Status and recent high light results from the LHAASO experiment

Songzhan Chen[1,2,*], *on behalf of the LHAASO collaboration*

[1]Key Laboratory of Particle Astrophyics, Institute of High Energy Physics, Chinese Academy of Sciences, 100049 Beijing, China
[2]TIANFU Cosmic Ray Research Center, 610000 Chengdu, Sichuan, China

Abstract. The Large High Altitude Air Shower Observatory (LHAASO) experiment, fully operational since July 2021, is a cutting-edge facility for detecting cosmic rays and gamma rays across a wide energy range. This paper offers an overview of the current status and recent significant scientific achievements of the LHAASO collaboration. These include the gamma-ray astronomy, charged cosmic ray physics and new physics.

1 Introduction

Cosmic rays are high-energy particles from space, with energies up to 3.2×10^{20} eV, far surpassing human-built accelerators. The origins and acceleration mechanisms of cosmic rays have long been a mystery in particle astrophysics. The energy spectrum ranges from bellow 10^{9}eV to 10^{20} eV, with a power-law distribution. Cosmic rays below 10^{15}eV are believed to originate within our galaxy. Detection of high-energy gamma rays is crucial for understanding cosmic ray origins, as they can be produced when cosmic rays collide with gas near their sources or in proton collision off radiation.

In recent years, high-energy gamma-ray astronomy has seen significant advancements, providing new insights into the universe. Space-based detectors like Fermi-LAT have identified over 7,000 GeV gamma-ray sources [1], while ground-based detectors have increased very-high-energy (VHE) gamma-ray sources from ten to nearly three hundred. LHAASO's observations in 2021 revealed 12 ultra-high-energy (UHE) gamma-ray sources [2], surpassing expectations and opening new avenues in UHE gamma-ray astronomy. These findings have increased the number of UHE sources to 43[3], offering key insights into cosmic ray origins.

LHAASO's observations of VHE and UHE gamma rays offer broad coverage, high sensitivity, and the ability to monitor sudden astronomical events. The facility's energy detection capabilities surpass previous devices, providing opportunities to explore new physics phenomena at higher energy levels. LHAASO's strong cosmic ray detection capabilities have enabled advancements in measuring the cosmic ray spectrum and daily variations in Sun shadow. These areas of research will also be discussed in this paper.

---

[*] e-mail: chensz@ihep.ac.cn

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

2 Status of LHAASO

The LHAASO facility is situated on Haizi Mountain in Daocheng County, Sichuan Province, China, at an elevation of 4410 meters above sea level [4]. It comprises a composite extensive air shower (EAS) detector array consisting of three sub-arrays: the Kilometer Square Array (KM2A), the 78,000 m^2 Water Cherenkov Detector Array (WCDA), and the Wide Field-of-view atmospheric Cherenkov Telescope Array (WFCTA).

The KM2A sub-array is primarily dedicated to detecting gamma rays with energies exceeding 10 TeV, with a particular emphasis on UHE gamma rays above 100 TeV. It consists of 5216 scintillator counters on the surface and 1188 underground muon detectors spread across a circular area of 1.3 km^2. The array was constructed incrementally, with full scientific operations commencing in July 2021, achieving an operational duty cycle exceeding 99% during full array operations (see Figure 1). The event rate is approximately 2.5 kHz, and detailed performance metrics such as angular resolution, core resolution, energy resolution, and cosmic-ray/gamma-ray discrimination power are available in previous publications [5, 6]. The long-term pointing error and angular resolution achieved using the Moon shadow is shown in Figure 1 and also in [7].

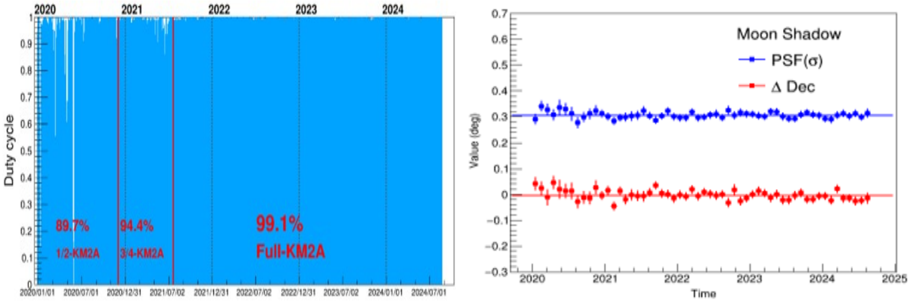

Figure 1. The duty cycle, pointing error (red line) and angular resolution (blue line) of LHAASO-KM2A as function of time .

