High energy neutrinos from gamma-ray burst fireballs

Irene Tamborra
GRAPPA Institute, University of Amsterdam, 1098 XH, Amsterdam, The Netherlands
E-mail: i.tamborra@uva.nl

Abstract. The diffuse high-energy neutrino emission from long and short gamma-ray bursts (GRBs) is studied within the fireball emission model. By requiring that the GRB high-energy neutrino counterparts follow up-to-date gamma-ray luminosity functions and redshift evolutions, we find that GRBs could contribute up to a few percents to the observed IceCube high-energy neutrino flux for sub-PeV energies, if the latter has a diffuse origin. Our findings suggest that larger exposure is mandatory to detect neutrinos from GRBs in future stacking searches.

1. Introduction
Gamma-ray bursts (GRBs) are among the most energetic events in the Universe and have been suggested as sources of ultra-high energy cosmic rays. They are usually divided into two distinct groups: Long-duration bursts (lasting for more than 2 s) and short-duration bursts (lasting for less than 2 s). Long duration bursts are thought to originate from the collapse of a massive star to a black hole [1], while short-duration ones should originate from coalescing neutron stars or black-hole–neutron-star mergings [2].

Although with different origin, short- and long-duration bursts might be driven by the same underlying mechanism: The fireball model [3, 4]. Neutrinos with energies of $\mathcal{O}(100)$ TeV are expected to be emitted from these sources because of lepto-hadronic interactions.

Over the past years, the IceCube telescope performed searches for muon neutrinos associated to GRBs, but with negative results (see Ref. [5] and references therein). The IceCube upper limits therefore started to put tight constraints on the expected GRB flux and on the theoretical models employed to explain the neutrino emission from these sources. The diffuse neutrino emission from GRBs has been recently invoked as a natural possibility to explain the PeV neutrino events discovered from IceCube [4, 6, 7], assuming that such events have a diffuse origin.

In light of the unsuccessful most recent IceCube stacking analysis and of the high-energy neutrino flux discovery, we provide an up-to-date estimation of the expected high-energy neutrino prompt emission from long- and short-duration GRB fireballs. Our results show that, for average GRB parameters compatible with observations, the diffuse neutrino emission from GRBs could contribute up to a few % to the IceCube high-energy neutrino flux in the sub-PeV region while GRBs might be the main source of the IceCube flux in the PeV range.

This manuscript is organised as follows. In Section 2 we introduce constraints coming from gamma-ray observations on the luminosity functions and redshift distribution of GRBs. In
Figure 1. Left: Redshift distribution of the HL-GRBs (light blue), LL-GRBs (violet), and sGRBs (orange). Each family is normalised to its local rate. The LL-GRB local rate is higher than the HL-GRB and the sGRB ones, and the sGRB rate quickly decreases for \( z \geq 1 \). Right: \( E_\nu^3 F_\nu (E_\nu) \) (black line) and \( E_\nu^3 F_\nu (dE_\nu) \) (red line) for a typical HL-GRB at \( z = 1 \) and without flavor oscillations.

Sec. 3, we discuss the expected neutrino spectrum. In Sec. 4, our results on the diffuse emission from these sources are shown. Conclusions are reported in Sec. 5.

2. Observational constraints

Long-duration GRBs are usually divided in two sub-categories: High-luminosity (HL) and low-luminosity (LL) GRBs. The source rate evolution as a function of the redshift \( z \) of the HL component is modelled as in Ref. [8] and it is shown in light blue in Fig. 1 (left panel). The HL-GRB typical luminosities vary in the interval \([10^{49}, 10^{54}] \) erg s\(^{-1}\) and we adopt the intrinsic isotropic luminosity function (LF) as in Ref. [9].

The LL-GRBs are characterised by a luminosity smaller than the HL-GRB one, i.e. \( 10^{46} \)–\( 10^{49} \) erg s\(^{-1}\). We define the LL-GRB redshift rate as in Ref. [10] and parametrized the LL-GRB LF as in Ref. [10, 11].

For both the LL- and HL-GRBs, we assume that the injected (inj) gamma-ray energy spectrum is fitted with a Band-spectrum. The photon break energy \( E_{\gamma,b} \) is usually expressed as a function of the isotropic energy in the GRB frame (\( E_{\text{iso}} \)) through the so-called “Amati relation” [12]. The isotropic energy of each GRB in the source rest frame can be expressed as a function of the isotropic luminosity (\( L_{\text{iso}} \)) by combining the “Yonetoku relation” [13] and the Amati one [12] for long-duration GRBs. We assume that the Amati and Yonetoku relations hold for LL- and HL-GRBs.

