

Recent LHAASO Results on UHE Gamma-Ray Sources: Probing Galactic PeVatrons and Cosmic-Ray Origin

Reporter: LIU Bing (刘冰)

on behalf of LHAASO collaboration

Purple Mountain Observatory, Chinese Academy of Science

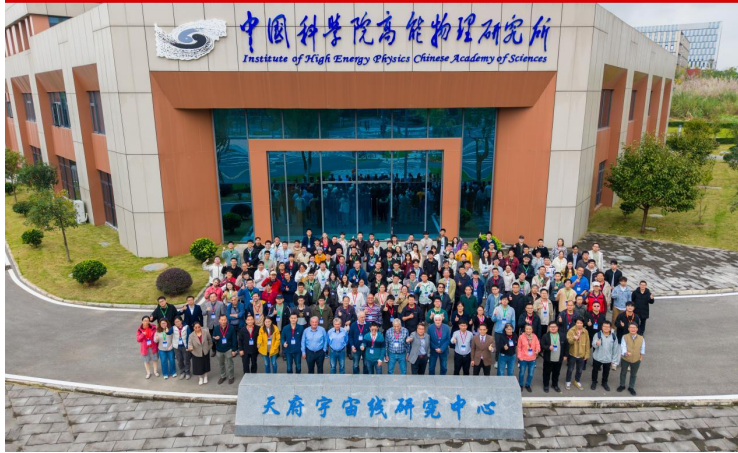
LHAASO Collaboration



Currently, **334** members from **39** institutions.

2025年LHAASO合作组第二次会议

四川成都 2025.10.22-26



The First LHAASO Collaboration Conference in 2026

Nanjing University Suzhou Campus, Jiangsu, China Apr.25-29 2026



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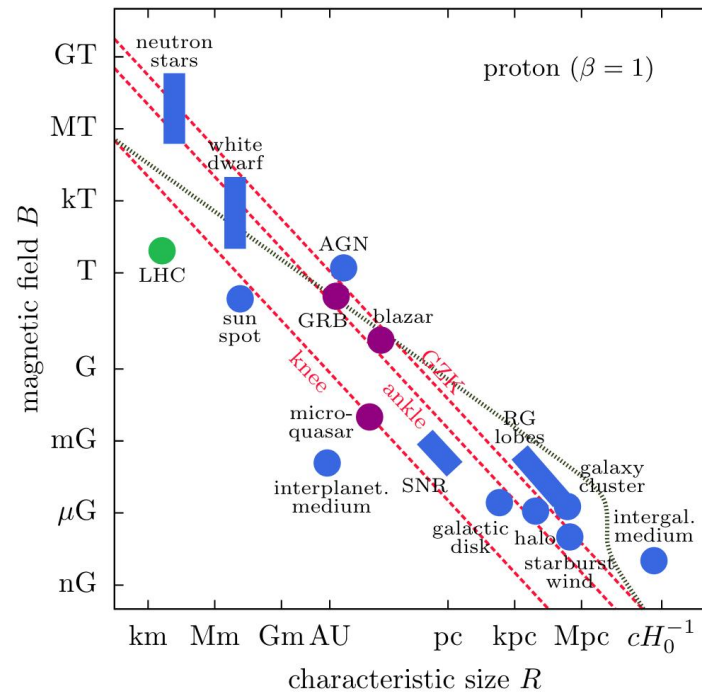
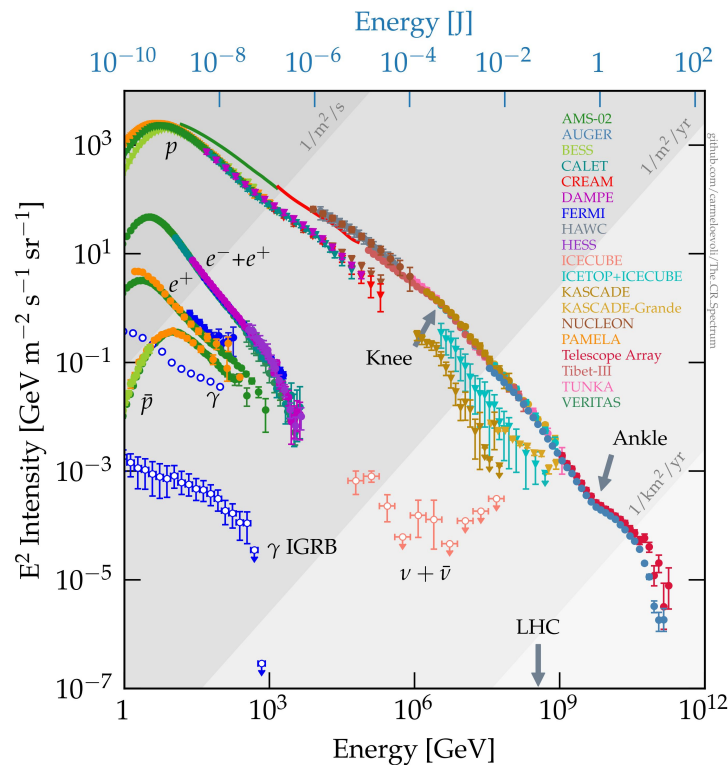
Outline

- Introduction: the LHAASO experiment
- LHAASO catalog and measurement of GDE
- Galactic Gamma-ray source observations
 - ✓ Supernova remnants
 - ✓ Pulsar wind nebulae and pulsar halos
 - ✓ Young massive star clusters
 - ✓ Binaries (Microquasar/Gamma-ray binary)
 - ✓ “Dark” sources, “Passive” GMCs
- Measurements of CR Spectra and Anisotropy
- Summary and prospect

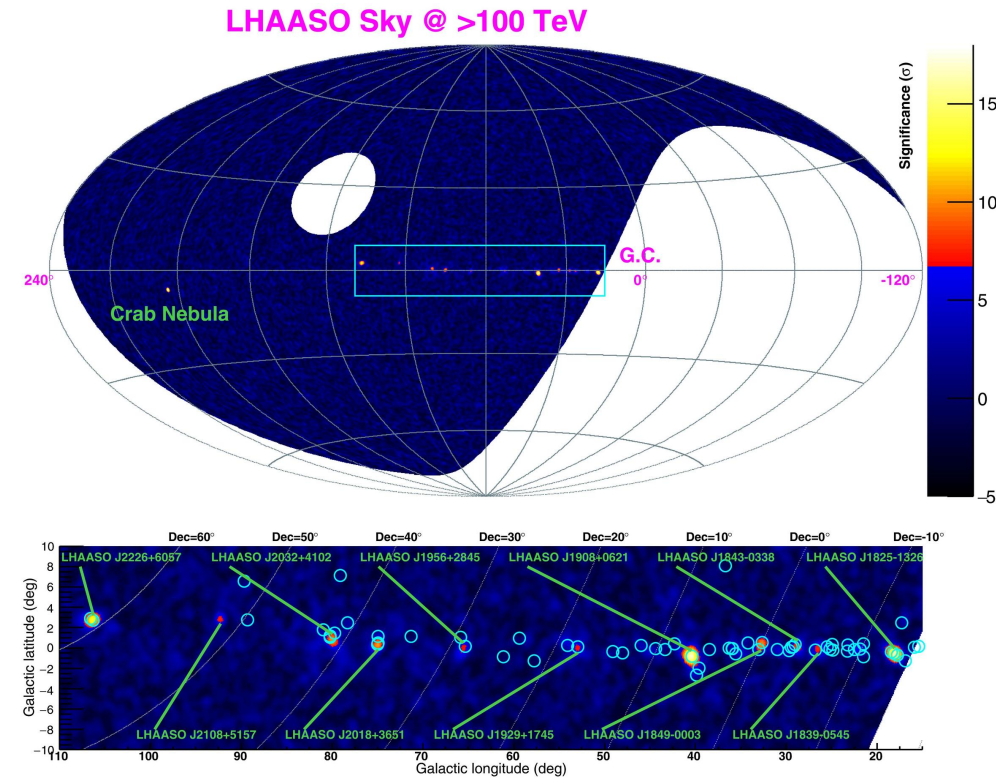
Probing the Origin of Galactic CRs with LHAASO

CRs are high-energy particles from outer space, those with $E < \sim 3$ PeV (around “**knee**” region) are believed to be accelerated within our Galaxy.

- Which kinds of Galactic sources are **PeVatrons** that can accelerate particles (especially protons) to the **PeV** regime?
- $E_{\text{max},p} \gtrsim \text{PeV}$ (via p-p interactions) $\rightarrow E_\gamma \gtrsim 100$ TeV



LHAASO successfully opens the PeV γ -ray window, revealing a number of **PeVatron candidates**.

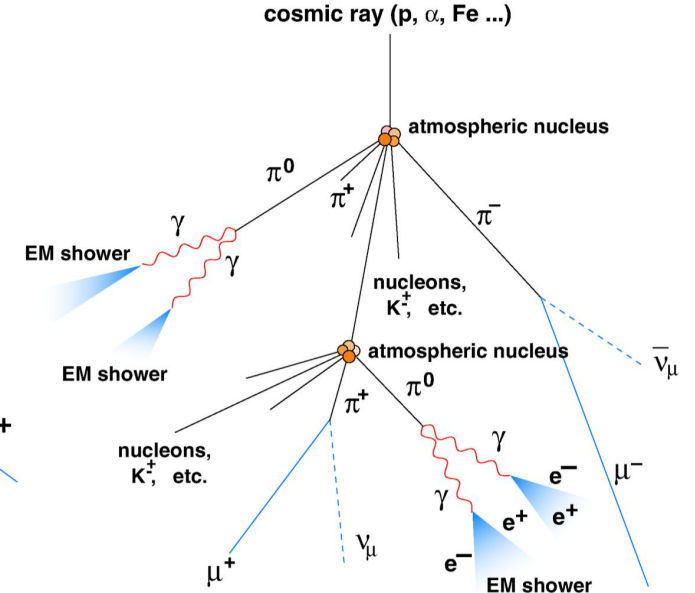
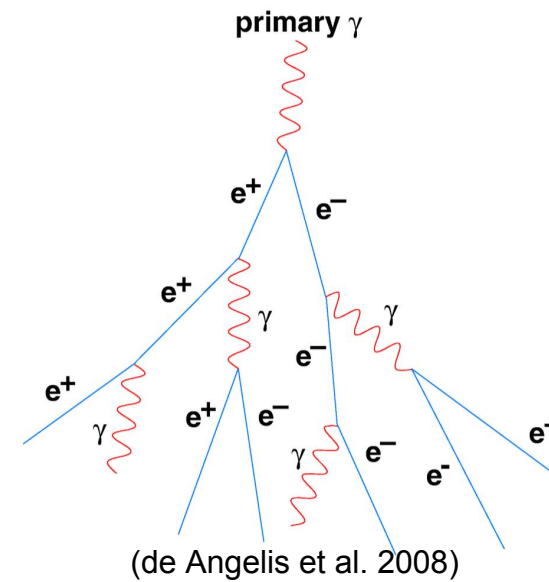
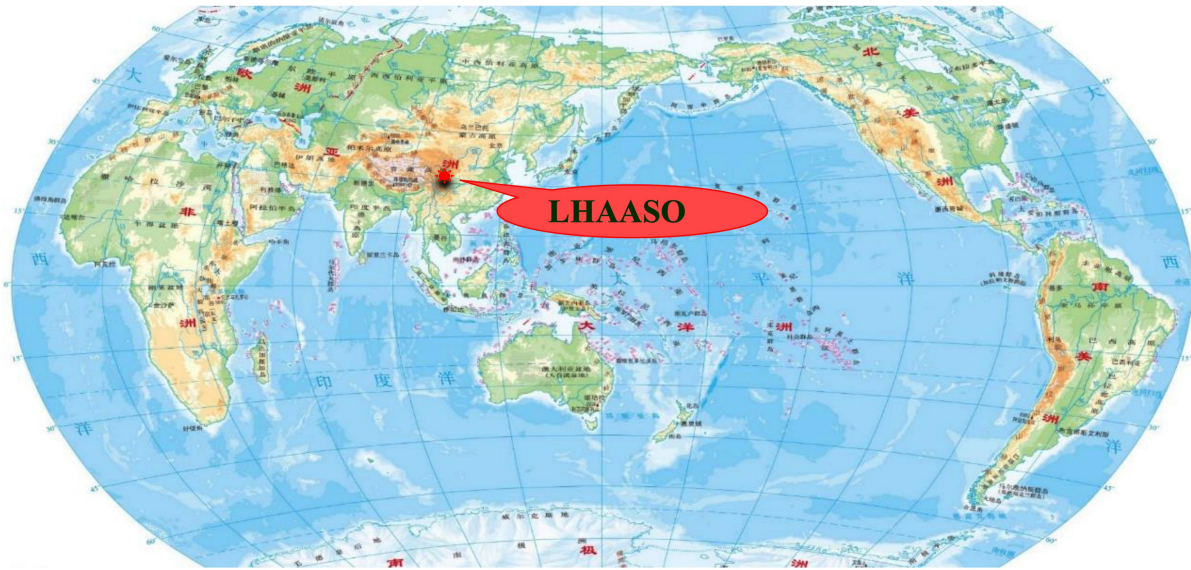


UHE photons up to 1.4 PeV from 12 γ -ray sources (Cao et al. 2021, Nature, 594, 33)

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LHAASO: Large High Altitude Air Shower Observatory



- Haizi mountain, Sichuan Province, China
- 4410m above the sea level
- A large-scale dual-purpose experiment for CR and γ -ray observations.
- Hybrid detector arrays to detect secondary products from CR air showers and γ -ray air shower.
- Full operation since July 2021



Layout of LHAASO

Square Kilometer Array (KM2A)

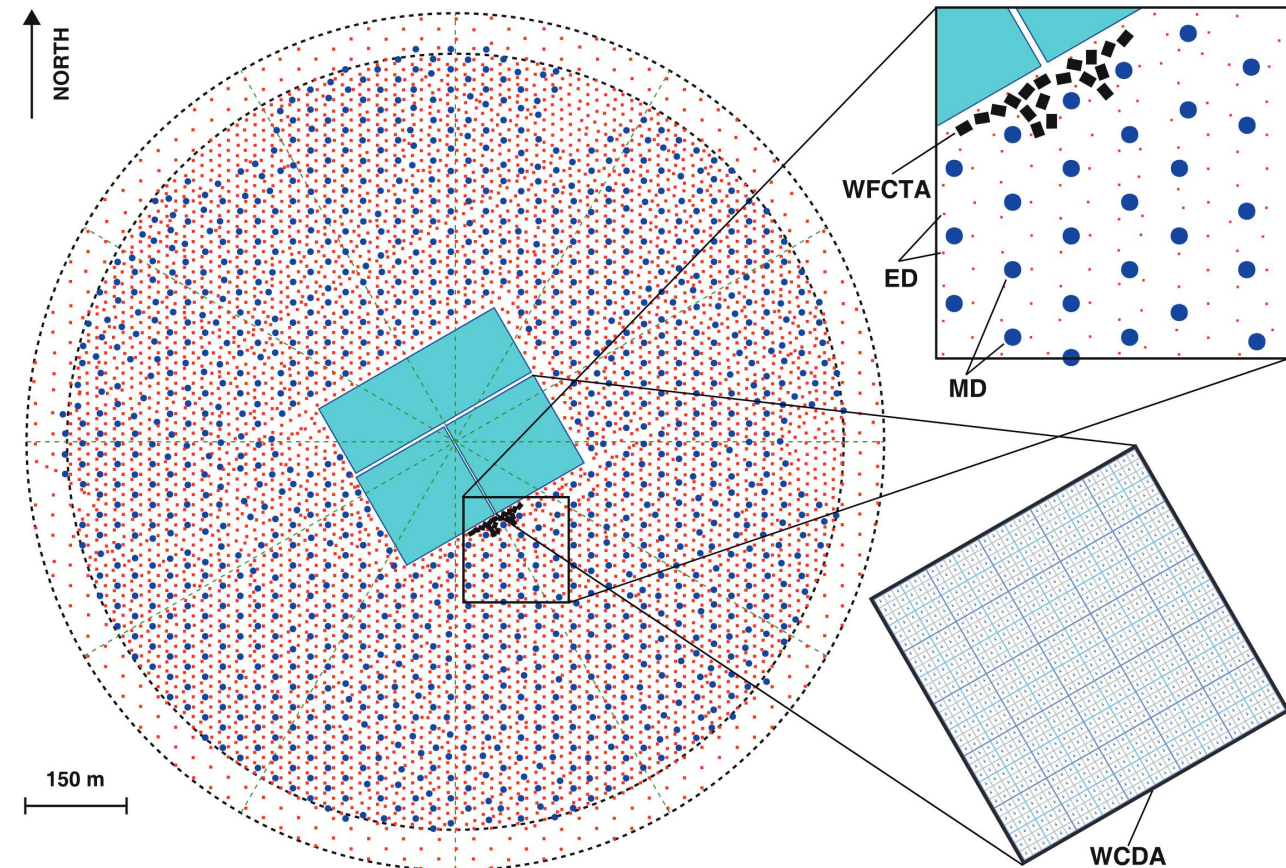
- 1.3 km² area
- 5216 EDs for energy and direction reconstruction
- 1188 MDs to distinguish gamma/hadron
- Energy coverage: ~10 TeV - 100 PeV

Water Cherenkov Detector Array (WCDA)

- 78000 m² water tanks
- 3120 WCDs to detect Cherenkov light produced by air shower particles in water
- Energy coverage: 100s GeV-10s TeV

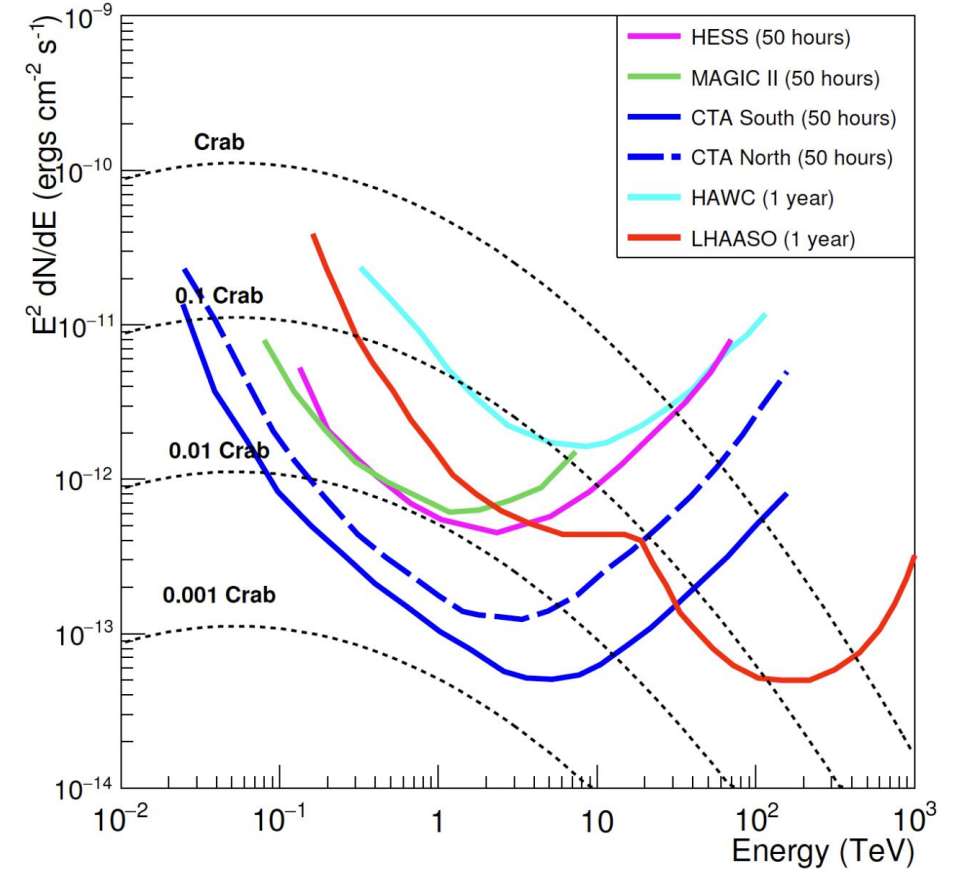
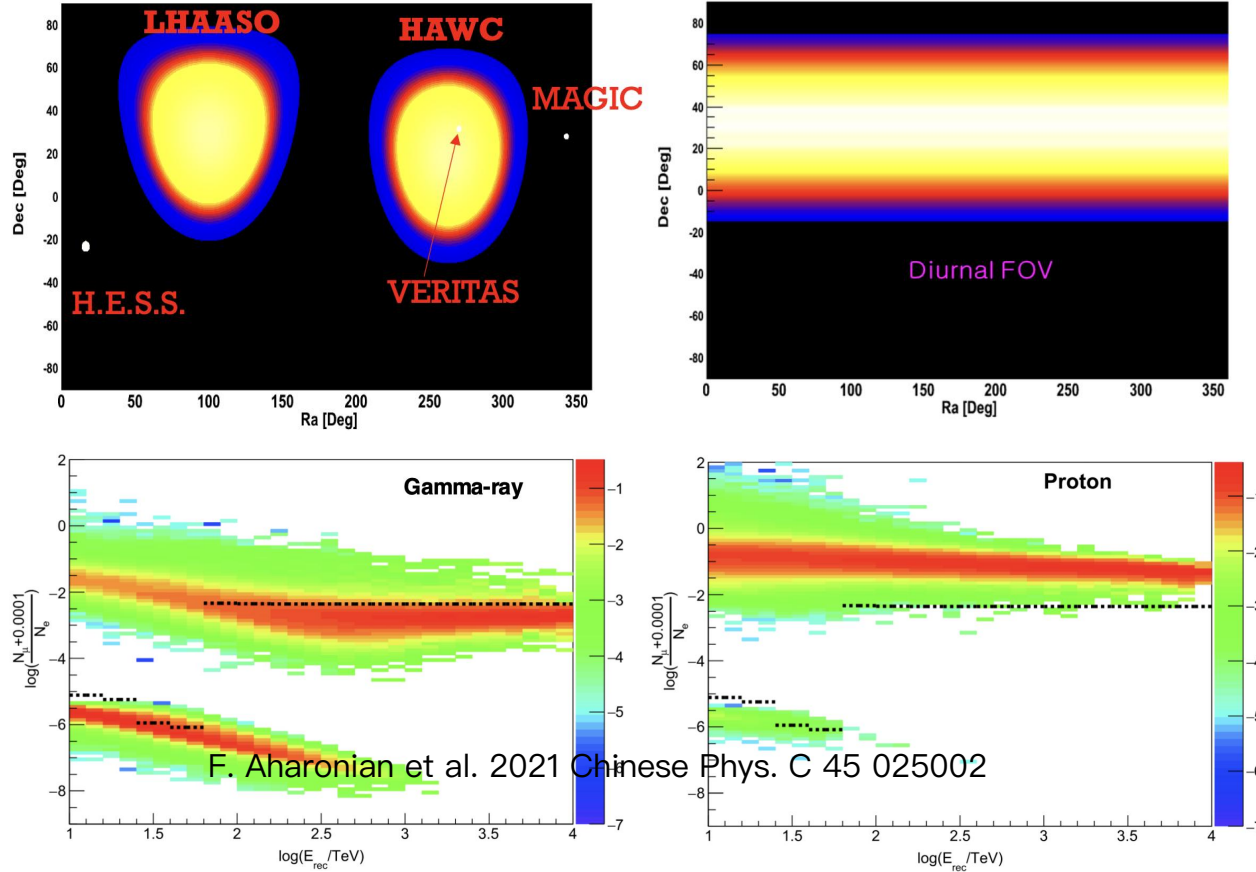
Wide Field-of-view Cherenkov Telescope Array (WFCTA)

- 18 WFCTs to distinguish particles with different mass, each one has an area of 4.7 m² and covers a square sky with area 16°×16°
- Dedicated to CR observations.



Chinese Physics C Vol. 46, No. 3 (2022) 030001

Performance of LHAASO



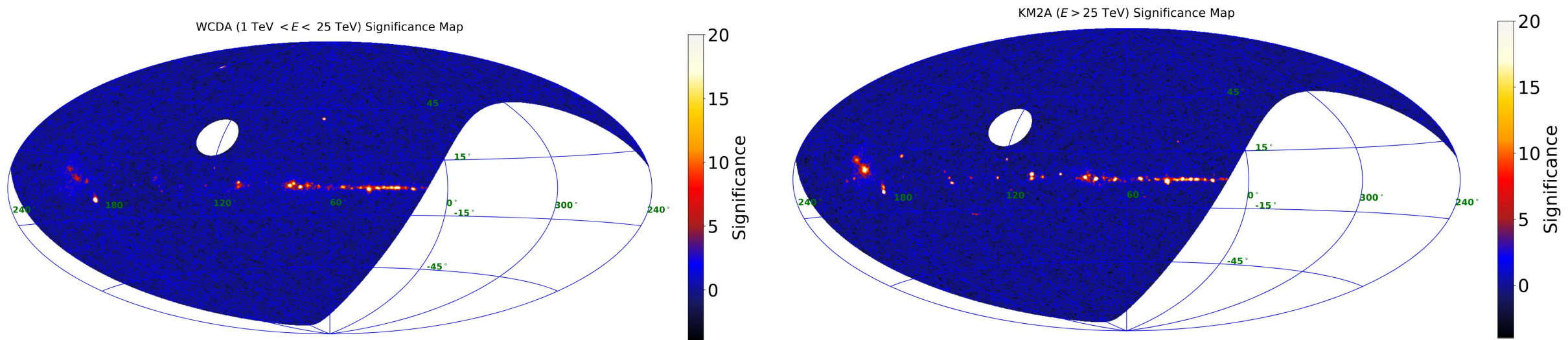
- Large effective area, wide FOV, powerful γ /hadron discrimination
 - Excellent sensitivity at multi-TeV to PeV energies
 - Exploring the origin of GCRs (knee region, PeVatrons).

