LHAASO，拉索，@2021-08

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

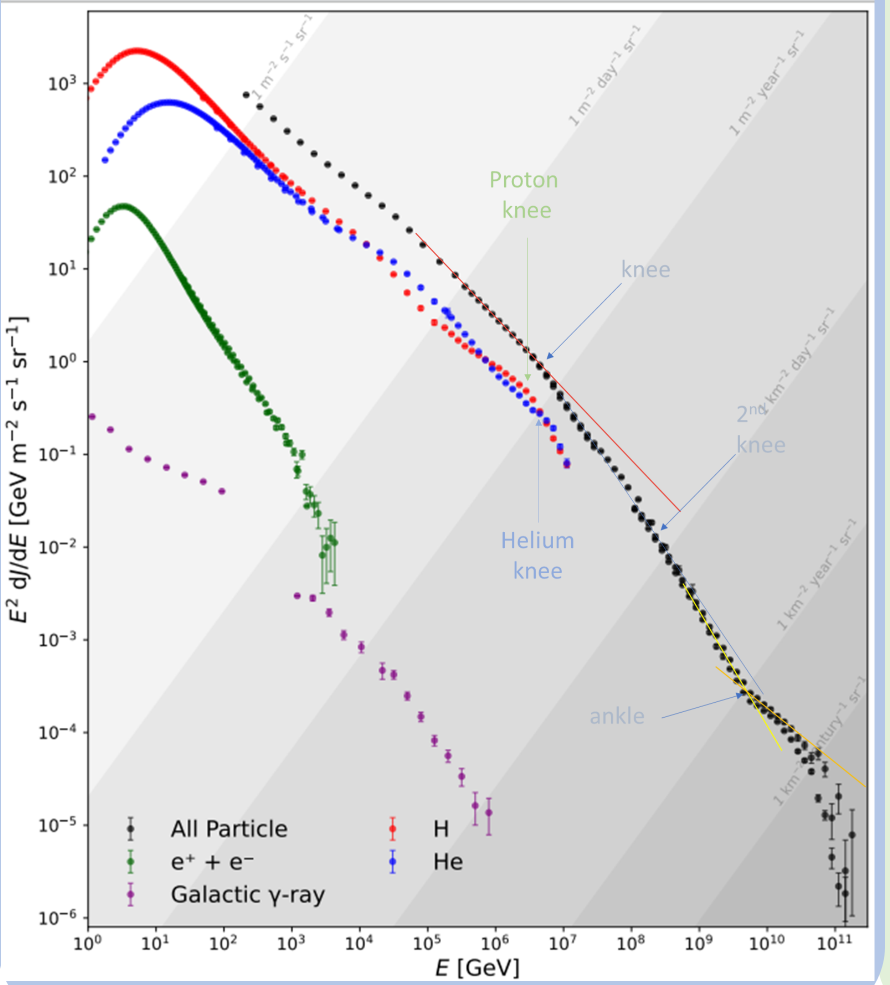
Cosmic Rays, SNRs & μ-Quasars in LHAASO’s View

by Zhen Cao 曹臻, IHEP, CRRC, China

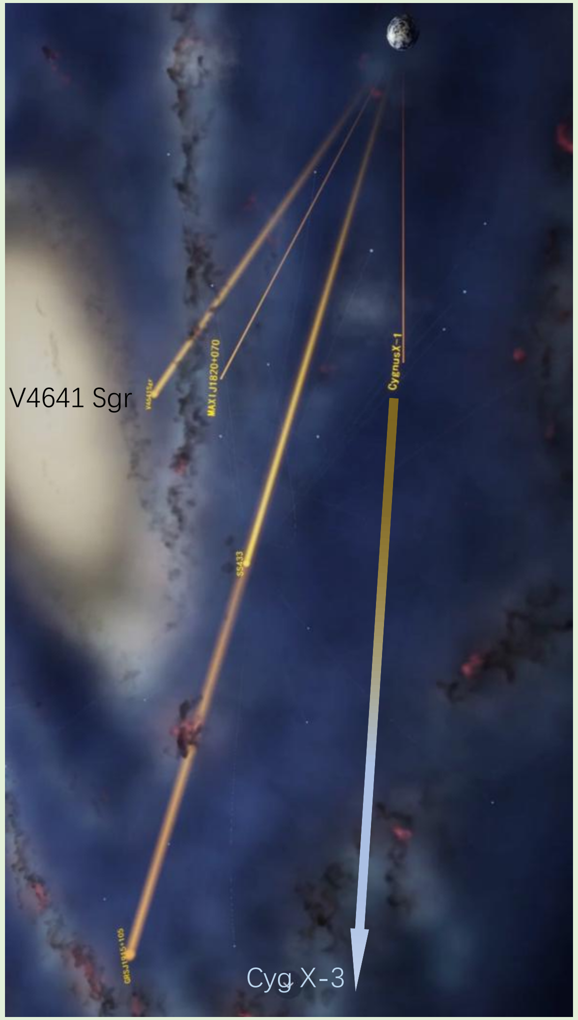
17th FCPPL Workshop, Lyon, France, 2026-06/07

LHAASO has done tree important measurements

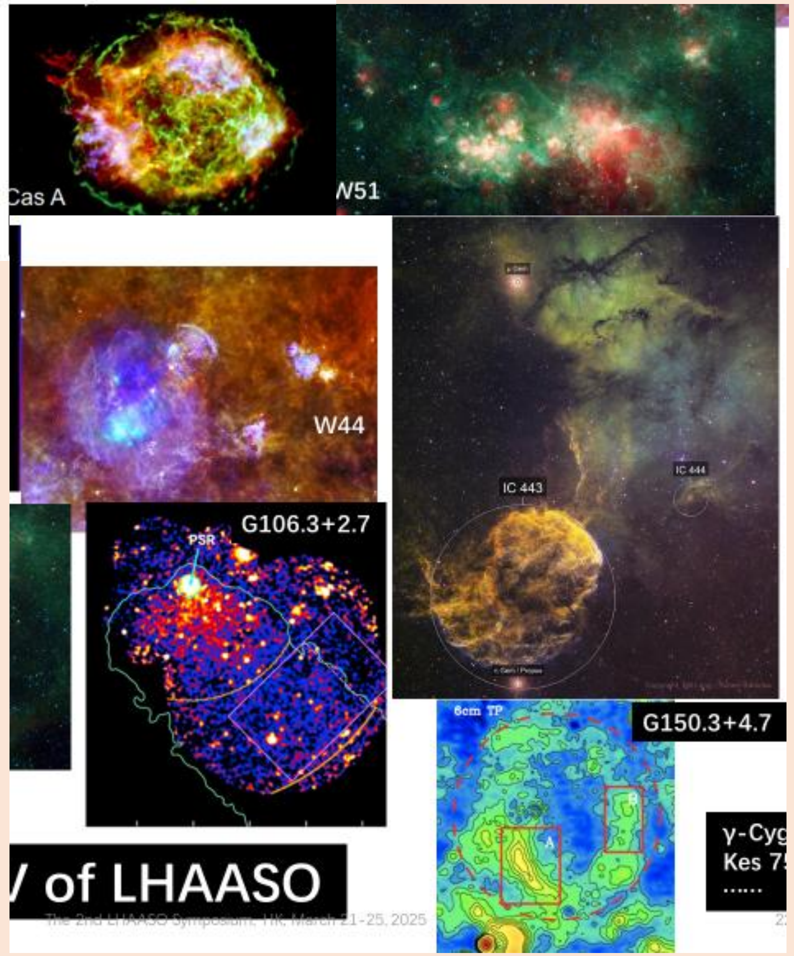
1. Measures knees of CR H & He



2. Discovers μQs being UHE emitters

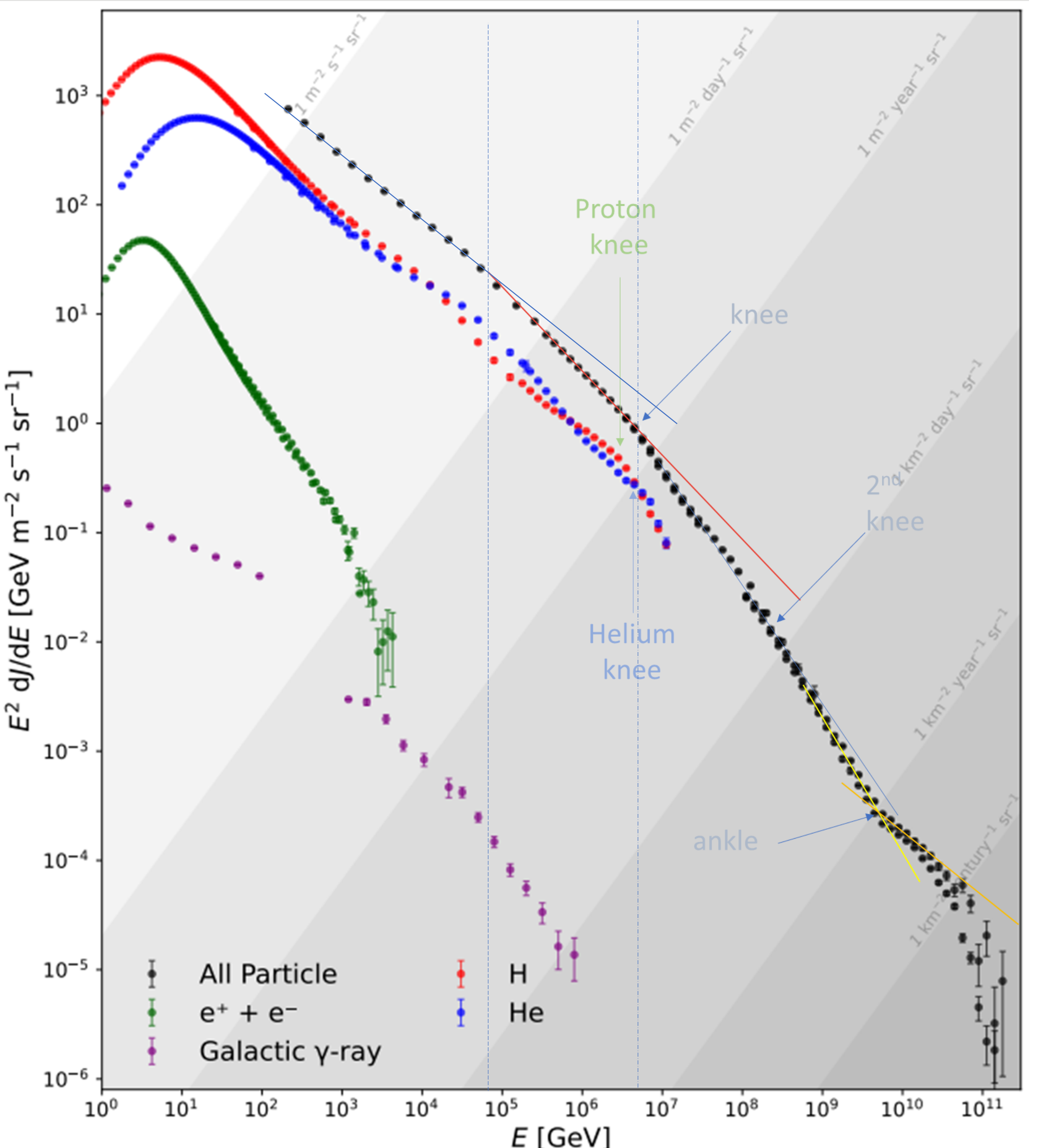


3. Observes SNRs in VHE band



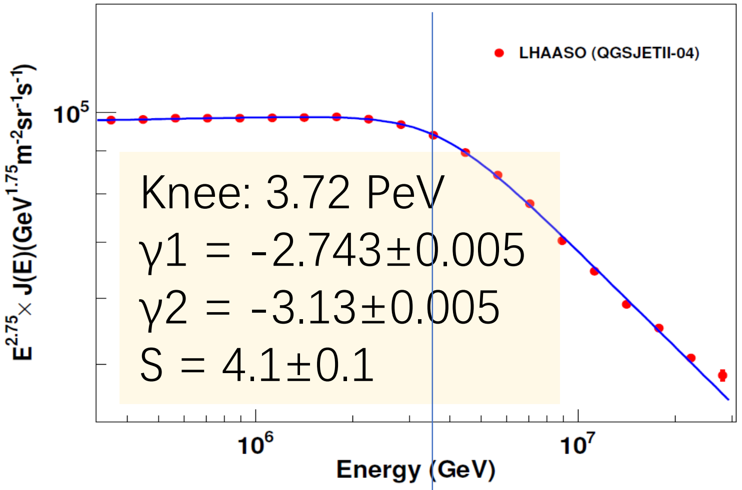
Content

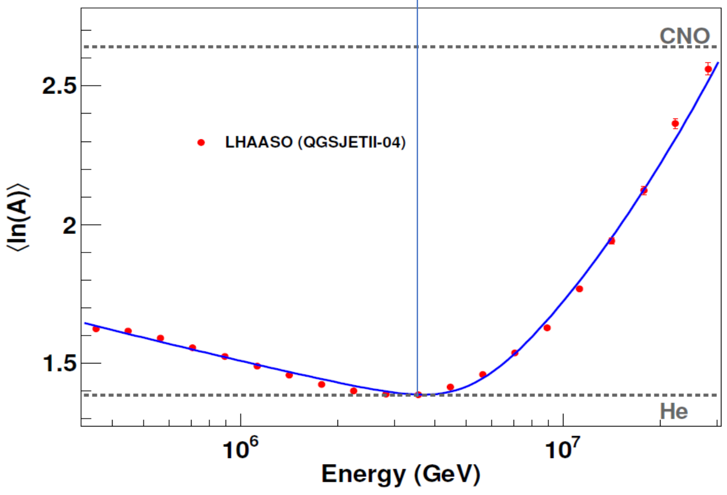
- CR measured at the solar system
- Supernova Remnants as the sources of the VHE-component
- μ-Quasars and the PeVatron-component
- Future expectations
- Summary

