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Implications from neutrino limits at IceCube from the brightest gamma-ray burst GRB 221009A

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The non-detection of neutrinos from the brightest gamma-ray burst (GRB), GRB 221009A at the IceCube neutrino observatory allows us to put constraints on GRB model parameters like the dissipation radius, the Lorentz factor, and the cosmic-ray loading factor. We model the neutrino spectra and discuss the resulting limits on allowed parameter spaces. We find that our results are strong enough to constrain proton acceleration near the photosphere. Our new limit from a single source, is comparable and hence complimentary to the IceCube stacking limit. We also discuss the prospects for quasi-thermal neutrinos from the subphotosphere region in the context of neutron decoupling and colliding neutron-loaded flows, where we find that the latter might lead to a few events at IceCube with dedicated searches. Such observations at next generation neutrino detectors like IceCube-Gen2 and KM3NeT are crucial and would provide important constraints and insights into understanding subphotospheric emissions from GRBs.

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1. Introduction

A sudden emission (burst) in the hard X-ray/soft-γ ray (10 keV - several MeV) band, lasting from a few milliseconds to thousands of seconds, as a result of explosive astrophysical phenomena at the highest energy scales, is known as a gamma-ray burst (GRB) (see for e.g. [1–3] for detailed reviews). The energy scales involved at production sites of GRBs make them ideal messengers to investigate the origin ultra-high energy cosmic rays (UHE CRs) and high energy neutrinos associated with the source. High-energy astrophysical phenomenona like compact object mergers and collapsars, eventually lead to the formation of a rapidly spinning black hole or a highly magnetized neutron star. This remnant launches a relativistic jet, which loses energy through internal energy dissipation which can be due to shocks or magnetic reconnection. These dissipation regions are ideal sights for acceleration of non-thermal electrons and protons. The accelerated electrons eventually cool down through the synchrotron process, leading to gamma-rays, which are then observed. The protons interact with the gamma-rays ($p\gamma$ interactions) to produce charged pions which then decay to produce high-energy neutrinos via the photo-meson process. Since their initial discovery in 1967, hundreds of GRBs have been detected, however no accompanied neutrino events have been found.

1.1 GRB 221009A

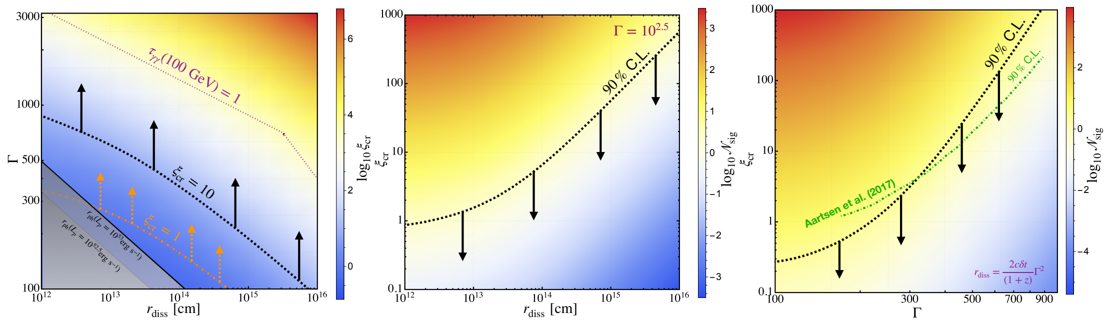
On October 9, 2022, the Gamma-ray Burst Monitor (GBM) on the Fermi satellite [4] and the Neil Gehrels Swift Observatory [5] jointly discovered an extremely bright long duration GRB. The main burst was $\sim$ 180s post the initial $\sim$ 10s long pulse. With the aid of afterglow emissions and follow-up observations the source was revealed to be at a redshift of $z = 0.151$ [6] and at a luminosity distance $d_{\rm L} \approx 740$ Mpc. The approximate isotropic-equivalent gamma-ray energy was estimated to be $\mathcal{E}_\gamma^{\rm iso} \sim 3 \times 10^{54}$ erg. The Swift observatory localized the GRB to be at a right ascension of 288.2645° and declination of +19.7735°. The high energy-gamma rays were detected by Fermi-LAT $\sim 200 - 600$s post the Fermi-GBM trigger [7]. The Large High Altitude Air Shower Observatory (LHASSO) detected $\sim$ 5000 events in the TeV range, including $\gtrsim$ 10 TeV photons [8].

