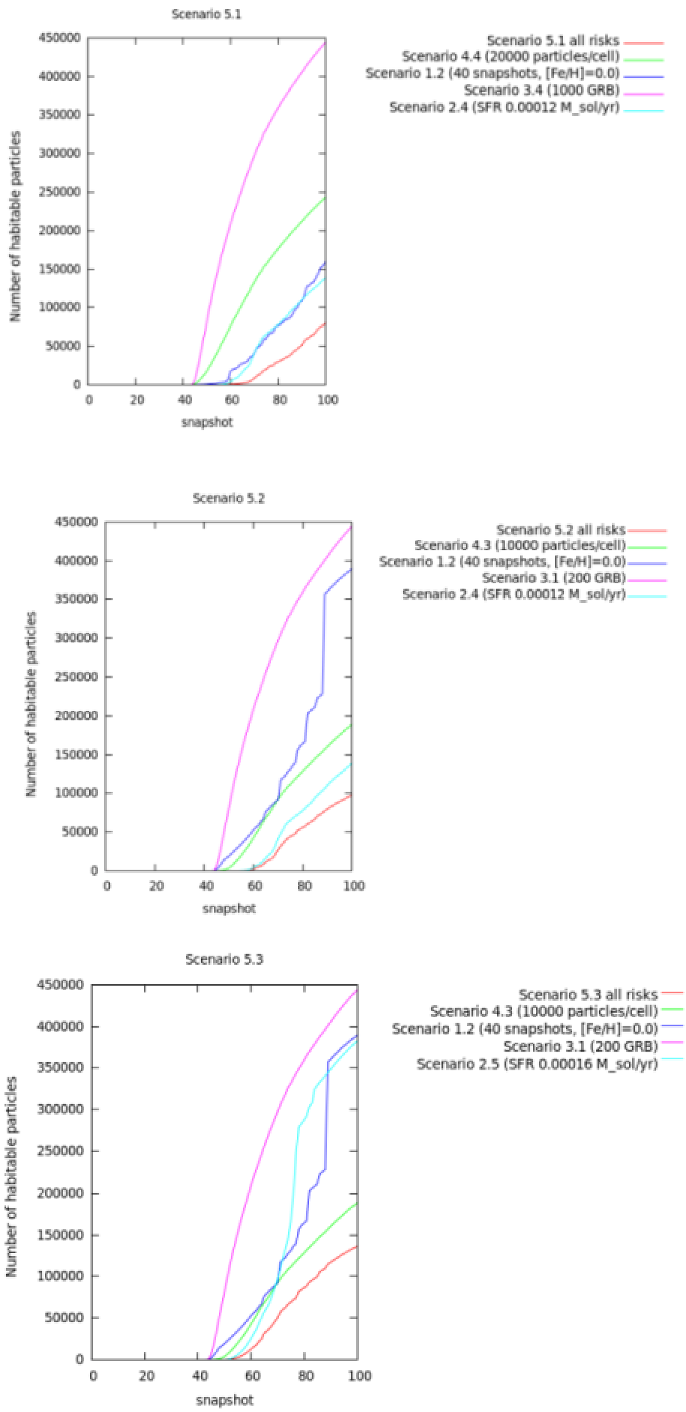


Figure 20: Cumulative plots for number of habitable particles of scenarios 5.1, 5.2 and 5.3 vs. time (snapshot number).

