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Possible Evidence for Lorentz Invariance Violation in Gamma-Ray Burst 221009A

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Abstract

The preliminary detections of the gamma-ray burst 221009A up to 18 TeV by LHAASO and up to 251 TeV by Carpet 2 have been reported through Astronomer's Telegrams and Gamma-ray Coordination Network circulars. Since this burst is at redshift $z = 0.1505$, these photons may at first seem to have a low probability to avoid pair production off of background radiation fields and survive to reach detectors on Earth. By extrapolating the reported 0.1–1.0 GeV Fermi Large Area Telescope spectrum from this burst to higher energies and using this to limit the intrinsic spectrum of the burst, we show that the survival of the 18 TeV photon detected by LHAASO is not unlikely with many recent extragalactic background light models, although the detection of a 251 TeV event is still very unlikely. This can be resolved if Lorentz invariance is violated at an energy scale $E_{\rm QG} \lesssim 49 E_{\rm Planck}$ in the linear ($n = 1$) case, and $E_{\rm QG} \lesssim 10^{-6} E_{\rm Planck}$ in the quadratic ($n = 2$) case (95% confidence limits), where $E_{\rm Planck}$ is the Planck energy. This could potentially be the first evidence for subluminal Lorentz invariance violation.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Gamma-ray astronomy (628); Quantum gravity (1314)

1. Introduction

The gamma-ray burst (GRB) 221009A (also known as Swift J1913.1+1946) was detected by the Swift Burst Alert Telescope (BAT; Kennea & Williams 2022) and the Fermi Gamma-ray Burst Monitor (GBM; Veres et al. 2022) as the brightest GRB ever detected. It was also detected by the Fermi Large Area Telescope (LAT; Bissaldi et al. 2022; Pillera et al. 2022). At a redshift of $z = 0.1505$ (Castro-Tirado et al. 2022; de Ugarte Postigo & Izzo 2022; Izzo et al. 2022) it is also one of the closest long-duration GRBs.

Perhaps most surprising is the possible detection of photons at $E > 10$ TeV from this burst. In the 2000 s after the start of the burst (T_0), it was detected by the Large High Altitude Air Shower Observatory (LHAASO) with its WCDA and KM2A detectors, and the latter detected photons from GRB 221009A with energies up to 18 TeV (Huang et al. 2022). At $T_0 + 4536$ s, there was a report of an astonishing 251 TeV photon detected from this burst by the Carpet 2 detector, which has an estimated probability of 1.2×10^{-4} (corresponding to 3.8σ; pretrial) of being a background event (Dzhappuev et al. 2022). There is a nearby HAWC source detected up to 140 TeV with a position consistent with both the reported LHAASO and Carpet 2 detection (HAWC Collaboration 2022) that is probably Galactic. This could be the source of the LHAASO detection, but it is unlikely to be the origin of the Carpet 2 detection; see Section 2.4 below.

Detection of these very-high-energy (VHE) photons from GRB 221009A is interesting for a number of reasons. They may be difficult to explain with synchrotron self-Compton due to the Klein−Nishina effect (Das & Razzaque 2022; González et al. 2022; Ren et al. 2022); but could be explained by proton synchrotron (Zhang et al. 2022); or photopion decay in the jet (Sahu & Medina-Carrillo 2022); or by ultrahigh-energy cosmic rays (UHECRs) interacting with the extragalactic background light (EBL) and cosmic microwave background (CMB) photons, and subsequent cascades (Alves Batista 2022; Das & Razzaque 2022). The intergalactic magnetic field needs to be of the order of 10^{-14} G for UHECR protons to be delayed by $\lesssim$2000 s in order to explain the LHAASO detection. The magnetic field needs to be much lower for UHECR nuclei, and in that case it would require GRB 221009A to have occurred in a void with a low intergalactic magnetic field strength (Mirabal 2022). The universe is expected to be extremely opaque to photons at these energies for the redshift of GRB 221009A, due to $\gamma\gamma$ interactions with background radiation fields. One finds absorption optical depths $\tau_{\gamma\gamma}(18\ {\rm TeV}) \gtrsim 10$ for all recent EBL models (e.g., Franceschini et al. 2008; Razzaque et al. 2009; Finke et al. 2010, 2022; Kneiske & Dole 2010; Dominguez et al. 2011; Helgason & Kashlinsky 2012; Stecker et al. 2012; Scully et al. 2014; Khaire & Srianand 2015; Stecker et al. 2016; Franceschini & Rodighiero 2017; Andrews et al. 2018; Khaire & Srianand 2019; Saldana-Lopez et al. 2021). These models give a survival probability of $\exp[-\tau_{\gamma\gamma}(18\ {\rm TeV})] \lesssim 4.5 \times 10^{-5}$; the situation is even worse at 251 TeV.

