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Constraining GRB 230812B Prompt Emission Parameters with IceCube Neutrino Upper Limits

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High energy neutrino detectors such as IceCube and ANTARES have followed up several bright gamma-ray bursts but have not found any associated neutrino signals, instead placing upper limits on the neutrino flux. In this work, we investigate the photo-hadronic interaction model during the prompt phase of GRBs and estimate the resulting neutrino flux. We use various models of the dissipation radius and its connection to the Lorentz factor to constrain the baryon loading parameter. Three emission scenarios, Baryonic Photosphere (BPH), Magnetically Dominated Photosphere (MPH), and Internal Shocks (IS), are analyzed to explore the dissipation radius, Lorentz factor, and baryon loading. For GRB 230812B, we scan the parameter space to identify allowed regions consistent with the neutrino non-detections. Based on the empirical correlation between the Lorentz factor and the isotropic gamma-ray energy, we consider $\Gamma = 187$ and report the dissipation radii in various models: $R_{\rm MPH} = 7.3 \times 10^{11}$ cm, $R_{\rm BPH} = 4.4 \times 10^{12}$ cm, and $R_{\rm IS} = 1.1 \times 10^{14}$ cm. We also estimate the baryon-loading parameter of the jet for these models. Further, we explore GRB parameter space relevant for neutrino detection using the sensitivity curves of the IceCube-Gen2 detector. Our analysis indicates that GRBs at low redshifts ($z \leq 0.5$) with Lorentz factors in the range $\Gamma \sim 500$–1500 and isotropic energies $E_{\gamma,\rm iso} \sim 3 \times 10^{52}$–$10^{54}$ erg are promising sources of detectable neutrino signals.

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1. Introduction

Gamma Ray Bursts (GRBs) are the most luminous explosions in the Universe, releasing up to $\sim 10^{54}$ erg of energy within a few seconds in the form of gamma rays [1]. In addition to electromagnetic radiation, GRBs have long been proposed as potential sources of high-energy neutrinos through hadronic interactions in their relativistic jets [2]. In the standard fireball framework, protons accelerated in the outflow can interact with the prompt gamma-ray photon field ($p\gamma$ interactions), producing charged pions that decay into neutrinos in the GeV–PeV range[3, 4]. High-energy neutrino observatories such as IceCube and ANATARES have followed the GRBs for a neutrino signal. However, despite numerous searches conducted by the neutrino observatories, no significant temporal or spatial association has been found between GRBs and neutrino events [5–7]. These non-detections impose stringent upper limits on the neutrino flux, which can be used to constrain key jet parameters such as the baryon loading factor (f_p), bulk Lorentz factor (Γ), and dissipation radius (R). The predicted neutrino flux from a GRB depends on the location and mechanism of the prompt emission region. Several model have been proposed to explain the prompt emission, Here we have discussed three models (i) the internal shock (IS) model, where emission arises from collisions between shells of varying Γ within the jet [8], (ii) the Baryonic Photosphere (BPH) model, in which radiation escapes near the Thomson photosphere of a baryon-dominated outflow [9]; and (iii) the Magnetic Photosphere (MPH) model, where a magnetically dominated jet becomes transparent at a smaller radius and exhibits suppressed hadronic emission [10]. Each of these models predicts distinct values of R and Γ, leading to different physical conditions for possible neutrino generation.

In this work, we present a detailed analysis of GRB 230812B as a representative case study. Based on its observed prompt emission properties, we estimate the expected high-energy neutrino flux under the three prompt emission frameworks: IS, BPH, and MPH models. The upper limit derived from the IceCube non-detection is then used to place constraints on the allowed parameter space of the jet, specifically on Γ, R, and f_p within these models. Finally, we explore how future neutrino detectors with improved sensitivity could probe regions of parameter space currently inaccessible to IceCube.