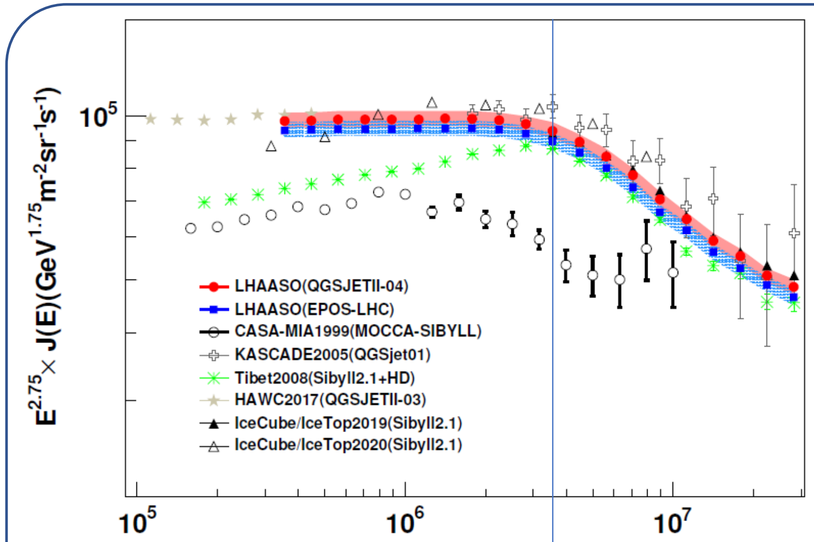


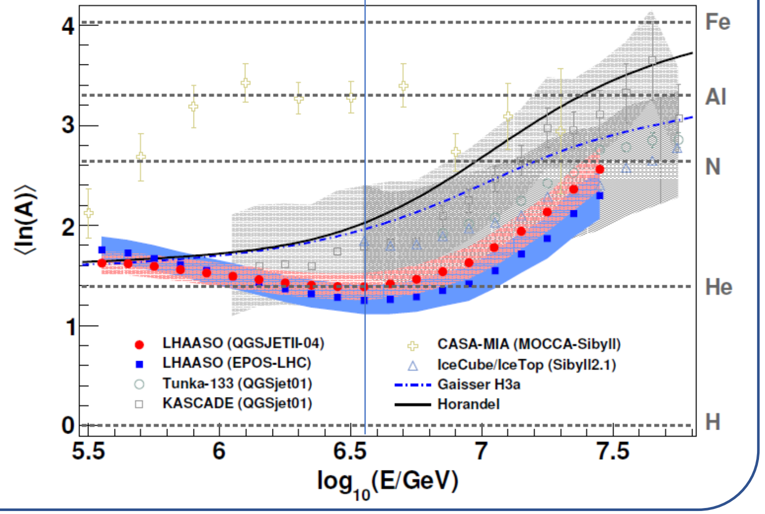
All-particle energy spectrum & composition by LHAASO

(from 0.3 to 30 PeV)





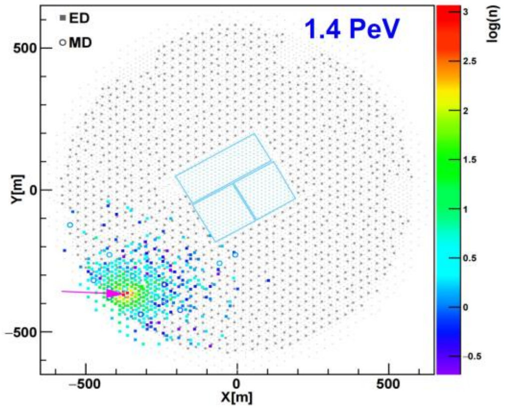


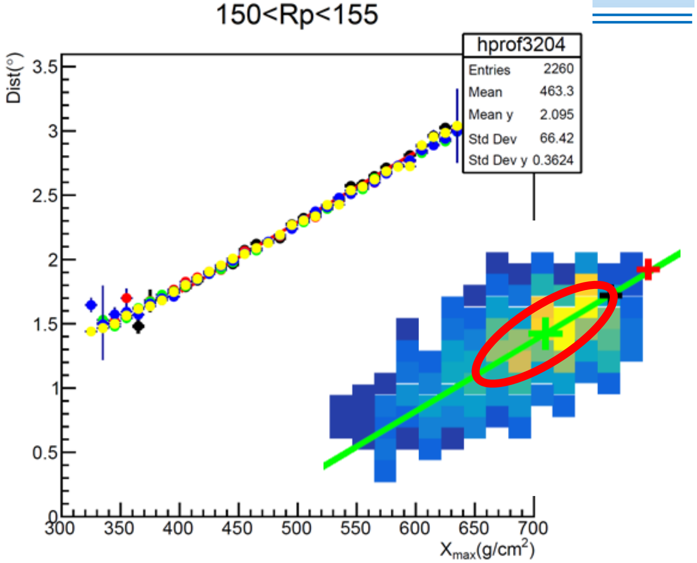


- Systematic uncertainties are sufficiently small
- This unveils a clear correlation between the flux and the composition at the knee

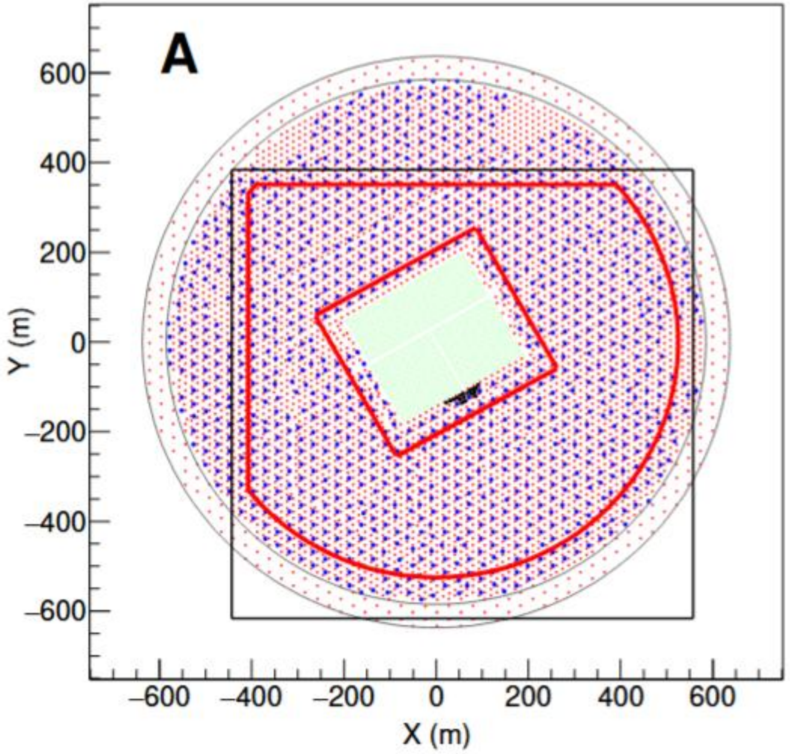
Hybrid Measurement of Cosmic Rays @ knee

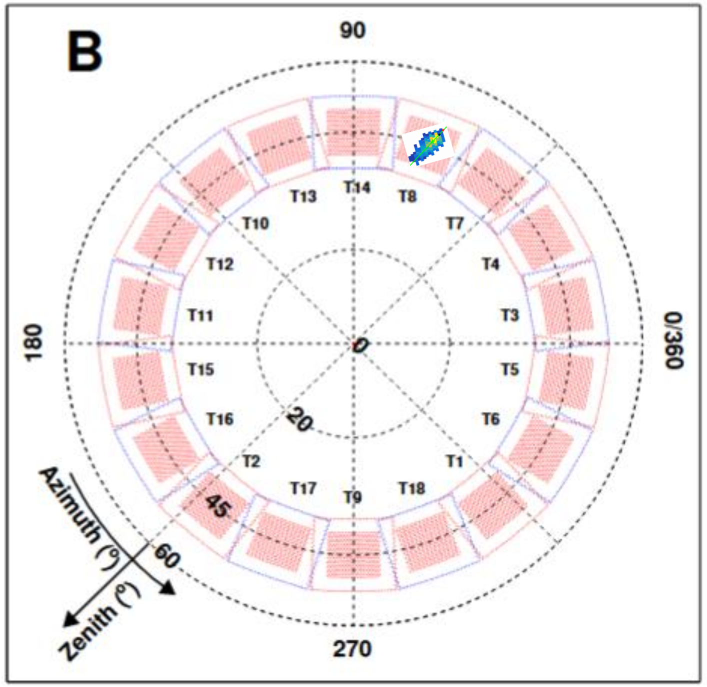
WFCTA: 18





KM2A: (ED, MD, 1 km^2)
ED: 5195
MD: 1188



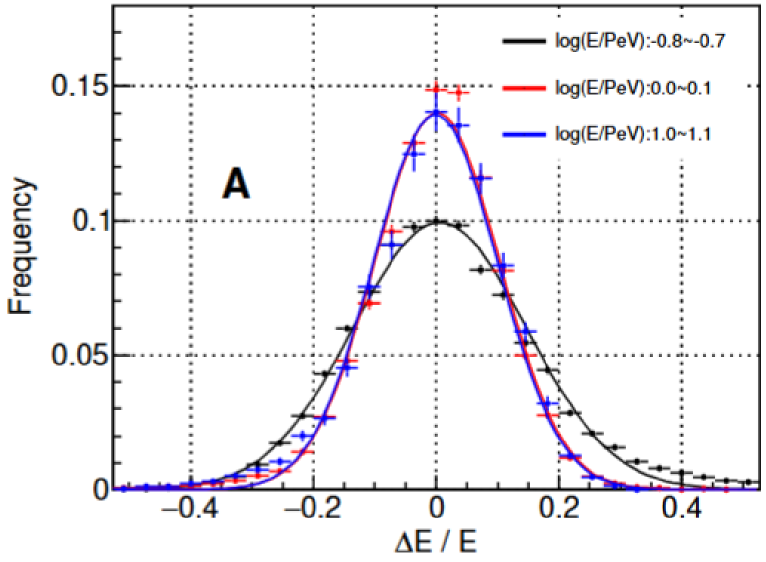


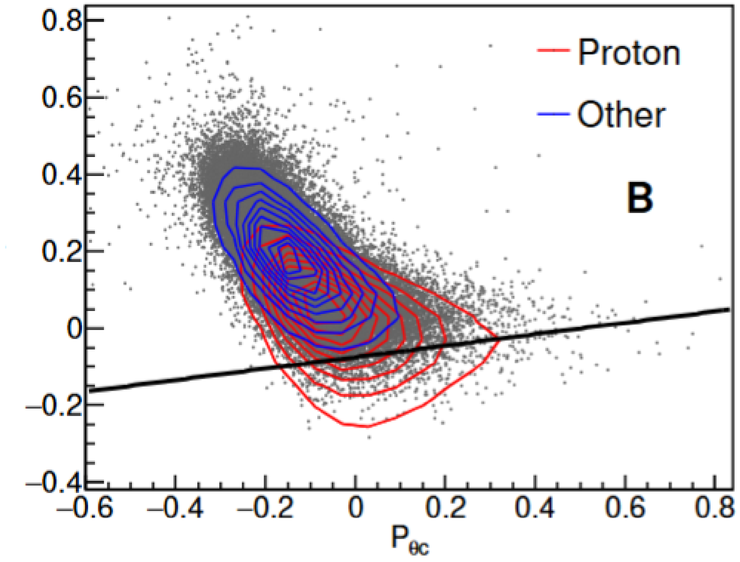
Reconstruction and Proton shower selection