The IceCube collaboration reported the non-detection of neutrinos from GRB 221009A at 90% C.L. [9, 10], which gives a corresponding limit on the neutrino fluence, $E_\nu^2 \phi_{\nu_\mu} \leq 3.9 \times 10^{-2}$ GeVcm^{-2} for an E_ν^{-2} spectrum. This non-detection bound allows us to place competitive constraints on the various GRB model parameters (the dissipation radius, the Lorentz factor, the cosmic ray loading factor) and the associated emission regions [11].

In Sec. 2 we discuss the neutrino constraints on the physical parameters from non-thermal neutrino emission. The prospects for expected quasi-thermal neutrino signatures from neutron decoupling and colliding neutron loaded flows is discussed in Sec. 3. We conclude in Sec. 4 and discuss the implications of our work.

2. Nonthermal emission: neutrino constraints

It is known that if the prompt phase of the GRB involves acceleration of the high energy cosmic rays (CRs), they should then interact with the GRB photons via the photomeson production process,



(a) (b) (c)

Figure 1: (Left (a)): Constraints on Γ as a function of $r_{\rm diss}$ for different values of the CR loading factor $\xi_{\rm cr}$. The region below $r_{\rm ph}$ is not considered for nonthermal neutrino production. (Middle (b)): Constraints on $\xi_{\rm cr}$ as a function of $r_{\rm diss}$ for a given Lorentz factor of $\Gamma = 10^{2.5}$, where color scale represents the number of signal events $\mathcal{N}_{\rm sig}$. (Right (c)): Constraints on $\xi_{\rm cr}$ as a function of Γ, where the internal shock model is assumed with $\delta t = 0.01$ s. The IceCube stacking limit at 90% C.L. [12] for this model is also shown.

which then produces charged pions that decay to give high-energy neutrinos [13]. The neutrino fluence from such a source is given by,

$$E_\nu^2 \phi_{\nu_\mu} \approx \frac{1}{8}\frac{(1+z)}{4\pi d_L^2}\min[1, f_{p\gamma}]\xi_{\rm cr}\frac{\mathcal{E}_\gamma^{\rm iso}}{\mathcal{R}_{\rm cr}} \sim 4\times 10^{-3}\ {\rm erg\ cm^{-2}}\min[1, f_{p\gamma}]\xi_{{\rm cr},1}\mathcal{E}^{\rm iso}_{\gamma,54.5}\mathcal{R}^{-1}_{{\rm cr},1.2}\,, \quad (1)$$

where, the factor $1/8$ arises from the fact that the $\pi^\pm/\pi^0$ ratio is ~ 1 in $p\gamma$ interactions due to the contribution from direct production combined with the fact that each flavor of neutrinos carries $\sim 1/4$ of the pion energy post mixing. The redshift and the luminosity distance of the source is given by z and d_L respectively, $f_{p\gamma}$ denotes the optical depth of $p\gamma$ interactions, $\xi_{\rm cr} = \mathcal{E}_{\rm cr}{\rm iso}/\mathcal{E}_\gamma^{\rm iso}$ is the cosmic ray loading factor [14], where, $\mathcal{E}_{\rm cr}^{\rm iso}$ is the isotropic-equivalent cosmic ray energy, and $\mathcal{R}_{\rm cr} \sim 15 - 20$ is a bolometric correction factor associated with a CR spectral index $s_{\rm cr} = 2$ and is also related to the CR maximum energy.

