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Constraining the diffuse flux from gamma-ray burst blastwaves with the KM3-230213A ultra-high-energy event

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KM3NeT/ARCA is a deep-sea Cherenkov neutrino telescope located 100 km off the coast of the southern tip of Sicily, Italy. When completed, the detector will instrument around one cubic kilometre of water with photodetectors to search for energetic neutrinos of cosmic origin. On February 13th 2023, a partial configuration of KM3NeT/ARCA detected the most energetic neutrino ever observed, with an estimated energy of 220 PeV. This intriguing discovery raises questions about the origin and potential sources capable of producing neutrinos of this energy. In this contribution, we will discuss lepto-hadronic interactions in gamma-ray burst blastwaves as possible production sites for neutrinos of this energy. Moreover, we will discuss how the observation of the first-ever ultra-high-energy neutrino and the corresponding ultra-high-energy diffuse neutrino flux can provide new constraints on theoretical model parameters driving the emissivity of ultra-high-energy neutrinos from a larger population of gamma-ray bursts.

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1. Introduction

Gamma-ray bursts (GRBs) are the most energetic transient events observed in the Universe in electromagnetic radiation. With an isotropic equivalent total energy release of up to $\sim 10^{54}$ ergs over a time window varying from less than a second to several hours. This enormous emissivity in high-energy radiation makes GRBs highly interesting potential sources for ultra-high-energy cosmic rays (UHECRs) [1]. Subsequent neutrino production is possible from the interactions of the accelerated cosmic ray protons with photons inside the GRB environment itself [2]. Moreover, high-energy neutrino production is possible when the accelerated outflow from the GRB, called a blastwave, interacts with the surrounding photon fields or with photons from the afterglow of the prompt emission phase [3, 4]. Charged particles are accelerated in internal forward and backwards shocks as the blastwave traverse from the GRB progenitor into the surrounding environment. Once the protons inside this blastwave has reached significant energies, they produce pions and kaons through photo-hadronic interactions and subsequent high-energy neutrinos will be produced through the different decays of the charged mesons. This neutrino flux may persist for an extended time, depending on the jet Lorentz factor of the outgoing blastwave, and detection of these neutrinos would confirm a baryonic component in the GRB blastwave, establishing GRBs as accelerators of UHECRs and yield valuable information about the GRB progenitor system [5].

Located 3.5 kilometres below the surface of the Mediterranean Sea, off the south-eastern coast of Sicily, Italy, the KM3NeT/ARCA telescope [6] is searching for neutrinos of cosmic origin. Despite not being completed yet, partial configurations of the telescope have already shown several promising results. On February 13, 2023, the 21 detection line configuration of KM3NeT/ARCA, out of a planned 230 lines, detected a horizontal-going muon with an estimated energy of 120^{+110}_{-60} PeV [7]. This event, dubbed KM3-230213A, is the highest-energy elementary particle ever detected. Considering the possible backgrounds at this declination and energy, the most probable scenario is that a muon was produced by a muon neutrino interacting in the sea water close to the detector. The corresponding best-fit parent muon neutrino energy is 220^{+570}_{-110} PeV [7], which corresponds to a per-flavour isotropic diffuse ultra-high-energy neutrino flux of $E^2\Phi^{1\mathrm{f}}_{\nu+\bar{\nu}}(E) = 5.8^{+10.1}_{-3.7} \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}, when considering the partial configuration and live time of KM3NeT/ARCA.

Despite a multitude of searches at lower energies [8], no neutrinos have been detected in coincidence with GRBs so far. However, even though direct correlation is yet to be detected, there is still a lot to be said about the total diffuse neutrino flux [9], and how much of a role GRBs play in its composition. The diffuse neutrino flux at sub-PeV energies is well measured by the IceCube Collaboration [10, 11], in which GRBs make up an insignificant fraction [12]. At ultra-high energies (>50 PeV) however, the diffuse flux remains mostly unexplored. Until recently, only upper limits on the UHE neutrino flux were available [13]. However, the recent detection of KM3-230213A signals the first observation of an UHE neutrino flux and opens the door to investigate possible astrophysical sources capable of producing such a flux.

In this work, we consider if a population of long-duration GRBs (lGRBs) are capable of producing the required UHE neutrino flux for KM3-230213A, and use this detected flux to constrain baryonic ratio in lGRB blastwaves and the density of the matter surrounding the GRB progenitor.

