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Searching for UHECR-associated gamma-ray sources with LHAASO-WCDA

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The origin of ultra-high-energy cosmic rays (UHECRs; $\gtrsim$ 10 EeV) is unknown. Gamma-rays and neutrinos produced in CR-induced hadronic interactions can serve as the smoking gun pointing back to sources. Motivated by the fact that IceCube-measured diffuse TeV neutrino flux is comparable to Waxman-Bahcall bound derived from the detected UHECR flux, we assume a common origin of UHECRs and TeV neutrinos, and expect TeV hadronic gamma-rays associated with UHECRs as well, the detection probability of which depends on UHECR source density. Here we use LHAASO-WCDA to search for TeV gamma-rays associated with UHECRs. A detailed data analysis based on LHAASO-WCDA sky map and UHECR events detected by Telescope Array results in non-detection of gamma-ray signals. A lower limit is put on the source number density, $n_s > 10^{-3.5}\,\mathrm{Mpc}^{-3}$, with 95% C.L.

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1. Introduction

The origin of ultra-high energy cosmic rays ($\gtrsim 10^{19}$eV; UHECRs) is still an open question. Deflection by magnetic field and small sample size of UHECRs are difficulties for searching UHECR sources directly. UHECRs spectrum is measured by Telescope Array (TA) and Pierre Auger Observatory (PAO). There is an "ankle" feature at several EeV, which might be attributed to the transition from Galactic to extra-galactic components. A cut off feature appears at the highest energy $\sim 10^{20}$ eV, may be caused by interactions of UHECRs with the cosmic background radiation, known as Greisen-Zatsepin-Kuzmin (GZK) cutoff. These features of CR spectrum indicate that UHECRs may come from extra-galactic sources.

CRs can produce high energy gamma-rays and neutrinos via pion decay, when cosmic rays interact with background photons or matter. This makes it possible to build connection between UHECRs and gamma-rays/neutrinos. Neutral particles are not deflected by magnetic fields, pointing back to the sources. Moreover, neutrinos hardly interact with other matter, which makes them a special kind of astrophysical messengers. High energy astrophysical neutrinos had been discovered by the IceCube neutrino detector, which open a window for high energy neutrino astronomy.

This work aims to study UHECR sources by searching for the UHECR associated gamma-ray sources. LHAASO-WCDA is used for the search due to its excellent performance on TeV gamma-rays [1]. The search is motivated by the apparent coincidence of Waxman-Bahcall bound [2] and IceCube neutrino flux. Waxman-Bahcall bound is an upper bound for high energy extra-galactic neutrino flux, given by assuming that CR energy is all converted to pions in the interaction with ambient medium. The IceCube measured neutrino flux [3] is closed to the Waxman-Bahcall bound, $\sim 2 \times 10^8$ GeV cm^{-2} s^{-1} sr^{-1}, which suggests that IceCube neutrinos may be produced by the same source responsible for these UHECRs [4, 5].

2. Theoretical prediction of detection

In ref [6] we had calculated the probability to detect gamma-ray sources in the directions of observed UHECRs as function of source number density, assuming a common origin of UHECRs and TeV diffuse neutrinos. UHECRs may escape quickly from their source environment, e.g., the host galaxy, due to their high rigidity, while lower energy CRs propagate in the host galaxy for longer time, and all of their energy is depleted in pp interactions with interstellar medium (ISM). Meanwhile, gamma-rays are produced in the pp interactions. In this scenario, the extra-galactic neutrino flux is similar to Waxman-Bahcall bound, and the host galaxies of UHECR sources are high energy gamma-ray sources as well.

We have considered the spatial and temporal associations between UHECRs and gamma-ray or neutrino sources in [6]. For UHECR protons with energy $E \sim 100$ EeV, the deflection by magnetic field during propagation is smaller than $\theta \sim 2°$ for sources within $d \sim 100$ Mpc. So it is expected to observe gamma-ray sources toward the UHECR directions within few degree in angular separation. Meanwhile, the deflection leads to an arrival time of UHECRs relatively delayed compared to photons emitted in the same time by a time $\delta t \sim \theta^2 d/c \sim 10^5$ yr. The arrival time spreads in a timescale similar to δt, if the UHECRs are produced by explosive events. These timescles are much smaller than the typical timescale of pp energy loss for CRs. Thus we expect to observe gamma-rays from the UHECR directions in the same time whether the UHECRs source is steady or explosive. If no gamma-ray sources detected, one still can put constraint on source properties.