In order to model the sGRB redshift distribution and their luminosity function, we follow Ref. [14]. The sGRB rate as a function of the redshift is plotted in Fig. 1 (orange band). The LF is fitted with a broken power law [14].

3. Prompt neutrino emission from gamma-ray bursts fireballs

The neutrino production in GRBs mainly occurs through \( p\gamma \) interactions. The main reactions that we study are \( p + \gamma \rightarrow \Delta \rightarrow n + \pi^+ , p + \pi^0 \) and \( p + \gamma \rightarrow K^+ + \Lambda/\Sigma \). Pions, kaons and neutrons in turn decay into neutrinos.

The neutrino energy spectrum for one flavor \( (\nu + \bar{\nu}) \) resulting from \( \pi, K \), and \( \mu \) decays will be a broken power law derived from the parent proton spectrum (that we assume proportional to \( E_p^{-2} \)) with further breaks defined according to the hierarchy of the cooling processes. In fact
the first break, \( E_{\nu,b} \), appears in correspondence of the \( \Delta \) resonance. Below \( E_{\nu,b} \), the number of photons with energy \( E_\gamma \) that a proton with energy \( E_p \simeq E_\nu/0.05 \) can interact with is suppressed by a factor of \( (E_\gamma/E_{\gamma,b})^{1-\beta_\gamma} = (E_{\nu,b}/E_\nu)^{1-\beta_\gamma} \), and the resulting neutrino spectrum is harder by a factor of \( E_\nu^{\beta_\gamma-1} \) with respect to the proton spectrum (\( \beta_\gamma \) being the spectral index of the Band spectrum) [15]. Above \( E_{\nu,b} \), the neutrino spectrum is the same as the proton spectrum and if the mesons produced by the \( p\gamma \) interactions decay faster than they cool, the correspondent neutrino spectrum is not affected. Otherwise, other neutrino break energies are determined by the radiative cooling (rc; synchrotron radiation and inverse Compton scattering), adiabatic cooling (ac), and hadronic cooling (hc) processes. Therefore the neutrino spectrum is modified by an additional factor of \( [1 - \exp(-t'_c m_a/E_0' \tau_a)] \), where \( a = \pi, K, \mu \) (the decay products of \( p\gamma \) interactions), \( \tau_a \) (\( m_a \)) is the lifetime (mass) of \( a \) and \( t'_c \) is the resultant cooling time.

For typical GRB parameters [15], the hadronic cooling is negligible for HL-GRBs and sGRBs. On the other hand, the radiative cooling and the adiabatic one are always relevant for all three GRB families for both pions and muons. However, such hierarchy among the cooling processes is a function of \( L_{iso} \) and \( z \) for other fixed GRB parameters; it will change within the luminosity and redshift range that we will consider for the computation of the diffuse neutrino emission. The resultant neutrino spectrum from kaon decay is affected, similarly to the one of pions, from hadronic, adiabatic, and radiative cooling processes. The hadronic cooling is negligible, while the adiabatic cooling is relevant for muons. The break energies in the neutrino spectrum due to the kaon radiative cooling occur at energies higher than the ones due to pion radiative cooling given the differences in the rest-mass and lifetimes of the two parent particles.

For each decay channel \( \nu_i \) (with \( i = \pi, K, \mu_\pi, \mu_K \)), the neutrino energy spectrum is normalized in terms of the total photon fluence:

\[
\int_0^\infty dE_\nu \frac{dN_\nu}{dE_\nu} = N_i \frac{h_{p,i}}{h_\gamma} \left[ 1 - (\langle \chi_p \rangle)^{\tau_{p\gamma}} \right] \int_0^\infty dE_\gamma \frac{dN_\gamma}{dE_\gamma} \quad .
\]