2. GRB blastwave neutrino production

GRBs are theorised to emit neutrinos by different physical processes at different stages. The most prominent emission happens in the prompt phase, where neutrinos at GeV-TeV energies are expected to dominate [e.g., 14, 15]. After the prompt emission phase, a significant amount of energy is expected to be converted to kinetic energy that can produce UHE neutrinos at a later time compared to the gamma-ray detectable prompt emission. The kinetic energy in the blastwave, E_k, is related to the isotropic gamma-ray luminosity, L_γ, through

$$\frac{E_k}{L_\gamma} = f_b \eta t^*, \tag{1}$$

where f_b is the baryonic loading, η is the efficiency of converting kinetic energy into gamma-ray luminosity and t^* is the typical time scale for the prompt emission.

2.1 Singe GRB neutrino fluence

Subsequent from the prompt emission phase, relativistic outflows form the GRB drive blastwaves in which high-energy particle acceleration is possible. As the blastwave propagates, it sweeps up gas from the surrounding medium and cools adiabatically. After some typical deceleration timescale $t_{\rm dec}$, protons accelerated in shocks in the outflow interact with photons from the GRB afterglow to produce high-energy neutrinos. The total neutrino fluence associated with a single GRB is thus given by integrating the flux after this deceleration timescale,

$$S_\nu = \int_{t_{\rm dec}}^{\infty} \phi(E_\nu, z, L_\gamma; \theta) dt, \tag{2}$$

where θ denotes all variable model parameters. We consider two different GRB blastwave models, one where the blastwave interacts with the interstellar medium (ISM) of constant density, and one where the density decreases with the square of the radius (WIND). Extensive details and model derivation can be found in [5].

2.2 Population of lGRBs

To reach a significant diffuse flux, the combined contribution from a large population of lGRBs must be taken into account. We thus adapt the redshift-luminosity distribution obtained from *Swift* and *Fermi*-GBM observation of lGRBs over the full sky [16] to construct the relevant evolution function. The distribution of lGRBs in gamma-ray luminosity and redshift are considered as independent of one another, and the full population evolution function is thus a product of a pure gamma-ray-dependent part and a pure redshift-dependent part. The gamma-ray dependent luminosity function $\psi(L_\gamma)$ is parametrised as a broken power law, whereas the redshift distribution function $\rho(z)$ is modelled with a single-power-law behaviour [16]. The combined lGRB population evolution function is

$$\Psi(L_\gamma, z) = \psi(L_\gamma)\rho(z) = c_0\rho_0 \left[\left(\frac{L_\gamma}{L_0}\right)^{-\alpha} + \epsilon \left(\frac{L_\gamma}{L_0}\right)^{-\beta} \right] \frac{(1+z)^{2.7}}{1+(\frac{1+z}{2.9})^{5.6}}, \tag{3}$$

where $\rho_0 = 5.5$ Gpc^{-3} yr^{-1} and c_0 being a normalisation constant found by integrating the luminosity-dependant part of the expression to unity. The break luminosity $L_0 = 3 \times 10^{53}$ erg s^{-1}

and $\epsilon = 1$. The exponential constants are $\alpha = 1.33$ and $\beta = 1.42$. The luminosity L_γ is the intrinsic isotropic luminosity of the GRBs in the Fermi-GRB energy range, and the range considered for the integration is $L_\gamma \in [10^{49}, 10^{54}]$ erg s^{-1}. The population is integrated out to $z_{\max} = 5$.

2.3 Diffuse neutrino flux

The total diffuse neutrino flux at ultra-high energies is calculated by convolving the expected fluence of a single lGRB with how the population of lGRBs evolve over cosmological distances and over the relevant gamma-ray luminosity range. The total diffuse flux on Earth is calculated as

$$\phi_\nu^{\text{tot}}(E_\nu;\theta) = \int_0^{z_{\max}} \frac{1}{1+z}\frac{dV}{dz}\int_{L_{\min}}^{L_{\max}} \Psi(L_\gamma, z) S_\nu(E_\nu, L_\gamma;\theta) dL_\gamma dz, \tag{4}$$

where $\frac{dV}{dz}$ is the differential comoving volume and the $1/(1+z)$ factor corrects for time dilation effects during propagation. We use θ to denote all other model parameters. The differential comoving volume is

$$\frac{dV}{dz} = \frac{4\pi c}{1+z}\left|\frac{dt}{dz}\right| d_L^2, \tag{5}$$

where d_L is the luminosity distance and the cosmic time is

$$\frac{dt}{dz} = \frac{-1}{H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \tag{6}$$

for a flat ΛCDM cosmological model [17]. We use $\Omega_m = 0.286$, $\Omega_\Lambda = 0.714$ and $H_0 = 69.32$ km s^{-1} [18].

