PeVatrons in LHAASO View

by Zhen Cao 曹臻, IHEP, CRRC, China

CDHY PeVatron Workshop, Columbia U., Oct., 2025

高海拔宇宙线观测站

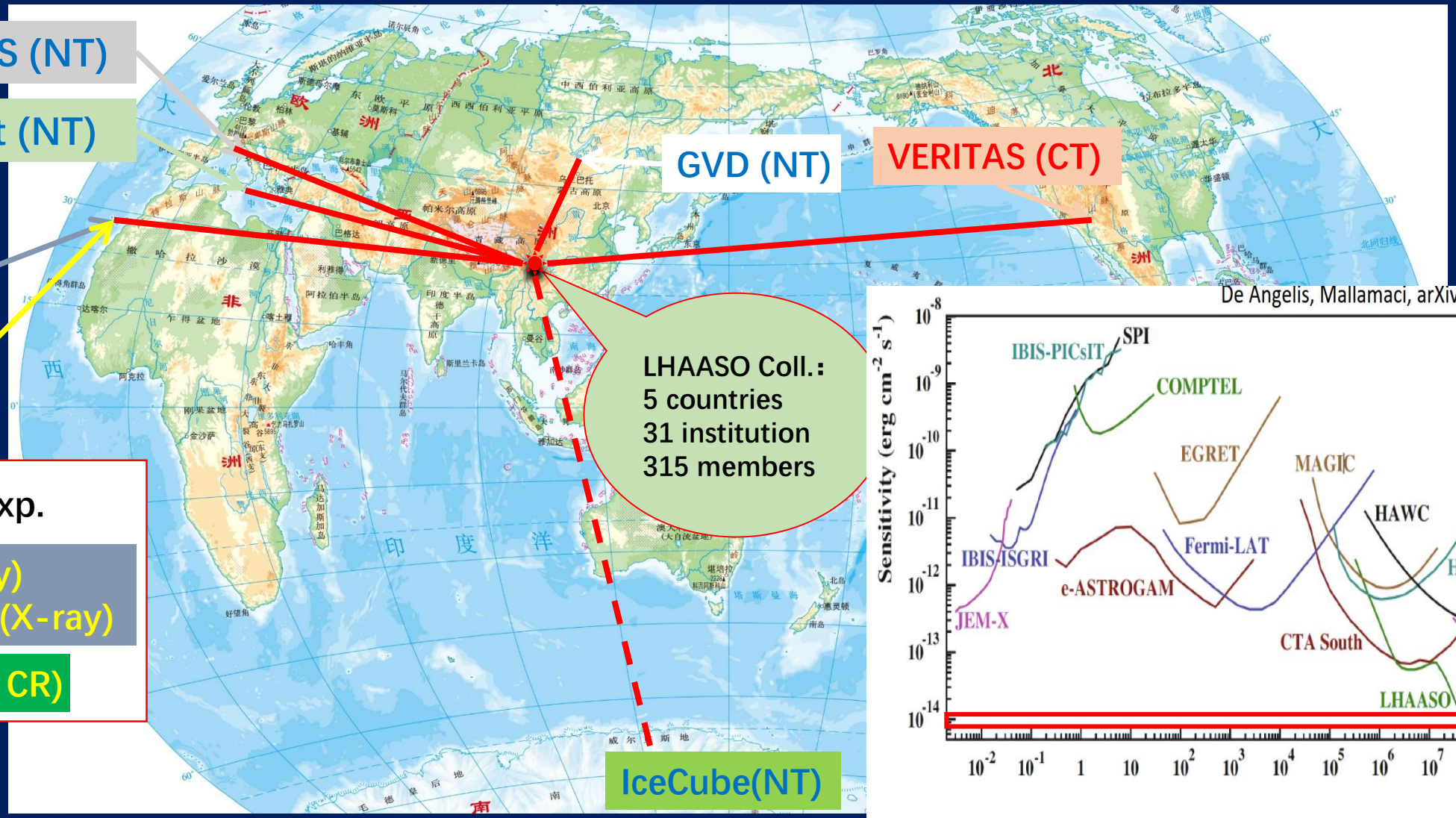
Large High Altitude Air Shower Observatory

拉索鸟瞰，@2021-08

LHAASO，拉索

- Location：29º21’ 27.6” N , 100º08’19.6” E
- Altitude: 4410 m
- 2021-07 建成

Multi-Messenger Collaboration Network



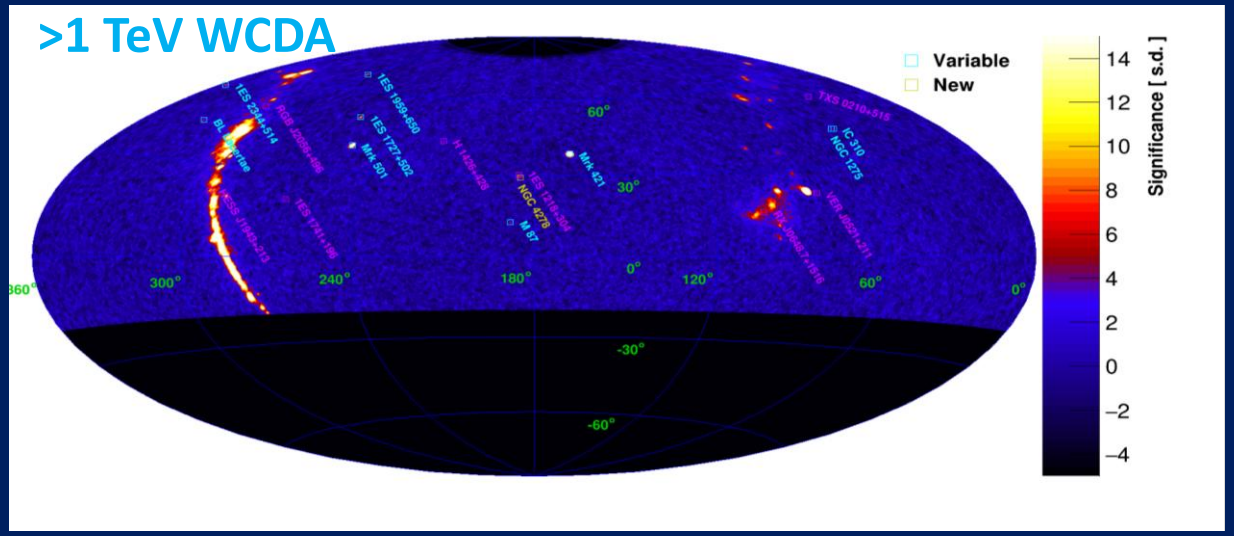
Space borne Exp.

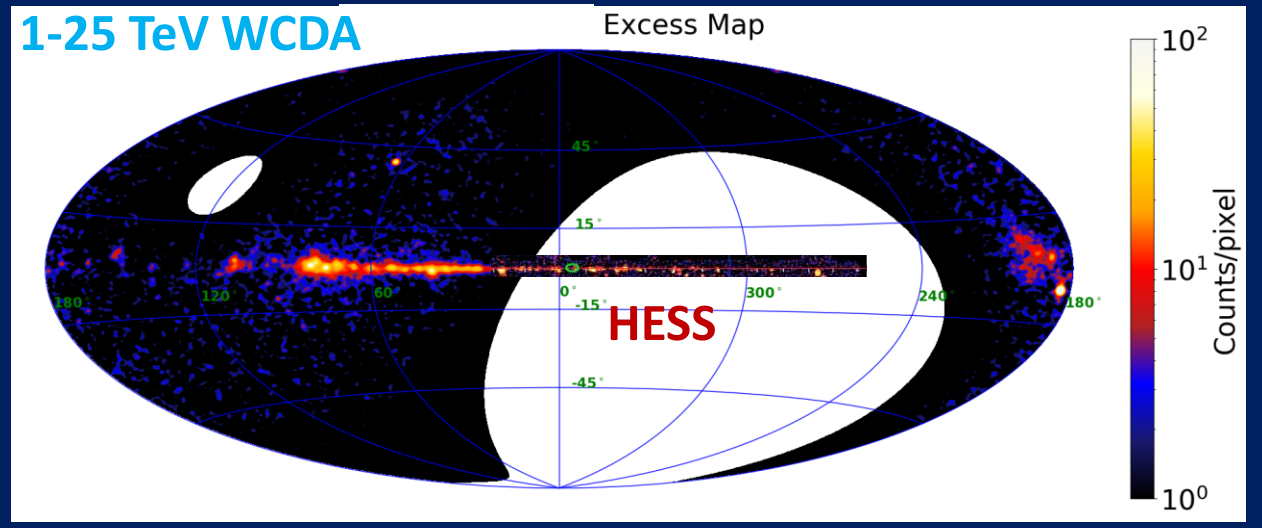
eROSITA(X-ray)
Einstein Probe(X-ray)

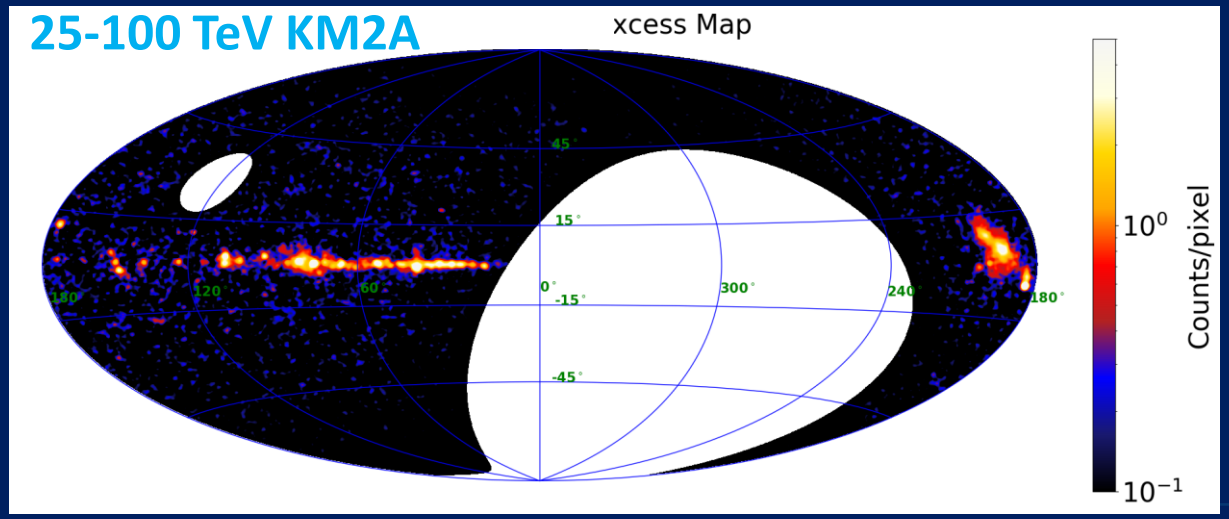
DAMPE(γ-ray, CR)

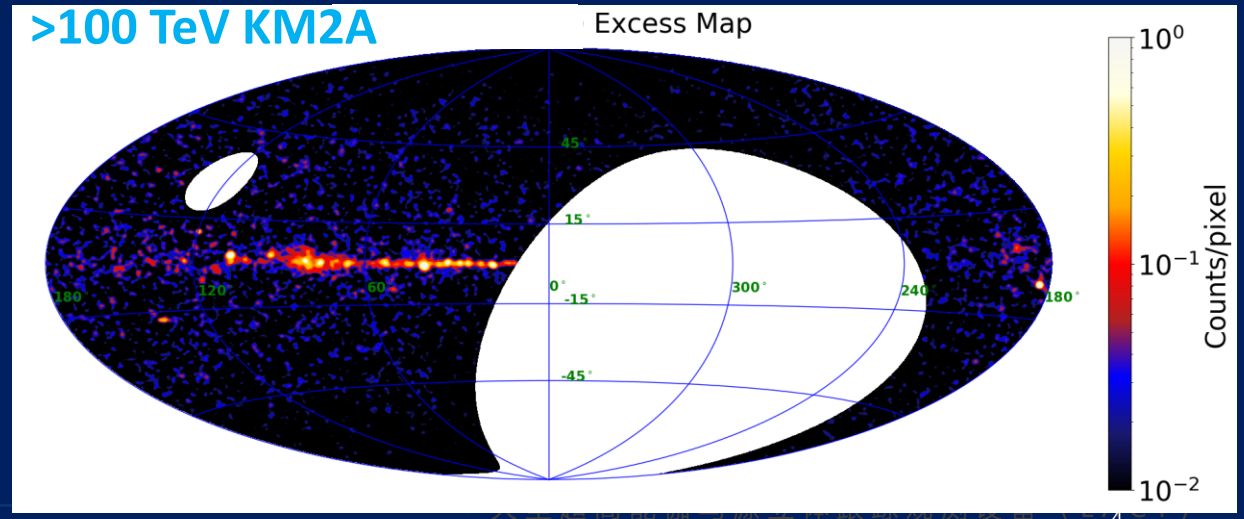
UHE γ-ray Astronomy: **survey for sources**

- **Survey discovered 40+ new sources, ~70 PeVatrons and diffuse γ-ray emission**

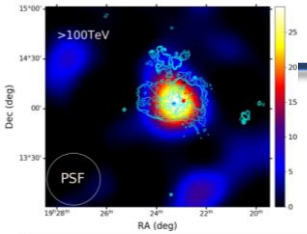






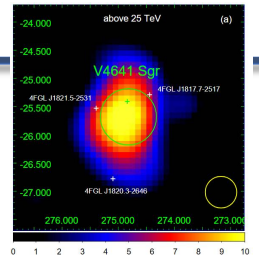


Some Examples of Candidates

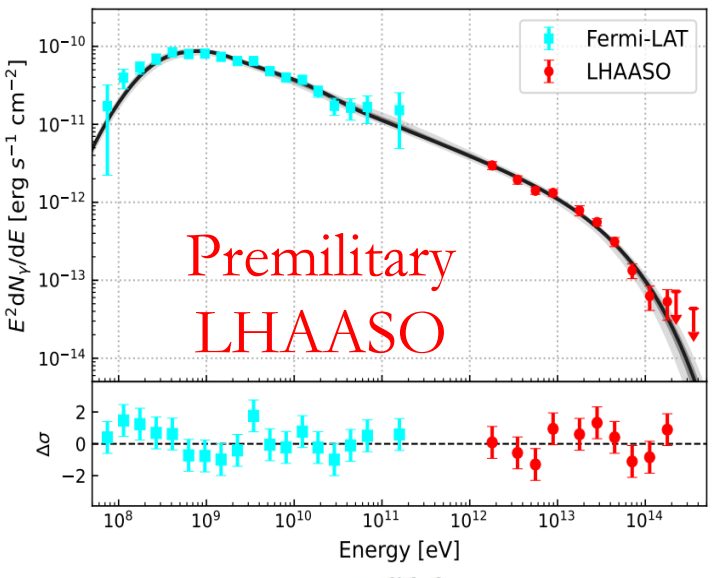


W51

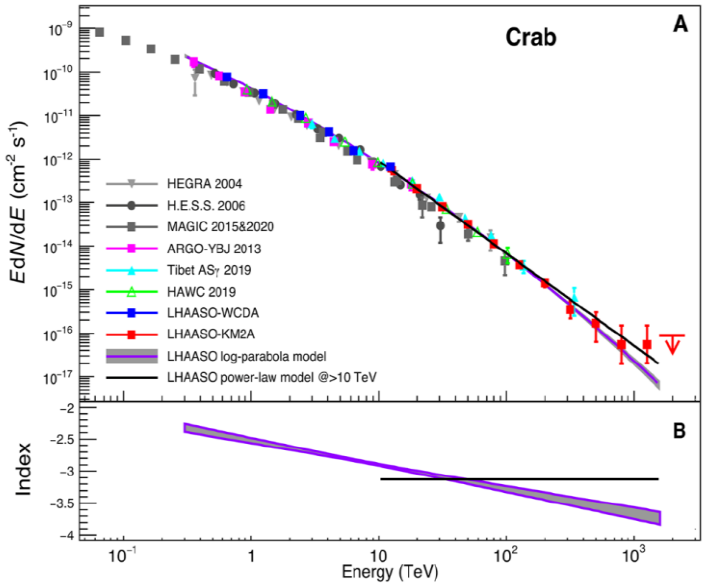
Crab



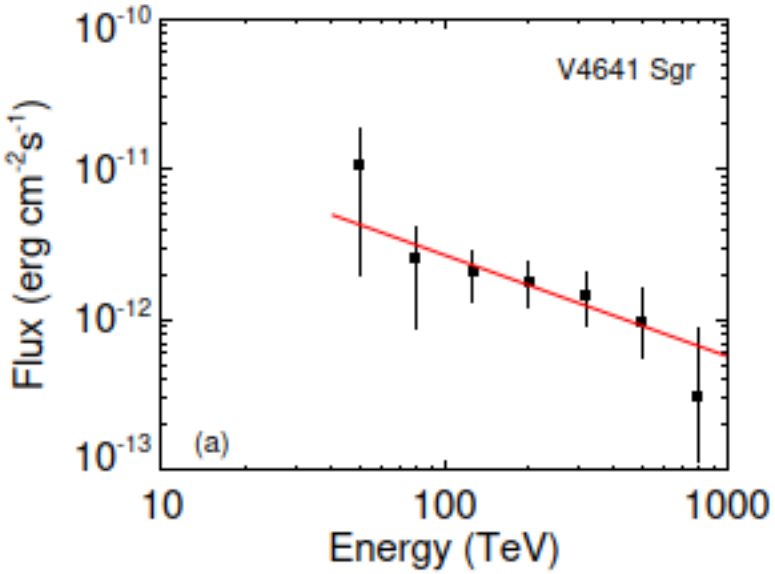
Sgr V4641



SNR



PWN



μ-quasar

...

Many types of γ-ray sources have the potential to accelerate particles to 1 PeV and above

A&A 671, A12 (2023)
Science 10.1126/science.abg5137 (2021).
The Astrophysical Journal, 913:115 (11pp), 2021 June 1

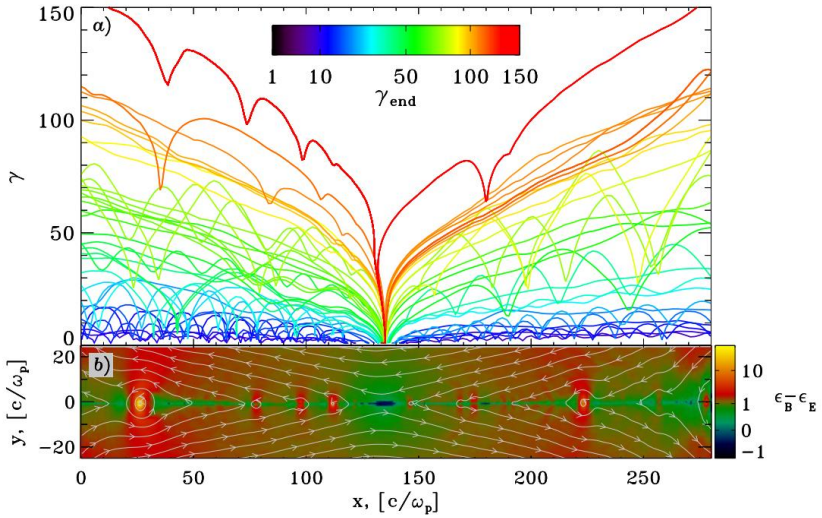
Content

- Introduction
- PeV Gamma Ray Sources
  - The Crab Nebula, Cyg X-3, Cygnus Bubble, J1849-0001, Sgr V4641, J2229+6114, ……
  - Summary on the Super-PeVatrons
- PeV Particle Generators
  - μ-quasars as CR Accelerators
  - PWNe
  - Staller Clusters and SNRs
  - Unidentified sources
- CR proton spectrum up to the ‘knee’: evidence of PeVatrons in our Galaxy
  - Pure Proton Sample and they spectrum

Young PWNe: Extreme Particle Accelerators

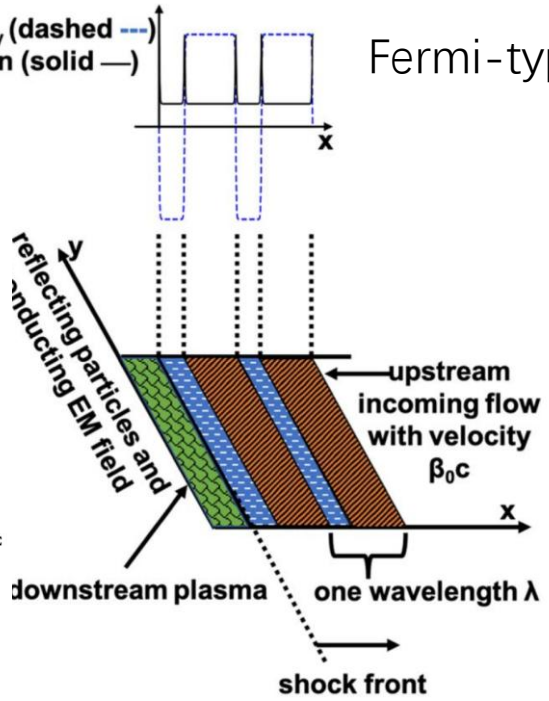
Sironi & Spitkovsky 2014, ApJ

X-points electric field



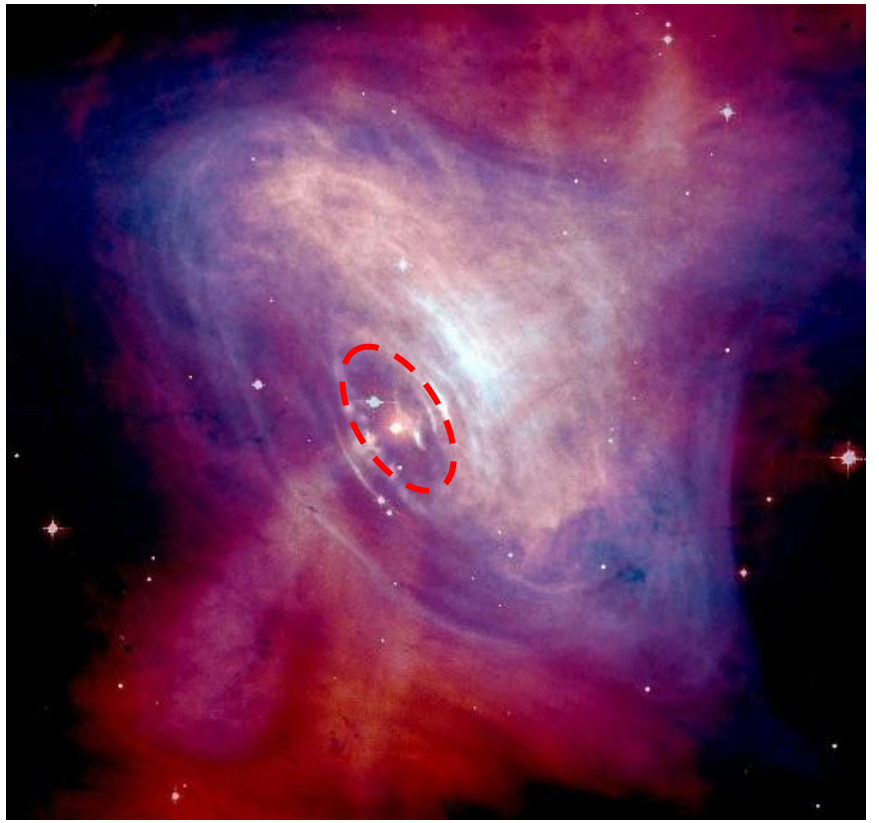
Lu et al. 2021, ApJ

Fermi-type



rotational energy → electromagnetic energy

nonthemral energy ← kinetic energy



Composite X-ray/Optical Image
Credit: NASA/ESA

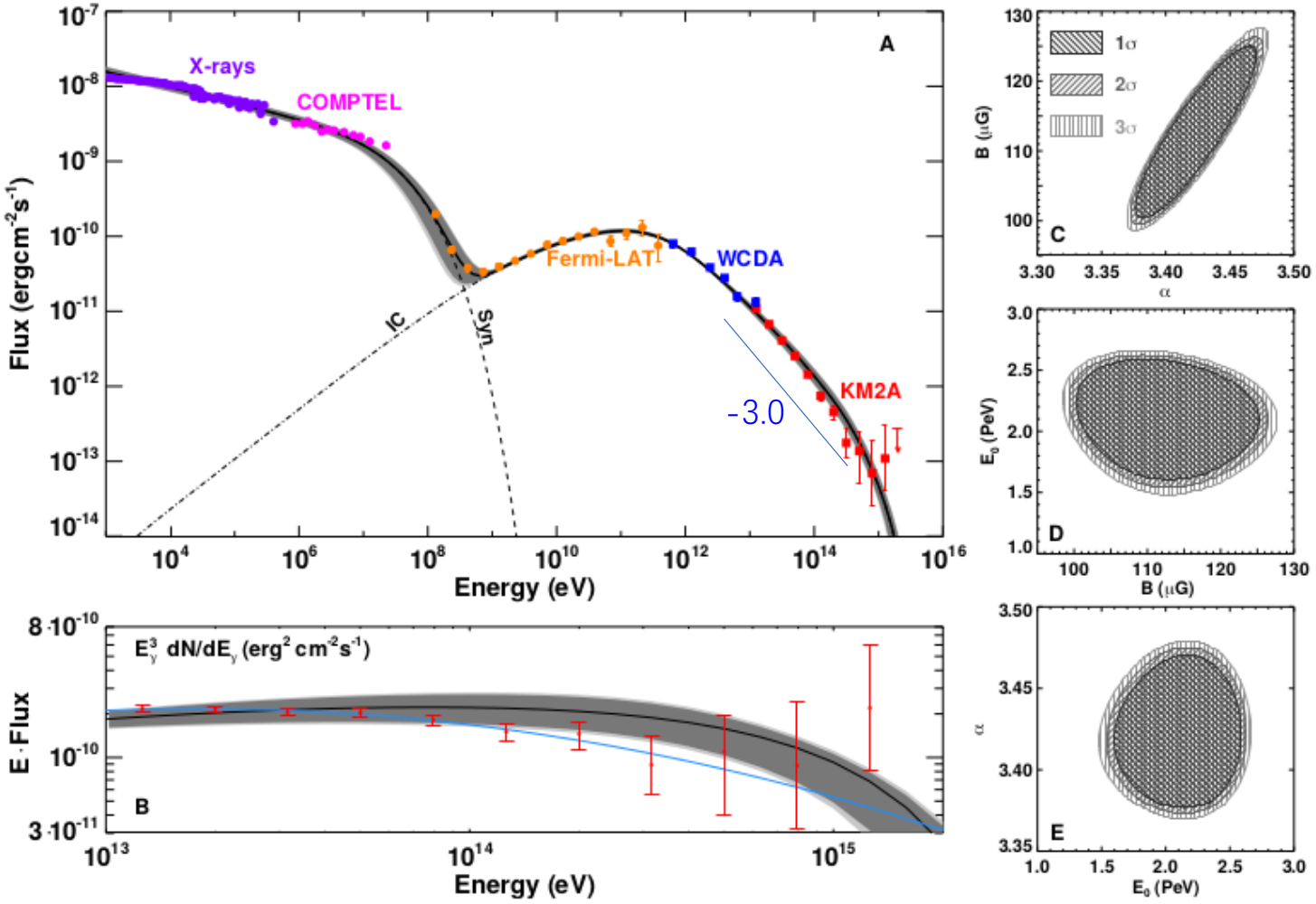
Limit from Hillas Condition

$$E_{\max} \approx 2\ \eta_e\ \eta_B^{1/2}\ \dot{E}_{36}^{1/2}\ \mathrm{PeV}$$

Limit from Synchrotron Cooling

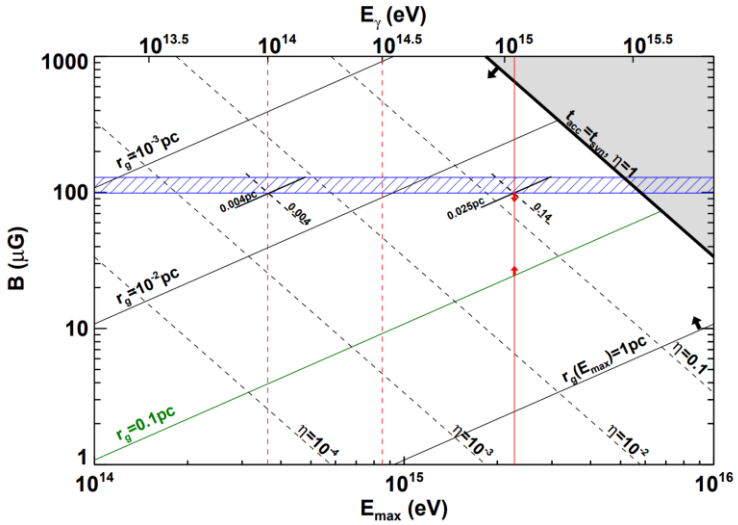
$$E_{e,\max} \approx 20\ \eta_e^{1/2} B_{-5}^{-1/2}\ \mathrm{PeV}$$

