

PeVatrons in LHAASO's View

—— Origins of CRs at the knee



Zhen Cao, on behalf of LHAASO Collaboration

天府宇宙线研究中心

LST Array Inauguration, La Palma, Oct. 2026

The Site

Bird's eye view of LHAASO, 2021-08

- Location: $29^{\circ}21'27.6''$ N , $100^{\circ}08'19.6''$ E
- Altitude: 4410 m
- 2021-07 completed built and in operation



稻城亚丁机场
Airport

G227

~10KM

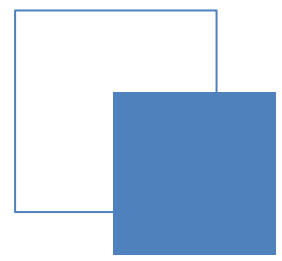
LHAASO

高海拔
宇宙线观测站



LHAASO, *Nature Astronomy* 5:849 (2021)

(Aug. 2018, at 4410 m a.s.l.)



High Energy Cosmic Rays

Large High Altitude Air Shower Observatory (LHAASO)

CATCHING RAYS

China's new observatory will intercept ultra-high-energy γ -ray particles and cosmic rays.

LHAASO Physics Topics

- Gamma Ray Astronomy
- Charged CRs measurement
- New Physics Frontier

18 wide-field-of-view
air Cherenkov
telescopes

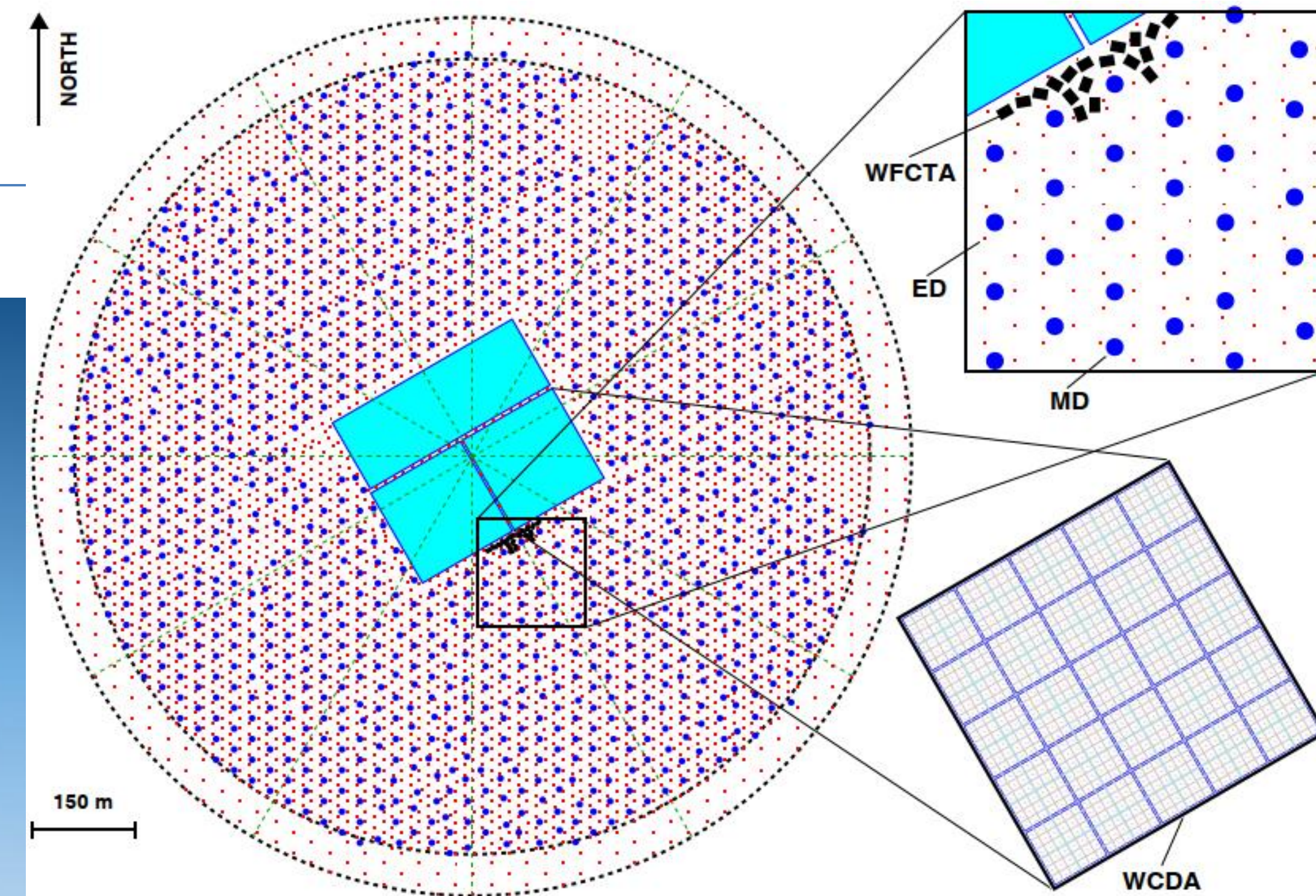
5,195 scintillator
detectors

78,000 -m² surface-
water Cherenkov
detector

1188 underground
water Cherenkov tanks
(muon detectors)

4,410 m

~25,000 m



Hybrid Detection of EAS

Survey for PeVatrons

More data+New method applied to measure GDE

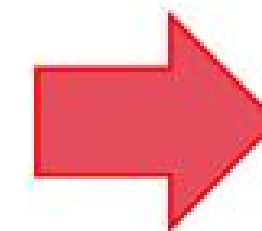


Resolved Sources (RS) Measurement / RS-DGE Separation

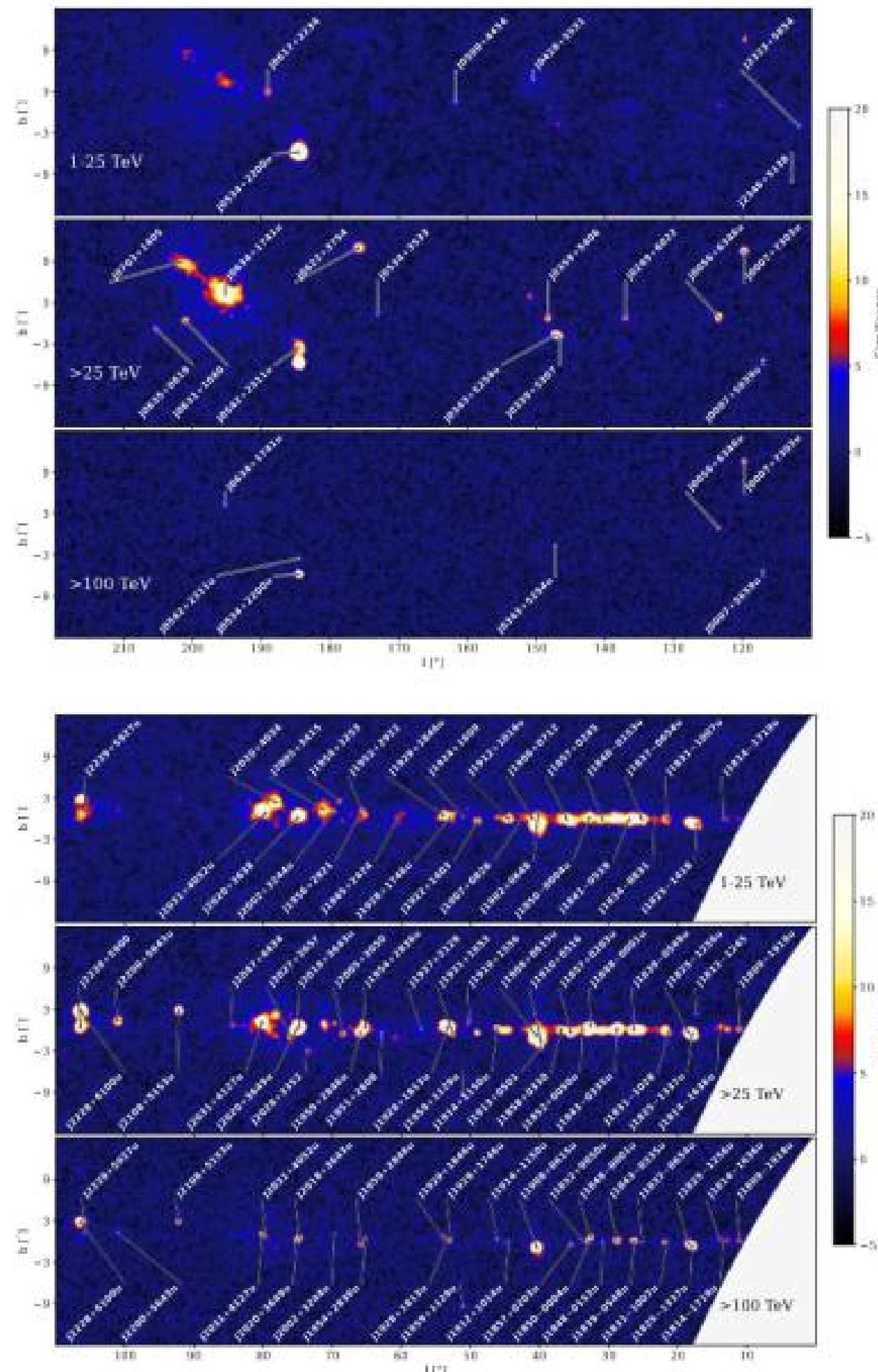
- RS:** Morphology - Gaussian
Spectrum - Log-Parabola (LP) / CutoffPowerLaw (ECPL)
- DGE:** Morphology - Planck Dust Map
Spectrum - Log-Parabola
- Iteration loop**
 - Fit RS + DGE
 - Check residual significance map
 - Add new RS if needed
 - Repeat with updated catalog

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



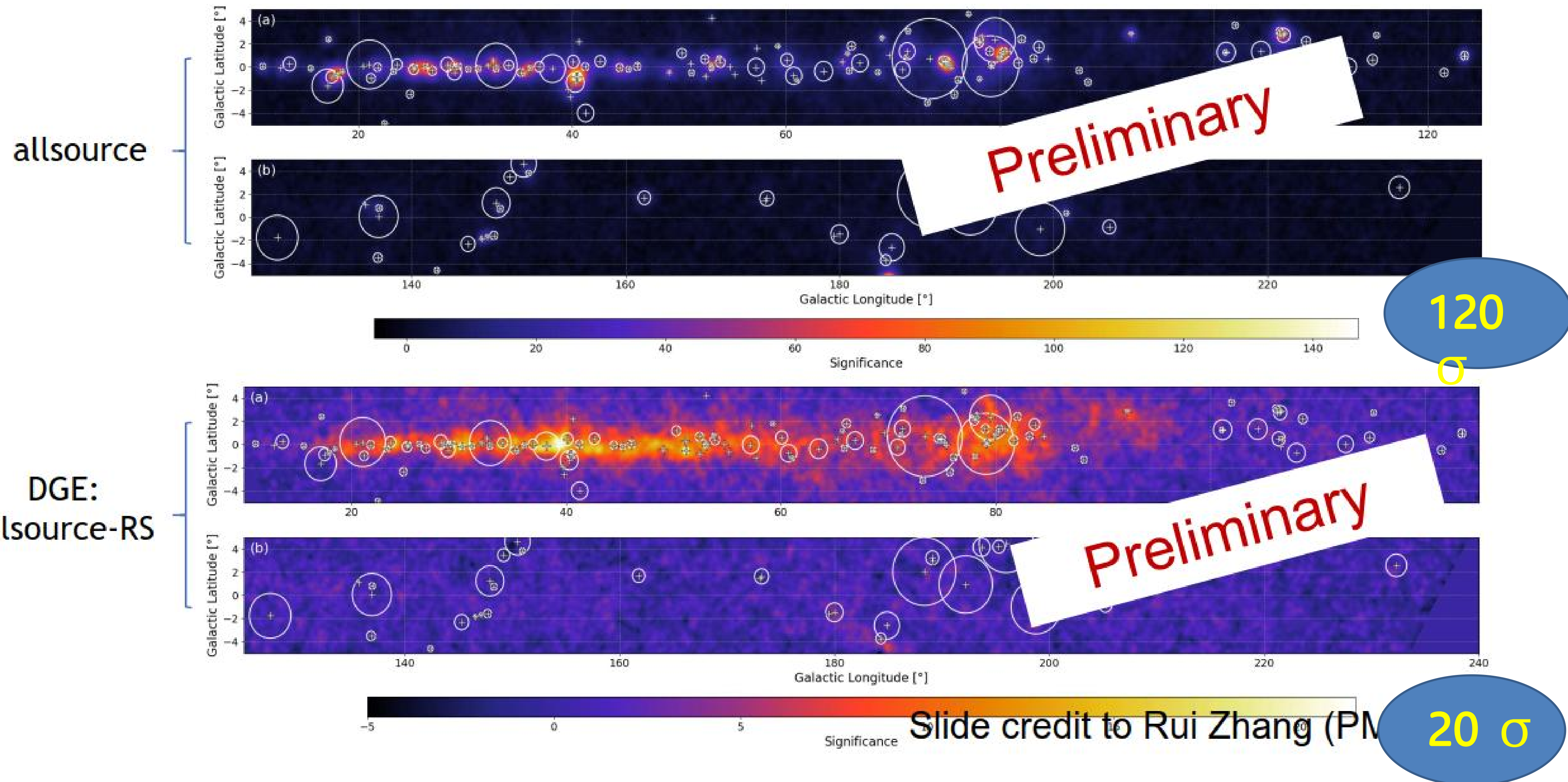
Slide credit to Rui Zhang (PMO)

~190 Sources (without AI-aid analysis)

More data + New method applied to measure GDE

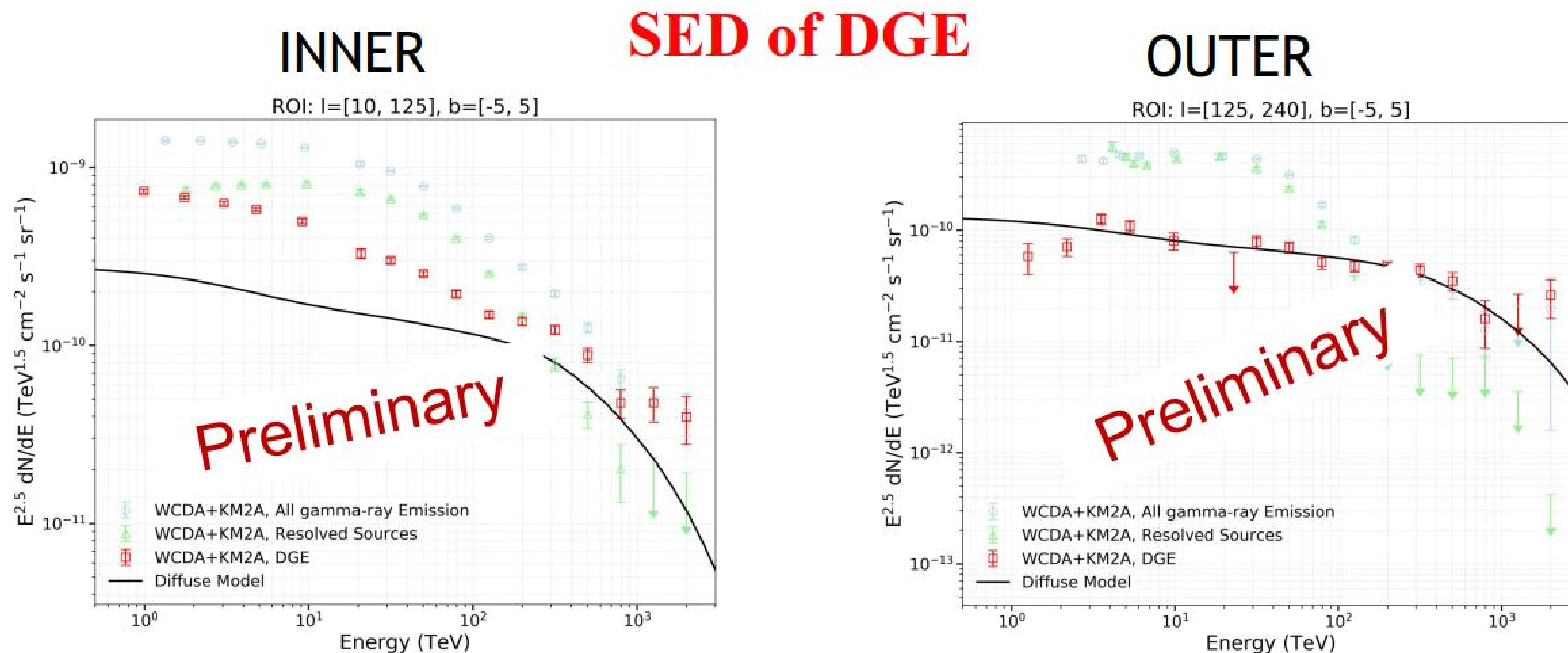


Significance Map before/after subtracting Resolved Sources



Better DGE measurements

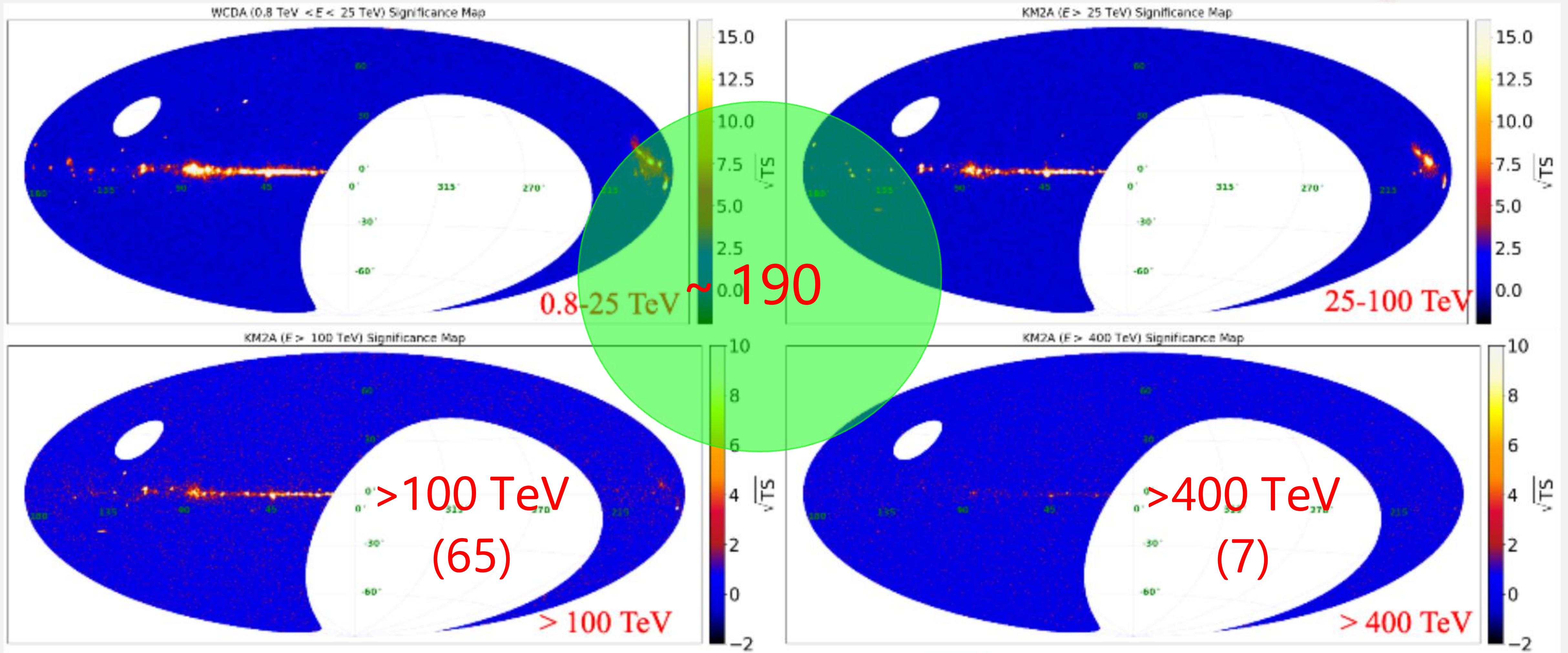
More data + New method applied to measure GDE

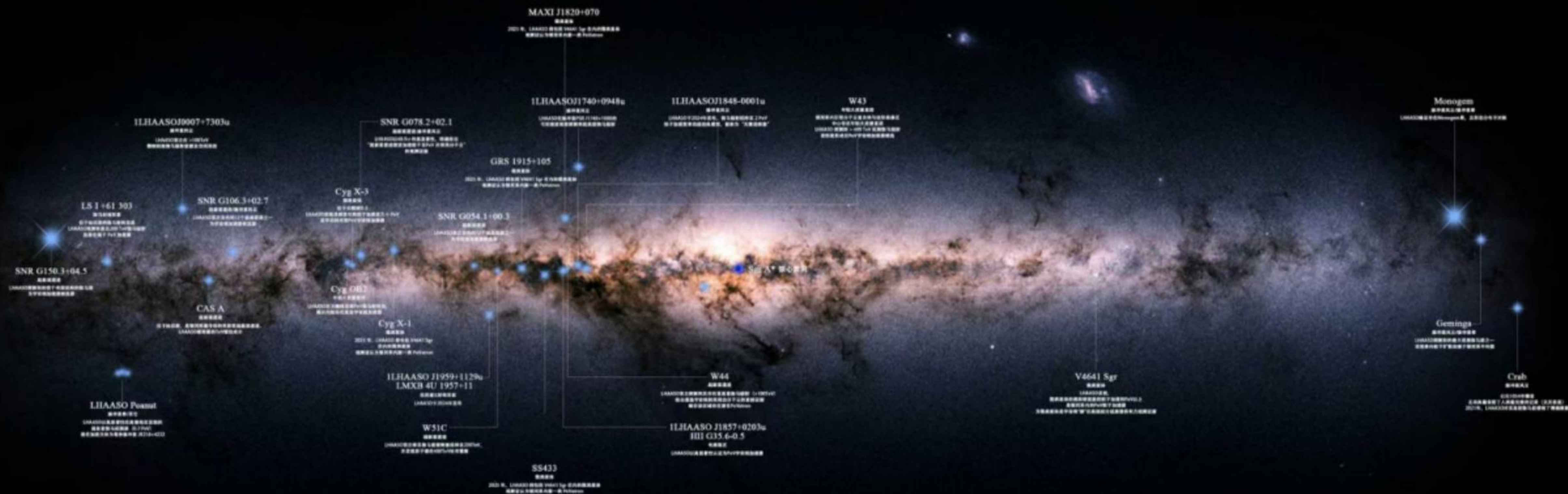


- Diffuse Model: LHAASO CR (p+He) spectrum + ISM, no CR distribution
- $E > 100$ TeV: similar spectral shape (index) as that of measurements
- $E < 100$ TeV: extra component with E_{cut} around tens of TeV for Inner Galaxy region

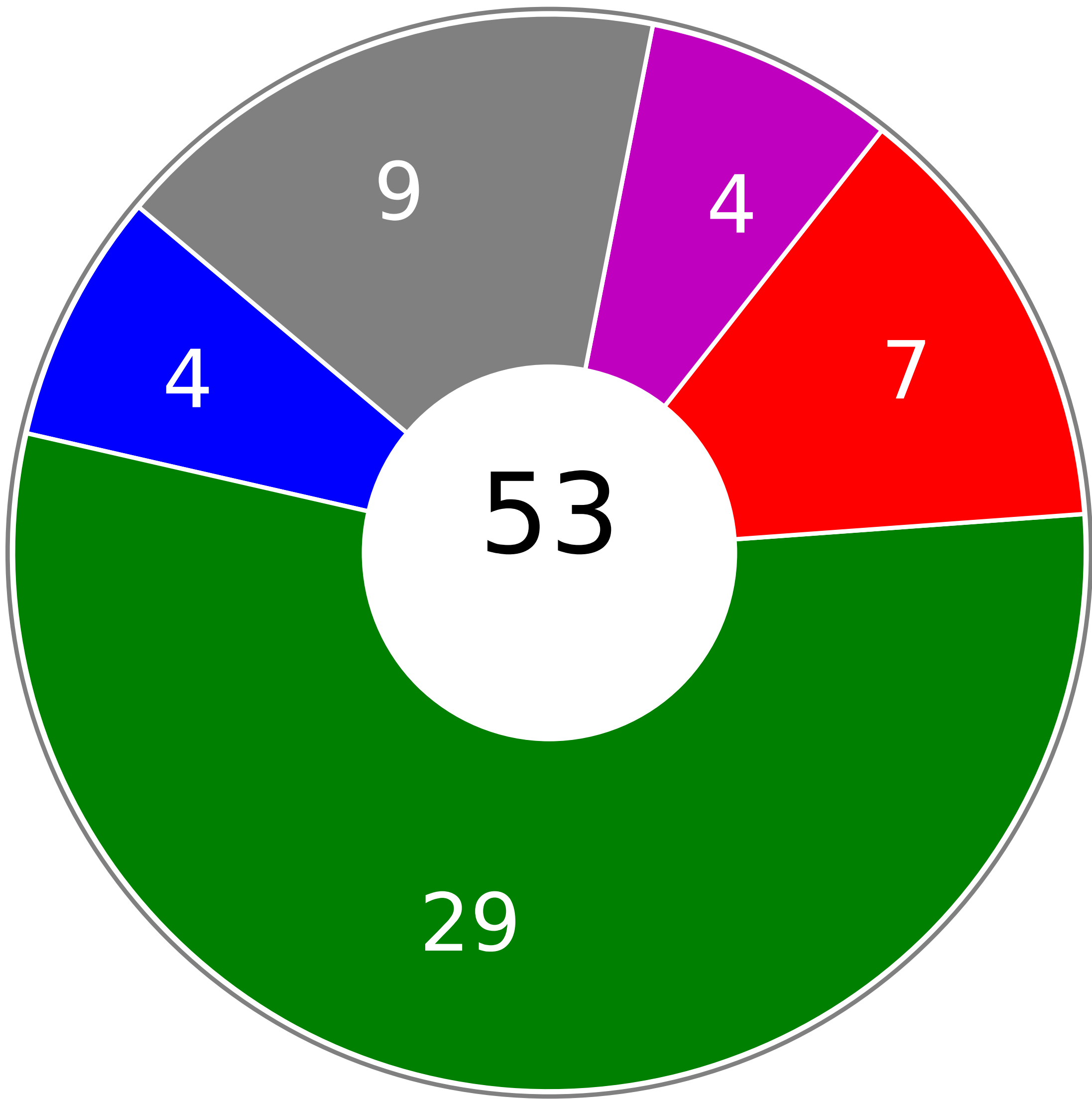
Slide credit to Rui Zhang (PMO)

● All-Sky maps

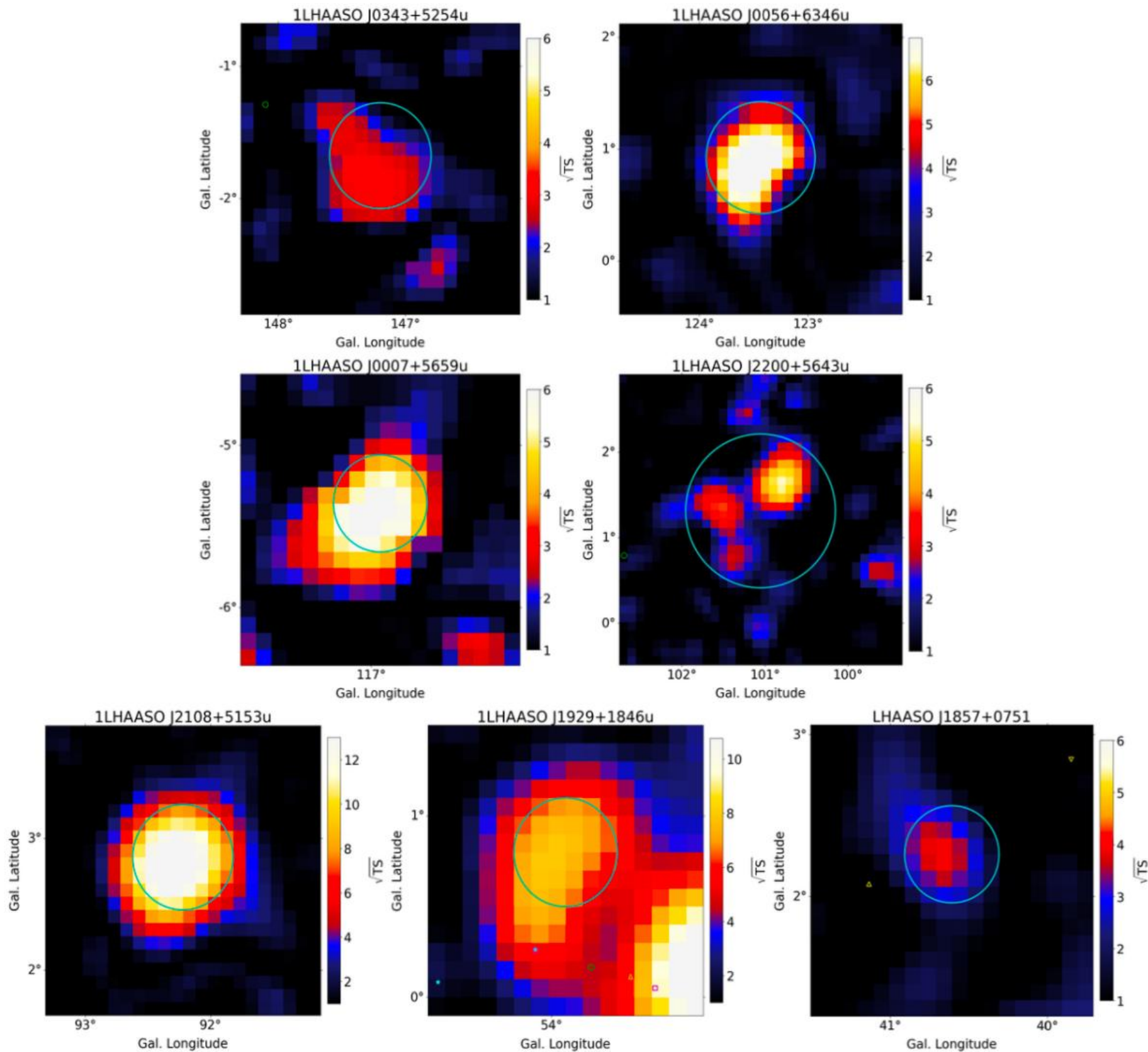




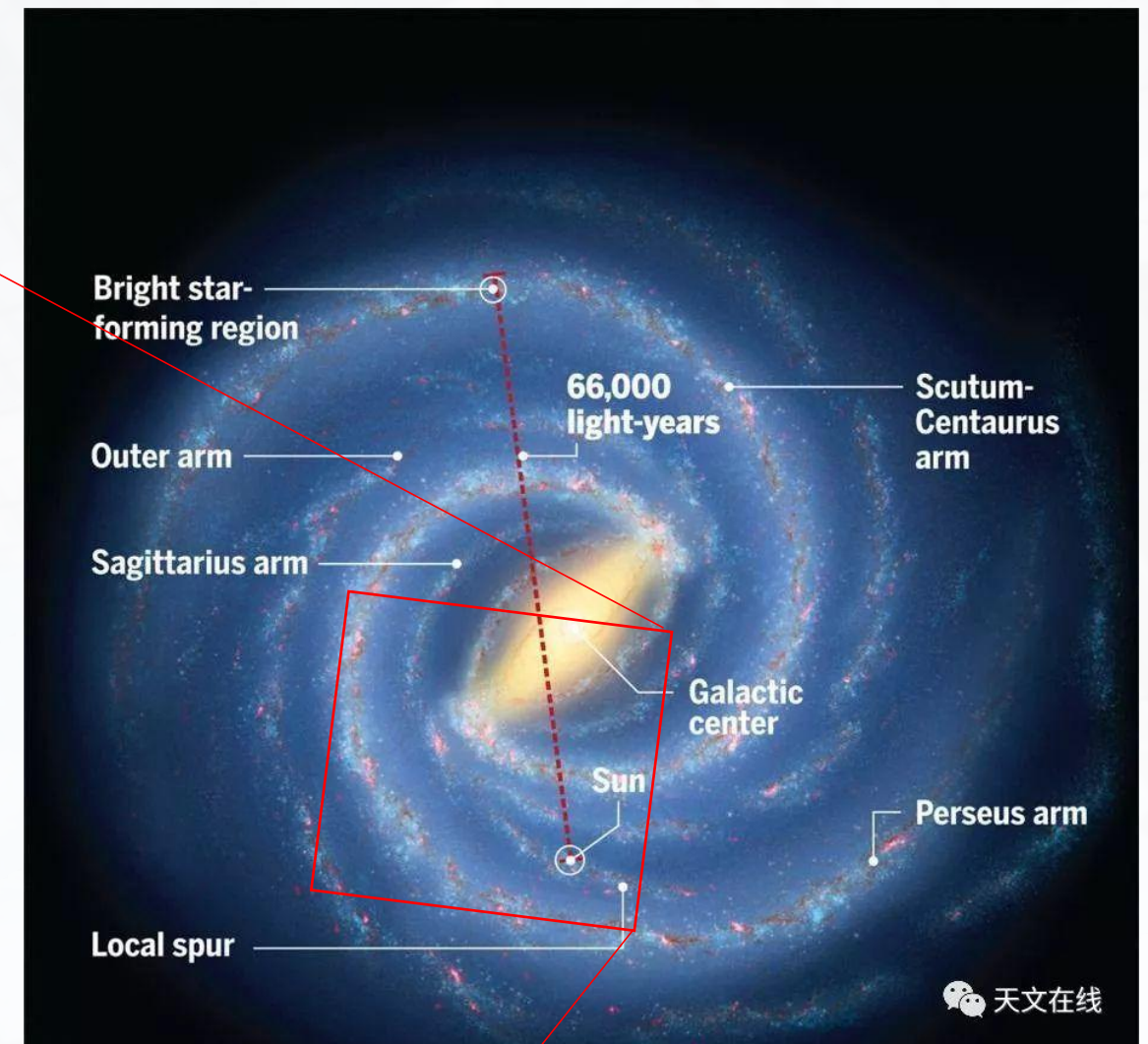
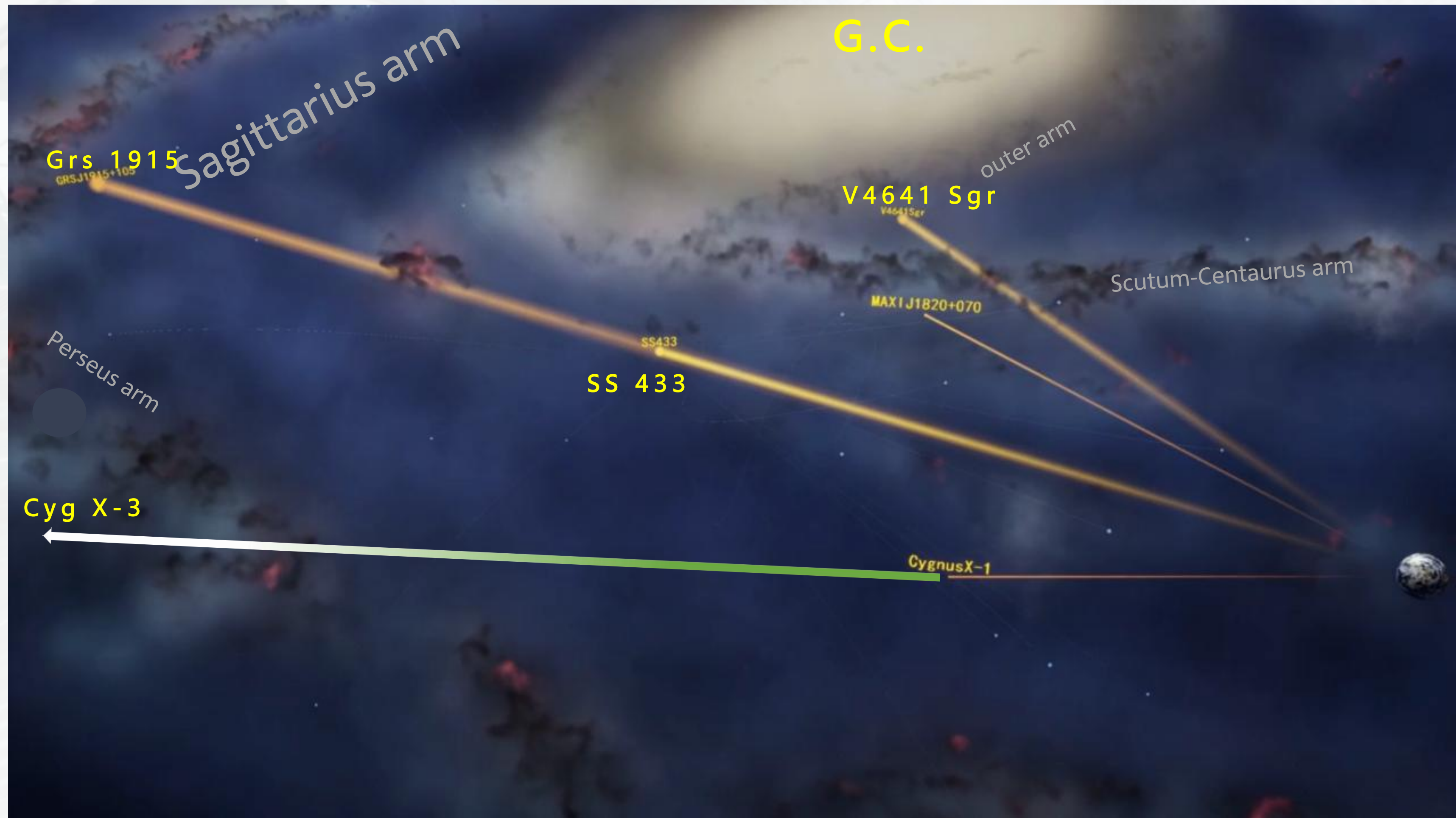
PeVatrons



