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ICRC 2025 Gamma-ray Astrophysics Rapporteur Talk

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This report summarizes the highlights of the Gamma-Ray Astrophysics session at the 39th International Cosmic Ray Conference (ICRC 2025). The session, featuring 368 contributions, was organized around three primary themes, including instrumental developments, Galactic sources and emission, and extragalactic sources with their broader astrophysical and cosmological implications. A central driver of the field remains the identification of Galactic PeVatrons and the understanding of the origin and propagation of cosmic rays. Key highlights include that a growing population of PeVatron candidates have been revealed, extending beyond supernova remnants to include microquasars and young massive stellar clusters; observations of supernova remnants and pulsar halos provide more clues for distinguishing between leptonic and hadronic emission processes; studies of Galactic diffuse emission shed further light on the distribution and propagation of cosmic rays throughout the Milky Way; and studies of extragalactic sources like active galactic nuclei and gamma-ray bursts are being used to probe the extragalactic background light, intergalactic magnetic fields, cosmology and fundamental physics. Furthermore, technical innovations including novel instrumentation, deep learning analysis techniques, and common software tools are pushing the performance of both current and future experiments. The upcoming deployment of next-generation observatories promises to further revolutionize our understanding of particle acceleration in the Universe in this multi-messenger and multi-wavelength era.

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1. Experiments

Advances in gamma-ray astrophysics are propelled by a diverse and complementary suite of instruments, which can be broadly divided into ground-based and space-based observatories. Ground-based detectors are highly sensitive to very high-energy (VHE, > 1 TeV) photons and are optimized for studying the most energetic processes in the universe. In contrast, space-based telescopes provide continuous, wide-field monitoring of the sky, enabling the study of transient phenomena and the keV to sub-TeV energy range. Together, these facilities form an integrated, multi-wavelength observational network that is essential for advancing our understanding of the non-thermal universe.

1.1 Ground Experiments

Ground-based gamma-ray observatories detect extensive air showers (EAS) generated by the interaction of VHE photons or cosmic rays (CRs) with the atmosphere of the Earth. These instruments are primarily divided into two classes: Imaging Atmospheric Cherenkov Telescopes (IACTs) and Particle Detector Arrays (PDAs), each with distinct observational advantages.

IACTs, such as the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes, the High Energy Stereoscopic System (H.E.S.S.), the Very Energetic Radiation Imaging Telescope Array System (VERITAS), and the Single-Mirror Small-Sized Cherenkov Telescope (SST-1M) [1–8], observe brief flashes of Cherenkov radiation emitted by relativistic secondary particles in an EAS. This technique offers excellent angular resolution ($< 0.1^\circ$) and deep sensitivity, making IACTs ideal for detailed morphological and spectral studies of individual sources. However, they are constrained by a limited field of view (a few degrees) and a low duty cycle (approximately 10-15%), as they require clear and moonless nights for observation.

In comparison, particle detector arrays, such as the High Altitude Water Cherenkov Observatory (HAWC), the Large High Altitude Air Shower Observatory (LHAASO), and the Tibet ASγ experiment, directly detect secondary particles that reach the ground from an EAS. These instruments feature a wide field of view (often exceeding one steradian) and a duty cycle of near 100%, allowing for continuous monitoring of large portions of the sky. The trade-off is a coarser angular resolution, typically on the order of 0.5° or larger.

Next-generation instruments in both categories are currently under development to significantly enhance VHE observation capabilities. Upcoming IACT facilities include the Cherenkov Telescope Array Observatory (CTAO)[9], ASTRI (*Astrofisica con Specchi a Tecnologia Replicante Italiana*) project, the Large Array of Imaging Atmospheric Cherenkov Telescopes (LACT)[10, 11], and Panoramic Search for Extraterrestrial Intelligence (PANOSETI) telescopes[12]. Meanwhile, next-generation particle detector arrays include the Southern Wide-field Gamma-ray Observatory (SWGO) [13], the Andes Large-area Particle detector for Cosmic-ray Physics and Astronomy (ALPACA)[14], the Probing Extreme PeVatron Sources (PEPS) project, and the Stereoscopic Water Cherenkov Detection Array (SWCDA) project[15–18]. The rapid evolution of ground-based gamma-ray experiments is motivated by overarching scientific questions, particularly the origin and mechanisms of CR acceleration. This pursuit is advancing on three primary fronts: First, achieving full-sky coverage to unlock the scientific potential of the Southern Hemisphere, especially for the Galactic Center region, with key contributions from H.E.S.S., SWGO, and CTA-South. This

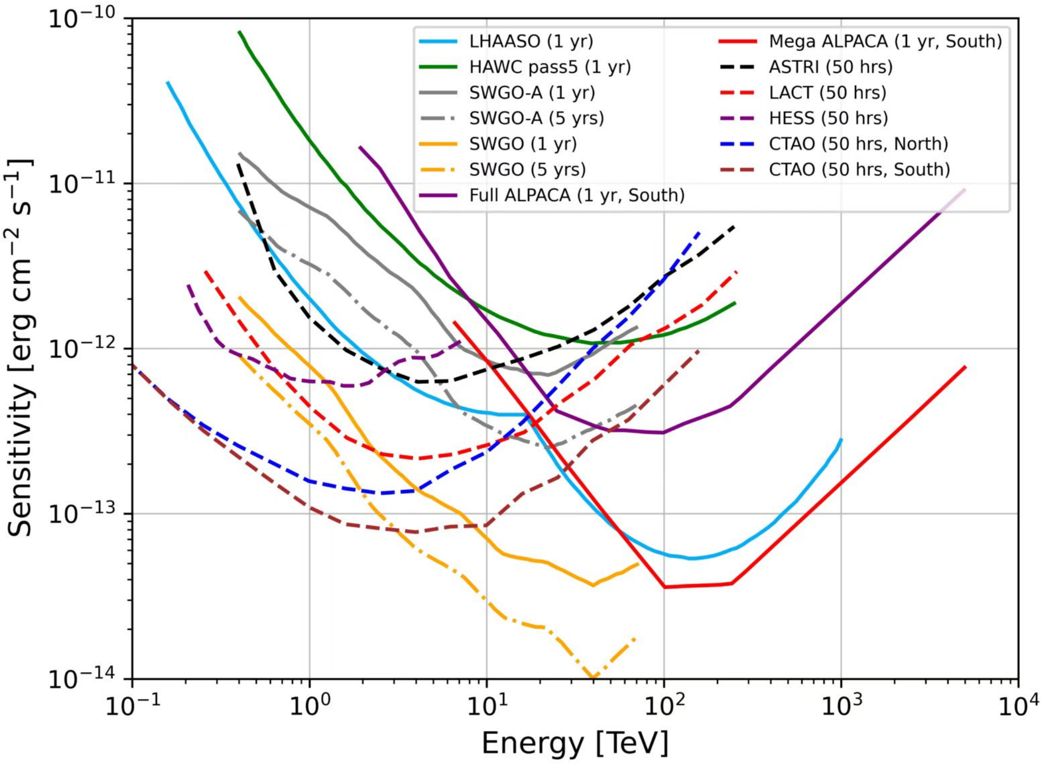

Figure 1: The sensitivity for current and future ground-based gamma-ray observatories[10, 14, 21, 22]. The curves for established instruments (e.g., H.E.S.S., HAWC, LHAASO) and next-generation projects (e.g., CTAO North & South, SWGO, ALPACA, Mega ALPACA, LACT, ASTRI) illustrate the significant gain in sensitivity and energy coverage anticipated in the coming years, which will be pivotal for population studies and deep observations of faint sources.

global network enables rapid multi-messenger follow-up of transients. Second, a concerted drive to enhance sensitivity across a broad energy range from sub-TeV to PeV, which is crucial for detecting fainter sources and probing deeper into the non-thermal universe. Third, the push for superior angular resolution[19, 20] is paramount to precisely pinpoint source morphologies, resolve complex regions, and firmly identify counterparts at other wavelengths. The progress in instrumental sensitivity is shown in Figure 1, while the timeline and milestones of the next-generation facilities are summarized in Table 1.

The **CTAO** is transitioning into an early operational phase, with the first Large-Sized Telescope (LST-1) already producing scientific results[25], including detections of active galactic nuclei and pulsars, and three additional LSTs under construction [9]. The completion of the four-LST subarray at the northern site is expected in 2026, enabling stereoscopic observations[9, 26]. As a next-generation flagship observatory with full-sky coverage and a wide energy range, CTAO will revolutionize very-high-energy gamma-ray astronomy.

The **ASTRI** project is developing a Mini-Array of nine telescopes in Tenerife, Spain, based on the Schwarzschild-Couder dual-mirror design optimized for the multi-TeV energy range with

Table 1: Timeline and key milestones of future ground-based gamma-ray instruments[9, 10, 13, 14, 23, 24].

