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Highlights from the Tibet ASγ experiment

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The Tibet ASγ experiment, observing cosmic rays/gamma rays above a few TeV, is located at 4,300 m above sea level, in Tibet, China. The experiment is composed of a 65,700 m^2 surface air shower array and 3,400 m^2 underground water Cherenkov muon detectors. The surface air shower array is used for reconstructing the primary particle energy and direction, while the underground muon detectors are used for discriminating gamma-ray induced muon-poor air showers from cosmic-ray (proton, helium,...) induced muon-rich air showers. Furthermore,the underground muon detectors turn out to be effective to select the proton component in cosmic rays. We present recent results on mainly sub-PeV cosmic gamma-ray observation from the Tibet ASγ experiment.

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1. Introduction

The TeV gamma-ray astronomy was established in 1989 by the Whipple experiment which succeeded in the first detection of TeV gamma rays from the Crab Nebula[1], using an imaging air Cherenkov telescope (IACT). Since then,there were and have been many experiments using IACTs which observed TeV gamma ray sources which now amount to more than 200. As a conventional air shower array, the Tibet ASγ experiment suceeded in the first detection of TeV gamma rays from the Crab Nebula in 1999[2] which was ten years later than the Whipple experiment.

An air shower array experiment has a poor angular resolution (approximately 1° in the case of the Tibet ASγ experiment) compared with that (typically 0.1°) in an IACT, while an air shower experiment has a wide field of view (typically two steradians), while in IACT has a narrow field of view (typically a few degrees×a few degrees). An air shower array experiment can continuouslly monitor the sky for 24 hours, day and night, while an IACT can observe the sky only at clear and moonless nights.

Beyond TeV energies, opening of the next energy window, Ultra-high-enery (UHE: > 100 TeV) gamma-ray astronomy, had to wait for 30 years since the TeV window had been opened in 1989[1]. The Tibet ASγ experiment succeeded in the first detection of gamma rays beyond 100 TeV at 5.6 σ from the Crab nebula in 2019[3], opening the UHE window in gamma-ray astronomy. Then, the detection was confirmed by the HAWC experiment[4, 5] and the LHAASO experiment[6, 7].

In 2021, The Tibet ASγ experiment succeeded in the first detection of diffuse UHE gamma rays along the Galactic plane[8]. The characteristics of the observed UHE gamma-ray events is most naturally interpreted[9] as those from neutral pion decay produced by PeV galactic cosmic rays interacting with the interstellar matter in the Galaxy. The LHAASO experiment recently reported the UHE Galactic diffuse gamma-ray flux[10] which is a few times lower than that observed by the Tibet ASγ experiment. However, as the LHAASO analysis masked many large regions in the Galactic plane where there are many gamma-ray sources. Therefore, we can not directly compare the fluxes measured by the Tibet ASγ and LHAASO experiments. Recently, the IceCube experiment succeeded in detection of Galactic diffuse ne utrinos in the 10 TeV region[11] around the 4.5 σ significance level without masking the Galactic plane[11]. Therefore, the IceCube neutrino flux should be compared with the UHE gamma-ray flux of cosmic-ray origin by the Tibet ASγ experiment. The IceCube neutrino flux in the 10 TeV region smoothly connects with the UHE n eutrino flux estimated from the Tibet ASγ UHE gamma-ray flux, assuming the π^0 flux model[11] and the hadronuclear (pp scenario[11]. The IceCube result supports that the Tibet ASγ UHE gamma rays along the Galactic plane are of cosmic-ray origin. More studies and obsevations will be needed to estimate the contributions of very faint unresolved sources with a hard energy spectrum to the observed Galactic UHE diffuse gamma rays by the Tibet ASγ experiment.

2. Experiment

The Tibet ASγ experiment is located at 4,300 m in altitude, in Tibet, China. The experiment is composed of a surface air shower array and a underground muon detector array. The surface air showr array is made up of 597 plastic scintillation detectors (each with 0.5 m^2 in area), covering

65,700 m^2. Under the air shower array, a water-Cherenkov-type muon detector array is set up, covering 3,400 m^2. The hybrid experiment started operation in 2014.

We measure the energy and direction of a cosmic ray as well as a gamma ray which interact with the air and produces an air shower above a few TeV. The energy resolution for gamma rays >100 TeV is estimated to be approximately 20 %[12], while the angular resolution is estimated to be around 0.2° for gamma rays >100 TeV.

The underground muon detector array detects muons, because the electromagnetic component is absorbed by the soil overburden before reaching the underground muon detector array. We discriminate a gamma-ray induced air shower from an cosmic-ray induced airshower by counting the number of muons detected by the underground muon array. An air shower accompanied with a large number of muons detected with the underground muon detector array is identified as originating from a cosmic ray, while a muon-poor air shower is identified as of gamma-ray origin. Thus, the S/N ratio is expected to be dramatically improved by the underground muon detector array[13]. For a typical gamma-ray point-source analysis, we can reduce the cosmic-ray backgroud down to 1/1000, keeping the gamma-ray efficiency to 90 % > 100 TeV by the hybrid experiment[3]. On the other hand, in the case of diffuse UHE gamma-ray analysis, we can reduce the cosmic-ray background to one millionth, keeping the gamma-ray efficiency 30 % around 400 TeV by employing a tighter number-of-muons cut[8] than in the point-source analysis. For more details, see [3, 8].