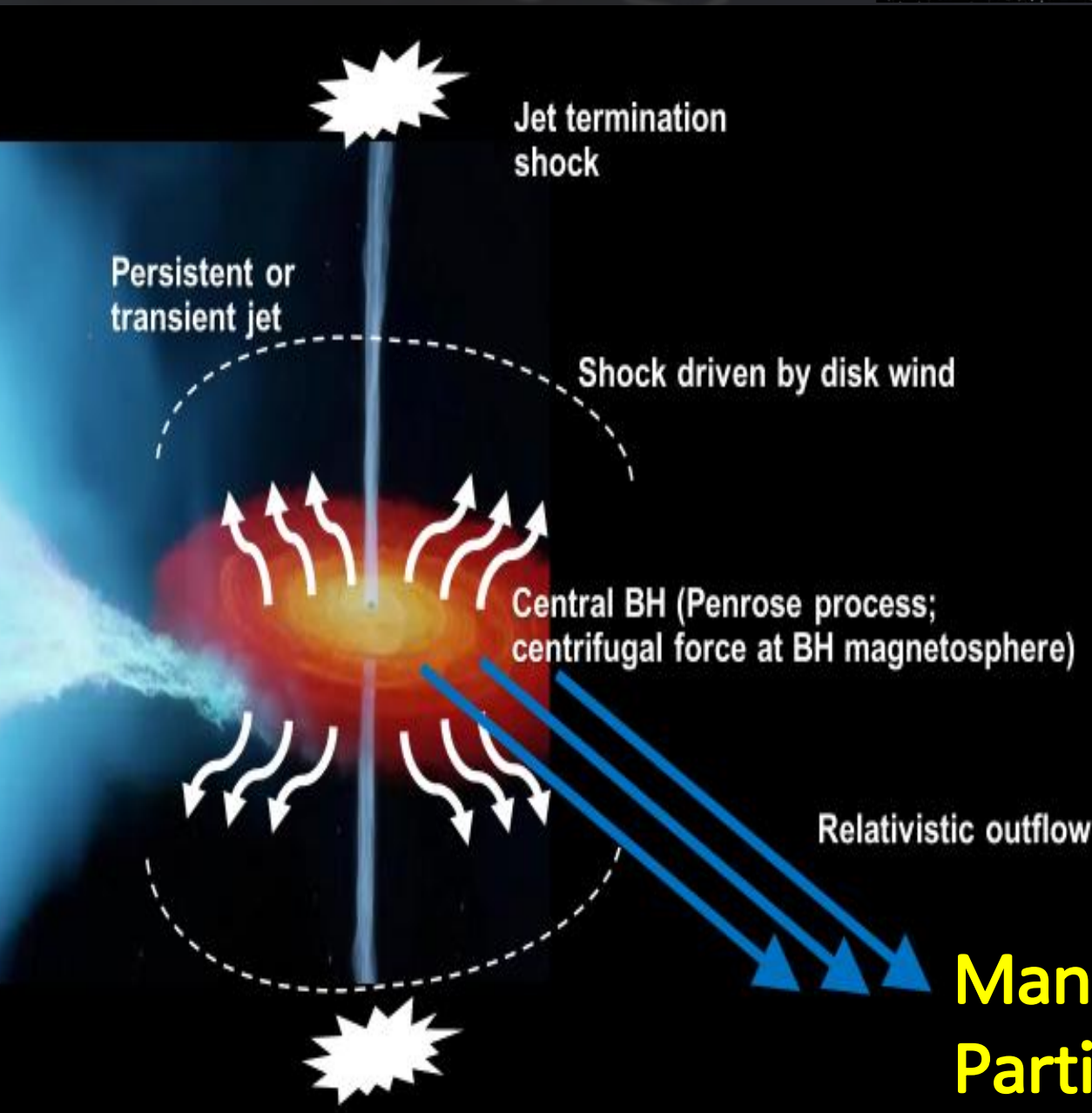
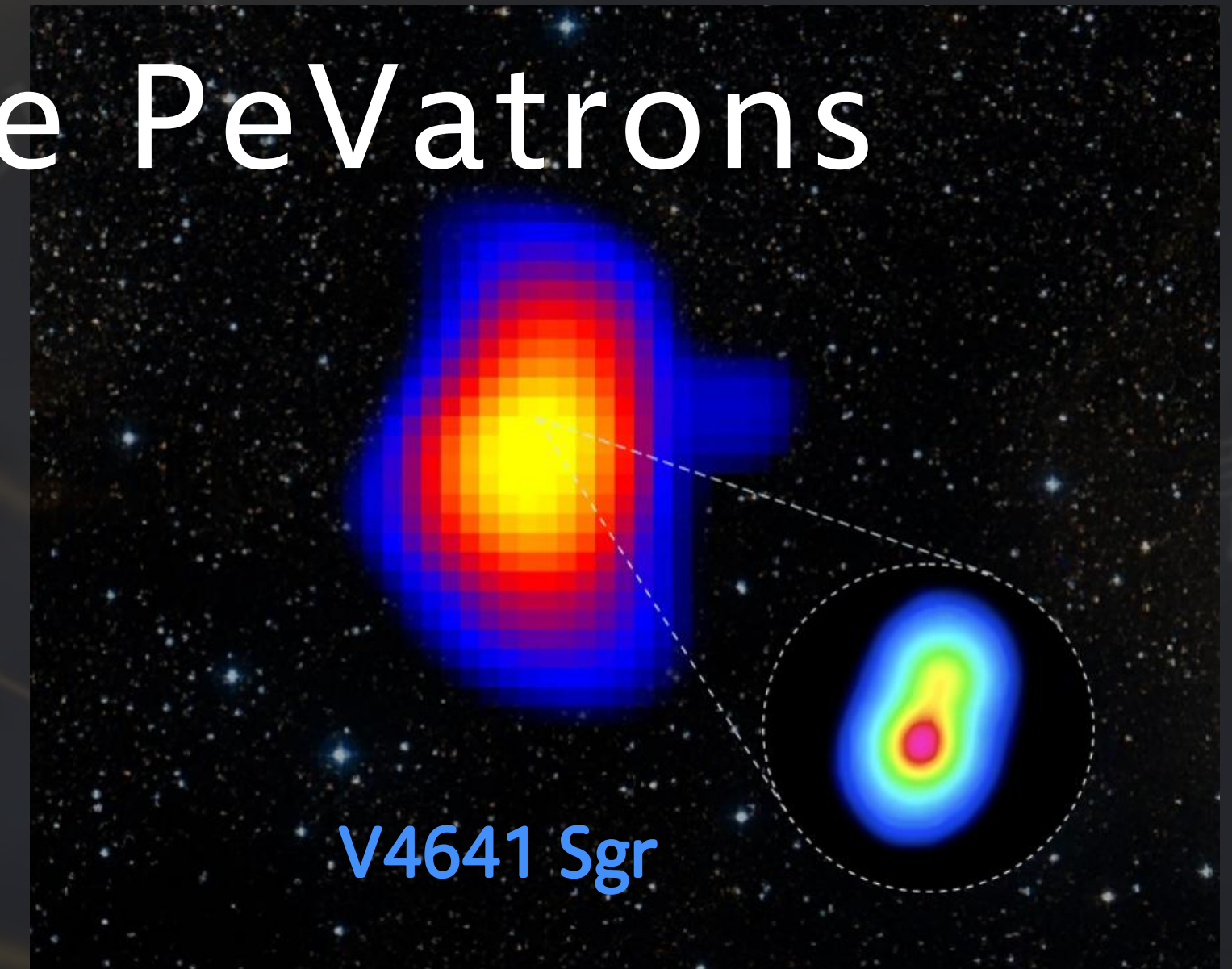
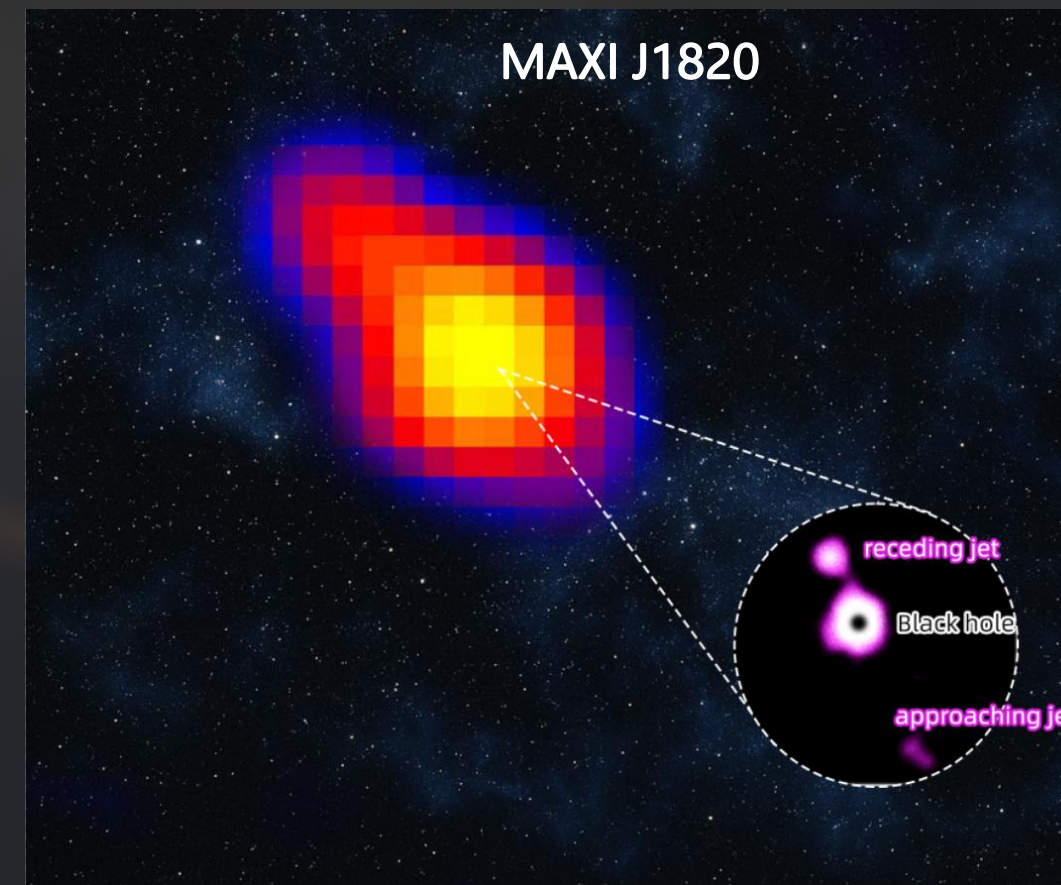
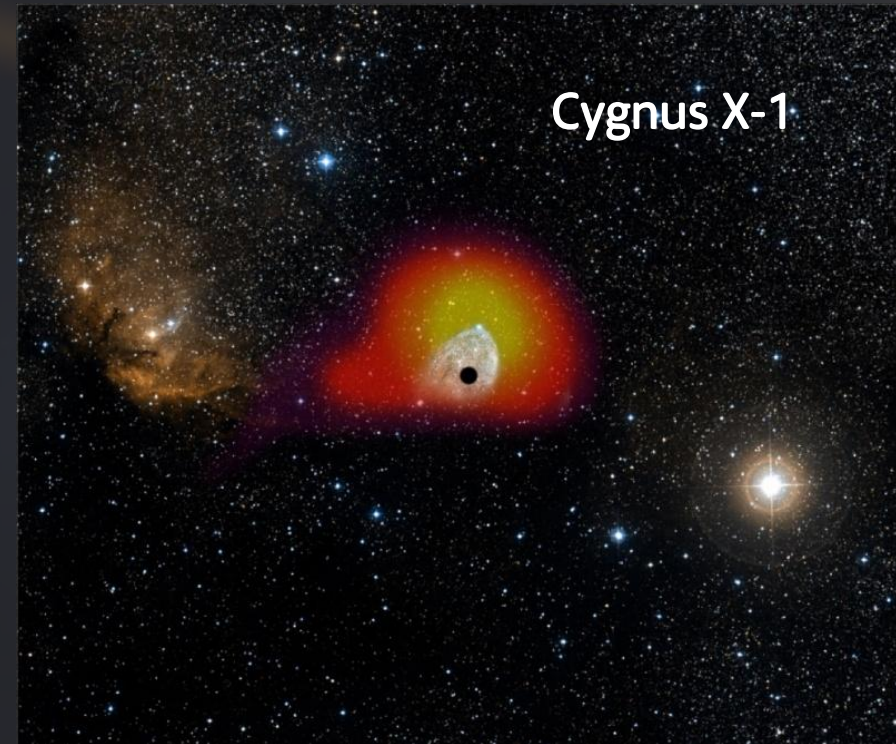
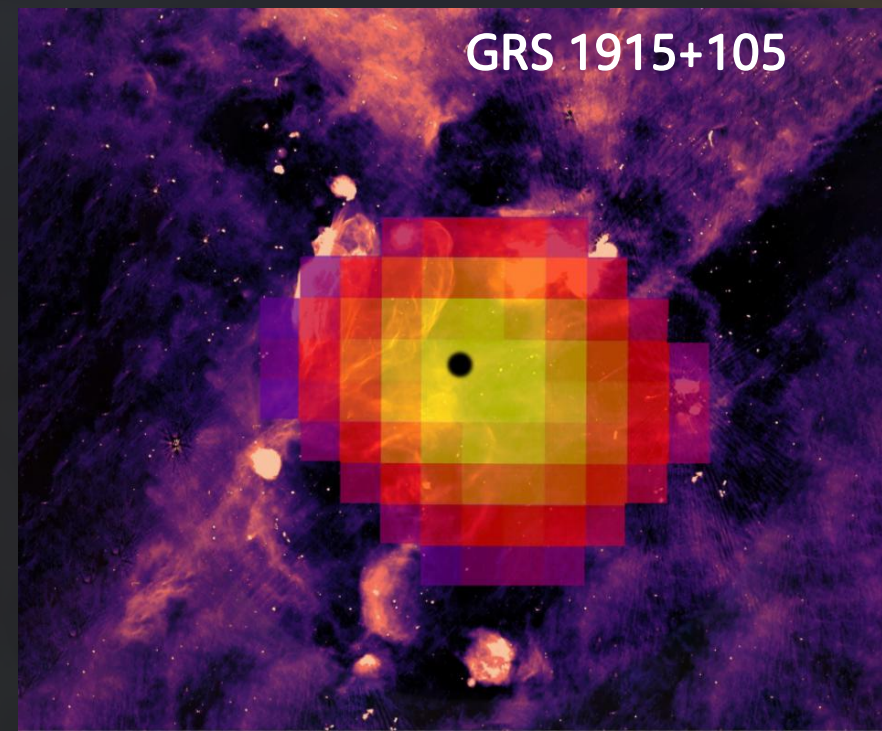
- SNR/S
- PWN/
- XB/M
- YMSC
- Unide



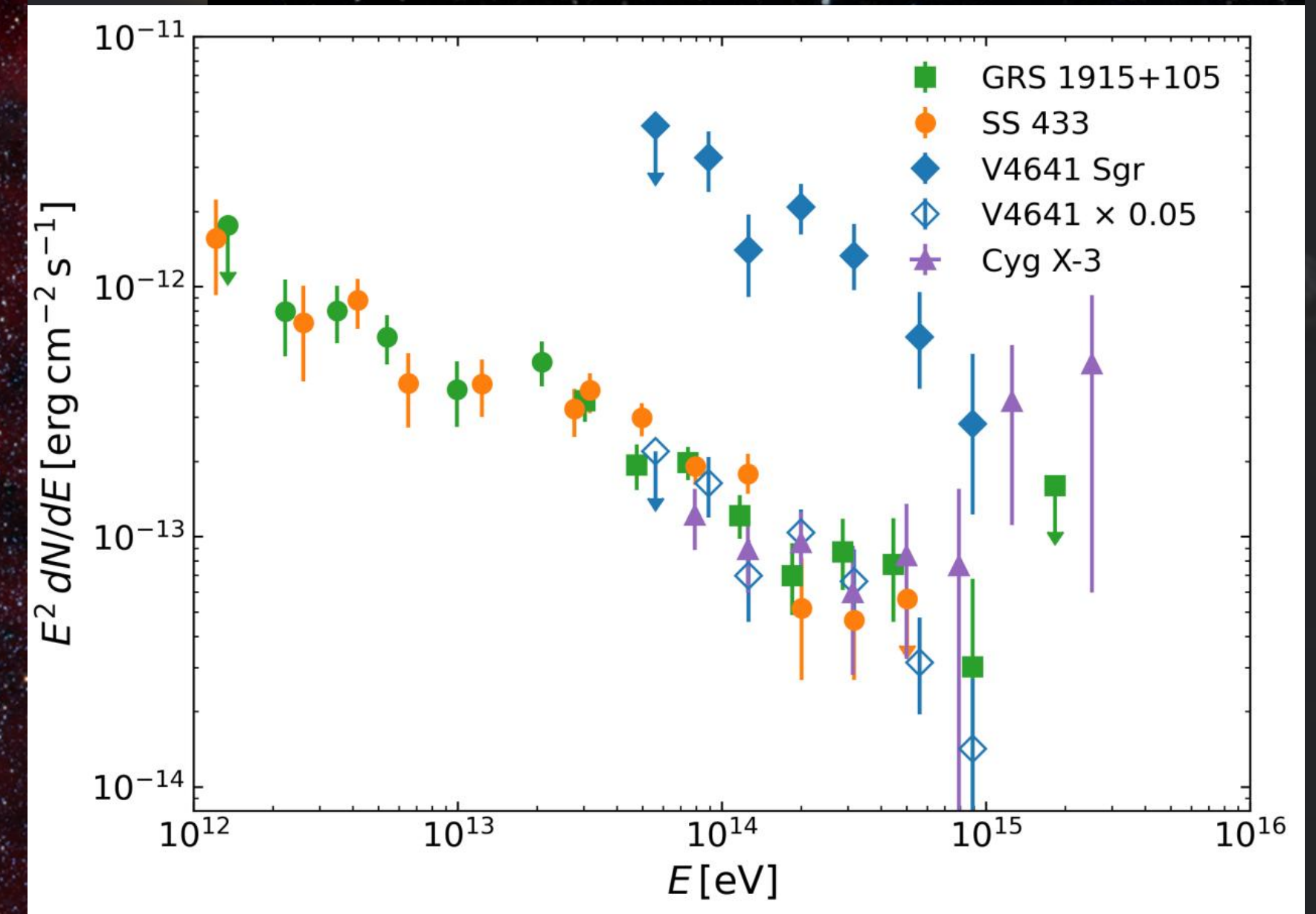
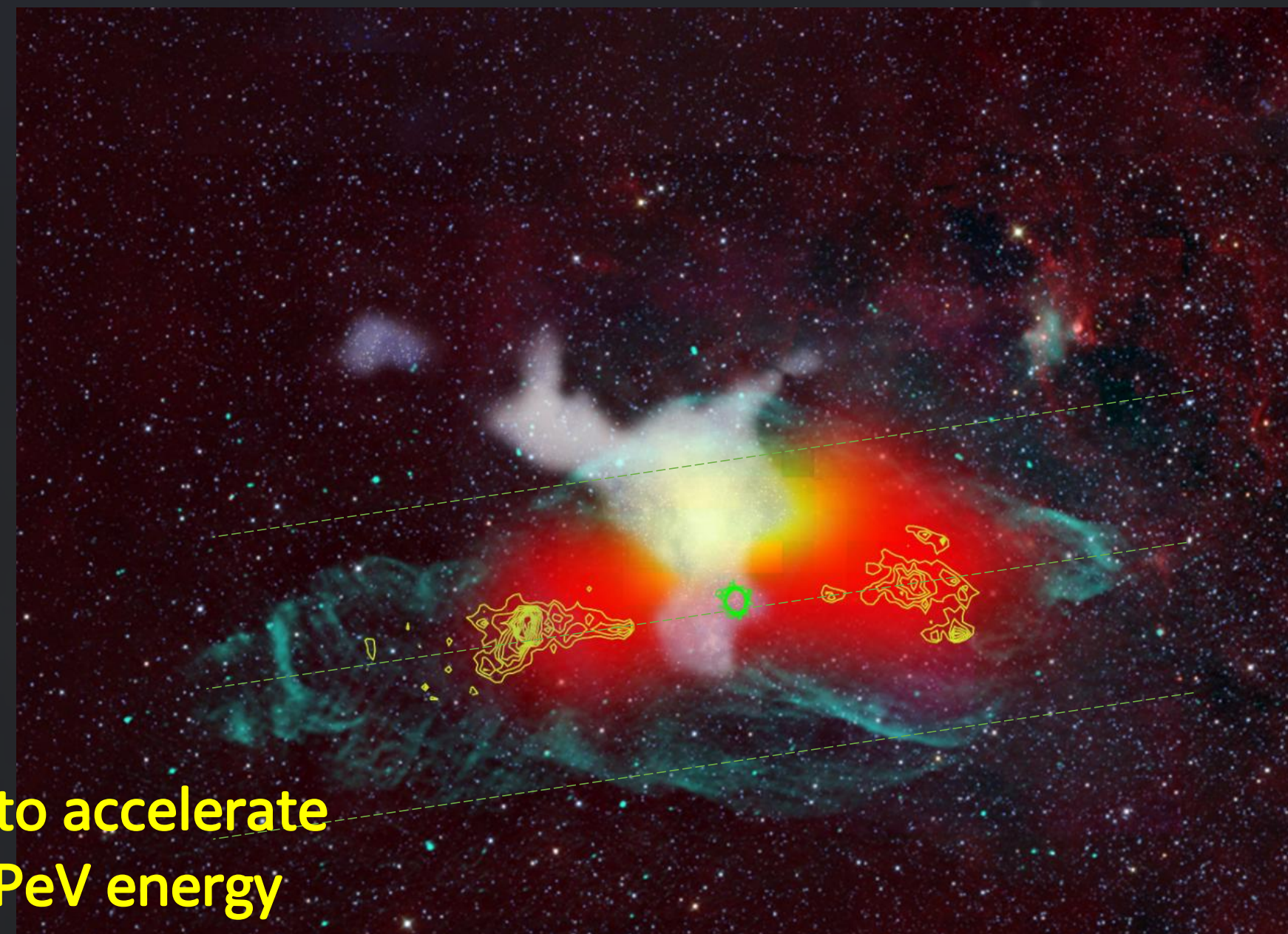
Six μ -Quasars in the Milky Way: PeVatrons



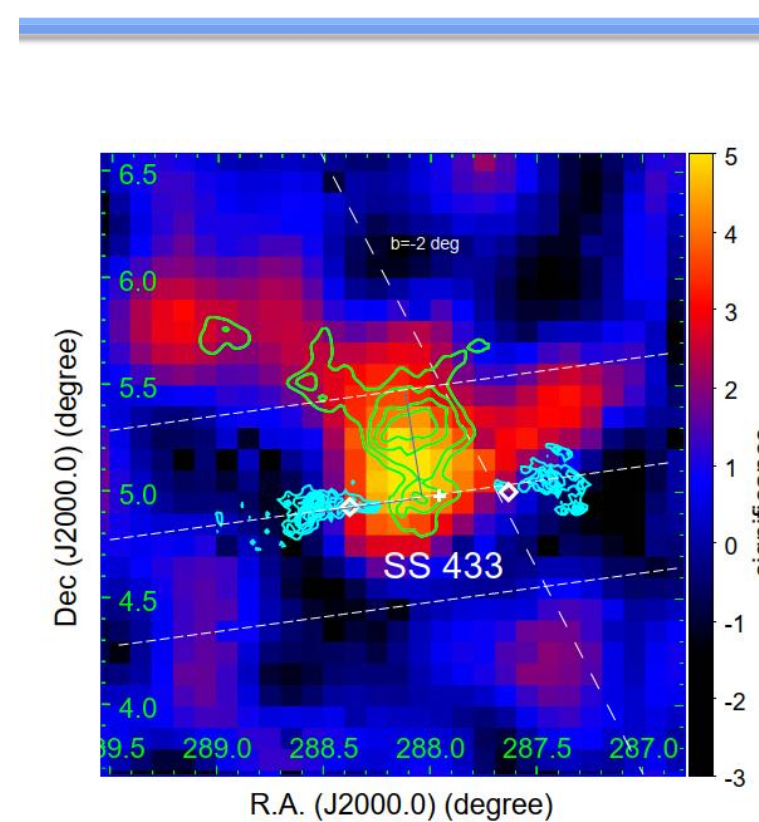
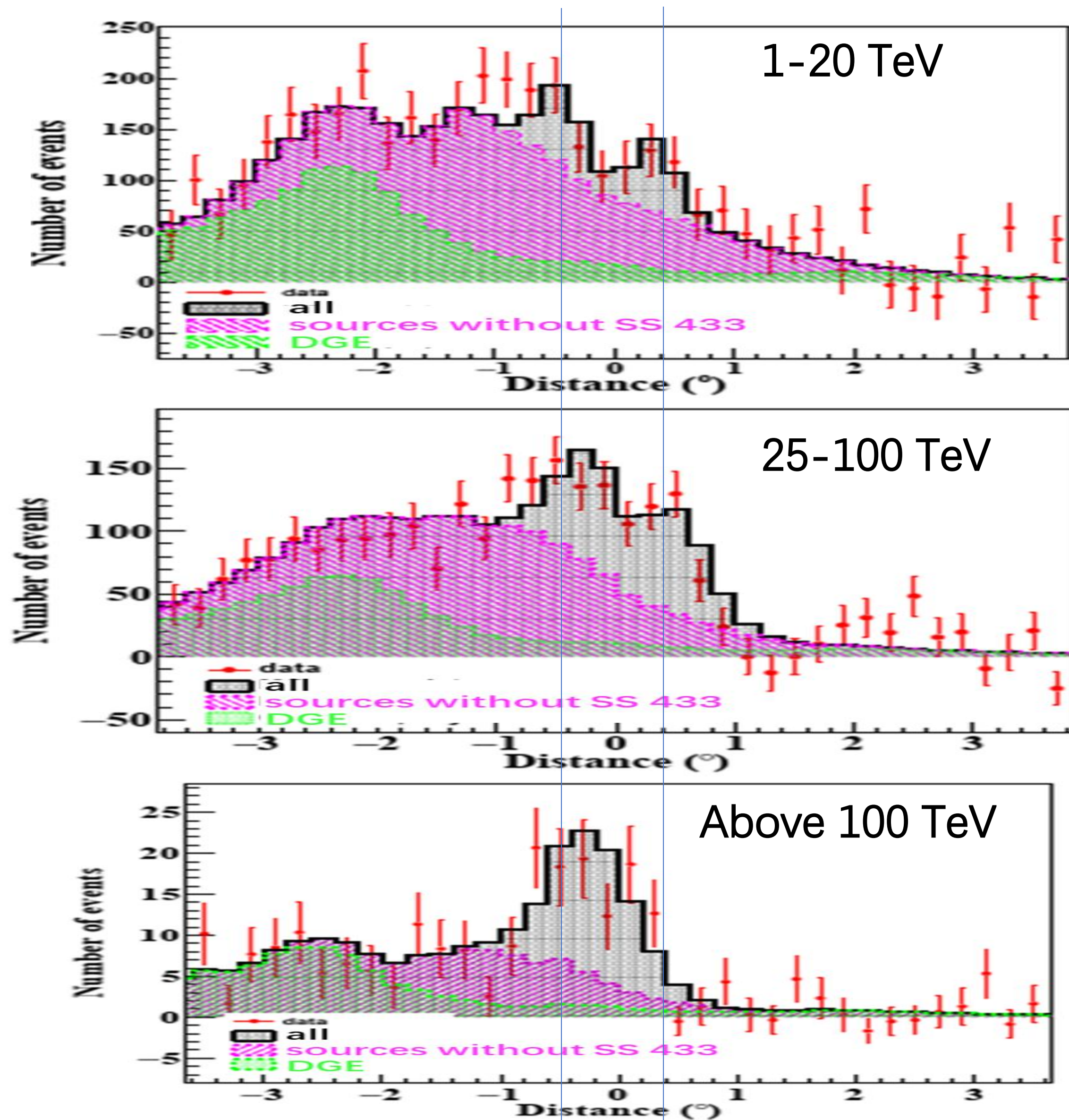
Six μ -Quasars are identified to be PeVatrons