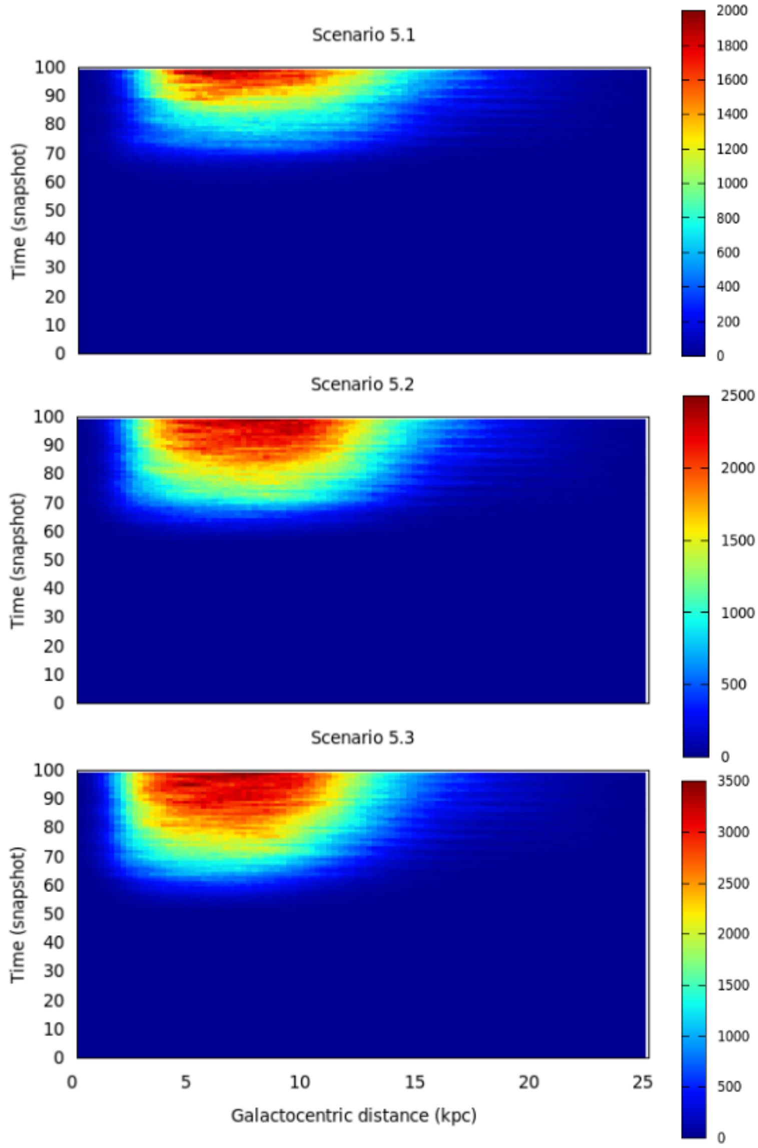


Figure 21: Distribution of habitable particles for scenarios 5.1, 5.2, 5.3

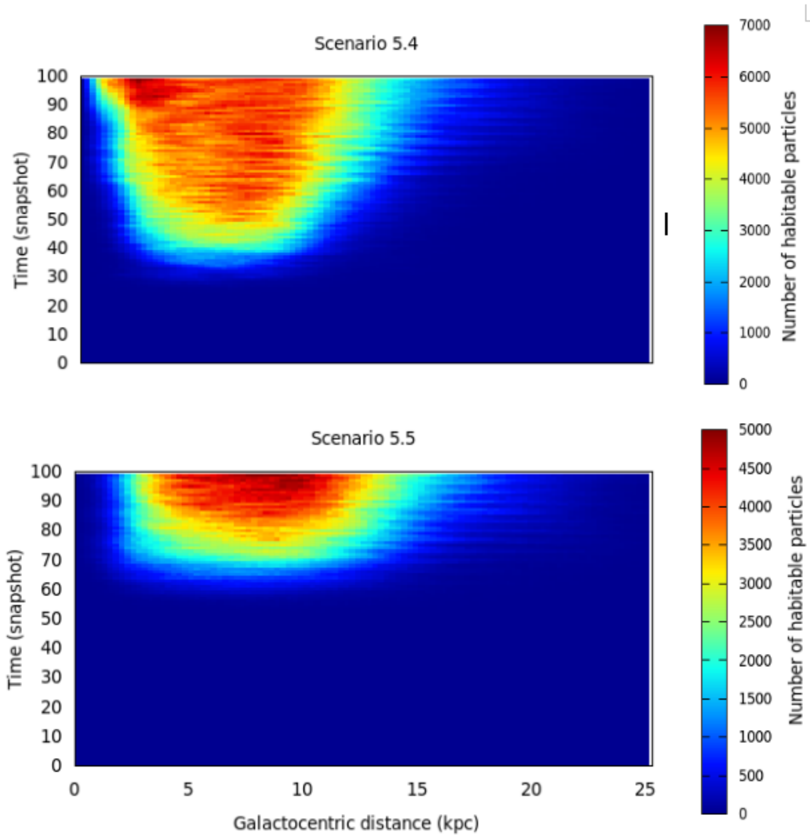


Figure 22: Distribution of habitable particles for scenarios 5.4 and 5.5

6 Discussion

We have seen how the different scenarios, which risk factors have been analysed working separately (scenarios 1 to 4) and together (scenario 5), affect galactic habitability. For our analysis we have used mostly unrealistic values for the relevant parameters. However, scenario 5.2 should be near to a 'realistic' model of galactic habitability.