The WCDA sub-array is primarily designed for detecting gamma rays with energies ranging from sub-TeV to 20 TeV. It comprises three ponds (WCDA-1, WCDA-2, and WCDA-3) with varying dimensions and numbers of detector units. WCDA-1 has been operational since April 2019, while the full WCDA array has been in operation since March 2021, with an event rate of around 35 kHz and a duty cycle exceeding 95%. Further details on the WCDA's performance characteristics can be found in previous publications [8].

The WFCTA sub-array is focused on detecting cosmic rays with energies ranging from 10 TeV to EeV and consists of 18 Cherenkov telescopes. The array has been operational with six telescopes since October 2019, and all 18 telescopes have been in operation since May 2021, with an observation time of approximately 1400 hours per year.

3 LHAASO recent highlight results on Gamma-ray astronomy

Recently, the LHAASO collaboration released the first catalog of gamma-ray sources detected using data from both the KM2A and WCDA detectors [3]. This catalog represents the outcome of the most sensitive large-scale survey of the gamma-ray sky above 1 TeV. The catalog comprises a total of 90 sources (see Figure 2), where 32 are newly identified TeV sources, and 43 exhibit ultra-high-energy emission (E>100 TeV) at a significance level exceeding 4σ. The catalog provides detailed information on the position, extension, and spectral characteristics of all the detected sources.

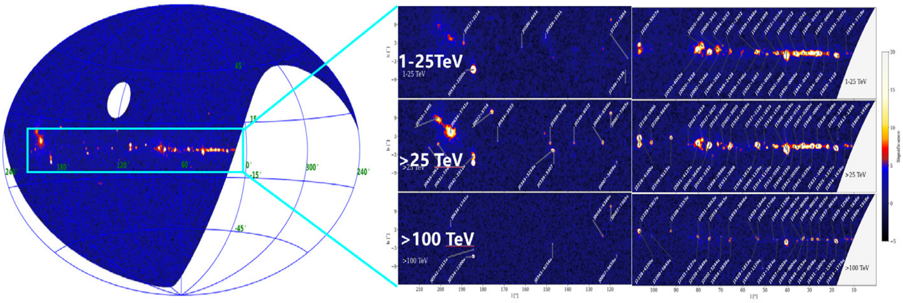

Figure 2. The sky map of the first LHAASO catalog. Figure is taken from [3].

In-depth analysis of the LHAASO sources involved multi-band identification efforts, leading to the discovery of associations with various astrophysical objects. Specifically, 10 sources were linked to known pulsar wind nebula (PWN), 4 to TeV halo, 6 to supernova remnant (SNR), 2 to binary source, 1 to a massive star, and 5 to active galactic nucleus (AGN). Additionally, 22 sources were found to be in proximity to bright pulsars, potentially associated with PWN or TeV halo, while 40 sources remain unclassified. The distribution of these identified sources is illustrated in Figure 2.

Subsequent to the catalog release, detailed investigations were conducted on individual sources, revealing significant findings utilizing LHAASO data. These results shed light on the high-energy phenomena occurring in these sources and contribute to our understanding of the cosmic gamma-ray sky.

3.1 Cygnus Cocoon

Cygnus-X is recognized as one of the most active and nearby star-forming regions in the Milky Way, located at a distance of approximately 1.4 kiloparsecs. Observations by the Fermi-LAT instrument have detected high-energy gamma rays originating from the direction of the massive star association Cygnus OB2. The source's angular extension was estimated to be around 2° and was named the "Cygnus Cocoon" [9]. Subsequently, the extended TeV gamma-ray source ARGO J2031+4157 was identified as the Cygnus Cocoon due to its similar extension size [10]. The HAWC collaboration also detected emissions approaching 100 TeV with a comparable extension size.

