Detection prospects for multi-GeV neutrinos from collisionally heated GRBs

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Abstract. Neutrinos with energies ranging from GeV to sub-TeV are expected to be produced in γ-ray Bursts (GRBs) as a result of the dissipation of the jet kinetic energy through nuclear collisions occurring around or below the photosphere, where the jet is still optically thick to high-energy radiation. So far, neutrino emission from the inelastic collisional model in GRBs has been poorly investigated from the experimental point of view. In the present work, we discuss prospects for identifying neutrinos produced in such collisionally heated GRBs with the large-volume neutrino telescopes KM3NeT and IceCube, including their low-energy extensions, KM3NeT/ORCA and DeepCore, respectively. We evaluated the detection sensitivity for neutrinos from both individual and stacked GRBs, exploring bulk Lorentz factor values ranging from 100 to 600. As a result of our analysis, individual searches appear feasible only for extreme sources, characterized by γ-ray fluence values at the level of $F\gamma \geq 10^{-2}$ erg cm $^{-2}$. In turn, it is possible to detect a significant flux of neutrinos from a stacking sample of ~ 900 long GRBs (which could be detected by current γ-ray satellites in about five years) already with DeepCore and KM3NeT/ORCA. The detection sensitivity increases with the inclusion of data from the high-energy telescopes, IceCube and KM3NeT/ARCA, respectively.

1 Introduction

Gamma-Ray Bursts (GRBs) are the most luminous astrophysical phenomena known to occur in the Universe. These sources emit non-thermal high-energy gamma (γ)-ray emission: the γ-ray energy flux peaks at a few hundred keV and, in many bursts, a long tail extending occasionally up to GeV is present. When the detector's energy sensitivity is wide enough, a typical GRB spectrum can be fitted with a smoothly joined broken power law, known as the Band function [1]. In the classical scenario, the observed γ rays are interpreted as result of synchrotron emission from non-thermal electrons accelerated at the shock fronts in the optically thin region of the GRB jet. Nevertheless, some observed GRB spectra are significantly harder at low energies than what is expected in case of synchrotron radiation. As a possible solution, it was hypothesized that GRB spectra include a bright photospheric component which results from strong subphotospheric heating originating from inelastic nucleon-neutron collisions. This so-called *inelastic collision model* for GRB prompt emission naturally predicts a broken power-law γ-ray spectrum through electromagnetic cascades and Coulomb heating [2, 3].

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2 Gamma-ray and neutrino production in the inelastic collisional model

The base assumptions of the inelastic collision model are the existence of a dense, hot and neutron-rich central engine, and a baryonic jet, not dominated by magnetic fields. According to this model, the jet composition could include free neutrons, produced by the dissociation of nuclei by γ-ray photons in the inner regions of the disk. These neutrons would decouple from protons at a radius $R_n < R_{ph}$, that is, below the photospheric radius, where the jet is optically thick. The region between R_n and R_{ph} is characterized by inelastic nuclear collisions between protons and neutrons (*pn* collisions), significantly affecting the dynamics of the jet (subphotospheric collision heating). Charged pions produced in these collisions decay producing positrons, which in turn scatter thermal photons by inverse Compton and produce γ-ray emission. The photospheric thermal radiation, released at R_{ph}, is expected to be modified by subphotospheric collisional heating, becoming nonthermal. From *pn* collisions and subsequent $\pi^{\pm}$ decays, also neutrinos would be produced with an energy correlated with the Lorentz factor of the jet (Γ), and with the relative Lorentz factor of the proton ($\Gamma_p \simeq \Gamma$) and neutron ($\Gamma_n \ll \Gamma$) components, $\Gamma_{rel} = \frac{1}{2}\left(\frac{\Gamma}{\Gamma_n} + \frac{\Gamma_n}{\Gamma}\right) \simeq \frac{\Gamma}{2\Gamma_n}$, through

$$E_\nu \approx 0.1\Gamma\,\Gamma_{rel}\,m_p c^2 \rightarrow E_\nu \simeq 100\,\text{GeV}\left(\frac{\Gamma}{500}\right)\left(\frac{\Gamma_{rel}}{2}\right), \tag{1}$$

implying $E_\nu \sim 10\text{-}100$ GeV neutrinos for Lorentz factors $\Gamma \sim 100 - 1000$ [4, 5]. Note that the neutrino energies involved in this model (sub-TeV) are much lower with respect to the ones investigated so far with neutrino searches from GRBs (TeV-PeV energies), assuming the classical internal-shock and/or magnetically dominated jet models. Since from these searches no GRB-neutrino correlation has been found, it is not possible yet to distinguish among the possible leptonic and hadronic nature of radiation from GRB jets. The search of multi-GeV neutrino emission could provide an alternative method to establish the baryonic nature of GRB jets. Furthermore, detecting neutrinos from GRBs at different energies could be crucial to discriminate among the various physical processes proposed for the GRB γ-ray emission. In particular, detecting multi-GeV neutrinos would support the photospheric scenario with collisional heating mechanisms (due to *pn* collisions) operating inside the jet.

