The best place and time to live in the Milky Way: the impact of Gamma Ray Bursts and Supernovae on planetary habitability

Riccardo Spinelli
riccardo.spinelli@inaf.it
INAF OA Palermo

In collaboration with:
G. Ghirlanda, INAF OA Brera
G. Ghisellini, INAF OA Brera
F. Haardt, University of Insubria

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

SPECULA PANORMITANA
MDCCXC

EXOPA

GAPS
GLOBAL ARCHITECTURE OF PLANETARY SYSTEMS

Ariel

Florence - Molecules and planets in the outer Galaxy: is there a boundary of the Galactic Habitable Zone? - Nov 14, 2024

The high energy radiation effects on exoplanets

➢ XUV (5-911 Å): hydrodynamic escape

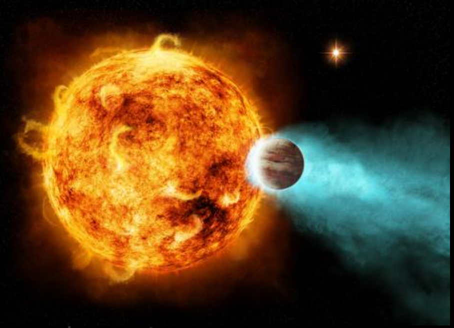
- Caldiroli, A., […], Spinelli, R., […] (2022), A&A 663, A122.
- Caldiroli, A., […], Spinelli, R., […] (2021), A&A 655, A30.
- Spinelli et al. (2023), ApJ, 165, 5

➢ NUV (200-280 nm): abiogenesis

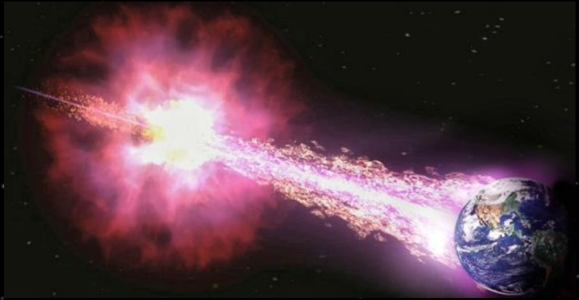
- Spinelli et al. (2019), A&A 627, A144.
- Spinelli et al. (2023), MNRAS, 522, 1.
- Spinelli et al. (2024), MNRAS, 533, 1

➢ GAMMA (KeV-MeV): habitability

- Spinelli et al. (2021), A&A 647, A41.
- Spinelli, R., Ghirlanda, G. (2023) Universe, 9, 60.



From the host star



From transient events

Outline

- Habitability and mass extinctions
- GRBs and SNe and their possible effects on planets
- The best place and time to live in the Milky Way

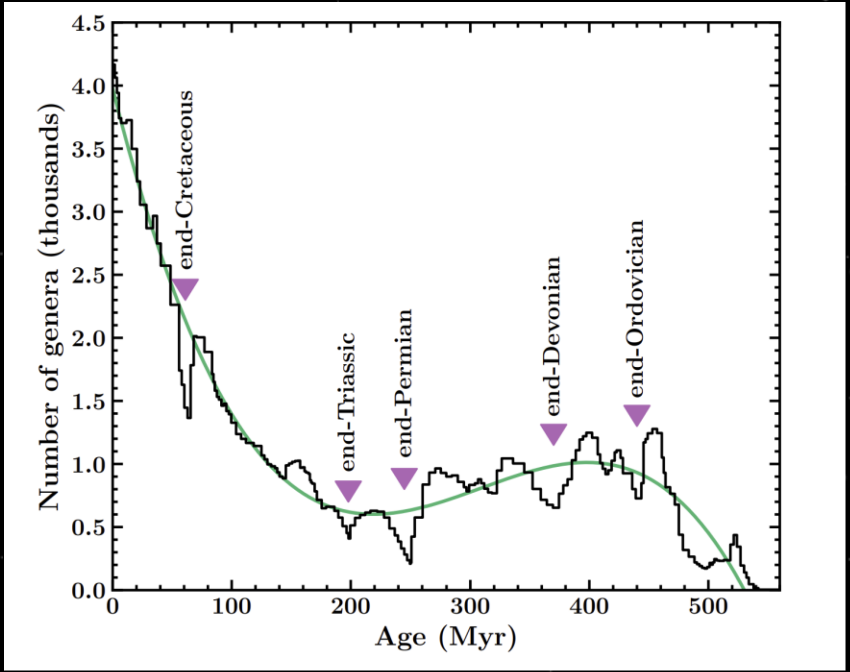
Habitability

Many ingredients are important for the existence of life on Earth:

- Intrinsic factors: property of the planet (geological properties, atmosphere)
- The environment - on the planetary system scale - where the planet was formed and evolved (the emission properties of the host star and the geometry of the planetary system).

Can the galactic environment and in particular high energy galactic transient events influence the habitability of a planet?

Mass extinctions



Number of genera over time for the 17,797 well-resolved marine animal genera of Sepkoski's Compendium of Fossil Marine Animal Genera data (Sepkoski 2002)

Five mass extinctions: events in which a large fraction of existing species completely disappears over a short geological timescale. Sudden holes in the biodiversity evolution.

The origins of these events are debated.
Climate changes induced by one or many of these events:

- volcanic eruptions (Wignall 2001, Self et al. 2006, Rampino 2019)
- plate tectonics (Li 2012, Snakin 2021)
- asteroid impacts (Alvarez et al. 1980)
- GRBs and SNe (Ruderman 1974, Gehrels et al. 2003, Melott & Thomas 2011)

GRB221009A

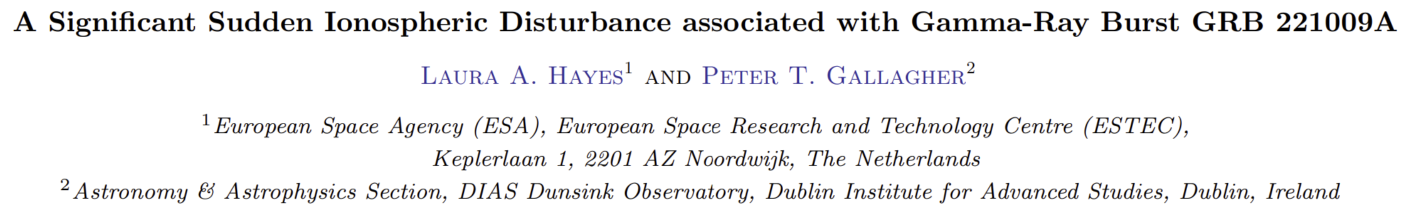
750 Mpc, it was powerful enough to affect Earth's atmosphere:

Article

https://doi.org/10.1038/s41467-023-42551-5

Evidence of an upper ionospheric electric field perturbation correlated with a gamma ray burst

