NEUTRINOS FROM THE BRIGHTEST GAMMA-RAY BURST?

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ABSTRACT

We discuss implications that can be obtained by searches for neutrinos from the brightest gamma-ray burst, GRB 221009A. We derive constraints on GRB model parameters such as the cosmic-ray loading factor and dissipation radius, taking into account both neutrino spectra and effective areas. The results are strong enough to constrain proton acceleration near the photosphere, and we find that the single burst limits are comparable to those from stacking analysis. Quasithermal neutrinos from subphotospheres and ultrahigh-energy neutrinos from external shocks are not yet constrained. We show that GeV-TeV neutrinos originating from neutron collisions are detectable, and urge dedicated analysis on these neutrinos with DeepCore and IceCube as well as ORCA and KM3NeT.

1. INTRODUCTION

Gamma-ray bursts (GRBs) are the most powerful explosive phenomena in the Universe, which have been extensively discussed as ultrahigh-energy (UHE) cosmic-ray (CR) accelerators (Waxman 1995; Vietri 1995). Accompanied high-energy neutrinos have been searched for, but no detection has been reported so far (Abbasi et al. 2012; Aartsen et al. 2017a; Albert et al. 2020). Canonical high-luminosity GRBs cannot make a major contribution to the all-sky neutrino flux measured in IceCube, and optimistic cases have been ruled out. The hypothesis that UHE CRs come from GRBs has not yet been excluded, and various possibilities of high-energy CR and neutrino production in GRBs have been investigated (see reviews Mészáros 2015; Kimura 2022, and references therein).

On October 9, 2022, an extraordinarily bright burst, GRB 221009A, was reported. This burst was reported by Swift-BAT as an unknown-type transient (Dichiara et al. 2022), and it had triggered Fermi-GBM about one hour before the BAT trigger time (Veres et al. 2022). The burst showed an initial pulse of $\sim 10$ s, followed by the main burst beginning at $\sim 180$ s after the GBM trigger time. The preliminary estimate of the gamma-ray energy fluence reported by Konus-Wind is $\sim 5 \times 10^{-2}$ erg cm$^{-2}$ (Frederiks et al. 2022). Afterglow emission has been observed at different wavelengths, and optical follow-up observations revealed that the redshift of this GRB is $z = 0.15$ (de Ugarte Postigo et al. 2022), which suggests that the isotropic-equivalent gamma-ray energy is $E_{\gamma}^{iso} \sim 3 \times 10^{54}$ erg. The detection of high-energy gamma-rays at $\sim 200 - 600$ s after the GBM trigger time was reported by Fermi-LAT. The highest-energy photon of 99 GeV was detected by LAT at 240 s after the trigger (Pillera et al. 2022). The Large High Altitude Air Shower Observatory observed more than 5000 very-high-energy photons in the TeV range, and even $\sim 10$ TeV photons were detected (Huang et al. 2022).

In this work, we demonstrate how observations of neutrinos from the brightest GRB can be used for learning about models of GRB neutrino emission. We focus on neutrinos emitted during the prompt phase, and consider not only nonthermal neutrinos accompanied by
CR acceleration but also quasithermal neutrinos produced by inelastic collisions with neutrons. We use \( Q_x/Q = 10^6 \) in CGS units and assume cosmological parameters with \( \Omega_m = 0.3, \Omega_\Lambda = 0.7 \) and \( h = 0.7 \).