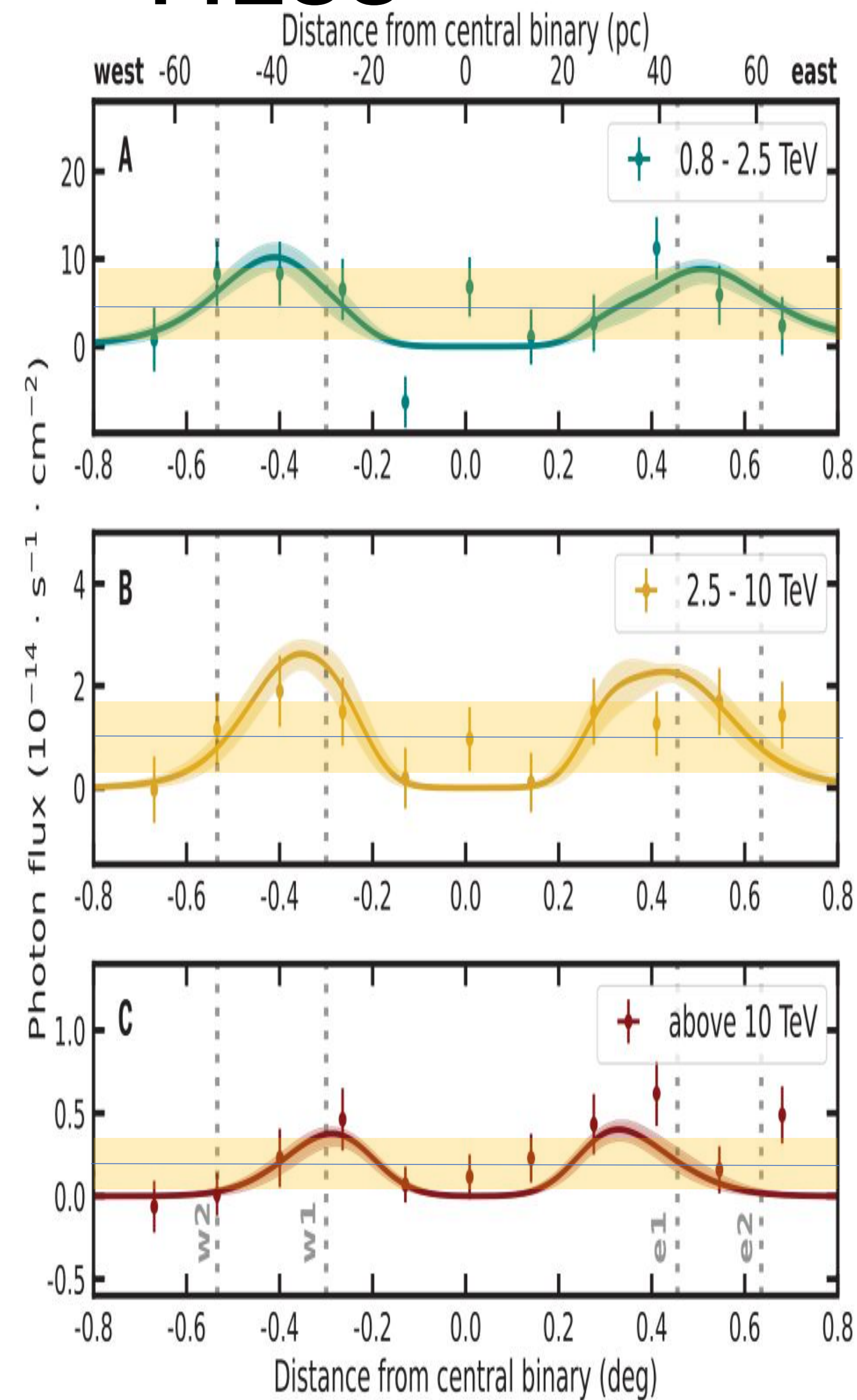
Many ways to accelerate
Particles to PeV energy



LHAASO

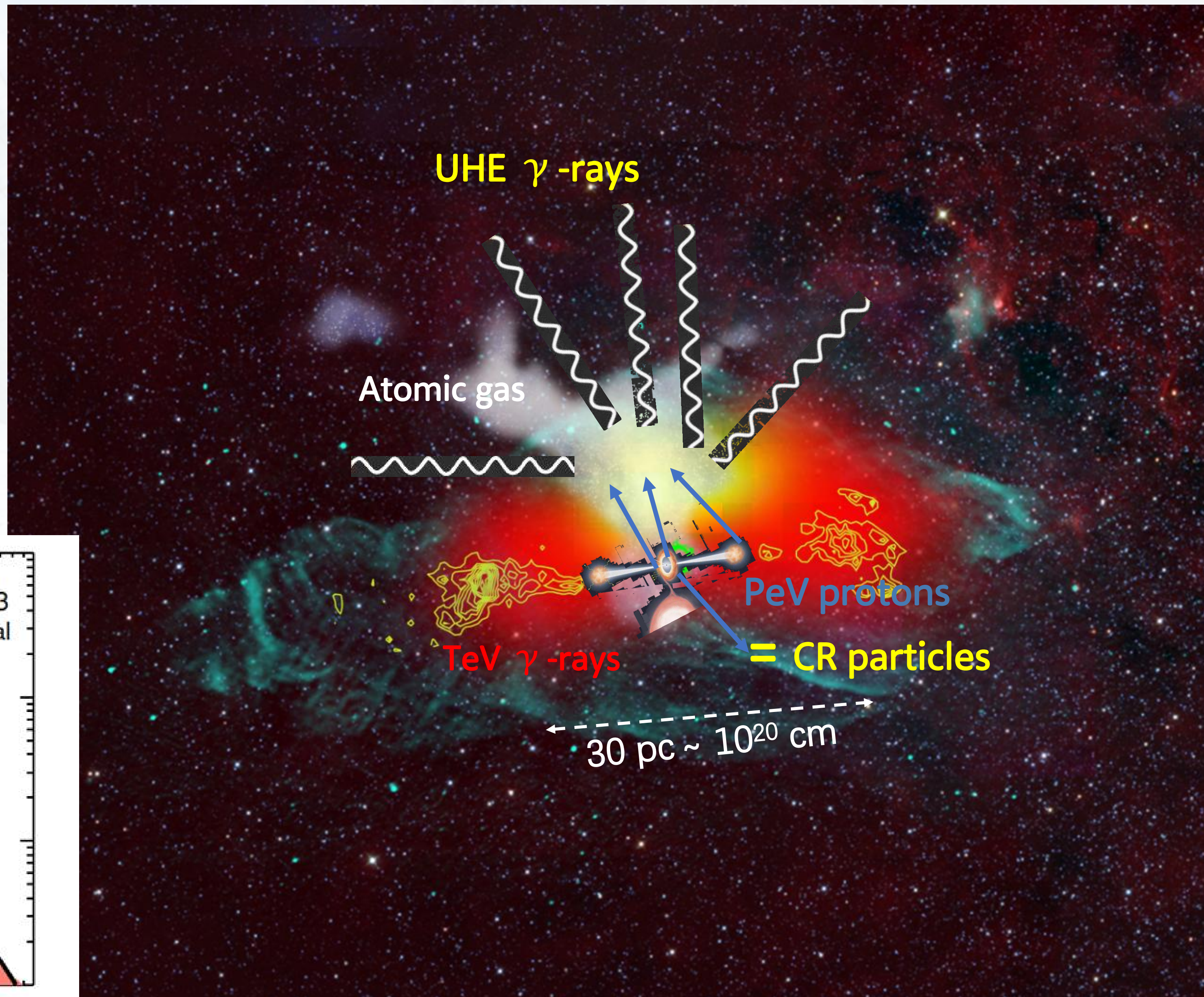
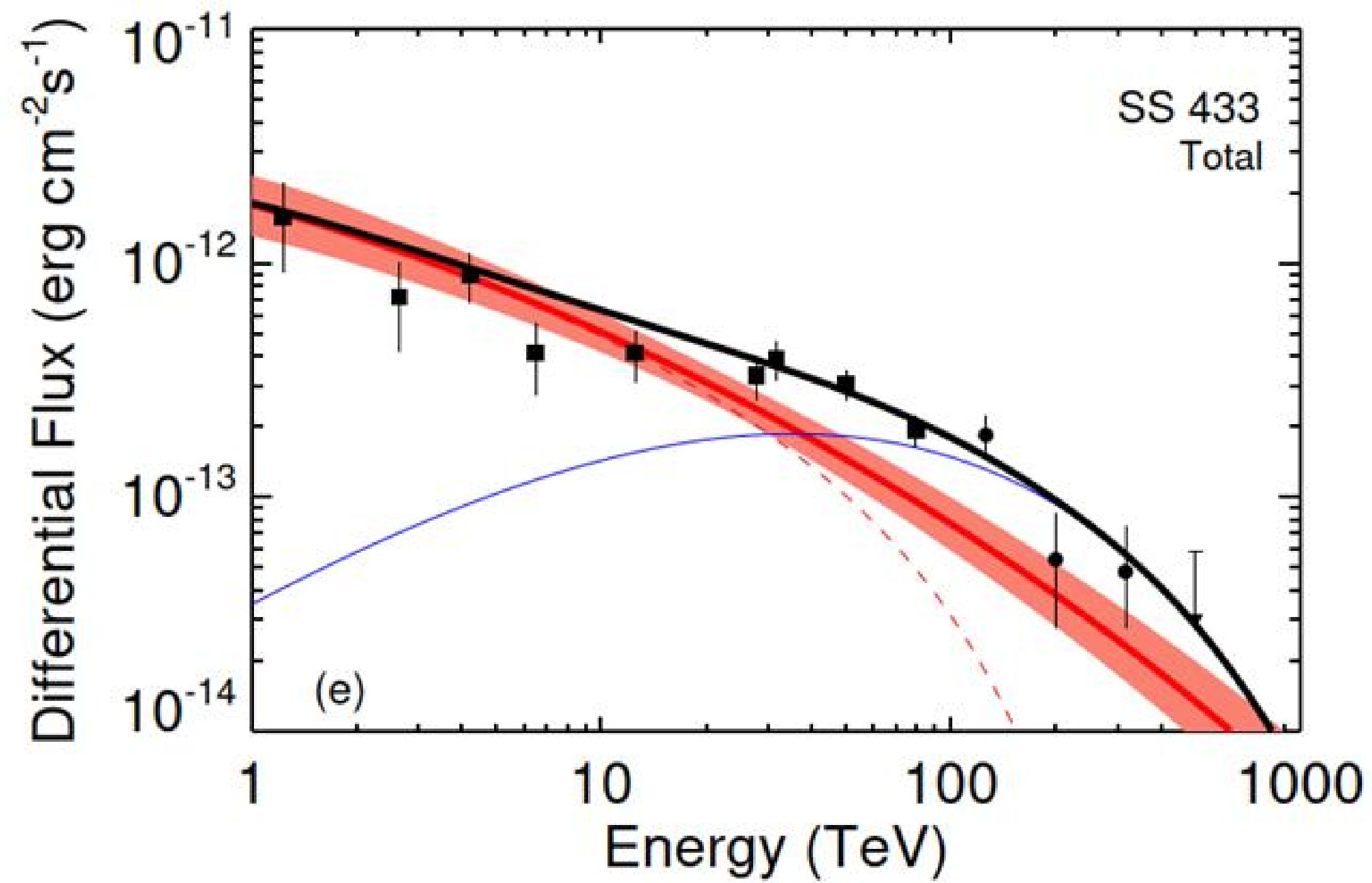


HESS



SS 433 SED

- ✓ LE: Leptons
- ✓ HE: Hadrons
- ✓ PeV proton power:
 $\sim 10^{38}$ erg/s
- ✓ ~ 10 sources are sufficient



Cyg X-3: 4.8 hour orbiting

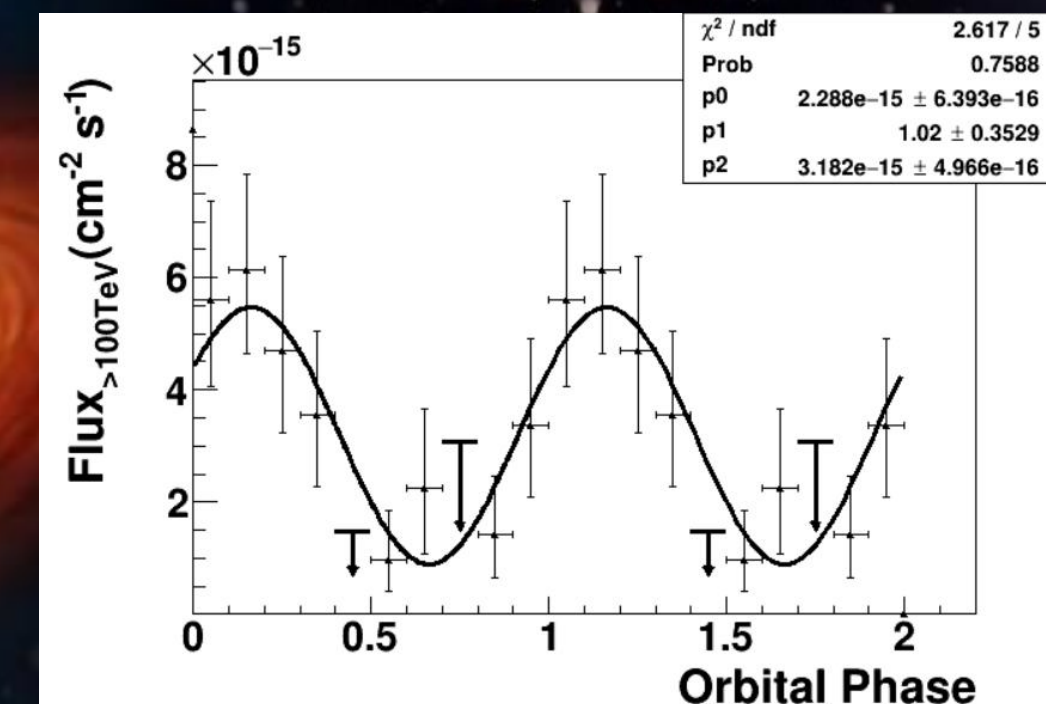
- This guarantees the proton accelerator

- ~ 4 PeV photons implies 40 PeV proton A super-PeVatron:

- For Protons > 40 PeV, radiation mechanism: proton- γ scattering

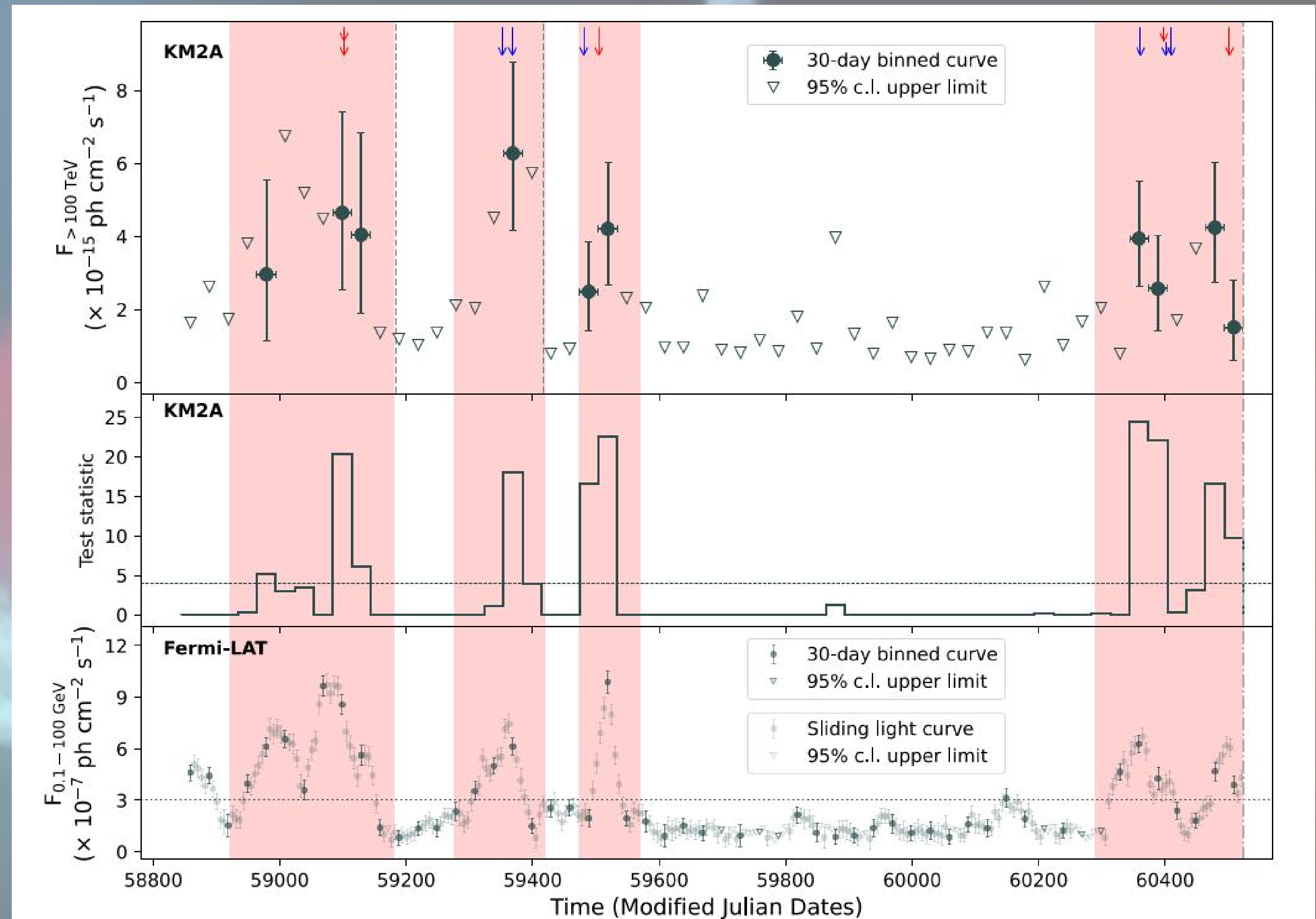
4.8 hour/circle

$3 R_{\odot} \sim 10^{11} \text{ cm}$

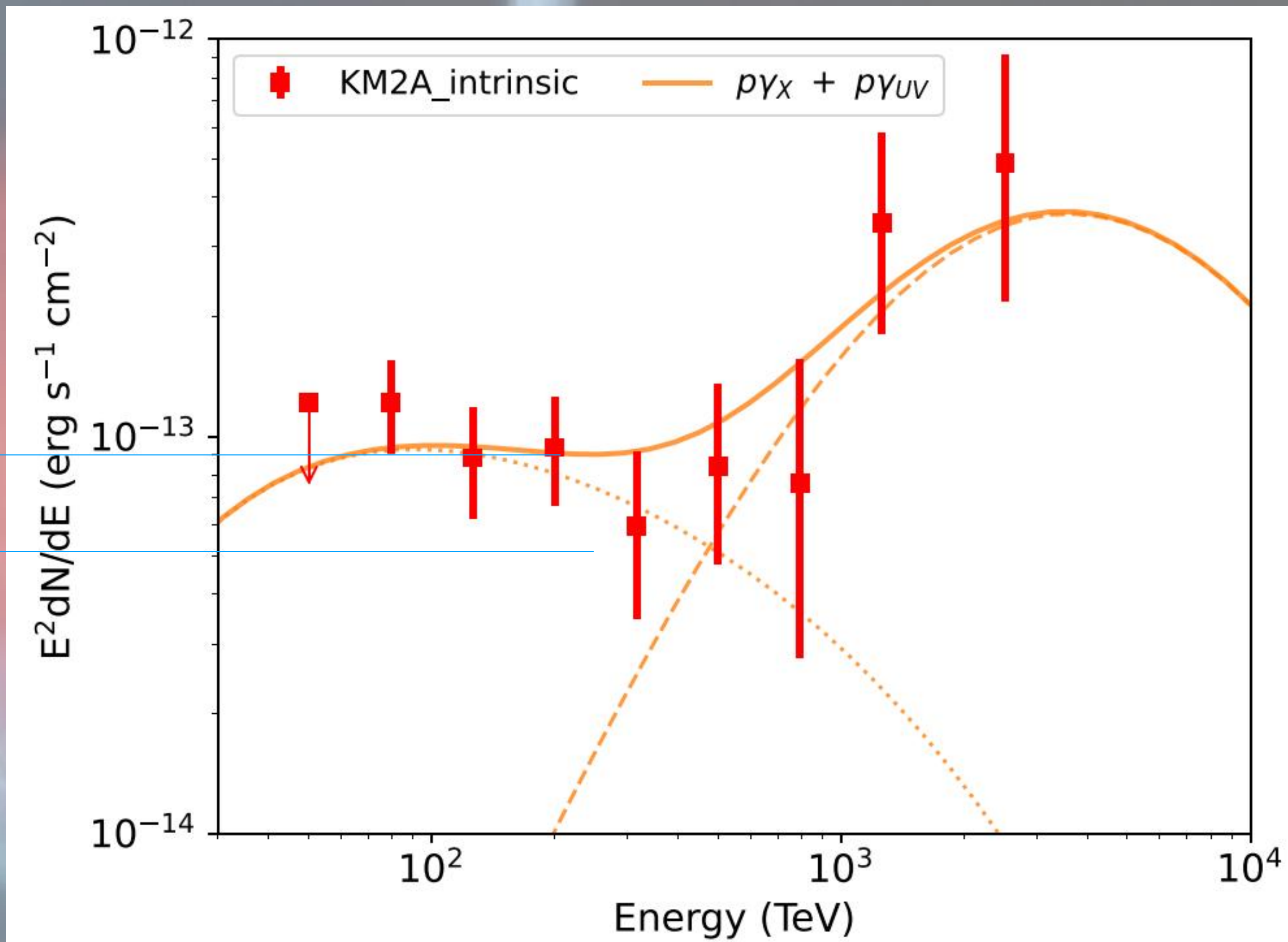
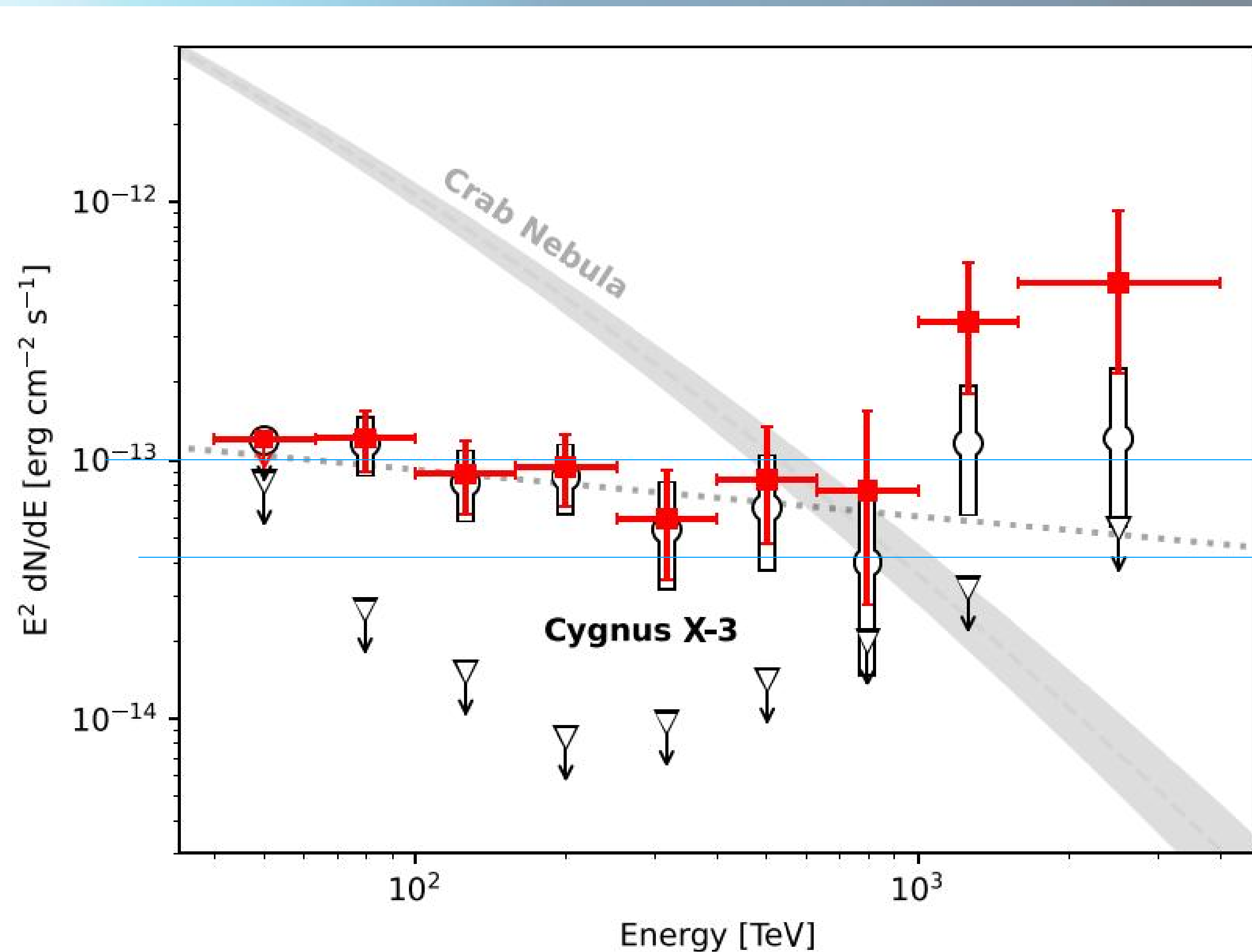


Flaring for months or a half years

- Flaring of the companion star of $14 M_{\odot}$
- Super-Eddington accretion
- Strong UV photon field during flares

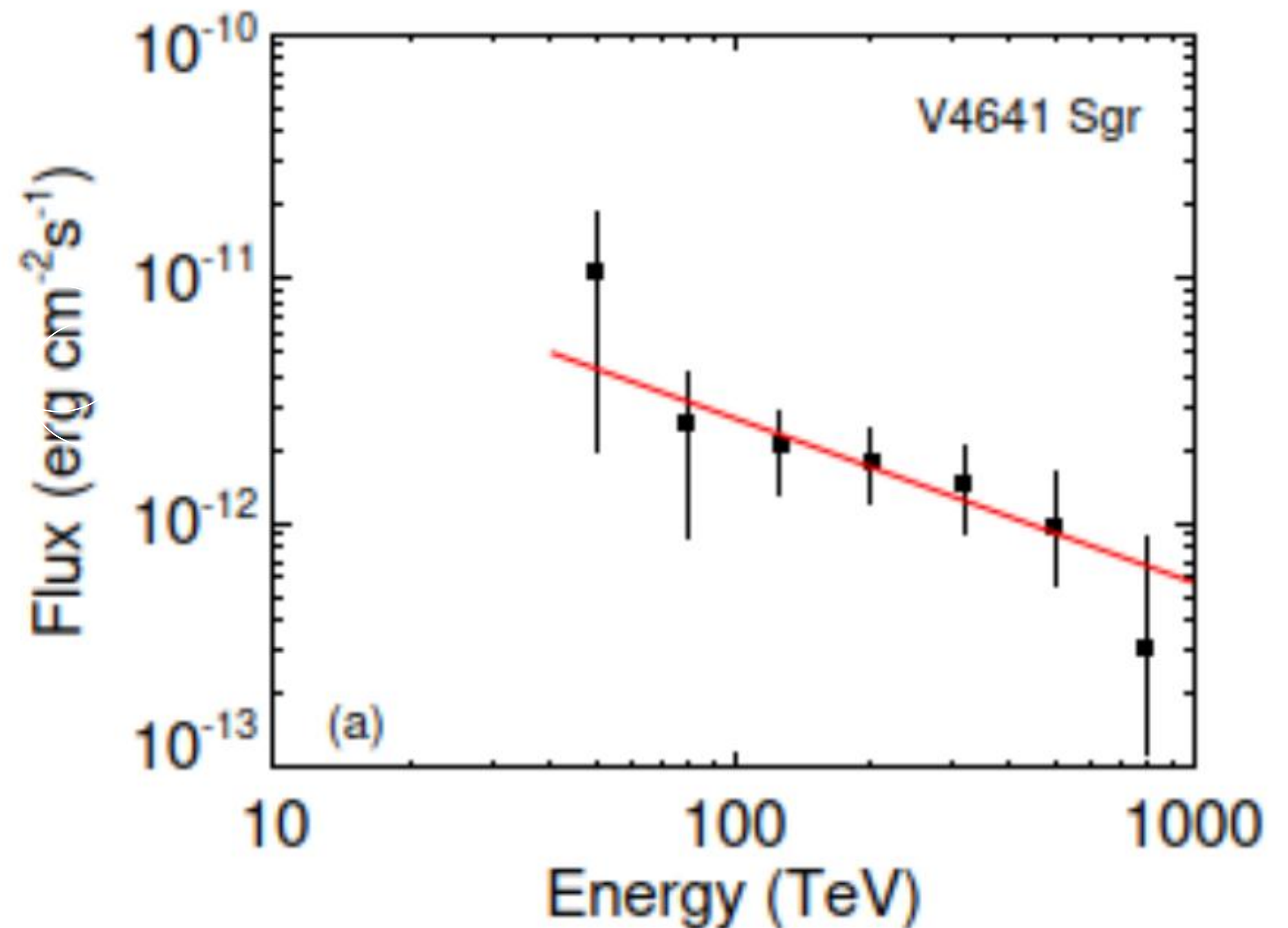
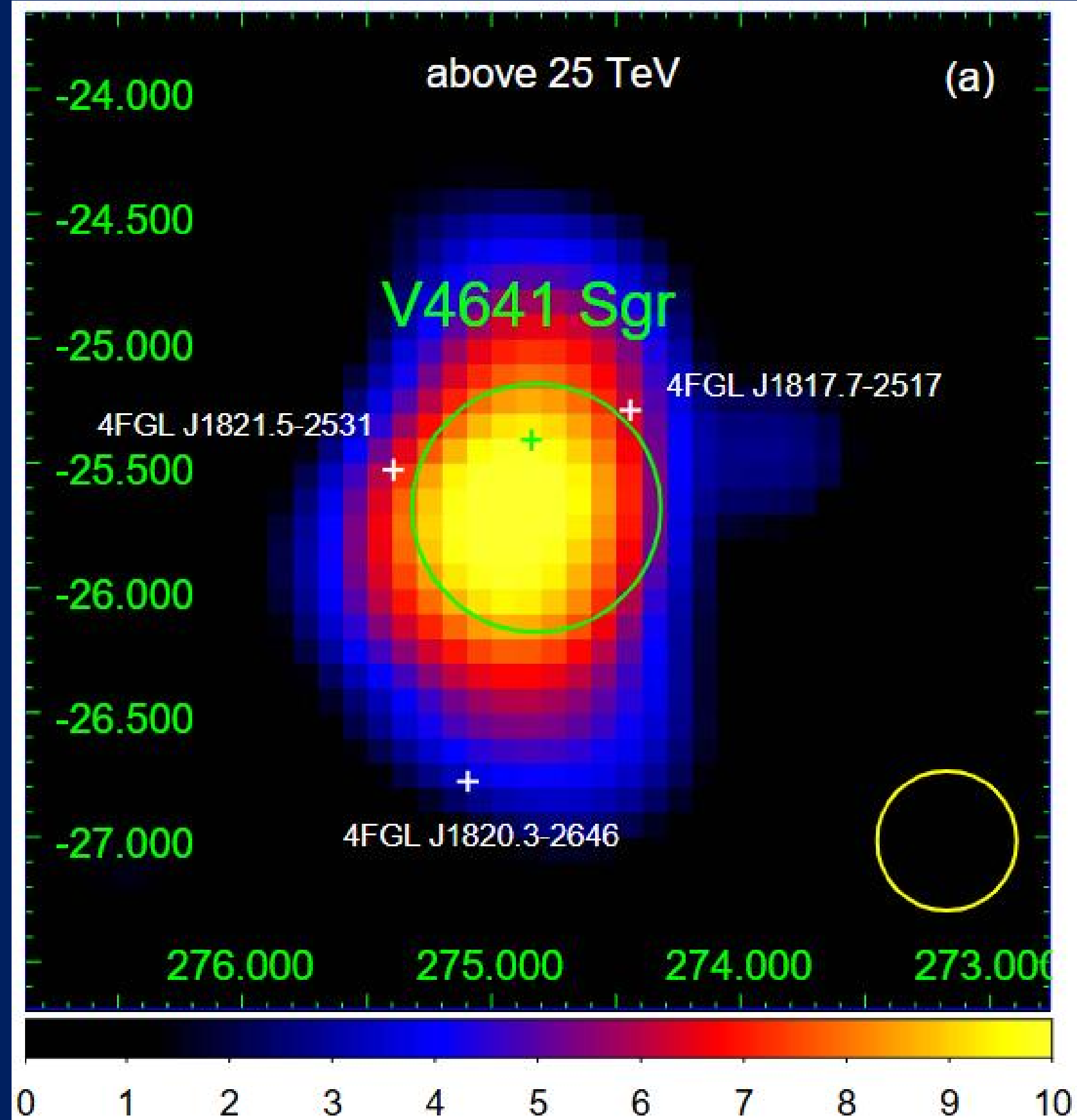


SED of a source of proton-photon scattering



Black Holes as super-PeVatrons?

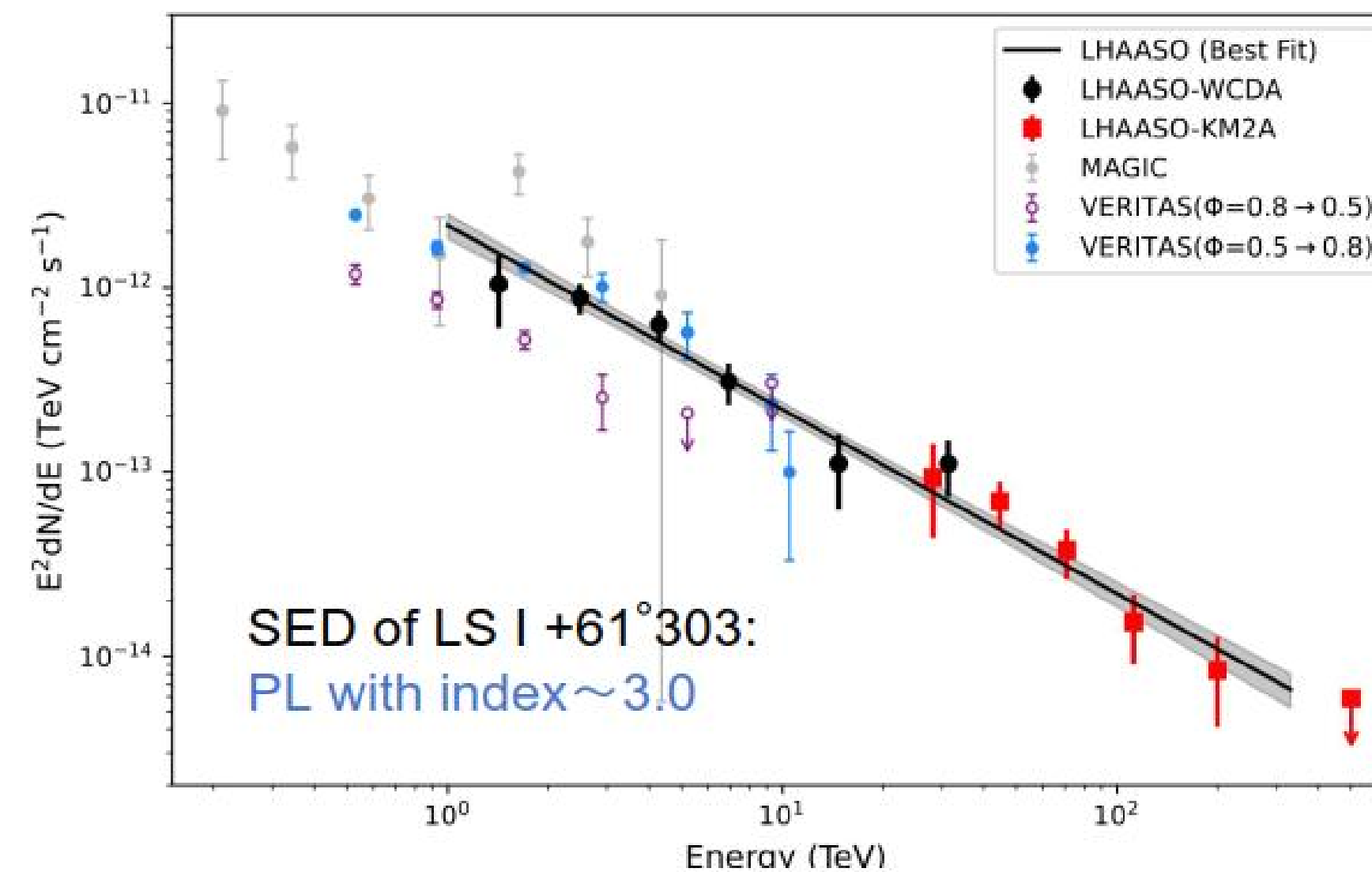
Very difficult to detect: not only due to the distant: $\sim 20,000$ light-year !
But also out of main field of view of LHAASO: a source in southern hemisphere
Powerful accelerator generating particle at $E > 10$ PeV !!



