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Multi-TeV photons from GRB 221009A: uncertainty of optical depth considered

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Abstract It is reported that the Large High Altitude Air Shower Observatory (LHAASO) observed thousands of very-high-energy photons up to ∼18 TeV from GRB 221009A. We study the survival rate of these photons via considering the fact that they are absorbed by the extragalactic background light. By performing a set of 10^6 Monte-Carlo simulations, we explore the parameter space allowed by current observations and estimate the probability of predicting that LHAASO detects at least one photon of 18 TeV from GRB 221009A. We find that the standard physics is compatible with the observations of 18 TeV photons within 3.5σ confidence interval. Our research method can be straightforwardly generalized to study more data sets of LHAASO and other experiments in the future.

1 Introduction

More than 5000 photons above 0.5 TeV emitted from GRB 221009A at redshift $z \simeq 0.151$[1] were observed by the Large High Altitude Air Shower Observatory (LHAASO)[2] within 2000 s after the first detection by Swift, Fermi-GBM, Fermi-LAT, and so on.[3] The highest energetic photons were reported to reach ∼ 18 TeV, representing the first observation of photons above 10 TeV from gamma-ray bursts (GRBs). Such observations intrigued studies on photon mixing with axion-like particles [1–9], Lorentz symmetry violation [3,10–16], ultra-high-energy cosmic rays [17], dark photon [5], sterile neutrinos [18–20], and misidentification of the showers [3]. In our work, we will investigate the survival probability of multi-TeV photons from GRB 221009A by considering the fact that they are significantly absorbed by the extragalactic background light intervening between the GRB and the Earth. We will further show whether the standard physics is still capable to interpret current observations.

Very-high-energy photons can dissipate their energies via annihilation with photons in cosmic microwave background (CMB) and extragalactic background light (EBL), producing electron-positron pairs. The threshold of this channel to happen is $E_{\rm th} = m_e^2/E_{\rm b}$, where m_e and E_b are the mass of electrons and the averaged energy of background light, respectively. Therefore, for CMB photons, this threshold is hundreds of TeV, implying that we can safely disregard the effect of CMB photons. However, the energy of EBL photons can be higher by several orders of magnitude than the CMB photons, changing the threshold to be lower by the same magnitude. For example, the threshold is ∼ 2.6 TeV if we consider $E_b \sim 0.1$eV. Therefore, we should take into account the suppression effect of EBL photons on the detected flux of ∼ 18 TeV photons by LHAASO.

2 Flux of TeV photons and EBL attenuation

The EBL-suppressed flux F_o depends on the intrinsic flux F_i and the optical depth $e^{-\tau}$ due to absorption by EBL. Therefore, we have

$$F_o(E) = F_i(E) e^{-\tau(E,z)} , \qquad (1)$$

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[1] https://gcn.gsfc.nasa.gov/gcn3/32648.gcn3.
[2] https://gcn.gsfc.nasa.gov/gcn3/32677.gcn3.
[3] https://gcn.gsfc.nasa.gov/gcn3_archive.html.

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where E is the observed energy of photons and z is the redshift of GRB 221009A. We use the tabulated data of the EBL and optical depth measured by Ref. [21]. The intrinsic flux of photons is approximated to be a power-law [22]

$$F_i(E) = A_i \left(\frac{E}{0.5\mathrm{TeV}}\right)^{\alpha_\mathrm{i}} e^{-\frac{E}{E_\mathrm{cut}}} , \tag{2}$$

where A_i is an intrinsic flux at a pivot energy scale 0.5 TeV, α_i denotes a spectral index, and E_cut is a cutoff energy scale. Based on the reports of Fermi-LAT, we have two measured values of α_i, namely, -1.87 ± 0.04[4] and -2.12 ± 0.11.[5] However, they were obtained at 0.1–1 GeV, which is an energy range beyond the capability of LHAASO. Meanwhile, there is not a report of spectral index from LHAASO at present. During our parameter inference processes, we assume that the spectral index α_i is -2 and -3, respectively. Our results can be adjusted to fit any value of α_i between -2 and -3 if it is reported by LHAASO in the future. Due to the same reason, we fix E_cut to 2 TeV, 5 TeV, and 10 TeV, respectively. Therefore, we leave A_i to be determined by the data sets of LHAASO.

