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Differential limit on an EHE neutrino flux component in the presence of astrophysical background from nine years of IceCube data

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We report the quasi-differential upper limits of extremely high energy (EHE) neutrino flux above 10 PeV based on the analysis of nine years of IceCube data. A complete frequentist approach to calculate the differential limit using the Poisson binned likelihood is developed. It enables the limit to be set in the presence of unknown astrophysical neutrino flux. An event with deposited energy clearly above 1 PeV was detected in addition to one event found in the previous EHE neutrino search. They are consistent with the astrophysical neutrino flux of a power-law-like spectrum but incompatible with predictions of cosmogenic neutrino fluxes with spectrum peaks at energies well above the PeV range. Thus, they are considered as the bulk of background events in setting the limits on EHE neutrino fluxes. The resultant differential upper limit is the most stringent to date in the energy range between 5×10^6 and 5×10^{10} GeV. This result indicates that cosmogenic neutrino models that predict a three-flavor neutrino flux of $E_\nu^2 \phi_{\nu_e+\nu_\mu+\nu_\tau} \simeq 2 \times 10^{-8}\ \mathrm{GeV/cm^2\ sec\ sr}$ at 10^9 GeV are constrained, bounding a significant parameter space on EHE neutrino models, which assumes a composition of proton-dominated ultra-high-energy cosmic rays.

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1. Introduction

The upper limits of cosmic neutrino fluxes depend on their energy spectrum. The spectral shape of the neutrino flux is often assumed to follow a power-law form, that is, $\phi_\nu \propto E_\nu^{-\alpha}$. However, in the extremely high energy (EHE) region above 10 PeV, many neutrino models predict energy spectra that do not follow a simple power law. A cosmogenic Greisen–Zatsepin–Kuzmin (GZK) neutrino spectrum [1], for example, represents a non-power-law structure mostly determined by unknown physical parameters, such as cosmological source evolution, the spectrum and evolution function of extragalactic background light, and the energy spectrum of primary ultra-high-energy cosmic ray (UHECR) nucleons [2]. Variations in the spectral shapes present difficulties for setting a generic upper limit for neutrino fluxes in the EHE region. Thus, we present model-dependent constraints for a few representative models [3].

An approach to set a generic, model-independent limit on UHECR source models with EHE neutrino observations is to calculate the *differential* upper limit of the EHE neutrino flux. This idea was originally proposed by Anchordoqui et al. [4]. For null detection with the 4π-averaged neutrino effective area A_i^ν for a neutrino flavor i, this limit is calculated analytically by:

$$\phi^{\mathrm{UL}}_{\nu_e+\nu_\mu+\nu_\tau}(E_\nu) = 3\frac{\mathrm{N}_{90}}{4\pi E_\nu T \mathrm{Ln}10 \sum_{i=\nu_e,\nu_\mu,\nu_\tau} A_i^\nu(E_\nu)}, \tag{1.1}$$

where T is the observation time and N_{90} is a 90% CL upper limit on the number of events. $\mathrm{N}_{90} = 2.4$ with the Feldman–Cousins method [5] in the case of negligible background. An equal flavor ratio of neutrino fluxes: $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at the Earth is assumed. This formula is derived from the expected number of events in an energy bin with a width of one decade, where

$$\Delta N = \frac{1}{3}\phi_{\nu_e+\nu_\mu+\nu_\tau} 4\pi E_\nu T \mathrm{Ln}10 \sum_{i=\nu_e,\nu_\mu,\nu_\tau} A_i^\nu(E_\nu). \tag{1.2}$$

This observation implies that the upper limit of Eq. (1.1) is equivalent to the limit on the normalization of the neutrino fluxes following E_ν^{-1} with an interval of one decade.

In the case where neutrino event candidates are detected, this formula needs to be modified. However, the approach to incorporate detected events in the calculation of the differential limit is not obvious. This lack of clarity arises because the probability density function (PDF) of the primary neutrino energy for the measured energy of a given event is broadly distributed. In particular, only a small portion of the parent neutrino energy is deposited in the detector for a neutrino-induced muon track event. This PDF depends on the unknown true neutrino spectrum.

