14 Other Topics

As discussed in Chapter 1, the GRB science has broader impacts in other disciplines. This chapter discusses several examples of these broader impacts. In connection with *fundamental physics*, GRB observations can be applied to constrain Lorentz Invariance Violation (LIV, §14.1), Einstein's Weak Equivalence Principle (WEP) (§14.2), and the photon mass (§14.3). The biological impacts of GRBs and a possible relation between GRBs and mass extinctions of life are discussed in §14.4.

14.1 GRB Observations and Lorentz Invariance Violation

14.1.1 Arrival Time Constraints on Lorentz Invariance Violation

It is believed that at the Planck scale ($\lambda_{\rm pl} = (\hbar G/c^3)^{1/2} \simeq 1.61 \times 10^{-33}$cm), quantum gravity (QG) effects are expected to strongly affect the nature of space-time. Lorentz invariance implies a scale-free space-time. The existence of the QG scale then implies *Lorentz invariance violation (LIV)*. One manifestation of LIV is an energy-dependent speed of light (Amelino-Camelia et al., 1998).

The energy-dependent speed of light can be derived by introducing the LIV terms in a Taylor series:

$$c^2 p_\gamma^2 = E_\gamma^2 \left[1 + \sum_{k=1}^{\infty} s_k \left(\frac{E_\gamma}{M_{{\rm QG},k} c^2} \right)^k \right], \tag{14.1}$$

where E_γ is photon energy, $s_k = 0, \pm 1$ is a model-dependent factor, and $M_{{\rm QG},k}$ is the energy scale at which QG effects become significant. Here

$$M_{\rm QG} \leq M_{\rm pl} \equiv \left(\frac{\hbar c}{G} \right)^{1/2} \simeq 1.22 \times 10^{19}~{\rm GeV}/c^2. \tag{14.2}$$

For $E_\gamma \ll M_{\rm QG} c^2$, the sum is dominated by the lowest order term with $s_k \neq 0$. The energy-dependent speed of light can therefore be expressed in terms of

$$v_\gamma = \frac{\partial E_\gamma}{\partial p_\gamma} \simeq c \left[1 - s_n \frac{1+n}{2} \left(\frac{E_\gamma}{M_{{\rm QG},n} c^2} \right)^n \right], \tag{14.3}$$

where $n = 1, 2$ correspond to linear and quadratic LIV, respectively. The coefficient s_n may be either positive ($s_n = +1$) for speed retardation (high-energy photons are slower) or negative ($s_n = -1$) for speed acceleration (high-energy photons are faster).

Within the framework of some LIV theories (e.g. the stringy-foam theory, Ellis et al. 2008), two photons with different energies emitted simultaneously from the same source would arrive at the observer at different times. For example, in the case of $s_n = +1$ (speed retardation), the photon with a higher energy (E_h) would arrive with respect to the photon with a lower energy (E_l) by a time delay (for a ΛCDM universe)

$$\Delta t = \frac{(1+n)}{2H_0} \frac{E_h^n - E_l^n}{(M_{\mathrm{QG},n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} dz'. \tag{14.4}$$

Here $(H_0, \Omega_m, \Omega_\Lambda)$ are standard cosmological parameters, and z is the redshift of the source.

In practice, it is not easy to prove LIV. When one detects a delay of high-energy photons with respect to low-energy photons, it is hard to exclude the possibility that the delay is of a pure astrophysical origin. In order to prove LIV, one needs to statistically collect many delay events and show that they all satisfy the condition (Eq. (14.4)).

On the other hand, it is relatively easy to place constraints on the *non-existence* of LIV at a certain energy scale. A smaller than expected observed delay of a high-energy photon from a distant object can be used to exclude a given model. GRBs, especially short-duration GRBs, are ideal phenomena that one can use to perform such tests since a short, sharp pulse from a GRB provides a natural reference time to measure the delay. The higher the photon energies, the shorter the time delay, and the larger the source distance, the more stringent constraint one can reach.