Implication from Crab Nebula



E_{syn}= 7MeV $(E_e/1PeV)^2$ (B/100μG)

E_{IC}= 0.37$(E_e/1\ PeV)^{1.3}$



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

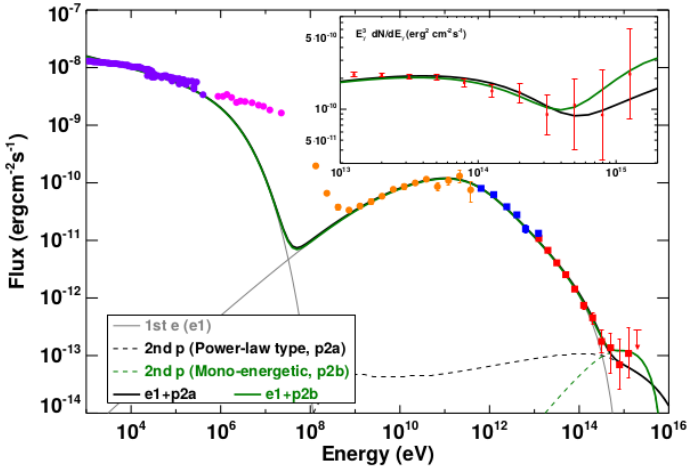
$$(\eta = \frac{\mathcal{E}}{B} < 1)$$

LHAASO Coll. 2021, Science

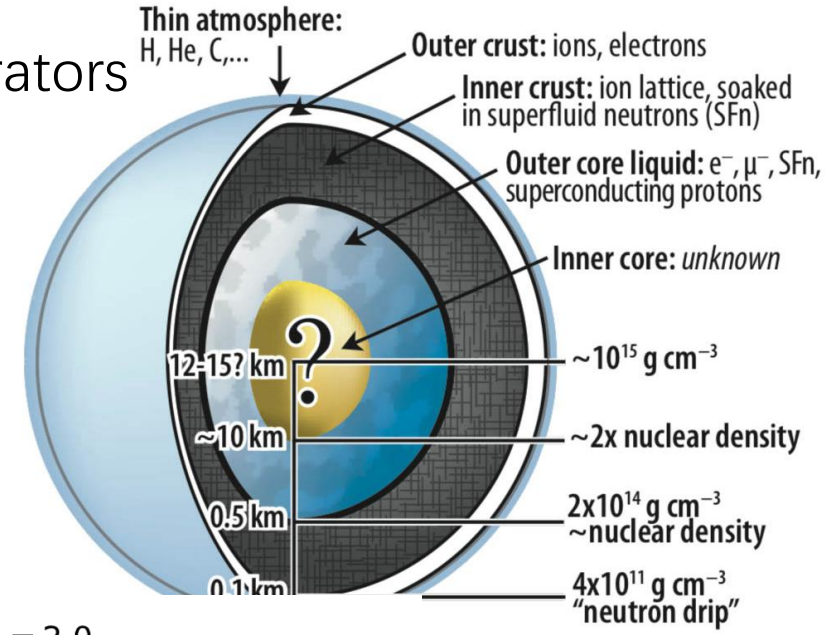
Extreme acceleration efficiency

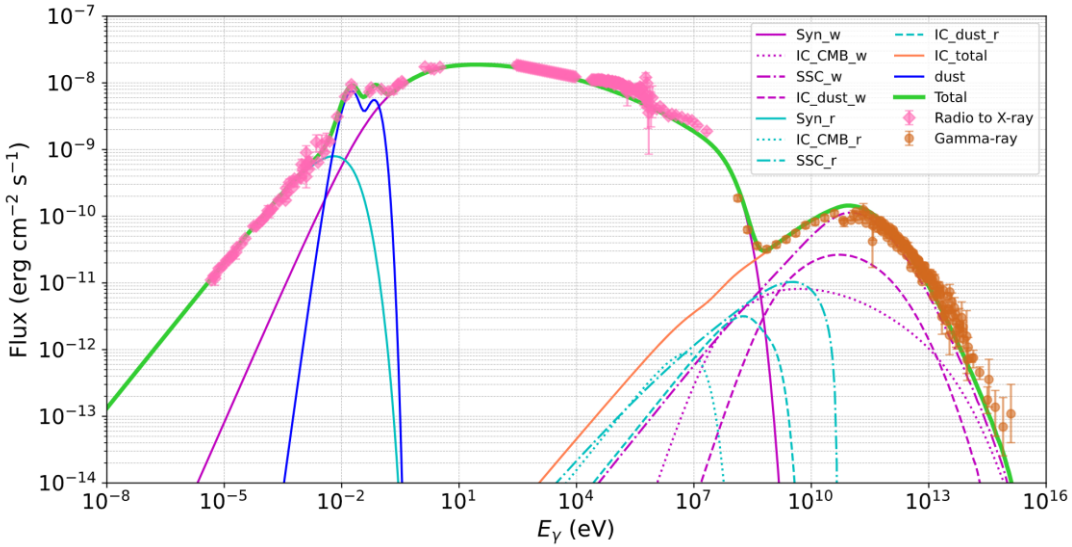
Are PWNe proton accelerators (and PeV CR sources)?

No doubt of strong capacity of young PWNe as particle accelerators

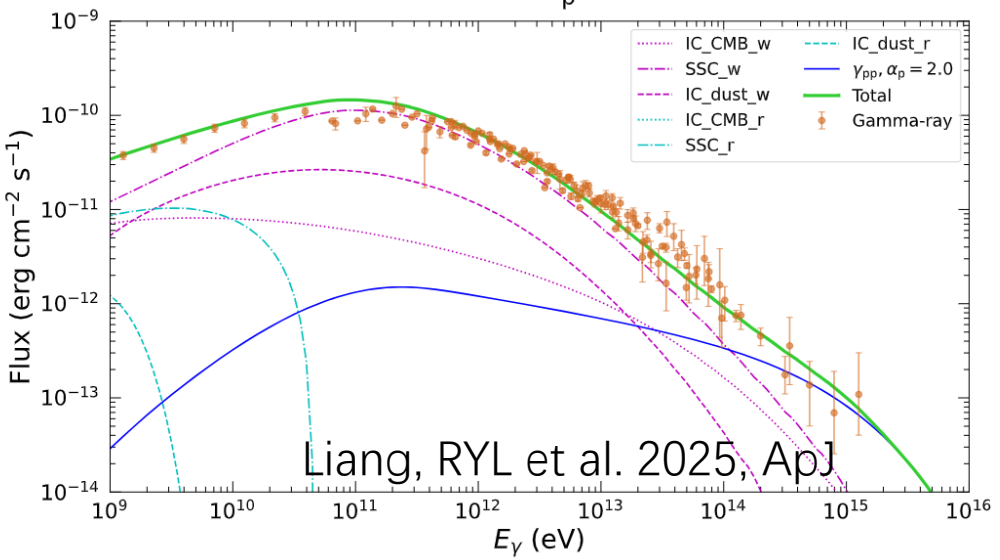


$$F(E_p) = \frac{c}{4\pi}\frac{\eta_p L_{\rm s,tot} t_{\rm esc}}{2\pi R_{\rm Gal}^2 H_{\rm CR}\ln(E_{p,\rm max}/E_{p,\rm min})}$$
$$\approx 2\times10^3\left(\frac{f_{\rm pul}\eta_p L_{\rm s,tot}}{10^{39}\,{\rm erg\ s^{-1}}}\right)\left(\frac{E_p}{10\,{\rm PeV}}\right)^{-1/3}$$
$$\times\left(\frac{H_{\rm CR}}{4\,{\rm kpc}}\right)\left(\frac{R_{\rm Gal}}{15\,{\rm kpc}}\right)^{-2}\ {\rm eV\ cm^{-2}s^{-1}sr^{-1}}$$





Case II: $\alpha_p = 2.0$

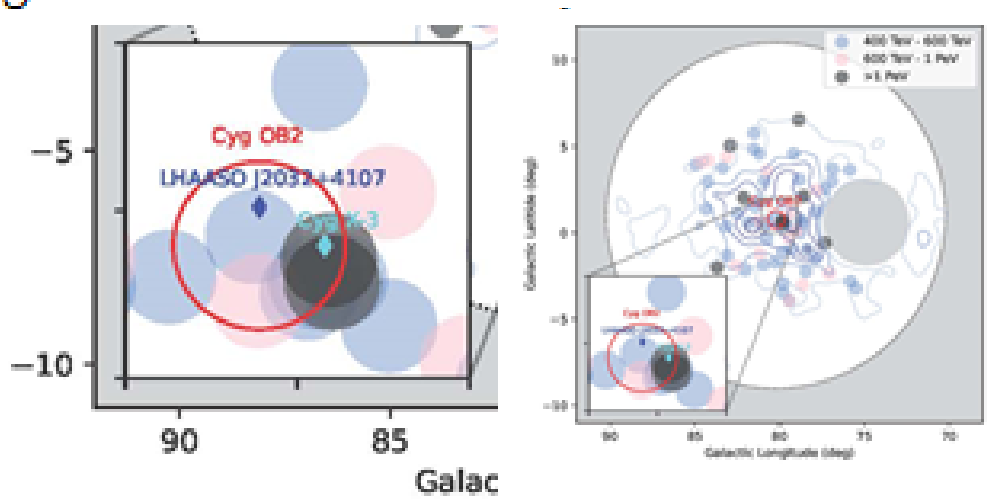


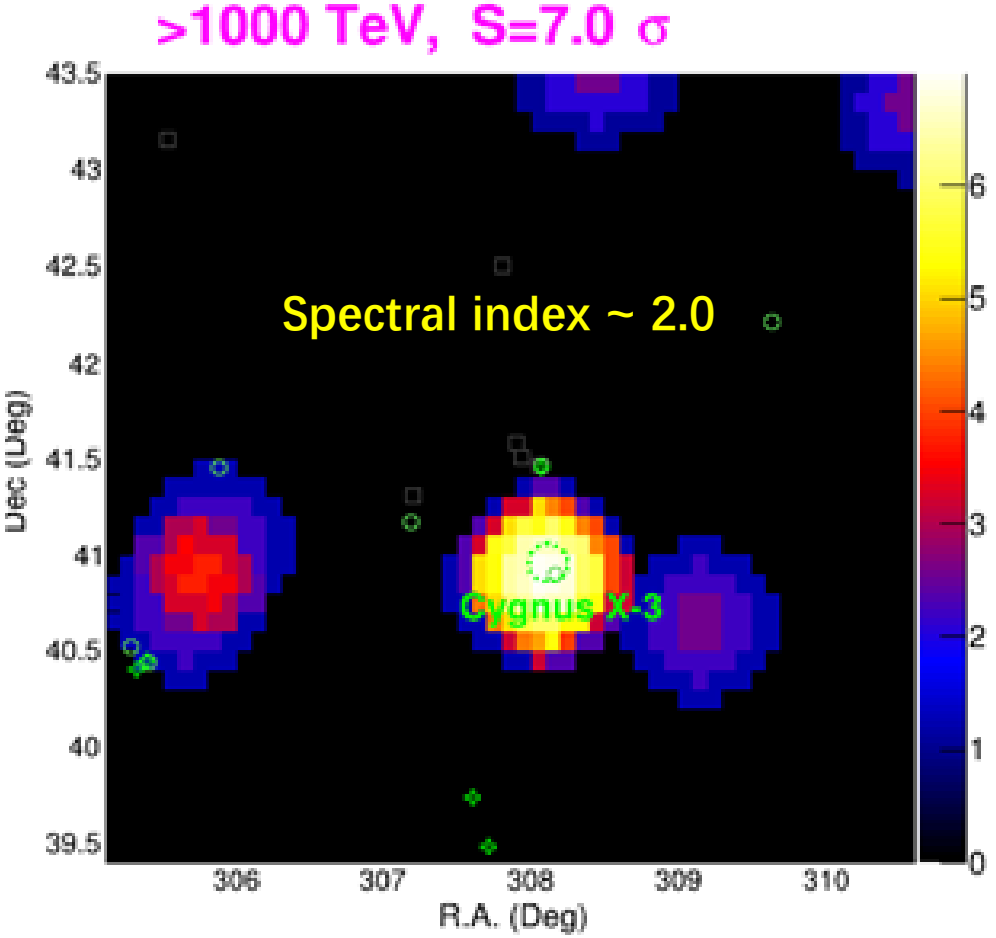
Cheng et al. 1990
Atoyan & Aharonian 1996
Amato et al. 2003
.....

relax $\varepsilon_e+\varepsilon_B=1$
5% of spin-down energy goes into protons

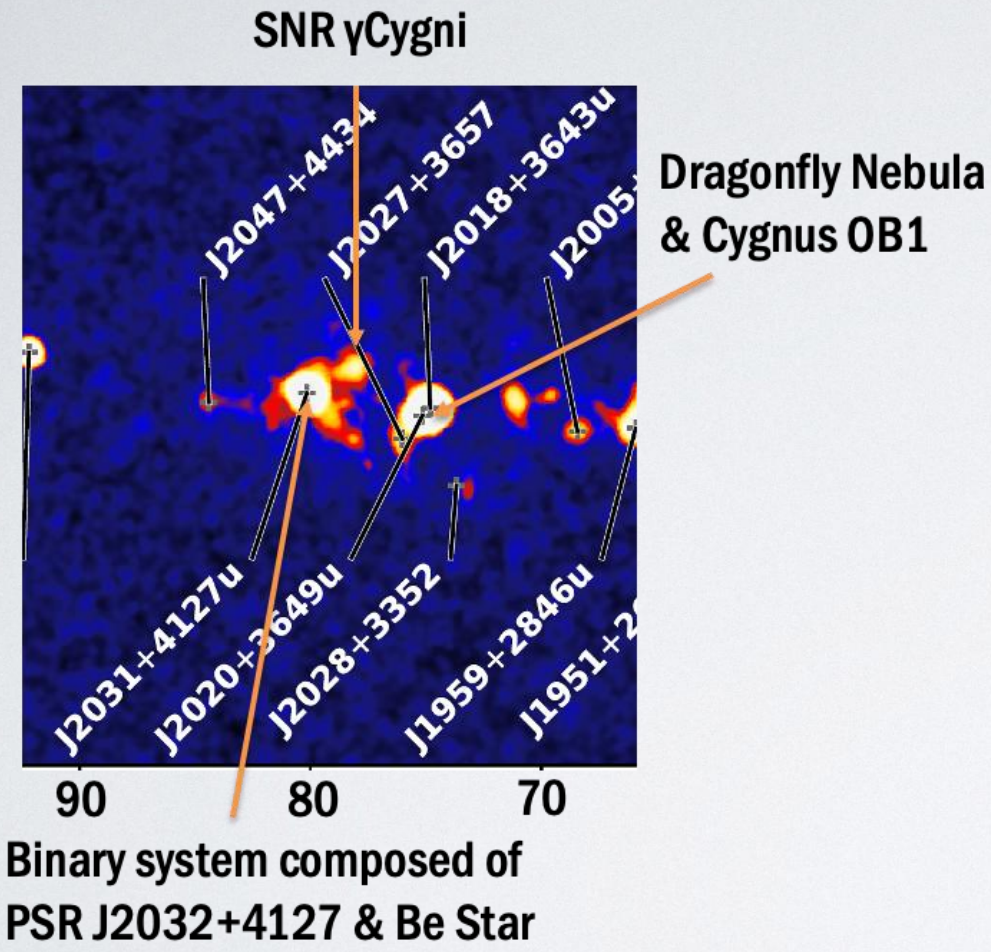
X-3 is the 1st observed PeV-Source

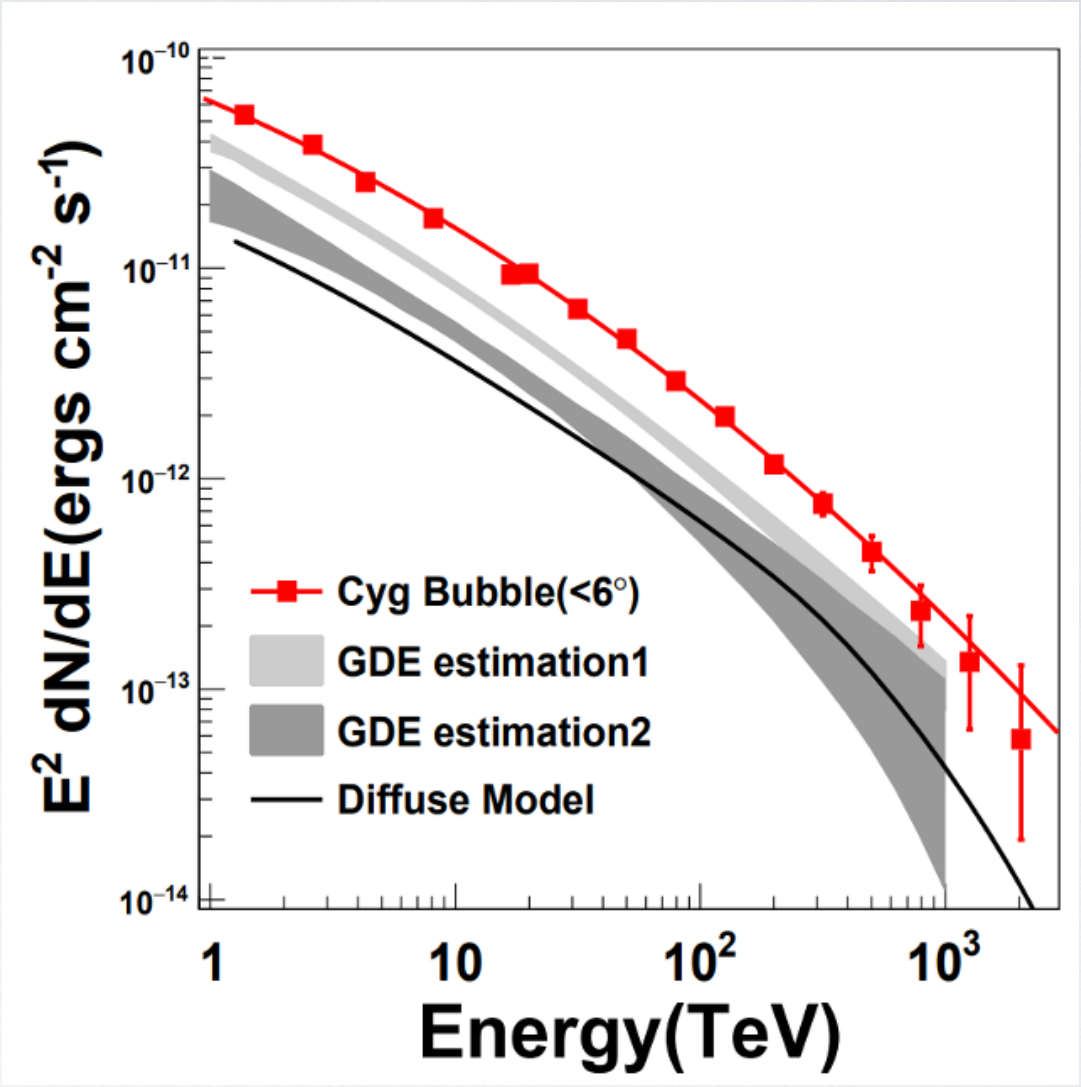
- The binary X-3 is found emitter of PeV γ-rays during flares
- 4 events above 1 PeV reaches 7σ above the CR background
- The highest energy is 3.7 PeV indicating at least 37 PeV protons emitted from a small region



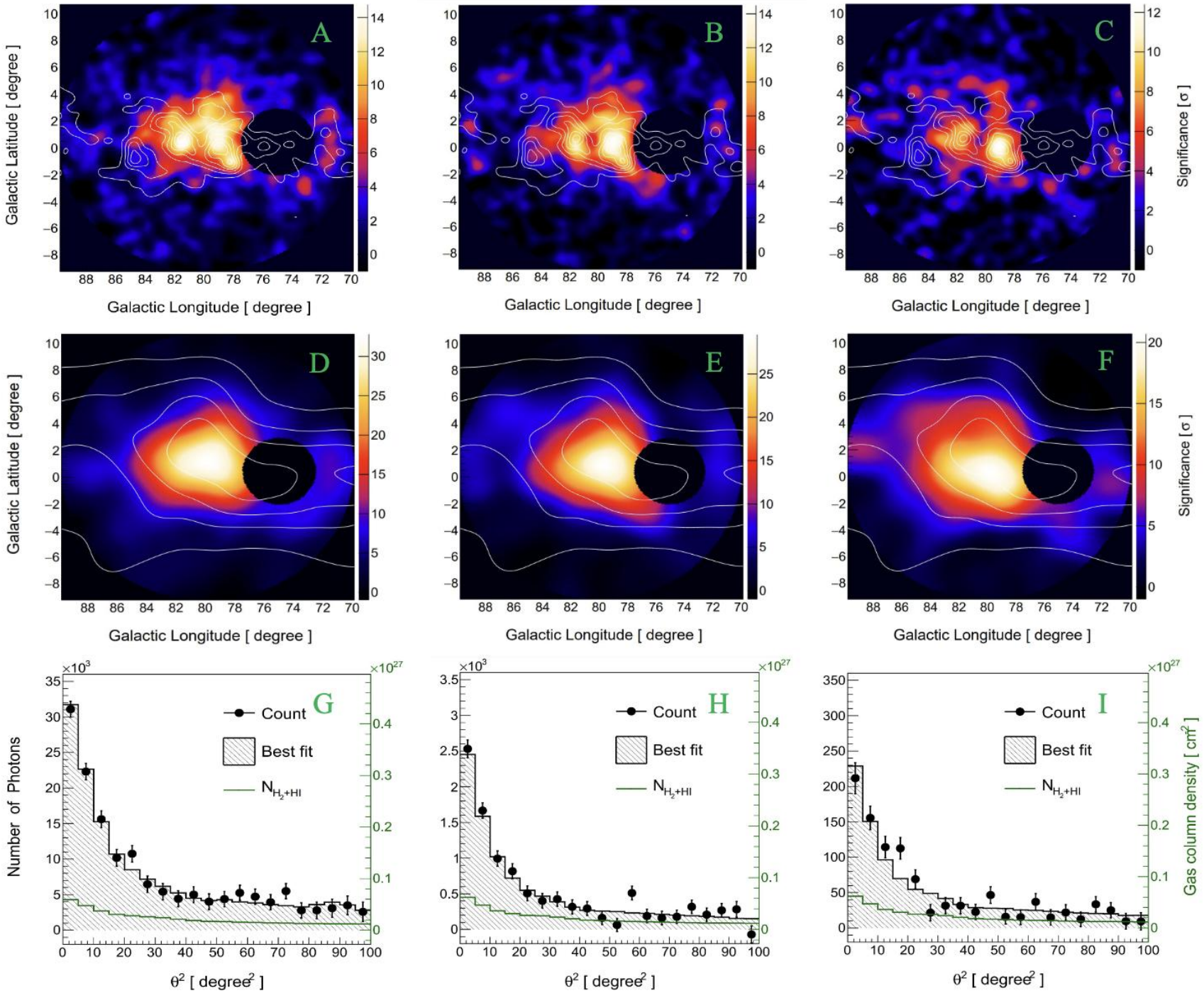


LHAASO VIEW ON CYGNUS





Galactic diffuse gamma-ray background (GDE) must be taken into account

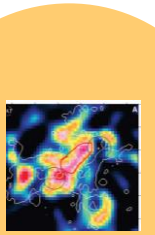


LHAASO VIEW ON CYGNUS

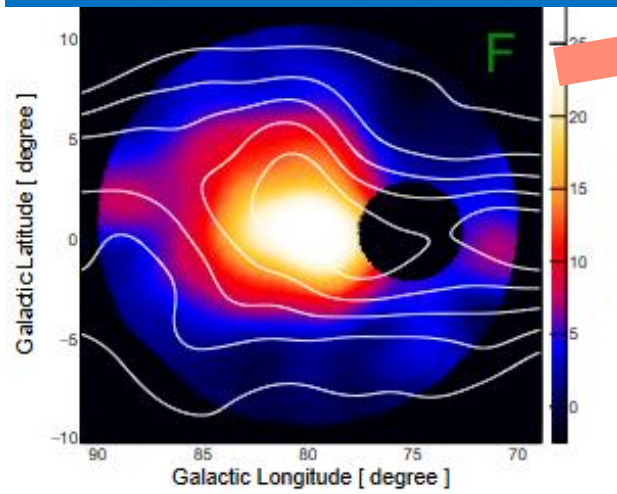
Huge bubble beyond ~10 degrees (200 pc)

