MeV–PeV Frontiers: New Perspectives in Gamma-Ray Astronomy and Particle Acceleration

Institute of High Energy Physics, Chinese Academy of Sciences

LHAASO

Discovering Galactic PeVatrons with LHAASO

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on behalf of the LHAASO collaboration

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Kavli IPMU, University of Tokyo, Kashiwa, Chiba, Dec. 16 - 28, 2025

Outline

- **Introduction to PeVatrons**
- **LHAASO experiment**
- **Progress in gamma-ray observations**
  - Supernova remnants
  - Pulsar wind nebulae and pulsar halos
  - Gamma-ray binaries
  - Young massive star clusters
- **Progress in cosmic ray measurements**
  - Spectra
  - Composition
  - Anisotropies
- **Summary**

Introduction to PeVatrons

Hillas criterion

- Particle energy is changed by electric field:

$$E_{max} \sim e\mathcal{E}R$$

- Conductivity of space plasma is typically very large, thus

$$\vec{\mathcal{E}} = \vec{\beta} \times \vec{\mathcal{B}}$$

- The energy gain at crossing the source

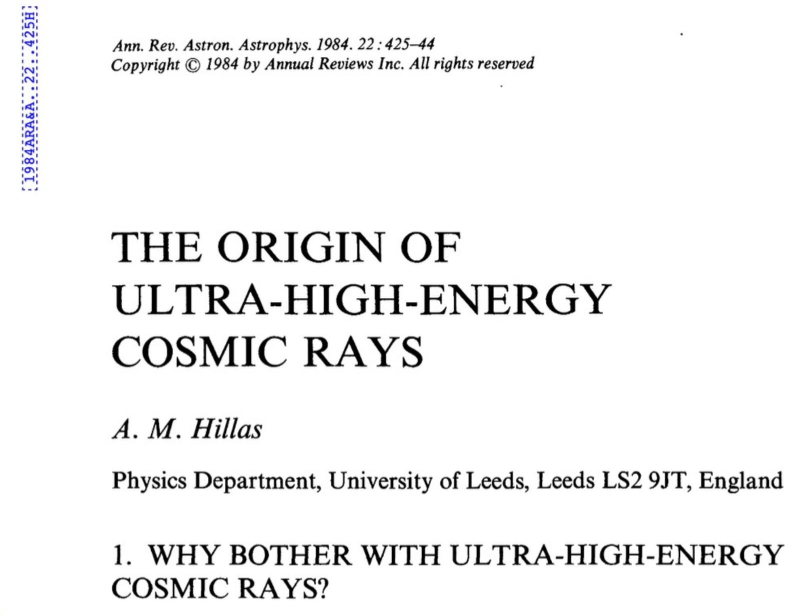
$$E_{max} \sim e\beta\mathcal{B}R$$

- The Poynting flux carries a fraction of the total source luminosity:

$$\frac{c\beta}{4\pi}\mathcal{B}^2 4\pi R^2 = \sigma L$$

- Maximum energy:

$$E_{max} \sim \sqrt{\sigma\beta}\sqrt{\frac{e^2L}{c}} \approx 5\sigma_{-1}^{1/2}\beta_{-1}^{1/2}L_{39}^{1/2}\ \text{PeV}$$


1984ARA&A..22..425H

Ann. Rev. Astron. Astrophys. 1984. 22 : 425–44
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THE ORIGIN OF ULTRA-HIGH-ENERGY COSMIC RAYS

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1. WHY BOTHER WITH ULTRA-HIGH-ENERGY COSMIC RAYS?

For efficient acceleration, one needs

- High luminosity, L
- Fast outflow, β
- High magnetization, σ

(obviously)

The maximum drop of electric potential is, however, only one of the conditions required for acceleration to this limit. Other constraints include

- Source age:

$$t_{acc} < t_{age}$$

- Confinement:

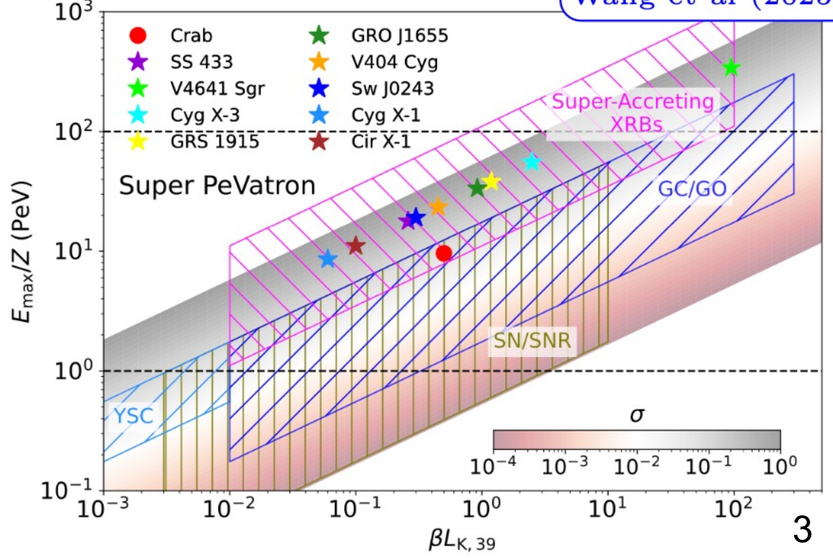
$$t_{acc} < t_{esc}$$

- Cooling:

$$t_{acc} < t_{cool}$$

Non of these is a necessary condition – one still needs an acceleration processes that can operate with efficiency η.

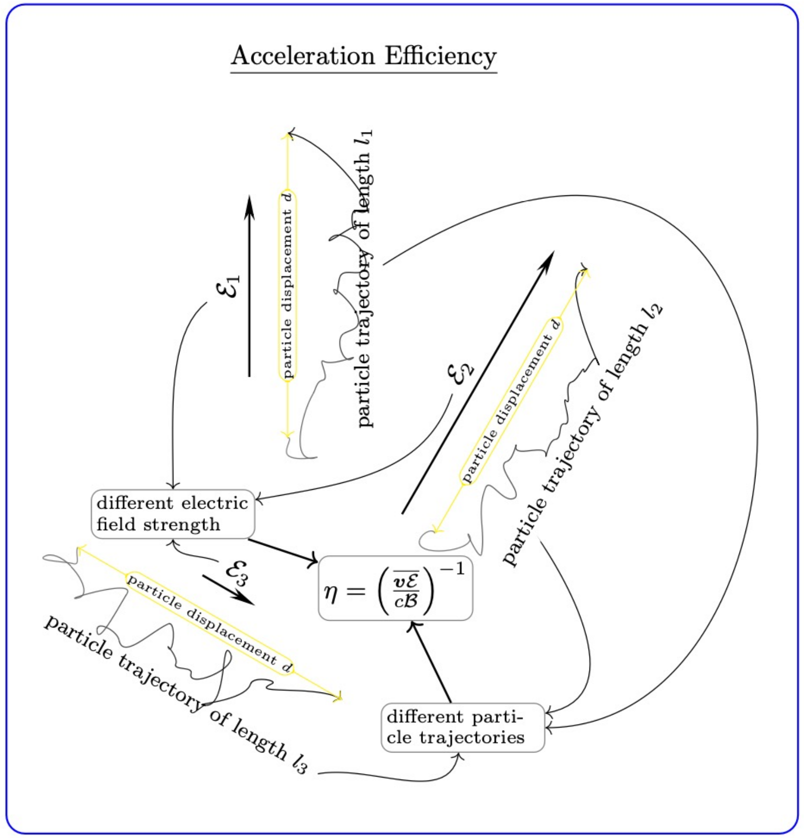
Wang et al (2025)



Introduction to PeVatrons

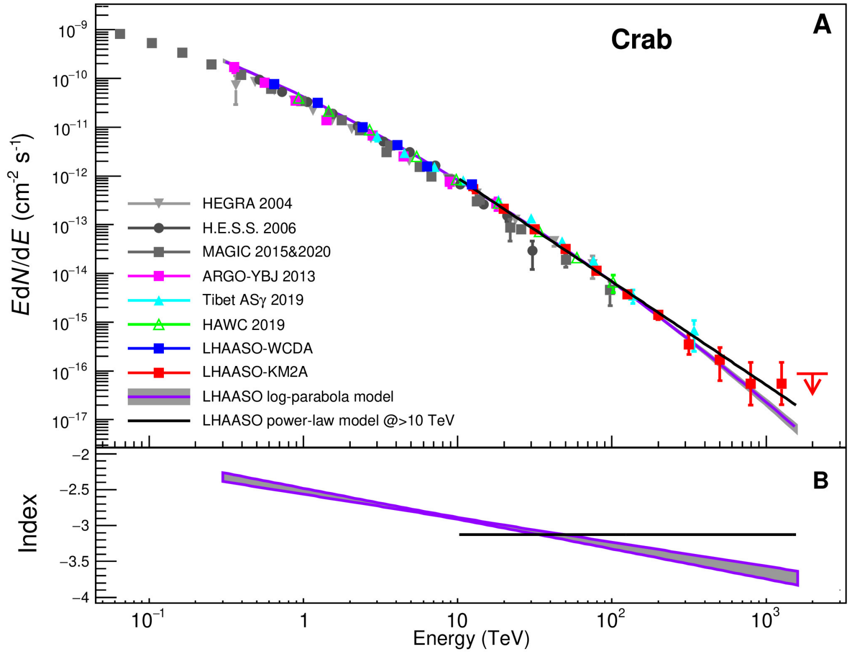
- Acceleration time: $t_{acc} = E/\dot{E}$
- Magnetic field $\mathcal{B}$ doesn't change particle energy
- Energy gain for a particle: $mc^2\dot{\gamma} = q\vec{v}\vec{\mathcal{E}}$
- Energy gain for ensemble of particles: $\dot{E} = q\overline{\vec{v}\vec{\mathcal{E}}}$
- Acceleration efficiency is dimensionless parameter: $t_{acc} = \eta r_{\mathcal{G}}/c$
- Naive algebra yields: $\eta^{-1} = \frac{a\overline{\vec{v}\vec{\mathcal{E}}}}{E}\frac{E}{q\mathcal{B}c} = \frac{\overline{\vec{v}\vec{\mathcal{E}}}}{\mathcal{B}c}$
- Typically $\mathcal{E} = \frac{v}{c}\mathcal{B} < \mathcal{B}$
- Trajectories are not straight lines: $\overline{\vec{v}\vec{\mathcal{E}}} \ll c\mathcal{E}$
- Thus, we should expect $\eta \gg 1$

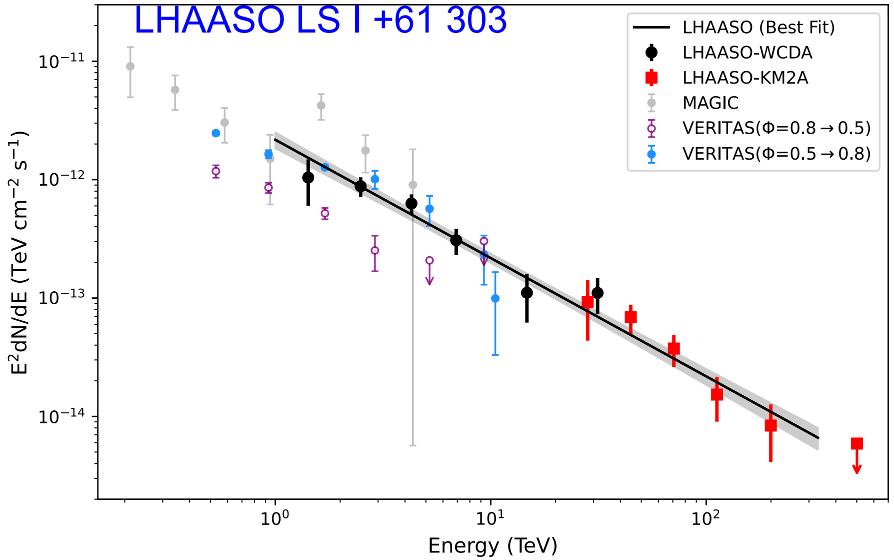
(for DSA $\eta = 2\pi\left(\frac{c}{v}\right)^2 = 2\pi\left(\frac{c}{v}\right)\left(\frac{c}{v}\right)$)



It looks an impossible task to get $\eta \to 1$ under realistic conditions

LHAASO Crab





Outline

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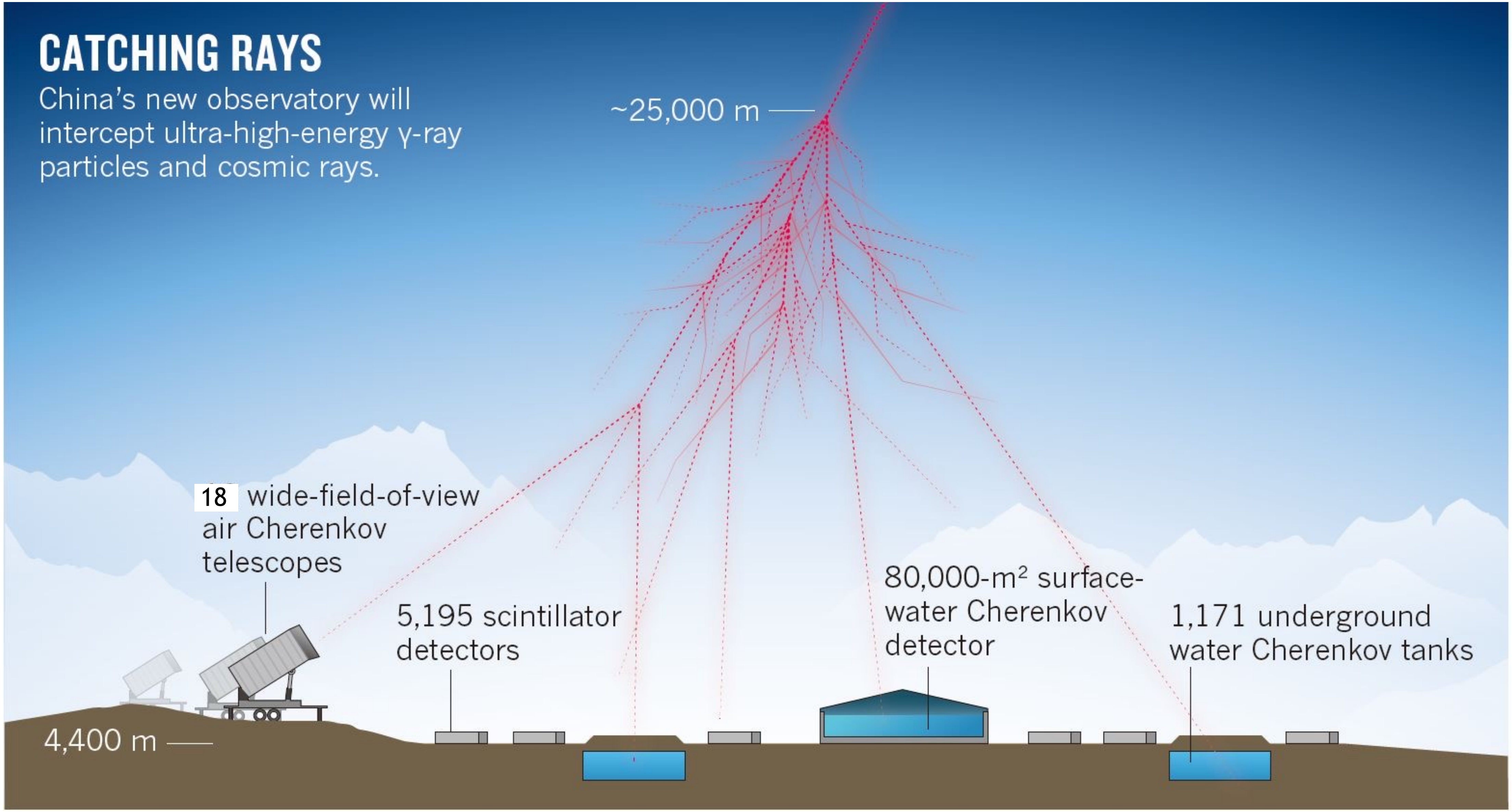
- **LHAASO experiment**
- **Progress in gamma-ray observations**
  - Supernova remnants
  - Pulsar wind nebulae and pulsar halos
  - Gamma-ray binaries
  - Young massive star clusters
- **Progress in cosmic ray measurements**
  - Spectra
  - Composition
  - Anisotropies
- **Summary**

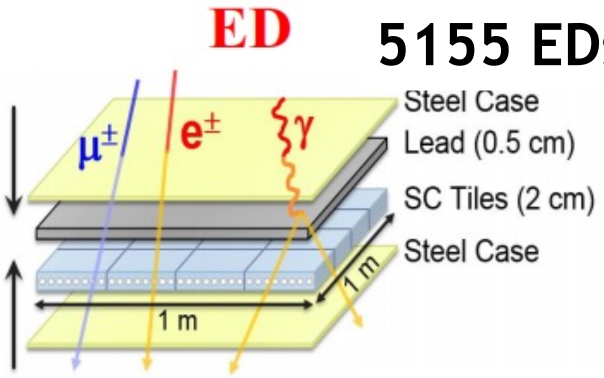
LHAASO: Large High Altitude Air Shower Observatory

- Haizi mountain, Sichuan, China, 4410 m above the sea level
- LHAASO uses hybrid detector arrays: the square kilometer array (KM2A), the water Cherenkov detector array (WCDA), and the wide field-of-view Cherenkov telescope array (WFCTA)
- Full operation since July 2021

Air shower detection of cosmic rays

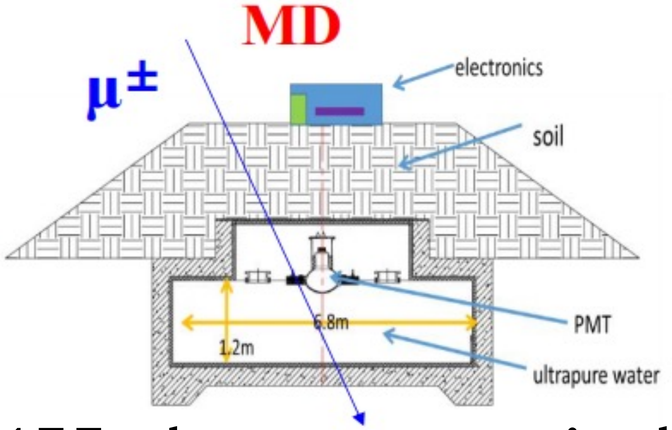


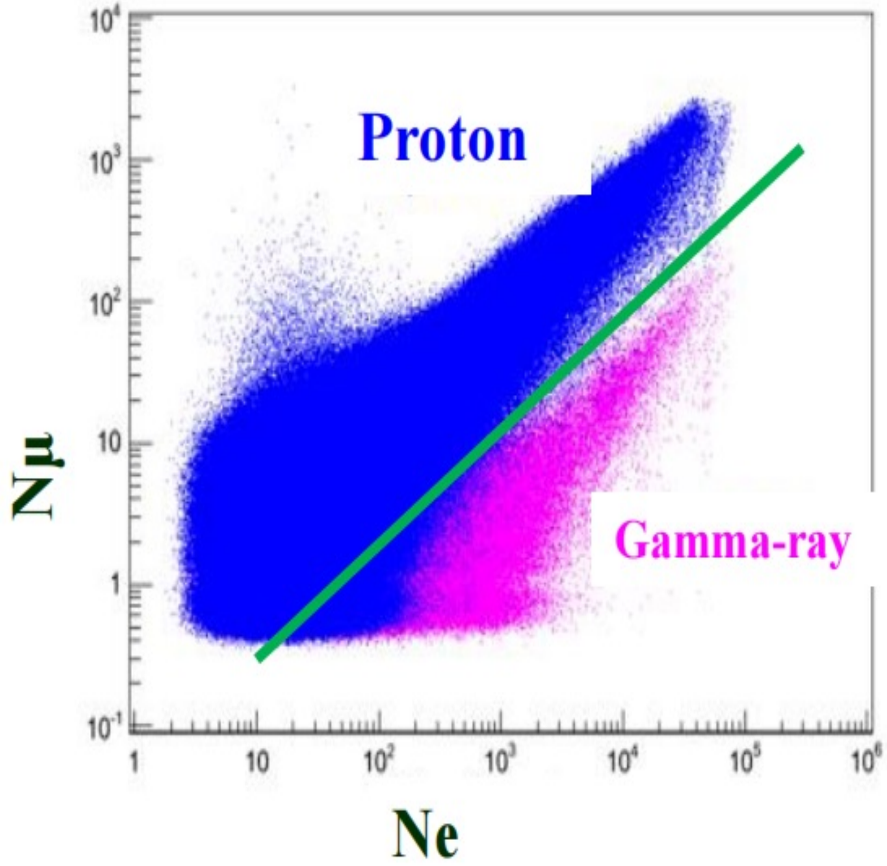
KM2A: Square Kilometer Array



5155 EDs

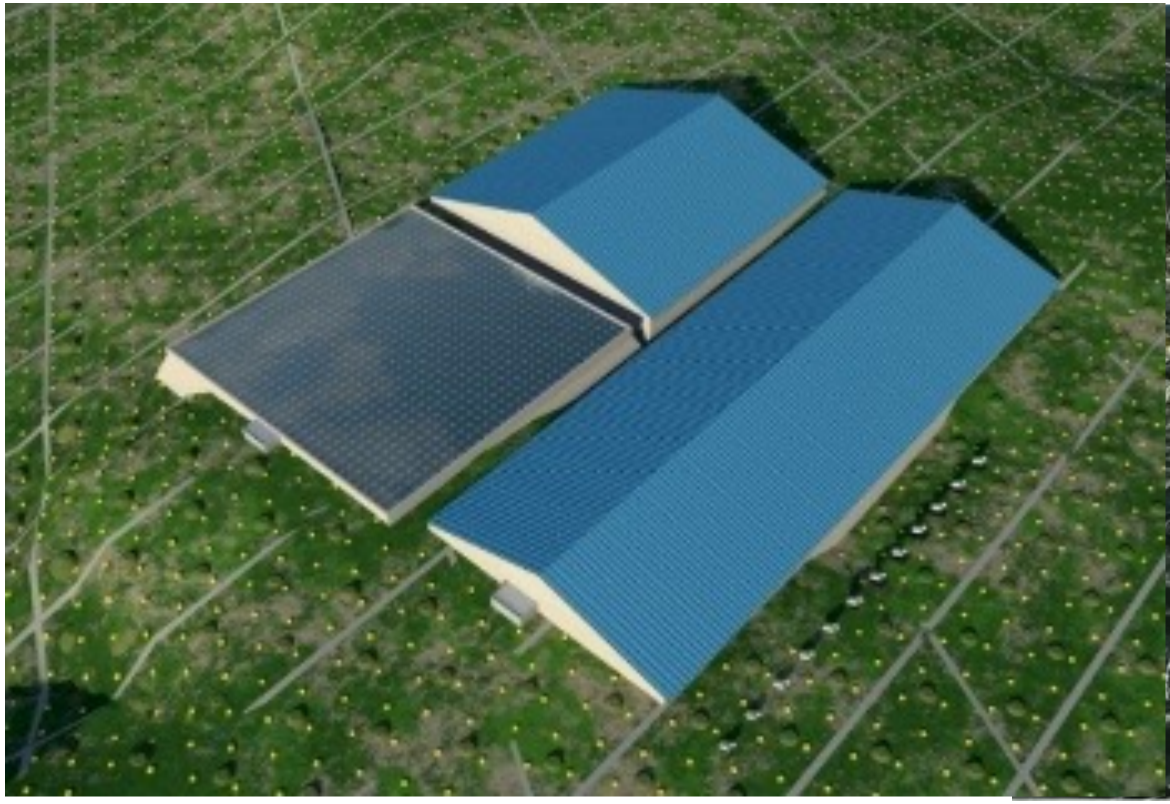
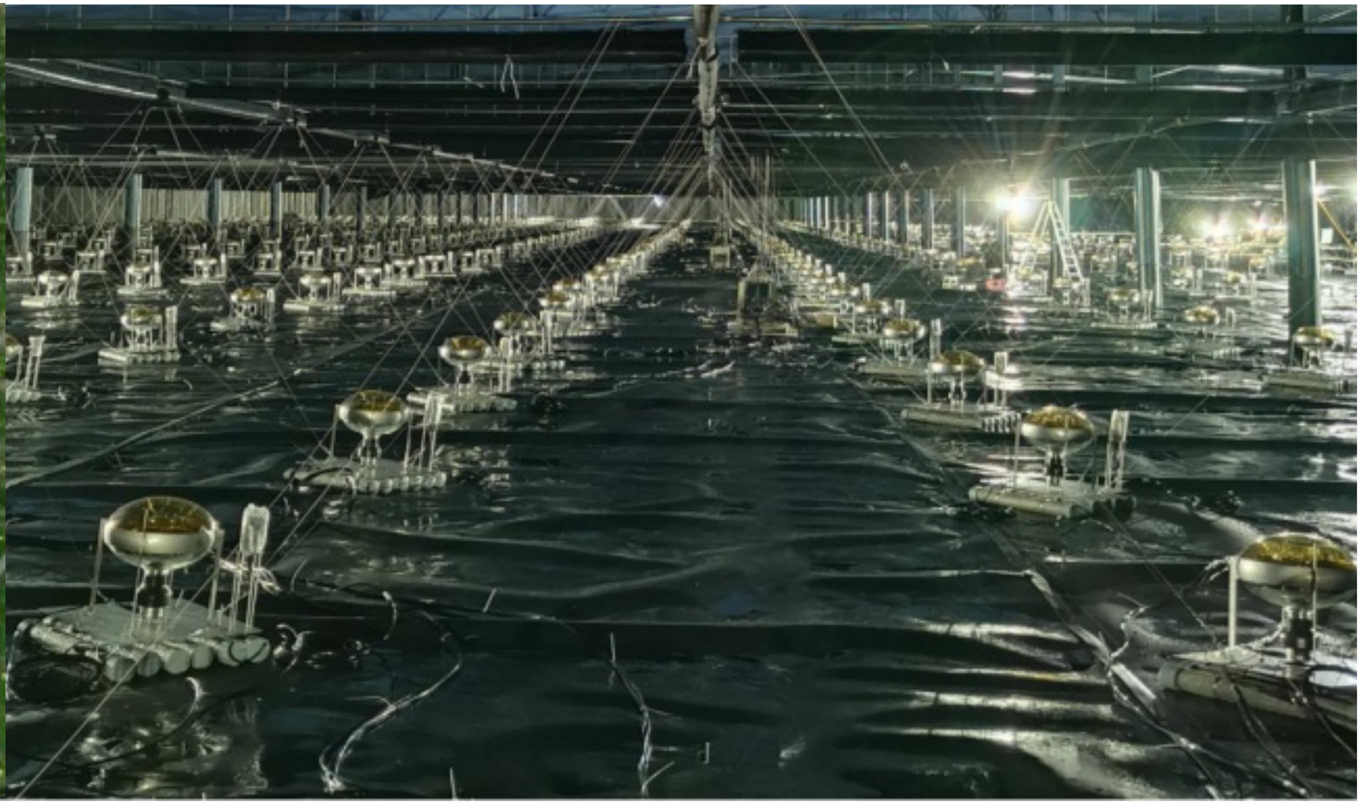
1188 MDs





- 1.3 km^2 area covered by 5155 electromagnetic detectors, used for energy and direction reconstruction
- 1188 muon detectors used for gamma/hadron separation
- Energy range: 10 TeV - 100 PeV