Recently, the LHAASO collaboration reported the detection of a gamma-ray bubble spanning at least 100 square degrees in UHE up to 2.5 PeV in the direction of Cygnus X, significantly larger than the Cygnus Cocoon [11]. The spectral energy distribution (SED) is connected with data from Fermi-LAT and ARGO-YBJ, focusing on the core region (see Figure 3). The morphology of the bubble and its energy spectrum are reasonably reproduced by considering the presence of a particle accelerator within the core region that continuously injects protons into the surrounding medium. Eight photons were detected with energies exceeding 1 PeV, indicating the existence of super PeV particle accelerator (PeVatron) capable of accelerating protons to at least 10 PeV. The observed features, including the bubble's structure, morphology, and energy distribution, suggest that the UHE gamma-ray emission is associated with molecular clouds in the region.

Detailed maps and SEDs illustrating these findings are presented in Figure 3, with additional comprehensive information available in the corresponding publication. The discoveries in the Cygnus X region provide valuable insights into the high-energy phenomena occurring in this active star-forming region and offer new perspectives on the potential role of super PeVatrons in accelerating cosmic rays to extreme energies.

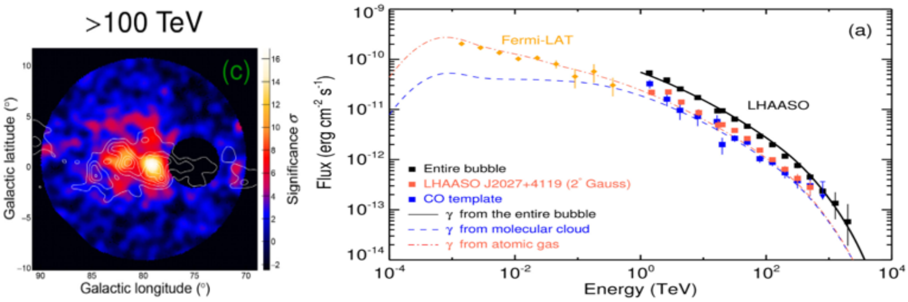

Figure 3. The sky map and SED of Cygnus region achieved by LHAASO. Figure is taken from [11].

3.2 SNR as cosmic ray sources

SNRs have long been recognized as key contributors to the Galactic cosmic ray population. The detection of a characteristic pion-decay feature in gamma-ray spectra has provided direct evidence of proton acceleration in SNRs. However, the very high-energy gamma-ray spectra of several young SNRs exhibit steep slopes or breaks at energies below 10 TeV, leading to uncertainties regarding the ability of SNRs to act as PeVatrons, accelerating particles to PeV energies.

The W51 giant molecular cloud is a prominent star-forming region in the Galaxy, hosting the middle-aged supernova remnant W51C, likely resulting from a highly energetic core-collapse supernova event. Previous observations across a wide energy range have reported gamma-ray emission from the W51 complex. The LHAASO collaboration recently made a significant detection of gamma rays emanating from the W51 complex in the energy range of 2 to 200 TeV [12](see Figure 4). These measurements represent the first extension of gamma-ray emission from the W51 complex beyond 100 TeV and reveal a notable spectral bending at tens of TeV.

By combining data featuring the "pion-decay bump" from the Fermi-LAT instrument, the broadband gamma-ray spectrum of the W51 region can be effectively characterized by a simple proton-proton collision model. The observed spectral bending at high energies suggests an exponential cutoff at around 400 TeV, potentially indicating the first evidence of SNRs acting as cosmic ray accelerators approaching the PeV energy regime. The significant findings from the LHAASO measurements, including detailed map and SED, provide valuable insights into the high-energy processes occurring in the W51 complex and shed light on the potential of SNRs as sources of PeV cosmic rays. For more in-depth information, additional details can be found in the corresponding publication.

