

LHAASO, 拉索, @2021-08

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

LHAASO Updates

by Zhen Cao 曹臻, IHEP, CRRC, China

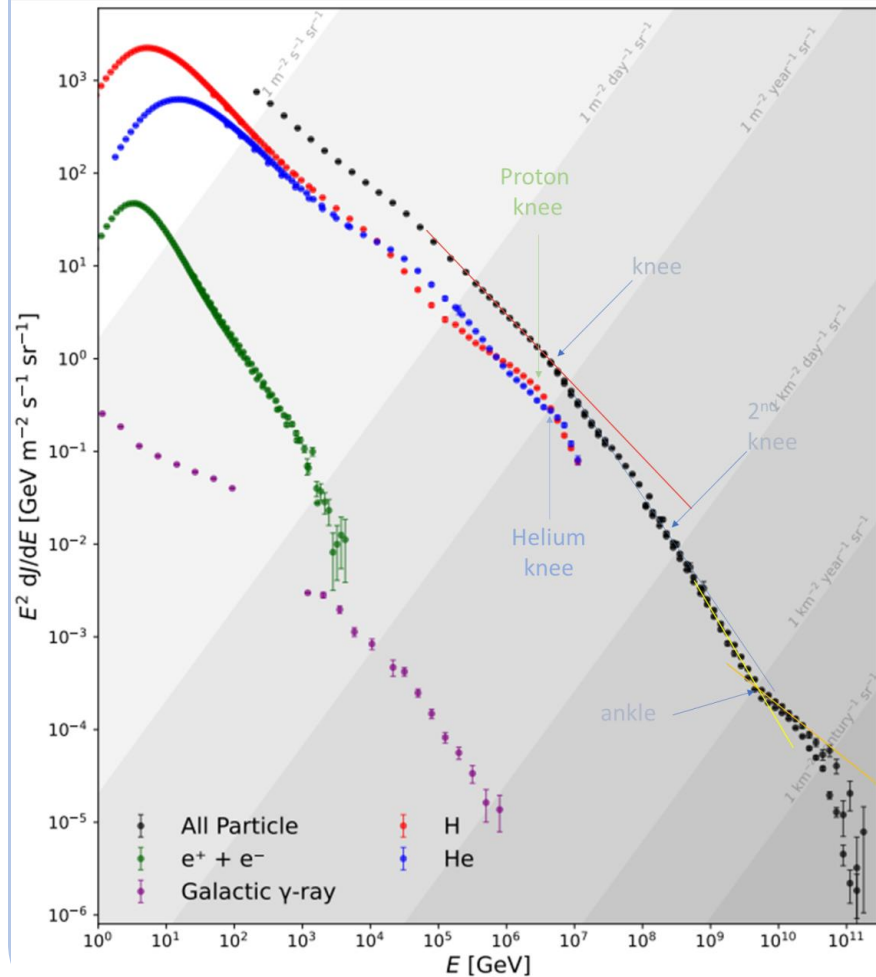
SISSA Workshop, Italy, 2026-09-07



LHAASO has done tree important measurements



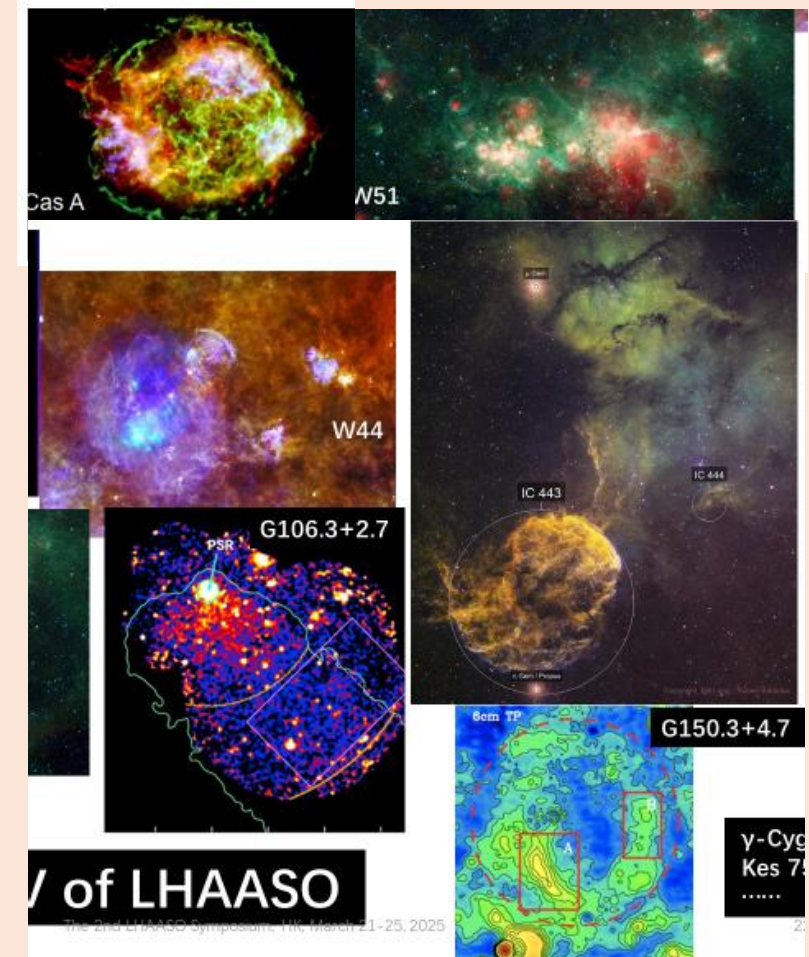
1. Measures knees of CR H & He



2. Discovers μ Qs being UHE emitters

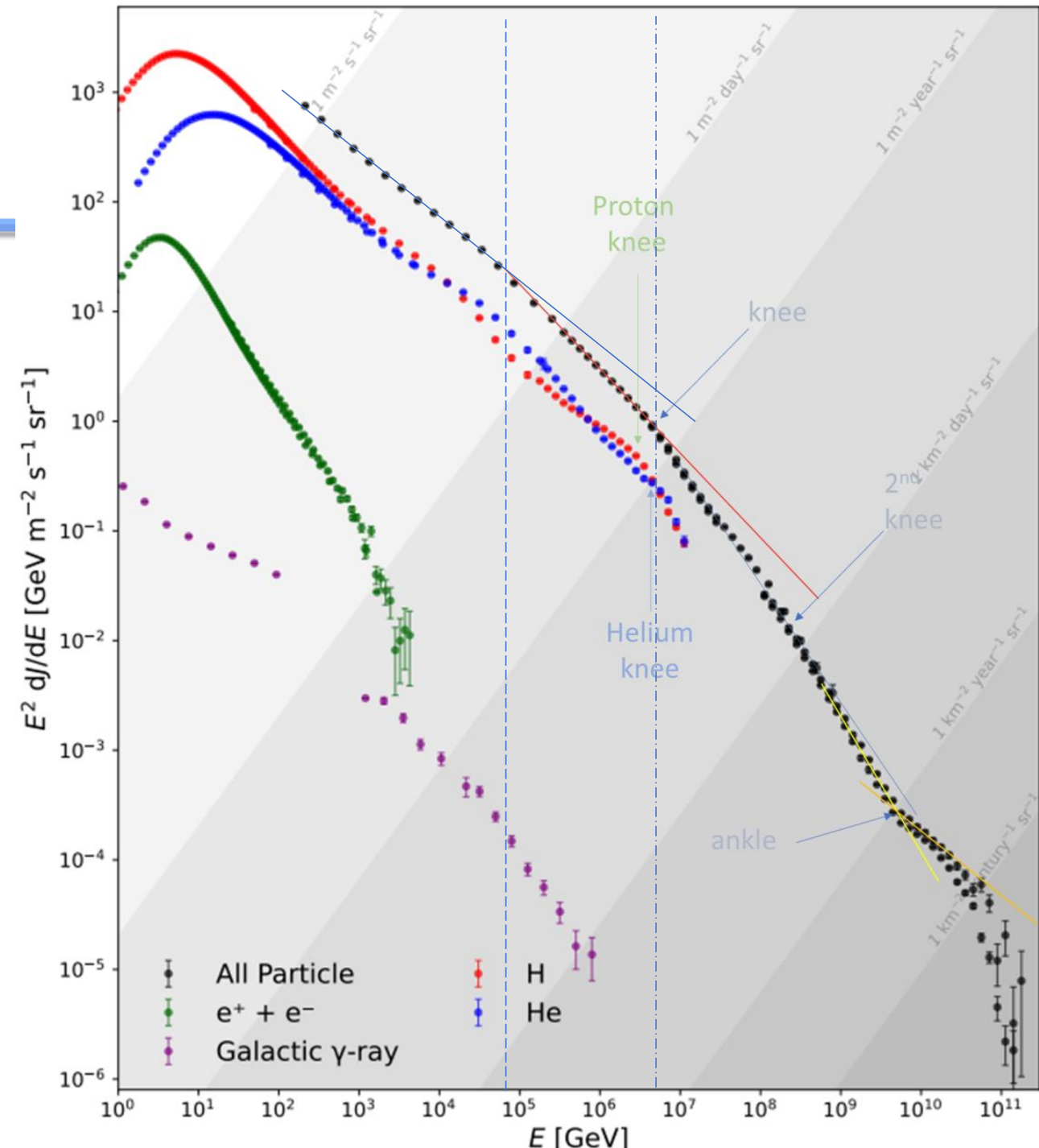
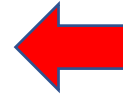


3. Observes SNRs in VHE band



Content

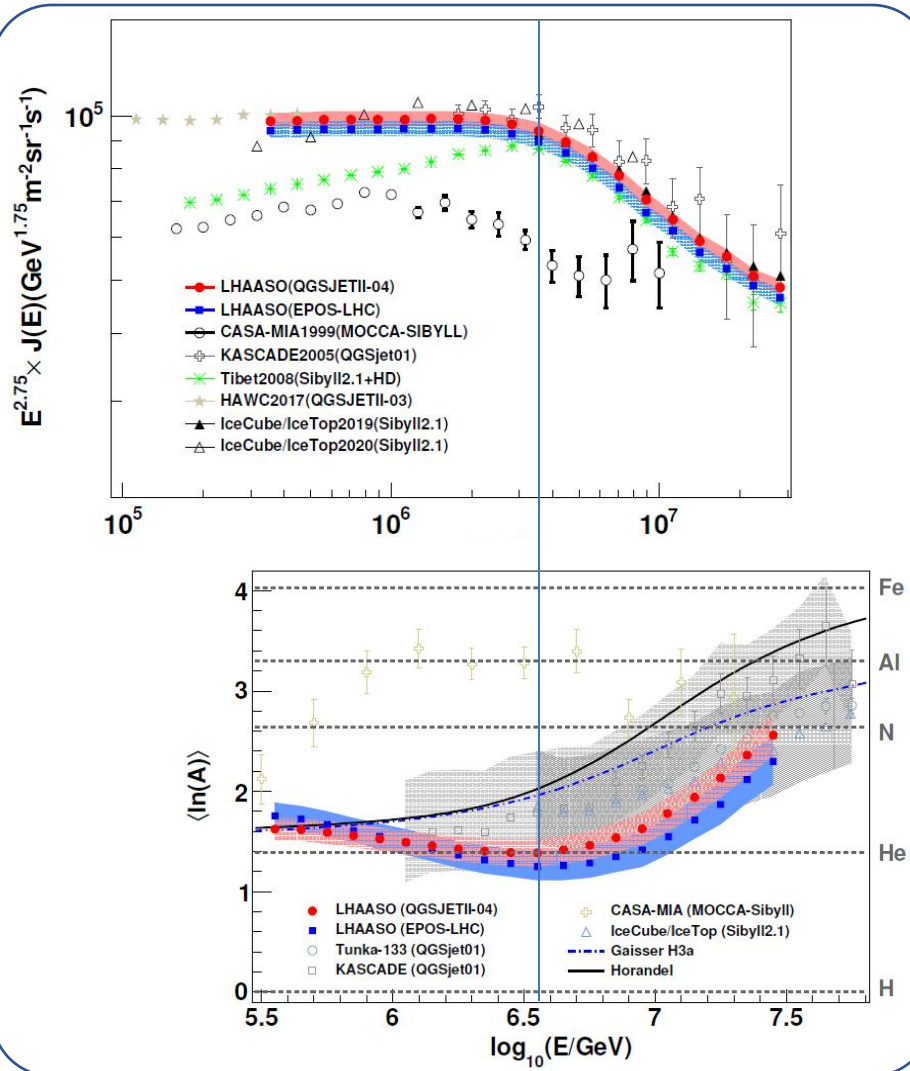
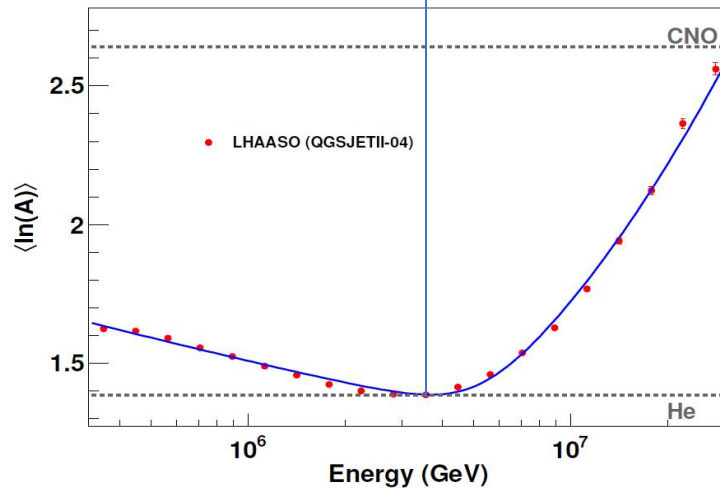
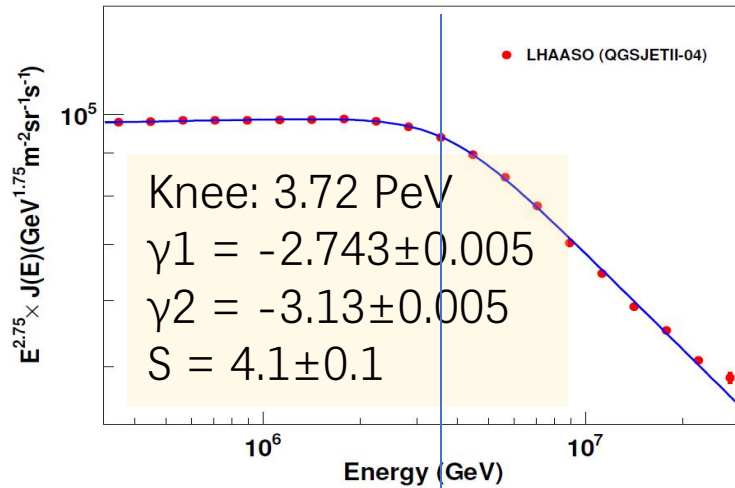
- CR measured at the solar system
- Supernova Remnants as the sources of the VHE-component
- μ -Quasars and the PeVatron-component
- Future expectations
- Summary



70 years old 'knee' : Updates by LHAASO

— composition does change accordingly

(from 0.3 to 30 PeV)

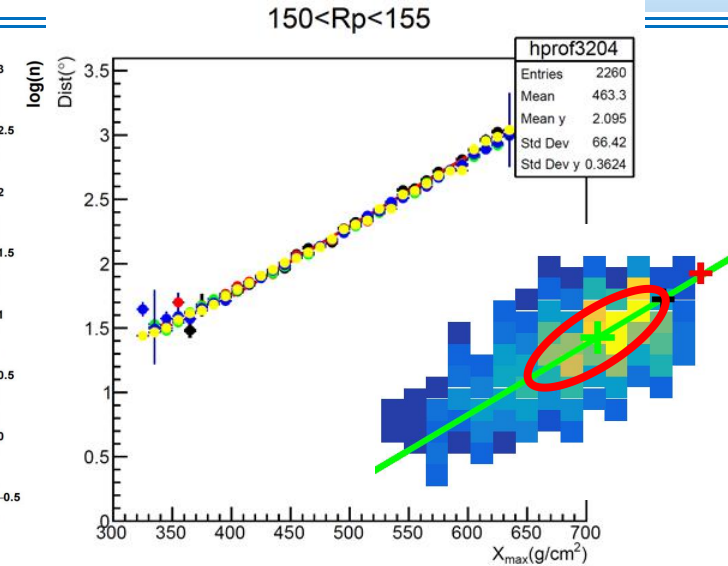
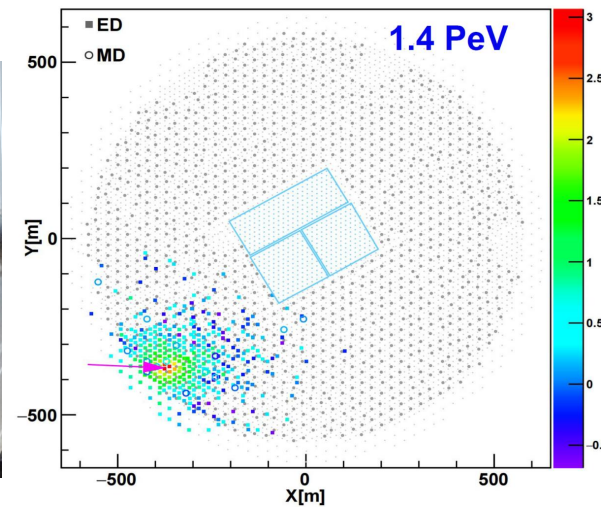


- Systematic uncertainties are sufficiently small
- This unveils a clear correlation between the flux and the composition at the knee

We need a breakthrough !

Hybrid Measurement of Cosmic Rays @ knee

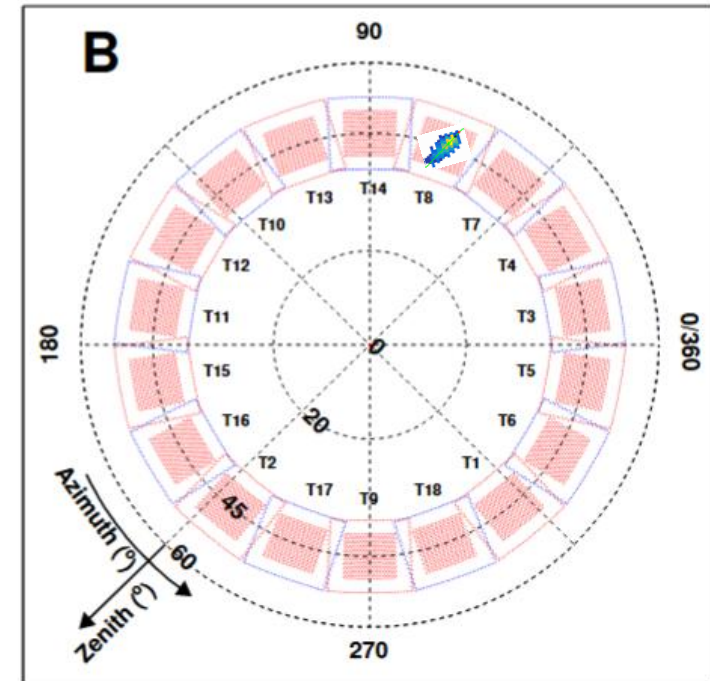
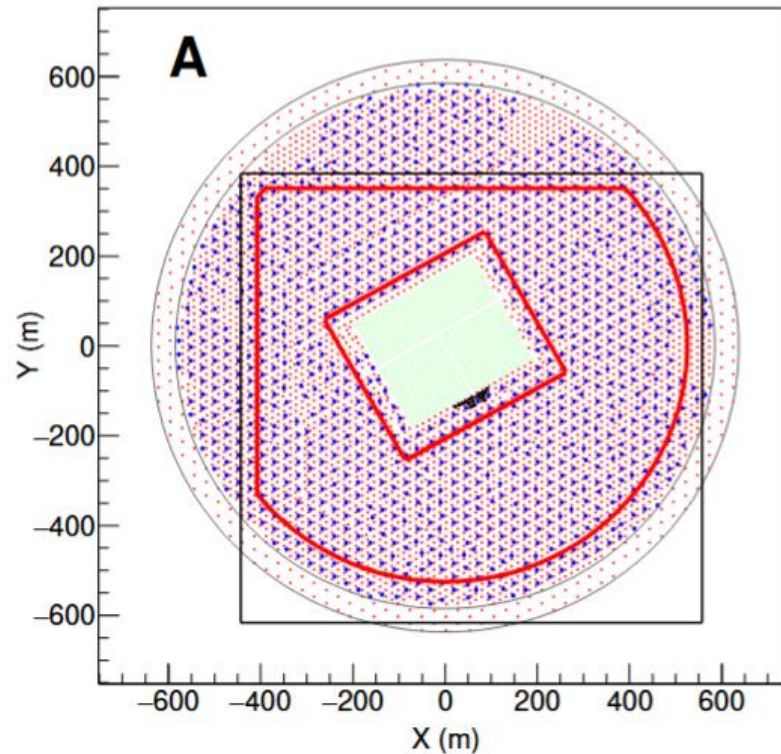
WFCTA: 18



KM2A: (ED, MD, 1 km²)

ED: 5195

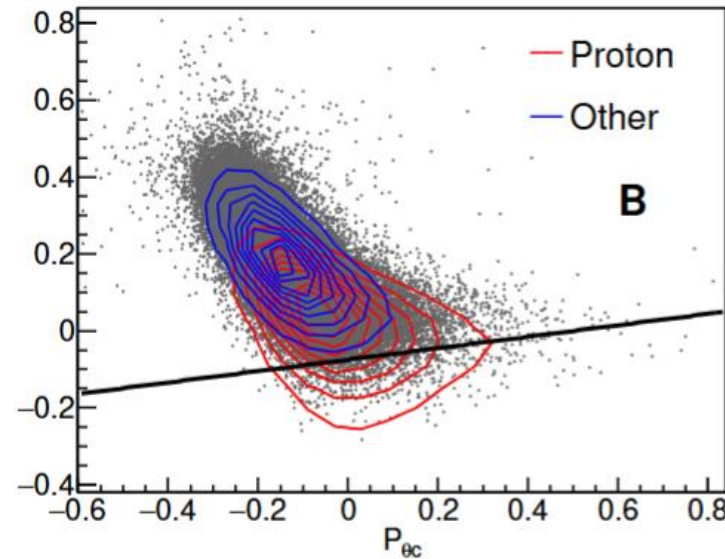
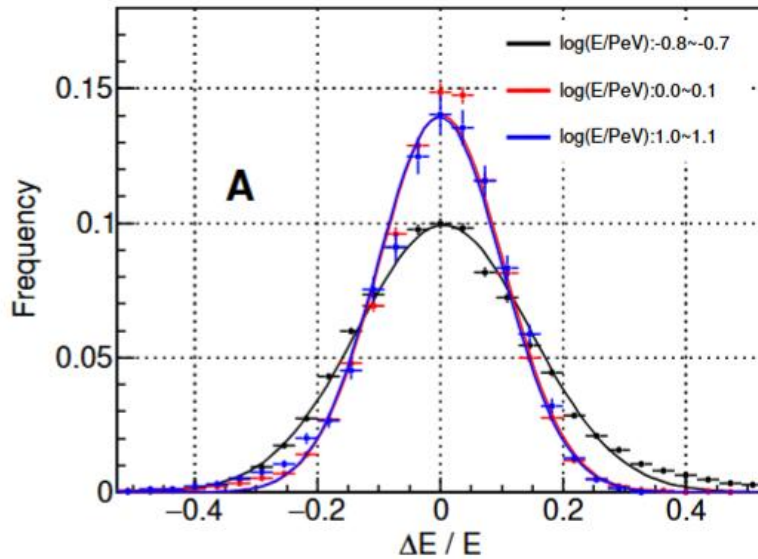
MD: 1188



Reconstruction and Proton shower selection

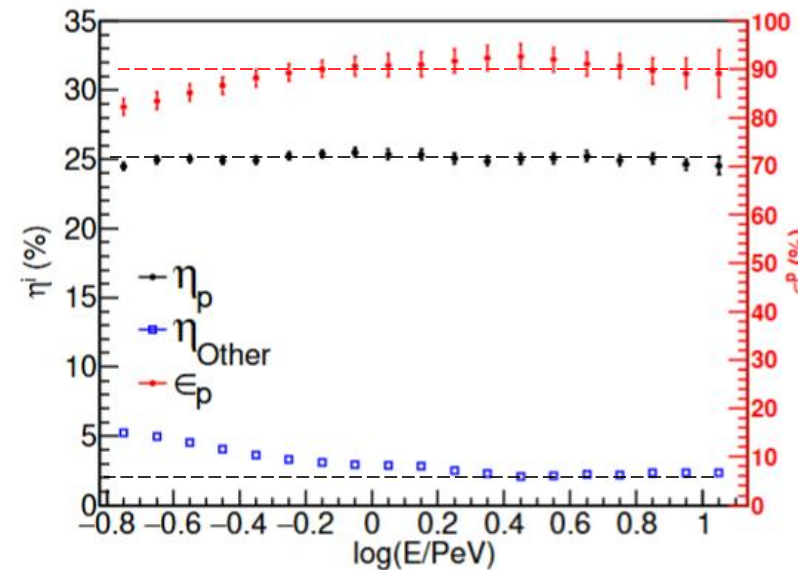
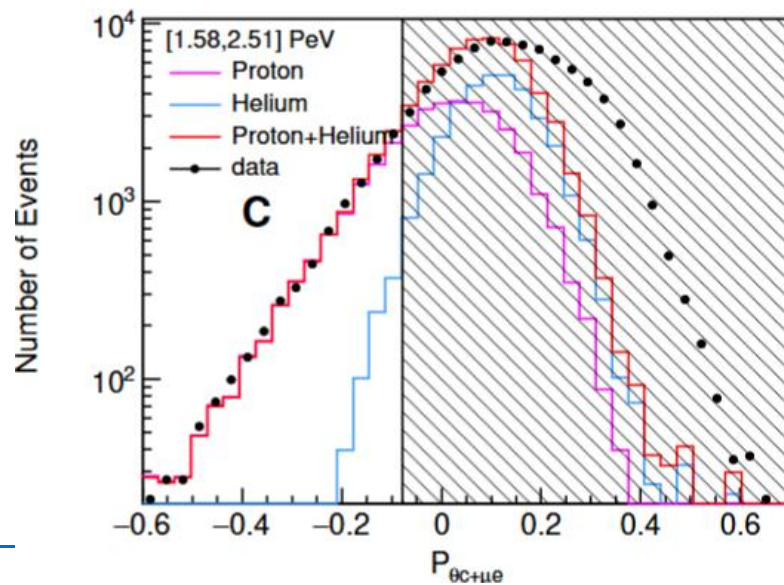
Energy
reconstruction