A single source should be luminous or close enough to be detected in gamma-rays. As in [6], for telescopes of certain sensitivity we can consider an "horizon" of cosmological redshift $z_{\rm max}$, within which gamma-ray sources can be detected. Tacking into account the detector sensitivity and gamma-ray absorption by extra-galactic background light (EBL) $z_{\rm max}$ is determined by

$$\int_{>E_\gamma} {\rm d}E'_\gamma \frac{{\rm d}L_\gamma}{{\rm d}E'_\gamma} e^{-\tau_{\rm EBL}(E'_\gamma, z_{\rm max})} = 4\pi d_L^2(z_{\rm max}) f_{\rm th}(>E_\gamma). \tag{1}$$

Here $\tau_{\rm EBL}$ is the optical depth of high energy gamma-rays due to EBL absorption, for which we adopt the observational results from [7], $f_{\rm th}(>E_\gamma)$ is the integral sensitivity of gamma-ray telescope at gamma-ray energy above E_γ, d_L is the luminosity distance, and ${\rm d}L_\gamma/{\rm d}E_\gamma$ is the typical specific luminosity of a single gamma-ray source related to UHECRs, which can be derived via

$$\xi_z \frac{c}{4\pi} t_H n_{\rm s} E_\gamma \frac{{\rm d}L_\gamma}{{\rm d}E_\gamma} = E_\gamma^2 \phi_\gamma, \tag{2}$$

with $E_\gamma^2\phi_\gamma$ the diffuse gamma-ray flux from UHECR sources without EBL absorption, scaled with diffuse neutrino flux as $E_\gamma^2\phi_\gamma = 2E_\nu^2\phi_\nu$, where $E_\gamma = 2E_\nu$. From the latest results of IceCube observations, we have $\phi_\nu = 1.44\times10^{-18}(E_\nu/100{\rm TeV})^{-2.28}\,{\rm GeV}^{-1}\,{\rm cm}^{-2}\,{\rm s}^{-1}\,{\rm sr}^{-1}$ [3] for single flavor. According to eqs (1) and (2), we can calculate $z_{\rm max}$, which is found to be function of the product of sensitivity and source number density, $n_{\rm s} f_{\rm th}$.

Consider the probability of detecting gamma-ray sources associated with UHECRs. For an UHECR detector with the effective area $A_{\rm eff}$ at a certain direction and an observation periond ΔT, the number of detected CRs originated from redshift $0 - z'$ per unit CR energy and per unit solid angle is

$$\frac{{\rm d}N(E,z')}{{\rm d}E{\rm d}\Omega} = \Delta T \int_0^{z'} {\rm d}z \frac{{\rm d}V}{{\rm d}\Omega{\rm d}z} Q(E(1+z)), z) e^{-\tau_{\rm GZK}(E(1+z)),z)} \frac{A_{\rm eff}(E)(1+z)^2}{4\pi d_L^2(z)}, \tag{3}$$

where $Q(E,z)$ is the specific production rate density of UHECRs, ${\rm d}V/{\rm d}\Omega{\rm d}z$ is the comoving volume per unit redshift and per unit solid angle. $\tau_{\rm GZK}$ accounts for the GZK effect, and details can be found in [6]. The probability of finding a gamma-ray source associated with a certain detected UHECR is

$$P(n_s, f_{\rm th}, E) = \frac{{\rm d}N(E, z_{\rm max})}{{\rm d}E{\rm d}\Omega} \bigg/ \frac{{\rm d}N(E,\infty)}{{\rm d}E{\rm d}\Omega}. \tag{4}$$

The dependence of P on $n_{\rm s}$, $f_{\rm th}$ and E is shown in Fig.1. The probability decreases with the product $f_{\rm th} n_{\rm s}$ and increases with E. For $E \sim 50$EeV, the probability of detecting gamma-ray sources with a telescope of sensitivity $f_{\rm th} = 10^{-12}{\rm erg\ s}^{-1}$ is $\sim 10\%$ if source number density is $n_{\rm s} \sim 10^{-5}\,{\rm Mpc}^{-3}$.

3. Observational results

3.1 Data sets

We use LHAASO-WCDA data to search for gamma-ray sources associated with UHECRs. We consider the CR events with $E > 50\,$EeV observed by Telescope Array (TA)[8]. Events near