In this report, we present a complete frequentist approach to calculate the flux limits and update the constraints using a collection of IceCube data taken over nine years from April 2008 to May 2017. This data sample contains two years of the newest data in addition to that on which the previous analysis [3] was based. All signal selection criteria are the same as in the previous publication. Three events that passed the EHE neutrino search criteria were found in the final sample. Energy proxies and reconstructed zenith angles of these events are consistent with the astrophysical origin that IceCube has been detecting in the TeV to PeV energy region[6], but not with the GZK-like EeV-energy neutrinos. Thus, they are considered as *astrophysical* background in searches for cosmogenic neutrinos. The new approach using a nuisance parameter to represent the unknown astrophysical background is described and the p-value calculations are carried out by a test statistic using the Poisson-binned likelihood ratio. The model-independent differential limits are presented. Lastly, the implications of the derived limits for explaining the origin of UHECRs are discussed.

2. Data and Simulation

IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole between depths of 1450 and 2450 m, forming a three-dimensional array of digital optical modules (DOMs)[7]. To form the detector, cable assemblies called strings were lowered into holes drilled downwards into the glacier ice with a horizontal spacing of approximately 125 m. The detector construction was completed in December 2010 and the observatory has been in full operation with 86 strings (IC86) since May 2011. During the construction period, it was partially operated with 40, 59, and 79 strings, in 2008-2009, 2009-2010, and 2010-2011, respectively. The analysis described here is based on data taken from April 2008 to May 2017. The effective live time of the sample was 3126 days. The newest two-year worth of data gives approximately 30% more exposure to the sample compared to that used in the previous EHE neutrino search [3].

There are two classes of atmospheric background events: atmospheric muon bundles, and events generated by atmospheric neutrinos. They were simulated using the CORSIKA [8] package with the SIBYLL hadronic interaction model [9], and by the IceCube neutrino-generator program based on the ANIS code [10], respectively. The EHE neutrino-induced events were simulated by the JULIeT package [11]. This package provides the GZK cosmogenic signal simulation sample as well as simulations of the *astrophysical* background events, whose spectrum is assumed to be described by an unbroken power law in the relevant energy region. The detailed simulation procedure used in this work is described in Ref. [12].

The EHE signal selection criteria is the same as in the previous analysis [3]. They are designed to find any events yielding Cherenkov light bright enough to be distinguishable from the atmospheric background, regardless of event topology recorded by the array of DOMs. The expected number of atmospheric background events in the data sample passing the selection criteria is $0.085^{+0.031}_{-0.051}$. The expected event rate from the GZK cosmogenic model following the source evolution of the star formation rate (SFR) [15] is $4.80^{+0.71}_{-1.05}$. The astrophysical neutrino flux [6], possibly extending to the EHE region, may yield astrophysical background with rates of $\lesssim 6$ events in the the present analysis sample, depending on its spectral shape.

3. Poisson-binned likelihood method

The Monte Carlo simulation events of the the IceCube EHE signals passing the final selection criteria of analysis [3] are filled into a histogram with bins of reconstructed zenith angle θ and energy proxy E_{proxy}. The energy proxy used in this analysis was optimized to reconstruct the energy deposited by EHE muon tracks [13]. Although it does not give the best possible estimate for cascade events, it provides an unified analysis scheme in the EHE region regardless of event topologies. θ is the result of reconstruction using a so-called single photoelectron log-likelihood (llh) fitting on the detector signals based on a track hypothesis [14]. For the events such as cascades, in which direction is not well reconstructed, only the energy proxy information is used in the present analysis. Events with llh values inconsistent with tracks are categorized in this *non-track-like* category.

The event-number distributions on the plane of E_{proxy} and $\cos(\theta)$ (energy-zenith plane) are obtained for different cosmic neutrino models. Similarly, the event-number distributions on the energy-zenith plane for atmospheric neutrino and muon background are obtained. To test a given cosmic neutrino model hypothesis, the expected number of signal and atmospheric background events in the i_{th} and j_{th} bins, $\mu_{i,j}^{\rm SIG}$ and $\mu_{i,j}^{\rm BG}$ are compared, respectively, with the observed number of events $n_{i,j}$ via the Poisson probability function $f_p(n_{i,j}, \mu_{i,j}^{\rm SIG} + \mu_{i,j}^{\rm BG})$, where i is the index of the cosine of zenith angle and j of the energy proxy.