Several ways have been proposed to avoid the γ-ray absorption at these energies; one is that the high-energy photons may avoid attenuation by converting to axion-like particles (ALPs) in the presence of magnetic fields in the GRB jet, host galaxy, or intergalactic space (Baktash et al. 2022; Carenza & Marsh 2022; Galanti et al. 2022b, 2022a; Nakagawa et al. 2022; Troitsky 2022; Zhang & Ma 2022). Another is through Lorentz invariance violation (LIV), as suggested by Dzhappuev et al. (2022), Baktash et al. (2022), and Li & Ma (2022).

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Lorentz invariance is a pillar of special relativity. It is the principle that there are no preferred inertial reference frames, and physical variables can be transferred from one frame to another with Lorentz transformations. However, some theories predict LIV, such as supersymmetry, string theory, and other models of quantum gravity (e.g., Amelino-Camelia et al. 1998; Amelino-Camelia & Piran 2001; Mattingly 2005; Christiansen et al. 2006; Jacobson et al. 2006; Ellis et al. 2008; Jacob & Piran 2008). Including LIV, the dispersion relation for photons is modified as

$$E^2 - p^2c^2 = \pm E^2\left(\frac{E}{E_{QG}}\right)^n, \quad (1)$$

where E_{QG} is an energy, usually thought to be close to the Planck energy, $E_{Planck} = 1.2 \times 10^{28}$ eV. Here n is the order of the leading correction, and the "+" represents superluminal LIV, and the "−" represents subluminal LIV (e.g., Martínez-Huerta et al. 2020). LIV effects are difficult to measure due to the extremely high energies involved; however, nature can produce photons and particles at energies unavailable to terrestrial accelerators, and they propagate through extremely large distances in the universe. Thus, there are several effects from LIV that are relevant to astrophysics. One is that the speed of photons becomes energy dependent. Time-of-flight measurements from high-energy astrophysical sources have constrained E_{GQ} (e.g., Abdo et al. 2009; Vasileiou et al. 2013; Ellis et al. 2019). Another relevant effect is the modification of the threshold for the $\gamma\gamma$ pair production interaction ($\gamma + \gamma \rightarrow e^+ + e^-$). This modification can decrease the threshold, increasing the absorption optical depth in the superluminal case, and increasing the threshold and decreasing the absorption optical depth in the subluminal case. Here we are concerned with the subluminal case, which allows the γ-ray absorption optical depth $\tau_{\gamma\gamma}$ at high energies to be lower than it otherwise would be (e.g., Jacob & Piran 2008). It is the latter effect that is relevant to the anomalous transparency of VHE photons from GRB 221009A that we explore here.

In Section 2 we present the relevant preliminary observations of GRB 221009A, based on Astronomer's Telegrams (ATels) and Gamma-ray Coordination Network (GCN) circulars. In Section 3 we calculate the LIV effect on the γ-ray flux attenuation and compare with VHE data. We discuss our results and conclude in Section 4.

2. Observations

2.1. Fermi-LAT

The Fermi-LAT detected GRB 221009A at 200–800 s after the burst, with a 0.1–1.0 GeV flux of $\Phi_{LAT,tot} = (6.2 \pm 0.4) \times 10^{-3}$ ph cm^{-2} s^{-1} and a spectral index of $\Gamma = 1.87 \pm 0.04$ (Pillera et al. 2022). The spectrum is described by a power law, given by

$$\left.\frac{dN}{dE}\right|_{LAT} = N_0\left(\frac{E}{E_0}\right)^{-\Gamma}, \quad (2)$$