Piersanti et al. 2023



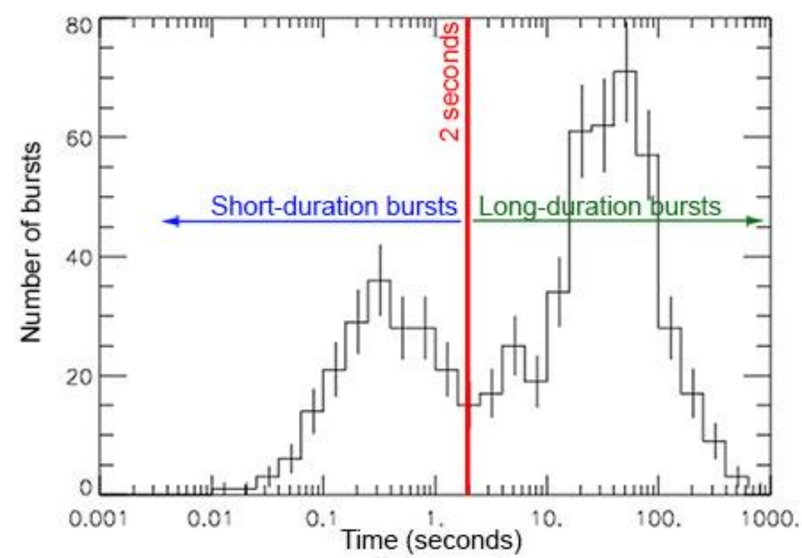
A Significant Sudden Ionospheric Disturbance associated with Gamma-Ray Burst GRB 221009A

Laura A. Hayes[1] and Peter T. Gallagher[2]

[1] *European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands*

[2] *Astronomy & Astrophysics Section, DIAS Dunsink Observatory, Dublin Institute for Advanced Studies, Dublin, Ireland*

Gamma Ray Bursts (GRBs) and Supernovae (SNe)

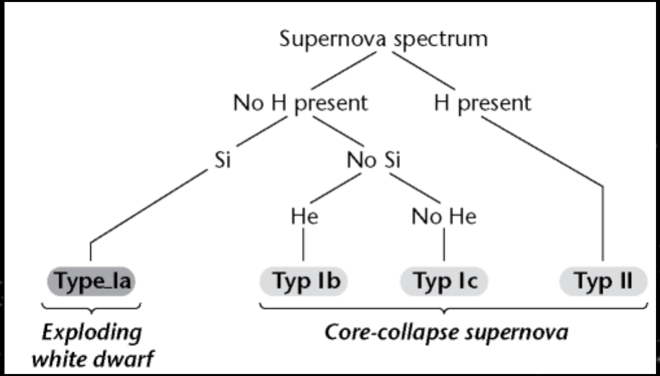


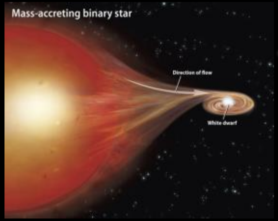
Duration separation → **Different progenitors**

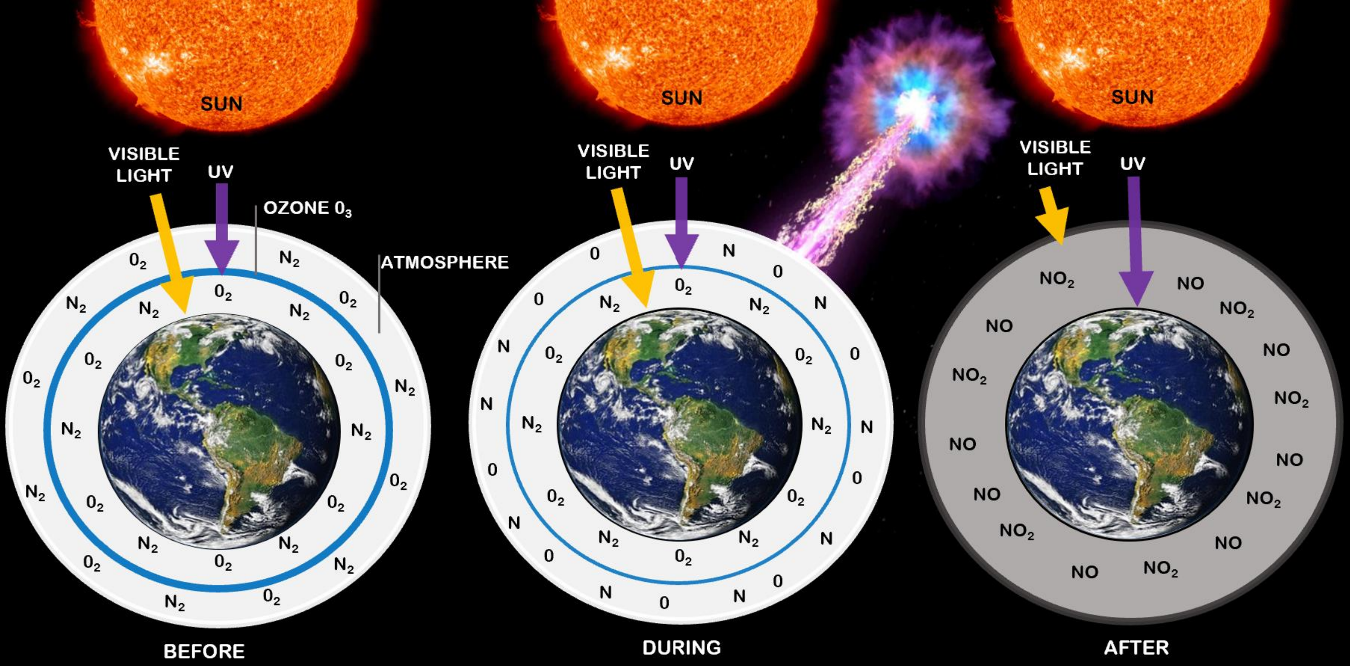
MERGER OF COMPACT BINARY HOSTING AT LEAST ONE NS

RAPIDLY ROTATING METAL POOR MASSIVE STAR

Less powerful than GBRs but more frequent. Divided in classes according to different chemical elements in their spectra


Supernova spectrum
No H present
H present
Si
No Si
He
No He
Type Ia
Typ Ib
Typ Ic
Typ II
Exploding white dwarf
Core-collapse supernova





Melott & Thomas 2011 (2D atmospheric model) a typical GRB at 1 kpc:

- would destroy most of the ozone layer
- could trigger a global cooling as a consequence of chemical changes in the atmospheric composition.