3 Current and future low-energy neutrino detectors

To search for sub-TeV neutrinos from GRBs, compact arrays of 3D photomultiplier sensors are needed. At the South Pole, IceCube is complemented with a smaller Cherenkov detector, named DeepCore, characterized by a higher concentration of optical modules, which allows the detection of neutrinos with energies down to 10 GeV. A similar neutrino telescope, KM3NeT-ORCA, is currently under construction in the Northern Hemisphere, off the French Mediterranean coast, with a much denser configuration of optical modules than that of the high-energy detector KM3NeT-ARCA (currently under construction close to Sicily, in Italy), instead designed for neutrino astroparticle physics studies. Even if the primary goal of low-energy neutrino detectors is to investigate intrinsic properties of neutrino particles (i.e., neutrino oscillations), we here exlore the possibility of astroparticle physics studies with both ORCA and DeepCore in the context of GRB analyses. In this contribution, we summarize the results published in [6].

4 Detector performances for GRB detection

We simulated a search performed by considering upgoing muon neutrinos from collisionally heated GRBs, as to explore sensitivity (at trigger level) of KM3NeT (ORCA+ARCA) and DeepCore+IceCube. Synthetic GRB characteristics were considered for such evaluations, as explained in the following.

Neutrino and background flux estimation

The neutrino spectra produced in collisionally heated GRBs were taken from [5] under the following assumptions: emission released at $R_{\rm ph}$, $\Gamma_{\rm rel} = 3$, and $\xi_{\rm N} = 4$, where $\xi_{\rm N}$ represents the ratio between the dissipated isotropic kinetic energy and the isotropic neutrino energy emerging from inelastic nuclear collisions. The neutrino fluence eventually produced in collisionally heated GRBs scales with the γ-ray fluence ($E_\nu^2 \phi_\nu \sim E_\gamma^2 \phi_\gamma = F_\gamma$), peaking around the energy indicated in Eq. (1), hence depending on Γ. The background of upgoing neutrinos due to the atmospheric neutrino flux depends on the duration of the burst (namely, on the temporal window during which 90% of the fluence is expected to be released, T_{90}), as well as on the search angular window around the GRB position, defined through the solid angle $\Omega = 2\pi(1 - \cos(\theta/2))$, where θ is the plane angle of the search cone around each GRB. Thus, F_γ, T_{90} and θ are parameters to be carefully chosen. In our estimations, F_γ and T_{90} have been assumed to follow the Fermi γ-ray Burst Monitor (GBM) distributions. Both short (SGRB) and long (LGRB) GRBs were considered, separately, as to correctly characterize the two different populations. Concerning the background estimation, we conservatively set the aperture of the search cone to $\theta = 3\theta_{\nu\mu}$, where $\theta_{\nu\mu}$ is the kinematic angle between the incoming neutrino and the emerging muon directions. The latter was calculated at the energy in which each neutrino telescope would observe the maximum number of neutrinos given the model (i.e., for a given Γ). For more details, see [6].

Detection prospects from an individual GRB

To investigate the possibility of detecting neutrinos from an individual collisionally heated GRB, we considered a GRB with high fluence ($F_\gamma \sim 2 \times 10^{-3}$ erg cm^{-2}) and evaluated neutrino fluences expected on Earth for several values of Lorentz factor, i.e., $\Gamma = 100$, $\Gamma = 300$ and $\Gamma = 600$ (see Fig. 1(a)). Although the GRB considered in this example is characterized by high fluence (comparable to the highest fluence among all GRBs in the Fermi-GBM catalog), we obtained only a small number of signal events observable in each neutrino telescope ($n_{\rm s} < 1$), even when the low-energy detectors are integrated with the corresponding high-energy ones (see Fig. 1(b) and Tab. 1). To allow an individual GRB to produce $n_{\rm s} \geq 1$ in at least one of the considered detectors, it has to be characterized by $F_\gamma \geq 10^{-2}$ erg cm^{-2}, i.e. only nearby and very energetic GRBs could do so. Such a fluentic GRB has never been observed to date.
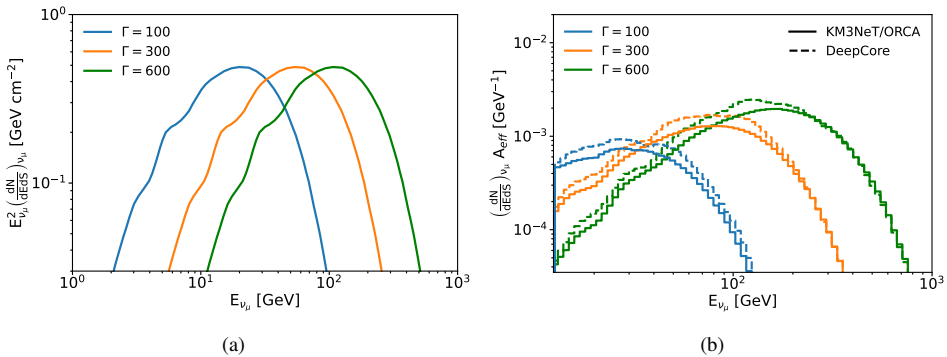