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VHE and UHE Gamma-Ray Sources in LHAASO's FOV

- ❑ The **first LHAASO catalog** of gamma-ray sources (based on data only up to September 2022): 90 sources, **32** newly reported, **43 UHE (>100 TeV)** sources detected at $> 4\sigma$ significance level (Cao et al. 2024, ApJS, 271, 25).
- ❑ Possible Association: SNRs, pulsars (PWNe or TeV halos) , star-forming regions, binaries, extragalactic sources,...
- ❑ To be updated: **2LHAASO** (much more VHE and UHE sources)

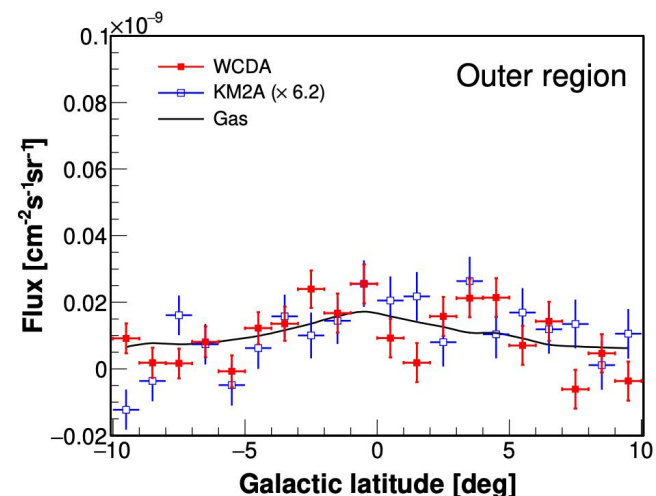
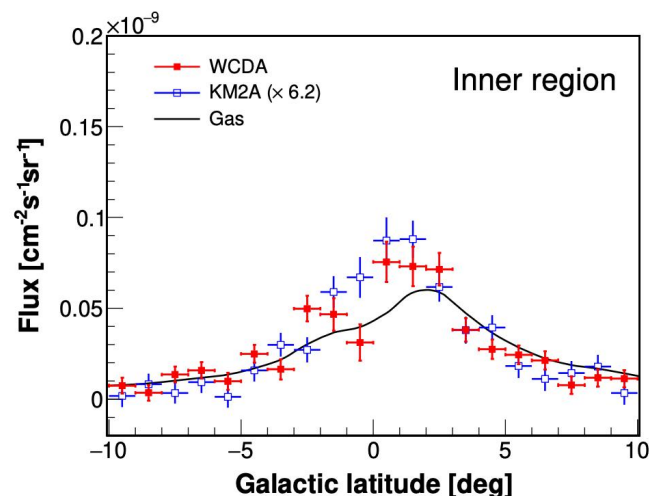
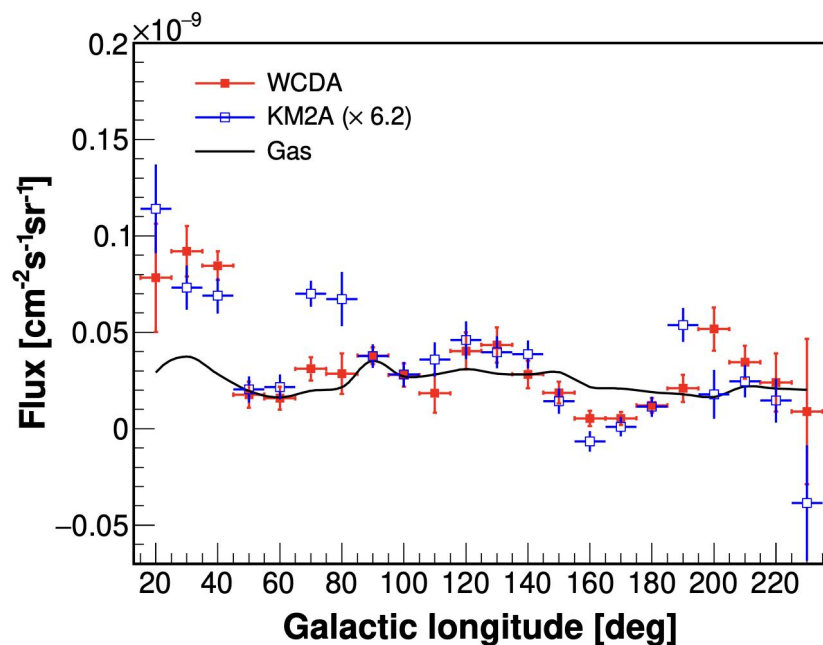
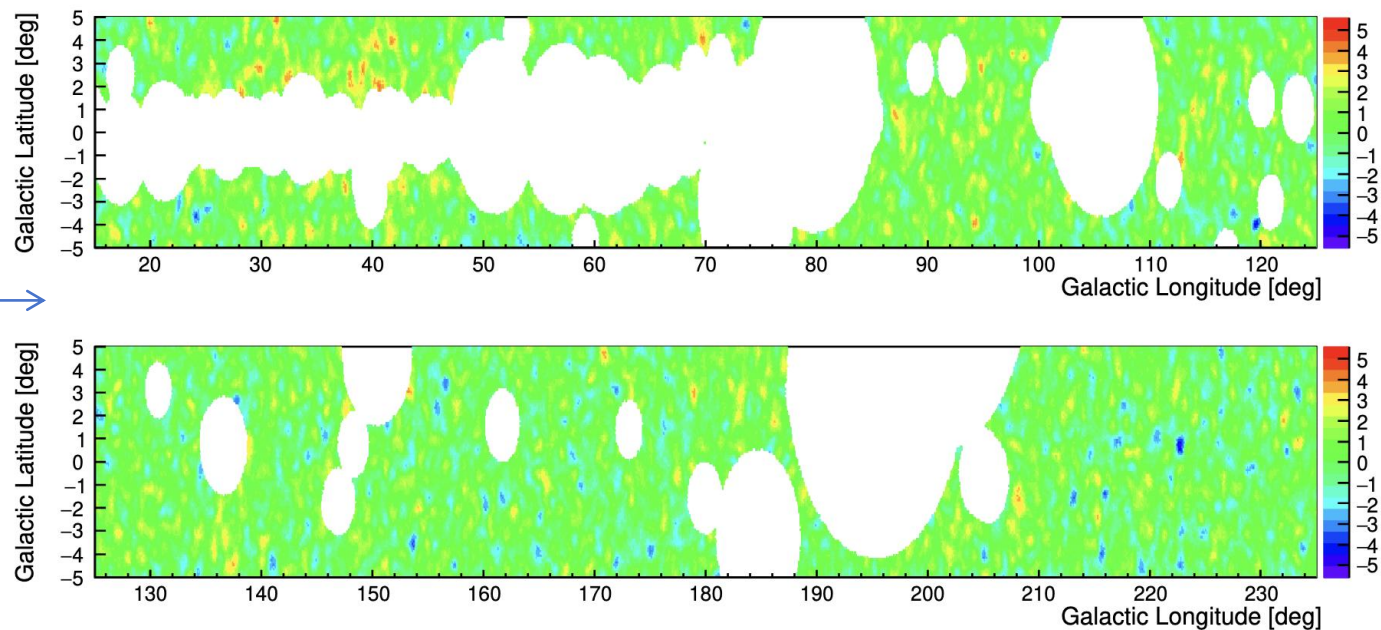


LHAASO has revealed a rich population of Galactic gamma-ray sources extending from tens of TeV to the PeV regime, pointing to multiple pathways of extreme particle acceleration.

Measurements of Galactic Diffuse Emission

Spatial distribution of GDE measured using masking method

The significance maps of the inner Galaxy region and outer Galaxy region for $N_{\text{hit}} \geq 200$ ($E >$ several TeV) after masking the resolved **1LHAASO** and **TeVCat** sources.



Measurements of Galactic Diffuse Emission

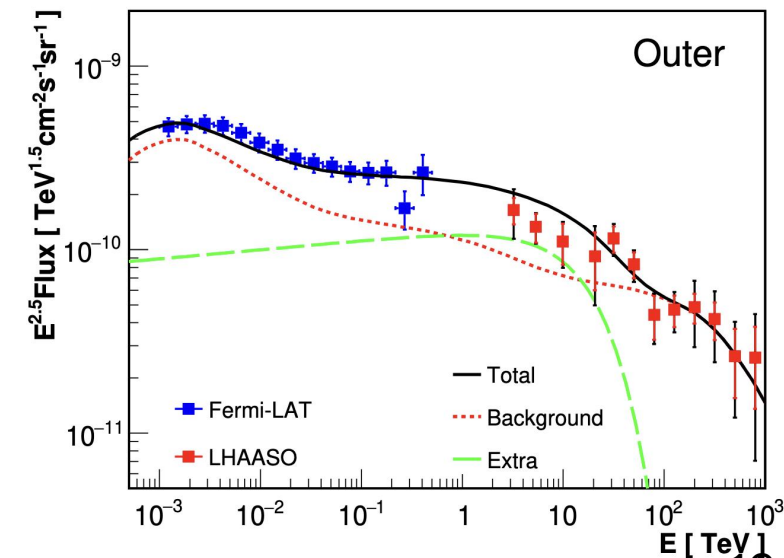
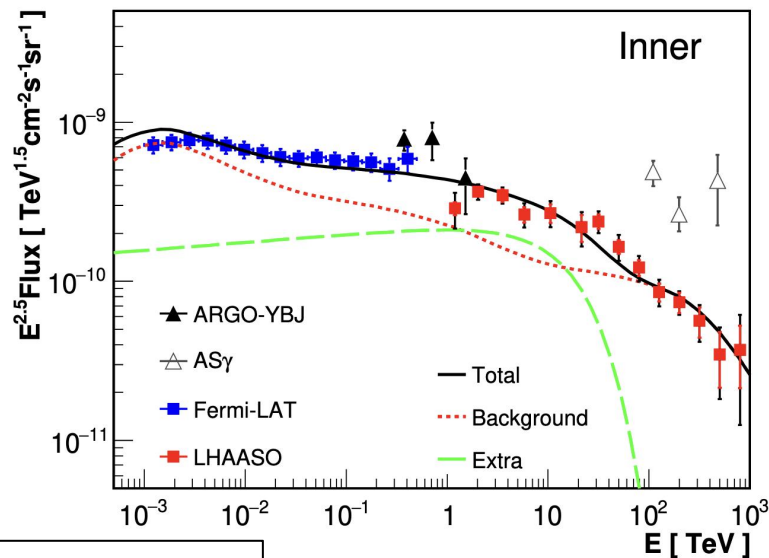
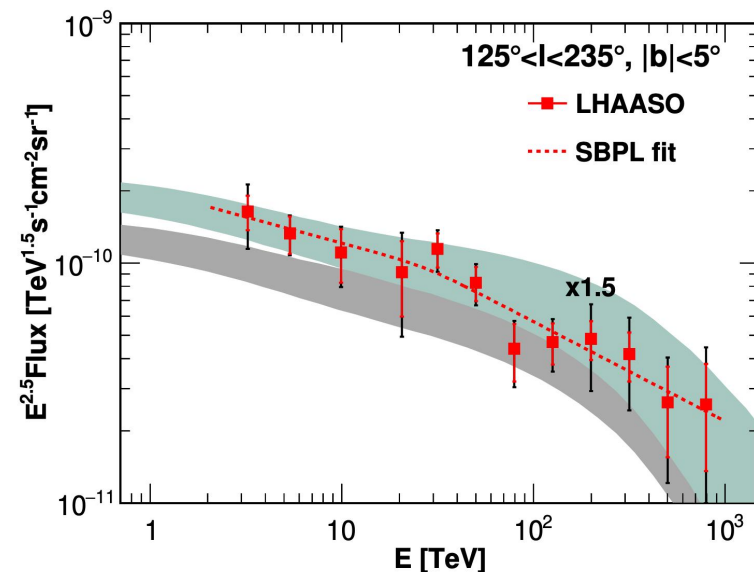
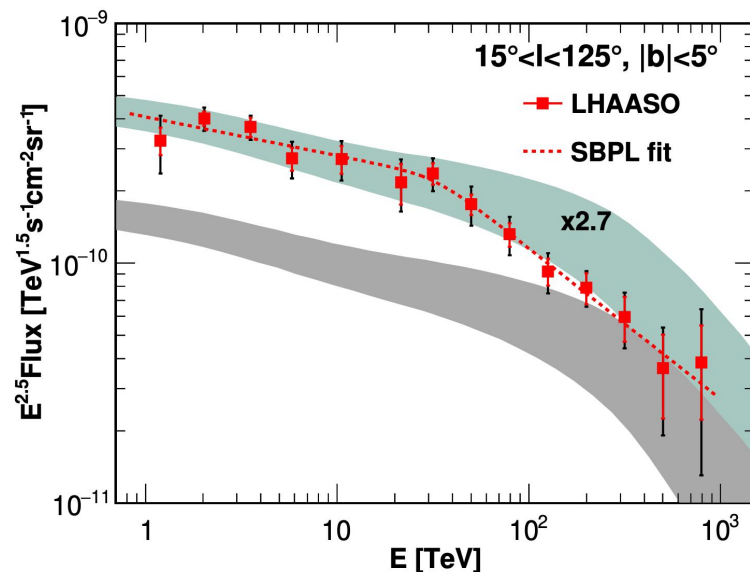
☐ Measured fluxes > model prediction
(local CR spectra+gas column density)

☐ Inner region: break around 30 TeV
(indices changing from ~ 2.7 to ~ 3.1).

☐ An empirical component with spectrum $\propto E^{-2.45} \exp(-E/20 \text{ TeV})$ added to CR propagation model can fit the measured excess.

Possible explanations:

- Unresolved sources?
(PWN/pulsar halo, YMCs...)
- Confinement and interaction of CRs around acceleration sites?
- Change of the canonical propagation scenario?
- ...



Resolved Sources (RS) Measurement / RS-DGE Separation

1. **RS:** Morphology - Gaussian
Spectrum - Log-Parabola (LP) / CutoffPowerLaw (ECPL)
2. **DGE:** Morphology - Planck Dust Map
Spectrum - Log-Parabola
3. Iteration loop

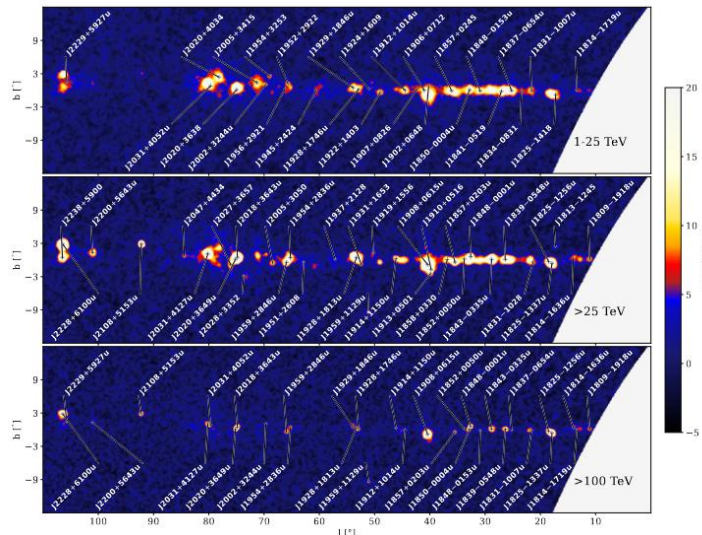
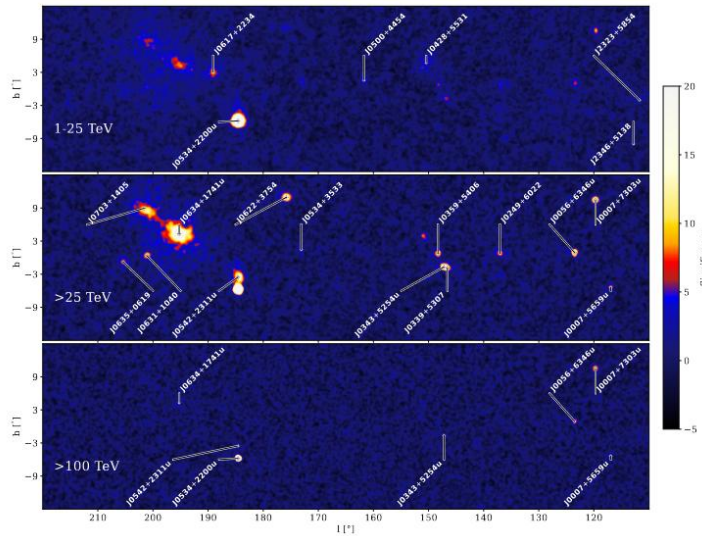
- Fit RS + DGE
- Check residual significance map
- Add new RS if needed
- Repeat with updated catalog

Preliminary

1st LHAASO Cat:
69 1-25 TeV ($> 5\sigma$)
75 > 25 TeV ($> 5\sigma$)
90 ALL



Galactic Plane ($|b| < 15$ degree):
171 resolved sources, WCDA
154 resolved sources, KM2A
194 resolved sources, JOINT-fit

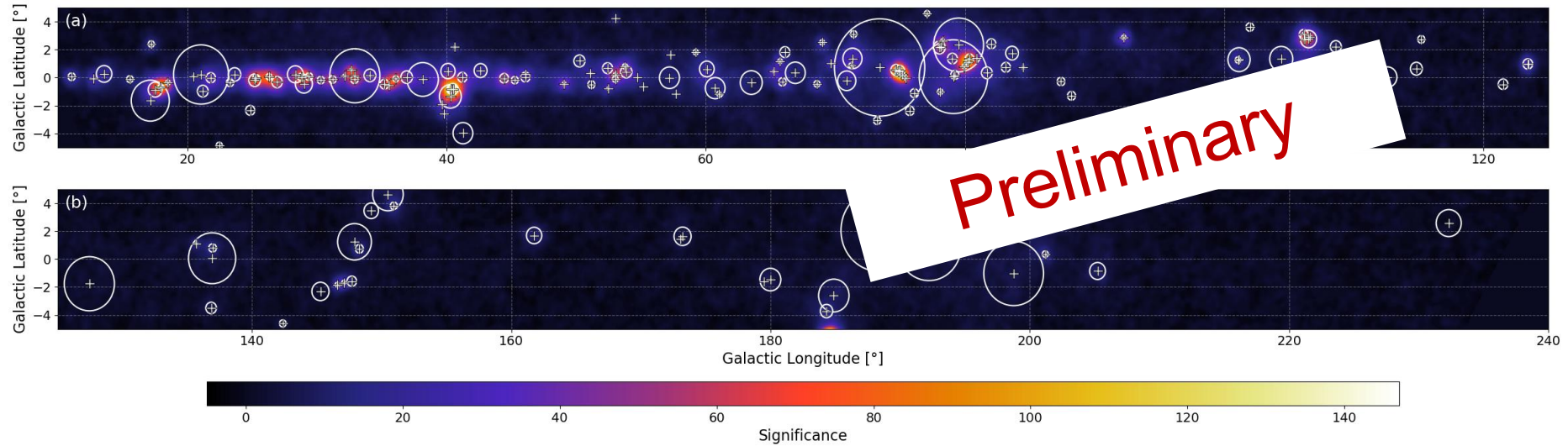


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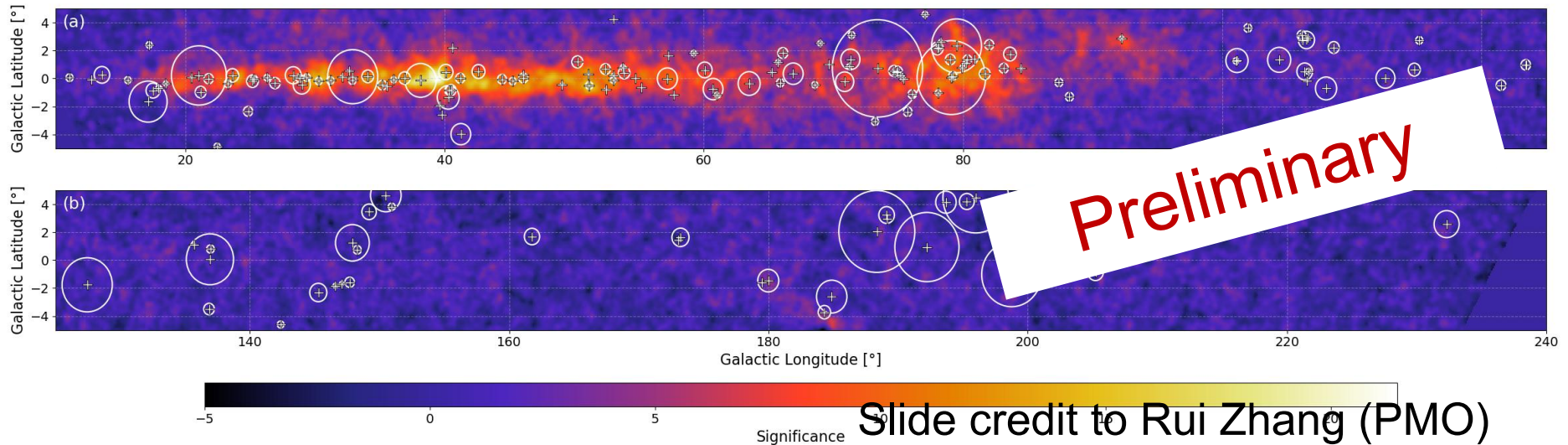
More data + New method applied to measure GDE

Significance Map before/after subtracting Resolved Sources

allsource



DGE:
allsource-RS

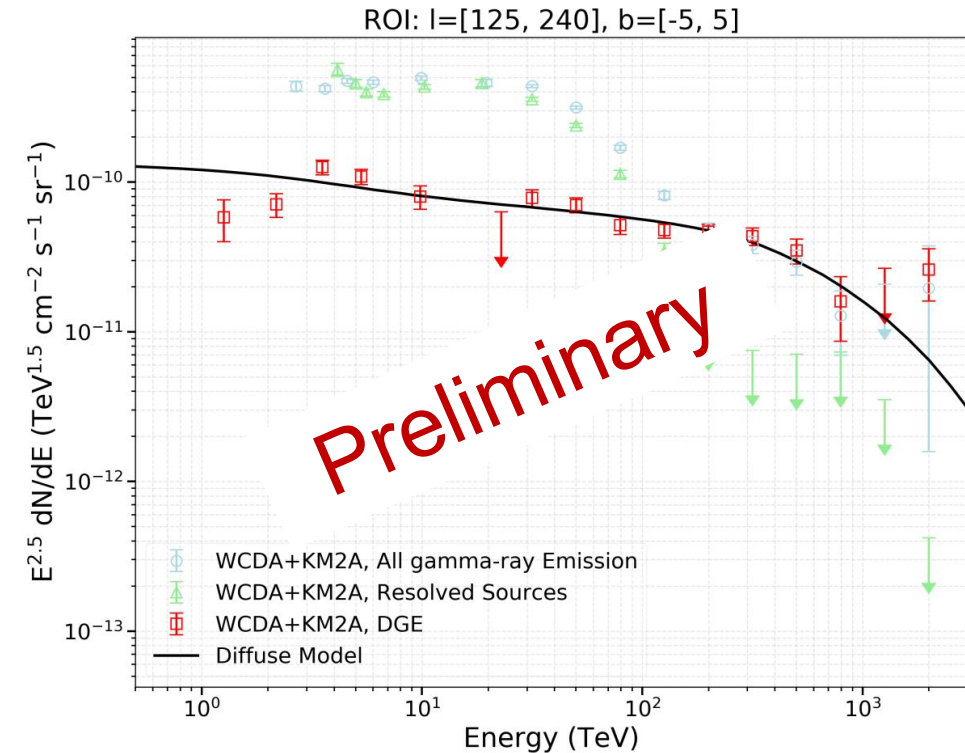
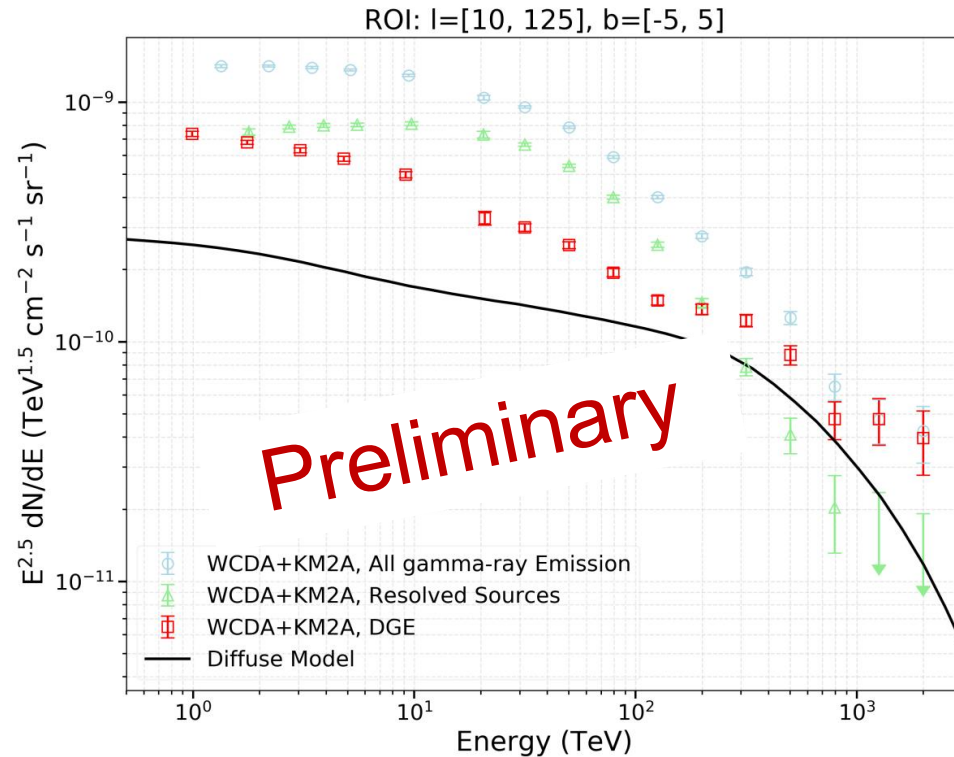


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INNER

SED of DGE

OUTER



- Diffuse Model: LHAASO CR (p+He) spectrum + ISM, no CR distribution
- $E > 100$ TeV: similar spectral shape (index) as that of measurements
- $E < 100$ TeV: extra component with E_{cut} around tens of TeV for Inner Galaxy region

Outline

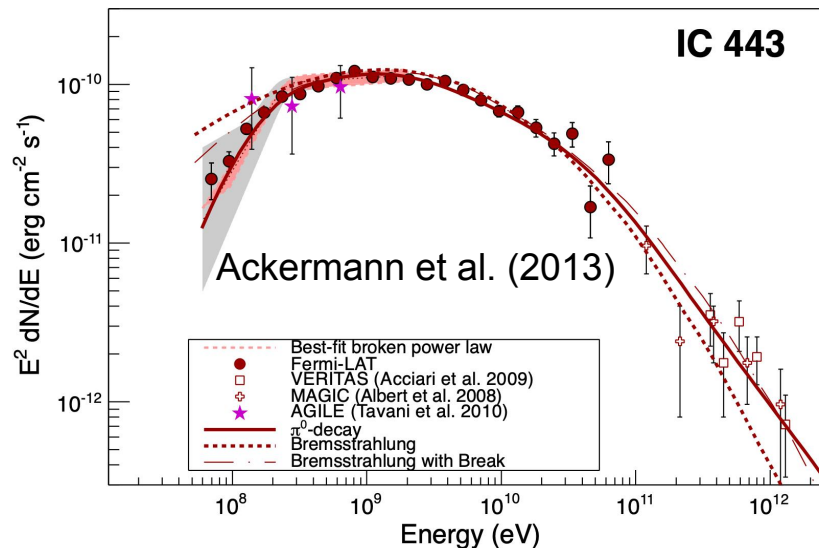
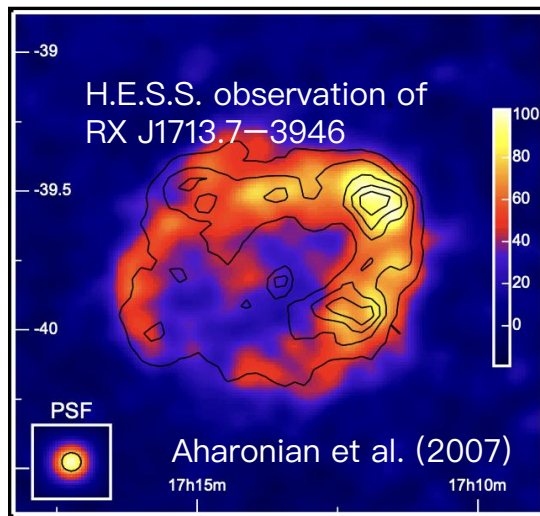
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 - ✓ Supernova remnants
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 - ✓ Young massive star clusters
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- Summary and prospect

SNRs: the leading candidates for GCRs

The SNR Paradigm

Energy budget: $E_{\text{SN}} \sim 10^{51}$ erg, $\sim 3/\text{century}$, $\eta \sim 10\% \rightarrow L_{\text{GCR}} \sim 10^{41}$ erg/s
Theories: DSA, $N(E) \propto E^{-\alpha}$, $D(E) \propto E^{\delta}$ ($\delta=0.3-0.7$) $\rightarrow$ local CR spectra, $\Gamma \sim 2.7-2.8$.

- Clear evidences from multi-wavelength observations show SNRs are **GeV–TeV** CR accelerators.
- The biggest challenge of the SNR paradigm is the **"PeVatron"** or maximum energy problem.



COSMIC RAYS FROM SUPER-NOVAE

By W. BAADE AND F. ZWICKY

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934

happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova star into a **neutron star**, consisting of a very small radius and can be packed much more closely. "gravitational packing" energy is large, and, under certain circumstances, nuclear packing fractions. A most stable configuration of hypothesis will be developed in some observations that tend to be mainly of neutrons.



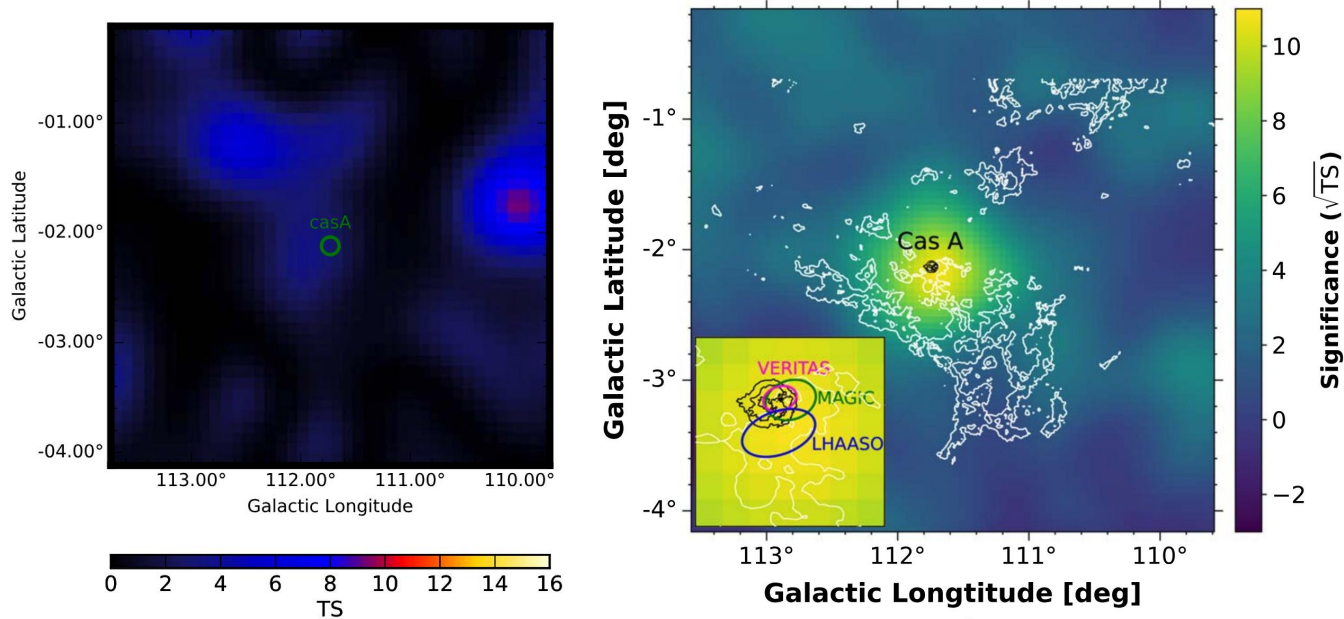
Baade & Zwicky (1934) :
SN $\rightarrow$ NS & CRs

D. Conclusions.—From the (1) Mass may be annihilated of atoms whose total mass is M may lose in the form of electromagnetic radiation and kinetic energy an amount of energy E_T which probably cannot be accounted for by the liberation of known nuclear packing fractions. Several interpretations of this result are possible and will be published in another place.

(2) The hypothesis that *super-novae emit cosmic rays* leads to a very satisfactory agreement with some of the major observations on cosmic rays.