In our numerical computations, we assume \( h_{\gamma\gamma} = L_{iso}/L_p = 10^{-2} \) for HL-GRBs and sGRBs and \( h_{\gamma\pi} = 10^{-3} \) for the LL-GRB family. The term \( [1 - (\langle \chi_p \rangle)^{\tau_{p\gamma}}] \) represents the fraction of the proton energy that goes to pion production with \( \langle \chi_p \rangle \simeq 0.2 \) the average fraction of energy transferred from protons to pions or kaons per \( p\gamma \) interaction, \( \tau_{p\gamma} \) is the \( p\gamma \) optical depth, \( N_i \) the multiplicity factor, and \( h_{p,i} \) is \( \simeq \ln(E_{\nu,second}/E_{\nu,first})/\ln(E_{p,max}/E_{p,min}) \) with \( E_{\nu,first} \) the minimum neutrino break energy and \( E_{\nu,second} \) the second neutrino break energy, both defined according to the hierarchy of the break energies determined by the cooling processes and \( E_{\nu,b} \). The minimum proton energy is \( E_{p,min} = \Gamma m_p c^2/(1+z) \) with \( m_p \) the proton rest mass, while the maximum proton energy is \( E_{p,max} \) and it is defined as the energy when the proton acceleration time is comparable with the proton cooling time [15]. Note that in order to consistently normalize the neutrino spectrum as in Eq. (1), we need to select the GRB parameters in such a way to have optically thin media. However, the latter condition does not apply to LL-GRBs as the average photon energy is lower than the pair production threshold.

The observed neutrino spectrum from a single source at redshift \( z \) is defined as

\[
F_\nu(E_\nu) = \frac{(1+z)^3}{4\pi \Gamma d_L'(z)} \left( \frac{dN_\nu}{dE_\nu} \right) \quad ,
\]

with \( E'_\nu = E_\nu(1+z)/\Gamma \) the comoving neutrino energy and \( d_L(z) \) the luminosity distance computed assuming a flat \( \Lambda \)CDM cosmology. The total \( \nu_e \) and \( \nu_\mu \) neutrino spectra from pion decay at the source and without flavor oscillation are: \( (dN_{\nu_e}/dE'_\nu)_{inj,\pi} = (dN_{\nu_\mu}/dE'_\nu)_{inj,\mu} \) and \( (dN_{\nu_e}/dE'_\nu)_{inj,\pi} = (dN_{\nu_\mu}/dE'_\nu)_{inj,\mu} + (dN_{\nu_\mu}/dE'_\nu)_{inj,\pi} \) and similarly for kaons. Note that no \( \tau \) neutrinos are produced. The right panel of Fig. 1 shows the resultant \( \nu_e \) (in black) and \( \nu_\mu \) (in red) neutrino
Figure 2. Diffuse $\nu_\mu$ intensity as a function of the neutrino energy after flavor oscillations for the HL-GRB (blue band), LL-GRB (violet band) and sGRB (orange band) families. The bands represent uncertainties related to the luminosity functions and local rates. The best fit estimation of the high-energy diffuse neutrino flux as in Ref. [17] is plotted in light blue, while the blue dot (IC-GRB) marks the upper limit of the GRB diffuse neutrino flux from the IceCube Collaboration [5].

energy spectra from pion and kaon decays as a function of the energy without flavor oscillations for a HL-GRB at $z = 1$. These spectra result from neutrino spectrum coming from muon decay from pions exhibiting four breaks, the first one corresponds to the first energy break ($E_{\nu,b}$), the second is due to the muon radiative cooling, the third to the adiabatic cooling of muons and the fourth occurs at the same energy of the second break of the pion spectrum and it is indeed due to the radiative cooling of the parent pion. For kaons only the first break energy is relevant, while the neutrino spectrum coming from muon decay from kaons is similar to the $\mu_\pi$ one. While neutrinos travel to reach the Earth, they are subject to flavor oscillations and therefore the three flavors will be equally abundant on Earth (see, e.g., Appendix B of Ref. [16]).

4. High-energy diffuse neutrino background from gamma-ray bursts

The diffuse neutrino intensity from each GRB component (X) can be defined in terms of the gamma-ray luminosity function, through $\Phi_X(\tilde{L}_{\text{iso}})d\tilde{L}_{\text{iso}} = \Phi_X(\tilde{L}_\nu)d\tilde{L}_\nu$ with $\Phi$ the LF:

$$I_X(E_\nu) = \int_{z_{\text{min}}}^{z_{\text{max}}} dz \int_{L_{\text{min}}}^{L_{\text{max}}} d\tilde{L}_{\text{iso}} \frac{c}{4\pi H_0 \Gamma} \frac{1}{\sqrt{\Omega_M (1 + z)^3 + \Omega_X}} R_X(z) \Phi_X(\tilde{L}_{\text{iso}}) \left( \frac{dN_{\nu\mu}}{dE'_\nu} \right)_{\text{osc}},$$

with $[z_{\text{min}}, z_{\text{max}}] = [0, 11]$, and $\tilde{L}_{\text{iso}} \in [L_{\text{min}}, L_{\text{max}}]$ with $\tilde{L}_{\text{min}}$ and $\tilde{L}_{\text{max}}$ defined as in Sec. 2 for each family X, and $E'_\nu = E_\nu (1 + z) / \Gamma$. Figure 2 shows the diffuse high-energy neutrino intensity for the HL-GRB (light-blue band), LL-GRB (violet band) and sGRB (orange band) components as a function of the neutrino energy.