Project	Type	Features/ Goals	Current Phase	Milestones
CTAO	IACT	• Full-sky coverage • Wide energy range • Next-generation flagship	• Early operation phase • LST-1 operational and producing scientific results	• 2026: Completion of 4-LST northern subarray
ASTRI	IACT	• Dual-mirror Schwarzschild-Couder design	• ASTRI-1 in commissioning phase	• 2026: Full ASTRI Mini-Array
LACT	IACT	• Synergy with LHAASO for morphology studies	• First telescope development	• 2026:8-telescope intermediate phase • 2028:Full 32-telescope array
SWGO	PDA	• Southern sky survey • High sensitivity (GeV–PeV) • Novel double-layer detector design	• SWGO-PF preparation/procurement • SWGO-A development/design	• 2026: SWGO-PF operations; SWGO-A preparation/procurement; Outer array development/design • 2031:Full array operations
ALPACA	PDA	• Southern sub-PeV window • Combined with muon detector • Idea of Mega ALPACA to reach PeV range	• ALPAQUITA (97 SDs) in oparation • ALPAQUITA+MD array under construction	• 2026: ALPAQUITA+MD will start sensitive gamma-ray observations

excellent angular resolution. The first telescope (ASTRI-1) is in the commissioning phase, and the three-telescope subarray should become operational by the end of 2025[23], allowing detailed studies of particle acceleration mechanisms in extreme astrophysical environments.

The **LACT** will consist of 32 telescopes deployed in China, operating in synergy with LHAASO to perform detailed morphological studies of very high-energy gamma-ray sources previously identified by LHAASO[10]. The project will progress from initial telescopes to an 8-telescope phase in 2026 and the full array in 2028, leveraging LHAASO's CR background suppression capabilities to enhance gamma-ray event selection[11].

The **SWGO** is a planned wide-field water-Cherenkov array in Chile, designed to survey the southern sky with unprecedented sensitivity from hundreds of GeV to PeV energies using a novel double-layer detector design [13, 27–31]. Its key scientific goals include identifying Galactic PeVatrons, studying extended sources like Fermi bubbles, monitoring transients, and contributing to multi-messenger astrophysics and dark-matter searches. It will be developed in stages, starting with a Pathfinder (SWGO-PF)[32] and an initial science array (SWGO-A), before expanding to the full ~ 1 km^2 array[13].

The **ALPACA** project is under construction in the Bolivian Andes to access the southern sub-PeV sky [14, 33]. The prototype array, ALPAQUITA (97 detectors), is complete and has begun early observations [34–39]. The full array (401 detectors and 4 muon detectors) is scheduled for gamma-ray observations, and a future Mega ALPACA (1477 detectors) sensitive to PeV energies is proposed to extend the energy reach for studying particle acceleration in Galactic sources[14].

1.2 Space Experiments

Space-borne experiments, operating unhindered by Earth's atmosphere, are fundamental to gamma-ray astronomy. They provide continuous, all-sky monitoring, making them indispensable for detecting unpredictable transients like Gamma-Ray Bursts (GRBs) and flaring active galactic nuclei (AGNs). Consequently, they serve as the primary alert system for the multi-wavelength and multi-messenger astrophysics community.

A central and persistent challenge in the field has been the "MeV Gap", a sensitivity gap in the 0.1-100 MeV range. This energy regime is critical for studying fundamental processes, including discriminating between leptonic and hadronic emission mechanisms, understanding non-thermal particle populations in supernova remnants, and identifying potential signatures of particle dark matter decay or annihilation. The session highlighted a strong drive to address this gap, with several next-generation missions under development. These include the All-sky Medium Energy Gamma-Ray Observatory eXplorer (AMEGO-X)[40], designed for all-sky monitoring and precise localization of transients, and the *newASTROGAM* concept[41], a breakthrough observatory covering 15 keV to 3 GeV. Furthermore, missions such as the Compton Spectrometer and Imager (COSI), scheduled to launch in 2027[42, 43].

The development of advanced detector technologies was a key theme, enabling new scientific capabilities. Balloon-borne missions play a crucial role in demonstrating these technologies in a near-space environment. Examples include the Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope (ADAPT)[44], which is testing a design optimized for Compton and pair-conversion regimes.

Polarimetry is emerging as a crucial new diagnostic tool. A new generation of instruments, such as POLAR-2 (the next-generation GRB polarimeter)[45], the CUbesat Solar Polarimeter (CUSP) for solar flares[46], and the WINK/Crystal Eye prototype[47], is set to provide definitive measurements of gamma-ray polarization. These observations will probe the geometry of magnetic fields and the mechanisms of particle acceleration in extreme astrophysical environments, from GRB jets to solar flares.

Finally, the scientific scope of space experiments continues to expand. Missions like the Galactic Annihilation Line Explorer (GALE) aim to resolve the origin of Galactic positrons through high-resolution mapping of the 511 keV line[48], while the Cosmic X-ray Background Explorer (CXBe) seeks to measure the cosmic X-ray background with unprecedented precision to constrain the evolution of supermassive black holes[49]. Long-lived observatories such as the DArk Matter Particle Explorer (DAMPE) continue to provide valuable data, refining our understanding of CR propagation and dark-matter signatures[50].

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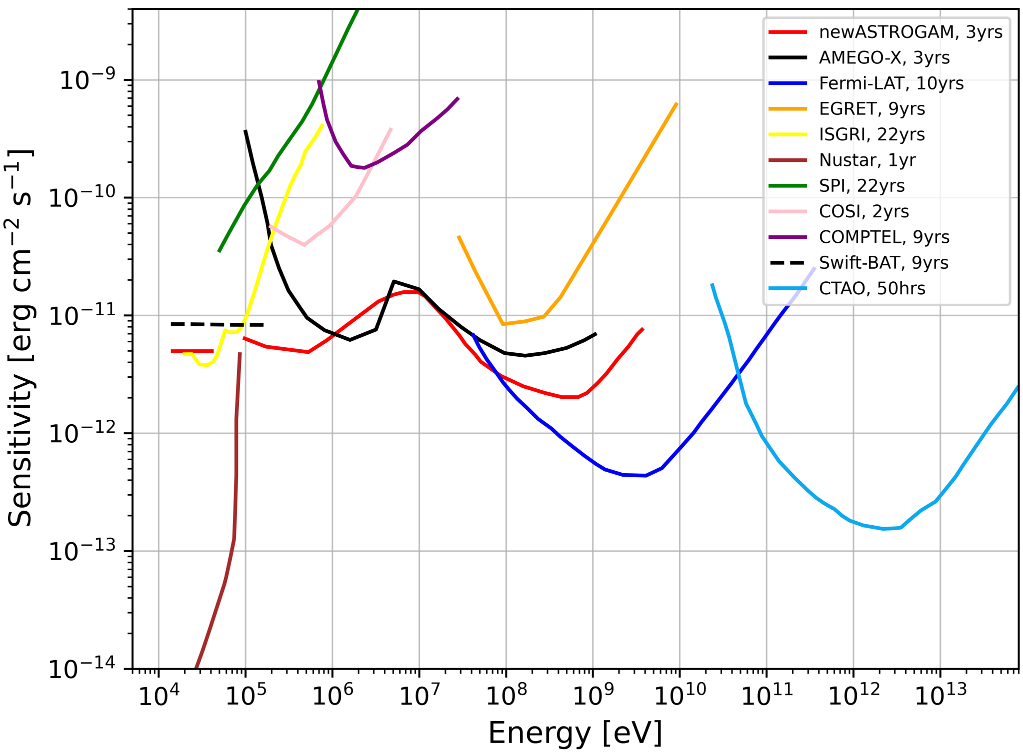


Figure 2: Sensitivities of current and future space-based gamma-ray missions[40, 41, 51]. The complementarity of various instruments is essential for providing a continuous view of the non-thermal universe from keV to TeV energies.

In summary, the field of gamma-ray space experiments is highly dynamic, with a clear pathway toward closing the MeV gap and leveraging new technological capabilities like polarimetry to address fundamental questions in astrophysics and particle physics. Figure 2 shows sensitivities of current and future space-based gamma-ray missions.

1.3 Technique Innovations, Software and Analysis Methods

The technical innovations were also prominent. The AdvCam is a next-generation camera for LSTs of the CTAO, based on silicon photomultipliers[52, 53]. NectarCAM is a Cherenkov camera that will equip the Medium-Sized Telescopes (MST) of the northern site of the CTAO[54, 55].

Beyond hardware, new analysis methods and software tools are presented. The Line of Sight Trigger (LOST)[56], a novel triggering method, was presented as a significant improvement over standard techniques. LOST leverages a constant-angle line transformation to provide an early and robust determination of the air shower's direction. This is achieved by exploiting the precise relative timing of signals across detector arrays, reducing the intrinsic time spread to the nanosecond level. Consequently, the necessary trigger window can be drastically shortened from approximately 300 ns to just 10 ns. This substantial reduction in window size dramatically enhances the rejection of accidental noise triggers and improves the overall efficiency and purity of recorded shower events.