3. Analysis

Due to the challenges of calculating the total diffuse flux from this GRB population numerically, we instead utilise a Bayesian inference framework as implemented in the `UltraNest` package [19]. By defining the total model integrand as a log-likelihood term, this approach allows us to solve the model through a parameter-free approach by sampling this nested sampling of this likelihood, with the integration range as priors. The marginal likelihood computed through this method, corresponds to the diffuse flux of the model. This approach allows us to continuously vary all integration parameters without any prior assumptions or fixed values.

3.1 Expected events in a global neutrino detector

The most-probable UHE neutrino flux associated with KM3-230213A is $E^2\phi^{1\text{f}}_{\nu+\bar{\nu}} = (7.4^{+13.1}_{-4.7})\times 10^{-10}$ GeV cm^{-2} s^{-1} sr^{-1} as reported in [tension paper], by considering that no similar events have been reported in the sensitive analyses for the IceCube and Pierre Auger collaborations. To calculate the total number of expected UHE neutrinos detected thus far, we consider the summed exposure from all these three experiments; $\mathcal{E}^{\text{tot}} = \sum_d T^d A^d_{\text{eff}}$, where $d \in \{\text{KM3NeT}, \text{IC}-\text{EHE}, \text{Auger}\}$. 'IC-EHE' denotes the extremely-high-energy analysis in IceCube [13], and 'Auger' denotes the Earth-skimming, low-zenith downward-going and high-zenith downward-going analyses from the Pierre Auger Observatory [20]. The total lifetimes and effective areas of the relevant analyses is denoted by T_d and $A^d_{\rm eff}$, respectively. This gives the total number of expected events of a single flavour as

$$n_{\rm exp}(E_k;\theta) = \frac{4\pi}{3}\int_{E_{\rm min}}^{E_{\rm max}} dE_\nu \mathcal{E}^{\rm tot}\phi_\nu^{\rm tot}(E_\nu;\theta), \tag{7}$$

where the factor $1/3$ corrects for the double-counting of all three neutrino flavours in both the effective area and the diffuse flux.

The likelihood is constructed with a simple Poisson counting term containing the probability of observing one event in any of the three experiments given the expected number of events from the diffuse UHE neutrino flux from our GRB model and the total exposure of the experiments:

$$\mathcal{L}(E_k;\theta) = \text{Poisson}(1; n_{\rm exp}(E_k;\theta)) = n_{\rm exp}(E_k;\theta)e^{-n_{\rm exp}(E_k;\theta)}. \tag{8}$$

Given the number of parameters that enter the GRB blastwave model, the full parameter space of this likelihood is complex. We thus freeze most of the parameters to reasonable values from the literature. The fixed values are listed in Table 1. We limit ourself to varying the fractional energy in the GRB blastwave compared to the gamma-ray luminosity, E_k/L_γ, and the density of the interstellar medium n_0. By scanning the full parameter space from $E_k/L_\gamma \in [1, 10^4]$ s and $n_0 \in [1, 100]$ cm^{-3}, we find a highly-degenerate likelihood space that allows for a large set of parameter combinations, as shown in Figure 1.

