PROCEEDINGS OF SCIENCE

Evolution of cosmic ray anisotropy with energy up to PeV observed by LHAASO-KM2A

Weiyan Zhang,[a] Wei Gao,[b,c,*] Shuwang Cui,[a] Huihai He[b,c] and Hongkui Lv[b,c] on behalf of the LHAASO collaboration

[a] *College of Physics, Hebei Normal University, 20 South Second Ring East Road, Shijiazhuang, Hebei, China*

[b] *State Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, Beijing, China*

[c] *TIANFU Cosmic Ray Research Center, 1500 Kezhi Road, Xinglong Street, Shuangliu District, Chengdu, Sichuan, China*

E-mail: gaowei@ihep.ac.cn

The evolution of cosmic ray large-scale anisotropy (LSA) with energy is essential for studying the origins of LSA, which are closely related to the origins and propagation of cosmic rays. However, due to both the low flux of cosmic rays and inconsistency among experiments, the observations of LSA above one hundred TeV are subject to large uncertainties. We utilize over three years data from the kilometer square array (KM2A) of LHAASO to observe the LSA. The measurements covered a wide energy range, reaching PeV, with high precision.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

*Speaker

PoS(ICRC2025)264

1. Introduction

The large-scale anisotropy (LSA) of cosmic rays is a crucial avenue for comprehending the origin and propagation of cosmic rays. Initially, small detector arrays detected LSA in the sub-TeV range. Over the past few decades, larger arrays such as Tibet, ARGO, IceCube, HAWC, et al have been installed to investigate LSA at higher energies ranging from TeV up to PeV. In ultra-high energy regimes, extremely large arrays like TA, Pierre Auger, and KASCADE-GRANDE extend the energy range up to EeV levels. The extensive array of observed results encompasses a wide energy spectrum for LSA spanning from sub-TeV to dozens of EeV. Notably, one significant characteristic is that the properties of LSA exhibit dependence on energy; evident through variations in amplitude and phase during its complex evolution with increasing energy levels [1].

Even though the LSA observations cover a wide energy range, there is a concentration of observations in the low-energy region with higher accuracy. Due to the limited statistics of high-energy cosmic rays, LSA above one hundred TeV exhibits poor accuracy. It is imperative to conduct more precise experimental observations in this energy range in order to obtain a definitive conclusion regarding the evolution of LSA with energy and subsequently establish a reliable foundation for theories on its origin and propagation.

With more than three years of operation, LHAASO has accumulated a sufficiently large statistical sample, allowing for anisotropy observations across a wide energy range from dozens of TeV to PeV range. The analysis of cosmic ray anisotropy focused primarily on the PeV range, utilizing data from KM2A. The obtained results are presented herein to evaluate the stability and observational capabilities of LHAASO-KM2A for studying anisotropy.

2. Experiment and Data Selection

LHAASO [2, 3] is located at Haizishan in Daocheng County, Sichuan Province, China. Its coordinates are 29.4°N latitude and 100.14°E longitude. The altitude is about 4410 m above sea level, which corresponds to an atmospheric depth of approximately 600 g/cm^2. LHAASO consists of a Water Cherenkov Detector Array (WCDA), the KM2A, and the Wide Field Cherenkov Telescopes Array (WFCTA). The analysis of cosmic ray anisotropy necessitates a large statistical sample. Thus, our work is based on the KM2A to detect high energy range anisotropy. The KM2A comprises two types of sub-arrays: a ground-based array consisting of 5,245 electromagnetic particle detectors (EDs) and an underground array comprising 1,188 muon detectors (MDs). Covering an area of 1.36 km^2, the KM2A is capable of measuring cosmic rays with energies ranging from tens of TeV to 100 PeV.