3. Recent progress

The recent status of the number of UHE sources versus calendar years is summarized in Fig. **??**, so-called Kifune plot as of 2023. More than 40 UHE sources have been observed since the first UHE gamma-ray source detection by the Tibet ASγ experiment in 2019.

3.1 UHE Galactic diffuse gamma rays

The Tibet ASγ experiment succeeded in the first detection of sub-PeV Galactic diffuse gamma rays above 100 TeV along on the Galactic disk [8]. The hadronic origin of the Tibet ASγ Galactic diffuse gamma-ray events is supported by the observation of Galacticneutrinos by IceCube, as the energy spectrum of the Tibet ASγ diffuse g amma rays converted into the neutrino flux assuming the hadronic interaction model smoothly connects at $\simeq$ 60 TeV with the all-sky Galactic-neutrino flux in the field of view of the Tibet ASγ experiment.

There was no overlapping between the Tibet ASγ Galactic diffuse gamma-ray events above 398 TeV with the known TeV sources along the Galactic disk, supporting the diffuse nature of them. Recently, the LHAASO collaboration published their first catalog (1LHAASO catalog) of gamma-ray sources detected in 1 TeV $< E <$ 25 TeV and/or $E >$ 25 TeV, among which 43 sources are also detected above 100 TeV with more than 4 σ detection significance [14]. The detection of the sub-PeV gamma-ray sources in the 1LHAASO catalog provide us with a good chance to investigate how much these sources contribute to the Tibet ASγ Galactic diffuse gamma-ray events above 398 TeV.

Subsequently, we found that no Tibet ASγ GDE events above 398 TeV have their arrival directions within the extensions of the sub-PeV LHAASO sources in the 1LHAASO catalog.

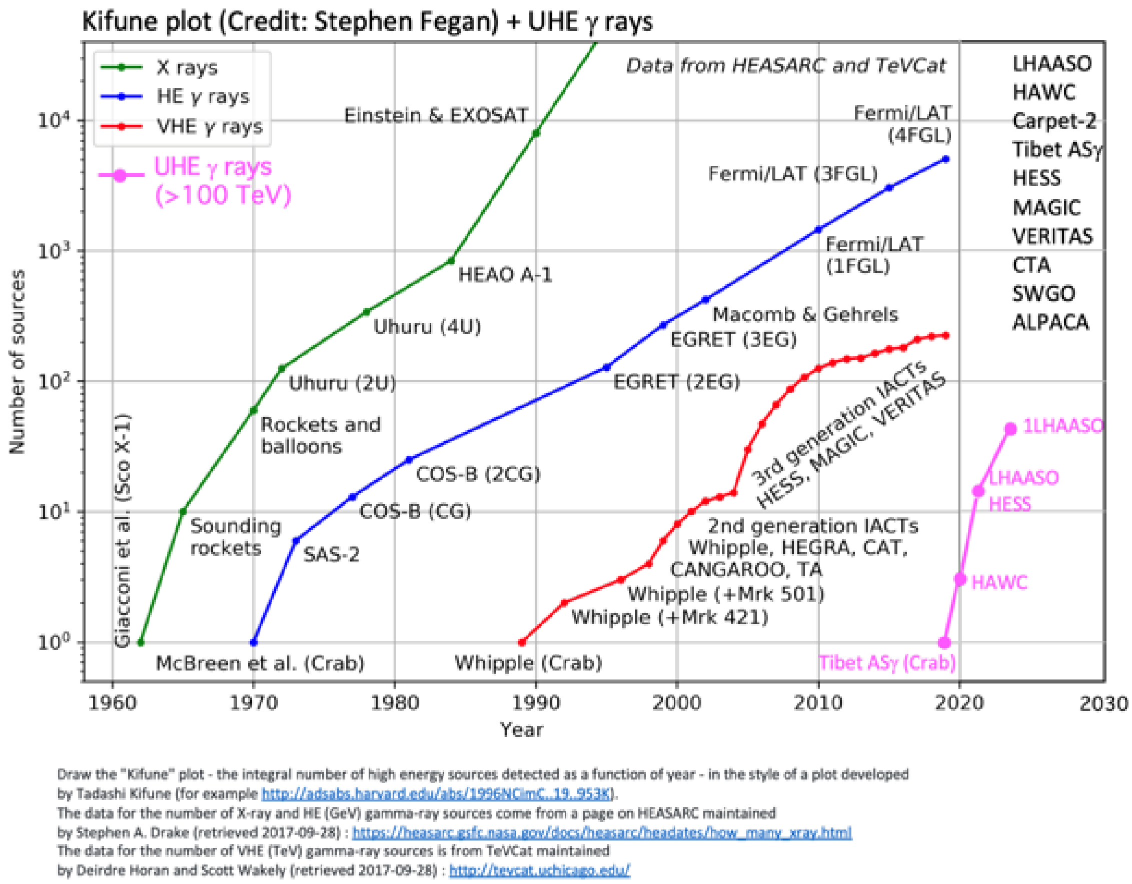

Figure 1: Kifune plot 2023. Number of sources as a function of calendar years.