2. NONTHERMAL EMISSION

2.1. Gamma-ray constraints

The detection of high-energy gamma-rays can be used for placing a lower limit on the bulk Lorentz factor \( \Gamma \) (e.g., Lithwick & Sari 2001) and/or the dissipation radius \( r_{\text{diss}} \) (e.g., Murase & Ioka 2008; Gupta & Zhang 2008; Zhang & Pe'er 2009). The detection of a \( \sim 100 \) GeV photon at \( \sim 240 \) s after the trigger (Pillera et al. 2022) suggests that the emission region has to be transparent to \( \gamma \gamma \rightarrow e^+e^- \). The two-photon annihilation optical depth for a gamma-ray with energy \( \varepsilon_\gamma \) is

\[
\tau_{\gamma\gamma} \approx 150 \eta_{\gamma\gamma, 1} \frac{L_{\gamma, 52.5}}{r_{\text{diss}, 14} \Gamma_{2.5}^{1.4} \varepsilon_{b, 5}^{0.4} \varepsilon_{\gamma, 9}^{0.9}} \begin{cases} (\varepsilon_\gamma/\varepsilon_b)^{\beta-1} & (\varepsilon_\gamma < \varepsilon_b) \\ (\varepsilon_\gamma/\varepsilon_b)^{\alpha-1} & (\varepsilon_\gamma > \varepsilon_b) \end{cases} ,
\]

where \( \eta_{\gamma\gamma} \sim 0.1 \) is a spectrum-dependent coefficient (Svensson 1987), \( L_\gamma \) is the isotropic-equivalent gamma-ray luminosity during the main brightest episode, where we take \( 10^{52.5} \) erg \( s^{-1} \) in the Komus-Wind band (so that the band correction is included), \( \varepsilon_b \equiv 1 \) MeV \( \varepsilon_{b, 5} \) is the photon break energy in the GRB frame, \( \alpha \) and \( \beta \) are low- and high-energy photon indices, respectively. The typical energy of high-energy gamma-rays interacting with target photons at a break energy is \( E_b = \varepsilon_b/(1+z) \approx \Gamma^2 m_e^2 c^4/\varepsilon_b/(1+z) \approx 23 \) GeV \( \Gamma_{2.5}^{1.4} (\varepsilon_{b, 5})^{-1} \) for GRB 221009A.

Requiring \( \tau_{\gamma\gamma}(E_\gamma = 100 \) GeV \( < 1 \), with \( \varepsilon_b \sim 1 \) MeV, \( \alpha \sim 1 \) and \( \beta \sim 2.6 \) (Frederiks et al. 2022), the dissipation radius can be constrained as

\[
r_{\text{diss}} \gtrsim \left( \frac{1.5 \times 10^{16} \text{ cm}}{L_{\gamma, 52.5} \Gamma_{2.5}^{-2}} \right) \left( \frac{1}{\Gamma_{2.5}^{-2.5}} \right) .
\]

(2)

We also obtain \( \Gamma \gtrsim 770 \) \( (L_{\gamma, 52.5} \delta t_{-2}^{-1/2} \) with \( r_{\text{diss}} \approx 2\Gamma^2 c\delta t/(1+z) \) that is expected in the internal shock scenario (where \( \delta t \) is the variability time scale), although this constraint can be relaxed in multi-zone models (Aoi et al. 2010). High-energy gamma-rays with \( \varepsilon_\gamma \gg 1 \) GeV are unlikely to be produced near the photosphere, as has been argued for some of the past bright GRBs (e.g., Zhang & Pe'er 2009).

2.2. Neutrino constraints

If the high-energy CRs are accelerated during the prompt phase, they should interact with GRB photons via the photomeson production process (Waxman & Bahcall 1997), leading to a flux of high-energy neutrinos via decay processes like \( \pi^+ \rightarrow \mu^+\nu_\mu \rightarrow \nu_\mu\bar{\nu}_\mu\mu e^+ \). The effective \( p\gamma \) optical depth is (e.g., Waxman & Bahcall 1997; Murase et al. 2006)

\[
f_{p\gamma} \approx 0.15 \frac{\eta_{p\gamma} L_{\gamma, 52.5}}{r_{\text{diss}, 14} \Gamma_{2.5}^{1.4} \varepsilon_{b, 5}^{0.4} \varepsilon_{\gamma, 9}^{0.9}} \begin{cases} (\varepsilon_p/\varepsilon_b)^{\beta-1} & (\varepsilon_p < \varepsilon_b) \\ (\varepsilon_p/\varepsilon_b)^{\alpha-1} & (\varepsilon_p > \varepsilon_b) \end{cases} ,
\]