2. Case Study: GRB 230812B

GRB 230812B is among the brightest GRBs detected in recent years and exhibits a prompt emission duration of $T_{90} \approx 3$ s, placing it near the boundary between short and long GRB populations. The isotropic luminosity and energy, derived from the time-integrated prompt spectrum, are estimated to be $L_{\rm iso} \sim 4.9 \times 10^{52}$ erg s^{-1} and $E_{\rm iso} \sim 1.2 \times 10^{53}$ erg [11]. Following the detection of GRB 230812B (R.A. = 326.7°, δ = +47.3°)[12], the IceCube Neutrino Observatory performed a dedicated search for muon neutrino events temporally coincident with the burst. No significant excess of neutrino flux above the expected background was reported. Assuming an E^{-2} neutrino spectrum, the 90% confidence level upper limit on the time integrated muon neutrino flux upper limit is 5.1×10^{-2} GeV cm^{-2} [13]. Using the declination-dependent effective area of IceCube for the range $30° < \delta < 90°$, we computed the expected number of neutrino events N_ν corresponding to this observational upper limit. The resulting value of N_ν should be below 0.245.

To estimate the expected neutrino flux from GRB 230812B, we adopt the analytical framework developed by [14]. In this framework, the neutrino flux is computed considering photo-hadronic ($p\gamma$) interactions between the accelerated protons and the target photon field in the prompt emission region. The formalism allows us to express the neutrino fluence as a function of the observed gamma-ray spectral parameters and physical jet quantities such as Γ, R, and f_p. Here baryon loading is defined by $f_p = \epsilon_p/\epsilon_e f_e$, where ϵ_p and ϵ_e are fractional energies available in protons and electrons and f_e is the efficiency of electrons radiating their energy as gamma-rays through synchrotron or inverse Compton radiation [15], the value of f_e is assumed to be 1. By implementing this formalism, we calculate the corresponding neutrino spectra for the IS, MPH, and BPH models, and compare the results with the IceCube 90% C.L. fluence upper limit derived for GRB 230812B. The asymptotic Lorentz factor, defined as $\eta = L/\dot{M}c^2$, is taken as a free parameter in our analysis. In the IS and BPH scenarios $\eta = \Gamma$, whereas in the MPH case, $\Gamma < \eta$. For GRB 230812B, we estimate the bulk Lorentz factor using the empirical correlation $\Gamma_0 \simeq 91 \left(E_{\gamma,\mathrm{iso}}/10^{52}\ \mathrm{erg}\right)^{0.29}$ [16], which yields $\Gamma_0 \approx 187$.

In figure 1 we show the allowed and excluded regions in the parameter space for each model along with a model-independent constraint derived from the IceCube sensitivity. In the IS model (Figure 1a), the blue horizontal line at the chosen $\Gamma = 187$ intersects the $N_{\mathrm{tot}} = 0.245$ contour at $\epsilon_p \approx 0.535$, setting an upper bound on the baryon-loading factor f_p. The allowed region is consistent with all values of ϵ_p and $\Gamma \geq 187$. For the BPH model (Figure 1b), the intersection occurs at $\epsilon_p \approx 0.195$, suggesting a more stringent upper limit on f_p compared to the IS case. The model also disfavors low Lorentz factors ($\Gamma \lesssim 200$) for typical micro-physical parameters $\epsilon_e = 10^{-3}$ and $\epsilon_B = 10^{-5}$. In the MPH model (Figure 1c), the contours are nearly parallel to the Lorentz factor axis, implying that the predicted neutrino flux is largely insensitive to η. The IceCube non-detection favours $\epsilon_p \lesssim 0.1$–0.4, indicating weak dependence on η and highlighting the overall inefficiency of neutrino production in magnetically dominated jets. Finally, the model-independent case (Figure 1d) illustrates the variation of the neutrino event number N_{tot} across the R_{13} and Γ, for baryon-loading factors $f_p = 600, 800, 1000$. The excluded regions below each contour have parameter combinations that would have produced more than 0.245 events and are therefore inconsistent with IceCube's upper limit. Predicted neutrino spectrum of GRB 230812B for the IS, BPH, and MPH models, along with IceCube-Gen2 ($\pm 500s$ time window) [17] and KM3NeT/ARCA (1000s time window) sensitivities [18] is shown in figure 3. The IceCube upper limits are shown with the black horizontal lines. The predicted neutrino spectrum for all three models are shown for two f_p values: the maximum allowed f_p and a second case where f_p values are numerical half of these maximum values. This allows us to examine how the neutrino spectrum varies with baryon loading. For $\Gamma = 187$ solid lines represent maximum baryon loading $f_{p,\mathrm{max}} = 535$ (IS), 195 (BPH), 141 (MPH), while dashed lines represent $f_p = 268$ (IS), 98 (BPH), 71 (MPH).