The adoption of common methods, software tools, or pipelines[57–66] for analysis and the application of deep learning techniques[5, 67–77] for tasks such as event reconstruction and background rejection push the performance of existing and future instruments beyond their original design specifications. These software-driven advances are crucial for standardizing analyses across collaborations and extracting maximum science from the increasingly complex data.

2. Galactic Sources and Emissions

The exploration of our Galaxy at VHE and ultra-high-energy (UHE, $>$ 100 TeV) gamma-rays bands is fundamentally driven by several interconnected grand challenges: the identification of the PeVatrons, the sources capable of accelerating particles(including hadrons and leptons) to PeV energies; the discrimination of hadronic emission processes (originating from proton-proton collisions) from leptonic scenarios (involving electron interactions) to pinpoint the sites of hadronic acceleration; the understanding of CR transport and diffusion mechanisms through the interstellar medium; and the interpretation of the Galactic diffuse emission (GDE) as a tracer of the global Galactic CR population and interstellar environment. Contributions in this session showcased significant progress on these fronts, leveraging the unprecedented sensitivity of VHE and UHE detectors such as LHAASO to probe a diverse population of astrophysical accelerators.

The hunt for PeVatrons has expanded beyond traditional candidates such as supernova remnants (SNRs) to include a wider array of objects. Evidence was presented across microquasars and gamma-ray binaries, which provide compact, powerful engines; young massive star clusters (YMCs), where collective winds and shocks may act as accelerators, and pulsars, pulsar wind nebulae (PWNe), and pulsar halos, which are increasingly recognized as significant contributors to the local electrons and positrons. The persistent existence of unidentified TeV sources further underscores that our census of Galactic particle accelerators remains incomplete. This section reviews contributions from these source classes, highlighting the sophisticated multi-wavelength and multi-messenger techniques employed to break the degeneracy between emission processes and to advance our understanding of CR origin and propagation.

2.1 Microquasars/Gamma-Ray Binaries

Microquasars are Galactic binary systems comprising a compact object, a stellar-mass black hole or a neutron star, accreting matter from a companion star, producing relativist jets. Recent observations, particularly from HAWC and LHAASO[78, 79], have significantly advanced the study of these systems in the UHE regime.

LHAASO reported the detection of UHE gamma-ray emission from five out of twelve microquasars within its field of view[79], including SS 433, V4641 Sagittarii (V4641 Sgr), GRS 1915 + 105, MAXI J1820 + 070 and Cygnus X-1. The significance maps of four microquasars measured by LHAASO are shown in Figure 3[79]. In particular, eight photons with energy above 1 PeV were detected in the Cygnus region, two of which originate in the vicinity of Cygnus X-3[80, 81], as shown in Figure 4. Complementary observations of Cygnus X-3 were also presented by *Fermi*-LAT and MAGIC[82].

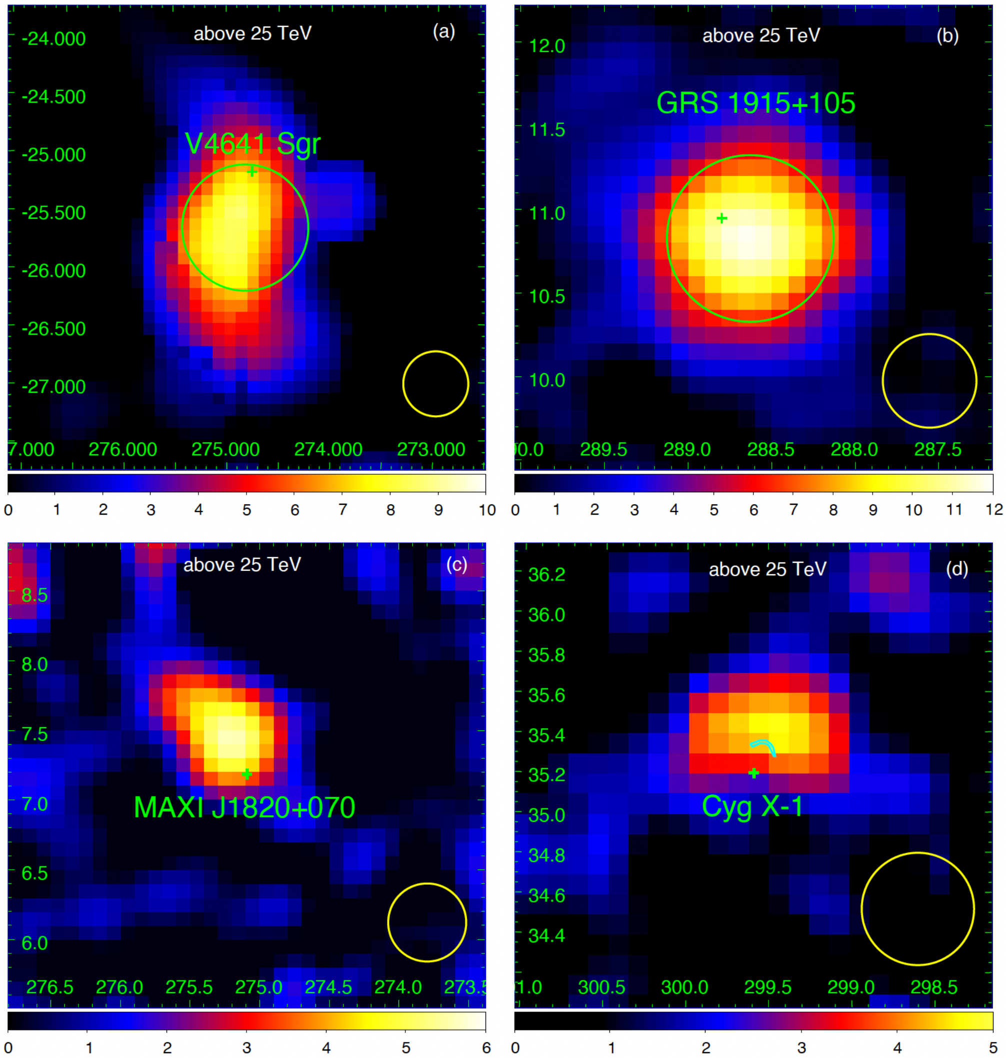


Figure 3: Significance maps of four other microquasars observed by LHAASO, in addition to SS 433. Panels (a)-(d) show V4641 Sgr, GRS 1915+105, MAXI J1820+070, and Cygnus X-1, respectively, at energies above 25 TeV. The green cross marks the position of the black hole in each system. The green circle indicates the 68% containment radius of the LHAASO source, and the yellow circle shows the 68% containment radius of the LHAASO point-spread function in the corresponding energy band. In panel (d), the cyan arc represents the bow-like radio structure inflated by the jet of Cygnus X-1[83]. The figure is adapted from [79].

A highlight of recent results is SS 433, which hosts precessing jets embedded in the W50 supernova remnant. Following the initial detection of TeV emission from its jet lobes by HAWC in 2018 [84], H.E.S.S. and HAWC also revealed energy-dependent morphology changes[85, 86], as shown in Figure 5. In this conference, LHAASO reported significant emission (>100 TeV) with significance $> 5\,\sigma$ from SS 433[80]. The UHE emission is partly overlapped with the HI cloud at the same distance and may give a hint for a hadronic origin[79]. VERITAS reinforced these findings, reporting VHE gamma rays from both the eastern and western lobes at a combined statistical significance of $8.8\,\sigma$, confirming particle acceleration to TeV energies in jets[87]. Multiwavelength