where \( \varepsilon_b \approx 0.5 \varepsilon_\Delta m_p c^2/\varepsilon_b \) is the proton break energy in the GRB frame, and \( \varepsilon_\Delta \sim 0.3 \) GeV. Here \( \eta_{p\gamma} \) is a correction factor that is \( \sim (2-3) \) for \( \alpha \sim 1 \) due to the effects of multipion production and high inelasticity (Murase & Nagataki 2006). The resulting typical neutrino energy is \( E_\nu^b \approx 0.03 \varepsilon_p/(1+z) \sim 0.6 \) PeV \( \Gamma_{2.5}^{1.4} (\varepsilon_{b, 5})^{-1} \).

By introducing the CR loading factor \( \xi_{\text{cr}} \equiv \xi_{\text{iso}}/\xi_{\text{sys}} \) (Murase & Nagataki 2006), the neutrino fluence

\[
E_\nu^2 \phi_{\nu}\nu \gtrsim \frac{1}{4} \left( \frac{1+(1+z)}{8} \right) \min[1, f_{p\gamma}] \frac{\xi_{\text{sys}}}{\xi_{\text{cr}}} \left( \frac{4 \pi d_L^2}{\varepsilon_{b, 5}} \right) \min[1, f_{p\gamma}] \frac{\xi_{\text{iso}}}{\xi_{\text{cr}}} \left( \frac{4 \pi d_L^2}{\varepsilon_{b, 5}} \right)
\]

\[
\sim 4 \times 10^{-3} \text{ erg cm}^{-2} \min[1, f_{p\gamma}] \xi_{\text{sys}, 1} \xi_{\text{iso}, 54.5} \xi_{\text{cr}, 1.2}^{-1}(4)
\]

where 1/8 comes from the fact that the \( \pi^\pm/\pi^0 \) ratio is \( \sim 1 \) in \( p\gamma \) interactions due to the contribution from direct production and each flavor of neutrinos after the mixing carries \( \sim 1/4 \) of the pion energy in the decay chain. Also, \( \xi_{\text{cr}} \) is a spectrum dependent factor that converts the bolometric CR energy to the differential CR spectrum. This naively infers

\[
\min[\xi_{\text{cr}, -1}, f_{p\gamma}, -2 \xi_{\text{cr}, 1}] \lesssim 2.
\]

(5)

However, this constraint is optimistic and it should not be used in general cases. Since GRB neutrino spectra are not described by a single power law, it is significantly relaxed when \( E_\nu^b \) is higher than \( 10-100 \) TeV, the regime in which IceCube is the most sensitive (Abbasi et al. 2021a).

Because the dissipation radius of prompt emission is not well-known and under debate, it is often more useful to treat \( r_{\text{diss}} \) as an uncertain parameter (Murase et al. 2008; Zhang & Kumar 2013). In Figure 1 left and middle, we present constraints in the \( r_{\text{diss}} - \Gamma \) plane (see also Gao et al. 2013, for GRB 130427A) and \( r_{\text{diss}} - \xi_{\text{cr}} \), respectively. The neutrino spectra are calculated using the prescription in He et al. (2012) and Kimura et al. (2017), assuming \( \xi_B = 1 \) for magnetic fields (Murase & Nagataki 2006). We adopt \( \varepsilon_b = 1.2 \) MeV, \( \alpha = 1.1 \) and \( \beta = 2.6 \) (Frederiks et al. 2022), which is sufficient for the purpose of this work to determine the constraints and to encourage further searches with detailed information on time-dependent spectra. We use
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Figure 1. (Left): Constraints on $\Gamma$ as a function of $r_{\text{diss}}$ for different values of the CR loading factor $\xi_{\text{cr}}$. The region below $r_{\text{ph}}$ is not considered for nonthermal neutrino production. (Middle): Constraints on $\xi_{\text{cr}}$ as a function of $r_{\text{diss}}$ for a given Lorentz factor of $\Gamma = 10^{2.5}$, where color scale represents the number of signal events $N_{\text{sig}}$. (Right): Constraints on $\xi_{\text{cr}}$ as a function of $\Gamma$, where the internal shock model is assumed with $\delta t = 0.01$ s. The IceCube stacking limit at 90% C.L. (Aartsen et al. 2017a) for this model is also shown.