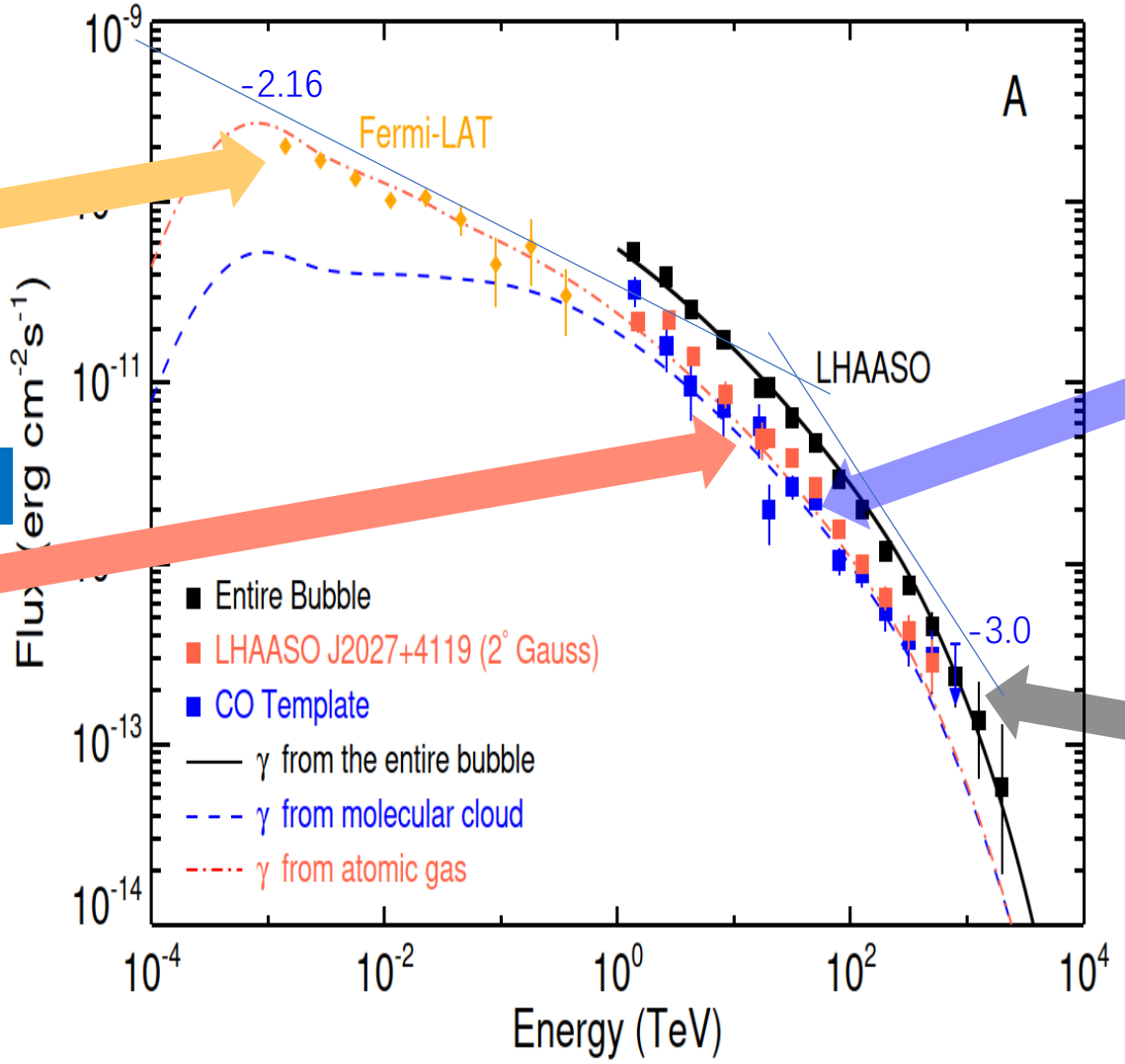
Model w 3 components : SED over 8 decades

Fermi Cocoon

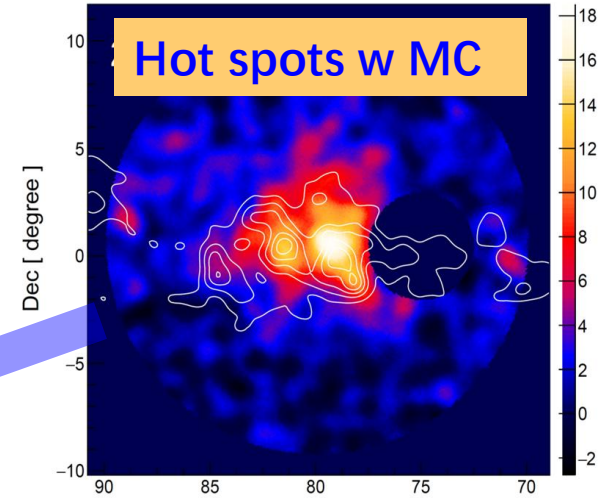


Extended Bubble w HI gas

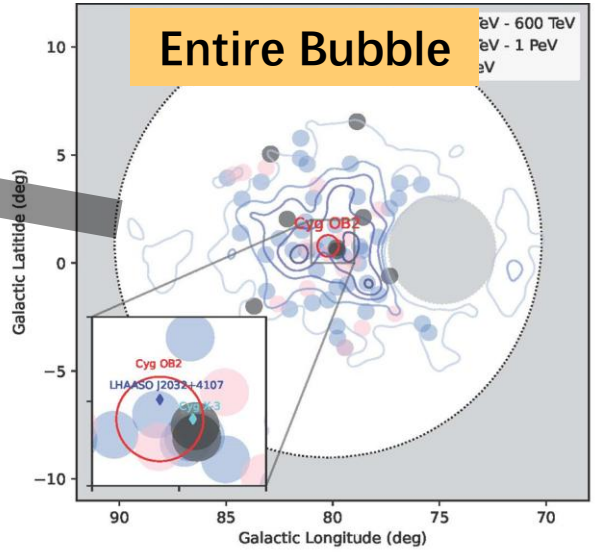




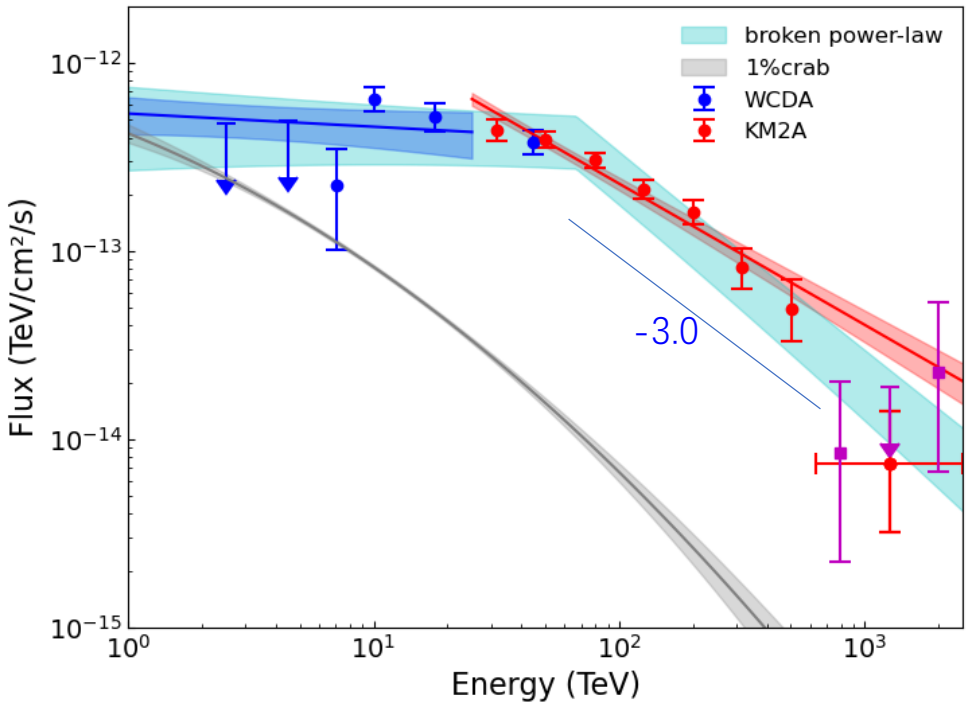
Hot spots w MC

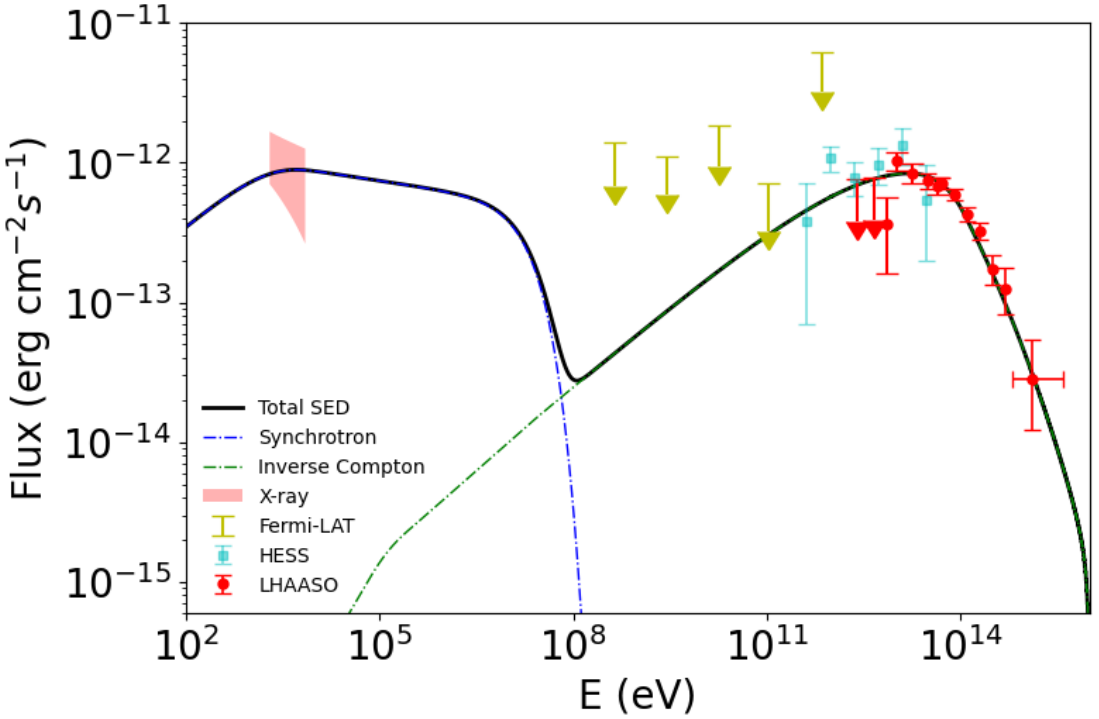


Entire Bubble



PSR J1849-0001: another extreme accelerator





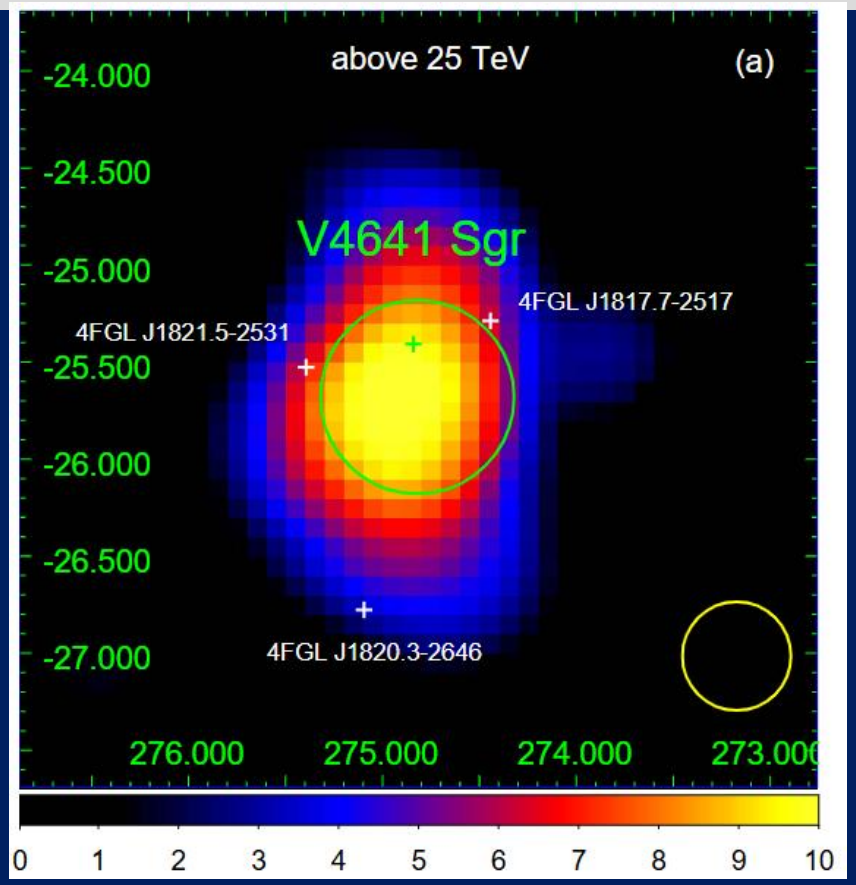
low magnetic field → size-limited acceleration

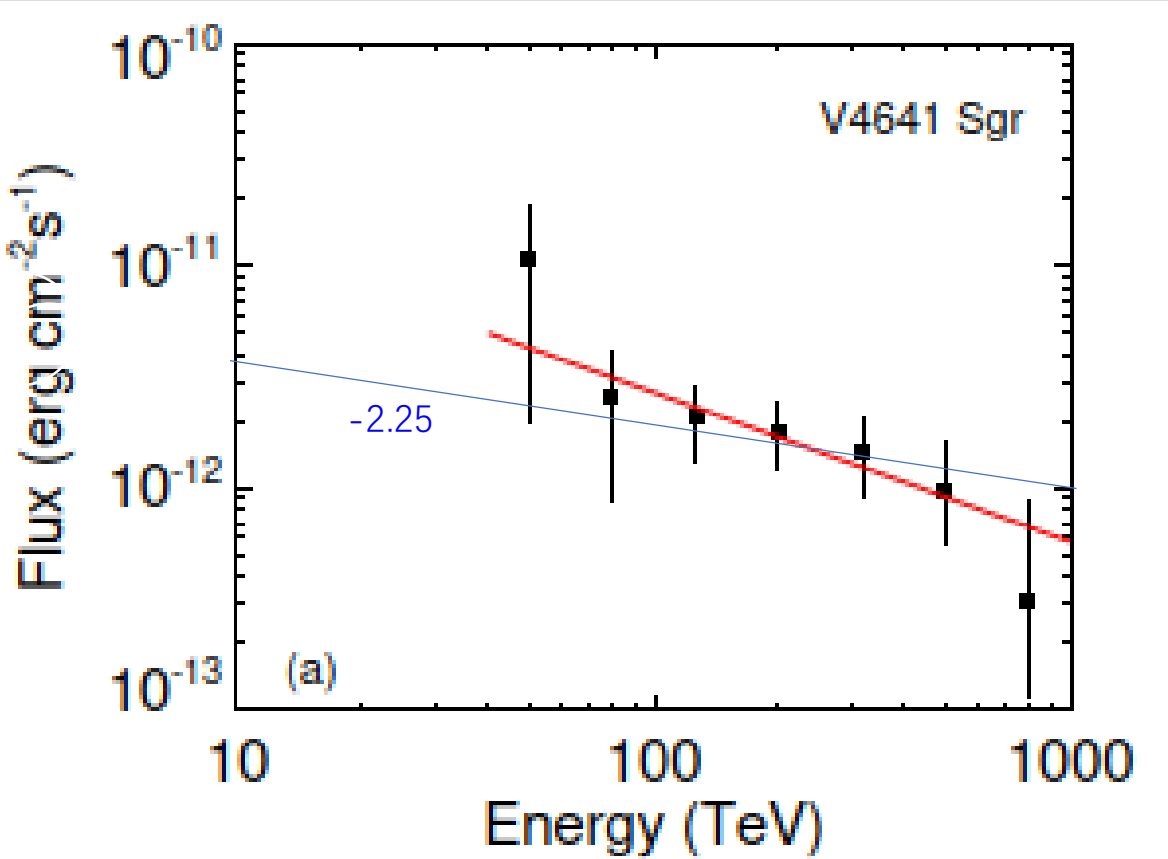
$B_{TS}^2/8\pi = \varepsilon_B L_s/4\pi R_{TS}^2 c \rightarrow \mathbf{E_H = eB_{TS}R_{TS}} = (2\varepsilon_B L_s/c)^{1/2} = 2.5\text{PeV}\ (L_s/10^{37}\text{ergs}^{-1})^{1/2}(\varepsilon_B/\mathbf{0.1})^{1/2}$

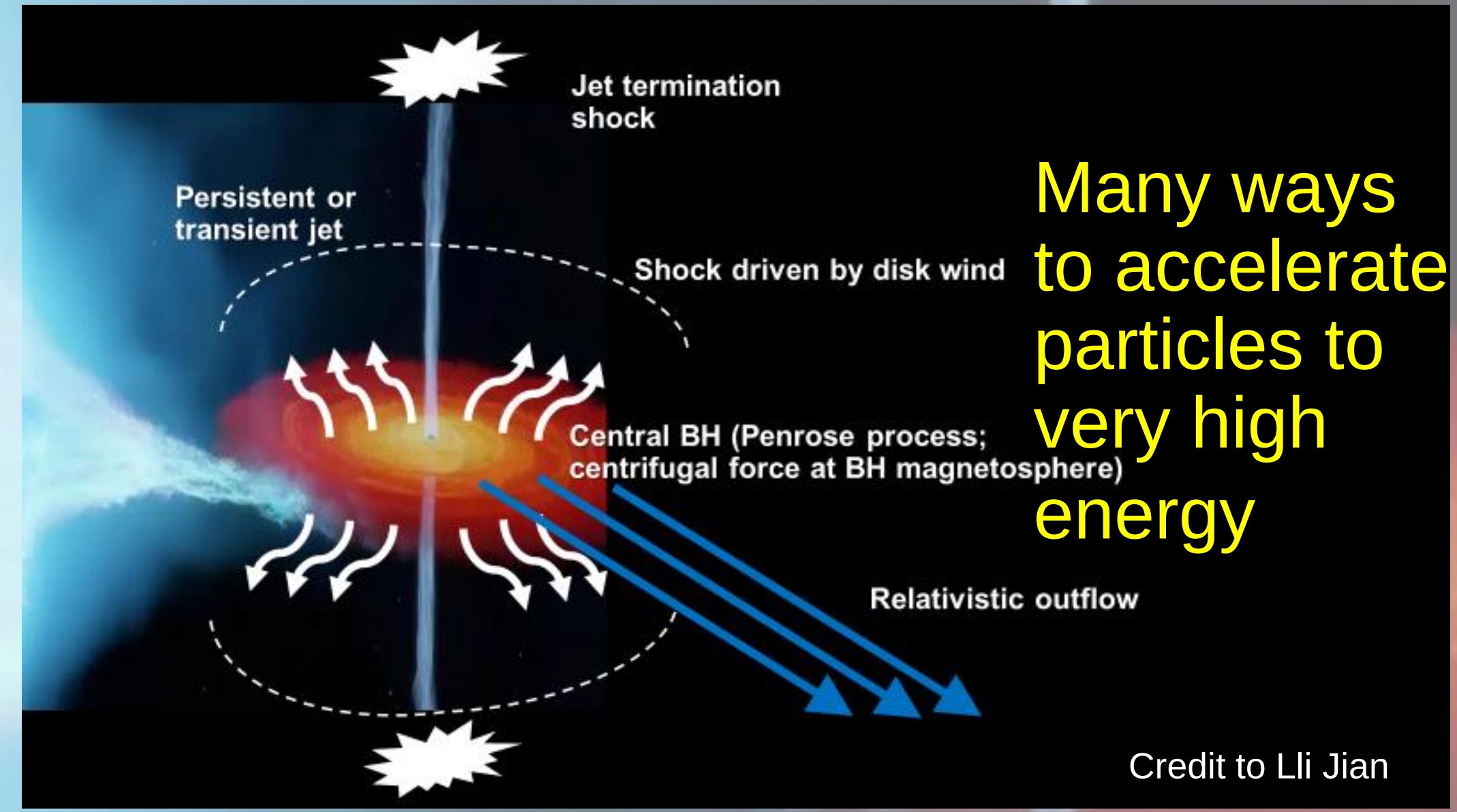
$$\eta = E_{e,max}/E_H$$

Black Hole as a super-PeVatron?

Very difficult to detect: not only due to the distant: ~20,000 light-year !
But also out of main field of view of LHAASO: a source in southern hemisphere
Powerful accelerator generating particle at E >10 PeV !!







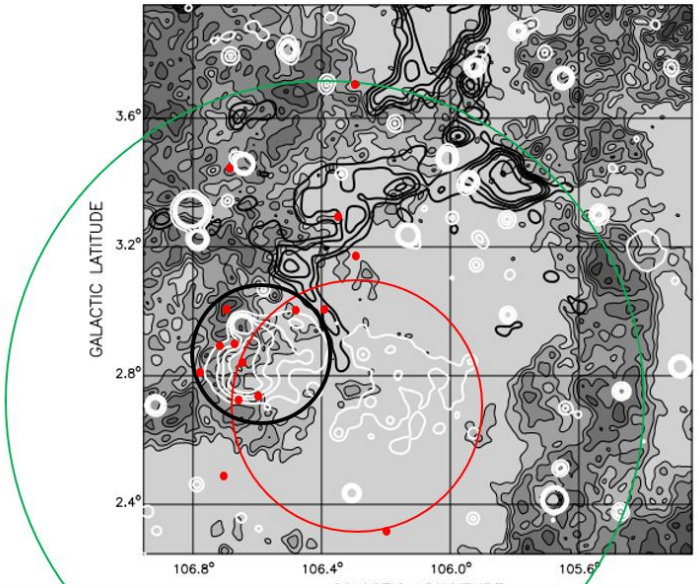
Many ways to accelerate particles to very high energy

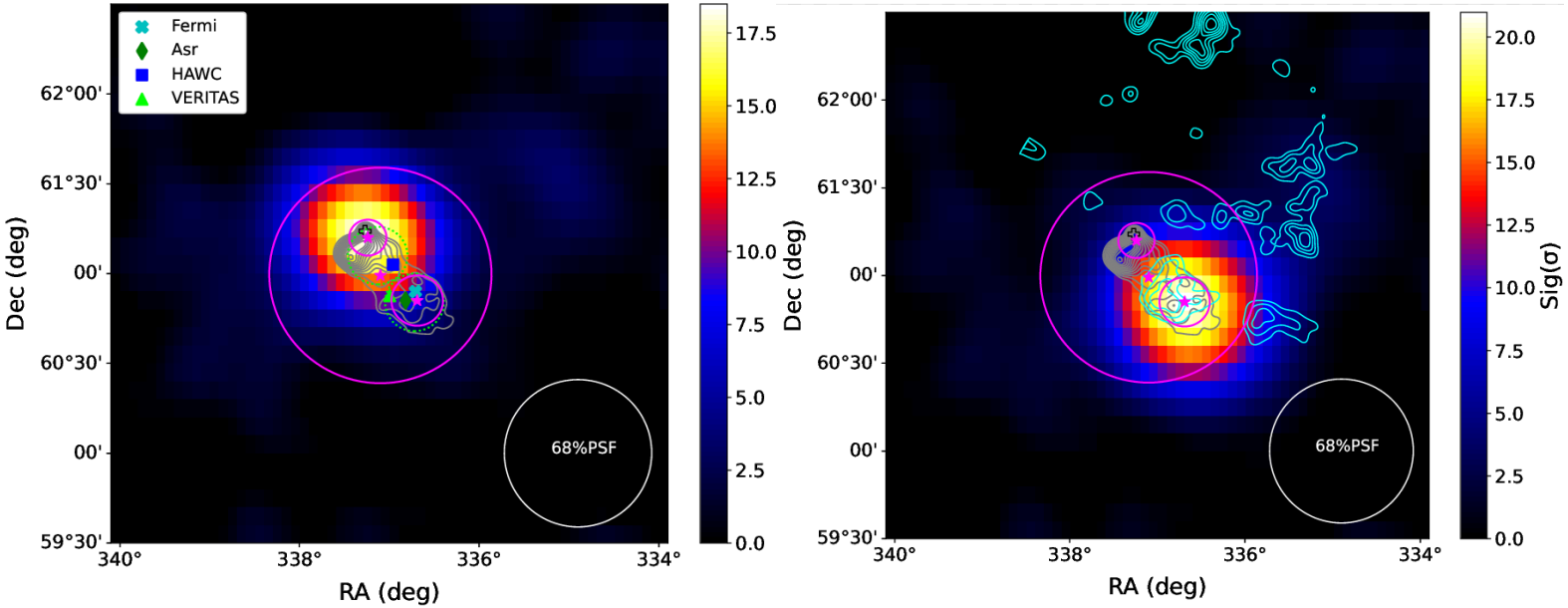
Credit to Lli Jian

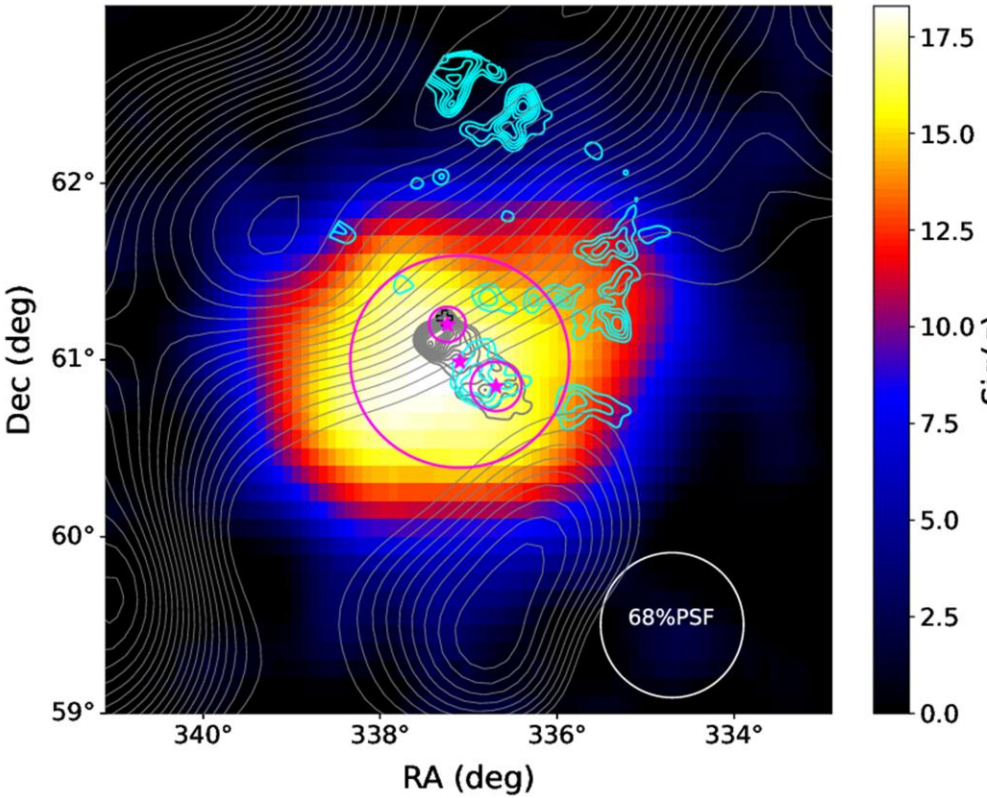
Particle escaping from the SNR or PWN?