Late Ordovician mass extinction event have some charactheristics coherent with this scenario:

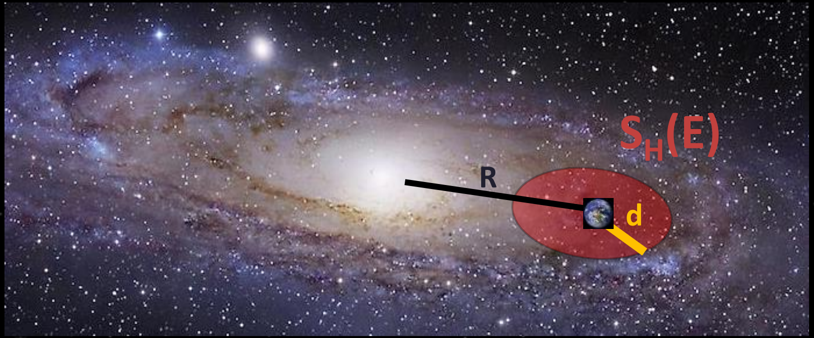
- A decrease in extinction intensity was observed with the increase in water depth. UV radiation strongly damages the organisms living on the surface of the ocean and not those living in deep-water.

- Brenchley et al. 1994 showed that the Ordovician extinction took place before the Ordovician glaciation. This phenomenon is coherent with the GRB scenario: the first effect of a GRB is the depletion of the ozone layer, and as a consequence, larger UV flux can reach the Earth's surface, and then chemical changes in the atmosphere lead to the global cooling.

- Melott & Thomas 2013 showed that the geographical pattern (latitudinal differential extinction rates) of the Ordovician extinction is consistent with the radiation of a GRB that primarily illuminated the South Pole.

Melott & Thomas 2011 suggested that the late Ordovician mass extinction event may have been caused by a Gamma ray burst.

→ **The safest region and time to live during our Galaxy evolution, more sheltered from these high energy events.**



An event with energy E is «lethal» for a planet if it occurs at a distance less than d, the distance within which it can hit the planet with a fluence > 100 kJ/m² (ozone layer depletion, Thomas & Melott 2011)

At a given time, for a planet at R from the galactic center, I calculated the rate of lethal events triggered by a high energy transient event of energy E:

Number of lethal event (R,t) = Number of stellar explosion in the entire galaxy with energy E x F(R,t)

F(R,t) is a «probability» that one of these events occurs within the red region S

Number of lethal event (R,t) = Number of stellar explosions in the entire galaxy with energy E x F(R,t)

$$\frac{dN_{MW}(R,t)}{dt} = \underbrace{V_{MW}(t)\xi(t)}\underbrace{\int_{S_H(E)} \frac{\Sigma_\star(s,R,t)}{M_\star(t)} f_{sSFR}(s,R,t) f_{Fe}(s,R,t)\, ds}$$

Milky way cosmological volume

Cosmological rate of events with E

LGBR Wanderman & Piran 2010
SGRB Ghirlanda et al. 2016
SNIbc/IIp Madau & Dickinson 2014
SNIa Maoz & Mannucci 2012.

Fraction of stellar mass in S + stars + lethal events

Star formation: GRB and CCSN prefer star forming region + SFR + GRB and CCSN

$$f_{\mathrm{sSFR}}(R,z) = \frac{sSFR(R,z)}{sSFR(z)}$$

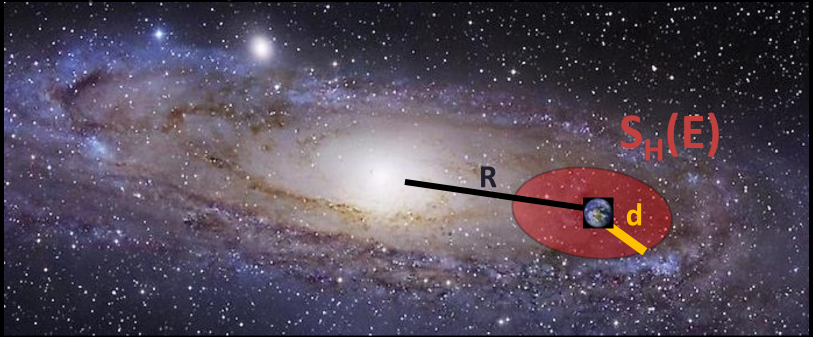
Madau & Dickinson 2014

Metallicity: LGRB prefer metal poor region - Metallicity + GRB

$$f_{\mathrm{Fe}}(R,z) = \frac{\Theta_{Z<Z_c}(R,z)}{\Theta_{Z<Z_c}(z)}$$

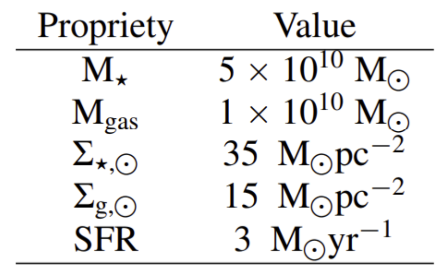
$$Z_c = 0.4\, Z_\odot$$

Bertelli et al. 1994
Virgili et al. 2011



Naab & Ostriker 2009

- Stellar density (R,t)
- Star formation (R,t)
- Metallicity (R,t)



Propriety	Value
$M_\star$	5×10^{10} $M_\odot$
M_{gas}	1×10^{10} $M_\odot$
$\Sigma_{\star,\odot}$	35 $M_\odot pc^{-2}$
$\Sigma_{g,\odot}$	15 $M_\odot pc^{-2}$
SFR	3 $M_\odot yr^{-1}$

Present-day Milky Way proprieties reproduced by model: total mass in stars, total mass in gas, stellar surface density at the solar radius, gas surface density at the solar radius, and global SFR.

2.5 Gyr: the bulge forms with a steep exponential surface density profile.
After 2.5 Gyr: start of the long and gradual formation of the disk.

Star formation evolution

Metallicity evolution

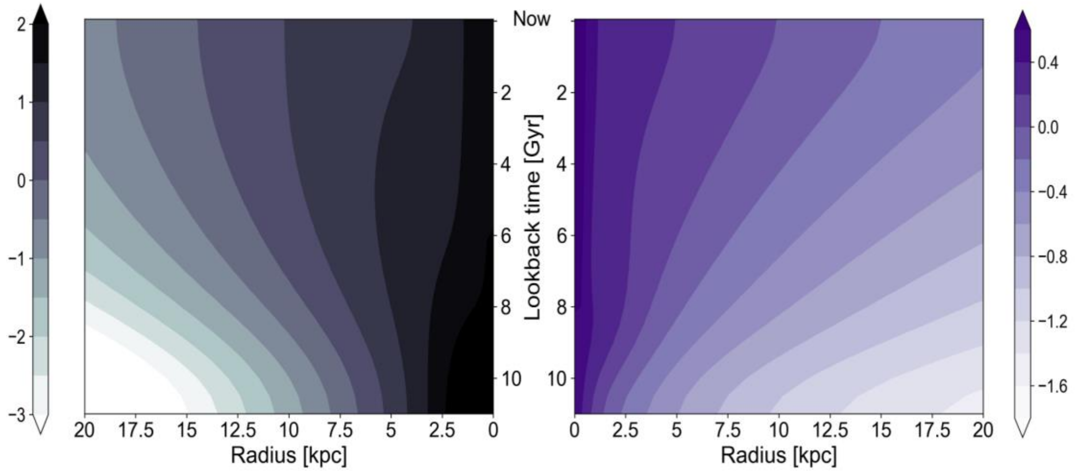
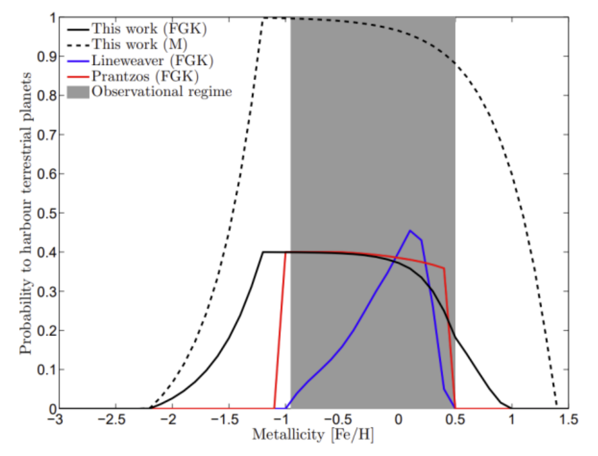


