Constraining gamma-ray burst parameters with KM3-230213A

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KM3NeT/ARCA is a deep-sea Cherenkov neutrino detector 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 [1]. This intriguing discovery raises questions about the origin and potential sources capable of producing neutrinos of this energy. We discuss lepto-hadronic interactions in gamma-ray burst blast waves as possible production sites for neutrinos of this energy. Moreover, we show how the observation of the first-ever ultra-high-energy neutrino and the corresponding ultra-high-energy diffuse neutrino flux provide new constraints on theoretical model parameters driving the emissivity of ultra-high-energy neutrinos from a larger population of gamma-ray bursts.

Gamma-ray burst model

Long-duration gamma-ray bursts (GRBs) are the most energetic events in the Universe, with an isotropic equivalent gamma-ray peak luminosity usually above 10^{50} erg/s. This makes them intriguing candidates for particle acceleration to ultra-high energies. GRBs launch highly collimated jets of plasma that drive a kinetic outflow often referred to as a blast wave. The acceleration of protons in forward shocks within these highly relativistic blast waves allows for PeV—EeV neutrino production through photo-pion interactions of ultra-high-energy protons with X—ray to optical photons of the GRB afterglow [2].

$$E_k/L_\gamma = f_b \eta T_{90}$$

The isotropic-equivalent kinetic energy of the blast wave connects to the prompt gamma-ray luminosity.

$$t_{\rm dec} \propto E_k^\alpha n^{-\alpha}$$

The kinetic energy and surrounding matter density determine the deceleration time for the blast wave.

$$\gamma'_c, \gamma'_m, \gamma'_s$$

The deceleration time decides the bulk Lorentz factor in the blast wave. Electrons accelerated exhibit distinct behaviours in three different regimes.

$$n(E_p) = \frac{\mathscr{E}_{\rm CR}(E_k, n)}{V E_p^2 \ln(\gamma'_{p,s}/\Gamma)}$$

Protons are co-accelerated together with electrons in the shocks. **These protons** then interact with the electron synchrotron radiation to produce ultra-high-energy neutrinos.

We want to constrain the **ratio of baryon energy to photon energy** f_b and the density of the surrounding medium n.

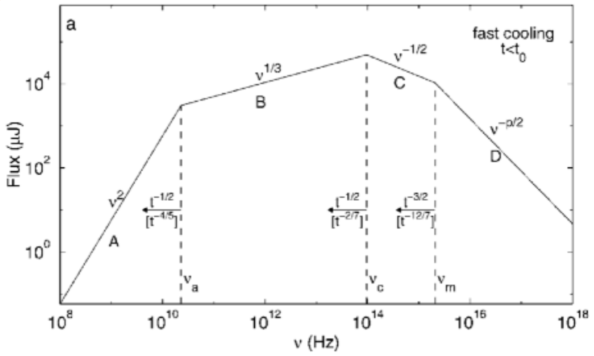

Fig. 1: Synchrotron spectrum of a relativistic shock with a power-law electron distribution in the fast cooling phase [3].

Two different scenarios are considered:

- Adiabatically evolving blast wave interacting with a constant density interstellar medium (**ISM**) with $\alpha = 1/3,\ n = n_0$
- Adiabatically evolving blast wave interacting with a wind-type medium (**WIND**) with $\alpha = 1,\ n \propto R^{-2} A_*$

GRB population and statistical analysis

To calculate the contribution of GRB blast waves to the diffuse flux of ultra-high-energy neutrinos, we need to consider the neutrino emissivity from GRBs with our model for varying input parameters representative of the full GRB population. We consider the luminosity function of long-duration GRBs from [4] and fit a log-normal distribution to the measured duration of the prompt emission as reported by the Fermi-GBM collaboration [5]. This fit is shown in **Fig. 2.** The diffuse ultra-high-energy neutrino flux is then found through Monte Carlo integration over the combined integral of the GRB model with the entire population. Finally, we perform a parameter space scan in the baryon loading and surrounding medium density to find the best-fit values of these parameters through a simple Poisson likelihood analysis.

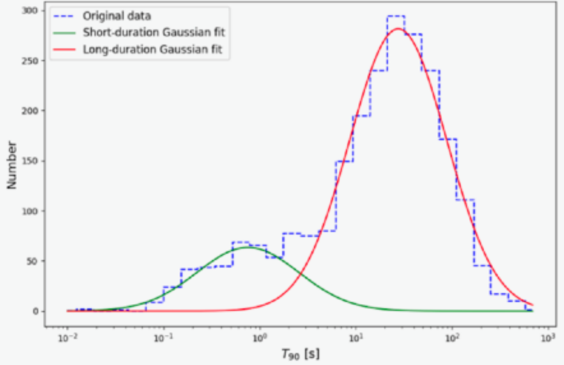

Fig. 2: Distribution of T_{90} for observed gamma-ray bursts [5] and log-normal fits to the short and long duration parts of the population.

Co-moving volume

The differential co-moving volume needs to be taken into account to account for the expansion of the Universe, and an additional factor $(1+z)^{-1}$ to correct for time-dilation between the source and Earth.

Diffuse flux

The **total diffuse flux** of ultra-high-energy neutrinos is calculated by integrating the blast wave model with the GRB population out to a maximum redshift $z_{\rm max}$. We compute this by Monte Carlo integration.