- Complex of 3 sources: PWN (Boomerang), SNR+MC (G106.3+27) and an extended associated with gas

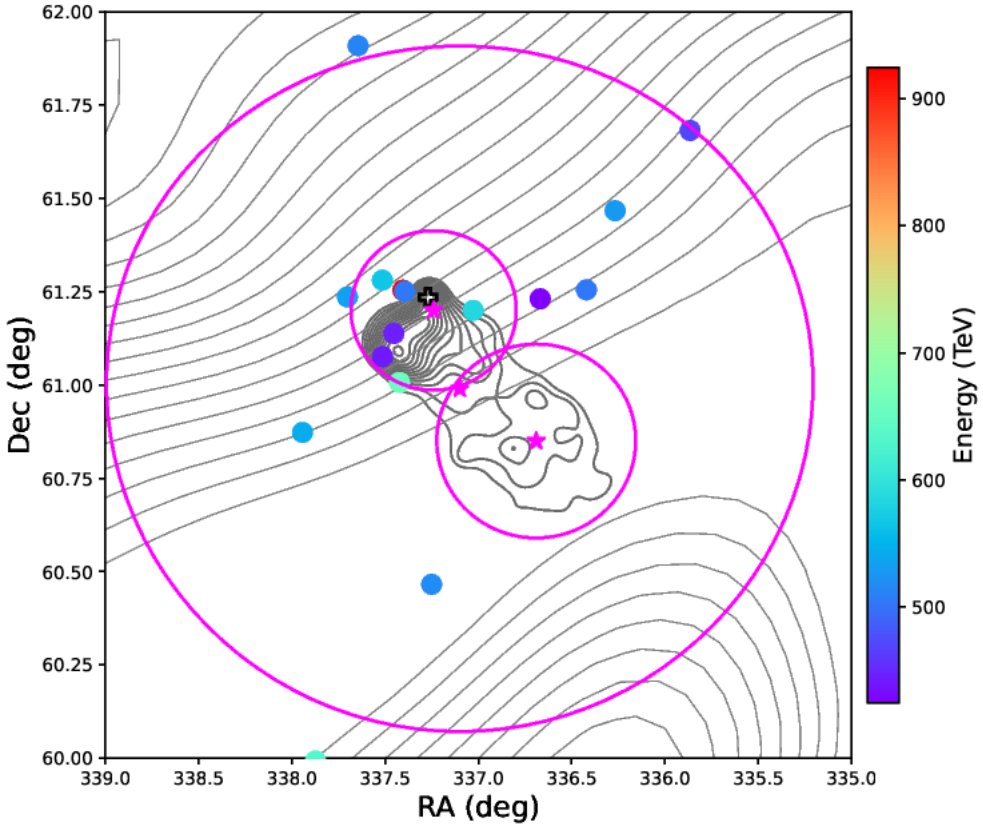
Templet	Ra(°)	Dec(°)	σ(°)	SED	alp1	alp2	Flux*10^{-12} (50TeV)	TS
Three Gaus	337.09±0.05	60.97±0.02	0.57±0.02	LP	2.48±0.11	1.06±0.19	4.37±0.22	11559.0(23)
	337.27±0.05	61.22±0.03	ps	PL	2.92±0.11	-	0.79±0.14	
	336.75±0.04	60.88±0.03	ps	LP	2.79±0.19	1.76±0.52	1.65±0.18	



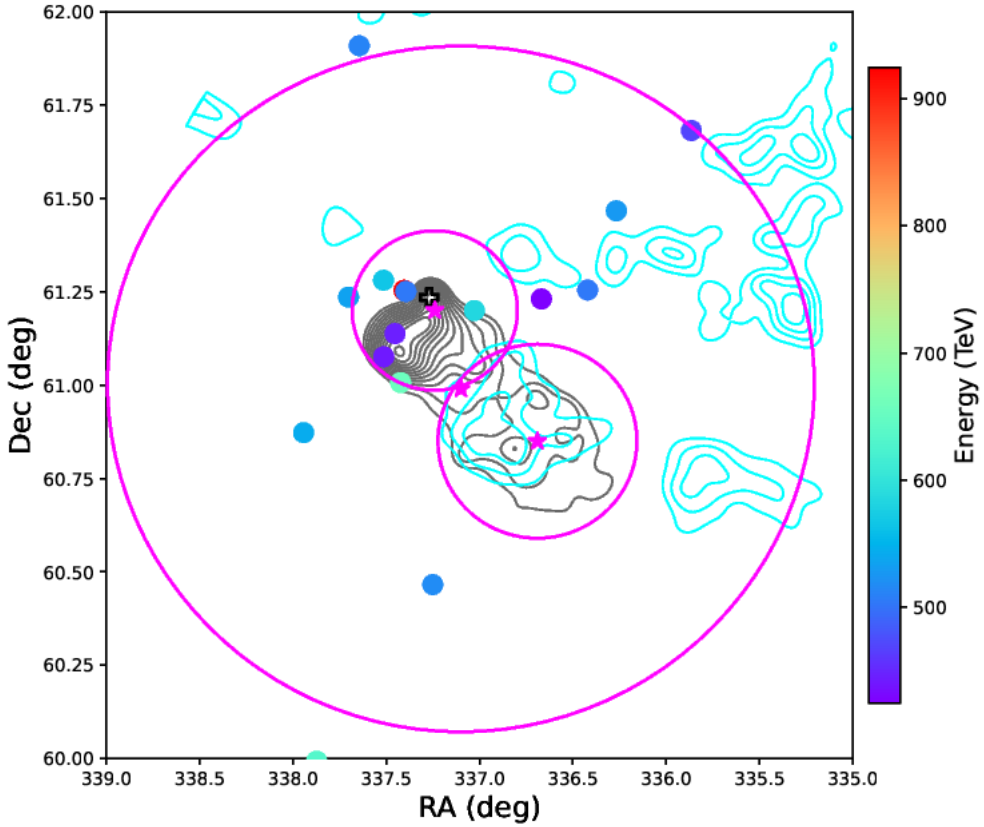




Photons with E>400 TeV



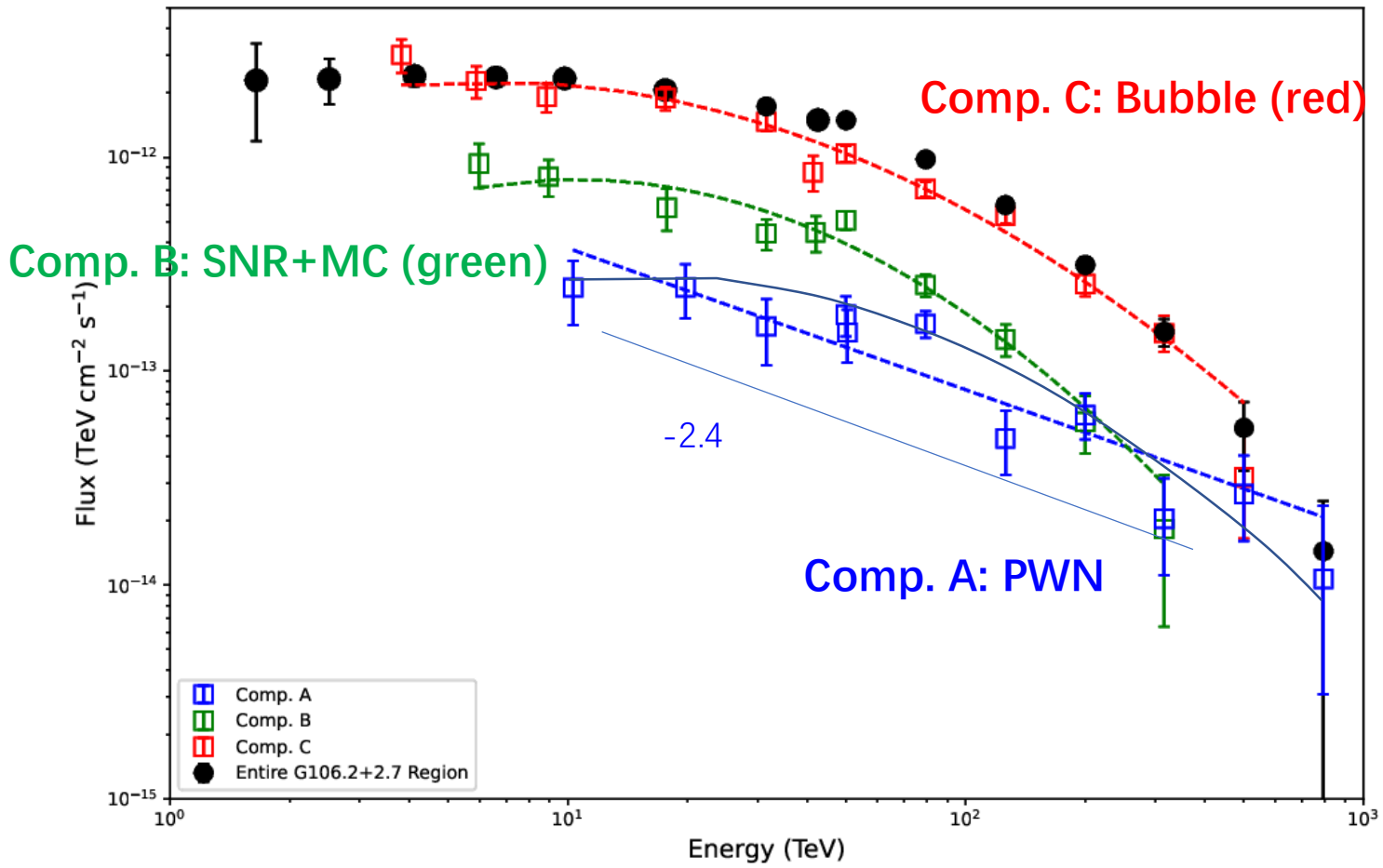
atomic gas distribution



molecular clouds

SEDs of the 3 Components

- Spatially separated SNR+MC component has a cut-off around 50TeV
- PWN has some HE photons near-by making the SED hard at HE, overall there exists a softening around 100 TeV
- The bubble also has a softening structure similar to the PWN's. Sharing the HE events with PWN is still an issue



Summary on the Super-PeVatrons

- PeV photons (1.4, 2.0, 2.5, 3.0, 3.7 PeV)
- Flat Power Law Spectra (from -2 to -3 for spectral indices)
- Many species: X-ray binary, PWNe, μ-quasars
- Characteristics: Compact Objects
- Challenge: still possible for electrons at few PeV !

Content

- Introduction

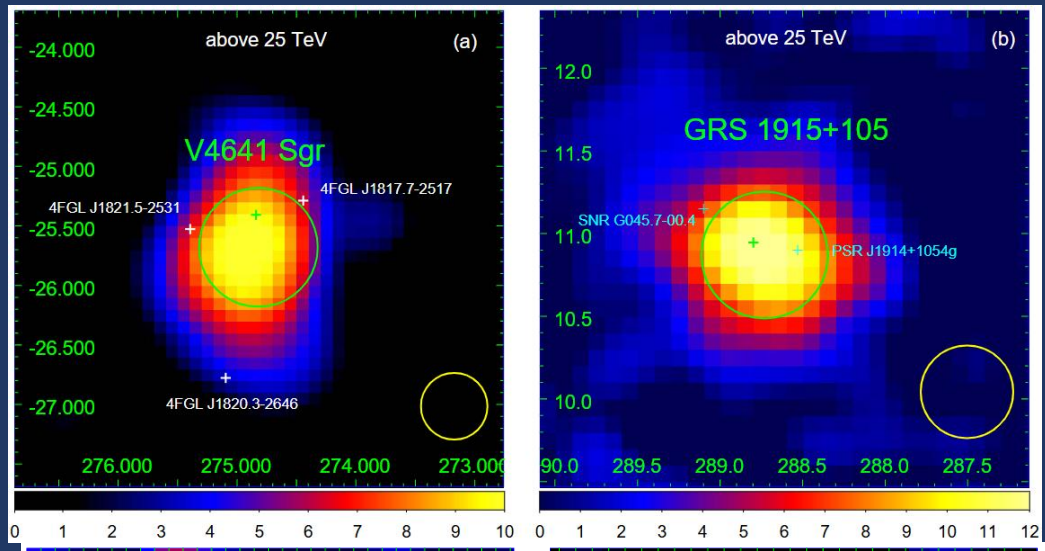
- PeV Gamma Ray Sources
  - The Crab Nebula, Cyg X-3, Cygnus Bubble, J1849-0001, Sgr V4641, J2229+6114, ……
  - Summary on the Super-PeVatrons

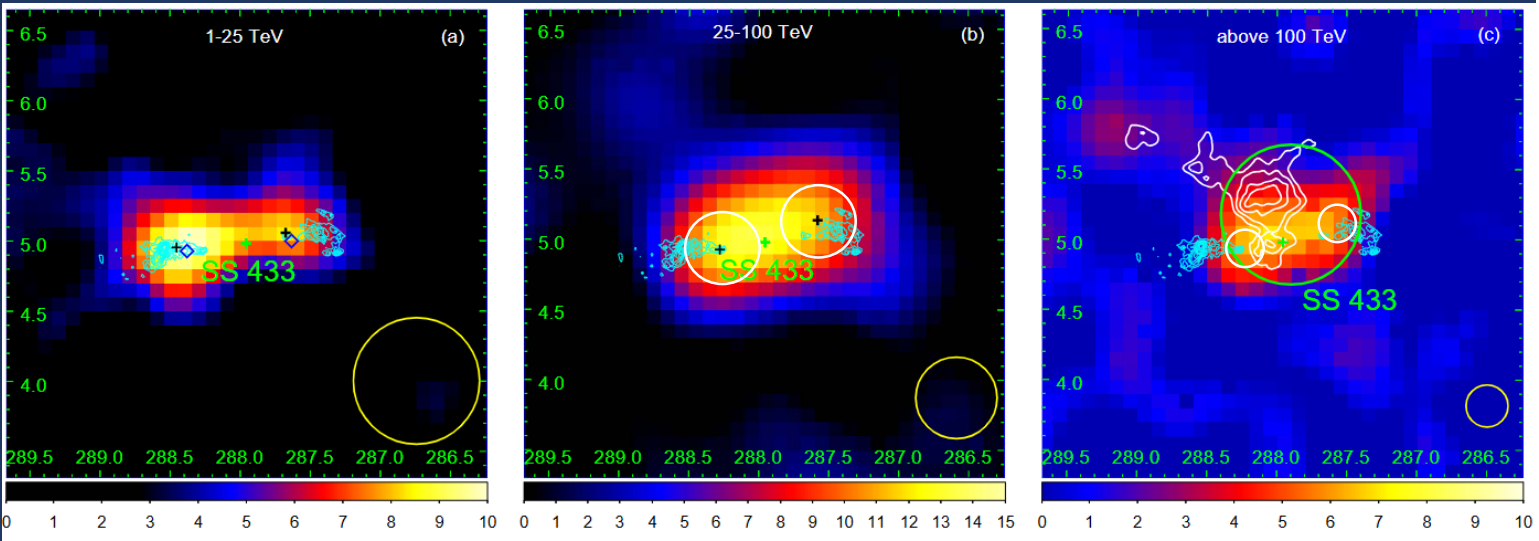
- PeV Particle Generators
  - µQuasars as CR Accelerators
  - PWNe
  - Staller Cluster
  - SNR ?
  - Unidentified sources

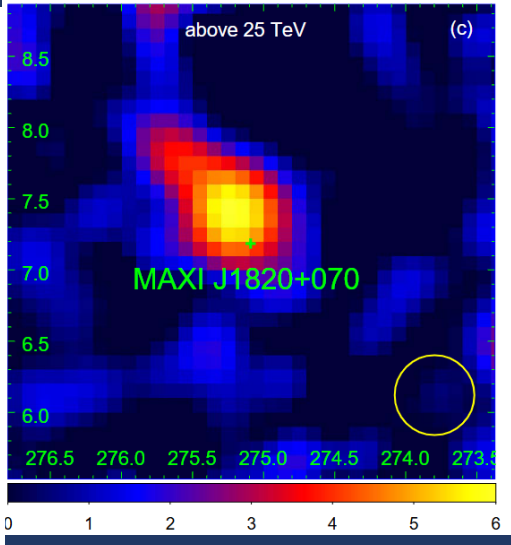
- CR proton spectrum up to the ‘knee’: evidence of PeVatrons in our Galaxy
  - Pure Proton Sample and they spectrum

