Journal Club:

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources (LHAASO)

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Links

- **LHAASO:**
  - https://www.nature.com/articles/s41586-021-03498-z
  - https://www.nature.com/articles/s41586-021-03498-z.pdf
  - Performance: https://arxiv.org/abs/2101.03508
  - http://english.ihep.cas.cn/lhaaso/index.html
  - https://en.wikipedia.org/wiki/Akaike_information_criterion
- **Crab Nebula:**
  - https://en.wikipedia.org/wiki/Crab_Nebula
  - https://cs.wikipedia.org/wiki/Krab%C3%AD_mlhovina
  - https://www.nasa.gov/feature/goddard/2017/messier-1-the-crab-nebula
  - https://www.cnet.com/news/the-crab-nebula-slammed-earth-with-highest-energy-gamma-rays-ever-seen/
- Nature:
  - results, then methods
- This presentation:
  - methods, then results


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Abstract

Article

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

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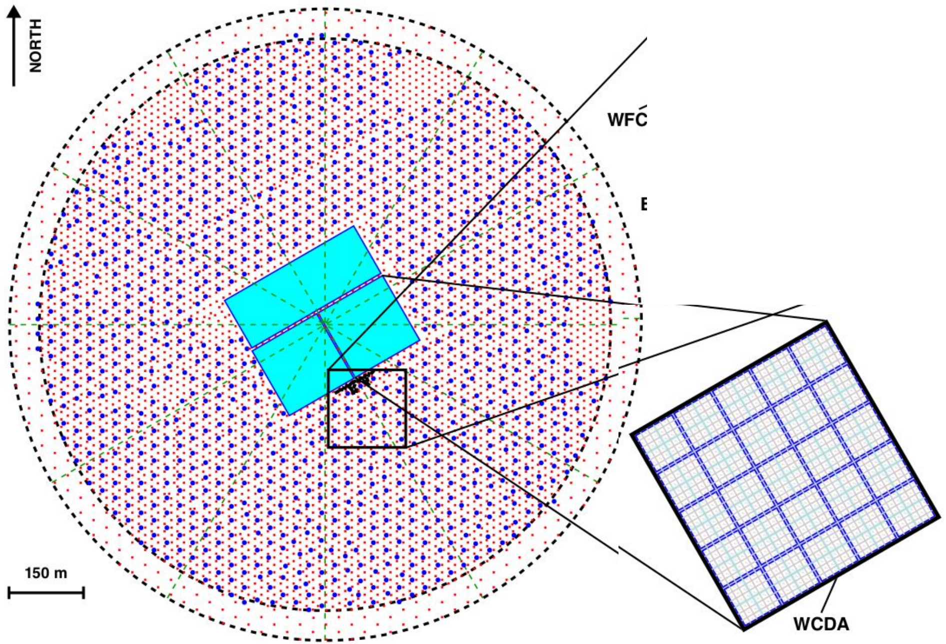
The extension of the cosmic-ray spectrum beyond 1 petaelectronvolt (PeV; 10^{15} electronvolts) indicates the existence of the so-called PeVatrons—cosmic-ray factories that accelerate particles to PeV energies. We need to locate and identify such objects to find the origin of Galactic cosmic rays[1]. The principal signature of both electron and proton PeVatrons is ultrahigh-energy (exceeding 100 TeV) γ radiation. Evidence of the presence of a proton PeVatron has been found in the Galactic Centre, according to the detection of a hard-spectrum radiation extending to 0.04 PeV (ref. [2]). Although γ-rays with energies slightly higher than 0.1 PeV have been reported from a few objects in the Galactic plane[3–6], unbiased identification and in-depth exploration of PeVatrons requires detection of γ-rays with energies well above 0.1 PeV. Here we report the detection of more than 530 photons at energies above 100 teraelectronvolts and up to 1.4 PeV from 12 ultrahigh-energy γ-ray sources with a statistical significance greater than seven standard deviations. Despite having several potential counterparts in their proximity, including pulsar wind nebulae, supernova remnants and star-forming regions, the PeVatrons responsible for the ultrahigh-energy γ-rays have not yet been firmly localized and identified (except for the Crab Nebula), leaving open the origin of these extreme accelerators.