高海拔宇宙线观测站 Large High Altitude Air Shower Observatory

Energy reconstruction

Gaussian energy resolution function

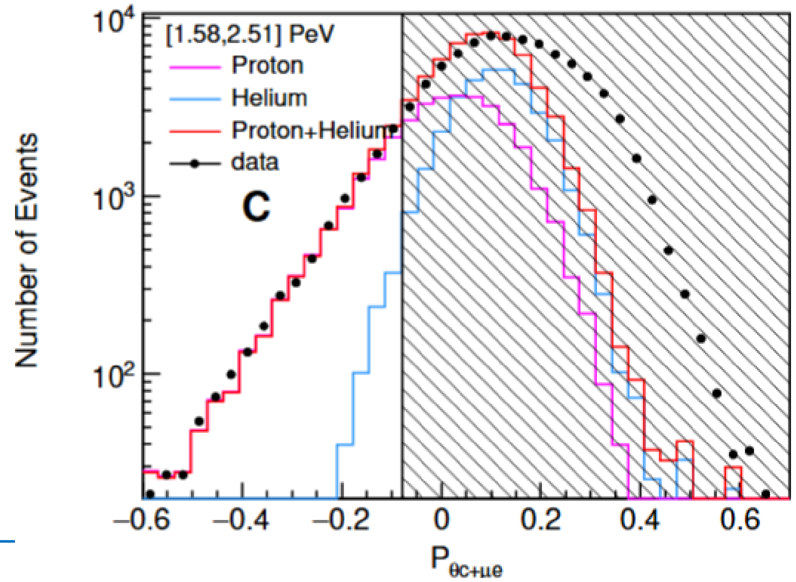


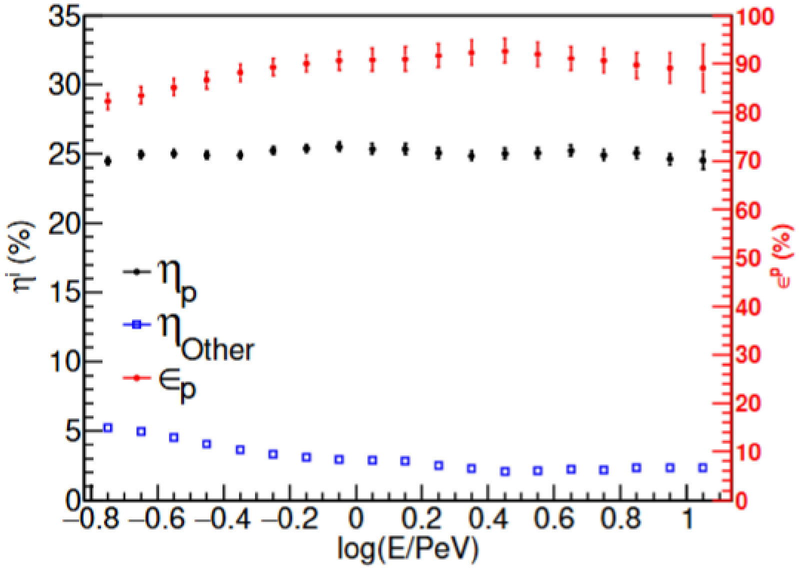


μ-content Vs. Shower maximum depth X_{max}

Combined species-sensitive Parameter Simulated vs data

Parameter





Selection purity & efficiency for protons and other nuclei

Proton spectrum

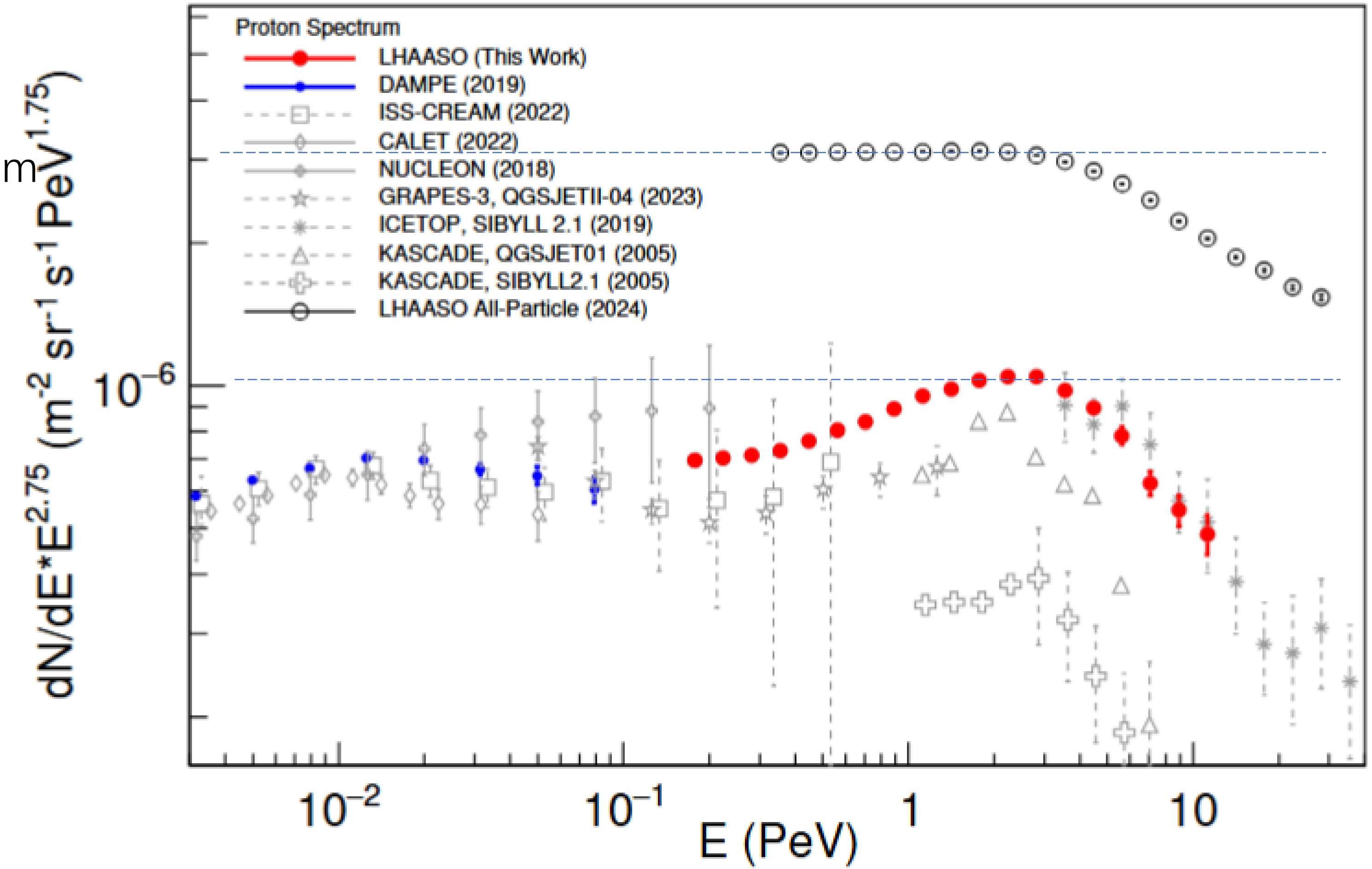
Hardening above 100 TeV

Knee @ knee of all-particle spectrum

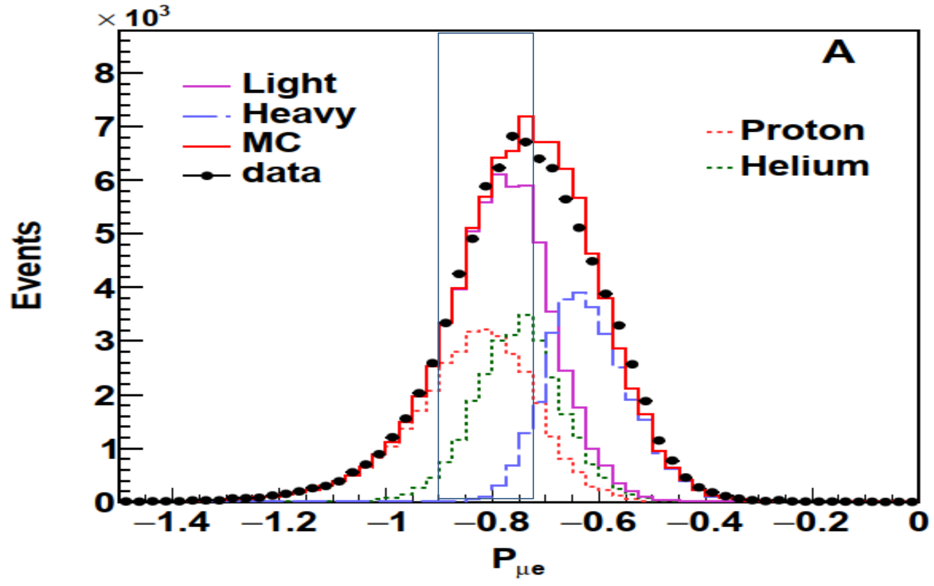
Steeper spectrum than all-particle

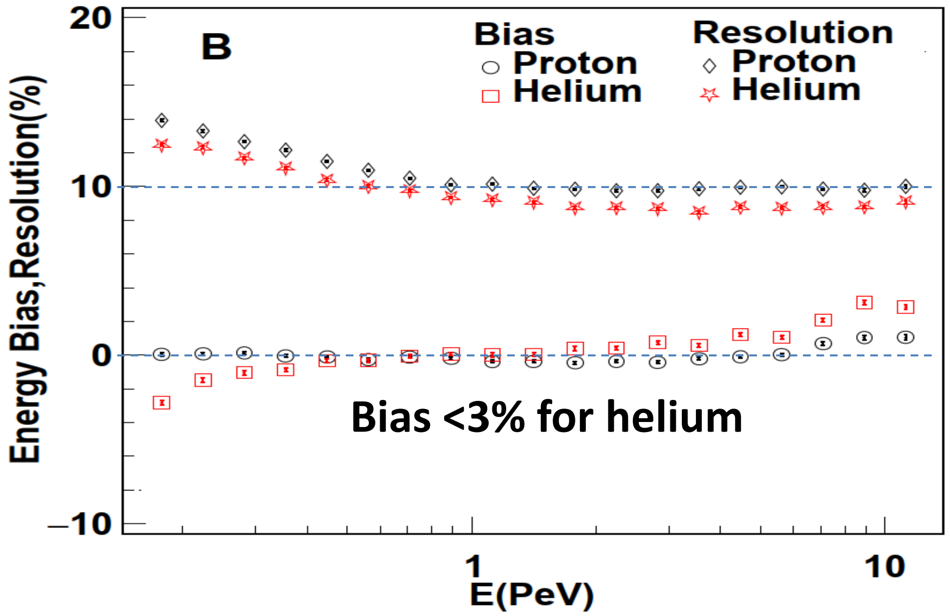
~1/3 fraction

New population of sources?



Light component (H+He) Selection





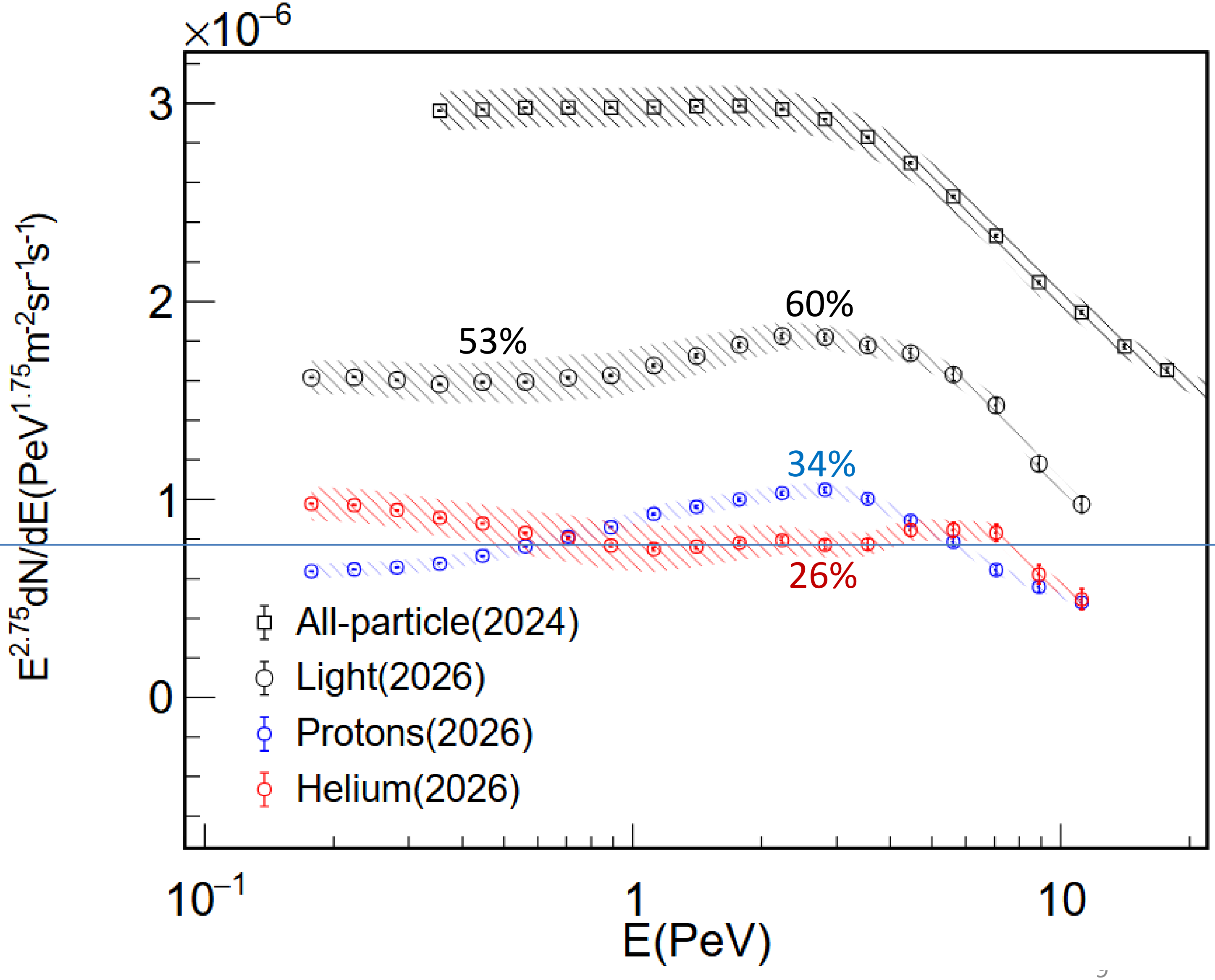
- Helium showers are very similar with proton showers
- it is impossible to separate helium from all other particles event by event

- 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

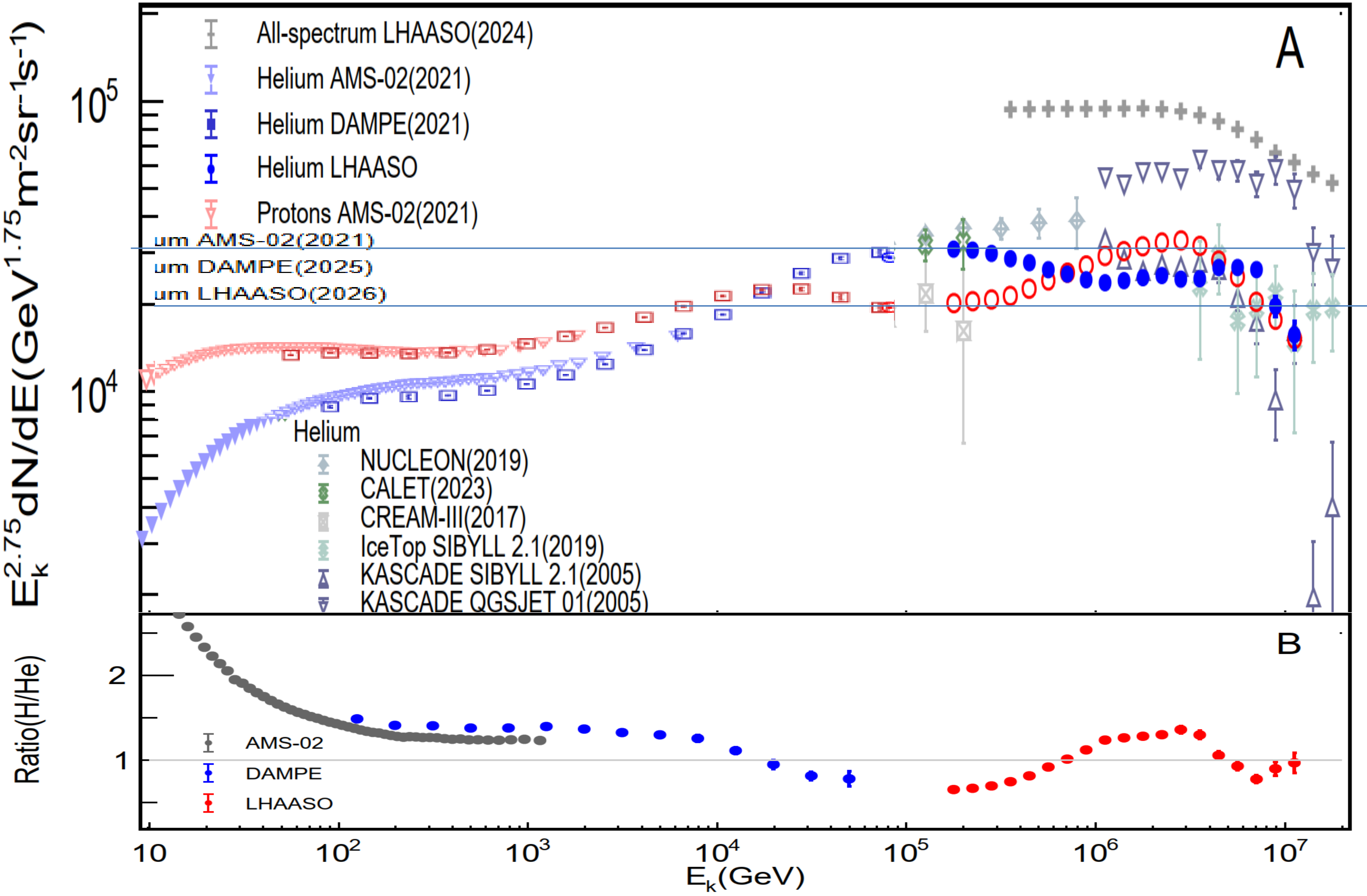
Spectra of Light CRs and Helium Nuclei

- High Precision J_{Light} (E) measurement
- Systematic errors: same sources as proton spectrum
- Inferred J_{helium} (E) = J_{Light} (E) - J_{proton} (E)
  - Clear hardening at 1.05 PeV: >10 σ
  - Knee at 7 PeV: 6 σ
  - Strong deviation from the single index power-law spectrum below 0.3 PeV: > 10 σ
- Iterations on J_{helium} (E) and J_{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 rage from 10 TeV to 10 PeV
- Complex source characteristics and propagation features
  - He-rich ~0.1 PeV
  - P-rich ~3 PeV