Our results should be compared with the recent IceCube discovery of high-energy neutrinos [17] (blue line in Fig. 2) as well as with the IceCube GRB searches [5]. The total estimated diffuse flux from the GRB prompt emission can be as large as $2 \times 10^{-9}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at $10^6$ GeV and it is therefore slightly lower than the best fit of the high-energy neutrino flux detected with IceCube. Our estimated total diffuse emission is smaller than the IceCube flux at lower energies and it scales differently as a function of the
neutrino energy. This implies that, assuming that the fireball model properly describes the GRB neutrino emission, GRBs cannot be the major contributors to the observed IceCube flux for the sub-PeV region.

Extrapolating from the high-energy neutrino flux recently detected, Ref. [5] estimates that the GRB diffuse emission at 100 TeV should be smaller than $2 \times 10^{-10}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (blue dot in Fig. 2, IC-GRB). Although it might be that such extrapolation on the GRB emission underestimates the real GRB diffuse flux, as IceCube is sensitive to the first break energy that occurs for $E_\nu > 100$ TeV, such upper bound is very close to our results for the HL-GRB family. In fact our estimated high-energy neutrino intensity at $E_\nu = 100$ TeV is $8 \times 10^{-11}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for HL-GRBs. We conclude that our results are compatible with current observations and in rough agreement with the updated computation of the Waxman-Bahcall flux [3] proposed by the IceCube Collaboration [5].

In all the studied scenarios, GRBs cannot explain the total detected IceCube high-energy neutrino flux in the sub-PeV energy range. However, for certain choices of the model parameters, the diffuse neutrino emission from GRBs can reach the IceCube band around PeV energies.

5. Conclusions
Gamma-ray bursts (GRBs) are considered to be high-energy neutrino emitters and candidate sources of the ultra-high energy cosmic rays. We present an analytical model to compute the neutrino flux from GRBs based on the fireball picture.

By adopting up-to-date luminosity functions, we found that the diffuse background intensity could be as large as $2 \times 10^{-9}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The low-luminosity GRBs seem to dominate the overall diffuse intensity in the sub-PeV region, while high-luminosity GRBs are the major source at larger energies. Such conclusions are also supported from variations of the model parameters within the range allowed from observations.

Gamma-ray bursts do not appear to be the leading sources originating the observed IceCube neutrino flux in the sub-PeV region. Moreover, our results suggest that larger exposure is required to discriminate neutrinos from high-luminosity GRBs in forthcoming stacking searches.

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References
[1] Woosley S 1993 Astrophys. J. 405 273
[2] Eichler D, Livio M, Piran T and Schramm D 1989 Nature 340 126
[3] Waxman E and J Bahcall J 1997 Phys. Rev. Lett. 78 2292
[4] Mészáros P 2015 Preprint arXiv:1511.01396 [astro-ph.HE]
[5] Aartsen M et al (IceCube Collaboration) 2015 Astrophys. J. 805 1, L5
[6] Aartsen M et al (IceCube Collaboration) 2013 Science 342 1242856
[7] Aartsen M et al (IceCube Collaboration) 2014 Phys. Rev. Lett. 113 101101
[8] Wanderman D and Piran T 2010 Mon. Not. Roy. Astron. Soc. 406 1944
[9] Howell E et al 2014 Mon. Not. Roy. Astron. Soc. 444 15
[10] Liu R, Wang X and Dai Z 2011 Mon. Not. Roy. Astron. Soc. 418 1382
[11] Dai X 2009 Astrophys. J. 697 L68
[12] Ghirlanda G et al 2012 Mon. Not. Roy. Astron. Soc. 420 483
[13] Yonetoku D et al 2004 Astrophys. J. 609 935
[14] Wanderman D and Piran T 2015 Mon. Not. Roy. Astron. Soc. 448 3026
[15] Tamborra I and Ando S 2015 JCAP 1509 036
[16] Anchordoqui L et al 2014 JHEP 1-2 1
[17] Aartsen M et al (IceCube Collaboration) 2015 Phys. Rev. D 91 2, 022001