3. Emission region for Neutrinos and Gamma rays using $\gamma - \gamma$ Opacity

To further constrain the location of the emission region in GRB 230812B, we examined the optical depth due to pair production ($\tau_{\gamma\gamma}$) and the N_ν as functions of R and Γ. The detection of a 100 MeV photon during the prompt emission phase [22] provides a lower bound on the transparency of the emitting region, since such a photon can only escape if $\tau_{\gamma\gamma} \leq 1$. We therefore adopted

Observable	Value	Model	Value	Derived	Value
z	0.36 [11]	Γ	187	R [cm] (IS)	1.095×10^{14}
$E_{\rm peak}$ [keV]	273 [19]	$\delta t_{\rm min}$ [s]	0.071 [20]	R [cm] (BPH)	4.397×10^{12}
α, β	$-0.8, -2.47$ [19]	ξ	0.1	R [cm] (MPH)	7.329×10^{11}
T_{90} [s]	3.3 [19]	ϵ_B	10^{-5}	B [G] (IS)	980
$E_{\rm iso}$ [erg]	1.2×10^{53} [11]	ϵ_e	10^{-3}	$f_{p,\rm max}$ (IS)	535
$L_{\gamma,\rm iso}$ [erg s^{-1}]	4.9×10^{52} [11]	—	—	$f_{p,\rm max}$ (BPH)	195
D_L [cm]	6.11×10^{27}	—	—	$f_{p,\rm max}$ (MPH)	141

Table 1: GRB 230812B Parameters. Observable parameters include redshift z, spectral peak energy $E_{\rm peak}$, Band indices (α, β), isotropic energy $E_{\rm iso}$ and luminosity $L_{\rm iso}$, luminosity distance, and duration (T_{90}). Model parameters include Γ, minimum variability timescale ($\delta t_{\rm min}$), and micro-physical parameters (ξ, ϵ_B, ϵ_e). Derived parameters include the R, B, and $f_{p,\rm max}$ for the IS, BPH, and MPH models.