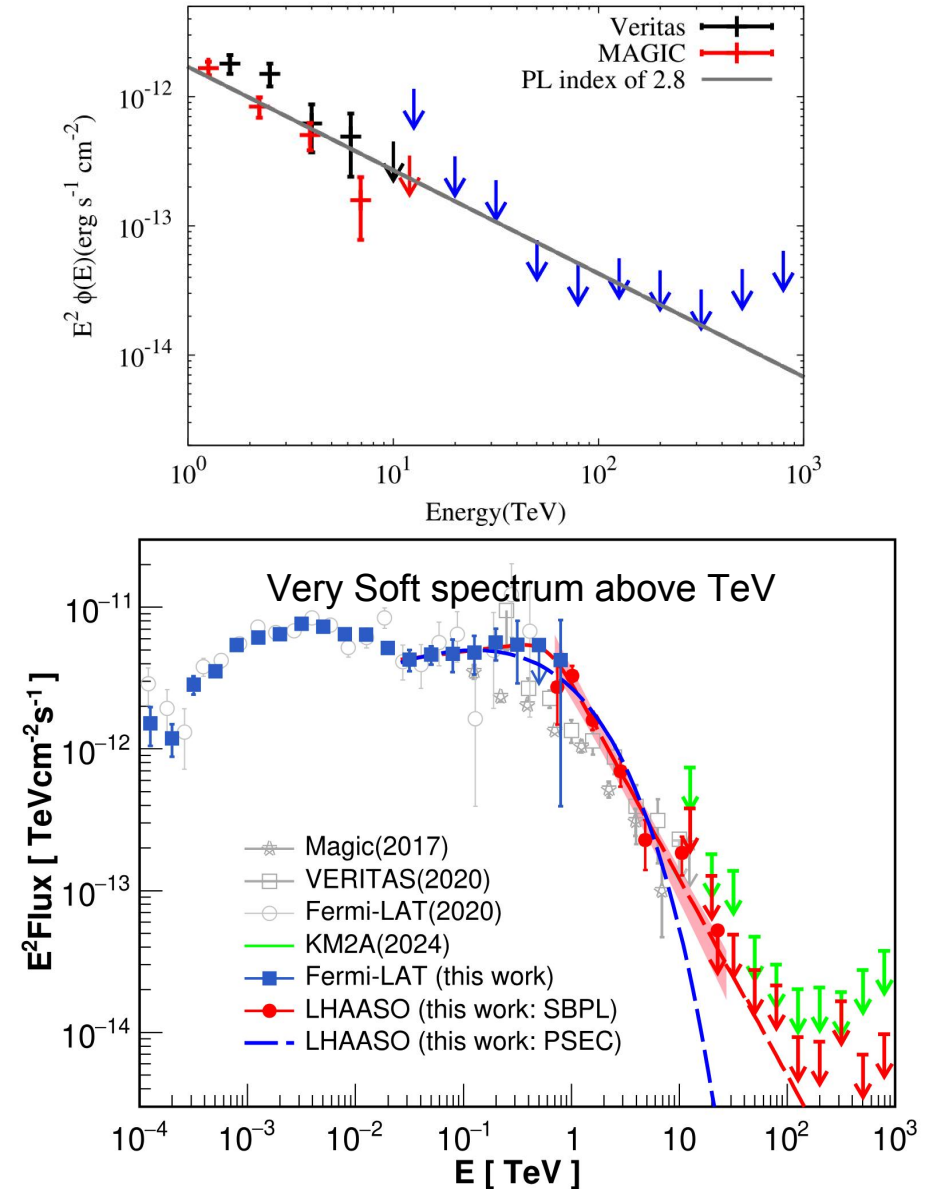
Young SNR: Cas A

Cas A: age~350 yr, $R \sim 2.5'$, $d \sim 3.4$ kpc



- $E_{y,break} \sim 1$ TeV, and no strong emission above 10 TeV detected yet: **challenges Cas A-type young SNR as PeVatron.**

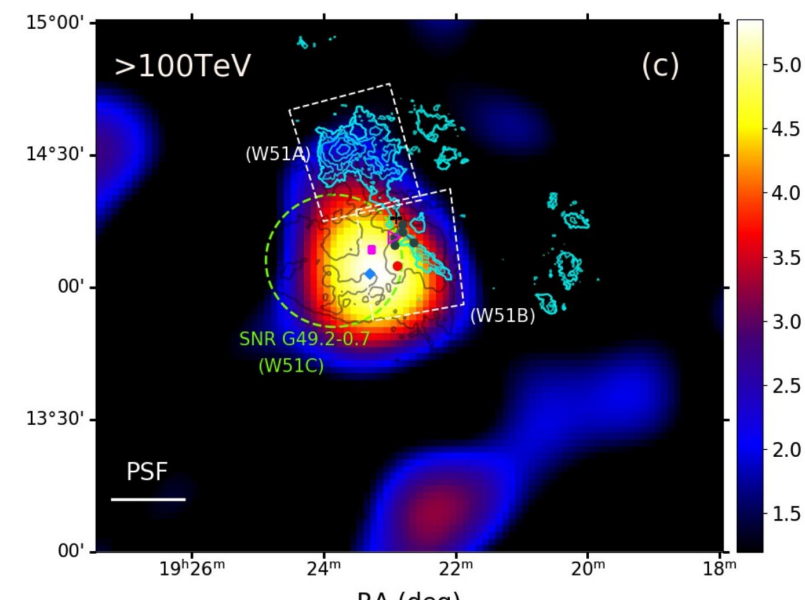
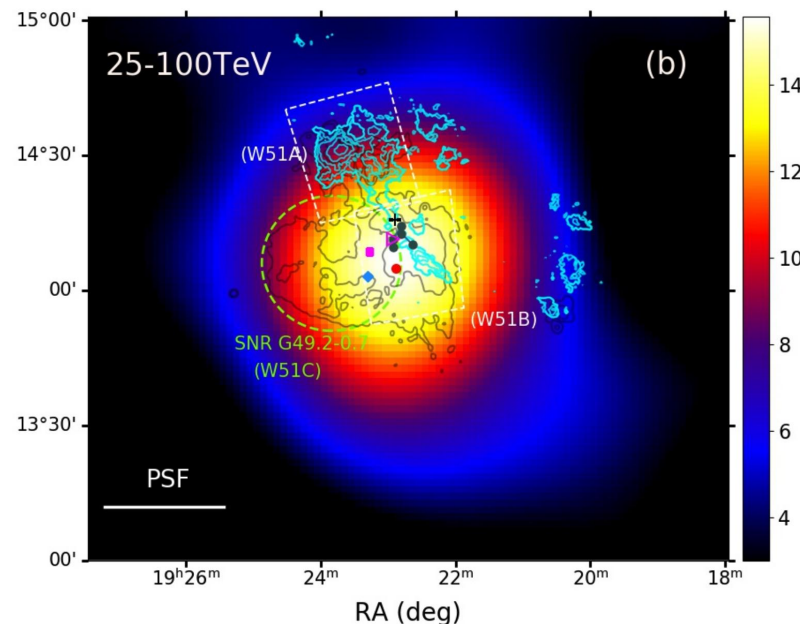
LHAASO, ApJL, 961, L43 (2024) arXiv: [2310.17082](https://arxiv.org/abs/2310.17082)
 LHAASO, ApJL, 982, L33 (2025) arXiv: [2502.04848](https://arxiv.org/abs/2502.04848)



Middle-aged SNR: W51C

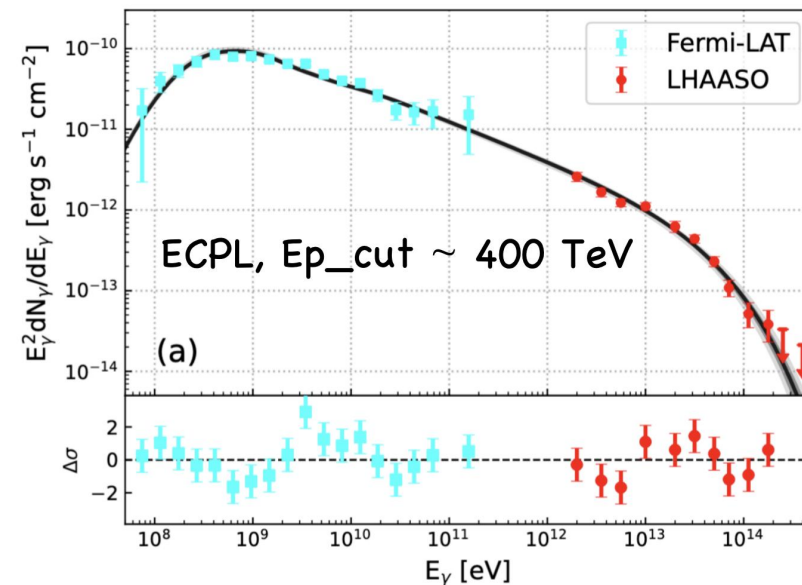
W51C

- Age~18 kyr, d~4.3 kpc.
- Evidence of molecular cloud (MC) interaction
- Hadronic emission detected (**pion-bump feature** by GeV observations).



- ❑ LHAASO detected extended emission coincident with observations of Fermi and MAGIC.
- ❑ The γ -ray spectrum can be fitted with a PL with $E_{\text{cut}} \sim 60$ TeV.
- ❑ The sed can be explained by pp interaction of proton+MC, the **cutoff energy of the proton spectra is >100 TeV**.
- ❑ Young star clusters within the W51 complex are also candidates.

LHAASO, Science Bulletin (2024) arXiv: [2407.00624](https://arxiv.org/abs/2407.00624)



Middle-aged SNR: IC 443

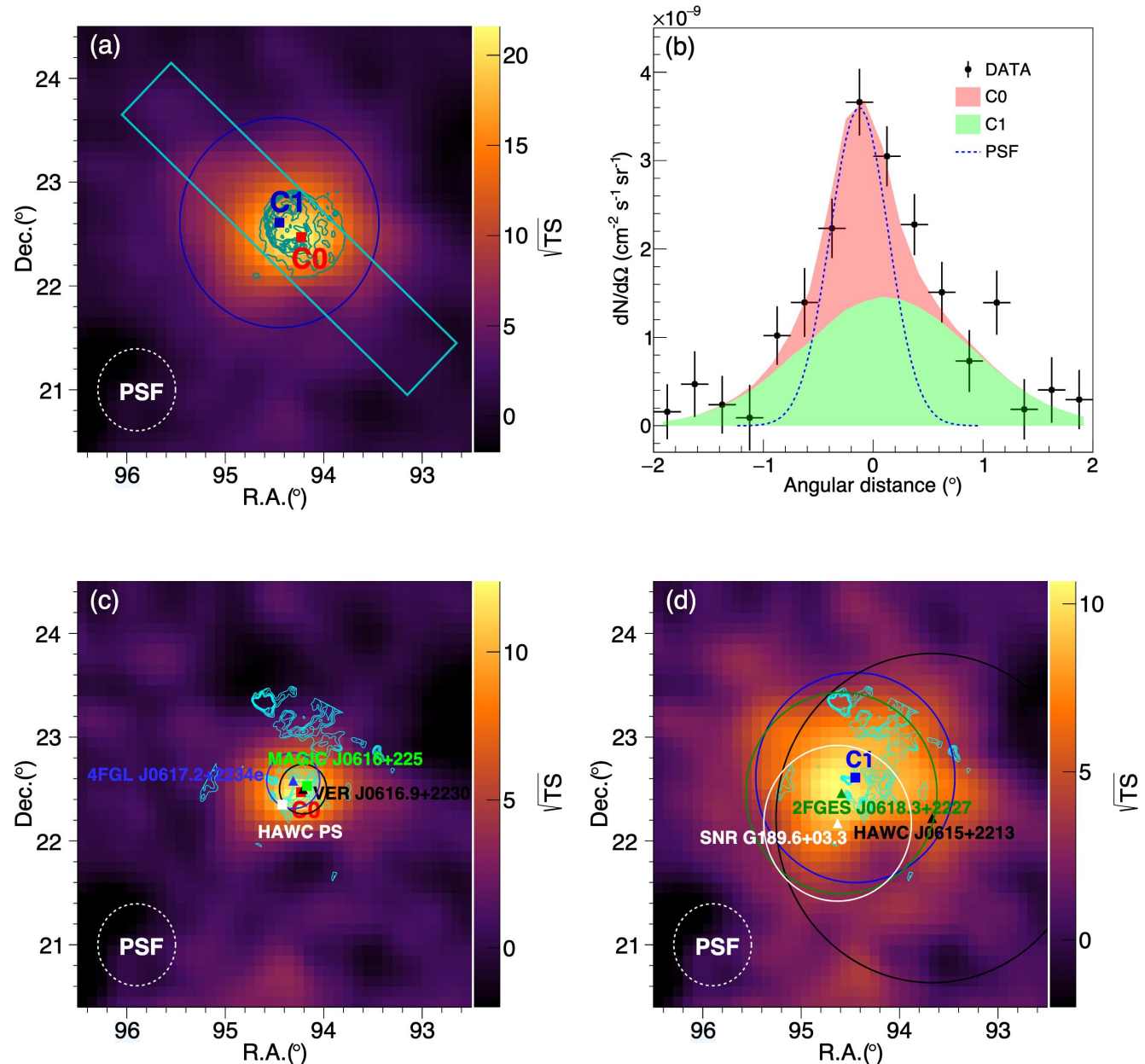
IC 443

- Age~3-30 kyr, d~1.5 kpc.
- Evidence of MC interaction
- Hadronic emission detected (pion-bump feature by GeV observations).

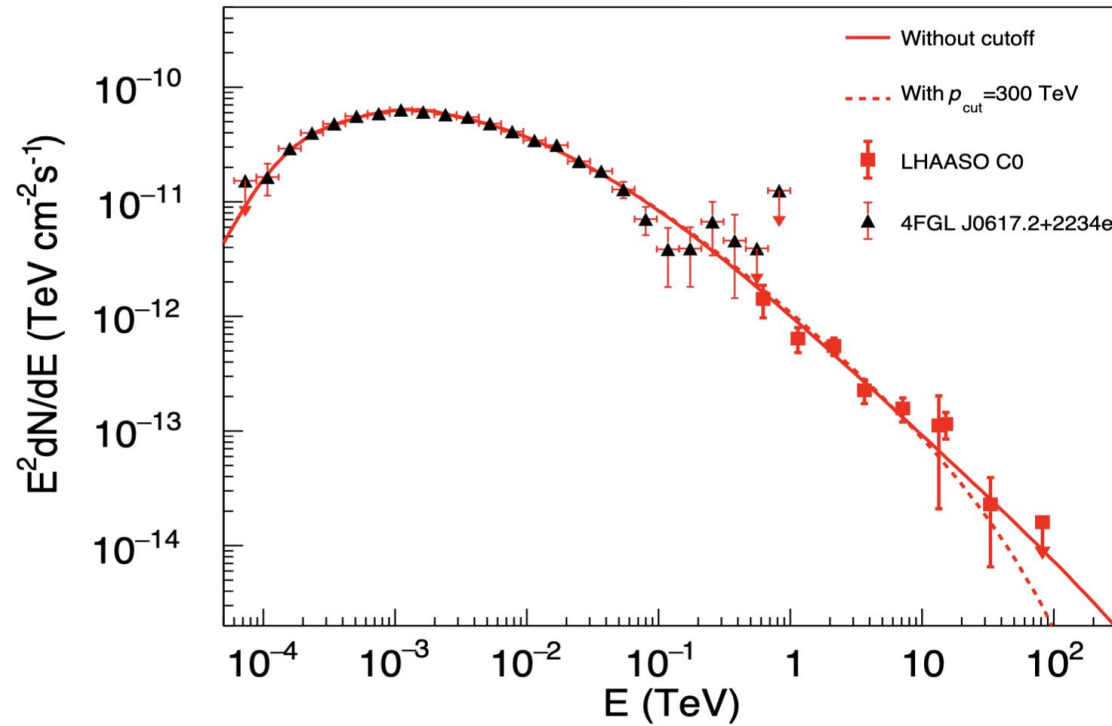
❑ LHAASO observation resolved the emission around IC443 into two components:

1. point-like compact source (C0)
2. extended source (C1) with $r_{39}=0.67^{\circ}\pm0.07^{\circ}$

LHAASO, PRL, 136, 161002 (2026)
arXiv: [2510.26112](https://arxiv.org/abs/2510.26112)

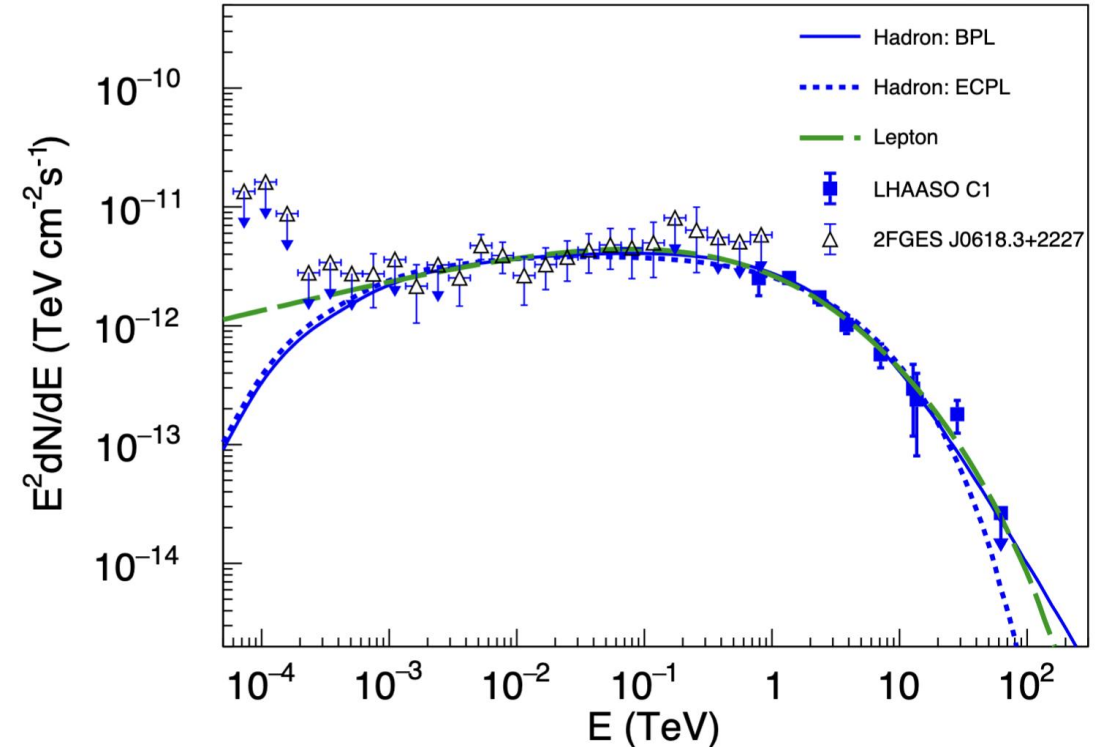


Middle-aged SNR: IC 443



Compact component C0:

- The γ -ray SED: PL with index ~ 3.0 without apparent cutoff.
- PP model: the 95% lower limit of $E_p \sim 300$ TeV $\rightarrow$ Hadronic sub-PeV particles are likely accelerated by IC 443.



Extended component C1:

- The γ -ray SED: PL with index ~ 2.5 and $E_{\gamma, \text{cut}} \sim 20$ TeV
- PP/IC model with $E_{p/e}$ reaching 100s of TeV.
- Possible origin: IC 443, SNR G189.6+3.3, or putative PWN CXOU J061705.3+222127

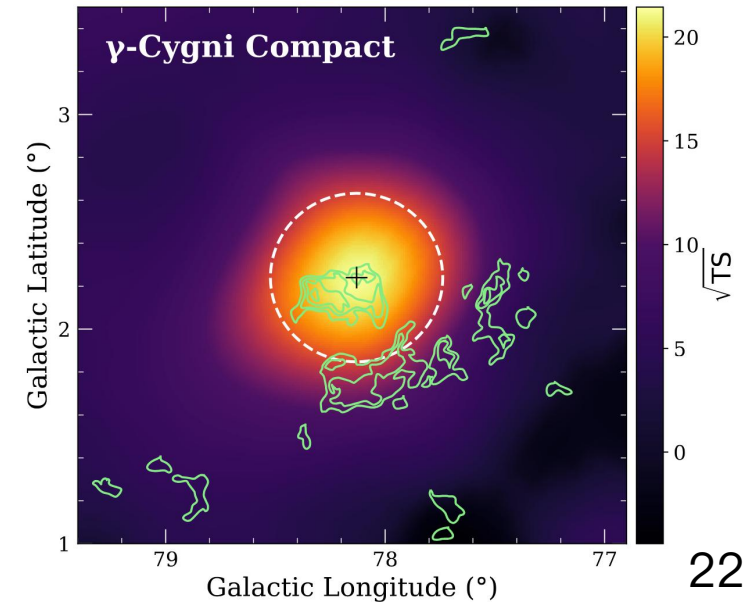
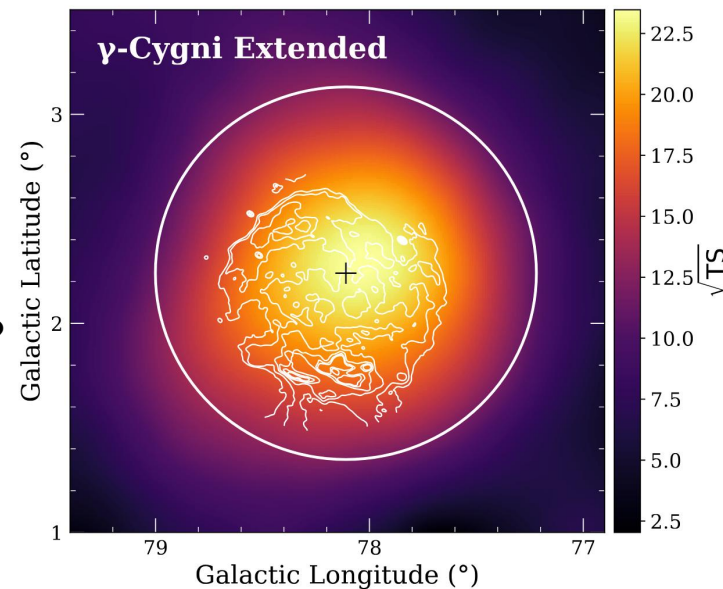
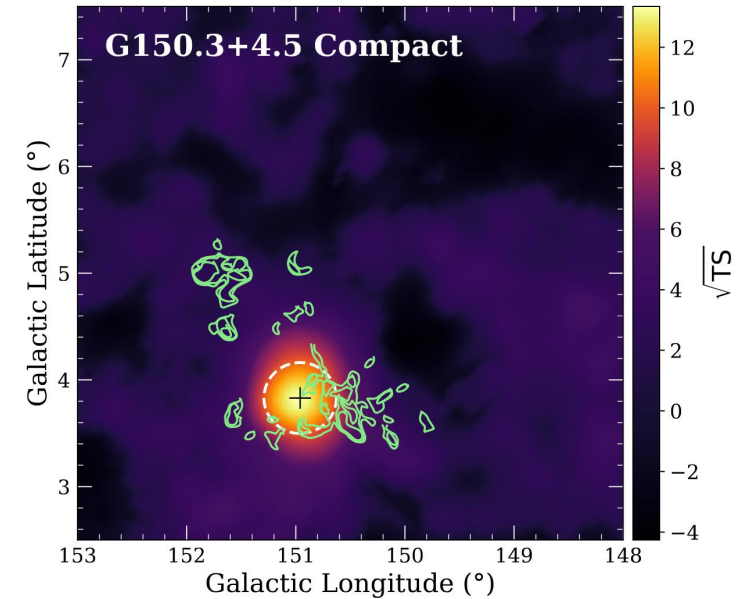
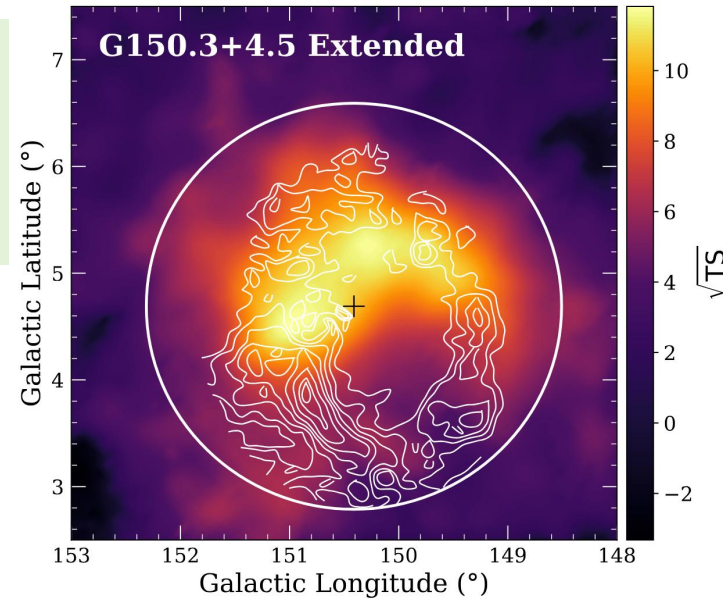
Middle-aged SNR: G150.3+4.5, γ -Cygni

- G150.3+4.5: $R \sim 1.3^\circ$, age $\sim (1-18) \times 10^4$ yr, $d \sim 740$ pc
- γ -Cygni: $R \sim 0.5^\circ$, age ~ 7 kyr, $d \sim 1.7$ kpc

LHAASO observation results:

- ❑ γ rays with $E > 100 \text{ TeV}$ detected ($> 3\sigma$).
- ❑ The emission was resolved into 2 (G150.3) or 3 (γ -Cygni) components:
 - Extended low-energy components coincide with the SNR shell
 - Trapped particles?
 - Compacter high-energy components coincide with nearby clouds
 - Escaped particles illuminating the clouds?