Gamma ray binaries

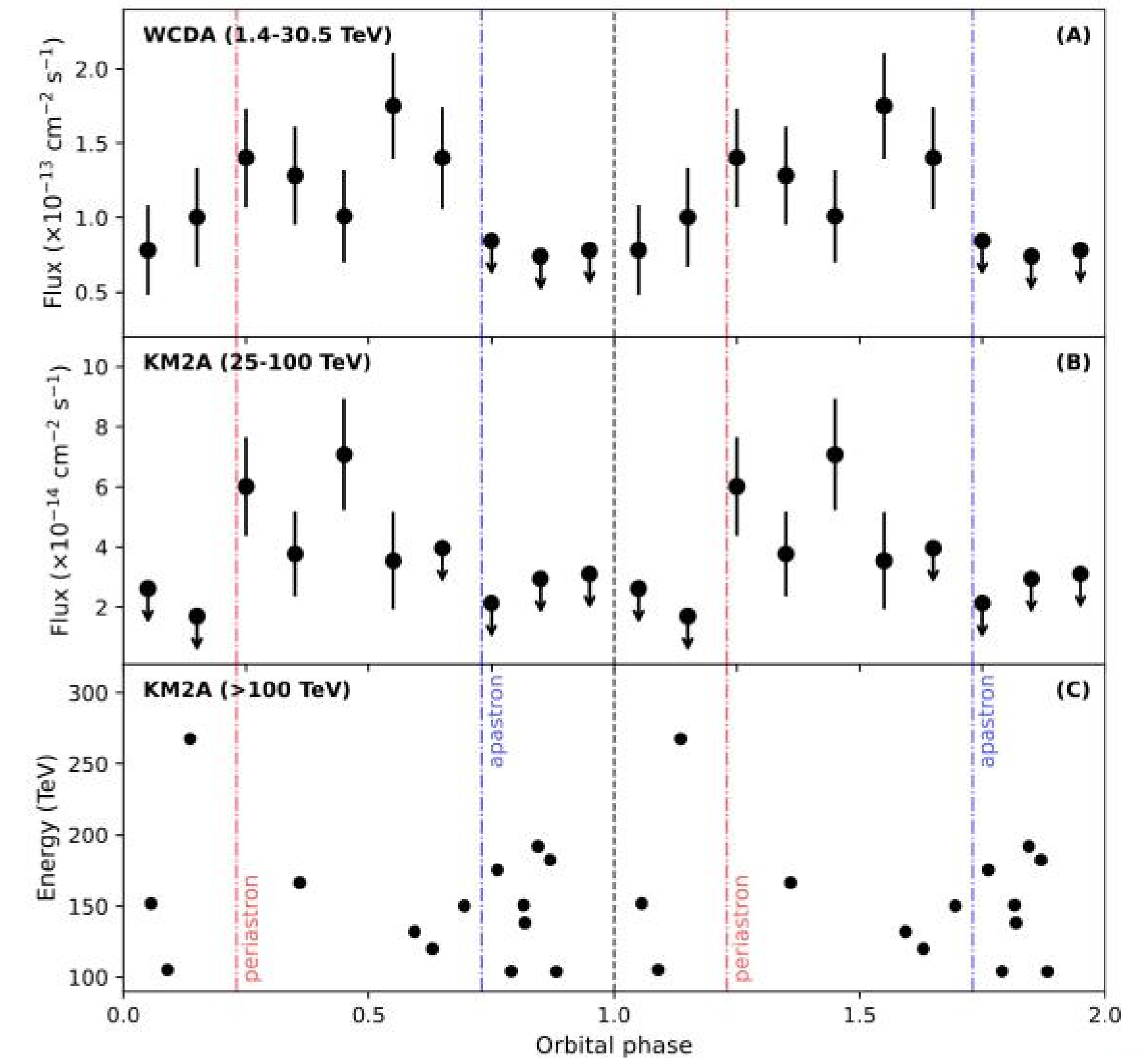
UHE emission from LS I +61°303

- 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.

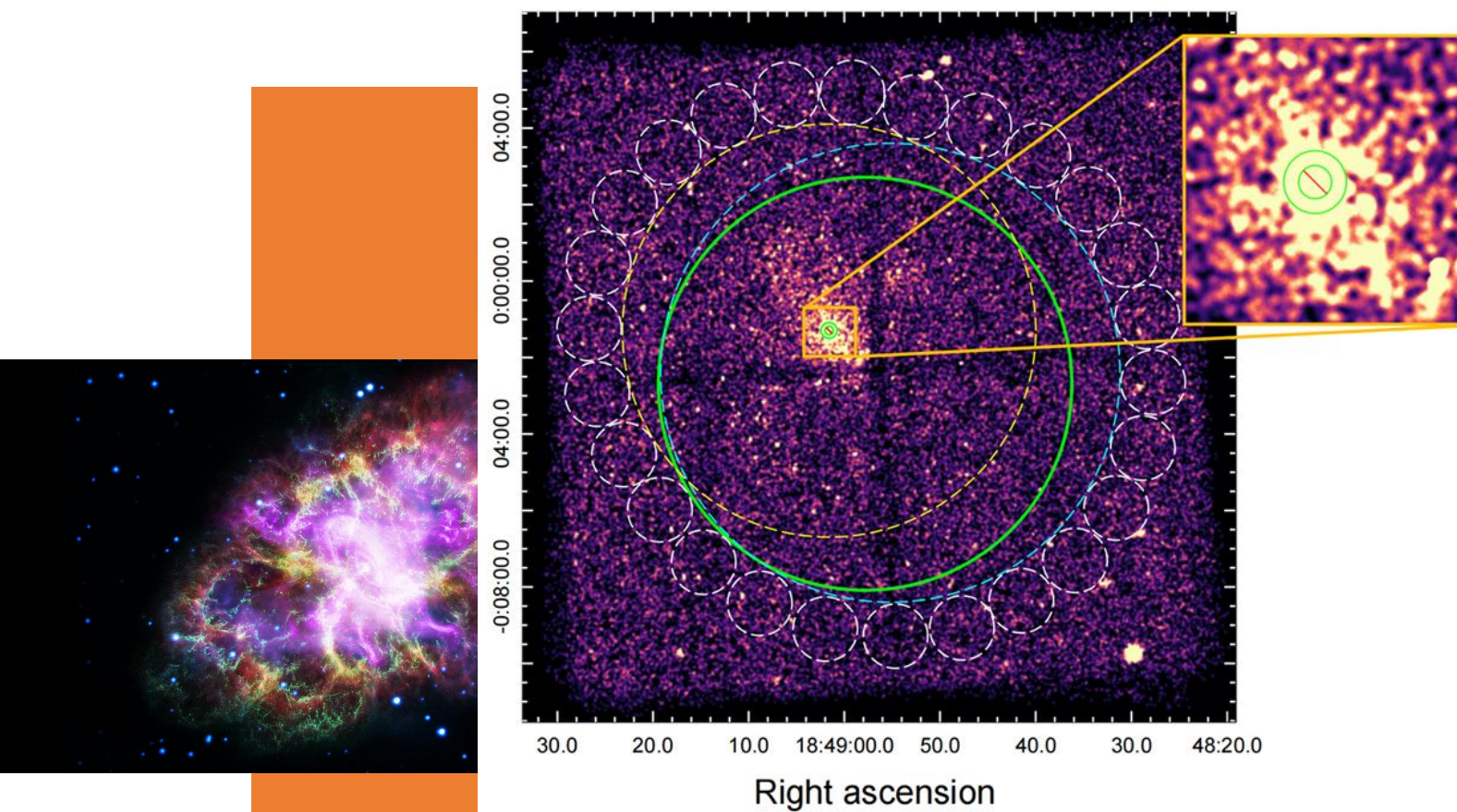


LHAASO, PRL, 136, 181001 (2026) arXiv:[2510.23345](https://arxiv.org/abs/2510.23345)

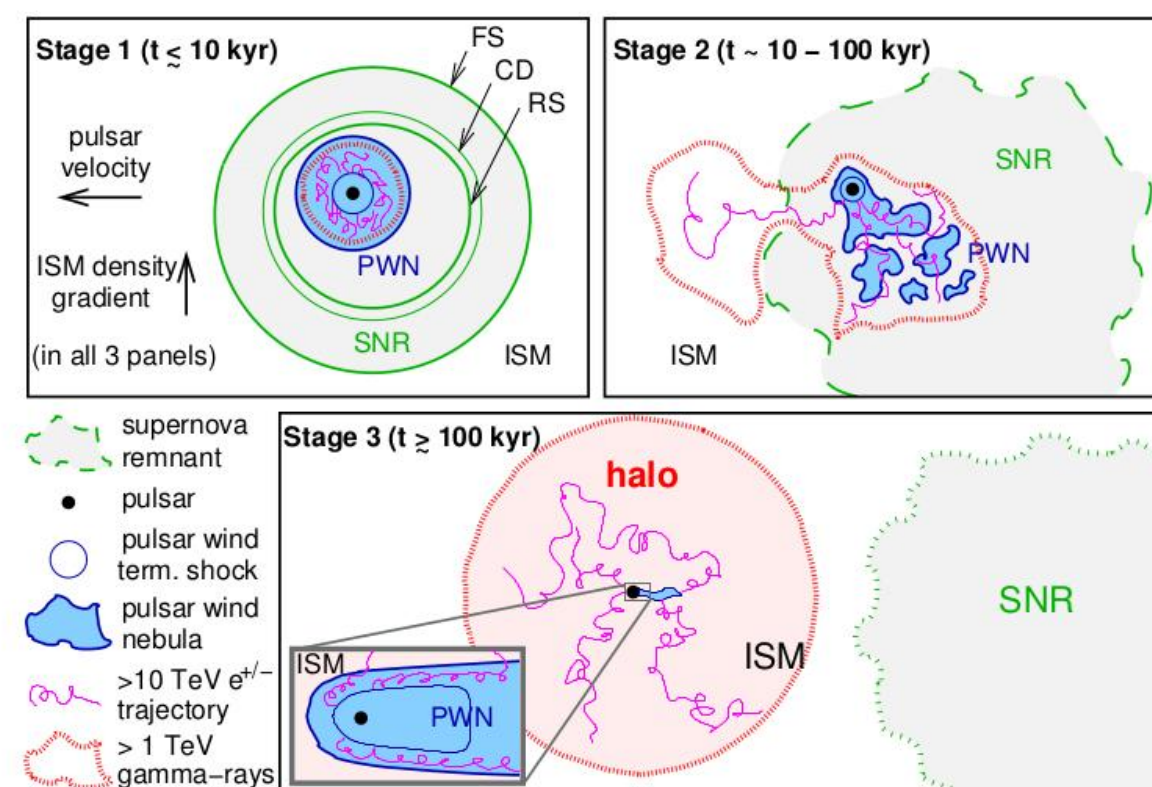
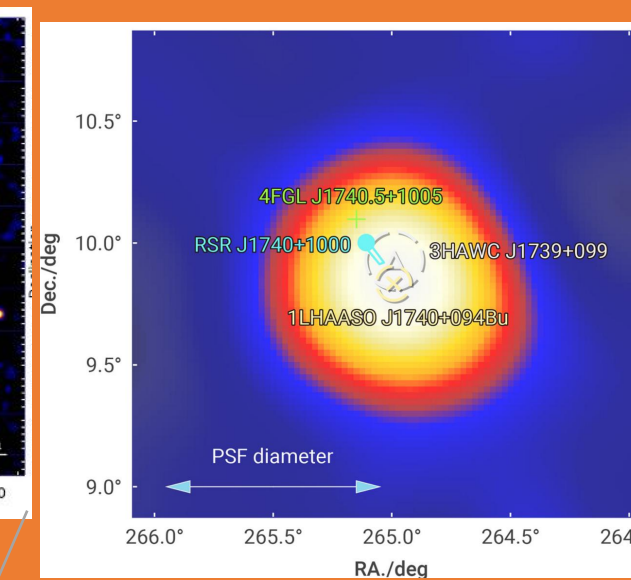
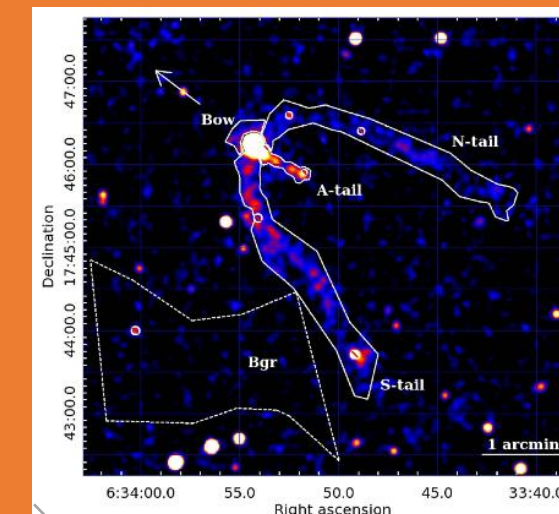
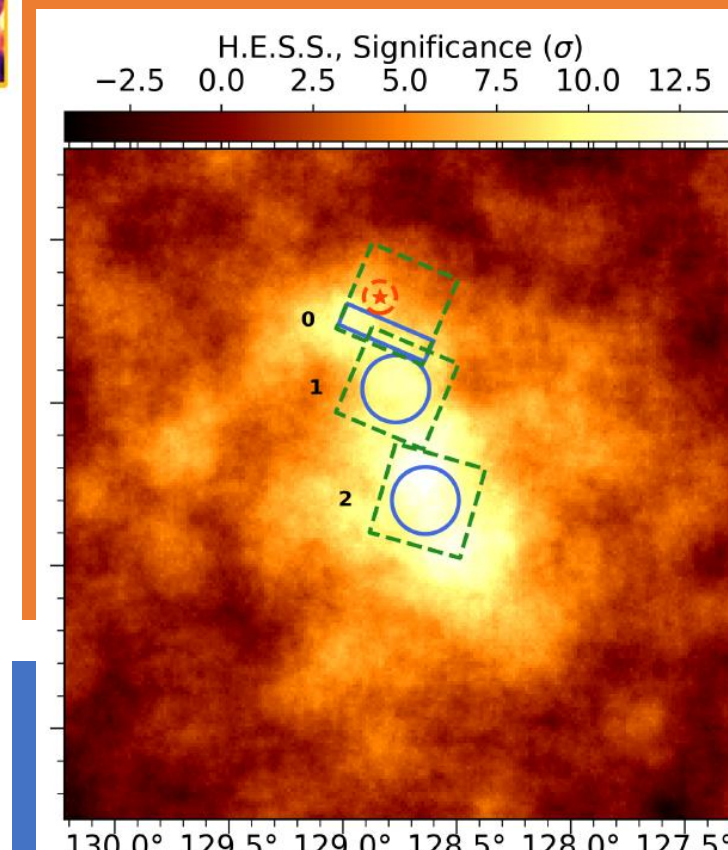
Phase-resolved emission of LS I +61°303 across different energy bands.



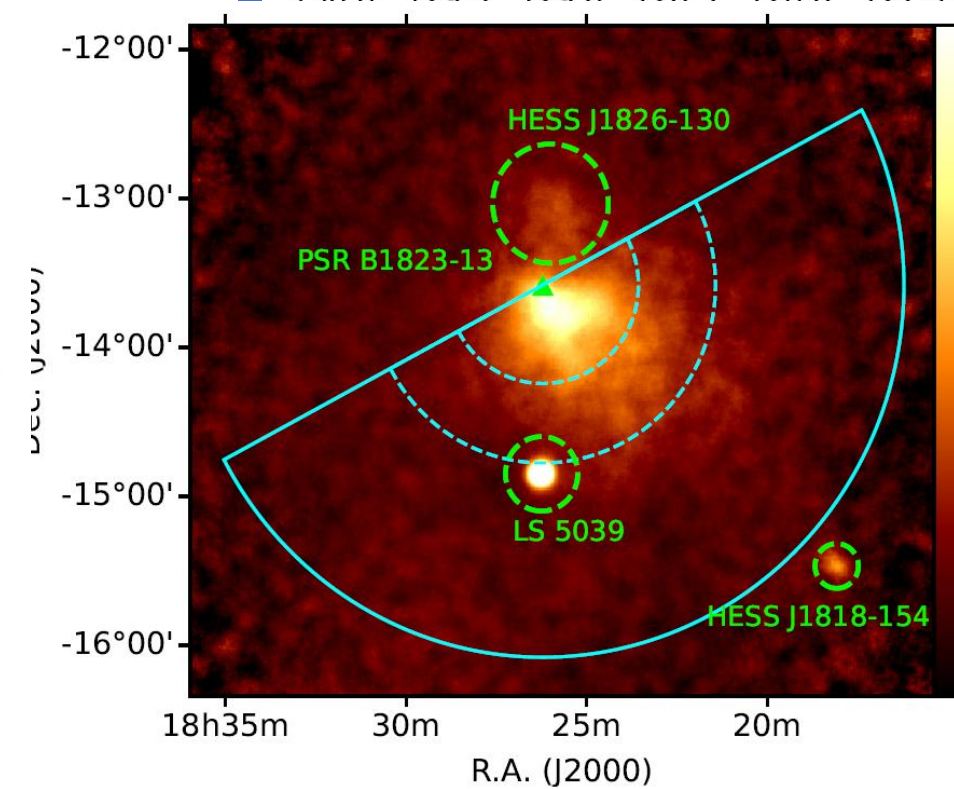
From PWNe to Pulsar Halos



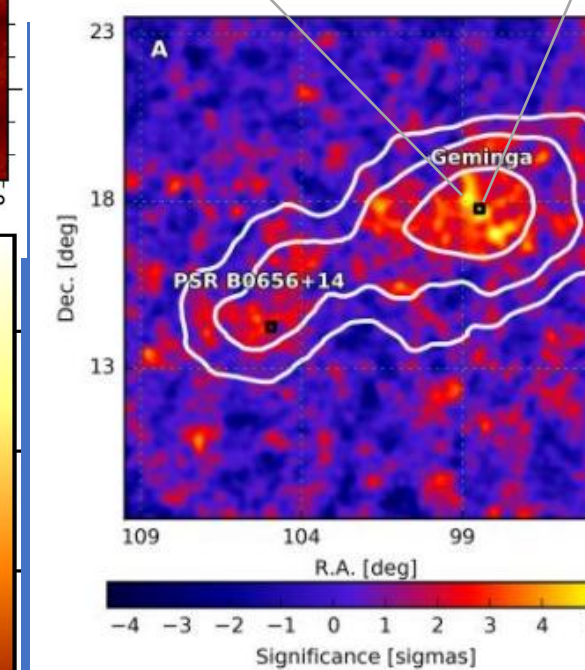
Pulsar Wind Nebula



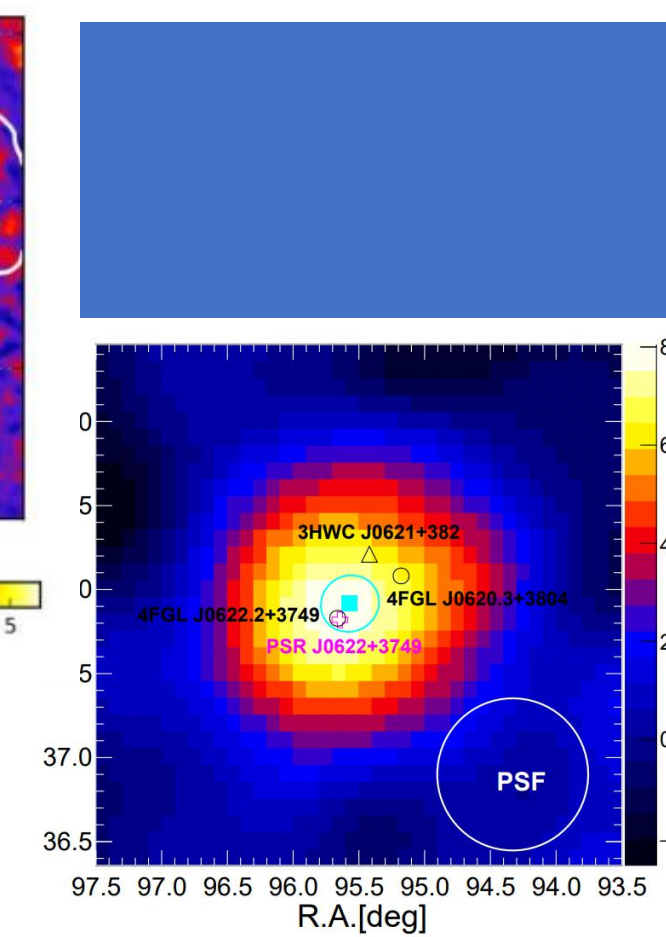
Free Expansion Phase



RS-interaction Phase

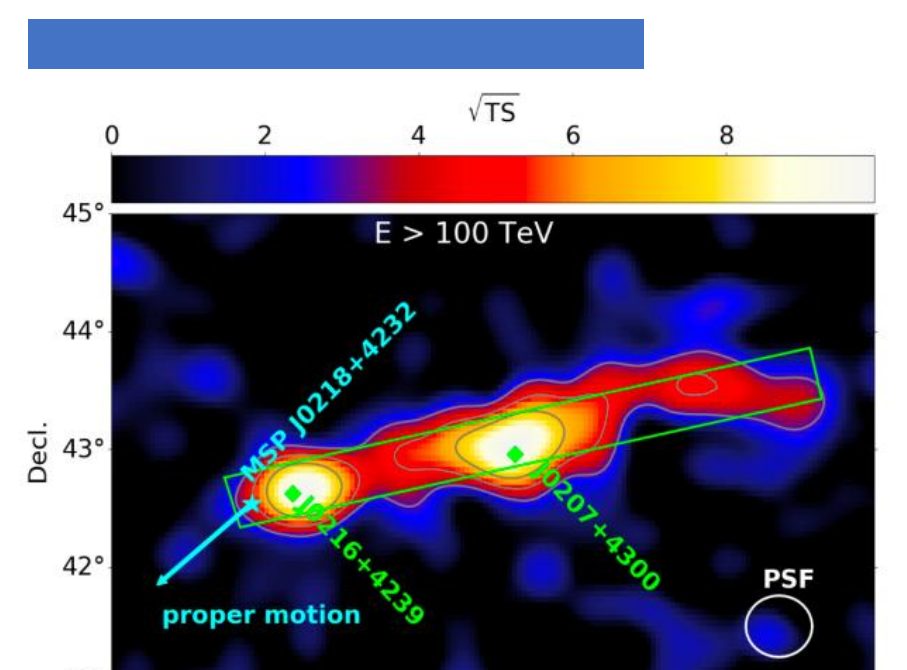
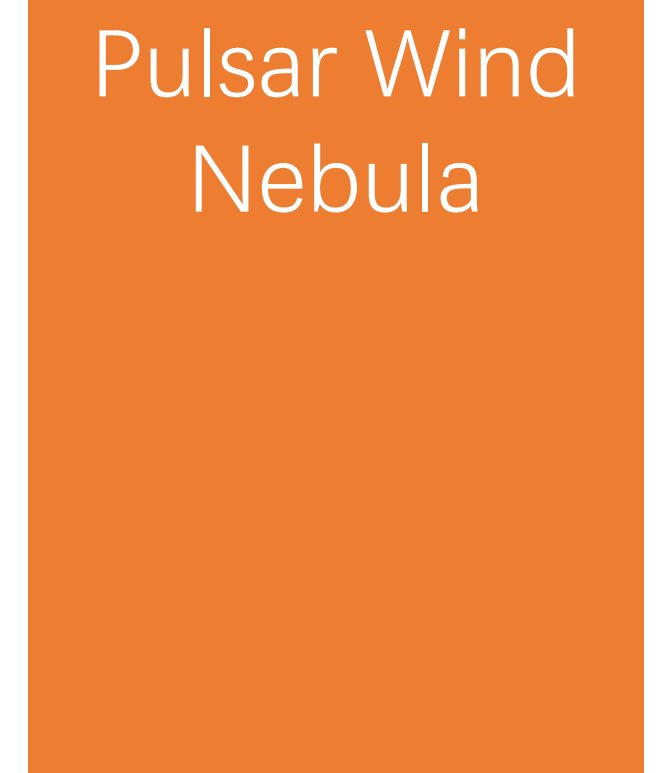


Pulsar Halos



Bow-Shock Phase

Too faint to be detected



Pulsar Halos

Isolated

Age of Pulsars

g-Binary

X-Binary(μ Q)

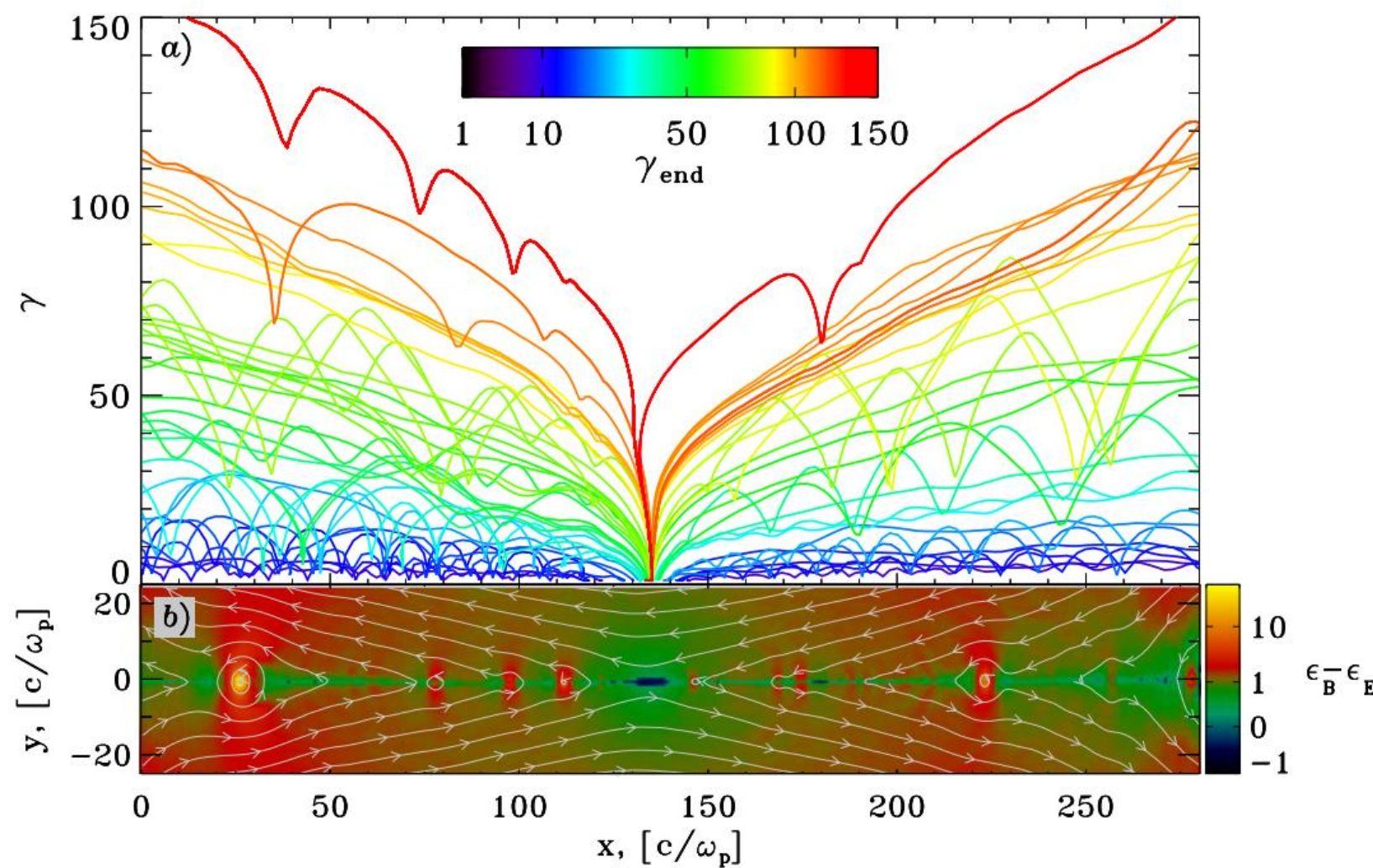
MSP

Binary

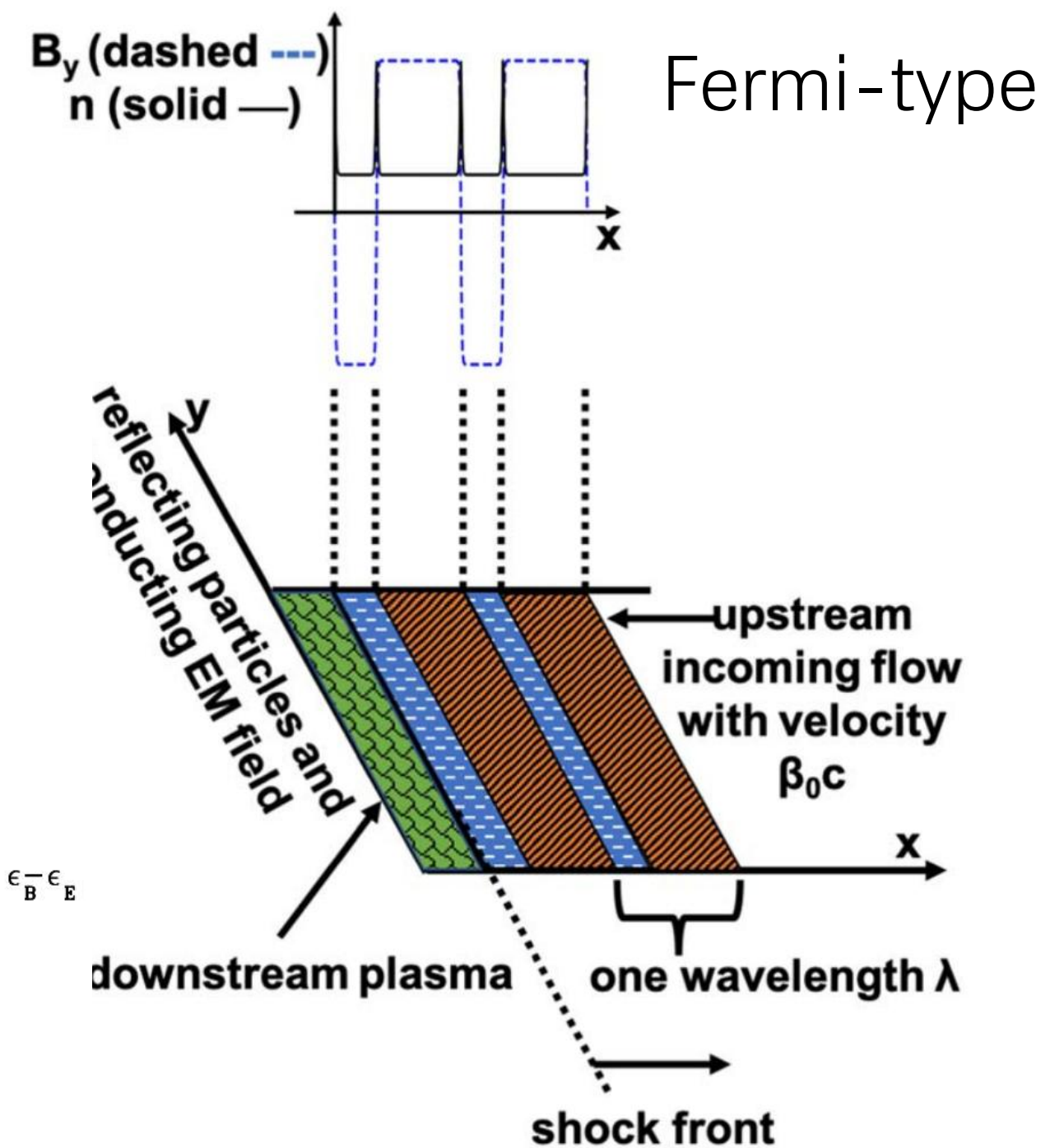
Young PWNe: Extreme Particle Accelerators

Sironi & Spitkovsky 2014, ApJ

X-points electric field



Lu et al. 2021, ApJ



rotational energy $\rightarrow$ electromagnetic energy
nonthermal energy $\leftarrow$ kinetic energy