LHAASO arrays

- **LHAASO :: The Large High Altitude Air Shower Observatory**
  - observe both cosmic rays and gamma rays in TeV -- PeV
  - Mountain Haizi (29° 21′ 27.6″ N,100° 08′ 19.6 ″ E),
  - 4,410 m above sea level, in Sichuan, China
- WCDA: Water Cherenkov Detector Array
- KM2A: KilometerSquareArray
  - A significance of 30σ obtained for the detection of the Crab Nebula in 136 days
  - since 27th December 2019, 308 live days.
- WFCTA: Wide Field-of-view Cherenkov Telescope Array

LHAASO arrays

- WCDA: Water Cherenkov Detector Array
  - Monte Carlo, Crab Nebula (0.1 photon/hour) alibrations
  - reject hadronic showers (CR) based on observed muons
  - 3 water ponds of 178 000 m^2, 4.5m deep!
  - angular resolution 0.2°, ⅙ of the sky, transient signals monitoring.



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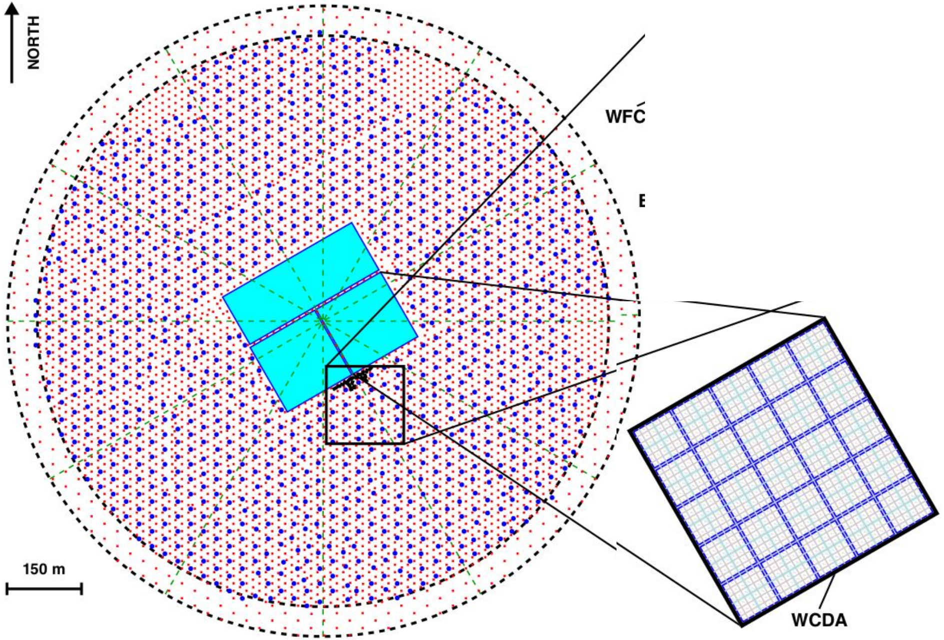
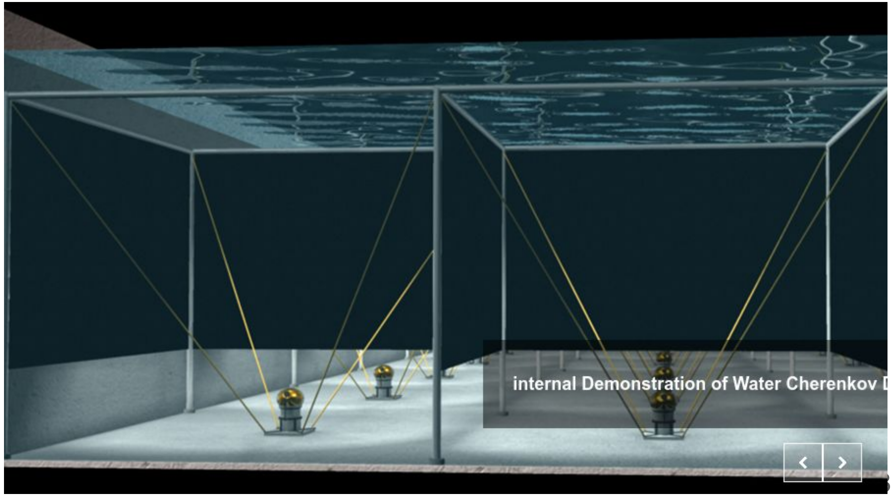
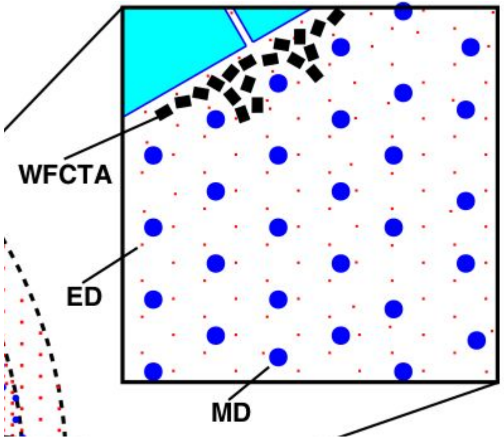