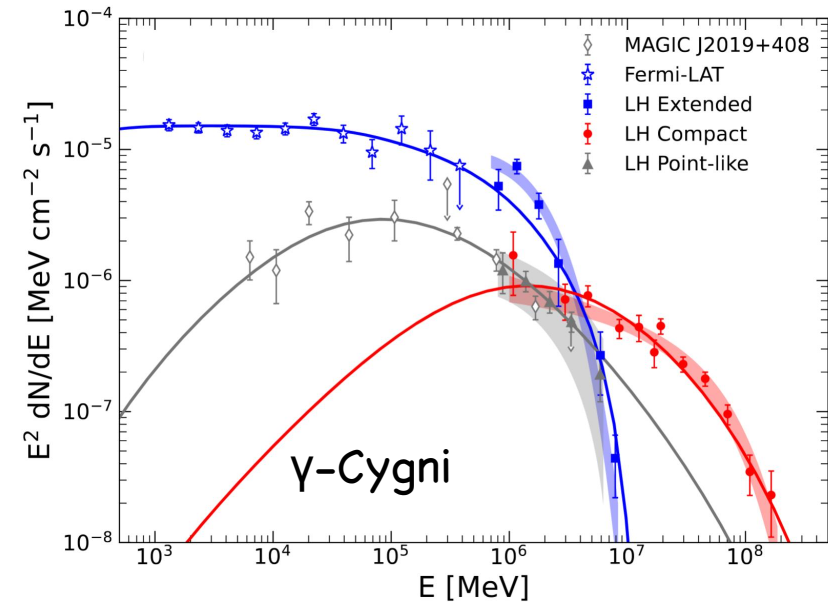
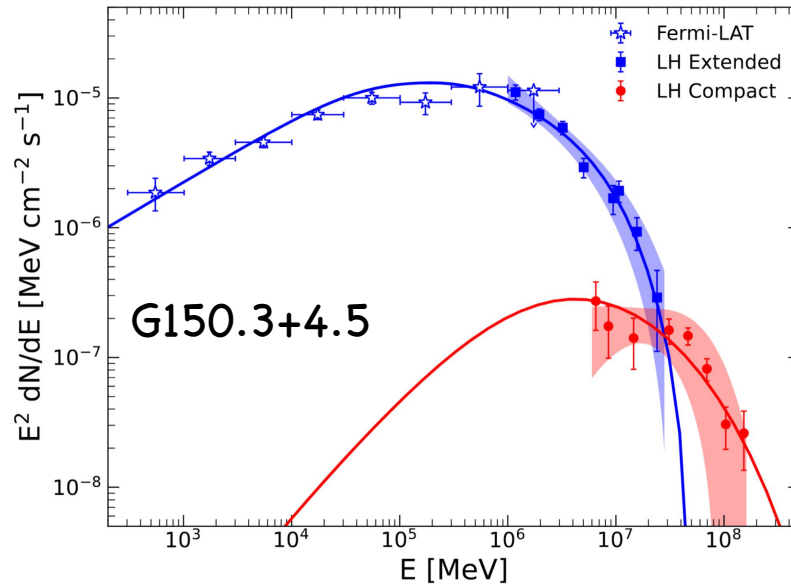
LHAASO (2026) arxiv: [2604.22621](https://arxiv.org/abs/2604.22621)



Middle-aged SNR: G150.3+4.5, γ -Cygni

The γ -ray SED modeling:

- IC (extended) + PP (compact)
- Particles were accelerated at early stage and then injected instantaneously.
- Injected spectra: broken PL+ exponential cutoff
- $E_{p, \text{cut}} \sim 0.8 \text{ PeV} \rightarrow$ Hadronic PeVatron candidates



$$Q_i(E_i) = Q_0^i \exp(-E_i/E_{\text{cut}}) \times \begin{cases} E_i^{-\alpha} & \text{if } E_i < E_{\text{br}} \\ E_{\text{br}} E_i^{-(\alpha+1)} & \text{if } E_i \geq E_{\text{br}} \end{cases}, \quad R_{\text{diff},i} = 2 \times \begin{cases} \left[\int_{E_i}^{E_{i,0}} D(E') \dot{P}^{-1}(E') dE' \right]^{1/2}, & i = \text{electron}, \\ [D(E_i) T]^{1/2}, & i = \text{proton}. \end{cases}$$

Source name	α	$E_{br} [\text{TeV}]$	$E_{cut} [\text{PeV}]$	$W_e [\text{erg}]$	$B [\mu \text{ G}]$	Age[kyr]	$D [\text{kpc}]$	Molecular clouds [$M_\odot$]
G150.3+4.5	2.0	3.0	0.8	2.3×10^{47}	3.0	20	0.74	$5.0 \times 10^3 \frac{W_p}{10^{50} \text{ erg}}$ for B with $R = 31 \text{ pc}$
γ -Cygni	2.0	0.1	0.8	1.6×10^{49}	10.0	7.0	1.7	$7.0 \times 10^4 \frac{W_p}{10^{50} \text{ erg}}$ for B with $R = 15 \text{ pc}$ $3.5 \times 10^3 \frac{W_p}{10^{50} \text{ erg}}$ for C with $R = 9.3 \text{ pc}$

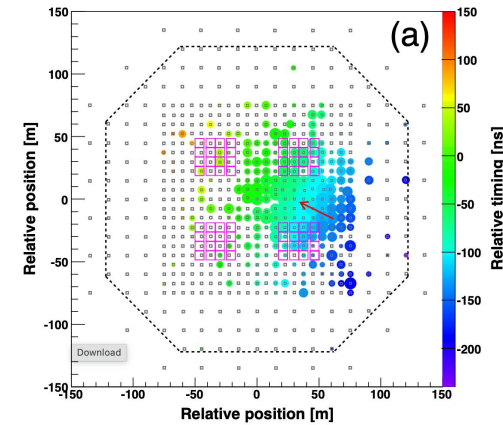
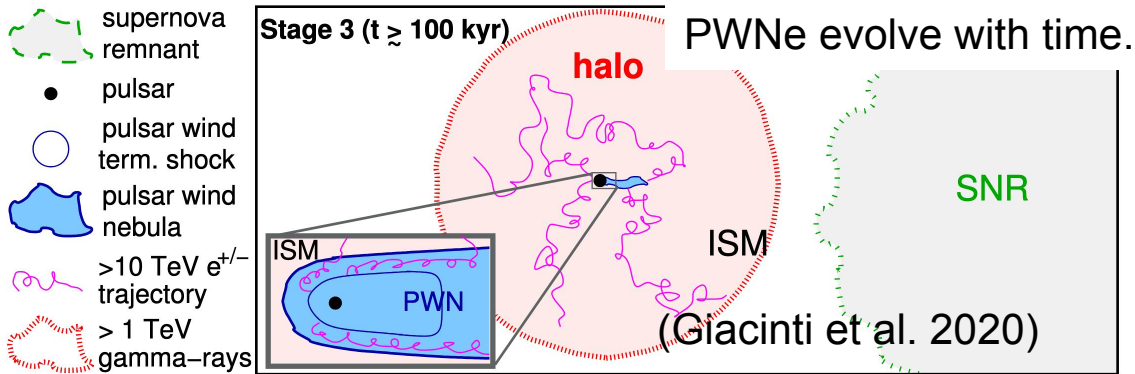
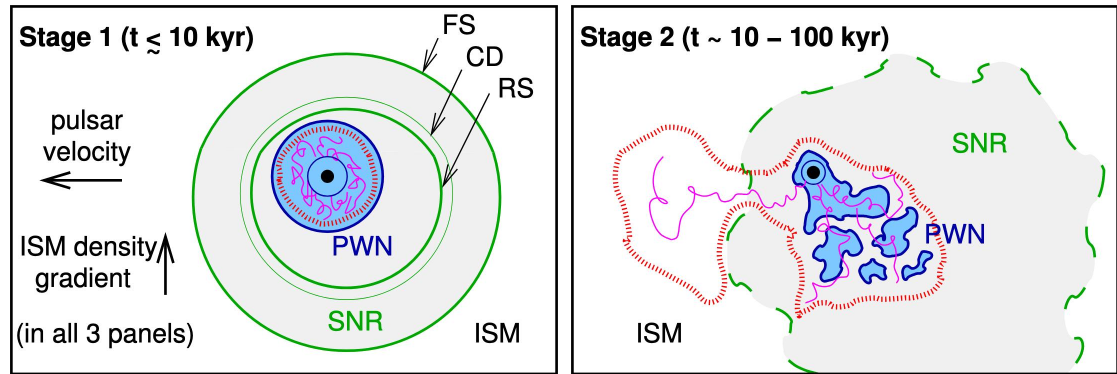
Outline

- Introduction: the LHAASO experiment
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 - ✓ **Supernova Remnants:** young SNR Cas A, $E_{\text{cut}} \sim 10$ TeV, not a PeVatron yet; hadronic UHE emission from middle-aged SNRs (e.g., W51C, IC443, directly interacting with MCs ; e.g., G150.3+4.5, γ -Cygni with escaping particle illuminating MCs) show the potential of SNRs to accelerate particles to sub-PeV to PeV regime, but may not contribute much above the knee.
 - ✓ Pulsar wind nebulae and pulsar halos
 - ✓ Young massive star clusters
 - ✓ Binaries (Microquasars/Gamma-ray binaries)
 - ✓ “Dark” sources, “Passive” GMCs
- Measurements of CR Spectra and Anisotropy
- Summary and prospect

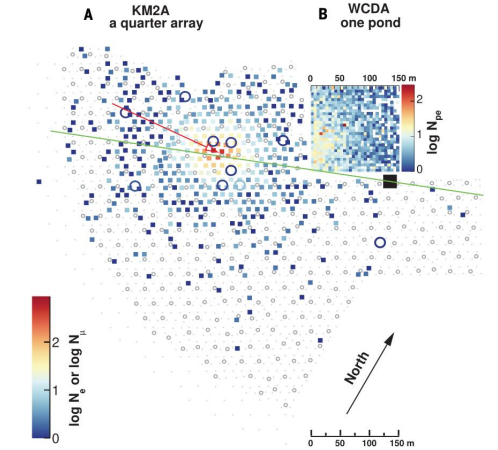
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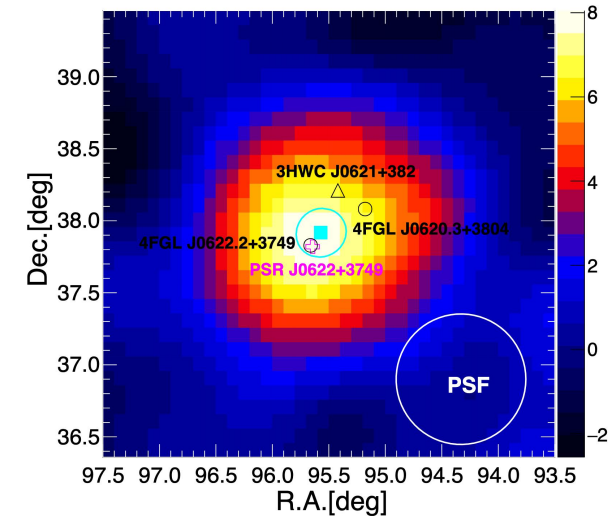
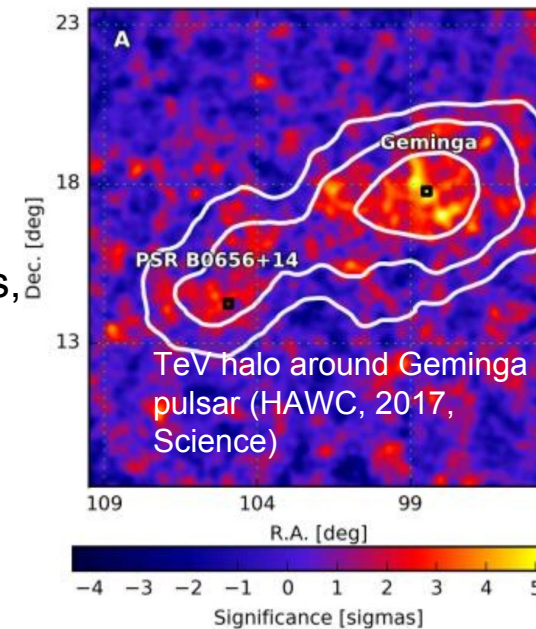
Pulsar Wind Nebulae and pulsar halos



251 TeV photon-like event from Crab nebula (Tibet ASy, 2019, PRL)



The 0.88-PeV γ -ray event from Crab nebula (LHAASO, 2021, Science)



Halo around PSR J0622+3749 (LHAASO, 2021, PRL) 26

- PWNe: one of the most numerous classes of Galactic TeV sources, samples to study the entire cycle from particle acceleration to particle escape and propagation.
- The **PeV** photons detected from the **Crab Nebula** demonstrated that young PWN could accelerate particles to the **PeV** regime.

Extreme particle accelerator powered by PSR J1849-0001

PSR J1849-0001:

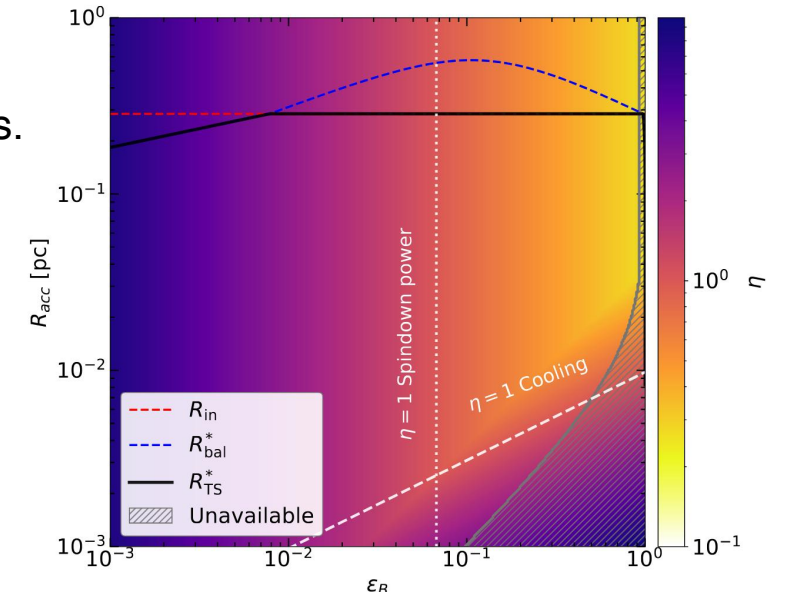
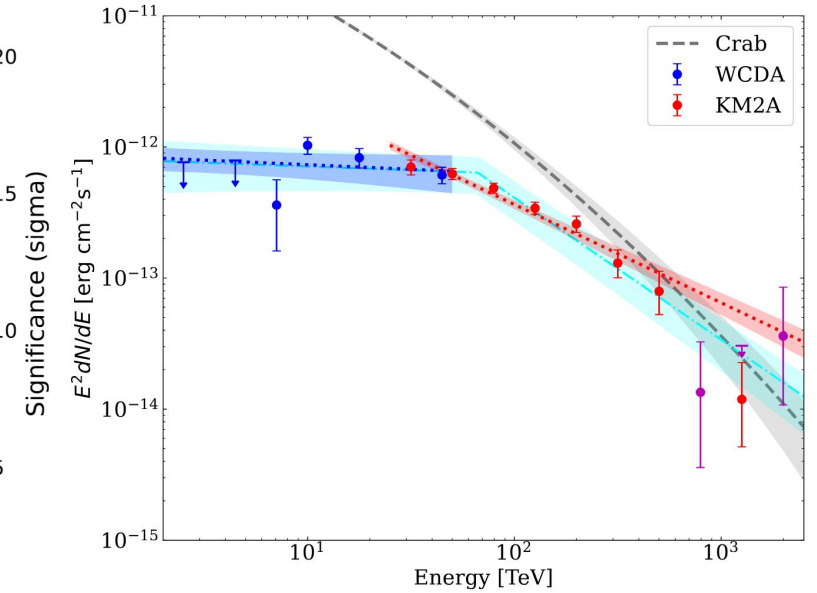
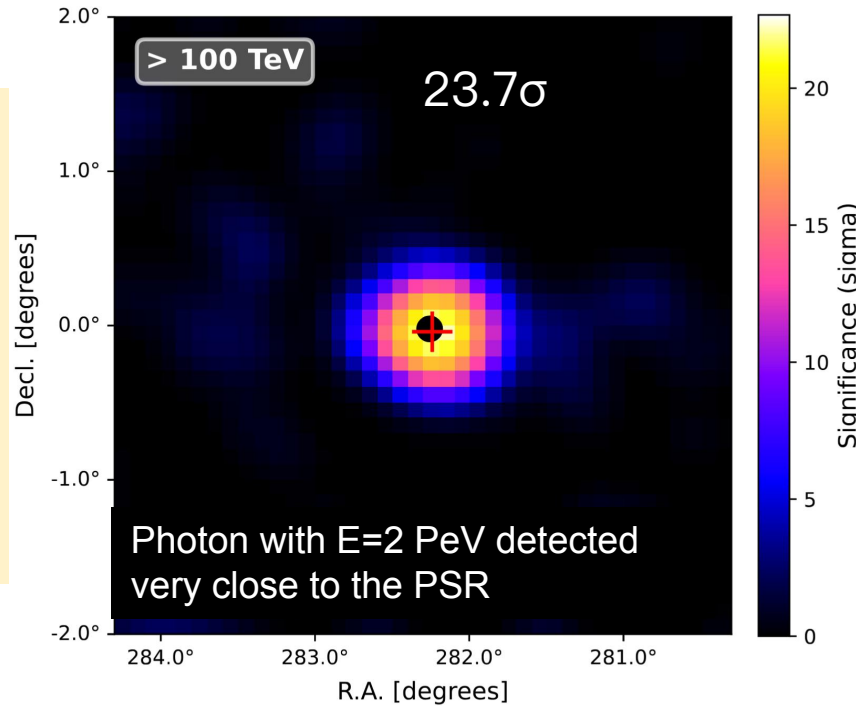
a fast-rotating pulsar initially discovered in the X-ray band.

$d=7$ kc, $\tau_c = 43.1$ kyr,

$P = 38.5$ ms (similar to Crab)

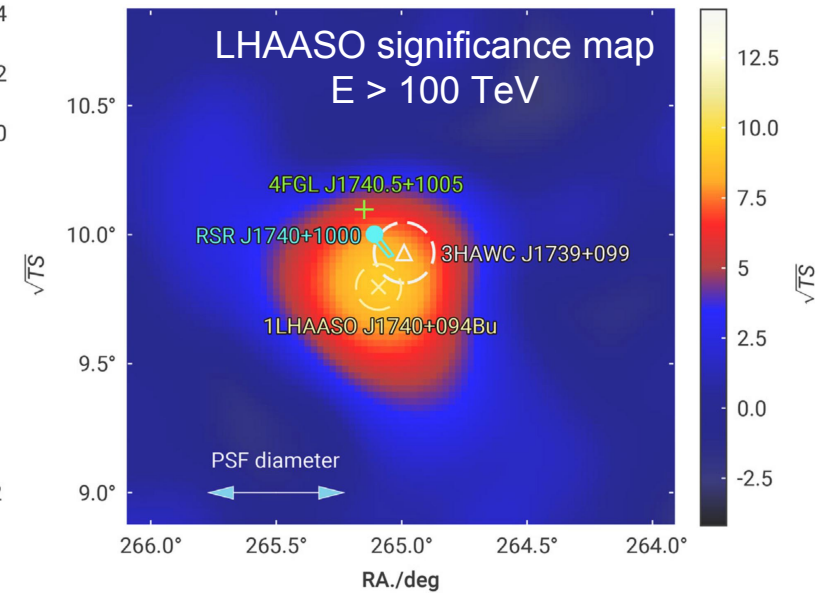
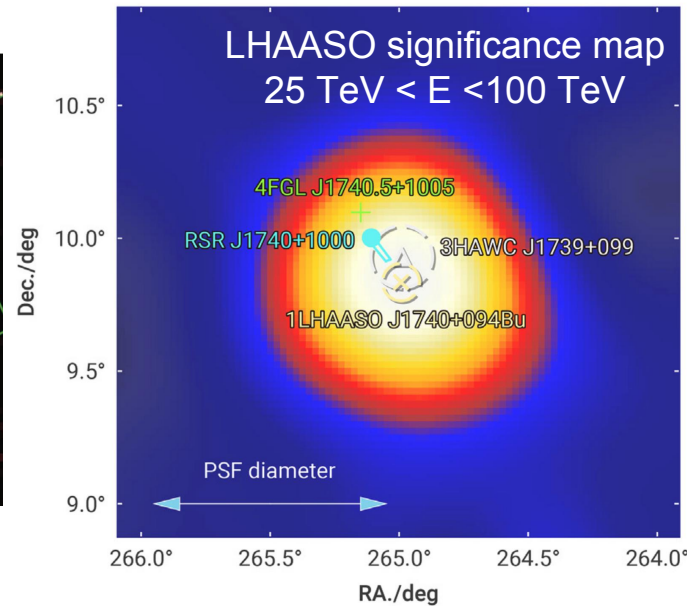
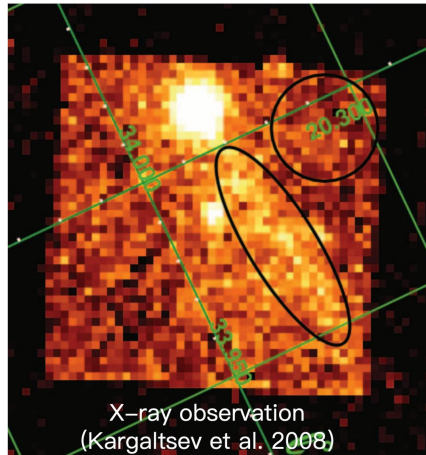
$L_{sd} = 9.8e36$ erg/s ($\sim 1/50$ Crab).

- ❑ LHAASO detected point-like UHE γ -ray source with spectrum up to **PeV** energies.
- ❑ The PeV luminosity is **higher than** that of the **Crab Nebula**.
- ❑ X-ray observations : **$B \sim 3$ μ G** within the PWN.
- ❑ Derived particle acceleration efficiency: approaching **1**, challenging the particle acceleration theory in PWN.



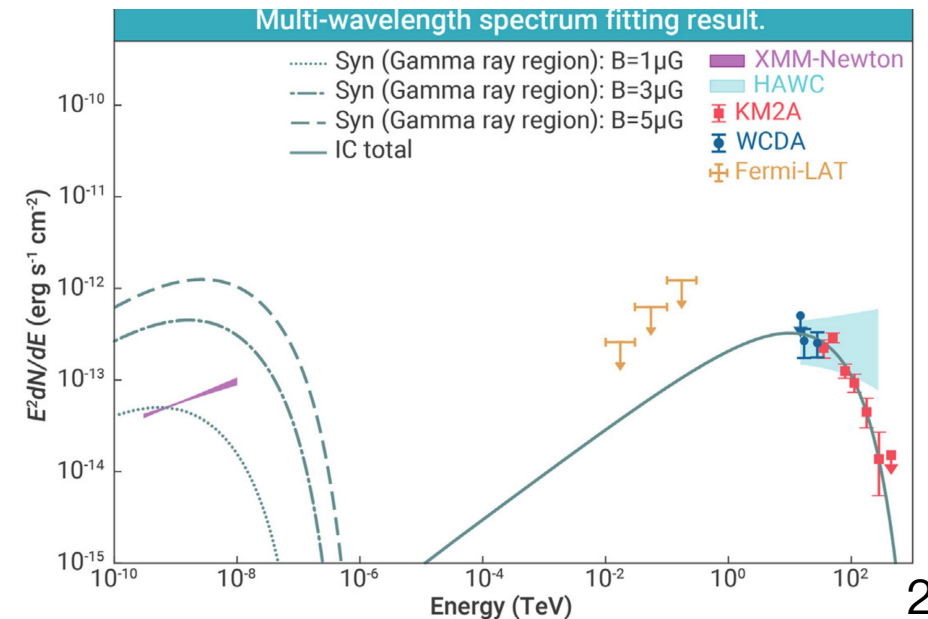
UHE emission associated with the tail of a BSPWN

PSR J1740+1000:
a middle-aged pulsar,
 $\tau \sim 114$ kyr,
 $d \sim 1.4$ kpc,
 $P = 0.154$ s,
 $L_{\text{sd}} = 2.32 \times 10^{35}$ erg/s,
X-ray: BSPWN



- ❑ LHAASO detected point-like UHE emission offset by $\sim 0.2^\circ$ from the pulsar, located at the extension of the X-ray tail.
- ❑ Emission may originate from reaccelerated electrons advected to the downstream of the bow-shock tail flow.
- ❑ Further researches are needed to confirm its nature (e.g. looking for potential gas targets for hadronic origin, x-ray, IACT)

LHAASO, The Innovation (2025) arXiv: [2502.15447](https://arxiv.org/abs/2502.15447)



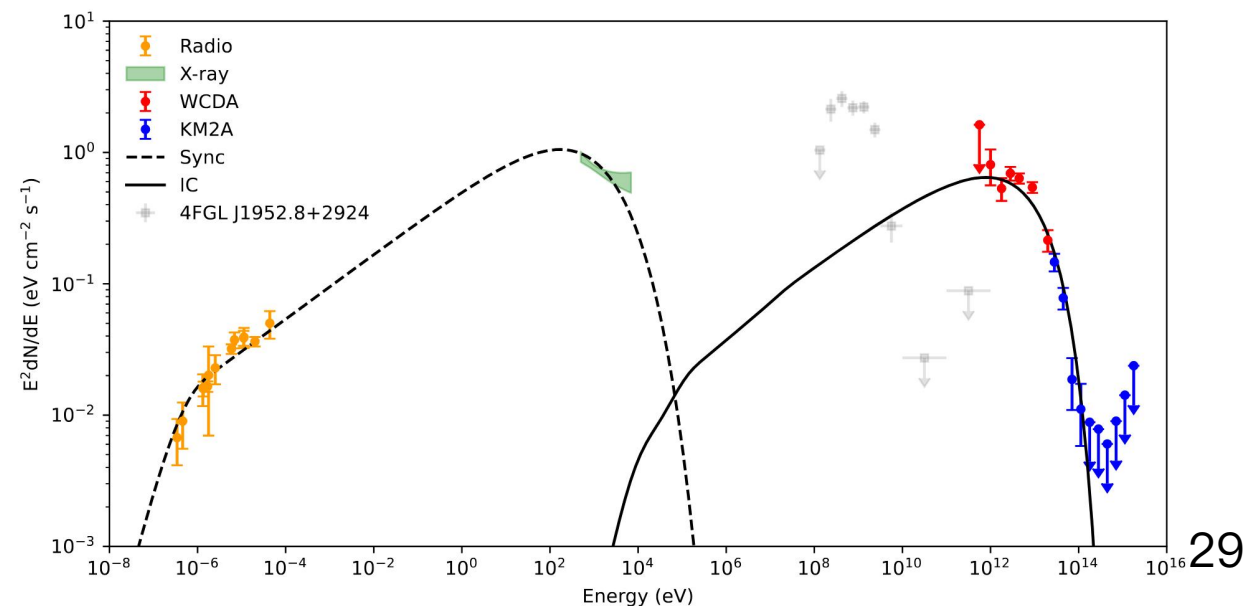
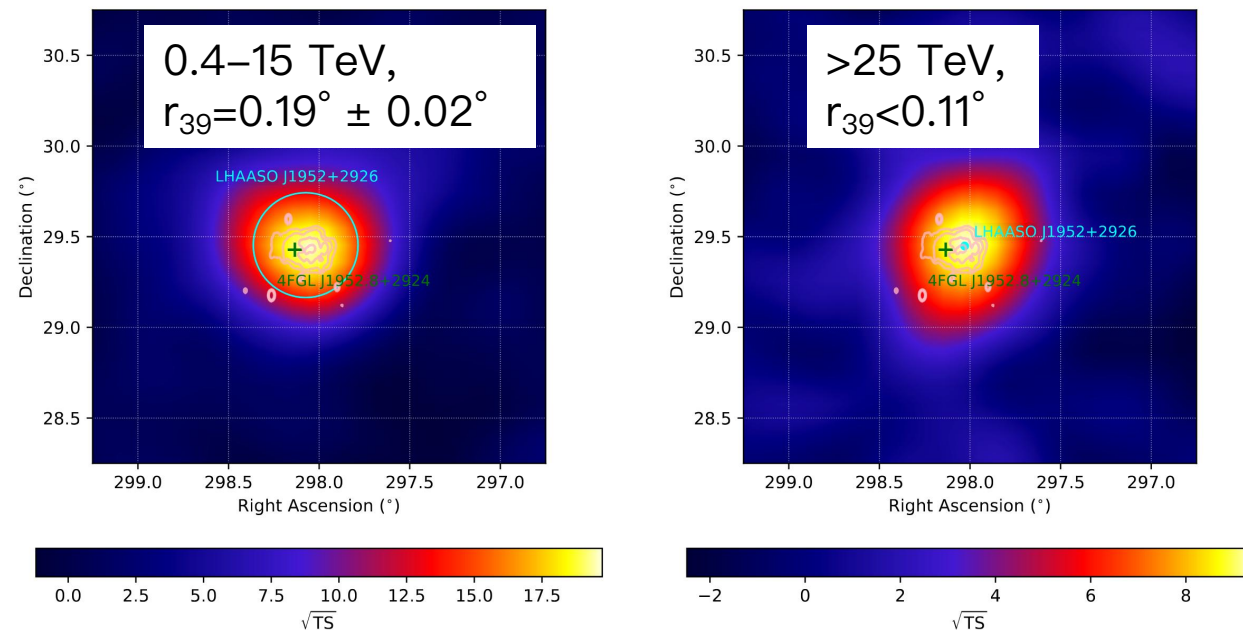
A PWN+halo system? DA 495

DA 495 (G65.7+1.2) : observed from radio to TeV γ -ray bands (Fermi, HAWC, VERITAS), but no detection of pulsation from its associated pulsar.

- ❑ LHAASO observation reveal its energy-dependent morphology.
- ❑ Multi-wavelength observations+SED fitting:
 1. one-zone leptonic model $\rightarrow B \sim 5 \mu\text{G}$
 2. time-dependent, two-zone model:
 - **convection**-dominated for inner region
 - **diffusion**-dominated for outer region

➤ **DA 495** may represent an evolved PWN with ongoing particle escape that gives rise to a TeV halo component.

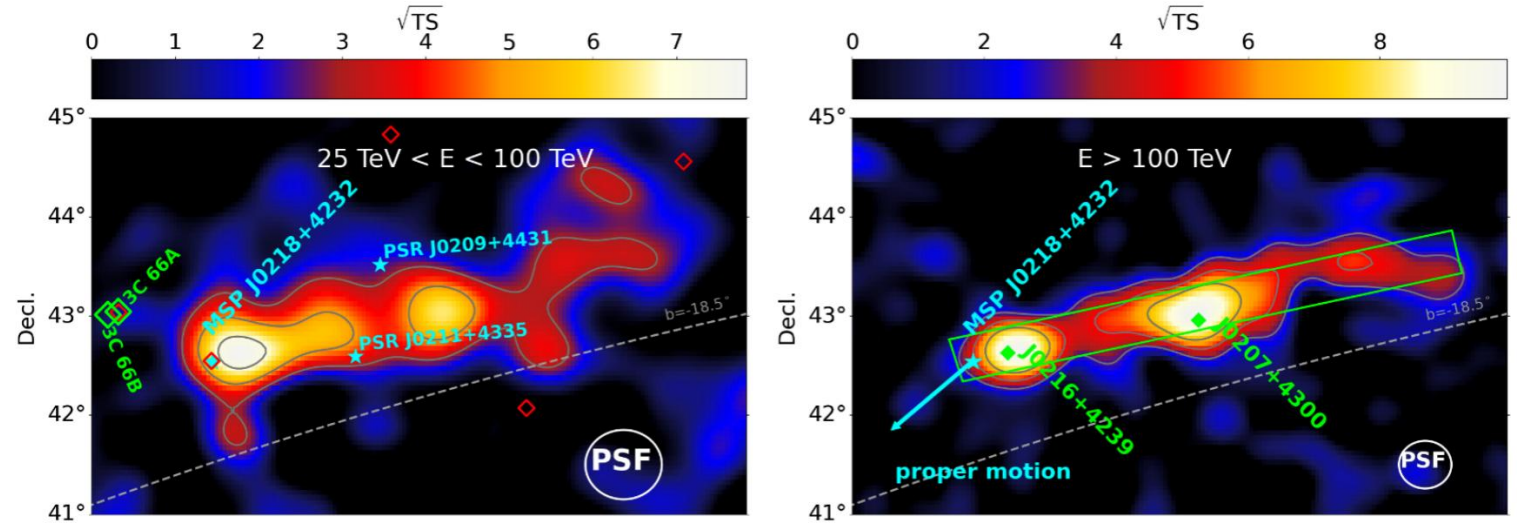
LHAASO (2026) arXiv: [2601.11071](https://arxiv.org/abs/2601.11071)



More PWNe and Halos

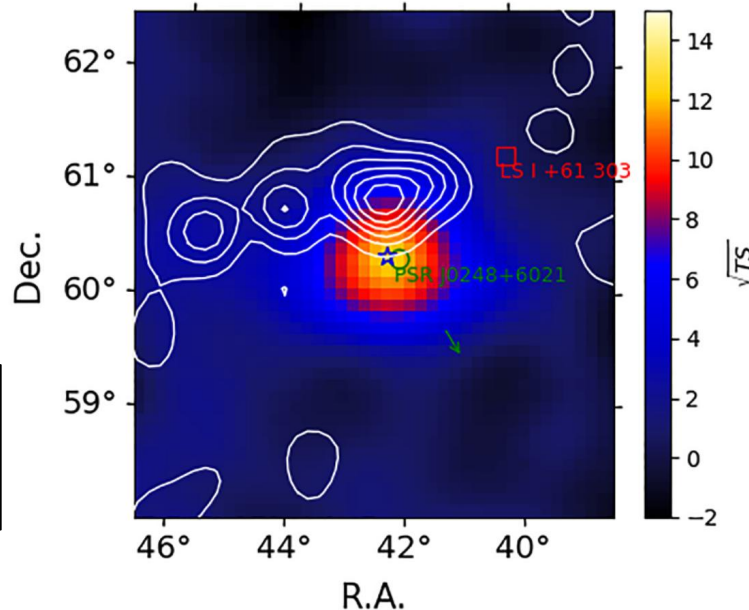
- A Giant Peanut-shaped UHE Gamma-Ray Emitter Off the Galactic Plane: possibly the first evidence of a millisecond pulsar powering PeV particles.