Therefore, none of the sub-PeV LHAASO sources is the origin of the Tibet ASγ Galactic diffuse gamma-ray events above 398 TeV. The number of accidental overlaps between the Tibet ASγ Galactic diffuse gamma-ray events above 398 TeV and the sub-PeV LHAASO sources is estimated to be 0.86, while the expected number of gamma-ray events from the 22 newly-reported sub-PeV LHAASO sources is 1.2. Therefore, it is statistically consistent that there is no overlapping between the Tibet ASγ Galactic diffuse gamma-ray events above 398 TeV and the sub-PeV LHAASO sources. No overlapping between the Tibet ASγ Galactic diffuse gamma-ray events above 398 TeV and the sub-PeV LHAASO sources supports the diffuse nature of the Tibet ASγ Galactic diffuse gamma-ray events above 398 TeV again[15].

As is mentioned in the introduction, the LHAASO experiment confirmed the Galactic diffuse gamma-ray emission in the UHE region, but the flux intensity was ∼30% that of the Tibet ASγ experiment. This may be caused by a difference in the source mask scheme when analyzing the Galactic diffuse gamma-ray flux[16]. The masked region of the LHAASO analysis is conservatively wider than that of the Tibet ASγ experiment. Additionally, we first investigate how much of source contributions is in the Tibet ASγ Galactic diffuse gamma-ray flux assuming the LHAASO UHE gamma-ray sources (1st LHAASO catalog)[14]. We found that the contamination of known gamma-ray sources is less than 30%[16]. Furthermore, we found that the difference in the Galactic diffuse gamma-ray flux between the Tibet ASγ and LHAASO experiments can be explained by the way the gamma-ray sources are masked in terms of their mask coverage, assuming the existing model distribution of the Galactic diffuse gamma-ray emissions[9].

3.2 P/gamma separation by the surface air shower array

We developed methods[17] to separate gamma-ray and cosmic-ray air showers using only surface array data, making the best of the data before the introduction of the underground muon detector array. Two neural network approaches were tested: one using features describing the lateral distribution of the air shower particles, and another using shower image data.

Monte Carlo simulations of vertically incident gamma-ray and proton showers were analyzed. For single-feature classification, the best feature gave AUC valuesof 0.701 at 10 TeV and 0.808 at 100 TeV. A multilayer perceptron (MLP) using multiple features improved AUC to 0.761 and 0.854, respectively, which represent s an improvement of approximately 5% in the AUC value compared with the single-feature case.

The CNN which employs shower images achieved AUC values of 0.781 at 10 TeV and 0.901 at 100 TeV, outperforming the MLP method by roughly 5%. Applying the CNN method to Monter Carlo gamma-ray events from the Crab Nebula (10 - 100 TeV) yielded AUCs of 0.753 - 0.879, improving the gamma-ray excess significance by a factor of 1.3 - 1.8 compared to no sparation.

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References

[1] T. C. Weekes *et al.*, Astrophys. J. **342**, 379, (1989).

[2] M. Amenomori *et al.*, Astrophys. J. **525**, L93-L96, (1999).

[3] M. Amenomori *et al.*, Phys. Rev. Lett. **123**, 051101(6pp), (2019) and Supplemental Material at https:// journals.aps.org/prl /supplemental/10.1103/PhysRevLett.123.051101.

[4] A. U. Abeysekara *et al.*, Astrophys. J. **881** 134, (2019).

[5] A. U. Abeysekara *et al.*, Phys. Rev. Lett. **124**, 021102(7pp), (2020).

[6] F. Aharonian *et al.*, Chin. Phys. C **45**, 025002, (2021).

[7] Z. Cao *et al.*, Science, **373**, 425, (2021).

[8] M. Amenomori *et al.*, Phys. Rev. Lett. **126**, 141101 (2021), and Supplemental Material at https://journals.aps.org/prl/ supplemental/10.1103/PhysRevLett.126.141101.

[9] P. Lipari and S. Vernetto, Phys. Rev. D **98**, 043003, (2018).

[10] Z. Cao *et al.*, Phys. Rev. Lett. **131**, 151001 (2023).

[11] R. Abbasi *et al.*, Science **380**, 1338-1343 (2023) and Supplemental Material at https://www.science.org/ doi/10.1126/science.adc9818.

[12] K. Kawata *et al.*, Experimental Astronomy **44**, 1-9 (2017).

[13] T. K. Sako *et al.*, Astropart. Phys. **32**, 177-184 (2009).

[14] Z. Cao *et al.*, Astrophy. J. Supplement **271**, 25 (2024).

[15] S. Kato *et al.*, Astrophy. J. **961**, L13 (2024).

[16] S. Kato *et al.*, Astrophy. J. **977**, L3 (2024).

[17] S. Okukawa *et al.*, Machine Learning: Science and Technology, **5** id.025016 (p1-21) (2024).

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