LHAASO arrays

- KM2A: KilometerSquareArray
  - partially completed (½), total will have 1km^2
  - 5.2k 1m^2 1cm thick scintillator counters (EDs) @ 15m grid
    - WLS fibres, PMT
  - 1.2k undersurface Muon Detectors (MDs) @ 30m grid
  - total will have 1,188,36 m^2
  - 2.5 m beneath the soil (20 radiation lengths)
  - filled with pure water 1.2 m in depth, 8'' PMT
  - operational ½: 578 MDs, 18,800 m^2

see ref. [8]. Here, we provide a brief description. The KM2A half-array currently in operation includes 2,365 EDs. Each ED is made of four plastic scintillation tiles (100 cm × 25 cm × 1 cm) covered by a 5-mm-thick lead plate. Embedded wavelength-shifting fibres transfer the scintillation light to a photomultiplyer tube (PMT). The charge output is used to measure the number of crossing shower particles with excellent linearity for up to more than 10^4 particles. The time resolution is about 2 ns. All of the EDs are synchronized within 0.2 ns. The shower trigger logic



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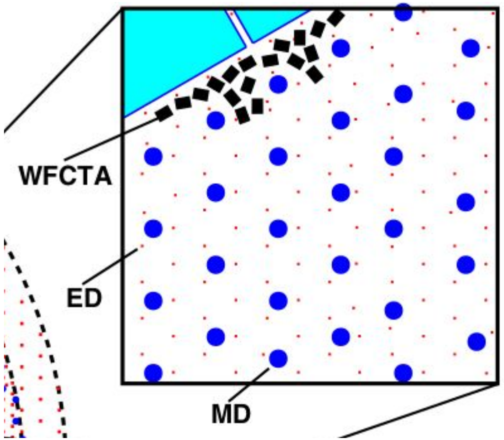
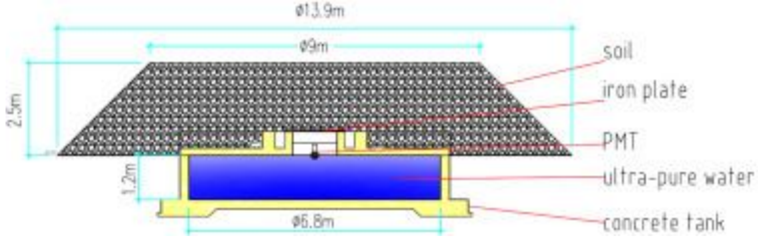
γ-ray-induced showers. A shower initiated by a high-energy γ contains fewer muons than a primary CR-induced air shower. Thus, using the ratio N_μ/N_e as a selection criterion (where N_μ is the total number of muons measured by MDs and N_e is the total number of particles counted by EDs), KM2A is capable of rejecting the CR background by a factor of 10^{-2} at 20 TeV and 10^{-4} above 100 TeV. Together with an angular resolution of 0.3° (68% containment angle of flux from a point source), the KM2A half-array is an essentially background-free γ-ray detector at energies >100 TeV. Quantitatively, the differential sensitivity of the