LHAASO, accepted, Science Bulletin (2026) arXiv: [2510.06786](#)



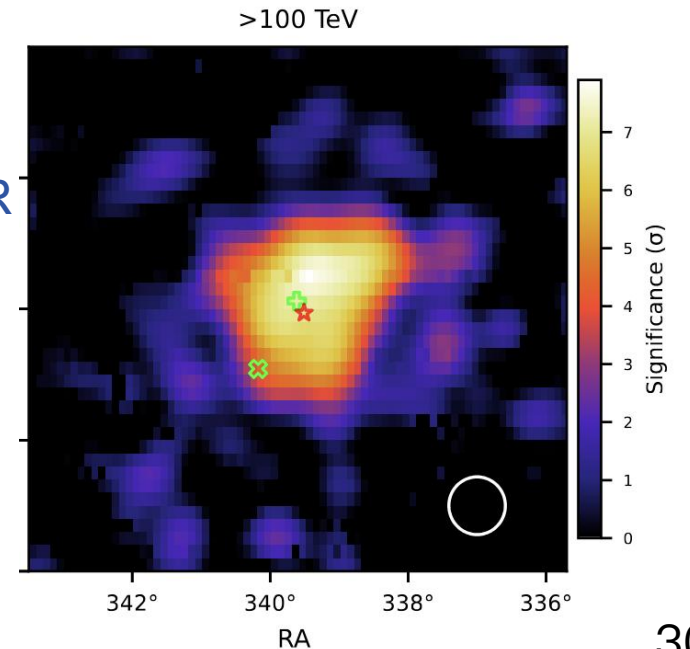
- γ -ray emission surrounding PSR J0248+6021

LHAASO, SCPMA, 68, 279504 (2025) arXiv: [2409.09499](#)



- γ -ray emission in the vicinity of PSR J2238+5903

LHAASO (2026) arXiv: [2607.21026](#)



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- Introduction: the LHAASO experiment
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- Galactic Gamma-ray source observations
 - ✓ Supernova remnants
 - ✓ PWNe and pulsar halos: a major class of UHE gamma-ray sources, extreme particle acceleration (as Pevatrons) and very high efficiency is revealed in young PWN (e.g, Crab, PSR J1849-0001) ; various cases in different environments at different evolution stages are investigated (e.g., PSR J1740+1000, DA 495, Peanut, ...) and better understanding of MHD physics as well as particle acceleration and propagation process are required.
 - ✓ Young massive star clusters
 - ✓ Binaries (Microquasars/Gamma-ray binaries)
 - ✓ “Dark” sources, “Passive” GMCs
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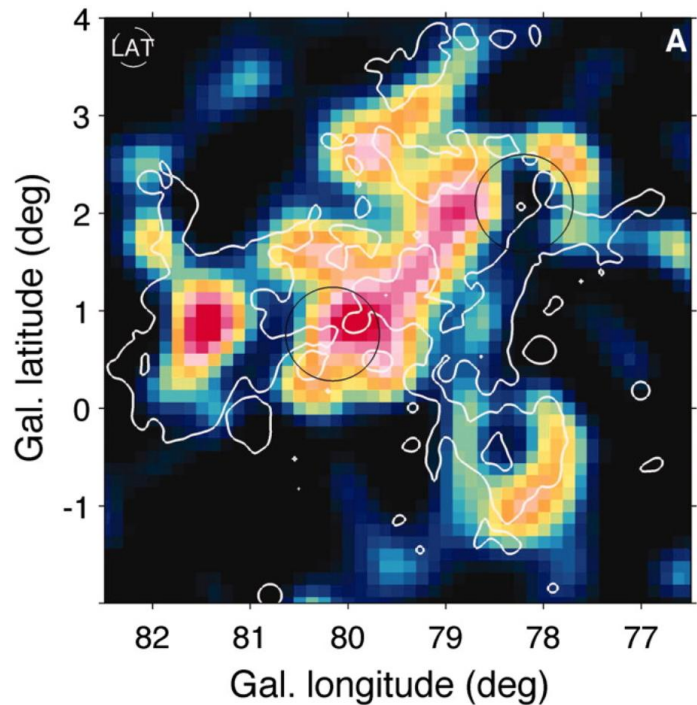
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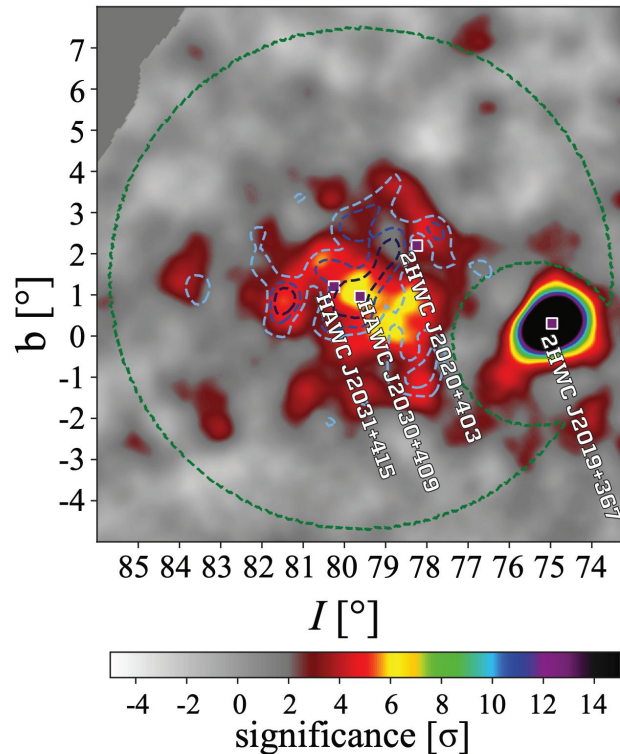
Young massive clusters/star-forming regions

Massive stars as important factories of GCRs: Most of OB stars exist in associations or clusters, their stellar winds can accelerate particles and last much longer than SNR shocks (e.g., Cesarsky & Montmerle 83, Aharonian et al. 2019).

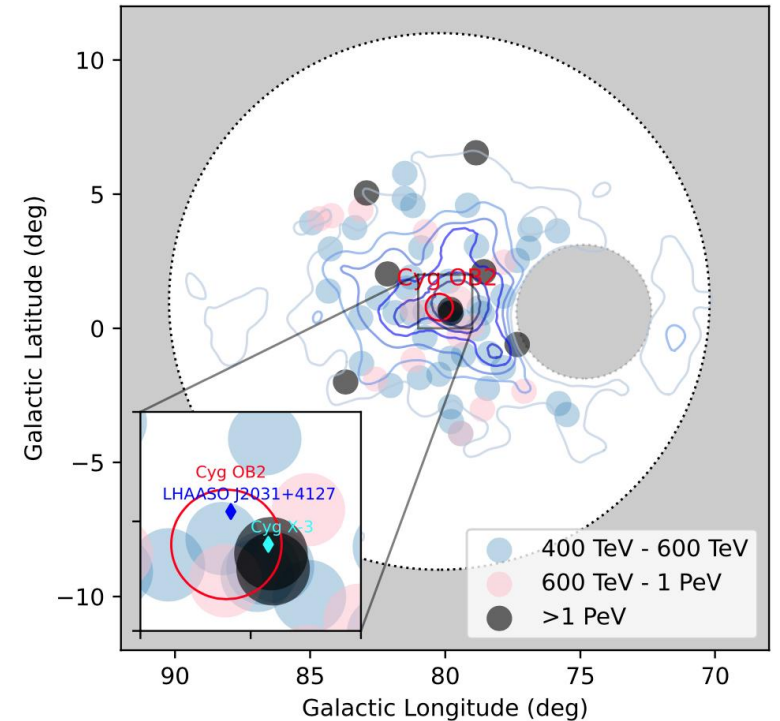
Cygnus-X region: potential of accelerating particles to TeV-multi PeV energies.



1-100 GeV gamma rays
Fermi-LAT, (2011) Science



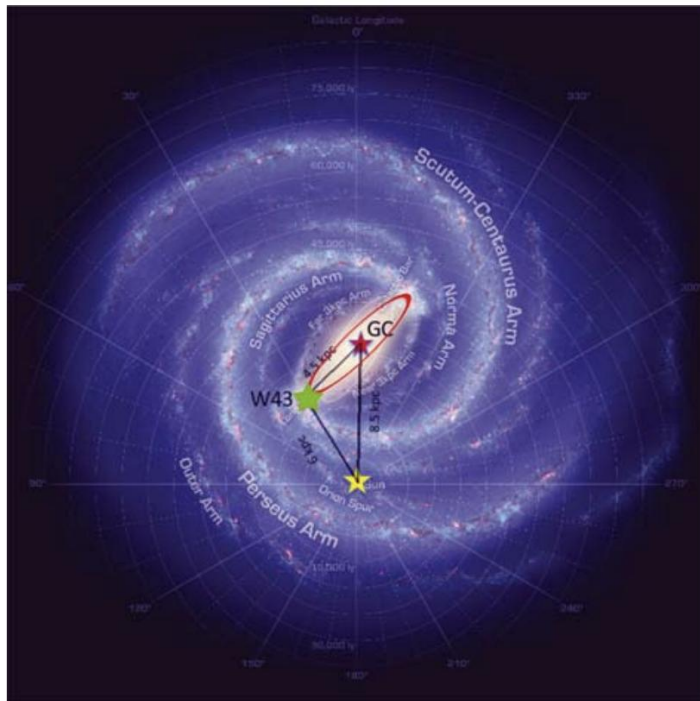
1-100 TeV gamma rays
HAWC, (2021) NA



100s TeV- PeV gamma rays
LHAASO, Science Bulletin, 69, 449 (2024)

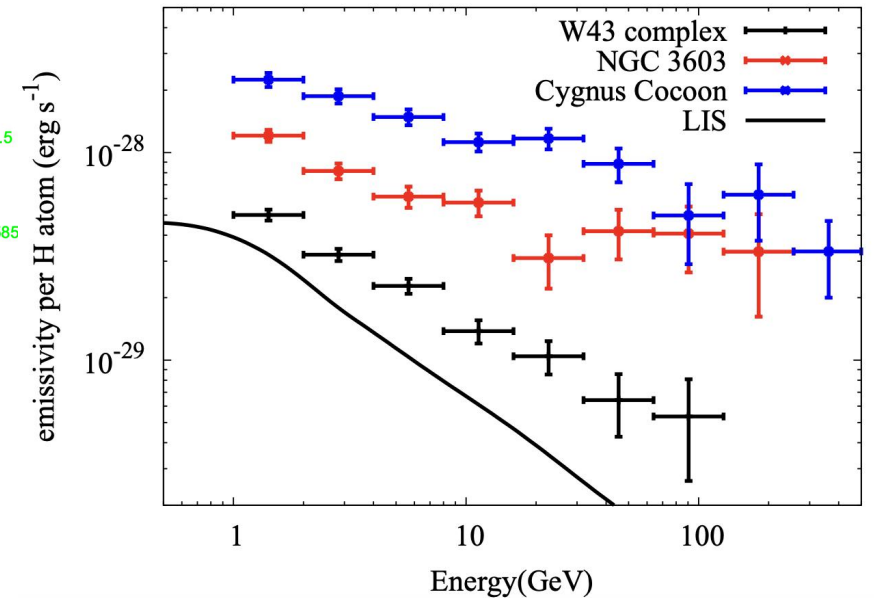
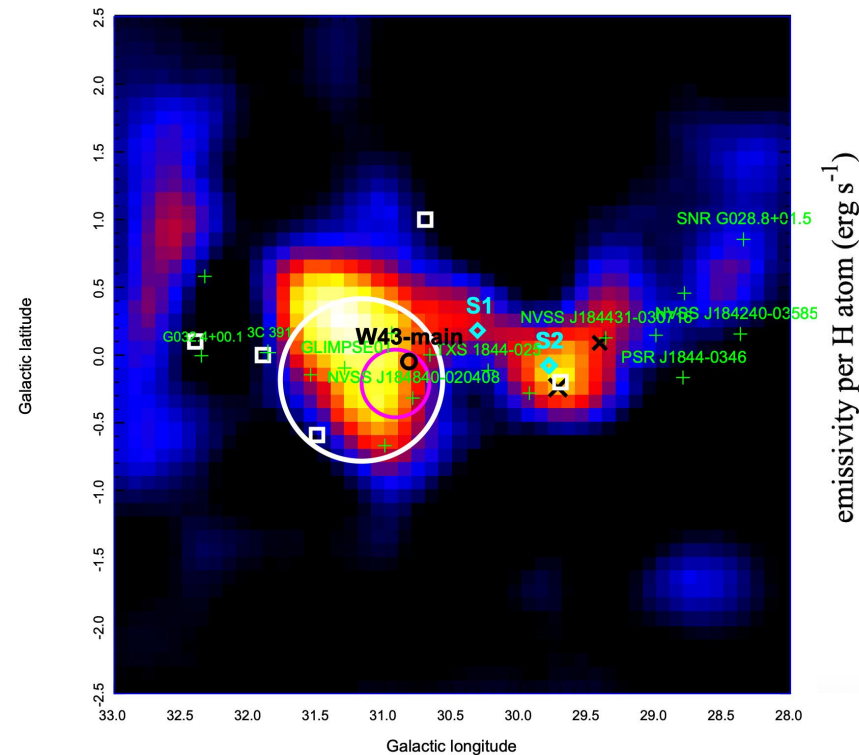
W43 region

W43: A "**mini-starburst**" region located ~ 5.5 kpc from Earth, contains huge HII region excited by central WR/OB cluster and contributes approximately **5%-10%** of the total star formation rate in the Milky Way.



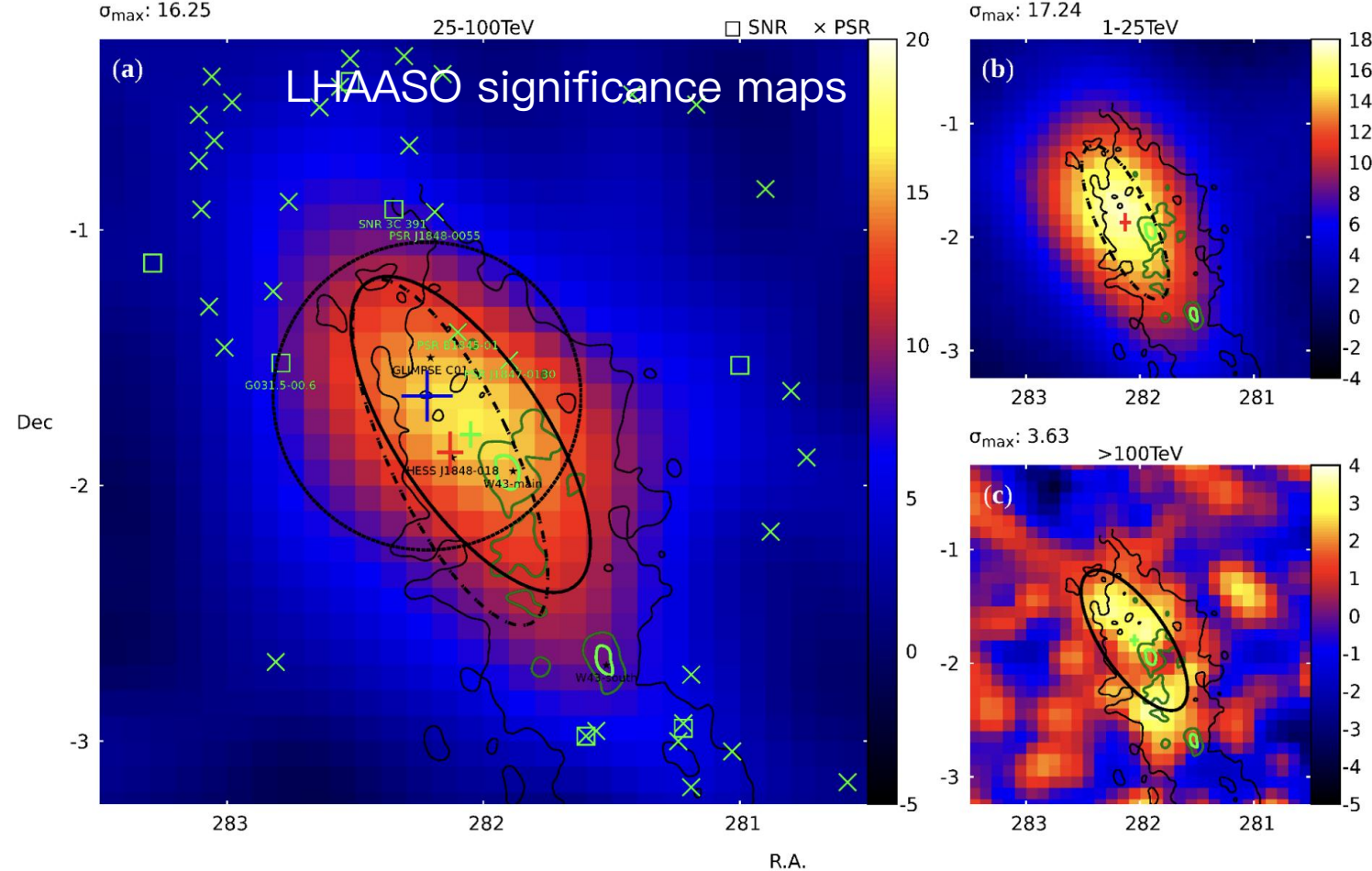
Location of W43

(Figure 9 from Nguyen Luong et al. 2011)

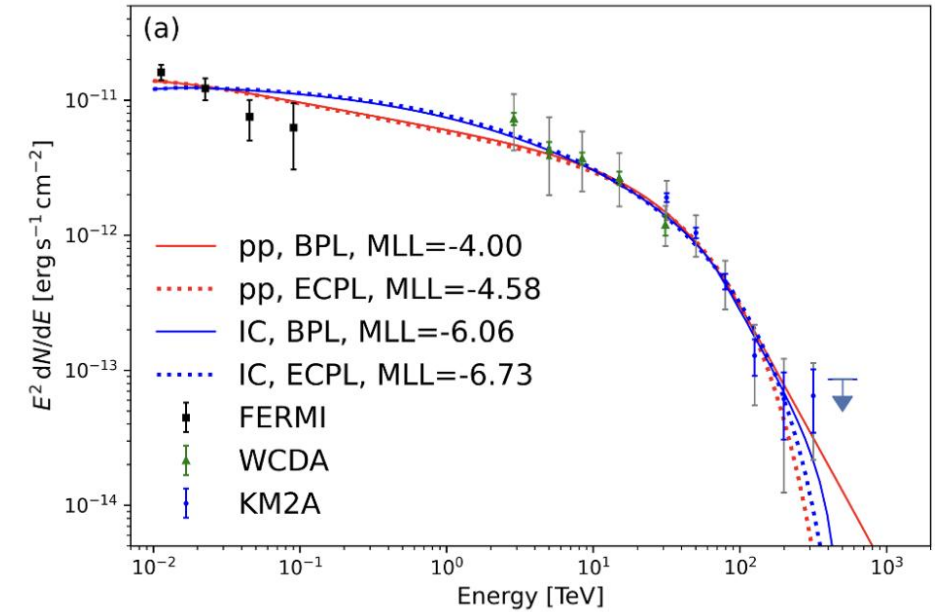


GeV gamma-ray detected (Yang & Wang, 2020)

W43 region



The γ -ray spectrum fitted with PP/IC model



	α/α_1	β/α_2	E_{cut}/E_b	$W_p (>1\text{TeV})$
ECPL(PP)	~ 2.3	~ 3.1	$\sim 406\text{TeV}$	$\sim 2.5e48$ erg
BPL(PP)	~ 2.3	~ 4.4	$\sim 211\text{TeV}$	$\sim 2.5e48$ erg

□ UHE γ -ray emission reveal good correlation with dense gas.

□ The γ -ray spectrum up to 400 TeV, with E_{cut} at ~ 30 TeV

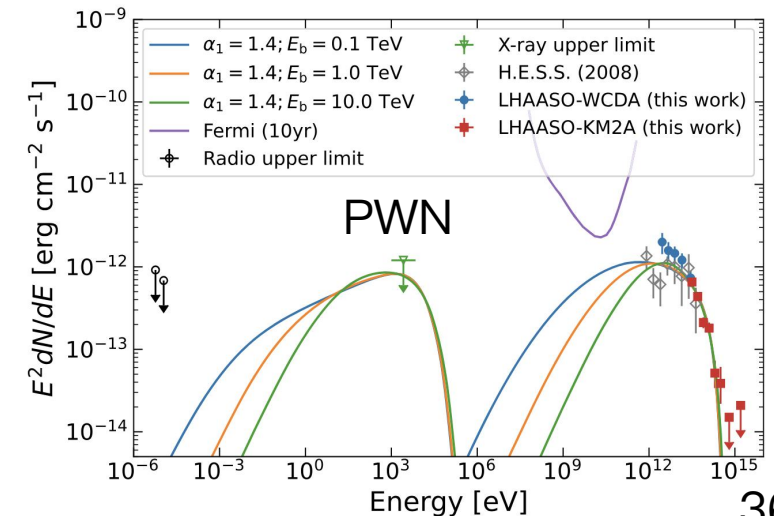
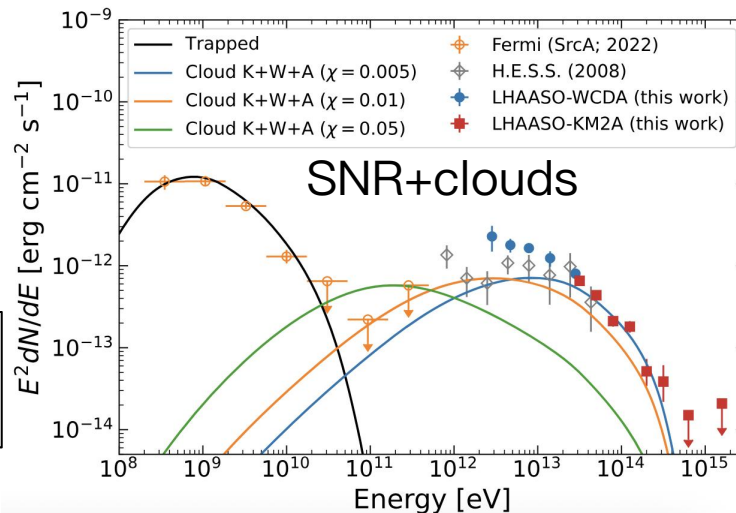
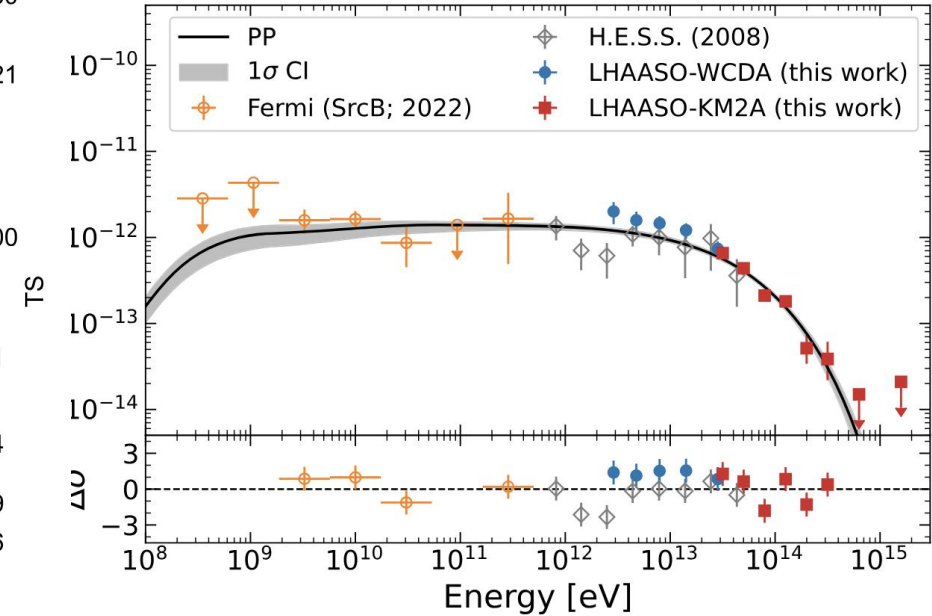
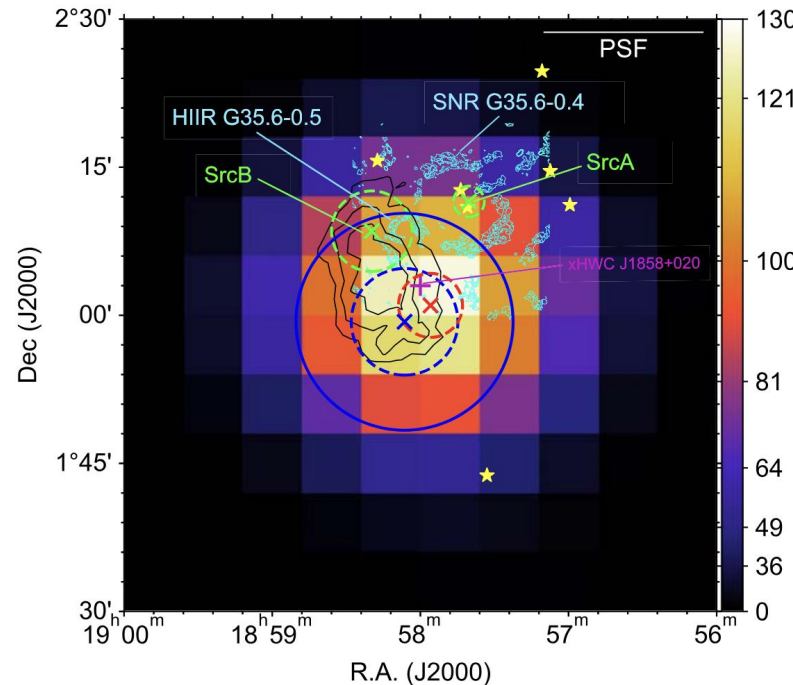
→ W43 possibly accelerated hadronic CRs to sub-PeV energies.

More studies on star-forming regions

H II Region G35.6-0.5

- UHE γ -ray sources: 11.6σ above 100 TeV
- GeV-TeV γ -ray SED: PP, proton spectrum: PL with index ~ 2.0 and $E_{\text{cut}} \sim 450$ TeV. $\rightarrow$ PeVatron from HII Region G35.6-0.5?
- SNR G35.6-0.4+clouds? unlikely
- PWN? Cannot be ruled out.