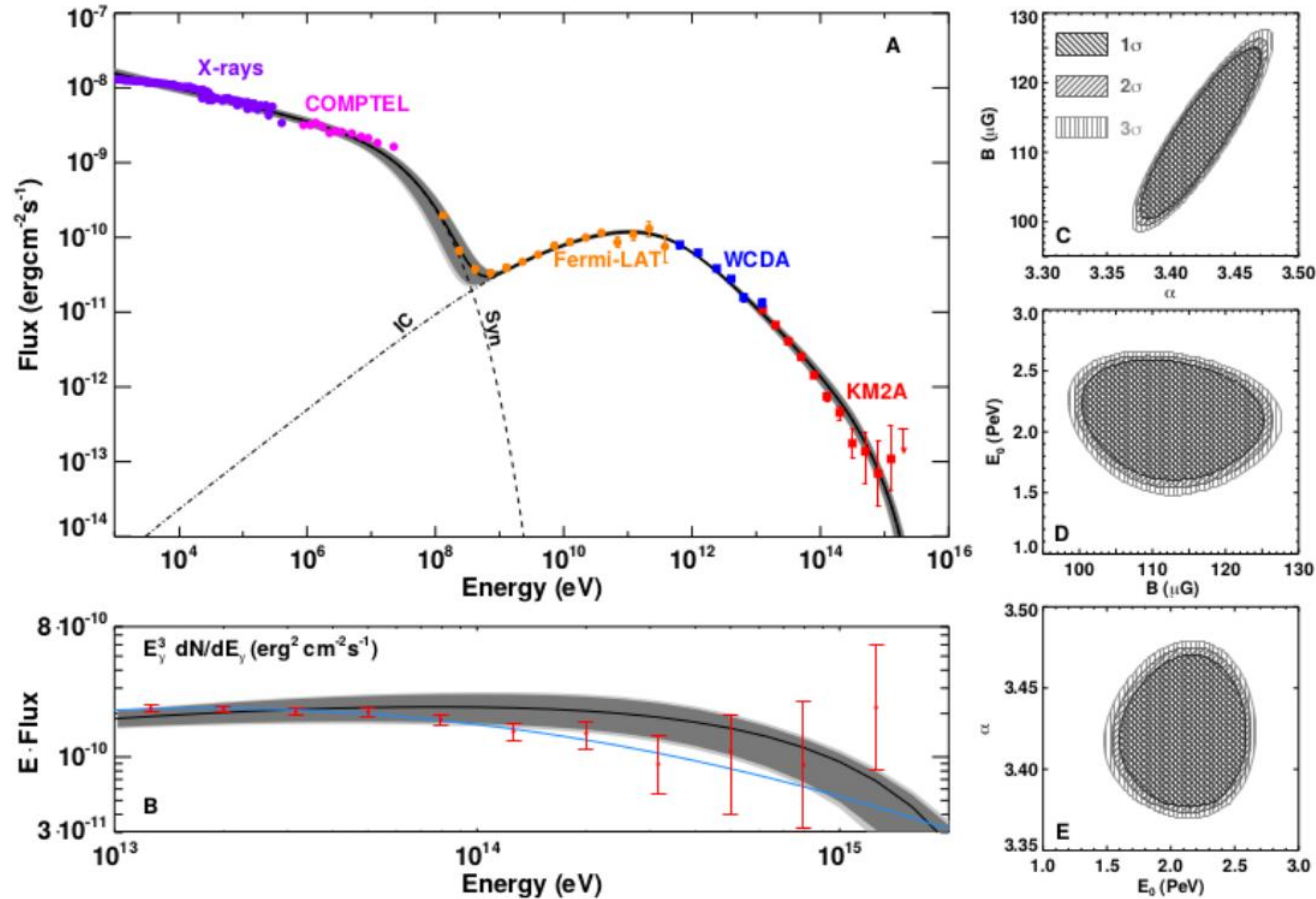
Limit from Hillas
Condition
Limit from
Synchrotron Cooling

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

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

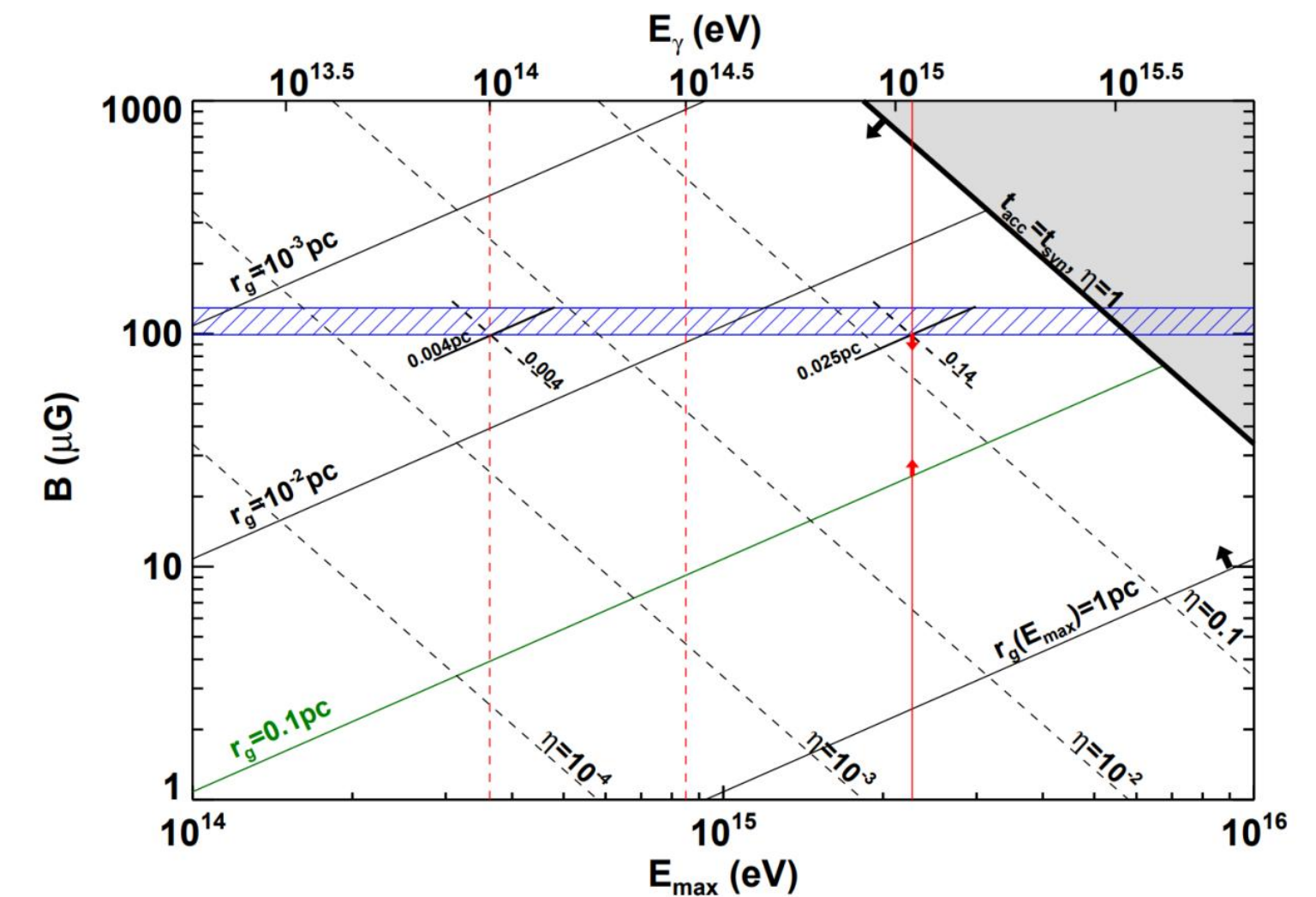
Composite X-ray/Optical Image
Credit: NASA/ESA

Implication from Crab Nebula



$$E_{\text{syn}} = 7 \text{ MeV} (E_e / 1 \text{ PeV})^2 (B / 100 \mu \text{ G})$$

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

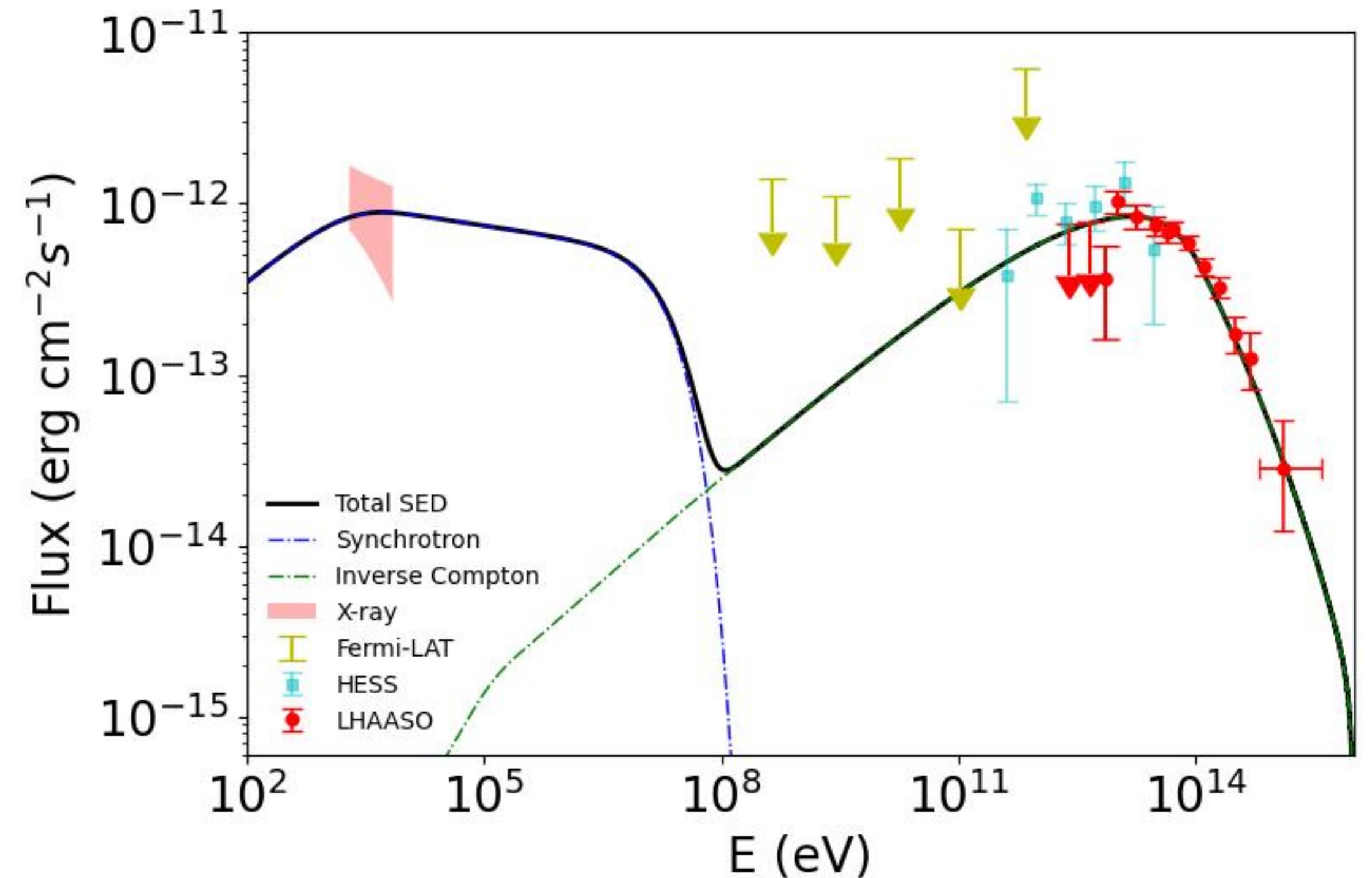
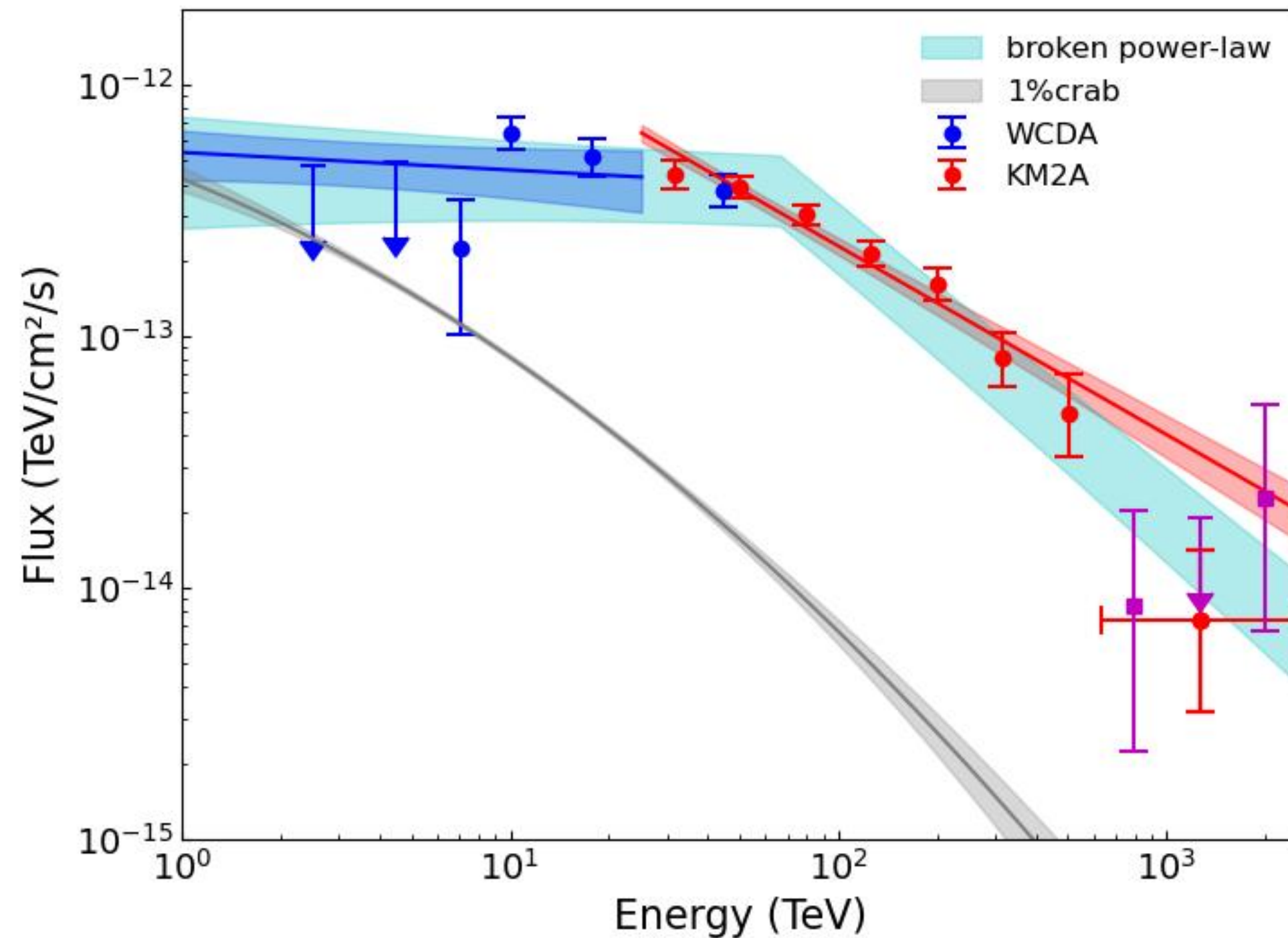


$$\eta = 0.14 (B / 100 \mu \text{ G}) (E_\gamma / 1 \text{ PeV})^{1.54}$$

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

Extreme acceleration efficiency

PSR J1849-0001: engine of another extreme accelerator



low magnetic field $\rightarrow$ size-limited acceleration

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

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

PWNe:

Extreme particle accelerator powered by PSR J1849-0001



PSR J1849-0001:

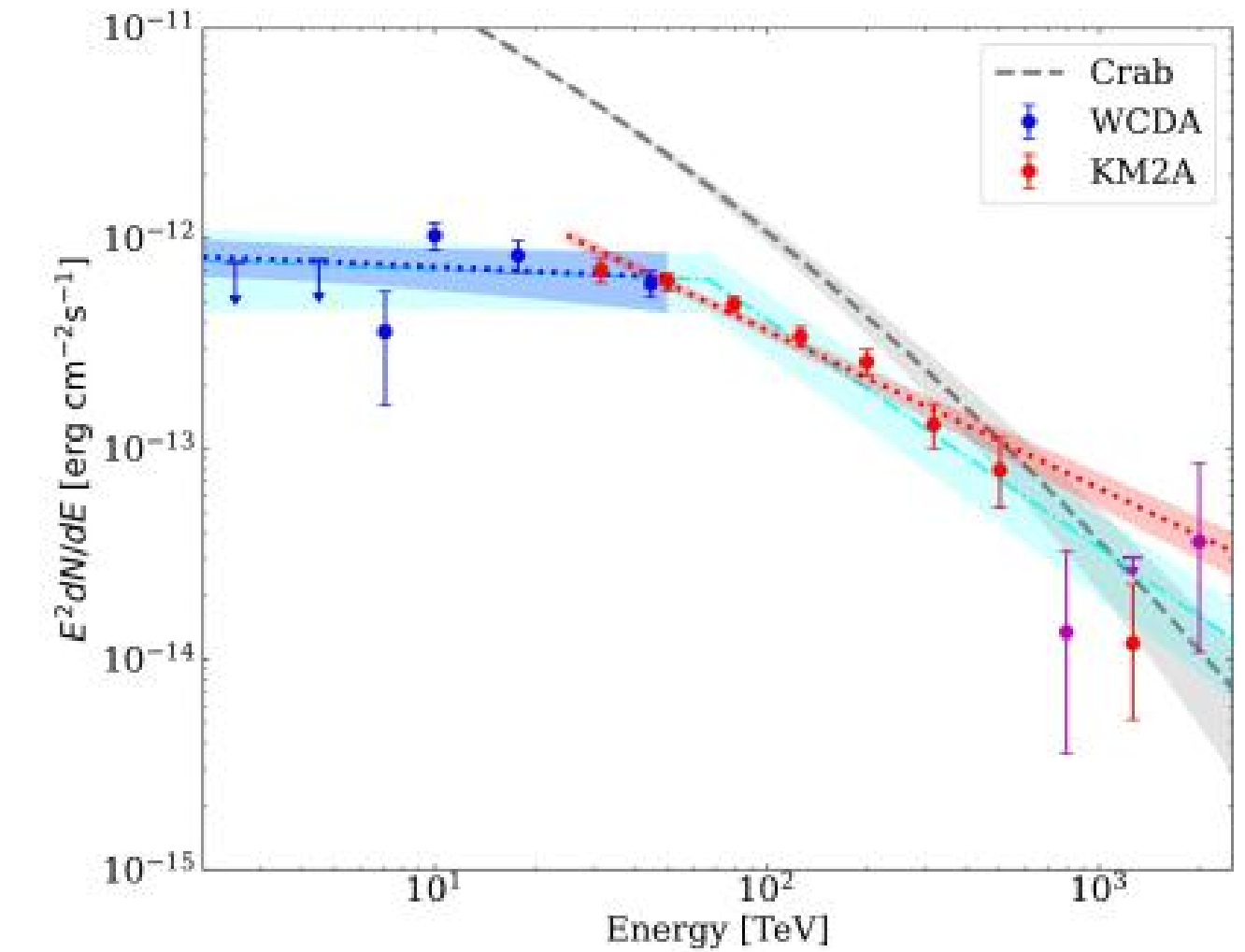
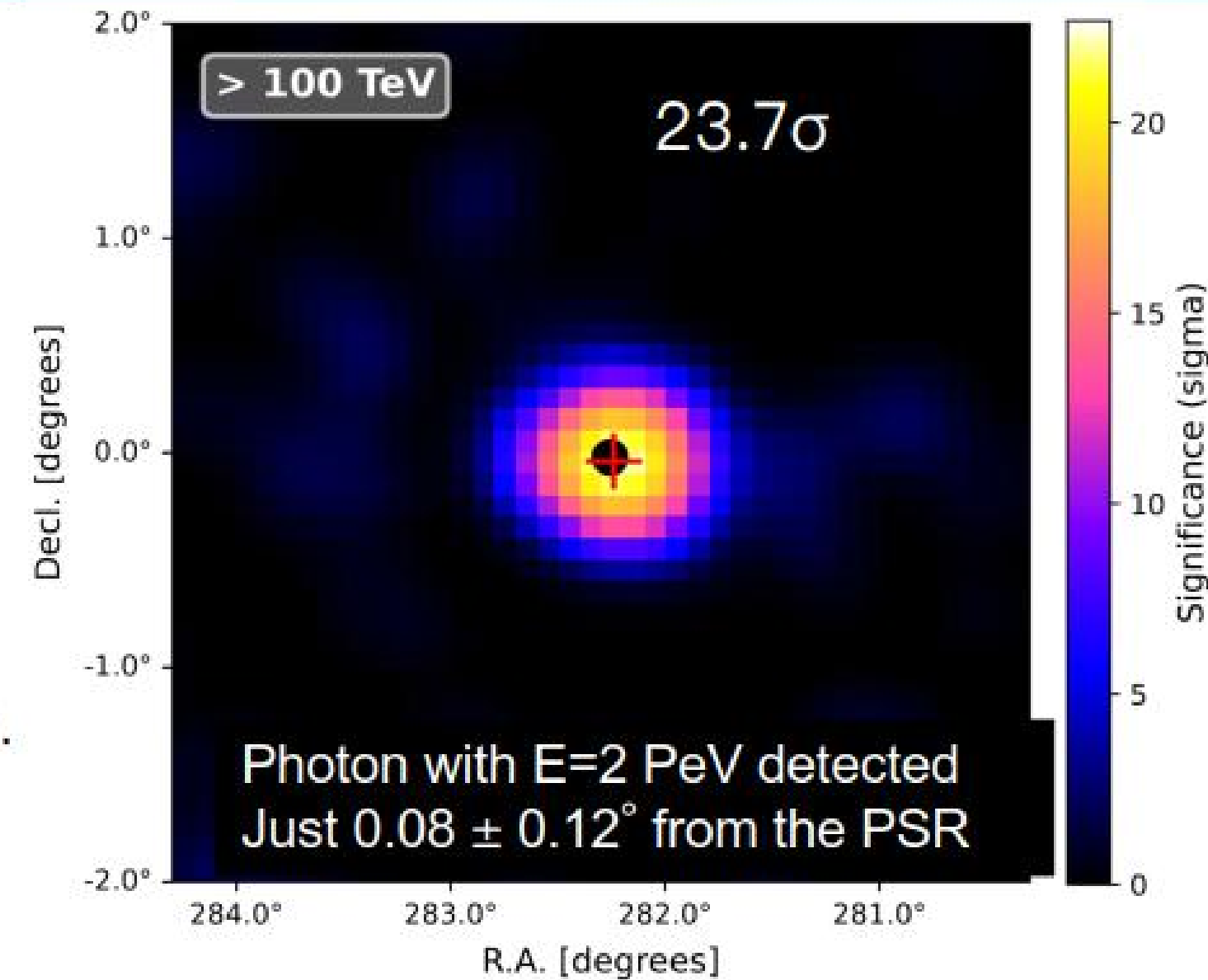
a fast-rotating pulsar initially discovered in the X-ray band.

$d=7$ kc

$\tau_c = 43.1$ kyr,

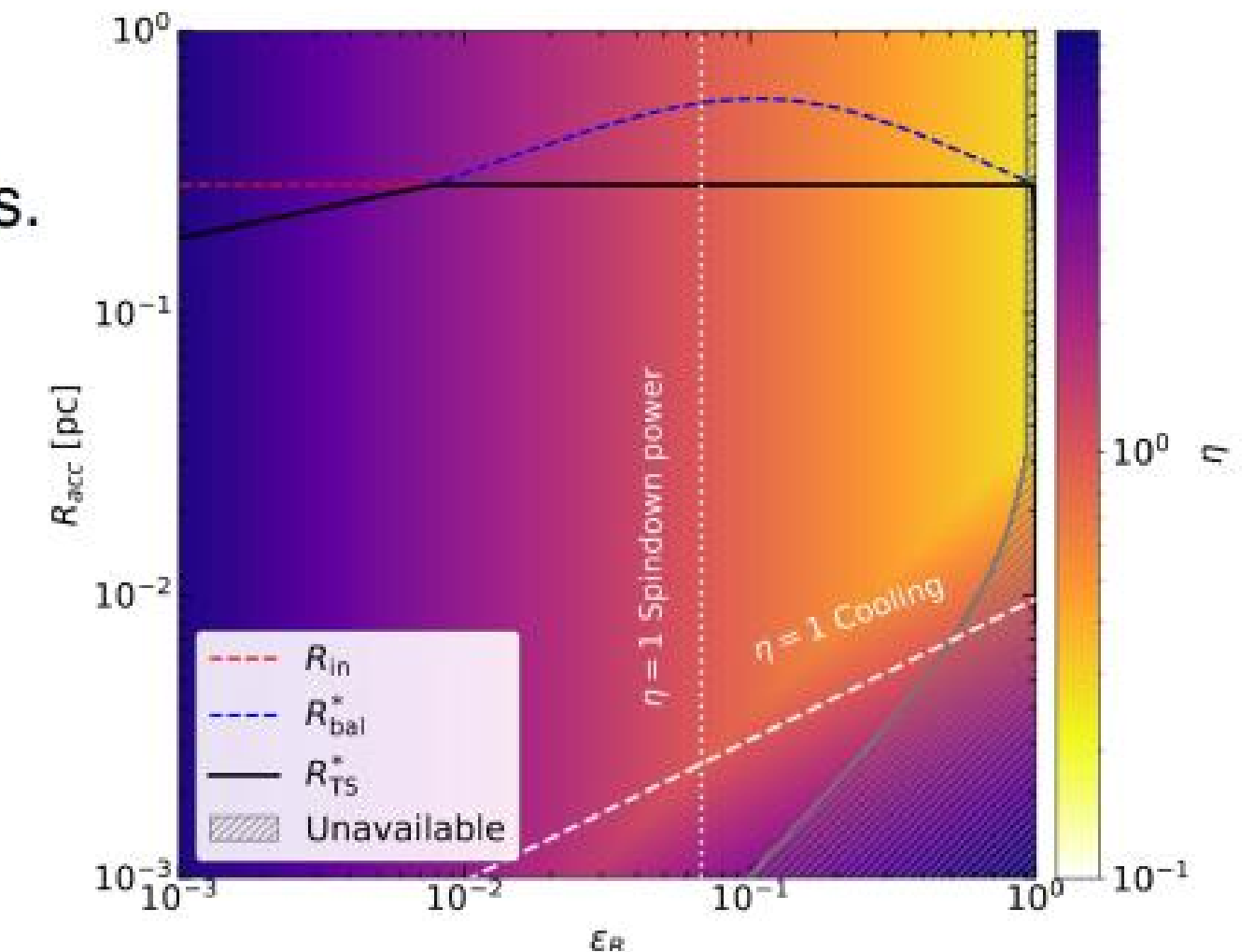
$P = 38.5$ ms (similar to Crab)

$L_{sd} = 9.8e36$ 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 : **$B \sim 3 \mu\text{G}$** within the PWN.
- ❑ Derived particle acceleration efficiency: approaching **1**, challenging the particle acceleration theory in PWN.

LHAASO, NatAs, (2026) arXiv: [2603.15537](https://arxiv.org/abs/2603.15537)



Einstein Probe (天关(Taurus)Telescope)

WXT:

- Fast Surveying
- 3' resolution

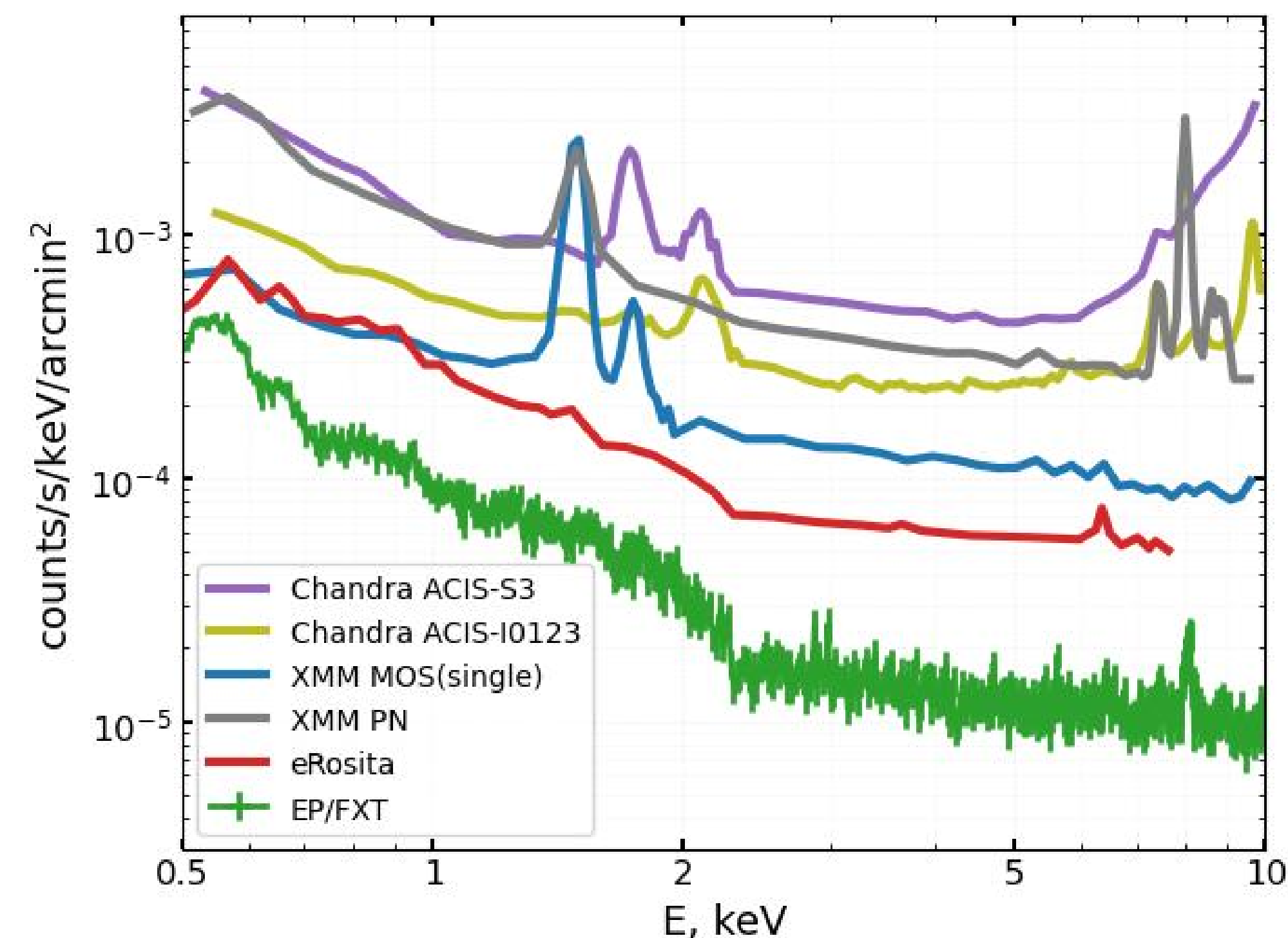
FXT:

- Large FoV
- Very low BG



Follow-up FXT

Wide FoV WXT

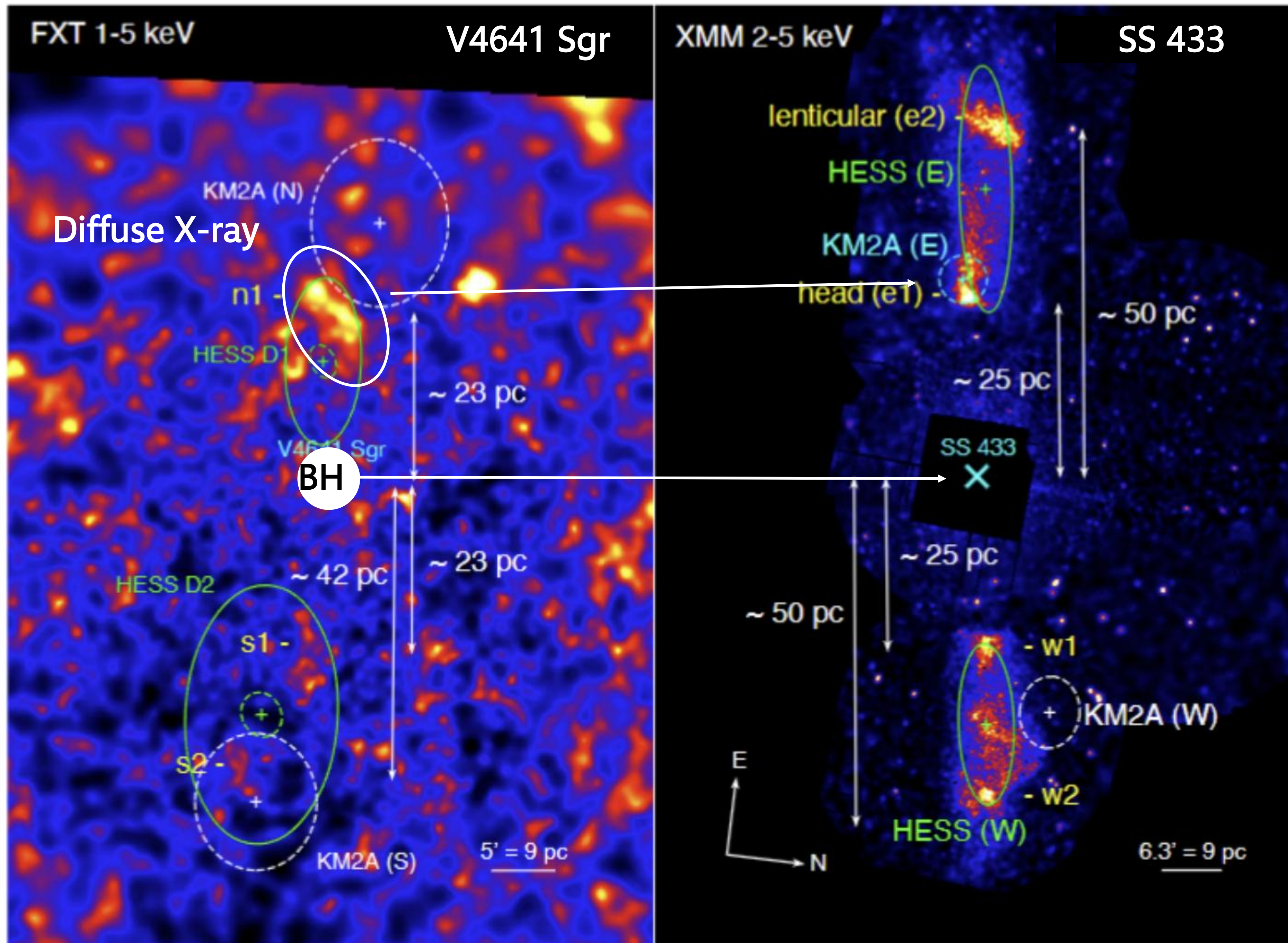


XMM-Newton

EP FXT

XMM	FXT
2400 cm ²	500 cm ²

(Cao et al. 2026)