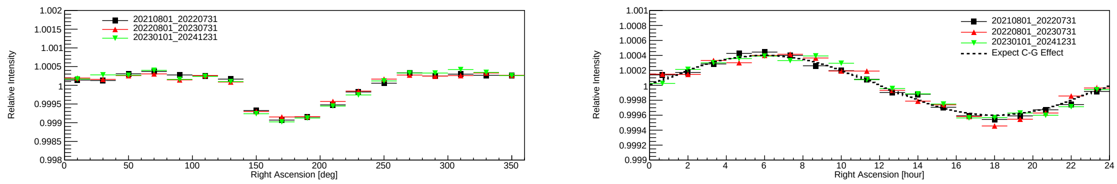
To ensure a reliable data sample for physical analysis, a quality monitoring system was constructed [4]. The data filtered by the quality monitoring system were subsequently used in the analysis. Beside the basic quality monitor filter, the data were selected in accordance with the following criteria. (1) The number of triggered EDs after noise filtering should larger than 19. (2) The reconstructed core position must be located within the inner array. (3) The zenith range of events is set at 40°, which means we can survey the sky with the declination region of $-10.64°$ to $69.36°$. (4) The number of electromagnetic particles ($N_e \geq 20$) was not less than 20, and the number of muons ($N_\mu \geq 10$) was also not less than 10. N_e and N_μ represent the particle count in the ring located at a distance of 40 to 200 meters from the reconstructed core. (5) Reconstructed energy should meet $\log(E/TeV) \geq 1.5$ (about 31.6 TeV).

KM2A data collected from August 1, 2021 to July 31, 2024 was used here. The total effective observation time spans approximately 1092 days over these three years. Finally, about 3.99×10^{10} events were survived after the data selection. The primary energy of events are reconstructed using a parameter that combines the charged particles detected by EDs and the number of muons detected by MDs[5]. In this analysis, we employed the equi-zenith angle method to estimate the background and investigate the anisotropy of cosmic rays [6, 7].

3. Results

3.1 Time Stability

The stability performance of KM2A's observability can be assessed with different time periods. The data was divided into three samples, each covering a one-year period: August 1st, 2021 to July 31st, 2022; January 1st, 2022 to December 31st, 2022; and August 1st, 2022 to July 31st, 2023. We compared both the sidereal anisotropy and solar anisotropy during these periods with the results from all available data. Figure 1 illustrates the observed sidereal anisotropy and solar anisotropy of cosmic rays during these specific time intervals. The well known feature of sidereal anisotropy and expected dipole anisotropy which due to Compton-Getting Effect [8] in solar time are all observed in each year. Further more the anisotropy demonstrates remarkable stability, affirming our array's consistent performance in observing such phenomena.



(a) Sidereal anisotropy **(b)** Solar anisotropy

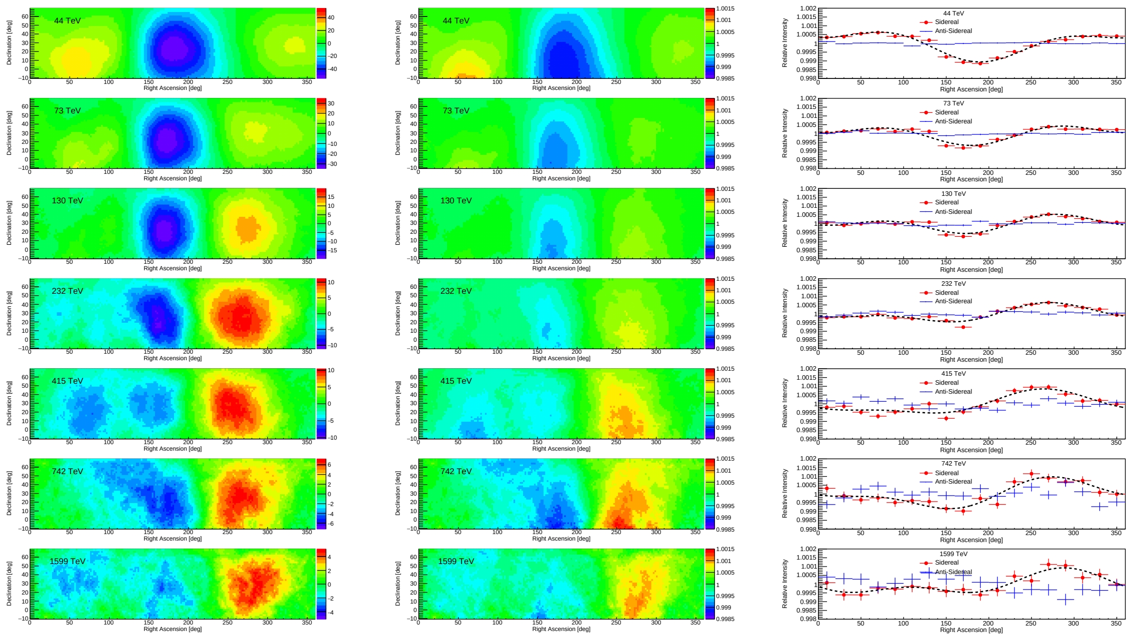
Figure 1: The anisotropies observed at different periods.