WCDA: Water Cherenkov Detector Array

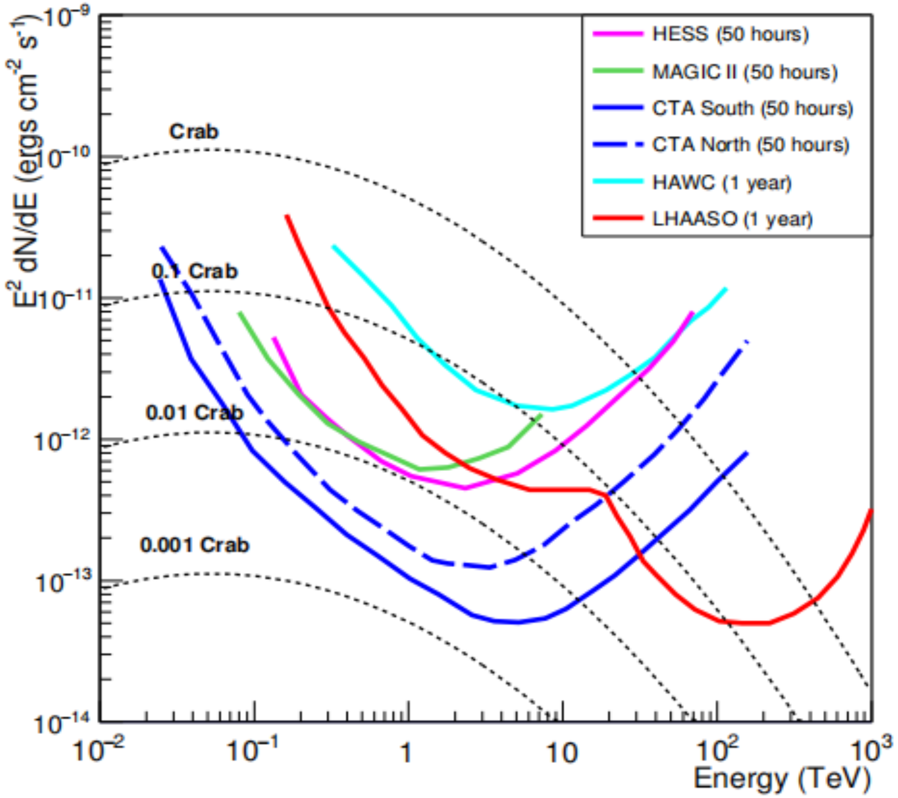
 

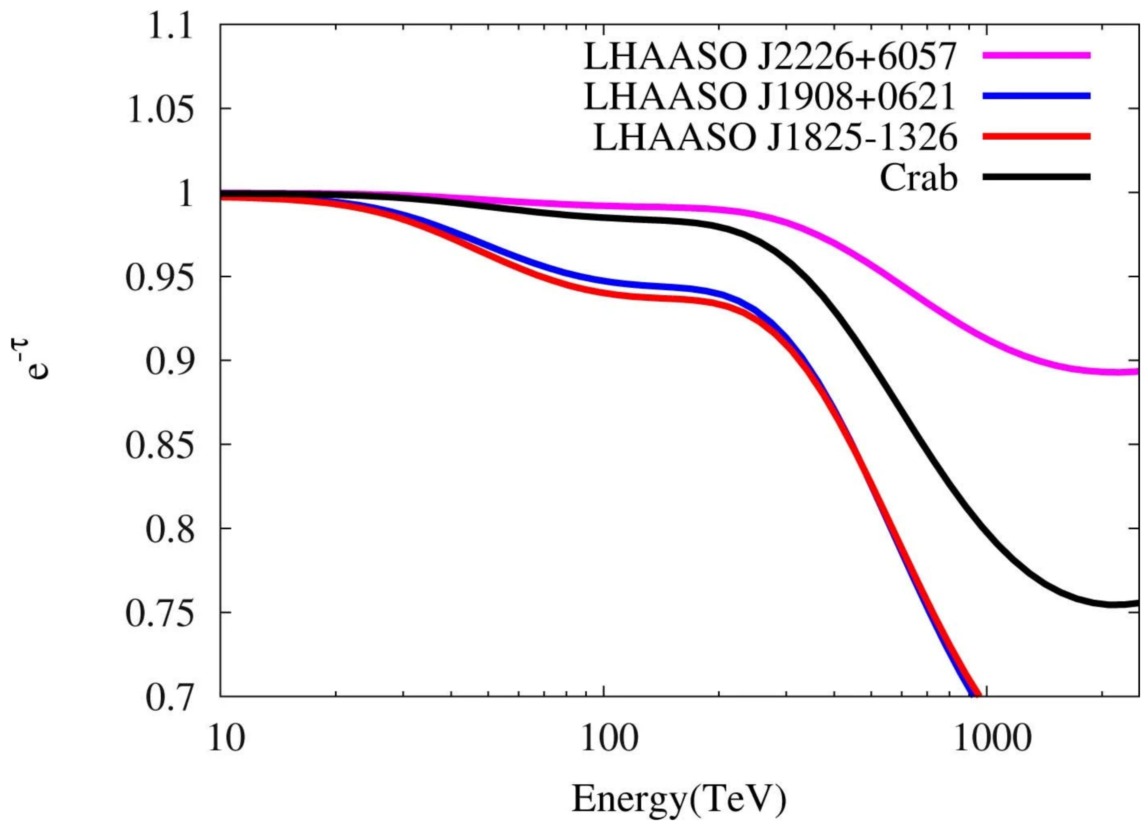
- 78000 m^2 water tank to detect Cherenkov light produced by air shower particles in water
- Energy range: 0.3 TeV - PeV

WFCTA: Wide Field Cherenkov Telescope Array

- 18 WFCTA used to separate particles with different mass; each detector has area of 4.7 m^2 each and covers a 16°×16° patch in the sky
- Energy range: 10s TeV - 100 PeV

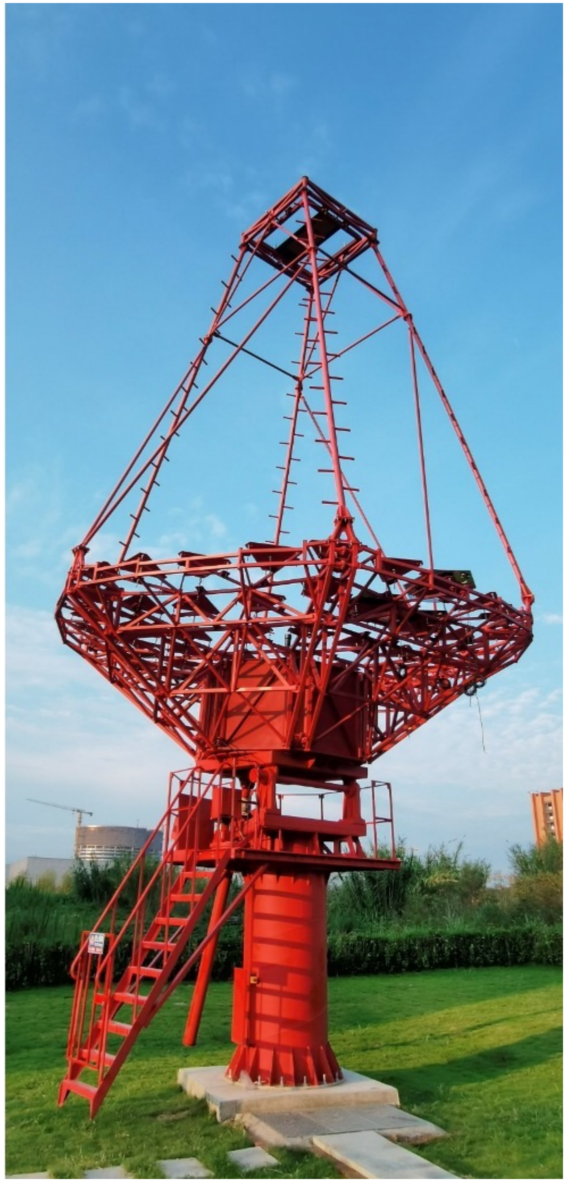
Objectives of LHAASO

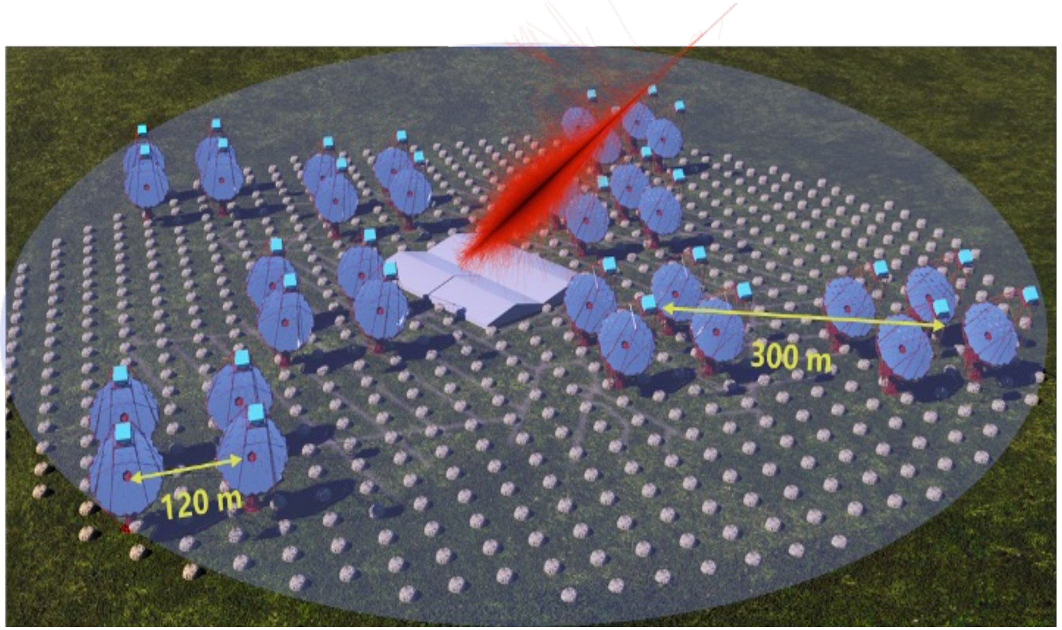


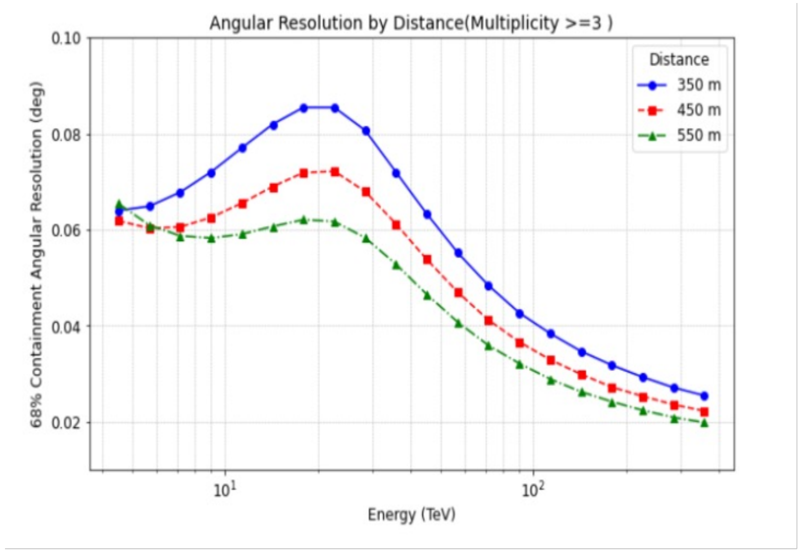


- Probe the origin of CRs, via precise measurements of spectra and anisotropies
- Study the UHE gamma-ray sky with unprecedented sensitivity (interestingly in the KM2A energy range attenuation is important already on the Galactic scale)
- Search for new physics

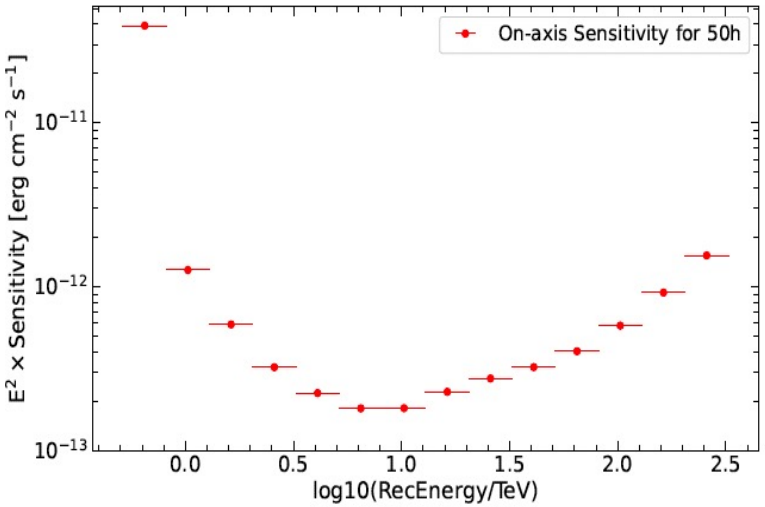
IACTs in LHAASO site (LACT)



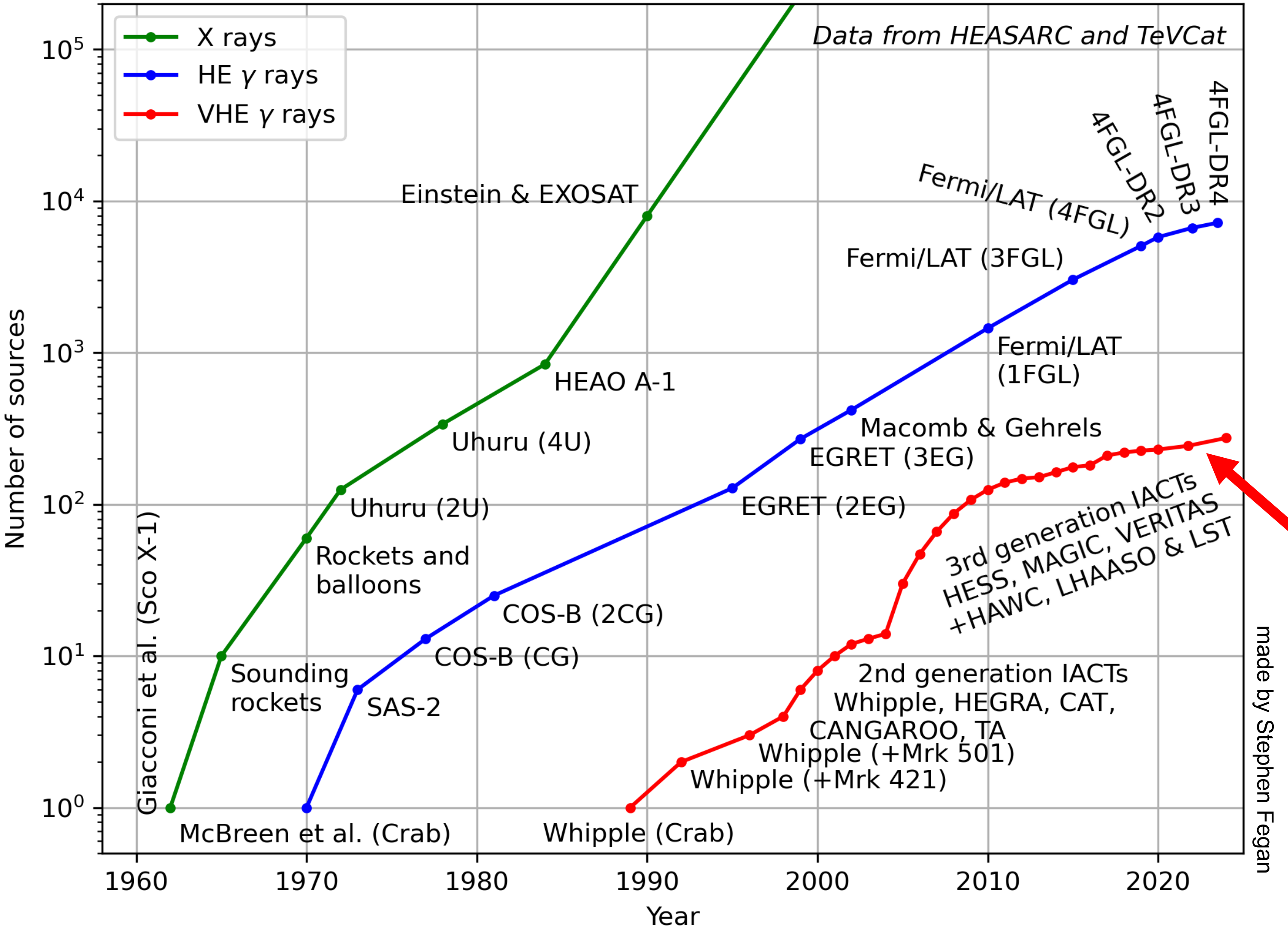




- Building started
- 8×4 array at LHAASO site
- 6-m telescopes
- Two proto-type telescopes
- First light soon!



Kifune plot: the high-energy Universe



LHAASO firmly opened the era of PeV γ-ray astronomy, not just revealing a number of PeVatrons, but finding a few classes operating as very efficient particle particle accelerators.

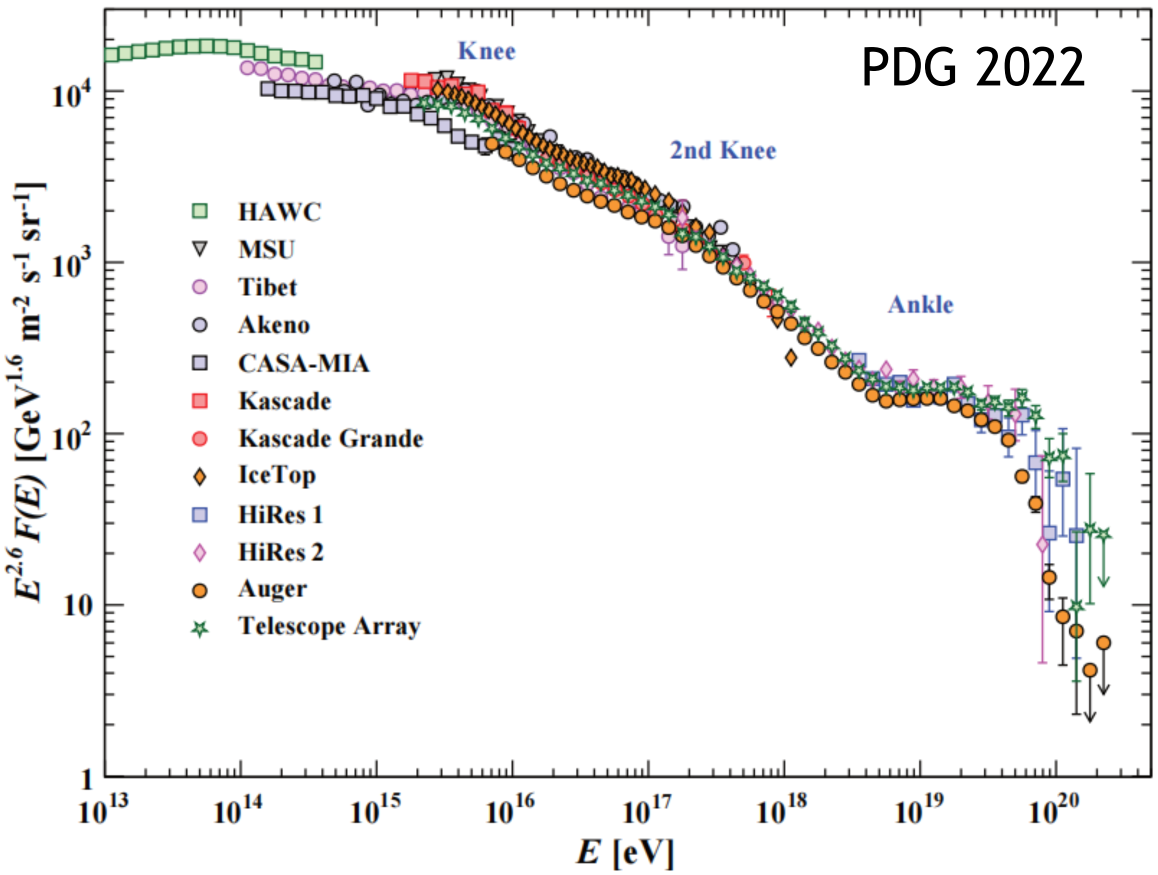
Tibet ASγ, HAWC, LHAASO

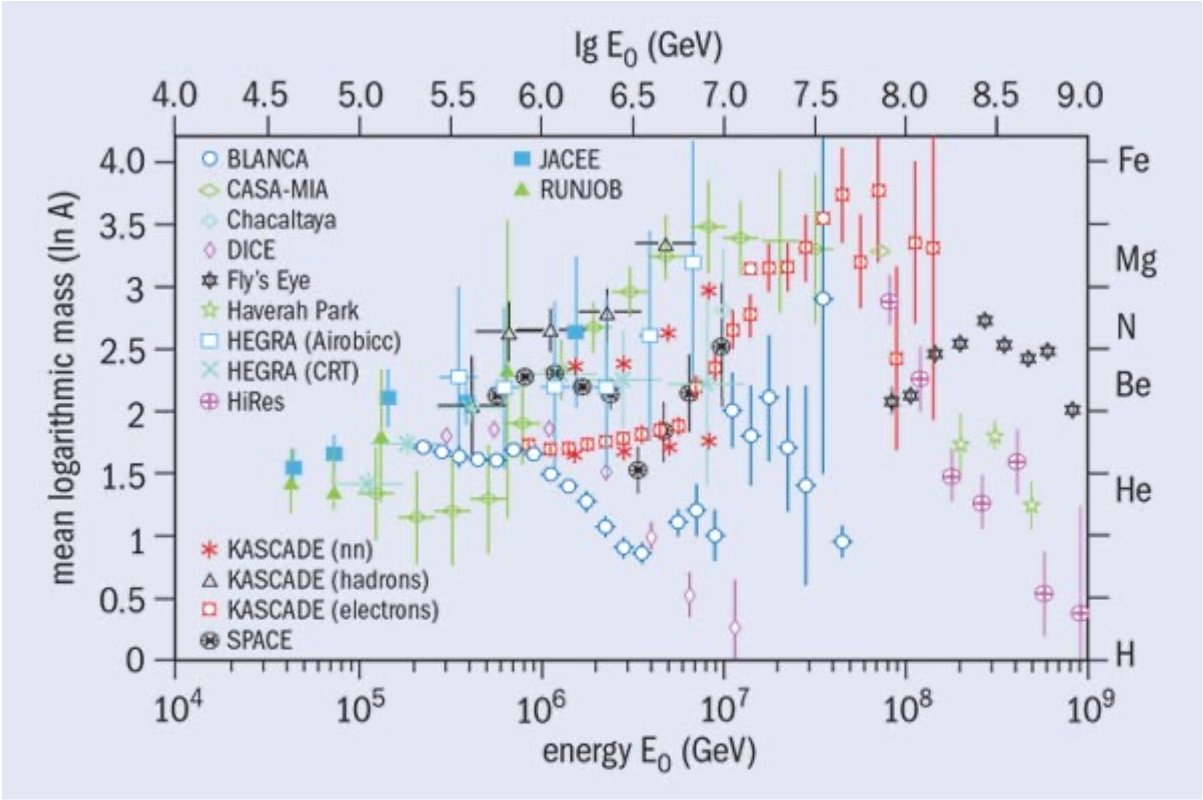
How LHAASO can Study PeVatrons?

- **Progress in cosmic ray measurements**
  - Spectra
  - Composition
  - Anisotropies

- **Progress in gamma-ray observations**
  - Supernova remnants
  - Pulsar wind nebulae and pulsar halos
  - Gamma-ray binaries
  - Young massive star clusters

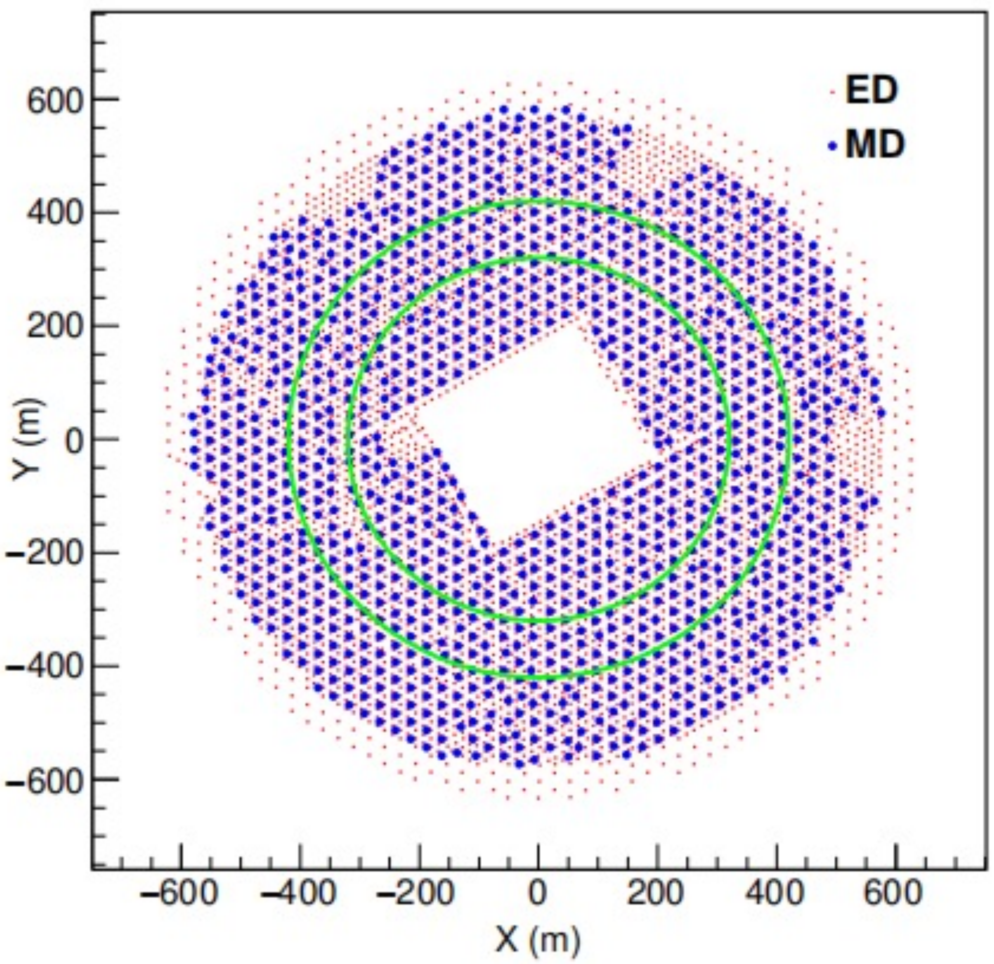
Cosmic ray spectra and <lnA> around the knee

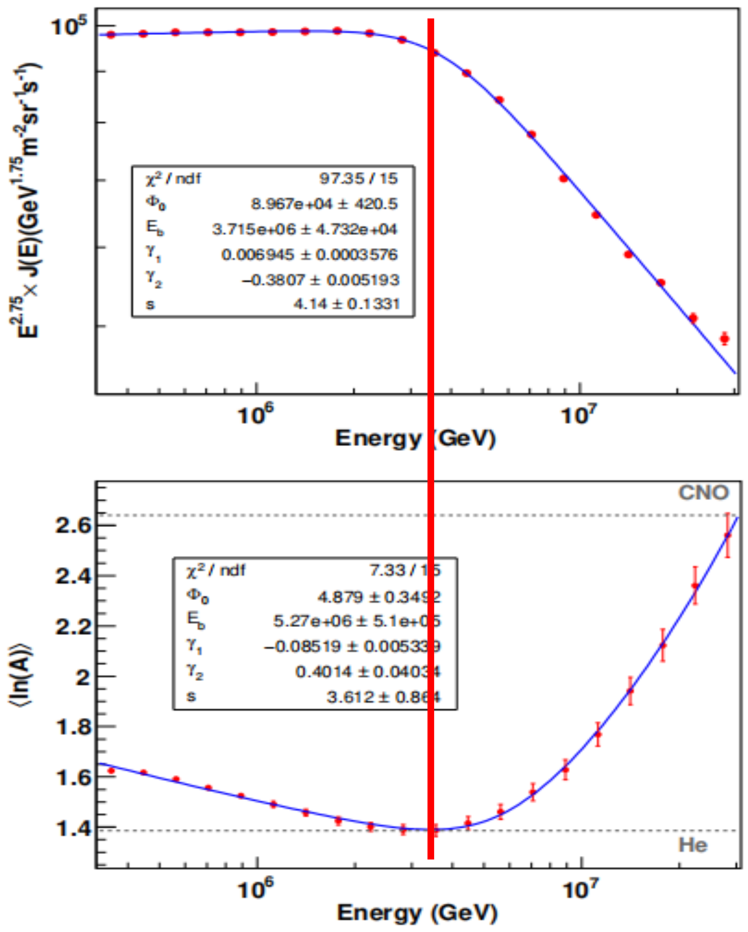




Precise measurements of energy spectra and mass composition of CRs are key to understanding the origin of the knee