LHAASO arrays



- KM2A: KilometerSquareArray
  - 1.2k undersurface Muon Detectors (MDs) @ 30m grid
  - total will have 1,188,36 (??) m^2
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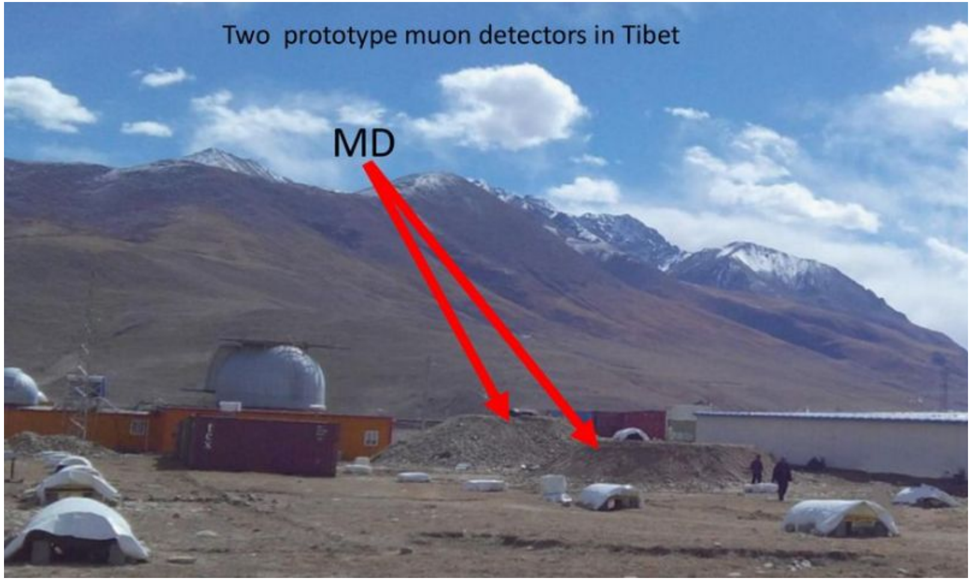
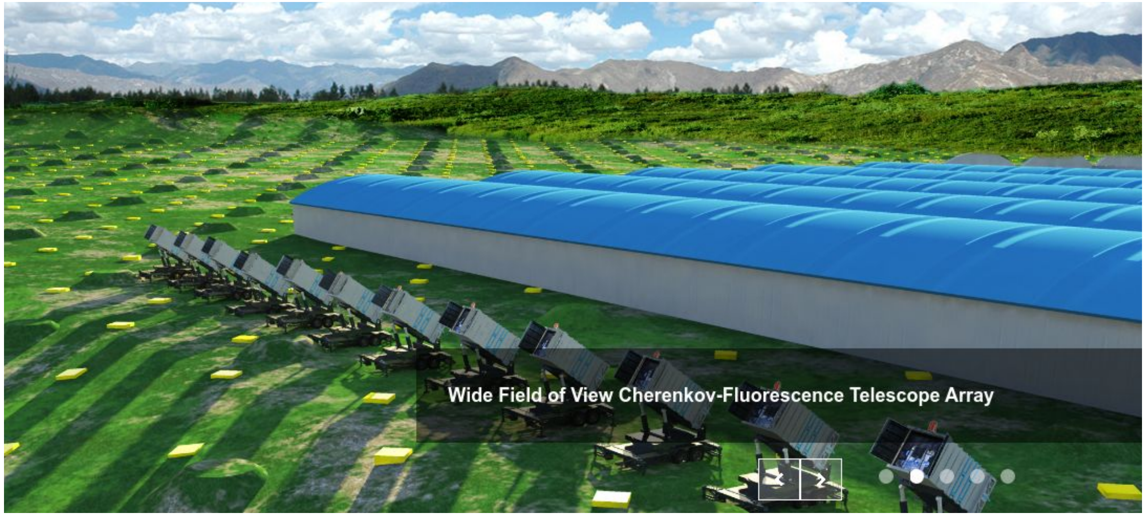
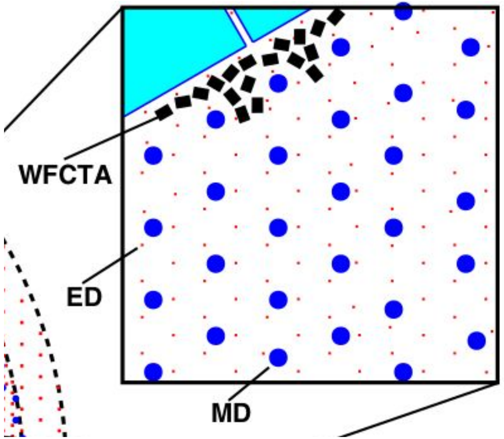