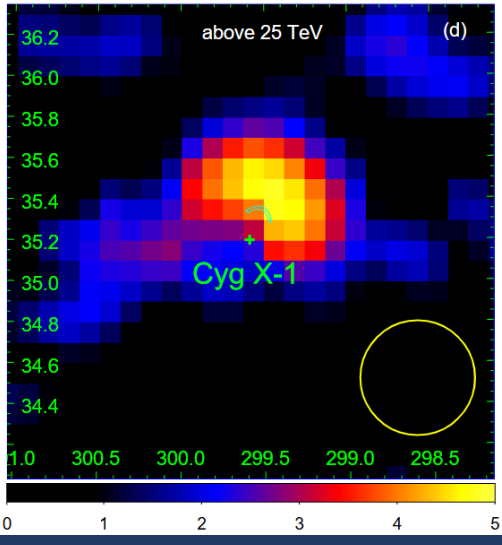
Black Holes and Jets: μQs

- Very important !!
- New CR source population particularly at energy E >3 PeV

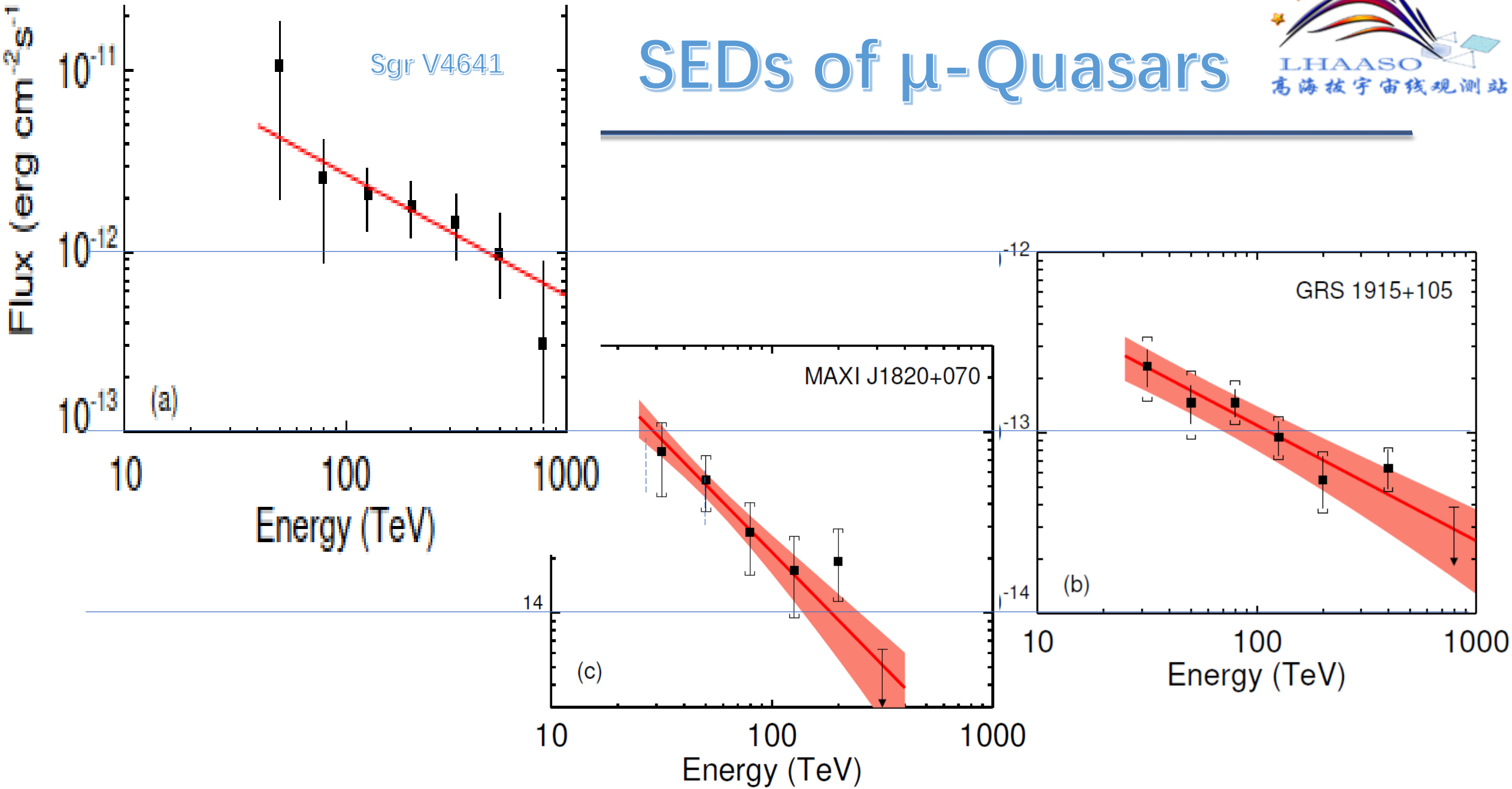






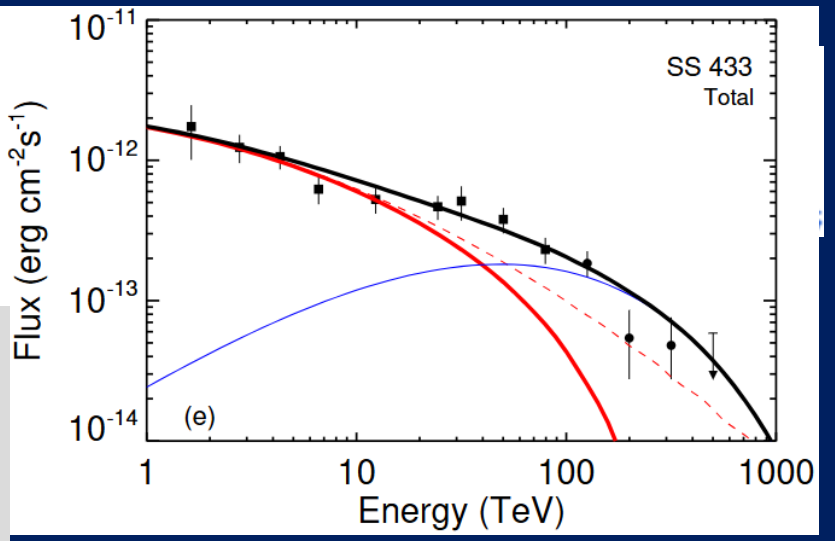


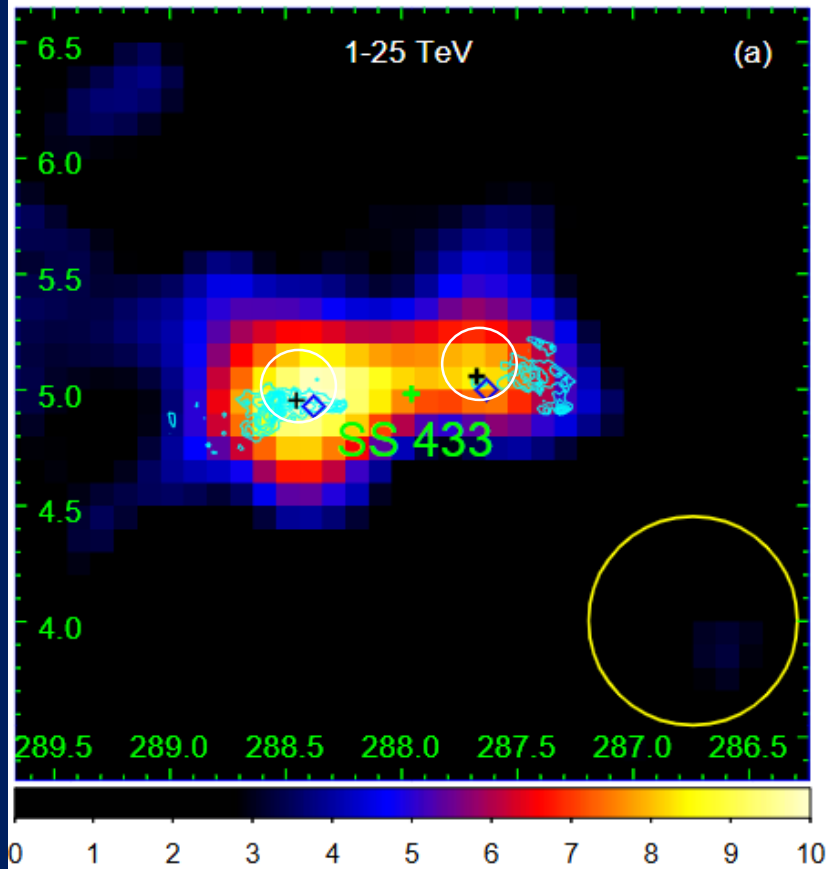
SEDs of μ-Quasars

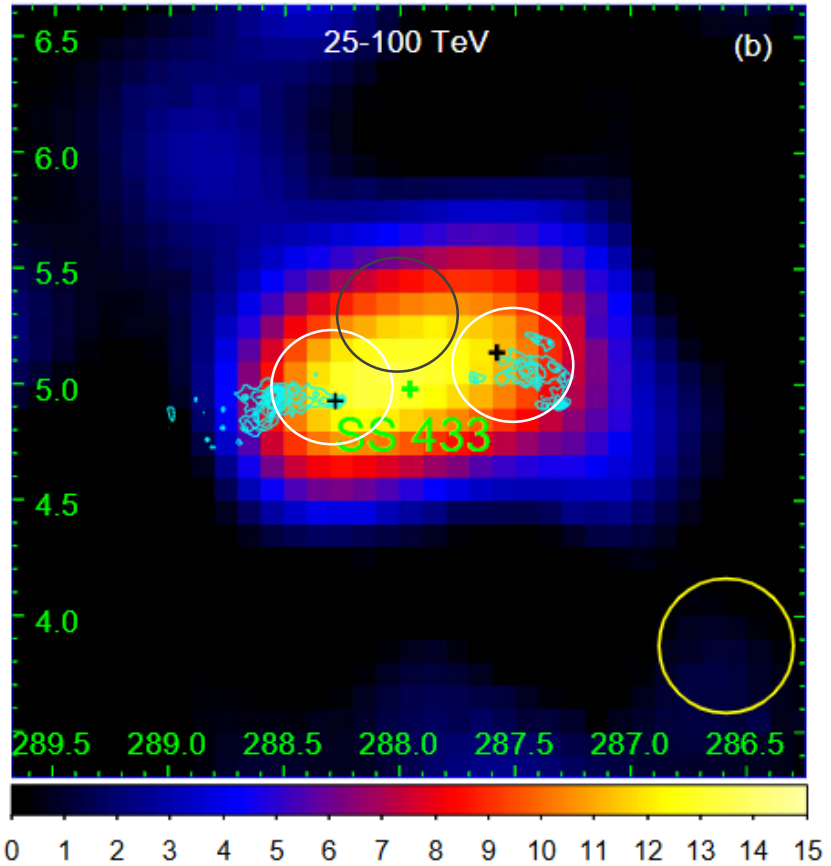


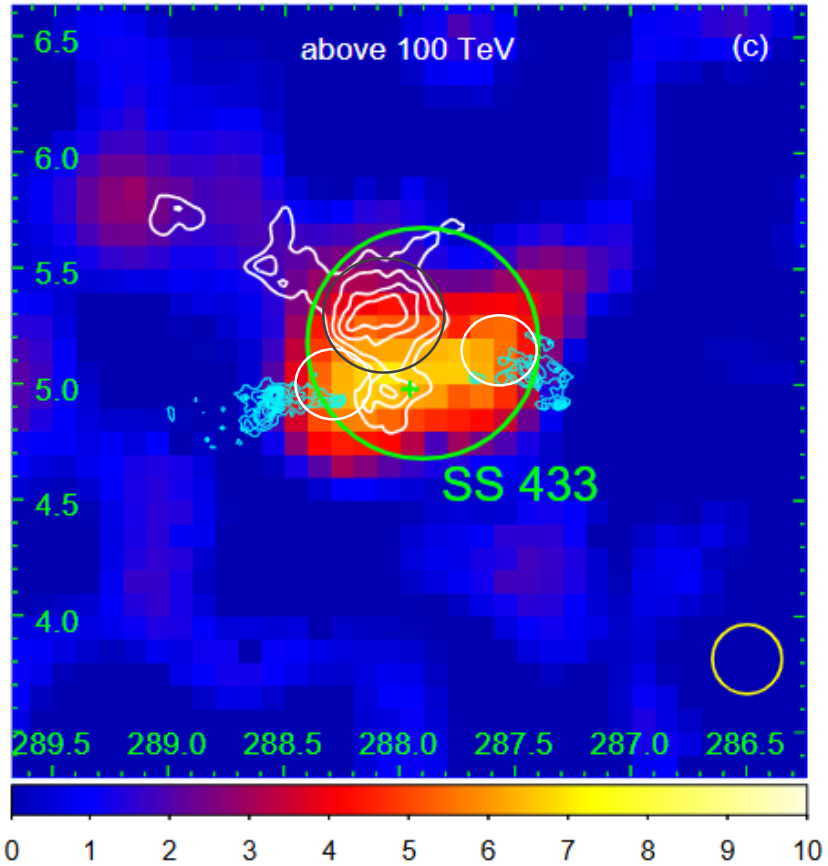
Black Holes and Jets

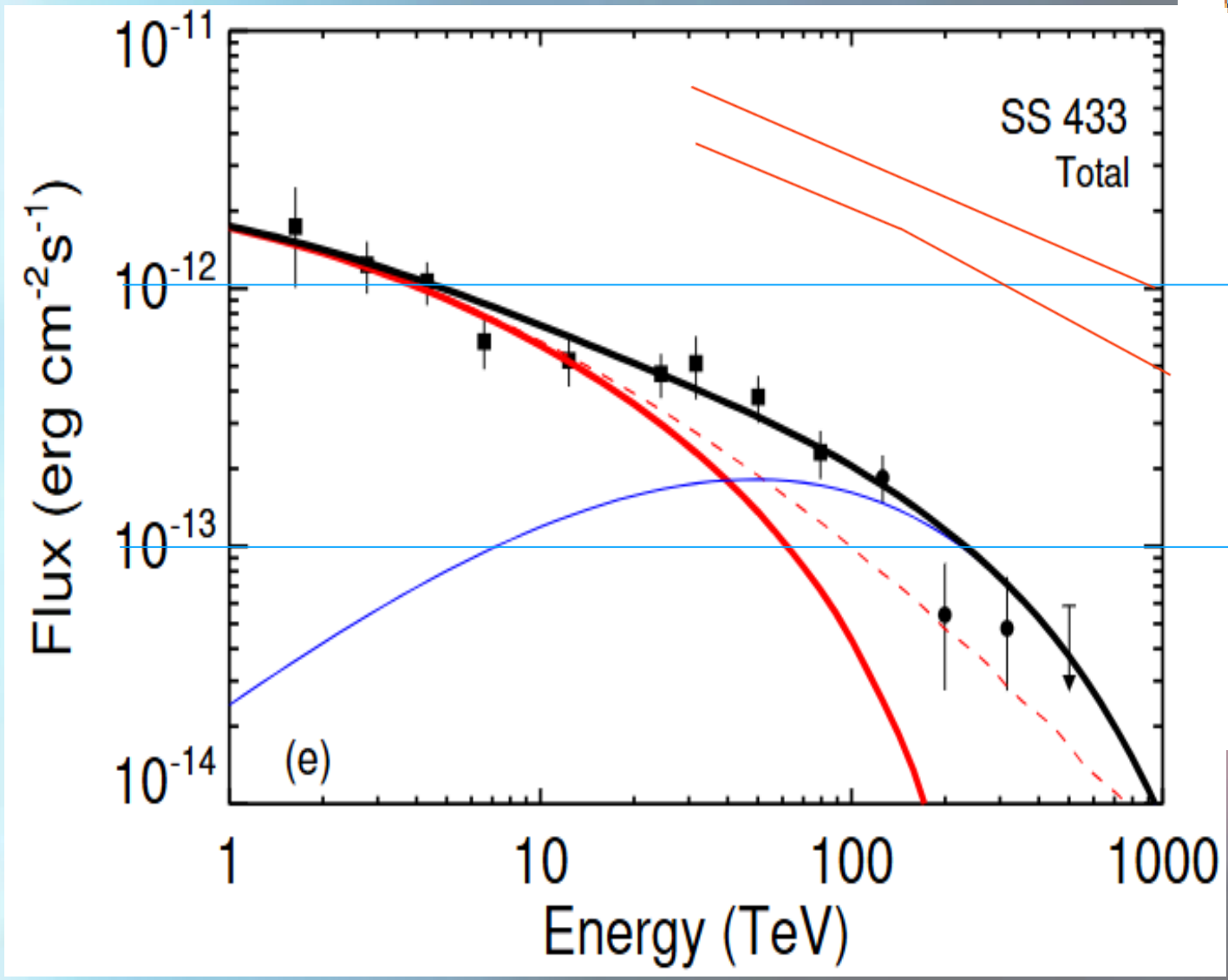
- LHAASO measured them clearly
- At low energy, the jets
- At higher energies, BH itself may have shown up

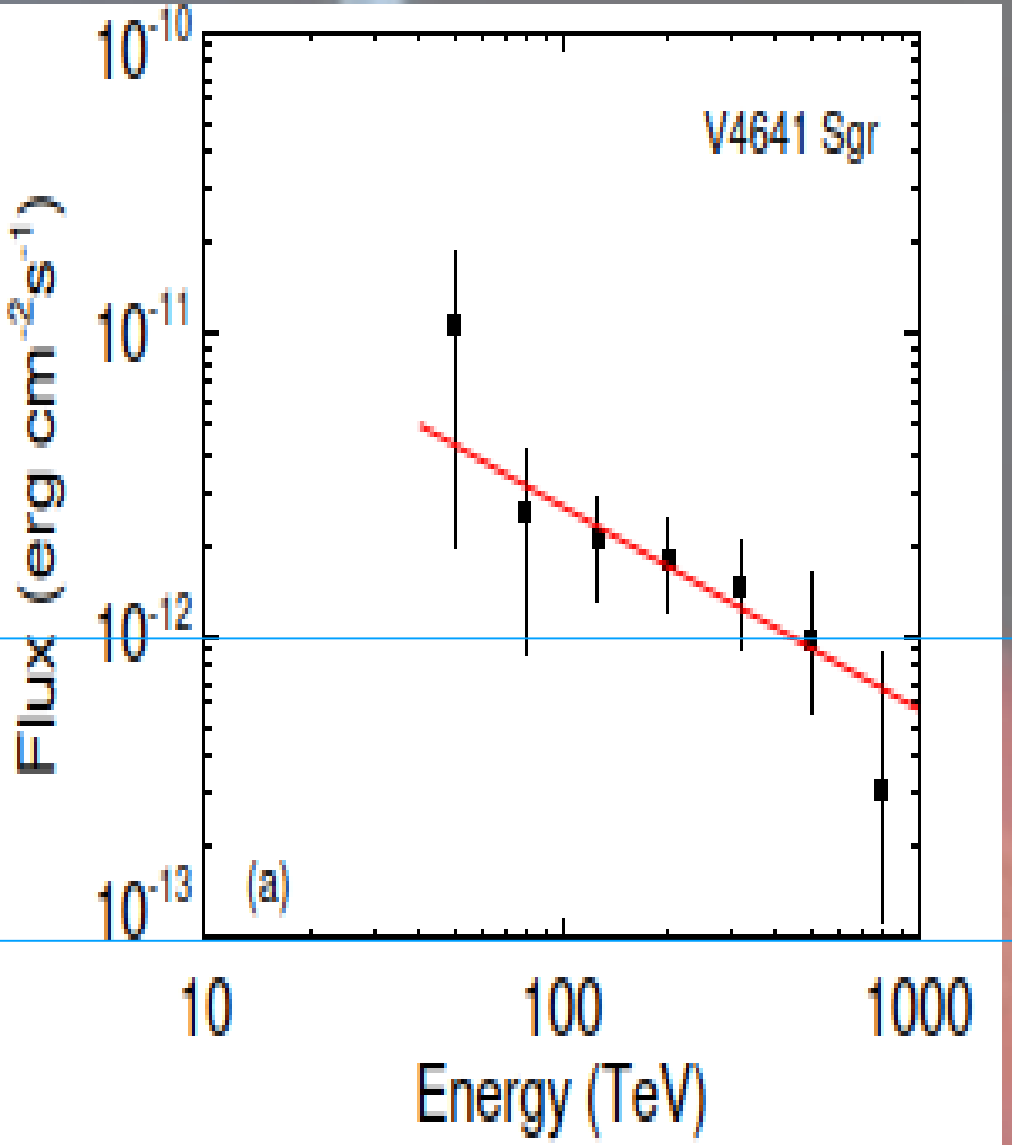






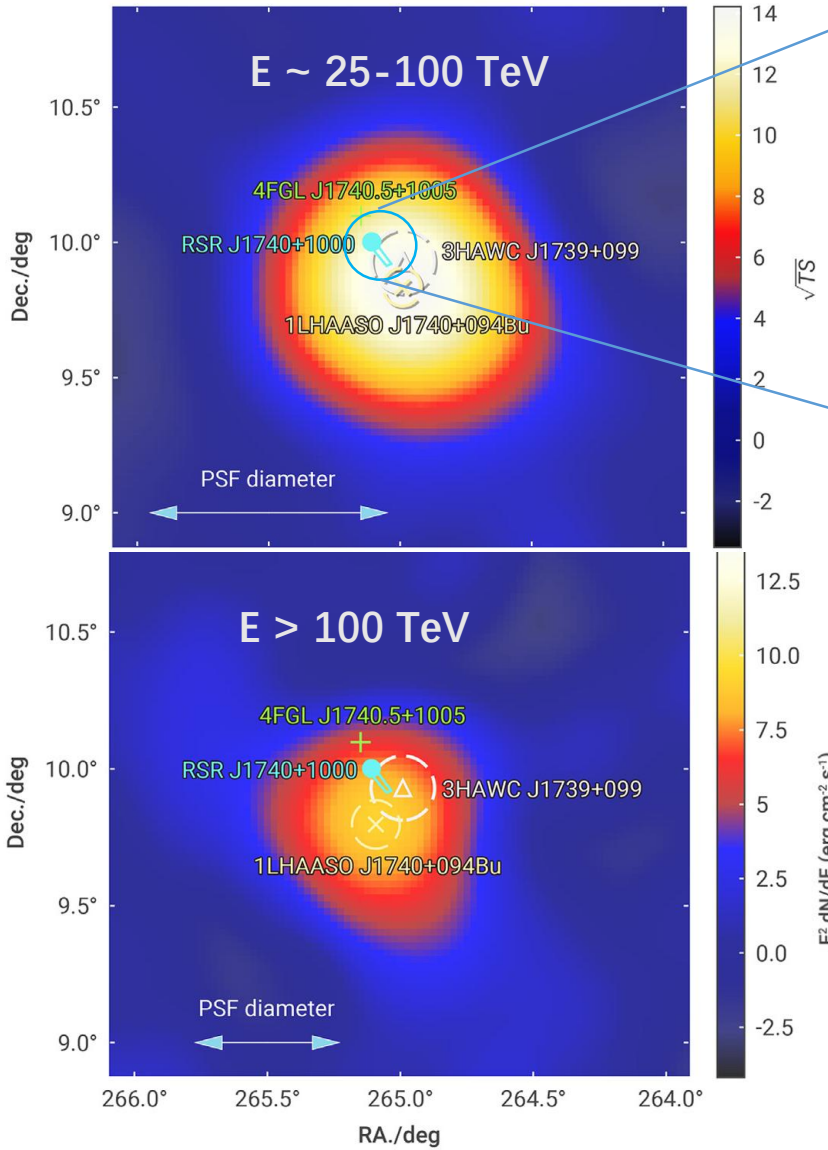


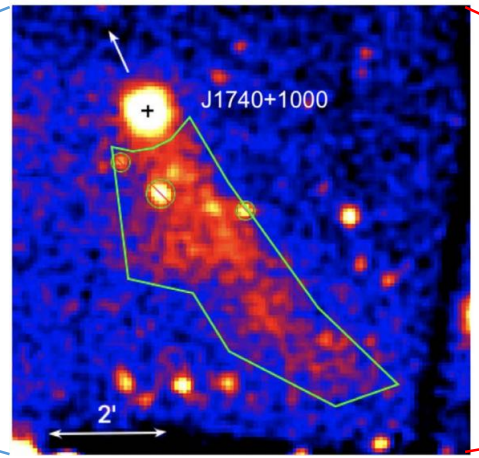

SS 433
Total
(e)
Flux (erg cm^{-2}s^{-1})
Energy (TeV)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1
10
100
1000


V4641 Sgr
(a)
Flux (erg cm^{-2}s^{-1})
Energy (TeV)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10
100
1000

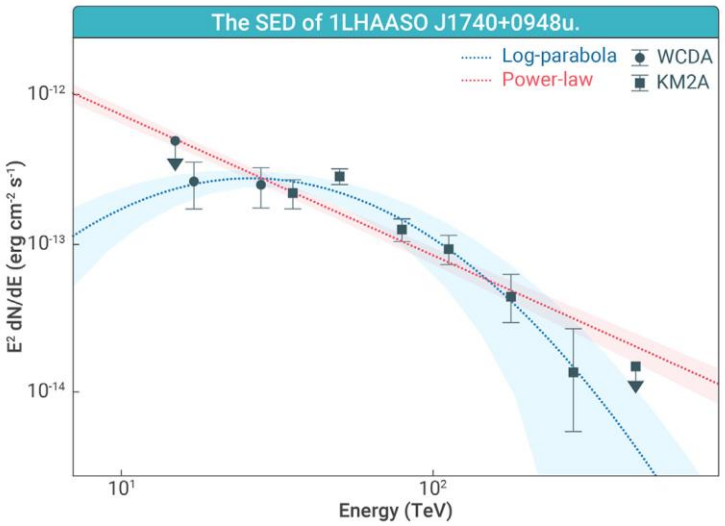
PWNe

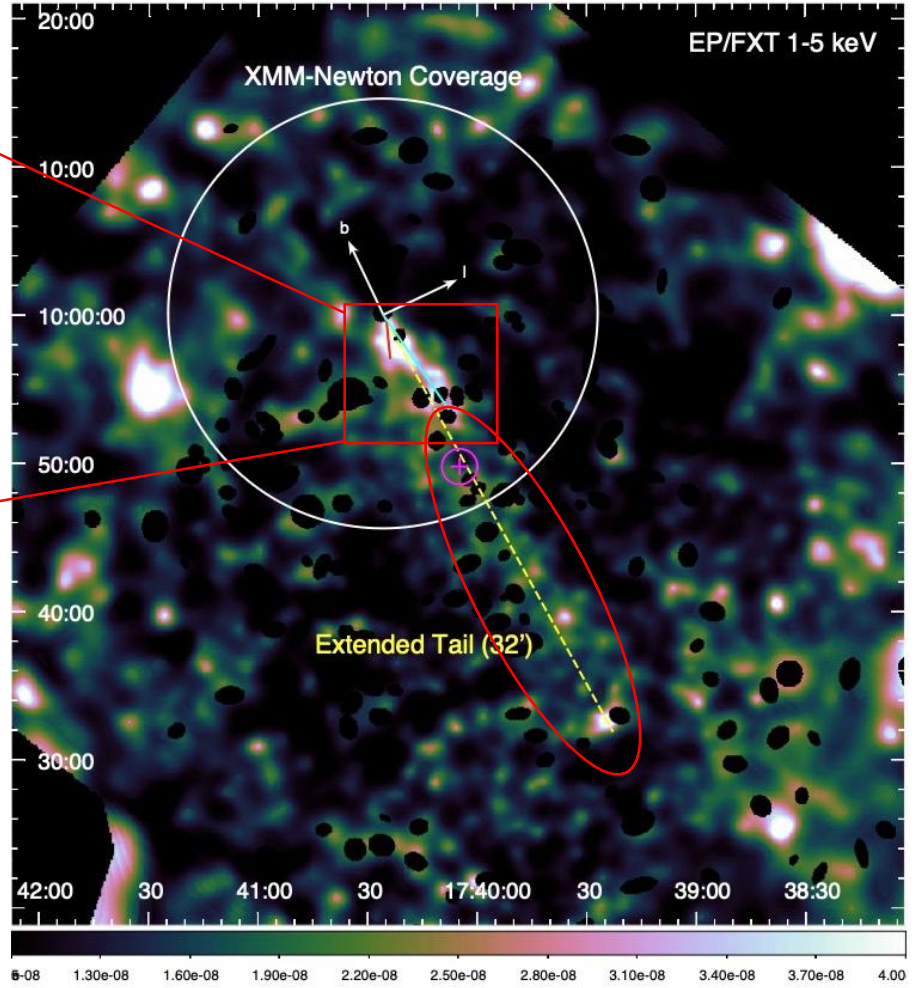
LHAASO J1740+0948: BSPWN tail





LHAASO Coll. 2025, The Innovation





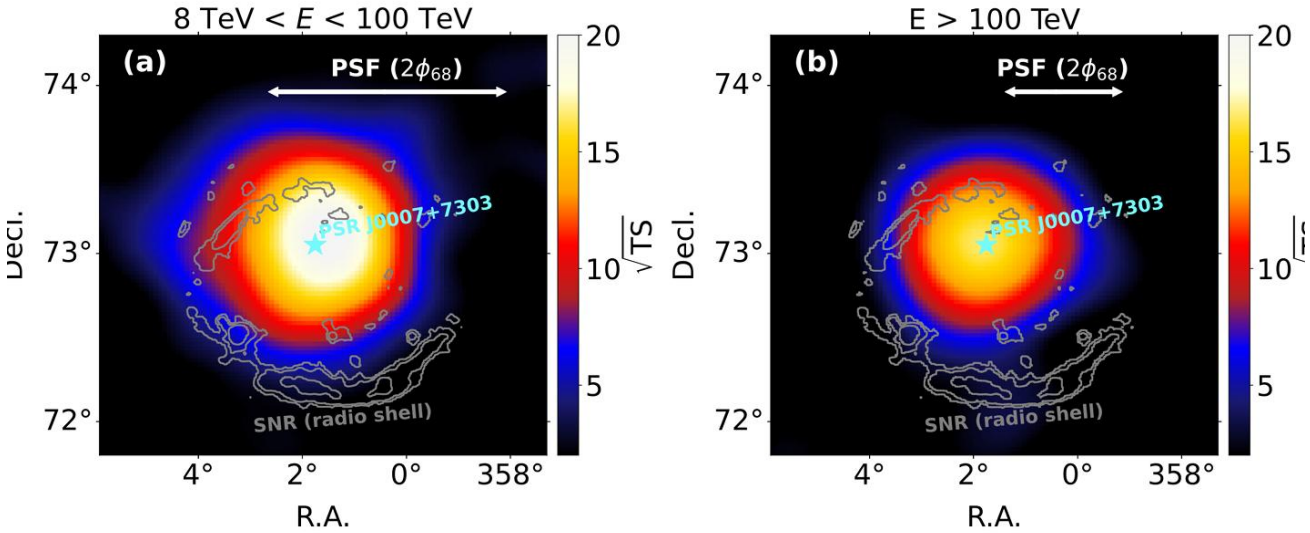
PSR J1740+1000

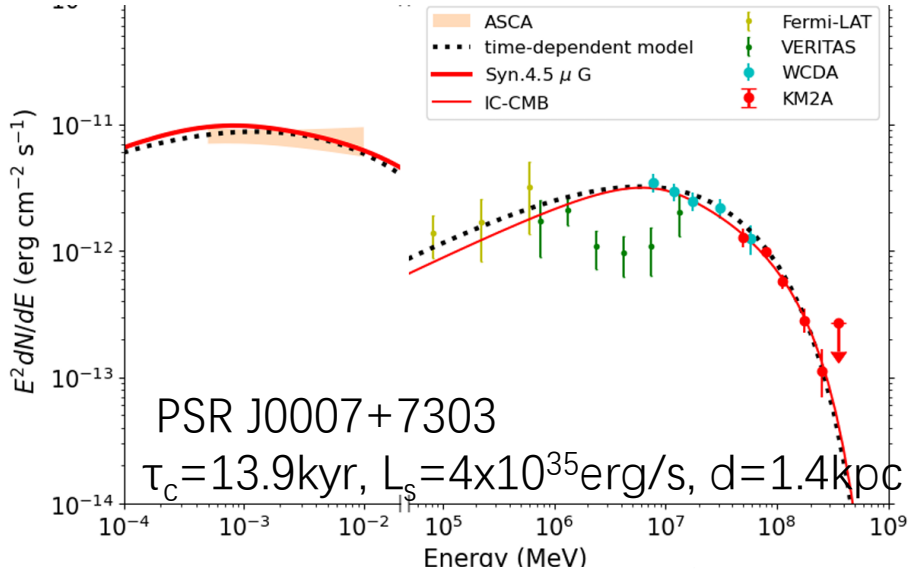
τ_c=114kyr, L_s=2x10^{35}erg/s,

d=1.4 kpc

More PWNe

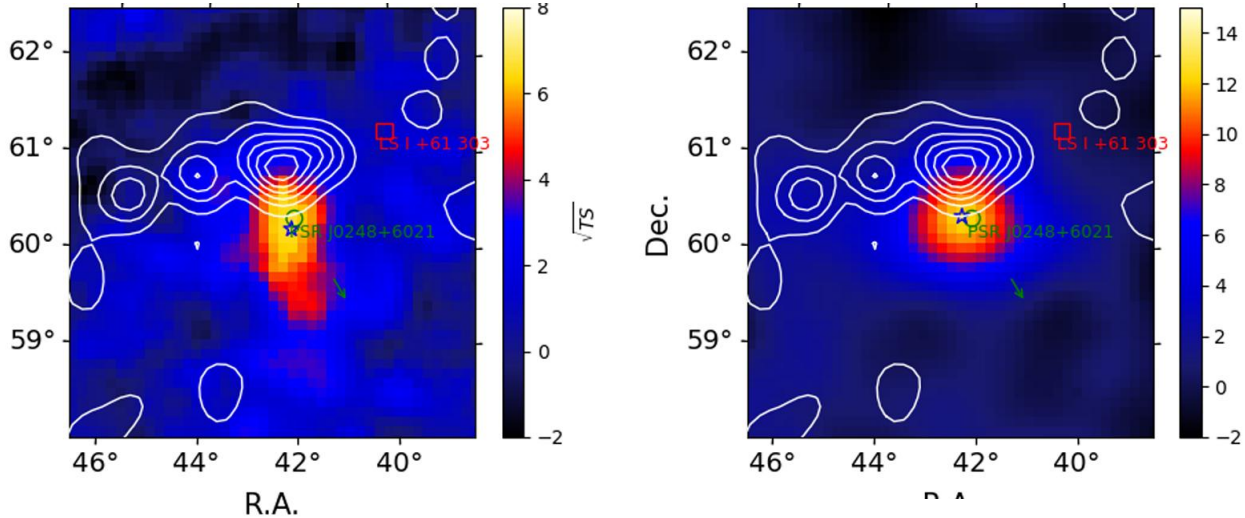
PSR J0007+7303

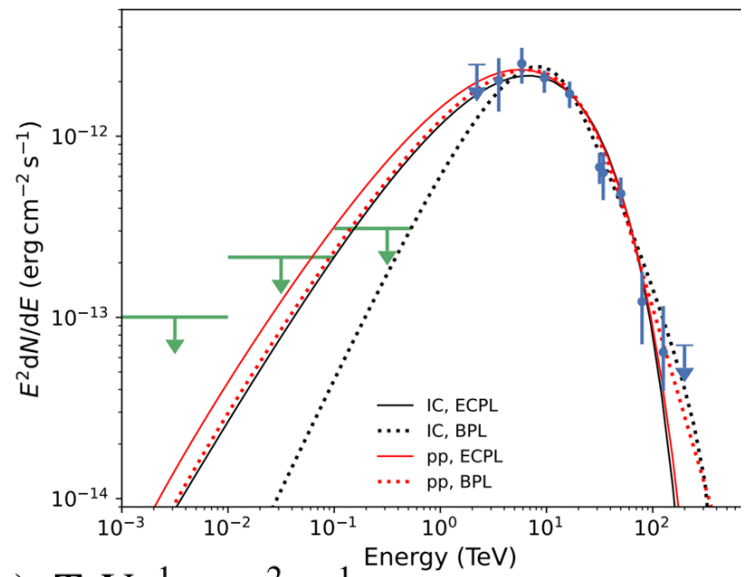


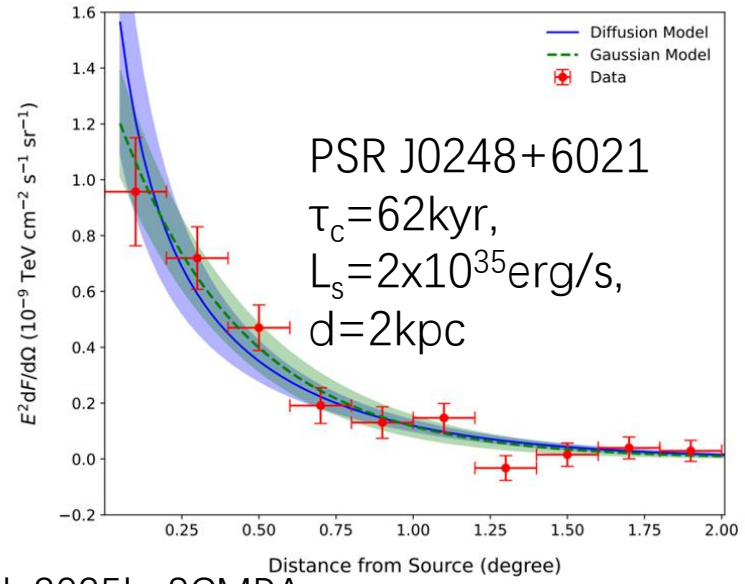


$$dN/dE = (42.4 \pm 4.1)(\frac{E}{20\ \mathrm{TeV}})^{-2.31\pm0.11} \exp(-\frac{E}{110\pm25\ \mathrm{TeV}})\ \ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