Cosmic ray spectra and <lnA> around the knee

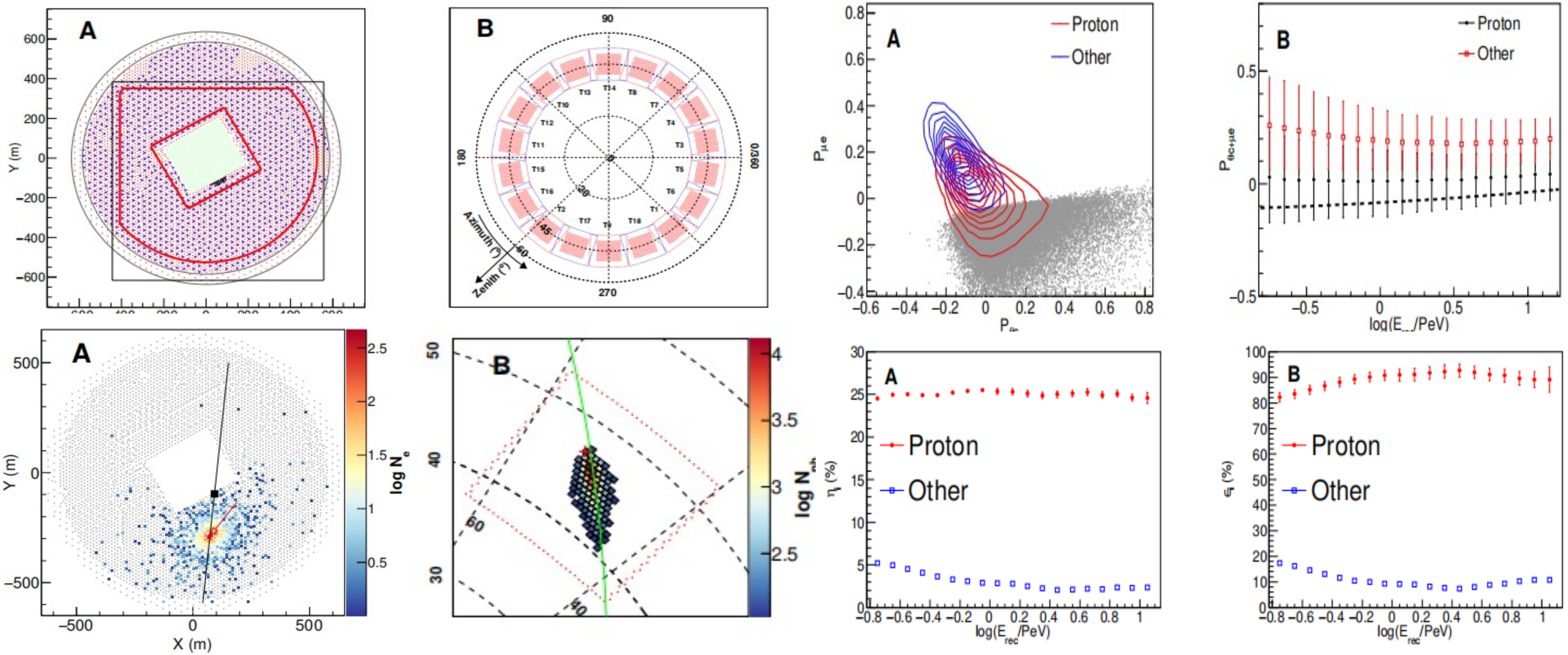




- Knee energy~3.7 PeV, index change~0.4
- Correlated spectra and <lnA> evolution
- All-particle knee is likely due to breaks of light composition

LHAASO (2024, PRL)

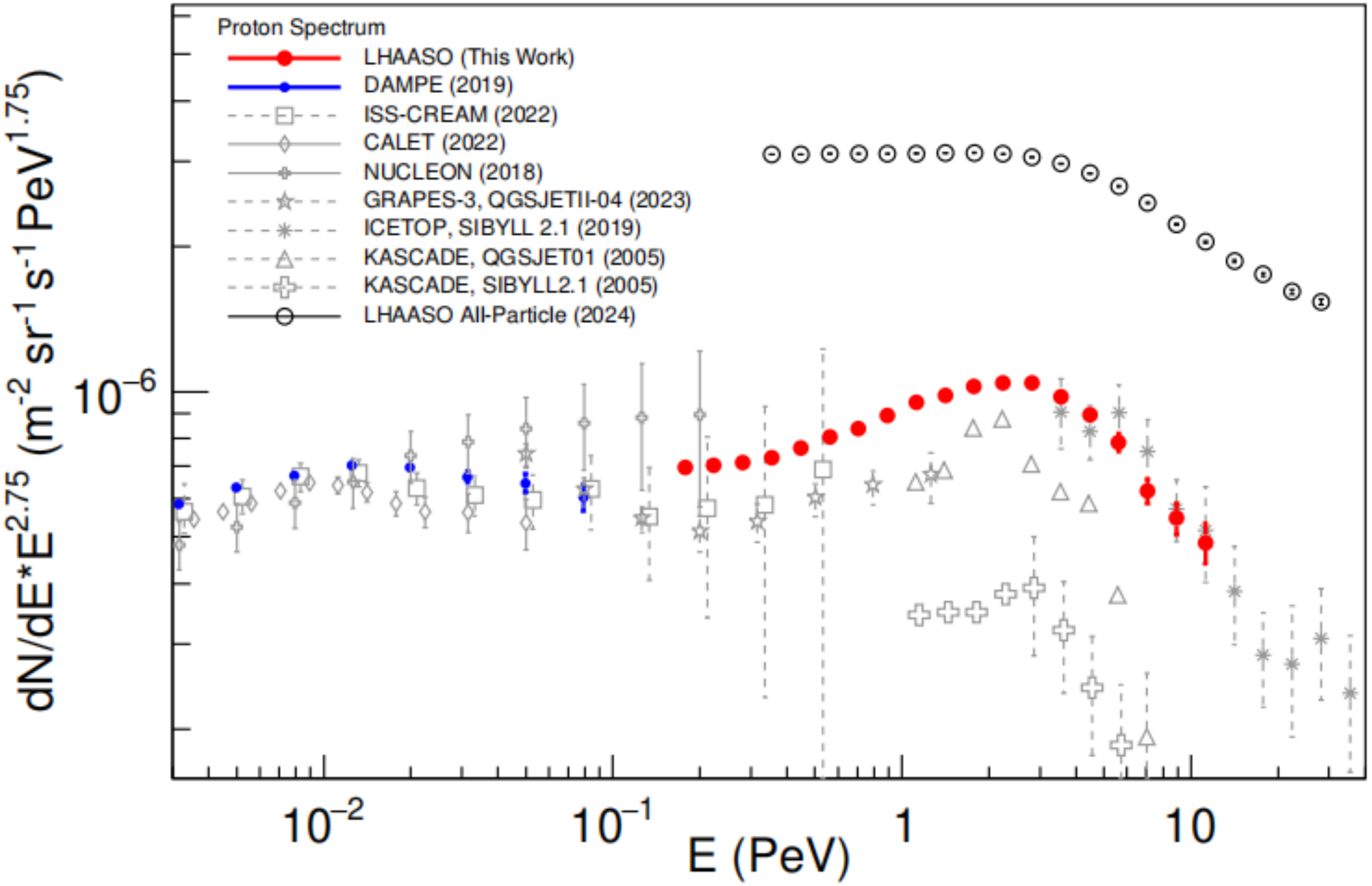
Spectrum of the proton component



LHAASO (2505.14447)

The combination of muon detectors and Cherenkov telescopes gives ~90% purity of proton sample with ~25% efficiency

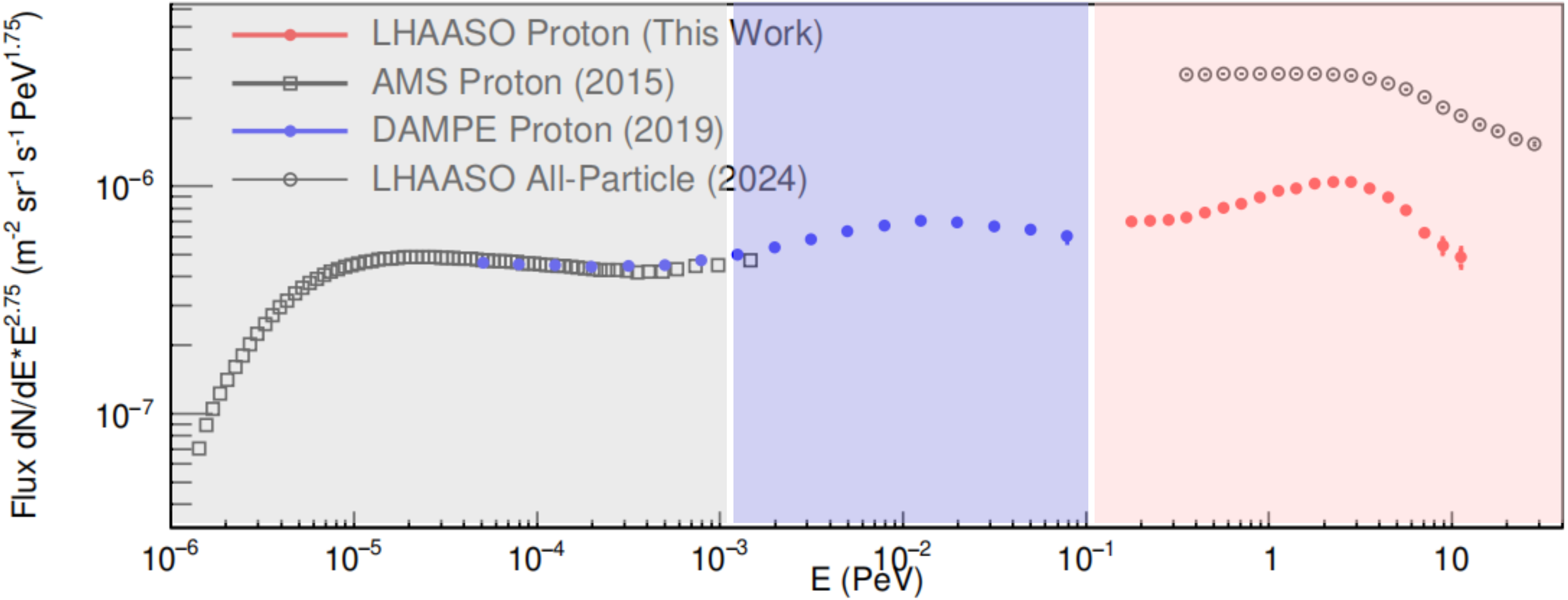
Spectrum of the proton component



- Hardening ~340 TeV, with index change ~ 0.2
- Softening (knee) ~3.3 PeV, with index change ~ -1.0
- Slightly earlier break and steeper spectrum above the break than the all-particle one

LHAASO (2505.14447)

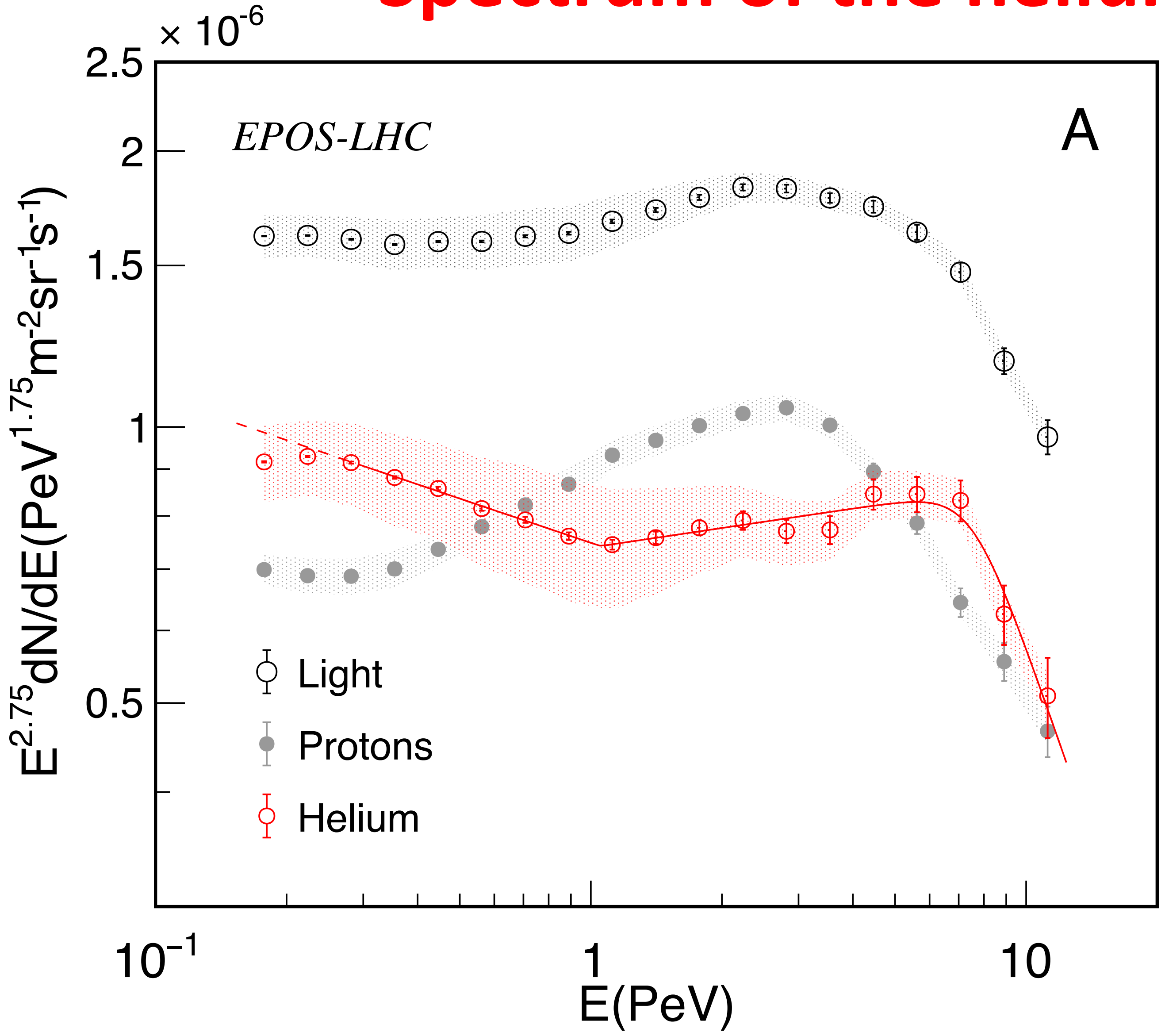
Wideband spectrum of protons



Different source populations as indicated by spectral structures? Probably related with gamma-ray source observations (SNRs, PWNe, μQs, ...)

LHAASO (2505.14447)

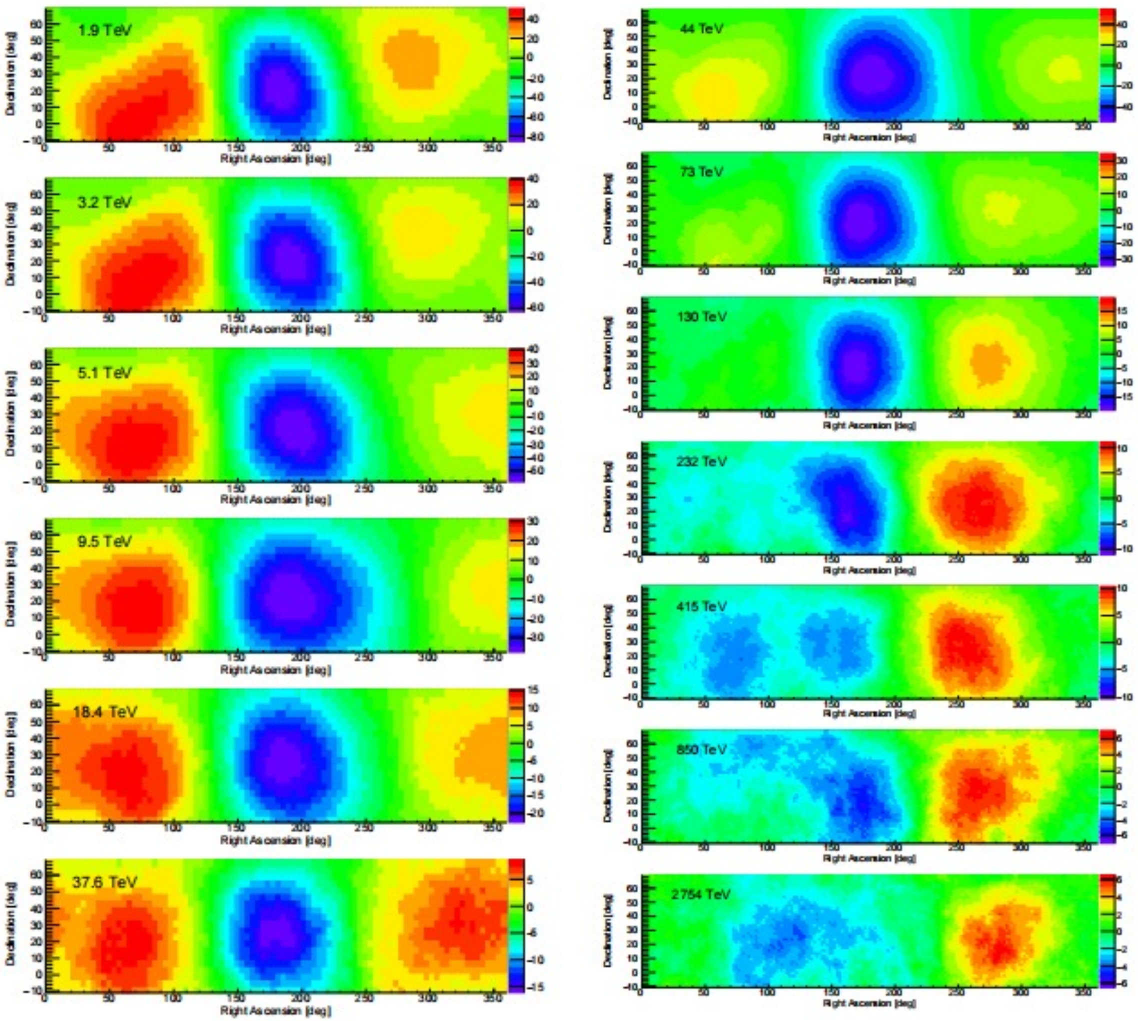
Spectrum of the helium component

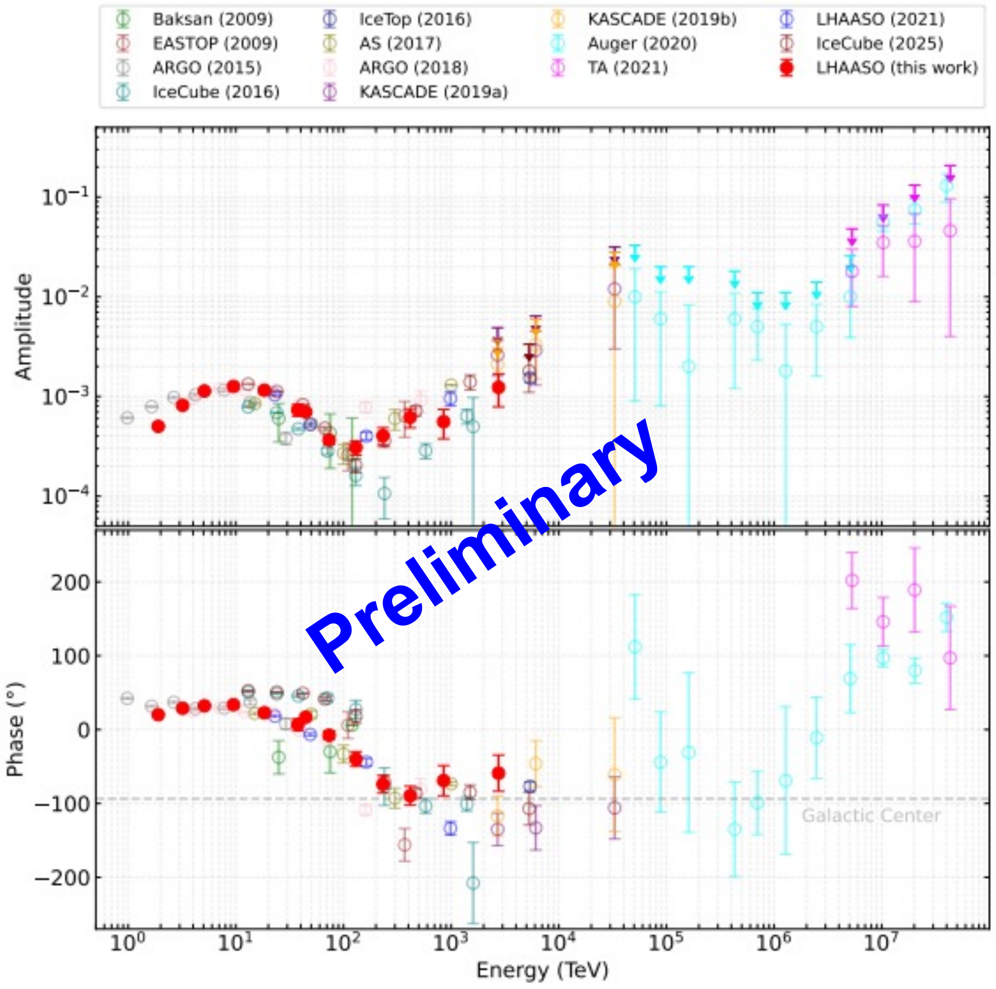


- Hardening ~1PeV
- Sharp Softening (knee) ~8 PeV
- No clear rigidity depence
- Different sources contributing close to the knee?

LHAASO (251105013)

Large-scale anisotropy of all particles





- ➢ Energy coverage: 1.9 TeV - 2.7 PeV
- ➢ Amplitude peaks at ~10 TeV, reaches a dip at ~100 TeV; phase change smoothly from ~30º to 270º (Galactic center)

Short summary on CR

- LHAASO measures the all-particle spectrum and <lnA> in the knee region, finding strong correlations between their energy evolution
- The all-particle knee is likely due to the breaks of light composition
- The proton spectrum in the knee region is measured with high precision, giving a hardening at ~340 TeV and a softening at ~3.3 PeV
- Helium component is precisely measured in the knee region
- The proton and helium spectra show a complex energy dependence that does not vanish after the rigidity correction
- Anisotropies at large and medium scales are measured, showing energy-dependent evolution

How LHAASO can Study PeVatrons?

- **Progress in cosmic ray measurements**
  - Spectra
  - Composition
  - Anisotropies

- **Progress in gamma-ray observations**
  - Supernova remnants
  - Pulsar wind nebulae and pulsar halos
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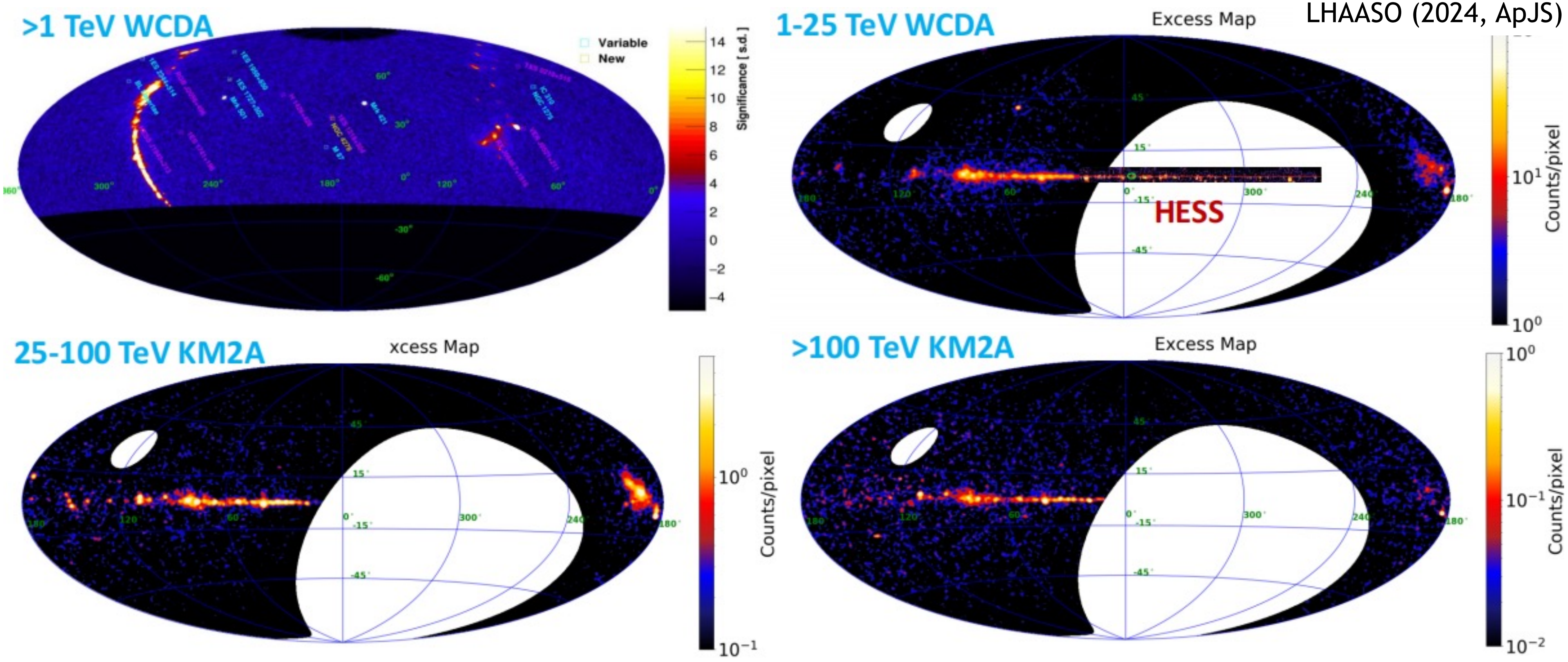
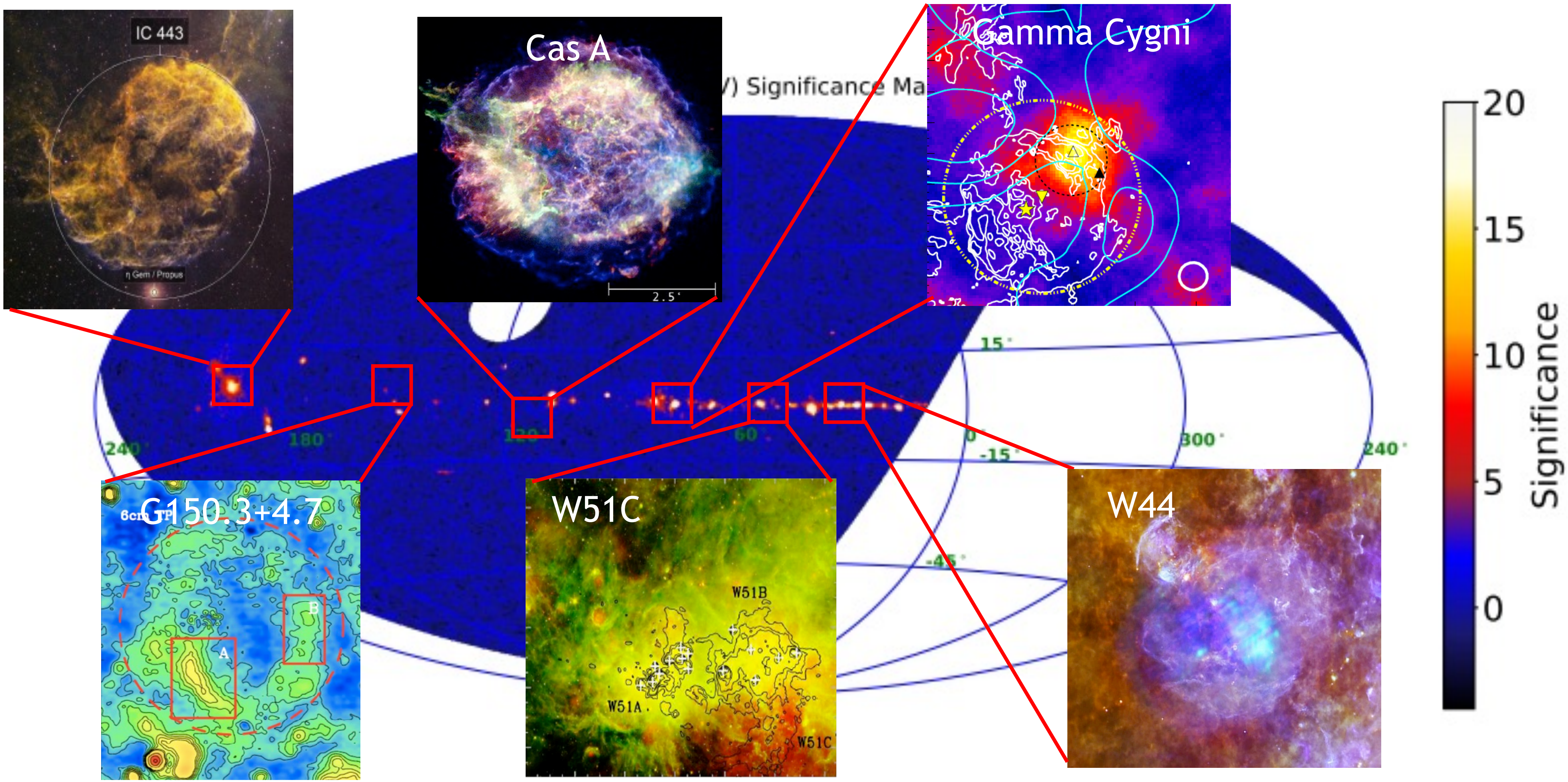
LHAASO catalog of VHE-UHE sources