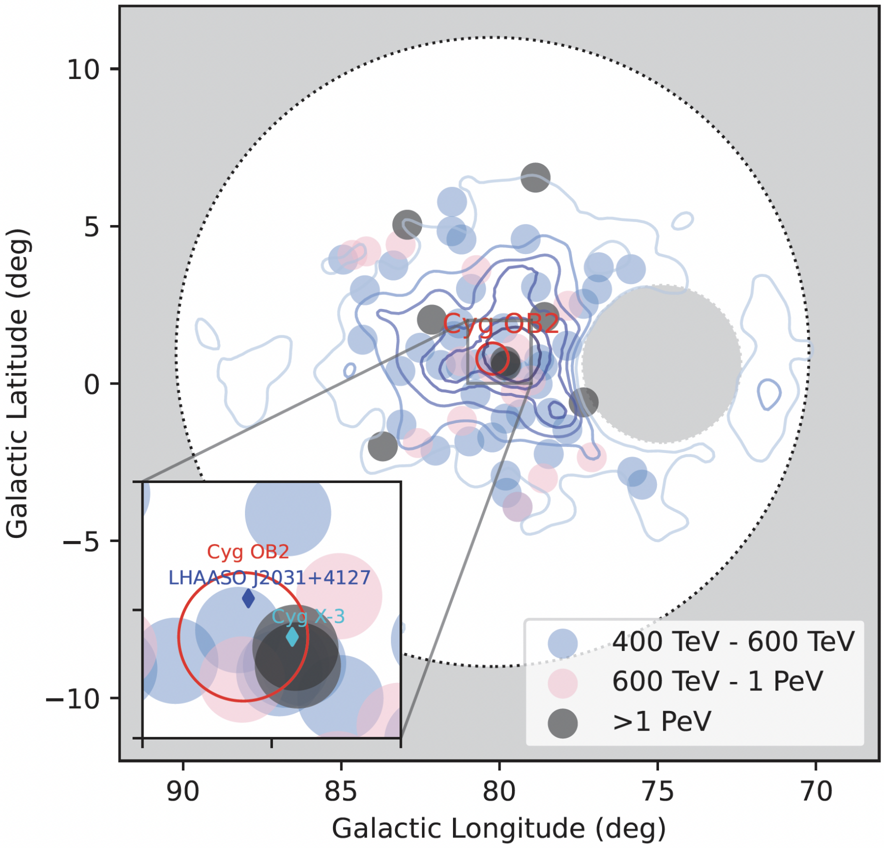


Figure 4: Photon distribution in the Cygnus-X region. Photons with energies above 400 TeV are shown, color-coded by energy: 8 events above 1 PeV (black circles), 12 events between 600 TeV and 1 PeV (pink), and 46 events between 400 TeV and 600 TeV (blue). The larger black-dotted circle outlines the region of interest (ROI) used in this analysis, inside which a shaded area marks the region masked around the unidentified source LHAASO J2018+3651. This figure is adapted from [81].

investigations include proper motion measurements and variability studies conducted with Chandra over a 20-year baseline, with additional insights anticipated from upcoming observations by XRISM, IXPE, NuSTAR, and XMM-Newtonn[88]. The observations on SS 433 with LHAASO, VERITAS and Chandra are shown in Figure 6.

For V4641 Sgr, new results presented at this conference include LHAASO's measurement of a hard spectrum extending up to 800 TeV[79]. The combined observations of the extended emission from V4641 Sgr with H.E.S.S.[89], HAWC[78], LHAASO (yellow, red, blue)[79], and the extended X-ray region with measurements from XRISM [90] are shown in Figure 7. The multi-messenger study incorporating XRISM data suggests a leptonic-hadronic hybrid model, which can be further tested with X-ray observations at the nebular edges[91].

Further significant results involve studies of the binaries LS 5039 and LS I +61° 303. For the former, LHAASO detected 100 TeV emission[92], while H.E.S.S. revealed periodic TeV variability[93]. For the latter, LHAASO reported UHE emission including orbital-period-correlated flares[94], and a separate analysis of VERITAS and Swift-XRT data reported a correlation between

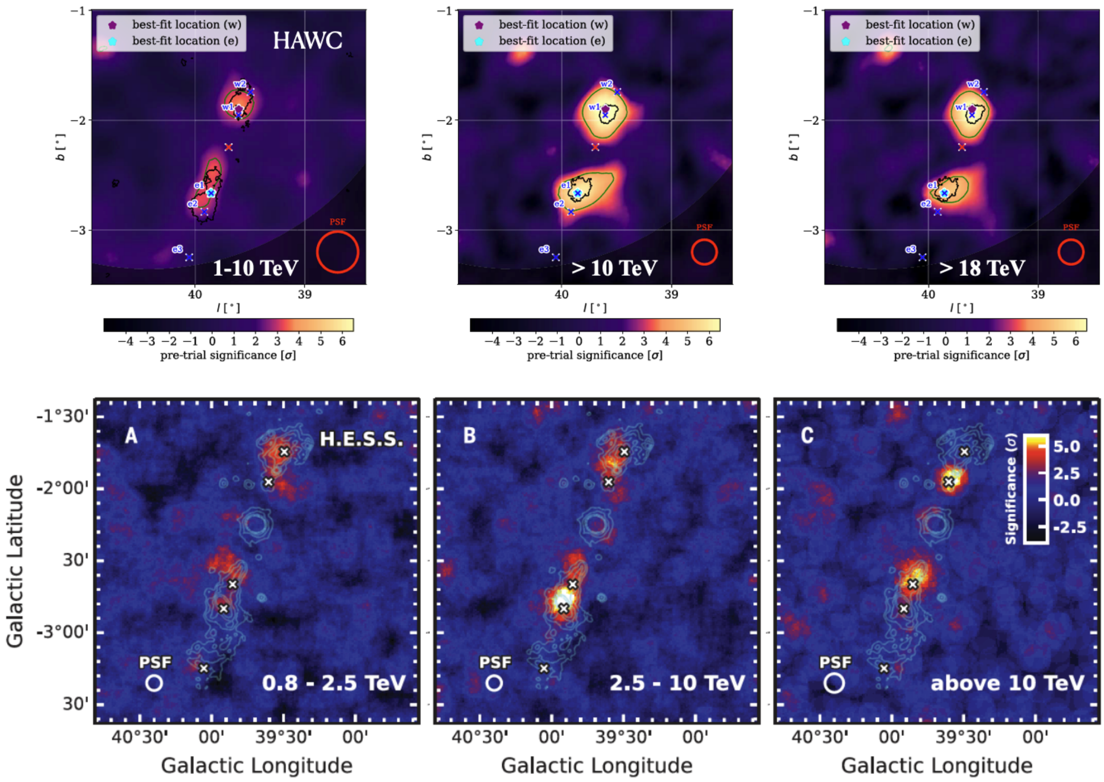


Figure 5: Top panels show the significance map of SS 433 measured by HAWC at various energy bands. The red circle indicates the angular resolution of the bin containing the most events, while the green and black contours represent the 3 σ (for the 1-10 TeV energy bin) or 4 σ (for the >10 TeV and >18 TeV energy bins) significance level in the HAWC and H.E.S.S. data, respectively. Bottom panels display the significance map of SS 433 measured by H.E.S.S. at different energy bands. The cyan contours denote previously published X-ray emission [96, 97], white crosses denote specific X-ray regions, the white circle denote for the 68% containment region of the H.E.S.S. point-spread function, and the green cross with a circle indicates the position and uncertainty of the Fermi source J1913+0515. The figures are adopted from [85] and [86], respectively.

X-ray and TeV fluxes[95].

2.2 YMCs

YMCs, which host numerous massive stars, including powerful Wolf-Rayet (WR) and OB types, are promising PeVatron candidates. Their collective stellar winds and subsequent shocks are capable of generating efficient particle acceleration. The dominant acceleration mechanism varies with the age of the cluster. In older clusters, SNR shocks become significant contributors [101]. In contrast, stellar winds dominate in young clusters such as NGC 6611 (with an age of ~1 Myr) in the Eagle Nebula, where the acceleration process is not contaminated by SNRs [101]. Winds from stellar clusters are believed to contribute to the Galactic CR population and could explain the observed overabundance of ^{22}Ne relative to ^{20}Ne [102]. Furthermore, WR stars themselves are proposed as potential particle accelerators; one study reported a spatial coincidence between four WR stars and unidentified gamma-ray sources [103]. To quantitatively address open questions

