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Detection prospects for low-energy neutrinos from collisionally heated GRBs with current and future neutrino telescopes

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Neutrino emission from Gamma-Ray Bursts (GRBs) has been heavily investigated in the last decades providing a wealth of models which, under different physical conditions, are able to reproduce the observed electromagnetic gamma-ray emission. Among these, the most exploited ones provide gamma rays, produced in the optically thin region of the jet from neutral pion decay, as well as neutrinos emitted in the TeV-PeV energy range as a result of charged pion decay. To date, though, no successful detection of such high-energy neutrinos from GRBs has been realized. However, within the framework of the so-called 'inelastic collision model', also lower energy neutrinos (GeV and sub-TeV ranges) could be produced from a dissipation mechanism through hadronic collisions (pp or pn) around or below the photosphere, where the jet is still optically thick. So far, dedicated searches for such low-energy neutrinos have not been undertaken yet. In the present work, we report preliminary detection prospects for neutrinos produced in collisionally heated GRBs, with KM3NeT and IceCube, as well as considering their low-energy extensions (ORCA and DeepCore, respectively).

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1. Introduction

Gamma-Ray Bursts (GRBs) are the most luminous astrophysical phenomena known to occur in the Universe. Since their discovery, gamma-ray satellites have been able to detect radiation from hundreds of such sources per year, characterized by non-thermal high-energy emission: the gamma-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]. Nonetheless, the spectrum is observed to strongly vary from one burst to another.

Addressing the origin of GRB spectra is a long-standing problem. In the classical scenario, the observed gamma rays are usually explained by synchrotron emission from non-thermal electrons accelerated at the shock fronts in the optically thin region. However, in such a framework, some key issues remain unsettled, as well as the fact that observed spectra are in conflict with this scenario. As an example, the low-energy spectra of some GRBs are significantly harder than what expected in case of synchrotron radiation emission.

As a possible solution, it was hypothesized that GRB spectra include a bright photospheric component which results from strong sub-photospheric heating. An efficient dissipative mechanism below the photosphere may originate from inelastic nucleon-neutron collisions. This so-called *inelastic collision model* for GRB prompt emission naturally predicts a broken power-law gamma-ray spectrum via electromagnetic cascades and Coulomb heating [2, 3].

2. Gamma-ray production in collisional mechanisms for GRB

The basic assumptions of the inelastic collision model are: (i) dense, hot and neutron-rich central engine; (ii) 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 gamma-ray photons in the inner regions of the disk. These neutrons would decouple from protons at a radius $R_\mathrm{n} < R_\mathrm{ph}$, i.e. below the photospheric radius, where the jet is optically thick. The region between R_n and R_ph is characterised by inelastic nuclear collisions between protons and neutrons, significantly affecting the jet dynamics (sub-photospheric collisional heating). Charged pions originated in these collisions decay producing positrons, that in turn scatter thermal photons by inverse Compton and produce gamma-ray emission. The photospheric thermal radiation, released at R_ph, is expected to be modified by sub-photospheric collisional heating, becoming non-thermal [2].

2.1 Neutrino production

From the inelastic collisions between protons and neutrons in the sub-photospheric region of GRB jets, also neutrinos would be produced. The expected energy of the emitted neutrinos is correlated with the Lorentz factor of the jet (Γ), and with the relative Lorentz factor of the proton ($\Gamma_\mathrm{p} \simeq \Gamma$) and neutron ($\Gamma_\mathrm{n} \ll \Gamma$) components, $\Gamma_\mathrm{rel} = \frac{1}{2}\left(\frac{\Gamma}{\Gamma_\mathrm{n}} + \frac{\Gamma_\mathrm{n}}{\Gamma}\right) \simeq \frac{\Gamma}{2\Gamma_\mathrm{n}}$, through:

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

implying $E_\nu \sim$ 10-100 GeV neutrinos for Lorentz factors $\Gamma \sim 100 - 1000$ [4, 5]. Therefore, measuring the neutrino energy in combination with the cosmological redshift of the burst could provide a direct handle on the Lorentz factor of the jet, which is a key parameter in GRB dynamics.