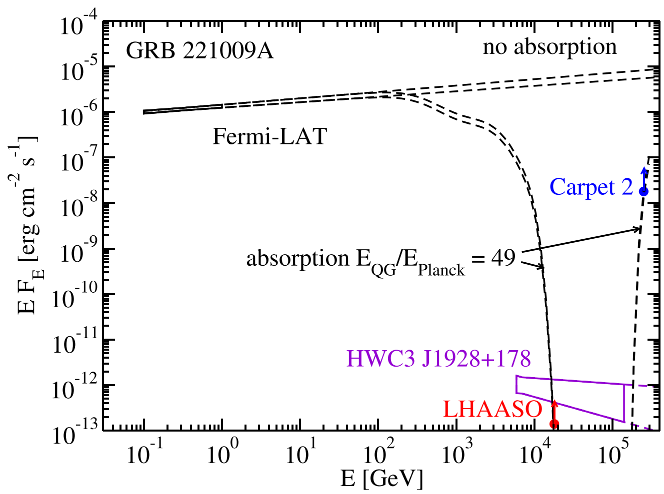

Figure 1. The SED for GRB 221009A with the Fermi-LAT spectrum and the LHAASO, and Carpet 2 95% lower limits. The dashed curve indicates the extrapolation of the LAT spectrum to higher energies without $\gamma\gamma$ absorption, and with $\gamma\gamma$ absorption assuming $E_{QG}/E_{Planck} = 49$, as indicated. The absorption assuming no LIV is identical to this curve at $E < 3 \times 10^5$ GeV, but does not have the $E > 10^5$ GeV part shown on the plot. We have also plotted the spectrum for the nearby HAWC source HWC3 J1928+178 and its extrapolation to higher energies.

where we take $E_0 = 1.0$ GeV. The normalization constant N_0 can be determined from the integral

$$\Phi_{LAT,tot} = \int_{E_1}^{E_2} dE \left.\frac{dN}{dE}\right|_{LAT}, \quad (3)$$

where $E_1 = 0.1$ GeV and $E_2 = 1.0$ GeV. The 0.1–1 GeV LAT spectrum for GRB 221009A can be seen in the spectral energy distribution (SED) in Figure 1. Since the brightness of this GRB decays with time (Ren et al. 2022; Zhang et al. 2022; Zheng et al. 2022), this spectrum can be considered an upper limit for the GRB in this energy range at later times.

2.2. LHAASO

LHAASO reported the detection of a VHE source within 2000 s of T_0 of GRB 221009A, and consistent with its location. It was detected by both LHAASO's WCDA and KM2A instruments, where the highest-energy photon observed by KM2A was $E = 18$ TeV (Huang et al. 2022). The effective area of LHAASO-KM2A at 18 TeV is $A_{eff} \approx 0.5$ km^2 (Cao et al. 2019). Since more photons at these energies may have been detected, we take the implied flux as a lower limit. The Poisson 95% lower limit for 1 count is 5.13×10^{-2} (Gehrels 1986). The observed flux can then be estimated as

$$\left.\frac{dN}{dE}\right|_{obs}(18 \text{ TeV}) \gtrsim \frac{5.13 \times 10^{-2}}{A_{eff}tE}$$
$$\gtrsim 2.9 \times 10^{-19} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ GeV}^{-1}. \quad (4)$$

Extrapolating the LAT spectrum out to 18 TeV, we find a flux of 9.3×10^{-12} ph cm^{-2} s^{-1} GeV^{-1}, much higher than the estimated LHAASO-KM2A flux. The LHAASO lower-limit flux estimate and the LAT extrapolation are plotted in Figure 1. The LAT observation (200–800 s after T_0) is not completely overlapping with the LHAASO one (0–2000 s after T_0). This is a caveat that should be kept in mind.