LHAASO, ApJ, 979, 70 (2025)
arXiv: [2412.00379](https://arxiv.org/abs/2412.00379)



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 - ✓ Pulsar wind nebulae and pulsar halos
 - ✓ Young massive star clusters: potentially sub-PeV to multi-PeV acceleration through collective stellar activity (e.g., Cygnus bubble, W43, G35.6-0.6) , but contributions from other sources need to be disentangled.
 - ✓ Binaries (Microquasars/Gamma-ray binaries)
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- Summary and prospect

Outline

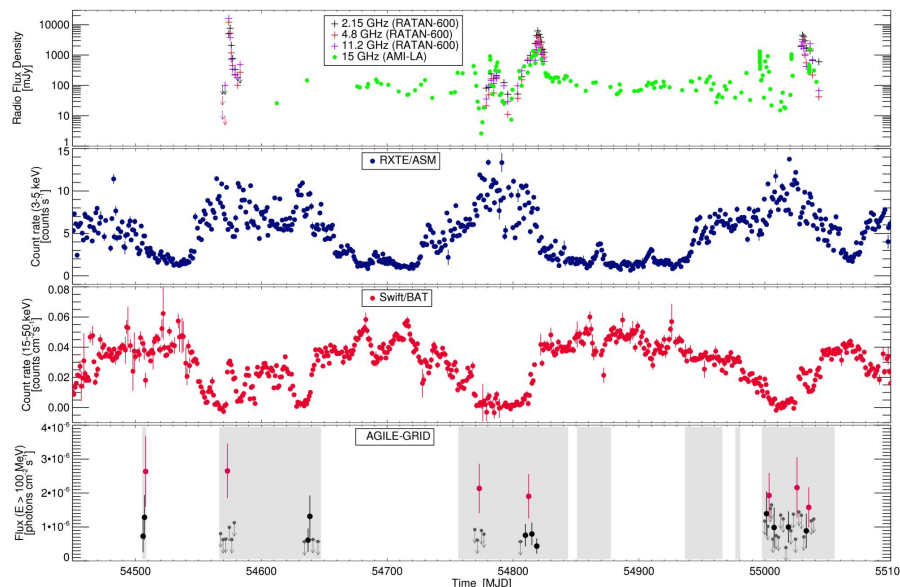
- Introduction: the LHAASO experiment
- LHAASO catalog and measurement of GDE
- **Galactic Gamma-ray source observations**
 - ✓ Supernova remnants
 - ✓ Pulsar wind nebulae and pulsar halos
 - ✓ Young massive star clusters
 - ✓ **Binaries (Microquasars/Gamma-ray binaries)**
 - ✓ “Dark” sources, “Passive” GMCs
- Measurements of CR Spectra and Anisotropy
- Summary and prospect

Binary systems

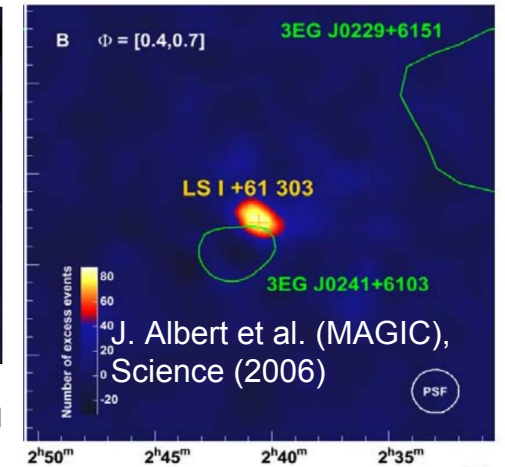
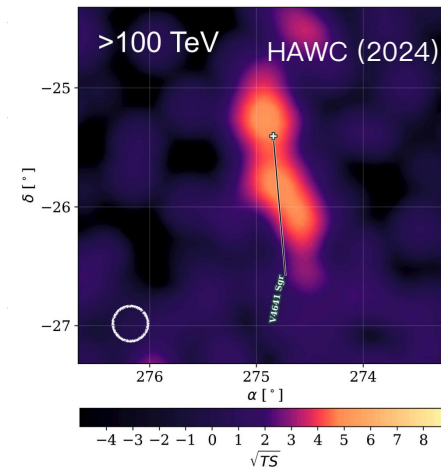
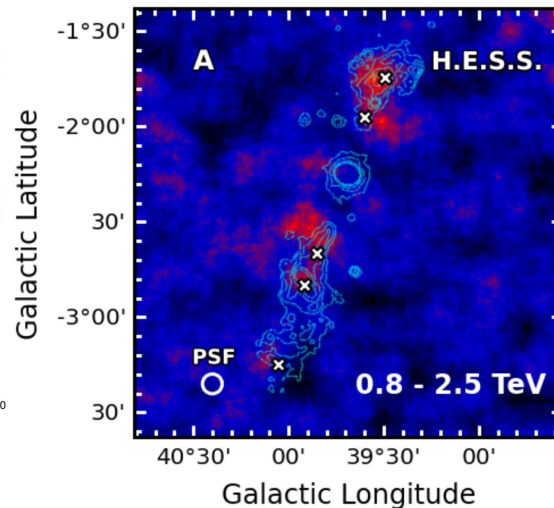
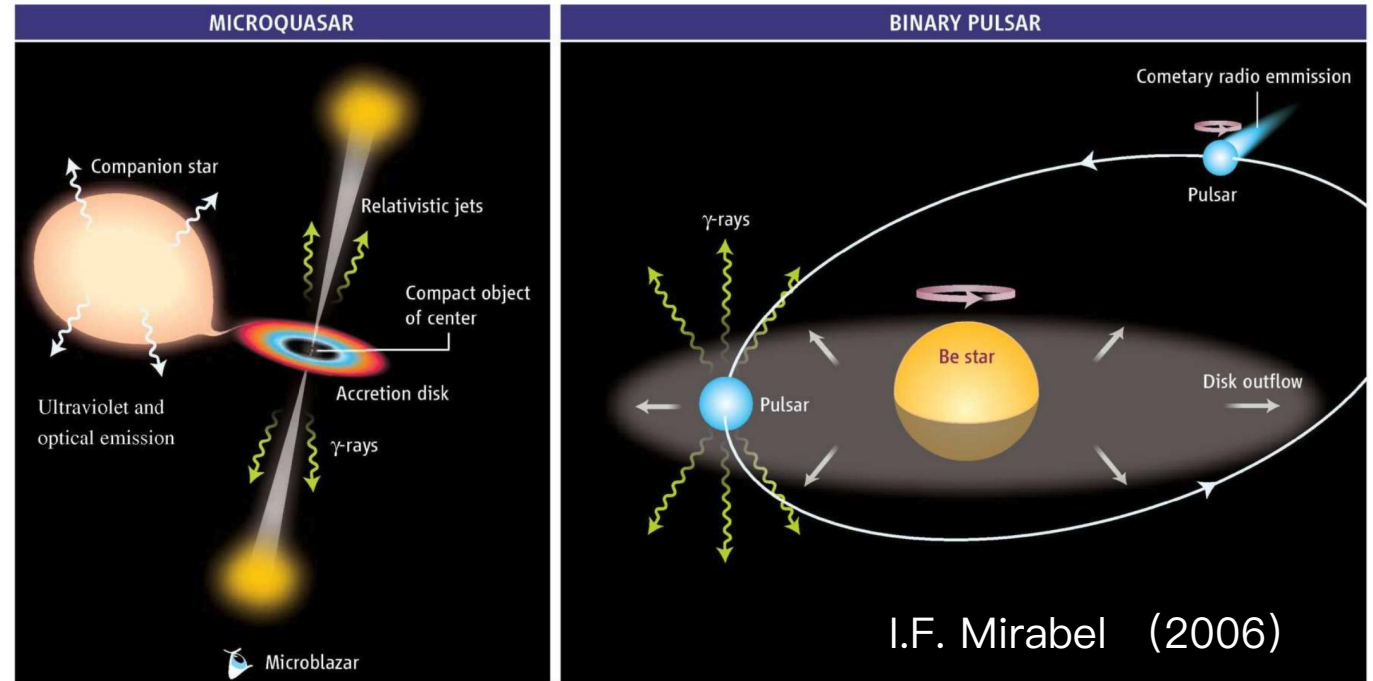
Binary systems containing compact objects:

extreme environment for particle acceleration
(strong magnetic fields, relativistic outflows, dense stellar environments...).

- **Microquasars:** accretion onto the compact object launch relativistic jets.
- **Gamma-ray binaries:** interaction between compact object and massive companion produces powerful non-thermal emission.



Multi-frequency light curve of Cygnus X-3 from 2007-December-12 to 2009-September-26 (Piano et al. 2011)



6 UHE-emitting Microquasars detected by LHAASO



Microquasar	Distance (kpc)	LHAASO Source	Significance (σ)	Photon Index	Energy Range (TeV)	Extension ^a	Flux ^b (Crab Unit)
SS 433 E.		J1913+0455	9.9 ^c	2.82 ± 0.16	25 – 100	$0.73^\circ \pm 0.07^\circ$	0.10
SS 433 W.	4.9 ± 0.4 [Su2018]	J1910+0509	6.3 ^c	2.94 ± 0.38	25 – 100		0.082
SS 433 central		J1911+0510	8.0	3.96 ± 0.25	100 – 630		0.32
V4641 Sgr	6.2 ± 0.7 [MacDonald14]	J1819-2541	10.5	2.84 ± 0.17	40 – 1000	$0.33^\circ \pm 0.08^\circ$	2.6
GRS 1915+105	9.4 ± 0.6 [Reid23]	J1915+1053	15.1	2.68 ± 0.13	25 – 1000	$0.28^\circ \pm 0.05^\circ$	0.11
MAXI J1820+070	2.96 ± 0.33 [Atri20]	J1821+0723	6.0	3.25 ± 0.26	25 – 400	$< 0.28^\circ$	0.02
Cygnus X-1	2.2 ± 0.2 [Miller-Jones21]	J1958+3522	4.4	3.98 ± 0.40	25 – 100	$< 0.22^\circ$	< 0.01
XTE J1859+226	4.2 ± 0.5 [Shaposhnikov09]	–	2.7	–	–	–	< 0.02
GS 2000+251	2.7 ± 0.7 [Jonker04]	–	2.3	–	–	–	< 0.04
Swift J1727.8-1613	2.7 ± 0.3 [Mata24]	–	0.7	–	–	–	< 0.04
GRO J0422+32	2.49 ± 0.3 [Gelino03]	–	0.7	–	–	–	< 0.01
V404 Cygni	2.39 ± 0.14 [Miller-Jones09]	–	1.5	–	–	–	< 0.03
XTE J1118+480	1.7 ± 0.1 [Gelino06]	–	0.4	–	–	–	< 0.02
V616 Mon	1.06 ± 0.1 [Cantrell10]	–	0.4	–	–	–	< 0.01

PHYSICS

Ultrahigh-energy gamma-ray emission associated with black hole-jet systems

The LHAASO Collaboration^{†,*}

ABSTRACT

Black holes (BH), one of the most intriguing objects in the universe, can manifest themselves through electromagnetic radiation initiated by the accretion flow. Some stellar-mass BHs drive relativistic jets when accreting matter from their companion stars, forming microquasars. Non-thermal emission from the radio to tera-electronvolt (TeV) gamma-ray band has been observed from microquasars, indicating the acceleration of relativistic particles. Here we report detection of four microquasars (SS 433, V4641 Sgr, GRS 1915+105, MAXI J1820+070) of spectrum extending to the ultrahigh-energy (UHE; photon energy $E > 100$ TeV) band and one microquasar (Cygnus X-1) of spectrum approaching 100 TeV, using the Large High Altitude Air Shower Observatory (LHAASO). Notably, the total emission associated with SS 433 cannot be interpreted with a single leptonic component. In the UHE band, its emission is in spatial coincidence with a giant atomic cloud, which is consistent with a hadronic origin. An elongated source is discovered from V4641 Sgr with the spectrum continuing up to 800 TeV. The detection of UHE gamma rays demonstrates that accreting BHs and their environments can operate as extremely efficient accelerators of particles out of 1 peta-electronvolt (PeV), suggesting microquasars to be important contributors to Galactic cosmic rays especially around the ‘knee’ region.

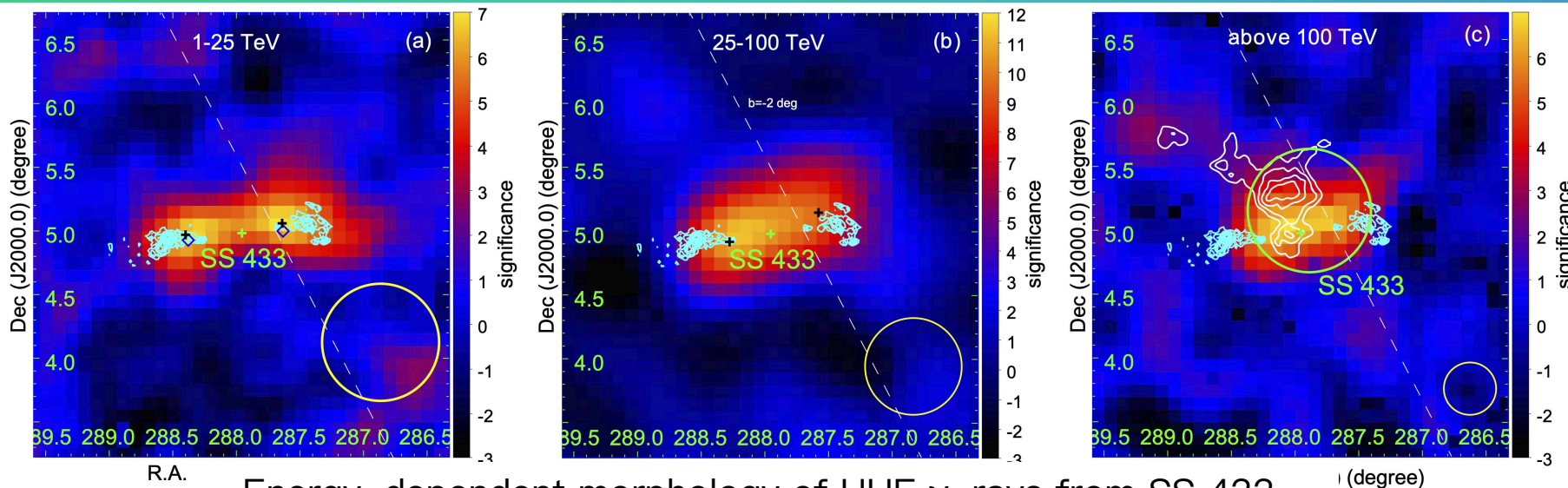
PHYSICS

Cygnus X-3: A variable petaelectronvolt γ -ray source

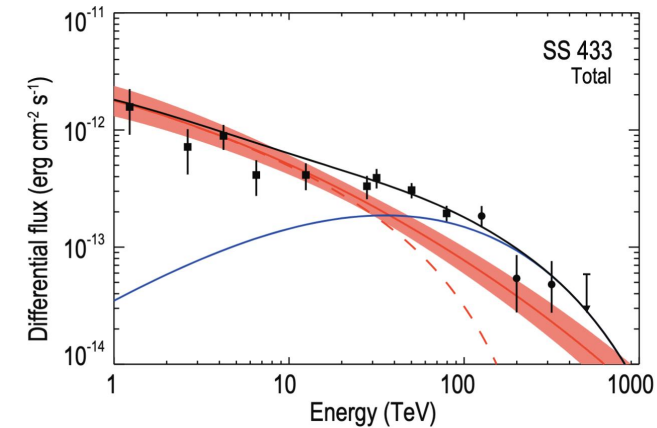
The LHAASO Collaboration^{†,*}

LHAASO, National Science Review (2025, 2026)

Hits of hadronic emission from SS 433 and GRS 1915+105



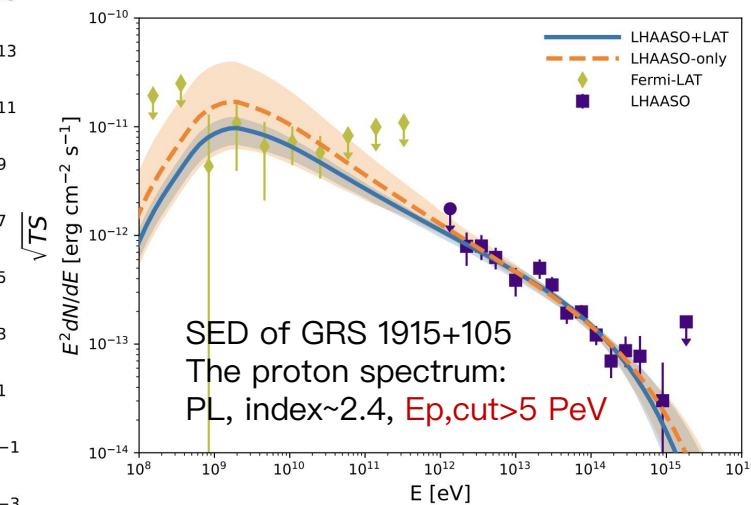
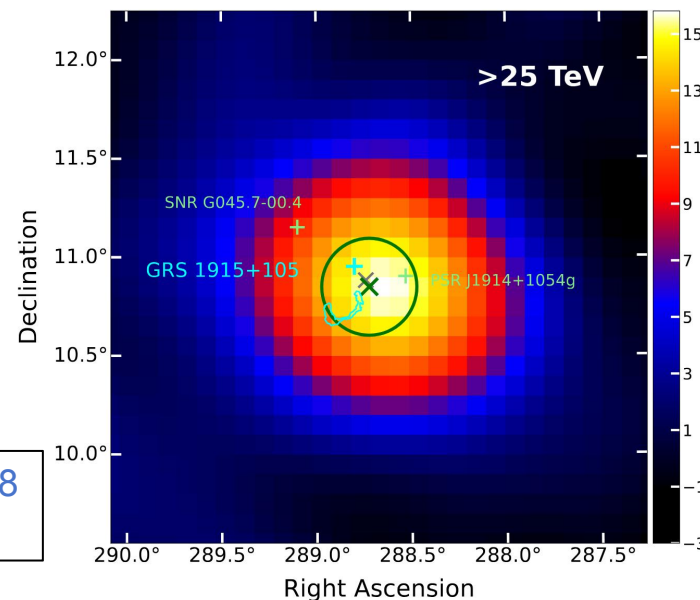
Energy-dependent morphology of UHE γ -rays from SS 433.



SED of SS 433 fitted with leptonic (IC, red band) and hybrid (IC, red dashed + pp, blue) models.

- ❑ **SS 433:** The >100 TeV emission partly overlapped with HI cloud at the same distance, may hint for a hadronic origin.
- ❑ **GRS 1915+105:** Shift of UHE γ -ray emission from the jet termination regions favors the hadronic pp scenario. (PL, $E_{p, \text{cut}} > 5$ PeV, super Pevatron)

LHAASO, National Science Review (2025) arXiv: [2410.08988](#)
LHAASO (2026) arXiv: [2606.25054](#)

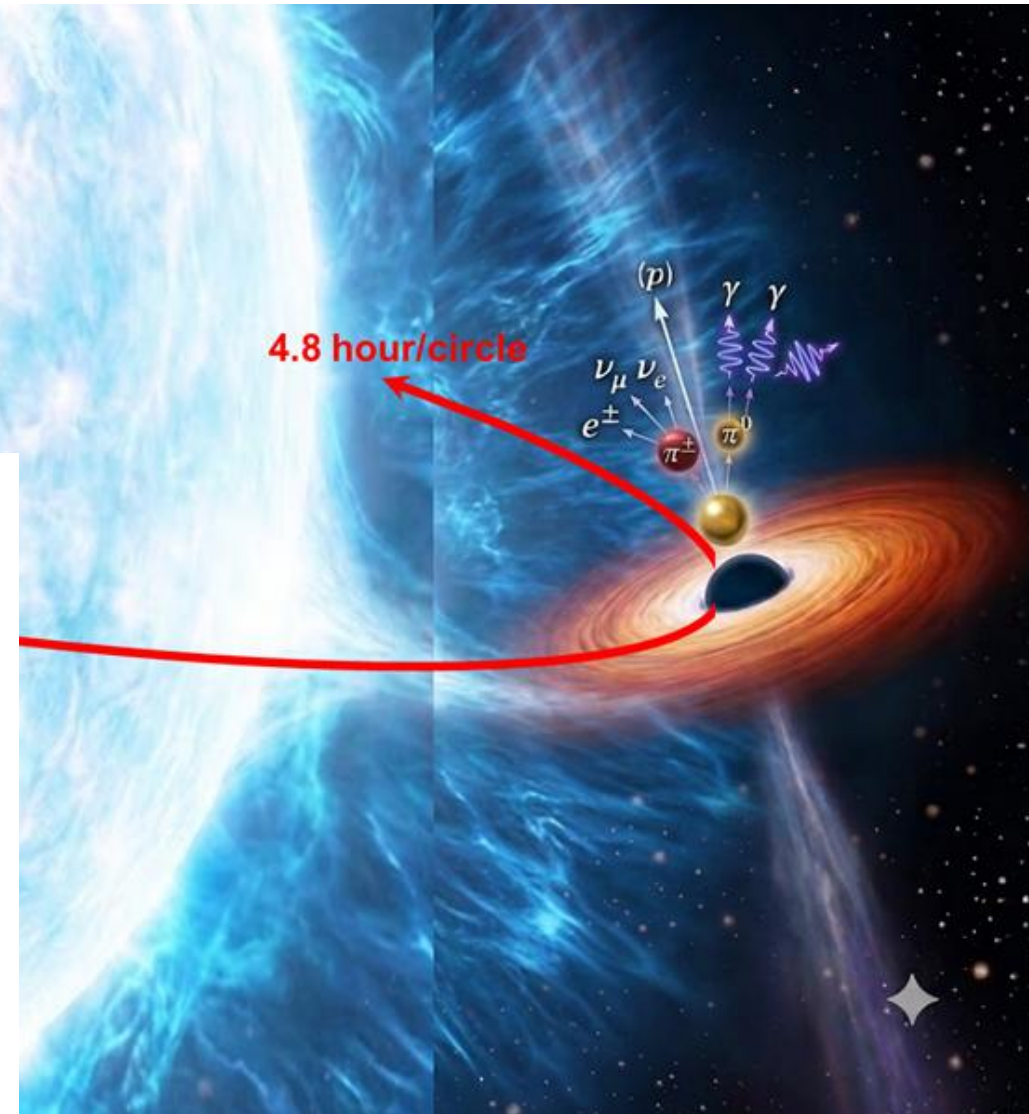
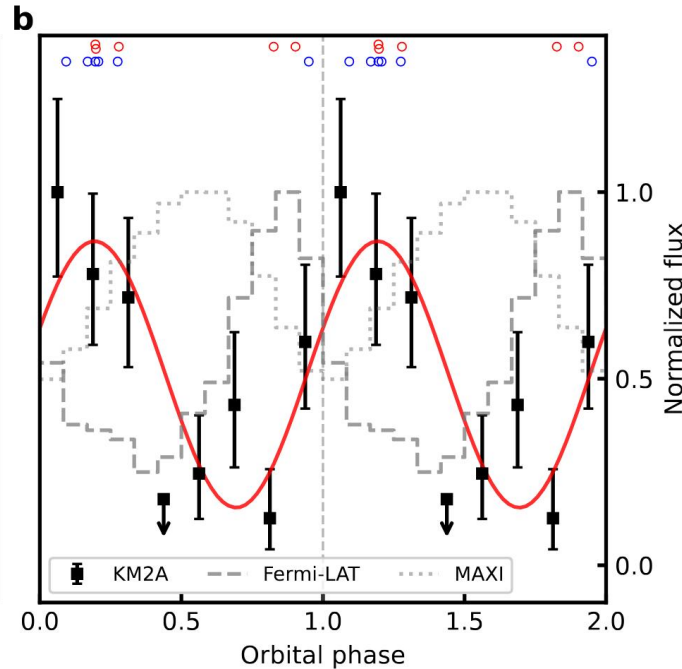
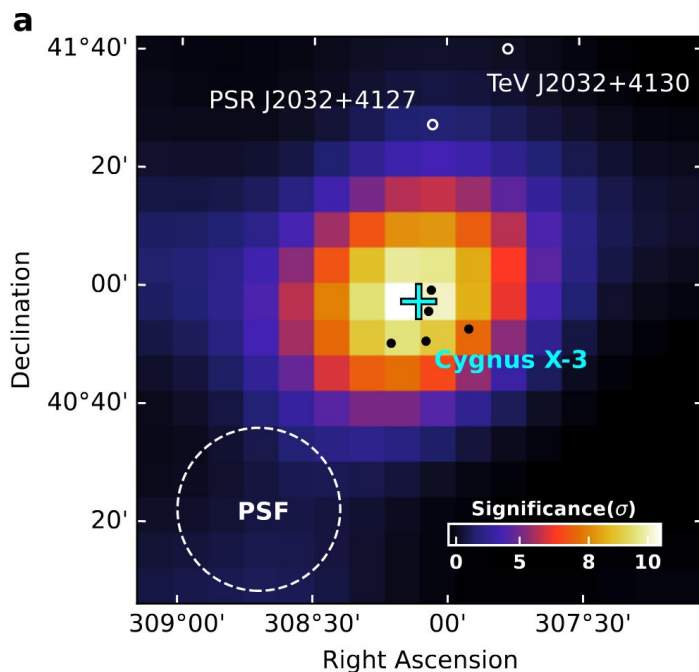


SED of GRS 1915+105
The proton spectrum:
PL, index ~ 2.4 , $E_{p, \text{cut}} > 5$ PeV

Cygnus X-3: A variable Super PeVatron

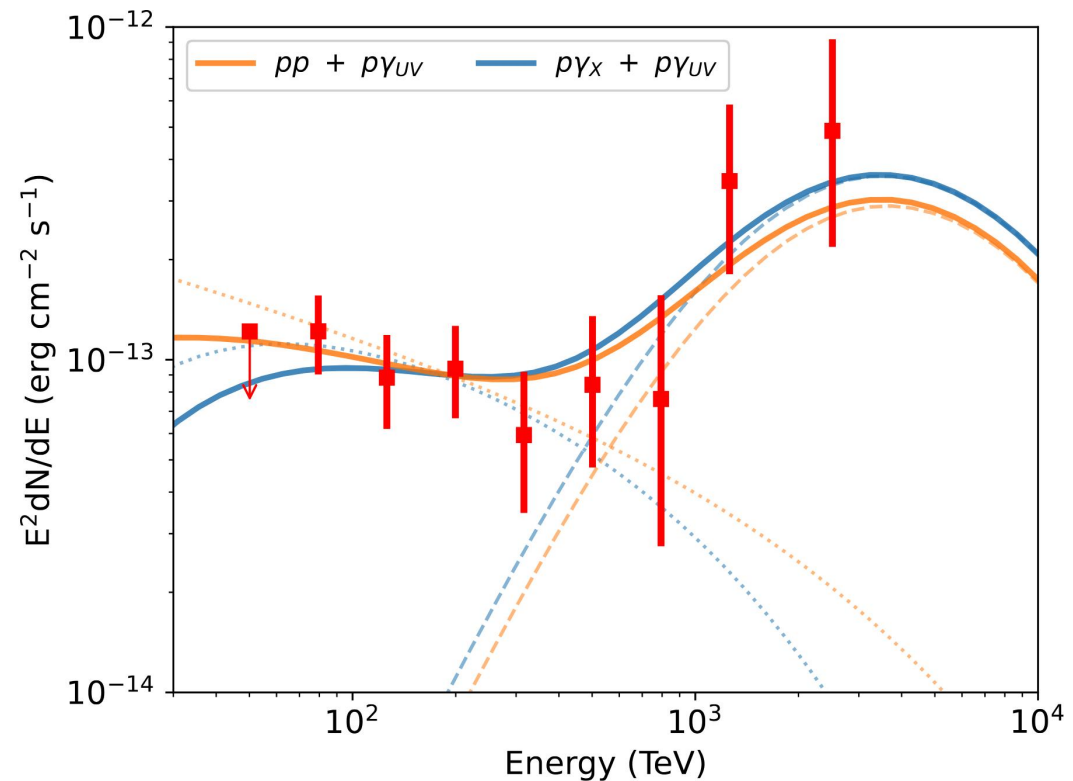
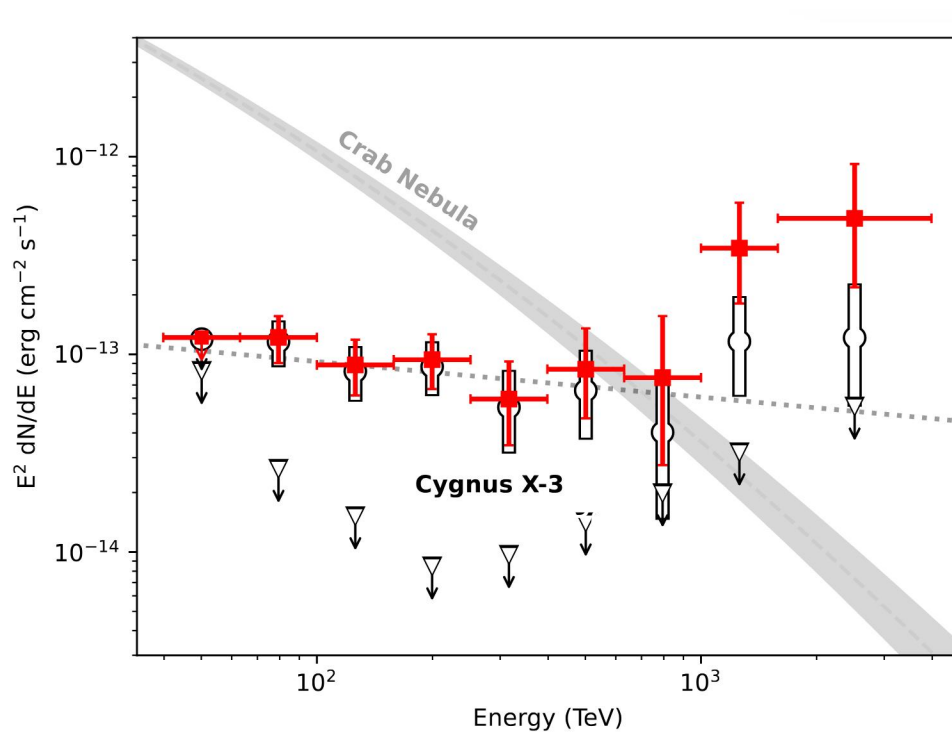
Cygnus X-3: A high-mass X-ray binary system (WR star+compact object) with a very short period of 4.8 hours.

- ❑ LHAASO detected **variable signal only at energies >100 TeV**. (GeV-defined **γ -ray high-state** : 11.5σ , low state: 2σ)
- ❑ Post-trial statistical significance of modulated signal: 3.2σ .
→ The PeV γ -rays is produced within or close to the binary system ($R \sim 3 \times 10^{11} \text{ cm}$).



Significance map and orbital light curve of ≥ 0.1 PeV photons measured by LHAASO.