An example is the short GRB 090510 jointly detected by *Fermi* GBM and LAT. The burst has a redshift $z = 0.903 \pm 0.003$. One 31 GeV photon was detected 0.829 s after the GBM trigger. The data are good enough to constrain LIV models that invoke linear LIV ($n = 1$). The *Fermi* team (Abdo et al., 2009a) was able to pose several stringent constraints on the allowed LIV (Fig. 14.1). If one associates the 31 GeV photon with the emission time of a particular low-energy photon (based on a certain reasoning), one can place a lower limit on the characteristic mass $M_{\mathrm{QG},1}$ of the linear LIV models:

- The most conservative constraint is derived by associating the 31 GeV photon with the trigger time. One therefore has $\Delta t \leq 859$ ms. This gives a conservative constraint $M_{\mathrm{QG},1} > 1.19 M_{\mathrm{pl}}$;
- If the 31 GeV photon was emitted at the beginning of the <MeV main emission episode, one has $\Delta t \leq 299$ ms, which gives $M_{\mathrm{QG},1} > 3.42 M_{\mathrm{pl}}$;
- If the 31 GeV photon was emitted at the beginning of the >100 MeV emission, one has $\Delta t \leq 181$ ms, which gives $M_{\mathrm{QG},1} > 5.12 M_{\mathrm{pl}}$;
- If the 31 GeV photon was emitted at the beginning of the >1 GeV emission, one has $\Delta t \leq 99$ ms, which gives $M_{\mathrm{QG},1} > 10.0 M_{\mathrm{pl}}$;
- Finally, if the 31 GeV photon is associated with the MeV spike that coincides with the photon in time, then a most stringent constraint $M_{\mathrm{QG},1} > 102 M_{\mathrm{pl}}$ can be reached.