The product of the Poisson probabilities over all zenith and energy bins gives the binned Poisson likelihood:

$$L(\lambda) = \prod_{i,j} f_p(n_{i,j}, \lambda \mu_{i,j}^{\rm SIG} + \mu_{i,j}^{\rm BG}), \tag{3.1}$$

where λ is the multiplier for a signal model. $\lambda = 1$ represents the signal model prediction.

A model test is performed by comparing the model hypothesis of $\lambda = 1$ against the alternative hypothesis $\lambda \neq 1$. A test statistic is the log-likelihood ratio:

$$\Lambda = \log \frac{L(\hat{\lambda})}{L(\lambda = 1)}, \tag{3.2}$$

where $\hat{\lambda}$ is the multiplier to maximize the Poisson likelihood L. An ensemble of pseudo experiments under the model hypothesis gives a PDF of the test statistic Λ. The p-value for a given model of cosmic neutrinos is subsequently calculated from the PDF by the frequency in which Λ is larger than the value obtained from the number of events in each bin, on the energy-zenith plane from the real data.

A test of the background-only hypothesis is also conducted using this scheme. The null hypothesis is represented by $\lambda = 0$ in this case.

3.1 Model compatibility calculation

One of the important questions is whether the observed data is consistent with the expectations from the GZK cosmogenic model or more compatible with a softer power-law flux, such as E_ν^{-2}, which is expected from astrophysical neutrinos. To test this hypothesis, a scheme similar to as one described in the previous section is used. In this case, the binned Poisson likelihood is introduced for both a GZK cosmogenic model and a power-law model:

$$\begin{aligned} L_{\rm GZK}(\lambda_{\rm GZK}) &= \prod_{i,j} f_p(n_{i,j}, \lambda_{\rm GZK} \mu_{i,j}^{\rm GZK} + \mu_{i,j}^{\rm BG}), \\ L_{E_\nu^{-\alpha}}(\lambda_\alpha) &= \prod_{i,j} f_p(n_{i,j}, \lambda_\alpha \mu_{i,j}^{\alpha} + \mu_{i,j}^{\rm BG}), \end{aligned} \tag{3.3}$$

where $\mu_{i,j}^{\rm GZK}$ is the number of events in a bin of the energy–zenith plane predicted by the GZK model, and $\mu_{i,j}^{\alpha}$ is the value attributable to a generic astrophysical $E_\nu^{-\alpha}$ power-law flux. The test statistic is:

$$\Lambda = \log \frac{L_{E_\nu^{-\alpha}}(\widehat{\lambda_\alpha})}{L_{\rm GZK}(\widehat{\lambda_{\rm GZK}})}. \tag{3.4}$$

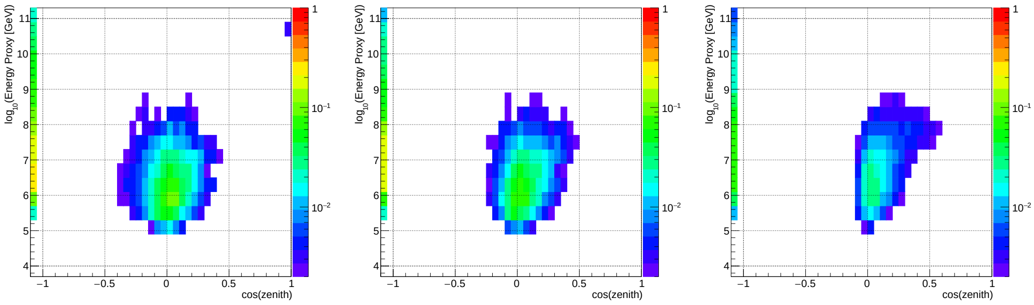

Figure 1: Expected event distributions on the plane of the energy proxy and cosine of the reconstructed zenith angle for the flux $\phi_{\rm Diff} = \kappa_E E_\nu^{-1}$, spanning a one-decade energy interval centered at E_ν^c. The event distributions are the sum of all three neutrino flavors. Events classified as the non-track-like category are plotted in the bins of $\cos\theta = -1.1$. From left to right, the distributions for $\log_{10}(E_\nu^c/\mathrm{GeV}) = 7.6, 8.0,$ and 9.0 are shown. Note that the energy proxy is not the best estimated deposited energy which can be obtained by dedicated energy reconstructions optimized for a given event topology. For display purposes, the normalization κ_E is set here so that the energy flux $E_\nu^2 \phi_{\rm Diff} = 1.0 \times 10^{-8}$ GeV/cm^2 sec sr, at an energy of E_ν^c.