LHAASO (2024, ApJS)

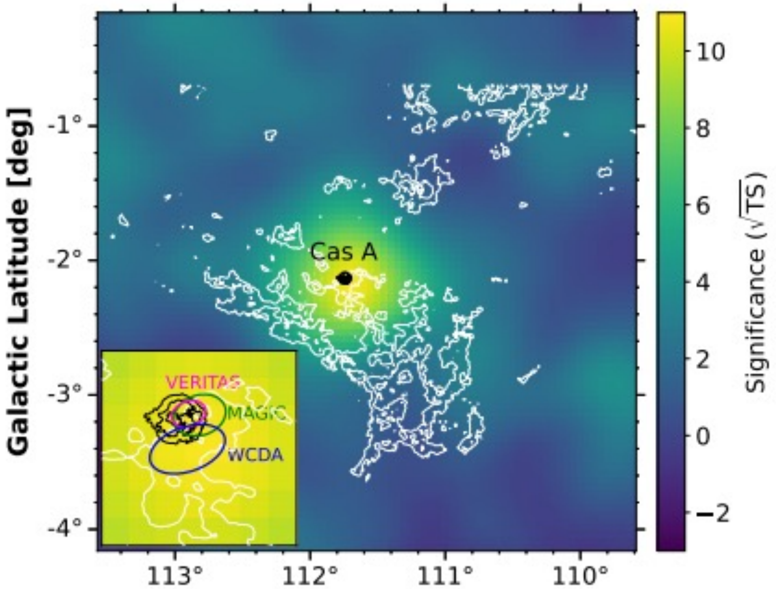


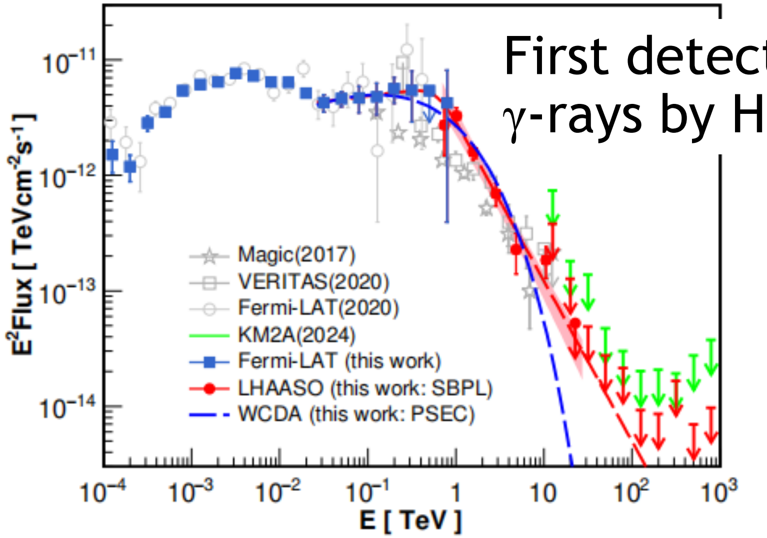
- 90 sources as of Sep. 2022, 32 newly reported, 43 with >100 TeV emission
- 77% by WCDA, 83% by KM2A, 61% by both

Supernova remnants

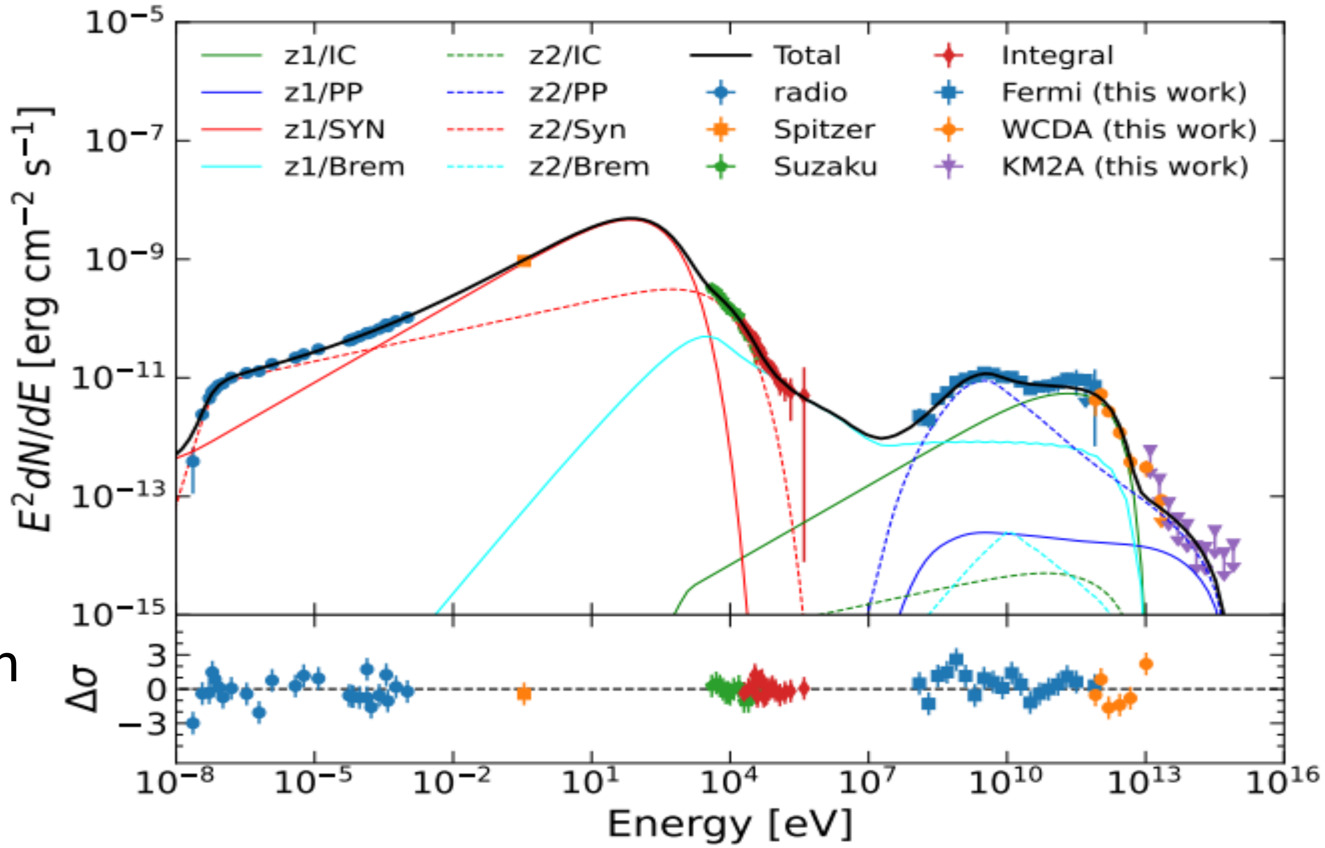


Historical SNR: Cas A





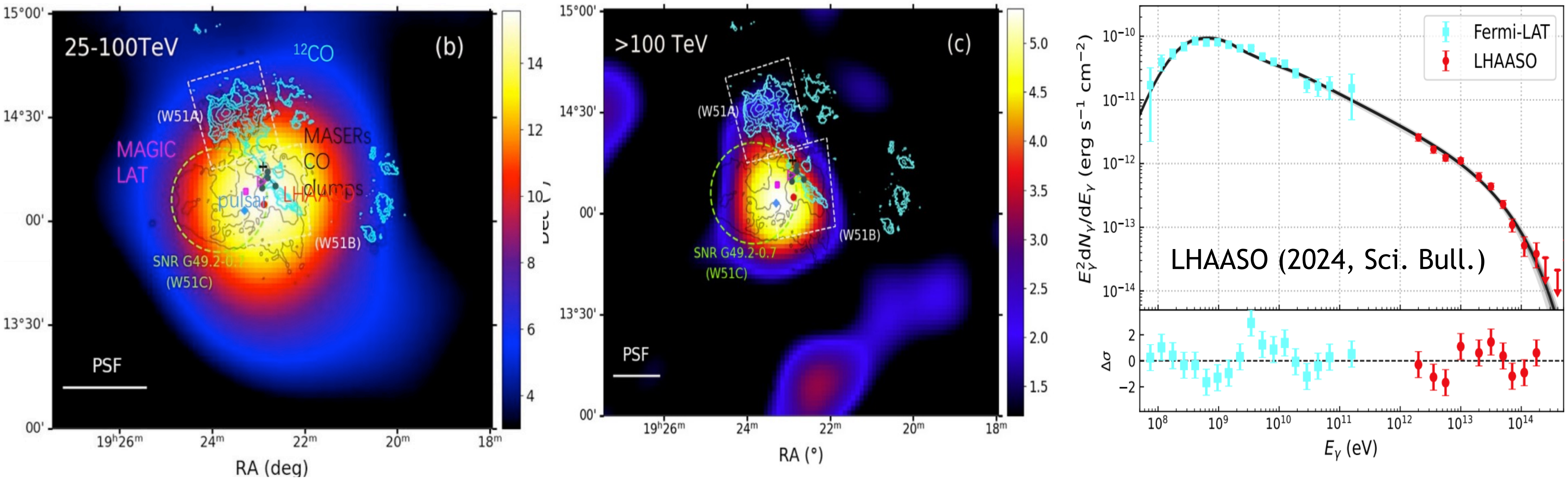
First detection in γ-rays by HEGRA



- T~350 yr, d~3.4 kpc, R~2.5’
- Soft spectrum above TeV and no strong emission above 10 TeV - challenges young SNR as PeVatron
- Bump spectrum: hybrid or two-zone emission

LHAASO (2024, ApJL; 2025 ApJL)

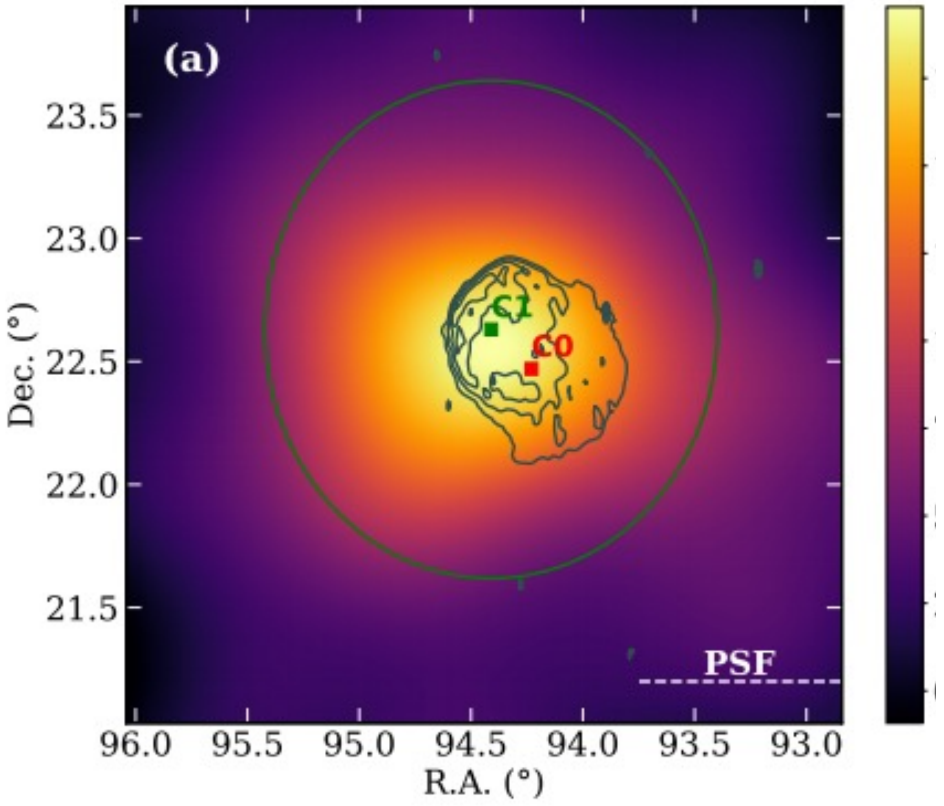
Middle-aged SNR interacting with MCs: W51C

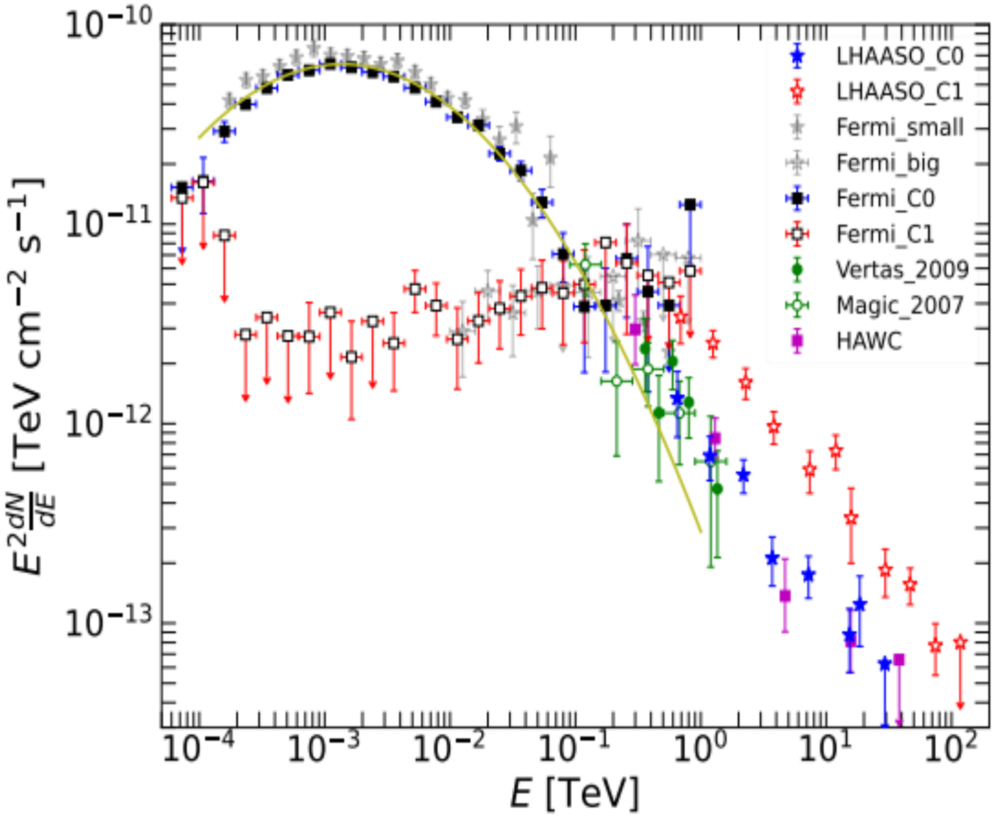


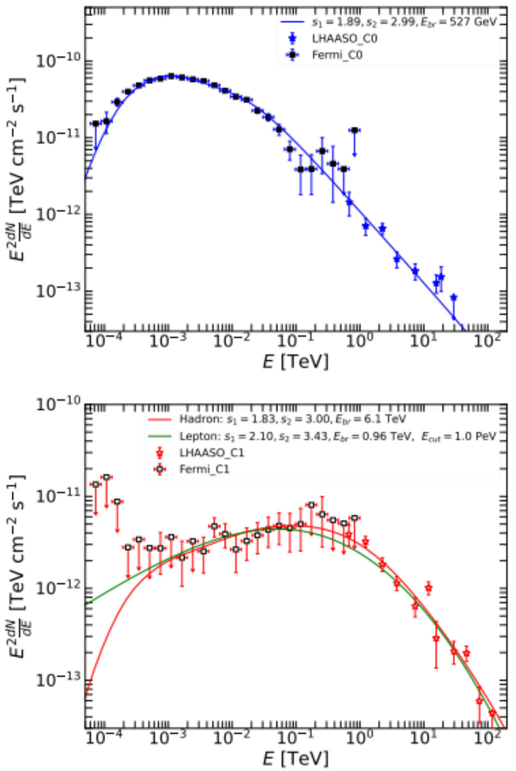
- T~18 kyr, d~4.3 kpc. Clear MC (molecular cloud) interaction, pion-bump seen by Fermi
- LHAASO detects an extended source coincident with Fermi and MAGIC
- The spectrum is consistent with a power-law-exponential cutoff at Ecut~60 TeV, suggesting a cutoff energy in the spectrum of accelerated protons of at ~300 TeV → SNRs could be PeVatrons, but may not contribute significantly to CRs all the way to the knee

Middle-aged SNR interacting with MCs: IC 443

LHAASO Col. (2025)

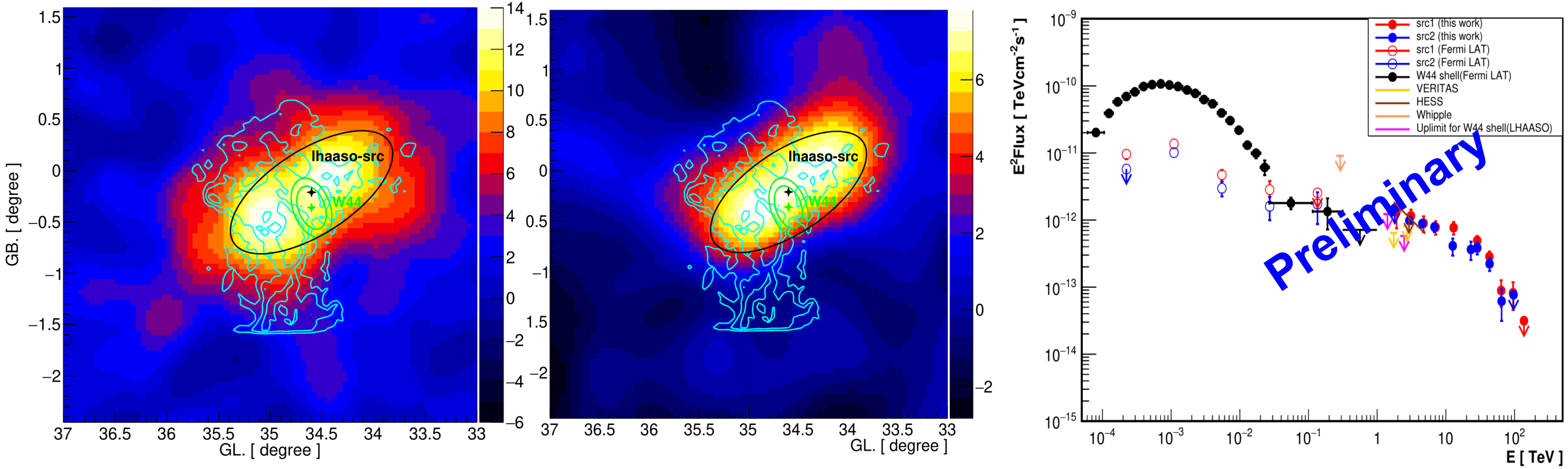






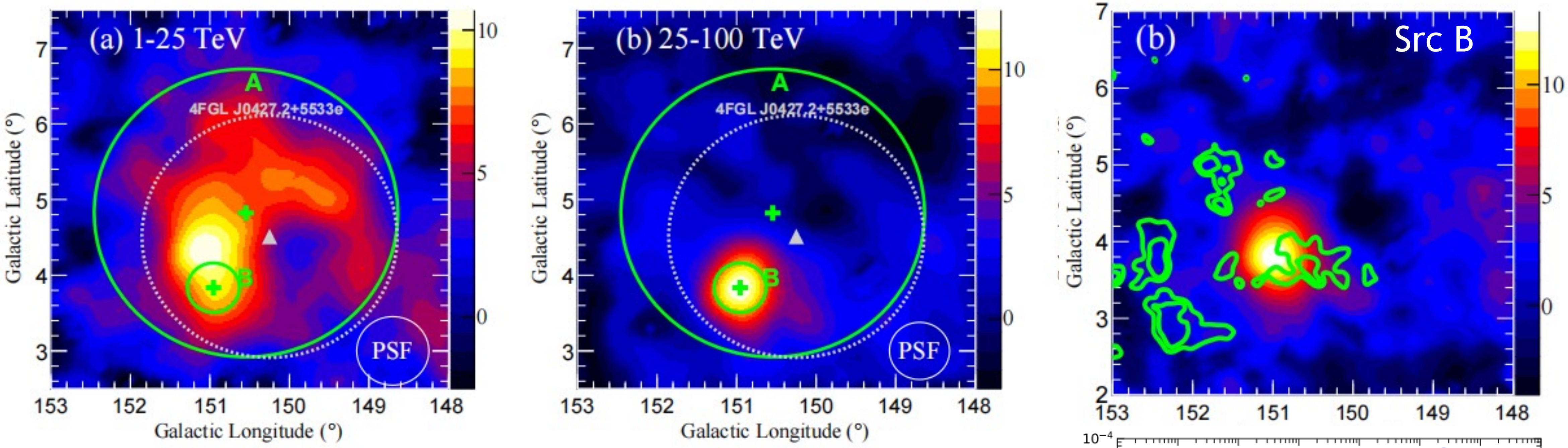
- T~3-30 kyr, d~1.5 kpc. Clear MC interaction, pion-bump feature seen by AGILE/Fermi
- LHAASO resolves two sources: a compact one (C0; pointlike) and an extended one (C1; R68~1°)
- C0 is likely coincident with the pion-bump component by Fermi, and extends to 20 TeV without clear spectral cutoff → 95% lower limit of proton acceleration is 400 TeV
- C1 is coincident with Fermi extended source, may be from escaping protons or electrons

Middle-aged SNR interacting with MCs: W44

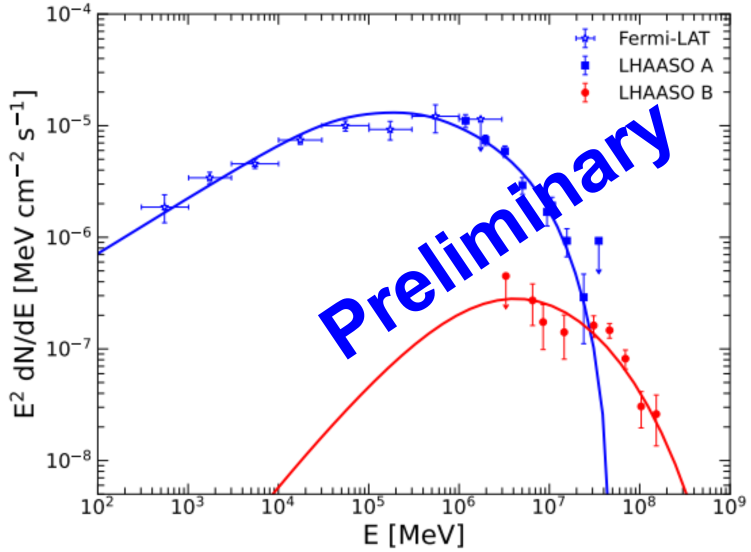


- T~20 kyr, d~2.9 kpc. Clear MC interaction, pion-bump feature seen by AGILE/Fermi
- LHAASO detects elongated emission associated with MC distribution
- Can be explained by protons escaping from the SNR and producing emission in the regions with dense target

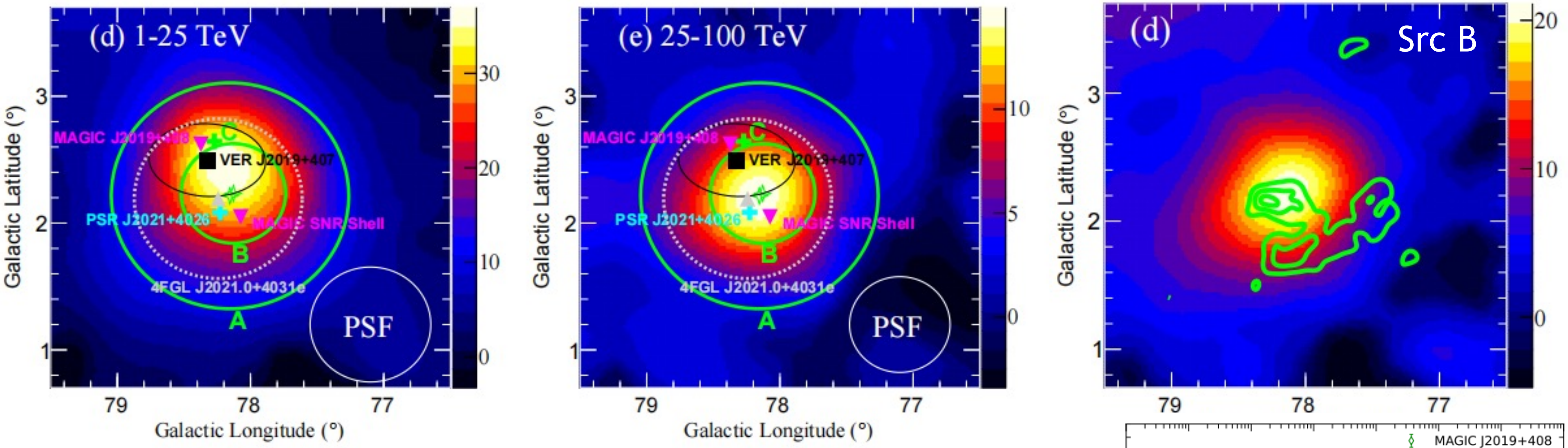
Middle-aged SNR likely interacting with MCs: G150.3+4.7



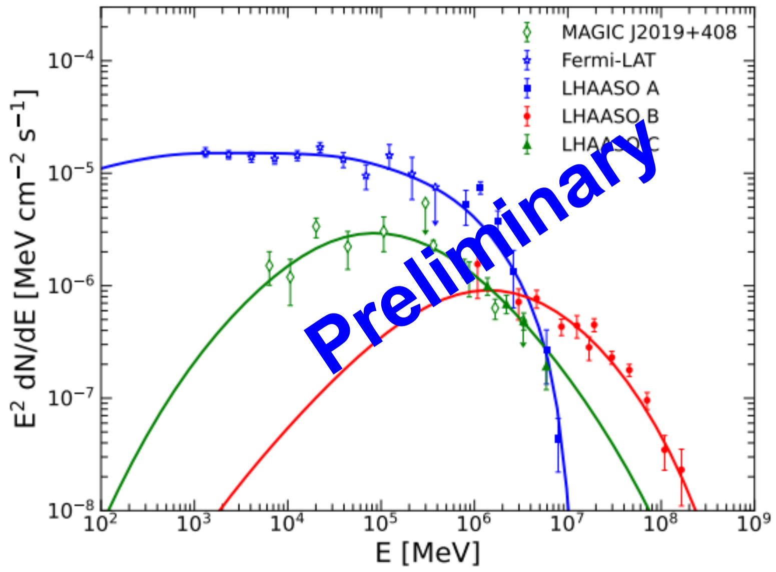
- T~26 kyr, d~0.74 kpc, R~1.3°
- Two components by LHAASO: extended Src A (R68~1.9°) at low energy and a compact Src B (R68~0.33°) at high energy
- Src A likely coincides with the radio and GeV shell, thus it could be due to leptonic emission
- Src B coincides with MCs, and it can be naturally explained by escaping protons that interact with target in MCs