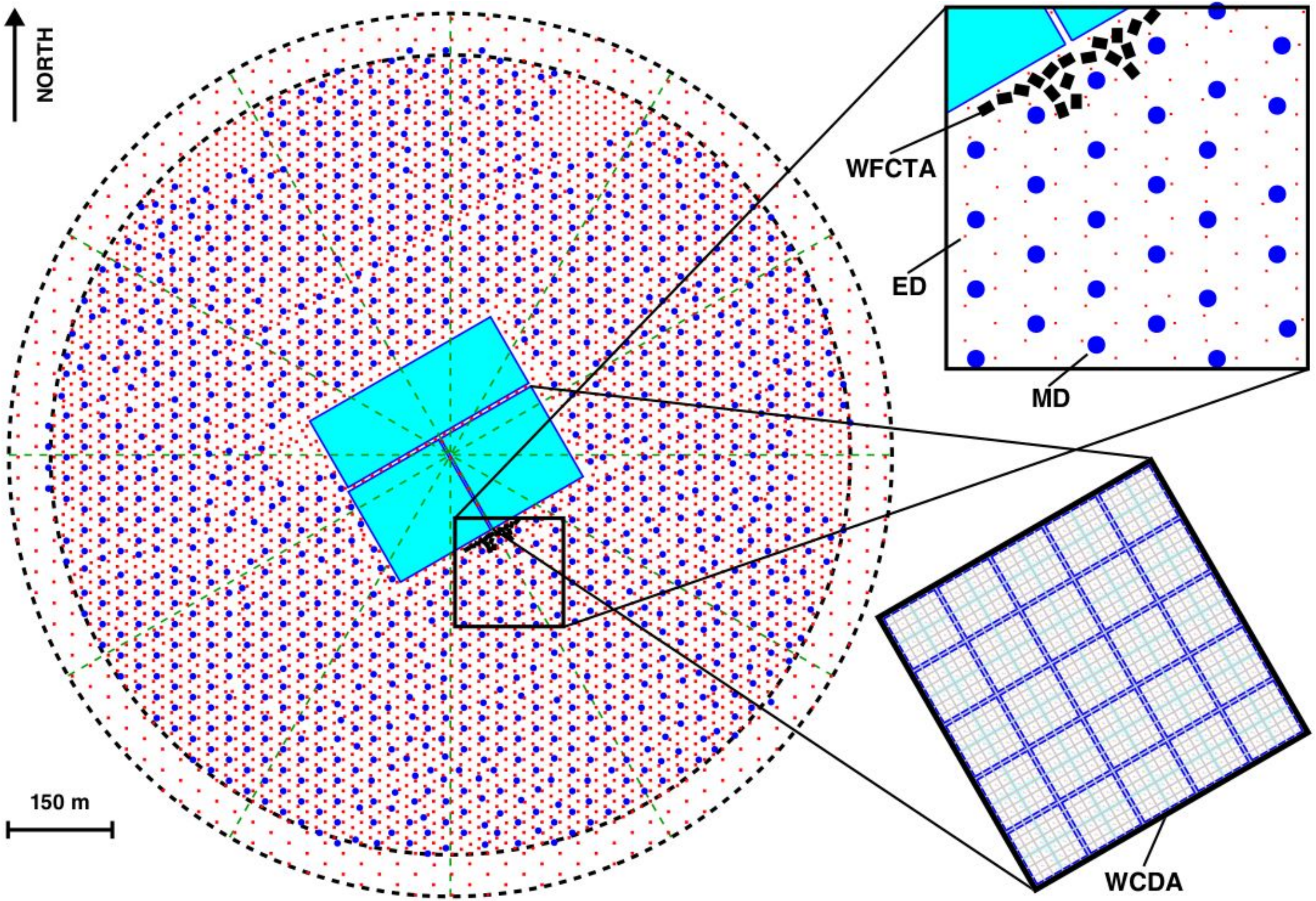
LHAASO arrays

- WFCTA: Wide Field-of-view Cherenkov Telescope Array
    - 18 telescopes for Cherenkov from CRs 50 TeV -- 100 PeV.
    - FOV 16° × 16° each
    - not used in the study





LHAASO



Event reconstruction

- Cuts: $N_\mu / N_e < 1/230$
  - 84,000 γ-like events.

All of the EDs are synchronized within 0.2 ns. The shower trigger logic requires, for the KM2A half-array, at least 20 EDs fired within a window of 400 ns. This trigger allows fully efficient detection of shower events of energy above 10 TeV. The ED signals are used to determine the impact point of the shower axis, the shower size and the arrival direction. Above 60 TeV, the core location is determined with an accuracy better than 3 m, enabling a high-precision measurement of the shower arrival direction with an angular resolution of ≤0.3° for γ-induced showers of up to 40° zenith angle. This is verified by the observation of well known

Energy determination

- Simulation-based.
- Bin purity: fraction of 67% around 100 TeV stay on the diagonal of the truth-reconstruction migration matrix.