(a)   (b)

Figure 1: (a) The $\nu_\mu + \bar{\nu}_\mu$ energy fluence for a GRB with observed γ-ray fluence $F_\gamma \sim 2 \times 10^{-3}$ erg cm^{-2} for Γ=100 (cyan), Γ=300 (orange) and Γ=600 (green). (b) Number of signal events per unit energy in GeV expected in KM3NeT/ORCA (solid lines) and DeepCore (dotted lines) for the neutrino energy fluences shown in (a).

| | n_s | | |
Detector	$\Gamma = 100$	$\Gamma = 300$	$\Gamma = 600$
KM3NeT/ORCA	4×10^{-2}	7×10^{-2}	1×10^{-1}
KM3NeT/ORCA+KM3NeT/ARCA	-	9×10^{-2}	2×10^{-1}
DeepCore	5×10^{-2}	9×10^{-2}	1×10^{-1}
DeepCore+IceCube	-	3×10^{-1}	8×10^{-1}

Table 1: Number of events from $\nu_\mu + \bar{\nu}_\mu$ interactions expected from a GRB with γ-ray fluence $F_\gamma \sim 2 \times 10^{-3}$ erg cm^{-2} in low-energy detectors (KM3NeT/ORCA and DeepCore) alone, or in a combined search with high-energy detectors (KM3NeT/ARCA and IceCube, respectively). All of these results are given at trigger level.

Stacking detection prospects

The expected detection rate can be greatly increased when summing up the contribution of many GRBs. By taking into account the rate of observed GRBs per year in half of the sky to account for upgoing events only ($N_{SGRB} = 75$ yr^{-1} and $N_{LGRB} = 175$ yr^{-1}), we built a synthetic population of sources where each GRB of the sample is described as explained in Sect. 4. For each extracted source, we estimated the expected neutrino fluence for $\Gamma = [100, 300, 600]$. The background inside the detector is evaluated in a temporal window as wide as $T_{90} \pm 0.3T_{90}$, and in a angular window defined as explained above. Once the GRB sample is defined, we first selected the GRB with the highest level of significance $\sigma = n_s / \sqrt{n_b}$ and, starting from such a GRB, we added one by one the others, choosing each time the GRB that provides the maximum increase of the total level of significance σ_{tot}. We repeated the above procedure 1000 times obtaining at the end the median level of significance and an uncertainty band calculated with percentiles at 1σ and 2σ. By requiring $\sigma_{tot} > 3$ and $n_{s,tot} \geq 1$ as minimum conditions to give a detection, we obtained that for $\Gamma \gtrsim 300$ there is a good chance to detect sub-TeV neutrinos by performing a stacking search of ~ 900 LGRBs with ORCA and DeepCore data, and this possibility is increased if low-energy detectors are integrated with high-energy ones.
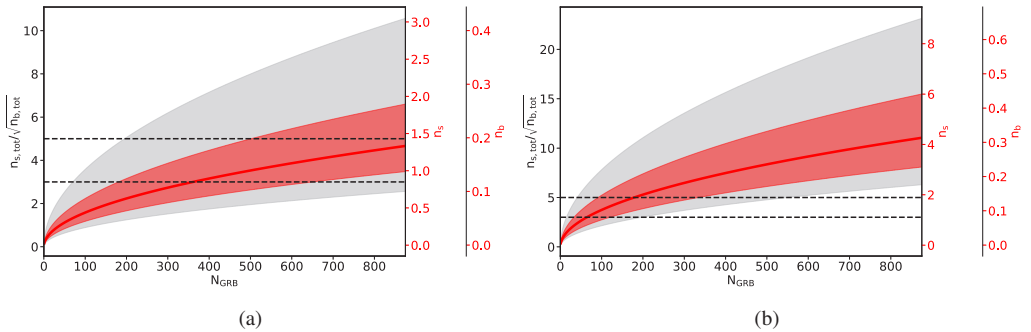

(a)   (b)

Figure 2: Level of significance $n_{s,tot} / \sqrt{n_{b,tot}}$ for (a) KM3NeT/ORCA+KM3NeT/ARCA and (b) Deep-Core+IceCube, achieved by stacking ~ 900 LGRBs with $\Gamma = 300$, within the framework of the inelastic collisional model. The shaded red and gray regions indicate the uncertainty bands at 1σ and 2σ, respectively. The horizontal dashed black lines highlight $\sigma_{tot} = 3$ and $\sigma_{tot} = 5$.

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