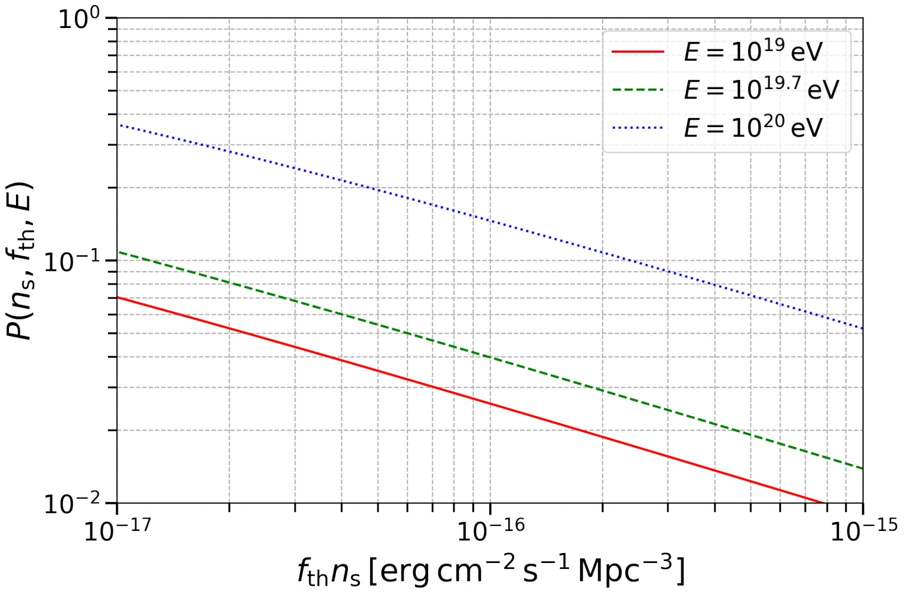

Figure 1: Detection probability of gamma-ray sources around UHECR directions as a function of the product of source number density and detector sensitivity $n_s f_{th}$. The three lines correspond to three CR energies, 10^{19} EeV, $10^{19.7}$ EeV and 10^{20} EeV.

the galactic plane ($|b| < 7°$) is excluded in this analysis in order to minimize the contamination of galactic gamma ray sources. There are 62 TA events away from the galactic plane in the field of view of LHAASO. The data of LHAASO-WCDA is used for the search, which is sensitive to gamma-rays with energies between 100GeV - 30TeV. WCDA covers an area of 78000 m^2 and is composed of 3,120 water Cherenkov detectors. We use the gamma-ray skymap from observations by LHAASO-WCDA from March 2021 to September 2022, which is the same as the data used in the first LHAASO catalog of gamma-ray sources [9]. Figure 2 shows the arrival directions of UHECR events and TeV skymap used in this analysis. The background image is the WCDA count map. The red dots represent the arrival directions of TA events. The white band is the galactic plane ($b \leq 7°$) masked out for both UHECR events and TeV skymap.

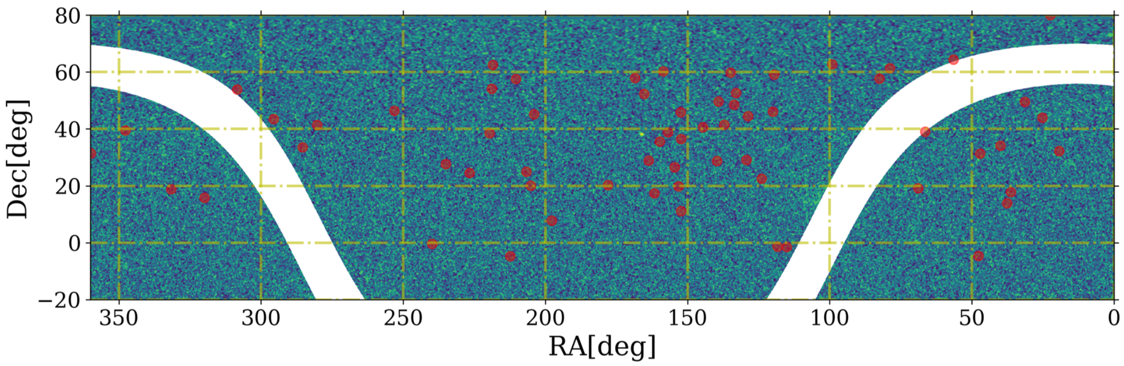

Figure 2: TeV count map of WCDA and arrival directions of TA events. The background is the WCDA count map and red dots are arrival directions of TA events. The white band is the galactic plane with $|b| \leq 7°$.

3.2 WCDA data analysis

Considering the magnetic deflection during UHECR propagation, the search is conducted within the region of interest (ROI) with a radius of 5° around each UHECR event, large enough to cover the UHECR sources. According to eq 2, we assume the spectrum of gamma-ray sources follows a $E^{-2.28}$ power law in the search. Due to the extragalactic origin of UHECRs, the gamma-ray sources would be unresolved for WCDA. Therefore, We use maximize likelihood to search point sources at each pixel within the ROIs for all UHECR events. If the significance of best-fit flux is below 5σ, we set a 5σ upper limit of the gamma-ray flux at the pixel concerned. Because WCDA sensitivity depends on the source coordinate, we take the highest upper limit in the ROI as the upper limit for an UHECR event.

We find no gamma-ray sources beyond 5σ level for the 62 UHECR events in this analysis, which suggests the number density of the UHECR sources is too high and the gamma-ray emission is too faint to be detected.

3.3 Constraint on source properties

The probability of source detection decreases with source number density, or in the other words, the probability of non-detection increases with source number density. According to the non-detection of UHECR-associated gamma-ray sources, we can put a lower limit of UHECRs source number density.