2.3. Carpet 2

Carpet 2 reported the detection of a 251 TeV photon 4536 s after the GBM trigger, and 1336 s after the Swift-BAT trigger for GRB 221009A, from a direction consistent with that burst (Dzhappuev et al. 2022). The effective area of Carpet 2 depends on source position in the sky; at this energy, the average effective area $A_{\rm eff} = 25\ {\rm m}^2$ (Dzhappuev et al. 2020). Using $t = 4536$ s and the same procedure as above for LHAASO, for the Carpet 2 detection,

$$\left.\frac{dN}{dE}\right|_{\rm obs}(251\ {\rm TeV}) \gtrsim 1.8 \times 10^{-16}\ {\rm ph\ cm^{-2}\ s^{-1}\ GeV^{-1}}. \quad (5)$$

This Carpet 2 lower-limit flux estimate is plotted in Figure 1. The LAT spectrum, (Section 2.1), extrapolated to 251 TeV, is 6.7×10^{-14} ph cm^{-2} s^{-1} GeV^{-1}. Since the LAT observation is from an earlier time, and its flux decreases with time, this is a strong upper limit for the flux implied by the 251 TeV photon detected at 4536 s after T_0.

2.4. Nearby HAWC Source

As reported by HAWC Collaboration (2022), the source HWC3 J1928+178 from the Third HAWC Catalog (Albert et al. 2020), detected up to 140 TeV, is consistent with the reported positions of the LHAASO and Carpet 2 detections. We plot the spectrum for this source in Figure 1. As seen in the figure, the HAWC source is consistent with our estimated LHAASO flux lower limit at 18 TeV, but its extrapolation to 251 TeV is much too faint to be consistent with the lower limit we derived from Carpet 2 detection. Thus it is unlikely that this source is responsible for the 251 TeV photon detected by Carpet 2.

There is also the possibility that a nearby (presumably Galactic; GRB 221009A had Galactic latitude $b \approx 4^\circ\!.2$) source was flaring contemporaneous with GRB 221009A, and the Carpet 2 detection is from that flare. But flaring Galactic γ-ray sources are rare. In the Second Fermi All-sky Variability Analysis (2FAVA) Catalog (Abdollahi et al. 2017), setting aside active galactic nuclei and GRBs, there are 73 flares at Galactic latitudes $-10^\circ < b < 10^\circ$ from known Galactic or unidentified sources in the 7.4 yr covered by the 2FAVA catalog. Approximately one-third of these flares are from the Crab. Based on this, the probability of *any* Galactic γ-ray source flaring at the same time as the Carpet 2 detection is approximately $73 \times (5000\ {\rm s})/(7.4\ {\rm yr}) \sim 10^{-3}$ and this does not take into account the spatial coincidence. Thus it is also quite unlikely that the Carpet 2 detection is from a flaring Galactic source.

3. Gamma-Ray Absorption and Lorentz Invariance Violation

3.1. Model Calculations

The $\gamma\gamma$ absorption optical depth for γ-rays from a source at redshift z with observed dimensionless energy $\epsilon_1 = E_1/(m_e c^2)$ with background radiation photons of proper frame energy density $u_p(\epsilon_p; z)$ is given by

$$\tau_{\gamma\gamma}(\epsilon_1, z) = \frac{c\pi r_e^2}{\epsilon_1^2 m_e c^2} \int_0^z \frac{dz'}{(1+z')^2} \left|\frac{dt_*}{dz'}\right| \times \int_{\frac{1}{\epsilon_1(1+z')}}^{\infty} d\epsilon_p \frac{\epsilon_p u_p(\epsilon_p; z')}{\epsilon_p^4} \bar{\phi}(\epsilon_p \epsilon_1 (1+z')), \quad (6)$$

where $r_e \approx 2.82 \times 10^{13}$ cm is the classical electron radius, m_e is the electron mass, $\bar{\phi}(s_0)$ is a function given by Gould & Schreder (1967) and Brown et al. (1973),

$$\frac{dt}{dz} = \frac{-1}{H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}, \quad (7)$$

and we use a flat ΛCDM cosmology where $(h, \Omega_m, \Omega_\Lambda) = (0.7, 0.3, 0.7)$, with $H_0 = 100\, h$ km s^{-1} Mpc^{-1}. Here for $u_p(\epsilon'; z)$ we use the EBL model from Finke et al. (2022) and the CMB, when appropriate. Following Jacob & Piran (2008) and Biteau & Williams (2015), to include the effects of LIV on $\gamma\gamma$ opacity, we allow

$$\epsilon_1 \to \frac{\epsilon_1}{1 + \frac{1}{4}\left(\frac{\epsilon_1 m_e c^2}{E_{\rm QG}}\right)^n \epsilon_1^2} \quad (8)$$

in Equation (6).