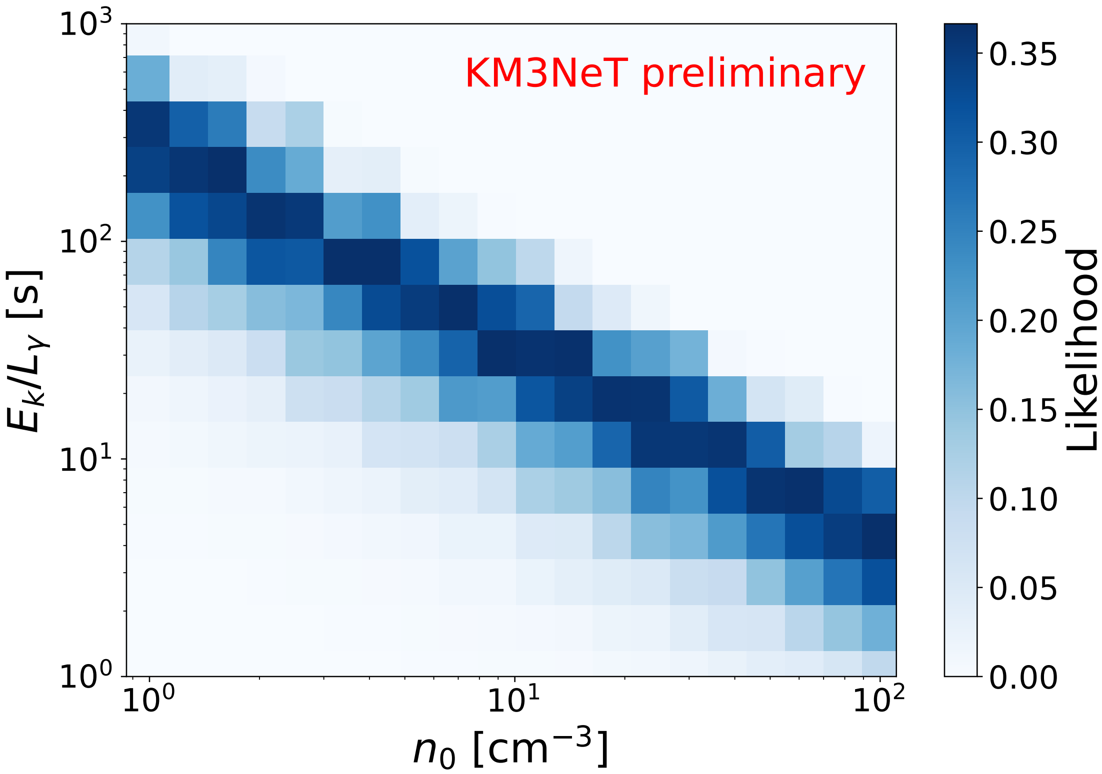

Figure 1: 2D scan of the likelihood in E_k/L_γ and n_0 for the ISM model. The likelihood is maximised for a constant product of E_k/L_γ and n_0, as indicated by the rectilinear behaviour.

Table 1: Fixed GRB blastwave model parameters.

GRB model	Γ_0	ϵ_B	ϵ_e	ϵ_p	ϕ	k	a
ISM	$10^{2.8}$	0.1	0.1	1.0	10.0	2.5	4

3.2 Posterior and parameter best-fits

Due to this high degeneracy in the likelihood parameter space, we consider instead the posterior probability density (PPD) with log-uniform priors on the two parameters of interest

$$P(E_k/L_\gamma, n_0; \theta) = \frac{\mathcal{L}(E_k; \theta) p(E_k/L_\gamma) p(n_0)}{\iint \mathcal{L}(E_k; \theta) p(E_k/L_\gamma) p(n_0) d(E_k/L_\gamma) dn_0}, \tag{9}$$

The priors on E_k/L_γ and n_0 follow reciprocal distributions, $\ln(E_k/L_\gamma) \sim \mathcal{U}(0,4)$ and $\ln(n_0) \sim \mathcal{U}(0,2)$. The marginalised probability, or 'evidence', remains degenerate for this posterior probability, and the best-fit is not well defined. We thus perform a coordinate transformation, leveraging the fact that the expected number of events scales similarly in both parameters of interest, i.e., $n_{\rm exp} \propto (E_k/L_\gamma)^{3/2} n_0^{3/2}$. By substituting in the new coordinates $x = L_k/L_\gamma \times n_0$ and $y = n_0$, we define a new, 1-dimensional PPD as

$$P(x, \theta) = \int P(E_k/L_\gamma, n_0; \theta) |J| dy, \tag{10}$$

where J is the Jacobian of the coordinate transformation. With this transformed PPD, we find the best-fit value of $x = 391.7^{+392.6}_{-306.7}$, which, by fixing the density of the interstellar medium to $n_0 = [1, 3, 10]$, translates into constraints on the baryonic loading factor of $f_b \leq [392, 131, 39]$ at 90% confidence through Equation (1).