We use the IceCube 10 years point-source (PS) effective area for this work [15], at a source declination of $\delta_{\rm src} \approx +19.8°$. The number of signal events $\mathcal{N}_{\rm sig}$ in the detector is given by,

$$\mathcal{N}_{\rm sig} = \int_{E_{\nu_\mu}=200\ {\rm GeV}}^{E_{\nu_\mu}=10^9 {\rm GeV}} \phi_{\nu_\mu}\mathcal{A}_{\rm eff}(E_{\nu_\mu}, \delta_{\rm src})dE_{\nu_\mu}\,, \quad (2)$$

where, $\mathcal{A}_{\rm eff}$ is the effective area. The neutrino emission spectra is calculated using the prescription in [16, 17]. For this work, we choose the energy fraction of the magnetic field compared to the radiation energy $\xi_{\rm B} = 1$, the photon break energy in the GRB frame $\varepsilon^b = 1.2$ MeV, the low and high energy photon indices $\alpha = 1.1$ and $\beta = 2.6$ respectively. The dissipation radius ($r_{\rm diss}$) associated with prompt emission is not very well-understood [18, 19], thus we use it as a free parameter in our analysis to provide estimates for the various models. In Fig. 1a and Fig. 1b we show the associated constraints from GRB 221009A on $r_{\rm diss} - \Gamma$ and $r_{\rm diss} - \xi_{\rm CR}$ planes respectively.

In Fig. 1a, in the limit that coasting occurs under the photosphere radius ($r_{\rm ph}$), we obtain competitive constraints on the fate of particle acceleration near the photosphere, $r_{\rm ph} \simeq 3.8\,\times$

10^{12} cm $\zeta_e L_{p,53}\Gamma_{2.5}^{-3}$, where, L_p is the proton luminosity and ζ_e is the number ratio of electrons and positrons to protons. We show the photosphere radii corresponding to $L_p = 10^{53}$ erg/s (solid black line) and $10^{52.5}$ erg/s. We do not consider non-thermal emissions from the subphotospheric regions (the quasi-thermal neutrino emission from subphotospheric regions is the focus of Sec. 3) shaded in gray. The dashed orange line (dashed black line) shows the lower limit for $\xi_{\rm CR} = 1$ in the $r_{\rm diss} - \Gamma$ for $\xi_{\rm CR} = 1$ ($\xi_{\rm CR} = 10$), where we find that for $\xi_{\rm CR} \leq 1$, $\Gamma \leq 300$. This is also seen from Fig. 1b, where we show $\mathcal{N}_{\rm sig}$ in the $r_{\rm diss} - \xi_{\rm CR}$ plane for $\Gamma = 300$. The dashed black line shows the constraint obtained from the IceCube limit. It is important to note here that although this excludes the possibility of baryonic photosphere scenario where, $\xi_{\rm CR} = 1$ and $\zeta_{\rm CR} = 1$, the constraints can be relaxed with larger values of Γ. We also note that the outer-zone models corresponding to large $r_{\rm diss}$ are allowed and consistent with the IceCube limits, where we find, $r_{\rm diss} \geq (2 - 20) \times 10^{14}$ cm for $\Gamma \sim 300$ and $\xi_{\rm CR} \sim 10 - 100$. This allowed parameter space besides ruling out the neutron escape scenario for UHE CRs [20] favors some of the magnetic reconnection models [19] and is where UHE CR are likely to be nuclei rather than protons [18].

The internal shock scenario is well motivated for prompt GRB emissions, suggesting UHE CR hypothesis likely require $\xi_{\rm CR} \sim 10 - 100$ [18]. In Fig. 1c we show $\mathcal{N}_{\rm sig}$ in the $\Gamma - \xi_{\rm CR}$ plane along with the constraint obtained from the IceCube limit (dashed black line). We assume the dissipation radius to be, $r_{\rm diss} \approx 2\Gamma^2 c\delta t/(1+z)$ as expected in the internal shock scenario, where δt is the variability timescale. We choose $\delta t = 0.01$s (which may have observational and model uncertainties). We conclude that for $\Gamma = 300$ which is often assumed in the literature, $\xi_{\rm CR} \leq 3$. This implies that the UHE CR hypothesis may be excluded. However, if the Lorentz factor is large to result in $r_{\rm diss} \geq (2-20) \times 10^{14}$ cm, the internal shock model is still valid and can be efficient sources for UHE CR acceleration. The IceCube limit obtained from stacking analysis [12] is also shown as a dot-dashed green line. Our limits are comparable and hence complimentary to the IceCube stacking limit, but has an advantage over the IceCube limit since it is from a single burst and thus comparatively free from systematic uncertainties associated with the analysis of many bursts.