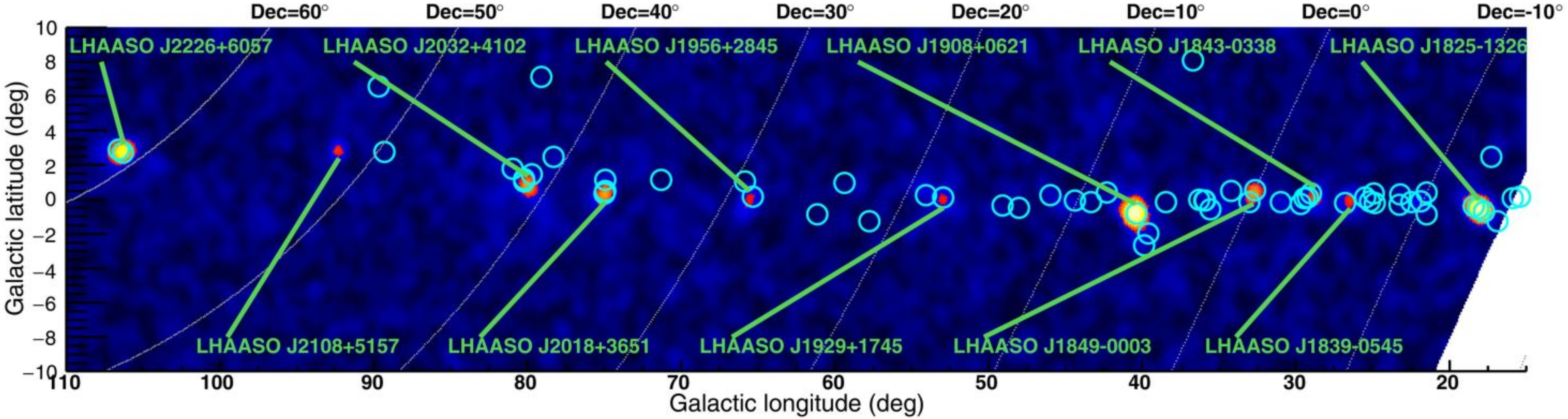
By reconstructing the shower profile, the particle density evaluated at a distance of 50 m from the shower core is used to estimate the energy of the primary γ-ray. The energy resolution is better than 14% for photons above 100 TeV arriving from a zenith angle of <35°. This defines the bin size of $\Delta(\log E) = 0.2$ in the measurements of the spectral energy distributions (SEDs) of the sources to minimize bin-to-bin migration mainly between adjacent bins. Further examination for any non-Gaussian tails of the energy resolution function—defined as the distribution of $(E_{rec} - E_{true})/E_{true}$, where E_{rec} is the reconstructed photon energy and E_{true} is the thrown-in energy in the shower/detector simulation—is carried out.

Best events

- Quest for observing gamma PeVatrons -- cosmic accelerators to PeV.
- Perhaps first evidence of PeV from SN remnant.

> While the study of the serendipitous search for γ-ray sources is underway, here we report 12 γ-ray sources with energies ≥100 TeV detected with statistical significance ≥7σ (see Table 1). From two of them, γ-rays with energy exceeding 0.8 PeV were detected, and the energy of the most energetic photon detected by LHAASO J2032+4102 is 1.4 PeV.

Sources



Dec=60°
Dec=50°
Dec=40°
Dec=30°
Dec=20°
Dec=10°
Dec=0°
Dec=-10°
LHAASO J2226+6057
LHAASO J2032+4102
LHAASO J1956+2845
LHAASO J1908+0621
LHAASO J1843-0338
LHAASO J1825-1326
LHAASO J2108+5157
LHAASO J2018+3651
LHAASO J1929+1745
LHAASO J1849-0003
LHAASO J1839-0545
Galactic latitude (deg)
Galactic longitude (deg)
10
8
6
4
2
0
−2
−4
−6
−8
−10
110
100
90
80
70
60
50
40
30
20

Sources

Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 - 0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 - 0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimated as the boundary values of the area that contains ±34.14% of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the error is 1σ.

Results

- Selected sources spectra, smoothed by PSF.