By considering the performance of LHAASO [23], we predict the number of events within energy range $0.5 - 10$ TeV to be

$$N_{>0.5\mathrm{TeV}} = T \int_{0.5\mathrm{TeV}}^{10\mathrm{TeV}} F_o(E) S_\mathrm{eff}(E, \theta) dE , \tag{3}$$

where S_eff is the effective area of LHAASO-WCDA, as provided in Fig. 6 of Chapter 3 in Ref. [23], $\theta \simeq 28°$ is the zenith angle of GRB 221009A, and $T = 2000$ s is the duration of LHAASO observing run.

To explore the parameter space, we perform Bayesian analysis by considering the fact that the number of photons above 0.5TeV is more than 5000, as reported by LHAASO.[6] We assume that the event number follows Poisson distribution with probability distribution function (PDF), i.e.

$$p(k) = \lambda^k e^{-\lambda}/k! \tag{4}$$

with $\lambda = 5000$ being the expectation and $k = N_{>0.5\mathrm{TeV}}$. Our results and conclusion are robust when choosing other value of λ within a range [5000, 6000). If we consider smaller values of λ, e.g., $\lambda = 4000$, our results would not be altered significantly, i.e., a difference of around 15%, which would not destroy our conclusions. We implement the Bayesian inference by using the affine-invariant Markov chain Monte Carlo (MCMC) ensemble sampler in *emcee* [24]. We assume that A_i has a uniform prior in the range $[10^{-5}, 10^{-2.5}]$ in units of $\mathrm{TeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}$. The optical depth is sampled by following the tabulated data of median value and uncertainties of τ,[7] as described in Ref. [21].

The results of Bayesian parameter inferences are shown as the one-dimensional posterior PDFs of A_i in Fig. 1. The left panel shows the results in the case of $\alpha_i = -2$ while the right one shows those in the case of $\alpha_i = -3$. For any case, we find $A_i \simeq$ few $\times\ 10^{-4}\ \mathrm{TeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}$. In the following, we do Monte Carlo simulations via sampling A_i following its posterior PDF and τ following the aforementioned tabulated data.

3 Probability of detecting TeV photons

Based on the above results, we will estimate the probability of predicting that LHAASO observes at least one photon ~18 TeV from GRB 221009A. During an observation of $T = 2000$ s, the event number of photons with energy centered at E is given by

$$N(E) = T \int_{10\mathrm{TeV}} F_o(E') S_\mathrm{eff}(E', \theta) P(E, E') dE' , \tag{5}$$

where $P(E, E') \propto \exp[-(E'/E - 1)^2/(2\sigma^2)]$ stands for a Gaussian PDF with $\sigma = \Delta E/E$ being the energy resolution of LHAASO-KM2A [25]. We consider the energy range above 10 TeV, with an emphasis on 18 TeV. For each given energy E, we perform a set of 10^6 Monte-Carlo simulations. We count the number of models that predict $N(E) \geq 1$ and compute the corresponding probability via dividing this number by 10^6.

Our results of Monte Carlo simulations are shown in Fig. 2. For a given energy, we estimate a probability of predicting that LHAASO detects at least one photon. The left (right) panel shows the results in the case of $\alpha_i = -2$ ($\alpha_i = -3$). The labeling of E_cut is the same as in Fig. 1. In particular, the dotted vertical lines denote 18 TeV in the two panels, while the dotted horizontal lines denote the probabilities of predicting that LHAASO is capable to detect at least one photon of 18 TeV from GRB 221009A. Correspondingly, we also list these probabilities in Table 1. We find that in either case the standard physics is compatible with the observations of 18 TeV photons from GRB 221009A within 3.5σ confidence interval. This prediction could be further tested with the observational data sets of LHAASO in the future.