Gaussian energy
resolution
function



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

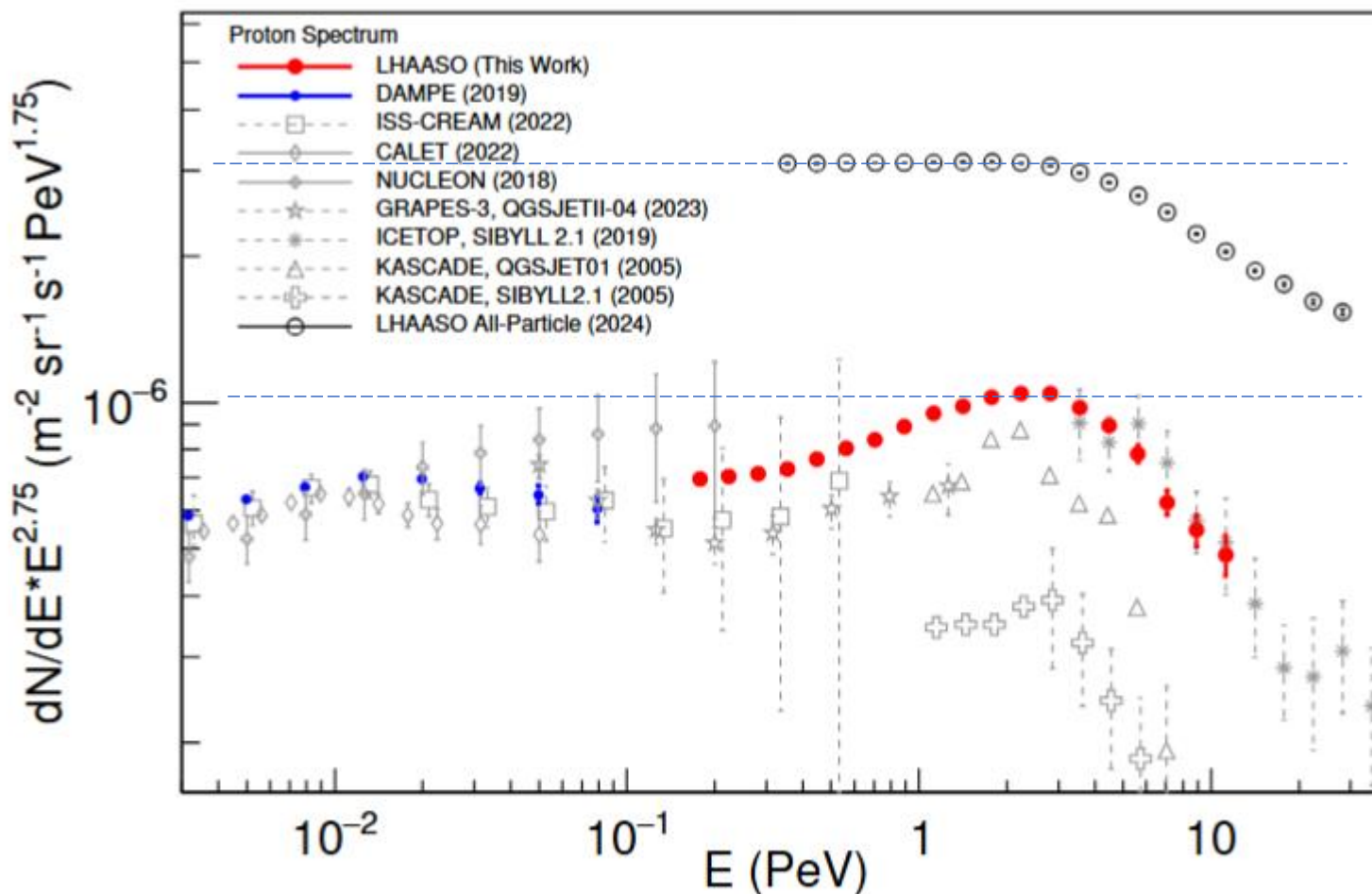
Combined
species-sensitive
Parameter
Simulated vs data
Parameter



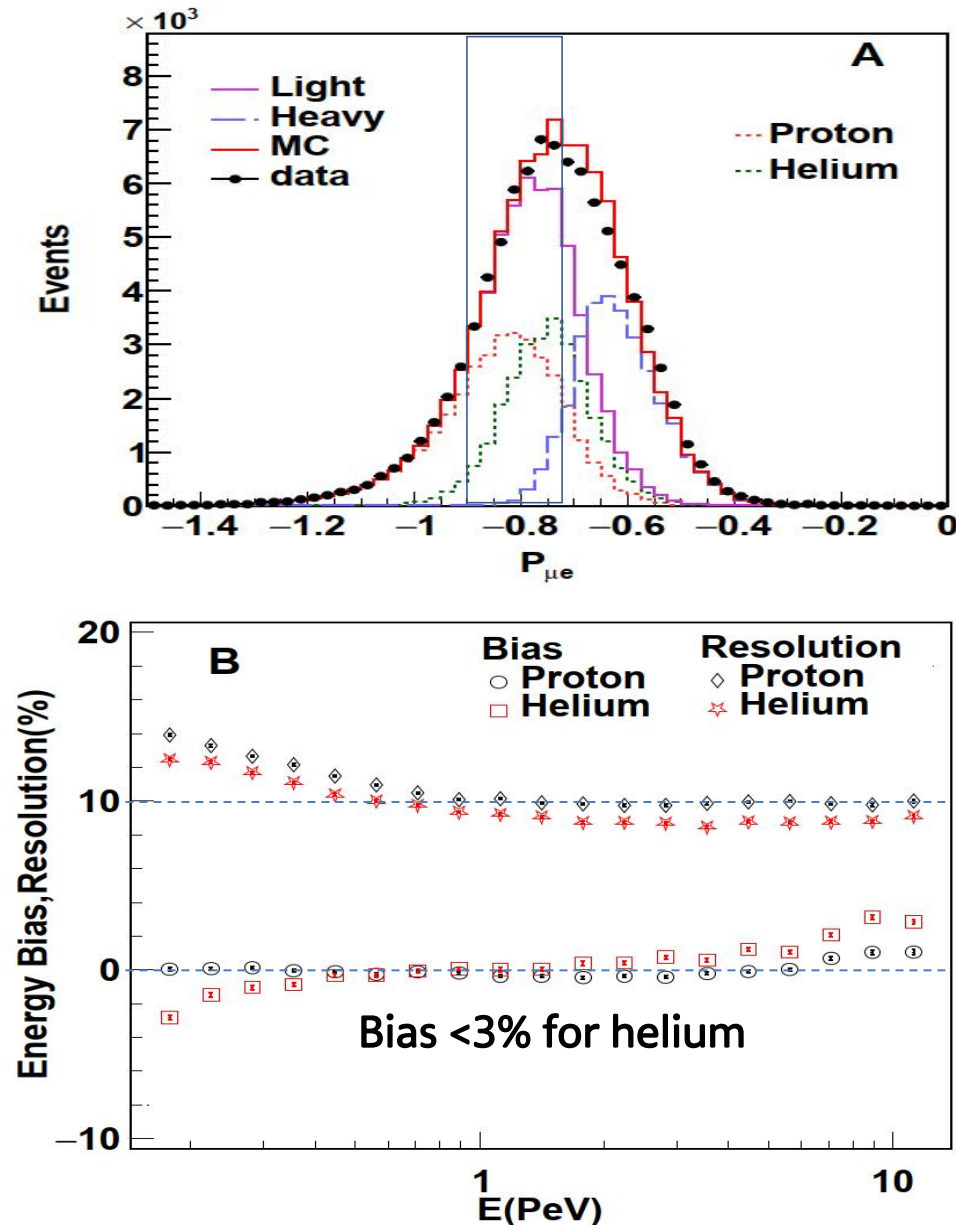
Selection purity
& efficiency for
protons and other
nuclei

Proton spectrum: BIG SURPRISE !

- No “knee” !
- A “bump” at ~3.3 PeV
- Indicating a new component
- Contributing ~1/3 fraction
- New population of sources?
- Characteristic energy: few PeV



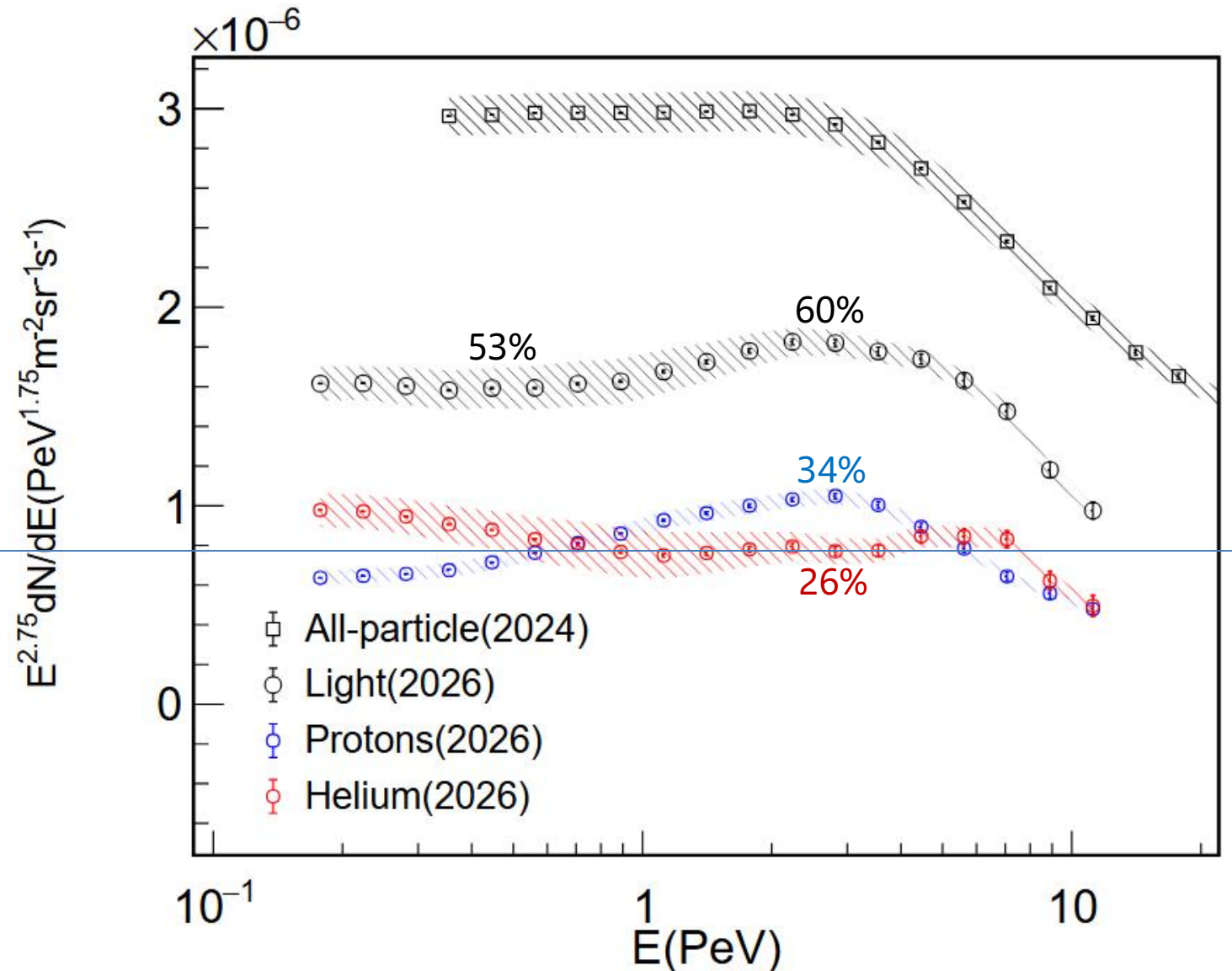
Can we do more? Light component (H+He) Selection



- Helium showers are very similar with proton showers
- it is impossible to separate helium from all other particles event by event
- Methodology:
 - Helium spectrum = $F_{P+He} - F_{proton}$
 - The same dataset and the same energy reconstruction as used in the proton energy spectrum
- High efficiency in selection for light showers: $>60\%$

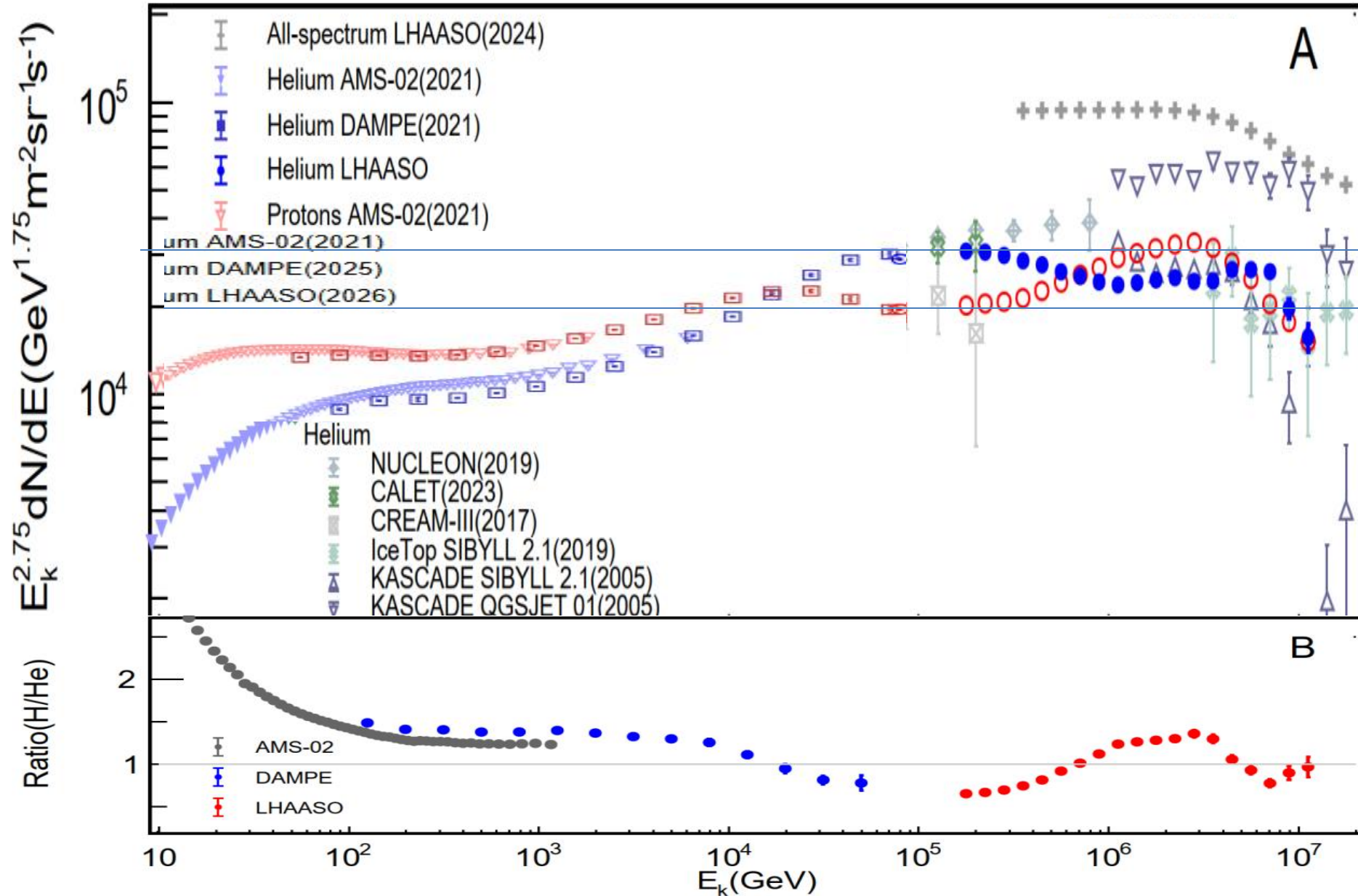
Spectra of Light CRs and Helium Nuclei

- High Precision $J_{\text{Light}}(E)$ measurement
- Systematic errors: same sources as proton spectrum
- Inferred $J_{\text{helium}}(E) = J_{\text{Light}}(E) - J_{\text{proton}}(E)$
 - Clear hardening at 1.05 PeV: $>10 \sigma$
 - Knee at 7 PeV: 6σ
 - Strong deviation from the single index power-law spectrum below 0.3 PeV: $>10 \sigma$
- Iterations on $J_{\text{helium}}(E)$ and $J_{\text{proton}}(E)$: significantly reducing uncertainty due to composition of CRs



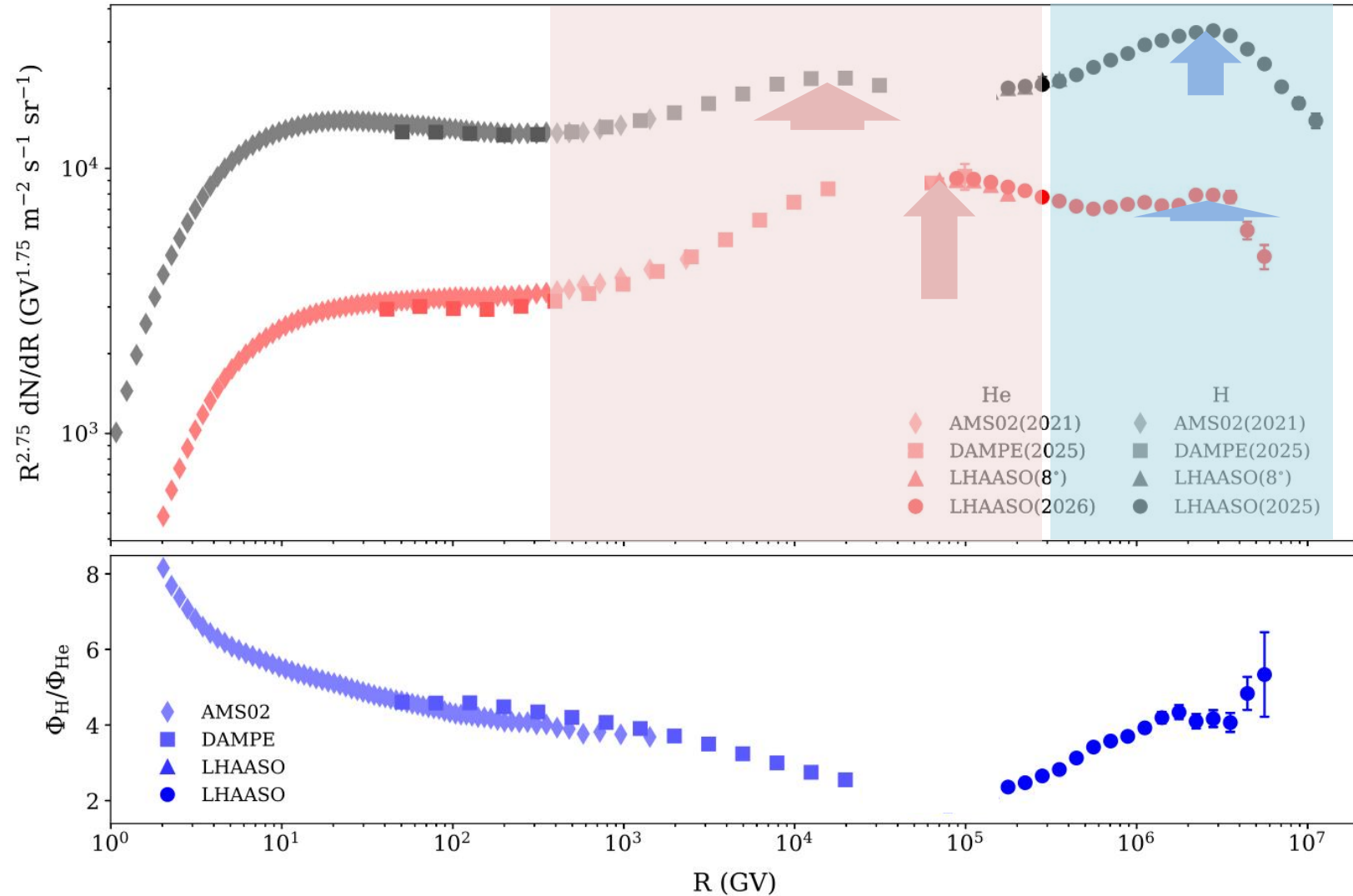
Helium Spectrum and p/He ratio

- Multiple components
- **Domination of proton at the knee**
- **p/He ratio reverses at least 3 times over the energy range from 10 TeV to 10 PeV**
- Complex source characteristics and propagation features
 - He-rich ~0.1 PeV
 - P-rich ~3 PeV



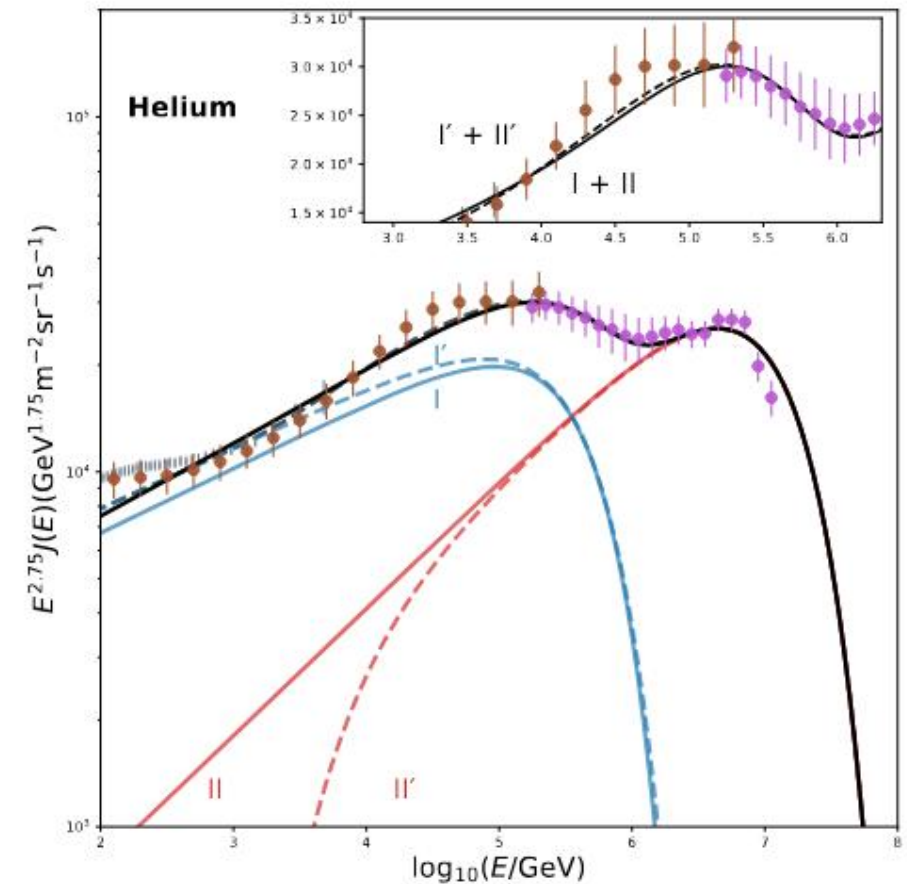
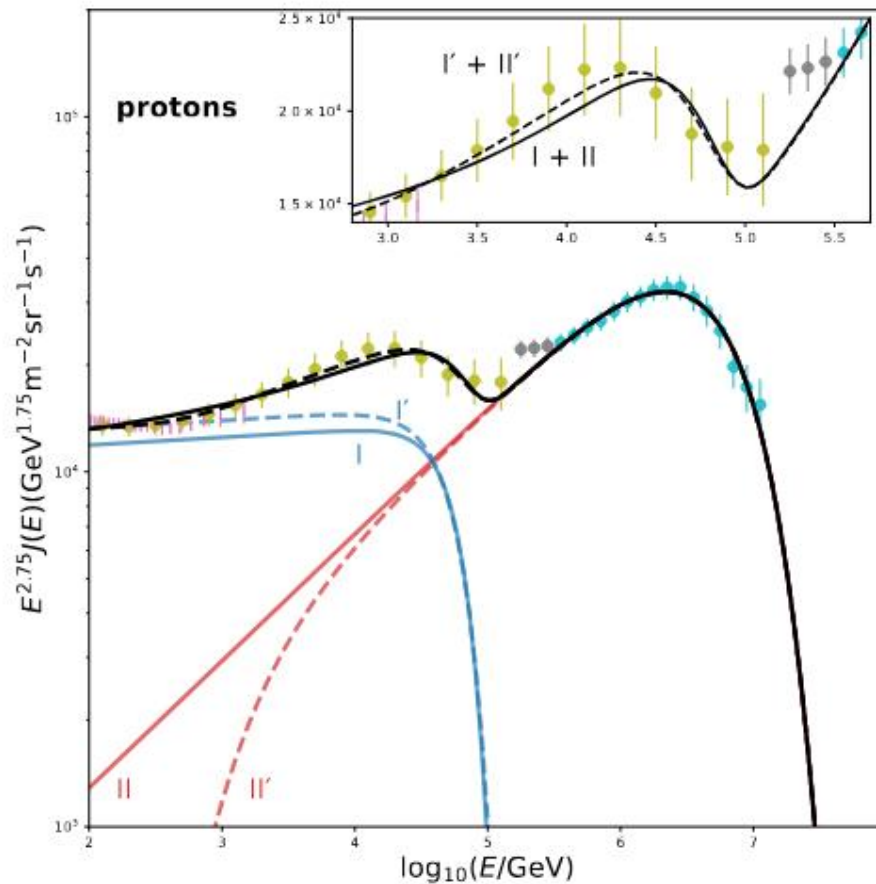
Spectra of Rigidity of protons and helium nuclei

- 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

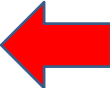


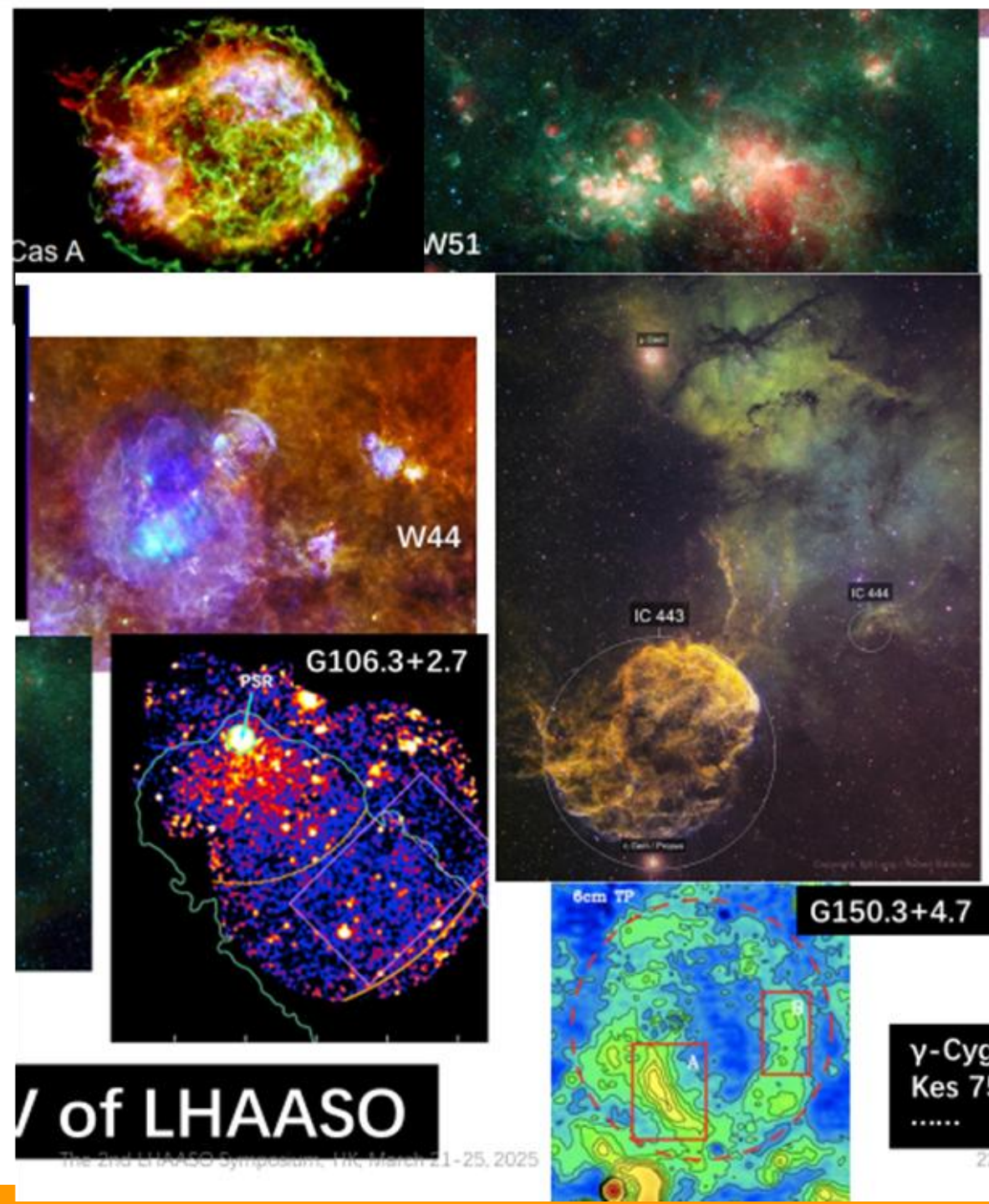
A HE-component: Rigidity Scaling ?