The multiplier with $\widehat{\ }$ is the value needed to maximize the likelihood function.

3.2 Nuisance parameter to represent the astrophysical neutrino flux

As the EHE IceCube data sample is expected to contain events consistent with contributions from a generic astrophysical power-law flux [3], a test of any GZK cosmogenic neutrino model must incorporate the existence of a power-law flux forming astrophysical backgrounds. We account for this likelihood by introducing a nuisance flux in the form $\phi_\alpha = \kappa_\alpha E_\nu^{-\alpha}$, where κ_α is an arbitrarily chosen normalization. A small modification of equation (3.3) gives:

$$L_{\rm GZK}(\lambda_{\rm GZK}, \lambda_\alpha) = \prod_{i,j} f_p(n_{i,j}, \lambda_{\rm GZK}\mu_{i,j}^{\rm GZK} + \lambda_\alpha \mu_{i,j}^{\alpha} + \mu_{i,j}^{\rm BG}), \tag{3.5}$$

where $\mu_{i,j}^{\alpha}$ is the number of events in a bin from the power-law flux with normalization κ_α. Taking λ_α as a nuisance parameter, the likelihood ratio is constructed using the profile likelihood:

$$\Lambda(\lambda_{\rm GKZ}) = \log \frac{L_{\rm GZK}(\widehat{\lambda_{\rm GZK}}, \widehat{\lambda_\alpha})}{L_{\rm GZK}(\lambda_{\rm GZK}, \widehat{\widehat{\lambda_\alpha}}(\lambda_{\rm GZK}))}, \tag{3.6}$$

where the double-hat notation indicates the profiled value of the nuisance parameter λ_α, defined as the value that maximizes $L_{\rm GZK}$ for the specified $\lambda_{\rm GZK}$. This likelihood ratio, in which $\lambda_{\rm GZK} = 1$, is the test statistic for a given GZK cosmogenic model. The baseline model of the nuisance flux is built with $\alpha = 2$. We confirm that the impact of different power-law indices are negligible when constraints are placed in the EHE region. The p-values and the upper limits of the selected GZK models, which appear in our latest publication [3], were obtained using this procedure.

3.3 Differential limit calculation

As described in Section 1 with Eqs. (1.1–1.2), the differential limit at a neutrino energy of E_ν^c is essentially the upper limit for the flux of $\phi_{\rm Diff} = \kappa_E E_\nu^{-1}$ ranging over an interval of one decade $[\log_{10}(E^c_\nu/\mathrm{GeV}) - 0.5, \log_{10}(E^c_\nu/\mathrm{GeV}) + 0.5]$. The corresponding likelihood is obtained from equation (3.5) by replacing the number of events from a GZK flux with the number obtained from ϕ_{Diff}, so that:

$$L_{\mathrm{Diff}}(\lambda_{\mathrm{Diff}}, \lambda_\alpha) = \prod_{i,j} f_p(n_{i,j}, \lambda_{\mathrm{Diff}}\mu^{\mathrm{Diff}}_{i,j}(E^c_\nu) + \lambda_\alpha \mu^\alpha_{i,j} + \mu^{\mathrm{BG}}_{i,j}), \tag{3.7}$$

where μ^{Diff} represents contributions from the flux ϕ_{Diff} with the one-decade energy centered at E^c_ν. Thus, this expression is a function of E^c_ν. Figure 1 shows the distribution of $\mu^{\mathrm{Diff}}_{i,j}$ on the energy-zenith angle plane.