3.2 The Energy-dependent Evolution of Anisotropy

The data sample is divided into seven energy intervals based on reconstructed energy. Each covering a range of 0.25 with $log(E_{rec}/GeV)$, except for the last interval where the reconstructed energy is $log(E_{rec}/GeV) \geq 6.0$. The median true energy is utilized to characterize each interval. The energies correspond approximately to 44, 73, 130, 232, 415, 742 and 1599 TeV respectively.

Figure 2 depicted the variation of cosmic-ray anisotropy with the increasing energy. The sky maps in left column are smoothed using a 30-degree solid angular radius. As the energy increases, the previously observed "tail-in" disappears and an "excess" towards the Galactic Center direction begins to be detected at 130 TeV. However, the "loss-cone" still exists at 742 TeV with only a slight significance of about 3σ. At an energy level of around 1.6 PeV, the observed "excess" structure demonstrates a reduction compared to that at 742 TeV and displays a slight shift towards larger right ascension direction. The plots in right column are projection of anisotropy on right ascension, and fitted by the below equation with $n = 2$ to obtain the amplitude and phase of the dipole component of anisotropy:

$$I = 1 + \sum_{i=1}^{n} A_i \cos \frac{i(x - \phi_i)}{2\pi} \tag{1}$$



(a) Significance **(b)** Relative Intensity **(c)** Projection on right ascension

Figure 2: The evolution of sidereal anisotropy with the energy increase.

Finally, the amplitudes and phase of the dipole component of sidereal anisotropy are together with other observations to exhibit the evolution of anisotropy with energy increase. As figure 3 shown, from 44 TeV to 130 TeV, the amplitude consistently decreases as energy increases, reaching its minimum at 130 TeV. At higher energies, there is a contrasting trend where the amplitude gradually increases as energy rises from 130 TeV to 1.6 PeV. At 742 TeV and 1599 TeV, their poor statistical significance, resulting in larger margin of errors. However, when compared to other experiments, this change exhibits a more gradual progression. Correspondingly, the phase of the anisotropy, which represents the orientation of the "excess" structure of the dipole anisotropy, also varies with energy. At 44 TeV, it indicates a right ascension of 17.55° and gradually shifts as the energy increases. For energies exceeding 130 TeV, the phase approaches towards aligning with the direction of galactic center's right ascension.

4. Discussion

The large-scale anisotropy of cosmic rays was observed using LHAASO-KM2A, and the data were collected from August 1, 2021 to July 31, 2024. Over this three-year period, anisotropies were detected in both sidereal time and solar time, exhibiting stable and remarkable. In the solar