- HE-Component (PeVatron-component) has a rigidity scaling
- Indicating fewer sources in the HE population which have close features in particle acceleration
- TeV-component has strong rigidity dependence
- Indicating diversity of acceleration features among the large number of sources in the LE population



Content

- CR measured at the solar system
- Observations in VHE γ -ray band and the discoveries 
 - SNRs in dense media
 - SNRs in the environment with few targets
 - A SNR in a cavity
- μ -Quasars and the New component at HE
- Future expectations
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Known for 90 years as a hypothesis



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

- SNRs are the most promising CR origin candidates
- Below 1 TeV, LAT found experimental evidences
- SNRs to be High Energy CR origin needs evidence
- Is there limit of the maximum CR energy from SNRs

COSMIC RAYS FROM SUPER-NOVAE

BY W. BAADE AND F. ZWICKY

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

Communicated March 19, 1934

happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a **neutron star**, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the "gravitational packing" energy in a *cold* neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such. The consequences of this hypothesis will be developed in another place, where also will be mentioned some observations that tend to support the idea of stellar bodies made up mainly of neutrons.

D. Conclusions.—From the data available on super-novae we conclude (1) Mass may be *annihilated* in bulk. By this we mean that an assembly of atoms whose total mass is M may lose in the form of electromagnetic radiation and kinetic energy an amount of energy E_T which probably cannot be accounted for by the liberation of known nuclear packing fractions. Several interpretations of this result are possible and will be published in another place.

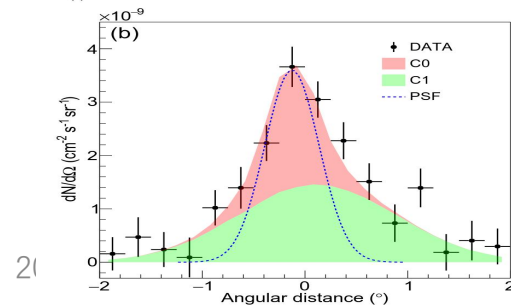
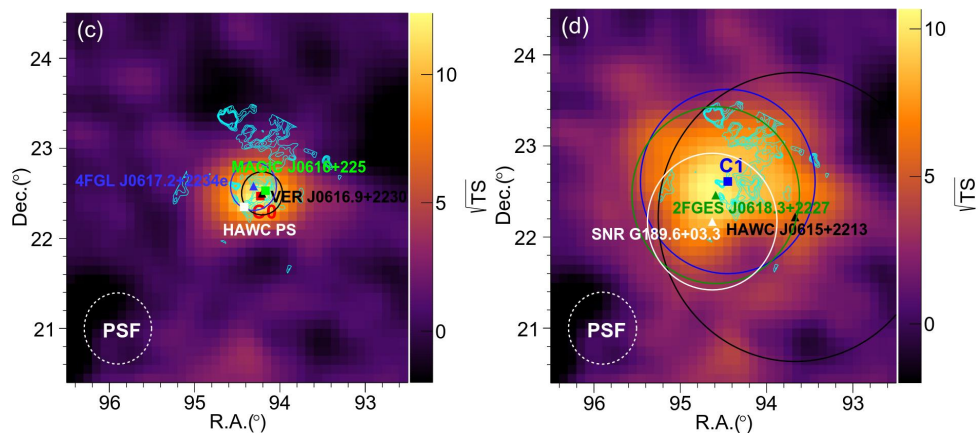
(2) The hypothesis that *super-novae emit cosmic rays* leads to a very satisfactory agreement with some of the major observations on cosmic rays.

IC 433, W44, W51 in dense medium

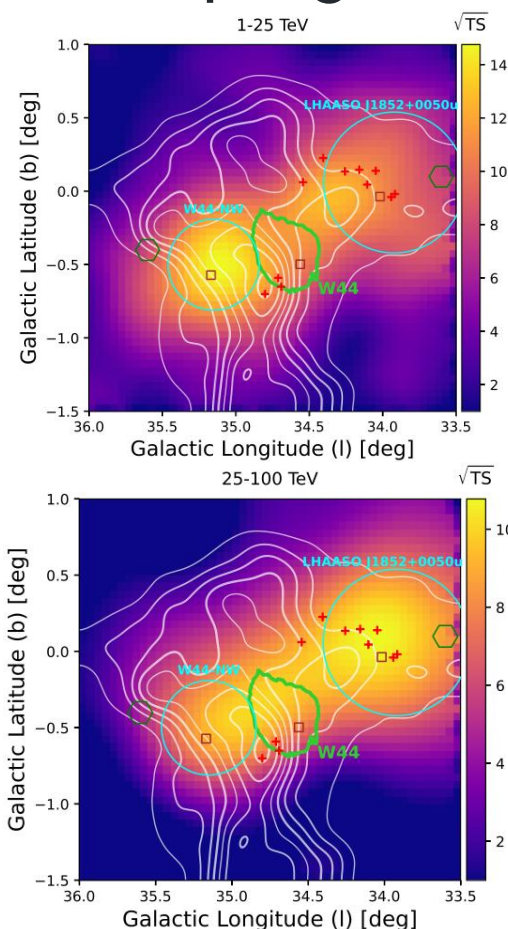
- Two sources at IC 443

Model	ΔTS	Name	R.A. (°)	Dec. (°)	Extension (°)
Two Components	40	C0	94.24 ± 0.03	22.43 ± 0.02	Pt
		C1	94.40 ± 0.07	22.58 ± 0.06	1.00 ± 0.11
One Component	-	-	94.30 ± 0.03	22.52 ± 0.03	0.58 ± 0.05

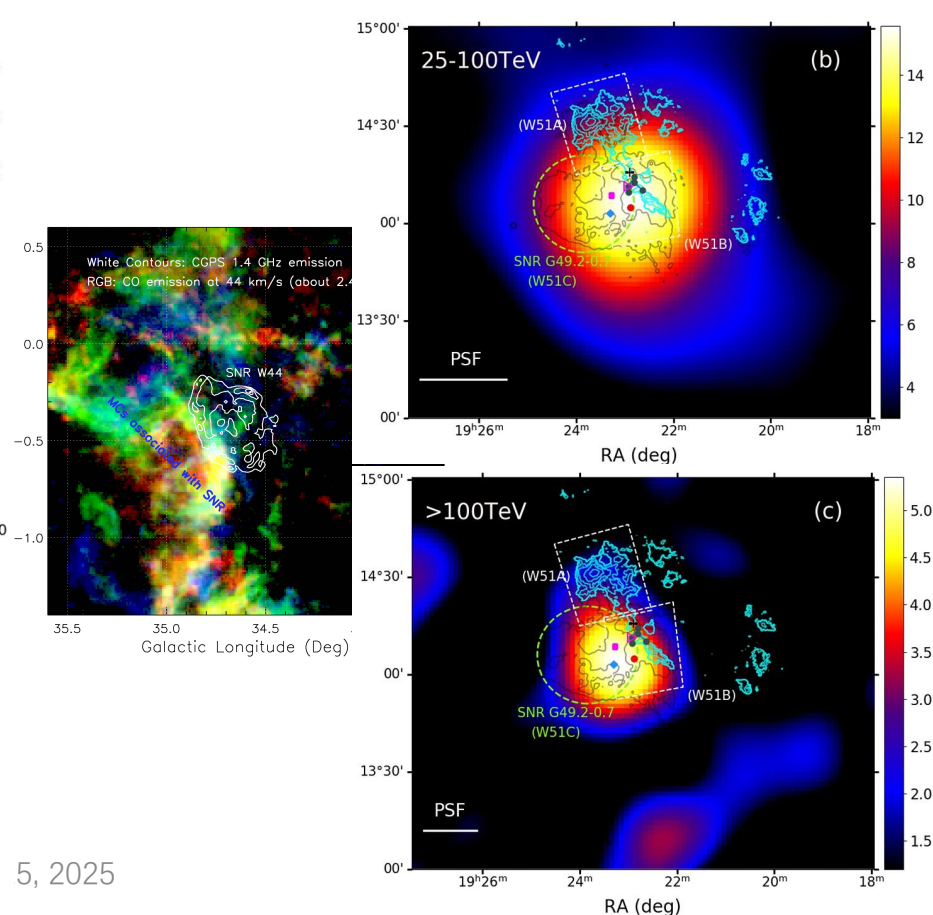
Table 1: Best-fitting results of different models for IC443. The Extension means R_{68} .



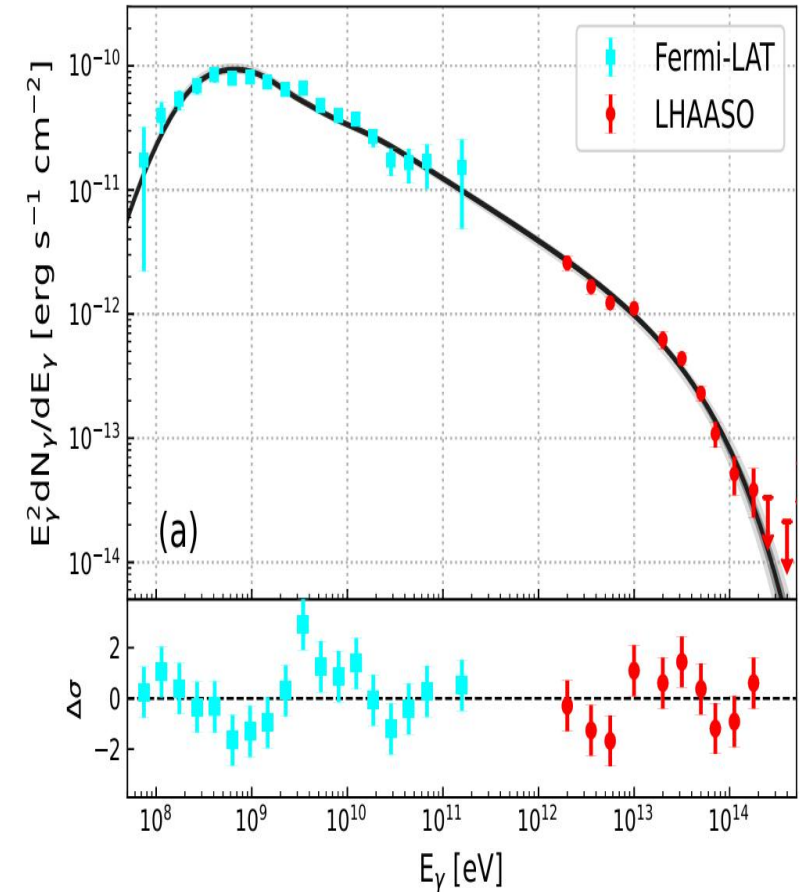
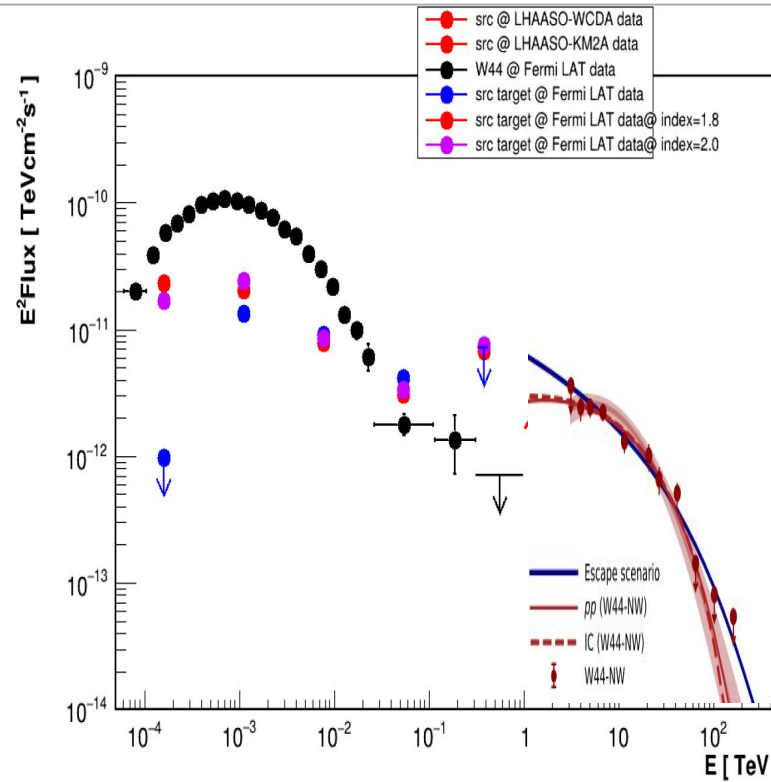
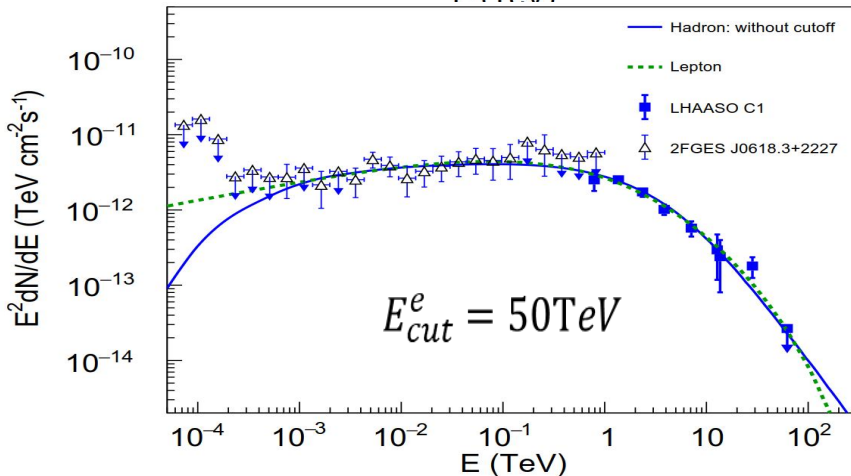
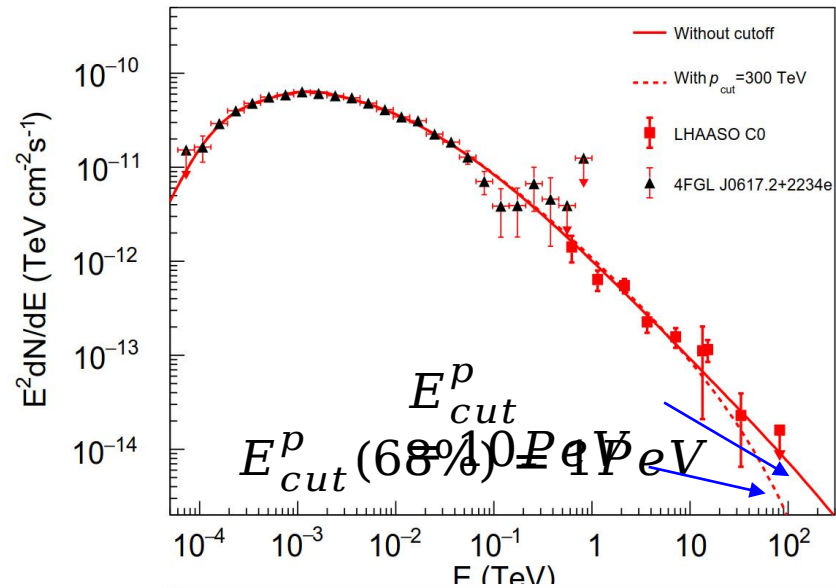
- Shell and escaping at W44



- SNR+MC indicating a PeVatron at W51



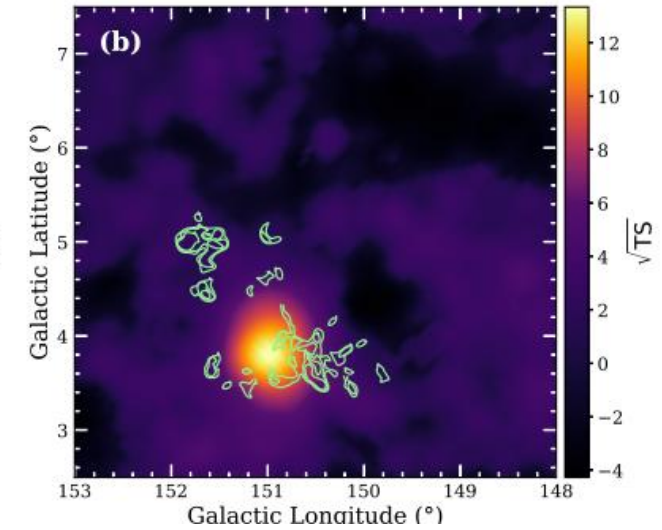
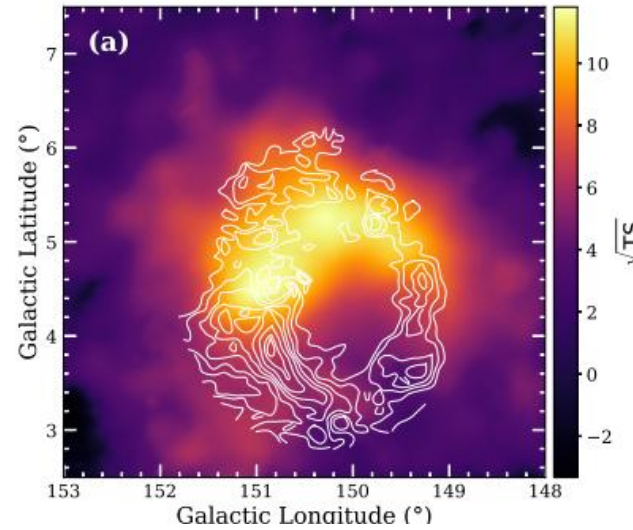
SEDs: They do produce CRs



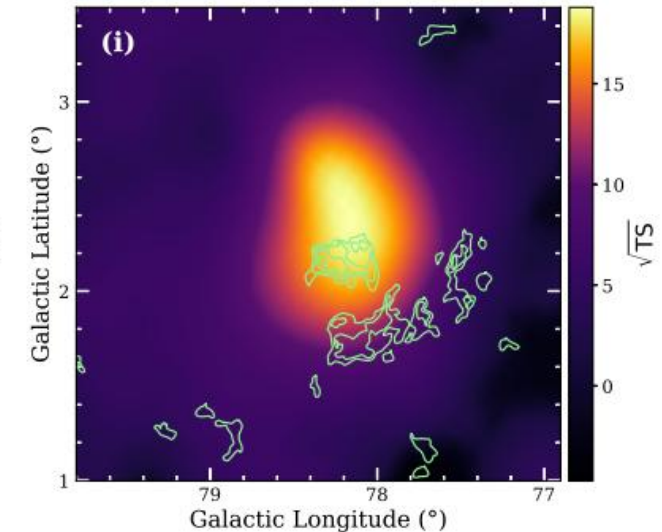
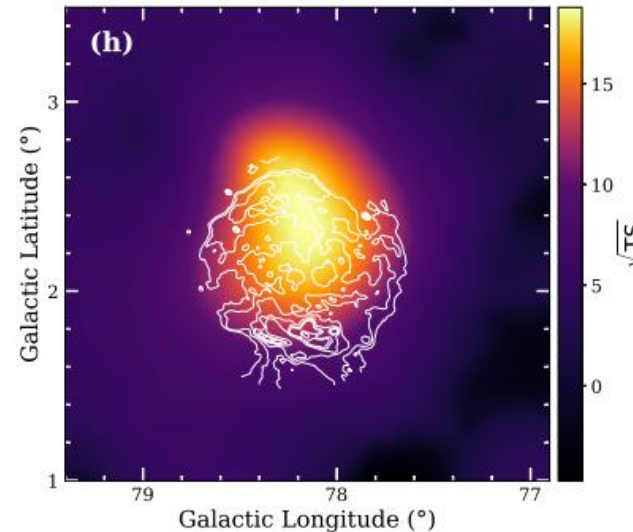
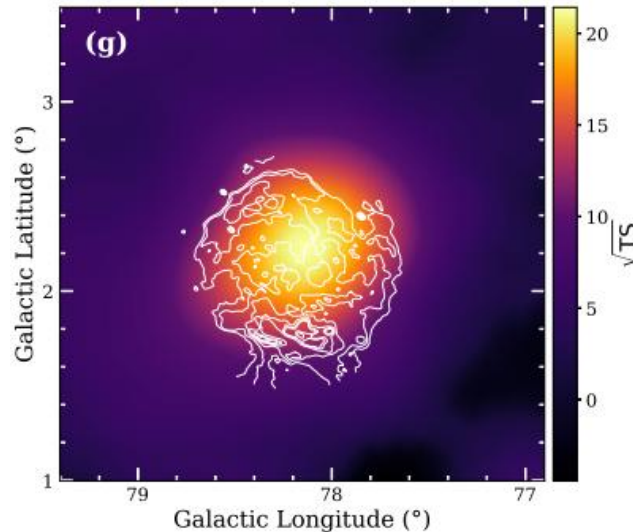
SNRs in an environment with fewer targets

2 components of G150.3+4.5
3 components of γ -Cygni

Source	Component	GL ($^{\circ}$)	GB ($^{\circ}$)	R_{39} ($^{\circ}$)	TS
G150.3+4.5	A	150.41 ± 0.09	4.69 ± 0.10	1.26 ± 0.07	466
	B	150.96 ± 0.04	3.83 ± 0.04	0.22 ± 0.04	172
γ -Cygni	A	78.11 ± 0.07	2.23 ± 0.05	0.59 ± 0.03	632
	B	78.13 ± 0.05	2.24 ± 0.03	0.26 ± 0.02	499
	C	78.27 ± 0.10	2.66 ± 0.05	Point Source	182



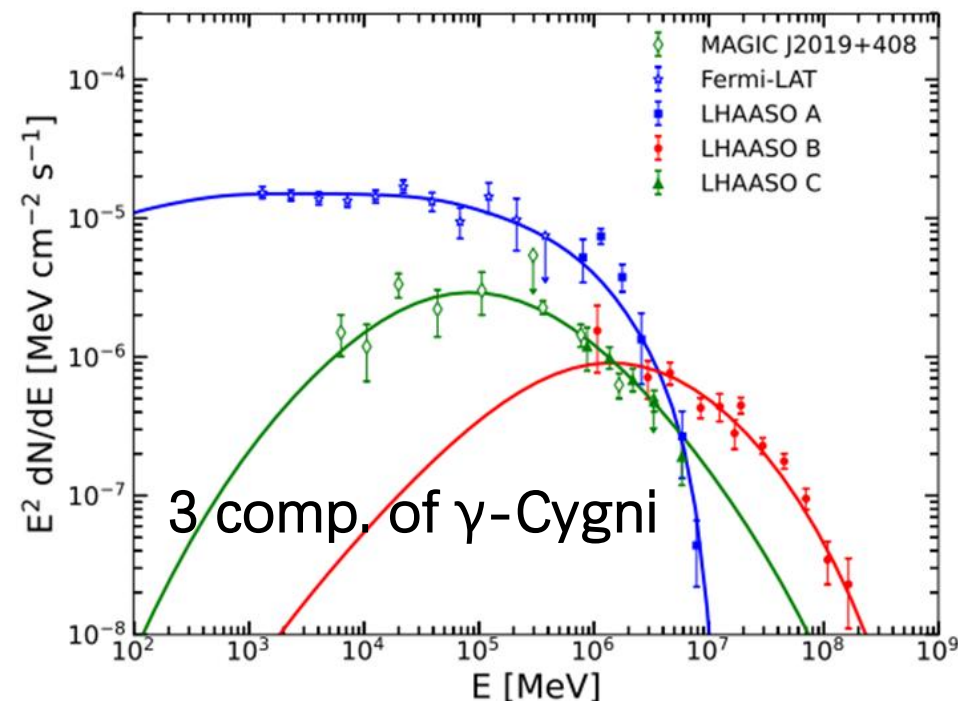
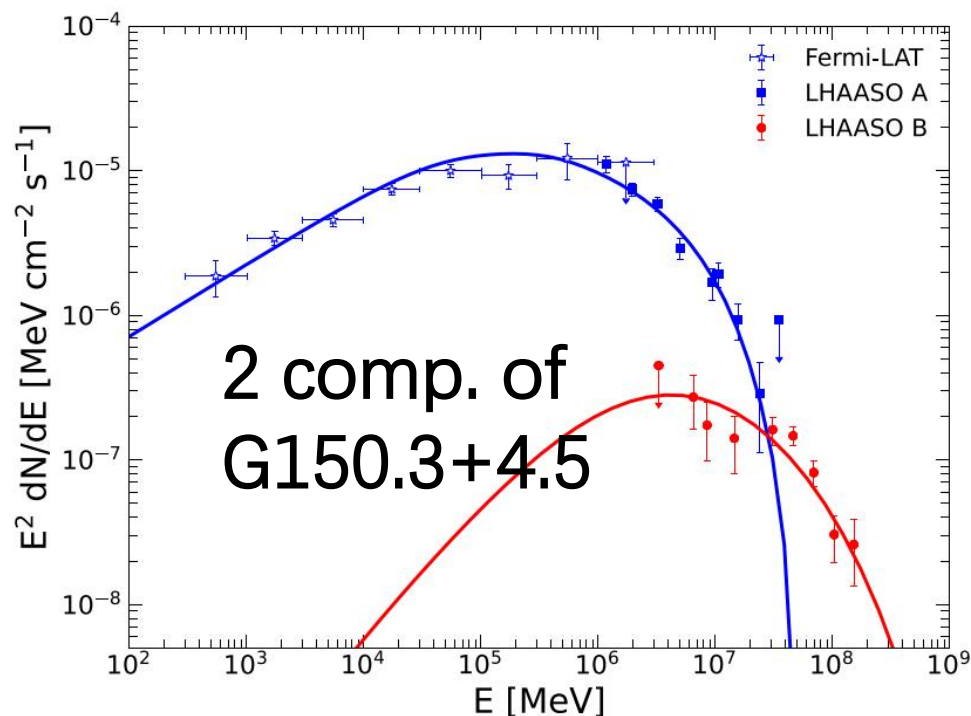
On shell comp.
Escaped comp.