Joint fit

We combine the **instrument response functions** of KM3NeT, IceCube and Pierre Auger to take into account that other telescopes have not observed astrophysical neutrinos at ultra-high energies [6].

$$n_{\rm exp}(f_b, n; \theta) = \frac{1}{3} 4\pi \int_{E_{\rm min}}^{E_{\rm max}} dE_\nu\, \mathscr{E}(E_\nu)\, \Phi_\nu(E_\nu; \theta)$$

Parameter scan

A Poisson likelihood analysis is performed over a parameter space scan in baryon loading and the surrounding medium density. Best-fit values and credible intervals are constructed from the conditional posterior probability density shown in **Fig. 3.**

Constraints

- $f_b \leq 51$ at 90% credibility for a constant density **ISM**.
- For the **WIND** model, the density parameter $A_* \leq 0.025$ at 90% credibility for typical values of the baryon loading.

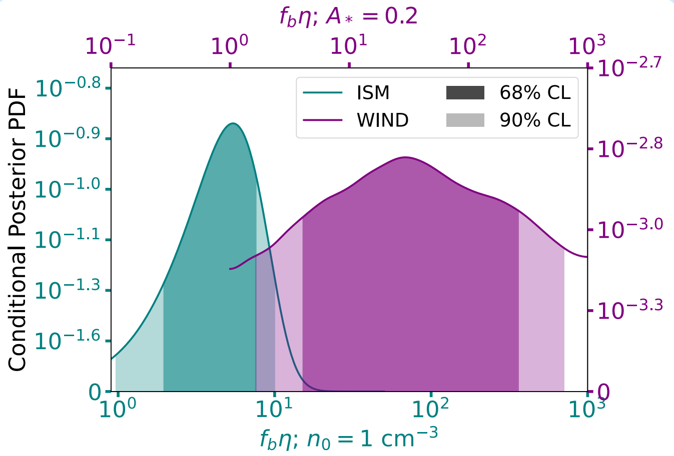

Fig. 3: Conditional posterior probability for fixed density parameters for the **ISM** and **WIND** models. The shaded area shows the (68%, 90%) credible intervals.

Diffuse flux of ultra-high-energy neutrinos

Fig. 4 displays the total diffuse flux of ultra-high-energy neutrinos from long-duration gamma-ray bursts (GRBs) using best-fit statistical parameters, alongside 68% credible intervals.

The considered GRB blast wave model successfully produces a compatible flux for the joint fit observation detailed in [6] across both evaluated scenarios.

GRB blast wave contributions remain subdominant to the diffuse flux measured by IceCube at TeV energies, aligning with previous experimental constraints.

Conclusion

We have used the first detection of an ultra-high-energy neutrino to place constraints on fundamental GRB model parameters for two distinct scenarios. These limits are derived solely from the detection of ultra-high-energy neutrinos and are well aligned with constraints from electromagnetic observations.

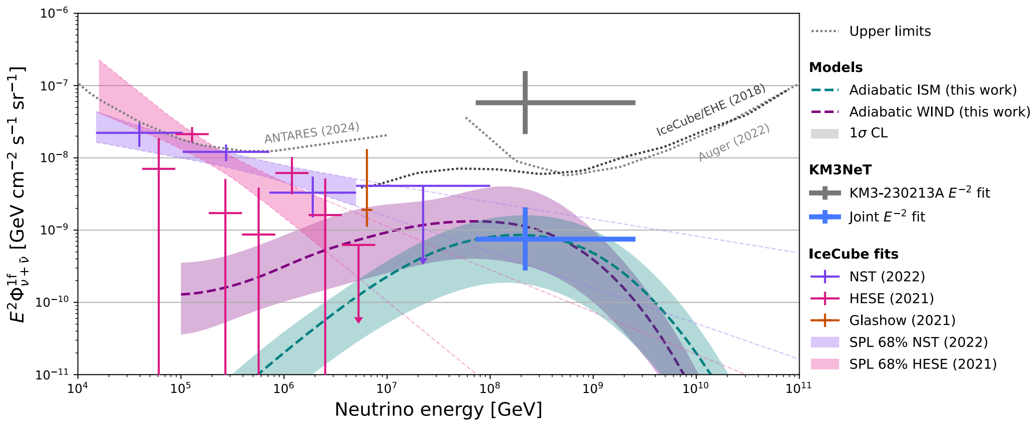

Fig. 4: Energy-squared per-flavour diffuse astrophysical neutrino flux. The KM3NeT-only flux from [1] is shown by the **grey** cross and the joint-fit flux from [5] in **blue**. Measurements and upper limits from other neutrino telescopes are also shown. The filled bands indicate the predicted UHE neutrino flux from our **ISM** and **WIND** models.

References

[1] S. Aiello et al. 2025, Nature, 638, 376
[2] S. Razzaque 2013, Phys. Rev. D, 88, 103003
[3] R. Sari et al. 1998, ApJ, 497, L17
[4] S. Banerjee et al. 2021, ApJ, 921, 79
[5] A. Von Kienlin et al. 2020, ApJ, 893, 46
[6] O. Adriani et al. 2025, Phys. Rev. X, 15, 031016