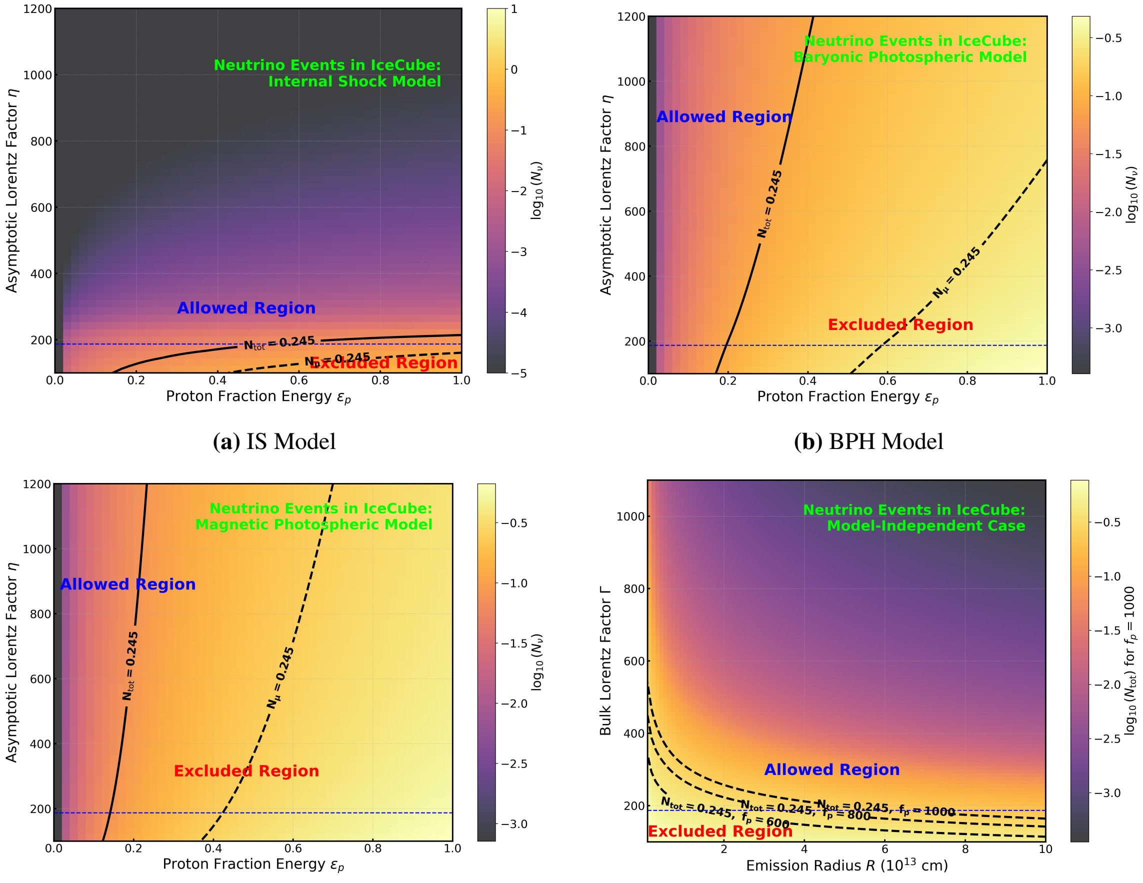
$E_{\rm cut} = 100$ MeV as the cutoff energy for our opacity calculations [22]. Figure 2 shows the resulting R–Γ parameter space for GRB 230812B. The red dashed line marks the $\tau_{\gamma\gamma} = 1$ contour, representing the boundary above which the emission region becomes transparent to high-energy photons. The purple contour corresponds to the $N_\nu = 0.245$ event. The blue dashed horizontal line indicates $\Gamma = 187$. For GRB 230812B, we find that the neutrino production region requires emission radii larger than the γ-ray photosphere for the same bulk Lorentz factor. This indicates spatially distinct zones for the γ-ray and neutrino emission.

4. Parameter Space Exploration for Future Detection

To explore the potential of future high-energy neutrino detections from GRBs, we performed a systematic parameter space analysis over a broad range of $E_{\rm iso}$, Γ, $E_{\rm p}$, and z. Figure 4 presents the kernel density distributions for the subset of GRBs whose predicted neutrino flux exceeds the IceCube Gen2 sensitivity threshold. The resulting distributions show that detectable GRBs are predominantly concentrated at low redshifts ($z \lesssim 0.5$). These bursts also exhibit relatively high Lorentz factors ($\Gamma \sim 500$–1500) and large isotropic energies ($E_{\rm iso} \sim 10^{52.5}$–$10^{54}$ erg). The $E_{\rm p}$ distribution lies primarily in the MeV range, consistent with the observations. Overall, the analysis highlights that nearby, energetic, and highly relativistic GRBs are the most promising candidates for future neutrino detections by IceCube and upcoming detectors such as IceCube-Gen2 and KM3NeT/ARCA.