The Radiation from the shell seems dominated by leptons, similar to the RX J1713 in the southern sky

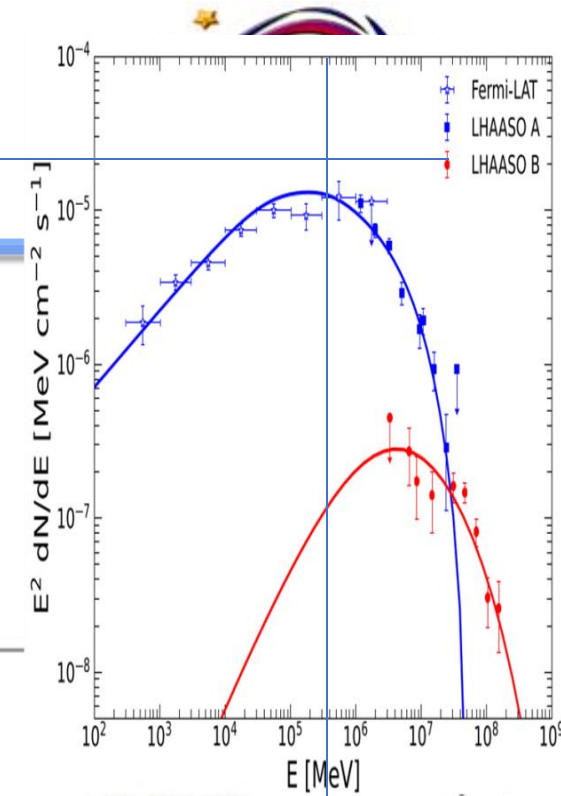
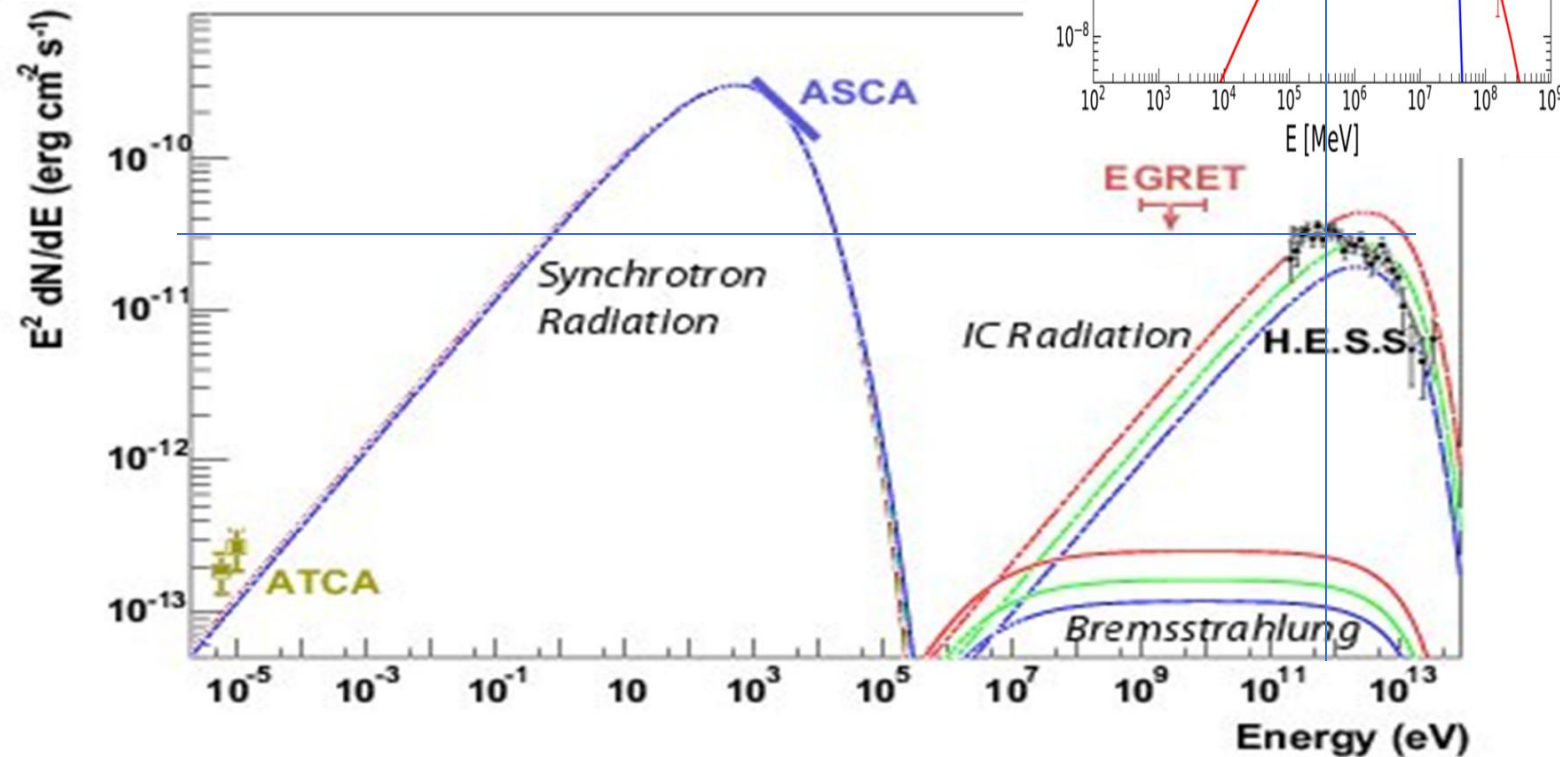
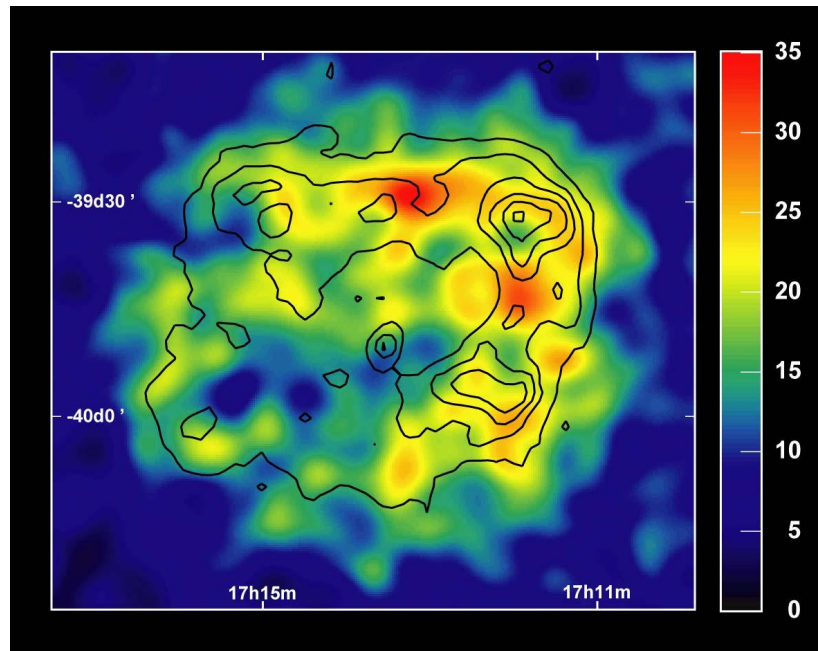
□ The more concentrated radiation seems from the interaction with the clumpy MC

□ It might represent the escaped high energy protons, could be as high as 1 PeV



RXJ1713.7-3946

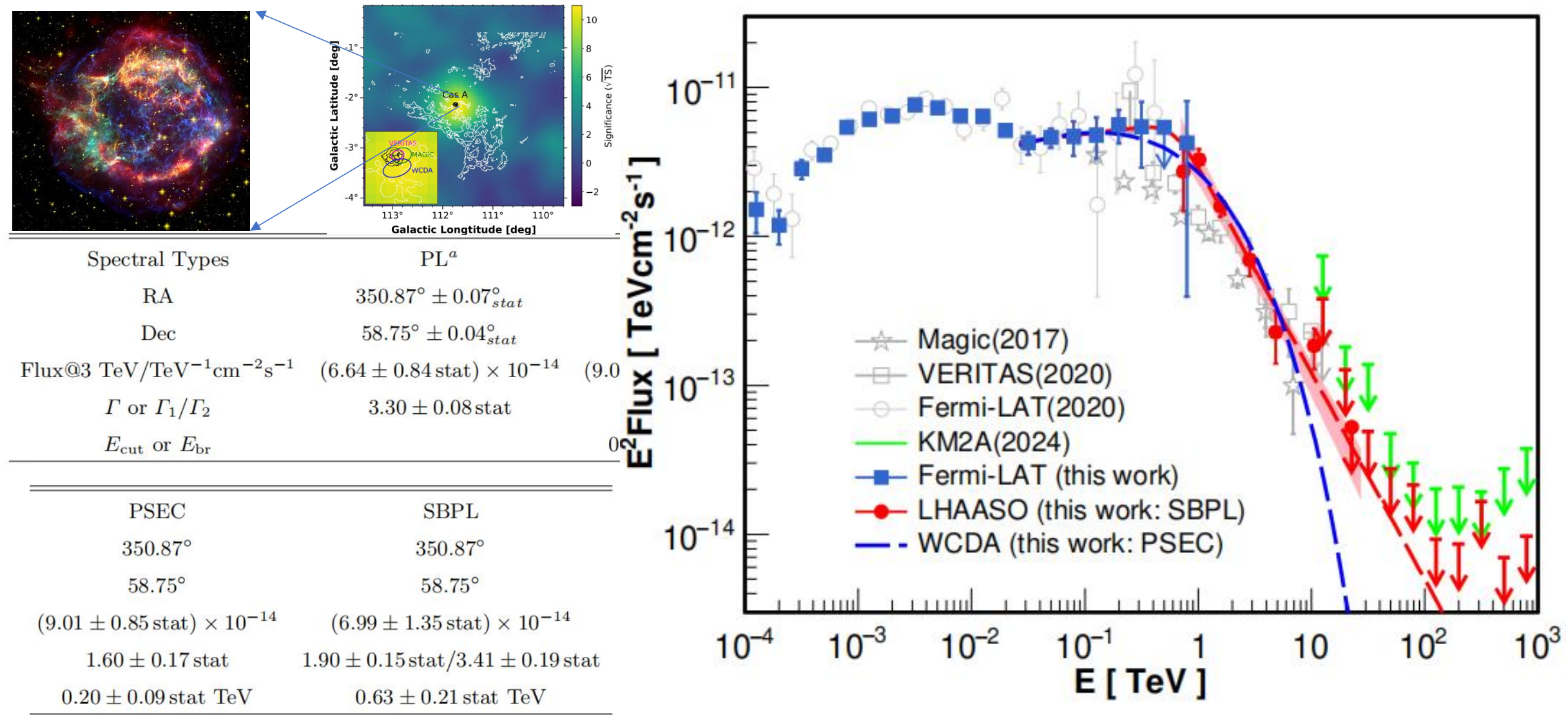
- ASCA data: synchrotron X rays
- Fine structures in the radiation morphology points to $B > 100 \mu\text{G}$
- If leptonic, **X/TeV ratio** requires
- $B \sim 10 \mu\text{G}$ (with $\sigma_{\text{IC}}/\sigma_{\text{Sync}} \propto B^{-2}$)



Yong SNR as a PeVatron?

T ~ 350 years old SNR
D ~ 3.4 kpc away
R ~ 2.5 pc ~ 2.5' radius

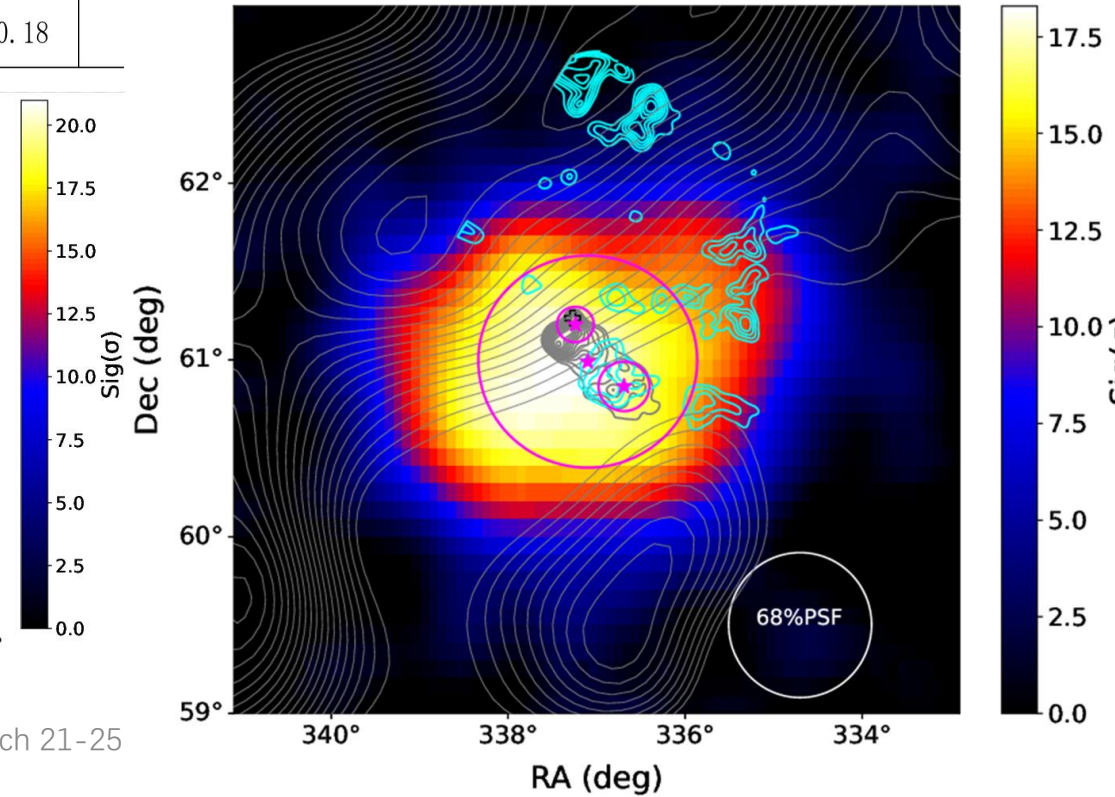
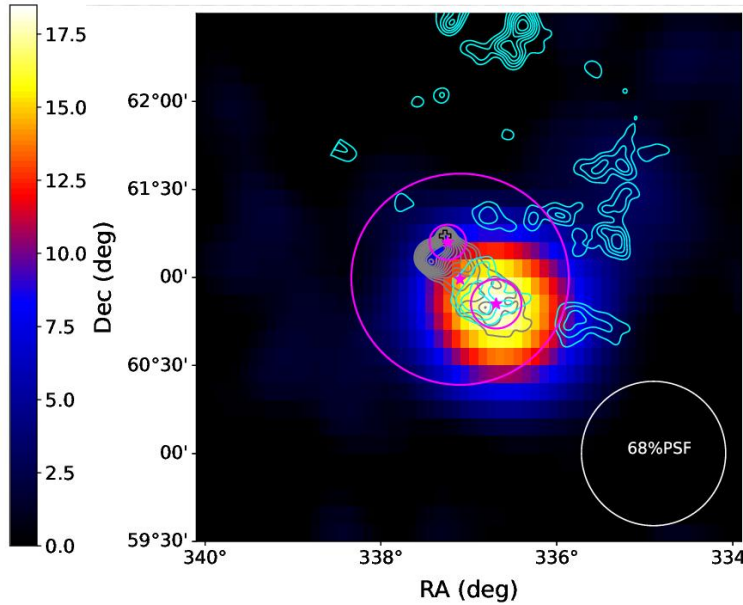
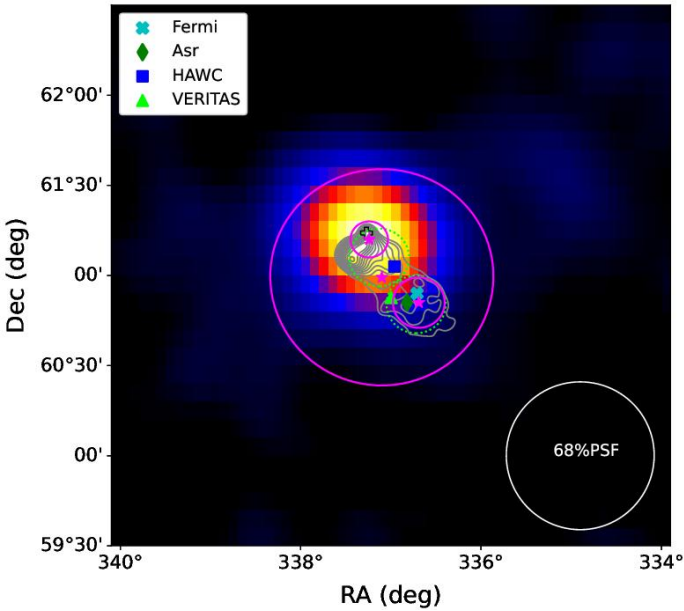
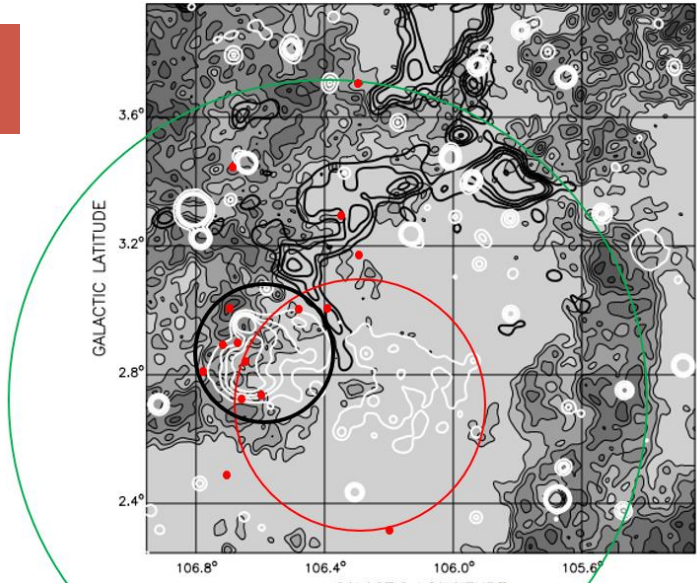
Broadband γ -ray spectrum of supernova remnant Cassiopeia A



Particle escaping from the SNR or PWN?

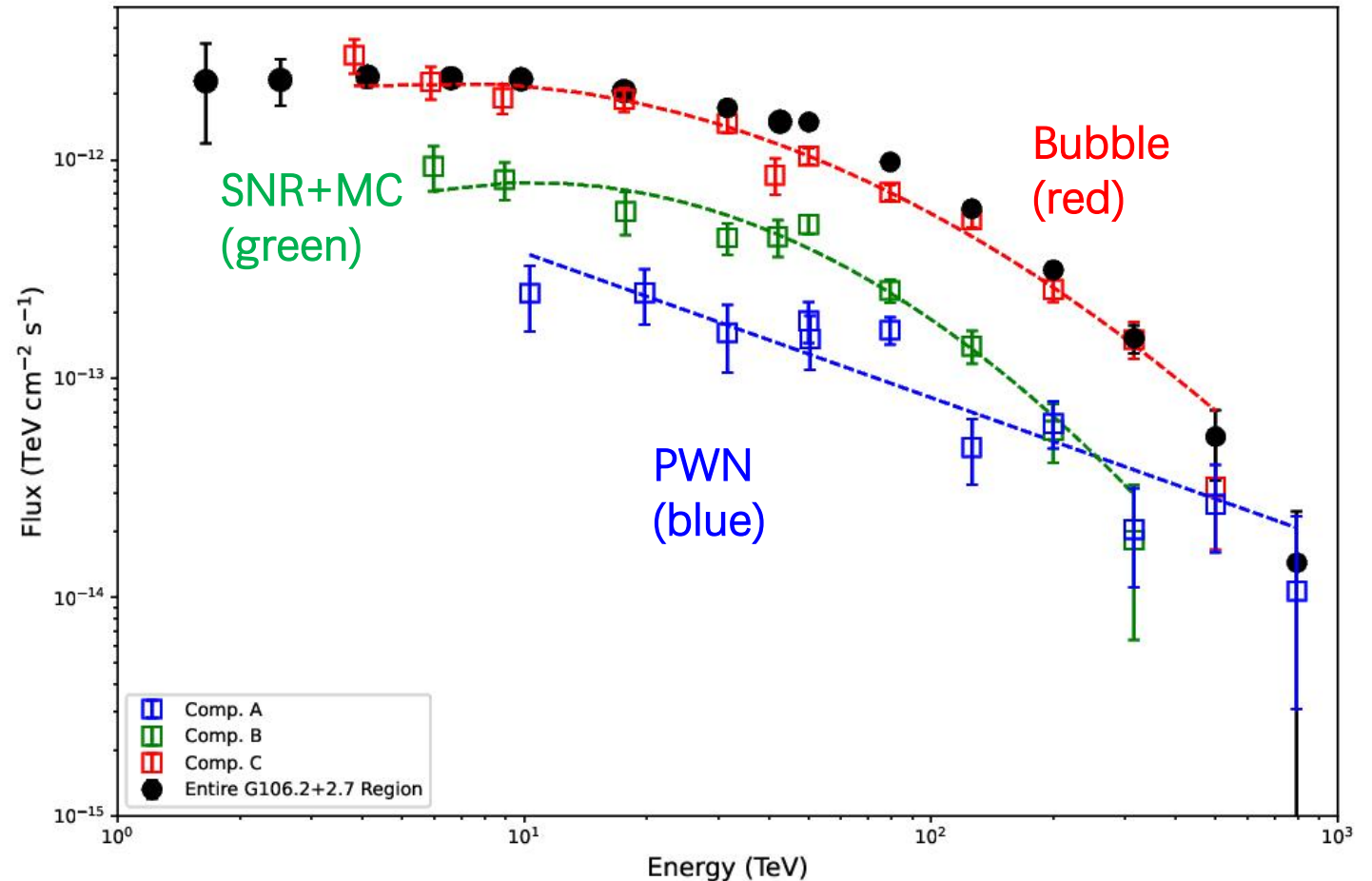
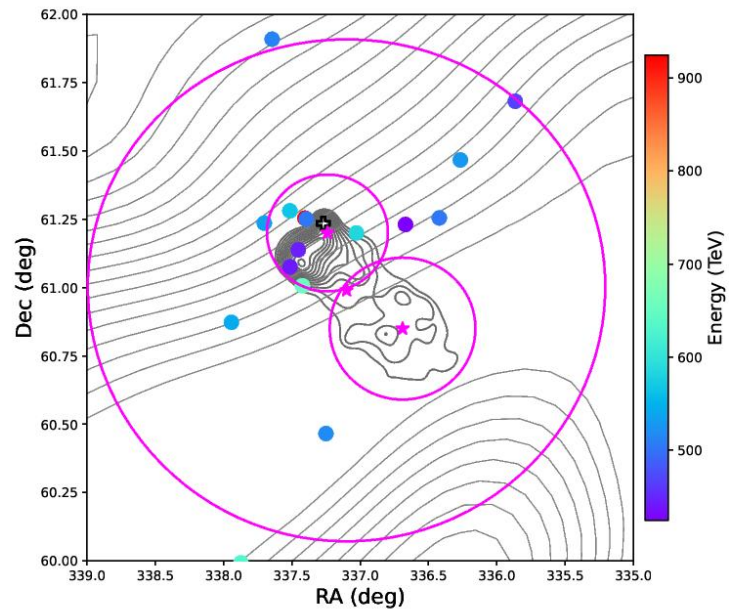
- Complex of 3 sources: PWN (Boomerang), SNR_(G106.3+27)+MC and an extended associated with gas

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	

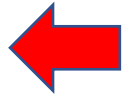


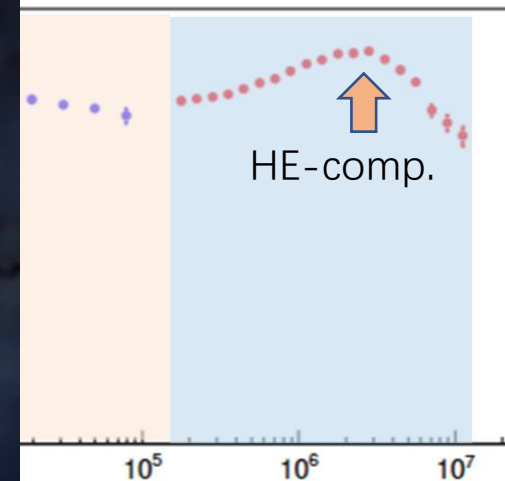
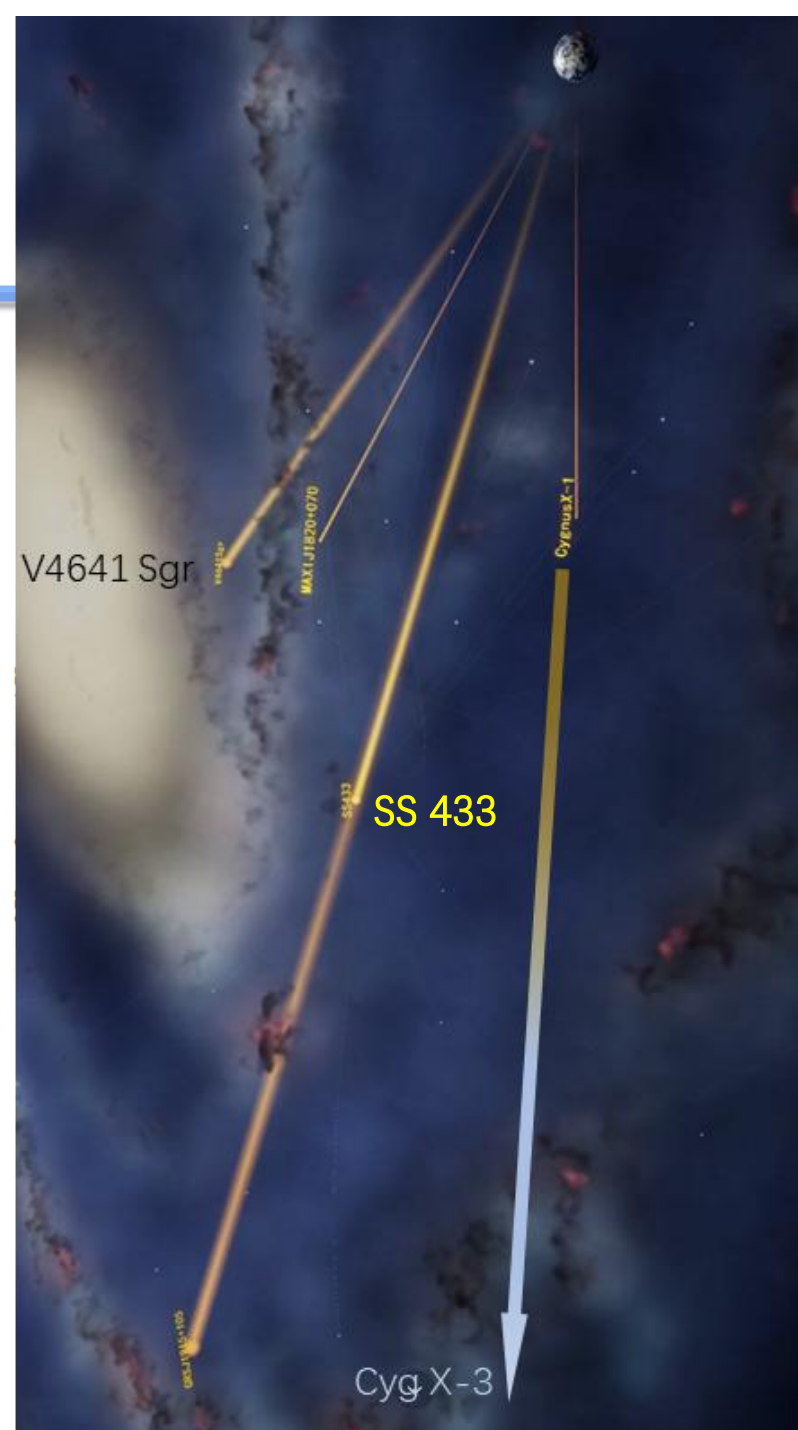
SEDs of the 3 Components