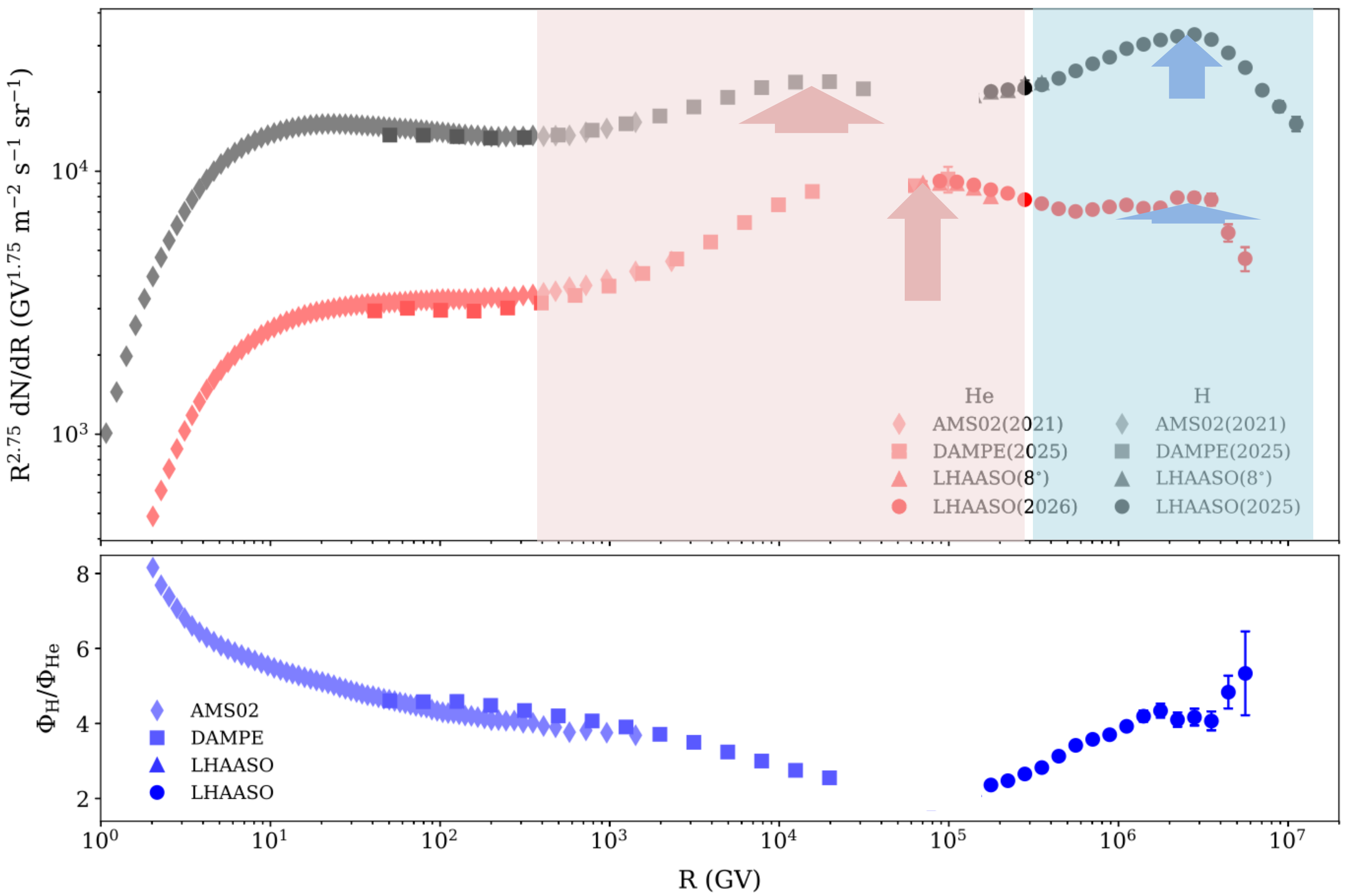
Spectra of Rigidity of protons and helium nuclei

- 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

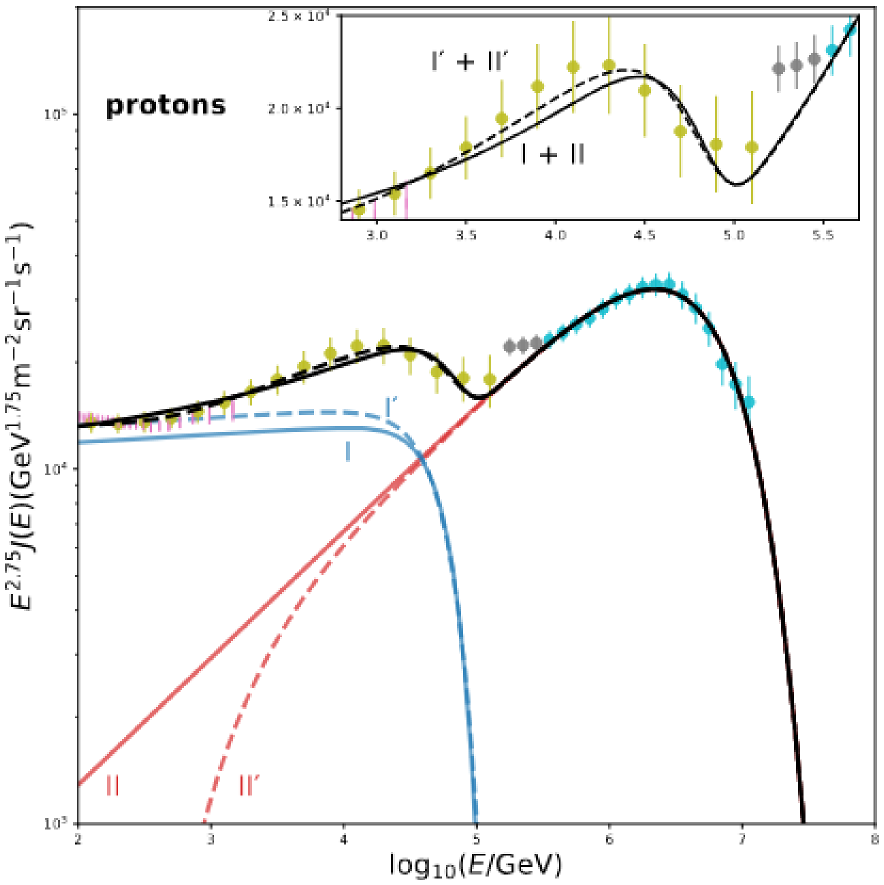
- No perfect rigidity dependence

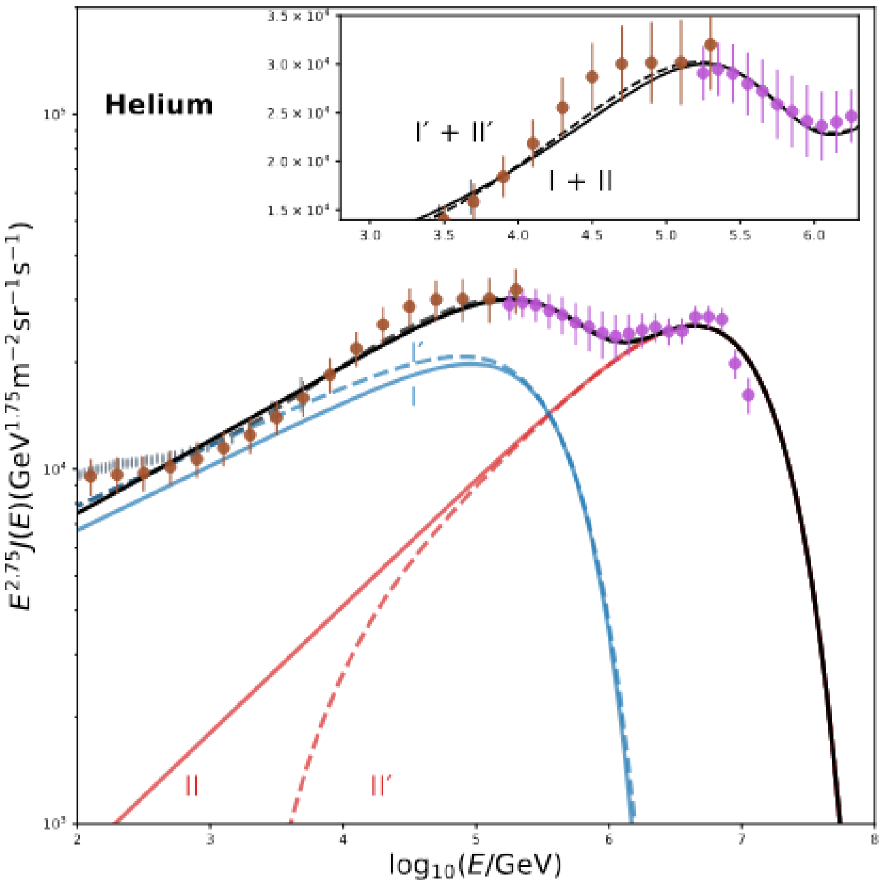


A simple two-component model describes the data reasonably

- PeVatron-component has a rigidity scaling
- Indicating fewer sources in the HE population which have close features in particle acceleration

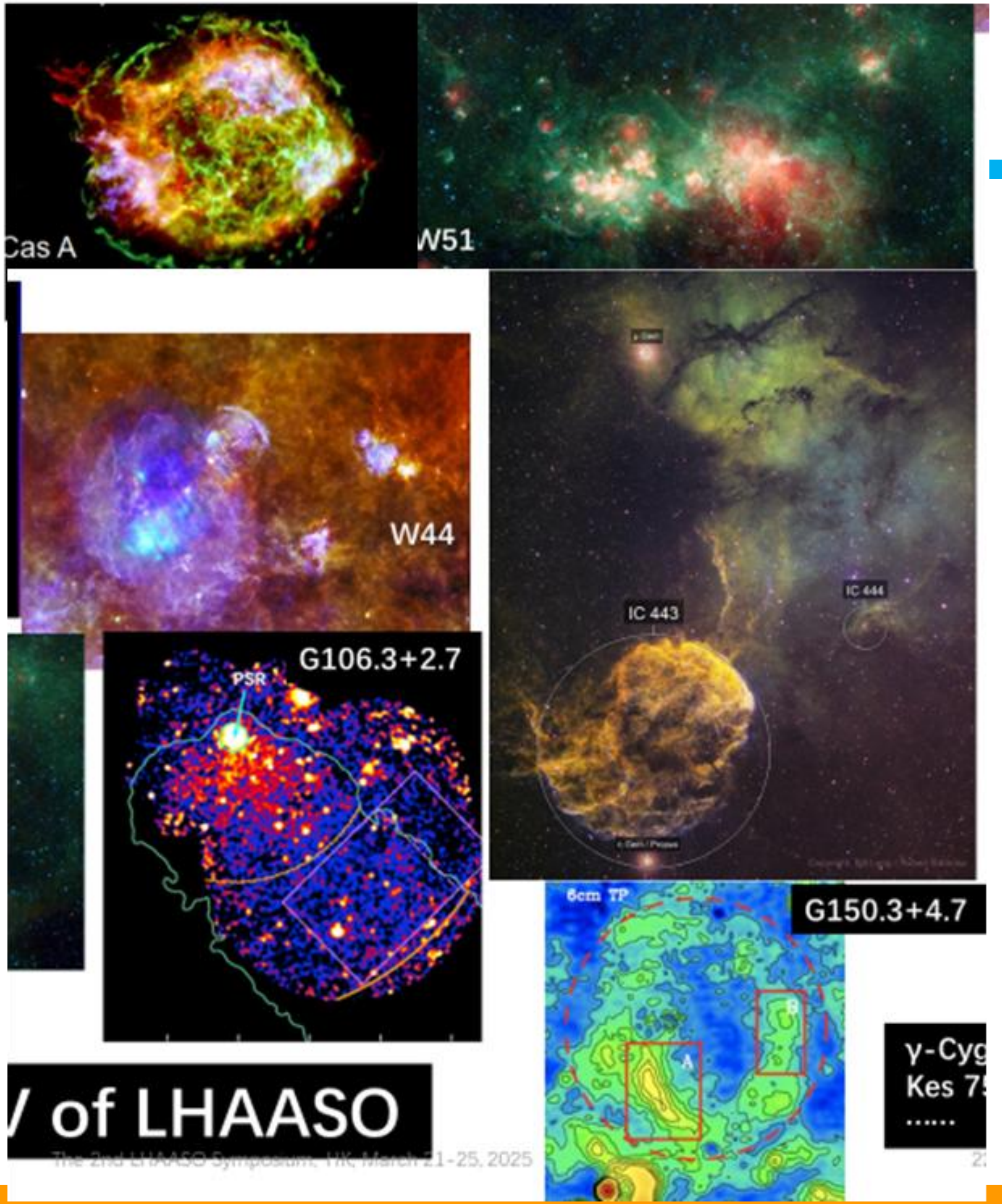
- TeV-component has complete rigidity dependence
- Indicating diversity of acceleration features among the large number of sources in the LE population





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
- Summary



Known for 90 years as a hypothesis ……

- 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.

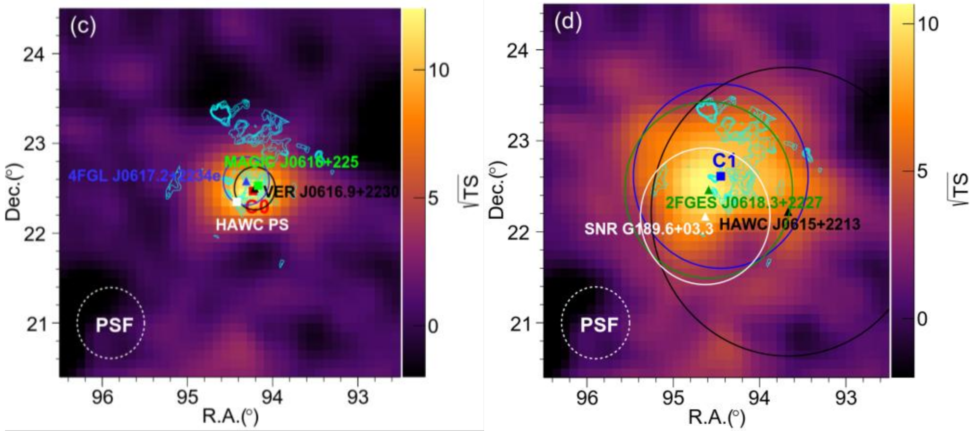
(2) The hypothesis that *super-novae emit cosmic rays* leads to a very satisfactory agreement with some of the major observations on cosmic rays.