4 Summary

In this work, we have investigated the survival rate of very-high-energy gamma rays within the energy range of

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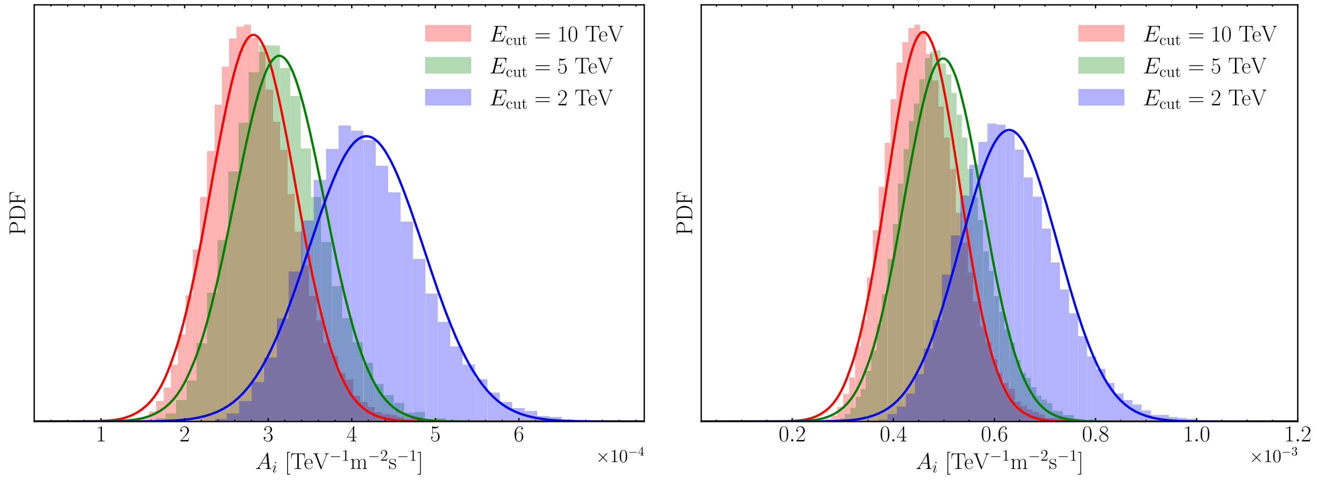
[4] https://gcn.gsfc.nasa.gov/gcn3/32658.gcn3.

[5] https://gcn.gsfc.nasa.gov/gcn3/32637.gcn3.

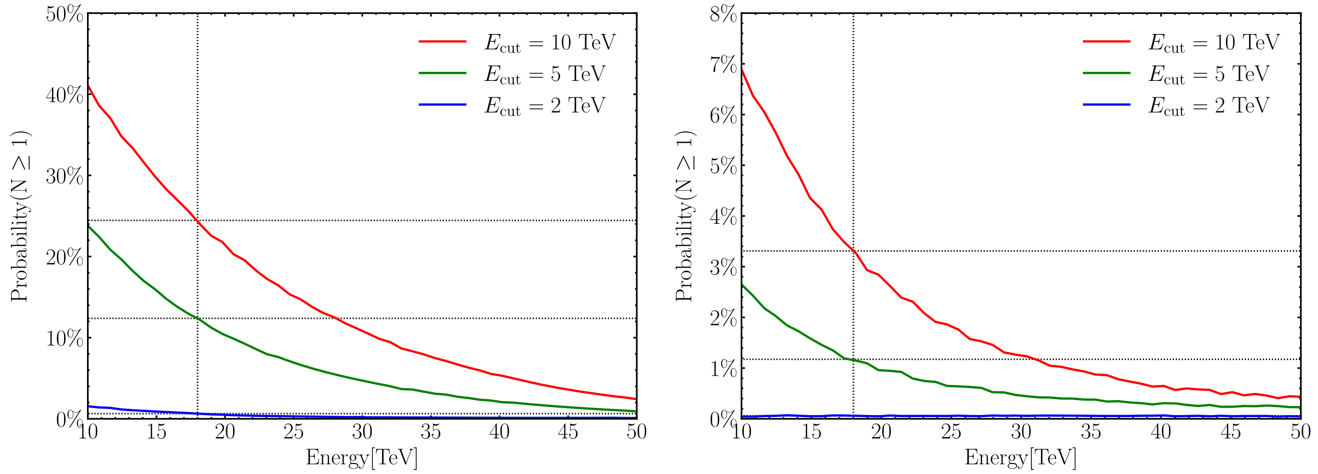
[6] https://gcn.gsfc.nasa.gov/gcn3/32677.gcn3.