- SNR+MC has $E_{\text{cut}} \sim 50\text{TeV}$
- PWN seems the source of UHE photons
- The bubble may associated with the gas distribution

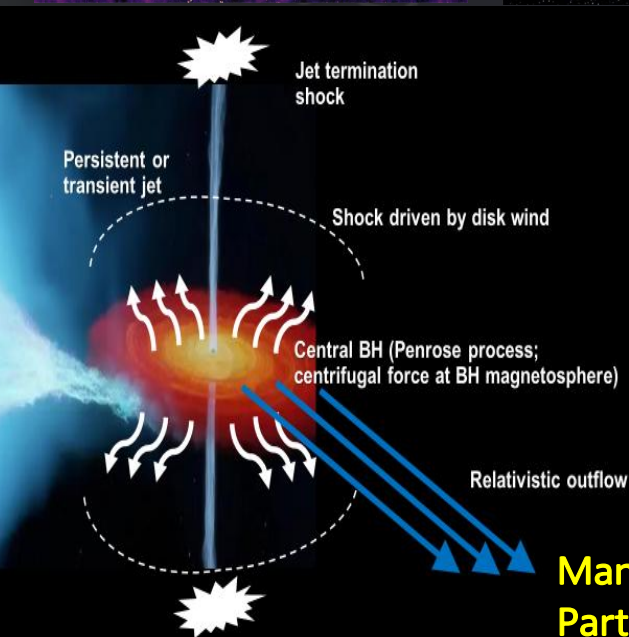
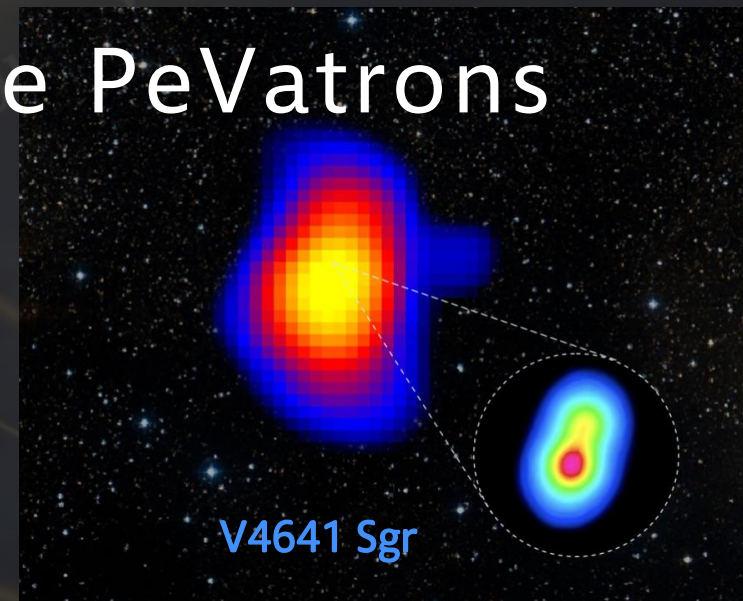
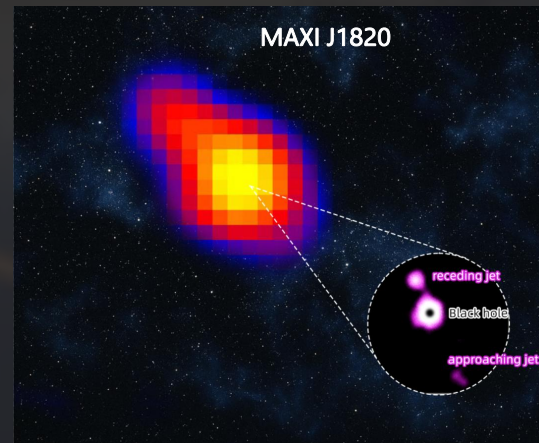
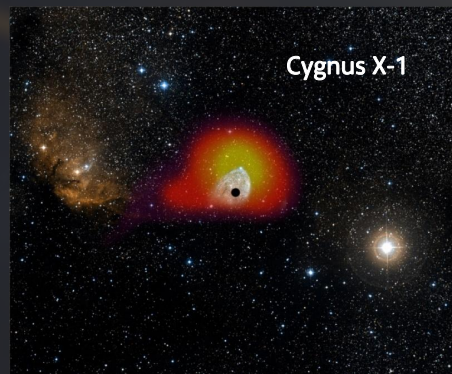
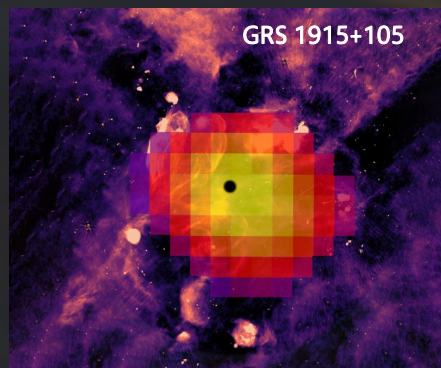


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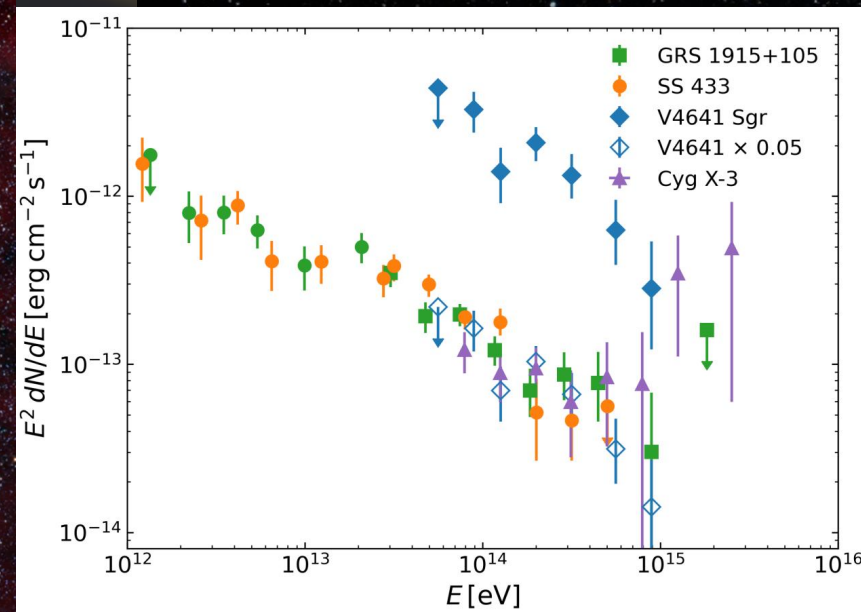
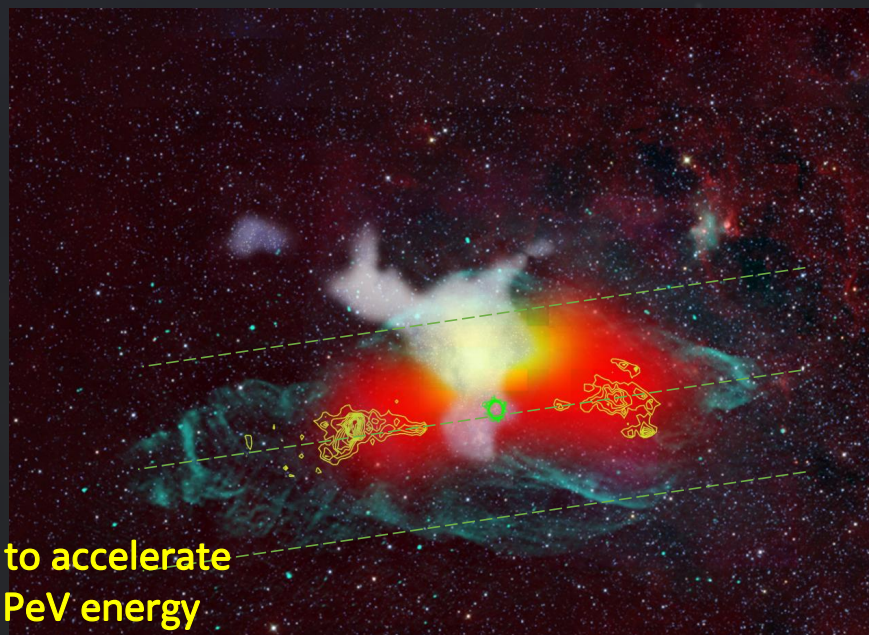
- CR measured at the solar system
- Supernova Remnants as the sources of the VHE-component
- μ -Quasars and the PeVatron- component 
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Six μ -Quasars are identified to be PeVatrons



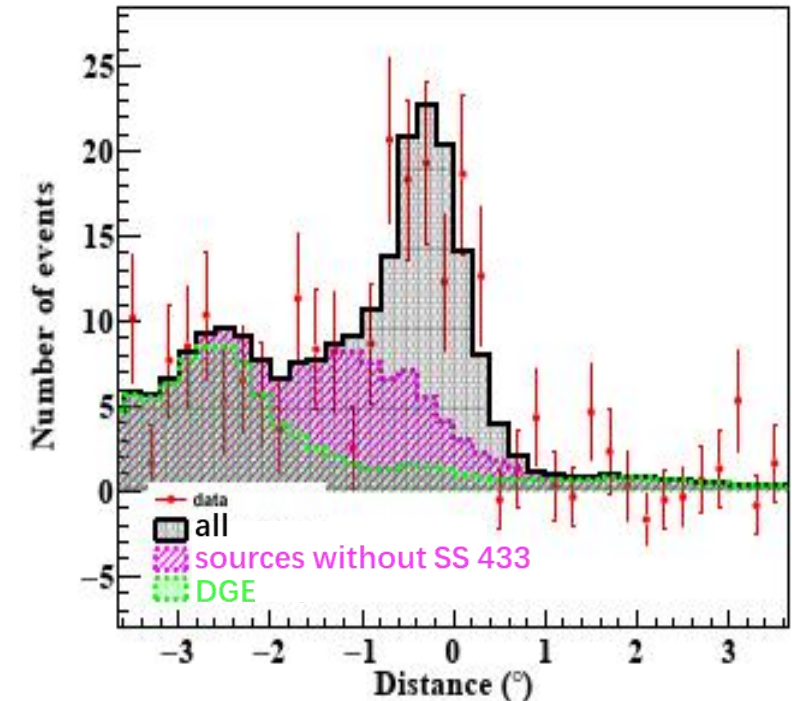
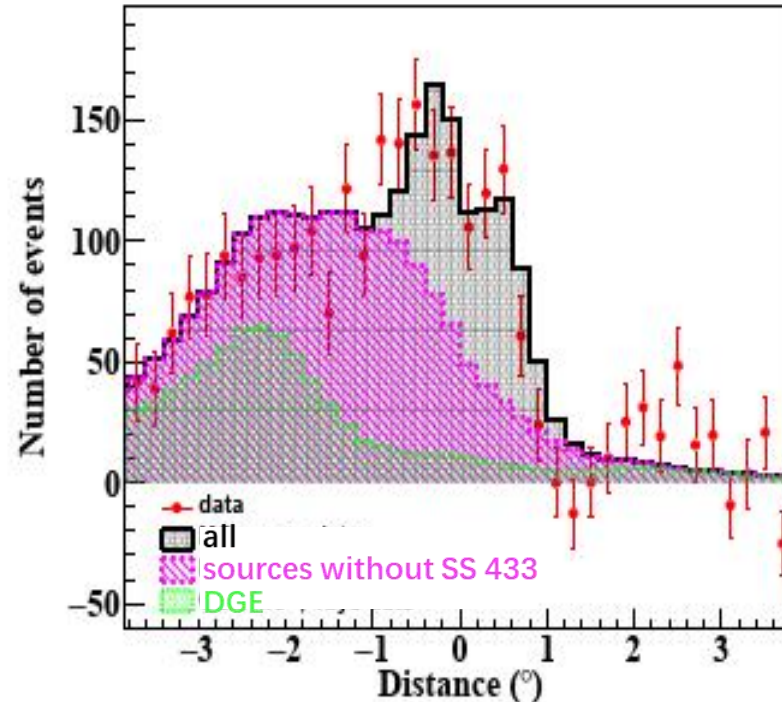
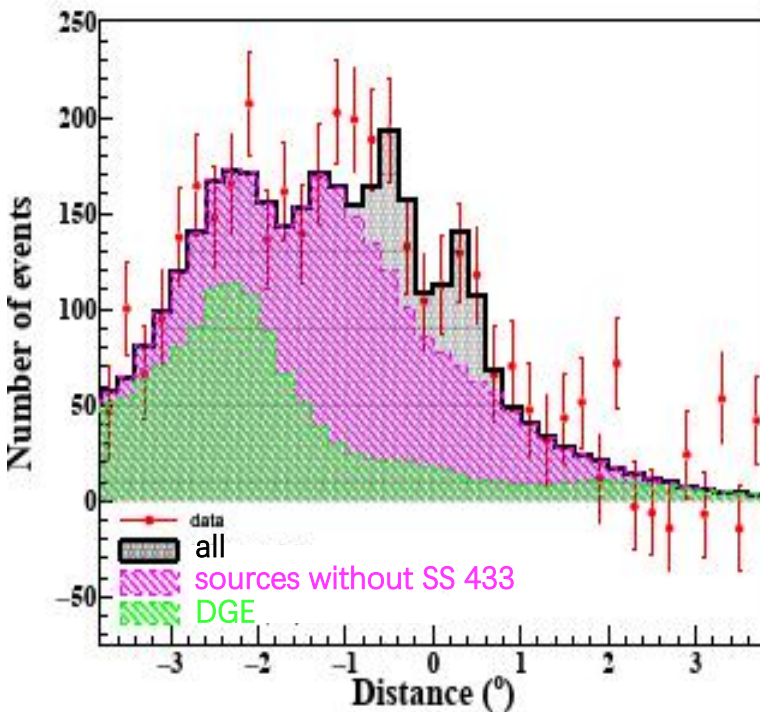
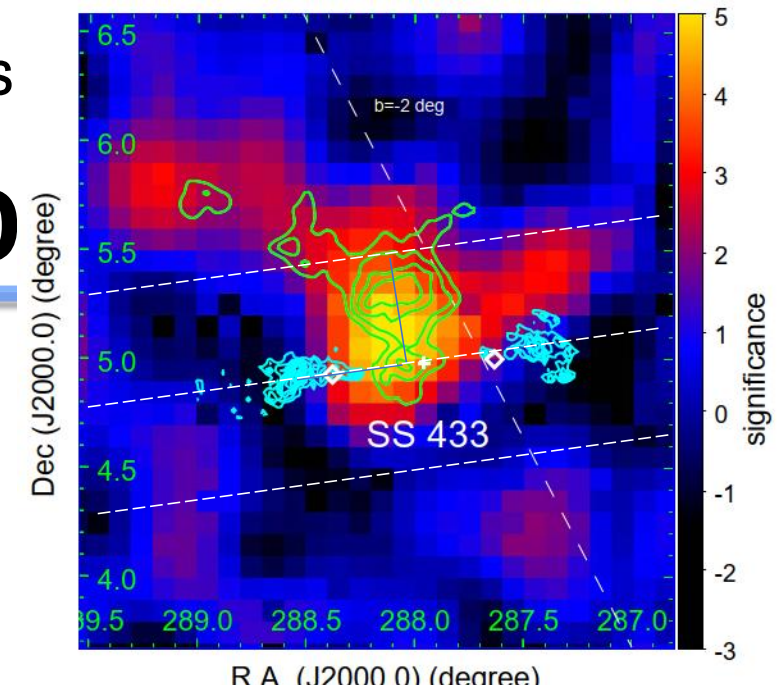
Many ways to accelerate
Particles to PeV energy



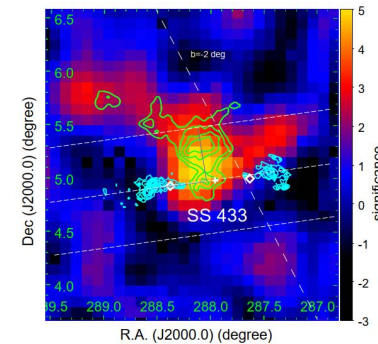
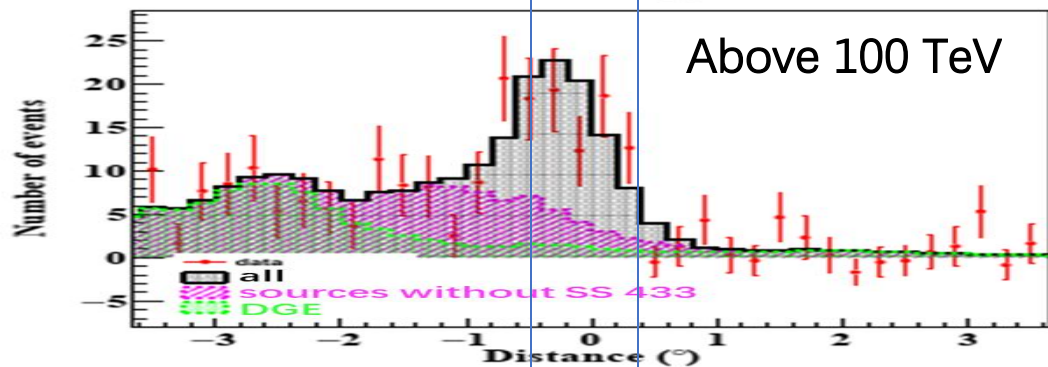
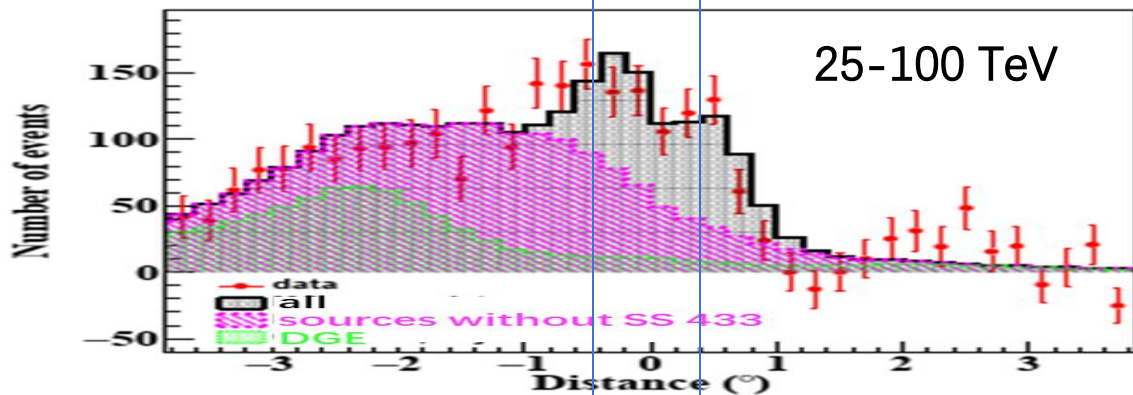
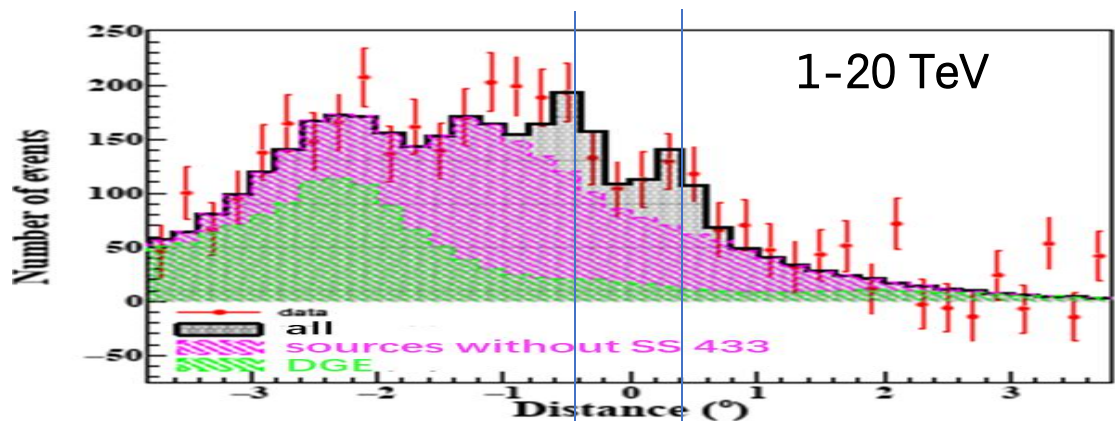
- Subtracting the jet-components

SS 433: High energy radiation at the central region

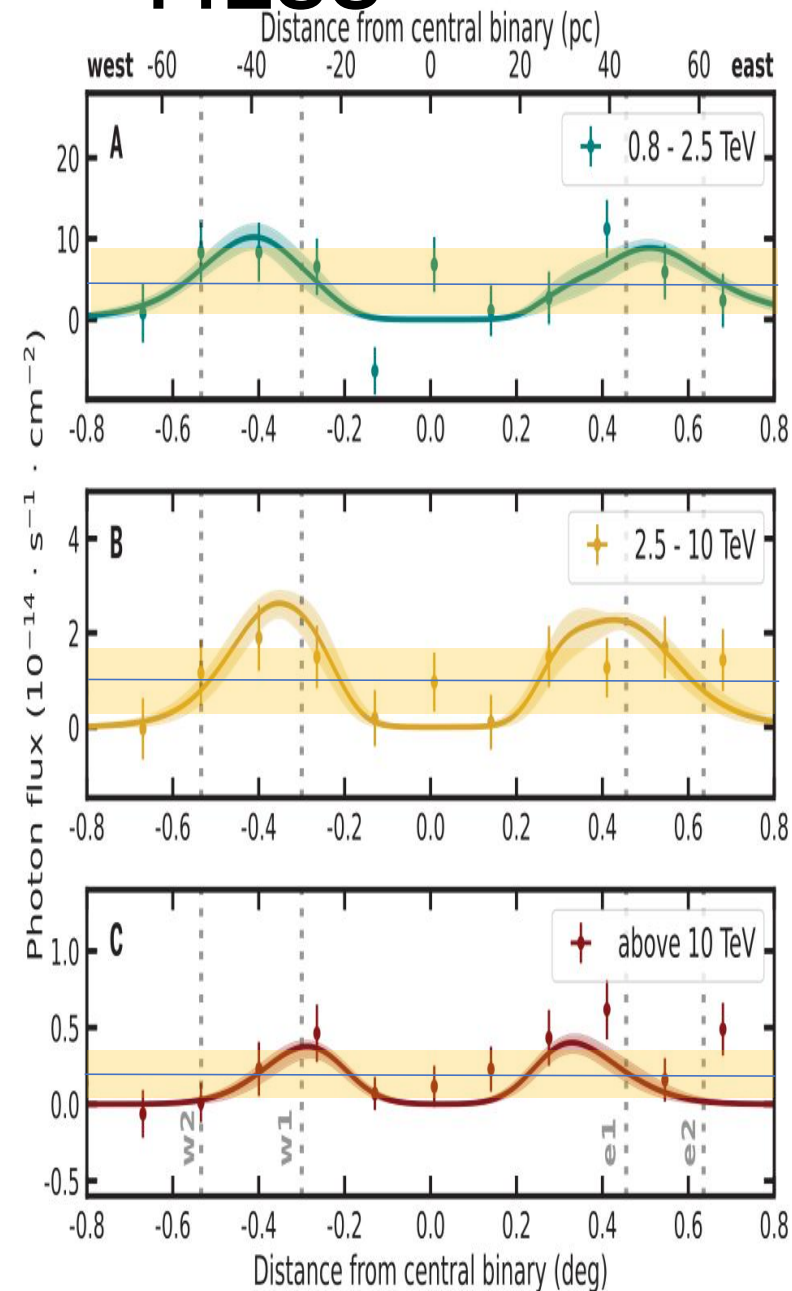
- 1-D #-of-photon distribution: extra central component



