Standard physics is capable to interpret ∼18 TeV photons from GRB 221009A

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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 by 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 find that the probability of predicting that LHAASO observes at least one photon of ∼18 TeV from GRB 221009A within 2000 seconds is 80\% and 25\% if assuming the spectral index of photon flux is $-2$ and $-3$, respectively. Hence, it is still possible for the standard physics to interpret the observation of LHAASO in the energy range of several TeV. 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 $z \simeq 0.151$ \textsuperscript{1} were observed by the Large High Altitude Air Shower Observatory (LHAASO) \textsuperscript{2} within 2000 seconds after the first detection by Swift, Fermi-GBM, Fermi-LAT, and so on \textsuperscript{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 \textsuperscript{1}, Lorentz symmetry violation \textsuperscript{2}, and both \textsuperscript{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 $E_{th} = m_e^2/E_b$, 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 $\sim 2.6$ 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 $\sim 18$ TeV photons by LHAASO.

2 Flux of TeV photons and EBL attenuation

The EBL-suppressed flux $F_0$ depends on the intrinsic flux $F_i$ and the optical depth $e^{-\tau}$ due to absorption by EBL. Therefore, we have

$$F_0(E) = F_i(E)e^{-\tau(E,z)},$$

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. [4]. The intrinsic flux of photons is approximated to be a power-law [5]

$$F_i(E) = A_i \left(\frac{E}{0.5\text{TeV}}\right)^{\alpha_i},$$

where $A_i$ and $\alpha_i$, respectively, stand for the intrinsic flux and spectral index at the pivot energy scale 0.5 TeV. Based on the reports of Fermi-LAT, we have two measured values of $\alpha_i$, namely, $-1.87 \pm 0.04$ and $-2.12 \pm 0.11$. 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. Therefore, during our parameter inference processes, we assume that the spectral index $\alpha_i$ is $-2$ and $-3$, respectively. Our results can be adjusted to fit any value of $\alpha_i$ between $-2$ and $-3$ if it is reported by LHAASO in the future. We leave $A_i$ to be determined by the dataset of LHAASO.

By considering the performance of LHAASO [6], we predict the number of events with energy above 0.5TeV to be

$$N_{>0.5\text{TeV}} = T \int_{0.5\text{TeV}} F_0(E)S_{\text{eff}}(E,\theta)\,dE,$$

where $S_{\text{eff}}$ is the effective area of LHAASO-WCDA, as provided in Fig. 6 of Chapter 3 in Ref. [6], $\theta \approx 28^\circ$ is the zenith angle of GRB 221009A, and $T = 2000$ seconds 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"
Fig. 1 Posterior probability distribution functions of $A_i$ estimated in the case of $\alpha_i = -2$ (red) and $-3$ (blue), respectively.

by LHAASO\(^6\). We assume that the event number follows Poisson distribution with probability distribution function (PDF), i.e.

$$p(k) = \lambda^k e^{-\lambda}/k!$$  \hspace{1cm} (4)

with $\lambda = 5000$ being the expectation and $k = N_{>0.5\text{TeV}}$. Our results and conclusion are robust when choosing other value of $\lambda$ within $[5000,6000)$. We implement the Bayesian inference by using the affine-invariant Markov chain Monte Carlo (MCMC) ensemble sampler in emcee\(^7\). We assume that $A_i$ has a uniform prior in the range $[10^{-5},10^{-3}]$ in units of $\text{TeV}^{-1}\text{m}^{-2}\text{s}^{-1}$. The optical depth is sampled by following the tabulated data of median value and uncertainties of $\tau$\(^7\), as described in Ref.\(^4\).

The results of Bayesian parameter inferences are shown as follows. At 68% confidence level, we find two sets of posteriors of $A_i$, namely, $A_i = (2.50^{+0.49}_{-0.43}) \times 10^{-4}$ in the case of $\alpha_i = -2$ while $A_i = (4.18^{+0.71}_{-0.62}) \times 10^{-4}$ in the case of $\alpha_i = -3$. We further depict the one-dimensional posterior PDFs of $A_i$ in Fig. 1. In the following, we do Monte Carlo simulations via sampling $A_i$ following its posterior PDF and $\tau$ 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 photons $\sim$18 TeV from GRB 221009A. During an

\(^6\)https://gcn.gsfc.nasa.gov/gcn3/32677.gcn3

\(^7\)http://side.iaa.es/EBL/
Fig. 2  Probability of predicting that LHAASO observes at least one photon from GRB 221009A within 2000 seconds. The vertical dotted line denotes 18 TeV. The coloring of curves is consistent with that of Fig. 1.

observation of $T = 2000$ seconds, the event number of photons in the energy range from $(1 - \Delta E/2)E$ to $(1 + \Delta E/2)E$ is given by

$$N(E) = T \int_{(1 - \Delta E/E)}^{(1 + \Delta E/E)} F_o(E') S_{\text{eff}}(E', \theta) dE',$$  

where $\Delta E(E)$ is the energy resolution of LHAASO-WCDA, as provided in Fig. 26 of Chapter 1 in Ref. [6]. We consider the energy range from 0.5 TeV to 100 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. The vertical line denotes 18 TeV in the figure. We find that the probabilities of predicting that LHAASO is capable to detect at least one photon of 18 TeV from GRB 221009A, are about 80% and 25% in the case of $\alpha_i = -2$ and $-3$, respectively. We find that in either case the standard physics is capable to interpret $\sim$18 TeV photons from GRB 221009A. We always expect the probability to be several tens of percents for $\alpha_i$ being larger than $-3$. This prediction could be tested with the observational dataset 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 LHAASO, by taking into account the effect of EBL attenuation. In the framework of standard physics, we simulated the probability of
detecting the $\sim 18$ TeV signal from GRB 221009A. We found that the probability is several tens of percents. For $\alpha_i$ being $-2$ (or $-3$), hints of new physics may be displayed at 95% level if photons above 27 TeV (or 22 TeV) from GRB 221009A are observed by LHAASO, when considering its energy resolution. The above conclusions might be altered if we consider other measurements of EBL and optical depth\cite{8,9,10,4,11,12,13,14}, 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. Moreover, our research method can be straightforwardly generalized to study more data sets of LHAASO and other experiments in the future.

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