3. Constraints for quasi-thermal neutrinos

The production of high-energy neutrinos do not necessarily have to rely on CR acceleration. In the absence of collisionless shocks and magnetic reconnections *neutrons* can provide neutrinos through either inelastic collisions between bulk flows or neutron diffusion [21]. Neutron decoupling [22] and/or internal collisions between neutron-loaded outflows [23, 24] are natural production mechanisms for *quasi-thermal neutrinos*. The quasi-thermal neutrino emissions from subphotospheric regions, is the focus of this section.

3.1 Neutrinos from neutron decoupling

As the GRB jet propagates within a star it can get collimated [25, 26], which leads to heating up of the jet material. In this post-collimation regime, the jet material's density is high such that $\tau_{\rm T} >> \tau_{np} >> 1$ (where, $\tau_{\rm T}$ is the Thomson optical depth and τ_{np} is the optical depth for np collisions). In this regime the protons and neutrons are coupled. However, after the jet breakout the hot jet material might expand similar to a fireball, with $\Gamma(r) \approx \Gamma_*(r/R_*)$ (where, Γ_* is the Lorentz factor at breakout and R_* is the radius of the star), in which case one can estimate the eventual

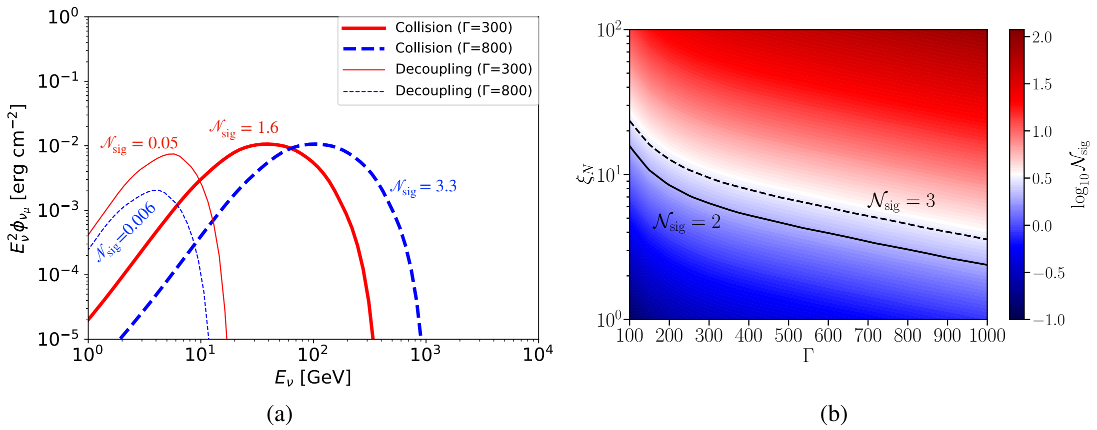


Figure 2: Left (a): Energy fluences of quasi-thermal ν_μ from GRB 221009A for both collision and decoupling scenarios, where $\xi_N = 5$ and $\mathcal{E}_\gamma^{\rm iso} = 10^{54.5}$ erg are used. The expected number of signal events at IceCube $\mathcal{N}_{\rm sig}$ are also shown. Right (b): Expected number of signal events, $\mathcal{N}_{\rm sig}$, in DeepCore+IceCube as a function of ξ_N and Γ. The solid and dashed lines show the parameter sets that lead to doublet and triplet events, respectively.

decoupling radius ($r_{n,\rm dec}$) by equating the np collision time ($t_{pn} = 1/(n'_p\sigma_{np}c)$, where, σ_{np} is the approximate np collision cross-section, n'_p is the proton density which depends on the maximum Lorentz factor $\Gamma_{\rm max}$ of the expanding fireball) and the expansion time of the fireball ($t_{\rm dyn} = (r/\Gamma c)$).