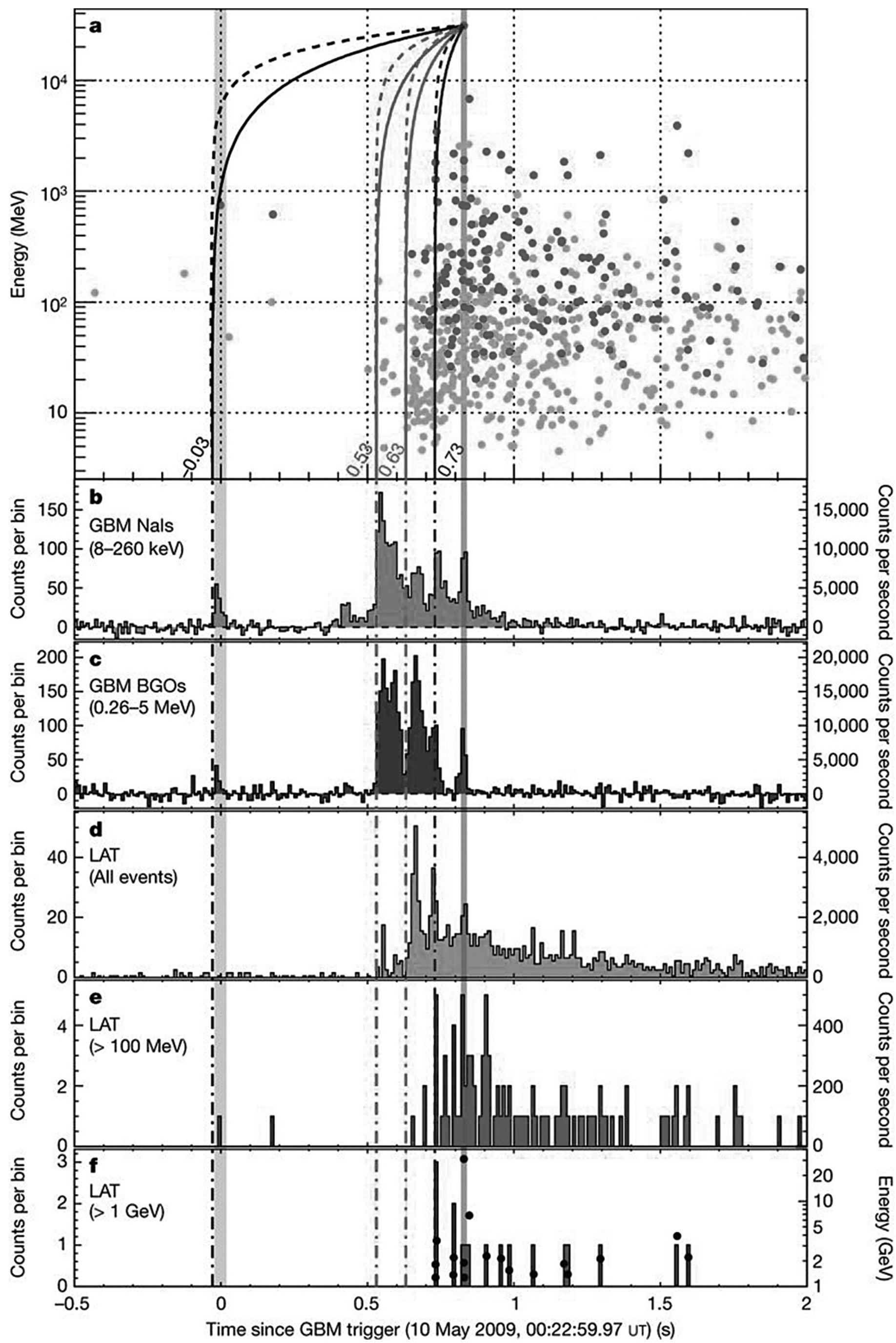

Figure 14.1 Using the 31 GeV photon detected from the short GRB 090510 to constrain LIV models. From Abdo et al. (2009a).

Since $M_{\mathrm{QG},1}$ is expected to be around M_{pl} and not much larger, these results greatly disfavor the linear LIV models, and are fully consistent with Lorentz invariance.

The constraints may be further improved if one can properly correct for the intrinsic astrophysical spectral lags. Wei et al. (2017a,b) derived the formalism of combining the intrinsic astrophysical delay and LIV-related delay and applied the method to the long GRB 160625B. The constraints are not better than for GRB 090510, but the method, when applied to future bright short GRBs, may lead to more stringent constraints on the LIV.

14.1.2 Polarization Constraints on LIV and CPT Violation

In QG models that invoke LIV, the CPT theorem, i.e. the invariance of physical laws under charge conjugation/parity transformation/time reversal, no longer holds. In the photon sector, these models invoke a Lorentz- and CPT-violating dispersion relation of the form (e.g. Myers and Pospelov, 2003)

$$E_{\pm}^2 = p^2 \pm \frac{2\xi}{M_{\mathrm{pl}}} p^3, \tag{14.5}$$

where $\pm$ denote two different circular polarization states, and ξ is a dimensionless parameter. For $\xi \neq 1$, two different polarization states have slightly different propagation group velocities. The polarization vector of a linearly polarized wave therefore rotates during propagation. At an infinitesimal time interval dt, the polarization vector rotates by a small angle $d\theta = (E_+ - E_-)dt/2 \simeq \xi p^2 dt/M_{\mathrm{pl}}$. For a GRB at redshift z, the total rotation angle is (Fan et al., 2007; Toma et al., 2012)

$$\Delta\theta(p_z, z) \simeq \xi \frac{p_z^2 F(z)}{M_{\mathrm{pl}} H_0}, \tag{14.6}$$

where $p_z = p/(1+z)$ is the momentum in the comoving frame, and the function $F(z)$ is a function related to the look back time, which reads (in the standard ΛCDM model)

$$F(z) = \int_0^z \frac{(1+z')dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}. \tag{14.7}$$

Observationally, photons with a range of energies are observed. If the rotation angles of these photons with different energies differ by more than $\pi/2$ over a range of the energy band, significant depletion of the net polarization degree is expected. The detection of a high polarization degree of emission therefore sets a constraint on these QG models.

Toma et al. (2012) applied the polarization data of three GRBs detected by the Gamma-ray burst Polarimeter (GAP) on board the Japanese solar-power-sail demonstrator *IKAROS*, i.e. GRB 110721A with $\Pi > 35\%$ at $z > 0.45$, GRB 100826A with $\Pi > 6\%$ at $z > 0.71$, and GRB 110301A with $\Pi > 31\%$ at $z > 0.21$, to perform such a birefringence smearing test. Stringent constraints on the value of ξ were obtained. In particular, the most stringent constraint was obtained with the data of GRB 110721A, which reads

$$|\xi| < 2 \times 10^{-15}. \tag{14.8}$$

Fan et al. (2007) earlier applied the same method to UV/optical polarization data of GRB afterglow and obtained a less stringent constraint on $|\xi|$.

14.2 GRB Observations and Einstein's Weak Equivalence Principle

Einstein's weak equivalence principle (WEP) states that all test particles have the same acceleration in a gravitational field, independent of their masses. This is the foundation of the geometric interpretation of gravity and the General Theory of Relativity (GR). A famous test of the principle was the legendary Galileo's Leaning Tower of Pisa experiment.