3.2. Results for GRB 221009A

A common method for constraining EBL absorption is to take the observed spectrum in a region where the EBL is unabsorbed, extrapolate that to a region where it is absorbed, and take that as the highest possible intrinsic flux $dN/dE|_{\rm int}$ (e.g., Chen et al. 2004; Schroedter 2005; Mazin & Raue 2007; Finke & Razzaque 2009; Georganopoulos et al. 2010; Meyer et al. 2012; Domínguez et al. 2013; Abdollahi et al. 2018; Desai et al. 2019). We note that in the 0.1–1.0 GeV energy range, the EBL should be completely transparent to γ-rays in all EBL models. At higher energies, the intrinsic flux is attenuated as

$$\left.\frac{dN}{dE}\right|_{\rm obs} = \left.\frac{dN}{dE}\right|_{\rm int} \exp[-\tau_{\gamma\gamma}(E)]. \quad (9)$$

If one has an upper limit on $dN/dE|_{\rm int}$, as described above, then it is possible to constrain the opacity as

$$\tau_{\gamma\gamma}(E) < \ln\left(\frac{dN/dE|_{\rm int}}{dN/dE|_{\rm obs}}\right). \quad (10)$$

Using this technique with the LAT spectrum extrapolated to 18 TeV and the LHAASO observation (Section 2.2), we get the constraint

$$\tau_{\gamma\gamma}(18\ {\rm TeV}) \lesssim 17. \quad (11)$$

We note that the limits here, and all those in this paper, are 95% constraints. For photons at 18 TeV from redshift $z = 0.1505$, this constraint is consistent with many, but not all, recent EBL models (Baktash et al. 2022) without the need for including LIV. The infrared EBL relevant here is somewhat uncertain, as reflected in different models. Our constraint on $\tau_{\gamma\gamma}$ here is a bit higher than that of Baktash et al. (2022), mainly because we estimate the more conservative 95% lower limit on flux at 18 TeV. Following the same procedure for the Carpet 2

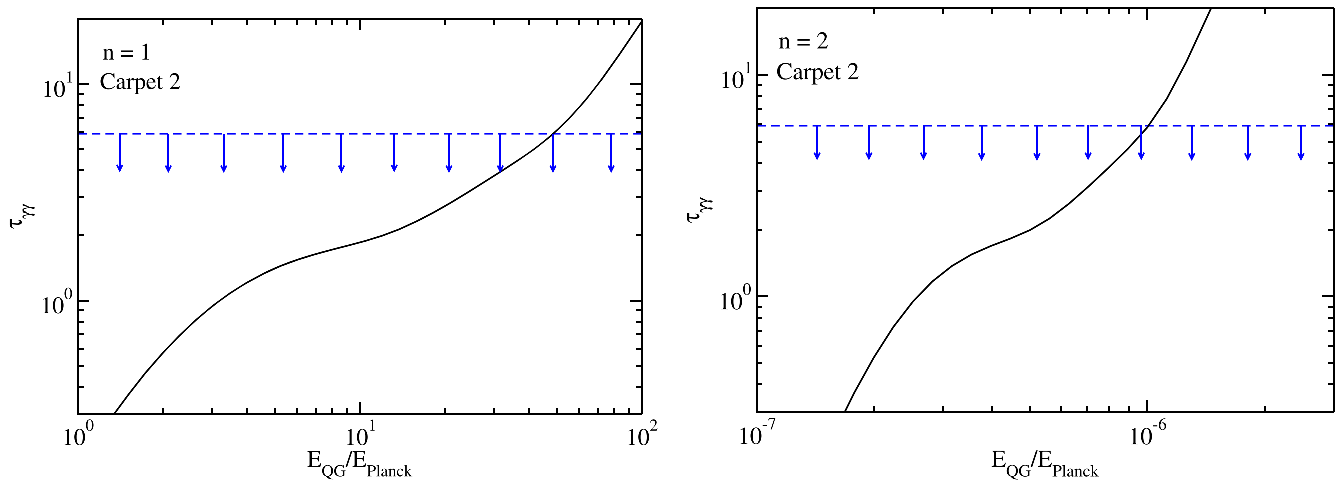

Figure 2. The γ-ray absorption optical depth at $z = 0.1505$ and $E = 251$ TeV (solid black curves). The left figure shows the result assuming the leading order correction is linear ($n = 1$); the right shows the result assuming the leading order correction is quadratic ($n = 2$). Dashed blue lines with arrows show the $\tau_{\gamma\gamma}$ upper limit from the Carpet 2 observations.