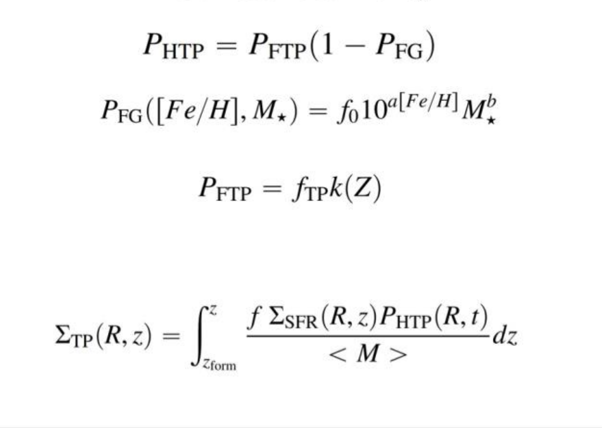
Figure 5. Left: star formation surface density as a function of the galactocentric radius R and lookback time. Color coding (left color bar) is in logarithmic scale and in units of $M_\odot pc^{-1} Gyr^{-1}$. Right: metallicity as a function of the galactocentric radius R and lookback time. The shaded regions (left color code) represent in logarithmic scale $Z/Z_\odot$

Milky way model (Naab & Ostriker 2009)

Terrestrial planets

Zackrisson et al. (2016) model to calculate the surface number density of TPs within the MW as a function of cosmic time and galactocentric distance:





$$P_{\mathrm{HTP}} = P_{\mathrm{FTP}}(1 - P_{\mathrm{FG}})$$

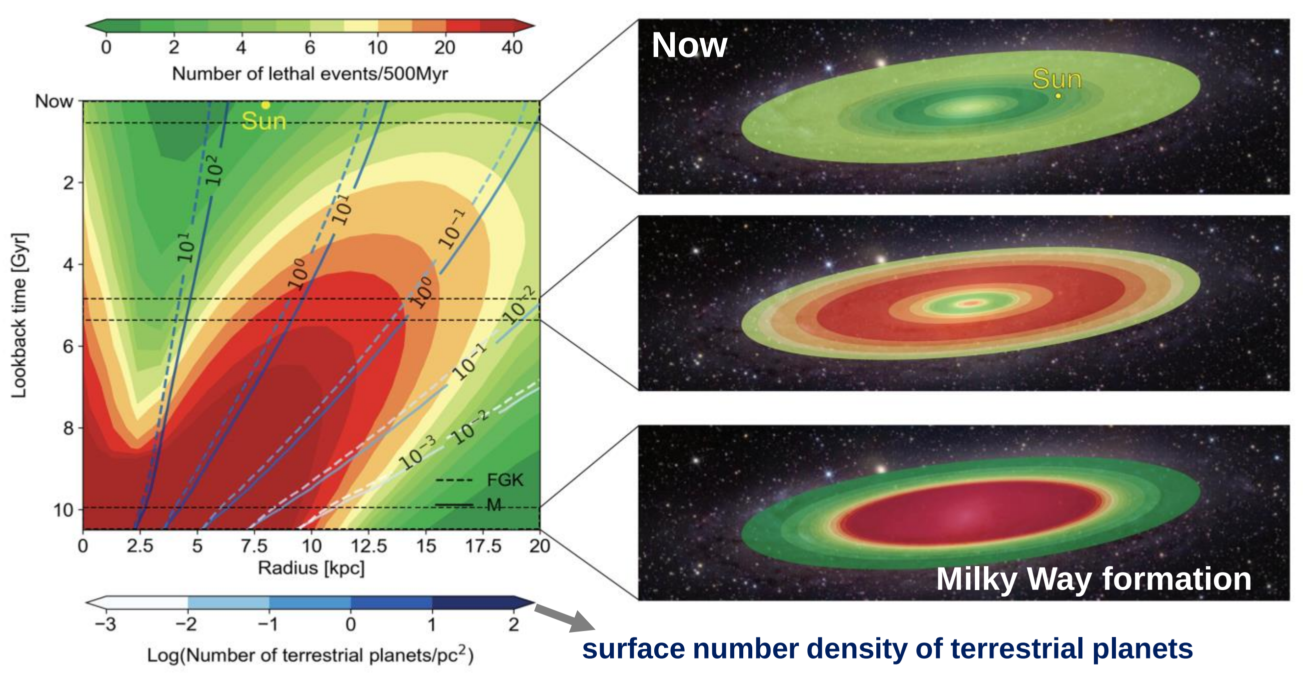
$$P_{\mathrm{FG}}([Fe/H], M_\star) = f_0 10^{a[Fe/H]} M_\star^b$$

$$P_{\mathrm{FTP}} = f_{\mathrm{TP}} k(Z)$$

$$\Sigma_{\mathrm{TP}}(R, z) = \int_{z_{\mathrm{form}}}^{z} \frac{f\, \Sigma_{\mathrm{SFR}}(R, z) P_{\mathrm{HTP}}(R, t)}{< M >} dz$$