Note that the neutrino energies involved in this model (GeV-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. By now, no any spatial and temporal coincidence between high-energy neutrinos and GRBs has been observed in data from ANTARES [6, 8] and IceCube [7, 9] Collaborations. The lack of a neutrino correlation does not allow to distinguish among the possible leptonic or hadronic nature of radiation from GRB jets. For this reason, the search of a multi-GeV neutrino emission could provide an alternative method to establish the baryonic nature of GRB jets, even if within the context of a model that involves a different emission mechanism with respect to the classical ones. Furthermore, detecting neutrinos from GRBs at different energies could be crucial to discriminate among the various physical processes proposed for the GRB gamma-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. IceCube is complemented with a smaller Cherenkov detector characterized by a higher concentration of optical modules (DeepCore [10]) 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 Mediterranean France coast. Its optical modules are being arranged in the dense configuration required for detecting events with energies as low as few GeV, i.e. three orders of magnitude lower that the typical energy scale probed by the high-energy detector KM3NeT-ARCA (currently under construction close to Sicily, in Italy), designed for neutrino astroparticle physics studies [11]. The primary goal of the low-energy neutrino detectors is to investigate the intrinsic properties of the neutrino particles (with neutrino oscillation studies). However, within the present work, we investigate the possibility of astroparticle physics studies with both ORCA and DeepCore in the context of GRB analyses.

The present studies are performed by considering the performances of each detector at trigger level: effective areas for $\nu_\mu + \bar{\nu}_\mu$ events in IceCube/DeepCore and ORCA/ARCA are taken by [10] and [11], respectively, Note that the ORCA effective area is not directly available from literature. For our purposes, we estimated it starting from the ORCA effective volume at trigger level for muon neutrino events, and extrapolating its behaviour at higher energies (until ~1 TeV) by using the same energy dependence as in DeepCore[1], for which effective area values are available [10] for muon (and anti-muon) neutrinos. A fit to DeepCore effective area provides:

$$A_{\mathrm{eff}}^{\mathrm{DeepCore}}(E_{\nu_\mu}) = 15 \left(\frac{E_{\nu_\mu}}{100\ \mathrm{GeV}} \right)^{1.6} \mathrm{cm}^2. \tag{2}$$

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[1] This assumption can be considered valid since the two detectors are characterised by very similar configurations.

By using this procedure, we can quantify the ORCA effective area at trigger level to amount to

$$A_{\rm eff}^{\rm ORCA}(E_{\nu_\mu}) = 12\left(\frac{E_{\nu_\mu}}{100\ \rm GeV}\right)^{1.6}\ \rm cm^2. \tag{3}$$

These parametrizations will be considered in the following. Hence, DeepCore and ORCA are expected to have comparable performances.

4. Detector performances for GRB detection

Estimations of detection prospects for low-energy neutrinos from collisionally heated GRBs with current (DeepCore/IceCube) and future (ORCA/ARCA) neutrino telescopes are here presented. Only upgoing muon neutrinos are considered in this search, as to explore astronomical performances of these detectors. Synthetic GRB characteristics are considered for such evaluations.

4.1 Neutrino and background flux estimation

The neutrino spectra produced in collisionally heated GRBs are taken from [5] under the following assumptions: emission released at the photosphere (i.e. 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 gamma-ray fluence ($E_\nu^2\phi_\nu \sim E_\gamma^2\phi_\gamma = F_\gamma$), peaking around the energy indicated in Equation (1), hence depending on the characteristic Lorentz factor of the jet. The background for upgoing neutrinos (constituted by the atmospheric neutrino flux and described by the Honda model [12]) depends on the duration of the burst (namely, on the temporal window during which the 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 taken accordingly with Fermi Gamma-ray Burst Monitor (GBM) distributions[2]. Particularly, each time a GRB was considered, we extracted its spectral parameters accepting only values of these parameters with ratio F_γ/T_{90} falling into the known distributions. This method was applied to short (SGRB) and long (LGRB) GRBs, separately, as to correctly characterize the two different populations. Concerning the background estimation, we conservatively set the aperture of the search cone to $\theta = 3\theta_{\nu\mu}$, $\theta_{\nu\mu} = 0.7°/(E_\nu[{\rm TeV}])^{0.7}$[13] being the kinematic angle between the incoming neutrino and the emerging muon directions. The latter was calculated at the energy $E^*_{\nu_\mu,\rm max}$ in which each neutrino telescope would observe the maximum number of neutrinos given the model (i.e. for a given Γ); see Table 1.