Cygnus X-3: A variable Super PeVatron



- Particles with $E > \text{PeV}$ accelerated within or close to the binary system ($R \sim 3 \times 10^{11} \text{ cm}$).
 - Hillas criterion (high B) + Synchrotron cooling effects (restrictive for e not for p)
- Hadronic origin is favored: the proton energy can reach tens of PeV and produce PeV γ -rays via photo-meson processes.

UHE emission from LS I +61°303

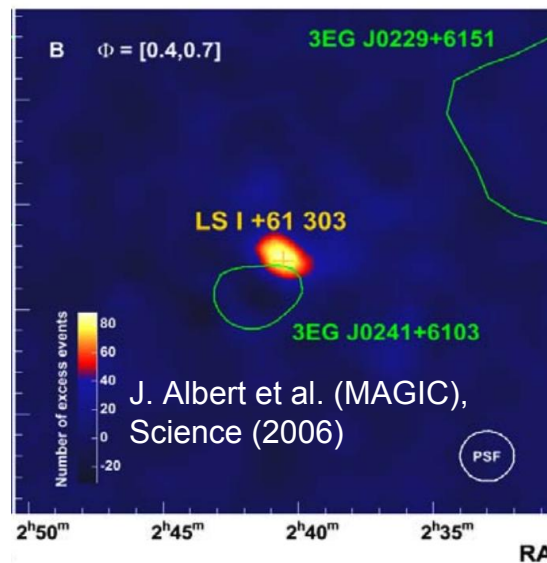
LS I +61° 303:

- A prototypical γ -ray binary system (Be star+compact object that is likely a pulsar), with orbital period ~ 26.5 days, $d \sim 2$ kpc.
- Variable VHE γ -ray emission (up to 10 TeV range) detected by MAGIC, VERITAS.

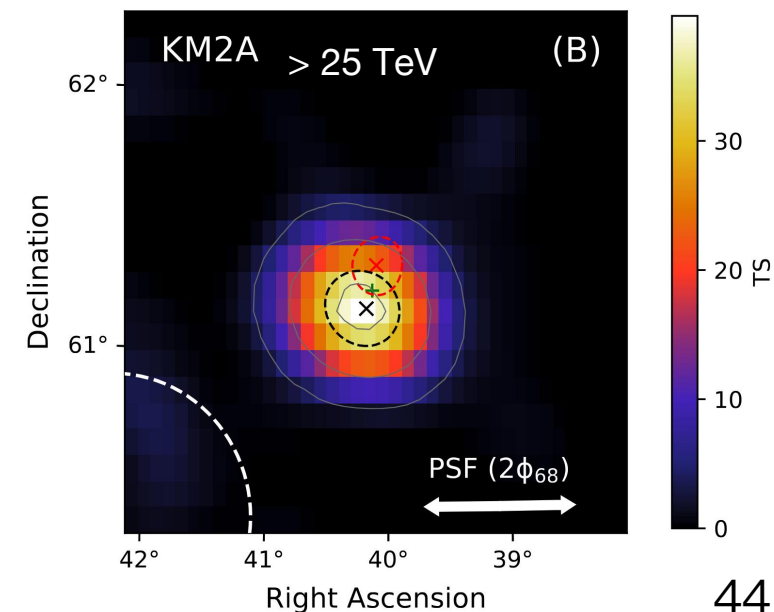
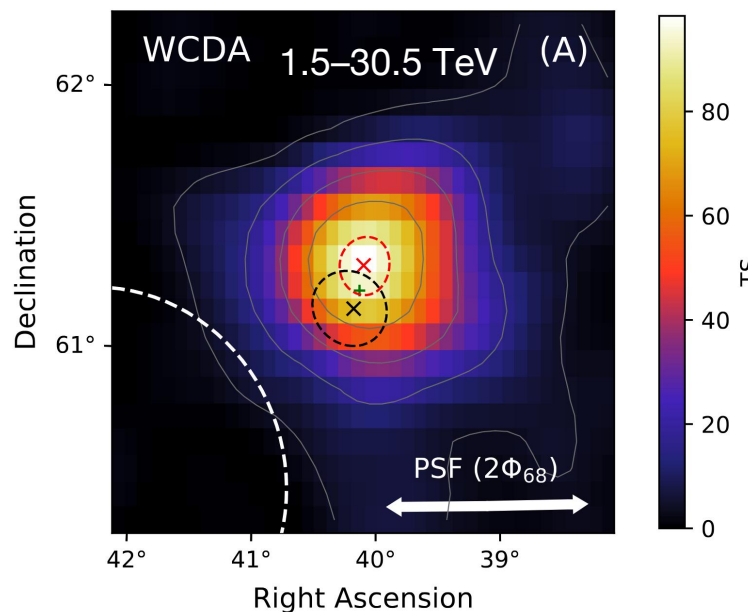
❑ LHAASO detected emission from LS I +61°303 up to the UHE regime, reaching **above 100 TeV**, revealed its potential as a Galactic **PeVatron candidate**.

LHAASO, PRL, 136, 181001 (2026)

arXiv:[2510.23345](https://arxiv.org/abs/2510.23345)

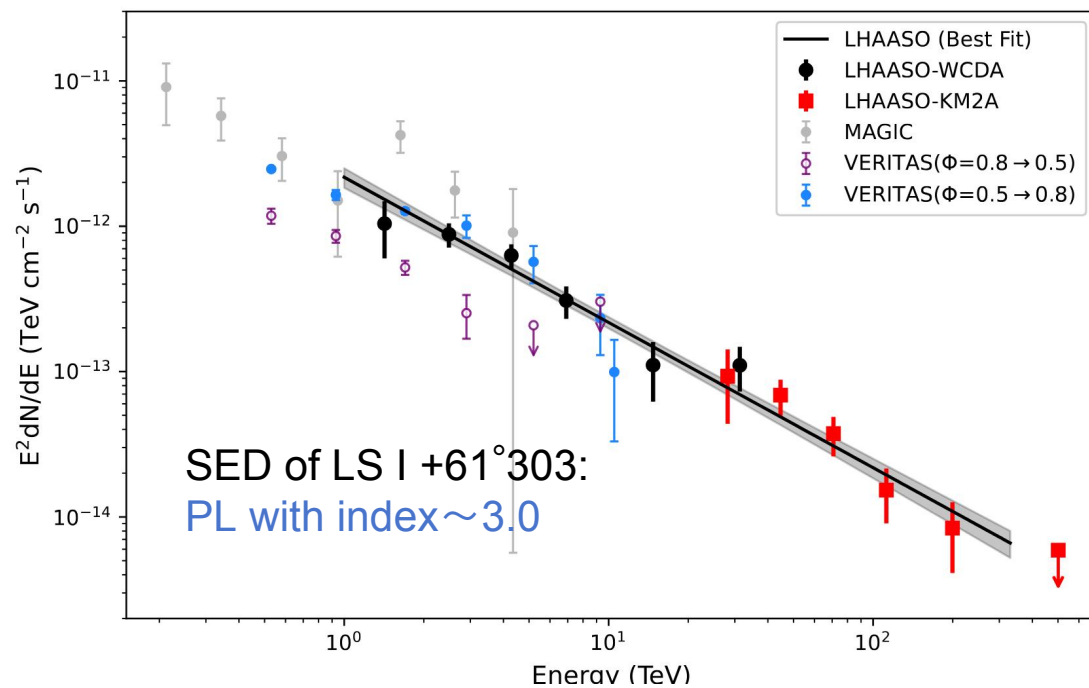


J. Albert et al. (MAGIC),
Science (2006)



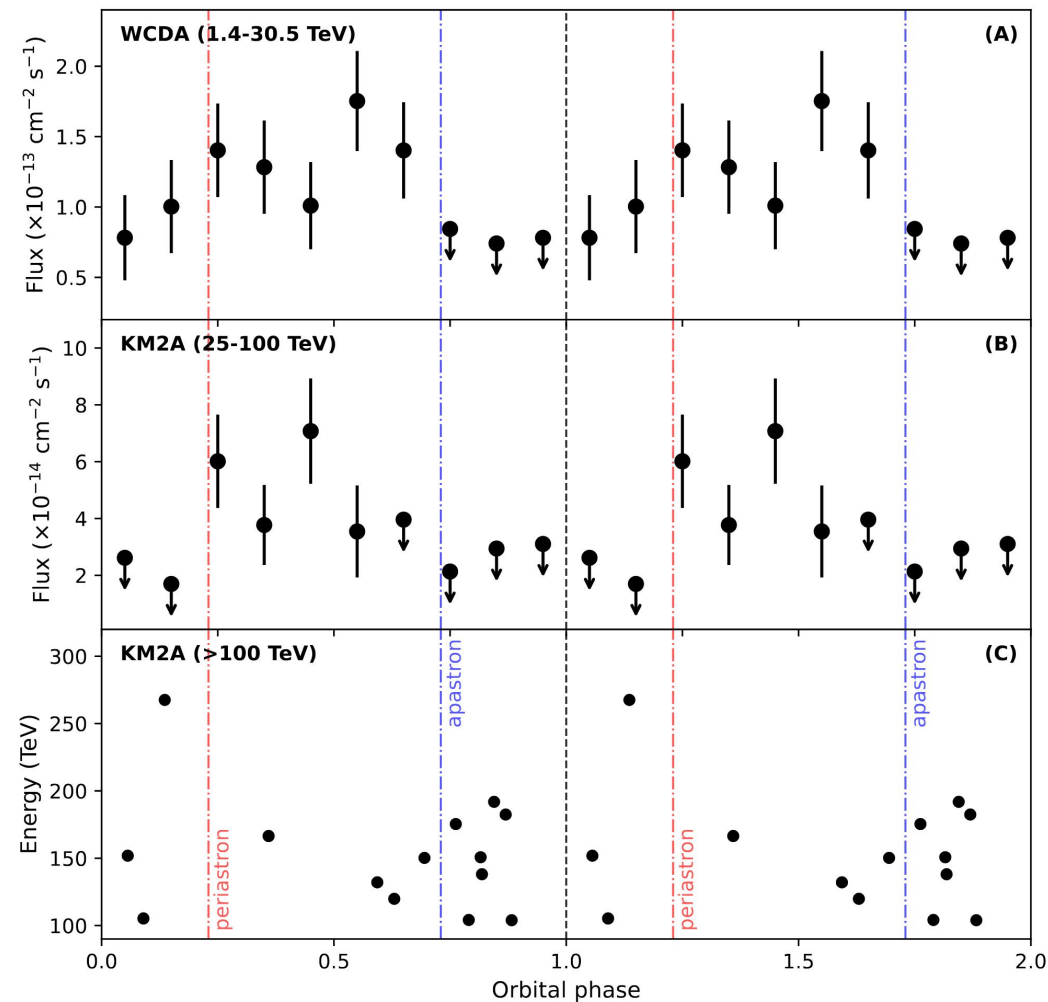
UHE emission from LS I +61°303

- ❑ LHAASO detects orbital modulation between 25 and 100 TeV, with hints of **energy-dependent modulation**. → The UHE γ -ray emission is closely connected to the changing environment of the binary system.



LHAASO, PRL, 136, 181001 (2026) arXiv:[2510.23345](https://arxiv.org/abs/2510.23345)

Phase-resolved emission of LS I +61°303 across different energy bands.



Outline

- Introduction: the LHAASO experiment
- LHAASO catalog and measurement of GDE
- Galactic Gamma-ray source observations
 - ✓ Supernova remnants
 - ✓ Pulsar wind nebulae and pulsar halos
 - ✓ Young massive star clusters
 - ✓ **Binaries:** UHE emission detected from 6 microquasars show BH+jet systems (relativistic jets) provide promising sites for extreme multi-PeV acceleration (e.g., variable super-PeVatron Cygnus X-3); hits of hadronic emission found in SS 433, GRS 1915+105 ; gamma-ray binaries are also PeVatron candidates indicated by the UHE emission from LS I +61°303.
 - ✓ “Dark” sources, “Passive” GMCs
- Measurements of CR Spectra and Anisotropy
- Summary and prospect

Outline

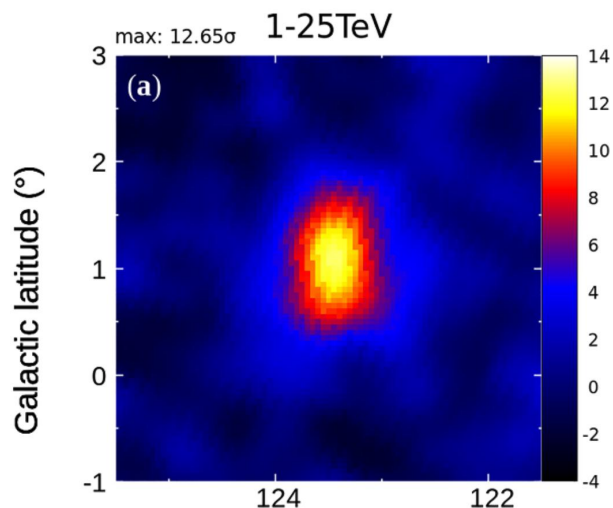
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“Dark” sources still require more investigation

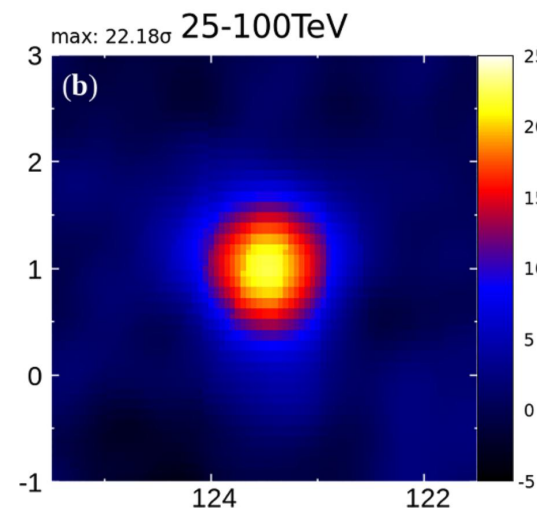
1LHAASO J0056+6346u:

- ❑ Not overlapped with known SNRs or pulsars.
- ❑ Both PP and IC can fit the γ -ray SED.
- ❑ Possible origin:
 - YMC Cas OB7,
 - SNR candidate G124.0+1.4
 - PWN/ halo from unknown pulsar
 - ...

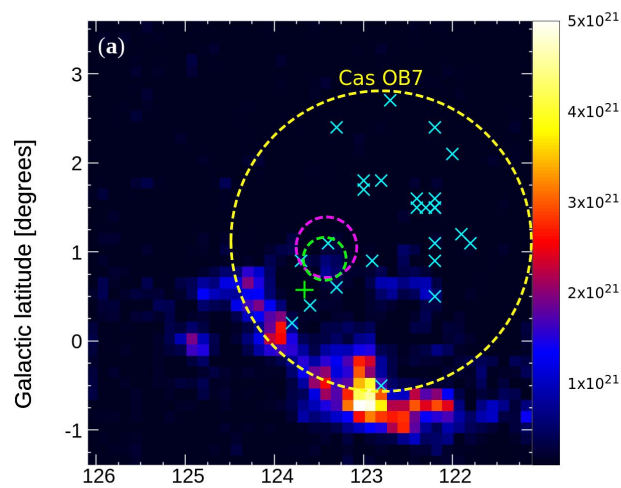
LHAASO, SCPMA 68,
279505 (2025)
arXiv: [2504.00601](https://arxiv.org/abs/2504.00601)



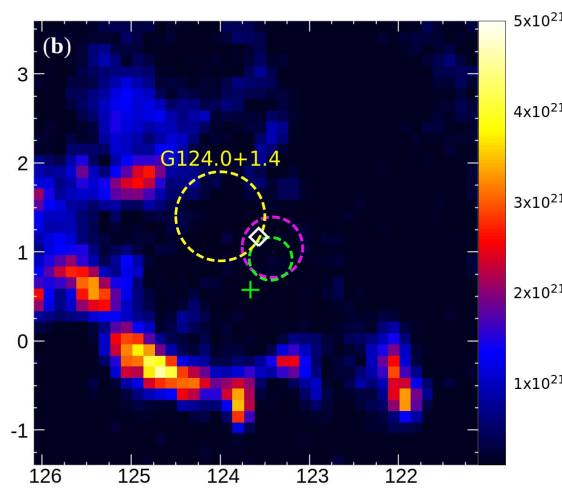
LHAASO significance maps



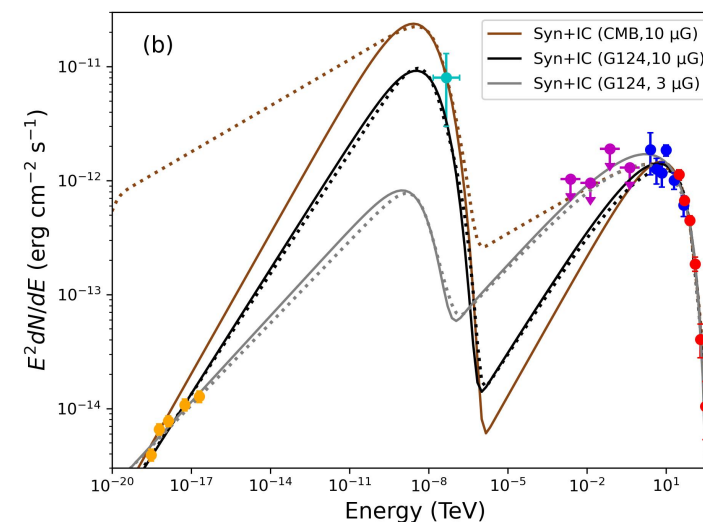
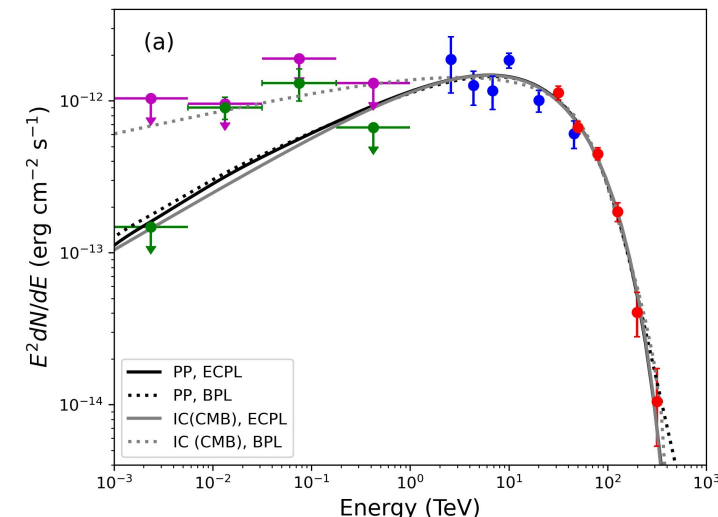
Galactic longitude (°)



Galactic longitude [degrees]



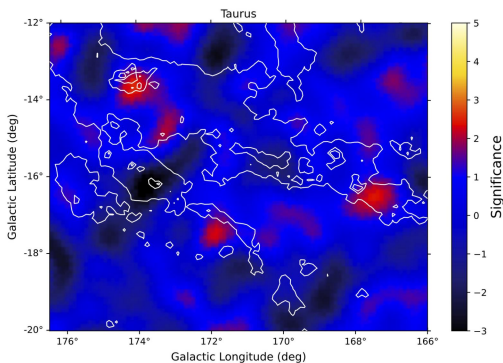
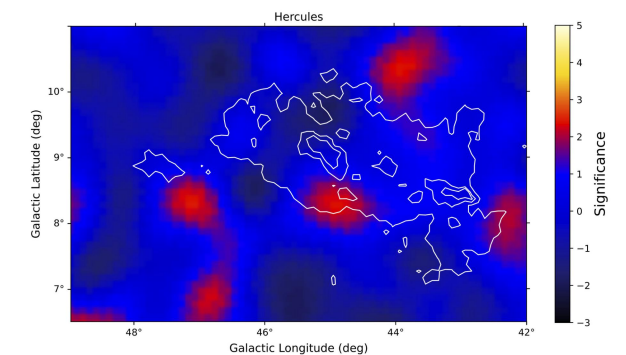
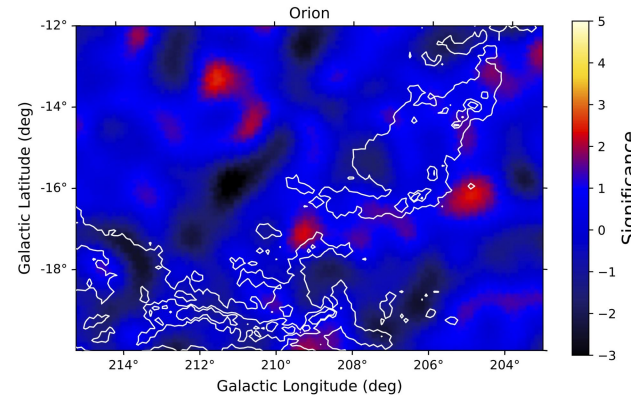
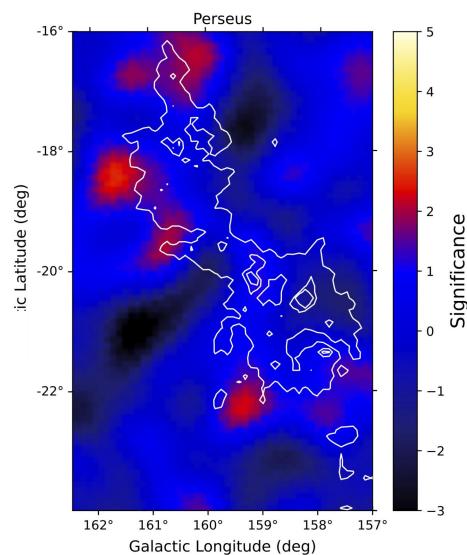
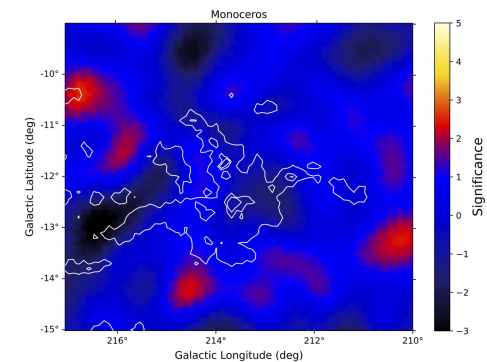
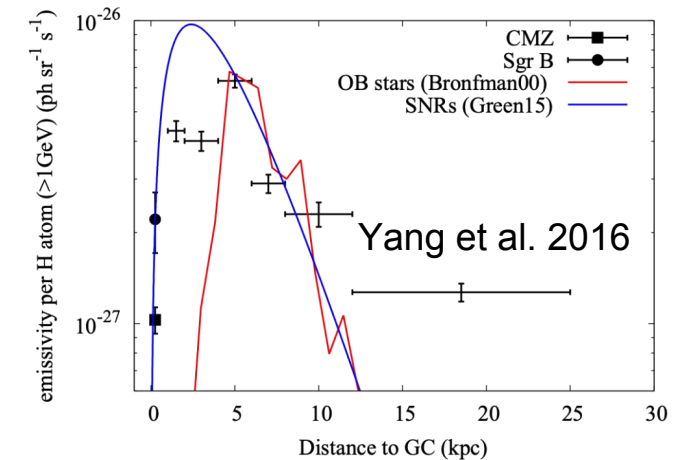
Molecular gas: -48 to -40 km/s (left), right -1 to 7km/s (right)



Probe local CR via γ -ray observation of GMCs

Giant Molecular Clouds (GMCs) : calorimeter of the CR ‘sea’, ideal targets to inspect the density and spectra of in-situ CRs (e.g., Aharonian 2001, Yang et al. 2016, Neronov A. et al. 2017) .

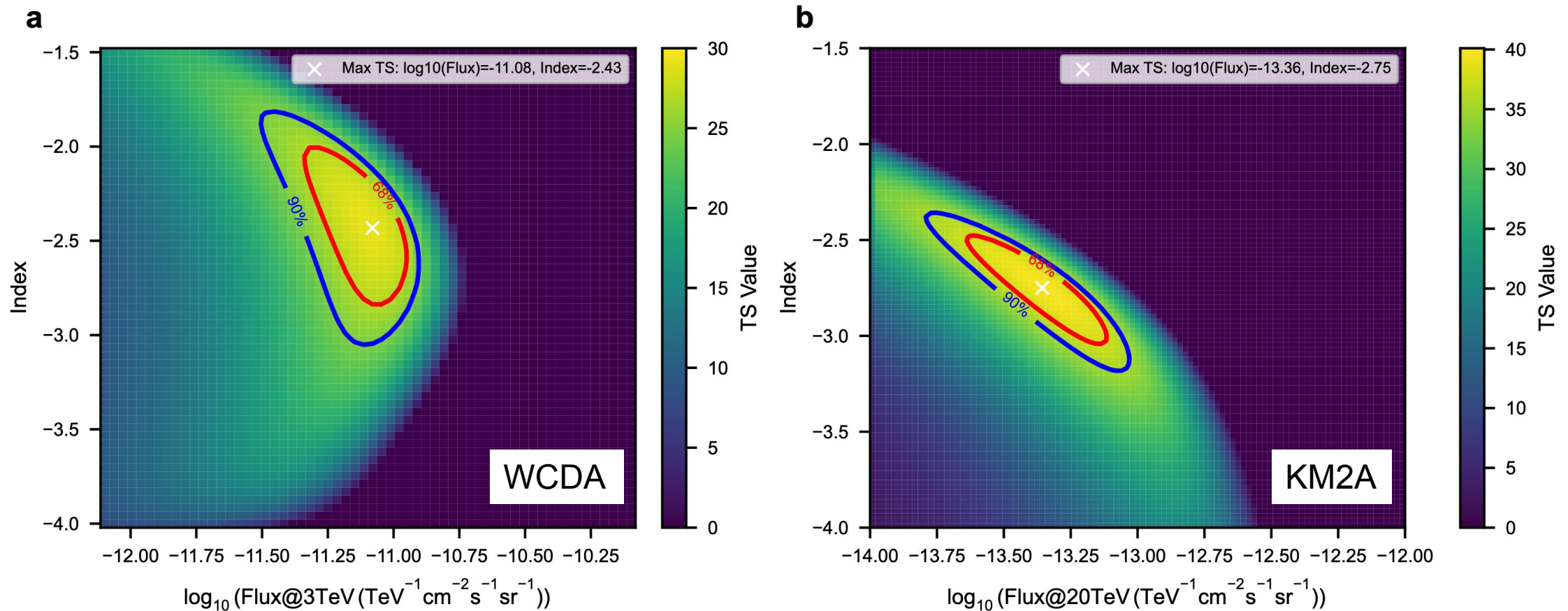
- ❑ To inspect the density and spectra of local CRs, LHAASO 4.5-year data used to search γ -ray emission from 5 nearby GMCs.
- No significant detection ($<5\sigma$) from individual samples (Hercules, Monoceros, Orion, Perseus, and Taurus) $\rightarrow$ **Stacking analysis**.