We have pointed the fact that our simulated galaxy contains far less stellar particles than a real galaxy. We may keep on mind that stellar particles doesn't represent individual stars, and that in a real galaxy, the number of stars in such regions of a galaxy must be much larger. Figure 17, upper panel, shows that for values between ~10000 - 20000 particles/cell show no variations in more than 6% on the number of habitable particles at the end of the simulation (snapshot 100). Taking in consideration that the mass of the stellar particles is $10^5 M_\odot$ and we consider then that 1 stellar particle contains around 10^5 stars, the chosen values for the number of particles per cell gives us a number of encounters above 1 for $\log[\mathrm{v/km\ s^{-1}}] > 1$ as shown in Figure 2 from Jiménez-Torres et al. (2013). Figure 23 shows the logarithm of velocities of stellar particles vs. galactocentric distance. We reset the astrobiological clock for all stellar particles in crowded environment, while the central regions show great velocity dispersions being inhospitable for the development of complex life.

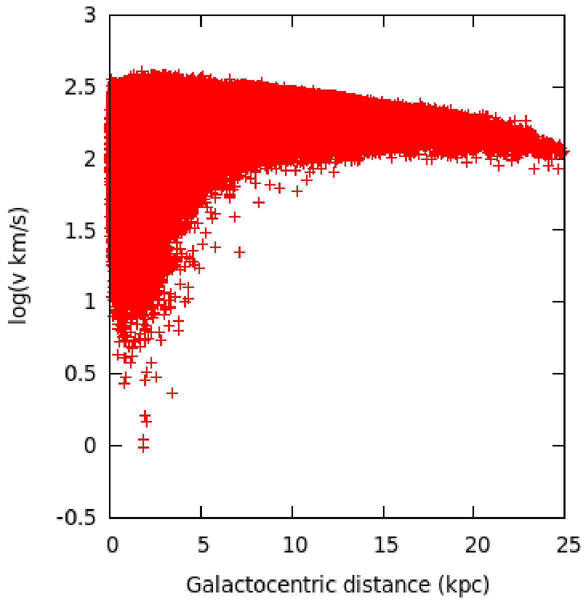


Figure 23: Log [v/km s^{-1}] vs. Galactocentric distance for stellar particles in the simulation (snapshot 100).

A similar case is that of supernovae. If we consider that they occur at rates of 1.98-2.40 x 10^{-2} yr^{-1} for the last Gyr (Gowanlock et al., 2011), these numbers give that between 2 snapshots near the end of the simulation we should have ~2x10^7 supernova explosions. That is one order of magnitude more that the total number of stellar particles in our simulation. If this numbers correspond to a galaxy with ~10^{11} stars, then in our simulation we can estimate that for the last snapshots we should have around ~10^2 supernovae. For that number, the SFR used of 0.00012 $M_\odot$/yr gives a good approximation. As expected, this choice of values make the supernovae to remain in the central parts of the galaxy and spiral arms, this is, star forming regions in the case of the Milky Way.

The case for GRB is a very interesting one in our model. As several authors argue (Annis, 1999; Vukotic & Cirkovic, 2007; Cirkovic & Vukotic, 2009; Domainko et al., 2013; Galante & Horvath, 2007), GRB can represent a risk factor for the development of complex life. However, in our model, GRB represent a minor impact compared, for example, with the case of SNe or high stellar number density. Melott et al. (2004) present a GRB rate of 1.5x10^{-7} gal^{-1} yr^{-1}. For the total temporal interval covered in our simulation, we obtain a total number of GRB of ~10^3. We can see that for that number of GRB the cumilative plot for number of surviving particles compare with the SN risk of 0.00012 $M_\odot$/yr (Fig. 22 scenario 5.1). However, we have seen that the number of stellar particles of the simulation is much smaller than the real number of stars of a spiral galaxy like the Milky Way. We decide to try the more conservative number of GRB, a 200, as shown in scenarios 5.2 to 5.5. Although in GRB section of our results, we have tested several values for the opening angles of the jet, and some authors imply that this angles can be as great as 14 degrees (Panaitescu & Kumar, 2003), or 12 degrees (Mizuta & Ioka, 2013), being the most angles smaller than these. We chose a 10 degree aperture, using the results from our analysis, showing that the variation on number of surviving particles depending on opening angle is of ~5% for opening angles between 0 and 10 degrees. The radius of influence was chosen to be of 10 kpc. It can be a little too large compared with the estimate of 3 kpc. given by Melott et al. (2004), but maybe sound a little conservative compared with the 150 kpc radius of influence from an extragalactic GRB (Galante & Horvath, 2007). We remain in the most conservative side of the spectrum. Figure 13 (upper panel) shows that the variation of number of particles for distances below 10 kpc is of less than 6%. As all our simulated GRB are from galactic origin, a radius of more than ∼50 kpc (the diameter of the simulated galaxy) makes no sense. We also consider that the jets are emitted in two directions, so a GRB occurring in near the center of the galaxy and with direction of emission contained in the plane of the galaxy will have an effective radius of 20 kpc.