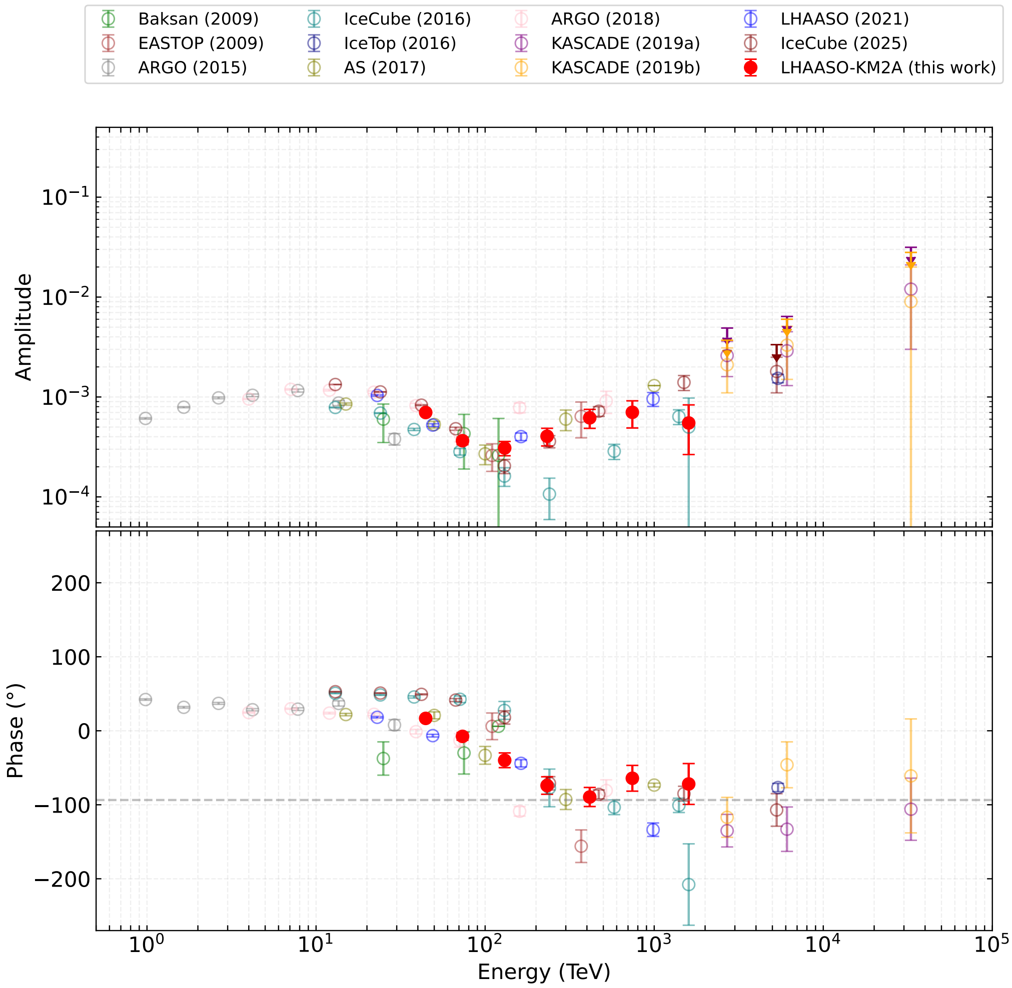


Figure 3: The amplitude and phase of anisotropies with energy.

time frame, a dipole anisotropy was observed, which closely aligns with the anticipated Compton-Getting effect resulting from Earth's revolution around the Sun. The well-known patterns of the sidereal anisotropy, namely "Tail-in" and "loss-cone", exhibit a prominent excess structure and deficit structure respectively at TeV energies. From 44 TeV to 1.6 PeV, the morphology of the large-scale anisotropy undergoes a complex transformation with increasing energy. The amplitude shows a dip around 130 TeV and gradually increases thereafter. Simultaneously, the phase progressively shifts towards the right ascension direction of the Galactic Center. Therefore, up until 1.6 PeV, the primary source of cosmic rays is likely to be predominantly within the confines of our own Milky Way galaxy. In a word, the LHAASO-KM2A experiment has achieved highly accurate measurements of anisotropy in the sub-PeV to PeV energy range within just three years of observation. In the future, we anticipate precise measurements at dozens of PeV energies, bridging the gap in large-scale anisotropy measurements within this energy range.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No.12373105, No. 12320101005, No.12405131) and the Natural Science Foundation of Sichuan Province (Grant No. 2024NSFSC1372).

References

[1] J. Becker Tjus and L. Merten, *Closing in on the origin of galactic cosmic rays using multimessenger information*, *Physics Reports* **872** (2020) 1.

[2] H. He, *Design of the LHAASO detectors*, *Radiation Detection Technology and Methods* **2** (2018) 7.

[3] X.-H. Ma, Y.-J. Bi, Z. Cao, M.-J. Chen, S.-Z. Chen, Y.-D. Cheng et al., *Chapter 1 lhaaso instruments and detector technology* *, *Chinese Physics C* **46** (2022) 030001.

[4] Z. Cao, F. Aharonian, Axikegu, Y. Bai, Y. Bao, D. Bastieri et al., *Data quality control system and long-term performance monitor of lhaaso-km2a*, *Astroparticle Physics* **164** (2025) 103029.

[5] H. Zhang, H. He and C. Feng, *Approaches to composition independent energy reconstruction of cosmic rays based on the lhaaso-km2a detector*, *Phys. Rev. D* **106** (2022) 123028.

[6] M. Amenomori, S. Ayabe, D. Chen, S.W. Cui, Danzengluobu, L.K. Ding et al., *A northern sky survey for steady tera-electron volt gamma-ray point sources using the tibet air shower array*, *The Astrophysical Journal* **633** (2005) 1005.

[7] T. Li, M. Liu, S. Cui and Z. Hou, *Evaluation of a wide-sky survey method for eas experiments*, *Astroparticle Physics* **39-40** (2012) 144.

[8] A.H. Compton and I.A. Getting, *An apparent effect of galactic rotation on the intensity of cosmic rays*, *Phys. Rev.* **47** (1935) 817.