5. Results and Discussion

We studied three emission models, IS, BPH and MPH for the prompt phase of GRB, and the predicted neutrino spectrum for these three models associated with GRB230812B is shown in figure 3. For $\Gamma = 187$, the dissipation radius for the prompt phase of the radiation models are $R_{MPH} \simeq 7.329 \times 10^{11}$ cm, $R_{BPH} \simeq 4.397 \times 10^{12}$ cm, and $R_{IS} \simeq 1.095 \times 10^{14}$ cm, respectively. The values of the micro-physical parameters are constrained to be $\epsilon_e = 10^{-3}$ and $\epsilon_B = 10^{-5}$. For GRB 230812B, at $\Gamma = 187$, the IS Model gives the maximum value of $\epsilon_p = 0.535$, which implies a baryon loading $f_p = 535$ (for $\epsilon_e = 10^{-3}$ and $f_e = 1$). In the BPH Model, the maximum value of $\epsilon_p = 0.195$, i.e., $f_p = 195$ (for $\epsilon_e = 10^{-3}$ and $f_e = 1$), which coincides with the upper



(a) IS Model

(b) BPH Model

(c) MPH Model

(d) Model Independent

Figure 1: Density plots of expected neutrino events in IceCube for GRB 230812A. (a) IS Model: Contours where $N_{\mathrm{tot}} = 0.245$ and $N_\mu = 0.245$ are shown by solid and dashed lines, respectively. The blue horizontal line marks $\eta = \Gamma = 187$, intersecting the $N_{\mathrm{tot}} = 0.245$ contour at $\epsilon_p = 0.535$, constraining the maximum baryon loading f_p. The other energy fractions are fixed to $\epsilon_e = 10^{-3}$ and $\epsilon_B = 10^{-5}$. (b) BPH Model: Conventions same as (a). The blue line $\eta = \Gamma = 187$ intersects $N_{\mathrm{tot}} = 0.245$ at $\epsilon_p = 0.195$, setting the f_p upper bound. (c) MPH Model: IceCube non-detection favours $\epsilon_p \lesssim 0.1 - 0.4$, weakly dependent on η. The $\eta = 187$ line intersects $N_{\mathrm{tot}} = 0.245$ at $\epsilon_p = 0.141$. (d) Model Independent: Density plot in the dissipation radius $R_{13} = (R/10^{13})$ cm vs. Γ. Darker colours denote fewer events. Dashed lines show $N_{\mathrm{tot}} = 0.245$ contours for $f_p = 600, 800, 1000$. Other parameters are fixed to $\epsilon_e = 10^{-3}$ and $\epsilon_B = 10^{-5}$. Based on IceCube's null result [21], the parameter space below each contour is disfavoured for the corresponding f_p.

limit as seen with the solid-dashed lines plotted for 0.245 neutrino events. In the MPH Model, when the magnetization parameter $\sigma >> 1$, the maximum value of $\epsilon_p = 0.141$, i.e., $f_p = 141$ (for $\epsilon_e = 10^{-3}$ and $f_e = 1$), which coincides with the upper limit of 0.245 neutrino events. We show that neutrino upper limits from any GRB are useful as they provide us with information on the dissipation radius and microphysical parameters of the GRB jets, baryon loading, etc. We also explored the parameter space for possible future detections by the IceCube-Gen2 detector and found GRBs at low redshifts ($z \leq 0.5$) with Lorentz factors in the range $\Gamma \sim 500$–1500 and isotropic energies $E_{\gamma,\mathrm{iso}} \sim 3 \times 10^{52}$–$10^{54}$ erg are promising sources of detectable neutrino signal.

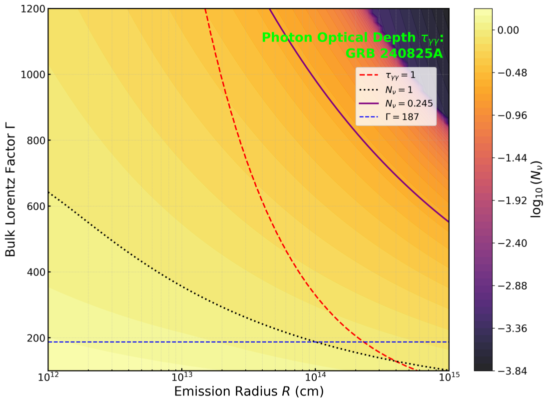


Figure 2: $R - \Gamma$ density plot for GRB 230812B showing neutrino event counts and photon optical depths. The $\tau_{\gamma\gamma} = 1$ curve represents the electromagnetic emission radius. The $N_\nu = 0.245$ contour is shown for GRB 230812B. Green dashed horizontal lines mark the corresponding Γ value.