During neutron decoupling, the flow experiences relativistic acceleration due to radiative acceleration leading to inelastic np collisions [22]. By definition, the np optical depth at $r_{\rm dec}$ is unity. The quasi-thermal neutrino energy fluence from neutron decoupling is given by,

$$E_\nu^2\phi_{\nu_\mu} \approx \frac{1}{12}\frac{(1+z)}{4\pi d_L^2}\zeta_n\left(\frac{\Gamma_{n,\rm dec}}{\Gamma}\right)\xi_N\mathcal{E}_\gamma^{\rm iso} \sim 0.01 \text{ erg cm}^{-2}\ \zeta_n(\Gamma_{n,\rm dec}/0.2\Gamma)\xi_{N,1}\mathcal{E}^{\rm iso}_{\gamma,54.5}\,, \quad (3)$$

where, the factor $1/12$ is a product of $1/2$ which is the assumed neutron inelasticity in np collisions and $1/6$ which is due to the fact that $2/3$ of the pions produced in np collisions are charged pions, $3/4$ of whose decay products are equally divided among the three neutrino flavors each post mixing (which gives a factor of $1/3$ for each flavor). The number ratio of neutrons to protons is given by ζ_n, the kinetic energy of the proton outflow is $\xi_N\mathcal{E}_\gamma^{\rm iso}$ with $\Gamma \gtrsim \Gamma_{n,\rm dec}$ and the nucleon loading factor is given by ξ_N. The typical energy for quasi-thermal neutrinos from neutron decoupling is predicted to be $\sim 1-10$ GeV. This can be estimated using, $E_\nu^{\rm qt} \approx 0.1\Gamma_{n,\rm dec}m_pc^2/(1+z)$. In Fig. 2a we show the quasi-thermal neutrino fluence corresponding to this scenario for $\Gamma = 300$ (thin solid red) and $\Gamma = 800$ (thin dashed blue). We choose $\zeta_n = 1$ and assume $\Gamma = \Gamma_{\rm max}$ which then gives $\Gamma_{n,\rm dec}$ using $\Gamma_{n,\rm dec}(r = r_{n,\rm dec}) \approx \Gamma_*(r_{n,\rm dec}/R_*)$.

3.2 Neutrinos from colliding neutron-loaded flows

In the previous section we considered the scenario of neutron decoupling assuming $\Gamma \approx \Gamma_{\rm max}$. However, if the decoupling happens when $\Gamma < \Gamma_{\rm max}$ the neutron flow is caught up by the proton flow resulting in pn collisions [27, 28]. If the coasting takes place before decoupling, internal collisions may lead to dissipation of neutrons around, $r_{n,\rm dec} << r_{ph}$.

The neutrino energy fluence in this case is given by,

$$E_\nu^2 \phi_{\nu_\mu} \approx \frac{1}{12} \frac{(1+z)}{4\pi d_L^2} \tau_{pn} \xi_N \mathcal{E}_\gamma^{\rm iso} \sim 0.03 \text{ erg cm}^{-2} \, \tau_{pn} \xi_{N,1} \mathcal{E}_{\gamma,54.5}^{\rm iso} \,,$$

where, the optical depth for pn collisions is given by, $\tau_{pn} \approx (\Gamma/\Gamma_{n,dec})(\zeta_n/\zeta_e)\tau_T$ in the region, $r_{n,\rm dec} << r_{ph}$. The kinetic energy of the interacting flow $\xi_N \mathcal{E}_\gamma^{\rm iso}$ sets the normalization. The neutrino energy fluence for this scenario assuming $\tau_{pn} = 1$ is shown in Fig. 2a. The neutrino spectra peaks at $E_\nu \sim 30$ GeV and $E_\nu \sim 180$ GeV corresponding to $\Gamma \sim 300$ (thick solid red) and $\Gamma \sim 800$ (thick dashed blue) respectively. This matches with the typical neutrino energies $\sim 30 - 300$ GeV for $\Gamma \sim 10^2 - 10^3$ expected from such a scenario [24], where we have, $E_\nu^{\rm qt} \approx 0.1 \Gamma \Gamma'_{\rm rel} m_p c^2/(1+z)$, where, $\Gamma'_{\rm rel} \sim 2$ is the relative Lorentz factor of the interacting flow.