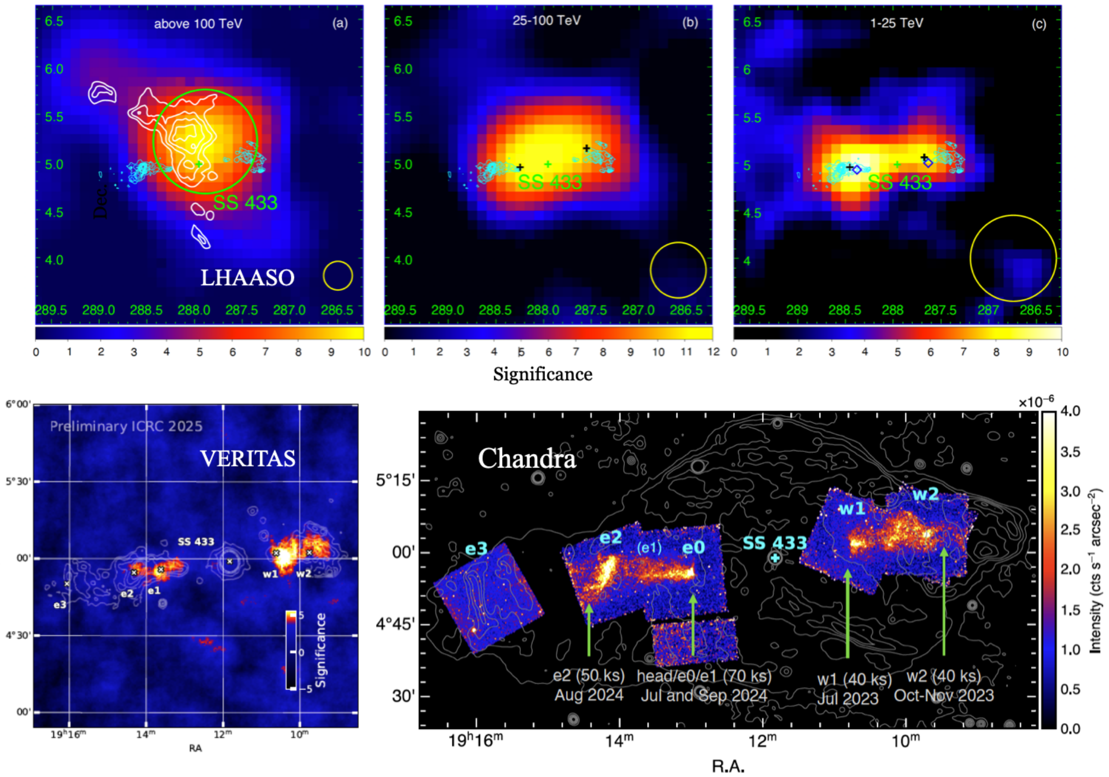


Figure 6: The observations on SS 433 with LHAASO (in the top panels), VERITAS (in the bottom-left panel) and Chandra (in the bottom-right panel). The figures are adapted from [79],[87] and [88], respectively. Top Panels (LHAASO): Significance maps in the energy ranges of (a) >100 TeV, (b) 25-100 TeV, and (c) 1-25 TeV. The green cross marks the position of the black hole. The green circle indicates the 68% containment radius of the detected source, while the yellow circle shows the 68% containment of the instrument's point-spread function. The white contour in (a) outlines H I atomic clouds at a distance consistent with SS 433 [98]. Black crosses in (b) and (c) indicate the positions of the two resolved point-like sources in their respective energy bands. Blue diamonds in (c) mark the positions of gamma-ray emission above 10 TeV detected by H.E.S.S. [86]. The cyan contour in (c) outlines the X-ray emission from the two lobes [99]. Bottom-Left (VERITAS): Significance map after subtracting the background source MGRO J1908+06. White crosses mark the emission regions along the eastern (e1-e3) and western (w1-w2) jets. The white contours indicate the corresponding ROSAT X-ray emission[96]. Bottom-Right (Chandra): X-ray image in the 0.5–7 keV band from 2023-2024 observations[88]. The white contours show the radio continuum emission at 1.4 GHz for comparison[100].

regarding the underlying particle spectra, acceleration efficiency, and magnetic field conversion, population synthesis studies are now being employed, confronting simulated YMSCs with current TeV catalogs from H.E.S.S. and LHAASO[104].

Notable observational results reinforce this picture. The LHAASO collaboration has detected photons with energies up to 2.5 PeV from the Cygnus region, identifying its YMC as a potential super-PeVatron. Morphological and spectral studies reveal a clear spatial correlation between VHE gamma-ray emission and an extended bubble structure traced by HI gas, as well as associations between the emissions with molecular clouds, indicating the presence of high-energy CRs [80].

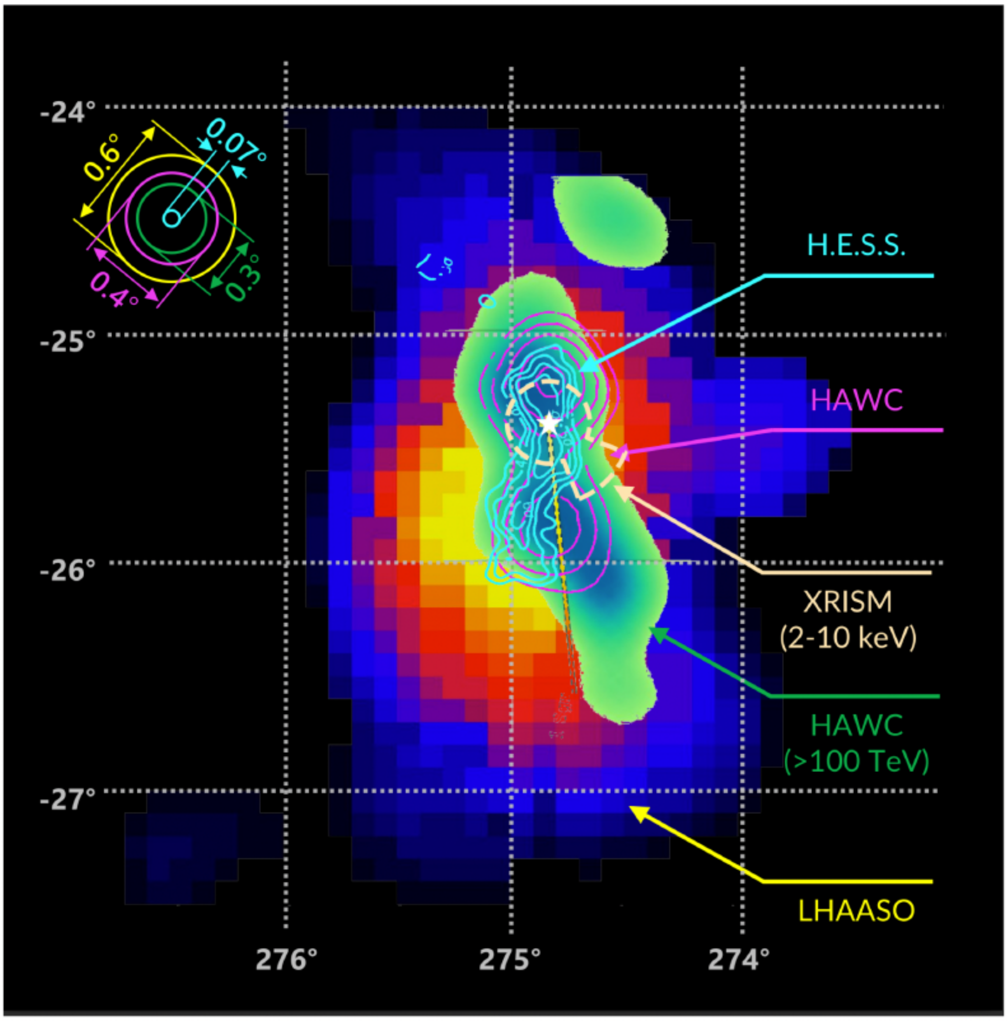


Figure 7: Combined observations of the extended emission from V4641 Sgr include H.E.S.S. (cyan)[89], HAWC (in magenta for all-energy, and in green/blue for >100 TeV)[78], LHAASO (yellow, red, blue)[79], and the extended X-ray region with measurements from XRISM (dashed line region)[90]. The figure is adapted from [91].

Furthermore, LHAASO has reported gamma-ray emission exceeding 100 TeV from the star-forming region W43, which also hosts a stellar cluster [105]. Observations of Westerlund 1 by H.E.S.S. and Fermi-LAT suggest the presence of a CR-loaded nascent outflow, providing evidence for anisotropic cosmic-ray transport [106].

2.3 SNRs

SNRs represent a primary class of PeVatron candidates that are capable of accelerating particles to very high energies. Recent observations have provided substantial evidence supporting their role in producing PeV cosmic rays.

Key evidence comes from several prominent sources. The W51 region, detected by LHAASO at energies greater than 100 TeV, reveals two distinct PeVatron candidates: W51C, an SNR that interacts with molecular clouds, and W51B, which harbors young stellar clusters [107]. Analysis of 16 years of Fermi-LAT data provides crucial morphological and spectral insights into particle acceleration processes in this region [108]. Furthermore, UHE gamma rays have been detected from the Boomerang Nebula (SNR G106.3+2.7) by LHAASO and the Tibet ASγ experiment [39, 109]. The source has been spatially resolved by MAGIC into distinct "head" and "tail" components [110], while follow-up observations with LST-1 confirm its extended nature, with a significance exceeding 5σ in the 3-100 TeV energy range [111].

A major challenge in identifying CR sources lies in distinguishing hadronic from leptonic emission processes. Several methods are employed to break this degeneracy, including spectral analysis, morphological studies, and considerations of the energy budget. A key indicator of hadronic processes is the spectral feature around 70 MeV known as the "pion bump," which has been identified in Fermi-LAT observations of SNRs W44, IC 443, and W51C [112]. LHAASO has further reinforced the hadronic scenario by demonstrating spatial correlations between gamma-ray morphology and interstellar gas in these remnants. Other middle-aged SNRs that likely interact with molecular clouds, such as G150.3+4.7 and γ Cygni, were also highlighted in the LHAASO results [113]. Further evidence comes from the IC 443 complex, where interaction with the S249 HII region and a spectral pion bump were detected in the G189-North region [114]. A correlation between LHAASO VHE emission and dust distribution near SNR G57.2+0.8 also supports a hadronic origin [115]. Alternative approaches include using radial profiles to search for escaped CRs, as demonstrated in preliminary studies of W28 and W51C [116]. X-ray morphological and spectral variability studies also provide valuable clues to differentiate emission mechanisms [117].