[7] http://side.iaa.es/EBL/.



(a) $\alpha_i = -2$ (b) $\alpha_i = -3$

Fig. 1 Posterior probability distribution functions of A_i estimated in the case of $E_{\rm cut} = 10,\ 5,\ 2$ TeV for $\alpha_i = -2$ and $\alpha_i = -3$, respectively



(a) $\alpha_i = -2$ (b) $\alpha_i = -3$

Fig. 2 Probability of predicting that LHAASO observes at least one photon of multi-TeV from GRB 221009A within 2000 s for $E_{\rm cut} = 10,\ 5,\ 2$ TeV respectively. The left panel shows the case of $\alpha_i = -2$ and the right panel shows the case of $\alpha_i = -3$. The dotted vertical lines denote 18 TeV photons while the dotted horizontal lines denote probabilities of observing at least one photon of around 18 TeV

LHAASO, by taking into account the effect of EBL attenuation. In the framework of standard physics, we simulated the probability of detecting the multi-TeV events from GRB 221009A. When considering the energy resolution of LHAASO, we found that the standard physics is still compatible with the observations of 18 TeV photons from GRB 221009A within 3.5σ confidence interval. The above conclusions might be altered if we consider other measurements of EBL and optical depth [26–32], that are beyond the scope of this paper. If the report of LHAASO can be confirmed in the future, we may derive a novel constraint on the models of EBL or even discriminate different models of EBL. We would leave such detailed studies to future works. Our research method can also be straightforwardly generalized to study more data sets of LHAASO and other experiments in the future. In addition, we did not consider other sources of astrophysical uncertainties, e.g., the effect of intergalactic magnetic fields. This effect may be considerable for GRB 221009A, especially in the Fermi-LAT energy band. In fact, the intergalactic magnetic field strength had been estimated to be $\sim 10^{-16}$ Gauss, if considering the delayed cascade photons observed by Fermi-LAT, as shown in Ref. [33]. Meanwhile, it was shown that LHAASO might have observed the cascade photons from this GRB. However, it is challenging

Table 1 List for probabilities of predicting that LHAASO observes at least one photon of ∼ 18 TeV from GRB 221009A within 2000 s

	$E_{\rm cut} = 10$ TeV	$E_{\rm cut} = 5$ TeV	$E_{\rm cut} = 2$ TeV
$\alpha_i = -2$	24.5 %	12.4 %	0.6 %
$\alpha_i = -3$	3.3 %	1.2 %	0.1 %

to discriminate them from photons due to other astrophysical processes in practice.

We also noticed that other experiments detected photons from GRB 221009A, but at energy bands different from LHAASO. For example, the Carpet-2 experiment[8] reported a single event ∼ 251 TeV in coincidence with GRB 221009A with statistical significance of ∼ 3.8σ. This event might imply an evidence of new physics due to such a high energy scale. However, another possibility was also proposed to be a cosmic-ray origin due to secondary emission from ultra-high-energy cosmic rays [17,34,35]. Therefore, further observations in future are necessary to remove these debates.

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