The test statistic is constructed as:

$$\Lambda(\lambda_{\mathrm{Diff}}, E^c_\nu) = \log \frac{L_{\mathrm{Diff}}(\widehat{\lambda_{\mathrm{Diff}}(E^c_\nu)}, \widehat{\lambda_\alpha})}{L_{\mathrm{Diff}}(\lambda_{\mathrm{Diff}}(E^c_\nu), \hat{\hat{\lambda}}_\alpha(\lambda_{\mathrm{Diff}}(E^c_\nu)))}. \tag{3.8}$$

An ensemble of pseudo experiments to construct the PDF of $\Lambda(\lambda_{\mathrm{Diff}}, E^c_\nu)$ gives the upper limit of λ_{Diff} with a given confidence level, at an energy of E^c_ν. By repeating the same procedure with varying E^c_ν, the differential upper limit as a function of neutrino energy is produced.

For the previously published differential EHE limit [3], no nuisance parameter was used to account for an astrophysical background flux. It was found that the PDF of the test static Λ, given by Eq.(3.8), depends on the astrophysical normalization κ_α. In the present analysis, a value of $\lambda_\alpha = 0$ is used in pseudo-experiments for the PDF calculation since it results in the most conservative limit.

4. Results and discussion

Two events passing the final selection criteria were observed. One event among them were found in the previous analysis and reported [3][1]. The newly found event was detected in December 2016. It appears an uncontained shower event. The energy proxy of this event used in the present analysis (E_{proxy}) is 2.72 PeV. Note that the best estimated energy of this uncontained shower event is different from the energy proxy value. Detail on its energy scale and the event topology classifications are not yet conclusive and are currently under investigation. We in particular study the possibility that it was produced by a prompt atmospheric muon from a decay of a charmed meson.

The hypothesis that they are backgrounds from atmospheric neutrinos and conventional atmospheric muons was tested by the likelihood ratio test statistic of Eq. (3.2) with $\lambda = 0$ and rejected with a p-value of 0.024% (3.5σ). They are compatible with a generic astrophysical E^{-2} power-law flux with a p-value of 78.8% while they are inconsistent with the GZK cosmogenic hypothesis with a p-value of 2.5% (2.0σ), calculated using the test statistic of Eq. (3.6). They exhibit signatures of astrophysical neutrinos originating in the spectrum, extending from TeV to PeV energies rather than in a GZK spectrum peaking at energies in the EeV range, and are considered astrophysical backgrounds.

Figure 2 presents the derived all-flavor-sum differential upper limit using the current method based on the nine-year set of IceCube data. The three observed events weaken the limit below

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[1] Of the two background events published in Ref. [3], one was discovered to be a detector artifact and has been removed.

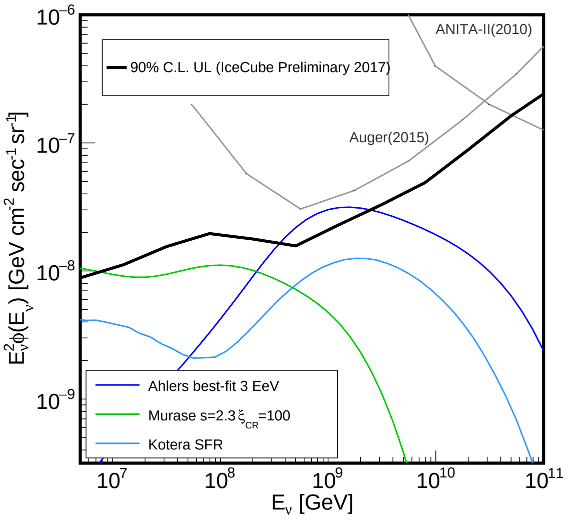

Figure 2: All-flavor-sum differential 90% CL upper limit based on the nine-year collection of IceCube data. Cosmogenic neutrino model predictions (assuming primary protons) by Kotera et al. [15], Ahlers et al. [16], and an astrophysical neutrino model by Murase et al. [17] are shown for comparison.

4×10^8 GeV. The limit displays the constraints of the EHE cosmic neutrino flux on top of the power-law flux of astrophysical neutrinos inferred by the present data sample. Any departure from $\alpha = 2$ in the nuisance ϕ_α model has a very minimal impact on the obtained limit, especially at energies of 300 PeV or higher, which is the main energy region of interest in this study. It was also confirmed that the present limit is insensitive to systematic uncertainties in the energy proxy and topology of the detected events.