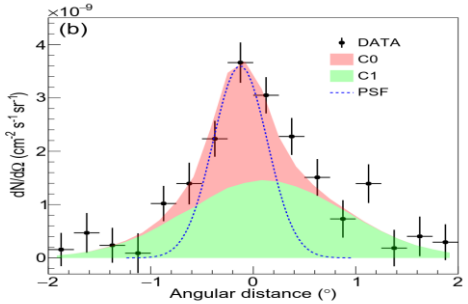
IC 433, W44, W51 in dense medium

- Two sources at IC 443

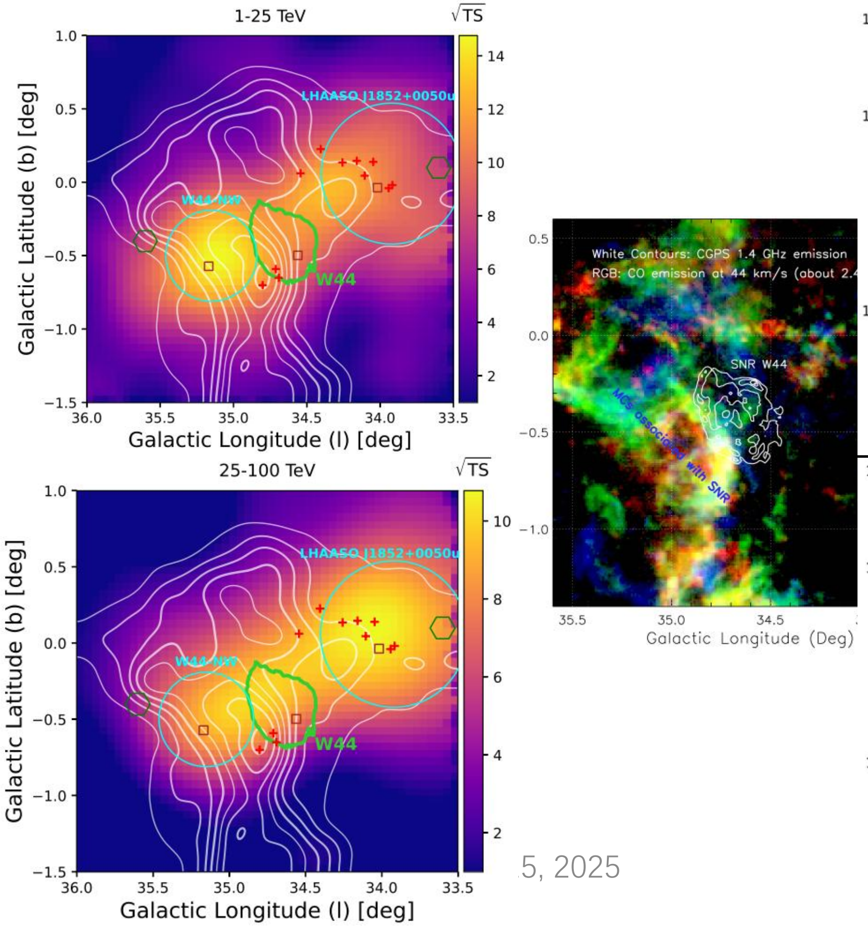
Model	ΔTS	Name	R.A. (°)	Dec. (°)	Extension (°)
Two Components	40	C0	94.24±0.03	22.43±0.02	Pt
		C1	94.40±0.07	22.58±0.06	1.00±0.11
One Component	-	-	94.30±0.03	22.52±0.03	0.58±0.05

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

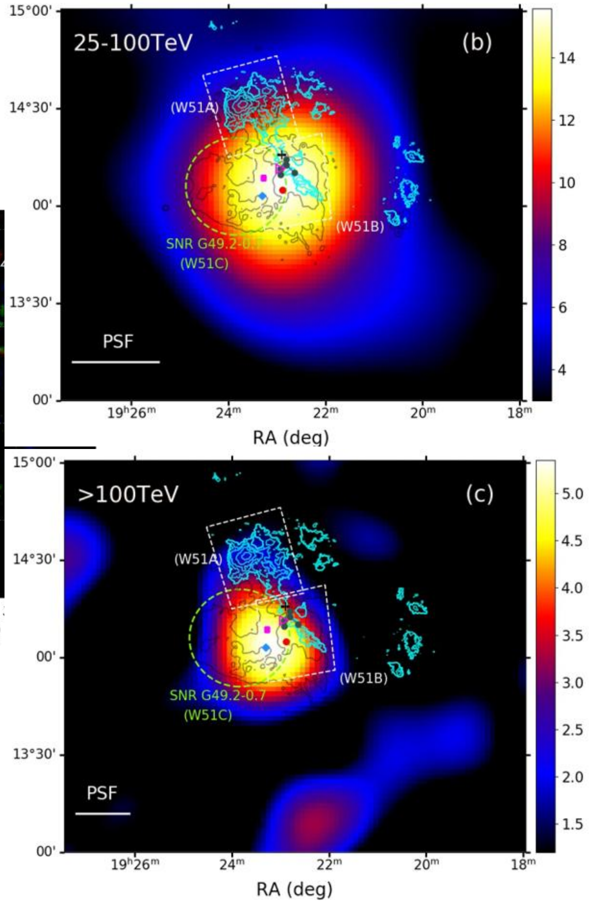




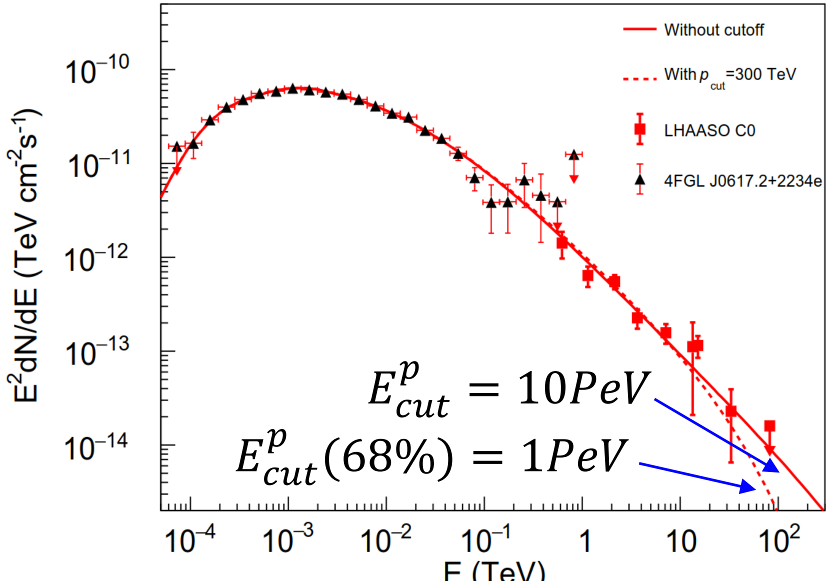
- Shell and escaping at W44

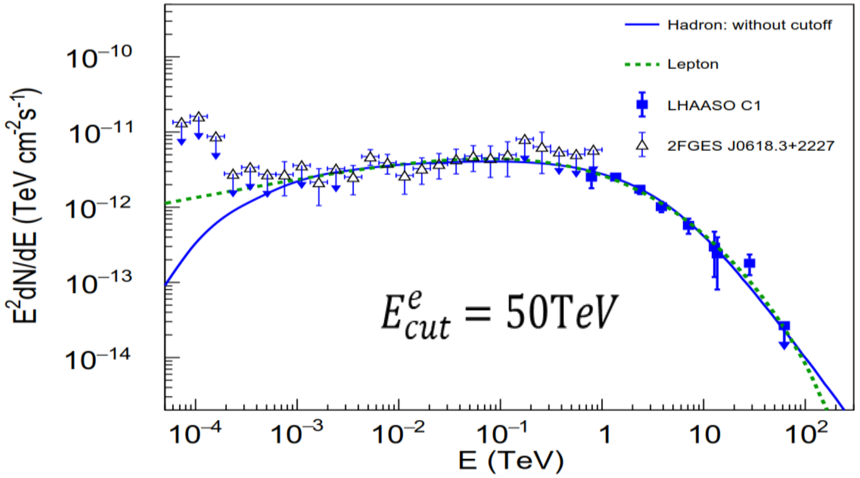


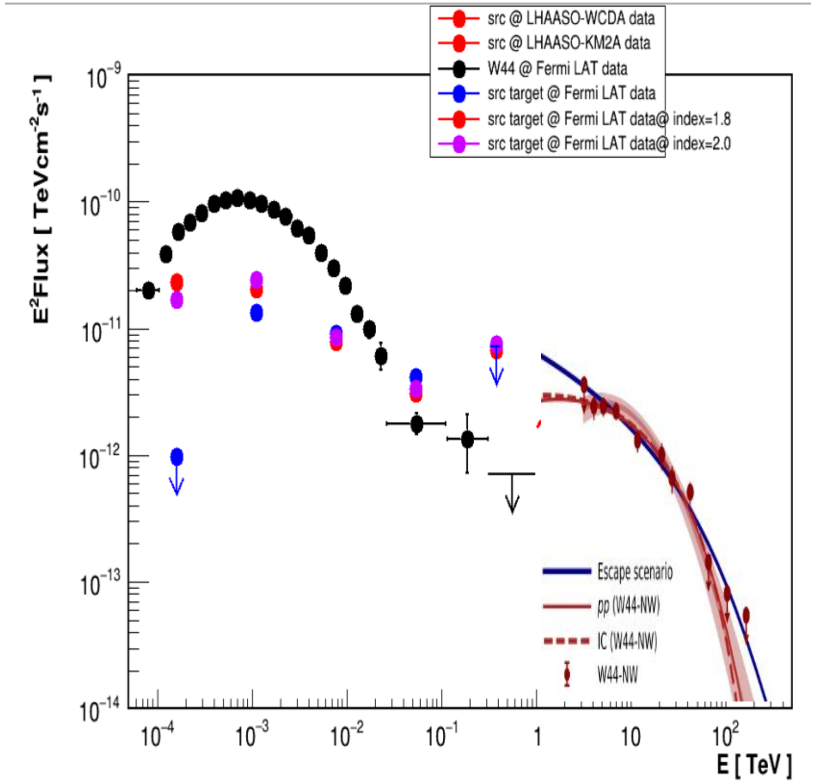
- SNR+MC indicating a PeVatron at W51

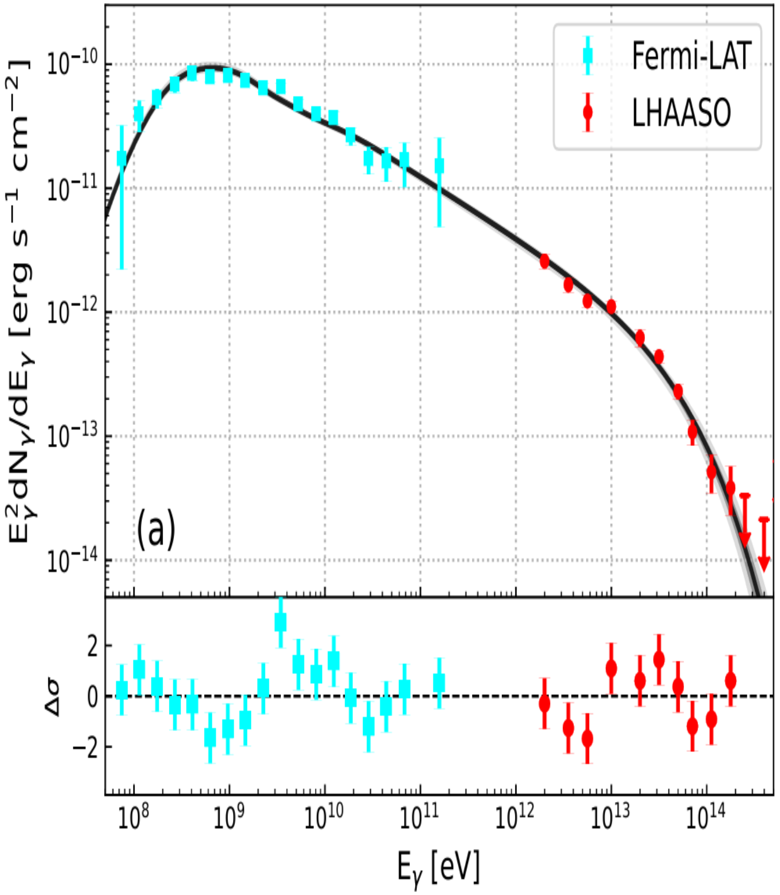


SEDs:


Without cutoff
With p_{cut}=300 TeV
LHAASO C0
4FGL J0617.2+2234e
$E^p_{cut} = 10PeV$
$E^p_{cut}(68\%) = 1PeV$
E²dN/dE (TeV cm⁻²s⁻¹)
E (TeV)


Hadron: without cutoff
Lepton
LHAASO C1
2FGES J0618.3+2227
$E^e_{cut} = 50TeV$
E²dN/dE (TeV cm⁻²s⁻¹)
E (TeV)

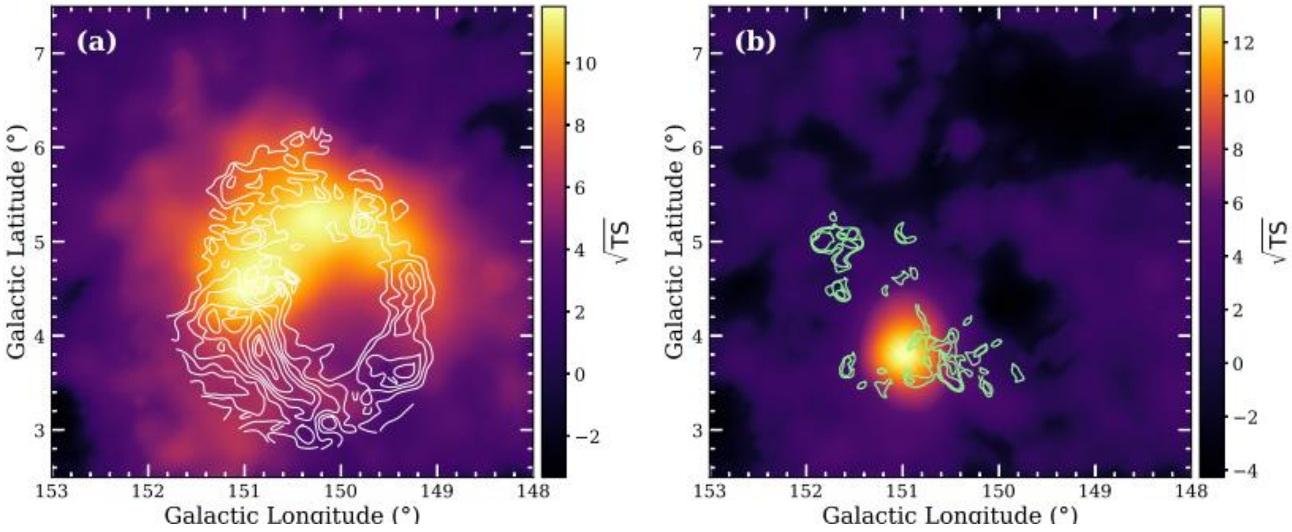

src @ LHAASO-WCDA data
src @ LHAASO-KM2A data
W44 @ Fermi LAT data
src target @ Fermi LAT data
src target @ Fermi LAT data@ index=1.8
src target @ Fermi LAT data@ index=2.0
Escape scenario
pp (W44-NW)
IC (W44-NW)
W44-NW
E²Flux [TeVcm⁻²s⁻¹]
E [TeV]