PSR J0248+6021

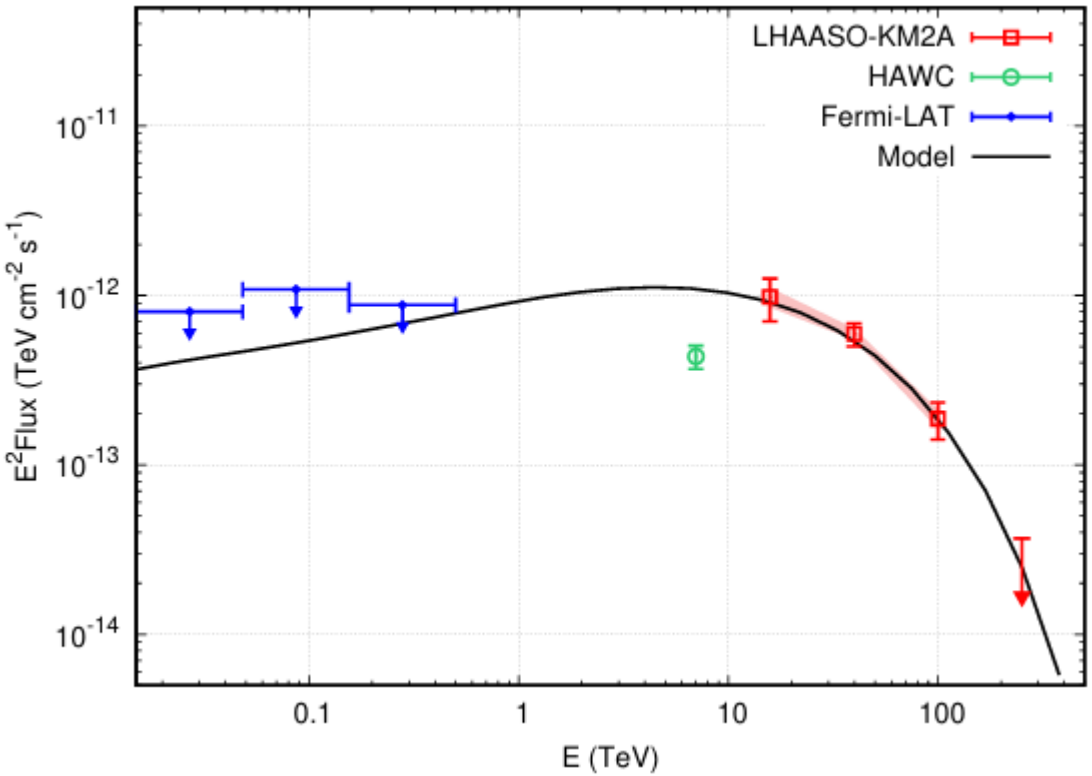


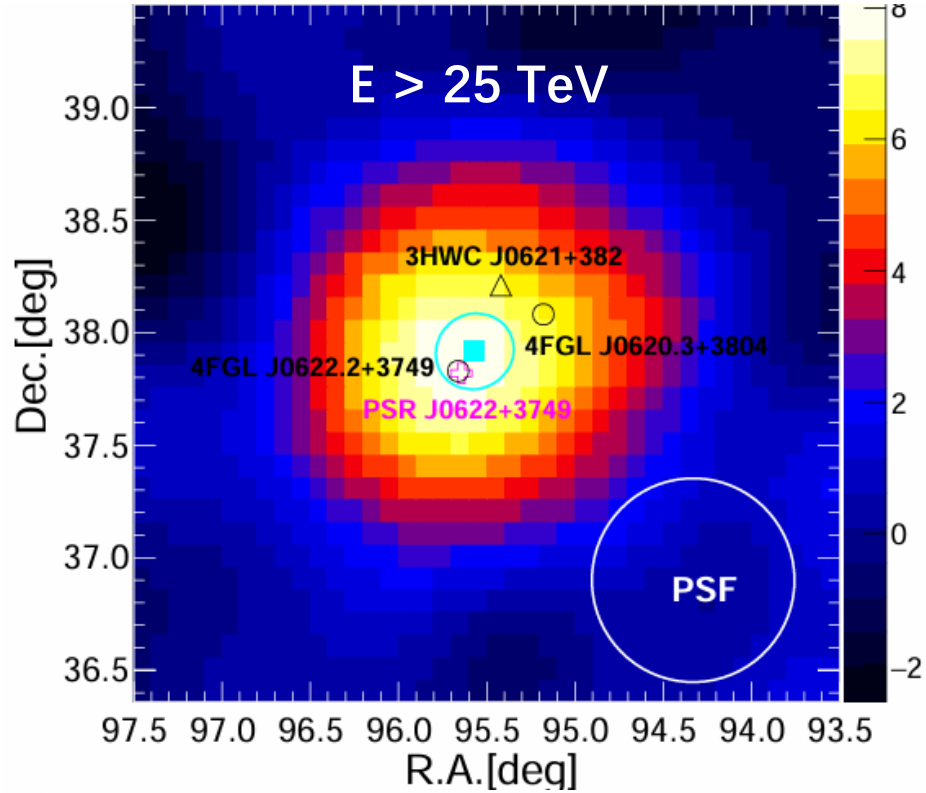


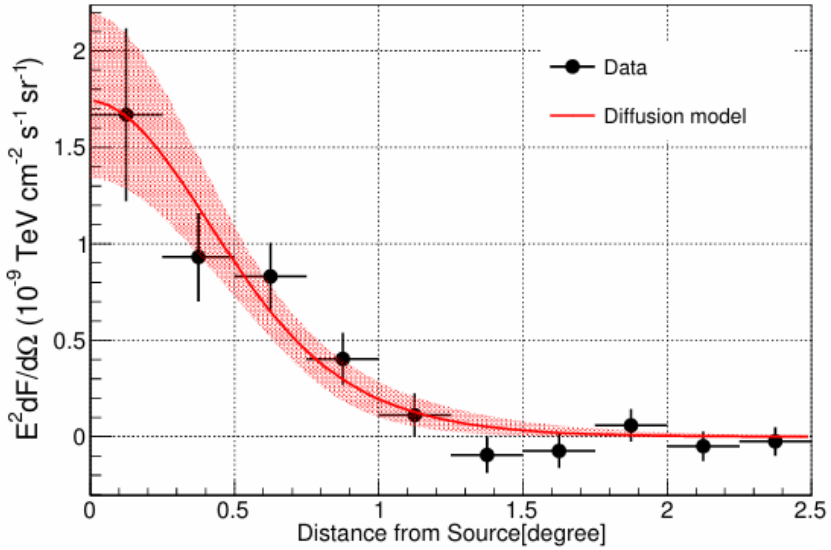


LHAASO Coll. 2025b, SCMPA

LHAASO J0621+3755 coincident with PSR J0622+3749 in 0.1°±0.1°
A candidate of TeV halo







GALACTIC MINI STARBURST W43

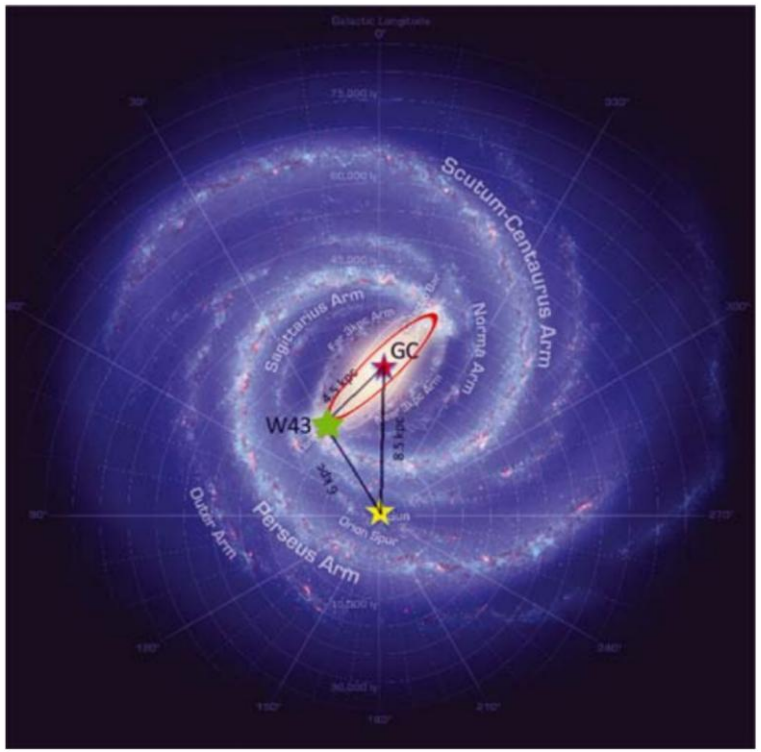
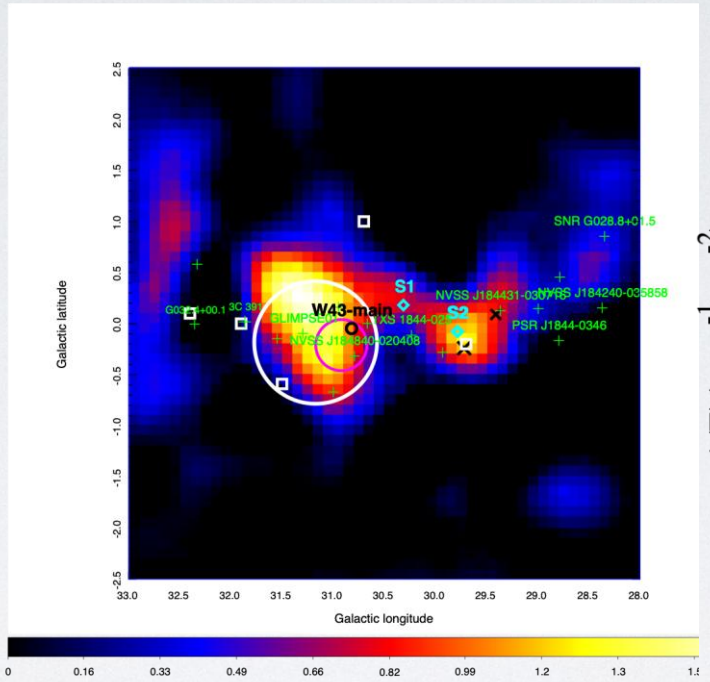
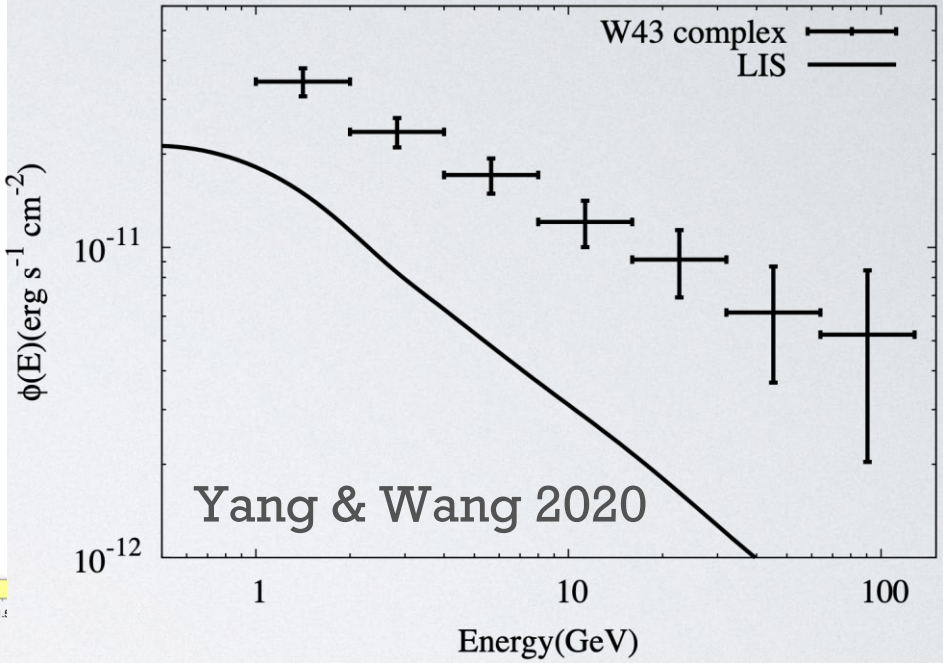


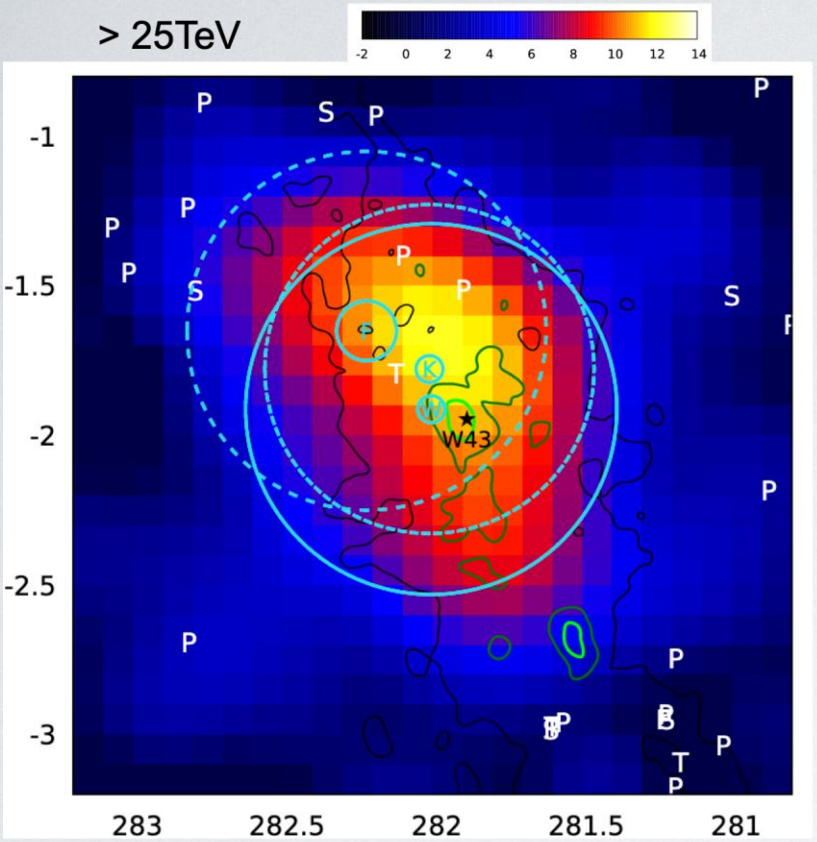
Fig. 9. Artist view of the Galaxy seen face-on with the "long bar" outlined by a red ellipse (Churchwell et al. 2009). W43 is located at the expected transition zone between the bar-dominated region (R_{GC} < 5 kpc) and the normal Galactic disk.

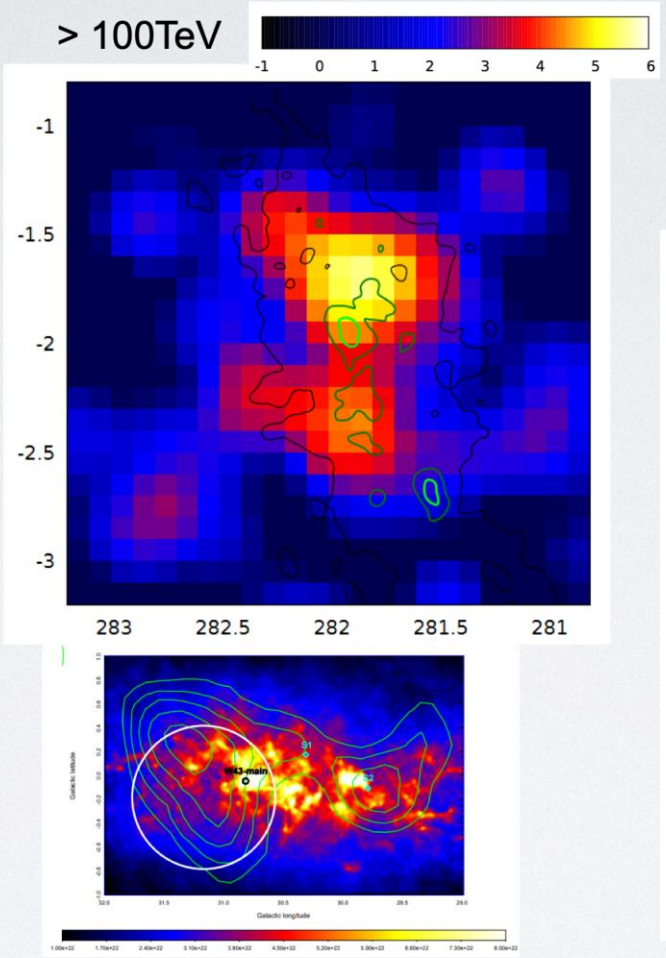


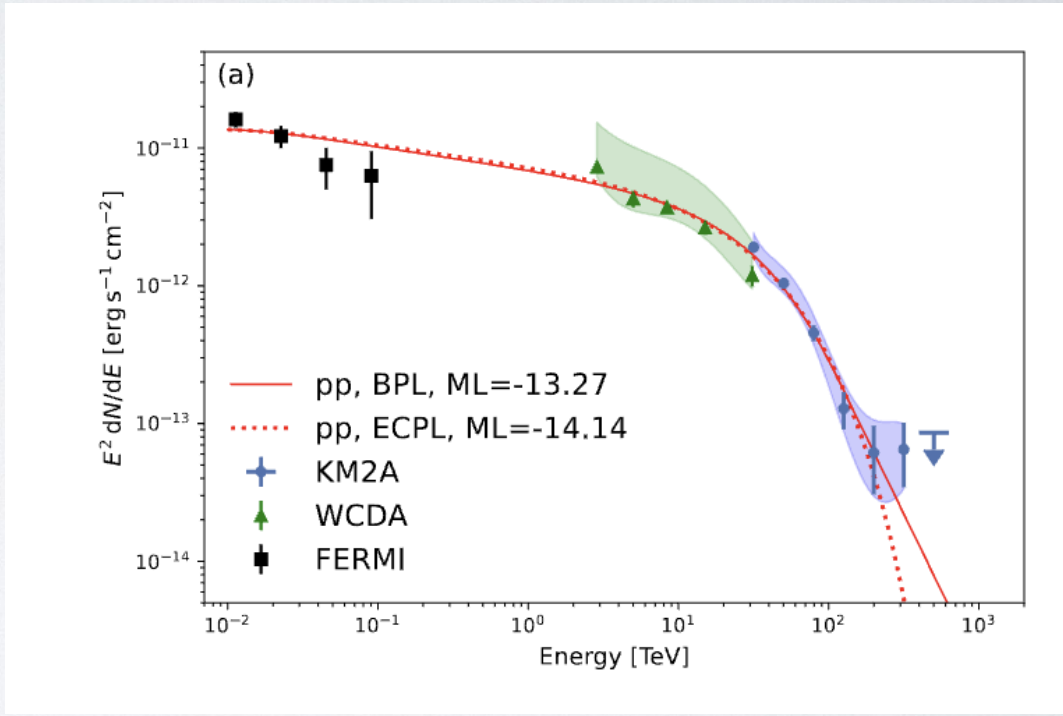


- Galactic mini star burst
- Contribute 10% of the Galactic star formation rate
- Huge HII region excited by central WR/OB cluster
- GeV detection

LHAASO VIEW ON W43



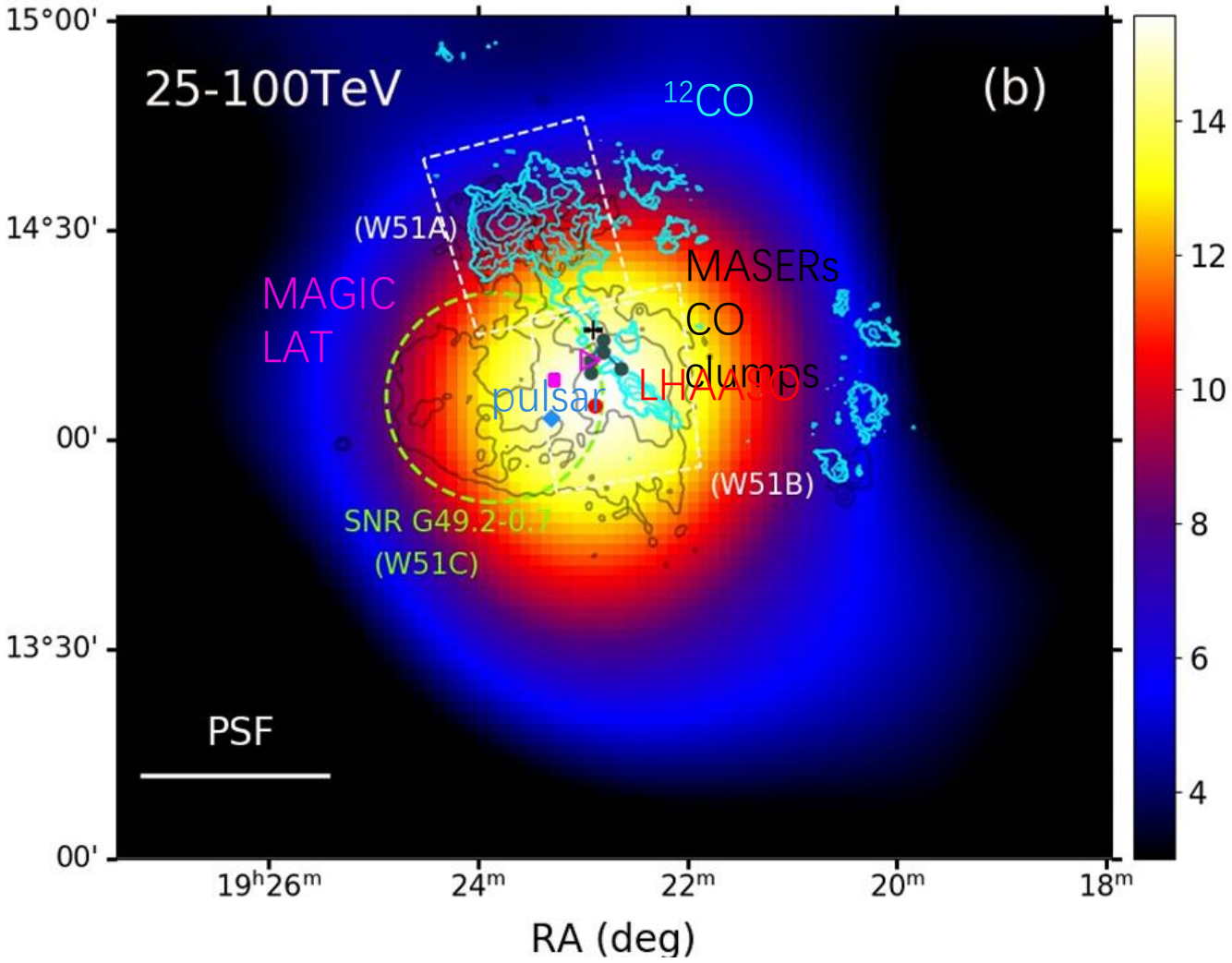


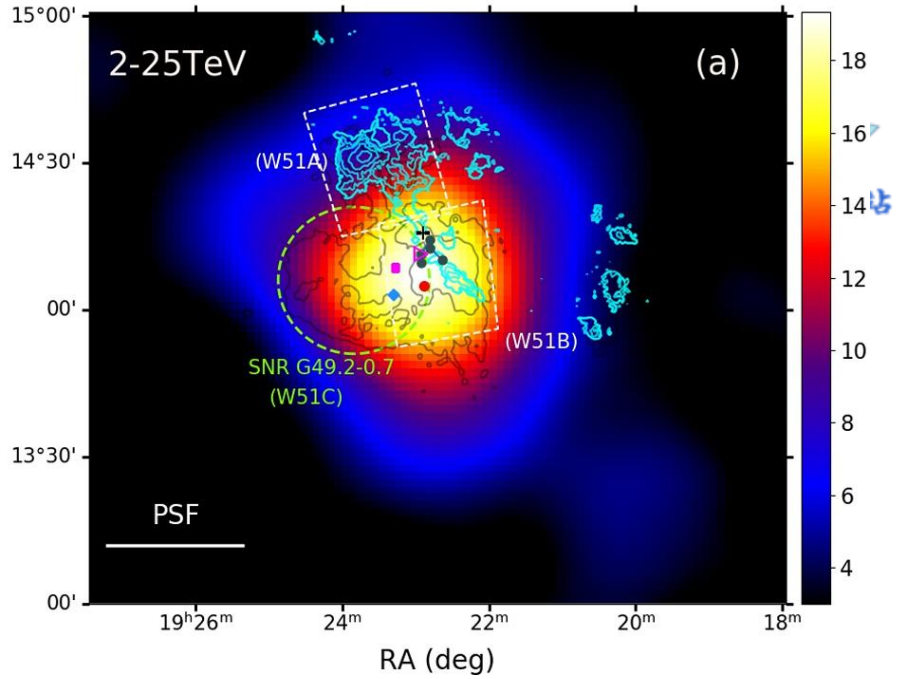


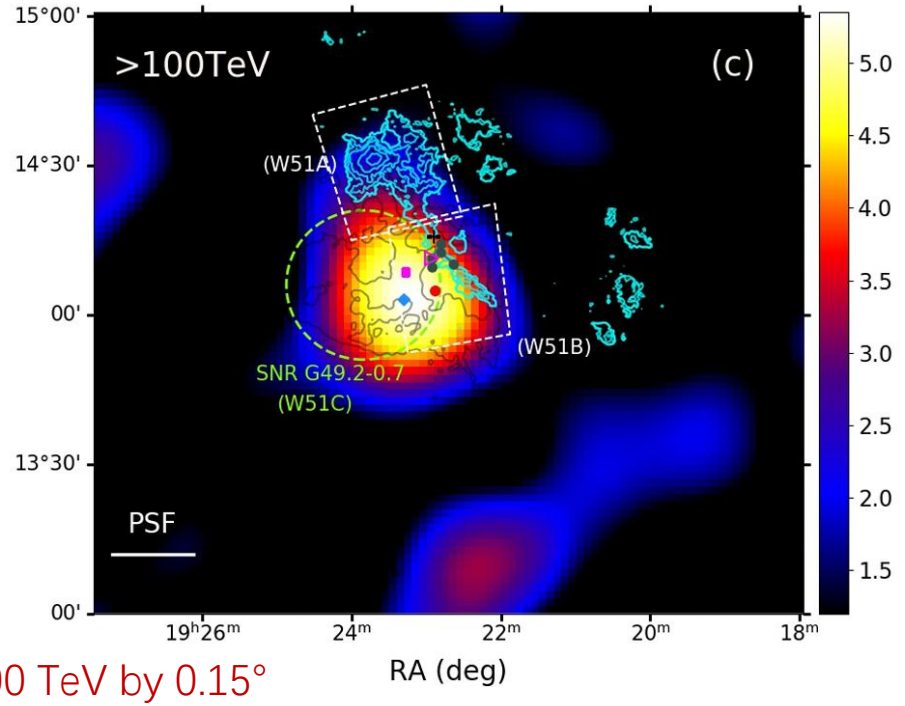
- UHE gamma-ray emission reveal good correlation with dense gas
- Spectrum up to 400 TeV