the point source effective area\(^1\) (Abbasi et al. 2021b) at declination, $\delta \approx 19.8^\circ$. The convolution of the neutrino flux and the effective area over a relevant energy range (200 GeV $\leq E_\nu \leq 10^9$ GeV) gives the number of signal events, $N_{\text{sig}}$. Our limit for an $E^{-2}$ spectrum also agrees with the IceCube limit (IceCube-Collaboration 2022). The results on $N_{\text{sig}}$ are not strongly affected by $\xi_B$. This is because the signal mainly comes from neutrinos around $E^\nu_0$, whereas $\xi_B$ is important for the neutrino flux suppression that occurs at much higher energies at $\sim 10 - 1000$ PeV (Murase & Nagataki 2006).

Remarkably, we obtain strong constraints on particle acceleration near the photosphere at $r_{\text{ph}} \approx 3.8 \times 10^{12}$ cm $\xi_L p_{53} \Gamma_{2.5}^{-3}$ in the limit that the coasting occurs under $r_{\text{ph}}$. Here $L_p$ is the proton luminosity and $\xi_L$ is the ratio of electrons and positrons to protons. From Figure 1 left and middle, we obtain $\xi_{\text{cr}} \lesssim 1$ for $\Gamma \lesssim 300$, which excludes the benchmark case of the baryonic photospheric scenario ($\xi_{\text{cr}} = 1$ and $\xi_{r} = 1$), although the limits can be relaxed with larger values of $\Gamma$. Note that these constraints on the baryonic photospheric scenario are largely insensitive to uncertainty in $L_\gamma$ because of $f_{\gamma \gamma} \approx 20(L_{\gamma,52.5}/L_{p,53})(\Gamma_{2.5}/\varepsilon_{53,\text{MeV}})\tau_{\gamma} \gg 1$ near the photosphere (Murase 2008), where $\tau_{\gamma}$ is the Thomson optical depth. Our results are conservative in the sense that we do not include $pp$ collisions that are relevant in the TeV range (Murase 2008; Wang & Dai 2009).

On the other hand, IceCube’s non-detection is consistent with outer-zone (i.e., large $r_{\text{diss}}$) models. For example, we obtain $r_{\text{diss}} \gtrsim (2 - 20) \times 10^{14}$ cm for $\Gamma \sim 300$ and $\xi_{\text{cr}} \sim 10 - 100$. Such parameter space is favored by the scenario where UHE CRs are nuclei rather than protons (see Figure 8 of Murase & Nagataki 2006) and some of the magnetic reconnection models (e.g., Zhang & Kumar 2013; Ptik et al. 2021). This also rules out the neutron escape scenario for UHE CRs (Ahlers et al. 2011). We also note that low efficiencies of the photomeson production process are also consistent with the detection of a $\sim 100$ GeV photon. From Eqs. (2) and (3) we obtain

$$f_{\gamma \gamma} \lesssim 3 \times 10^{-3} \eta_{\gamma \gamma,0.5} \left\{ \begin{array}{ll}
1 & (\Gamma \lesssim 700) \\
\left(\Gamma_{2.5}^2/5\right)^{1.6} & (\Gamma \gtrsim 700)
\end{array} \right. \ , \quad (6)$$

This limit does not depend on $L_\gamma$ and $r_{\text{diss}}$, and it is applicable to all proton energies given $\alpha \sim 1$. Although Eq. (6) is robust as long as neutrinos and gamma-rays are co-produced, it is worthwhile to note that their emission regions may be different. For example, in the photospheric scenario, sub-TeV gamma-rays are unlikely to escape and hence should come from large dissipation radii, e.g., at the external reverse shock.