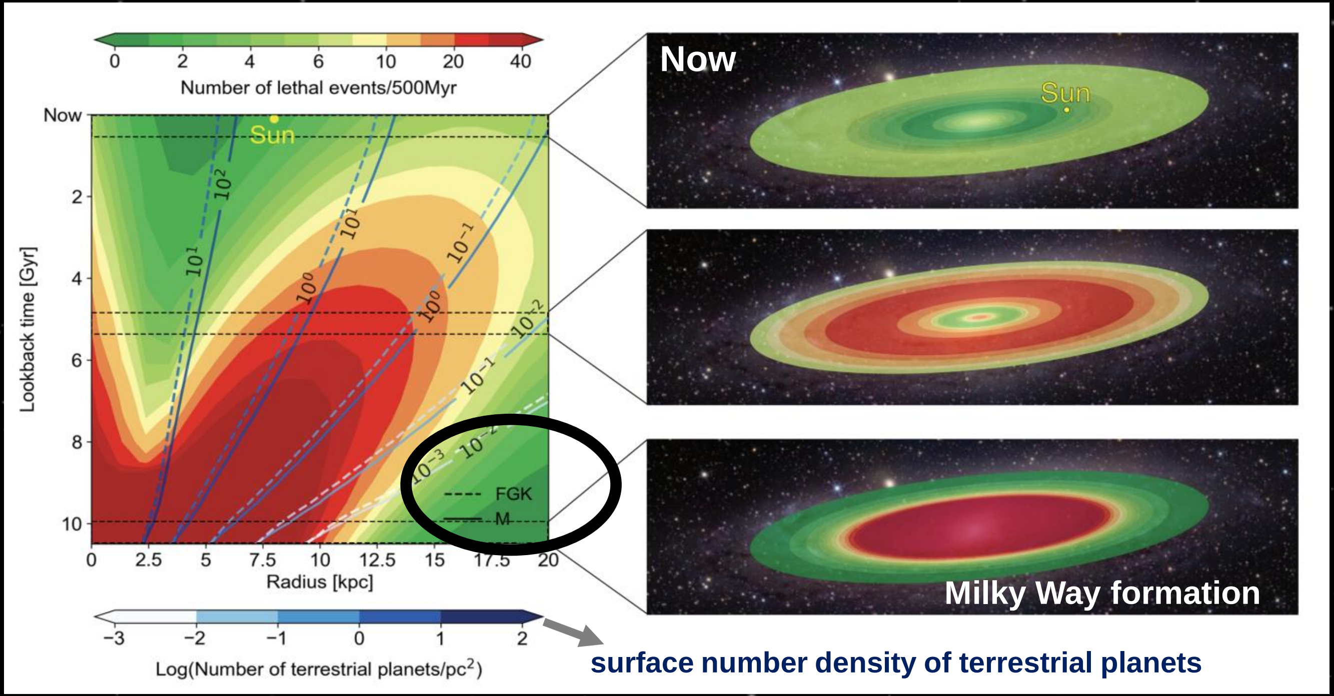
Zackrisson et al. (2016)

Metal-enriched environments favours the formation of close-orbit giants that destroy the prospect of harboring “stable” TPs.
In a very low metallicity environment, planet formation is inhibited.
The model assumes that the probabilities of forming “stable” TPs (PFTP) is higher at intermediate metallicity.



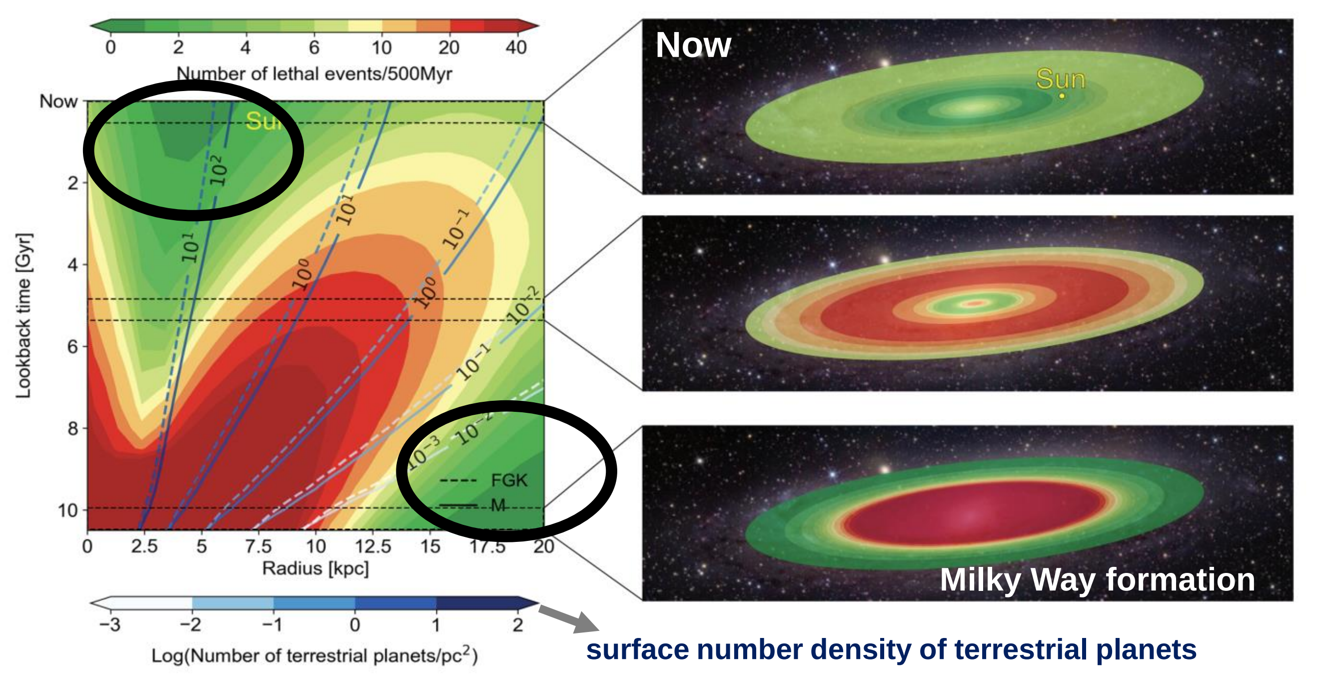
surface number density of terrestrial planets

Number of lethal events (Sne, GRBs, top colorbar) per bins of time of 500 Myr as a function of the distance from the Galactic Center (x-axis) along the Milky Way cosmic history (y-axis, the lookback time): 2 green valleys (safe regions, along the MW disk and its cosmic history).