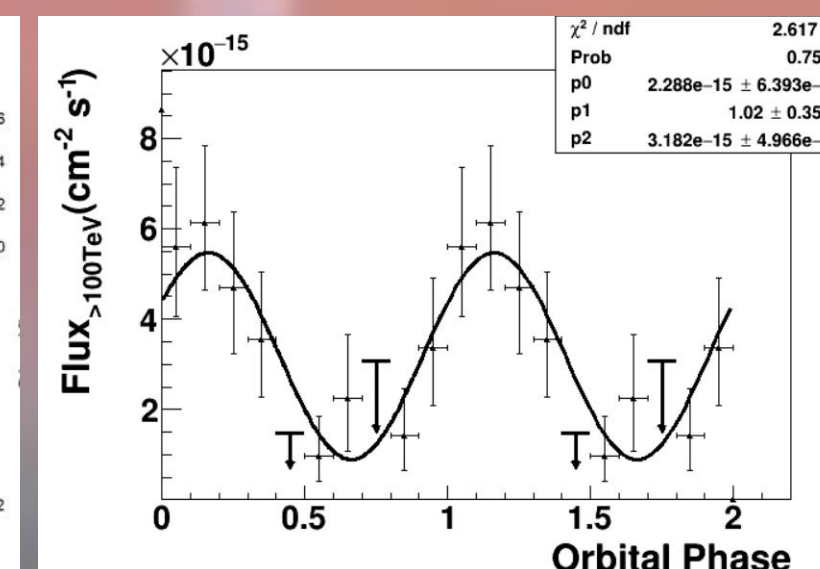
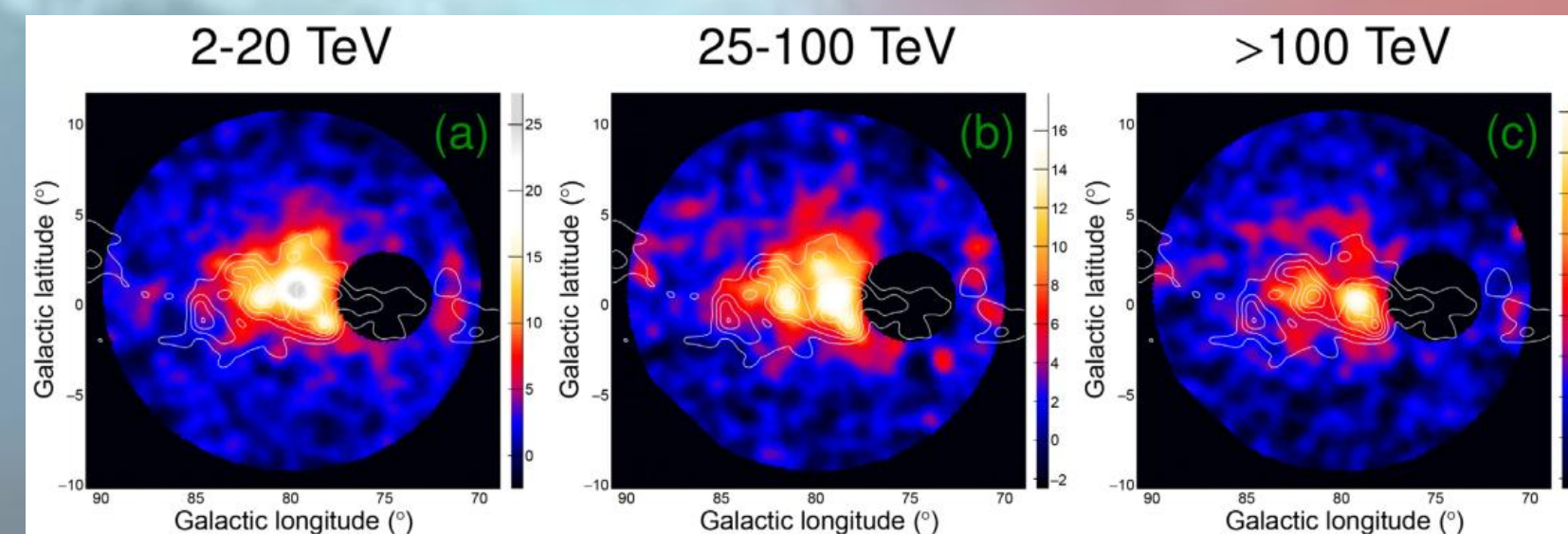
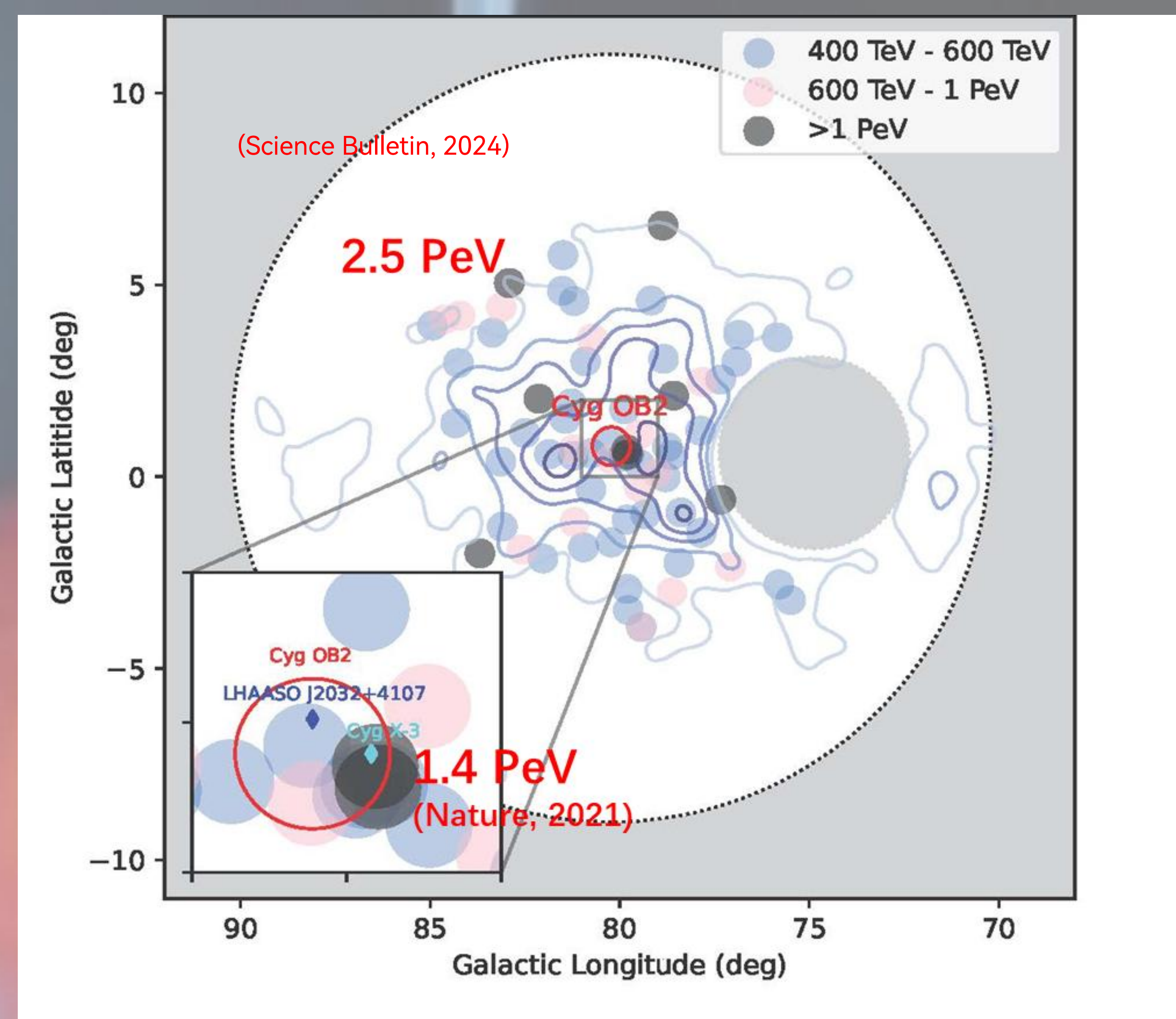
V4641 vs. SS 433

Similar pattern
Much Lower luminosity
Activity, low B-field
Version of SS 433

(Chi et al. 2026, submitted)

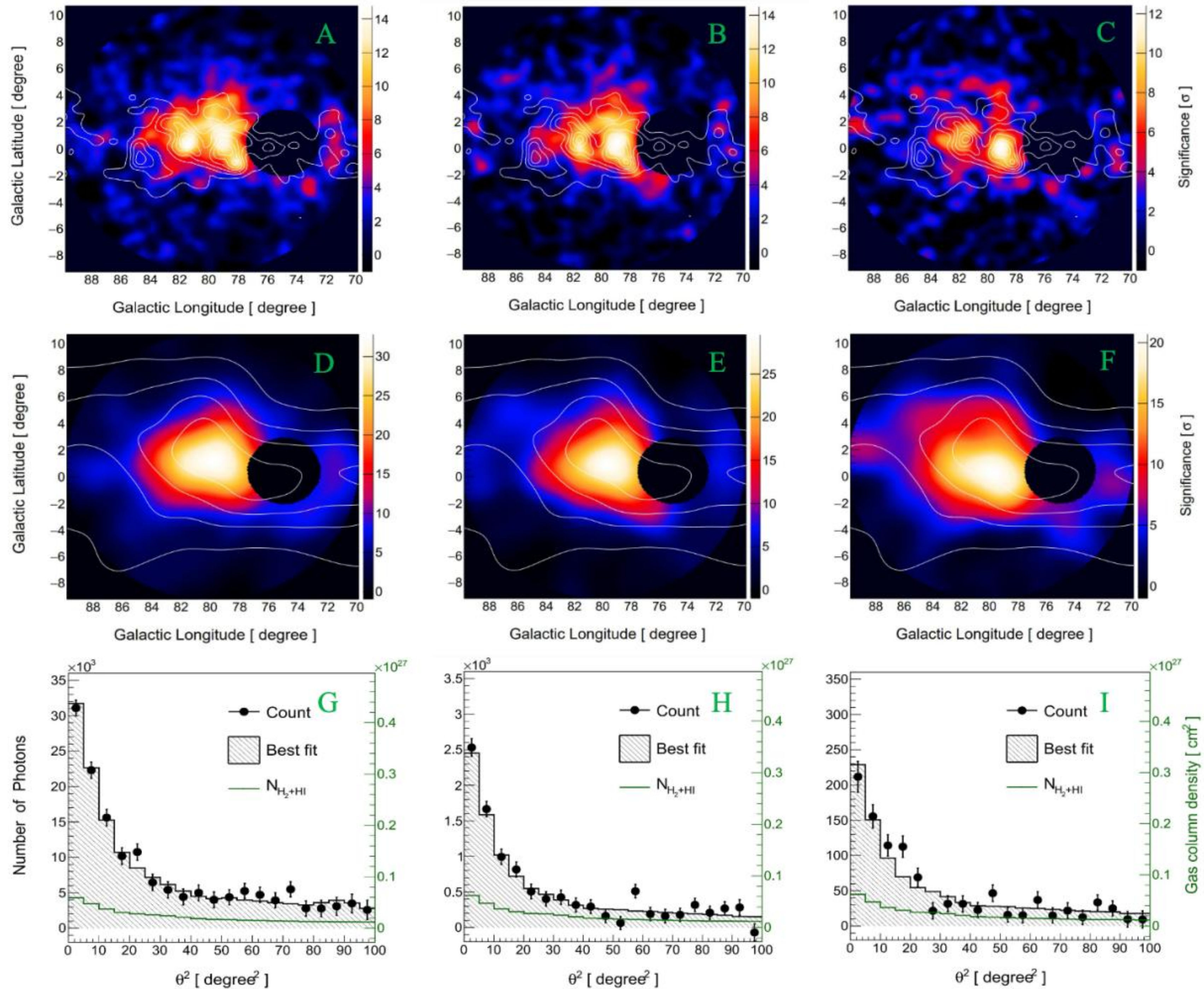
Cygnus Bubble with a size of $\sim 10^\circ$

- This guarantees the proton source
- ~ 2.5 PeV photon implies
25 PeV protons propagation
- Slow diffusion yields the bubble
- Size of 300 pc or 1 kpc
- Distance is unclear

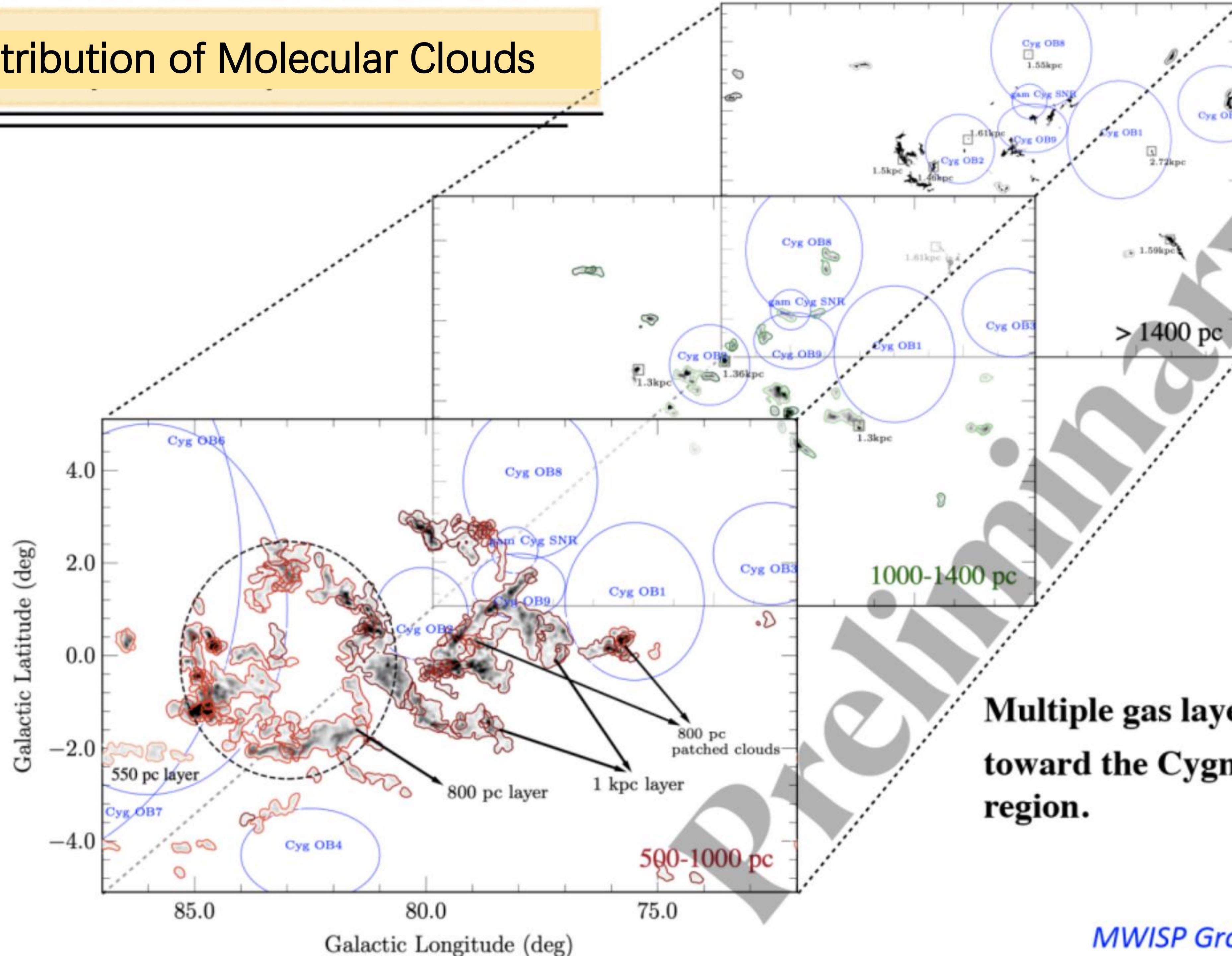


LHAASO VIEW ON CYGNUS

Huge bubble
beyond ~ 10
degrees (200 pc)



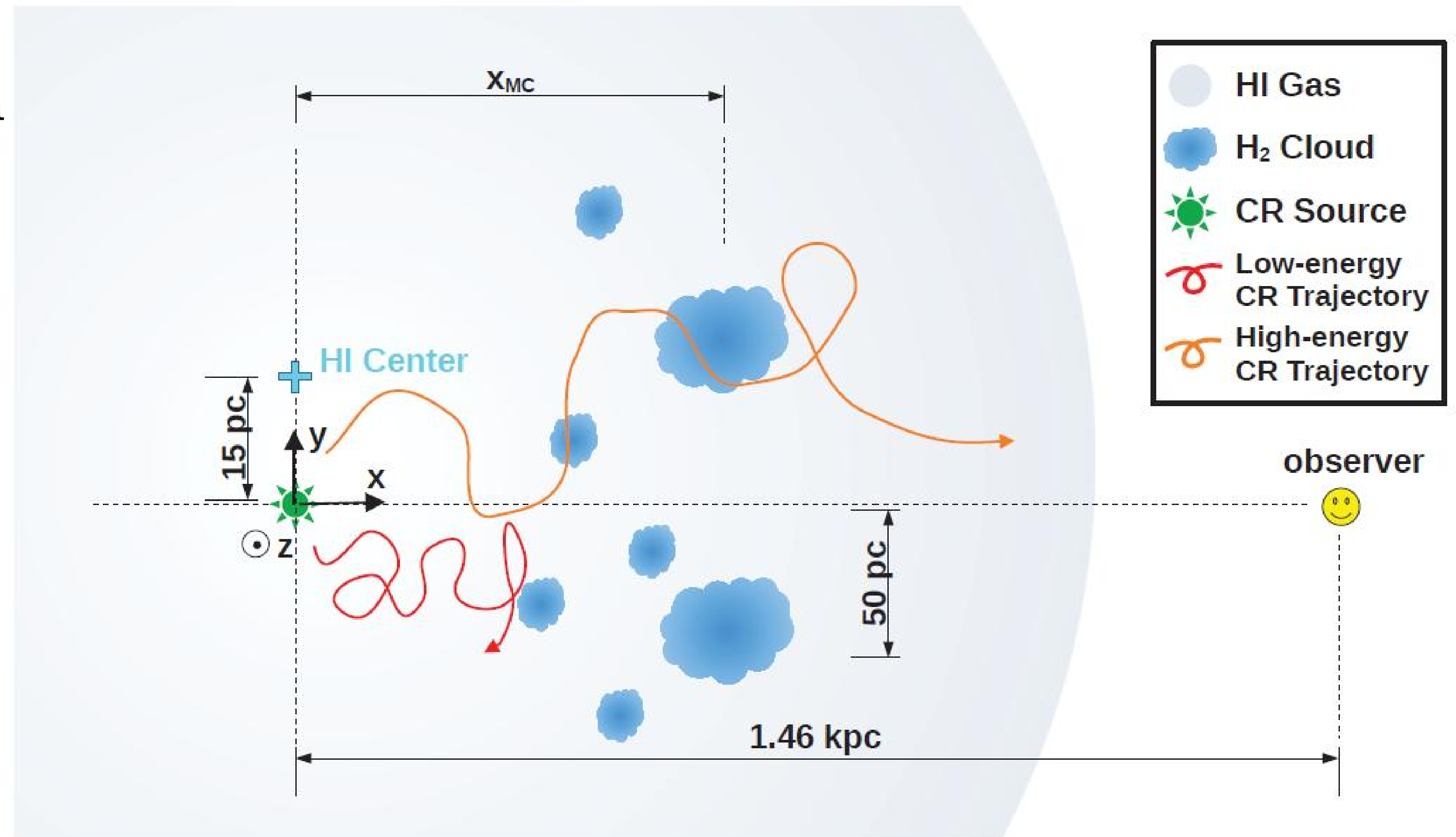
3-D distribution of Molecular Clouds



**Multiple gas layers
toward the Cygnus
region.**

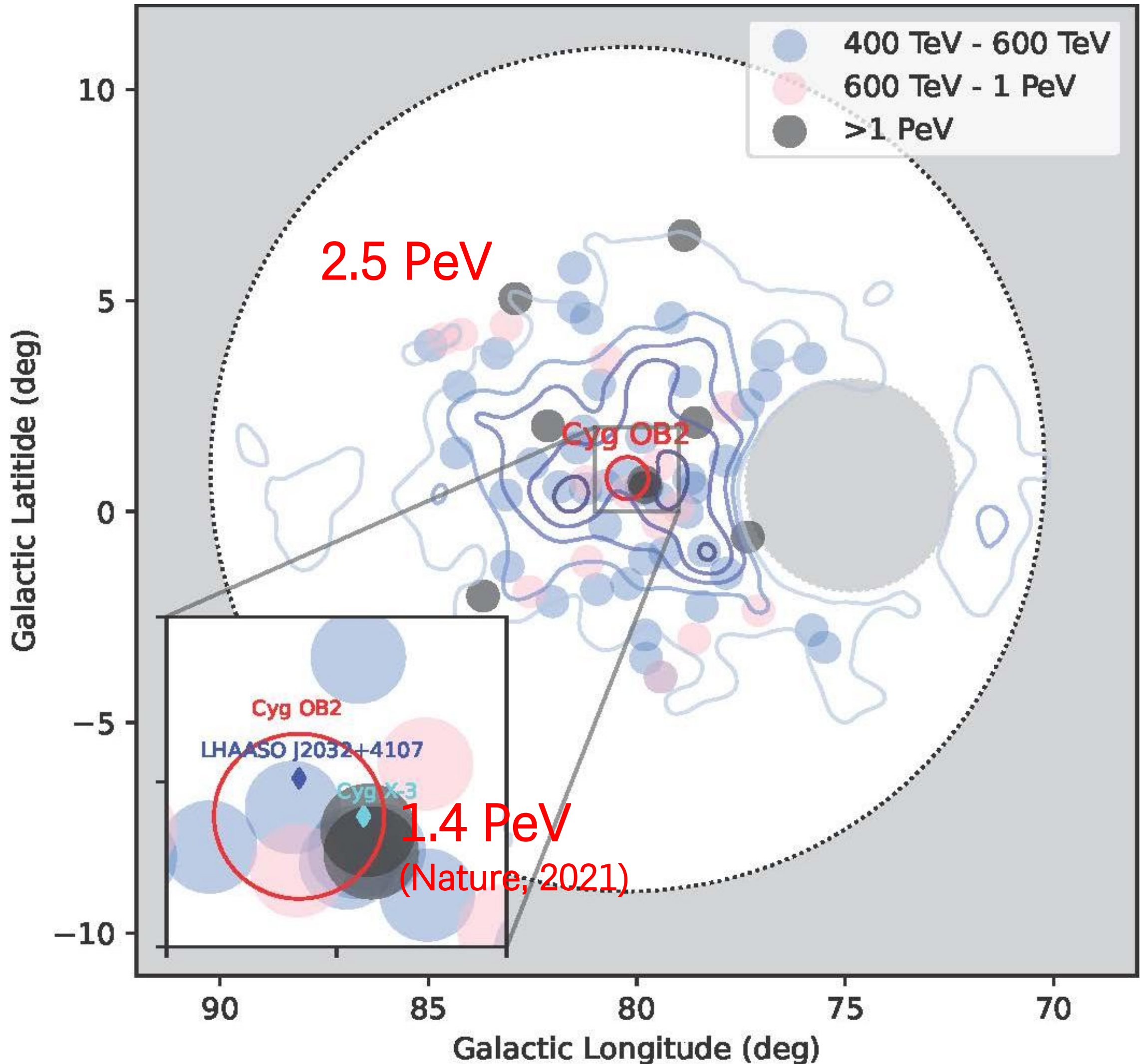
HE Protons injection from the core region

- High energy cosmic rays escape from the accelerator in the core
- Diffusing through the H1 gas and producing γ 's in p-p collisions
- Hitting on clumpy molecular clouds making hot-spots
- Slow diffusion $\sim 1\%DC$ in ISM



A Bubble of UHE γ 's centered at a complex core

Cygnus OB2, binary J2032+4107, MQ X-3

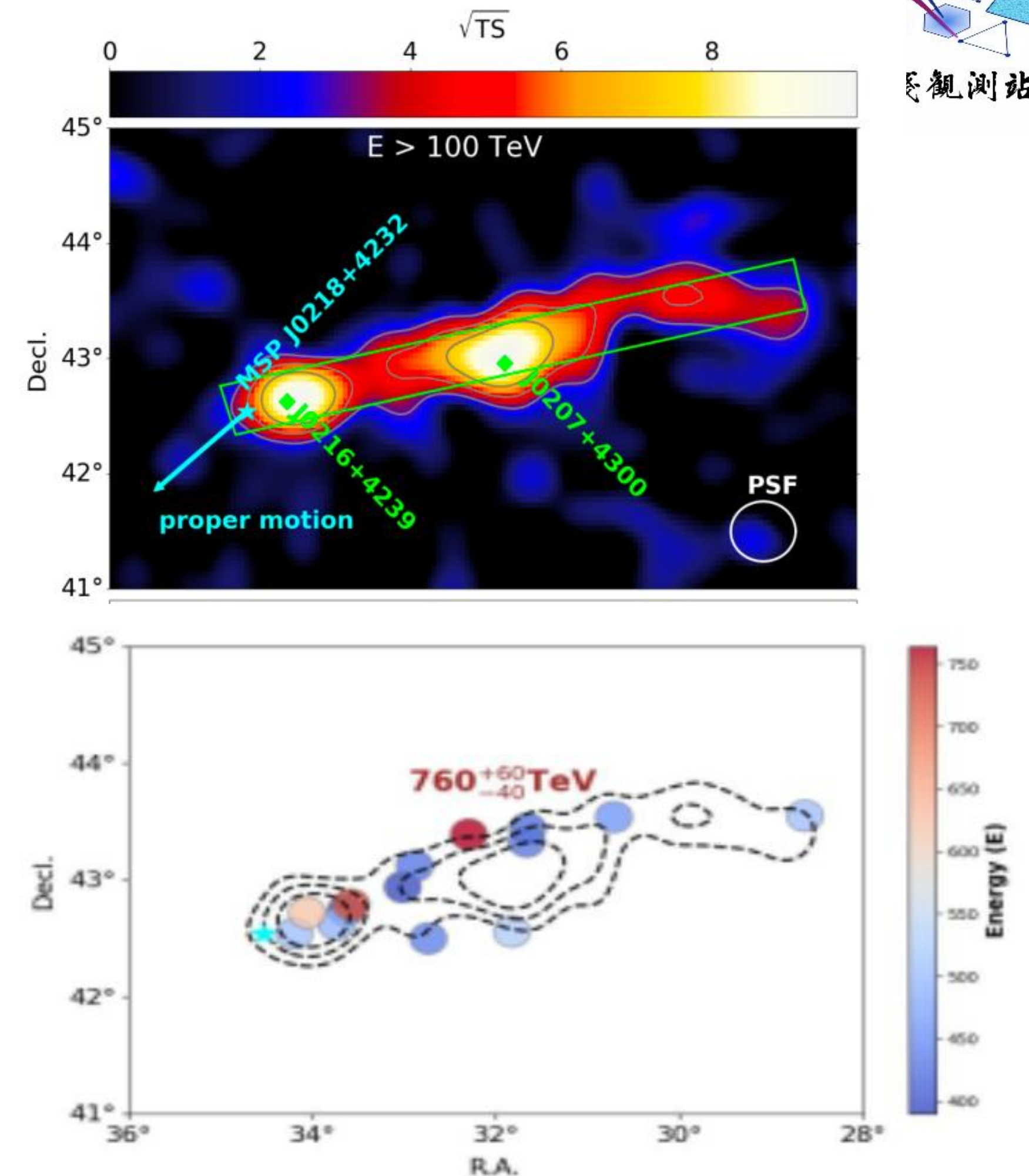
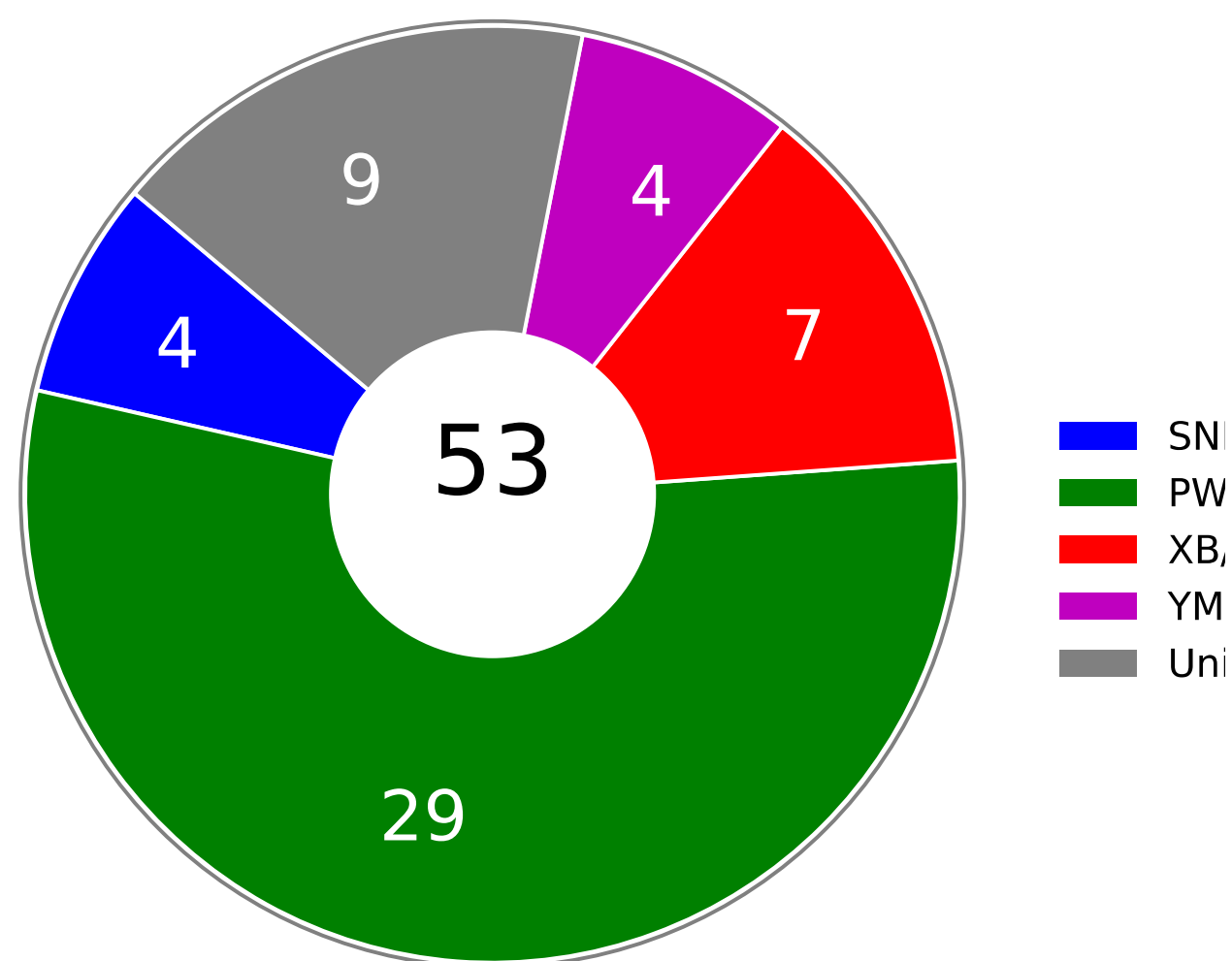
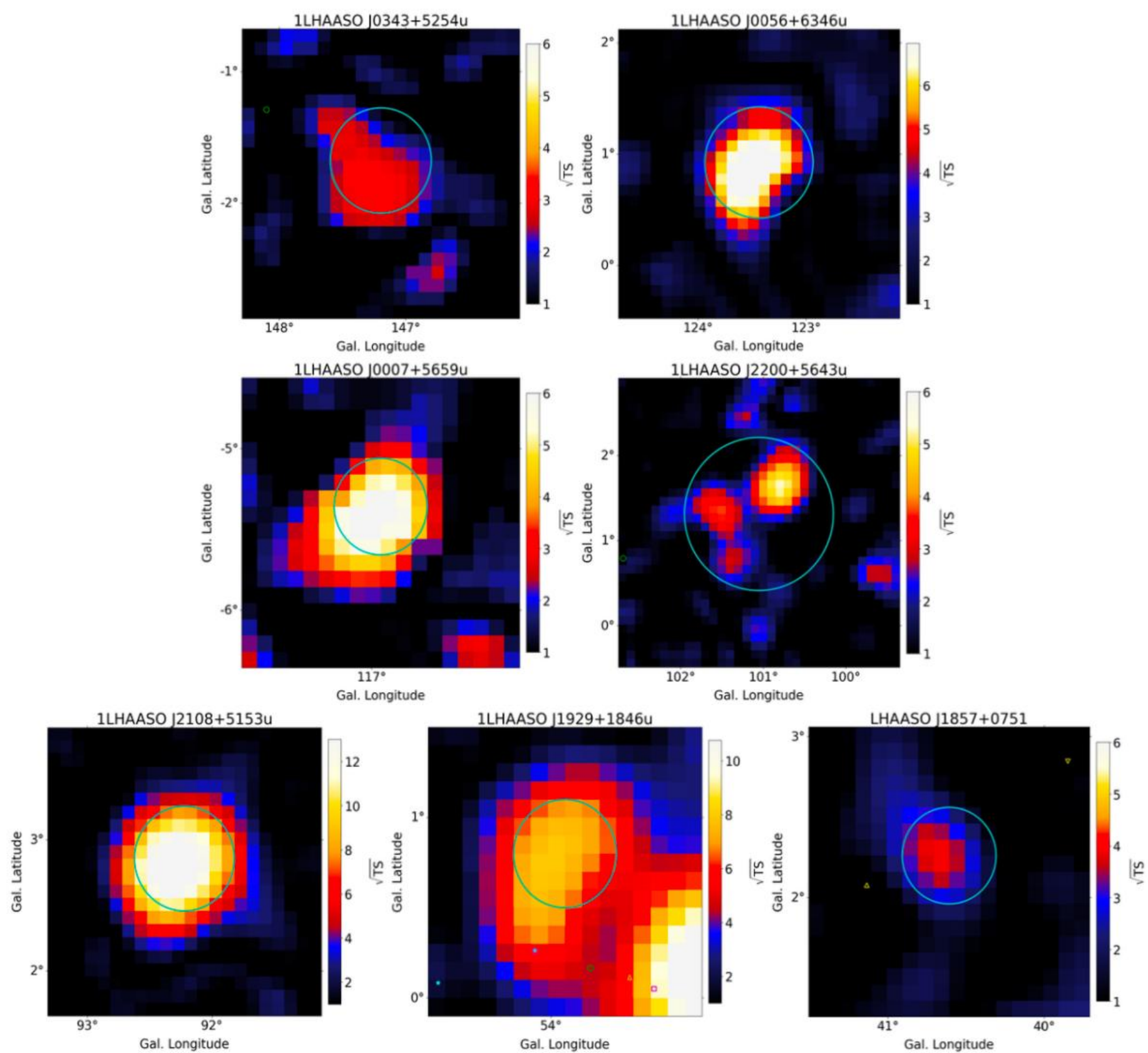
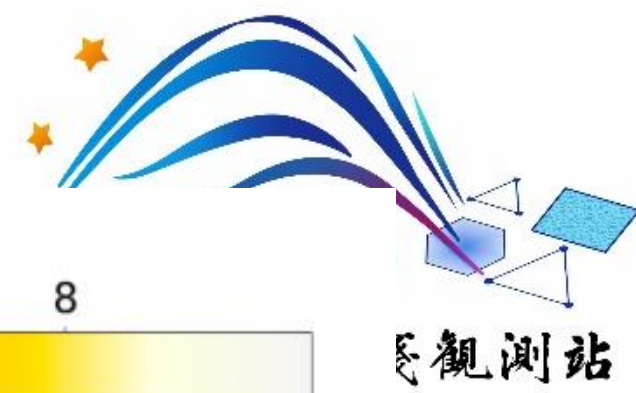


8 γ 's above 1 PeV!