4.2 Detection prospects from an individual GRB

To investigate the possibility to detect neutrinos from an individual collisionally heated GRB, we here present an example for a very fluentic GRB ($F_\gamma \sim 2\times10^{-3}$ erg cm^{-2})[3]. By considering

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[2] Fermi-GBM catalogue: https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html. Fermi is the gamma-ray satellite with the widest energy band observations, giving a better estimate for the gamma-ray fluence with respect to the other available detector.

[3] This value is comparable to the one of the GRB with the highest fluence in the Fermi-GBM catalogue, i.e. GRB130427A.

	$\Gamma = 100$		$\Gamma = 300$		$\Gamma = 600$	
Detector	$\mathrm{E}^*_{\nu_\mu,\mathrm{max}}$ [GeV]	θ [deg]	$\mathrm{E}^*_{\nu_\mu,\mathrm{max}}$ [GeV]	θ [deg]	$\mathrm{E}^*_{\nu_\mu,\mathrm{max}}$ [GeV]	θ [deg]
ORCA	27	26	73	13	121	9
ARCA	75	13	129	9	227	6
DeepCore	27	26	78	13	165	8
IceCube	132	9	156	8	258	5

Table 1: Energy values $\mathrm{E}^*_{\nu_\mu,\mathrm{max}}$, in GeV, at which each detector might potentially observe the highest number of $\nu_\mu + \bar{\nu}_\mu$ induced events, and corresponding plane angle values θ, in degrees, adopted to search for such events around GRBs, corresponding to a solid angle $\Omega = 2\pi(1 - \cos(\theta/2))$.

	n_s		
Detector	$\Gamma = 100$	$\Gamma = 300$	$\Gamma = 600$
ORCA	4×10^{-2}	7×10^{-2}	1×10^{-1}
ORCA+ARCA	4×10^{-2}	9×10^{-2}	2×10^{-1}
DeepCore	5×10^{-2}	9×10^{-2}	1×10^{-1}
DeepCore+IceCube	6×10^{-2}	3×10^{-1}	8×10^{-1}

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

neutrino fluences expected at Earth for several values of Lorents factor, i.e. $\Gamma = 100$, $\Gamma = 300$ and $\Gamma = 600$ (see Figure 1(a)), we obtain the expected number of signal events reported in Table 2, also shown in terms of parent function for DeepCore and KM3NeT-ORCA in Figure 1(b). Though the GRB considered in this example is characterized by a high fluence (comparable to the highest fluence among all GRBs in the Fermi-GBM catalogue), the number of signal events observable in each neutrino telescope is quite contained ($n_\mathrm{s} < 1$), even when the low-energy detectors are integrated with the corresponding high-energy ones. We observe that, to allow an individual GRB to produce $n_\mathrm{s} \geq 1$ in at least one of the considered detectors, it has to be characterized by $\mathrm{F}_\gamma \geq 10^{-2}$ erg cm^{-2}, i.e. only nearby and very energetic GRBs could do so. No such kind of GRBs has ever been observed so far.

4.3 Stacking detection prospects

The expected detection rate can be greatly increased when summing up the contribution of many GRBs in the form of a diffuse flux. For this reason, we here present a preliminary study on expected performances of current and future neutrino detectors after 5 years of stacking analysis (half-sky search). By taking into account the rate of observed GRBs per year in the half of the sky to account for upgoing candidates only ($\mathrm{N_{SGRB}} = 75$ yr^{-1} and $\mathrm{N_{LGRB}} = 175$ yr^{-1})[4], we built a synthetic population of sources detectable in half-sky by gamma-ray satellites in 5 years. Each GRB of the sample is described by values of F_γ and T_{90}, selected as explained in Section 4.1.