LHAASO

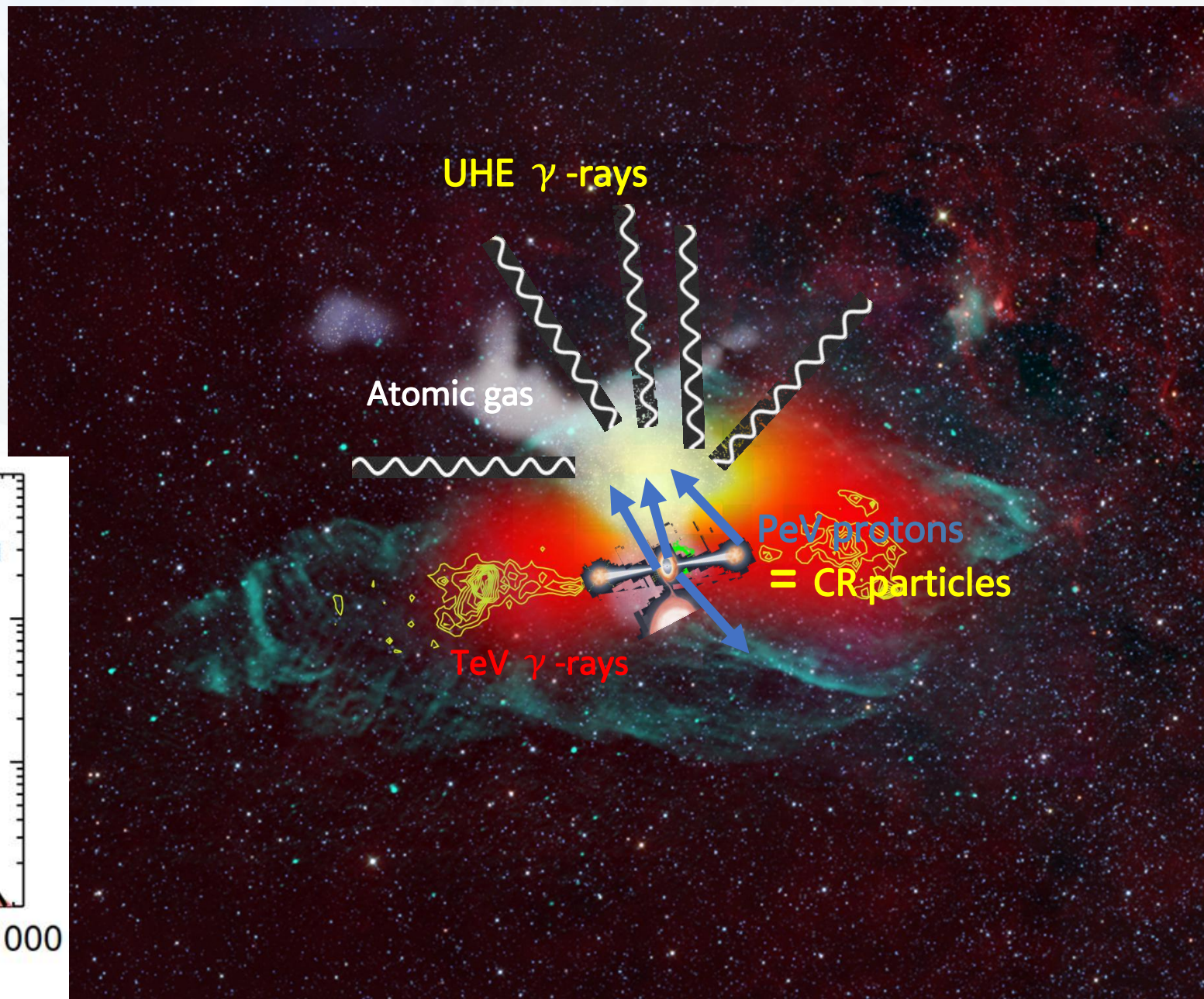
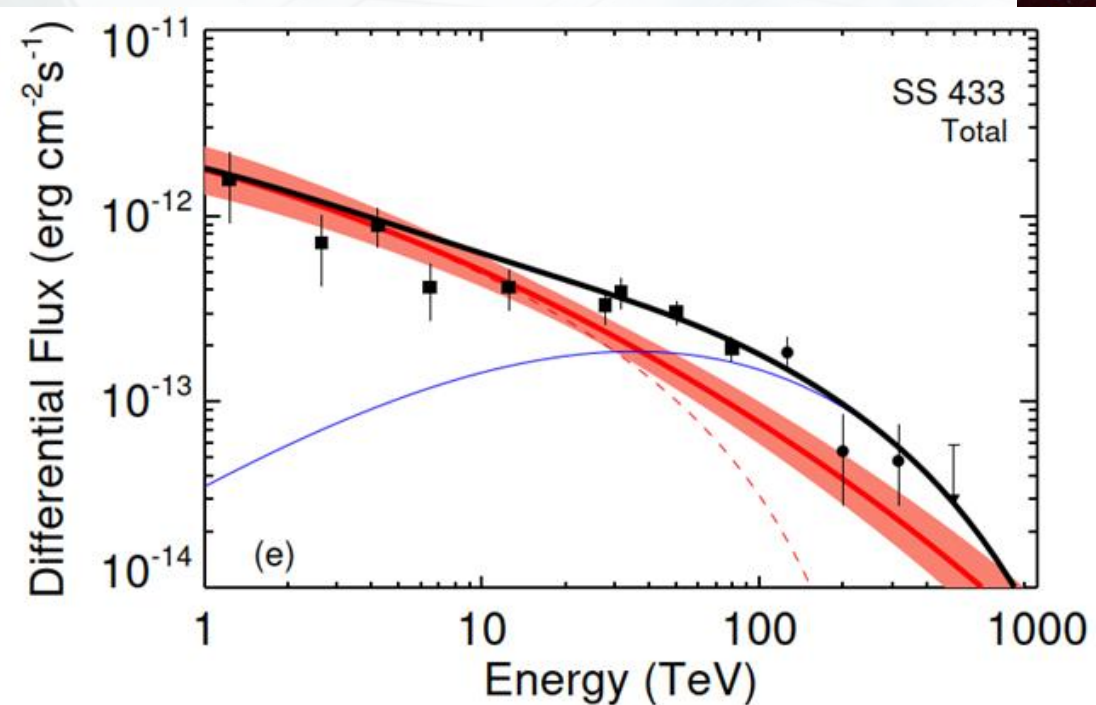


HESS



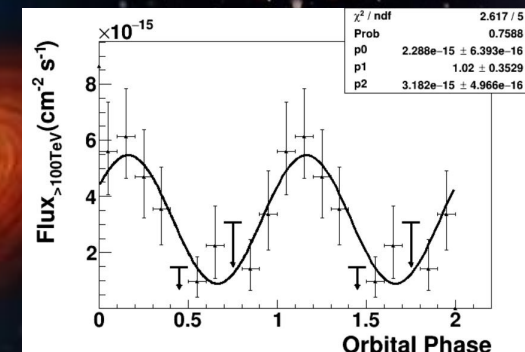
SS 433 SED

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

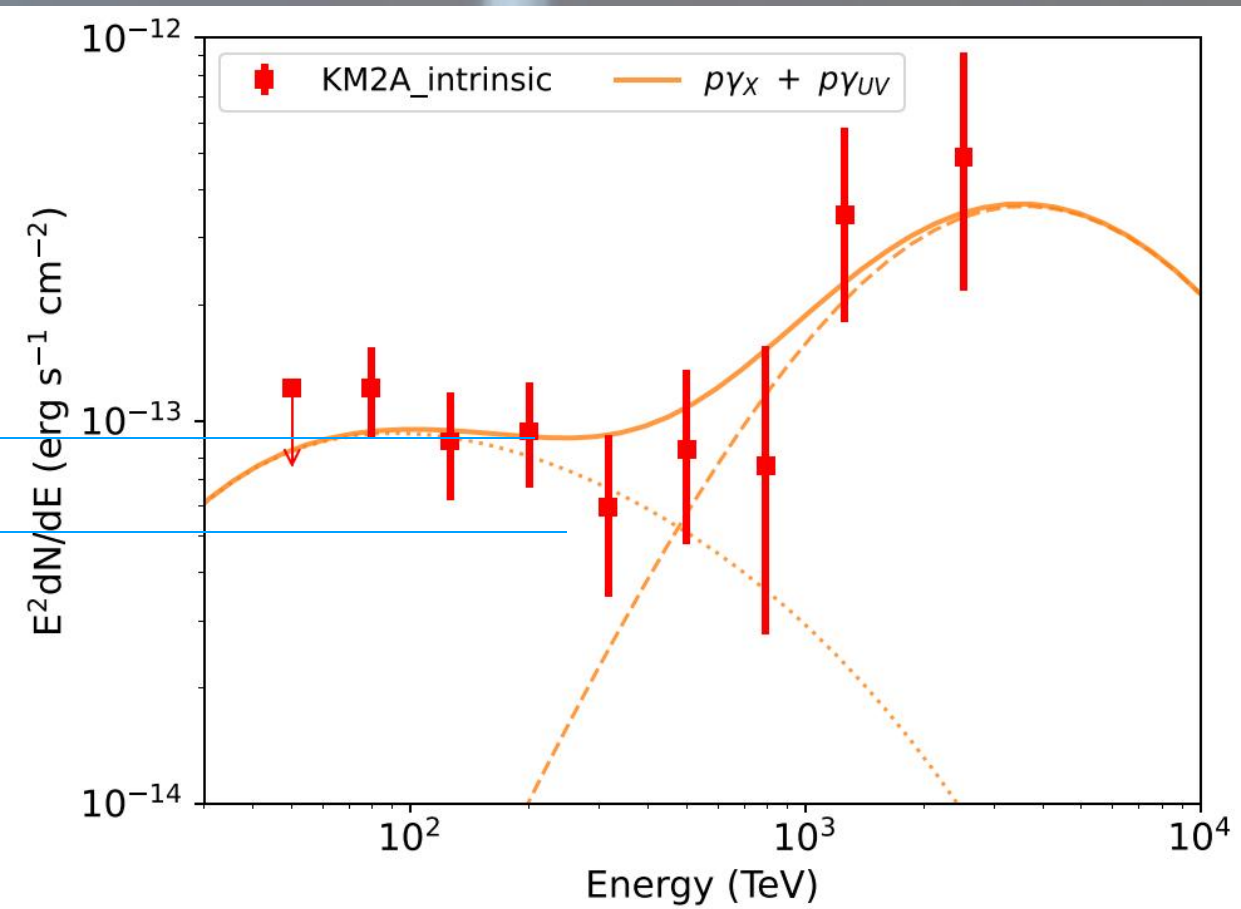
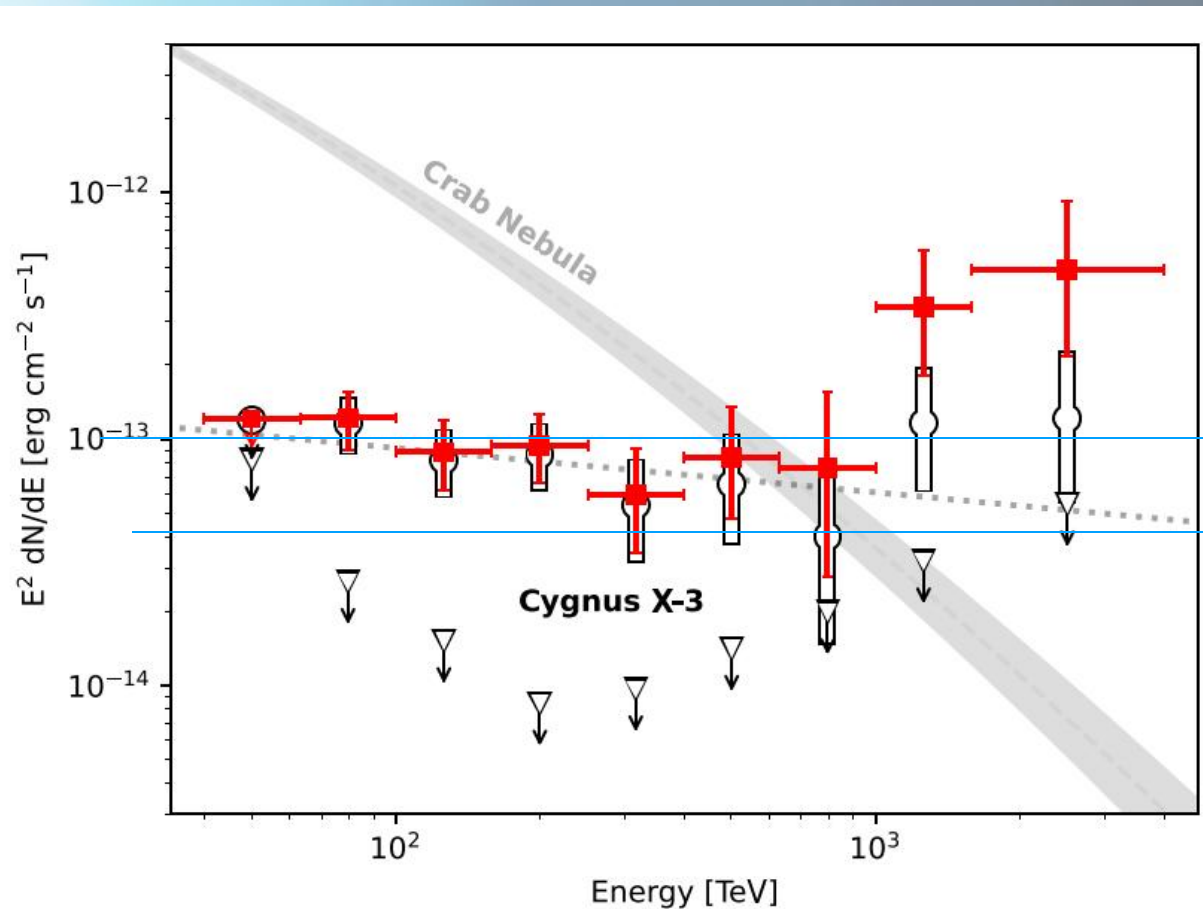


Cyg X-3: 4.8 hour orbiting

- This guarantees the proton accelerator
- ~4 PeV photons implies 40 PeV proton A super-PeVatron:
- For Protons >40 PeV, radiation mechanism: proton- γ scattering

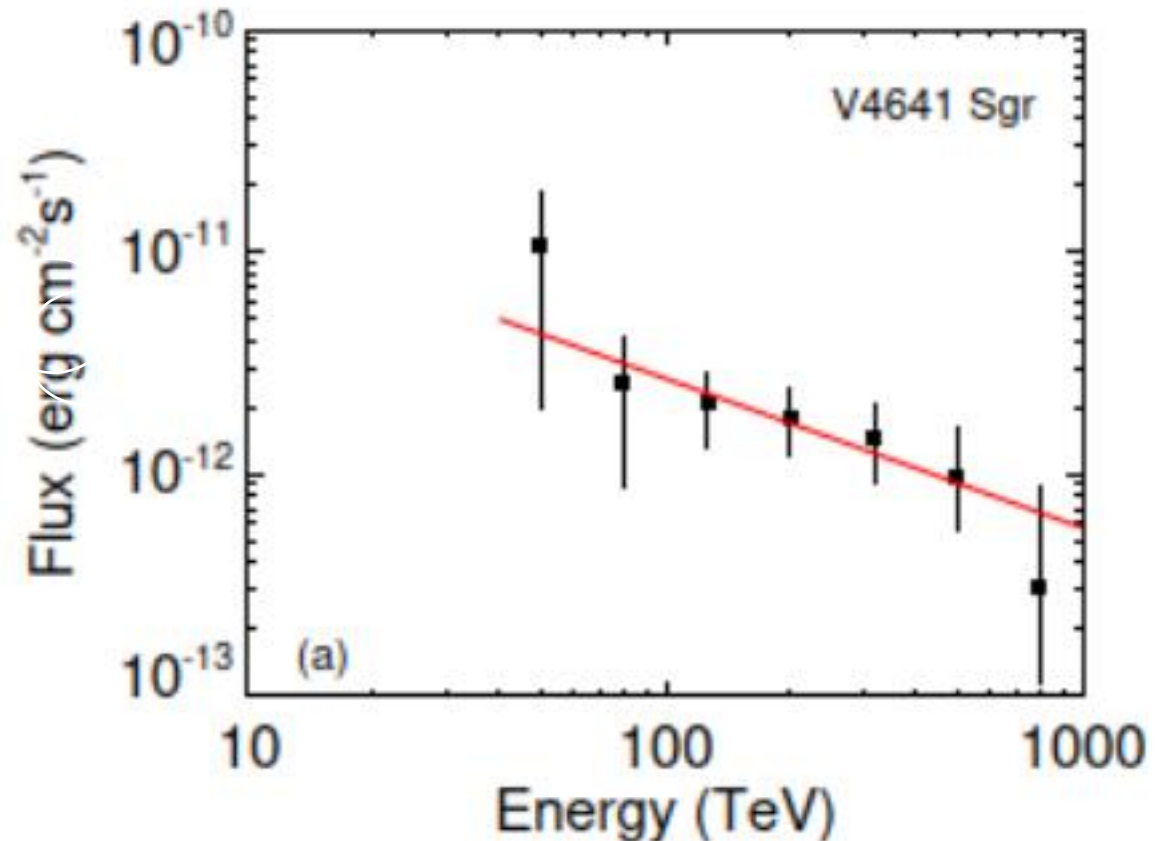
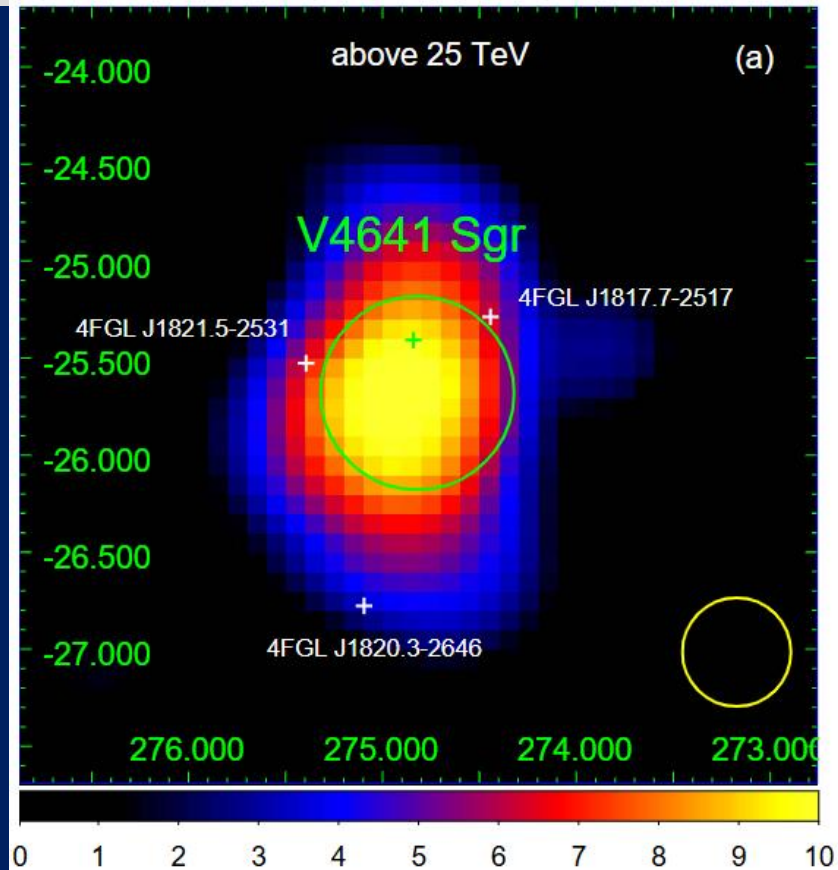


SED of a source of proton-photon scattering



Black Hole as a super-PeVatron?

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 !!



Content

- CR measured at the solar system
- Supernova Remnants as the sources of the VHE-component
- μ -Quasars and the New component at HE
- Propagation of CRs in MW
- Summary



Resolved Sources (RS) Measurement / RS-DGE Separation

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

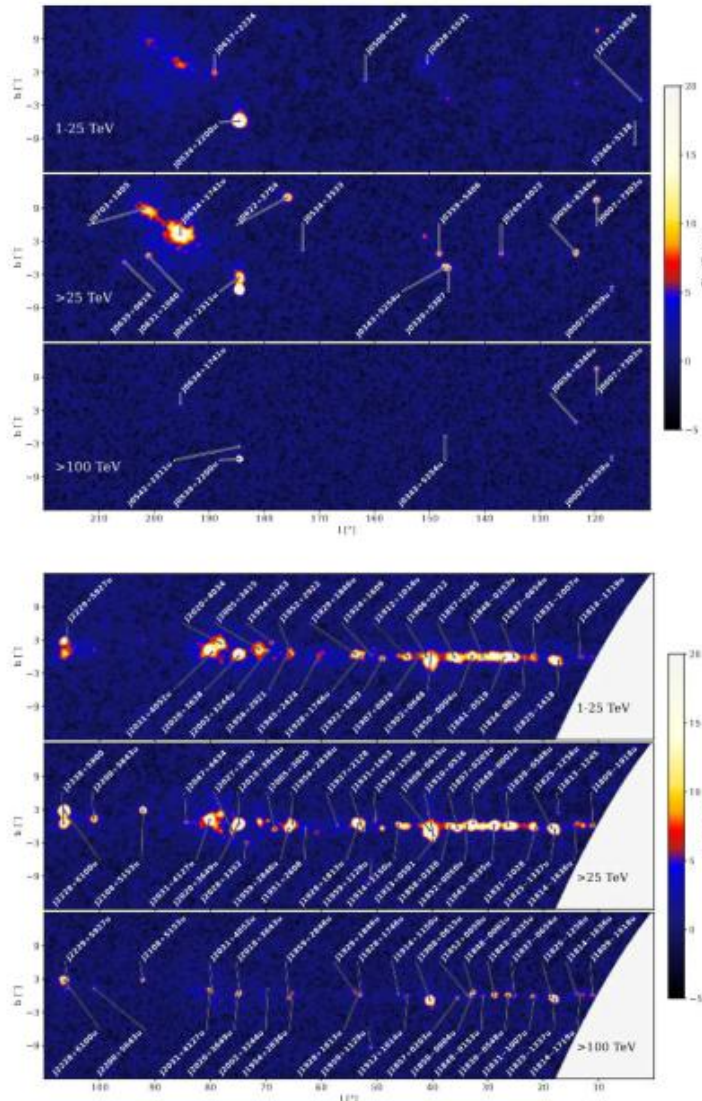
Preliminary

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



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

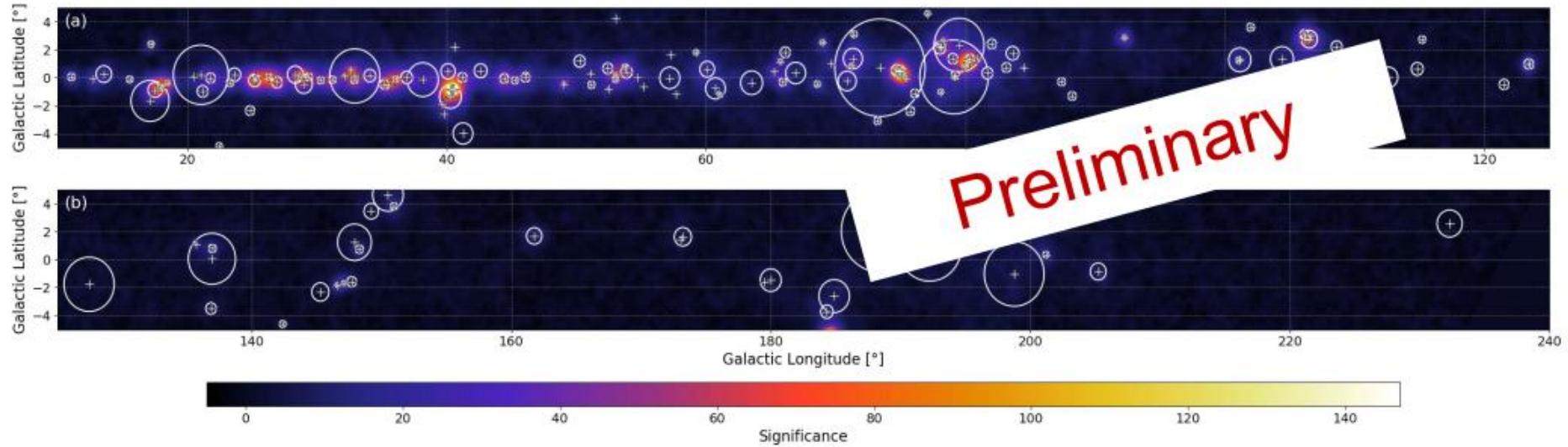
Slide credit to Rui Zhang (PMO)



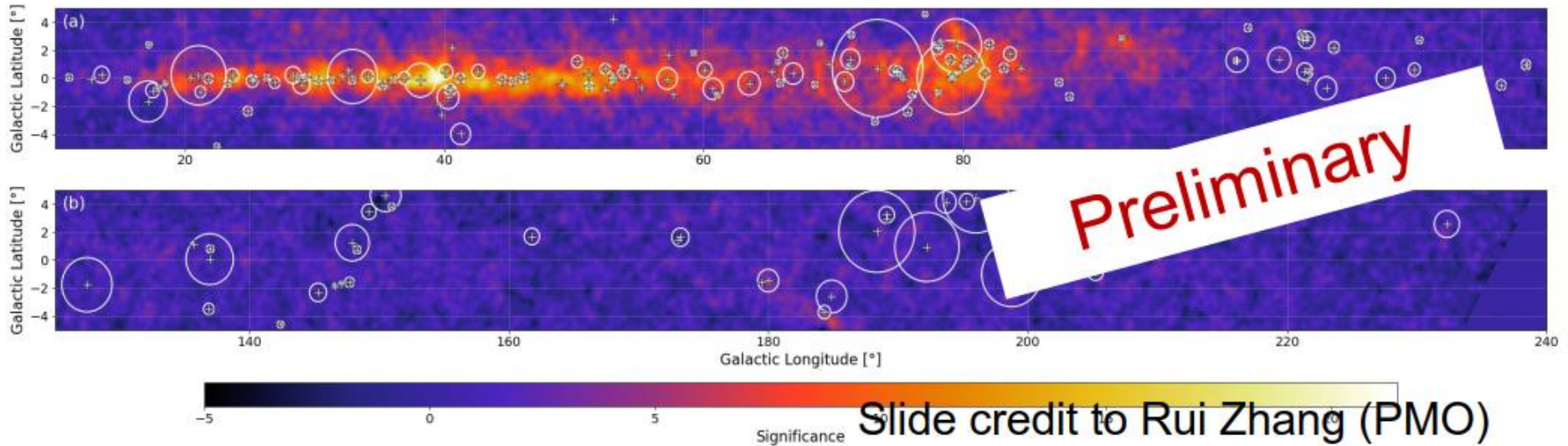
More data + New method applied to measure GDE

Significance Map before/after subtracting Resolved Sources

allsource



DGE:
allsource-RS

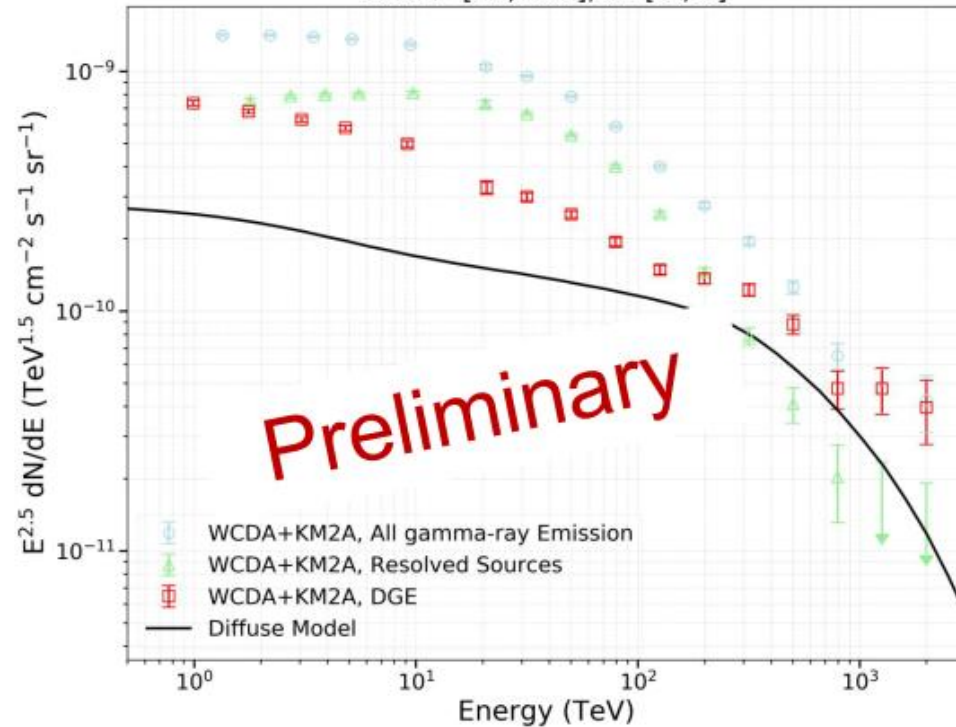


Slide credit to Rui Zhang (PMO)