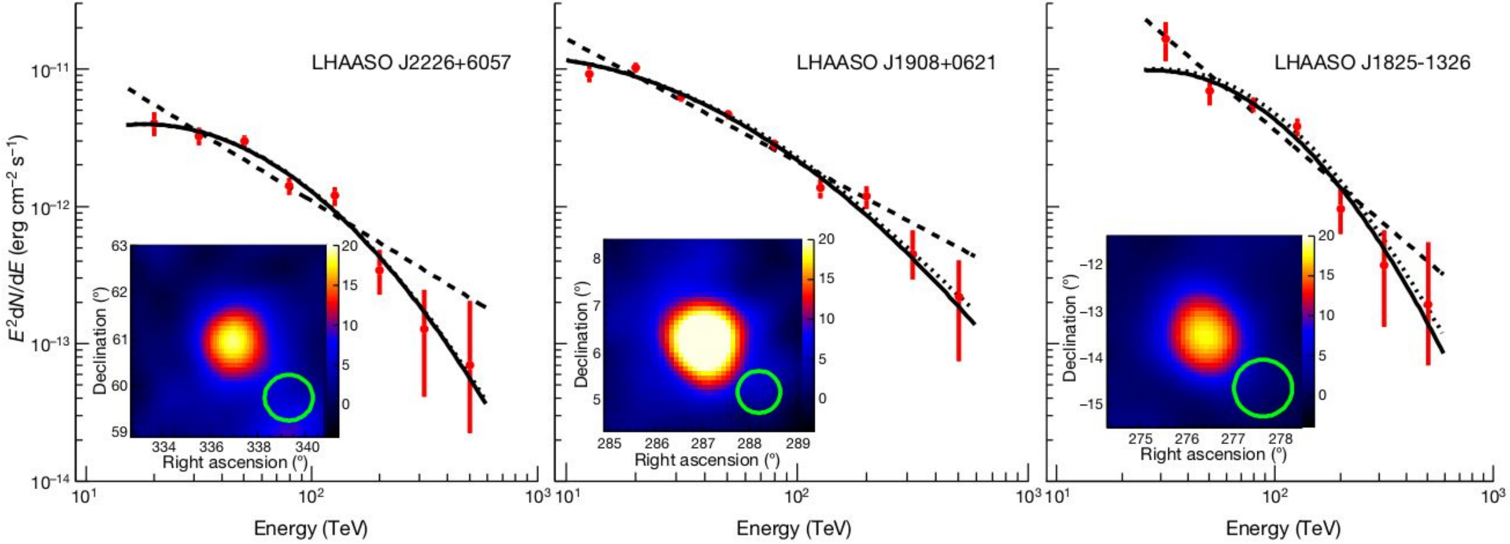


Fig. 1 | Spectral energy distributions and significance maps. a–c, Data are shown for LHAASO J2226+6057 (**a**), LHAASO J1908+0621 (**b**), and LHAASO J1825-1326 (**c**). Spectral fits with a log-parabola function (solid lines) in the form of $[E/(10\text{ TeV})]^{-a-b\log[E/(10\text{ TeV})]}$ are compared with the power-law fits $E^{-\Gamma}$ for: $a=1.56$, $b=0.88$ and $\Gamma=3.01$ (**a**); $a=2.27$, $b=0.46$ and $\Gamma=2.89$ (**b**); and $a=0.92$, $b=1.19$ and $\Gamma=3.36$ (**c**). The dotted curves correspond to the log-parabola fits corrected for the interstellar γ–γ absorption (see Methods for the radiation fields and Extended Data Fig. 6 for the opacity curves). The comparison of the power-law (PL) model and the log-parabola (LOG) model with the Akaike Information Criterion[20] (AIC) gives: $AIC_{LOG}=12.3$ and $AIC_{PL}=24.4$ for LHAASO J2226+6057; $AIC_{LOG}=15.1$ and $AIC_{PL}=30.1$ for LHAASO J1908+0621; and $AIC_{LOG}=11.6$ and $AIC_{PL}=14.8$ for LHAASO J1825-1326. The insets show the significance maps of the three sources, obtained for γ-rays above 25 TeV. The colour bars show the square root of test statistics (TS), which is equivalent to the significance. The significance ($\sqrt{TS}$) maps are smoothed with the Gaussian-type point spread function (PSF) of each source. The size of PSFs (68% contamination regions) are shown at the bottom right of each map. We note that the PSFs of the three sources are slightly different owing to different inclination angles. Namely, the 68% contamination angles are 0.49° for LHAASO J2226+6057, 0.45° for LHAASO J1908+0621 and 0.62° for LHAASO J1825-1326. Error bars represent one standard deviation.