2.4 Pulsars/PWNe/Pulsar halos

Pulsar wind nebulae (PWNe) and TeV halos serve as unique laboratories for studying the transport and diffusion of electrons, offering insights into suppressed diffusion mechanisms, magnetic-field environments, and their connection to large-scale Galactic structures.

Recent observations continue to expand the catalog of such systems. A newly identified, largely extended source, LHAASO J1847+0925, spatially associated with the middle-aged pulsar J1846+0919, represents the first promising candidate for the pulsar halo detected in the inner Galaxy[118]. Similarly, the VHE source HESS J1831-098 is well explained by a pulsar halo model, yielding a suppressed diffusion coefficient consistent with those derived for the Geminga and Monogem halos[119]. Significant extended TeV emission around PSR B1055-052 has also been reported by H.E.S.S.[120]. Analysis of the HAWC DA 495 region further clarifies the complex nature of these systems, identifying the central source as a PWN and two additional nearby sources as candidates for the TeV halo[121].

In particular, a study by Bourguinat *et al.* [122] revealed that nearly half of pulsars with ages around 200 kyr reside within wind-blown bubbles or superbubbles (WBB/SB), contrary to the previous expectation that pulsars older than 40-60 kyr should be located outside such structures. This suggests a significantly reduced diffusion coefficient in these regions, which could be a result of progenitor-induced turbulence.

The morphology of these halos provides critical information on particle transport. LHAASO's observation of an asymmetric morphology around the Geminga pulsar points toward inhomogeneous or anisotropic diffusion in its vicinity[113]. This is supported by simulations illustrating the influence of the interstellar magnetic field on halo asymmetry[123]. Multiwavelength observations, particularly in X-rays with XMM-Newton and NuSTAR, are crucial to constraining the magnetic field properties within these halos[124]. For example, the detection of X-ray emission around PSR B0656+14 with eROSITA, which is more extended than its associated PWN and shows a decrease in radial flux, provides further evidence of this complex particle transport[113].

The Crab Nebula, a young PWN and the first source ever detected in the VHE gamma-ray band, remains a benchmark for VHE astronomy. LHAASO's groundbreaking detection of PeV emission from the Crab Nebula in 2021 established it as a compelling PeVatron candidate[109]. Long-term monitoring by the KM2A array has further constrained its behavior at tens of TeV, revealing no significant flux variations during a GeV flare detected in December 2023, thus providing upper limits on correlated variability in this energy regime[125]. In this conference, the SST-1M collaboration presented an analysis of 92.7 hours of Crab Nebula data, reporting a 4.4σ detection above 50 TeV. Their spectral measurements are in excellent agreement with previous observations, independently validating the instrument's calibration and sensitivity in the multi-TeV range[4].

Further supporting the diversity of PeVatron candidates, LHAASO has reported ultra-high-energy emission from LHAASO J1740+0948, likely associated with a bow-shock PWN[126]. The Tibet ASγ experiment presented UHE observations of the middle-aged PWN HESS J1849-000[39]. Additionally, H.E.S.S. reported hard-spectrum multi-TeV emission from the pulsar J1509-5850; its spectral characteristics hint at a potential PeVatron, though confirmation awaits future observations in the ultra-high-energy regime.

2.5 Unidentified Sources

Investigations into unidentified gamma-ray sources were presented, with a focus on LHAASO J0534+3535, LHAASO J1908+06, LHAASO J0341+5258 and LHAASO J2018+3651. LHAASO J0534 + 3535 is a possible unidentified pulsar halo in the starforming region G172.8 + 1.15, with no strong correlation between the CO distribution and the detected gamma-ray emissions[127]. The source MGRO J1908+06 is known as the PeVatron LHAASO J1908+06 [109]. For LHAASO J0341+5258, multi-wavelength data analysis suggests that its gamma-ray emission could be modeled either as a PWN or as an interaction between a SNR and a molecular cloud [19]. The LHAASO J2018+3651 region remains one of the most promising PeVatron candidates, with its gamma-ray spectrum extending up to 300 TeV [49].

2.6 The galactic diffuse emission

The Galactic diffuse emission (GDE) constitutes the non-thermal radiation from the Milky Way that remains after the removal of resolved sources. Studying this emission across the electromagnetic spectrum, from radio, infrared, and optical to X-rays, and from GeV gamma-rays (as mapped by Fermi-LAT) to UHE gamma-rays (observed by LHAASO and Tibet ASγ), is fundamental to understanding the origin, acceleration, and propagation of CRs. Multimessenger observations, combining gamma-ray data with neutrino and other CR measurements, are essential for unraveling the origin of both the GDE and Galactic CRs.

Recent observations from multiple instruments have advanced our view of the GDE. LHAASO presented updated measurements using a source-subtraction method [128] in this conference. The

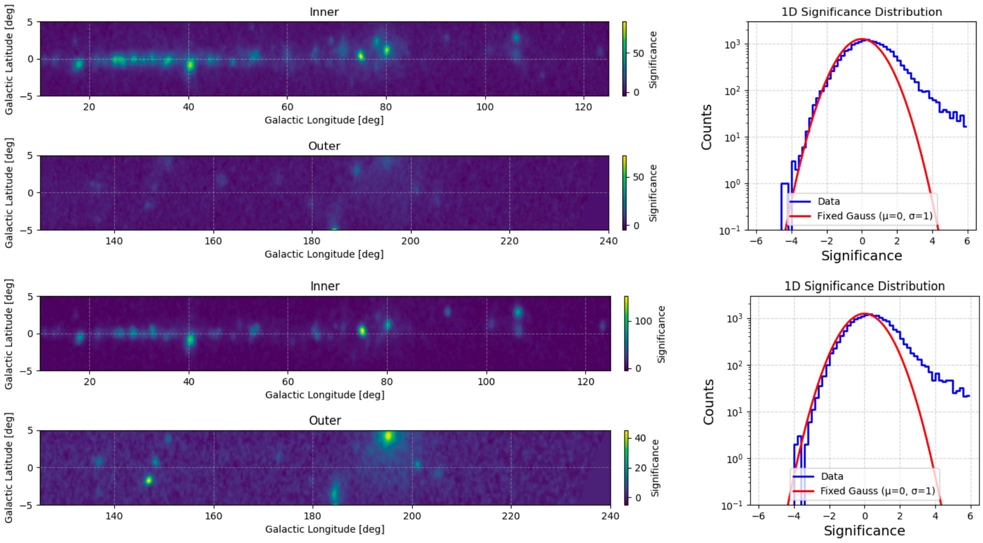


Figure 8: Significance map of Galactic Plane at WCDA (Upper panels) and KM2A (lower panels) energy range containing resolved sources and DGE [128].

significance maps of the Galactic plane observed by LHAASO in the WCDA and KM2A energy range containing resolved sources and DGE are plotted in Figure 8. Cross-comparisons were facilitated by Tibet ASγ [129, 130] and the HAWC collaboration, which presented an 8-year data set and a comparison with LHAASO GDE using masking analysis [73]. Furthermore, the absence of a significant correlation between intermediate/high-velocity clouds and Tibet ASγ UHE events places constraints on CR populations in the inner Galactic halo [131].

A key phenomenological finding arises from a comparison of the GDE spectrum with a model based on the LHAASO proton spectrum. This simple model, which does not account for the spatial distribution of the CRs, can explain the observed emission above 100 TeV. However, an additional component is required to account for flux below 100 TeV [128].

The interpretation of the GDE is being addressed through three main approaches. First, the contribution of various source populations is considered. "Cocoons" confining CRs near their sources could enhance the diffuse flux below $\sim$1 TeV, explaining the gamma-ray excess in the inner galaxy [132]. Microquasars have been proposed to explain the observed 1-10 PeV CRs and the GDE above 100 TeV [133]. Individual sources have also been emphasized to be properly considered for correct GDE modeling [134].

Second, refinements to CR models are essential. This includes exploring anisotropic diffusion [135], as well as updating CR emission models. For example, one study updates the KRAγ model by replacing exponential cutoffs with broken power-laws, showing that the resulting Galactic CR sea naturally explains the diffuse gamma-ray emission from GeV to PeV without a strong need for an extra component [136]. Meanwhile, another study demonstrates that the inverse Compton emission of leptonic CRs is capable of explaining the observed GDE of LHAASO, although these leptons are injected from discrete sources with finite lifetimes [137].

Finally, a crucial cross-check is proposed, which involves verifying the gas column density (a key input for emission models) using independent measurements of interstellar dust opacity [138].

2.7 Galactic Center and Bubbles

The Galactic Center (GC) region is a unique laboratory for studying a wide range of astrophysical phenomena, including CR acceleration and diffusion, large-scale outflows, Galactic evolution, magnetic fields, and potential dark-matter signatures.

Several key observational results have been reported. DAMPE presented observations of the Galactic Center Excess (GCE) between 2 GeV and ~10 GeV [50, 139], while CTAO LST-1 reported TeV diffuse gamma-ray emissions from the GC region based on 39 hours of data [25, 26]. Progress in reproducing the GeV GCE using CALET data is ongoing [140].