SED of DGE

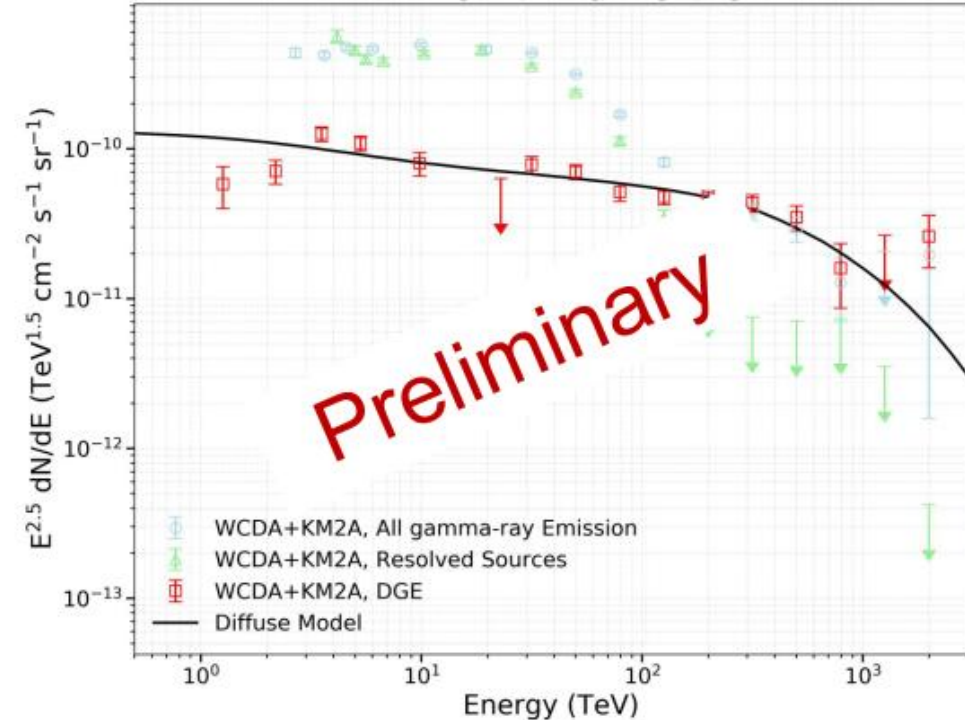
INNER

ROI: $l=[10, 125], b=[-5, 5]$



OUTER

ROI: $l=[125, 240], b=[-5, 5]$



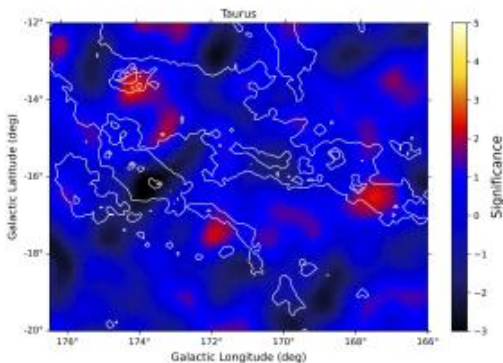
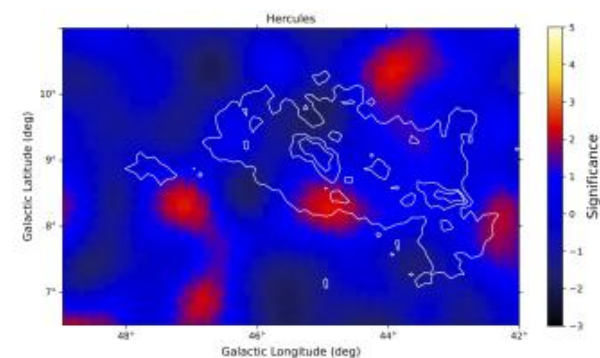
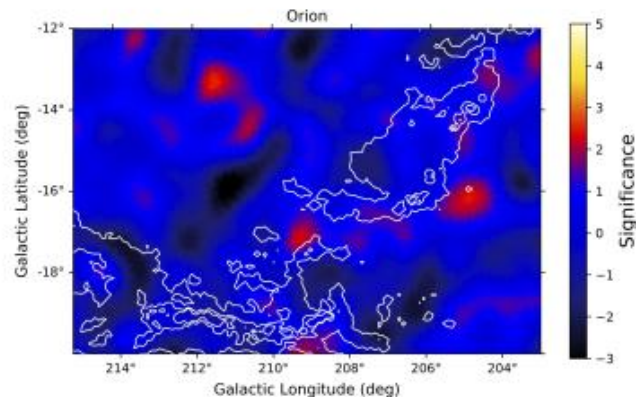
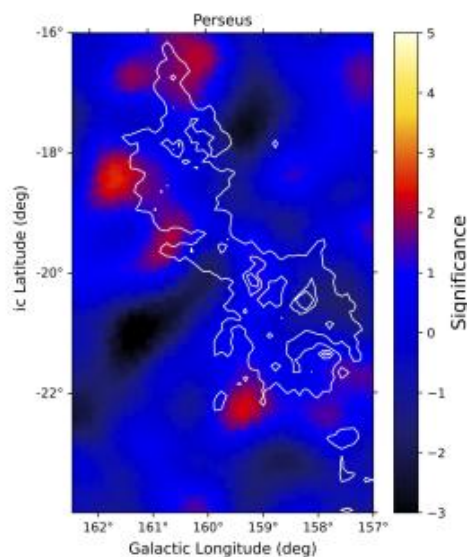
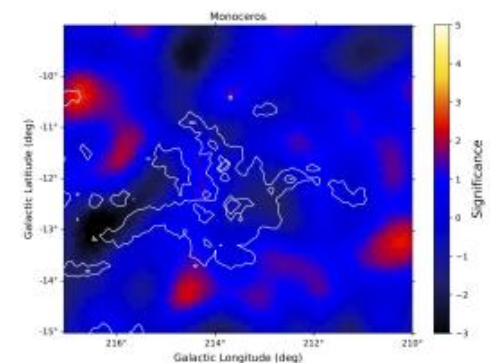
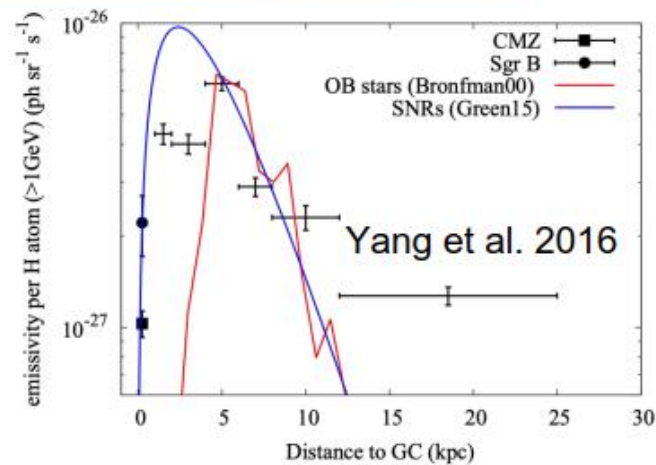
- Diffuse Model: LHAASO CR (p+He) spectrum + ISM, no CR distribution
- $E > 100$ TeV: similar spectral shape (index) as that of measurements
- $E < 100$ TeV: extra component with E_{cut} around tens of TeV for Inner Galaxy region

Slide credit to Rui Zhang (PMO)

Probe local CR via γ -ray observation of GMCs

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

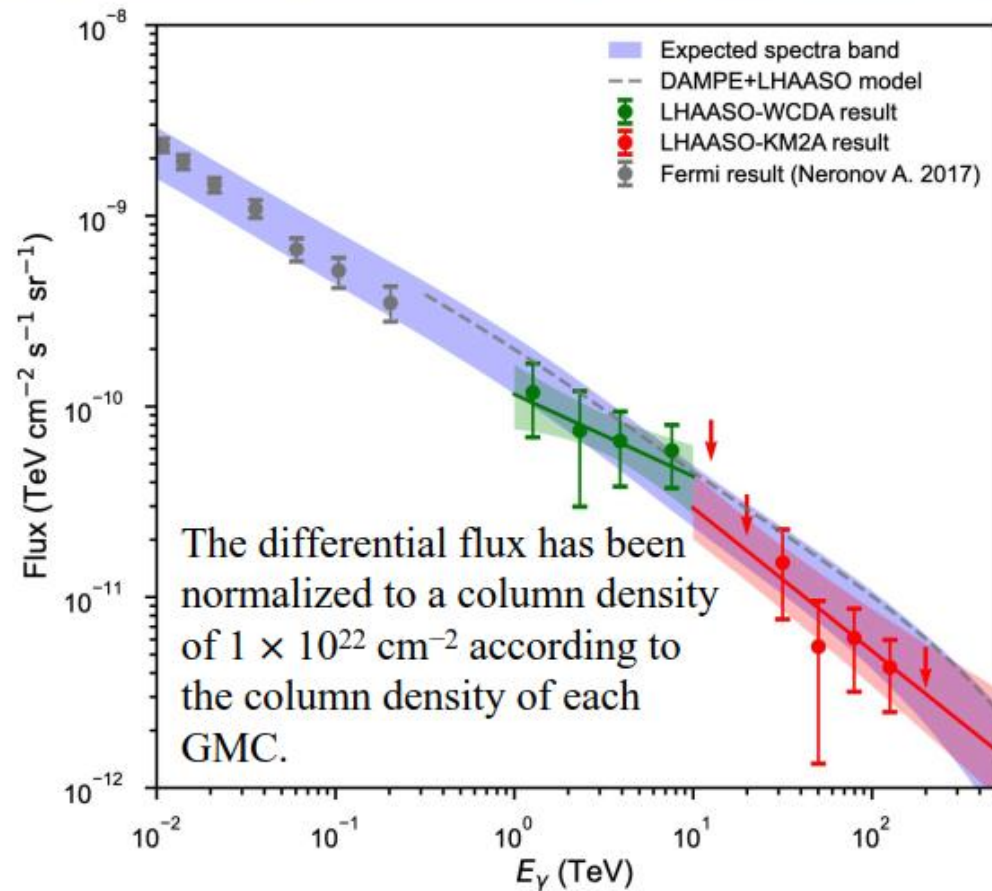
- ❑ To inspect the density and spectra of local CRs, LHAASO 4.5-year data used to search γ -ray emission from 5 nearby GMCs.
- No significant detection ($<5\sigma$) from individual samples (Hercules, Monoceros, Orion, Perseus, and Taurus) $\rightarrow$ **Stacking analysis**.



LHAASO significance maps of individual GMC samples

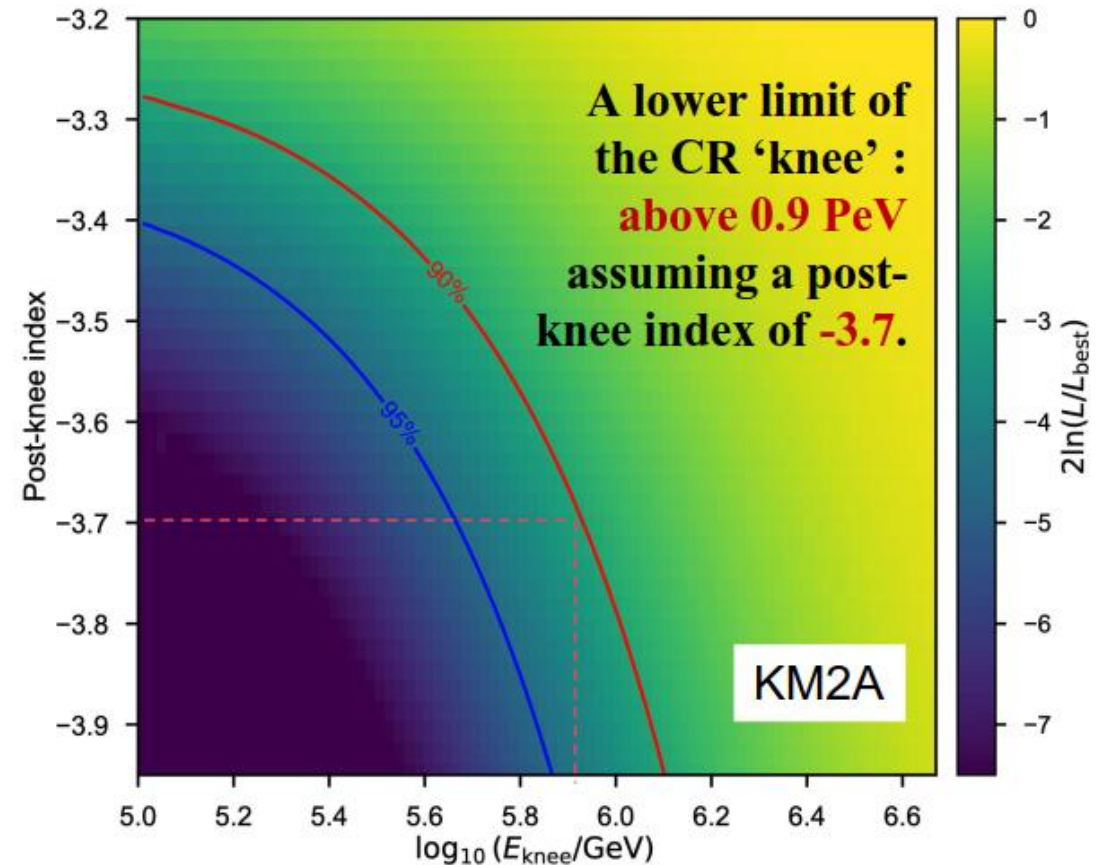
LHAASO, accepted by NA (2026) arXiv:2511.05015

Probe local CR via γ -ray observation of GMCs



The SED of the GMC as measured by LHAASO.

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



Constraints on the CR 'knee' parameters.

LHAASO, accepted by NA (2026)
arXiv:2511.05015

Content

- CR measured at the solar system
- Supernova Remnants as the sources of the VHE-component
- μ -Quasars and the New component at HE
- Future expectations
- Summary



**Survey power:
AI-aid analysis**

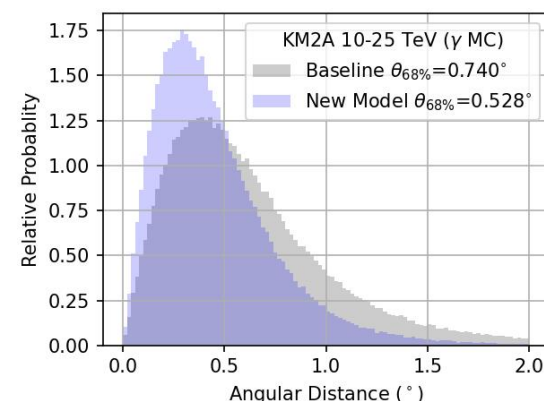
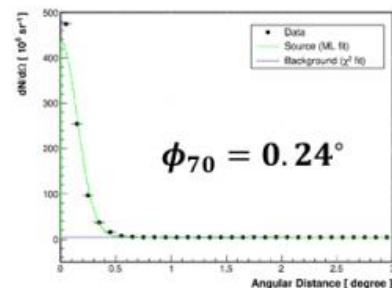
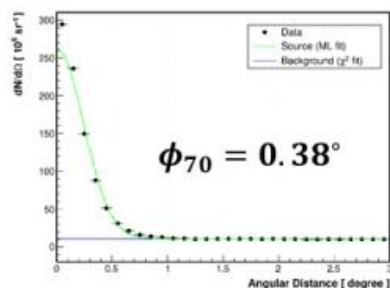
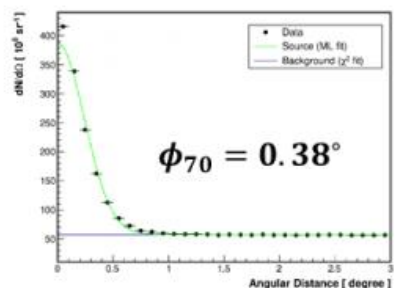
**LACT: angular
res.~ 3 arcmin**

**Galactic
– source: 30
km³ detector**

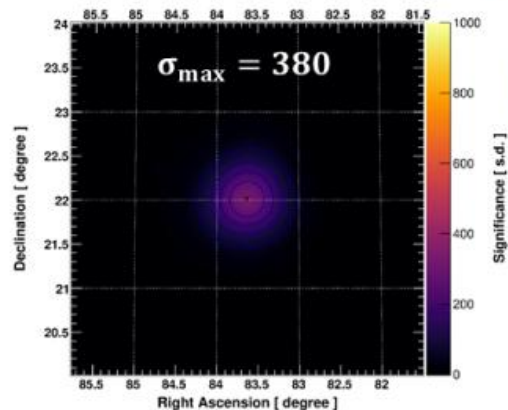
AI helps to enhance the discovery power

WCDA was designed with 13 mCU $\longrightarrow$ 5 mCU

KM2A angular res. $\sim 0.36^\circ \longrightarrow 0.27^\circ$

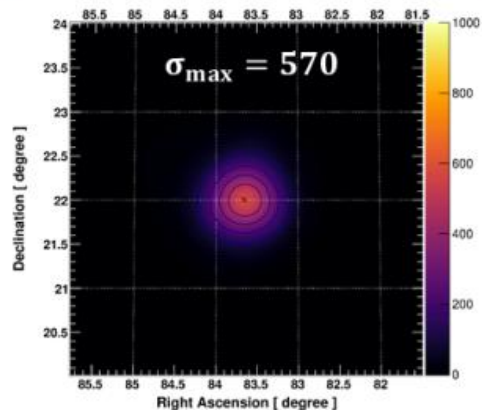


Classification

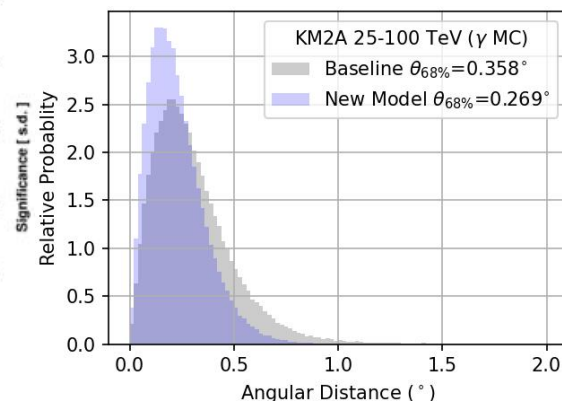
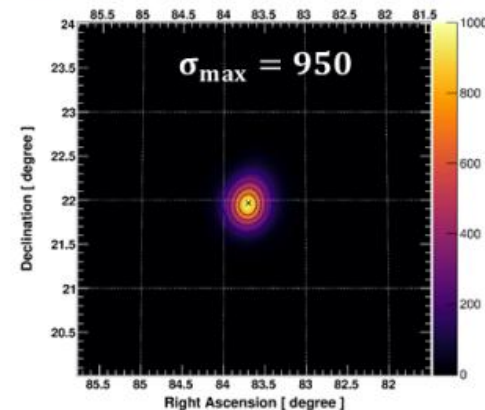


1.5 $\times$

Reconstruction



1.7 $\times$



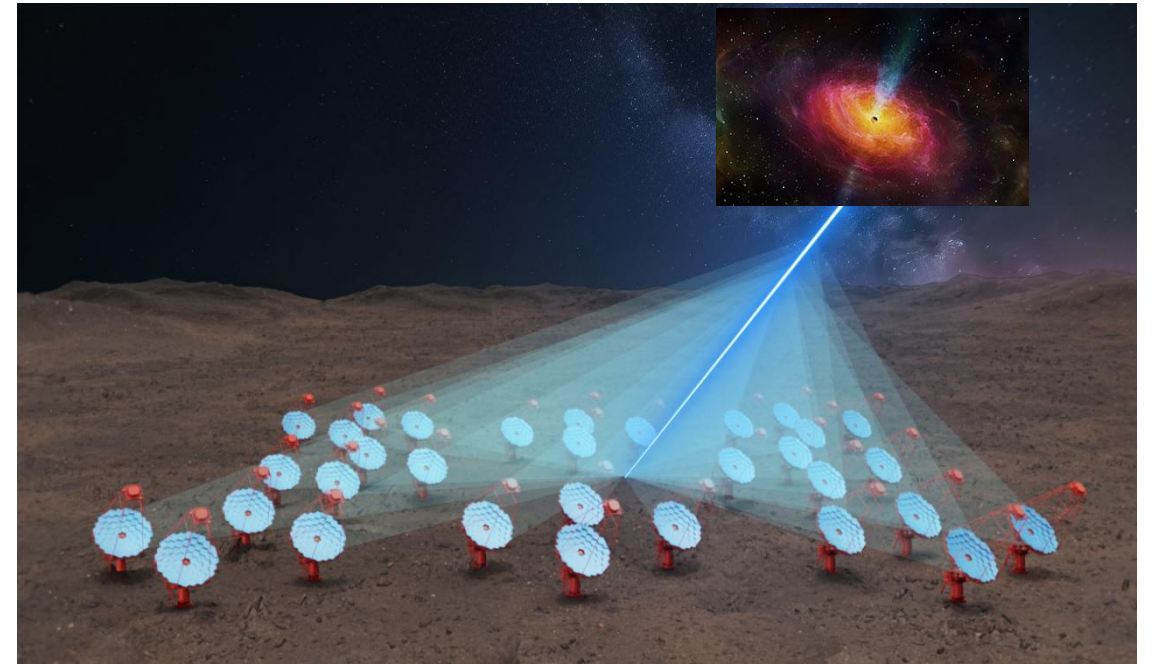
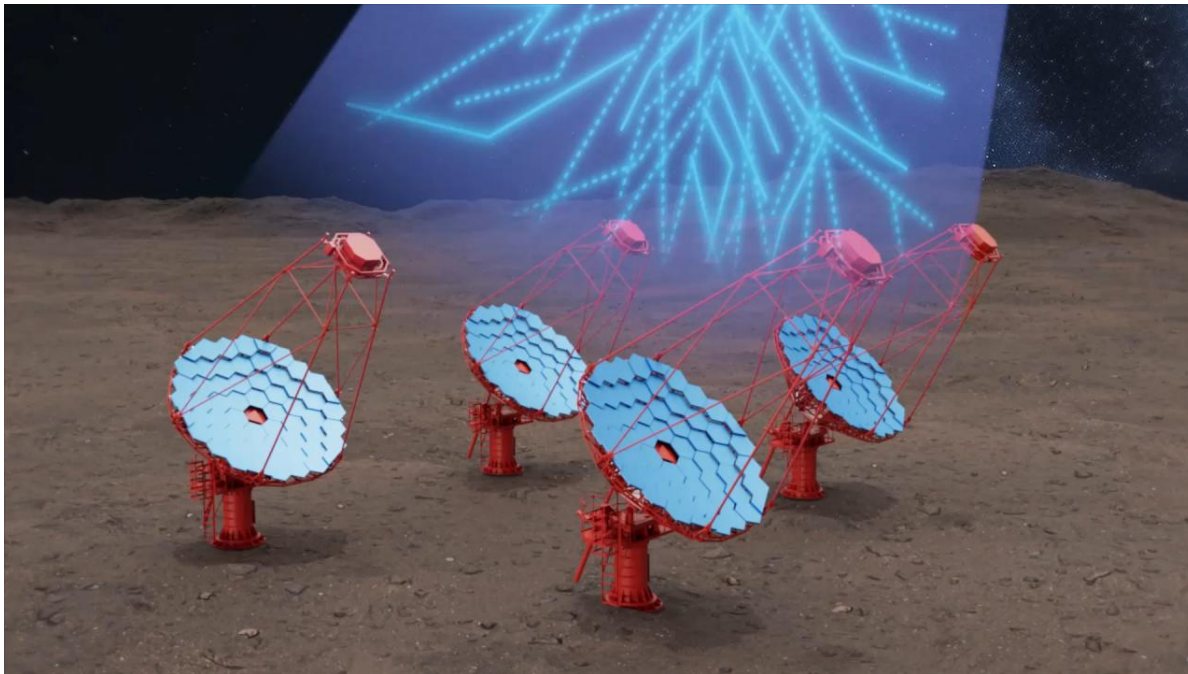
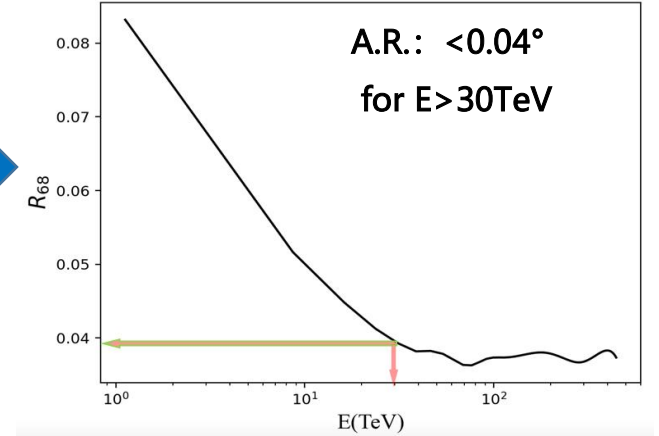
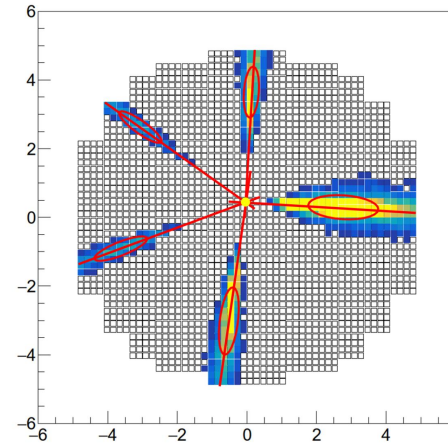
LACT (36 MST) as the upgrading of LHAASO