LHAASO Sky

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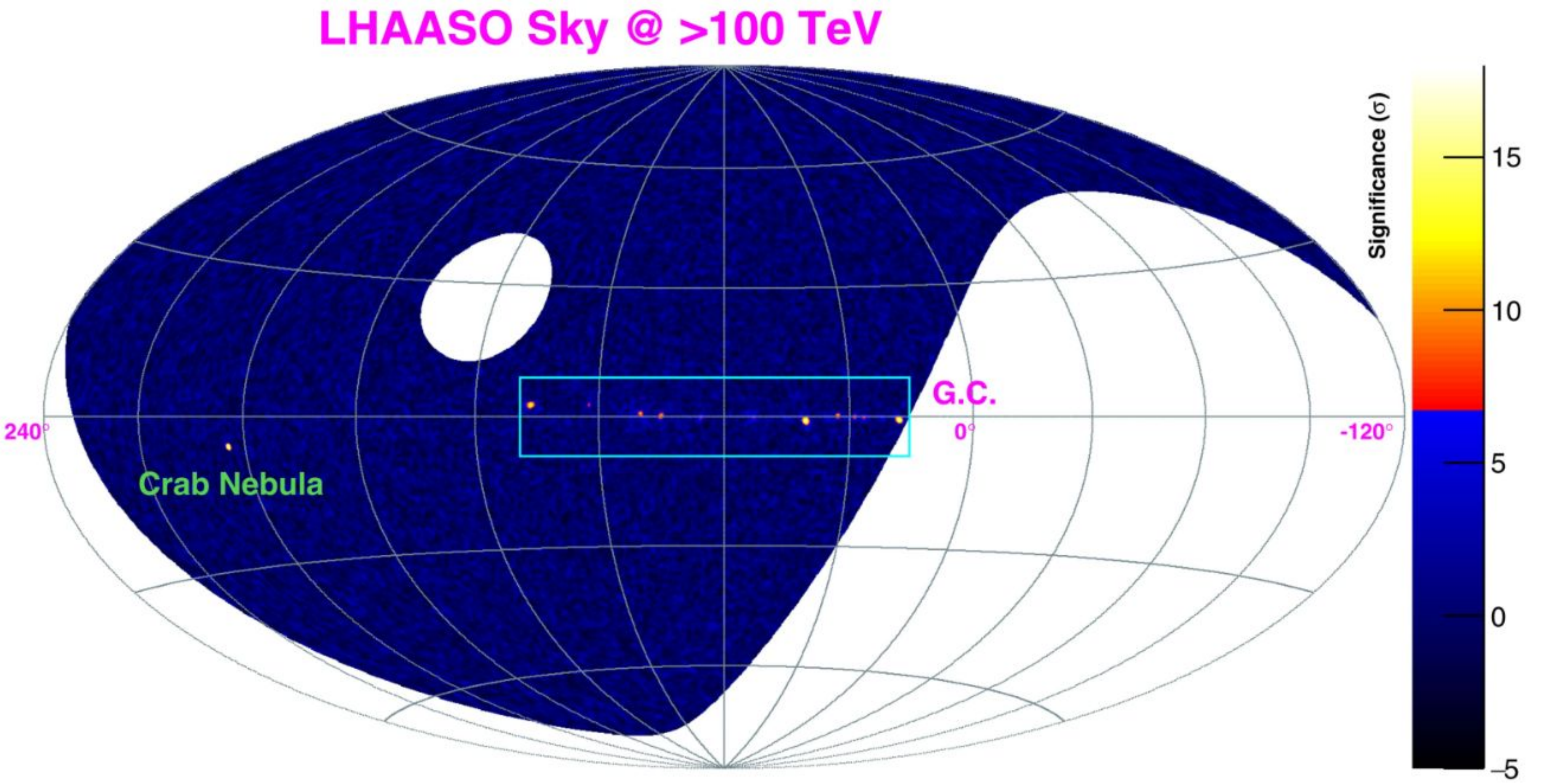

LHAASO Sky @ >100 TeV
G.C.
240°
0°
-120°
Crab Nebula
Significance (σ)
15
10
5
0
−5

The End

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