Significant findings related to the large-scale Fermi and eROSITA bubbles were also highlighted. The H.E.S.S. collaboration reported the detection of an extended gamma-ray emission spatially coincident with the base of Fermi bubbles [141]. DAMPE also reported observations of Fermi Bubbles, showing that they extend by tens of degrees [50]. Theoretically, it has been proposed that these bubbles form naturally in models that explain the star formation rate puzzle, indicating that they are a by-product of Galactic evolution [142].

2.8 Galactic Transients: Historical SNRs and Novae

Investigating high-energy transient emission from SNRs and Novae is key to understanding stellar evolution and particle acceleration processes. Of the five historically recorded Galactic supernovae with identified remnants, four, SN 1006, Tycho's SN, Kepler's SN, and the Crab Nebula have been deeply studied and detected at TeV energies, with fluxes ranging from 1 Crab to 0.3% Crab. H.E.S.S. has observed TeV emission from SN 1006 and Kepler's SN, while VERITAS has detected Tycho's SNR [143]. In particular, LHAASO has recently reported significant detections of Cas A in 0.8-10 TeV [144]. The fifth historical supernova, SN 1181, was just associated with its remnant Pa 30 in 2021, a rare Type Iax "zombie star" remnant[143]. VERITAS has since conducted the first TeV study of this unique object, setting an upper limit on its gamma-ray emission [143]. VHE detections of the symbiotic nova RS Ophiuchi by H.E.S.S. [145] and the LST-1 [146], as well as of the classical nova MGAB-V207 by H.E.S.S. [145].

3. Extragalactic Sources and Implications

The study of extragalactic sources is pivotal in unraveling the origins of ultrahigh-energy CRs (UHECRs) and astrophysical neutrinos. This conference featured research on multiple candidate source classes, including AGNs, galaxy clusters, starburst galaxies, and transients such as fast radio bursts (FRBs), GRBs, and kilonovae, shedding new light on their roles as potential CR accelerators.

Significant updates on extragalactic source catalogs were also presented. The VERITAS catalog includes 8 new AGN identifications since ICRC 2023.The LHAASO WCDA collaboration reported a TeV extragalactic sky map featuring 19 sources [147], as shown in the LHAASO extragalactic sky map. Furthermore, the H.E.S.S. extragalactic sky survey covering data from 2004 to 2012 was reported [148, 149]. The fourth HAWC catalog was announced for imminent release [150], and the upcoming 5FGL *Fermi*-LAT source catalog will incorporate a new interstellar emission model [151]. The sky maps of these catalogs are shown in Figure 9.

3.1 AGNs

The rich suite of multi-wavelength and VHE gamma-ray observations of AGNs presented at this conference provides powerful constraints on their underlying physics, from the central engine to relativistic jets and their cosmic impact.

Central Engine and Jet Physics: The question of the nature of AGN jets leads directly to the central energy mechanism. Studies of jet radio power were used to constrain the black hole energy extraction mechanism, suggesting that BL Lacertae objects (BL Lacs) have jets primarily powered by extracting black hole spin energy (Blandford-Znajek process), while flat-spectrum radio quasar (FSRQ) jets may be powered by the accretion disk (Blandford-Payne process)[152].

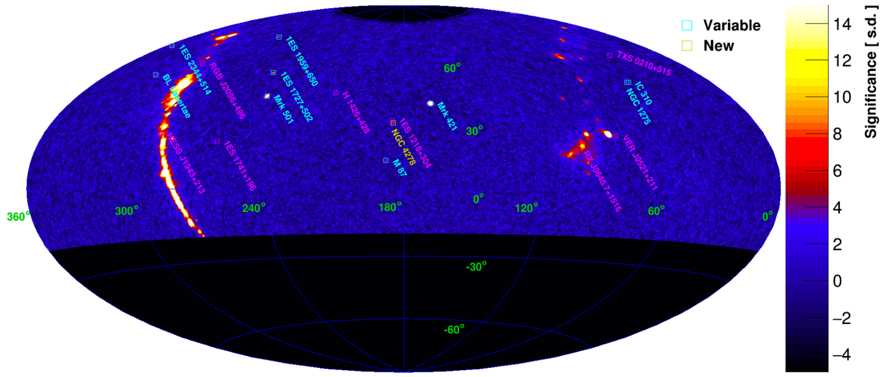
Radiation Mechanisms and Particle Acceleration: Modeling the spectral energy distribution (SED) from radio to TeV energies is fundamental for classifying AGNs and distinguishing dominant radiation mechanisms, from leptonic to potentially hadronic processes. Blazars are a class of active galactic nuclei whose jets are aligned close to our line of sight. They are systematically categorized into two main types based on their optical spectral features, including FSRQs with strong and broad emission lines, and BL Lacs with weak or absent emission lines. For BL Lacs, astronomers further subclassify them based on the frequency of the peak of their synchrotron emission. This scheme includes Low-frequency peaked BL Lacs (LBLs), Intermediate-frequency peaked BL Lacs (IBLs), High-frequency peaked BL Lacs (HBLs), and Extreme High-frequency peaked BL Lacs (EHBLs) with even higher peak frequencies intermediate-frequency peaked blazars (IBLs), high-frequency peaked blazars (HBLs), and extreme HBLs [153, 154]. A significant theme was the study of "changing-look" AGNs (e.g., OP 313[155, 156] and BL Lacertae[157]), which exhibit dramatic shifts in their spectral type and luminosity, challenging traditional models and offering real-time insights into accretion dynamics and jet formation.

Extreme variability on timescales as short as about 200 s for PKS 2155-304[158] suggests a very compact emission region, challenging standard one-zone models. A multi-blob stochastic dissipation model has been proposed to reproduce both this rapid variability and the observed SED[159].

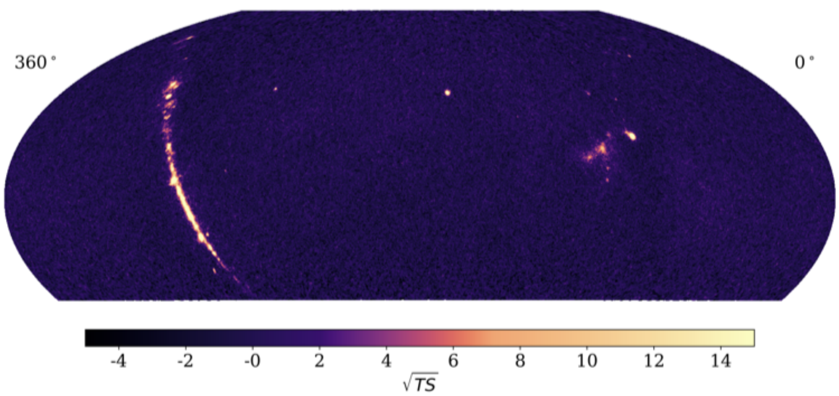
Polarization measurements offer a unique window into the magnetic field structure and particle acceleration processes. Polarization data from IXPE and Robopol for HBLs such as Mrk 501, Mrk 421,[160], and PKS 2155-304are being compared with multi-zone simulations[e.g. 161] to constrain the properties of the emission regions, such as whether the turbulent cells are identical or nonidentical [162].

Flux Variability and Multi-wavelength Flares: Flux variability across diverse timescales probes the size and location of emission regions. Intense monitoring campaigns captured high-states and outbursts from a diverse population of blazars and radio galaxies. Key events included major flares from OP 313 with VERITAS[155], BL Lacertae with LHAASO[147, 157], and PG 1553+113 with MAGIC[163]. In addition, LHAASO reported flare activities from sources such as NGC 4278, IC 310, 1ES 1959+650, Mrk 501 and the radio galaxy NGC 1275[147, 164–166].

A notable multi-instrument campaign targeted Mrk 421, with flares detected by LHAASO (March 2021 - March 2024, 0.4-20 TeV)[147, 166], MAGIC (December 2023, 0.2-1 TeV and >1



(a)



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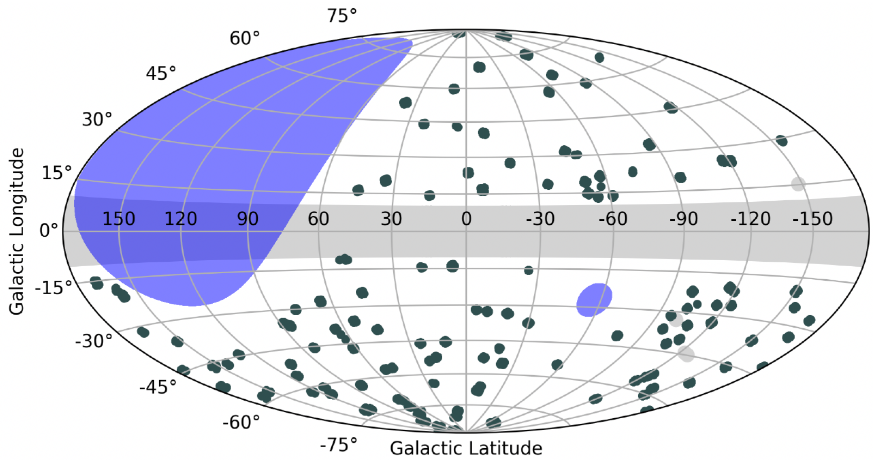

(c)

Figure 9: The extragalactic sky maps with (a) LHAASO WCDA (in Equatorial coordinate) [147], (b) HAWC (in Equatorial coordinate) [150], and (c) H.E.S.S. (in Galactic coordinate) [148, 149].