Fermi-LAT
LHAASO
(a)
$E^2_\gamma dN_\gamma/dE_\gamma$ [erg s⁻¹ cm⁻²]
Δσ
E_γ [eV]

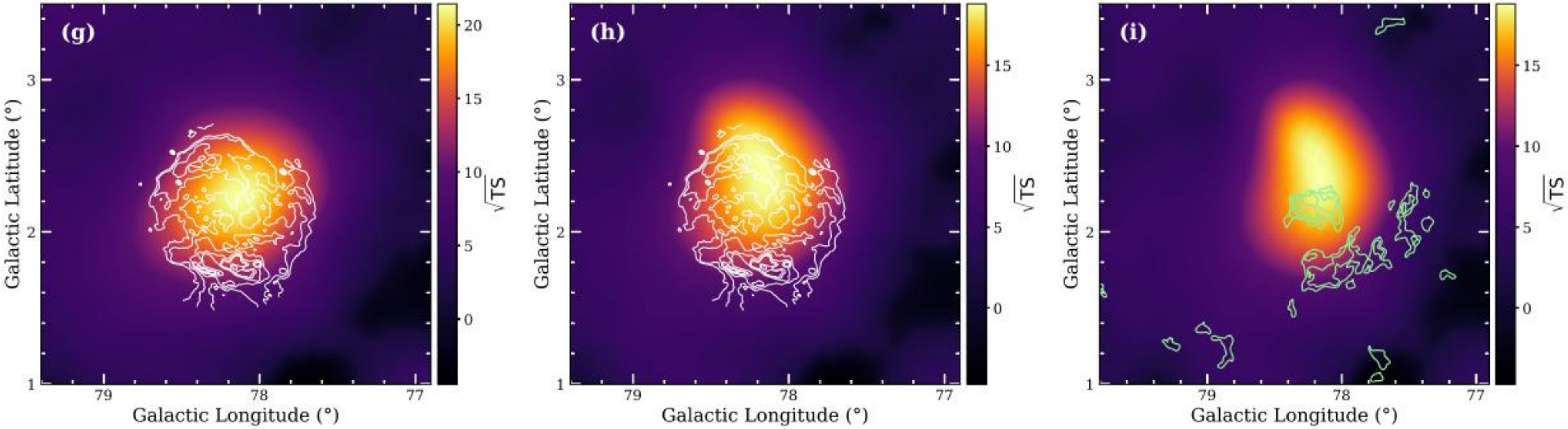
SNRs in an environment with fewer targets

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

Source	Component	GL (°)	GB (°)	R_{39} (°)	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

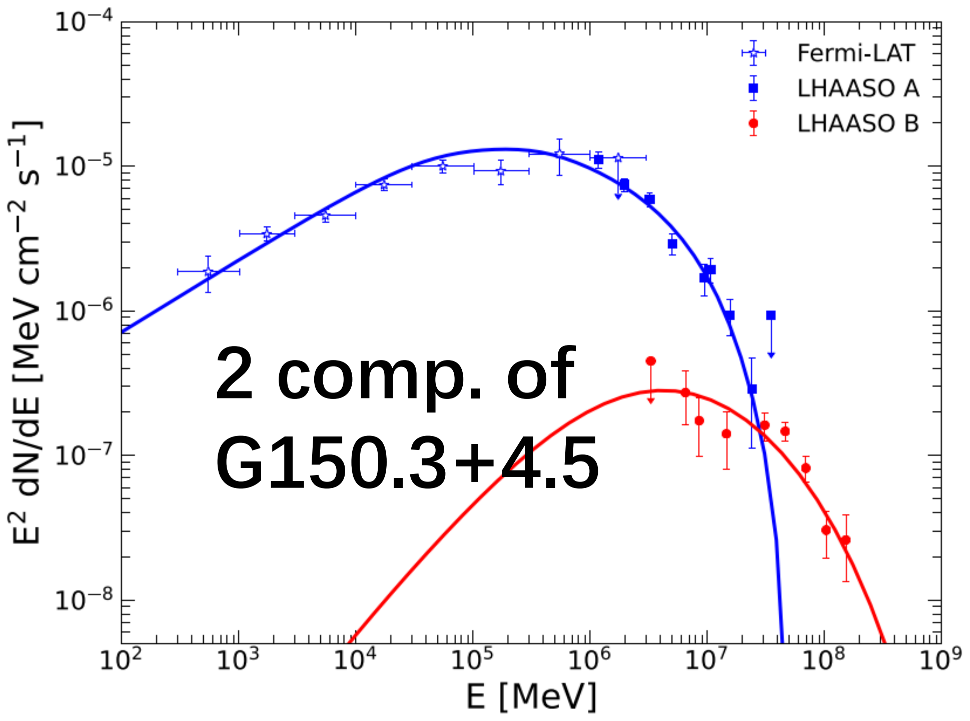


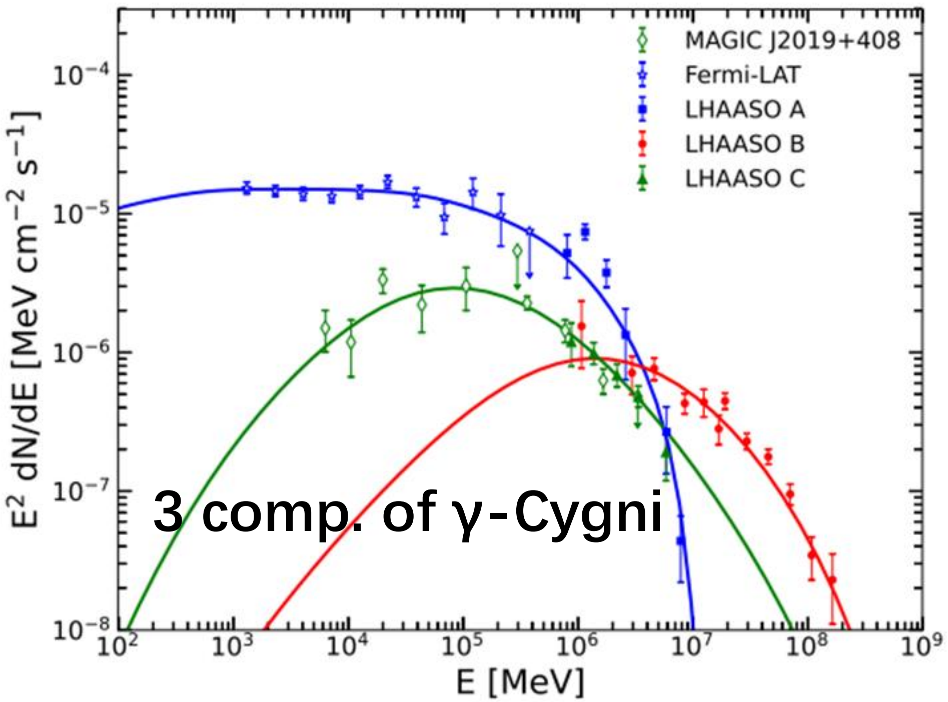
On shell comp.
Escaped comp.



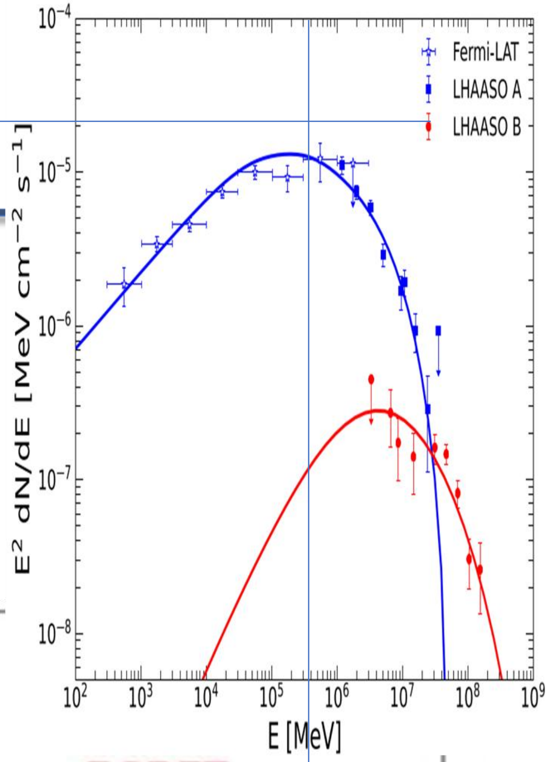
The Radiation from the shell seems dominated by leptons, similar to the RX J1713 in the southern sky

- 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



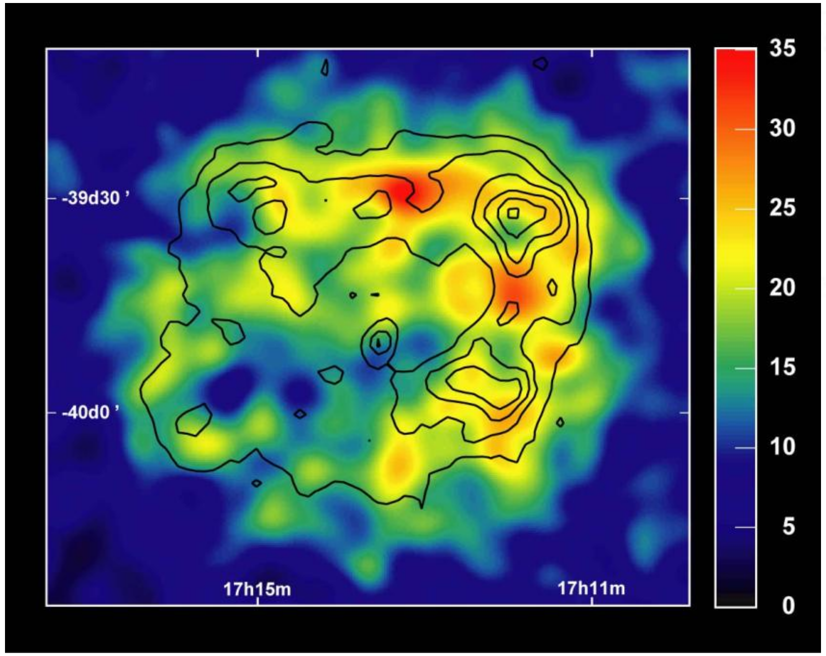


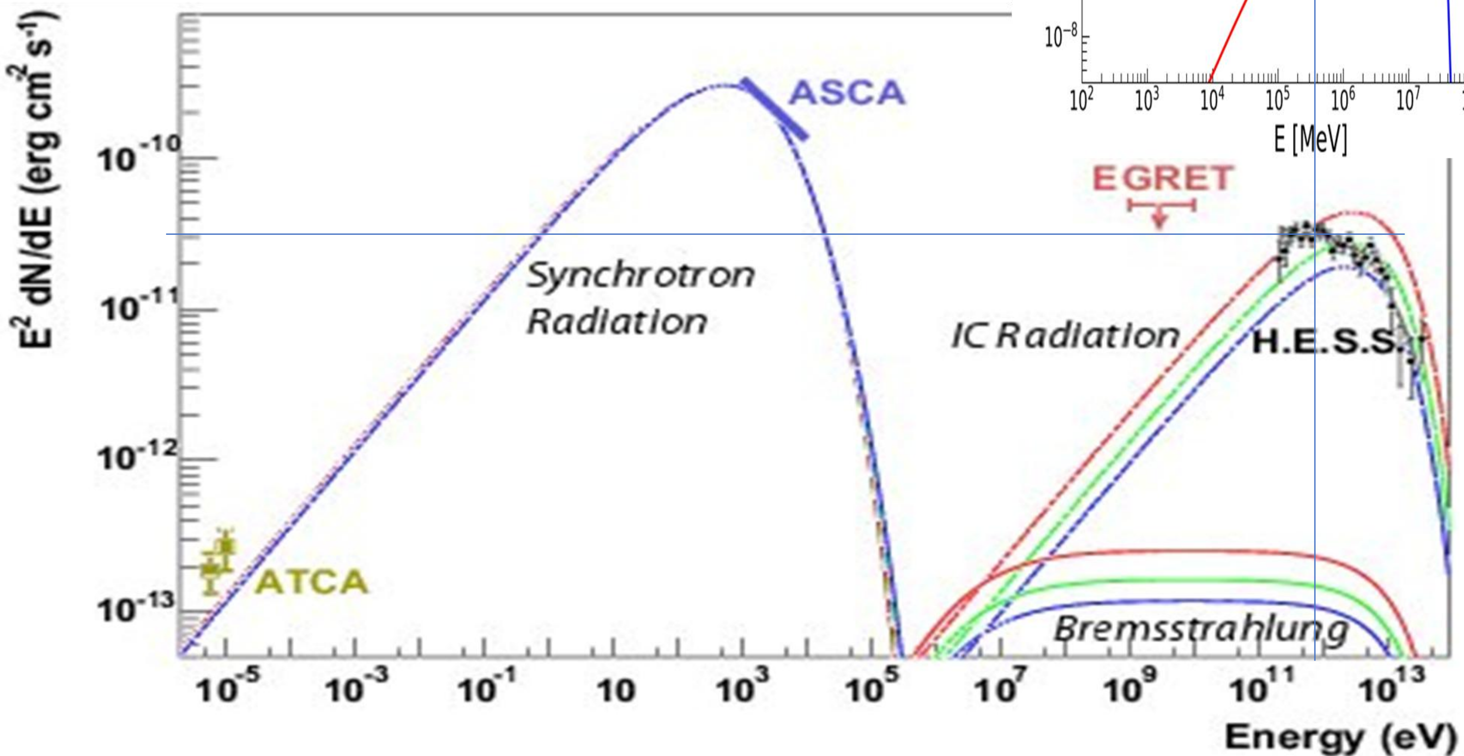
RXJ1713.7-3946



ASCA data: synchrotron X rays

- Fine structures in the radiation morphology points to B>100μG
- If leptonic, X/TeV ratio requires B~10μG (with $\sigma_{IC}/\sigma_{Sync} \propto B^{-2}$)



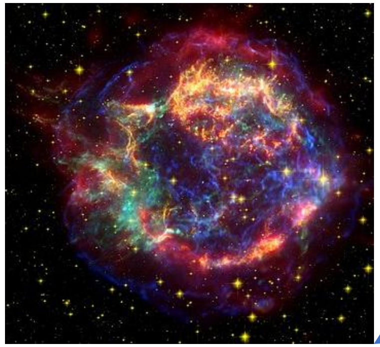


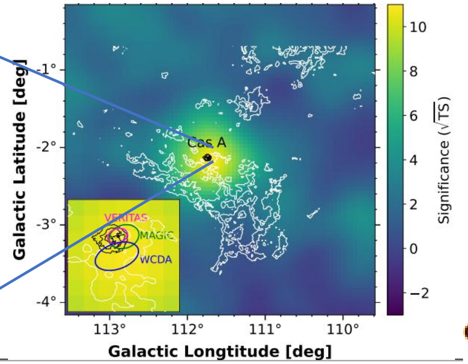
The Astrophysical Journal Letters, 961:L43 (7pp), 2024 February 1
https://doi.org/10.3847/2041-8213/ad1d62

Yong SNR as a PeVatron?