SNR: W51

D~ 4.3 kpc
T~18 kyr
MC~10^5 solar mass



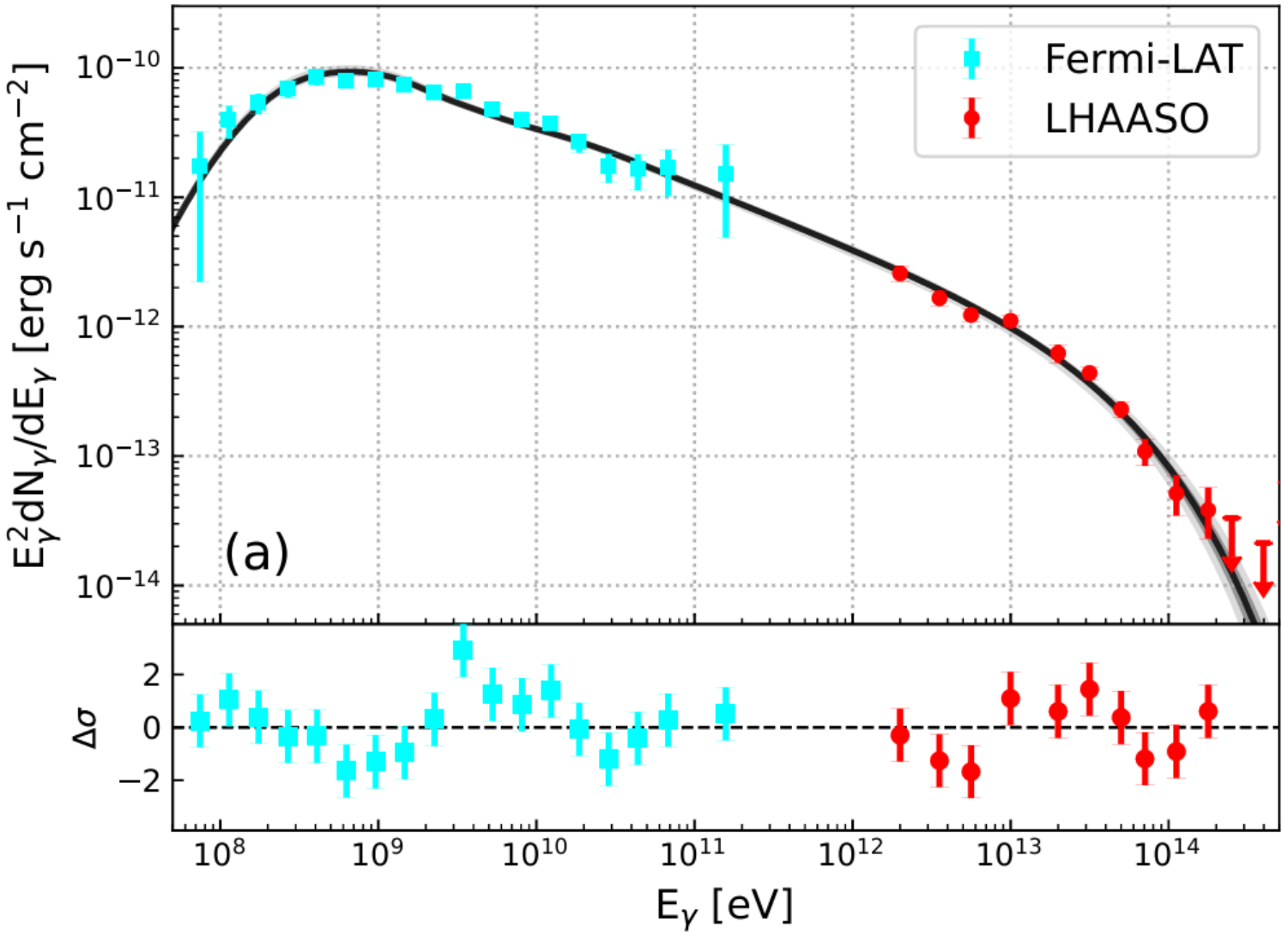




Note: LHAASO centroid shifted towards the **pulsar CXO J192318.5+140305** above 100 TeV by 0.15°

Protons may be same originated as those generated the π^0-bump measured by LAT

- 1st evidence about the SNRs are generating CR protons up to 1 PeV
- Cut-off feature is rather evident with the proton E_{cut} ~ 500 TeV for the accelerator



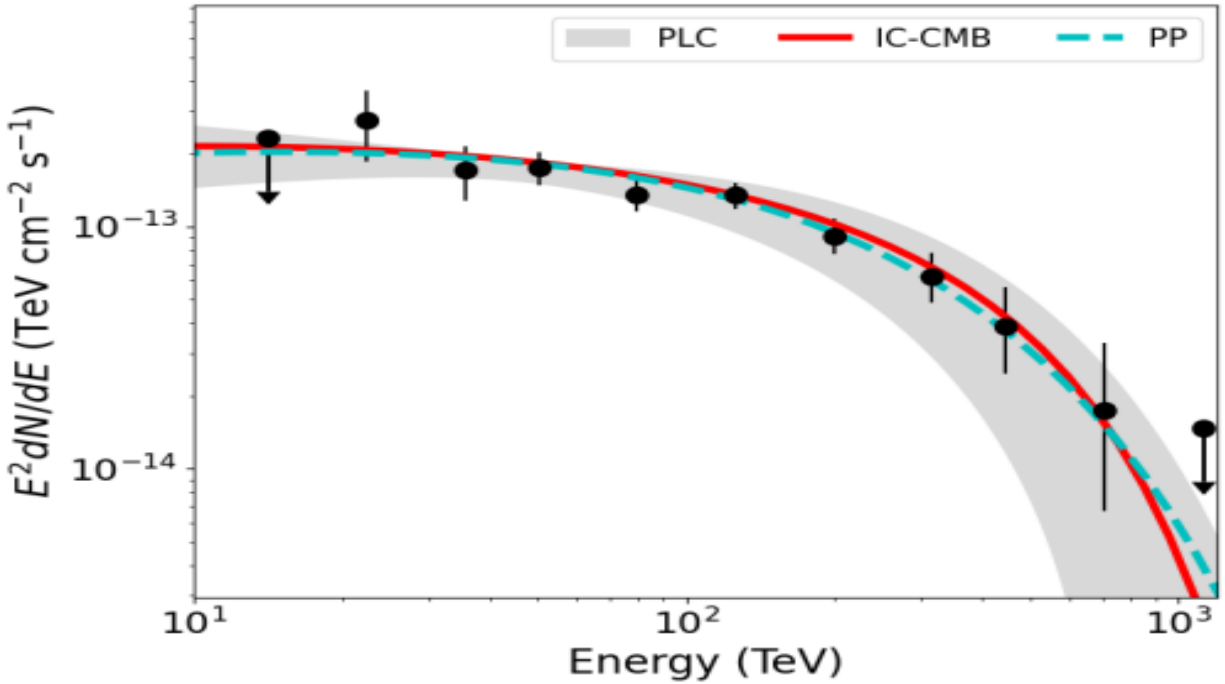
Unidentified Sources

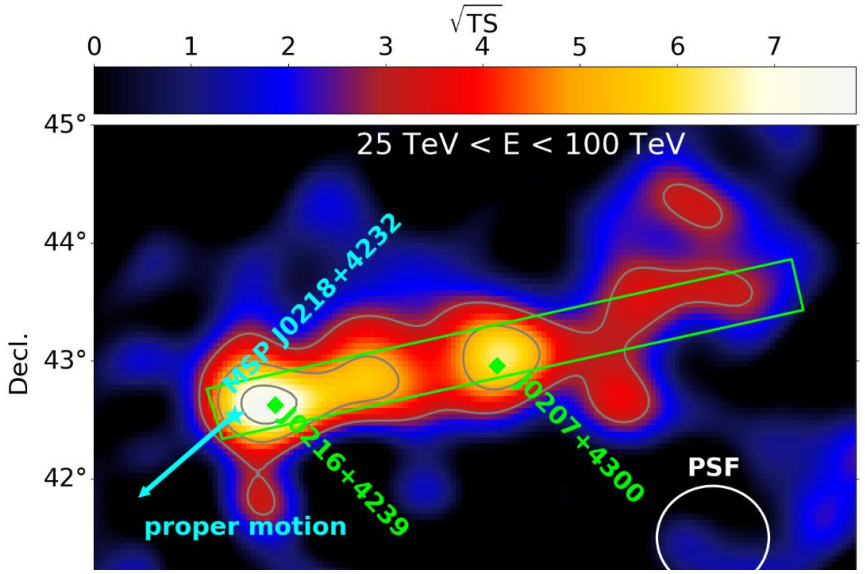
two hotspots + one strip (4.5 deg x 0.5 deg)

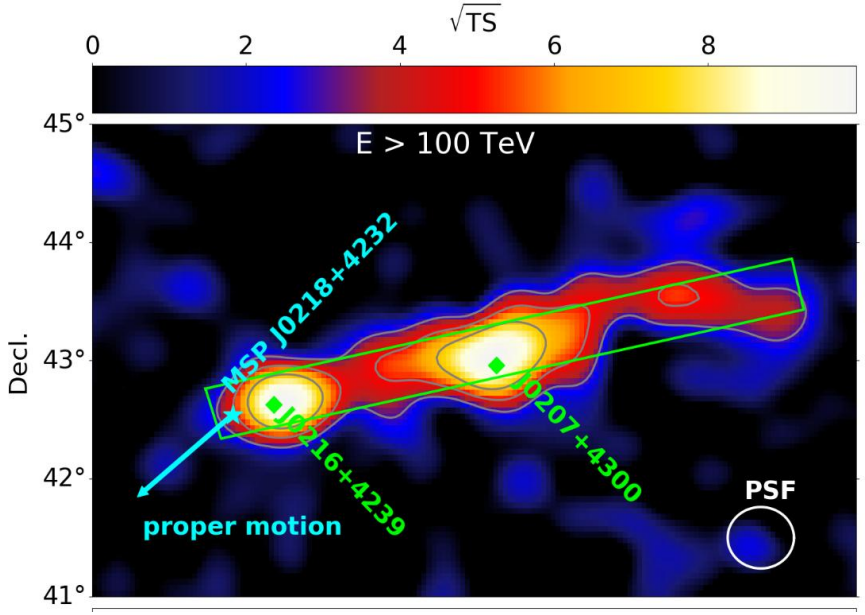
PEANUT at b~17.5°

Properties of MSP J0218+4232

Period, P (ms)	2.32309053
1st period derivative, $\dot{P}$ (s s^{-1})	7.739×10^{-20}
Characteristic age, τ_c (yr)	4.8×10^8
Spin-down power, $\dot{E}$ (erg s^{-1})	2.4×10^{35}
Surface B-field strength, B_S (G)	4.3×10^8
Light-cylinder B-field, B_{LC} (G)	3.1×10^5
Distance, d (kpc)	$3.15^{+0.85}_{-0.60}$
ON pulse region	(0.34–0.98)
OFF pulse region	[0,0.34)∪(0.98,1]



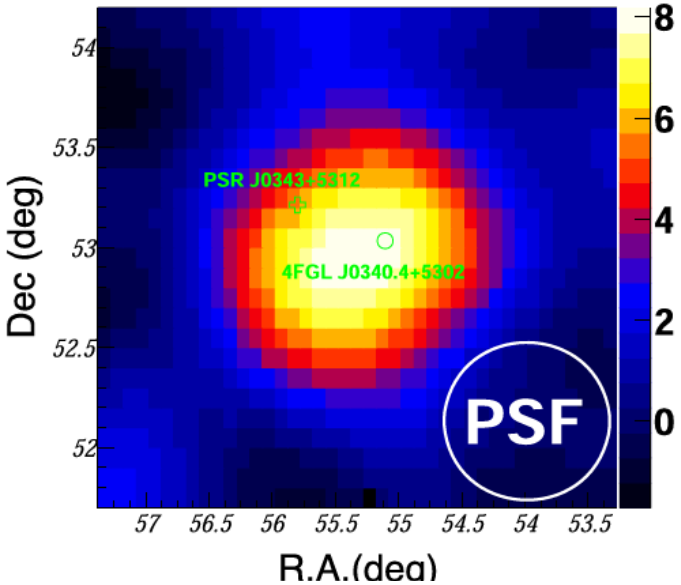


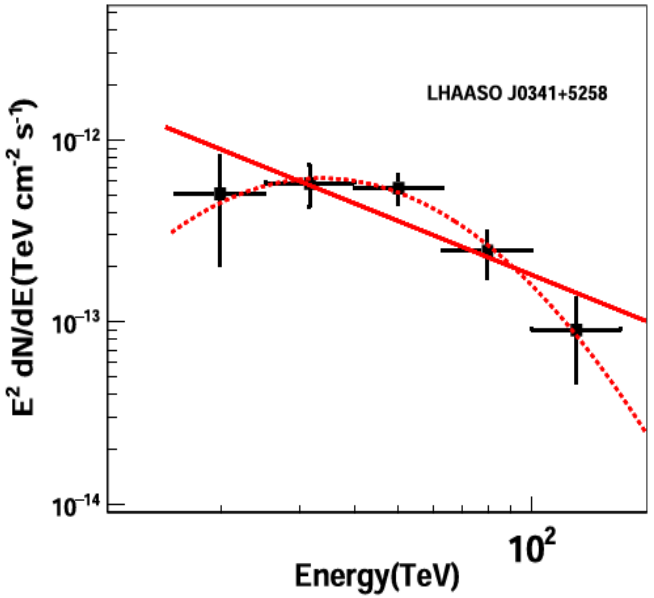


More unidentified

LHAASO J0341+5258

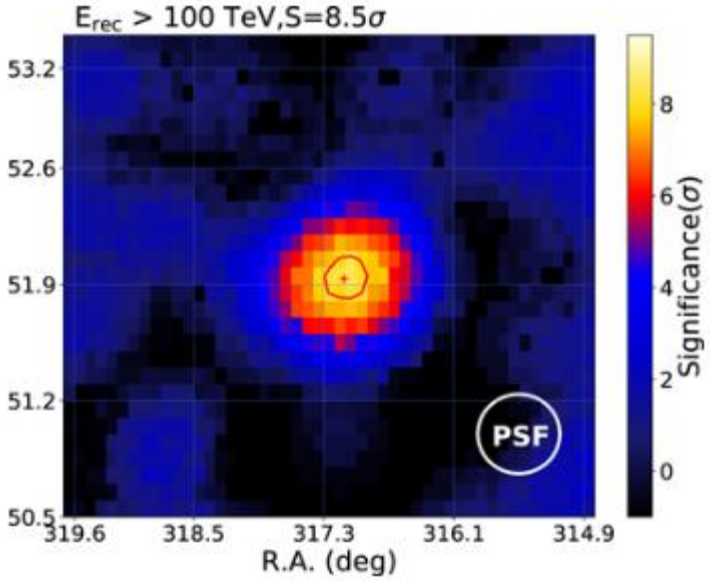
The Astrophysical Journal Letters, Volume 917, Issue 1, id.L4, 7 pp.

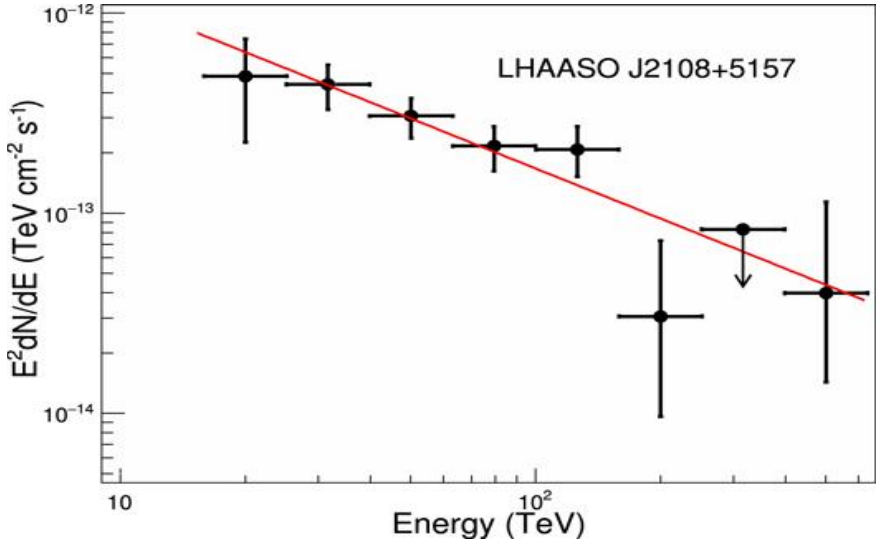




LHAASO J2108+5157

The Astrophysical Journal Letters, Volume 919, Number 2





Short Summary

- Many sources have emission above 100 TeV, some of them are strong, however, SEDs are cut typically below 100 TeV
- μQuasars, PWNe and Staller Cluster are the main population
- Some sources are very interesting but remain **unidentified**
- Is something missing? —— **SNR**

Content

- Introduction

- PeV Gamma Ray Sources
  - The Crab Nebula, Cyg X-3, Cygnus Bubble, J1849-0001, Sgr V4641, J2229+6114, ……
  - Summary on the Super-PeVatrons

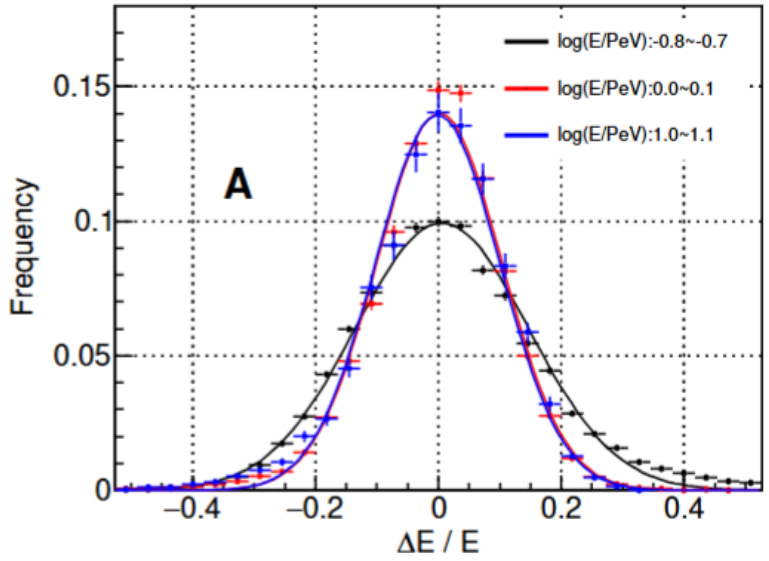
- PeV Particle Generators
  - μ-quasars as CR Accelerators
  - PWNe
  - Staller Clusters and SNRs
  - Unidentified sources

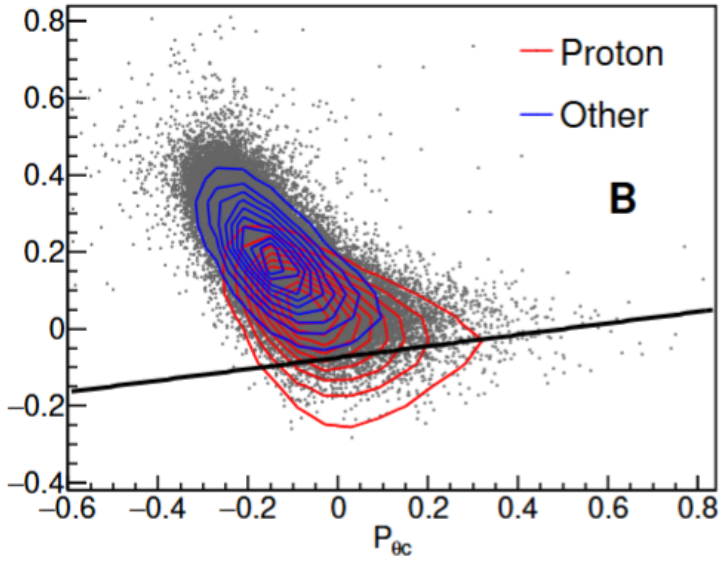
- CR proton spectrum (10 GeV to 10 PeV):
  - Evidence of PeVatrons in our Galaxy: Pure Proton Sample and New Component around the knee

Reconstruction and Proton shower selection

Energy reconstruction

Gaussian energy resolution function

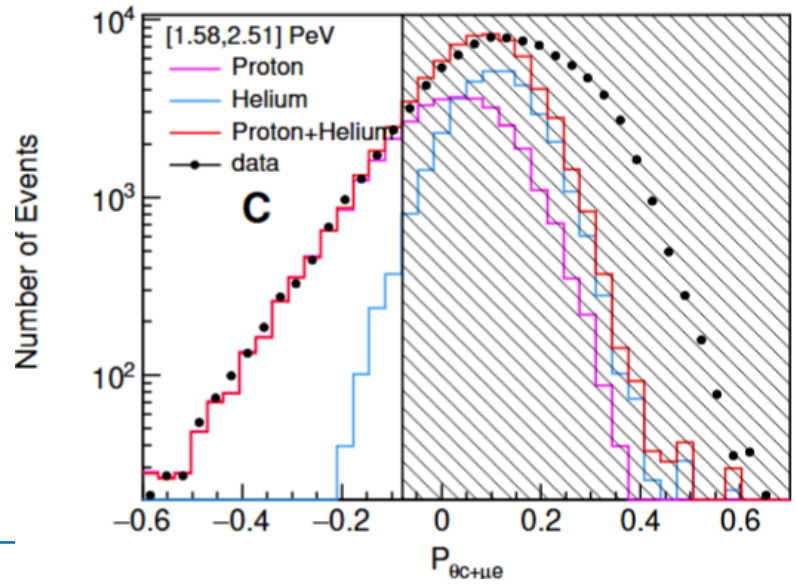


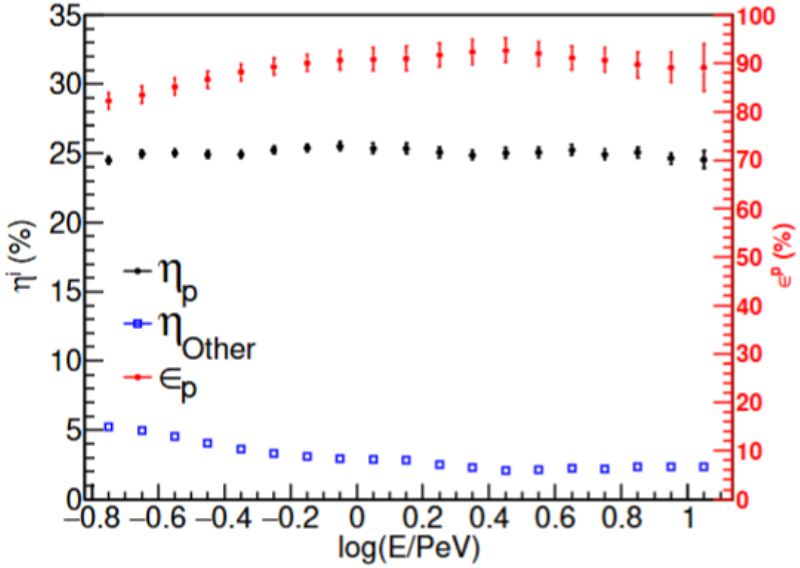


μ-content
Vs.
Shower maximum depth X_{max}

Combined species-sensitive Parameter
Simulated vs data

Parameter





Selection purity & efficiency for protons and other nuclei

Proton spectrum

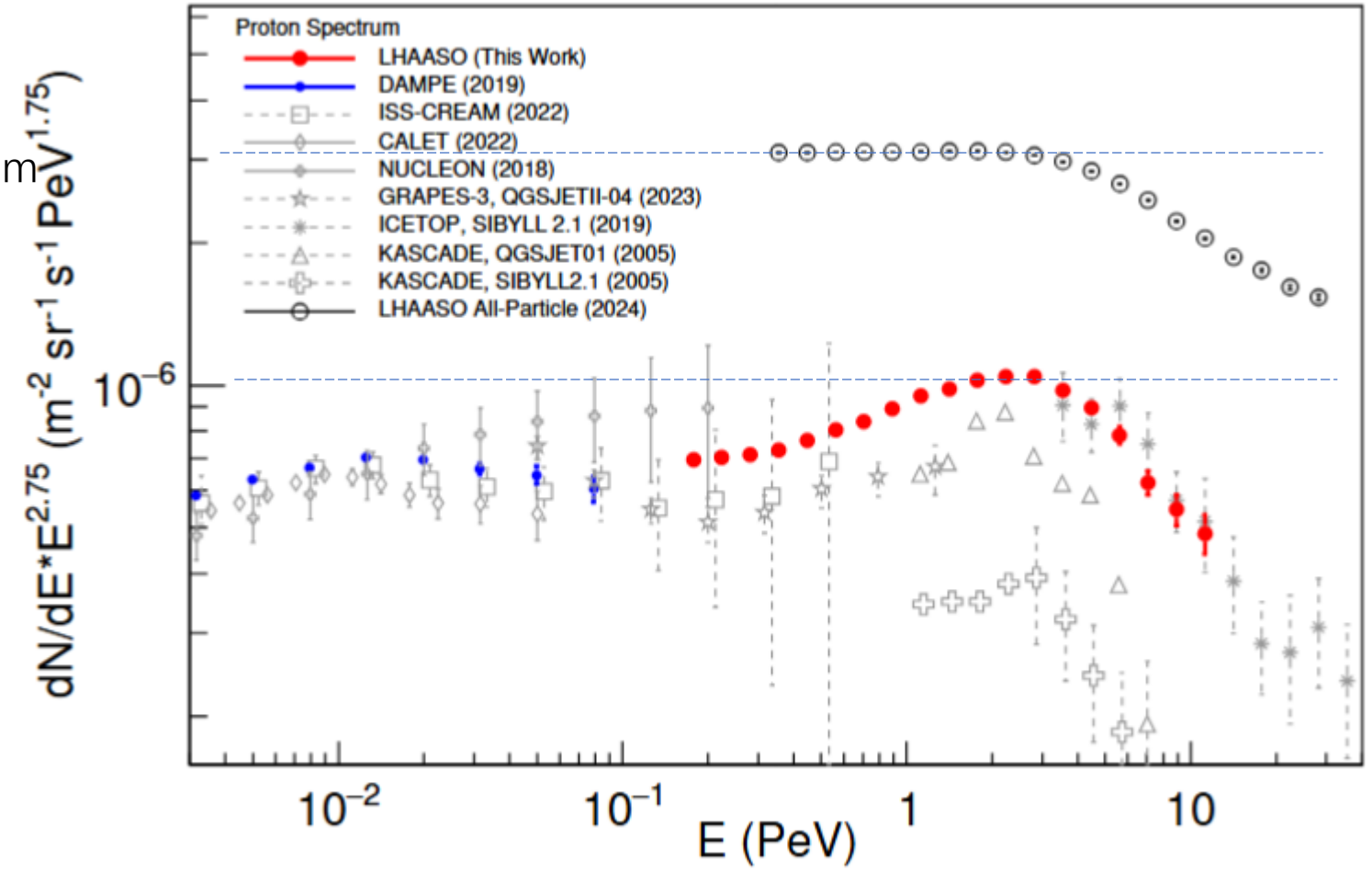
Hardening above 100 TeV

Knee @ knee of all-particle spectrum

Steeper spectrum than all-particle

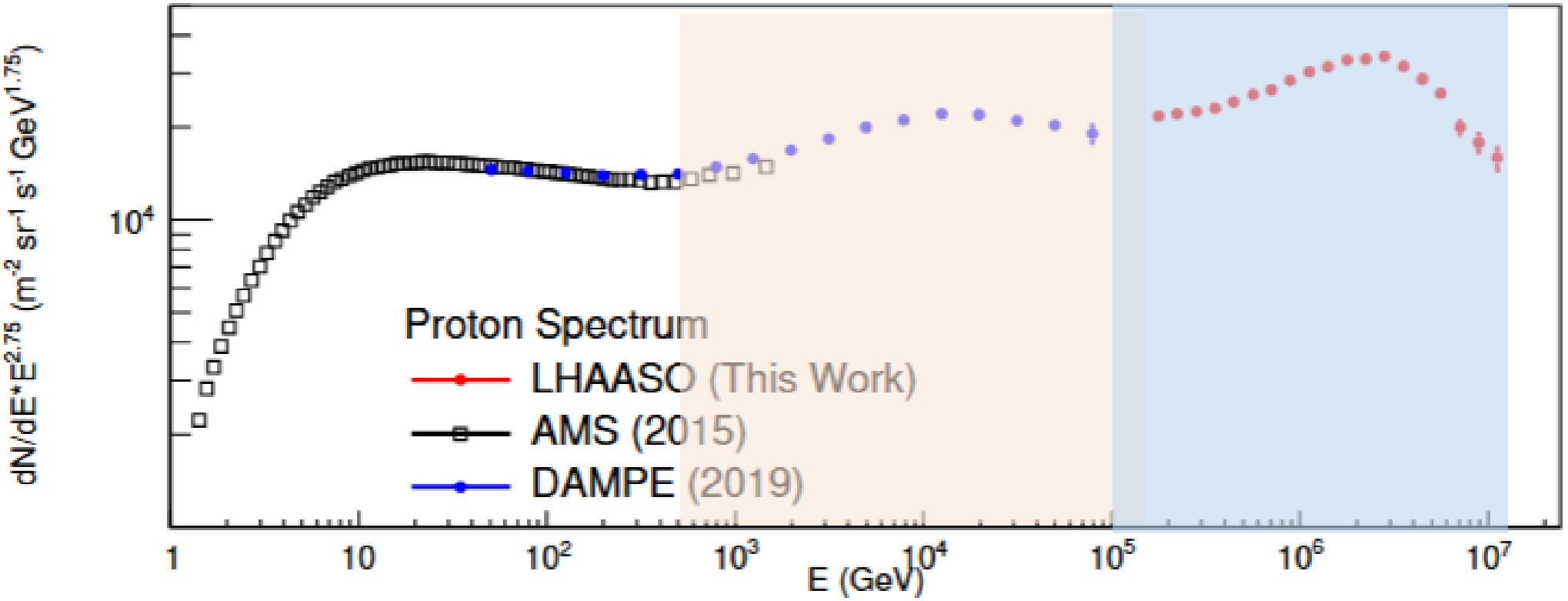
~1/3 fraction

New population of sources?