Energy (TeV)	Ne	Nu	Theta (deg)	Dr (m)
1087	5904	13	19.4	143
1188	5480	14	34.4	73
1208	6939	13	14.2	131
1350	6938	8	27.1	43
1379	6469	9	17.4	52
1421	6258	7	12.7	57
1784	6665	13	18.0	41
2481	13815	29	33.0	99

- PeV Photons are scattered in the Bubble, and seem not to associate with any small scale sources

Dark PeVatrons



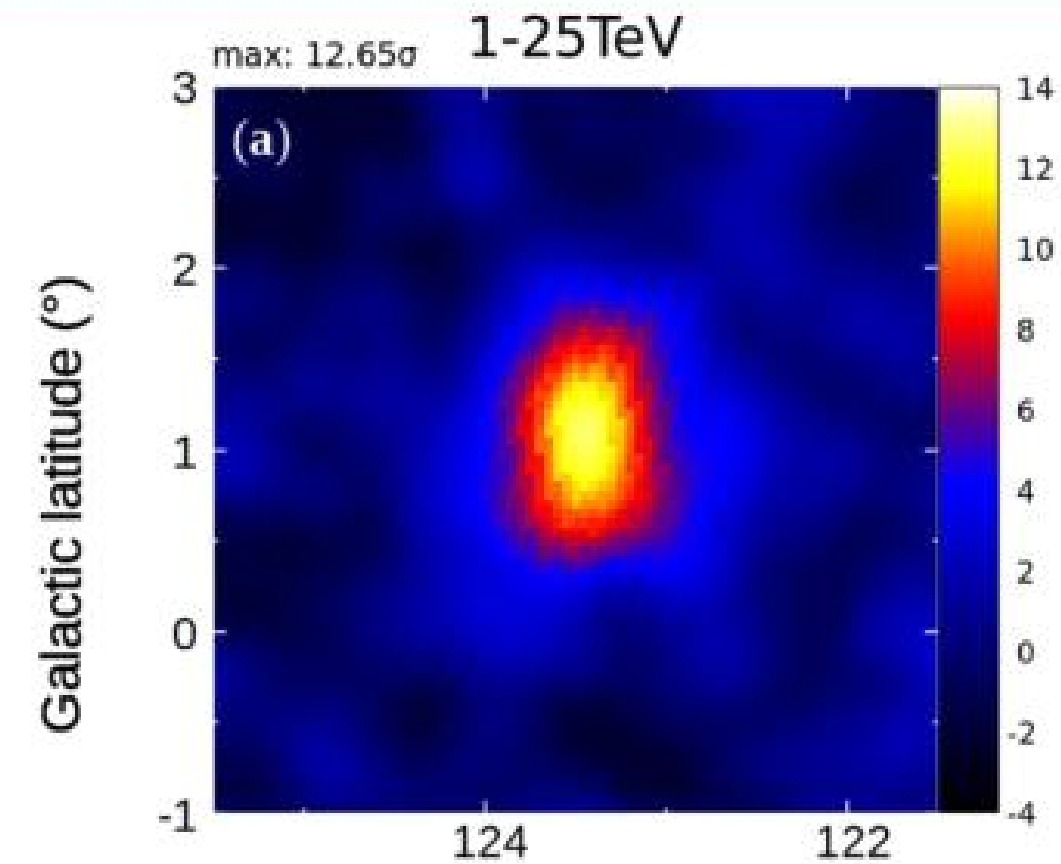
LHAASO J0212+4254 is a bar of 5° at $b \approx -17.5^\circ$
 seem have a head LHAASO J0216+4237 with a
 high energy knot LHAASO J0206+4302

DARK PEVATRONS

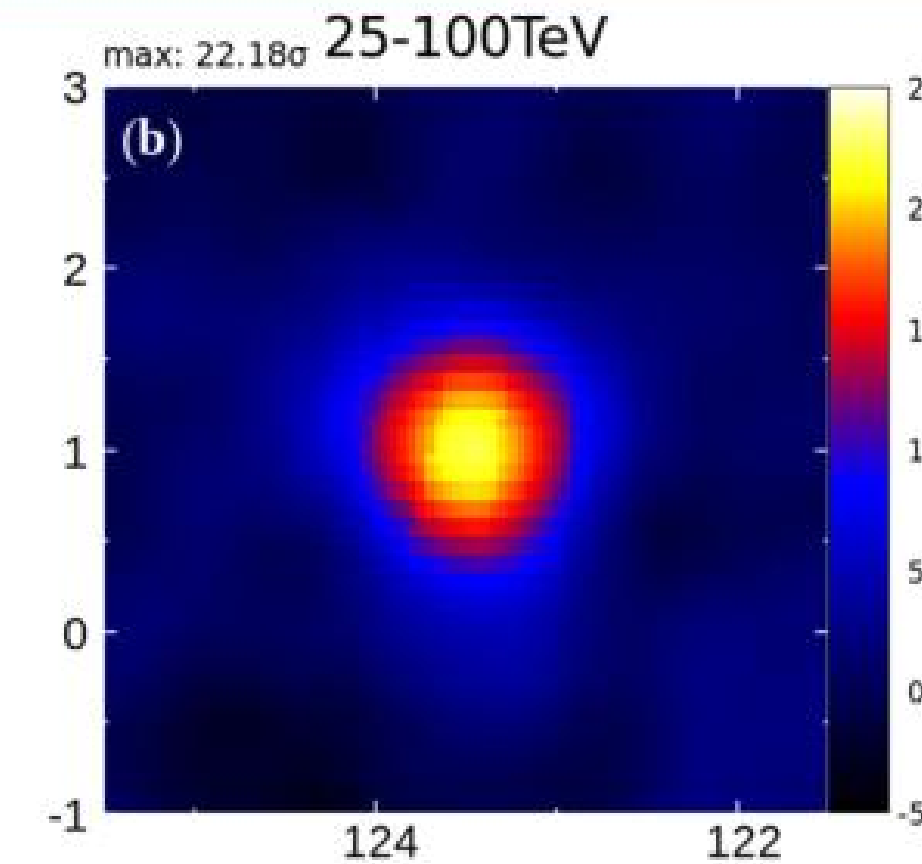
1LHAASO J0056+6346u:

- ❑ 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
 - ...

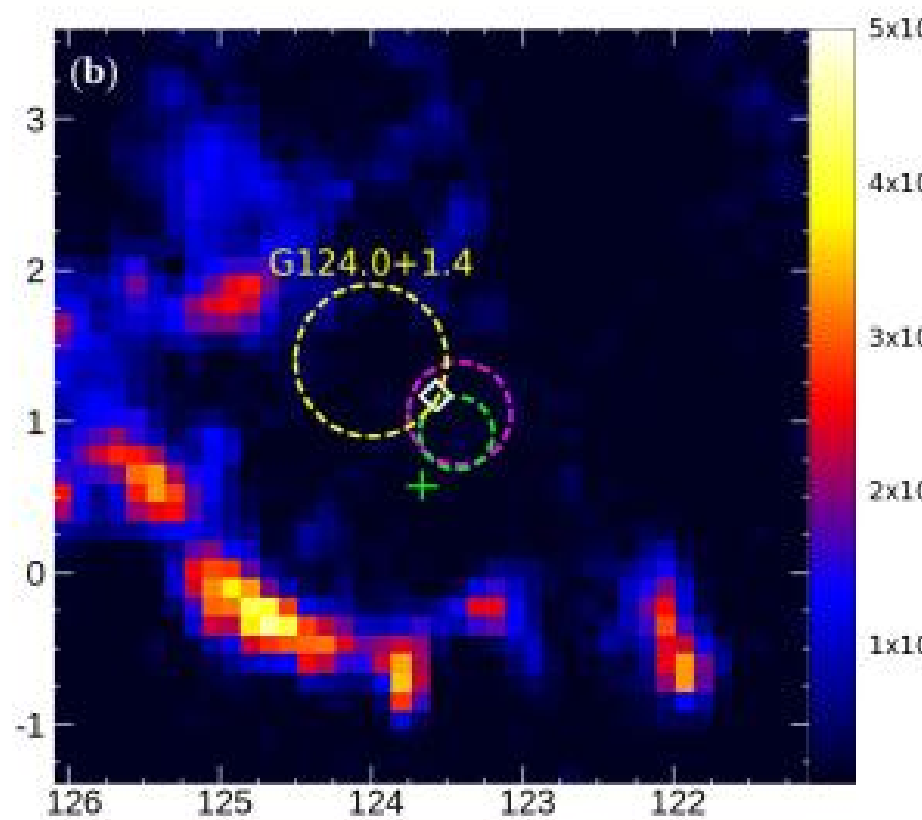
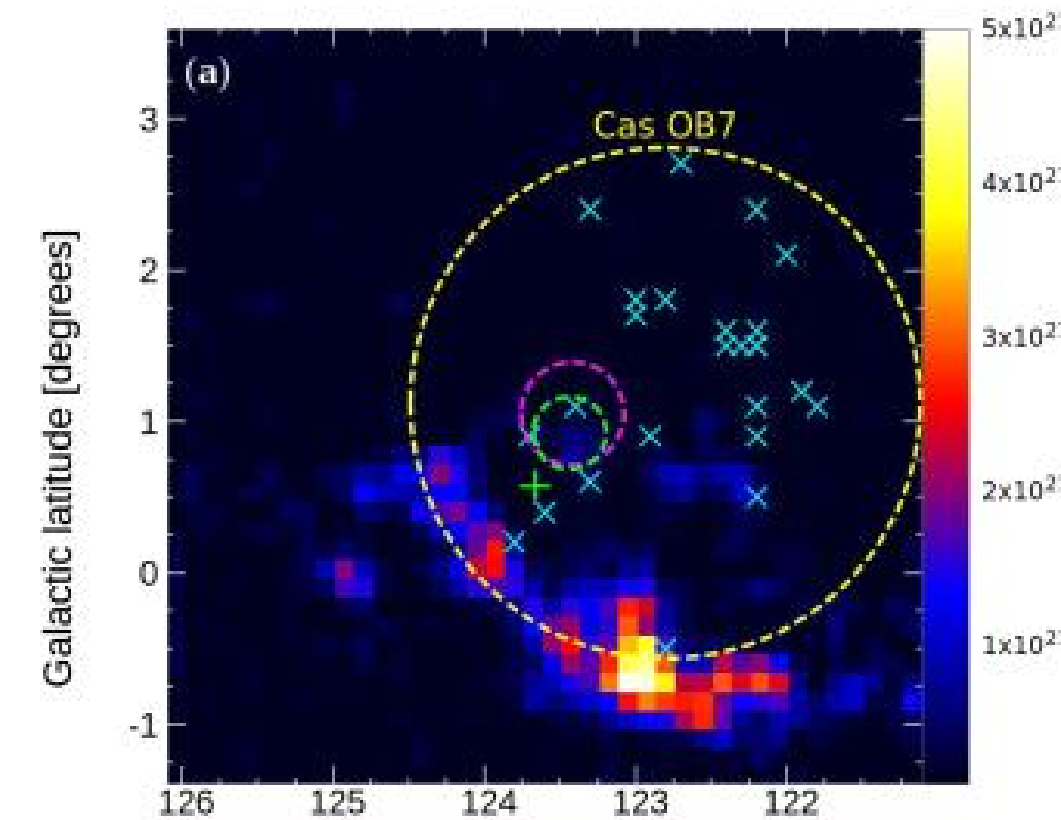
LHAASO, SCPMA 68,
279505 (2025)
arXiv: [2504.00601](https://arxiv.org/abs/2504.00601)



LHAASO significance maps

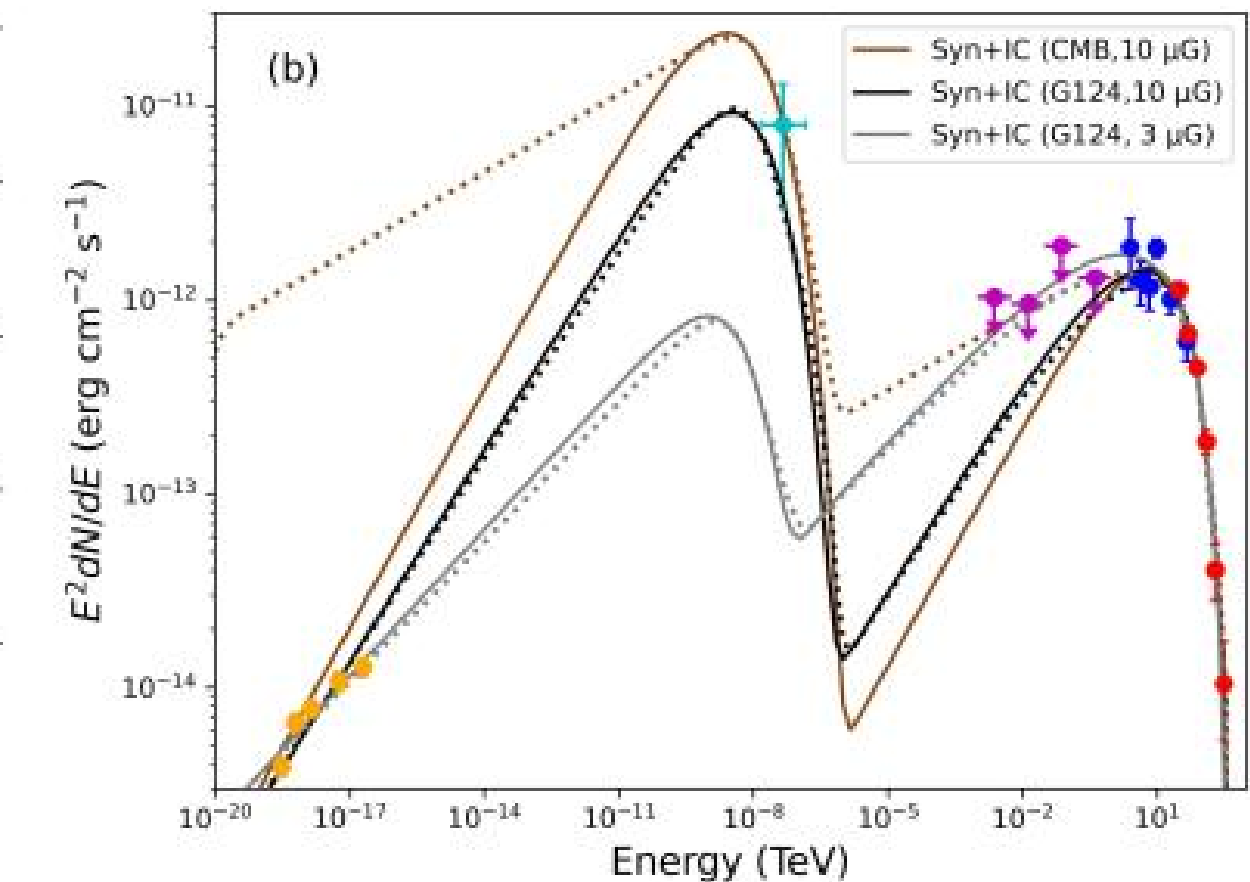
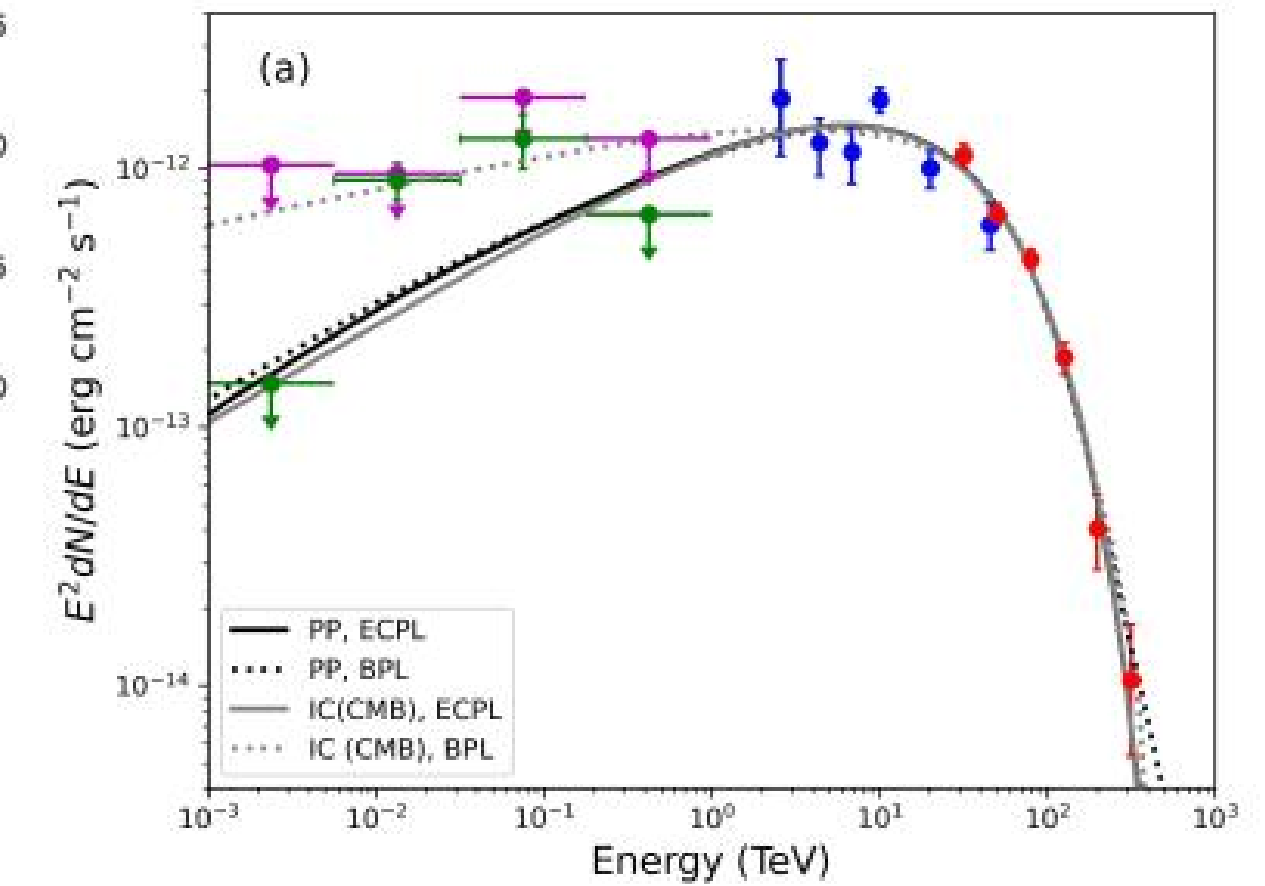


Galactic longitude (°)



Galactic longitude [degrees]

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



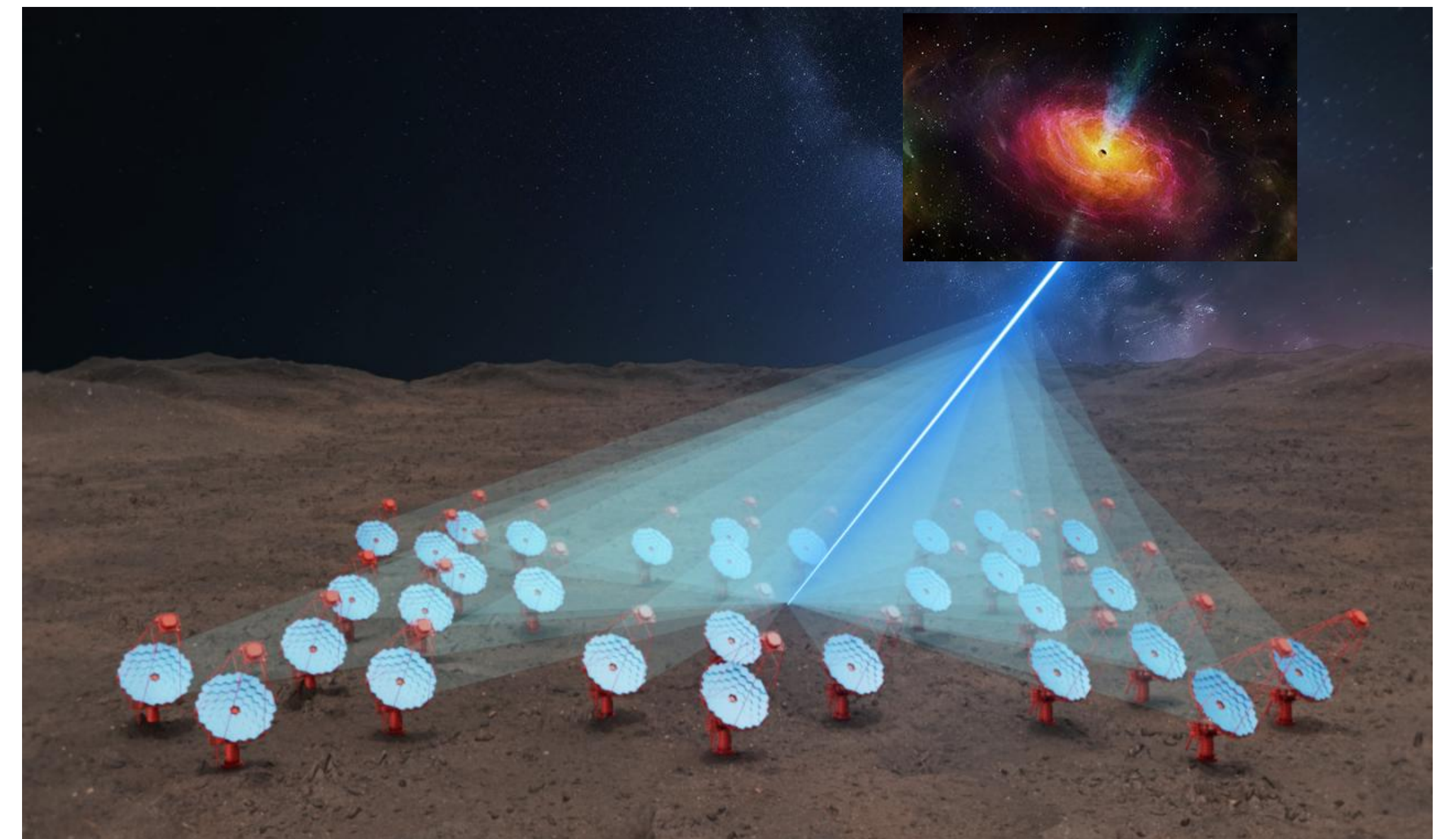
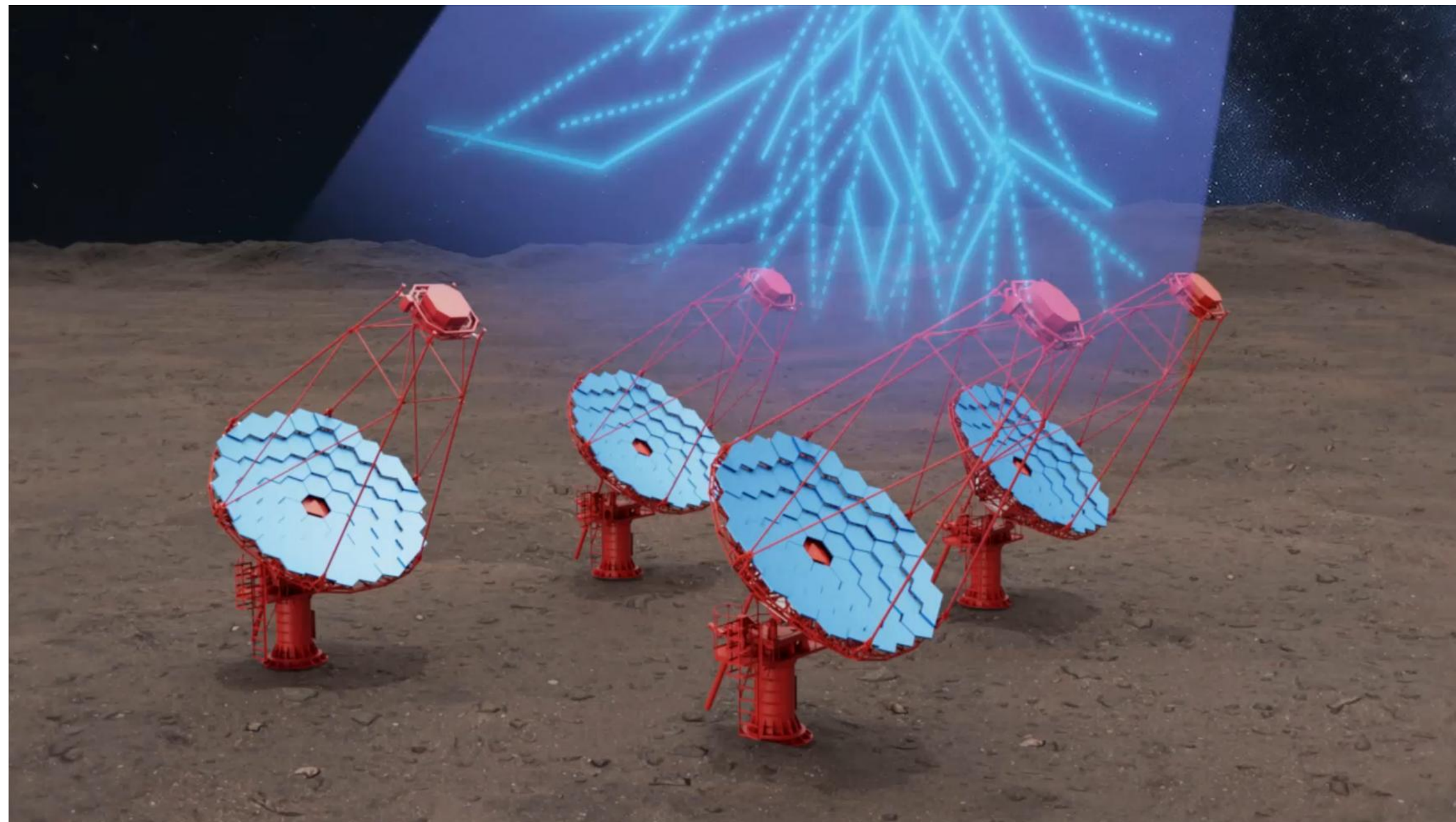
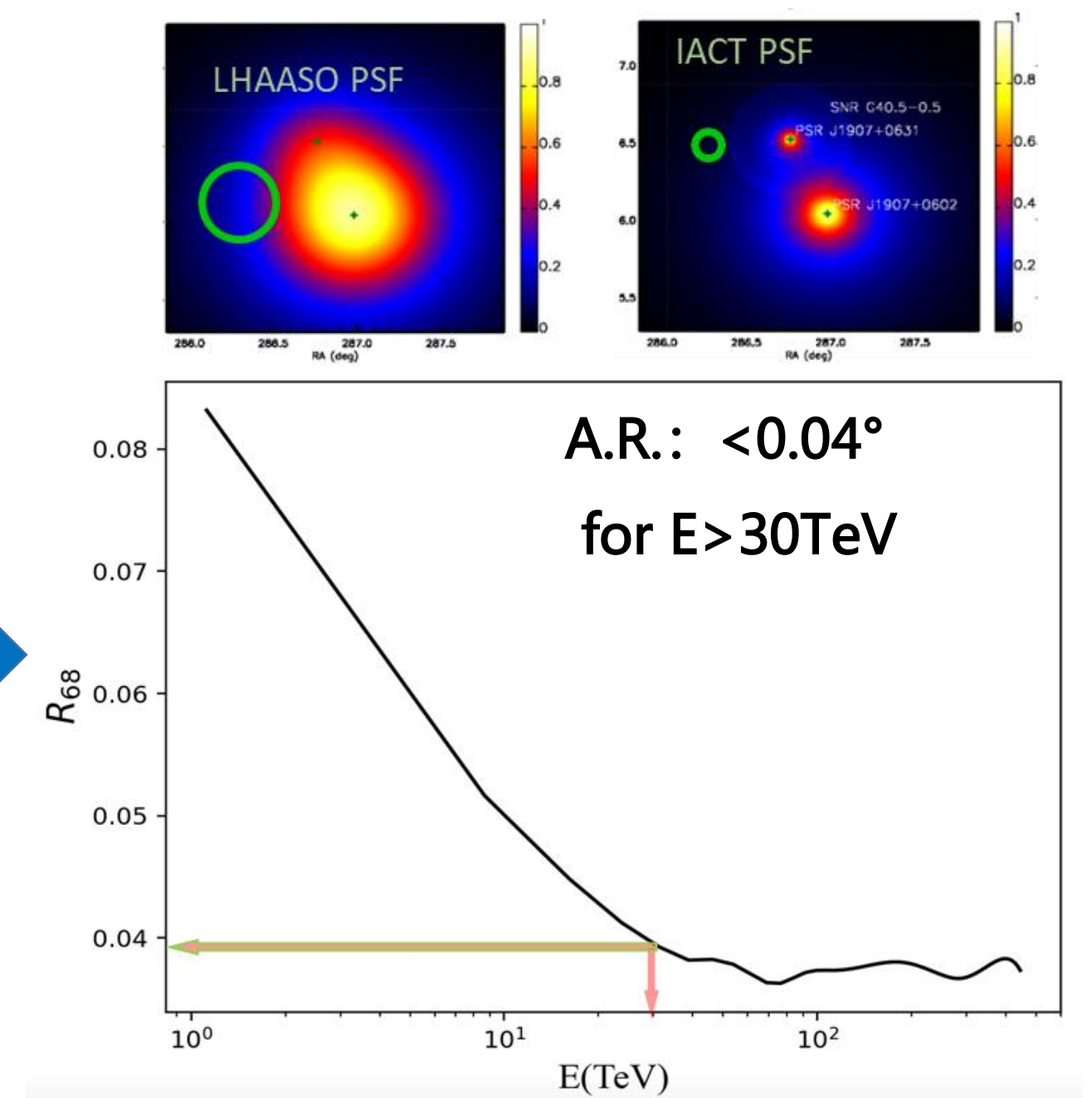
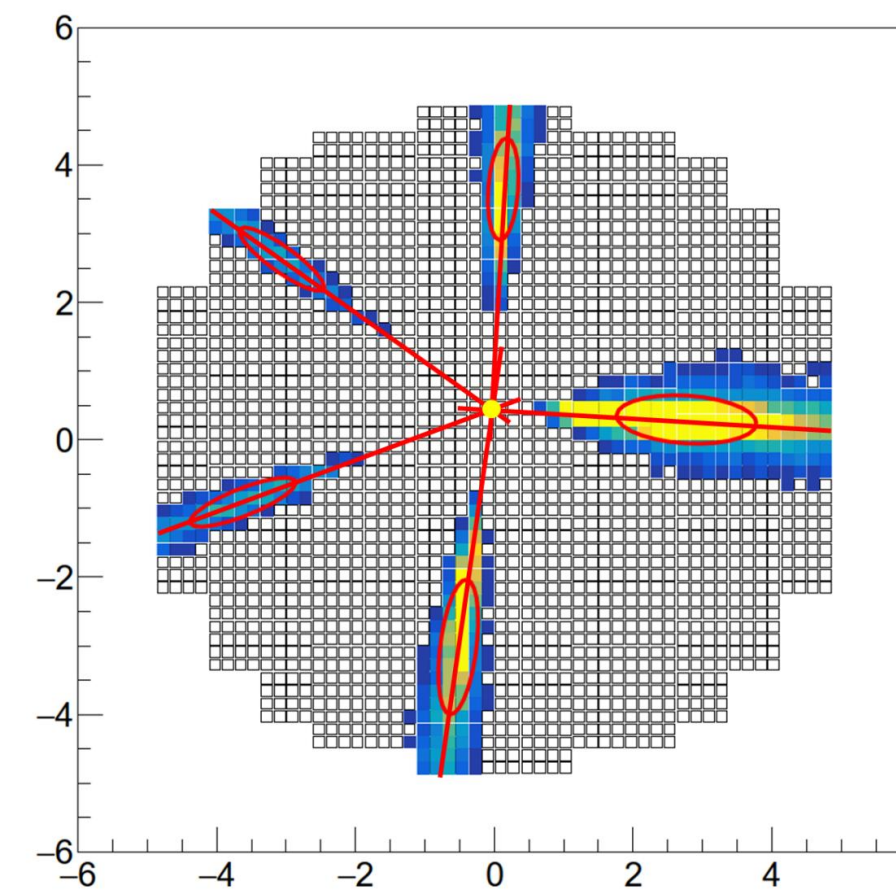
LACT (36 MST) as the upgrading of LHAASO