TeV)[167]; November 2009 to June 2010, > 100 TeV[168]), and HAWC (January 2020 - January 2021, >1 TeV)[169]. SST-1M also presented observations on Mrk 421 with data from January 2024 to May 2024 (>1 TeV) and presented a spectrum with 32.9-hour data[170]. Polarization measurements from IXPE (2-8 keV), R-band, and radio were reported for this source. Other key sources observed include PKS 2155-304 by MAGIC and LST-1[171], and B2 1811+31 in a joint MAGIC and *Fermi*-LAT campaign[172].

These intensive monitoring efforts also extended to nearby radio galaxies, with particular focus on the iconic M87. High-resolution imaging, notably with the Event Horizon Telescope (EHT), has been instrumental in directly connecting jet kinematics to the central supermassive black hole in M87. Coordinated multi-wavelength campaigns on M87 in 2017 (a quiescent state) and 2018 (which captured a rare gamma-ray flare) provided crucial data, compared through heuristic models to investigate the origin of its gamma-ray emission[173]. LHAASO reported a UHE flare from M87 in 2022, providing spectra for both low and flaring states[147]. This detection is supported by HAWC, which reported a 5.21σ detection from the source[174].

Multi-messenger Observations and CR Origin: The connection between gamma-ray emission and astrophysical neutrinos is a key avenue for identifying hadronic acceleration sites. NuSTAR/Fermi/VERITAS observations under a Target-of-Opportunity program found a possible association between PKS 0446+11 and IceCube neutrino alert IC240105A, and PKS 1217+02 and IC241224A[175]. Investigation of HAWC data (2015-2024) with IceCube alerts showed spatial coincidence with Mrk 421[176]. In contrast, MAGIC 29-hour observations on NGC 4151, the second probable neutrino source after NGC 1068, set a low upper limit of 0.1 to 10 TeV, further constraining the environment of the source[177]. Furthermore, high-resolution X-ray imaging of the jets of Cen A resolved X-ray knots on a 10-pc scale, which can be explained by jet/stellar wind collision, thus providing potential UHECR acceleration sites[178].

Population Studies and Future Prospects: Population studies are essential for understanding the evolution of AGN and their contribution to the diffuse extragalactic gamma-ray background, informing the detection prospects for future observations. The luminosity functions were reported on the basis of the VERITAS HBL survey, H.E.S.S. HEGS catalog[179], and CTAO simulation[180].

3.2 Galaxy Clusters, Starburst Galaxies

Galaxy clusters and starburst galaxies are proposed as potential sources of UHECRs, neutrinos, gamma-ray photons, and dark matter.

Significant observational progress has been reported for galaxy clusters. The LHAASO WCDA collaboration has detected VHE gamma-ray emission from NGC 1275, the central galaxy of the Perseus Cluster, with a significance of 8.3σ [147]. Complementary theoretical work explored the contribution of Perseus-like clusters to UHECR, neutrino, and gamma-ray fluxes [181]. In a broader survey, an analysis of 48 local galaxy clusters using *Fermi*-LAT data resulted in the detection of the Coma Cluster with a significance of 4σ.

For starburst galaxies, observations of M82 were updated with new data from the VERITAS Starburst Galaxy Discovery Program [182]. Subsequent multiwavelength modeling of M82 favors a hadronic origin for its gamma-ray emission [180, 182]. To assess the collective impact of such galaxies, a comprehensive population study finds that star-forming galaxies contribute at most 50-

60% of the extragalactic gamma-ray background around a few GeV, leaving a significant portion to other source classes [183].

3.3 Transients: FRBs, GRBs, Kilonovae, Superluminous Supernovae

Studies of high-energy transients, including FRBs, GRBs, and Kilonovae, were presented at the conference, offering insight into some of the most energetic phenomena in the universe.

FRBs are transient astrophysical phenomena characterized by brief, intense radio emissions. Their high luminosities, short timescales, and large dispersion measures all indicate an extragalactic provenance, with magnetars representing a leading candidate source. The rapidly growing sample of detected FRBs including numerous repeating sources has motivated extensive multi-wavelength follow-up campaigns. The H.E.S.S. collaboration reported a follow-up program searching for VHE gamma-ray counterparts. No significant emission was detected, placing constraints on their VHE luminosity [184].

Recent progress in GRB studies has emphasized systematic VHE follow-up and multi-wavelength correlation analyses. A systematic investigation into the long-standing challenge of VHE detections revealed a low detectable GRB rate of <1 per year for current IACTs, which is expected to increase to approximately 4 per year with future CTAO[185]. The MAGIC Collaboration reported the detection of two GRBs, GRB 190114C and GRB 201216C, through its extensive follow-up program [186], while 15 years of HES observations have not produced additional VHE detections [187]. A scenario further supported by multi-wavelength modeling of the short GRB 160821B, which is best explained by a synchrotron plus synchrotron self-Compton (SSC) model in a wind environment [188].

Multiple studies focused on the brightest-of-all-time (BOAT) event, GRB 221009A, revealing its complex temporal and spectral evolution. The afterglow light curve exhibited two components of rapid variability superimposed on a smooth decay [164]. LST-1 observations provided key constraints on structured jet afterglow models [189], with the TeV light curve showing an unexpected break around one day post-burst. A unified model was proposed to explain both late-time TeV behavior and earlier emission [190].

Kilonovae were discussed as potential VHE sources via two channels, shock acceleration in the ejecta [191] or inverse Compton scattering by the GRB jet [192]. The upper limits from H.E.S.S. and HAWC for GRB 170817A are already constraining the latter model [192]. Contributions of kilonovae to the diffuse MeV background [191] were also presented.

In the domain of superluminous supernovae (SLSNe), an analysis of *Fermi*-LAT data has identified high-energy emission from SLSN 2017egm at a distance of 135 Mpc, with a test statistic (TS) value greater than 16 [193].

3.4 Implications

Extragalactic gamma-ray observations are a pivotal tool for astrophysics and cosmology. They are crucial for constraining the diffuse extragalactic background light (EBL) and the intergalactic magnetic field (IGMF), which govern photon propagation and particle acceleration in the extragalactic medium.

EBL models have been constrained using LHAASO data on Mrk 421 [194] and updated optical depth measurements combining TeV observations from STeVECat with 15-year *Fermi*-LAT GeV

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data [156]. For IGMF, the non-detection of pair-echo emission from GRB 221009A by CTAO suggests a lower limit of $B_{\rm IGMF} > 2.5 \times 10^{-17}$ G. Future observations of such echoes with the full CTAO array are expected to set more stringent limits [195], as will continued studies of blazars such as 1ES 0229+200 [196].

Furthermore, these high-energy gamma-ray observations provide a unique probe for investigating fundamental physics, such as probing Axion-like Particles[197, 198], constraining the Hubble constant[198], and searching for the Lorentz Invariance Violation[199, 200]. From a cosmological perspective, measuring time delays in gravitationally lensed gamma-ray sources offers a powerful method to study matter distribution and cosmological parameters [201]. On a galactic scale, the contribution of globular clusters to galactic gamma-ray emission provides a tracer of galaxy evolution [202].

4. Summary

Gamma-ray astronomy stands at the forefront of addressing the long-standing mysteries surrounding the origin, acceleration, and propagation of CRs. This report has synthesized key advances presented at the conference and highlighted significant progress on multiple fronts.

Notable developments include the emergence of microquasars as promising PeVatron candidates, alongside growing evidence for hadronic acceleration processes in sources such as supernova remnants and pulsar halos. Observations of Galactic diffuse emission and its correlation with CR distributions have provided deeper insights into the transport mechanisms pervading the Milky Way.

In the extragalactic domain, AGNs and GRBs allow us to constrain the extragalactic background light, intergalactic magnetic fields, and potential signatures of Lorentz invariance violation or axion-like particles.

Technological and analytical innovations, including next-generation instrumentation such as CTAO, SWGO, and LACT, as well as advanced software and deep learning methods, are pushing the sensitivity and resolution of observations to new heights.

The upcoming deployment of these cutting-edge observatories promises to further transform our understanding of particle acceleration across the Universe, solidifying gamma-ray astronomy's essential role in multi-messenger and multi-wavelength astrophysics.

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