What LHAASO Observations Tell Us…

- Many evidences collected for the SNRs accelerate CRs to very high energy, W 51, W 44, IC 433, Cas A
- Almost all of them cut at energies around 10 TeV or even lower
- Before the SNR contribution completely dying away, the on-set of a new component is observed with the hardening of the spectrum

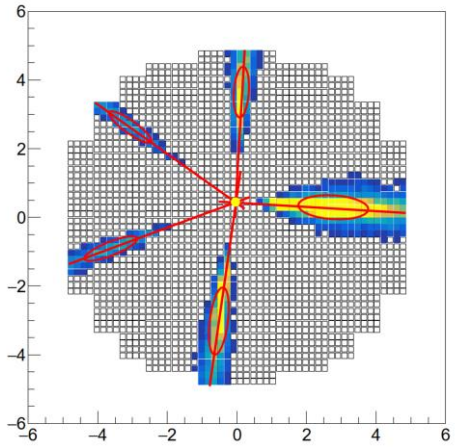


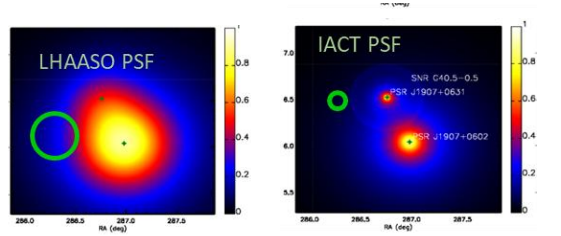
Summary

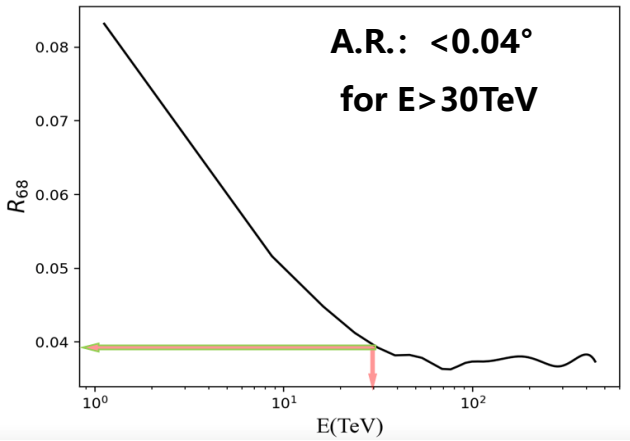
- LHAASO has been finding PeVatrons everywhere in the Milky Way
- Cosmic Ray Super-PeVatrons are found among many species
- μQuasars and PWNe are the major contributors: compact objects
- Many μQuasars, PWNe, Staller clusters, Unidentified PeVatrons with cut-off feature below 10 PeV, and SNR seems missing
- Proton spectrum with 90% purity: a new component around the knee implying non-SNR origin, another hump above 10 PeV?
- LACT with the resolution of 3' for deep investigations on super-PeVatrons in 2 years

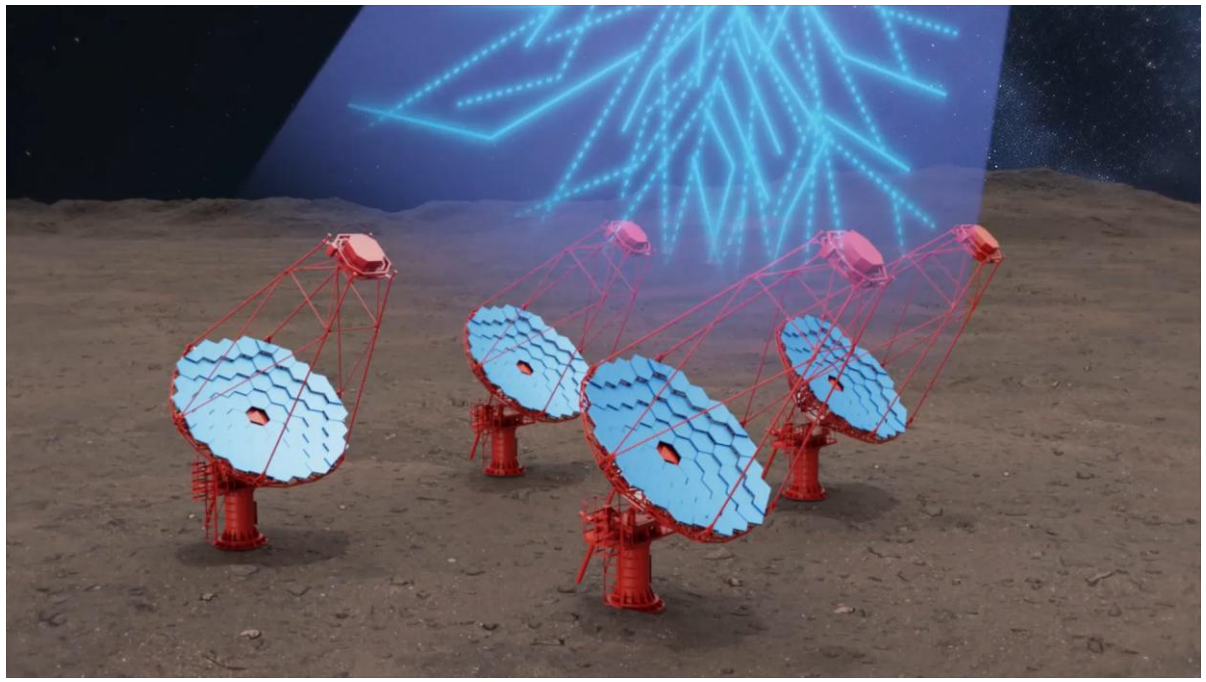
LACT as the upgrading of LHAASO

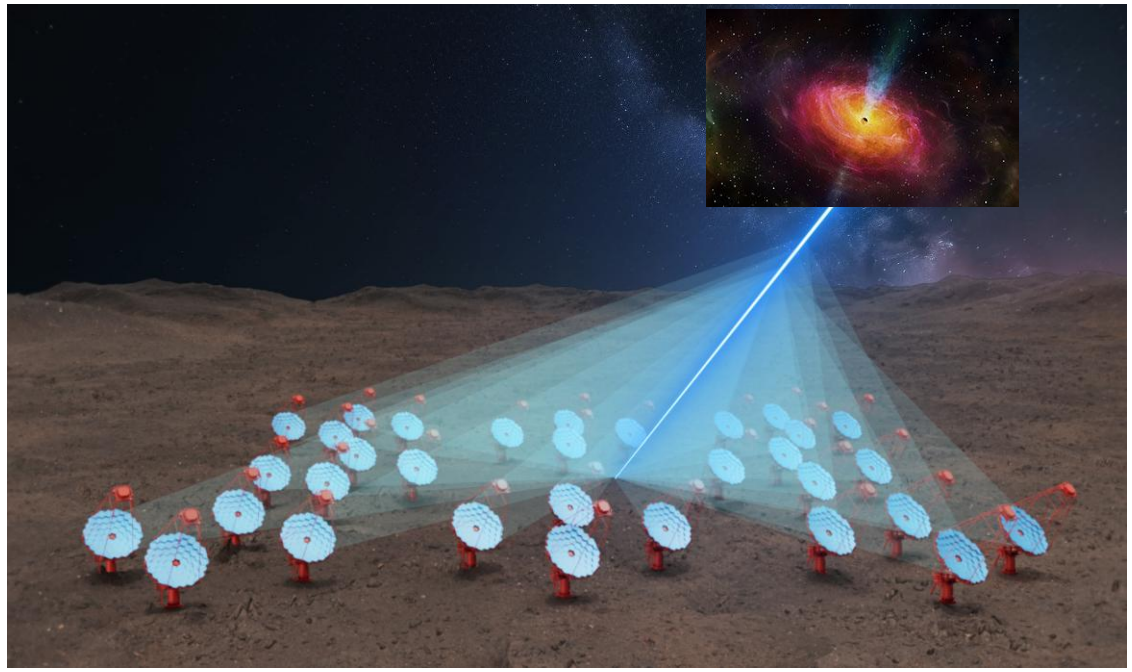
- **Stereo measurement of Cherenkov image**
  - **At least 4 telescopes simultaneously**
- **Reconstruction**
  - Angular resolution **0.04° for E**>30 TeV



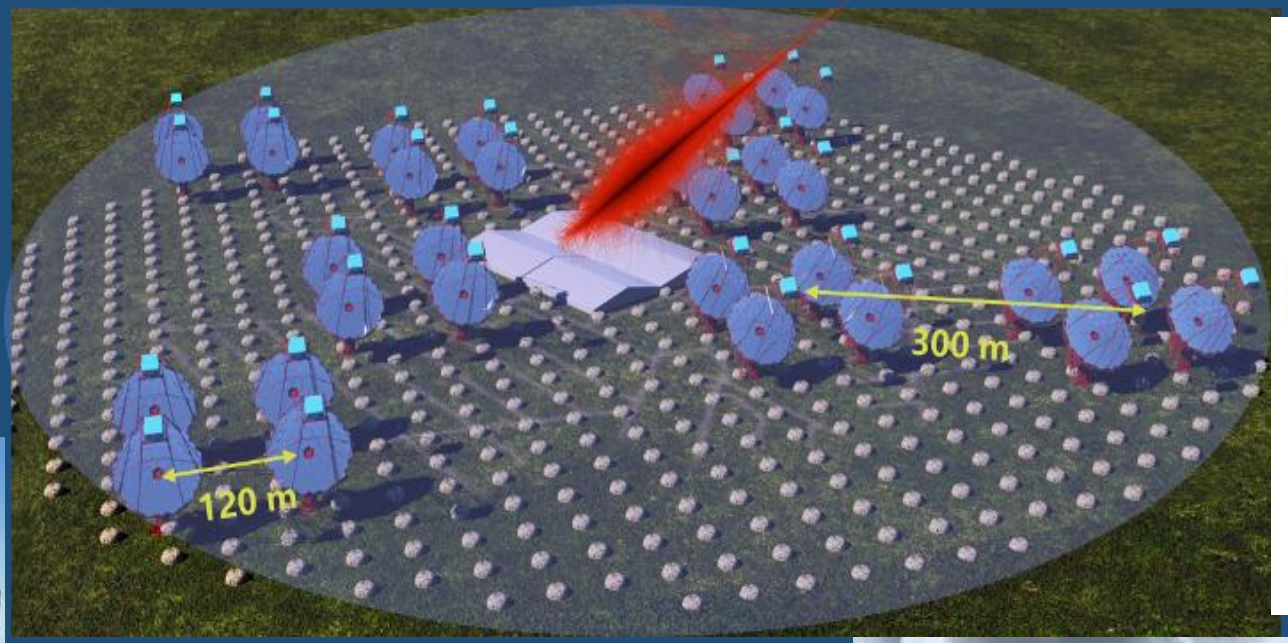


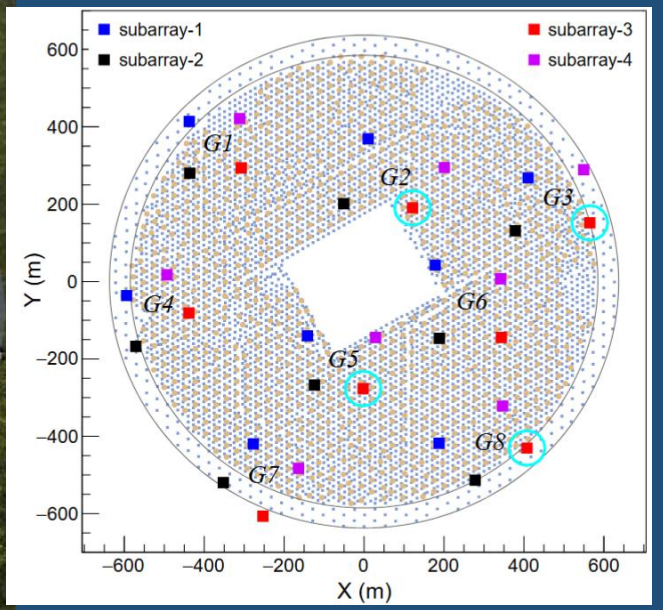






LACT : an IACT array in LHAASO

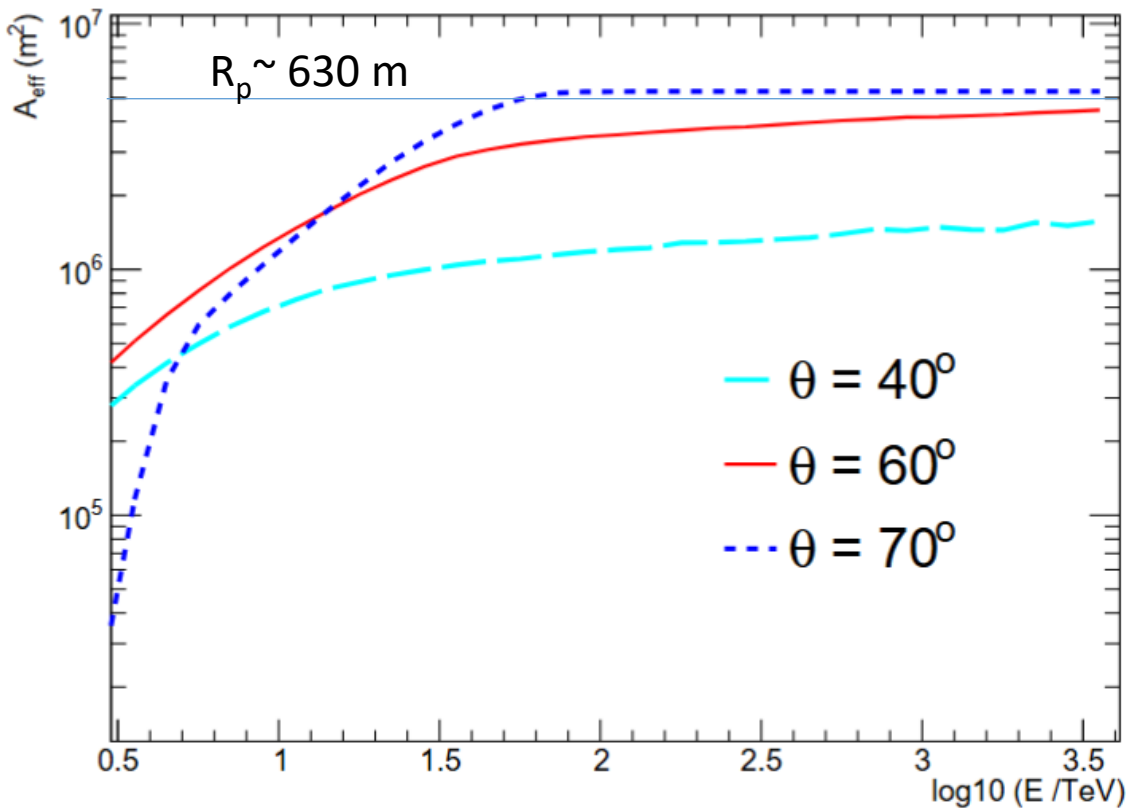


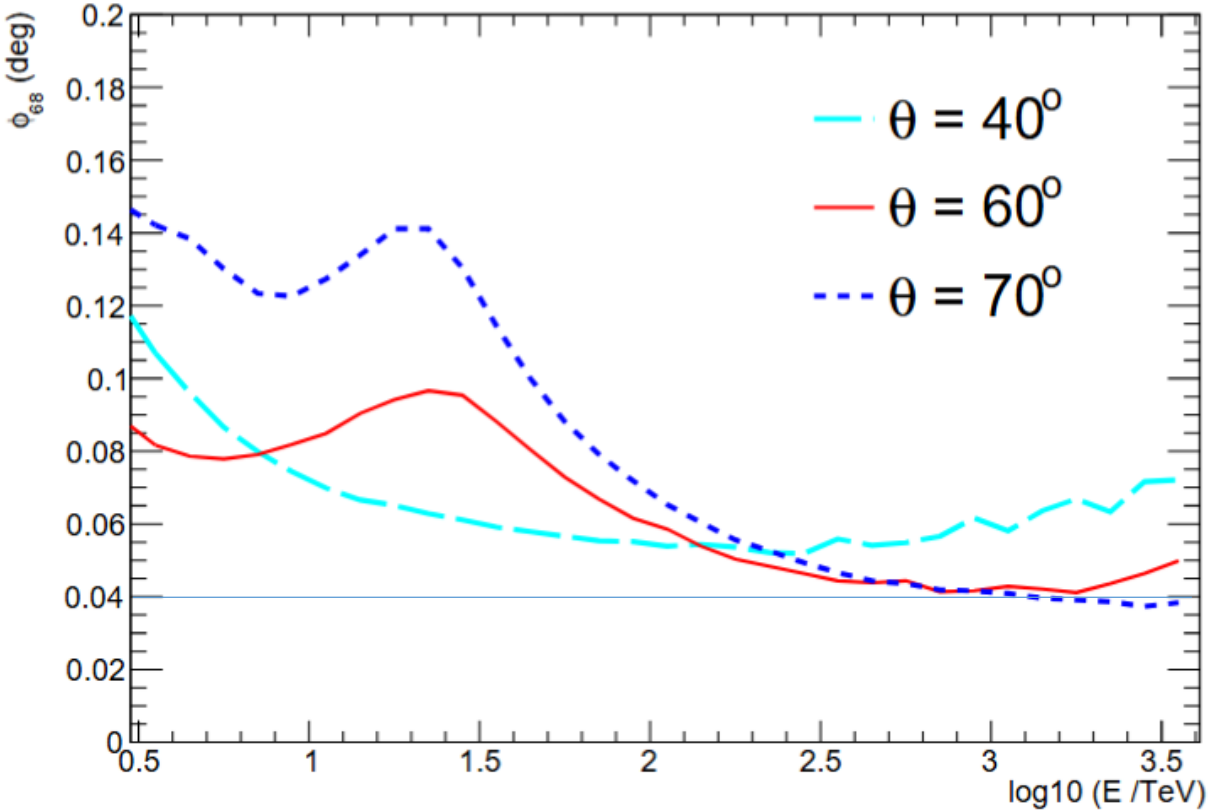


- Funded
- 8X4 array at LHAASO site
- 6-m telescopes
- two proto type telescopes
- First light soon in this year!

4 Telescope Array Performance

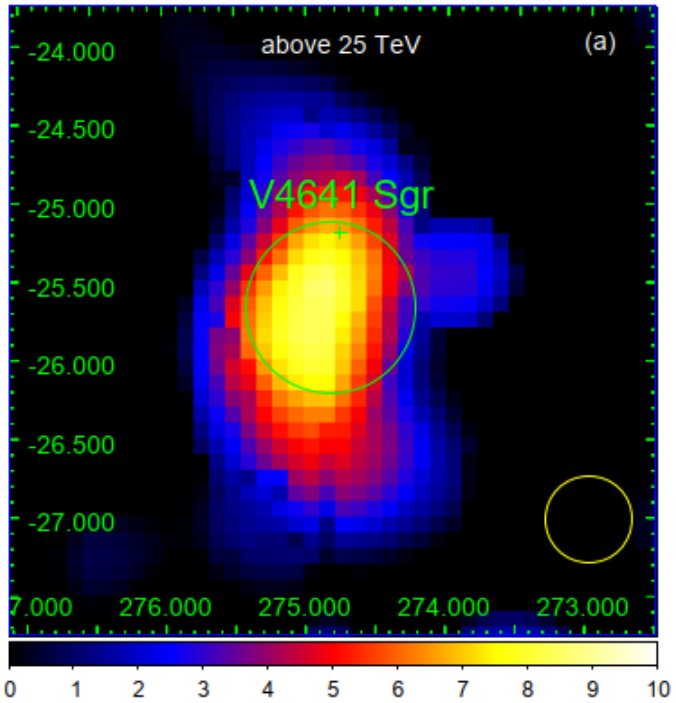
- Effective area for small elevation targets
- Angular resolution

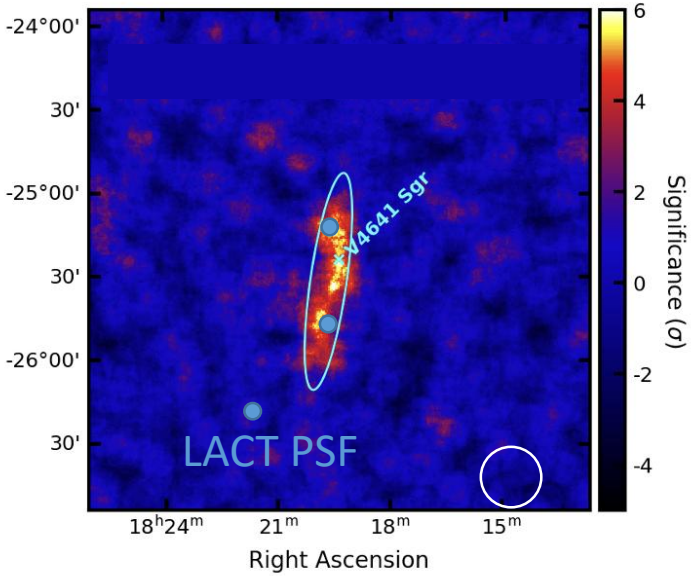


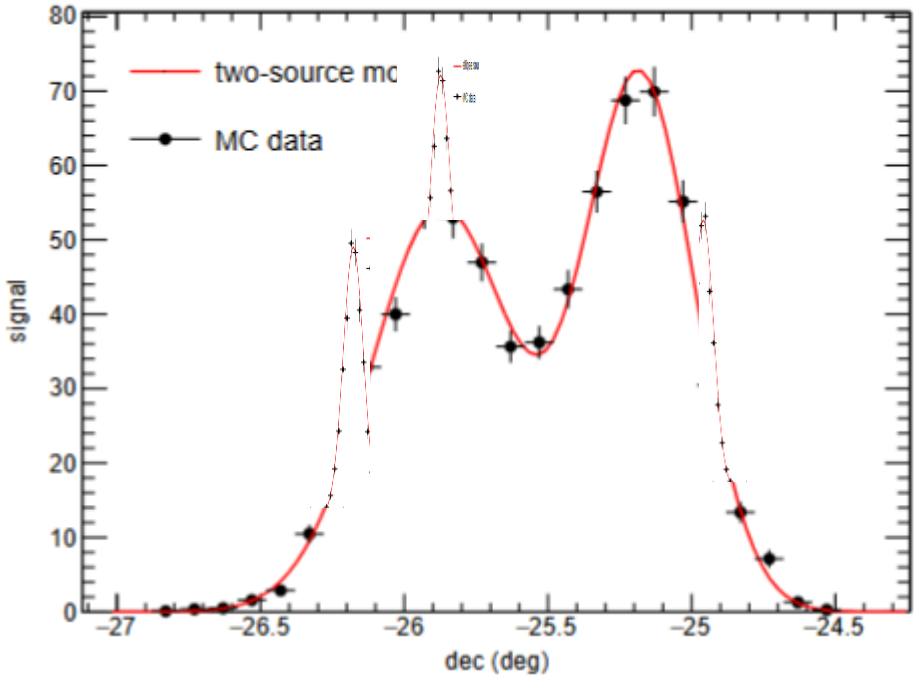


Jet Termination vs central accelerator

- LHAASO vs. LACT (either two point sources or complex morphology)







Expected flux measured in one year with the 4 Telescopes of LACT for different assumed cut-off energy E_{cut}