measurement, we get

$$\tau_{\gamma\gamma}(251\ \mathrm{TeV}) \lesssim 5.9. \quad (12)$$

For the 251 TeV photon from redshift $z = 0.1505$, the relevant photon field for $\gamma\gamma$ interactions is the CMB (e.g., Fazio & Stecker 1970; Protheroe & Biermann 1996; Dermer & Menon 2009). Unlike the infrared EBL, the CMB is known to very high precision. We show the model calculation of $\tau_{\gamma\gamma}$ (from Equation (6)) as a function of $E_{\mathrm{QG}}/E_{\mathrm{Planck}}$ in Figure 2 for the Carpet 2 case. From this figure we can see that the 251 TeV photon from Carpet 2 gives the constraint

$$E_{\mathrm{QG}}/E_{\mathrm{Planck}} \lesssim 49\ (n = 1)$$
$$E_{\mathrm{QG}}/E_{\mathrm{Planck}} \lesssim 1.0 \times 10^{-6}\ (n = 2). \quad (13)$$

4. Discussion

We have made estimates, based on preliminary observations reported in ATels and GCNs, of γ-ray fluxes detected by LHAASO and Carpet 2 from observations of GRB 221009A. We compared these to the extrapolated LAT spectrum (Pillera et al. 2022) and used these to make estimated constraints on subluminal LIV, particularly on E_{QG}. We use LHAASO and Carpet 2 lower limit flux estimates; if they are significantly larger, the constraints on $E_{\mathrm{QG}}/E_{\mathrm{Planck}}$ would be lower (and therefore stronger). Our results do not depend on the detailed spectrum and analysis of the LHAASO and Carpet 2 results, and our assumptions are quite conservative, taking robust 95% lower limits for the implied flux from the reported photons. Detailed analysis by the LHAASO and Carpet 2 collaborations will likely strengthen these results, as long as they are not retracted. Our constraints are broadly consistent with other authors work on constraining $\tau_{\gamma\gamma}$ and LIV from this burst (e.g., Baktash et al. 2022; Galanti et al. 2022b; Zhao et al. 2022; Zheng et al. 2022).

If confirmed, this would be the first known upper limit on E_{QG}; however, there have been some previous lower limits. Lang et al. (2019) found 2σ lower limits $E_{\mathrm{QG}}/E_{\mathrm{Planck}} > 10$ ($n = 1$) and $E_{\mathrm{QG}}/E_{\mathrm{Planck}} > 1.9 \times 10^{-7}$ ($n = 2$) using VHE γ-ray spectra of blazars detected by imaging atmospheric Cherenkov telescopes. Vasileiou et al. (2013) find $E_{\mathrm{QG}}/E_{\mathrm{Planck}} > 7.6$ ($n = 1$) and $E_{\mathrm{QG}}/E_{\mathrm{Planck}} > 10^{-9}$ ($n = 2$) from time-of-flight measurements of photons from GRBs. Our results are compatible with all previous E_{QG} lower limits for subluminal LIV. *Our result could be the first observational evidence for LIV.*

However, it does come with a number of caveats. We assume that the γ-ray spectrum of GRB 221009A is well behaved at VHEs, and that the spectrum does not "curve up" above the LAT bandpass; although it is difficult to imagine a GRB being much brighter at these energies. The results of Lang et al. (2019) make a similar assumption about the spectra of blazars. Another possibility is the anomalous transparency could be explained by photon conversion to ALPs, or another mechanism that has yet been proposed. The Cherenkov Telescope Array will be sensitive at $\gtrsim$10 TeV and may be able to marginally detect LIV effects in blazar spectra within current LIV constraints, i.e., $10 \lesssim E_{\mathrm{QG}} \lesssim 50$ for $n = 1$, especially if the true value is on the lower end of this range (Abdalla et al. 2021). It may also be able to confirm or rule out our result with detections of future GRBs, if VHE emission out to 100 s of TeV from these sources turns from out to be at all common.

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