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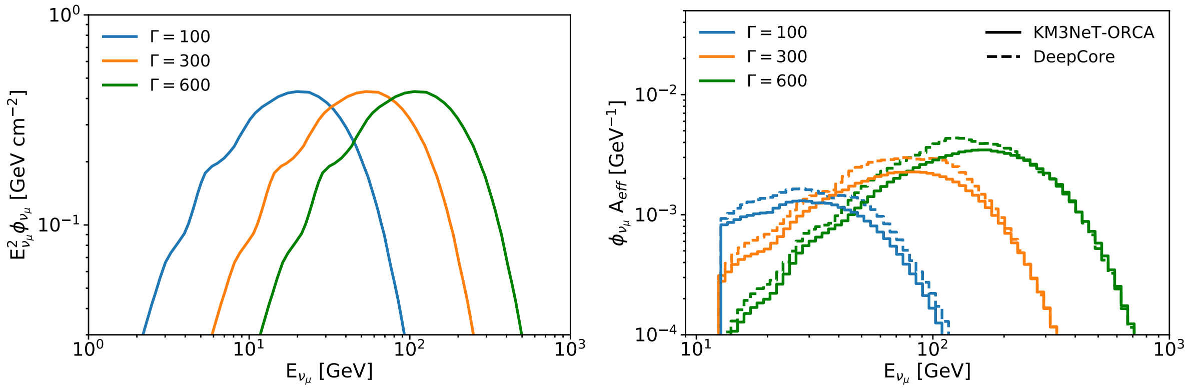
[4] Such values were obtained from the Gamma-Ray Bursts from the Interplanetary Network (IPNGRB) database `https://heasarc.gsfc.nasa.gov/w3browse/all/ipngrb.html`.



(a)

(b)

Figure 1: (a) The $\nu_\mu + \bar{\nu}_\mu$ energy fluence for a GRB with observed gamma-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 expected events per energy bin in KM3NeT-ORCA (solid line) and DeepCore (dotted line) for the neutrino energy fluences shown in (a). These results are given at trigger level.

For each extracted source, we estimated the expected neutrino fluence for three different values of Lorentz factor, i.e. Γ= [100,300,600][5]. Furthermore, we estimated the expected background inside the detector 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 proceeded in the following way: we selected the GRB with the highest level of significance $\sigma = n_\mathrm{s}/\sqrt{n_\mathrm{b}}$ and, starting from such a GRB, we added one by one the others, choosing each time the GRB providing the maximum increase of the total level of significance σ_tot. We repeated the above procedure 1000 times, obtaining the median value of significance after 5 years of stacking analysis with an uncertainty band calculated, with percentiles at 1 and 2 standard deviations.

By requiring $\sigma_\mathrm{tot} > 3$ and $n_\mathrm{s,tot} \geq 1$ as minimum conditions to give a detection, we have obtained that: (i) the detection is possible if LGRBs are included in the search, since SGRBs alone would not provide signal enough from this model to guarantee a detection, in spite of the particularly low background level; (ii) the model with $\Gamma = 100$ is characterised by a too small signal over background ratio; (iii) there is a good chance to detect sub-TeV neutrinos in 5 years of observation with ORCA and DeepCore for higher values of Γ; (iv) such a possibility is increased if low-energy detectors are integrated with the high-energy ones. So far, the presented estimations have been performed assuming that all observed GRBs can be described by a collisional mechanism in GRB jets. The results obtained with $\Gamma = 300$ for all detectors are shown in Figure 2. Though assuming $\Gamma = 600$ a higher statistical significance was obtained, we here present only the results for $\Gamma = 300$, since these are expected to more realistically describe an entire population of sources.