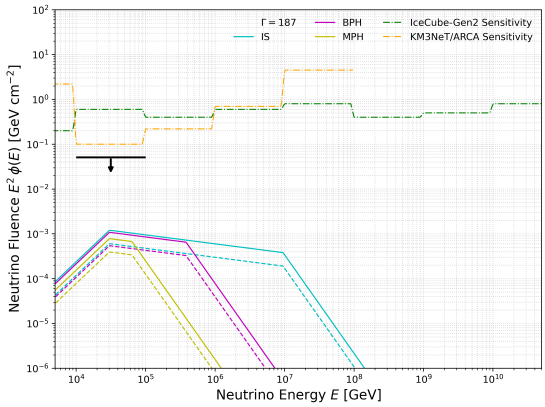


Figure 3: Predicted neutrino spectrum of GRB 230812B for the IS, BPH, and MPH models, compared with IceCube-Gen2 (±500 s time window) [17] and KM3NeT/ARCA (1000 s time window) sensitivities [18]. The IceCube upper limit is shown as black horizontal lines.

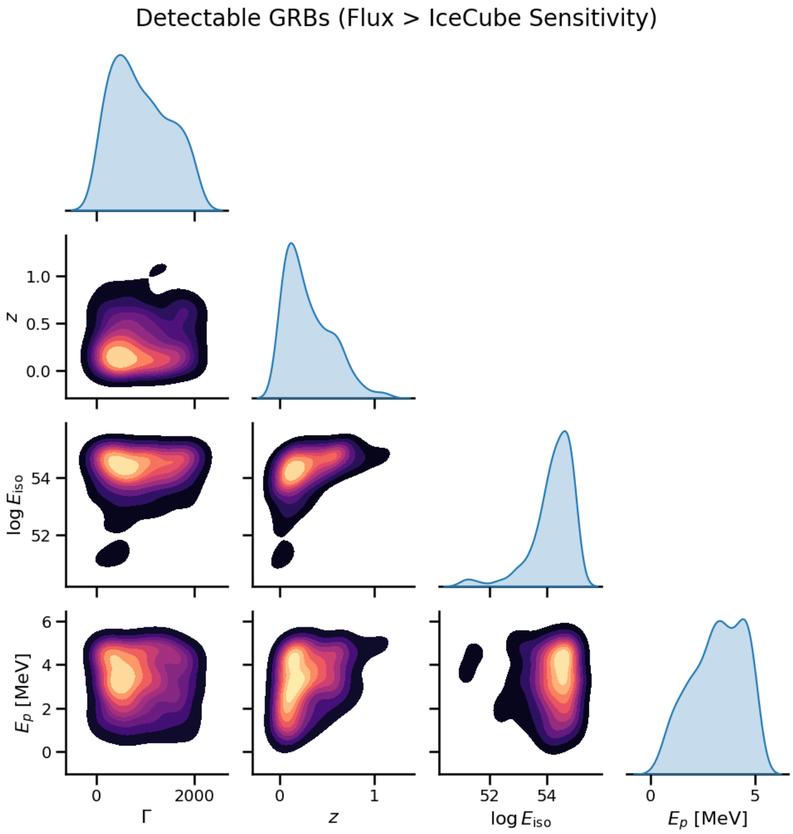


Figure 4: Parameter space showing the region of favourable GRB characteristics for future neutrino detection. The shaded region highlights the combination of high $E_{\rm iso}$, large Γ, and low redshift z for potential detections by the IceCube.

6. Acknowledegment

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