Middle-aged SNR likely interacting with MCs: γ-Cygni



- T~7 kyr, d~1.7 kpc, R~0.5°. A weak PWN in radio and X ray
- Three components by LHAASO: an extended Src A (R68~0.9°) at low energy, an extended Src B (R68~0.4°) at high energy, and a point Src C at low energy
- Src A likely coincides with the radio and GeV shell, thus it could be due to leptonic emission
- Src B and Src C coincide with MCs, and they can be explained by escaping protons interacting with dense target in MCs



Short Summary on SNRs

- LHAASO detects a number of SNRs with emission up to 100 TeV, most of the sources show a complicated morphology and spectra
- Compelling evidence of hadronic emission with likely association with MCs has been obtained, and indicating that SNRs can at least accelerate protons to sub-PeV energies
- Proton spectral cutoff of hundred TeV is shown for some sources, suggesting that they may not major contributor to CRs above the knee

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- **Progress in cosmic ray measurements**
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- **Progress in gamma-ray observations**
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  - Gamma-ray binaries
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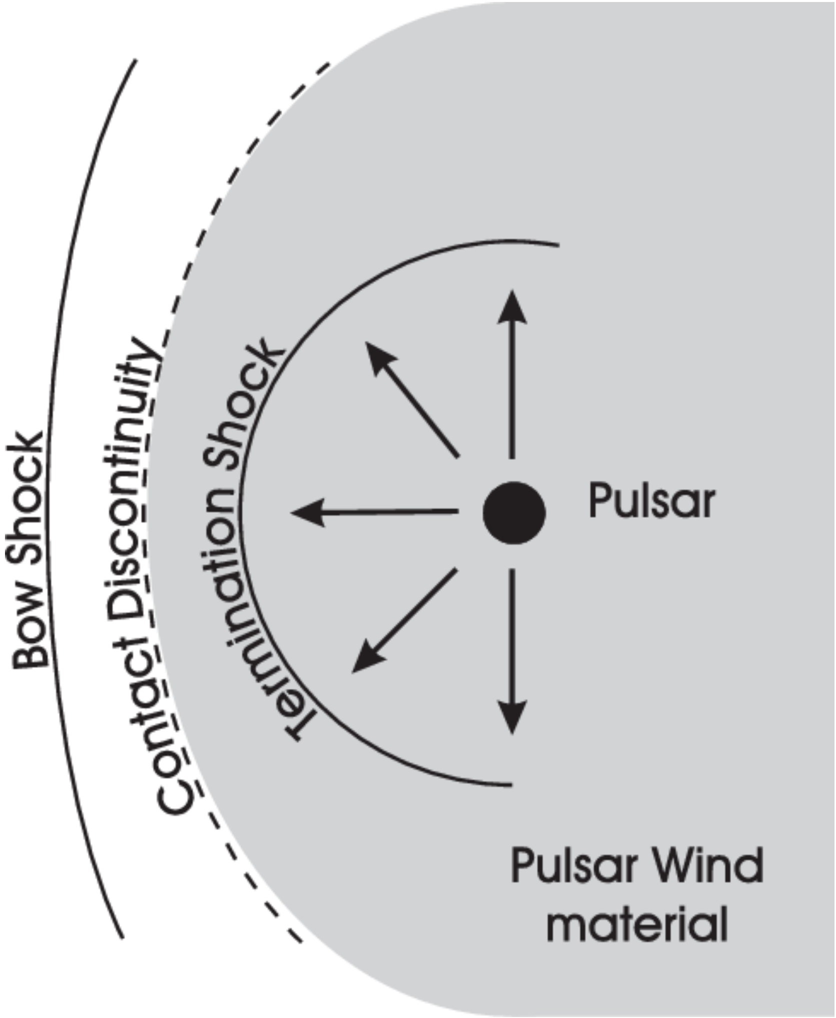
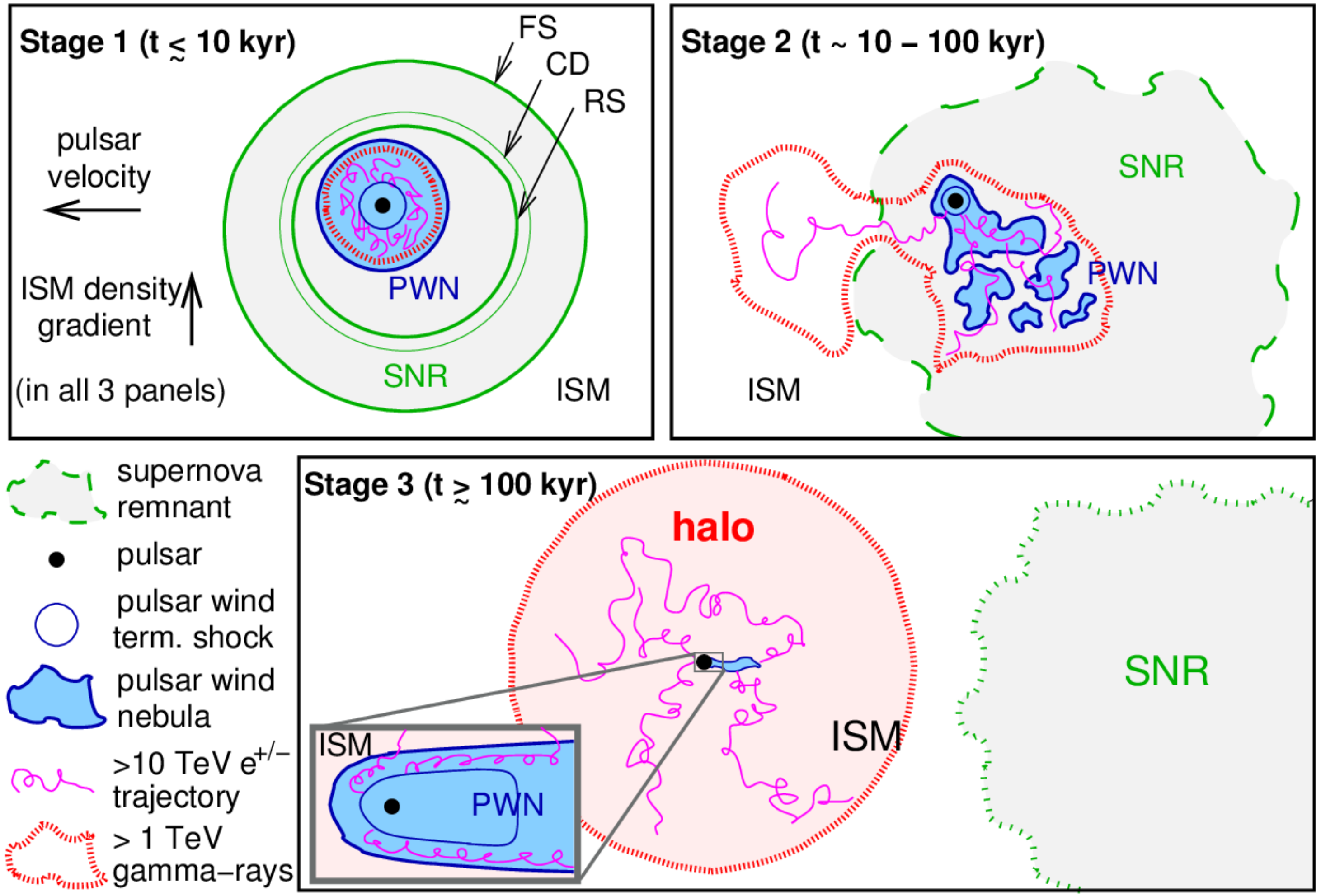
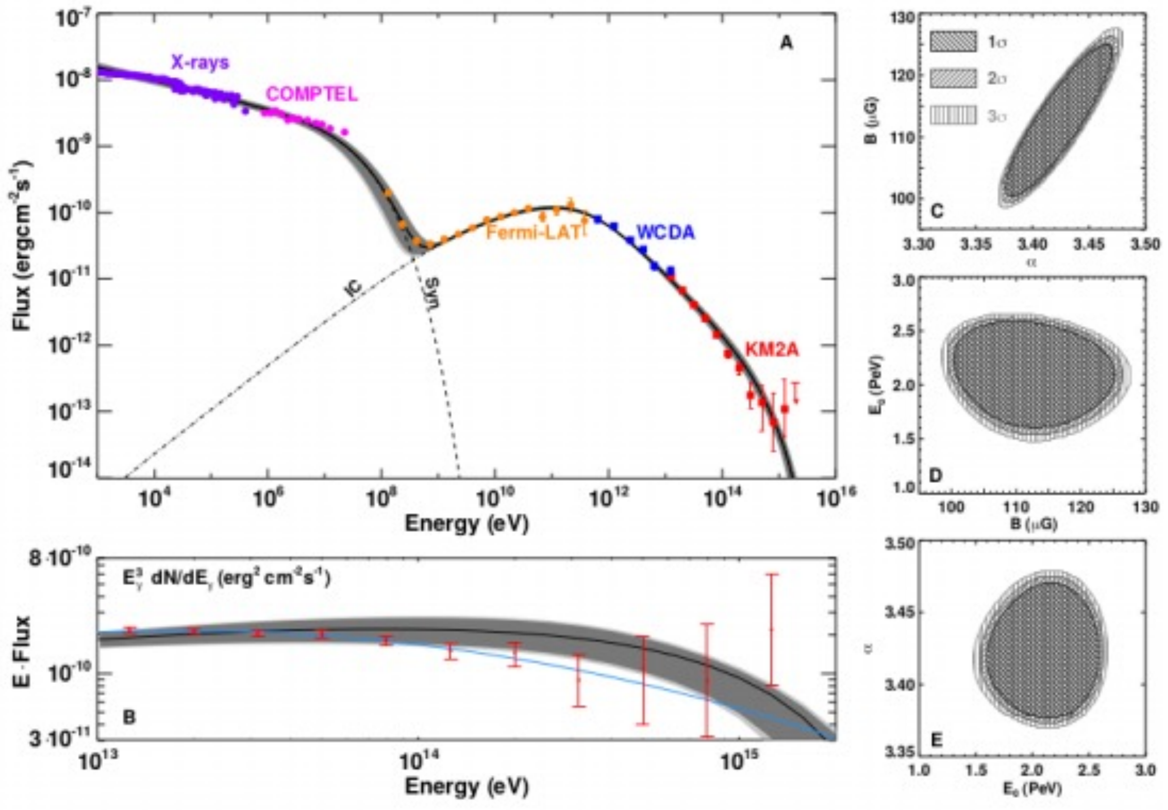
PWN and pulsar halos

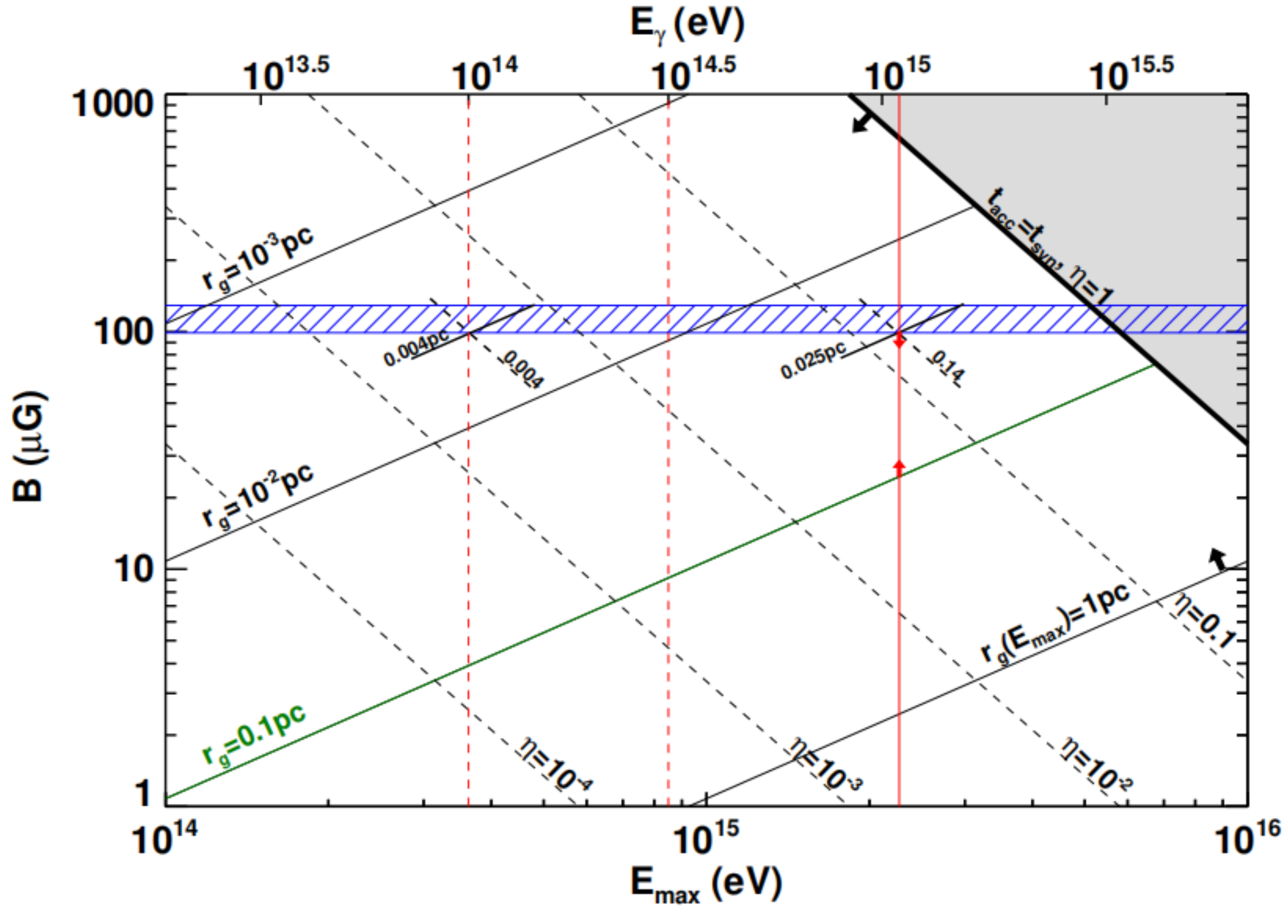




Giacinti + (2020, A&A)

Young PWN: crab nebula



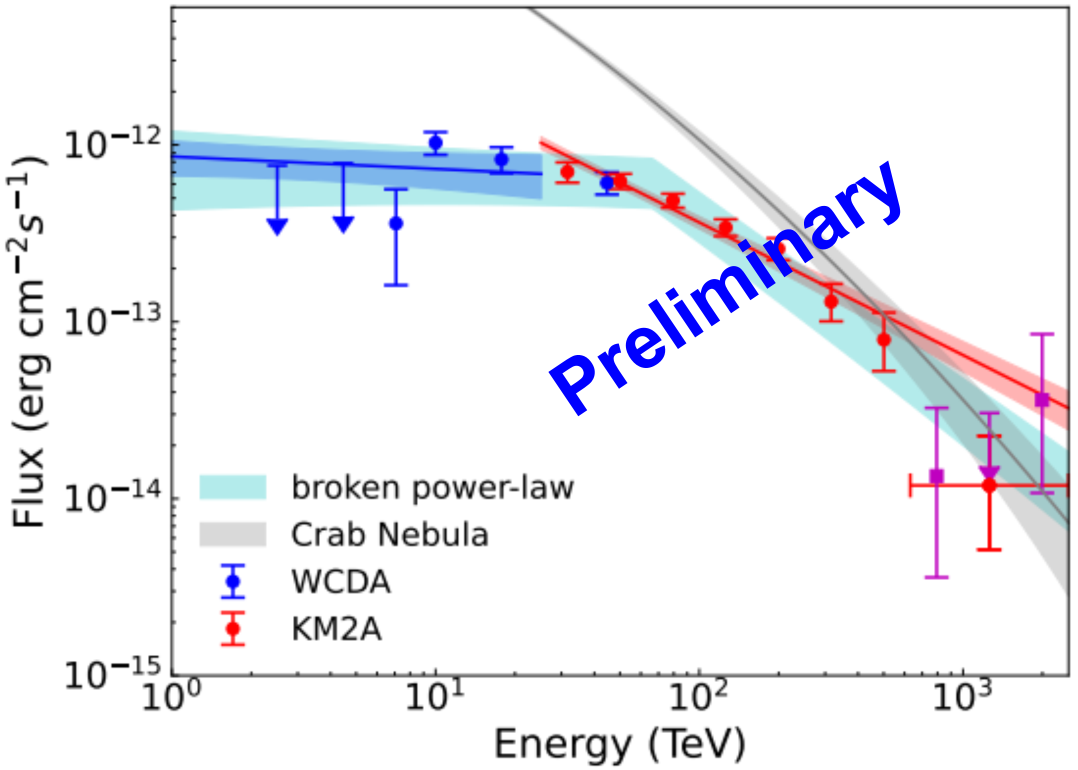


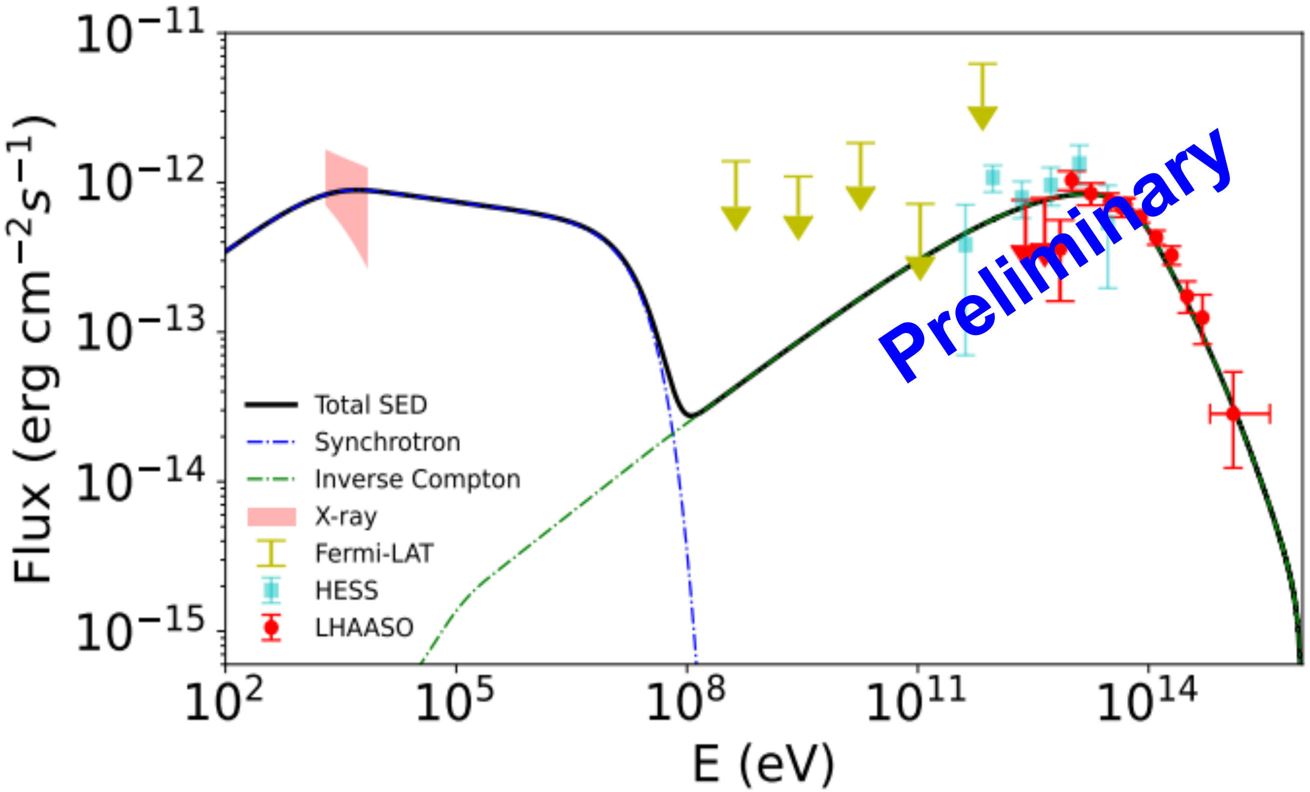
E_{syn} = 7MeV $(E_e/1\text{PeV})^2$ (B/100μG)
E_{IC}= 0.37$(E_e/1\text{ PeV})^{1.3}$

$$\eta = 0.14(B/100\mu G)(E_\gamma/1\text{ PeV})^{1.54}$$

LHAASO (2021, Science)

PSR J1849-0001: extreme accelerator



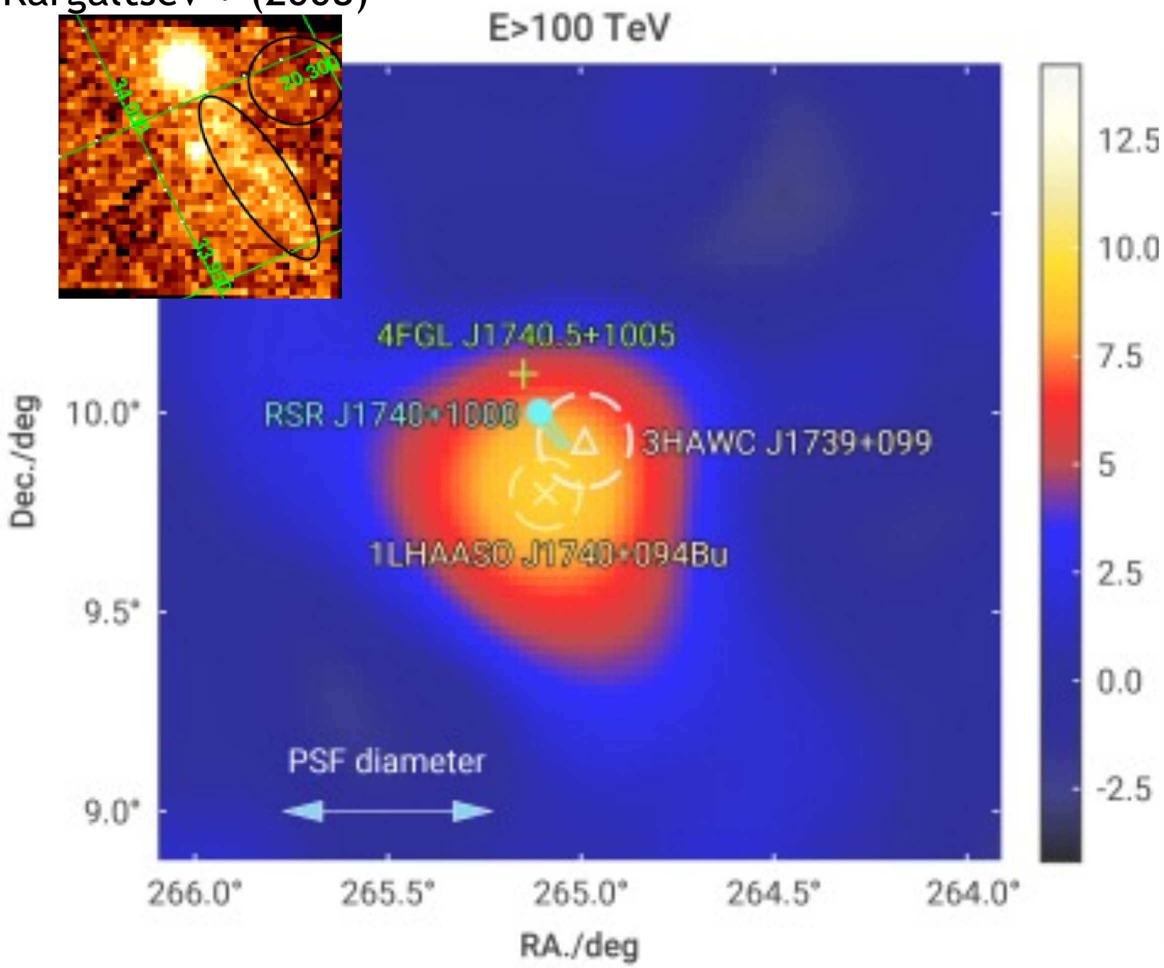


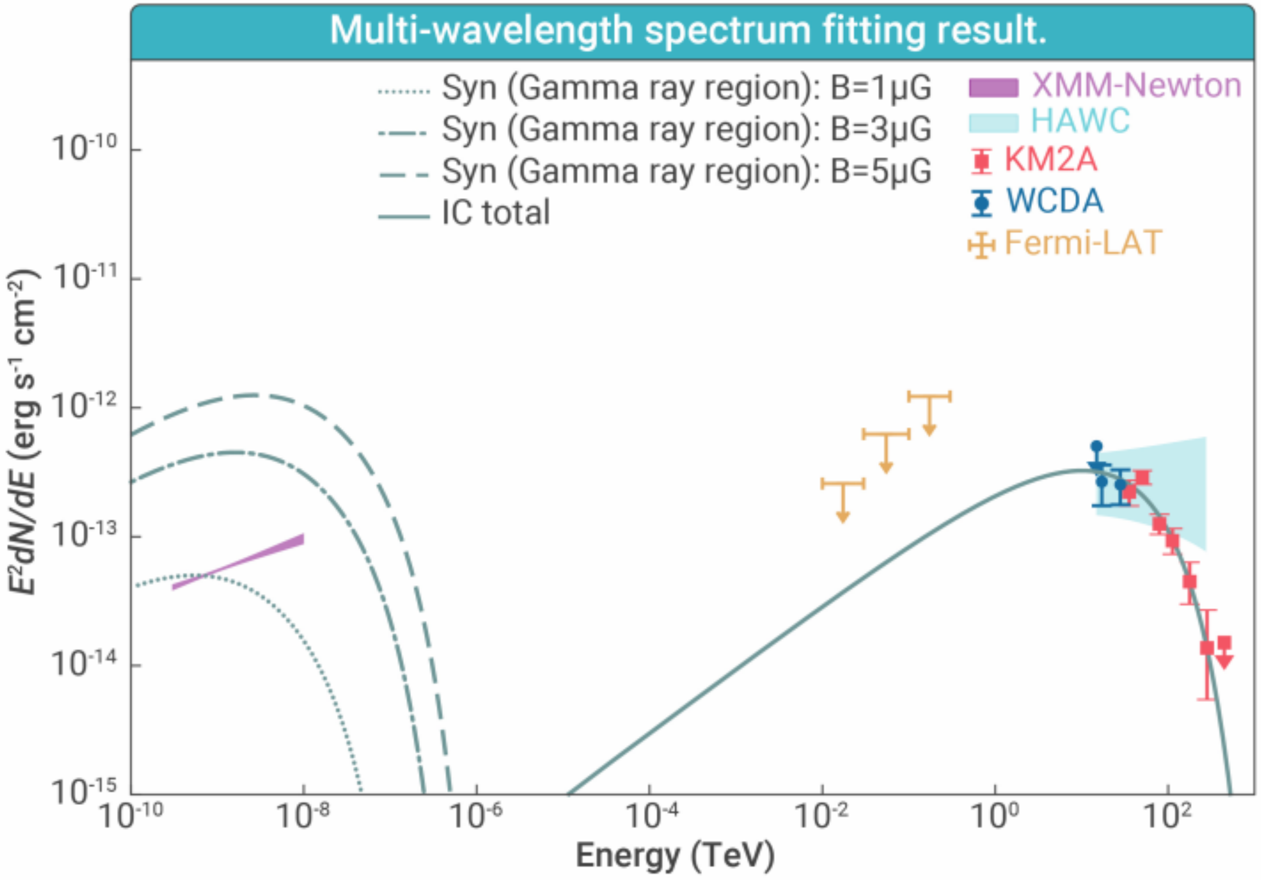
- T~43 kyr, d~7 kpc, L~10^{37} erg/s
- Most energetic photon has an energy of ~2 PeV → maximum electron energy ~3.7 PeV
- Very extreme particle acceleration with η>1, challenging the particle acceleration in PWN