3.3 New Phenomena from PWNs

PWNs, generated by the termination of the ultra-relativistic wind from the pulsar, represent a significant population of VHE sources within our Galaxy, and the diffusion of particles

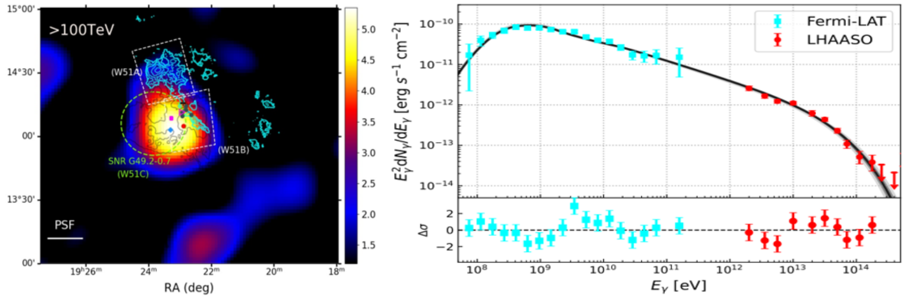

Figure 4. The sky map and SED of the W51 region achieved by LHAASO. Figure is taken from [12].

escaping from a PWN can result in extended VHE gamma-ray emission, often referred to as a "TeV halo." To investigate the role of PWN and TeV halos, the ATNF pulsar catalog was used to search for pulsars associated with LHAASO sources, resulting in the identification of 35 associated pulsars with a chance probability of less than 1% [3]. Analysis of the spin-down power versus age of these associated pulsars revealed that the TeV-gamma associated pulsars tend to exhibit higher spin-down power, with many of the energetic pulsars within the field of view of LHAASO being associated with LHAASO sources. This suggests that the PWN of energetic pulsars serve as promising sources of VHE gamma-ray emission.

Among these associations, the LHAASO collaboration has made notable discoveries related to PWN. For instance, the Crab Nebula, a well-known PWN with an age of 1.1 thousand years, was detected with ultra-high-energy photons reaching up to 1.1 PeV. This observation suggests the presence of a PeV electron accelerator within the nebula, operating at an acceleration rate exceeding 16% of the theoretical limit [13]. Additionally, LHAASO detected UHE gamma-ray emission up to 300 TeV from the tail of a bow-shock PWN associated with the pulsar PSR J1740+1000, potentially originating from re-accelerated electron/positron pairs in the bow-shock tail [3].

Furthermore, LHAASO identified a new TeV halo surrounding PSR J0622+3749 [14] and observed asymmetric diffusion in the known TeV halo associated with Geminga, providing insights into the dynamics of these regions. Notably, LHAASO may have detected UHE emission from a millisecond pulsar, PSR J0218+4232, potentially indicating the presence of VHE and UHE emission around millisecond pulsars for the first time [3]. These findings contribute to our understanding of the high-energy processes occurring in PWN and pulsars, shedding light on the mechanisms responsible for the generation of VHE and UHE gamma-ray emission in these astrophysical objects.

3.4 AGN NGC 4278

AGNs are galaxies that emit strong and variable non-thermal radiation. The very high-energy extragalactic gamma-ray sky is dominated by radio-loud AGNs, particularly blazars. Out of the 89 known VHE AGNs, 83 are blazars with relativistic jets oriented close to our line of sight. LHAASO recently detected a new TeV source identified as the low-luminosity AGN (LLAGN) NGC 4278 [15] (see Figure 5). This observation by LHAASO revealed moderate variability with a timescale of months, providing evidence that even compact and less powerful radio jets can effectively accelerate particles to very high energies and produce TeV photons. This discovery offers valuable insights into the high-energy processes taking place within AGNs, shedding light on the mechanisms involved in particle acceleration and gamma-ray production in these astrophysical objects.