When the source number density is n_s, the probability of non-detection is given by

$$\mathcal{P}(x|n_\mathrm{s}) = \prod_i (1 - P_i(n_\mathrm{s}, f_{\mathrm{th},i}, E_i)), \tag{5}$$

where x represents the non-detection result, i represents the ith UHECR events, P_i is the probability of detecting the associated gamma-ray source, $f_{\mathrm{th},i}$ is the WCDA sensitivity at the UHECR event's arrival direction, E_i is the CR energy. The source number density n_s is an overall property of UHECR sources. We give a 95% confidence level lower limit by finding n_th which make $\mathcal{P}(x|n_\mathrm{th}) = 0.05$. The relation between the probability $\mathcal{P}(x|n_\mathrm{th})$ and n_s is shown in Fig. 3. When $n_\mathrm{s} < n_\mathrm{th}$, the probability of non-detection $\mathcal{P}(x|n_\mathrm{s})$ is smaller than 0.05, which means such source density is exluded by our result at 95% confidence level. The constraining result of the UHECR source density is $\sim 10^{-3.5}$ Mpc^{-3} at 95% confidence level.

4. Discussion and Conclusion

The lower limit of the source number density in section 3.3 is a conservative constraint. We use the highest upper limit in the searching region around each UHECR as the overall sensitivity of the ROI of each UHECR in the calculation. As mentioned in section 2, the probability is a function of the product $f_\mathrm{th} n_\mathrm{s}$. Therefore, a worse sensitivity leads to a lower limit on source density, i.e., a conservative lower limit.

Besides hadronic processes, gamma-ray can be produced by the other processes, such as leptonic gamma-ray sources. The detection probability of gamma-ray sources around UHECRs will be larger when such pollution to hadronic gamma-rays is considered. If we neglect the pollution

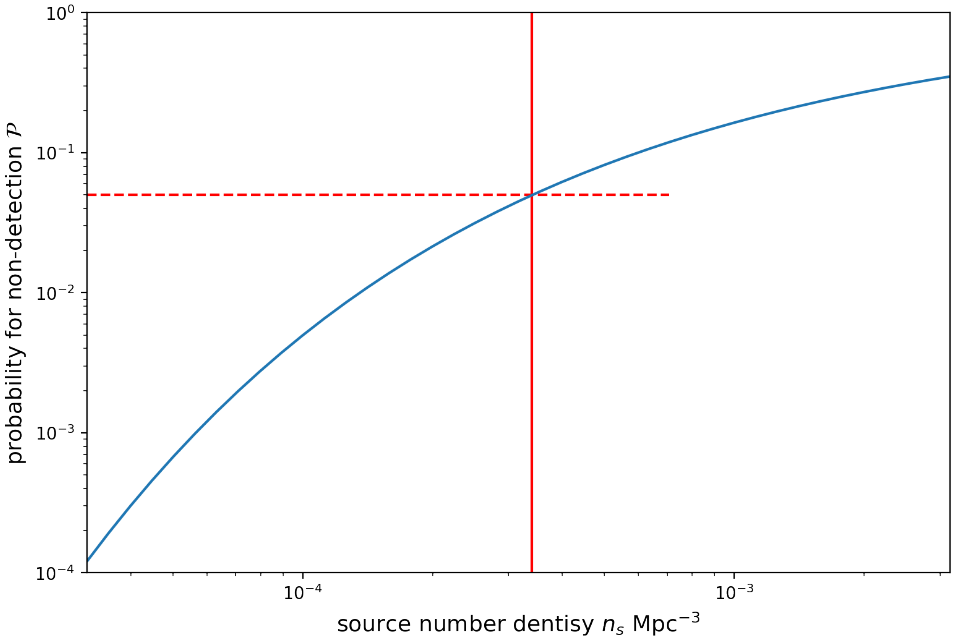

Figure 3: Probability for non-detection as a function of the source number density. Dashed line shows the 95% confidence level, and the corresponding limit is shown by the vertical solid line.

in the constraint, upper limits for probabilities P_i are worse than that taking pollution into account. This also make the lower limit of n_s conservative.

In this work, we search for UHECR-associated gamma-ray source. This is motivated by the coincidence of Waxman-Bahcall bound and IceCube diffuse neutrino flux. We search TeV gamma-ray sources with LHAASO-WCDA around UHECR events observed by TA. No gamma-ray source is found in the search, where a lower limit with 95% confidence level for UHECR source number density can be set, $n_\mathrm{s} > 10^{-3.5}\,\mathrm{Mpc}^{-3}$.

UHECR source host galaxies are also neutrino sources in our model. Searching UHECR-associated neutrino sources is also needed for the same motivation, which can provide unique evidence of the hadronic interactions. Combining searches of neutrino and gamma-ray sources will give a better result.

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