surface number density of terrestrial planets

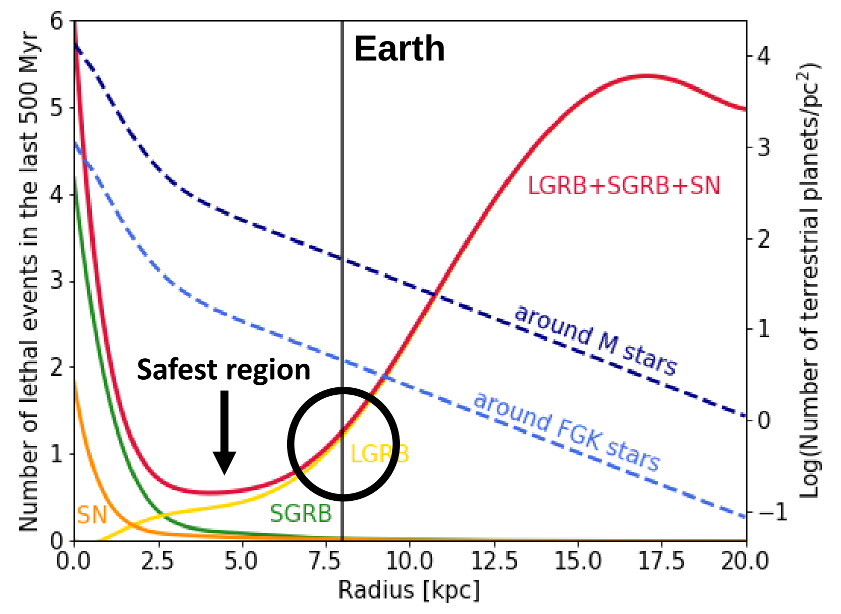
First green valley: in the peripheral region during the early stages of galaxy evolution (few lethal events because star formation is low – but the possibilities of life in this region is hampered by the low TP surface density).



surface number density of terrestrial planets

Second "green valley" is between 2 and 8 kpc from 4 Gyr ago to now: LGRBs are dominant lethal event until 6 Gyrs ago but, later on, the progressive increase of metallicity inhibits the formation of LGRBs. The higher density of TPs in this region makes this zone the best zone for the emergence and resilience of life over the last 4 Gyrs.

Number of lethal events in the last 500 Myr as a function of the galactocentric distance



- In the last 500 Myr the safest zone is between 2 and 8 kpc (minimum of the red line)
- At the Earth position, within the last 500 Myr, we estimated one lethal long GRB. A value coherent with the hypothesis that the Ordovician mass extinction event was triggered by a long GRB (Thomas & Melott 2004).

Conclusions

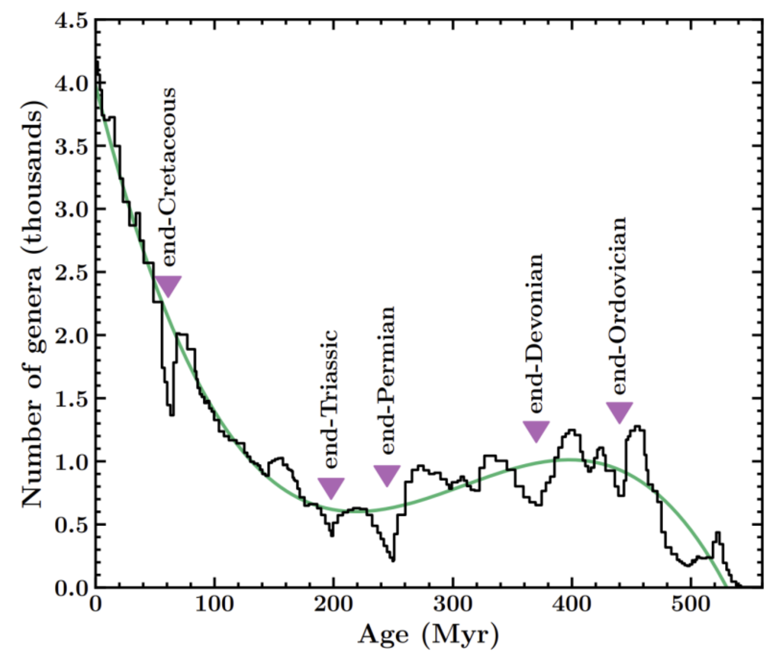
- LGBRs are the dominant lethal events
- Two green zones
- In the last 500 Myr: 1 LGRB at 8 kpc

Future prospects

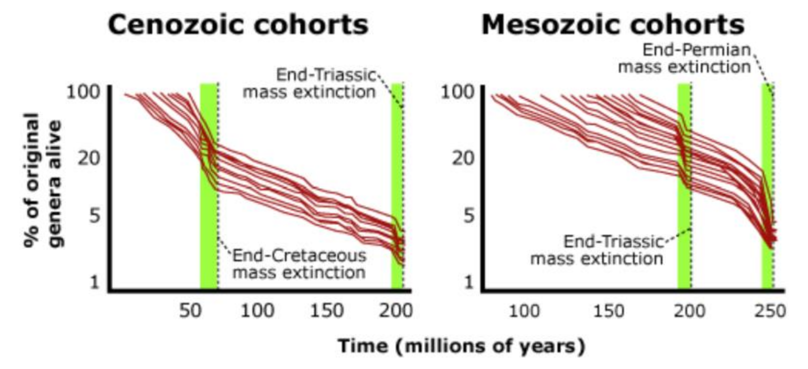
We can apply this model for different types of Galaxy and also in a cosmological context to find the best galaxy and the best cosmic epoch to live in the Universe.

Mass extinctions can “favor” the long run for the expansion of biodiversity.

After mass extinctions the surviving species has the opportunities to experiment new environments without competition, and thus, the can evolve and diversify very quickly.
This can explain the rapid increases in biodiversity following mass extinctions.



Mass extinctions occurring at the right pace could have played a pivotal role in the evolution of complex life forms on Earth(Sepkoski 1985; Raup 1994; Jablonski 2001; Krug & Jablonski 2012; Stroud & Losos 2016).



Burst of origination events follows each mass extinction
Krug & Jablonski 2012

Thanks for your attention

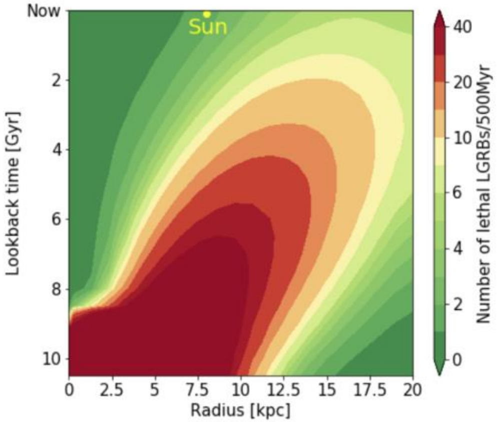


Fig. 7. Number of lethal LGRBs per bins of 500 Myr as a function of the Galactic radius and lookback time.

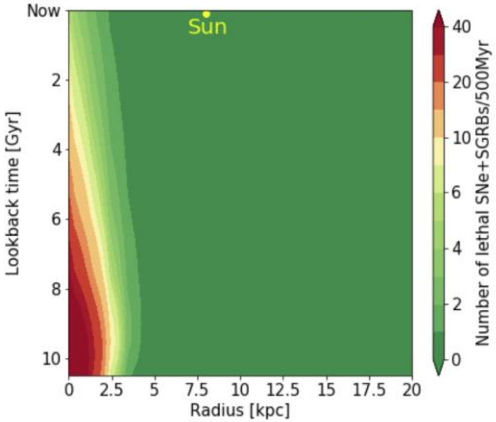


Fig. 8. Number of lethal SGRBs and SNe per bins of 500 Myr as a function of the Galactic radius and lookback time.