LHAASO (2025, submitted)

LHAASO J1740+0948: bow-shock PWN

Kargaltsev + (2008)

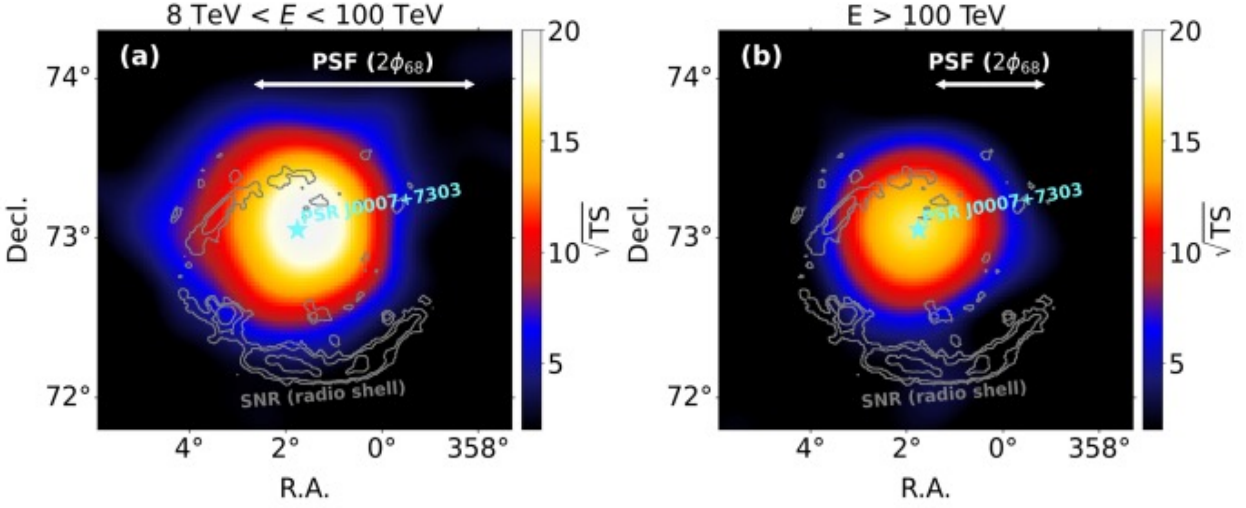


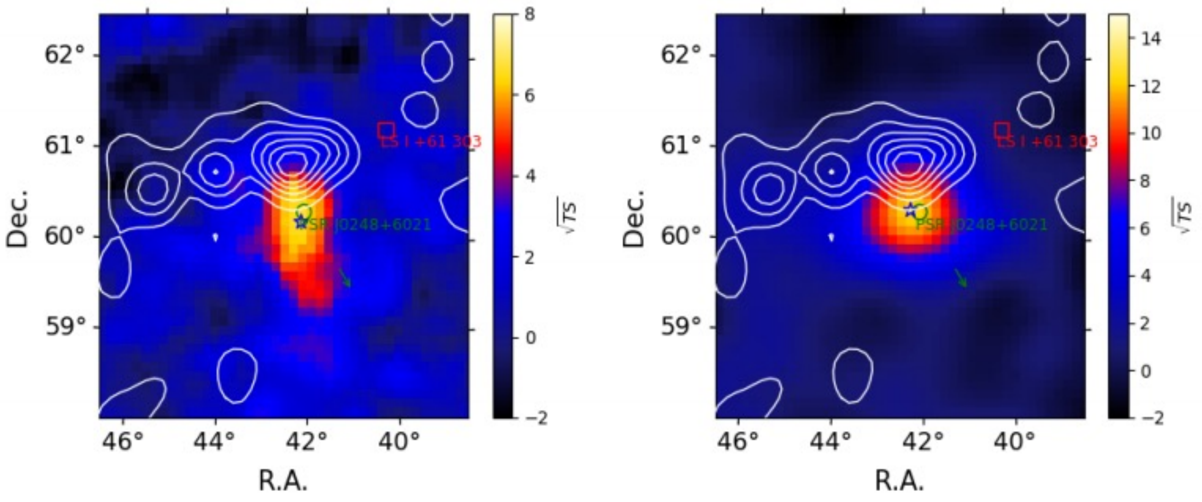


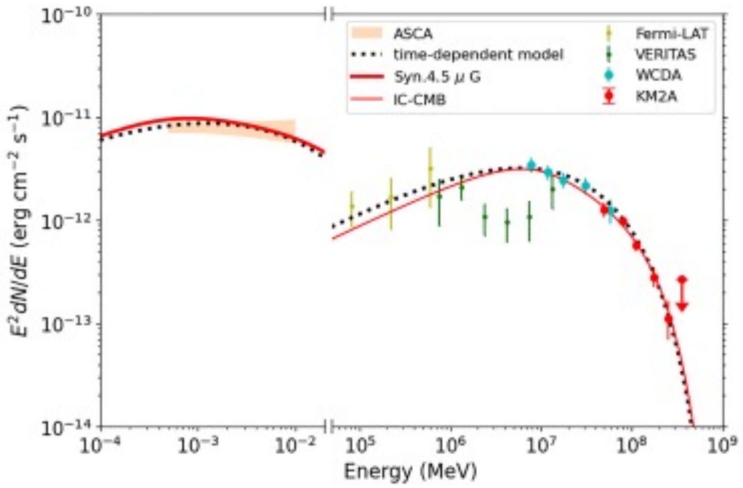
LHAASO (2025, The Innovation)

- T~114 kyr, d~1.4 kpc, L~2×10^{35} erg/s
- Emission offset by ~0.2o from the pulsar, located at the extension of X-ray tail
- Emission may originate from reaccelerated electrons advected away from the bow shock tail

More PWNe

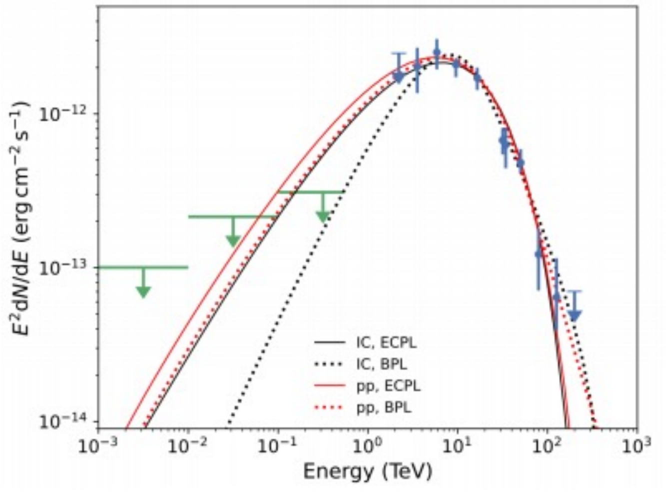






LHAASO (2025a, SCPMA)

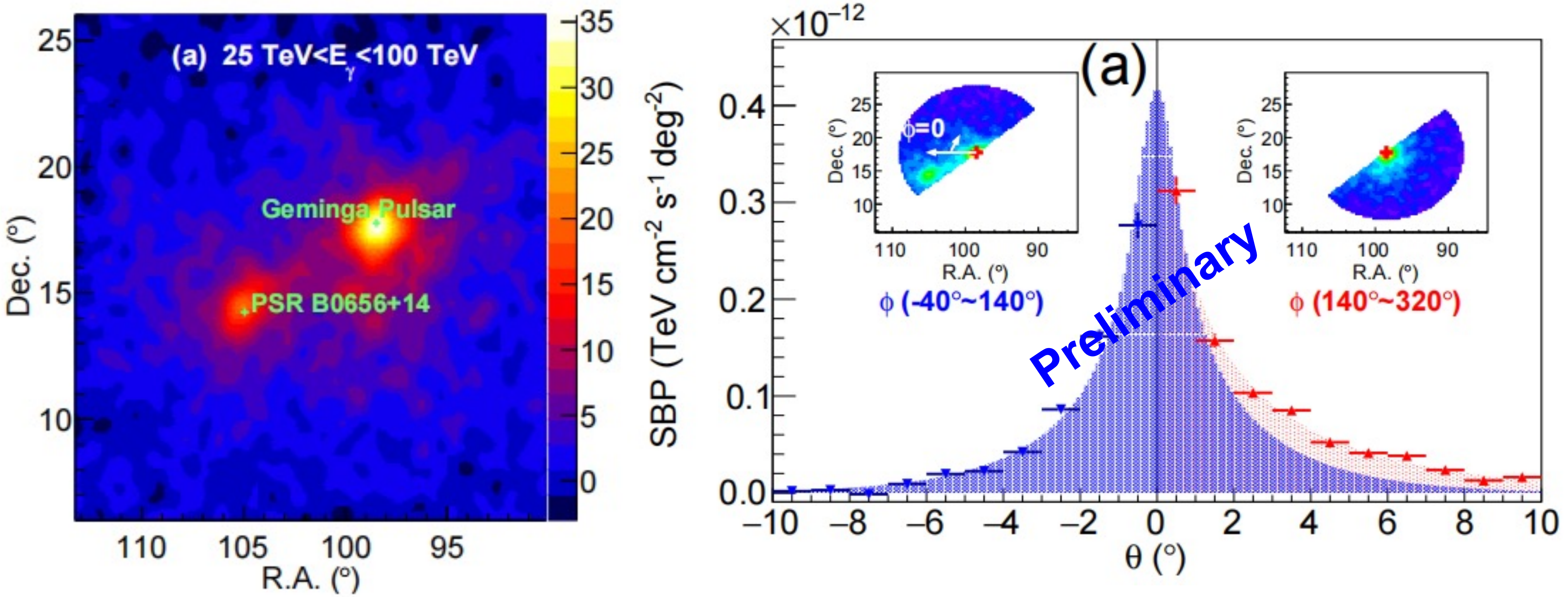
LHAASO (2025b, SCPMA)



CTA1 (J0007+7303): T=13.9 kyr, d~1.4 kpc, L~4×10^{35} erg/s

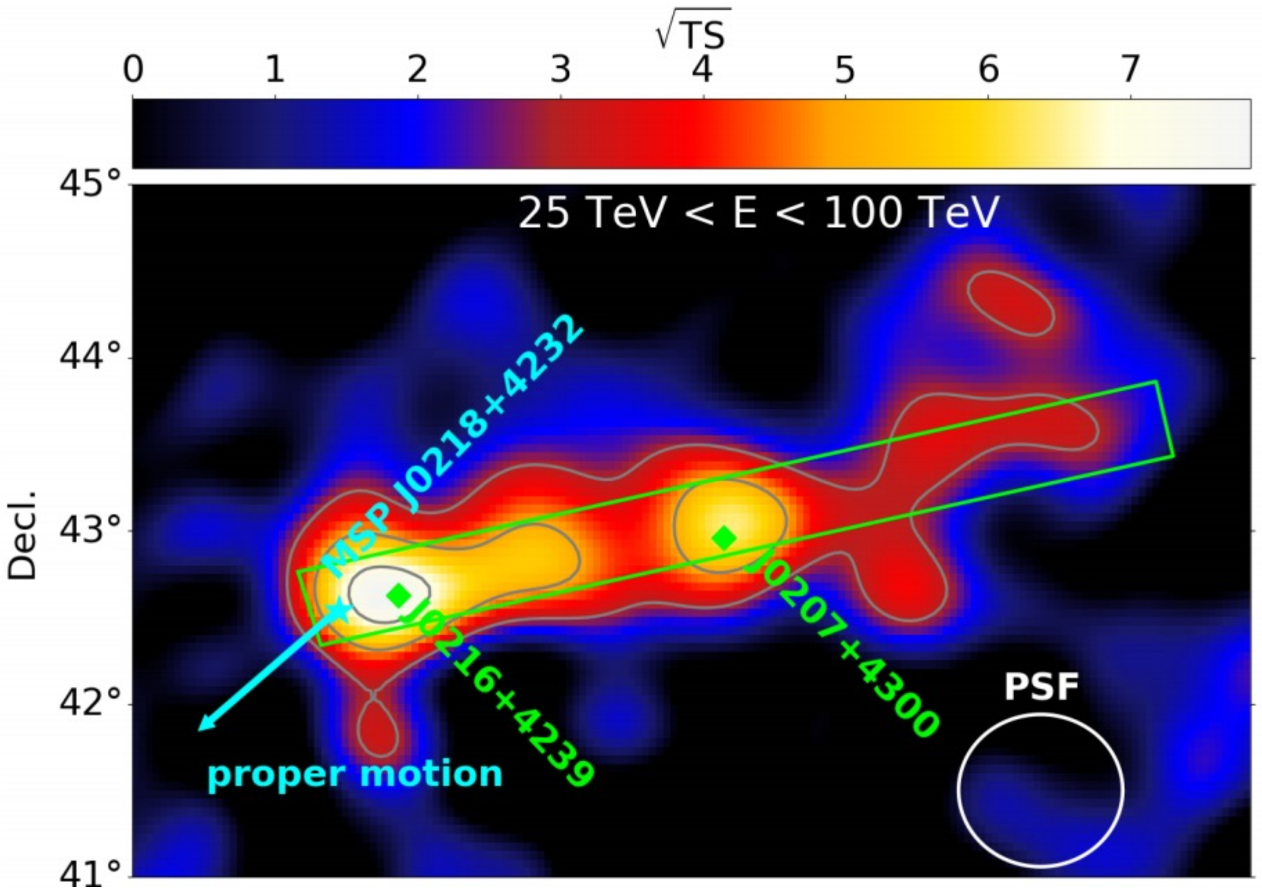
J0248+6021: T=62 kyr, d~2 kpc, L~2×10^{35} erg s^{-1}; no MW counterpart, possibly forming a halo

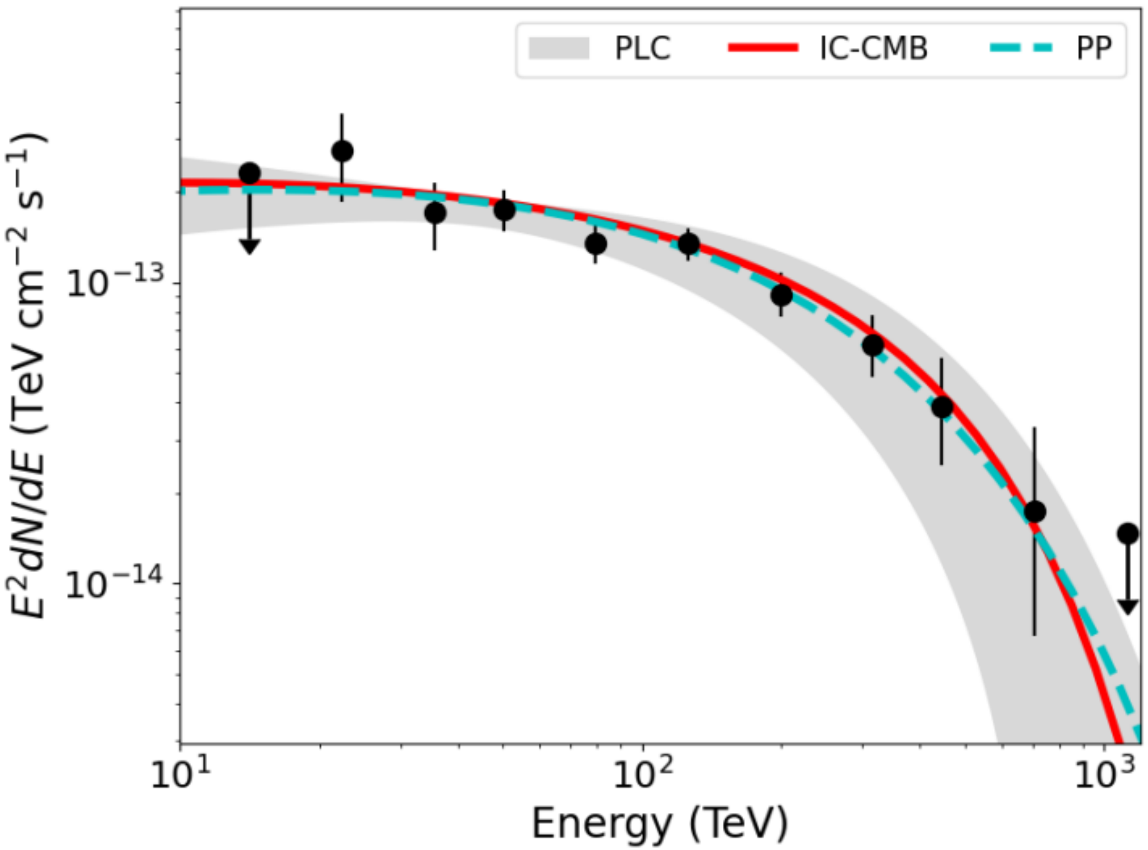
Middle-aged pulsar halos



Asymmetric morphology of pulsar halos suggesting inhomogeneous/anisotropic diffusion in the vicinity of pulsars

PEANUT possibly associated with an MSP





- P=2.3 ms, T<0.5 Gyr, d~3 kpc, L~2.4×10^{35} erg/s
- LHAASO detects peanut-shape emission (250 pc×25 pc), with highest energy photon of 740 TeV
- The morphology may indicate electron diffusion along large-scale magnetic fields

Short summary on PWN and pulsar halos

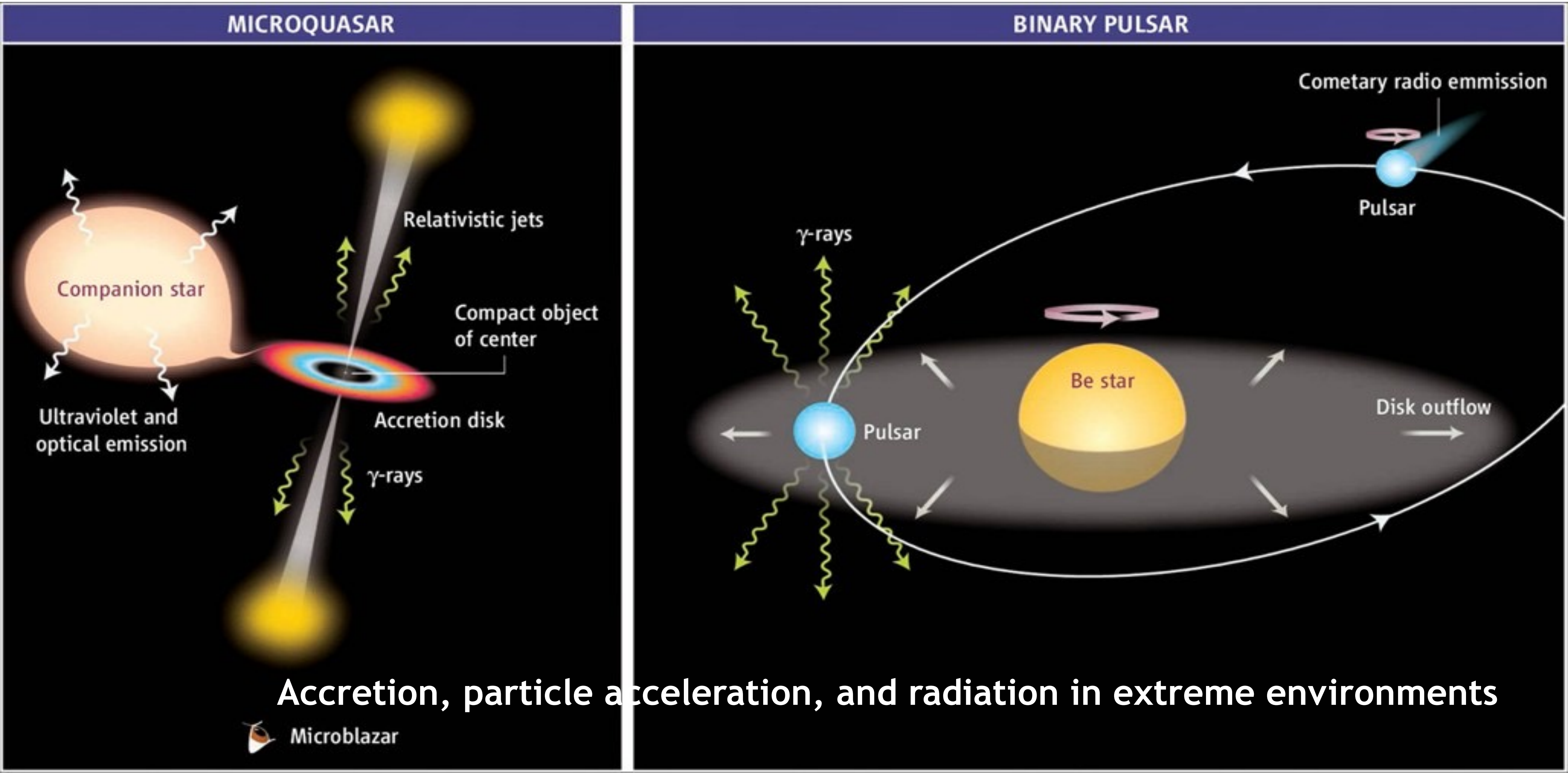
- PWN and pulsar halos are found to be a major class of sources emitting UHE gamma-ray radiation
- Very high acceleration efficiency is revealed in young PWN
- Asymmetric morphologies for Geminga and Monogem halos have been found, indicating inhomogeneous or anisotropic diffusion of particles
- PEANUT shape emission possibly associated with an MSP indicates interesting particle propagation in the ISM

How LHAASO can Study PeVatrons?

- **Progress in cosmic ray measurements**
  - Spectra
  - Composition
  - Anisotropies

- **Progress in gamma-ray observations**
  - Supernova remnants
  - Pulsar wind nebulae and pulsar halos
  - Gamma-ray binaries
  - Young massive star clusters

Gamma-ray binaries



Accretion, particle acceleration, and radiation in extreme environments

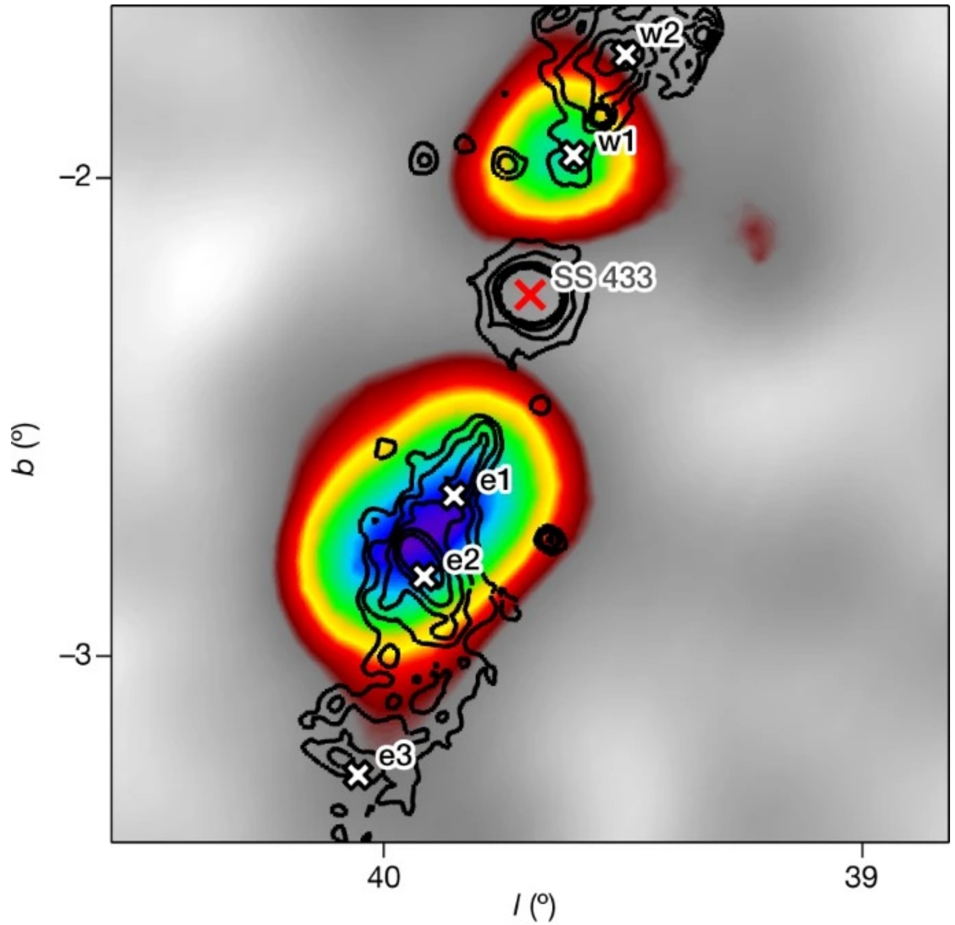
Microquasars

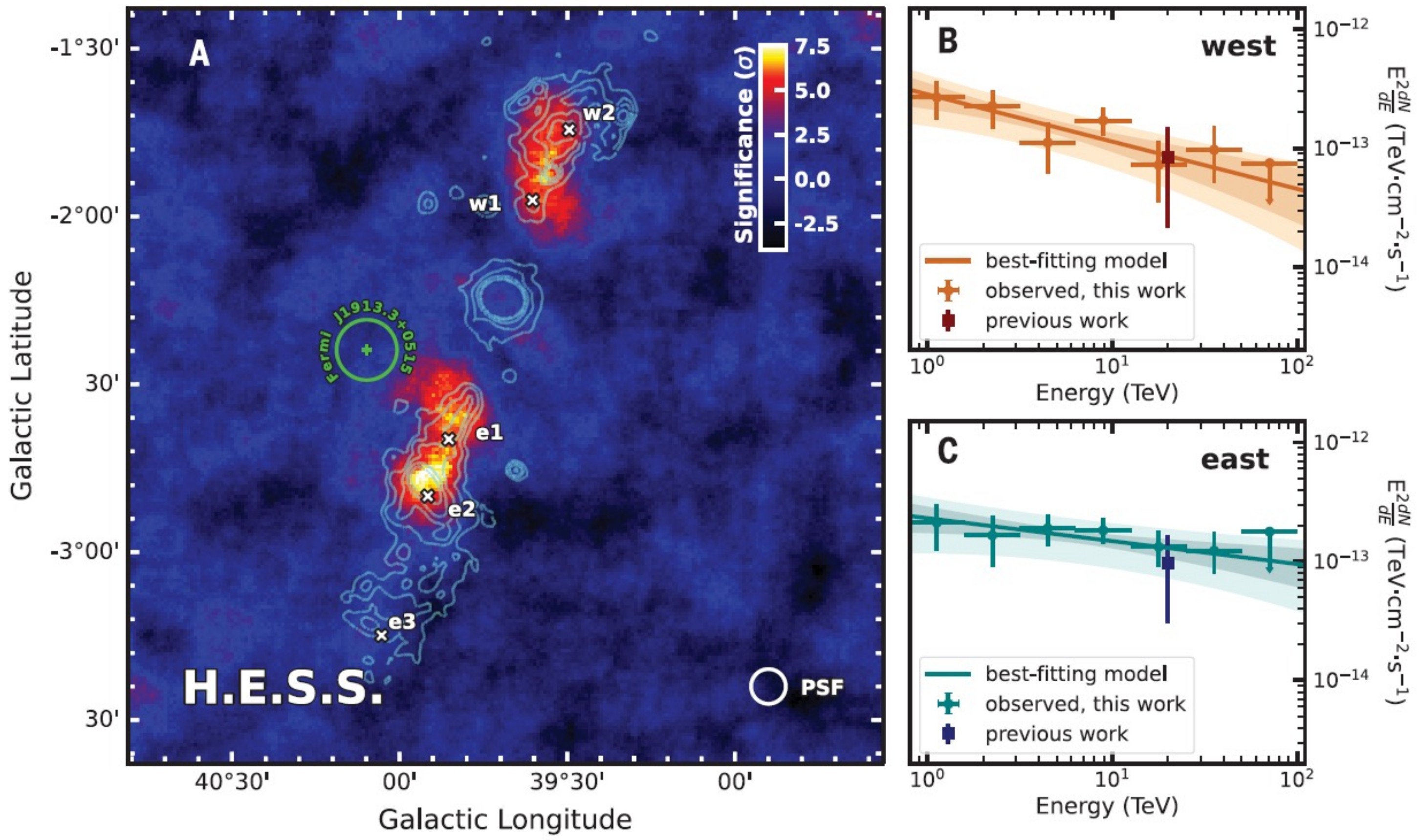
Microquasar	Distance (kpc)	LHAASO Source	Significance (σ)	Photon Index	Energy Range (TeV)	Extension[a]	Flux[b] (Crab Unit)
SS 433 E.		J1913+0455	9.9[c]	2.82 ± 0.16	$25 - 100$	$0.73° \pm 0.07°$	0.10
SS 433 W.	4.6 ± 1.3[31]	J1910+0509	6.3[c]	2.94 ± 0.38	$25 - 100$		0.082
SS 433 central		J1911+0510	8.0	3.96 ± 0.25	$100 - 630$	$0.32° \pm 0.04°$	0.32
V4641 Sgr	6.2 ± 0.7[32]	J1819-2541	10.5	2.84 ± 0.17	$40 - 1000$	$0.33° \pm 0.08°$	2.6
GRS 1915+105	9.4 ± 0.6[33]	J1915+1052	13.9	2.64 ± 0.14	$25 - 1000$	$0.25° \pm 0.05°$	0.11
MAXI J1820+070	2.96 ± 0.33[34]	J1821+0723	6.0	3.25 ± 0.26	$25 - 400$	$< 0.28°$	0.02
Cygnus X-1	2.2 ± 0.2[35]	J1958+3522	4.4	3.98 ± 0.40	$25 - 100$	$< 0.22°$	< 0.01
XTE J1859+226	4.2 ± 0.5[36]	–	2.7	–	–	–	< 0.02
GS 2000+251	2.7 ± 0.7[37]	–	2.3	–	–	–	< 0.04
CI Cam	$4.1^{+0.3}_{-0.2}$[38]	–	1.6	–	–	–	< 0.02
GRO J0422+32	2.49 ± 0.3[39]	–	0.7	–	–	–	< 0.01
V404 Cygni	2.39 ± 0.14[40]	–	1.5	–	–	–	< 0.03
XTE J1118+480	1.7 ± 0.1[41]	–	0.4	–	–	–	< 0.02
V616 Mon	1.06 ± 0.1[42]	–	0.4	–	–	–	< 0.01

From 12 microquasars in the LHAASO FoV, 5 were detected!