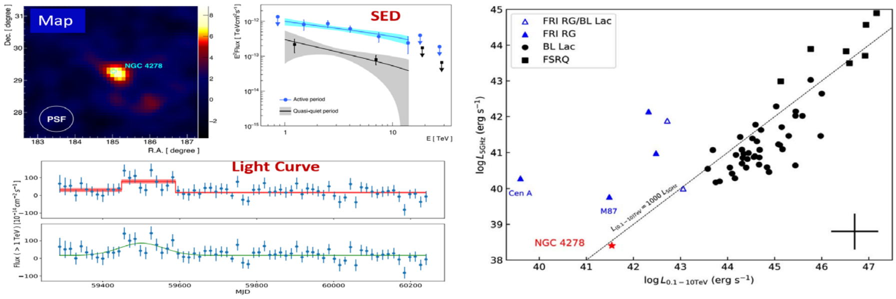

Figure 5. The sky map, SED, light curve and luminosity of the NGC 4278 achieved by LHAASO. Figure is taken from [15].

3.5 The BOAT GRB 221009A

Gamma-ray bursts (GRBs) are sudden explosions of gamma-rays that occur in random directions from cosmological distances, originating from collapsing massive stars and compact star mergers. While prompt flashes and long-lasting afterglows of GRBs have been extensively studied across a wide range of energies, observations of VHE gamma-rays during the prompt phase of GRBs and early afterglows have been limited due to technological constraints in ground-based detection. However, on October 9, 2022, the brightest GRB 221009A in human history was recorded by a space satellite.

Thanks to LHAASO's large field of view and high sensitivity, humanity has witnessed the complete evolution process of TeV afterglow radiation from a GRB, from its rise to its decline [16] (see Figure 6). LHAASO's measurements of the brightness peak time of GRB 221009A allowed for the estimation of the Lorentz factor of the initial jet velocity of the gamma-ray burst to be around 440, significantly faster than typical GRB jet speeds. LHAASO observed a rapid rise in TeV radiation in the early stages, a phenomenon not previously observed in other wavelength afterglows, suggesting a large injection of energy by the central engine in the early stages. Additionally, LHAASO detected a rapid decline in brightness around 700 seconds, leading to the inference that the jet's opening angle is only 0.8°, making it the narrowest gamma-ray burst jet ever discovered.

Furthermore, LHAASO detected the highest photon energy from GRB 221009A reaching 13 TeV, marking the first observation of GRBs at 10 TeV and representing a milestone in the sixty-year history of GRB research [17]. The intrinsic energy spectrum of gamma-rays from the GRB can be described by a power-law after correcting for extragalactic background light absorption (see Figure 6). This hard spectrum challenges the synchrotron self-Compton scenario of relativistic electrons for afterglow emission above several TeV. Observations of gamma-rays up to 13 TeV from a source with a measured redshift of z = 0.151 suggest greater transparency in intergalactic space than previously anticipated, indicating a lower intensity of infrared cosmic background light compared to existing cosmological models.

4 LHAASO recent highlight results on Charged Cosmic rays

In addition to its groundbreaking work in gamma-ray astronomy, LHAASO has made significant strides in the realm of charged cosmic rays.

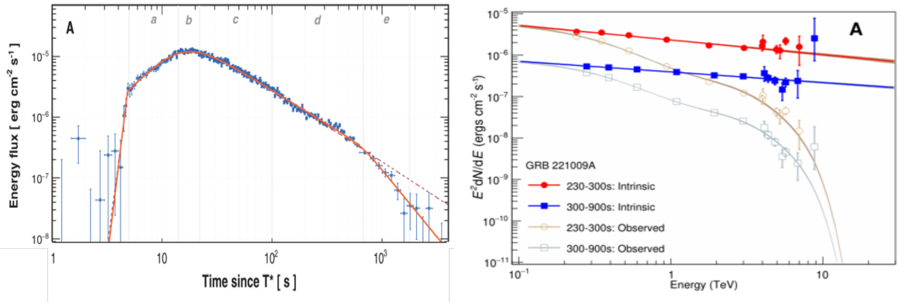

Figure 6. The light curve and SED of the GRB 221009A achieved by LHAASO. Figure is taken from [16, 17].