➤ Stereo measurement of Cherenkov image

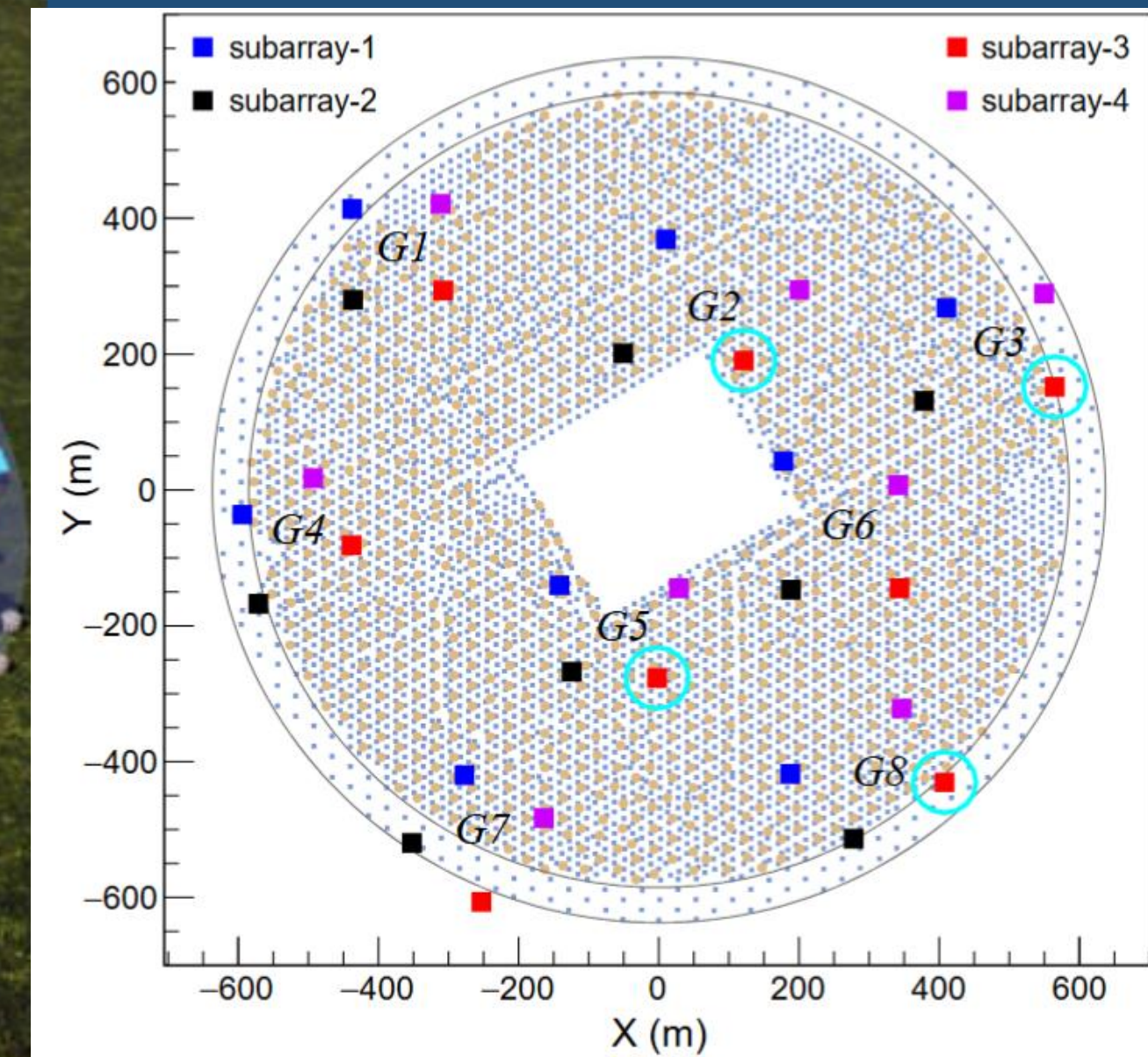
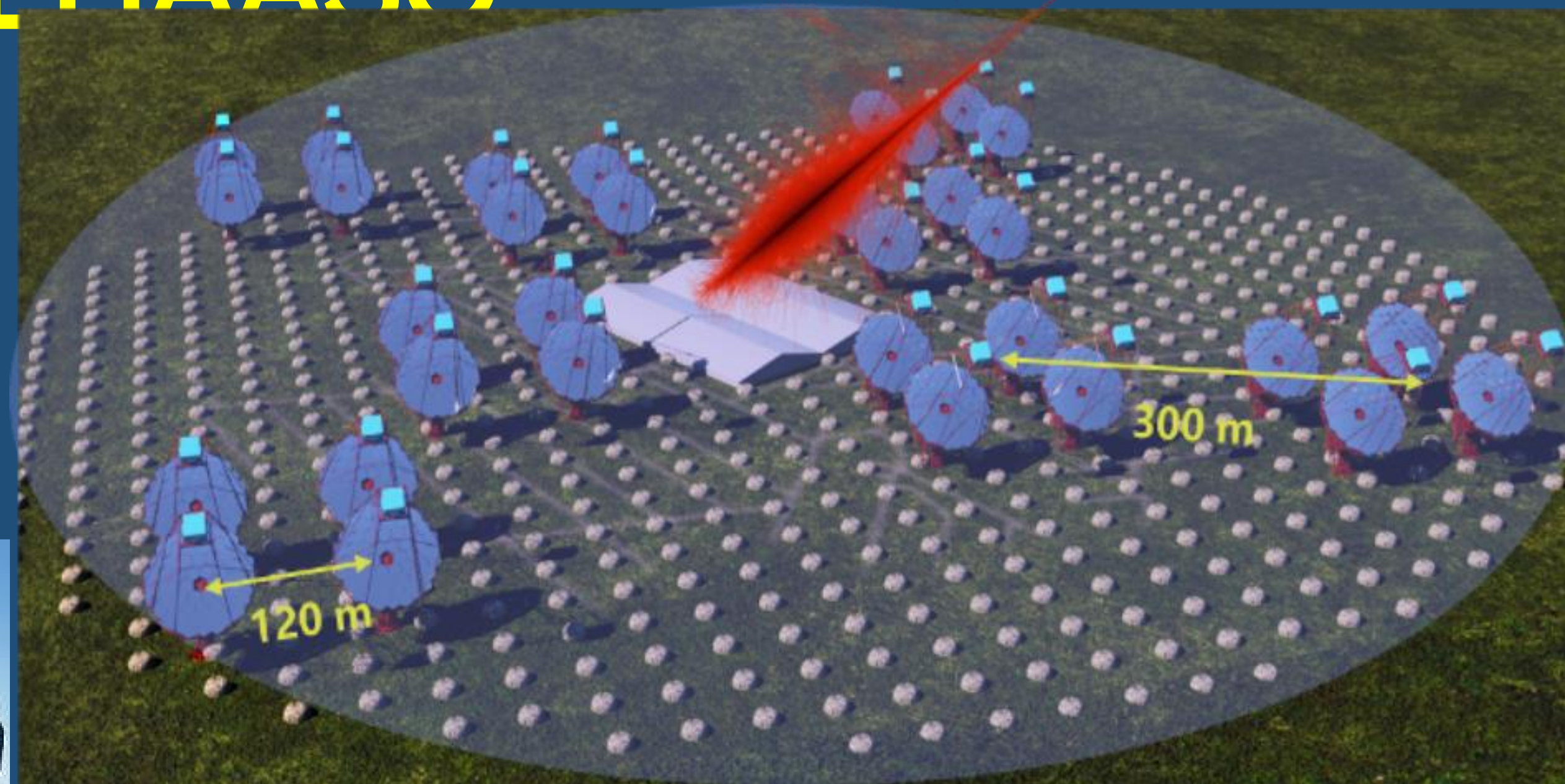
❑ At least 4 telescopes simultaneously

➤ Reconstruction

❑ Angular resolution 0.04° for $E > 30$ TeV



LACT : an IACT array in LHAASO

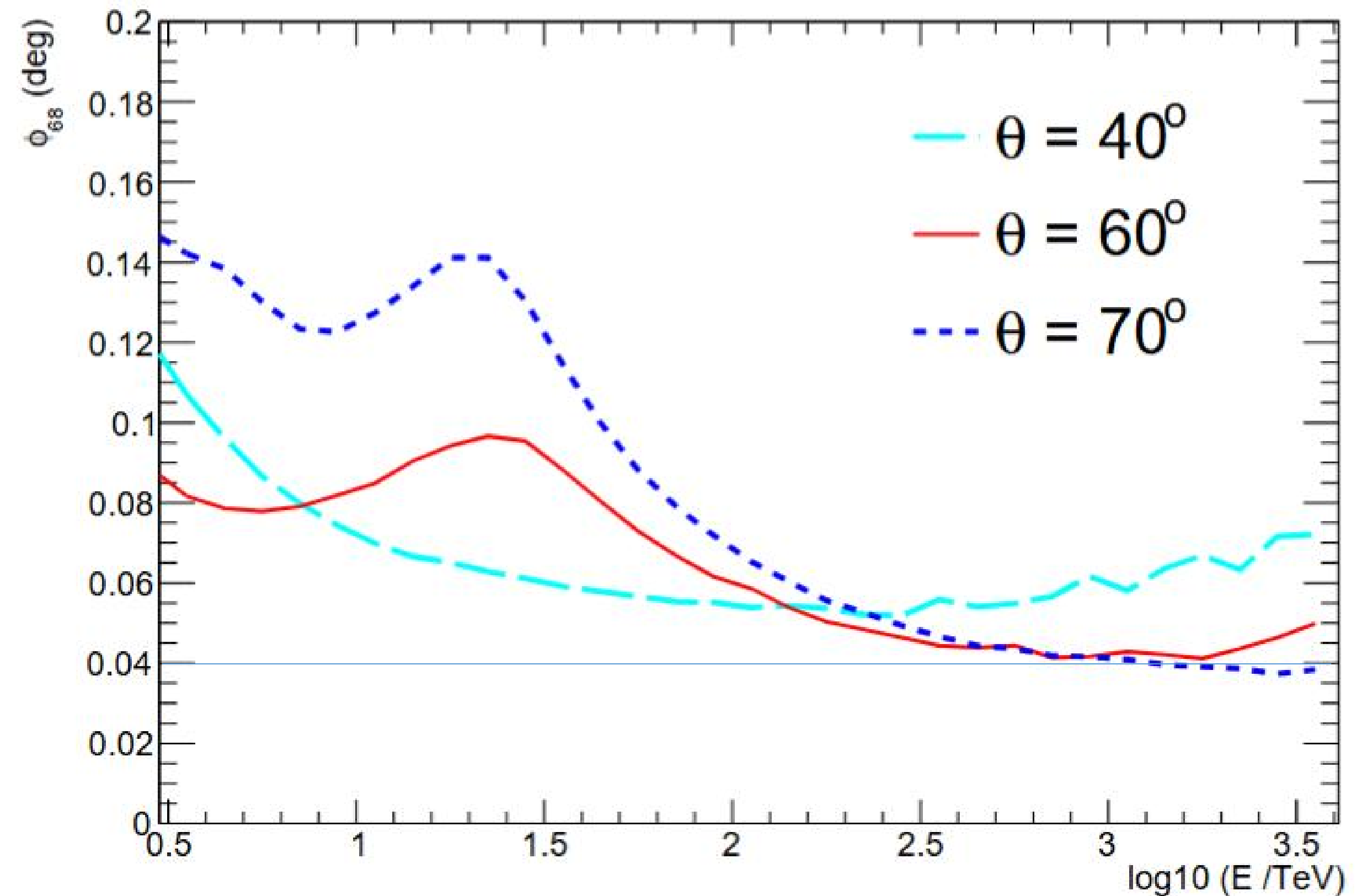
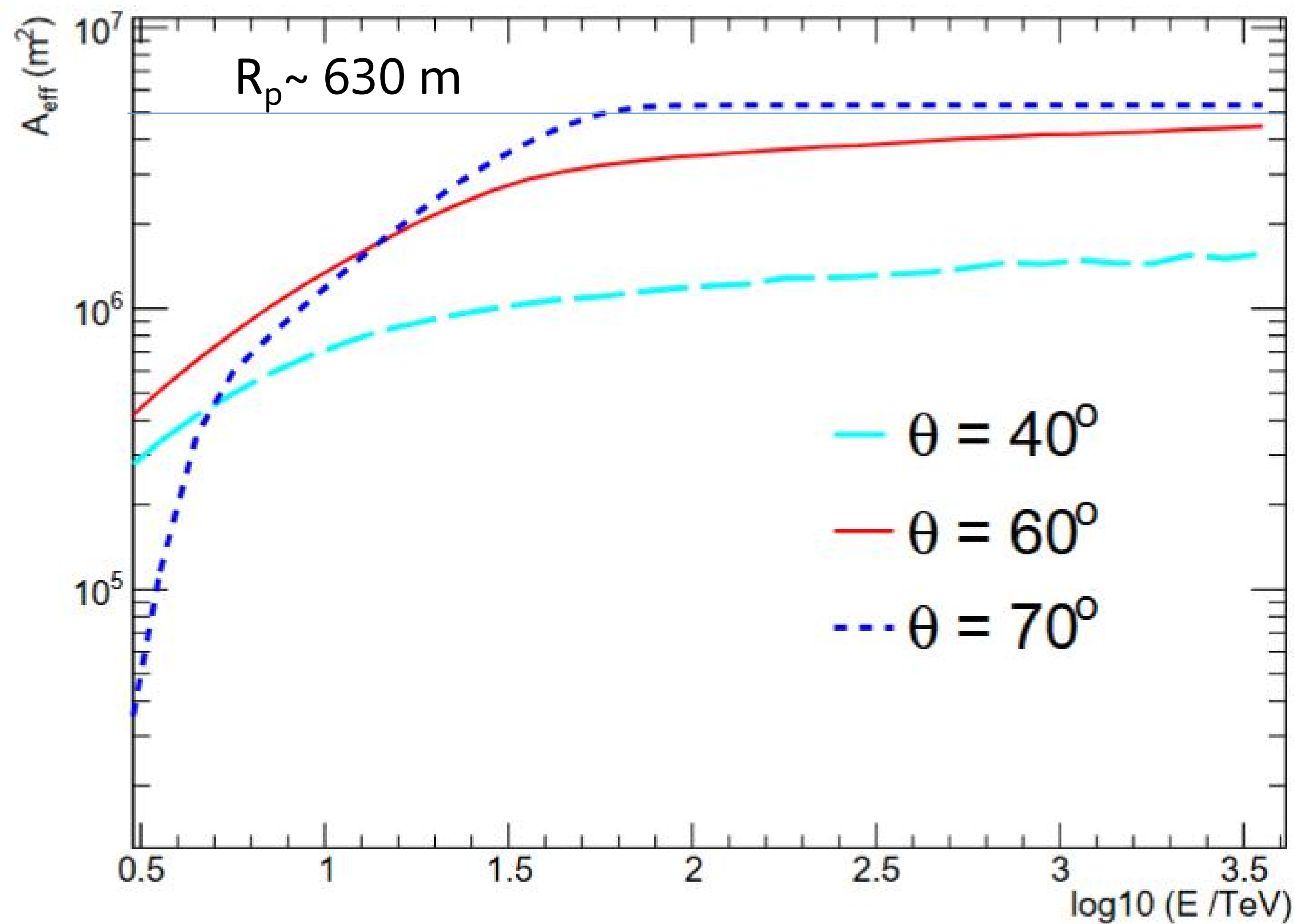


- Funded
- 8X4 array at LHAASO site
- 6-m telescopes
- two proto type telescopes
- First light soon in this year!



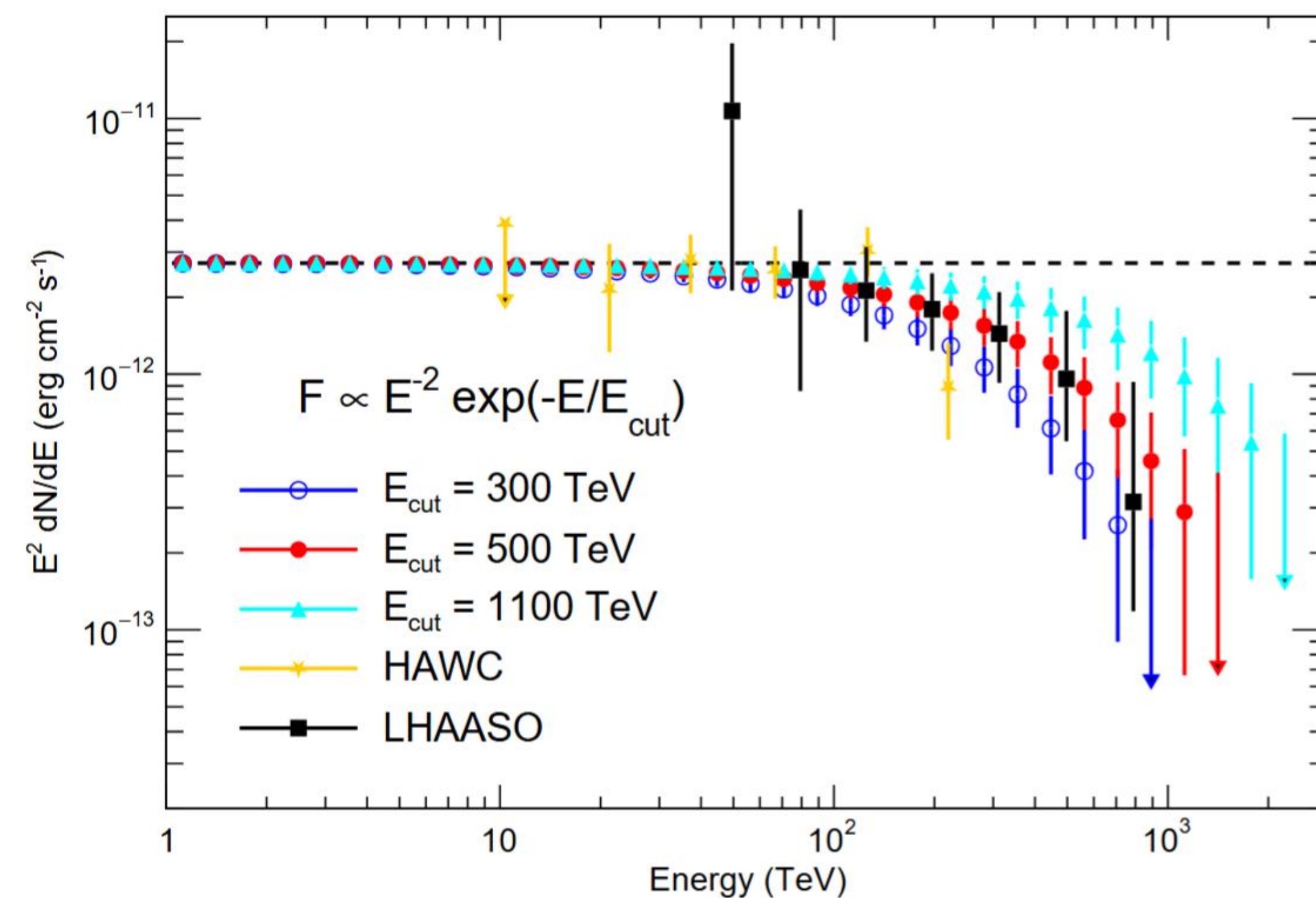
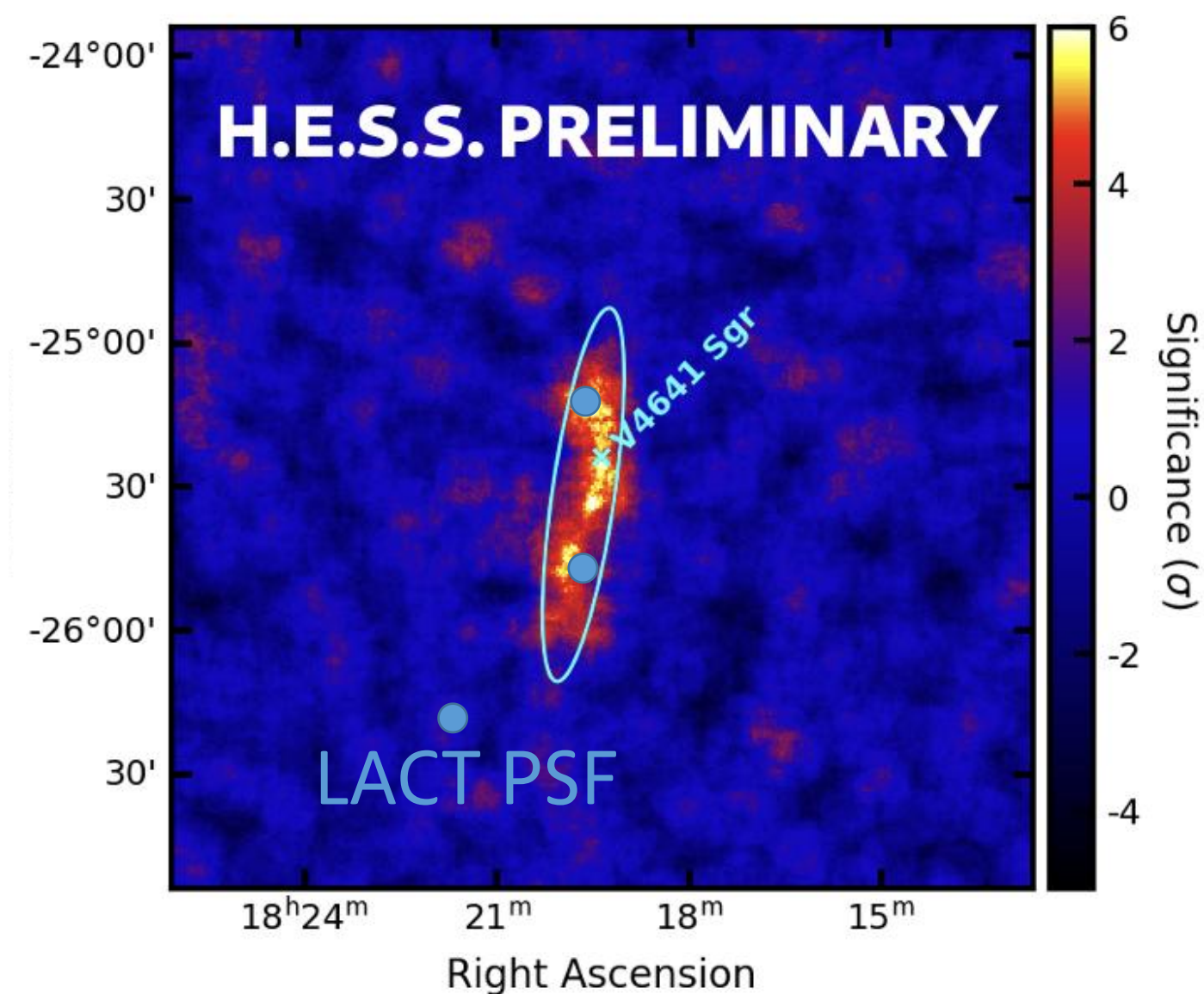
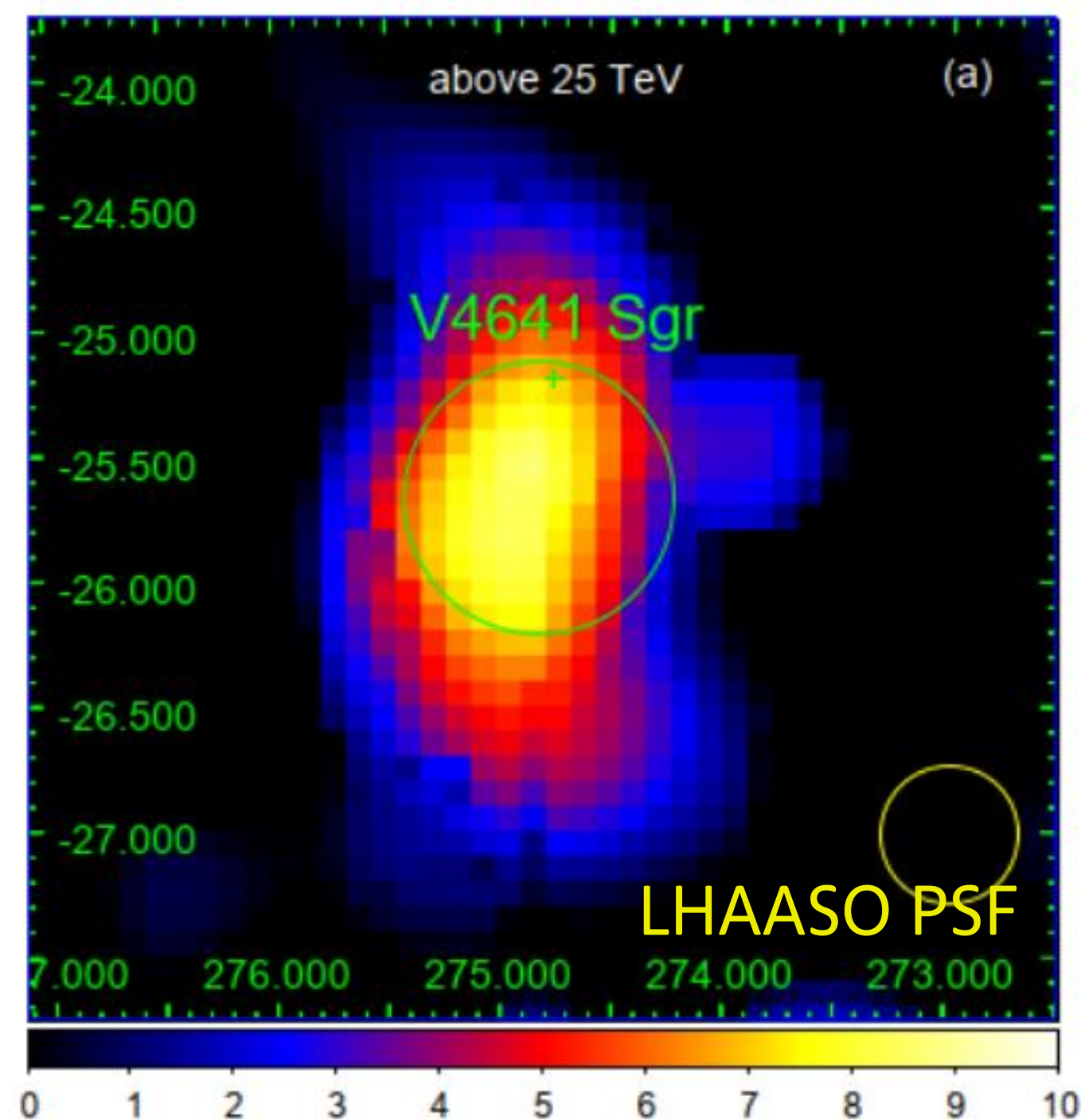
4 Telescope Array Performance

- Effective area for small elevation targets
- Angular resolution



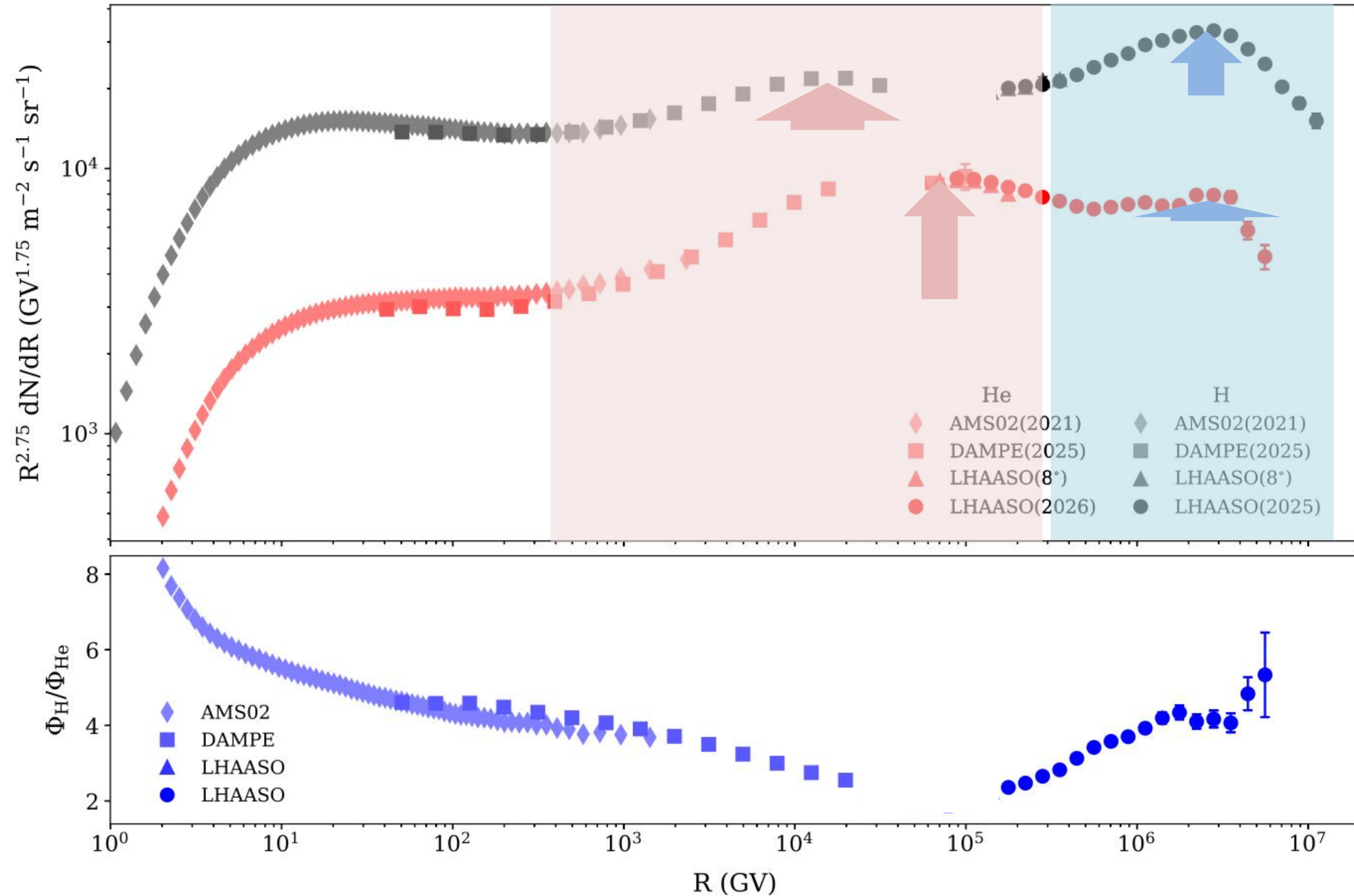
Jet Termination vs central accelerator

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



Spectra of Rigidity of protons and helium nuclei

- Two or Three Components existence
- Strong enhancement of proton flux in the component around the knee
- Proton-rich source population
- Strong enhancement of helium flux in the component below 100 TV
- Helium-rich source population
- No perfect rigidity dependence



Summary



- LHAASO updated the survey for TeV-PeV sources with improved analysis combining the DGE and source measurements together
- DGE is measured with better statistics and agreed with the prediction in “out-galaxy” and still large shortage in the “inner-galaxy”
- More than 50 UHE sources are found with the total number of sources exceeding 190
- Micro-quasars are found the most important population of PeVatrons and unveiling detailed radiative mechanisms particularly by their temporal and spatial features
- Extreme accelerators are found among PWNe which pose challenges to basic rules such as Hillas limit
- Special morphological investigation together with multi wavelength deep observation reveals particle propagation features in source regions
- In future, the improved **spatial resolution** enables a deeper investigation for the very interesting extended sources revealing Super-Pevatrons
- High precision measurements of proton and helium spectra reveal a new **component** of CRs in the “knee” which naturally associated with the PeVatrons or even Super-Pevatrons