3.3 Implications for quasi-thermal neutrinos

Having discussed the neutrino spectra expected for quasi-thermal neutrinos in the above sections, we focus on their detection prospects and implications in the context of GRB 221009A in this section. In Fig. 2a we show the number of signal events $\mathcal{N}_{\rm sig}$ expected in IceCube. In this case, unlike in the previous section, we use the latest all-flavor effective areas for GRECO (GeV-Reconstructed Events with Containment for Oscillations) selection [29] and through-going muon neutrinos [15]. While the prospects for the decoupling model seem bleak ($\mathcal{N}_{\rm sig} \sim 10^{-2} - 10^{-3}$), the collision model however has good prospects ($\mathcal{N}_{\rm sig} \sim$ a few events) to detect ~ 100 GeV neutrinos, particularly for large Lorentz factors and $\xi_N \sim 10$. The number of signal events in the $\xi_N - \Gamma$ plane is shown in Fig. 2b. The constraints that can be obtained from doublet (solid black line) and triplet (dashed black line) neutrino detections from GRB 221009A in the GeV-TeV range are also shown, which give $\xi_N \sim 6.5(10)$ for $\Gamma \sim 300$ corresponding to $\mathcal{N}_{\rm sig} = 2(3)$.

4. Conclusions and Discussion

The non-detection of neutrinos by IceCube from the brightest GRB 221009A, and the corresponding limit on the muon neutrino fluence obtained at 90% C.L. can be used to constrain important GRB model parameters, in particular, the dissipation radius, the Lorentz factor and the cosmic ray loading factor which is relevant in understanding the production mechanism and region for high energy neutrinos and UHE CRs. Our main results are shown in Figs. 1 and 2. We found that for non-thermal neutrino emissions $\xi_{\rm CR} \lesssim 1$ for $\Gamma \lesssim 300$. We conclude that the outer zone emission models are still consistent with the IceCube observations, where we have a large $r_{\rm diss}$, $r_{\rm diss} \geq (2 - 20) \times 10^{14}$ cm for $\Gamma \sim 300$ and $\xi_{\rm CR} \sim 10 - 100$. For typical values of $\Gamma \sim 300$ in the internal shock model, we find $\xi_{\rm CR} \lesssim 3$ given our assumption of the dissipation radius. However, neutrinos and gamma-rays may come have different emission regions in which case, detailed investigations with multi-zone emission models are required. For such large values of $r_{\rm diss}$ and Γ, GRB internal shocks can still accelerate UHE CRs. Our new limit from GRB 221009A is comparable and hence complementary to the IceCube stacking limit and is consistent with the fact that the contribution of canonical high-luminosity GRBs to the all-sky neutrino flux $\lesssim 1\%$.

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We also considered the prospects for quasi-thermal neutrino emissions from subphotospheric regions in the context of neutron decoupling and colliding neutron-loaded flows. We found that in the GeV - TeV range IceCube might be able to detect ∼ a few events for the collision model, however the results are less optimistic for the decoupling model. Dedicated searches for these neutrinos, with an appropriate time-window and input from other messengers, would then provide constraints on the nucleon loading factor (ξ_N), which we explored in the context of GRB 221009A. With the upcoming next generation neutrino detectors like IceCube-Gen2, KM3NeT and advances in electromagnetic telescopes, we hope to better understand the physics of GRBs and hence probe the origins of UHE CRs and high-energy neutrinos at the production sites.

References

[1] Tsvi Piran. The physics of gamma-ray bursts. *Rev. Mod. Phys.*, 76:1143–1210, 2004.

[2] Pawan Kumar and Bing Zhang. The physics of gamma-ray bursts \& relativistic jets. *Phys. Rept.*, 561:1–109, 2014.

[3] Shigeo S. Kimura. Neutrinos from Gamma-ray Bursts. 2 2022.

[4] P. Veres et al. GRB 221009A: Fermi GBM detection of an extraordinarily bright GRB. *GCN CIRCULAR*, 32636:1, October 2022.

[5] S. Dichiara, J.D. Gropp, J.A. Kennea, et al. Swift J1913.1+1946 a new bright hard X-ray and optical transient. *GCN CIRCULAR*, 32632:1, October 2022.

[6] A. de Ugarte Postigo, L. Izzo, G. Pugliese, et al. GRB 221009A: Redshift from X-shooter/VLT. *GCN CIRCULAR*, 32648:1, October 2022.

[7] R. Pillera, E. Bissaldi, N. Omodei, G. La Mura, and F. Longo. GRB 221009A: Fermi-LAT refined analysis. *The Astronomer's Telegram*, 15656:1, October 2022.

[8] Y. Huang et al. LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV. *GCN CIRCULAR*, 32677:1, October 2022.