Prompt GRB neutrinos have been best studied in the context of the internal shock scenario, and the UHE CR hypothesis requires $\xi_{\text{cr}} \sim 10 - 100$ (Murase et al. 2008; Biehl et al. 2018). The constraints with the assumption of $r_{\text{diss}} \approx 2\Gamma^2 c \delta t/(1+z)$ are presented in Figure 1 right. Here, for the purpose of the comparison with the IceCube result (Aartsen et al. 2017a), we use $\delta t = 0.01$ s, although the chosen value is subject to both observational and model uncertainties (e.g., Murase & Nagataki 2006; Murase et al. 2008; Zhang & Kumar 2013).

We find $\xi_{\text{cr}} \lesssim 3$ for $\Gamma = 300$. This implies that for a benchmark Lorentz factor of $\Gamma = 300$ that is often used in the literature (e.g., Aartsen et al. 2017a), the case motivated by the UHE CR hypothesis may be excluded, where the constraint given in Eq (2) should be alleviated if neutrinos and the highest-energy gamma-rays come from different regions (e.g., Bustamante et al. 2015; Zhang et al. 2023). Alternatively, GRB inter-

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\(^1\) In general the GFU effective area (Aartsen et al. 2017b) should be used for real time follow-ups. But the publicly available data do not have a sufficiently fine binning in the zenith angle.
nal shocks are still viable for UHE CR acceleration if the Lorentz factor is high enough to lead to large \( r_{\text{disc}} \gtrsim (2 - 20) \times 10^{14} \) cm, as used in Murase et al. (2008). Interestingly, our new limit shown in Figure 1 is comparable to the IceCube stacking limit (Aartsen et al. 2017a). Our results are useful because the latter is subject to systematic uncertainties coming from the aggregation of many bursts. One single burst provides complementary constraints, and support that canonical high-luminosity GRBs contribute less than \( \sim 1\% \) of the all-sky neutrino flux.

3. QUASITHERMAL EMISSION

Subphotospheric neutrino production at \( \tau_T \gtrsim 1 \) is efficient if CRs exist. However, CR acceleration at radiation-mediated shocks is inefficient, and the detection of nonthermal neutrinos from deep subphotospheres is unlikely for canonical high-luminosity GRBs (Murase & Ioka 2013). However, high-energy neutrinos can still be produced without relying on CR acceleration. Neutrons can provide neutrinos through inelastic collisions between bulk flows or neutron diffusion (Mészáros & Rees 2000), without involving collisionless shocks or magnetic reconnections. Such “quasithermal” neutrinos are naturally produced during neutron decoupling (Bahcall & Mészáros 2000) and/or by internal collisions between neutron-loaded outflows (Murase et al. 2013; Bartos et al. 2013; Zegarelli et al. 2022).

3.1. Neutrinos from neutron decoupling

Recent studies have shown that a GRB jet is collimated during its propagation inside a star (e.g., Bromberg et al. 2011; Mizuta & Ioka 2013; Hamidani & Ioka 2020; Gottlieb et al. 2022). The jet becomes hot and the post-collimation distance is so high that \( \tau_T \gg \tau_{np} \gg 1 \), in which protons and neutrons are coupled. After the breakout, the hot jet material may expand with \( \Gamma(r) \approx \Gamma_0 (r/R_*) \) like a fireball, where \( \Gamma_* \approx 1/\theta_j = 10 \theta_j^{-1} \) is the Lorentz factor at the breakout. By equating the \( np \) collision time \( \tau_{np}' \approx 1/(n_p' \sigma_{np} c) \) (where \( \sigma_{np} \approx 3 \times 10^{-26} \) cm\(^2\)) and the proton flow, leading to \( \Gamma \)-dependent collisions are calculated with \( 3 \) of their decay products are equally shared by each flavor of neutrinos after the neutrino mixing\(^2\) Also, \( \zeta_n \) is the number ratio of neutrons to protons, \( \xi_{n,\gamma,\nu} \) is the kinetic energy of the proton outflow with \( \Gamma \gtrsim \Gamma_{n,\text{dec}} \) and \( \xi_N \) is the nucleon loading factor.