4.1 All particle cosmic ray SED

Recently, the LHAASO collaboration has reported measurements of the all-particle energy spectrum and mean logarithmic mass of cosmic rays ranging from 0.3 to 30 PeV using data collected by LHAASO-KM2A, marking the most precise characterization of the knee to date [18]. With its capability for conducting calorimetric measurements, LHAASO-KM2A exhibits equal sensitivity to cosmic rays regardless of their atomic number. This unique property facilitated an accurate measurement of the knee and revealed that the knee aligns with a shift in the cosmic ray composition— a decrease in atomic number with increasing energy, followed by an increase right across the knee. The discovery that these cosmic rays are lighter in mass may help elucidate their higher energies. These findings offer fresh insights into the origin of the knee.

4.2 Monitor the daily variation of interplanetary magnetic field(IMF) using cosmic ray

The Sun exerts a profound influence on the planet's environment. Monitoring solar activity and forecasting space weather between the Earth and the Sun have emerged as crucial scientific endeavors. However, monitoring methods within this expansive region have historically been a weak link in the monitoring system, struggling to offer a comprehensive and instantaneous view of changes in the interplanetary magnetic field.

VHE galactic cosmic rays, consisting mainly of positively charged particles moving near the speed of light, can travel from the Sun to the Earth within approximately 8 min. Their trajectories are affected by the magnetic field along the Sun-Earth line. Therefore, the cosmic-ray Sun shadow, caused by VHE charged cosmic rays blocked by the Sun and deflected by the magnetic field, can be used to explore the transverse IMF between the Sun and Earth before their variations transmitted to the vicinity of Earth (see Figure 7).

LHAASO, with its exceptional sensitivity, has achieved real-time daily observations of this phenomenon for the first time [19]. The LHAASO collaboration has effectively gauged the intensity and fluctuations of the interplanetary magnetic field on a daily basis from March to October 2021, utilizing data on the daily movement of the Sun shadow's position. Their findings indicate that these measurements lead by 3.31±0.12 days compared to those obtained by spacecraft near Earth, introducing a novel approach for long-term monitoring of the interplanetary magnetic field and its transformations.

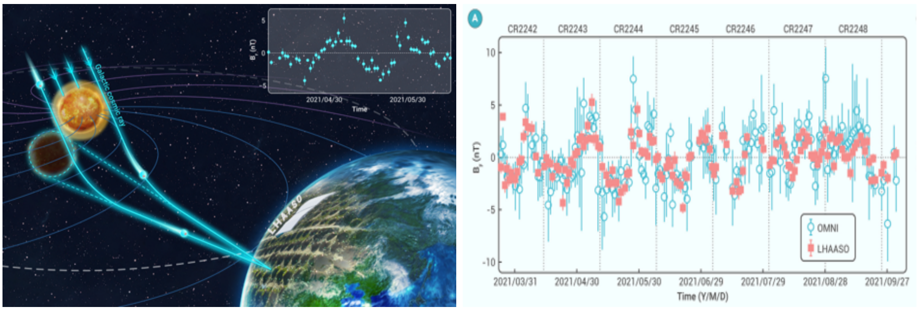

Figure 7. Left: A schematic for using solar daily shadows to measure IMF. Right: Daily By (y component of the IMF in the geocentric solar ecliptic coordinate system) at L1 Lagrange point as predicted by LHAASO and measured at L1 3.31 days later. Figure is taken from [19].

5 LHAASO recent highlight results on New Physics Frontier

Equipped with unparalleled sensitivity for UHE gamma-ray observations, LHAASO's gamma-ray detections also illuminate new physics scenarios, including dark matter and Lorentz invariance violation (LIV).

5.1 LHAASO constraints on dark matter

Dark matter stands as a cornerstone of fundamental physics and cosmology. Gamma-ray observations have long served as a potent tool in the quest for dark matter, as high-energy gamma-rays may arise from the decays or annihilations of massive dark matter particles. Through UHE gamma-ray observations in the Galactic Halo region, the LHAASO collaboration has established some of the most robust constraints on the lifetime of heavy dark matter particles with masses ranging from 10^5 to 10^9 GeV [20]. By examining possible gamma-ray signals resulting from dark matter annihilation in 16 dwarf spheroidal galaxies, the LHAASO collaboration has derived the most stringent constraints on ultra-heavy dark matter annihilation cross-sections up to the Exa-electronvolt (EeV) scale [21].