The consistency with WEP is delineated by one parameterized post-Newtonian (PPN) formalism parameter, γ, of a particular gravity theory. In GR, γ is predicted to be strictly 1. Some other gravity theories also predict $\gamma = 1$. In any case, a deviation of γ from 1 would suggest a violation of WEP. The tests may be performed for different masses, but can be extended to other particles with different energies, including photons, neutrinos, and gravitational waves.

Photons (and other massless particles) would experience a time delay (named the Shapiro delay) in a gravitational field. The delay time can be written as (Shapiro, 1964; Krauss and Tremaine, 1988; Longo, 1988)

$$\delta t = -\frac{1+\gamma}{c^3} \int_{r_e}^{r_o} U(r) dr, \tag{14.9}$$

where r_e and r_o are the locations of the source of emission and observer, respectively, and $U(r)$ is the gravitational potential along the way. The absolute deviation of γ from unity for photons has been constrained to $\gamma - 1 \leq (2.1 \pm 2.3) \times 10^{-5}$ from the travel time delay of a radar signal in the radio band via Doppler tracking of the *Cassini* spacecraft (Bertotti et al., 2003).

On an astrophysical scale, Longo (1988) and Krauss and Tremaine (1988) used the observed delay between photons and neutrinos (<6 hours) and the delay between 7.5 MeV and 40 MeV neutrinos (<10 s) from SN 1987A to set $|\gamma_\nu - \gamma_\gamma| \leq 3.4 \times 10^{-3}$ and $|\gamma_{\nu,40\mathrm{MeV}} - \gamma_{\nu,7.5\mathrm{MeV}}| \leq 1.6 \times 10^{-6}$.

Gao et al. (2015b) (see also Sivaram 1999) suggested that one can use the arrival time delay of photons of different energies from transient sources to constrain WEP, i.e.

$$\Delta t_{\mathrm{obs}} > \frac{\gamma_1 - \gamma_2}{c^3} \int_{r_e}^{r_o} U(r) dr > \frac{\gamma_1 - \gamma_2}{c^3} \int_{r_e}^{r_o} U_{\mathrm{MW}}(r) dr, \tag{14.10}$$

where γ_1 and γ_2 are the respective γ values for the two energy bands under investigation, and $U_{\mathrm{MW}}(r)$ is the Milky Way gravitational potential, which can be quantified based on the arrival direction of a transient source. They applied the method to GRBs and obtained $\gamma_{\mathrm{GeV}} - \gamma_{\mathrm{MeV}} < 2 \times 10^{-8}$ for GRB 090510, and $\gamma_{\mathrm{eV}} - \gamma_{\mathrm{MeV}} < 1.2 \times 10^{-7}$ for GRB 080319B. Together with the Shapiro delay constraint on the absolute γ deviation of optical emission $\gamma_{\mathrm{eV}} - 1 \leq 0.3\%$ (Froeschle et al., 1997), this extends the 0.3% accuracy to the GeV band.

The same method can be applied to other transient sources such as fast radio bursts (Wei et al., 2015), TeV blazars (Wei et al., 2016), and a sharp nanosecond giant pulse of the Crab pulsar (Yang and Zhang, 2016), which give more stringent constraints in different pair frequencies. The method can also be applied to gravitational wave sources with electromagnetic counterparts so that the relative γ difference between photons and GWs can be measured (Wu et al., 2016b). GRB 170817A is delayed by 1.7 s with respect to the merger time of GW170817 (Abbott et al., 2017b; Zhang et al., 2018a). This gives $-2.6 \times 10^{-7} \leq \gamma_{\rm GW} - \gamma_{\rm EM} \leq 1.2 \times 10^{-6}$ by considering only the gravitational potential of the Milky Way outside a sphere of 100 kpc (Abbott et al., 2017b). A more stringent limit $|\gamma_{\rm GW} - \gamma_{\rm EM}| \lesssim 0.9 \times 10^{-10}$ can be achieved when the gravitational potential of the Virgo Cluster is considered (Wei et al., 2017c).

Wu et al. (2017) suggested that multi-band photons with different polarizations from GRBs and other astrophysical transients can also be used to constrain WEP through the Shapiro time-delay effect.