LHAASO (2025)

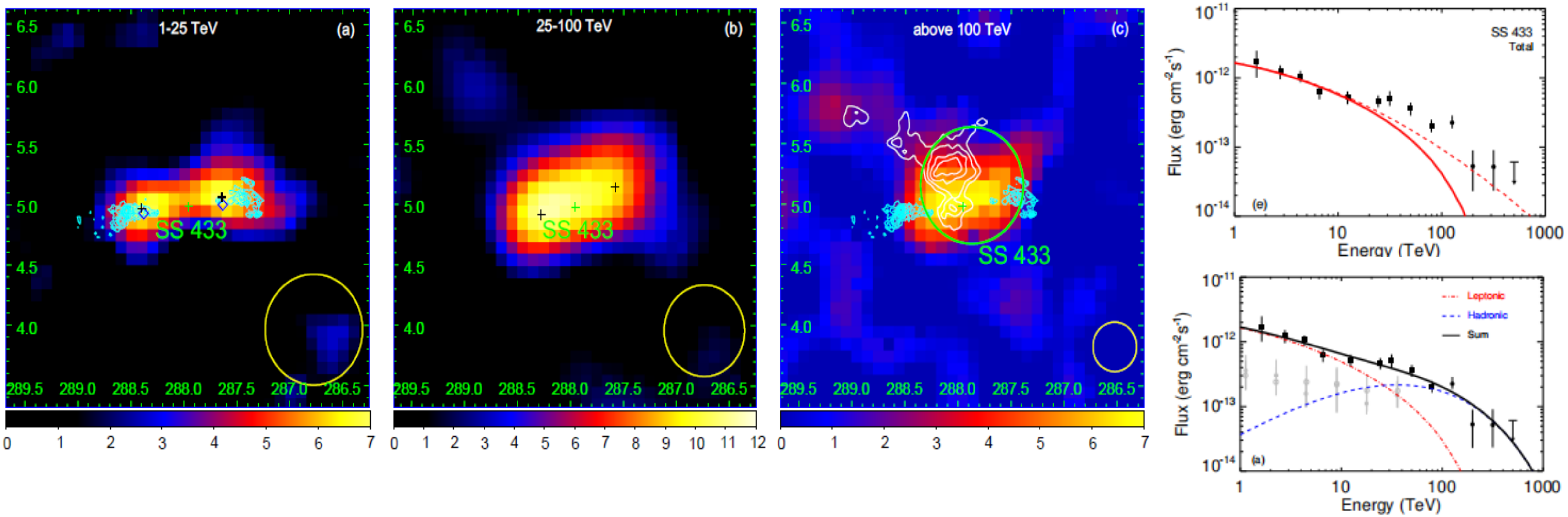
SS 433





- ➢ TeV emission from jet lobes of SS 433 by HAWC (Abeysekara+ 2018)
- ➢ Shift of position of TeV with energy reported by HESS (HESS Collaboration 2024)

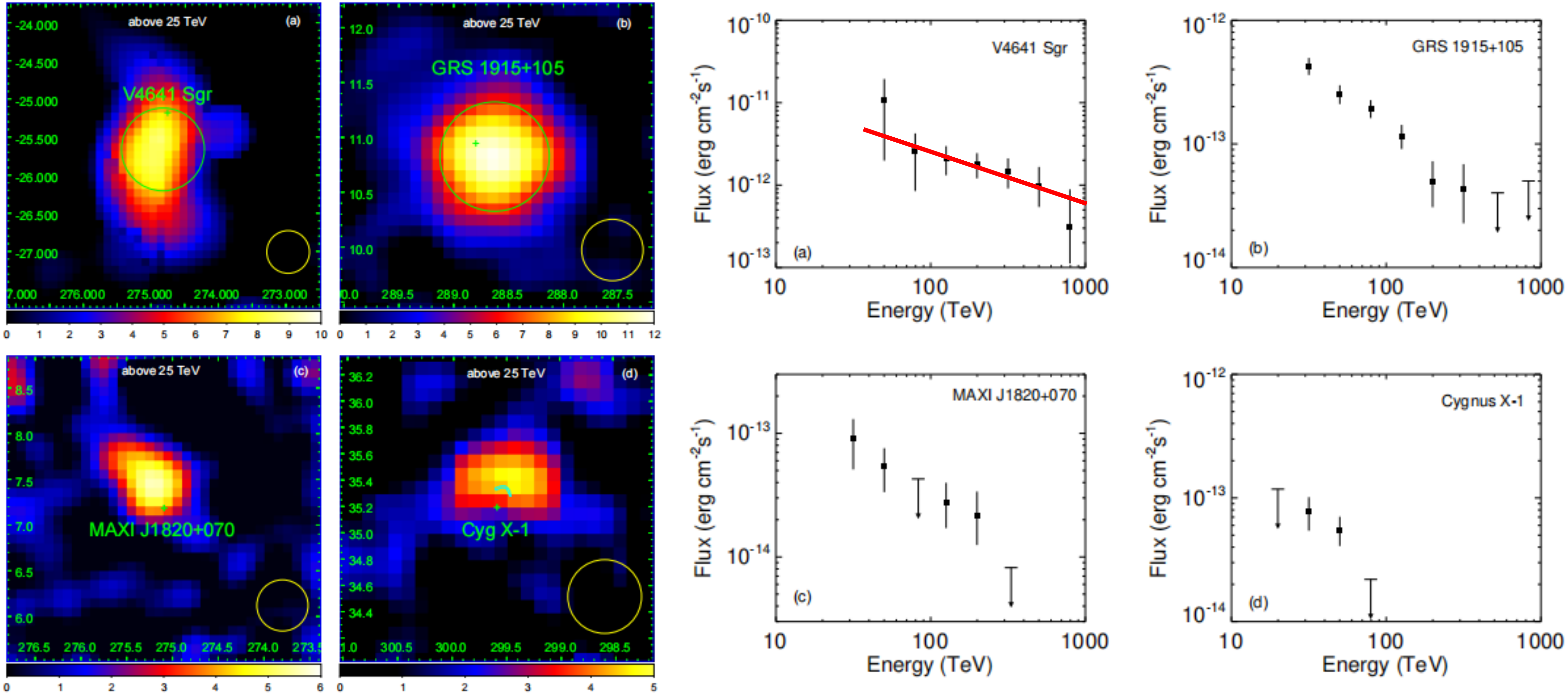
SS 433



- Detection of ultra-high-energy emission with significance with LHAASO
- The UHE emission is partly overlapped with HI cloud at the same distance, may hint for a hadronic origin, although absence of spectral features favors a common origin

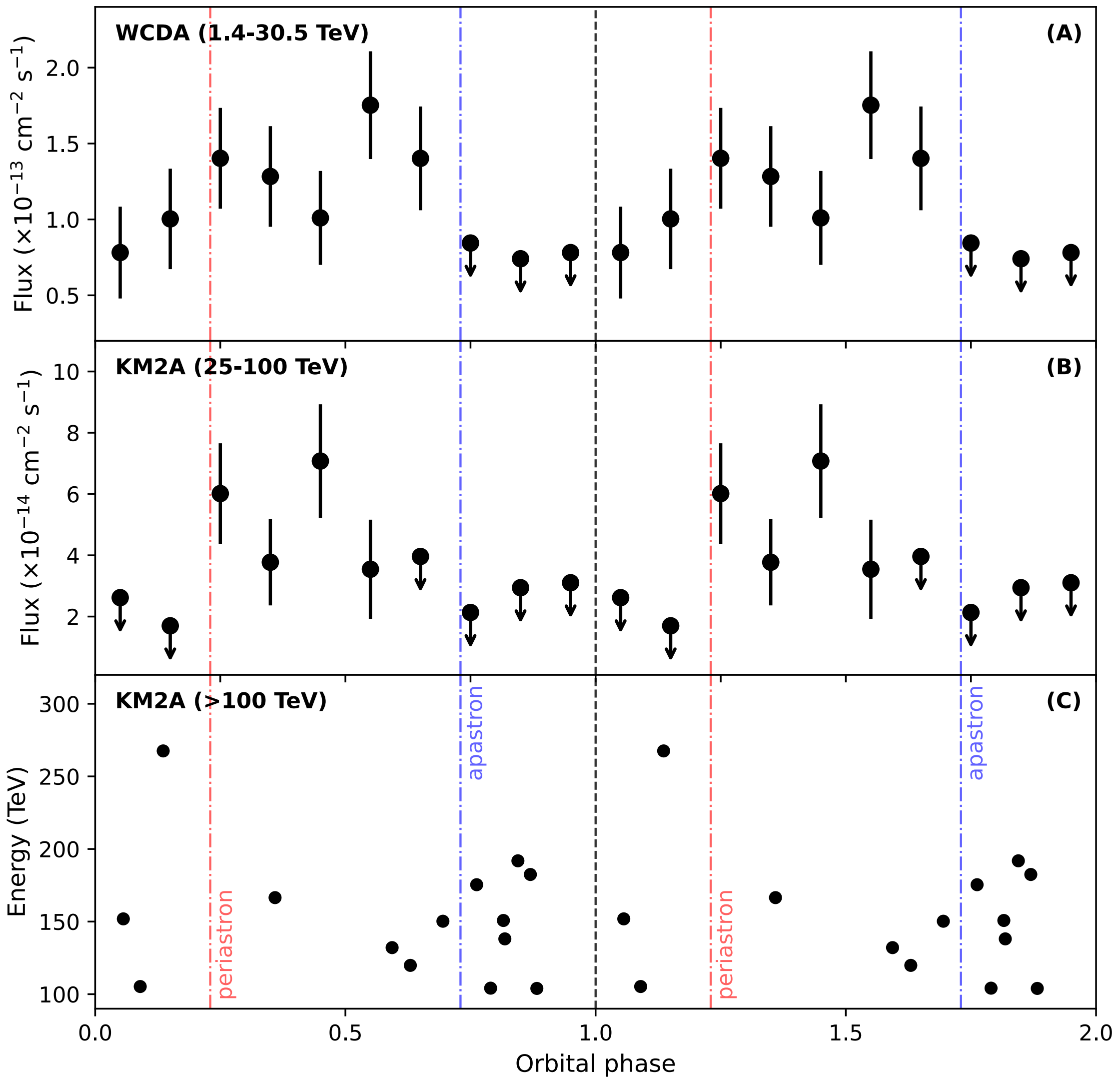
LHAASO (2025)

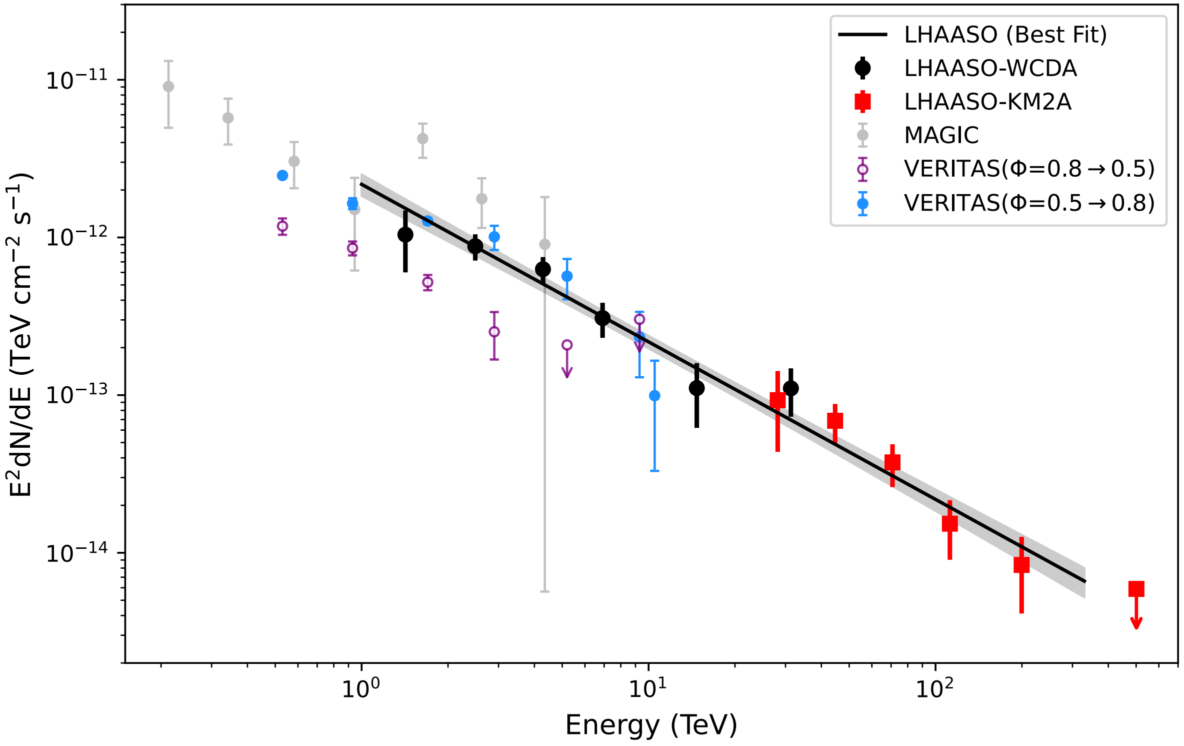
Other microquasars



LHAASO (2025)

LSI + 61º303





- ➢ Be companian, compact object with unknown origin
- ➢ Orbital period: 26.4960 days

- ➢ About 6σ detection above 25 TeV
- ➢ Maximum photon energy ~200 TeV
- ➢ Hint of orbital modulation

Short summary on binaries

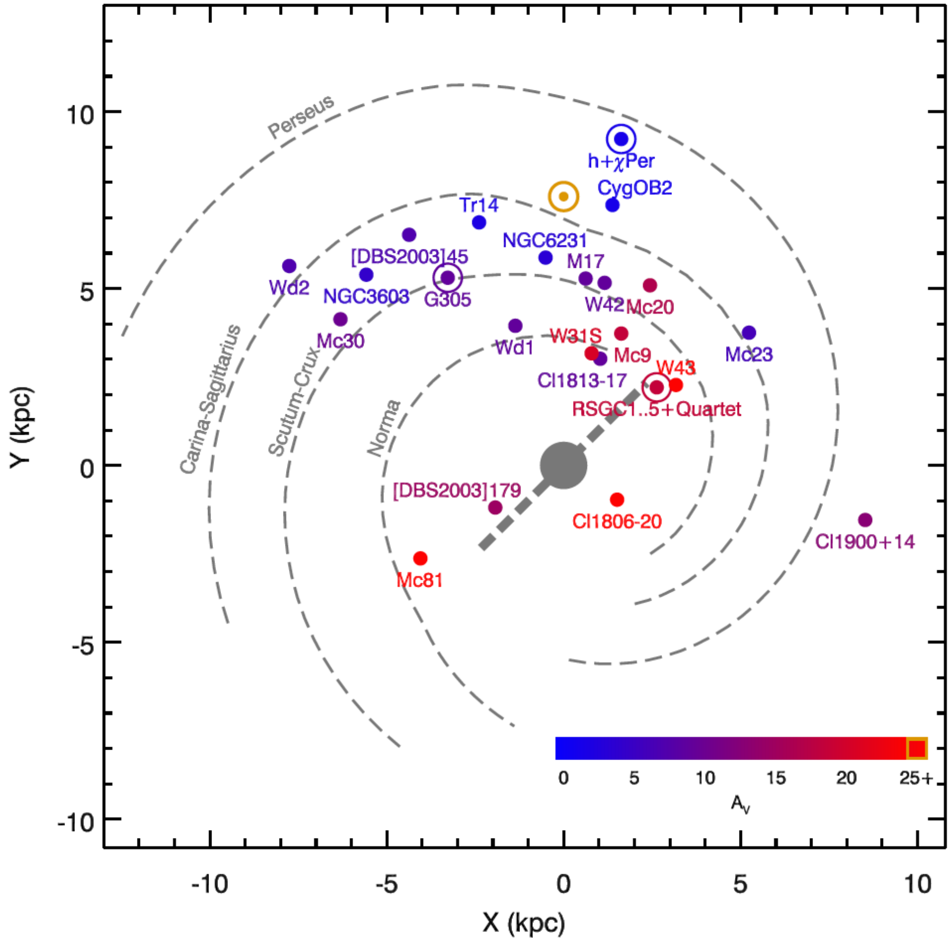
- LHAASO detects UHE emission from 5 microquasars (out of 12 in the FoV), some with maximum photon energy reaching ~PeV, indicating that microquasars are a class of powerful accelerators of cosmic rays beyond PeV
- UHE emission from gamma-ray binary LSI + 61^{o}303 has also been detected

How LHAASO can Study PeVatrons?

- **Progress in cosmic ray measurements**
  - Spectra
  - Composition
  - Anisotropies

- **Progress in gamma-ray observations**
  - Supernova remnants
  - Pulsar wind nebulae and pulsar halos
  - Gamma-ray binaries
  - Young massive star clusters

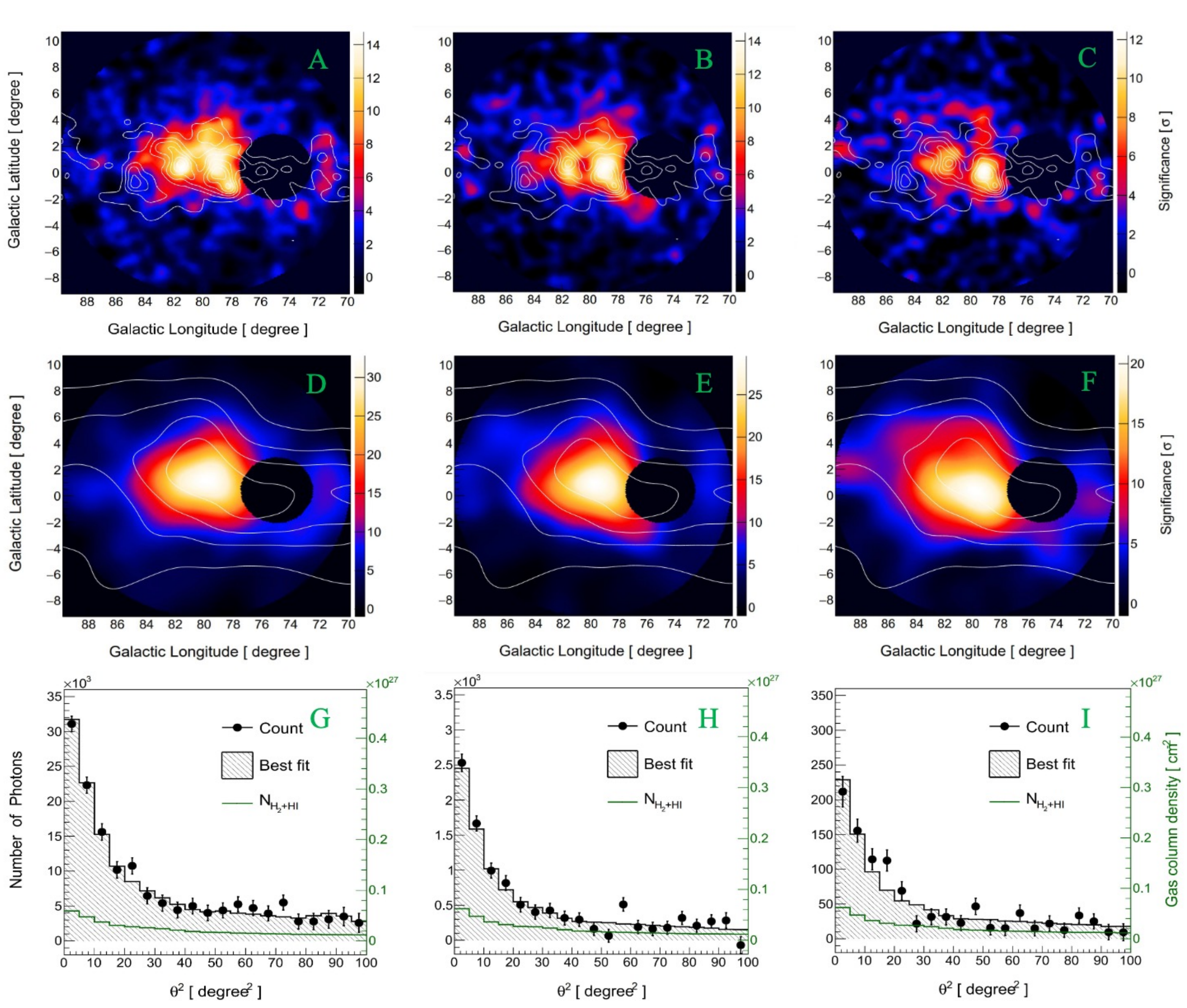
Young massive star clusters

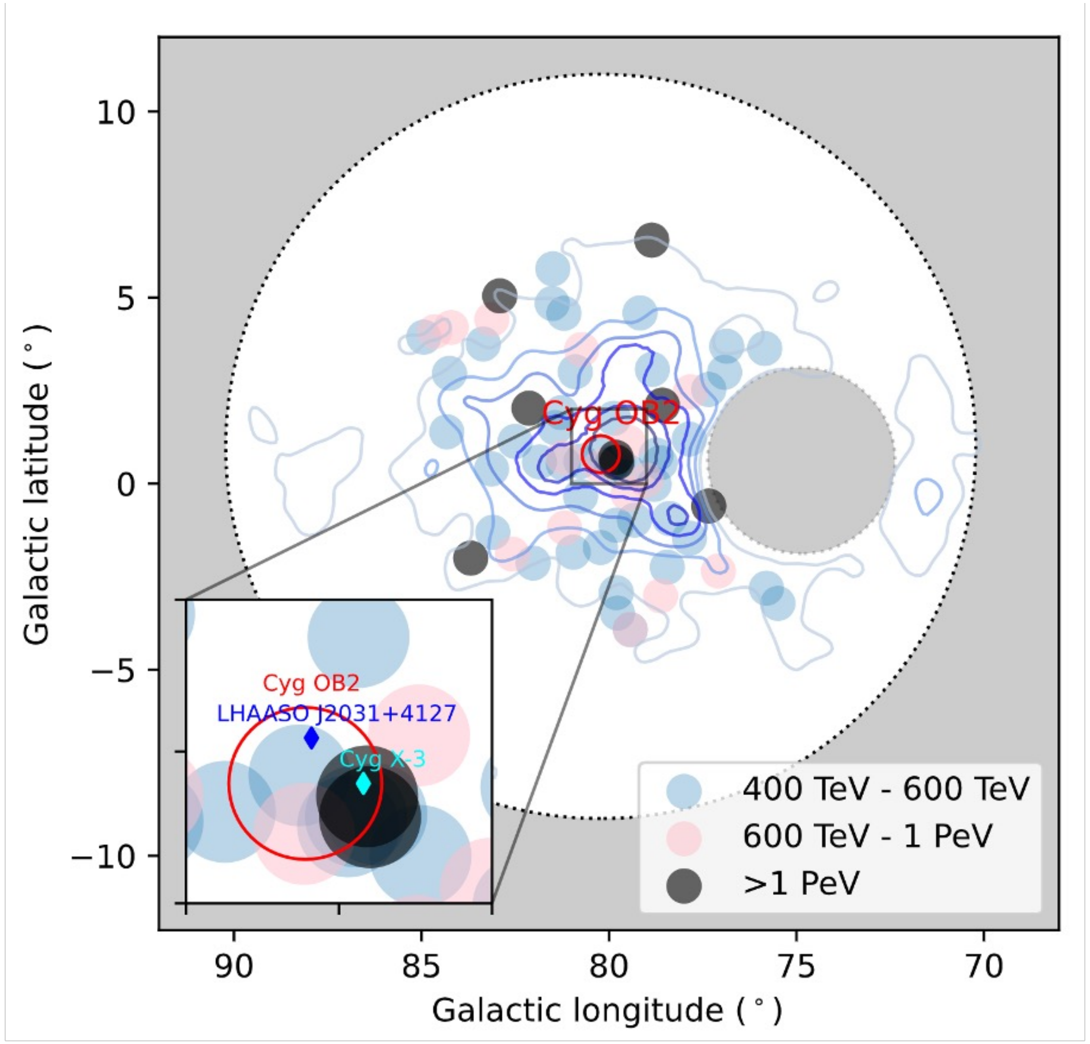


Davies et al. 2011

- About 20 YMCs in our Galaxy
- Dozens of OB and WR stars
- The wind power of a single young star can be as high as 10^{37} erg/s
- Particle acceleration by stellar wind induced shocks (continuous, high-speed wind)
- Some have been found to emit UHE photons