The presented differential upper limit in the energy region between 5×10^6 and 5×10^{10} GeV is the most significant model-independent upper limit currently reported. It indicates that models predicting a flux of $E_\nu^2 \phi_{\nu_e+\nu_\mu+\nu_\tau} \simeq 2 \times 10^{-8}$ GeV/cm^2 sec sr at 10^9 GeV are disfavored by the current IceCube observation.

The present limit constrains a significant parameter space in EHE neutrino models that assume a proton-dominated UHECR composition. This constraint arises because the energy flux of UHECRs at 10 EeV, $\sim 2 \times 10^{-8}$ GeV/cm^2 sec sr, is comparable to the present neutrino differential limit. The UHECR flux contributes only to the local universe at a radius of $R_{\rm GZK} \sim 100$ Mpc because of the energy attenuation of UHECR protons colliding with the cosmic microwave background. However, neutrinos are able to travel cosmological distances of $O(c/H_0) \sim 4$ Gpc. Thus, UHECR sources within a sphere of $\sim c/H_0$ contribute to the expected neutrino flux. This volume effect generally increases the neutrino flux relative to the UHECR flux by a factor of $\sim c/H_0/R_{\rm GZK} \sim O(10)$. This balances the energy conversion factor from a UHECR proton to its daughter neutrino ($5 \sim 10\%$), leading to an amount of neutrino energy flux comparable to the energy flux of UHECRs, if the observed UHECRs are protons, independent of the details of the neutrino production model.

5. Summary

We have introduced a new method that employs the binned Poisson likelihood method for deriving the quasi-differential upper limits of neutrino flux using a nine-year IceCube data set. A method using a nuisance parameter to represent astrophysical background determined by the observation data is presented. The differential upper limit based on nine years of IceCube data is obtained. The limit is the most stringent recorded to date in the energy range between 5×10^6 and 5×10^{10} GeV. It indicates that any cosmic neutrino model that predicts a three-flavor neutrino flux of $E_\nu^2 \phi_{\nu_e+\nu_\mu+\nu_\tau} \simeq 2 \times 10^{-8}$ GeV/cm^2 sec sr at 10^9 GeV is constrained.

References

[1] V. S. Berezinsky and G. T. Zatsepin, *Phys. Lett.* **28B** (1969) 423.

[2] S. Yoshida and A. Ishihara, *Phys. Rev. D* **85** (2012) 063002.

[3] M. G. Aartsen et al., (IceCube Collaboration), *Phys. Rev. Lett.* **117** (2016) 241101.

[4] L. A. Anchordoqui et al., *Phys. Rev. D* **66** (2002) 103002.

[5] G. J. Feldman and R. D. Cousins, *Phys. Rev. D* **57** (1998) 3873.

[6] M. G. Aartsen et al., (IceCube Collaboration), *Phys. Rev. Lett.* **113** (2014) 101101; M. G. Aartsen et al., (IceCube Collaboration), *Astrophys.J.* **833** (2016) no.1, 3.

[7] M. G. Aartsen et al., (IceCube Collaboration), Journal of Instrumentation,**12** (2017) P03012.

[8] D. Heck et al., *Report* **FZKA** 6019 (1998);

[9] E. J. Ahn, R. Engel, T. K. Gaisser, P. Lipari and T. Stanev, *Phys. Rev. D* **80** (2009) 094003.

[10] A. Gazizov and M. P. Kowalski, *Comput. Phys. Commun.* **172** (2005) 203.

[11] S. Yoshida et al., *Phys. Rev. D* **69** (2004) 103004.

[12] M. G. Aartsen et al., (IceCube Collaboration), *Phys. Rev. D* **88** (2013) 112008.

[13] M. G. Aarsten et al., (IceCube Collaboration) *J. Instrum.* **9** (2014) P03009.

[14] J. Ahrens et al. (AMANDA Collaboration), *Nucl. Instrum. Methods Phys. Res.,* Sect. A **524** (2004) 169.

[15] K. Kotera, D. Allard, and A. Olinto, *J. Cosmol. Astropart. Phys.* **2010** (2010) 013.

[16] M. Ahlers et al., *Astropart. Phys.* **34** (2010) 106.

[17] K. Murase, Y. Inoue, and C. D. Dermer, *Phys. Rev. D* **90** (2014) 023007.