4. Conclusions and prospects

In the presented work, we have shown that a large population of lGRB blastwaves can produce the required UHE neutrino fluence to be responsible for a newly measured UHE neutrino flux associated with KM3-230213A, when considering KM3NeT-IceCube-Auger joint analysis. Moreover, we have used the diffuse UHE neutrino flux to put constraints on crucial model parameters, namely the baryonic loading and the density of the surrounding medium, for GRB blastwaves. By utilising the Bayesian inference approach as implemented in the `UltraNest` python package, we allowed all integration parameters in our model to vary over the relevant parameter space, resulting in a more realistic prediction than possible when fixing the values to standard candle GRBs, which are typically in the upper echelon of the population. This means that the lGRBs making up the bulk of the luminosity function, and centred at lower luminosities, are systematically accounted for.

We have considered different models for how the GRB blastwave interacts with the surrounding environment. In the case of a constant density medium following the interstellar medium density, the baryonic loading in the GRB blastwave is constrained to be $< [392, 131, 39]$ at 90% confidence for typical values of $n_0 = [1, 3, 10]$. For a blastwave interacting with a WIND-type medium, where the density decreases with the square of the radius, we find the baryonic loading to be constrained as $< [20, 50, 100]$ at 90% confidence for varying density parameter $A_* = [0.05, 0.06, 0.07]$.

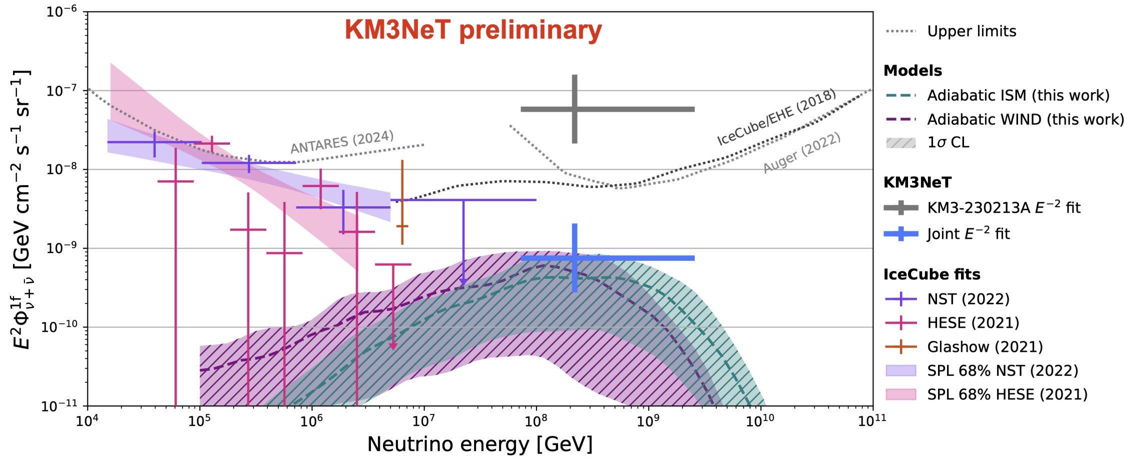

Figure 2: Energy-squared per-flavour diffuse astrophysical neutrino flux assuming ($\nu_e : \nu_\mu : \nu_\tau = 1:1:1$) flavour equipartition. The KM3NeT-only reported flux is shown by the gray cross [7], whereas the combined fit with IC and Auger is shown by the blue cross [21]. The 68% CL contours from IC northern sky tracks (purple) and high energy starting tracks (pink) are shown by the filled butterfly contours. The corresponding segmented fits are shown with crosses of the same colour. The dotted lines shows upper limits from the ANTARES, IC extremely-high-energy and Auger analyses. The teal (purple) dashed lines and surrounding contours shows the best-fit and 68% CL for the ISM (WIND) GRB model.

As can be seen in Figure 2, our results show that the full population of lGRBs is capable of expelling enough energy in neutrinos to produce the UHE neutrino flux most-likely associated with the KM3-230213A event. Furthermore, we have shown that the required GRB model parameters associated with this diffuse flux are in line with estimations from gamma-ray observations and from the non-detection of neutrinos from the prompt phase. The results found in this work are still quite weakly constraining, and continued observations by the growing KM3NeT detector and other sensitive neutrino telescopes are required to further characterise the diffuse UHE neutrino flux. Additional observations of GRBs by electromagnetic telescopes, and UHECR correlations are required to more stringently nail down the role of GRBs as potential UHECR accelerators.

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