Cygnus bubble: super PeVatron

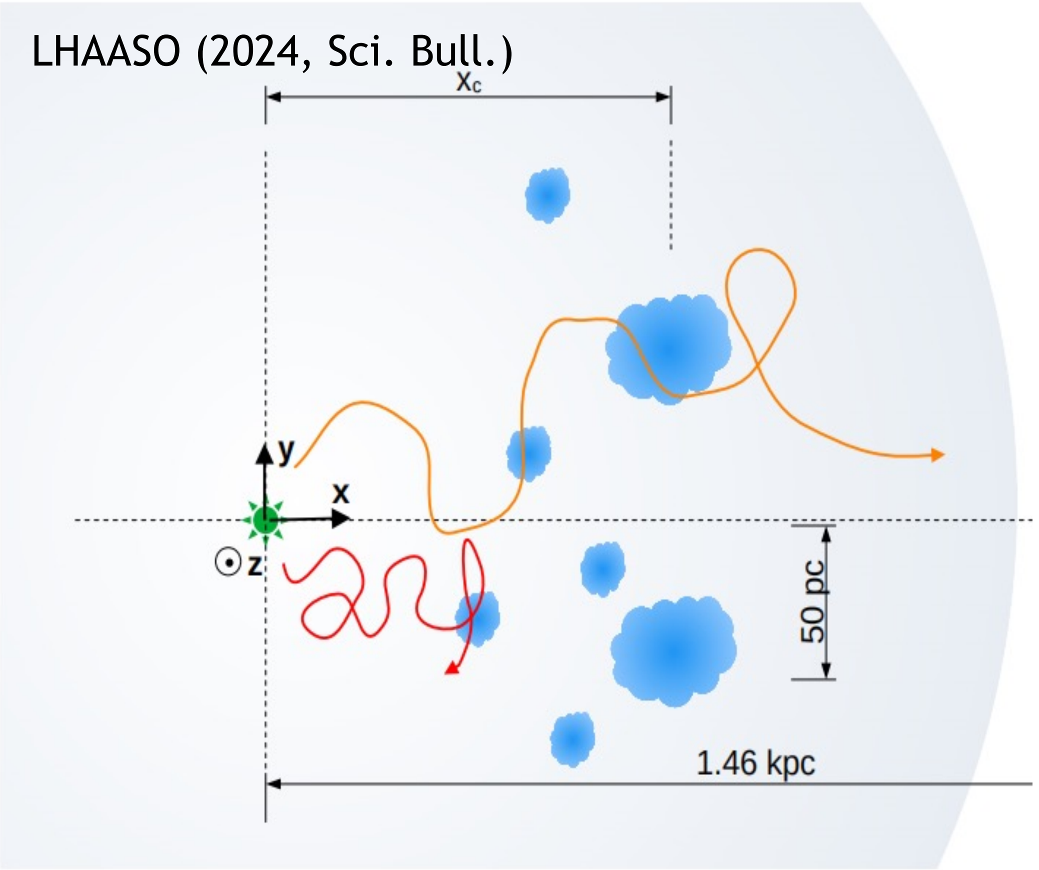


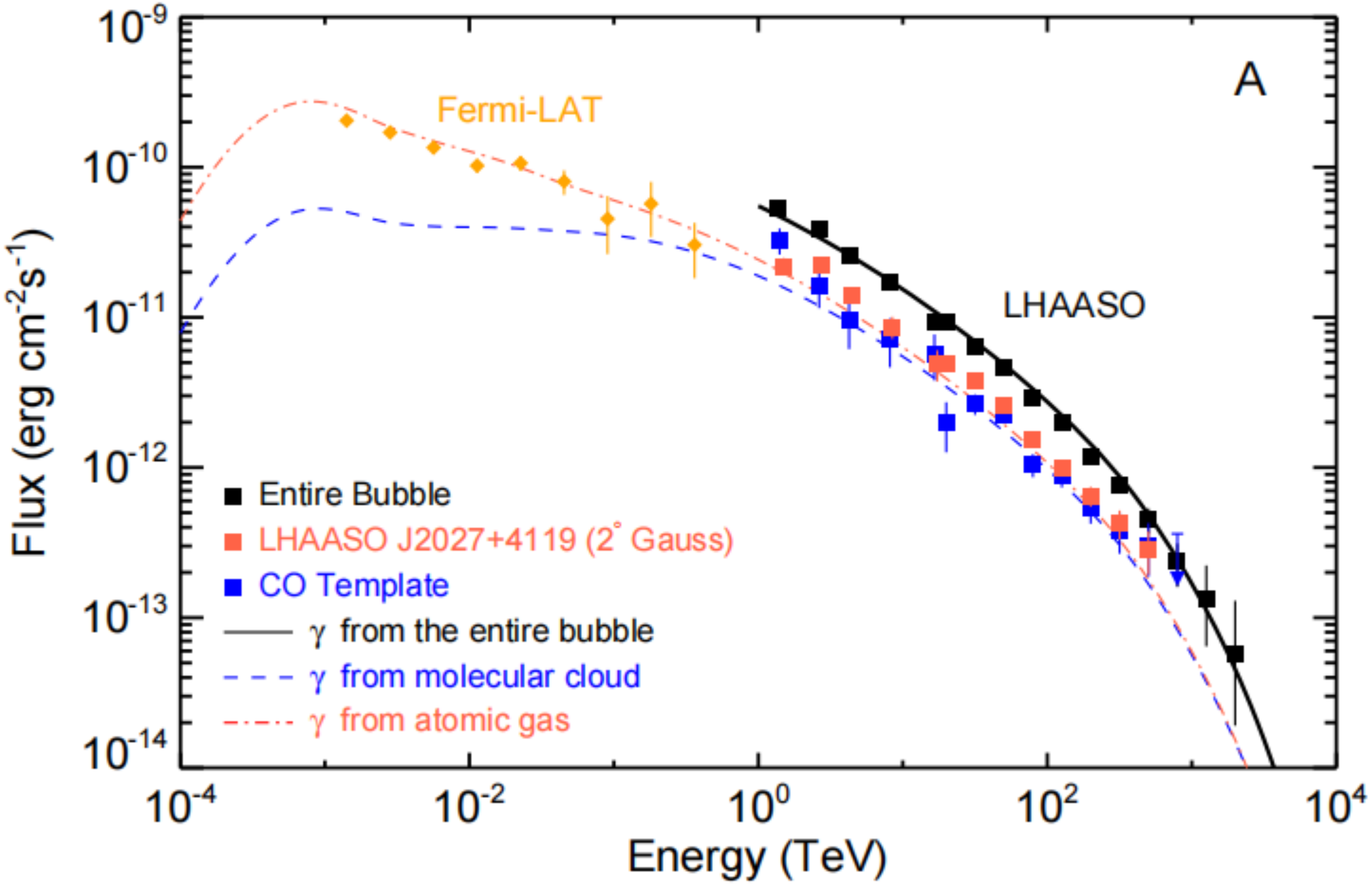


8 PeV events, highest energy of 2.5 PeV

LHAASO (2024, Sci. Bull.)

Cygnus bubble: super PeVatron





Morphological and spectral decomposition: extended bubble w HI gas + hot spots w MCs

W43: Galactic mini-starburst

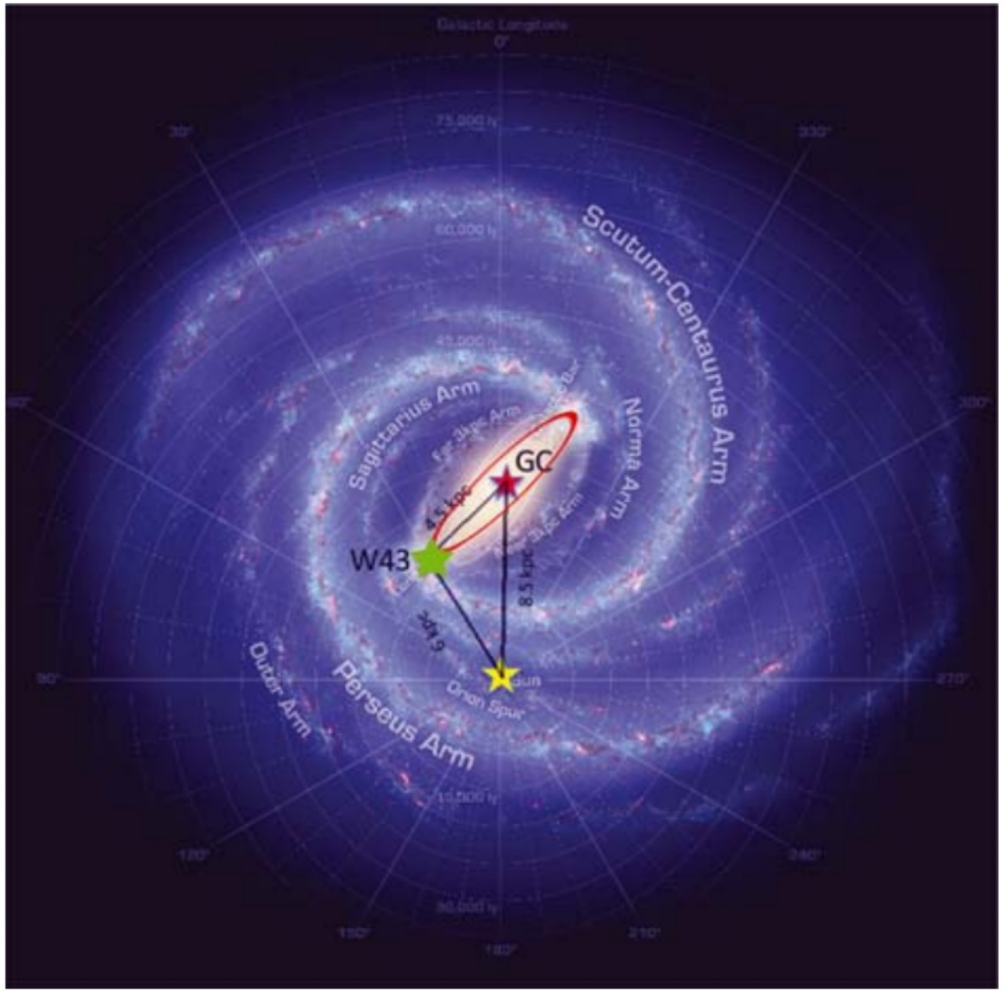
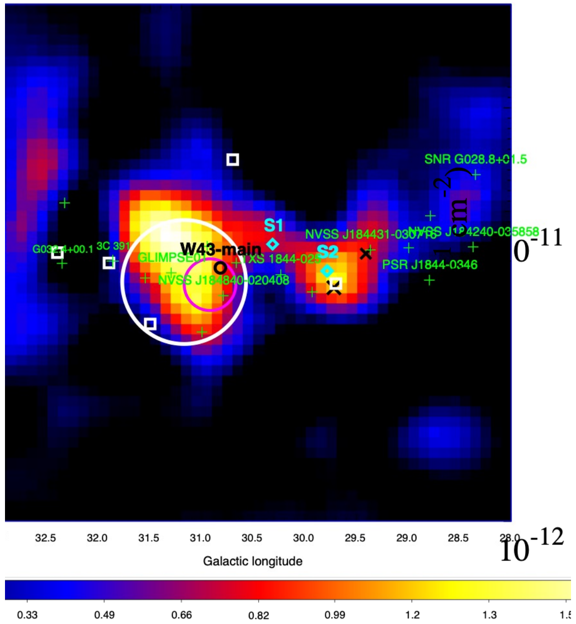
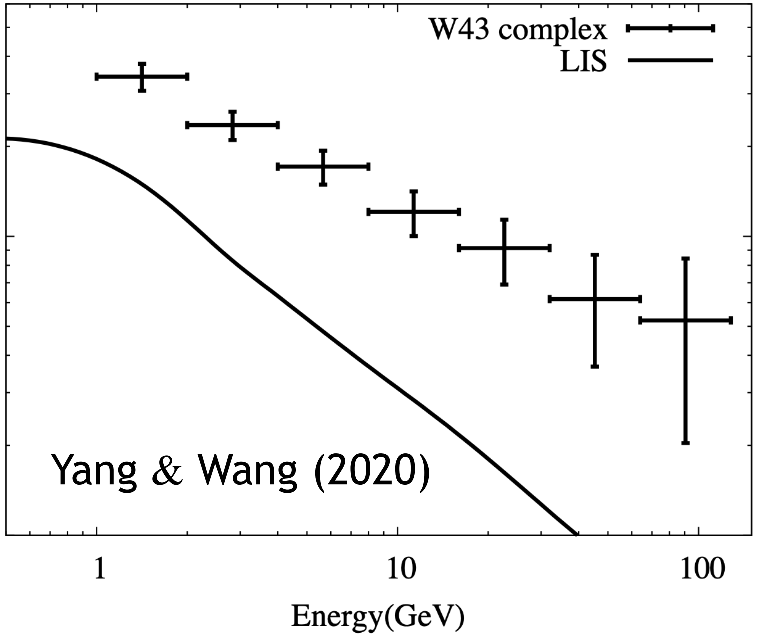


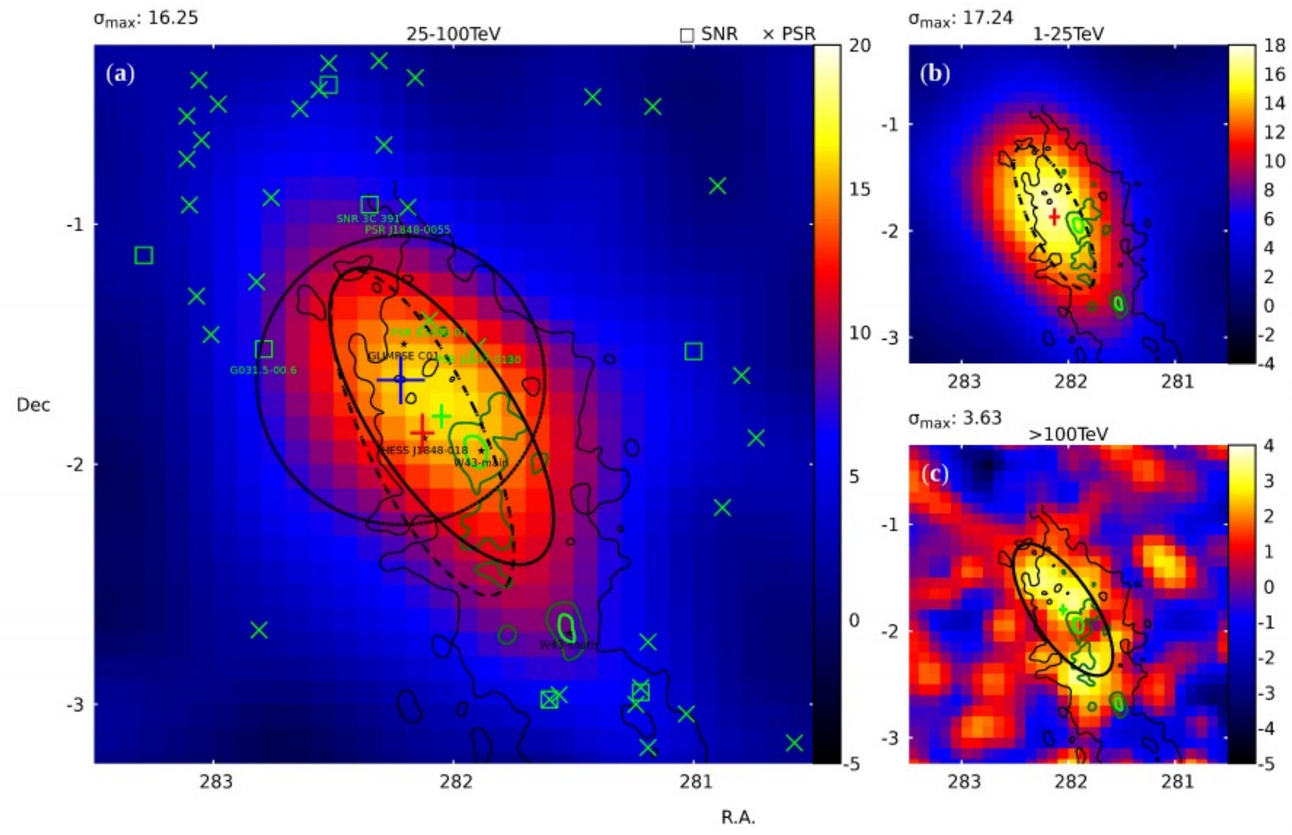
Fig. 9. Artist view of the Galaxy seen face-on with the "long bar" outlined by a red ellipse (Churchwell et al. 2009). W43 is located at the expected transition zone between the bar-dominated region ($R_{GC} < 5$ kpc) and the normal Galactic disk.

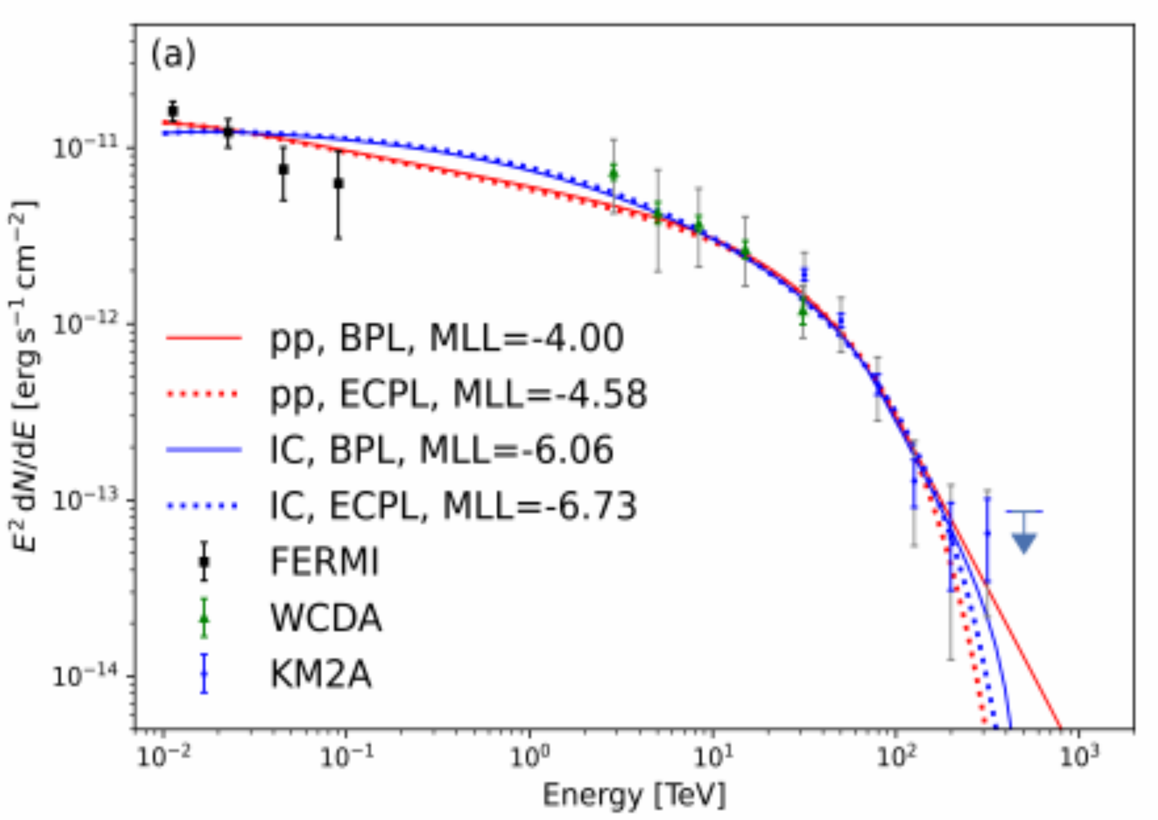




- ➢ Contribute ~10% of the Galactic star formation rate
- ➢ Huge HII region excited by central WR/OB cluster
- ➢ GeV gamma-ray detection

W43: Galactic mini-starburst





- UHE gamma-ray emission reveal good correlation with dense gas
- Spectrum up to 400 TeV, with cutoff at ~30 TeV
- W43 can likely accelerate hadronic CRs to PeV energies

LHAASO (2025, SCPMA)

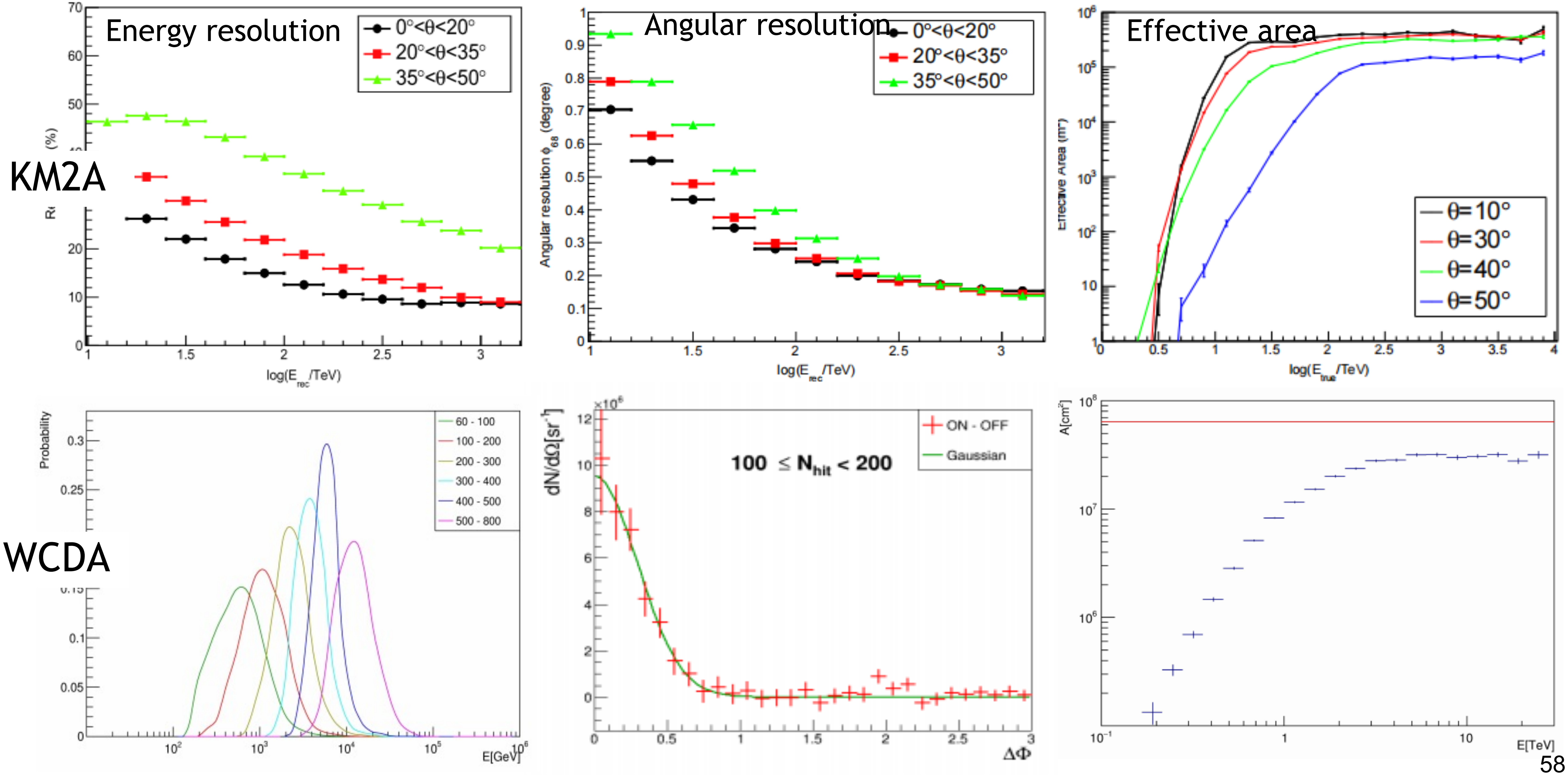
Outline

- **Introduction to PeVatrons**
- **LHAASO experiment**
- **Progress in gamma-ray observations**
  - Supernova remnants
  - Pulsar wind nebulae and pulsar halos
  - Gamma-ray binaries
  - Young massive star clusters
- **Progress in cosmic ray measurements**
  - Spectra
  - Composition
  - Anisotropies
- **Summary**

Summary of the talk

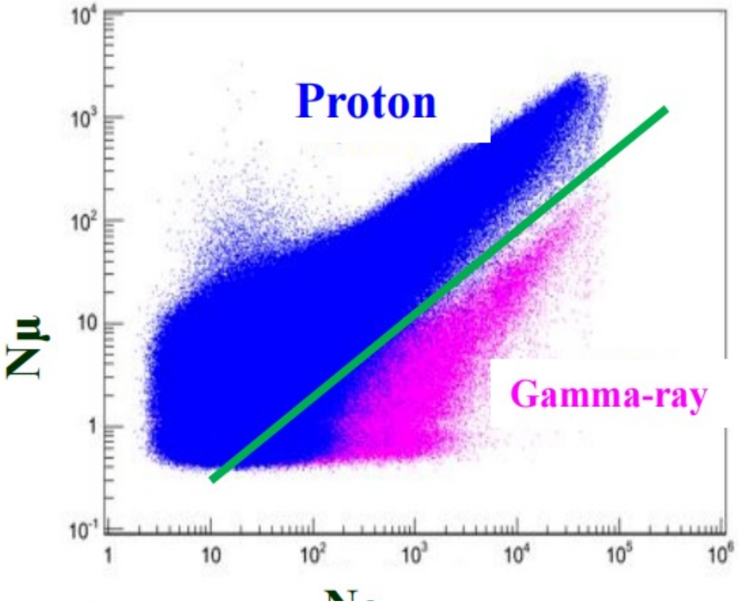
- LHAASO is a km^2 scale, hybrid technique CR and gamma observatory started in operation since July 2021
- LHAASO opens sucessfully the PeV window of the gamma-ray sky, and detects dozens of PeVatrons which may closely related with the origin of CRs
- Precise measurements of the energy spectra of all-particles, protons, and helium give new insights in understanding the knee problem and the origin of CRs
- Anisotropies at different spatial scales, for different mass groups, as well as time variations are very helpful in understanding the propagation of CRs

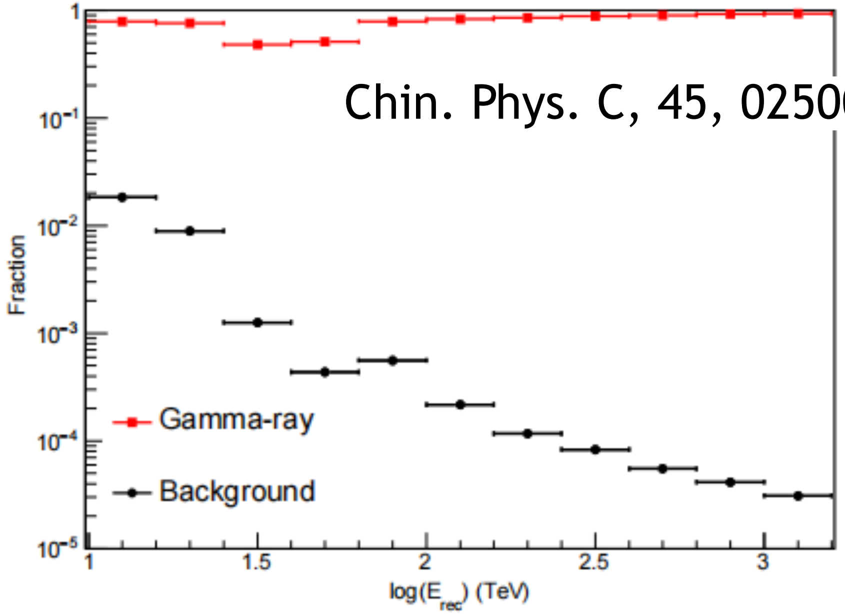
Gamma-ray performance



Gamma-CR discrimination

KM2A





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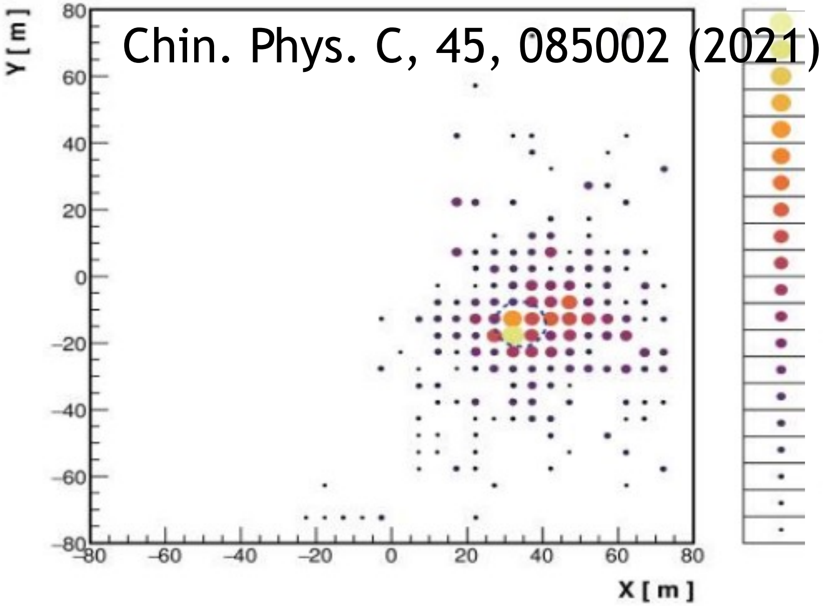
WCDA



Chin. Phys. C, 45, 085002 (2021)