The fact that the chosen value of 200 GRB gives a minor risk compared with supernovae or high density of stars environment must not mislead us in the role that GRB play in the evolution of galactic habitability. GRB are the only candidates to induce 'catastrophic' landscape. For instance, *in general trends in our model*, once a zone is out of supernovae or high stellar density, it remains like that for the later evolution of the galaxy (with exception of the movement of spiral arms). However, if it is true that the number of GRB are decreasing with time following the SFR, their reach can affect almost *any* place of the galaxy. In our model, there is no GRB free zone, either in space or time.

As in the case of Lineweaver et al. (2004) the requirement for a minimum metallicity was tested for the case of solar metallicity, but we also include the value of [Fe/H]=-1.0 (scenario 5.5). This change of metallicity working as the only risk gives very different outputs (a 27% difference in total number of habitable particles, see scenarios 1.1 and 1.5) the final shape and duration of habitable zone remains the same with a factor of 2 difference in total number of habitable particles (scenarios 5.2 and 5.5).

Finally we present two choices for time required for life to develop.. Following the approach of Lineweaver et al. (2004) taking as time required to develop complex life 4±1 Gyr which is the time that life has existed on Earth. In the work of Vukotic & Cirkovic (2008) the authors also adopted this time-scale as fairly typical, without any 'Copernican' assumption. However, for the sake of completeness, we also relax that requirement in scenario 5.4. In this last scenario the time required to achieve the habitability status is 1 Gyr.

The cumulative plots presented in Section 5 (Figure 21) show also the characteristics of those seen in Figure 24 taken from Vukotic & Cirkovic (2008). These authors define a probability function Q "measuring conveniently averaged severity of the resetting events that can be regarded as both (1) a geometrical probability of an average habitable planet being in the lethal of a GRB, and (2) probability describing more complex effects dealing with the physics and ecology of the extinction mechanism". Being values of Q near to zero the less lethal events, and the most lethal those close to 1. In that sense, for the values chosen for scenario 5.2, we can calculate the Q factor as[3]:

Q = 0.5 for 40 snapshots time and solar metallicity.
Q = 0.63 for 200 GRB.
Q = 0.82 for 10000 stellar particles/cell.
Q = 0.86 for SN explotions (for SFR=0.00012 $M_\odot$/yr).
Q = 0.91 for all risks.

A notable remark is that the probability function Q is not the sum of all functions working together. We cannot apply a *ceteris paribus* reasoning when we take in account different scenarios of habitability. The final risk function value is dominated by the greatest of the risk functions working. In scenario 5.2, is the case of supernova explosions and high stellar density environments. This has a consequence on the fact that habitable sites remain in places where stars are farther from each other, making detection of biological activity, or even chances of communication between civilizations more difficult.

Finally, figure 25 shows a histogram of habitable particles vs. galactocentric distance. Our greatest number lies at ~8.2 kpc. This plot will be used to calculate the boundaries of the Galactic Habitable Zone.

[3]the calculation was done as 1 - percentage of surviving particles.