14.3 GRB Observations and Photon Rest Mass

The Maxwell equations and special relativity require that the photon rest mass, m_γ, is strictly zero. Many experiments or observations have already posed very stringent upper limits on m_γ. An ultimate upper limit is defined by the uncertainty principle, i.e. $m_\gamma \leq \hbar/(\Delta t)c^2 \simeq 2.7 \times 10^{-66}$ g, where $\Delta t \sim 1.38 \times 10^{10}$ yr is taken as the age of the universe. The most stringent upper limit on m_γ adopted by the Particle Data Group is $m_\gamma \leq 1.783 \times 10^{-51}$ g (Olive and Particle Data Group, 2014).

The most straightforward way to constrain m_γ is through measuring the time delay of photons with different energies. This is because, with a non-zero m_γ, photons with different energies travel with different Lorentz factors and hence, over a long travel distance, would show a difference in the arrival times even if they were emitted at the same time.

For a non-zero m_γ photon, the energy of the photon is $E = h\nu = (p^2c^2 + m_\gamma^2 c^4)^{1/2}$. The dispersion of the group velocity of photons in vacuum would be

$$v = \frac{\partial E}{\partial p} = c\left(1 - \frac{m_\gamma^2 c^4}{E^2}\right)^{1/2} \simeq c(1 - 0.5A\nu^{-2}), \tag{14.11}$$

where

$$A = \frac{m_\gamma^2 c^4}{h^2}. \tag{14.12}$$

If A could be constrained from the observations, the photon mass would be derived as

$$m_\gamma = A^{1/2}hc^{-2} \simeq (7.4 \times 10^{-48}\ \text{g})A^{1/2}. \tag{14.13}$$

For a cosmological transient, the A parameter can be derived from the time delay Δt between two frequencies ν_1 and ν_2 through (Wu et al., 2016a)

$$A = \frac{2H_0\Delta t}{(\nu_1^{-2} - \nu_2^{-2})H(z)}, \tag{14.14}$$

where

$$H(z) = \int_0^z \frac{dz'}{(1+z')^2\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}. \tag{14.15}$$

One can see that A is smaller for a lower value of ν_1 (the smaller of the two frequencies). This is understandable, since a lower frequency corresponds to a lower Lorentz factor of the photon, so that the deviation of the speed from c may be more significant.

Schaefer (1999) used the radio–γ-ray delay in GRB 980703 to set $m_\gamma < 4.2 \times 10^{-44}$ g. Zhang et al. (2016a) systematically investigated a sample of GRBs with well-defined radio lightcurves and constrained m_γ using the radio–γ-ray delay and relative delay between different radio frequencies. They achieved better constraints than Schaefer (1999): for GRB 050416A, the radio–γ-ray delay gives $m_\gamma < 1.062 \times 10^{-44}$ g. Using the peak time difference between two different frequencies (1.43 GHz and 8.46 GHz) in GRB 991208, Zhang et al. (2016a) derived $m_\gamma < 1.161 \times 10^{-44}$ g.

Due to their low-frequency nature and much shorter durations, fast radio bursts are better transients for constraining m_γ. Wu et al. (2016a) and Bonetti et al. (2016) showed that m_γ can be constrained to $\sim 10^{-47}$ g using individual FRBs. A tighter constraint can be achieved statistically with a sample of FRBs within a Bayesian framework (Shao and Zhang, 2017).

14.4 Biological Impact of GRBs and Mass Extinction

As the most luminous explosions in the universe, GRBs may become dangerous if they are near to a planet that harbors life. A number of studies (e.g. Ruderman, 1974; Thorsett, 1995; Dar et al., 1998; Scalo and Wheeler, 2002; Gehrels et al., 2003; Melott et al., 2004) suggested that major atmospheric ionizing radiation events such as GRBs and supernovae inevitably lead to significant ozone depletion in the stratosphere, which causes an increase of solar UV irradiation at Earth's surface and in the top tens of meters of the ocean. It has been hypothesized that such events with sufficient intensity (if they are close enough to Earth) would cause a severe biological impact leading to a mass extinction (e.g. Melott et al., 2004; Thomas et al., 2005b,a; Melott and Thomas, 2011).