LHAASO significance maps of individual GMC samples

LHAASO, accepted by NA (2026) arXiv:2511.05015

Probe local CR via γ -ray observation of GMCs

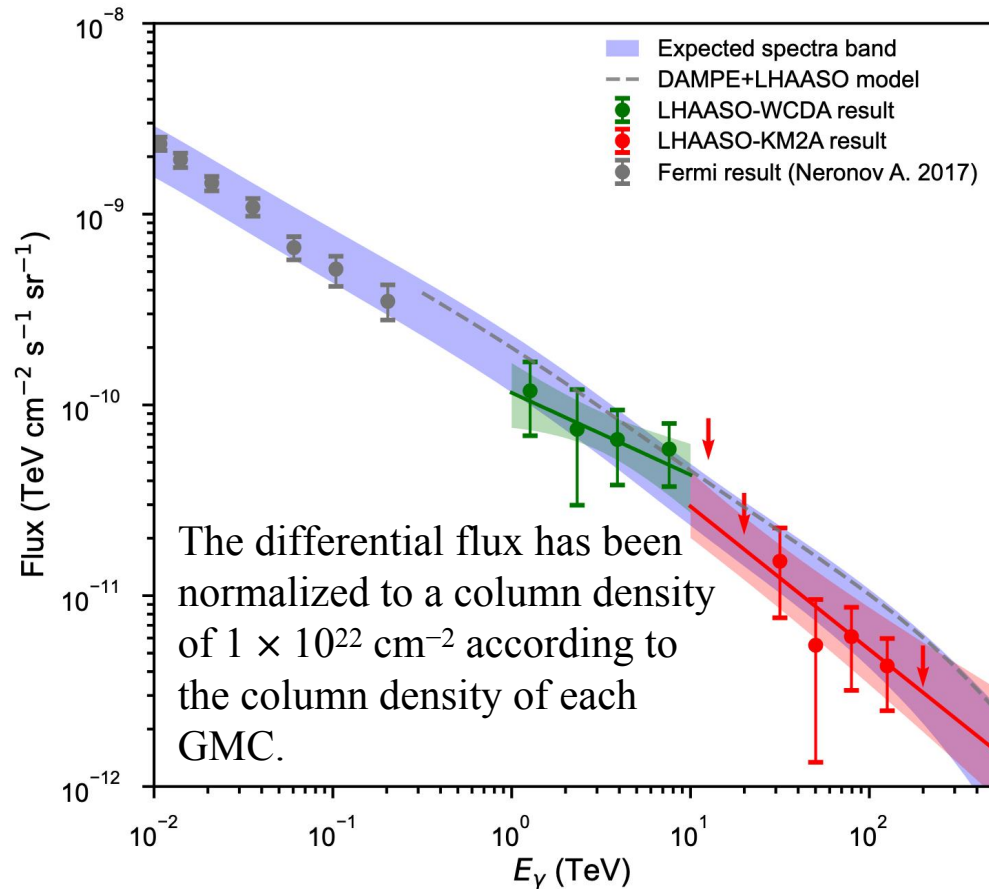


Stacking analysis results (the γ -ray spectrum of the GMCs is assumed to be PL):

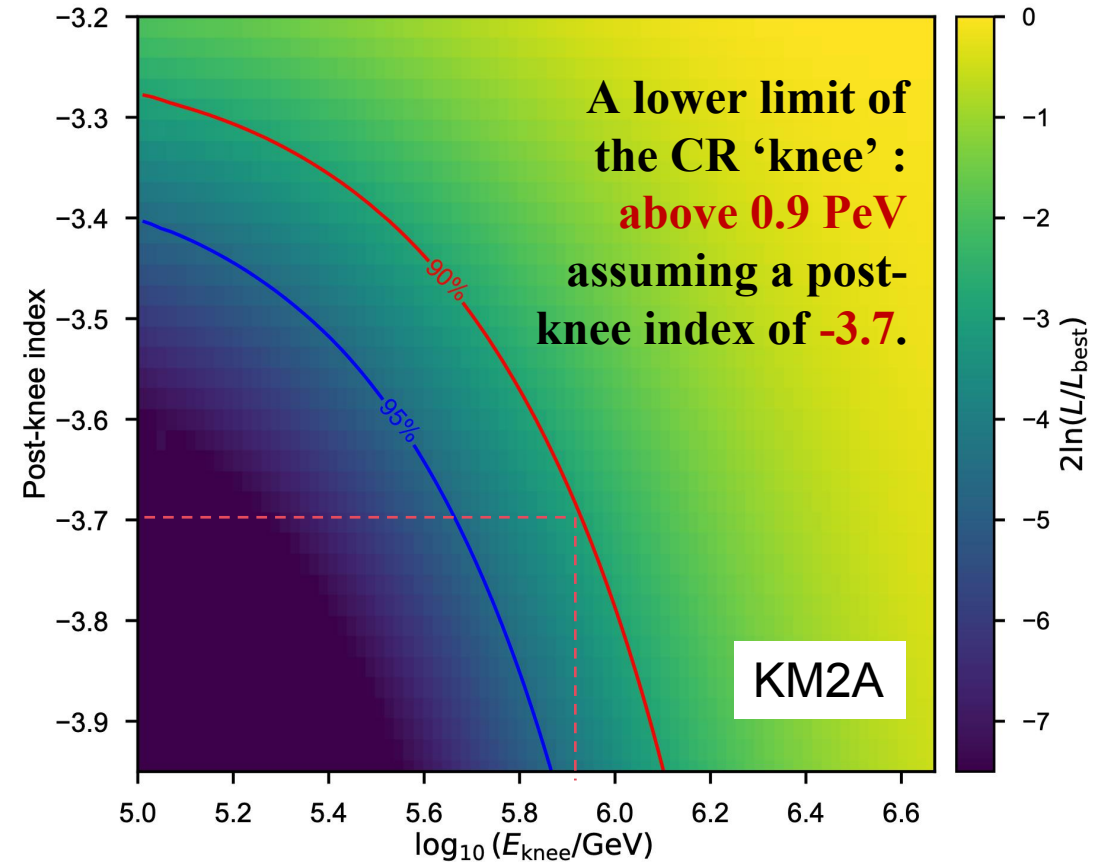
1. WCDa data: maximum TS value 30.0 ($\sim 5.0\sigma$) is obtained for index -2.43.
2. KM2A data: maximum TS value 40.1 ($\sim 5.9\sigma$) is obtained for index -2.75.

LHAASO, accepted by NA (2026)
arXiv:2511.05015

Probe local CR via γ -ray observation of GMCs



The SED of the GMC as measured by LHAASO.



Constraints on the CR 'knee' parameters.

LHAASO, accepted by NA (2026)
arXiv:2511.05015

- Indirect results from γ -ray observations towards nearby GMCs are consistent with recent CR spectra measurements from DAMPE+LHAASO.

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 - ✓ “Passive” GMCs, “Dark” sources
- **Measurements of CR Spectra and Anisotropy**
- Summary and prospect

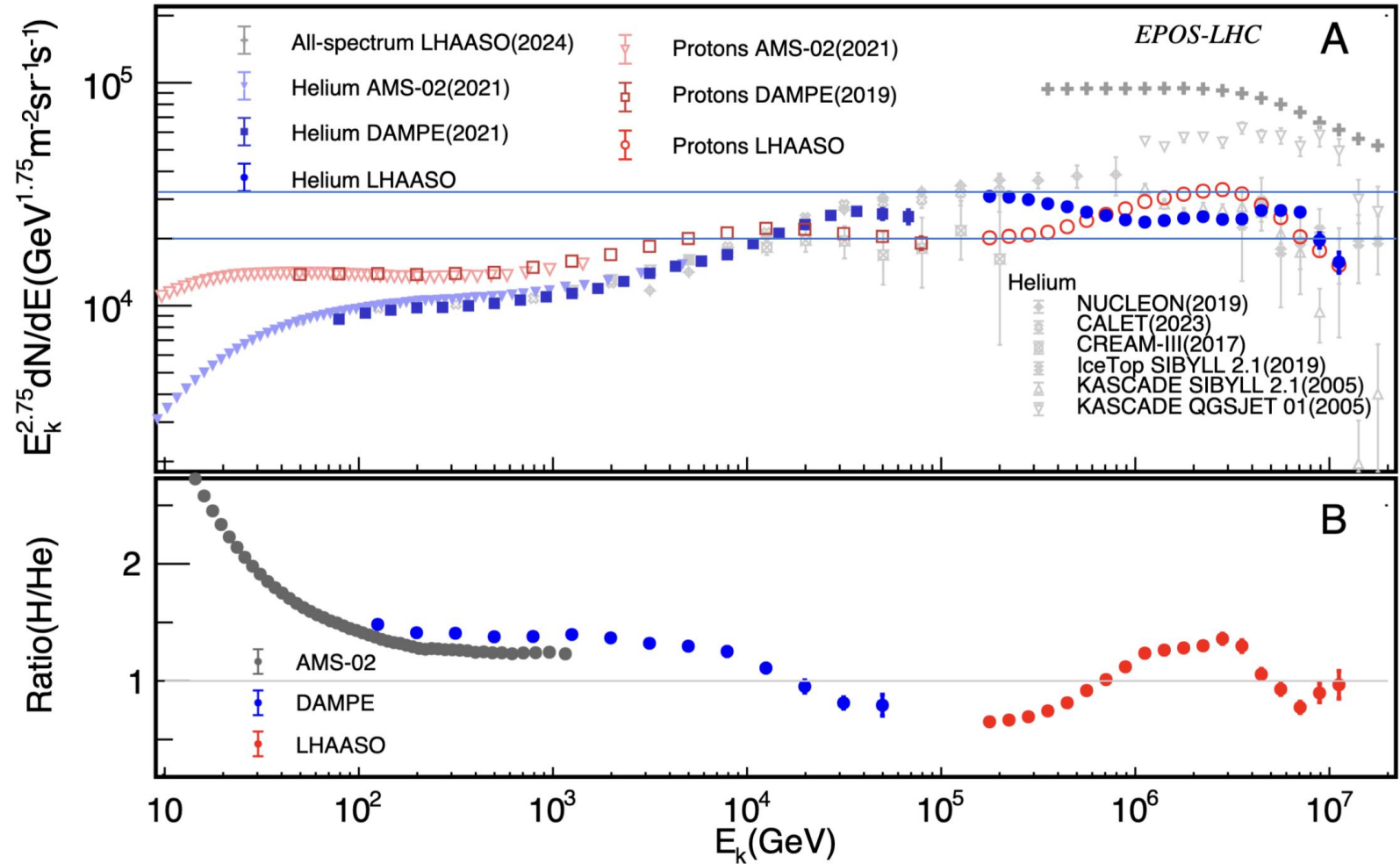
Measurement of CR proton and helium spectra

❑ The “knee” is not simply a single cutoff, p and He show different spectral structures and different characteristic energies.

❑ p: hardening at ~340 TeV, softening (knee) at ~3.3 PeV

❑ He: hardening at ~ 1.1 PeV, softening (knee) at ~7 PeV

❑ p/He ratio reverses at least 3 times over the energy range from 10 TeV to 10 PeV (He-rich ~0.1 PeV, P-rich ~3 PeV)



LHAASO, Science Bulletin, 70, 24 (2025) arXiv: [2505.14447](https://arxiv.org/abs/2505.14447)
LHAASO, PRL, 136, 121001 (2026) arXiv: [2511.05013](https://arxiv.org/abs/2511.05013)

Measurements of CR proton and helium spectra

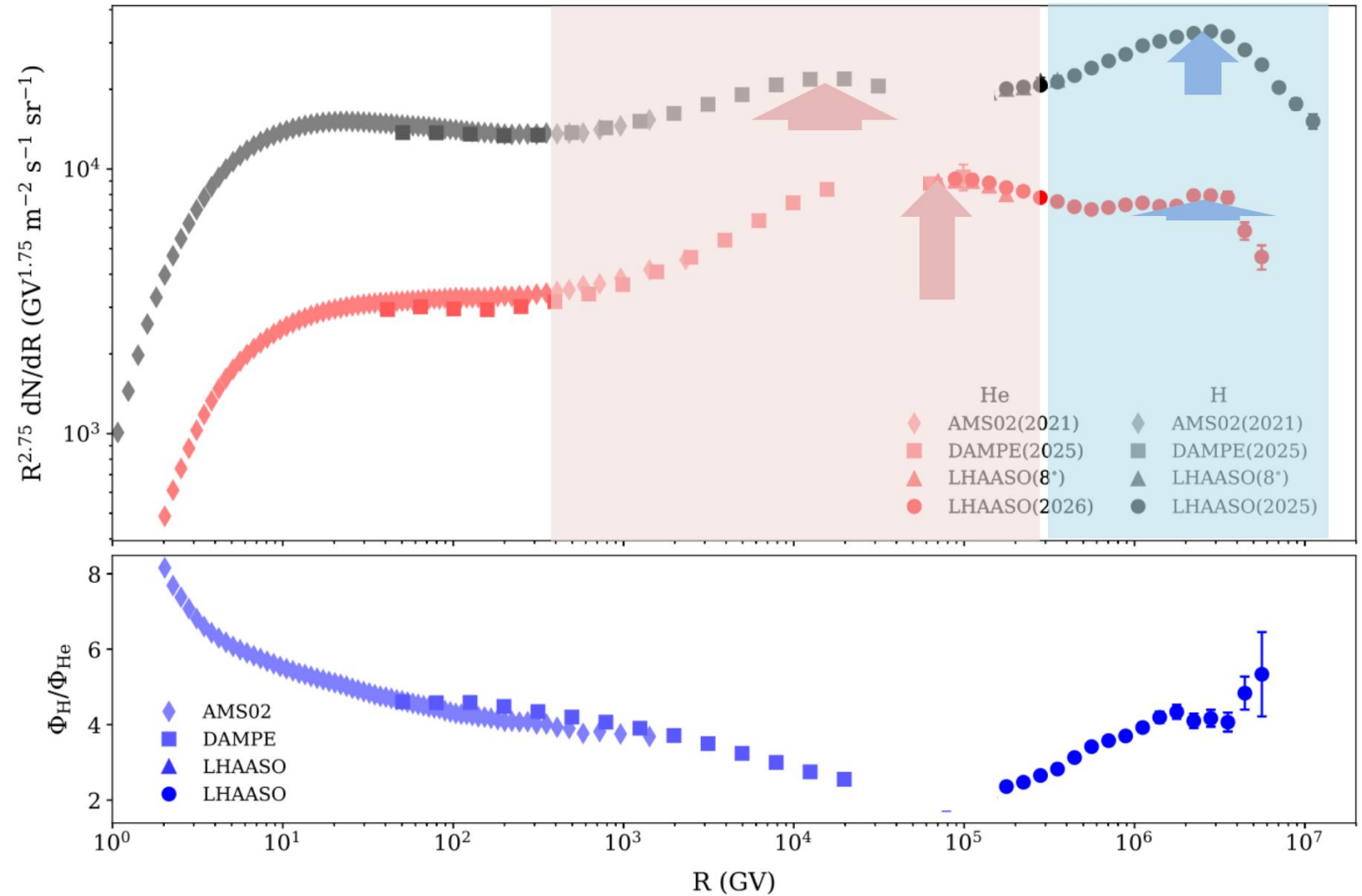
❑ Rigidity spectra of p and He:

No perfect rigidity dependence

❑ Two major humps in the rigidity ranges of (0.1, 100) TV and (0.1, 10) PV. They may represent different source populations.

❑ H/He ratio: decreases from 10 GV to ~100 TV, then increases up to a few PV.

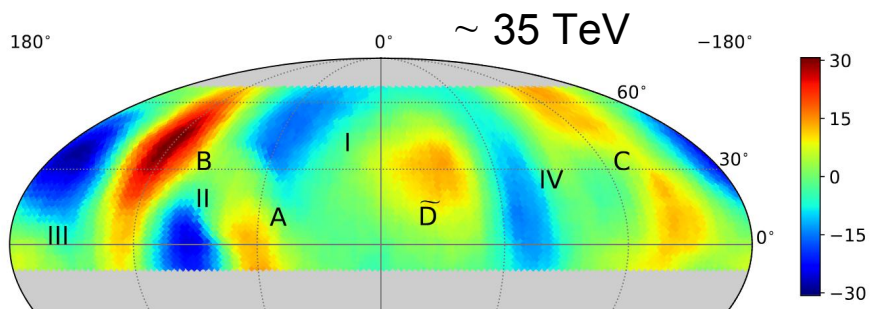
1. Strong enhancement of p flux in the component around the knee
→ p-rich source population
2. Strong enhancement of He flux in the component below 100 TV
→ He-rich source population



LHAASO, Science Bulletin, 70, 24 (2025) arXiv: [2505.14447](https://arxiv.org/abs/2505.14447)
LHAASO, PRL, 136, 121001 (2026) arXiv: [2511.05013](https://arxiv.org/abs/2511.05013)

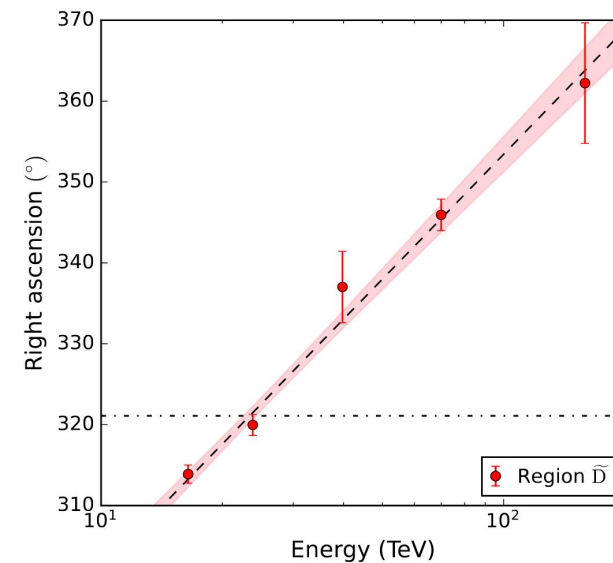
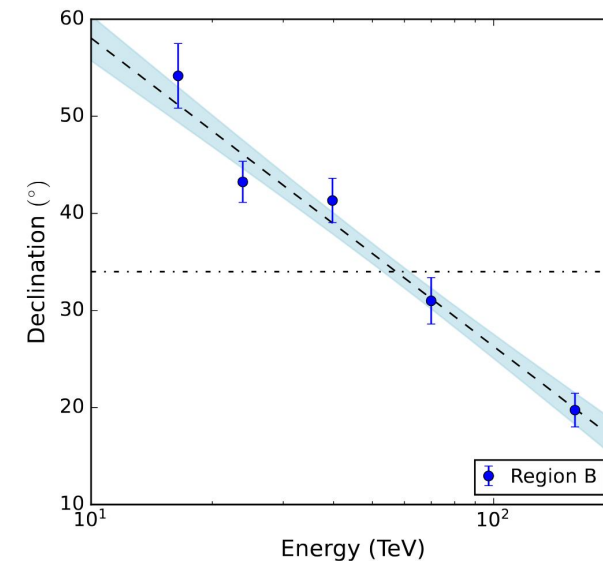
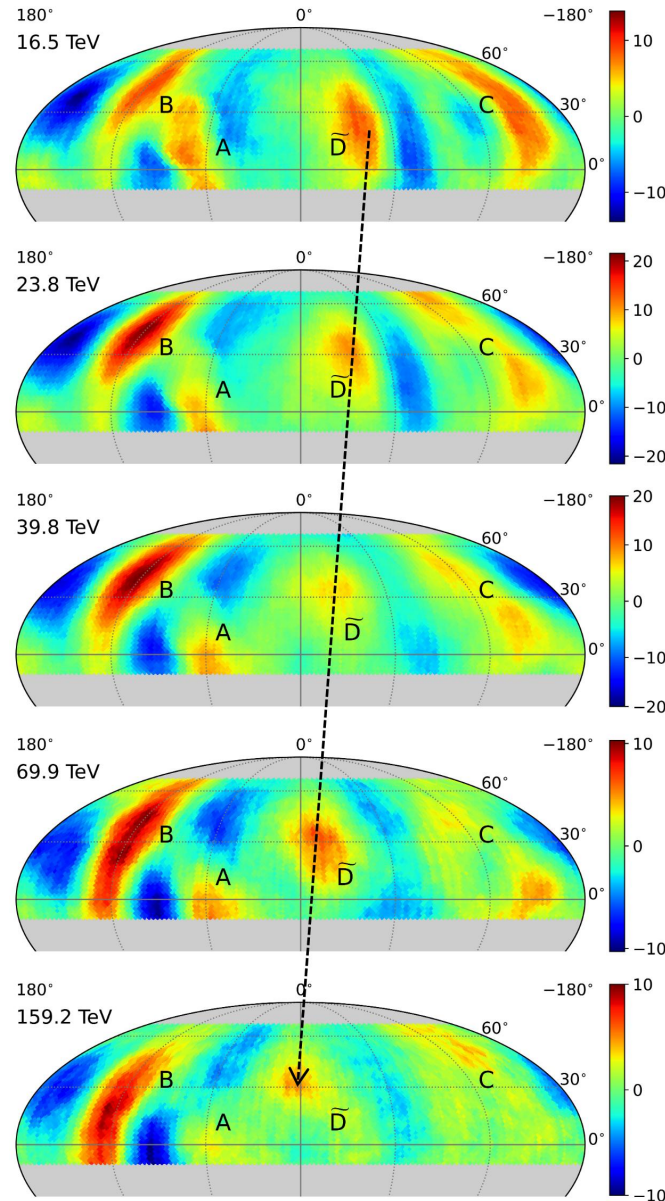
Measurements of CR Anisotropy

Energy-Dependent Shifts of Medium-Scale Anisotropies in Very-High-Energy Cosmic Rays Observed by LHAASO-KM2A



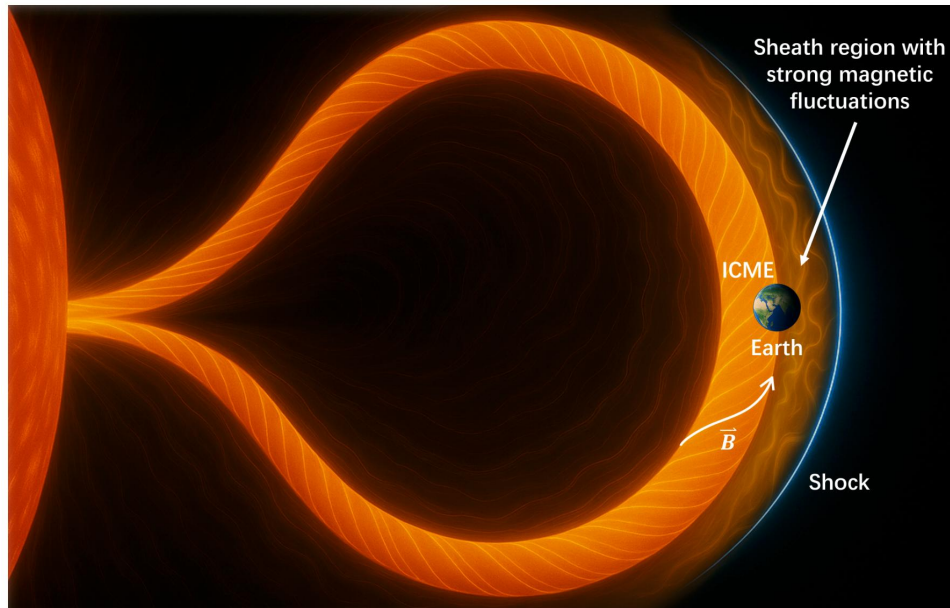
LHAASO, PRL, 137, 051004 (2026)

arXiv: [2512.18401](https://arxiv.org/abs/2512.18401)

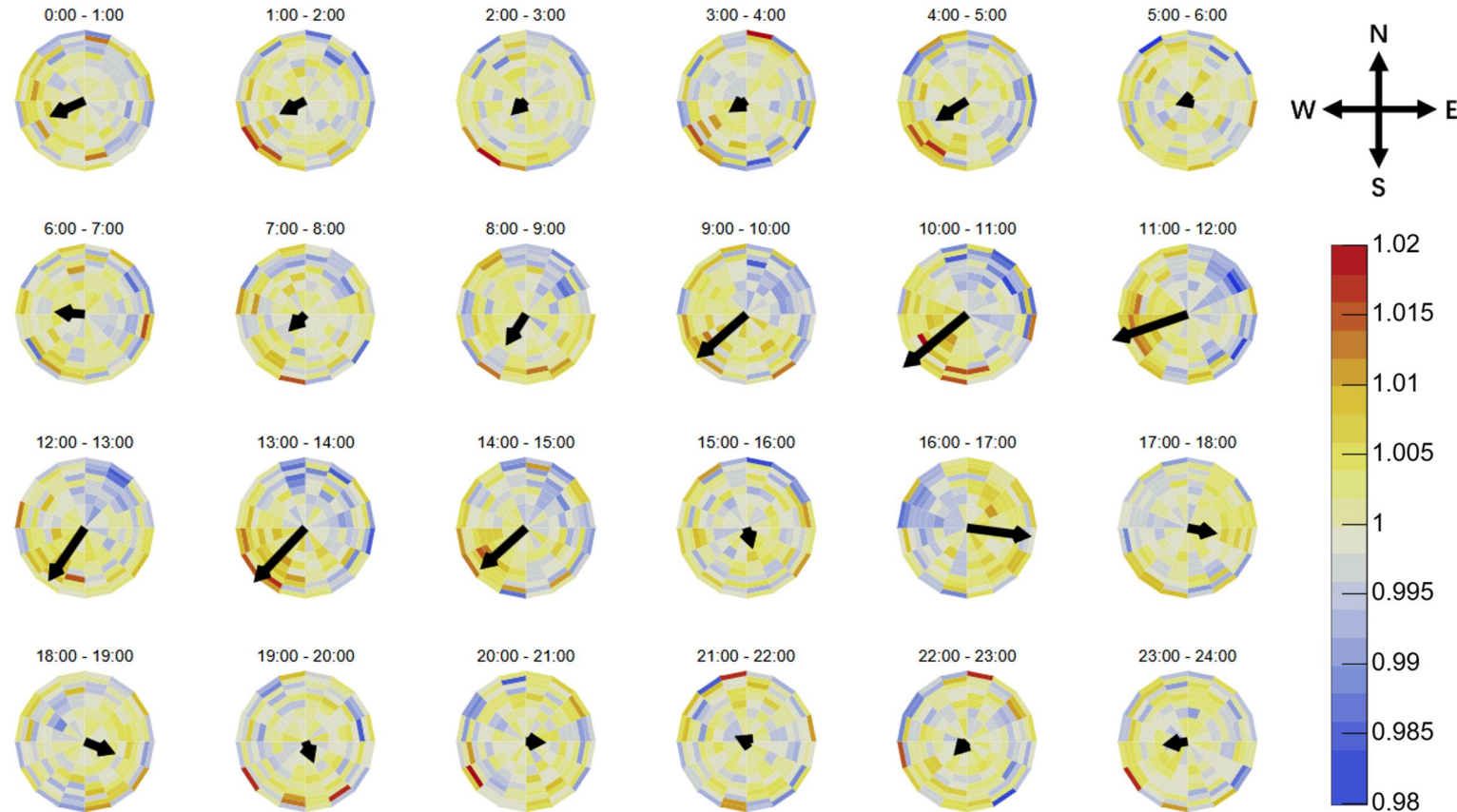


Measurements of CR Anisotropy

Transient Large-Scale Anisotropy in TeV Cosmic Rays due to an Interplanetary Coronal Mass Ejection



LHAASO, PRL, 136, 251002 (2026)
arXiv: [2601.02801](https://arxiv.org/abs/2601.02801)



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Summary and Prospect

With its excellent sensitivity from tens of TeV to PeV energies, LHAASO is transforming our view of the origin of Galactic CRs.

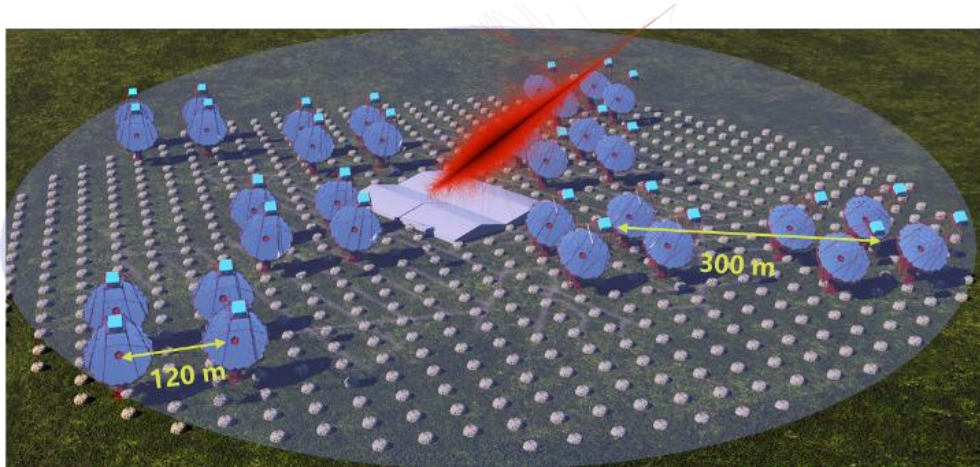
- ✓ A rich population of UHE sources that are potential **PeVatrons** even **super PeVatrons** in our Galaxy as revealed by LHAASO. Investigation of individual sources show diverse acceleration channels (SNR shocks, pulsar winds, collective stellar winds, relativistic jets) with different potentials.
- ✓ **Measurements of GDE**: the spatial distribution deviates from the gas distribution; spectral break ~ 30 TeV (inner region) and the flux excesses require explanation.
- ✓ **Precise measurements of CR p+He spectra** reveal fine structures around the knee, which indicate multiple CR components and source populations.

Summary and Prospect

Next-generation IACTs with better angular resolution → Resolve source morphology and distinguish hadronic vs. leptonic scenarios.

IACTs in LHAASO site (LACT)

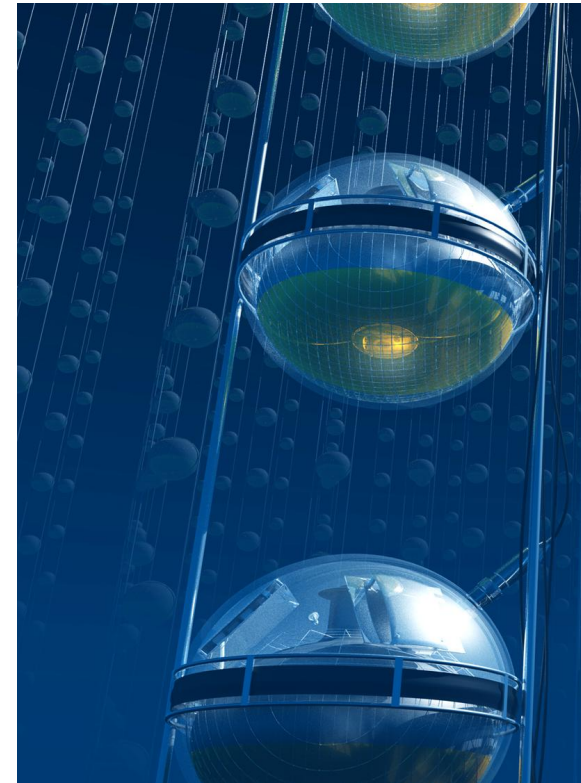
- Funded
- 8X4 array at LHAASO site
- 6-m telescopes
- two prototype telescopes
- First light soon in this year!



High-energy neutrino telescopes to directly probe hadronic acceleration through neutrino emission → Provide a crucial test of Galactic PeVatron candidates.

High energy Underwater Neutrino Telescope (HUNT)

- Volume: $\sim 30 \text{ km}^3$
- Angular resolution: $\sim 0.1^\circ$ (tracks), $< 3^\circ$ (cascades)
- Energy resolution:
 $\Delta \log E \sim 0.3$ (tracks),
 $\Delta E \sim 10\text{-}30\%$ (cascades)
- Discovering ν sources ($> 100 \text{ TeV}$) at 5σ level within several years





Tendo
Japan

August 30 - September 4, 2026

Thank you !