[9] The IceCube-Collaboration. GRB 221009A: Upper limits from a neutrino search with IceCube. *GCN CIRCULAR*, 32665:1, October 2022.

[10] R. Abbasi et al. Limits on Neutrino Emission from GRB 221009A from MeV to PeV Using the IceCube Neutrino Observatory. *Astrophys. J. Lett.*, 946(1):L26, 2023.

[11] Kohta Murase, Mainak Mukhopadhyay, Ali Kheirandish, Shigeo S. Kimura, and Ke Fang. Neutrinos from the Brightest Gamma-Ray Burst? *Astrophys. J. Lett.*, 941(1):L10, 2022.

[12] M. G. Aartsen et al. Extending the search for muon neutrinos coincident with gamma-ray bursts in IceCube data. *Astrophys. J.*, 843(2):112, 2017.

[13] Eli Waxman and John N. Bahcall. High-energy neutrinos from cosmological gamma-ray burst fireballs. *Phys.Rev.Lett.*, 78:2292–2295, 1997.

[14] Kohta Murase and Shigehiro Nagataki. High energy neutrino emission and neutrino background from gamma-ray bursts in the internal shock model. *Phys. Rev.*, D73:063002, 2006.

[15] R. Abbasi et al. IceCube Data for Neutrino Point-Source Searches Years 2008-2018. 1 2021.

[16] Hao-Ning He, Ruo-Yu Liu, Xiang-Yu Wang, Shigehiro Nagataki, Kohta Murase, et al. Icecube non-detection of GRBs: Constraints on the fireball properties. *Astrophys.J.*, 752:29, 2012.

[17] Shigeo S. Kimura, Kohta Murase, Peter Mészáros, and Kenta Kiuchi. High-Energy Neutrino Emission from Short Gamma-Ray Bursts: Prospects for Coincident Detection with Gravitational Waves. *Astrophys. J.*, 848:L4, 2017.

[18] Kohta Murase, Kunihito Ioka, Shigehiro Nagataki, and Takashi Nakamura. High-energy cosmic-ray nuclei from high- and low-luminosity gamma-ray bursts and implications for multi-messenger astronomy. *Phys.Rev.*, D78:023005, 2008.

[19] Bing Zhang and Pawan Kumar. Model-dependent high-energy neutrino flux from Gamma-Ray Bursts. *Phys. Rev. Lett.*, 110(12):121101, 2013.

[20] Markus Ahlers and Jordi Salvado. Cosmogenic gamma-rays and the composition of cosmic rays. *Phys. Rev.*, D84:085019, 2011.

[21] P. Mészáros and M. J. Rees. Multi GeV neutrinos from internal dissipation in GRB fireballs. *Astrophys. J. Lett.*, 541:L5–L8, 2000.

[22] John N. Bahcall and Peter Mészáros. 5-GeV to 10-GeV neutrinos from gamma-ray burst fireballs. *Phys. Rev. Lett.*, 85:1362–1365, 2000.

[23] I. Bartos, A. M. Beloborodov, K. Hurley, and S. Márka. Detection Prospects for GeV Neutrinos from Collisionally Heated Gamma-ray Bursts with IceCube/DeepCore. *Phys. Rev. Lett.*, 110(24):241101, 2013.

[24] Kohta Murase, Kazumi Kashiyama, and Peter Mészáros. Subphotospheric Neutrinos from Gamma-Ray Bursts: The Role of Neutrons. *Phys. Rev. Lett.*, 111:131102, 2013.

[25] Omer Bromberg, Ehud Nakar, Tsvi Piran, and Re'em Sari. The propagation of relativistic jets in external media. *Astrophys. J.*, 740:100, 2011.

[26] Akira Mizuta and Kunihito Ioka. Opening Angles of Collapsar Jets. *Astrophys. J.*, 777:162, 2013.

[27] Andrei M. Beloborodov. Collisional mechanism for GRB emission. *Mon. Not. Roy. Astron. Soc.*, 407:1033, 2010.

[28] P. Mészáros and M. J. Rees. GeV Emission from Collisional Magnetized Gamma Ray Bursts. *Astrophys. J. Lett.*, 733:L40, 2011.

[29] R. Abbasi et al. Search for sub-TeV Neutrino Emission from Novae with IceCube-DeepCore. 12 2022.