Some basic ozone-related chemical reactions include the following (Gehrels et al., 2003):

- Formation of ozone molecules: An oxygen molecule can easily be photodissociated by a UV photon into two atoms of oxygen (O), each attaching to an O_2 molecule through a three-body process to form an O_3 molecule:

$$\mathrm{O_2} + h\nu(<242\,\mathrm{nm}) \rightarrow \mathrm{O} + \mathrm{O}, \tag{14.16}$$

$$\mathrm{O} + \mathrm{O_2} + \mathrm{M} \rightarrow \mathrm{O_3} + \mathrm{M}. \tag{14.17}$$

  Here M is a third-body molecule, which is usually either N_2 (78% of the atmosphere) or O_2 (21% of the atmosphere).
- Ozone can be destroyed through a number of catalytic reactions involving NO_y and several other families of molecules. In particular, odd nitrogen NO_y can be created from cosmic rays or γ-rays impacting the atmosphere. An example of NO_y destroying ozone is

$$\mathrm{NO} + \mathrm{O_3} \rightarrow \mathrm{NO_2} + \mathrm{O_2}, \tag{14.18}$$

$$\mathrm{NO_2 + O \rightarrow NO + O_2}, \tag{14.19}$$

which gives a net reaction

$$\mathrm{O_3 + O \rightarrow O_2 + O_2}, \tag{14.20}$$

with NO serving as the catalyst.

There are many chemical processes that contribute to formation and destruction of ozone in the atmosphere. Computer simulations are needed to resolve the net effect.

Thomas et al. (2005b) simulated the impact of a GRB with $E_{\gamma,\mathrm{iso}} = 5 \times 10^{52}$ erg (a 10 s duration burst with mean luminosity of $L_{\gamma,\mathrm{iso}} = 5 \times 10^{51}$ erg s^{-1}) at 2 kpc away from Earth, which would give a γ-ray fluence 100 kJ m^{-2} = 10^8erg cm^{-2}. They found that the γ-rays would penetrate the stratosphere leading to rapid increase of nitrogen compounds (NO and NO_2) in the atmosphere, causing an on-average 35% of ozone depletion, with depletion reaching 55% at some latitudes. Significant depletion would persist for over 5 years after the burst. A 50% decrease in ozone column density would lead to $\sim$3 times the normal UVB (280–315 nm) flux from the Sun. As a result, such a disastrous event would lead to damage of DNA and widespread extinction of life forms on Earth. Other effects include production of NO_2, which would cause a decrease of the visible sunlight and therefore global cooling, as well as deposition of nitrates through nitric acid rain (Thomas et al., 2005a).

The event rate of these classical high-luminosity GRBs beaming towards Earth within the Milky Way is about once per Gyr. The late Ordovician mass extinction, which happened $\sim$447 Myr ago, has been hypothesized as due to a GRB (Melott et al., 2005).

Piran and Jimenez (2014) discussed the chance of lethal GRBs damaging life forms in the Galaxy and the universe, and concluded that the inner Milky Way is inhospitable to life because of the high event rate of GRBs, and that life as it exists on Earth could not take place at $z > 0.5$. Piran et al. (2016) further argued that the universe we are living in (the one with a cosmological constant Λ of the measured value) is favorable for the survival of life against GRBs.

Li and Zhang (2015) used the measured star formation rate and metallicity data of Sloan Digital Sky Survey (SDSS) galaxies and estimated the GRB rate in each of those galaxies. Taking 1 per 500 Myr as a conservative duty cycle for life to survive, as evidenced by our existence (after the Ordovician mass extinction $\sim$447 Myr ago), they found that a good fraction of $z > 0.5$ galaxies are still "habitable". Through Monte Carlo simulations, they estimated that the fraction of benign galaxies is $\sim$50% at $z \sim 1.5$ and $\sim$10% even at $z \sim 3$. Indeed we are living in an era when the GRB rate is low enough to allow life to develop in abundance, but early life forms back in $z \sim 1.5$–3 may also survive GRBs if they were able to develop and happened to live in habitable galaxies.

Later more detailed studies suggested that the biological impacts of GRBs on life on Earth may not be as simple as early results indicated. For example, Neale and Thomas (2016) showed that the biological damage to some ocean phytoplankton species is smaller than previously believed, so that a collapse of the base of the marine food chain, as initially expected, may be unlikely. The biological impact on life of an ionization event such as a

GRB may be less significant than previously hypothesized. More detailed chemical and biological studies are needed to draw a firmer conclusion.

An opposite hypothesis (Chen and Ruffini, 2015) suggested that a GRB event 500 pc away might have triggered the Cambrian explosion 540 Myr ago through inducing genetic mutations, which led to the rapid growth of life on Earth.