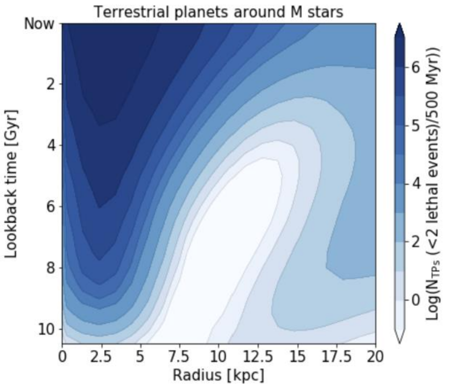


Fig. 9. Number of TPs around M stars that experienced fewer than two lethal events in 500 Myr. The number is obtained from the surface density of planets integrated in annuli of constant width (= 1 pc).

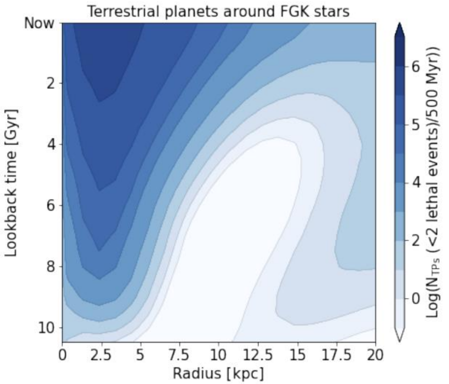
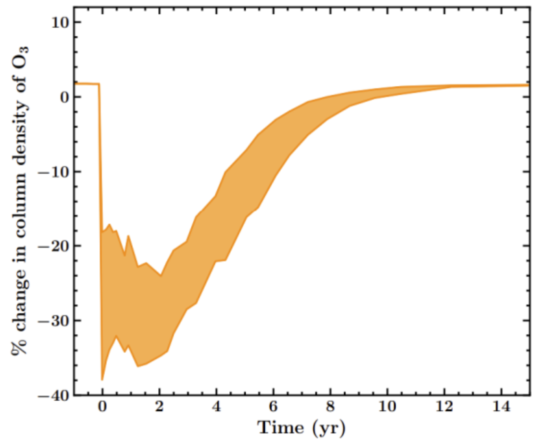
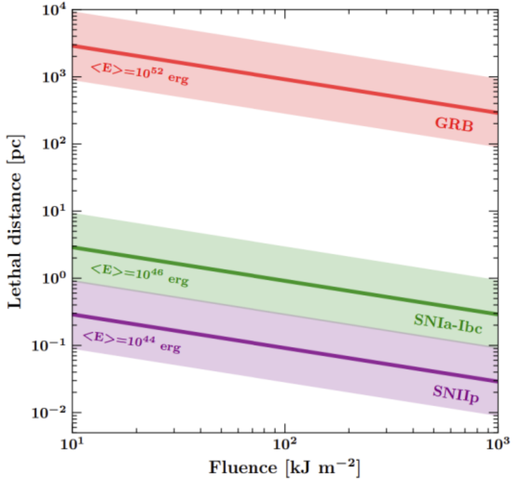


Fig. 10. Same as fig. 9, but for FGK stars.





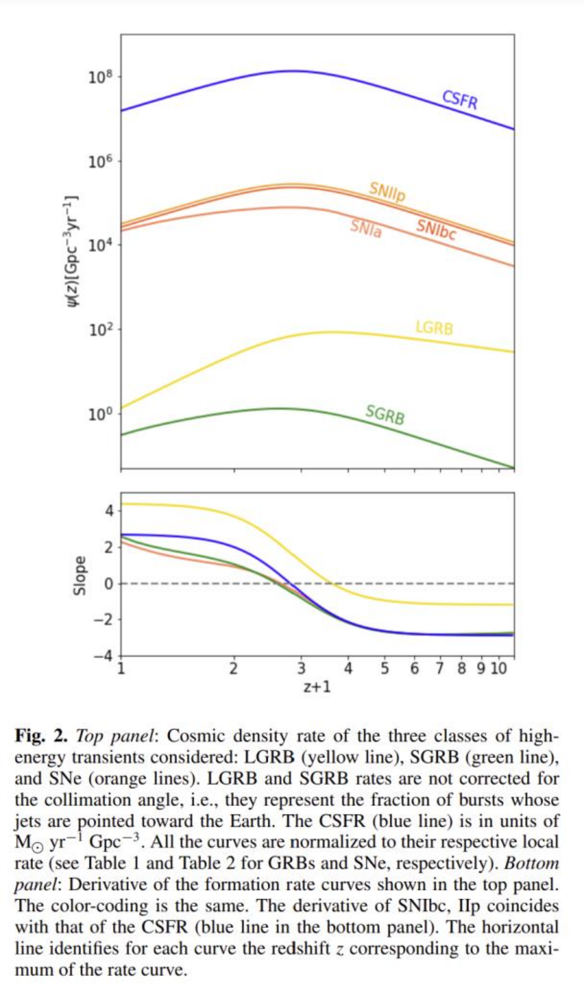
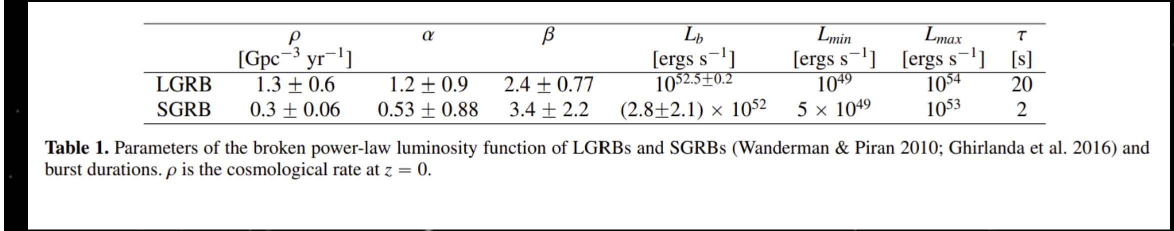
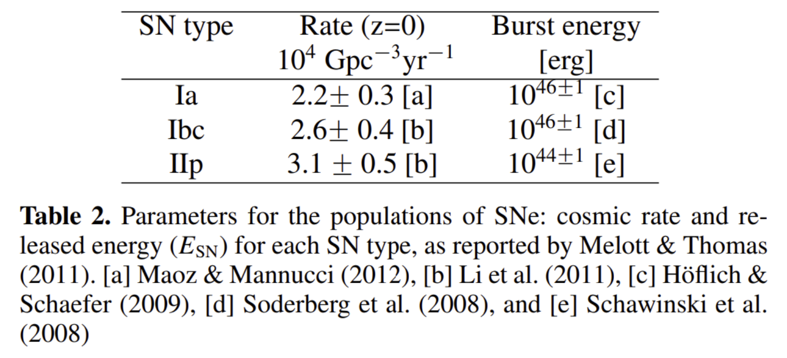


Fig. 2. *Top panel*: Cosmic density rate of the three classes of high-energy transients considered: LGRB (yellow line), SGRB (green line), and SNe (orange lines). LGRB and SGRB rates are not corrected for the collimation angle, i.e., they represent the fraction of bursts whose jets are pointed toward the Earth. The CSFR (blue line) is in units of $M_\odot$ yr^{-1} Gpc^{-3}. All the curves are normalized to their respective local rate (see Table 1 and Table 2 for GRBs and SNe, respectively). *Bottom panel*: Derivative of the formation rate curves shown in the top panel. The color-coding is the same. The derivative of SNIbc, IIp coincides with that of the CSFR (blue line in the bottom panel). The horizontal line identifies for each curve the redshift z corresponding to the maximum of the rate curve.