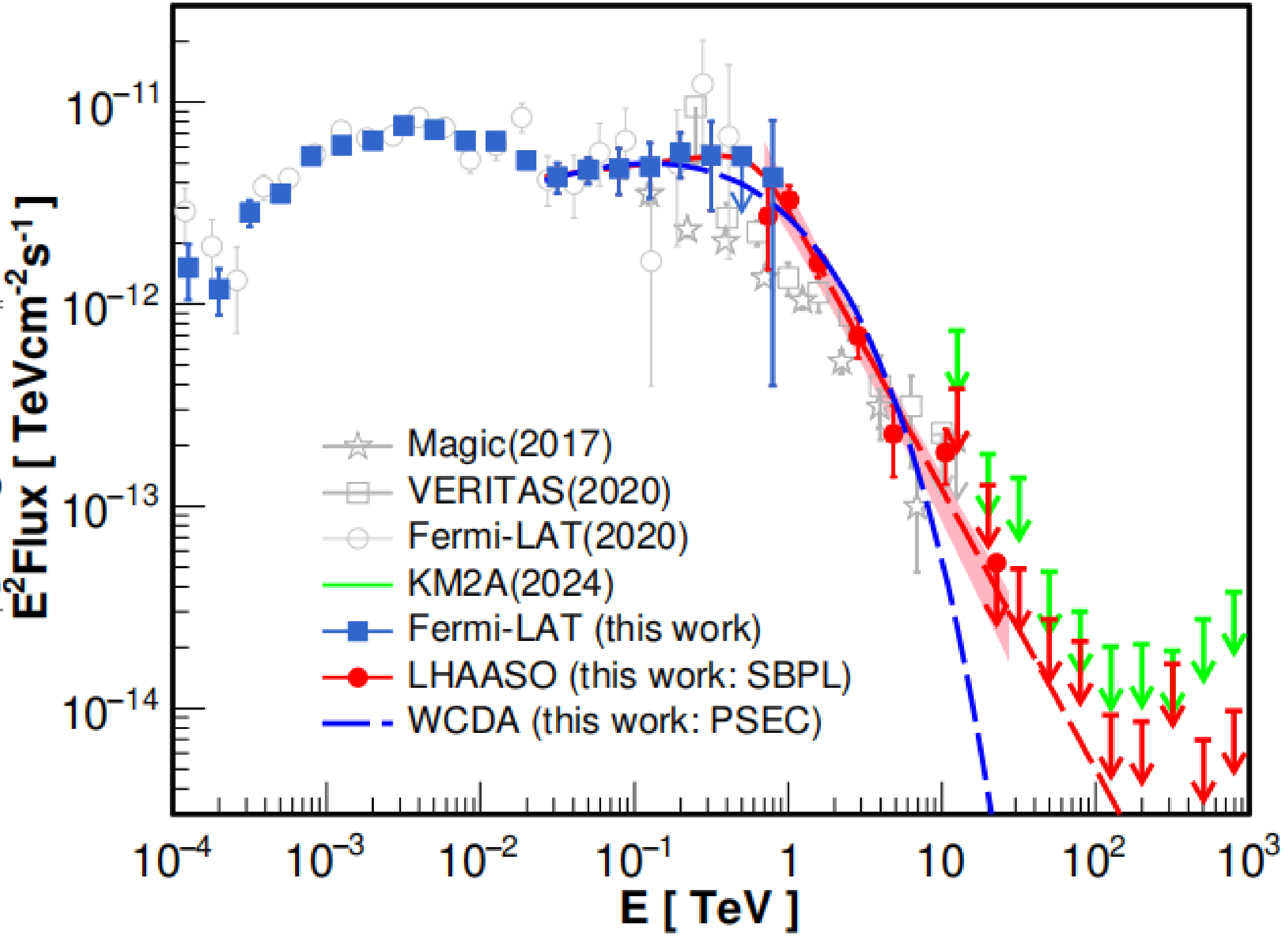
T ~ 350 years old SNR
D ~ 3.4 kpc away
R ~ 2.5 pc ~ 2.5' radius

Broadband γ-ray spectrum of supernova remnant Cassiopeia A



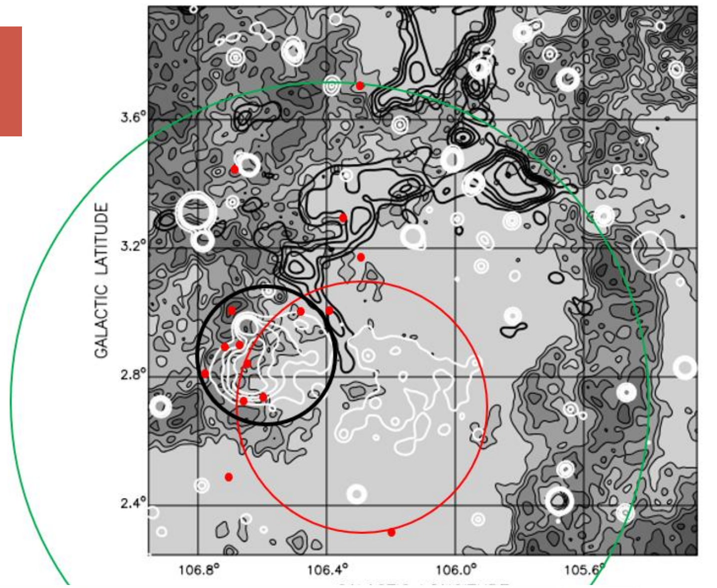


Spectral Types	PL[a]	PSEC	SBPL
RA	$350.87° \pm 0.07°_{stat}$	350.87°	350.87°
Dec	$58.75° \pm 0.04°_{stat}$	58.75°	58.75°
Flux@3 TeV/$\mathrm{TeV^{-1}cm^{-2}s^{-1}}$	$(6.64 \pm 0.84\,\mathrm{stat}) \times 10^{-14}$	$(9.01 \pm 0.85\,\mathrm{stat}) \times 10^{-14}$	$(6.99 \pm 1.35\,\mathrm{stat}) \times 10^{-14}$
Γ or Γ_1/Γ_2	$3.30 \pm 0.08\,\mathrm{stat}$	$1.60 \pm 0.17\,\mathrm{stat}$	$1.90 \pm 0.15\,\mathrm{stat}/3.41 \pm 0.19\,\mathrm{stat}$
$E_{\rm cut}$ or $E_{\rm br}$		$0.20 \pm 0.09\,\mathrm{stat}$ TeV	$0.63 \pm 0.21\,\mathrm{stat}$ TeV

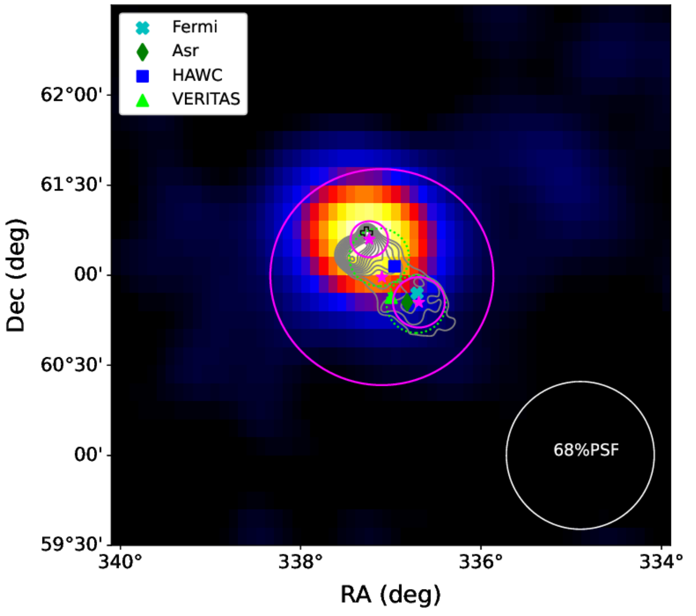


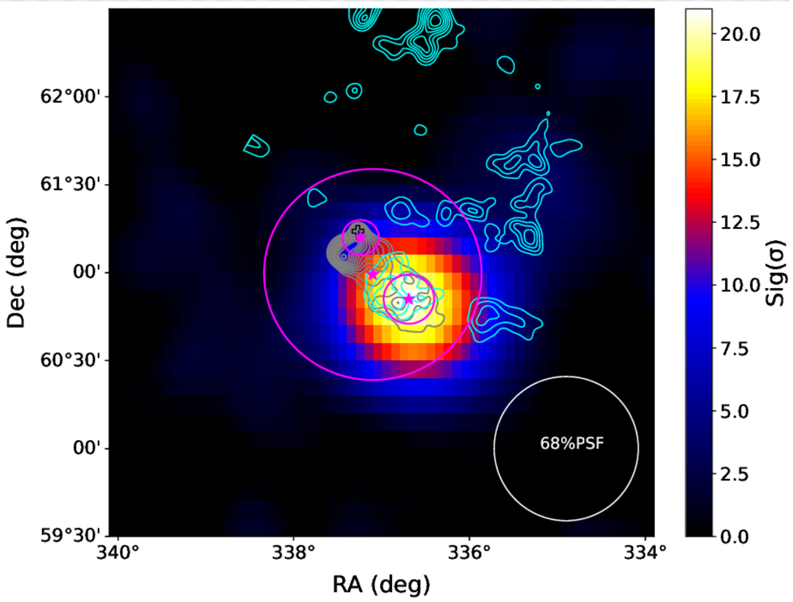
Particle escaping from the SNR or PWN?

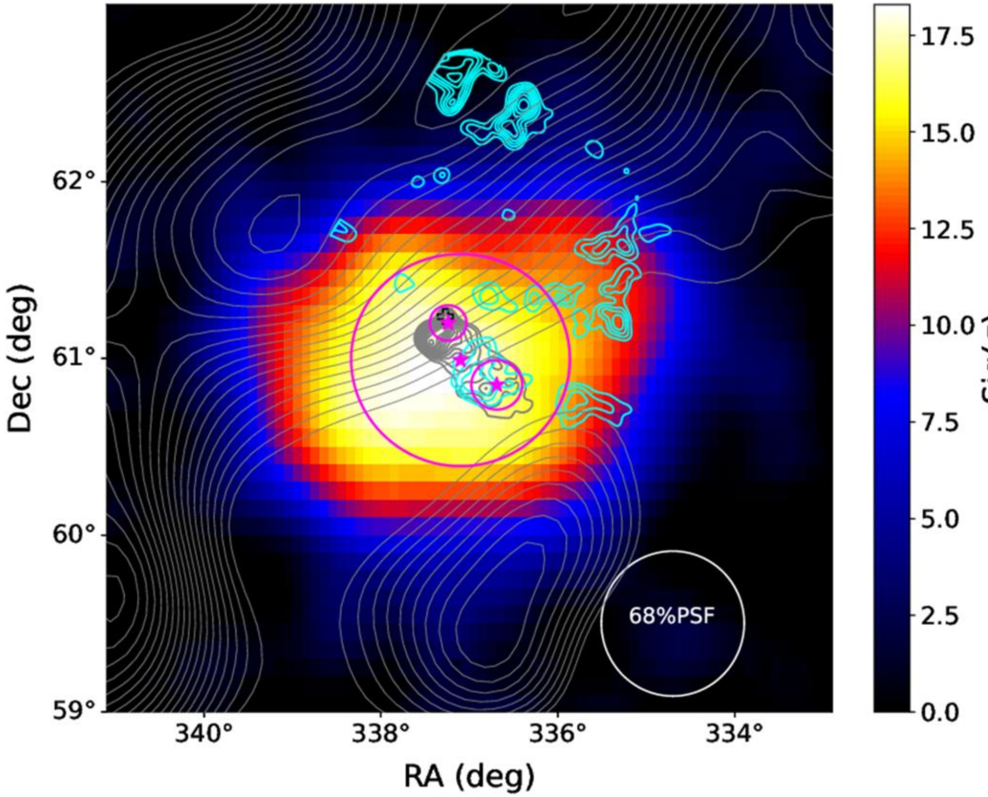
- Complex of 3 sources: PWN (Boomerang), SNR(G106.3+27)+MC and an extended associated with gas