Axions and axion-like particles are theoretical entities introduced by models extending beyond the Standard Model (SM), standing out as compelling candidates for cold dark matter. Through analyzing the SED of GRB 221009A, the LHAASO collaboration has placed a stringent constraint on the axion-gamma-ray coupling constant [17].

5.2 LHAASO Constraints on LIV

Lorentz invariance is a foundational principle in modern physics. However, certain theories aiming to unify quantum mechanics and general relativity may propose LIV at energy scales approaching the Planck scale, $M_{PL} = 1.22\times10^{28}$eV. This potential violation could open the door to intriguing phenomena that would otherwise be considered impossible.

LHAASO has achieved the first detection of PeV gamma-rays from astrophysical sources, offering a highly sensitive means to study the effects of Lorentz invariance violation. By analyzing the two highest energy sources, the LHAASO collaboration has established new lower limits on the LIV energy scale [22].

Another implication of LIV is the potential alteration of interaction thresholds. For GRBs, a slight increase in the threshold for interaction with the extragalactic background light (EBL) could suppress processes, making the universe more transparent. By analyzing the SED of GRB 221009A, the LHAASO collaboration has placed constraints on the LIV effect [17].

Furthermore, LIV could impact the speed of light in a vacuum. Through analyzing the time delay of gamma-rays of different energies from GRB221009A, the LHAASO collaboration has set stringent constraints on the energy dependence of the speed of light in a vacuum [23].

6 Summary and outlook

As the most sensitive detector of UHE gamma rays, LHAASO has been operating steadily since July 2021. With the data collected in the first few years, LHAASO has uncovered 43 UHE sources and made numerous new discoveries related to Massive star, SNR, PWN, AGN, GRB, and more. These findings shed light on cosmic ray physics and push the boundaries of new physics.

The LHAASO detector is expected to remain operational at least until 2040. With the accumulation of data and increased sensitivity, there are still many more intriguing phenomena waiting to be discovered! It is worth noting that the upgrade plan for LHAASO, the Large Array of Imaging Atmospheric Cherenkov Telescopes (LACT), has been approved by the Chinese local government. From October 2024 to September 2028, 32 6-meter telescopes will be constructed within the LHAASO detector array as part of LACT, utilizing LHAASO's unique muon detector array to enhance gamma-proton discrimination at UHE. LACT will enable LHAASO to enhance its angular resolution to less than 0.05 degrees.

This research work is supported by the following grants: The National Natural Science Foundation of China under grand No.12393851, No.12393854.

References

[1] S. Abdollahi et al. (Fermi-LAT), *Fermi* Large Area Telescope Fourth Source Catalog, Astrophys. J. Suppl. **247**, 33 (2020), `1902.10045`. 10.3847/1538-4365/ab6bcb

[2] Z. Cao et al. (LHAASO), Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources, Nature **594**, 33 (2021). 10.1038/s41586-021-03498-z

[3] Z. Cao et al. (LHAASO), The First LHAASO Catalog of Gamma-Ray Sources, Astrophys. J. Suppl. **271**, 25 (2024), `2305.17030`. 10.3847/1538-4365/acfd29

[4] X.H. Ma et al., Chapter 1 LHAASO Instruments and Detector technology *, Chin. Phys. C **46**, 030001 (2022). 10.1088/1674-1137/ac3fa6

[5] F. Aharonian et al., The observation of the Crab Nebula with LHAASO-KM2A for the performance study, Chin. Phys. C **45**, 025002 (2021), `2010.06205`. 10.1088/1674-1137/abd01b

[6] Z. Cao et al. (LHAASO), LHAASO-KM2A detector simulation using Geant4, Radiat. Detect. Technol. Methods **8**, 1437 (2024), `2404.04801`. 10.1007/s41605-024-00467-8

[7] Z. Cao et al. (LHAASO), Data quality control system and long-term performance monitor of LHAASO-KM2A, Astropart. Phys. **164**, 103029 (2025), `2405.11826`. 10.1016/j.astropartphys.2024.103029