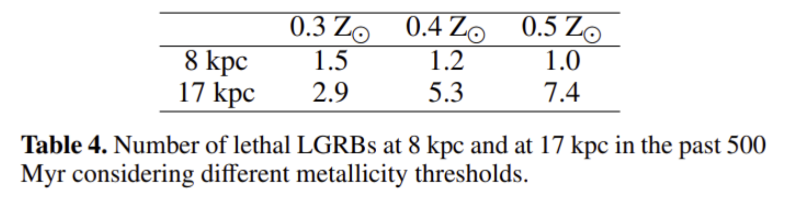
	ρ [Gpc^{-3} yr^{-1}]	α	β	L_b [ergs s^{-1}]	L_{min} [ergs s^{-1}]	L_{max} [ergs s^{-1}]	τ [s]
LGRB	1.3 ± 0.6	1.2 ± 0.9	2.4 ± 0.77	$10^{52.5 \pm 0.2}$	10^{49}	10^{54}	20
SGRB	0.3 ± 0.06	0.53 ± 0.88	3.4 ± 2.2	$(2.8 \pm 2.1) \times 10^{52}$	5×10^{49}	10^{53}	2

Table 1. Parameters of the broken power-law luminosity function of LGRBs and SGRBs (Wanderman & Piran 2010; Ghirlanda et al. 2016) and burst durations. ρ is the cosmological rate at $z = 0$.



SN type	Rate (z=0) 10^4 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$	Burst energy [erg]
Ia	2.2 ± 0.3 [a]	$10^{46 \pm 1}$ [c]
Ibc	2.6 ± 0.4 [b]	$10^{46 \pm 1}$ [d]
IIp	3.1 ± 0.5 [b]	$10^{44 \pm 1}$ [e]

Table 2. Parameters for the populations of SNe: cosmic rate and released energy (E_{SN}) for each SN type, as reported by Melott & Thomas (2011). [a] Maoz & Mannucci (2012), [b] Li et al. (2011), [c] Höflich & Schaefer (2009), [d] Soderberg et al. (2008), and [e] Schawinski et al. (2008)



	$0.3\ Z_\odot$	$0.4\ Z_\odot$	$0.5\ Z_\odot$
8 kpc	1.5	1.2	1.0
17 kpc	2.9	5.3	7.4

Table 4. Number of lethal LGRBs at 8 kpc and at 17 kpc in the past 500 Myr considering different metallicity thresholds.

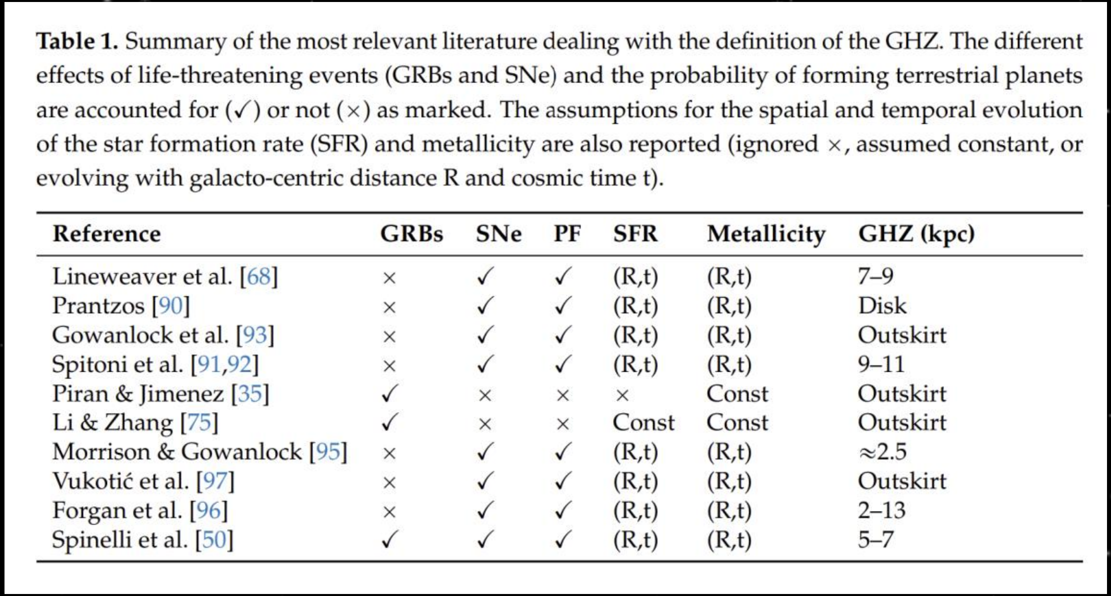


Table 1. Summary of the most relevant literature dealing with the definition of the GHZ. The different effects of life-threatening events (GRBs and SNe) and the probability of forming terrestrial planets are accounted for (✓) or not (×) as marked. The assumptions for the spatial and temporal evolution of the star formation rate (SFR) and metallicity are also reported (ignored ×, assumed constant, or evolving with galacto-centric distance R and cosmic time t).

Reference	GRBs	SNe	PF	SFR	Metallicity	GHZ (kpc)
Lineweaver et al. [68]	×	✓	✓	(R,t)	(R,t)	7–9
Prantzos [90]	×	✓	✓	(R,t)	(R,t)	Disk
Gowanlock et al. [93]	×	✓	✓	(R,t)	(R,t)	Outskirt
Spitoni et al. [91,92]	×	✓	✓	(R,t)	(R,t)	9–11
Piran & Jimenez [35]	✓	×	×	×	Const	Outskirt
Li & Zhang [75]	✓	×	×	Const	Const	Outskirt
Morrison & Gowanlock [95]	×	✓	✓	(R,t)	(R,t)	≈2.5
Vukotić et al. [97]	×	✓	✓	(R,t)	(R,t)	Outskirt
Forgan et al. [96]	×	✓	✓	(R,t)	(R,t)	2–13
Spinelli et al. [50]	✓	✓	✓	(R,t)	(R,t)	5–7