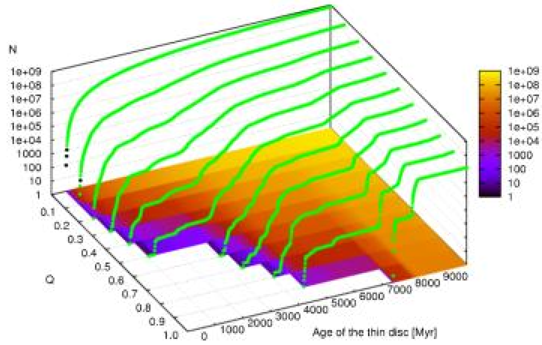


Figure 24: Cumulative plots from Vukotic & Cirkovic (2008), showing number of particles achieving Noogenesis for different values of the Q value.

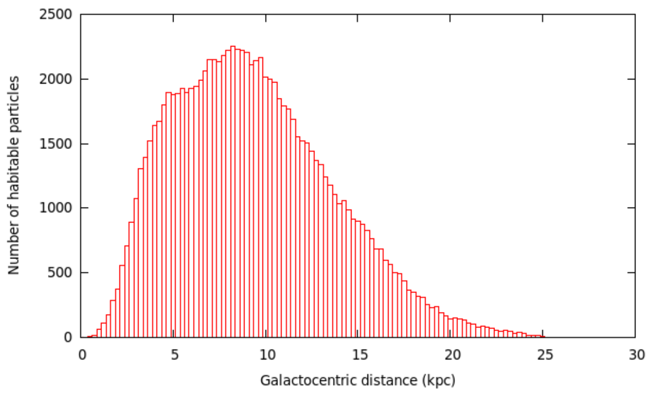


Figure 25: Histogram of habitable particles of scenario 5.2

7 Conclusions

We propose a new method for using N-body simulation of galactic dynamics to analyse galactic habitability. Taking as risk factors GRBs, Supernovae and stellar encounters, and asking for enough metallicity and time to develop complex life, we can quantify the corresponding impact that the different risk factors concerning habitability have on the final number of habitable sites in a galaxy.

Our model offers the possibility of analysing different risk scenarios working either separated or combined, giving different results. It also provides a very useful tool to prove in a simple way different values for the parameters associated to each of the risk factors considered.

The main drawbacks of our model resides in the accuracy of the simulation. Our simulated galaxy contains, for example, much less stellar particles than the Milky Way, which is the galaxy from which we obtained most of the values for our astrobiological analysis. Although we tried to be as realistic as possible, and to justify the values chosen for each of our models, we are aware that the models can be improved in enormous ways with better simulations. The question of the values used can also be argued, and as we have seen it is a hot topic in astrobiological research, but the main point of this work was the proposal of a new kind of research concerning habitability in our Universe. Our model has the main advantage to include the galactic dynamics on the exploration of habitability. With the current work we were able to obtain results showing how the distribution of habitable sites changes with time, like those presented by Lineweaver et al. (2004) (Figure 1) but taking a different approach.

The present work also permit us to calculate *inner and outer bounds* of habitable zone. 77% of the habitable sites lie between 3 and 14 kpc, which agrees strongly with the boundaries calculated by Cirkovic (2005) between 3 and 13.5 kpc. The peak of our distribution of habitable sites (Figure 25) lies between 7 and 10 kpc which agrees strongly to the boundaries of Lineweaver et al. (2004) of 7 and 9 kpc for present time. As we have pointed, it is hard to give a sharp definition of galactic habitable zone boundaries, but the fact that different habitability criteria give similar results imply that GHZ is a viable model platform.

Several of the traditional risks considered for life to develop, in this case, high metallicities, supernova explosions and high stellar number densities, remain in the same places of the galaxy. This is, mainly the central regions and in minor degree, the spiral arms. The second coincidence is that the time when the SFR is high, and that makes larger the probability of SNe and GRBs to occur, are also the times when there is not enough time or enough metallicity for life to arise and develop complexity. This traduces in:

1) When the greater is the risk of transient radiation events to occur, there is not enough metallicity for life to arise or not enough time to achieve complexity.

2) Once there is enough time and metallicity, most of the risk factors remain mainly in the same places of the galaxy. Leaving relatively undisturbed the resting regions for large periods of time.

3) The only potential risk remaining is the contingent case of GRBs, which indeed induces a "catastrophic" trend in the cumulative functions.

These facts may reinforce the idea of Annis (1999), the galaxy can suffer a phase transition, from an almost dead one to one full of complex life. Maybe the SETI projects will begin to have success in a couple of years. But we still have to do more research to get a better insight...

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