[8] F. Aharonian et al. (LHAASO), Performance of LHAASO-WCDA and observation of the Crab Nebula as a standard candle, Chin. Phys. C **45**, 085002 (2021). 10.1088/1674-1137/ac041b

[9] M. Ackermann et al., A Cocoon of Freshly Accelerated Cosmic Rays Detected by Fermi in the Cygnus Superbubble, Science **334**, 1103 (2011). 10.1126/science.1210311

[10] B. Bartoli et al. (ARGO-YBJ), Identification of the TeV Gamma-ray Source ARGO J2031+4157 with the Cygnus Cocoon, Astrophys. J. **790**, 152 (2014), `1406.6436`. 10.1088/0004-637X/790/2/152

[11] Z. Cao et al. (LHAASO), An ultrahigh-energy γ-ray bubble powered by a super PeVatron, Sci. Bull. **69**, 449 (2024), `2310.10100`. 10.1016/j.scib.2023.12.040

[12] Z. Cao et al. (LHAASO), Evidence for particle acceleration approaching PeV energies in the W51 complex, Sci. Bull. **69**, 2833 (2024), `2407.00624`. 10.1016/j.scib.2024.07.017

[13] Z. Cao et al. (LHAASO*†, LHAASO), Peta–electron volt gamma-ray emission from the Crab Nebula, Science **373**, 425 (2021), `2111.06545`. 10.1126/science.abg5137

[14] F. Aharonian et al. (LHAASO), Extended Very-High-Energy Gamma-Ray Emission Surrounding PSR J0622+3749 Observed by LHAASO-KM2A, Phys. Rev. Lett. **126**, 241103 (2021), `2106.09396`. 10.1103/PhysRevLett.126.241103

[15] Z. Cao et al. (LHAASO), Discovery of Very High Energy Gamma-Ray Emissions from the Low-luminosity AGN NGC 4278 by LHAASO, Astrophys. J. Lett. **971**, L45 (2024), `2405.07691`. 10.3847/2041-8213/ad5e6d

[16] Z. Cao et al. (LHAASO), A tera–electron volt afterglow from a narrow jet in an extremely bright gamma-ray burst, Science **380**, adg9328 (2023), `2306.06372`. 10.1126/science.adg9328

[17] Z. Cao et al. (LHAASA, LHAASO), Very high-energy gamma-ray emission beyond 10 TeV from GRB 221009A, Sci. Adv. **9**, adj2778 (2023), `2310.08845`. 10.1126/sciadv.adj2778

[18] Z. Cao et al. (LHAASO), Measurements of All-Particle Energy Spectrum and Mean Logarithmic Mass of Cosmic Rays from 0.3 to 30 PeV with LHAASO-KM2A, Phys. Rev. Lett. **132**, 131002 (2024), `2403.10010`. 10.1103/PhysRevLett.132.131002

[19] Z. Cao et al. (LHAASO), Monitoring the daily variation of Sun-Earth magnetic fields using galactic cosmic rays, The Innovation **5**, 100695 (2024), `2410.09064`. 10.1016/j.xinn.2024.100695

[20] Z. Cao et al. (LHAASO), Constraints on Heavy Decaying Dark Matter from 570 Days of LHAASO Observations, Phys. Rev. Lett. **129**, 261103 (2022), `2210.15989`. 10.1103/PhysRevLett.129.261103

[21] Z. Cao et al. (LHAASO), Constraints on Ultraheavy Dark Matter Properties from Dwarf Spheroidal Galaxies with LHAASO Observations, Phys. Rev. Lett. **133**, 061001 (2024), `2406.08698`. 10.1103/PhysRevLett.133.061001

[22] Z. Cao et al. (LHAASO), Exploring Lorentz Invariance Violation from Ultrahigh-Energy γ Rays Observed by LHAASO, Phys. Rev. Lett. **128**, 051102 (2022), `2106.12350`. 10.1103/PhysRevLett.128.051102

[23] Z. Cao et al. (LHAASO), Stringent Tests of Lorentz Invariance Violation from LHAASO Observations of GRB 221009A, Phys. Rev. Lett. **133**, 071501 (2024), `2402.06009`. 10.1103/PhysRevLett.133.071501