➤ Stereo measurement of Cherenkov image

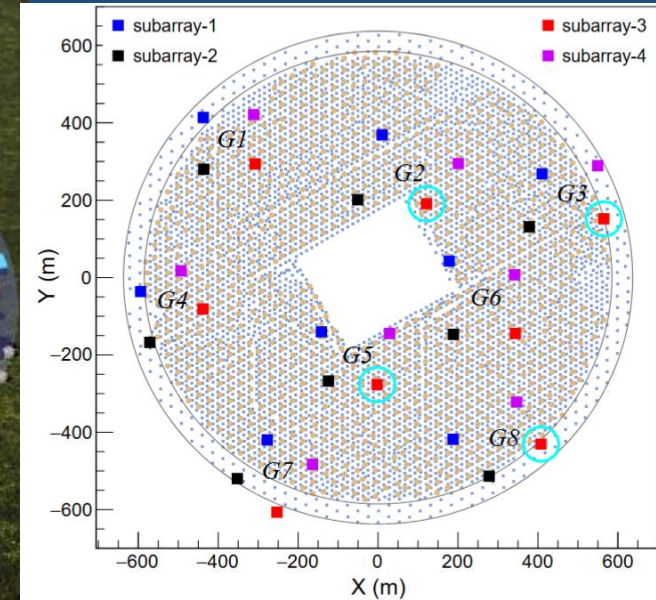
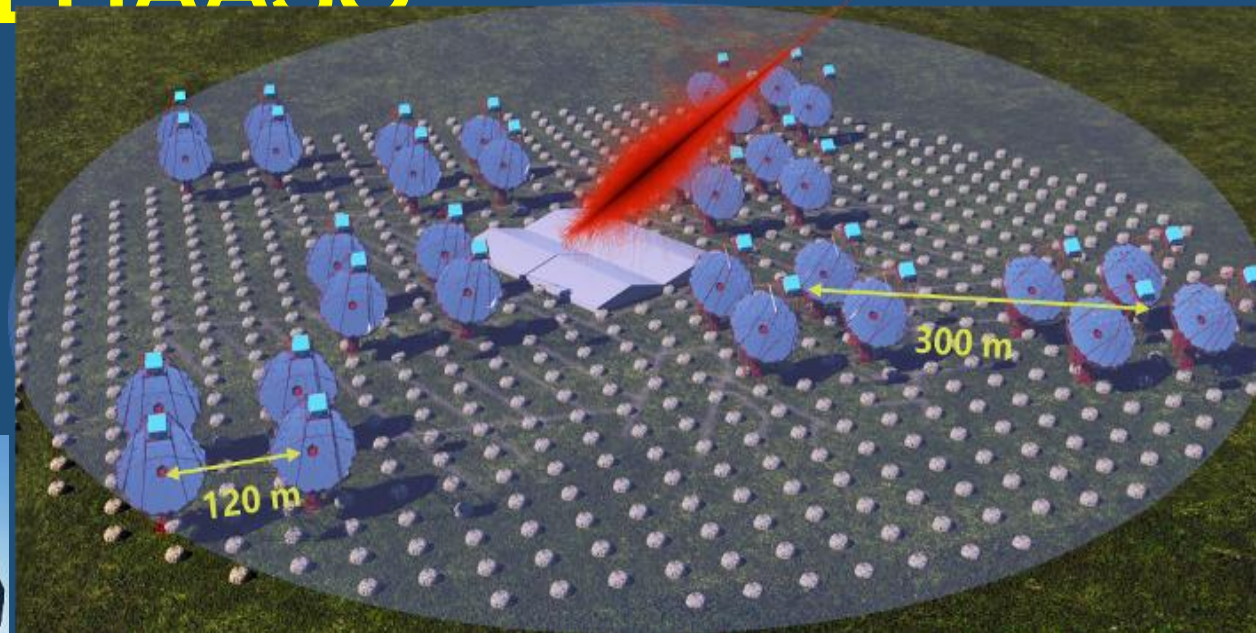
- ❑ At least 4 telescopes simultaneously

➤ Reconstruction

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



LACT : an IACT array in LHAASO

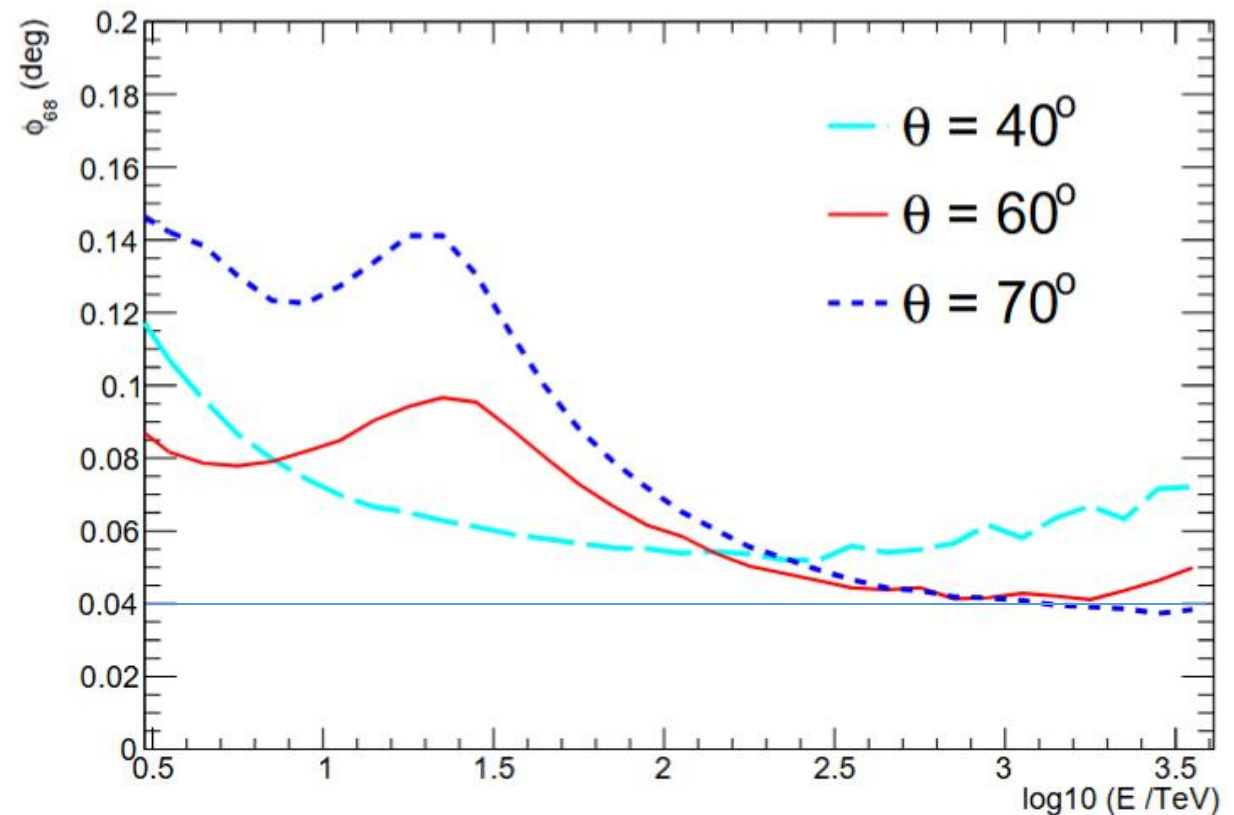
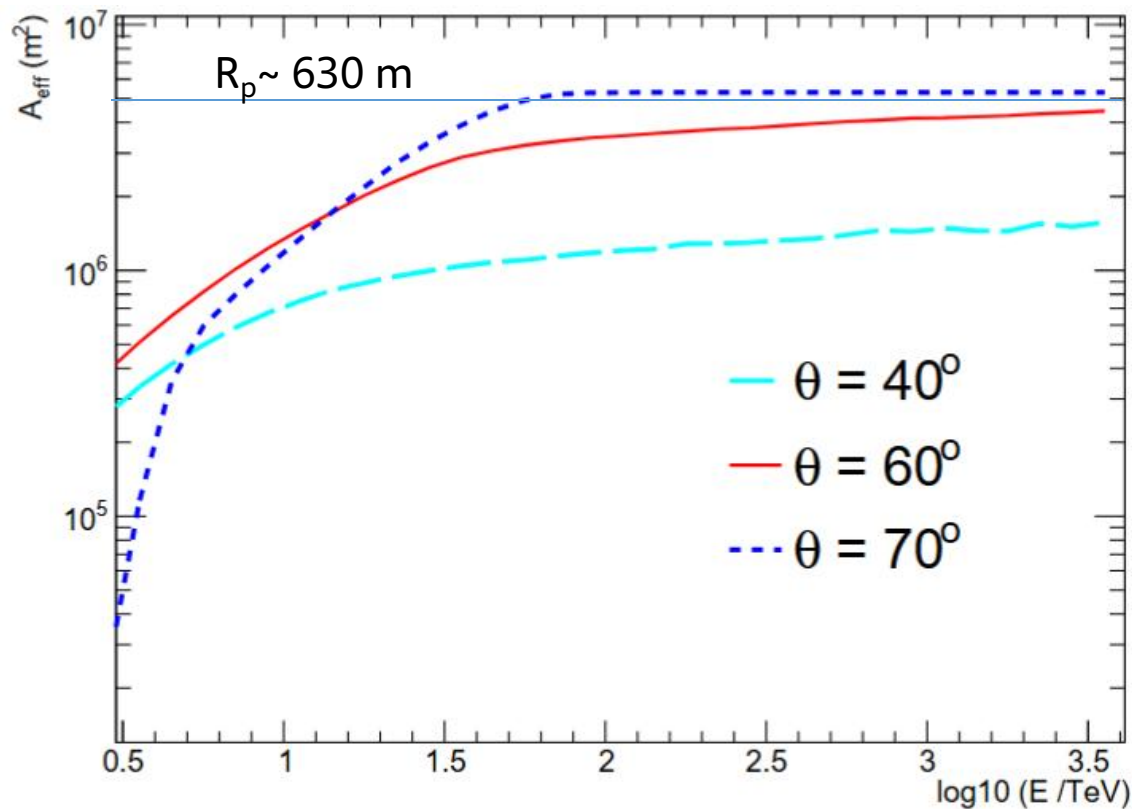


- Funded
- 8X4 array at LHAASO site
- 6-m telescopes
- two proto type telescopes
- First light soon in this



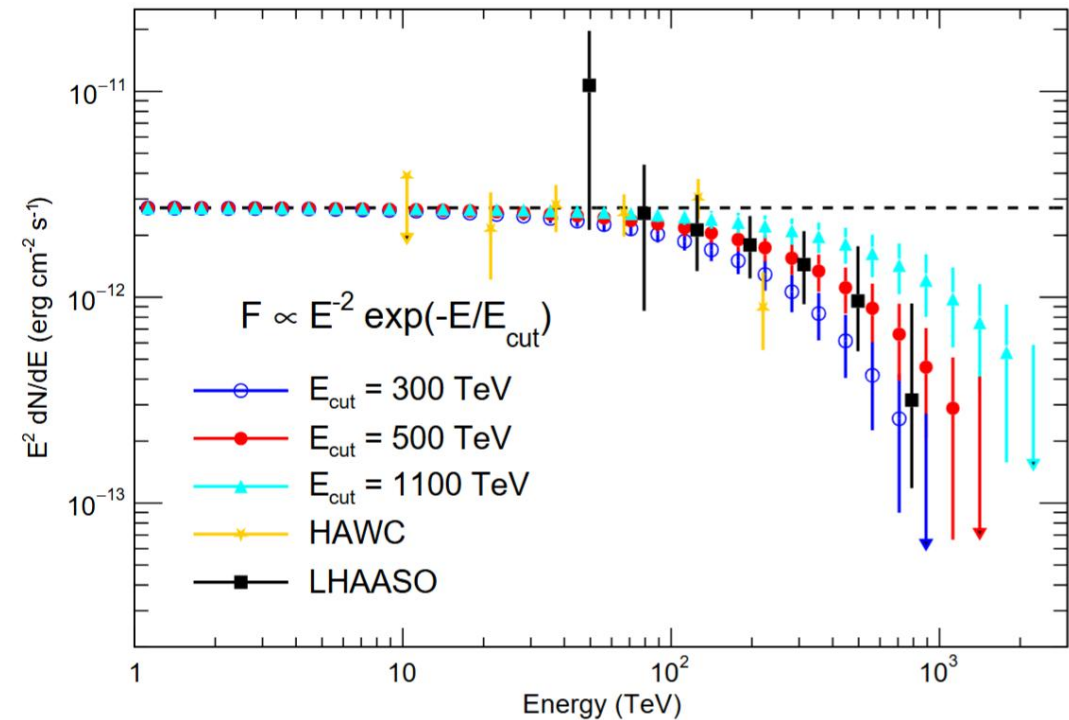
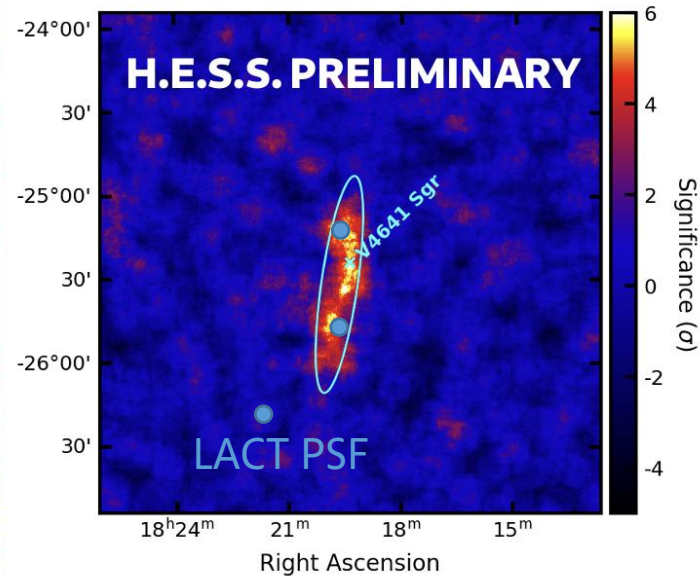
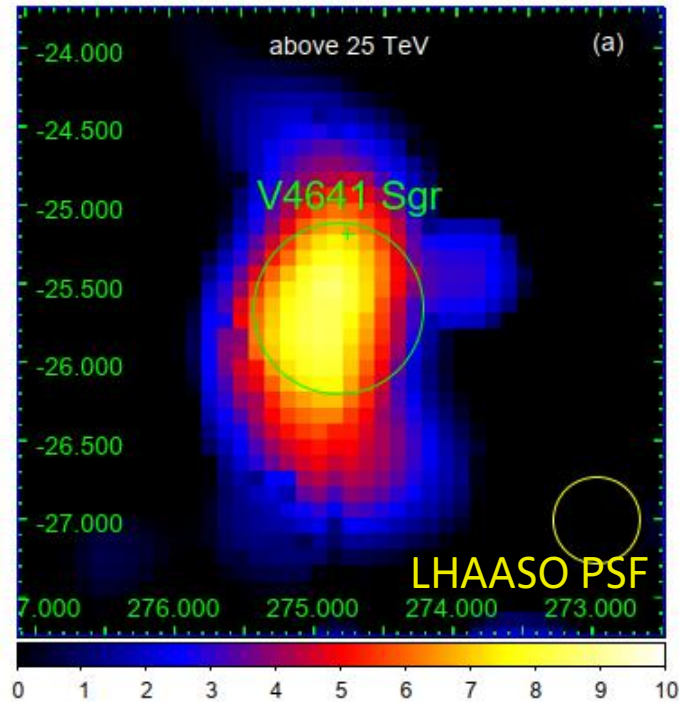
4 Telescope Array Performance

- Effective area for small elevation targets
- Angular resolution

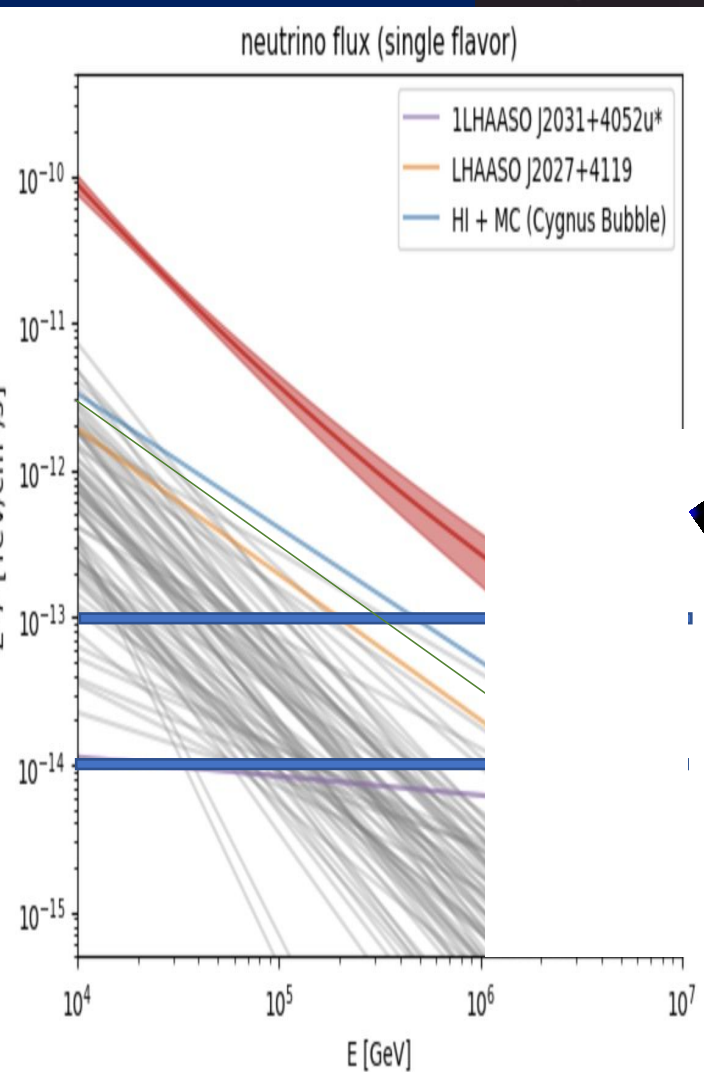


Jet Termination vs central accelerator

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



Guaranteed ν -sources in our galaxy



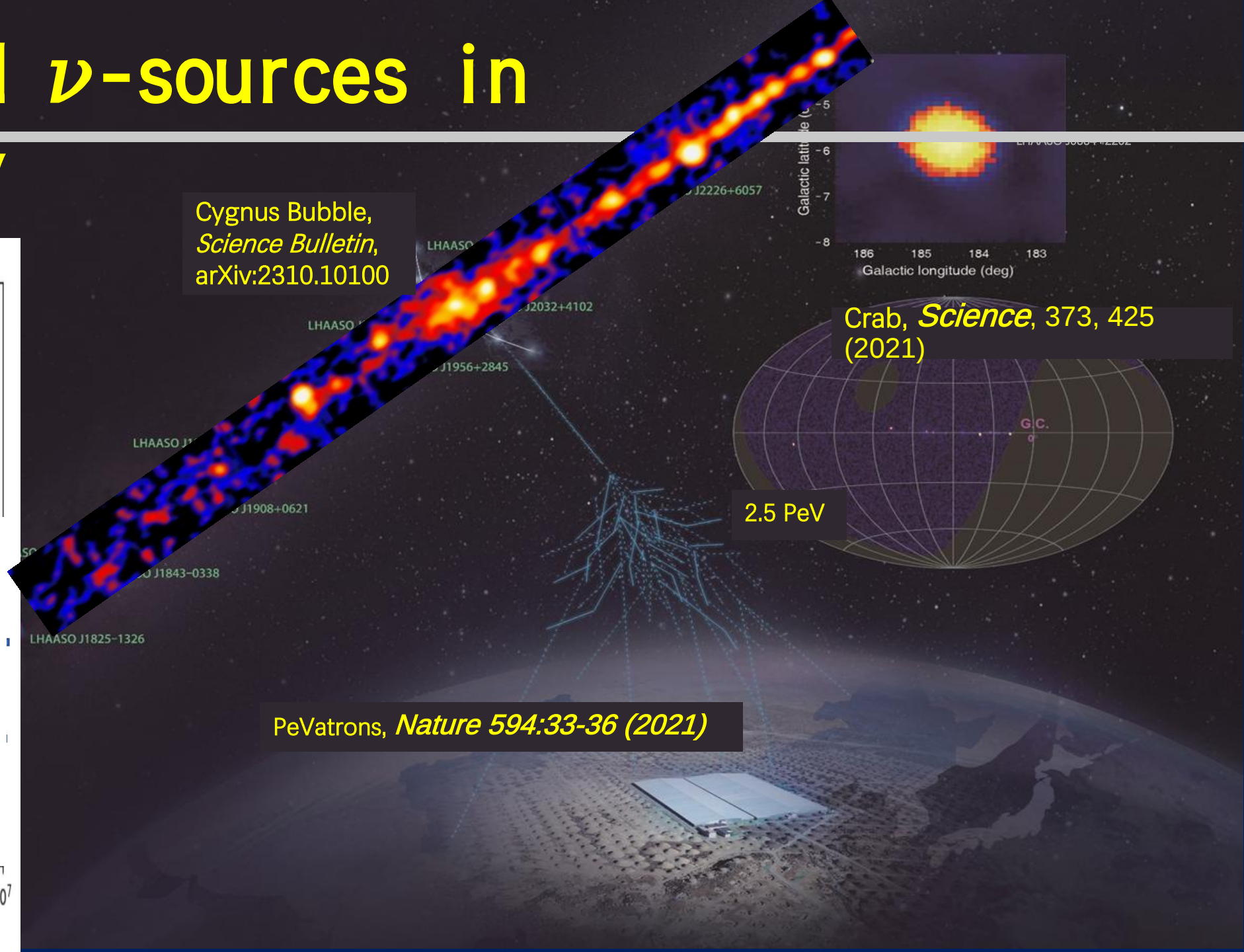
Cygnus Bubble,
Science Bulletin,
arXiv:2310.10100



Crab, *Science*, 373, 425
(2021)

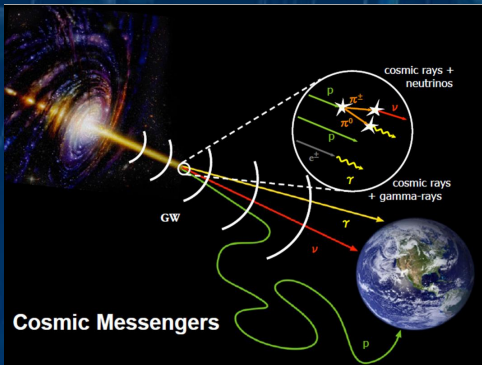
2.5 PeV

PeVatrons, *Nature* 594:33-36 (2021)



High-energy Underwater Neutrino Telescope

H U N T



36 m

- Resolution $\sim 0.1^\circ$ (tracks), $< 3^\circ$ (cascades)
- Energy resolution: $\Delta \log E \sim 0.3$ (tracks)
 $\Delta E \sim 10-30\%$
(cascades).

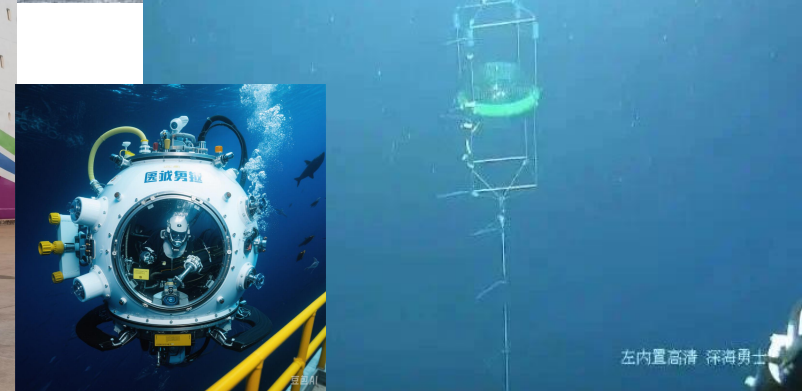
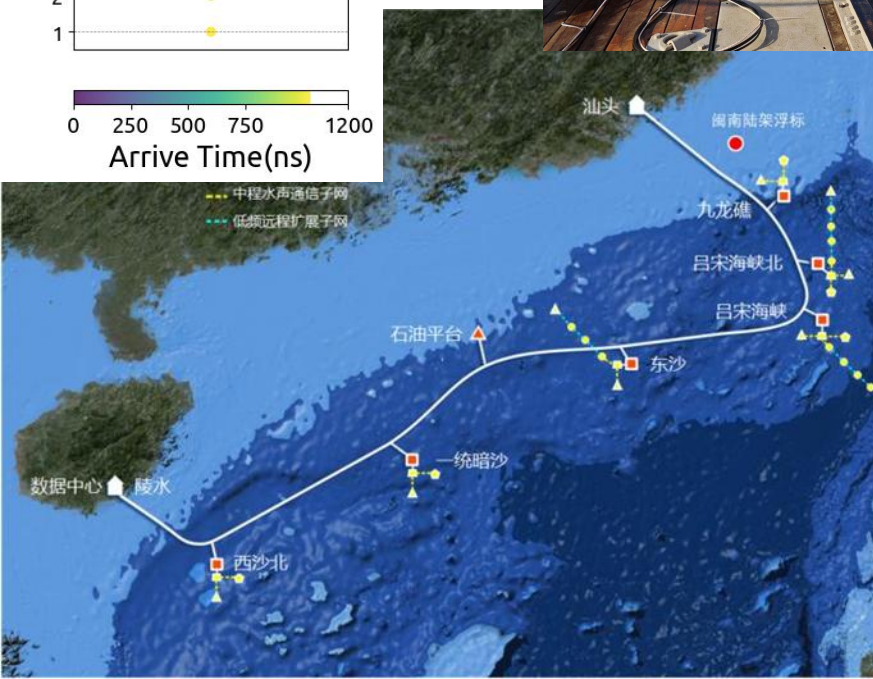
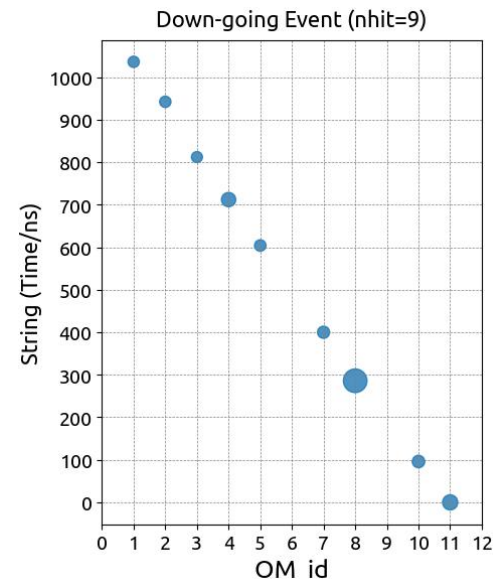
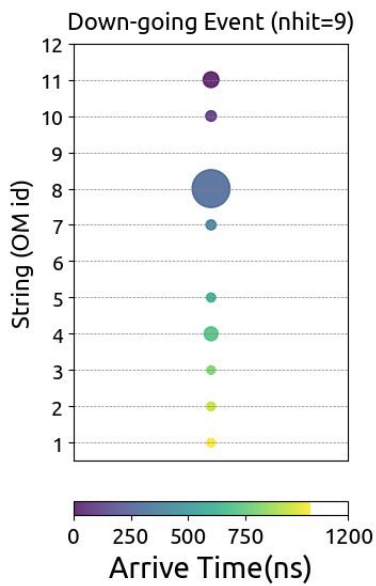
- Discovering Neu sources (> 100 TeV) at

- Volume: $6 \times 6 = 36 \text{ km}^2$, **$\sim 30 \text{ km}^3$**
- Separations of strings: $D_{\text{string}} \sim 130 \text{ m}$
- Separation of optical modules : DOM $\sim 36 \text{ m}$
- Length of each string: $\sim 860 \text{ m}$
- $\sim 2,300$ strings, 24 OM in each string, 55000 OM in total

130 m

Prototype tests at GVD at L. Baikal

and in South China sea



Summary



- Proton spectrum is measured for the first time with a 90% purity sample
- The “knee” is actually a new **component** which naturally associated with Super-PeVatrons
- **SNRs are extensively studied as the cosmic ray sources & escaping is found clearly**
- $E_{\max}$ is an unavoidable issue
- unveiled the new CR accelerator population for the
- Cosmic Ray Super-PeVatron is found among the BH+jet systems and PWNe
- In future, the improved **spatial resolution** enables a deeper investigation for the very interesting extended sources revealing Super-PeVatrons
- **30 km³** neutrino detector is really necessary for confirming those (super-PeVatrons) to be galactic CR sources. Prototyping is going on at sites in L. Baikal and South China Sea