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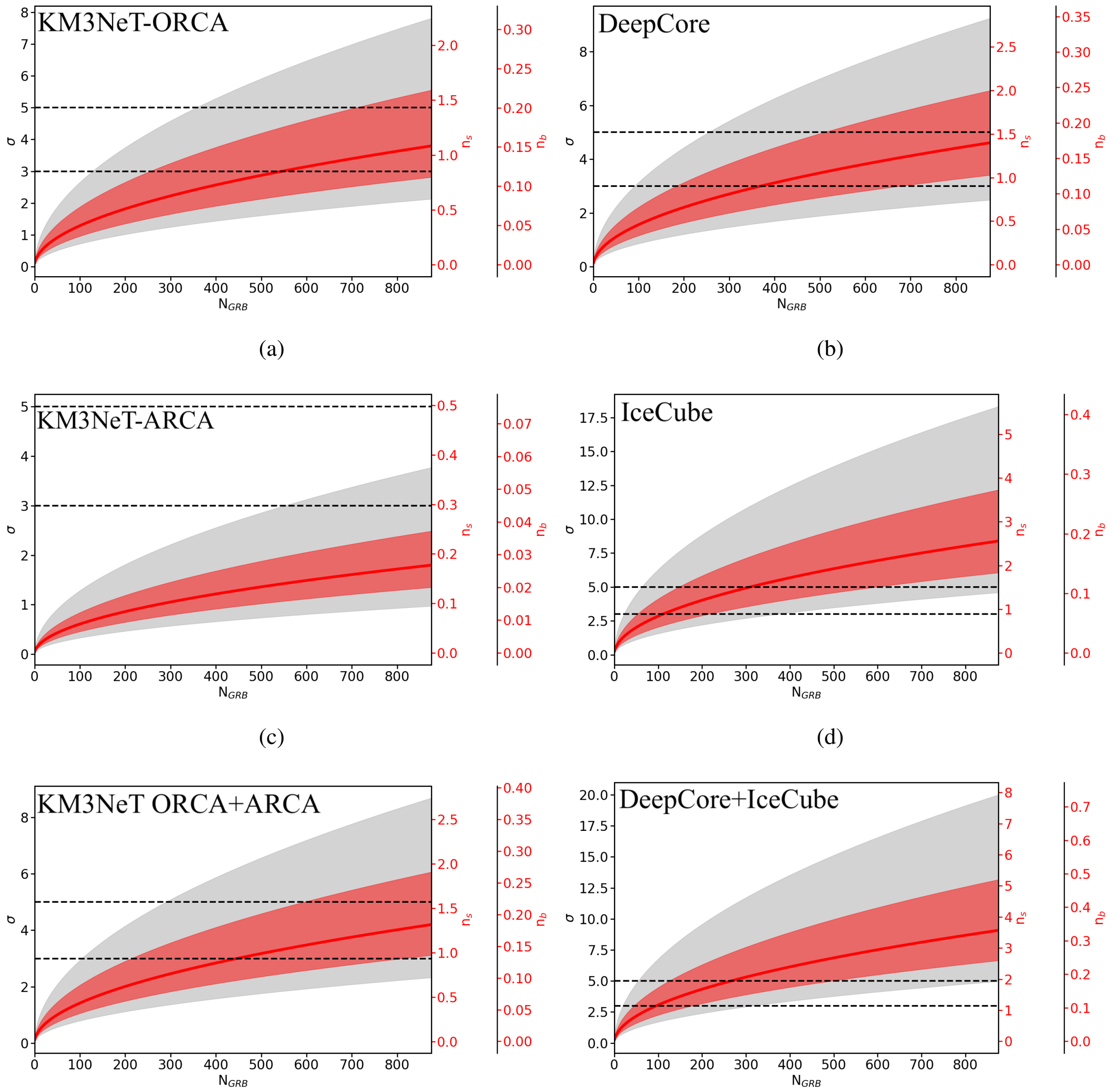
[5] The chosen Lorentz factor values of the jet correspond to $\Gamma_\mathrm{n} \simeq 20$, $\Gamma_\mathrm{n} \simeq 50$ and $\Gamma_\mathrm{n} \simeq 100$, respectively.



(a) (b) (c) (d) (e) (f)

Figure 2: Level of significance $\sigma_{\mathrm{tot}} = n_{\mathrm{s,tot}}/\sqrt{n_{\mathrm{b,tot}}}$ (left y-axis) achieved by stacking 875 LGRBs (equivalent to ∼ 5 years of half-sky search) with $\Gamma = 300$, under the assumption that the gamma-ray prompt emission is originated by pn collisions at sub-photospheric radii (inelastic collision model). The level of signal and background in each detector (indicated in the right y-axis for the median result) are estimated at trigger level. Results are shown for the following neutrino detectors: (a) ORCA, (b) DeepCore, (c) ARCA, (d) IceCube, (e) ORCA+ARCA, (f) DeepCore+IceCube. The shaded red and grey regions indicate the error bands at 1 and 2 standard deviations, respectively, obtained with percentiles.

5. Conclusions

In this work, assuming the inelastic collision model at the origin of the radiation observed from GRBs, we estimated the detection prospects for current and future neutrino telescopes. We encourage stacking analyses with low-energy extensions of IceCube and KM3NeT; indeed, assuming effective areas at trigger level for the several detectors, we obtain that there is a good chance to detect multi-GeV neutrinos by stacking ∼900 LGRBs (equivalent to about 5 years of half-sky observations) under the hypothesis their prompt gamma-ray emission is explained by such a model. The detection of low-energy neutrinos in coincidence with gamma-ray photons would have significant implications for GRB physics. It would confirm dissipative nuclear collisions in the jet providing information on the jet composition, shedding light on the long-standing problem of the emission mechanism responsible for GRBs prompt emission.

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