In Figure 2 left, we show neutrino fluxes in the neutron “decoupling” model with \( \zeta_n = 1 \). We set \( \Gamma_{n,\text{dec}} \) from Eq. (7) assuming \( \Gamma = \Gamma_{\text{max}} \). The spectra of neutrinos from \( np \) collisions are calculated with Geant4 following Murase et al. (2013).

3.2. Neutrinos from colliding neutron-loaded flows

If the neutron decoupling occurs before \( \Gamma \approx \Gamma_{\text{max}} \) is achieved, the neutron flow will be caught up by the proton flow, leading to \( pn \) collisions (Beloborodov 2010; Mészáros & Rees 2011). Alternatively, if the coasting occurs earlier than the decoupling, the dissipation of neutrons via internal collisions between the compound flows may happen. Such collisions are expected around \( r_{\text{dec}} \ll r_{\text{ph}} \), where the \( pn \) optical depth is \( \tau_{pn} \approx 1 \) (\( \Gamma/\Gamma_{n,\text{dec}} \) (\( \zeta_n/\zeta_\nu \))\( \tau_T \)). The typical energy of neutrinos is given by (Murase et al. 2013)

\[
E_{\nu}^{\text{eq}} \approx 0.1 \Gamma'_{\text{rel}} m_p c^2 (1 + z),
\]

where \( \Gamma'_{\text{rel}} \sim 2 \) is the relative Lorentz factor of the interacting flow and \( \sim 30 – 300 \) GeV neutrinos are expected for \( \Gamma \sim 10^2 – 10^3 \).

\(^2\) This is a good approximation especially for successful jets but neutrinos produced deep inside a star are subject to neutrino oscillation due to effects of matter and neutrino self-interaction (Carpio & Murase 2020; Abbar et al. 2022).
The neutrino energy fluence is

\[ E^2 \phi_{\nu} \approx \frac{1}{12} \frac{(1 + z)}{4\pi d_L^2} \tau_{pn} \xi_N E^{54,5} \]

\[ \sim 0.03 \text{ erg cm}^{-2} \tau_{pn} \xi_N E^{54,5} \]  

(12)

where the normalization is set by \( \xi_N E^{54} \) as the kinetic energy of the interacting flow. It has been suggested that dissipation induced by internal collisions between neutron-loaded flows may be relevant for sub-photospheric dissipation (Beloborodov 2010; Mészáros & Rees 2011), in which \( E^2 \phi_{\nu} \sim E^2 \phi_{\gamma} \) and \( \xi_N \sim 3 - 30 \) can be considered as fiducial values.

In Figure 2 left, we show neutrino fluences in the “collision” model for \( \Gamma = 300 \) and \( \Gamma = 800 \), where \( \tau_{pn} = 1 \) is assumed.

3.3. Implications

We calculate the number of signal events using the latest all-flavor effective areas for GRECO selection (Abbasi et al. 2022, 2023) and through-going muon neutrinos (Abbasi et al. 2021b) in IceCube\(^3\). The values of \( N_{\text{sig}} \) for different models are shown in Figure 2 left. Although the decoupling model is difficult to test with IceCube and other detectors such as KM3Net and Baikal-GVD, we find that the collision model is promising. A few events of \( \sim 100 \text{ GeV} \) neutrinos can be detected for \( \xi_N \sim 10 \) especially if the Lorentz factor is sufficiently large (e.g., \( \Gamma \sim 800 \)). These results are encouraging and we urge dedicated searches for GeV–TeV neutrinos for GRB 221009A with the existing IceCube data.

In Figure 2 right, we also show the sensitivity to \( \xi_N \) as a function of \( \Gamma \) for double and triplet detections of signal neutrinos from GRB 221009A. Although the expected signal can dominate if angular uncertainty is not far from the kinematic angle (Murase et al. 2013), the actual detectability depends on the atmospheric background rate, so dedicated analyses at sub-TeV energies are necessary. A search time window \( (\Delta T) \) will also need to be carefully considered. The burst duration may vary depending on energy bands (e.g., Zhang et al. 2014), and the engine duration is uncertain. Neutrino emission may be dominated by the main episode that lasts for \( \Delta T \sim 100 \text{ s} \), and luminosity-weighted searches could also be helpful in more general.

Note that in both the decoupling and collision models, neutrinos and gamma-rays are mainly produced deep inside the photosphere, from which gamma-rays with \( \varepsilon_{\gamma} \geq \Gamma m_e c^2 \) cannot escape (e.g., Murase & Ioka 2008). Residual neutrons would eventually decay after \( \sim 880/\Gamma_{n,\text{dec}} \text{ s} \) in the observer frame, but the resulting electron antineutrino energy is \( \sim 0.48 \Gamma_{n,\text{dec}} \text{ MeV} \), which is difficult to detect with IceCube-like detectors. Electrons may lose their energies via synchrotron and inverse-Compton emission but their signatures may easily be overwhelmed by other components.

4. SUMMARY AND DISCUSSION

We considered how observations of neutrinos from the brightest GRB can be used for constraining GRB model parameters, including the CR baryon loading factor that is a critical parameter for the production of high-energy neutrinos and UHE CRs. We showed that the IceCube non-detection of TeV-PeV neutrinos from GRB 221009A leads to intriguing constraints on the parameter space of \( r_{\text{diss}} \), \( \Gamma \), and \( \xi_{\text{cr}} \), which are comparable to those from the stacking analysis that is subject to systematics from
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While we were finalizing the manuscript, the related work (Ai & Gao 2023) came out. The approaches are different, and we impose constraints on GRB parameters based on projecting expected events with model spectra, instead of the reported single power-law upper limit. Our study also includes calculations of nonthermal as well as quasithermal neutrinos.

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Many GRBs with different properties. We found that CR acceleration near the photosphere is likely to be subdominant and obtained $\xi_{cr} \lesssim 1$ for $\Gamma \lesssim 300$. We also pointed out that the non-detection of high-energy nonthermal neutrinos is not surprising in light of the gamma-ray constraint. This is consistent with outer-zone models (e.g., Murase et al. 2008; Zhang & Kumar 2013). However, neutrinos and gamma-rays may come from different dissipation regions, and further investigation with multi-zone models (Bustamante et al. 2017; Rudolph et al. 2020) might be relevant.

Quasithermal neutrinos, which are naturally expected if neutrons are loaded into GRB outflows, are not yet constrained. We found that in the collision model the detection of GeV-TeV neutrinos is possible with IceCube’s low- and high-energy channels, or reasonable constraints on $\xi_N$ can be obtained. Even higher-energy neutrinos may be produced via the neutron-proton-converter acceleration mechanism (Kashiyama et al. 2013), and we encourage dedicated searches by considering appropriate time windows focusing on the bright episodes of prompt emission.

Finally, we note that UHE CRs could be accelerated by external shocks during the early afterglow (Waxman & Bahcall 2000; Murase 2007; Razzaque 2013), in which PeV-EeV neutrinos are expected and the predicted fluxes have not been reached by the current IceCube. Future UHE neutrino detectors (Ackermann et al. 2022) such as IceCube-Gen2, Trinity, and GRAND will be required to test those afterglow models.