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	

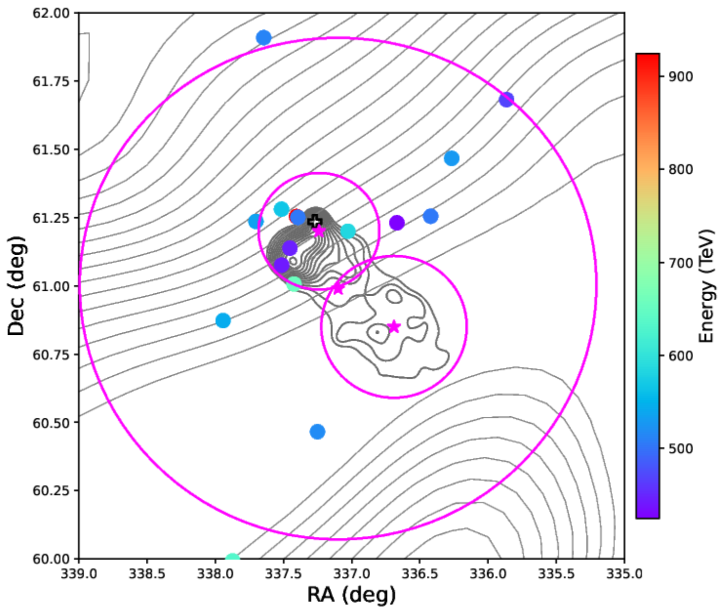


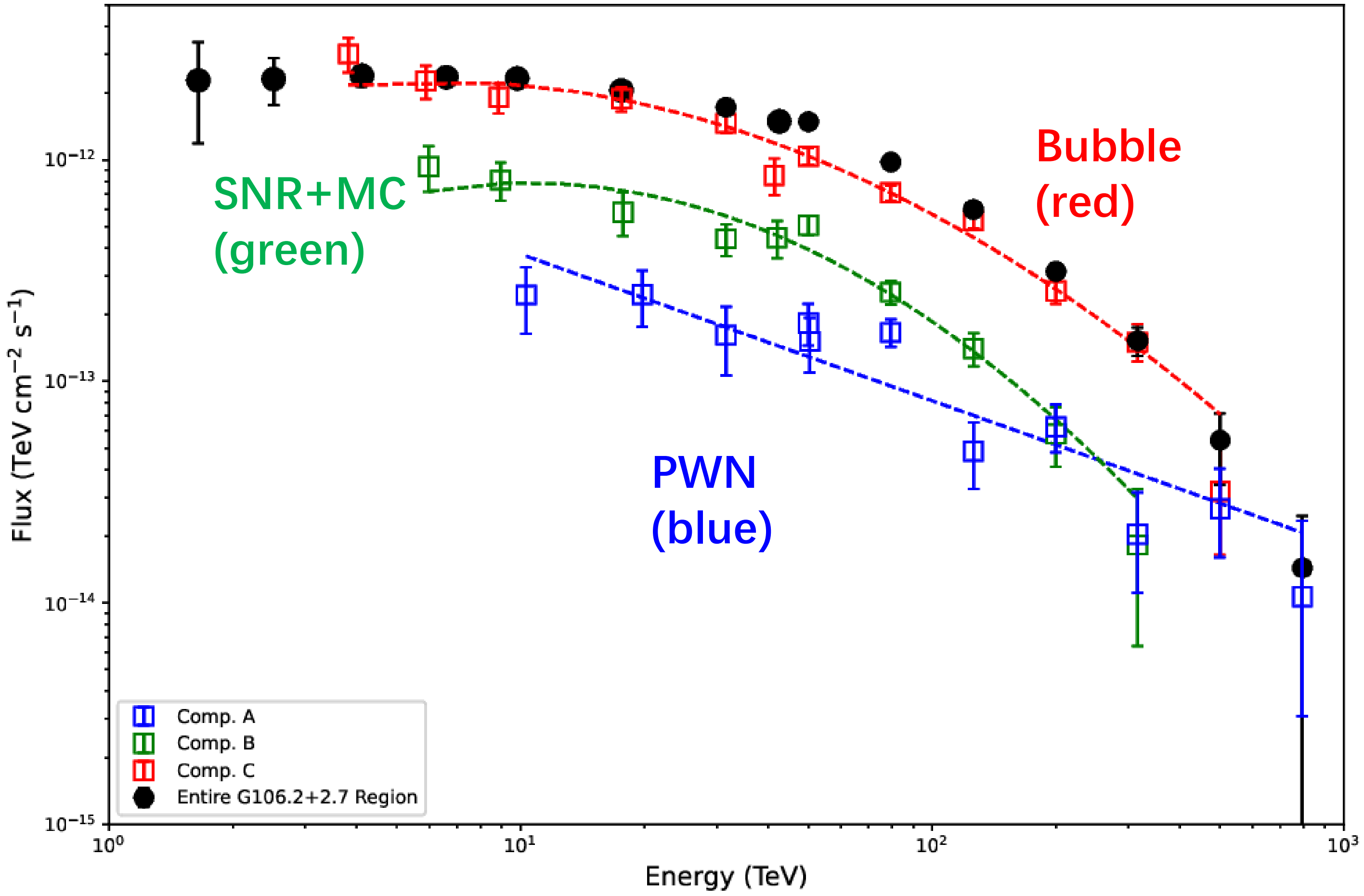




SEDs of the 3 Components

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





LHAASO
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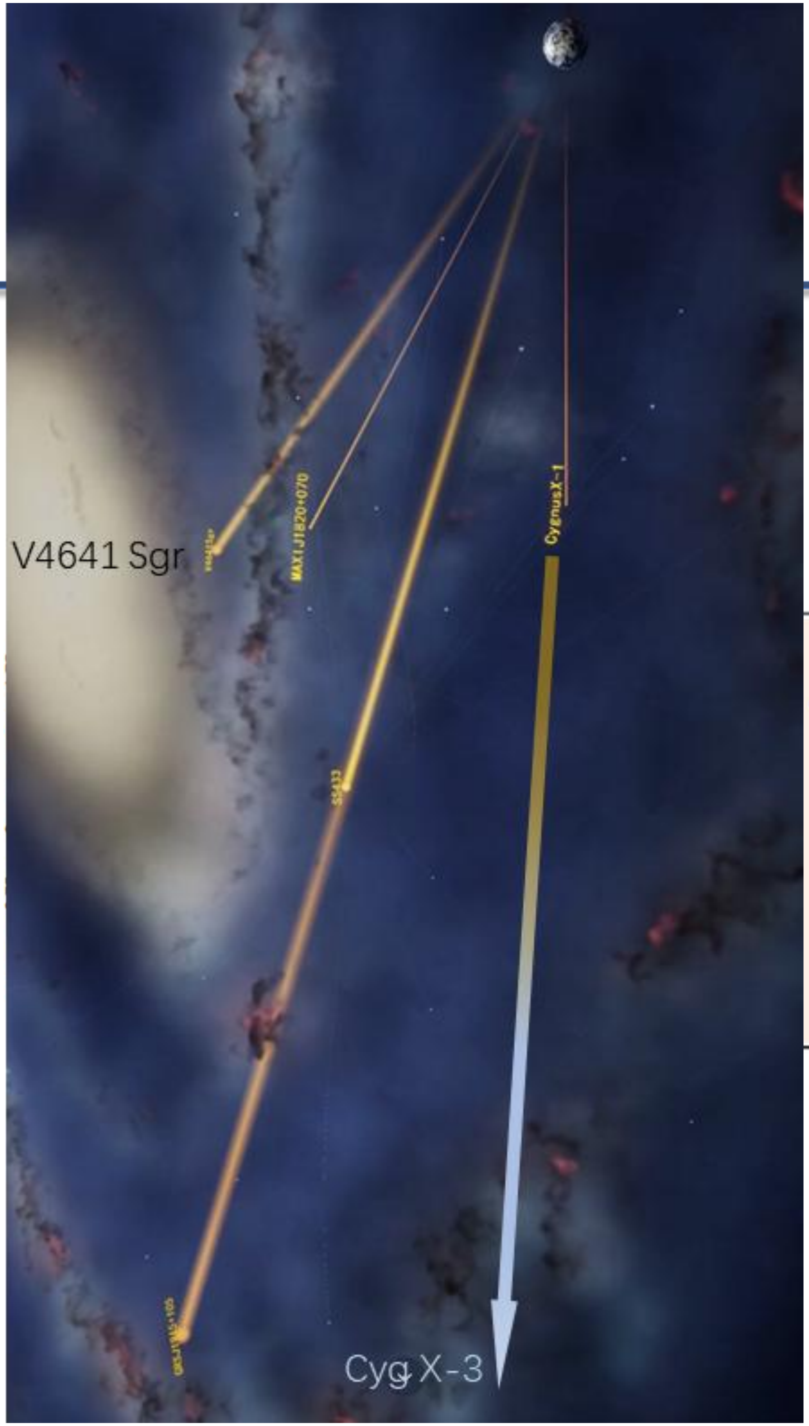
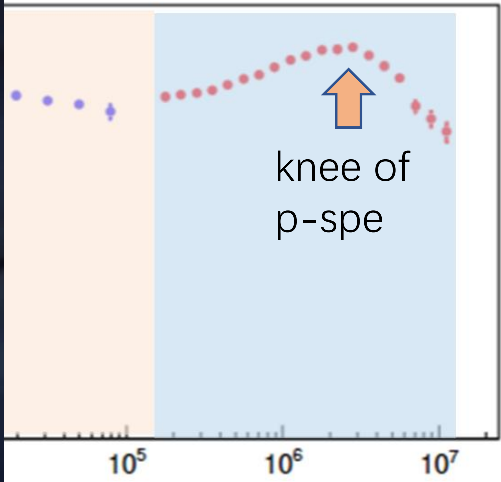
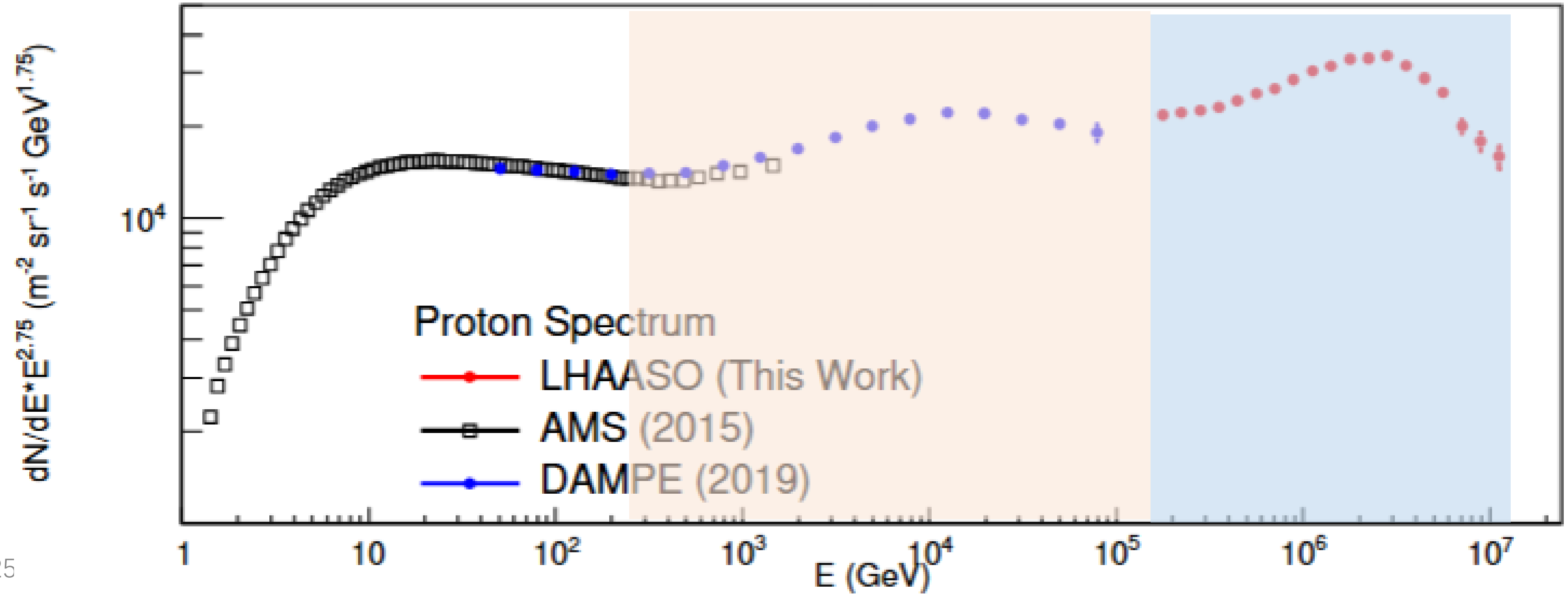
- Future expectations
- Summary



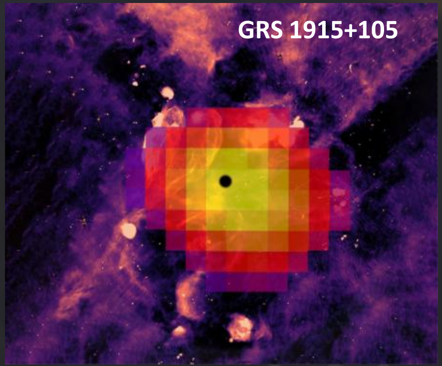


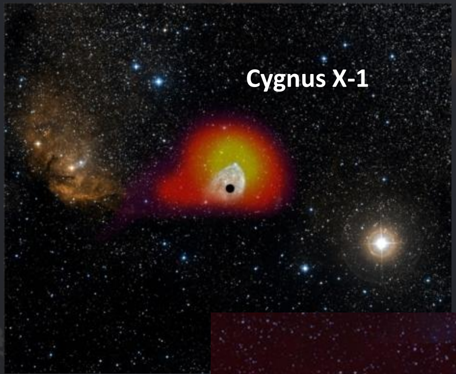
New Component Responsible to the Knee

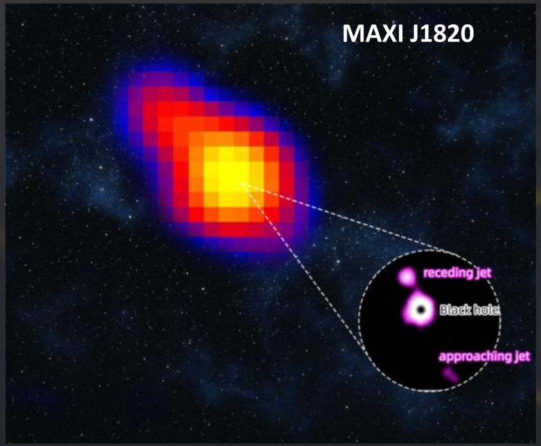
- SNRs accelerate CRs to very high energy, W 51, W 44, IC 433, Cas A ···
- IC 433: the π^0-decay spectrum extending to tens of TeV without cut-off
- Almost all of them cut at energies around 10 TeV or even lower
- New component is indicated by the hardening of the spectrum
- Stronger enhancement of the flux than that observed in 10 TeV range

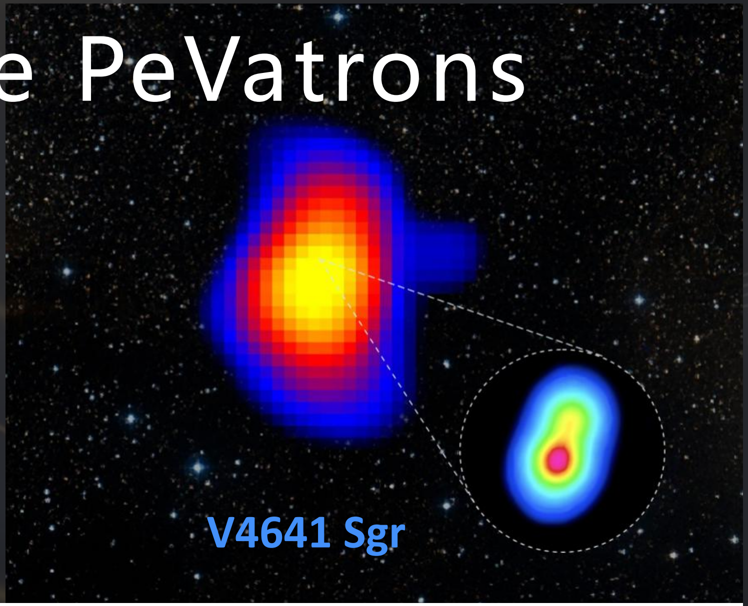


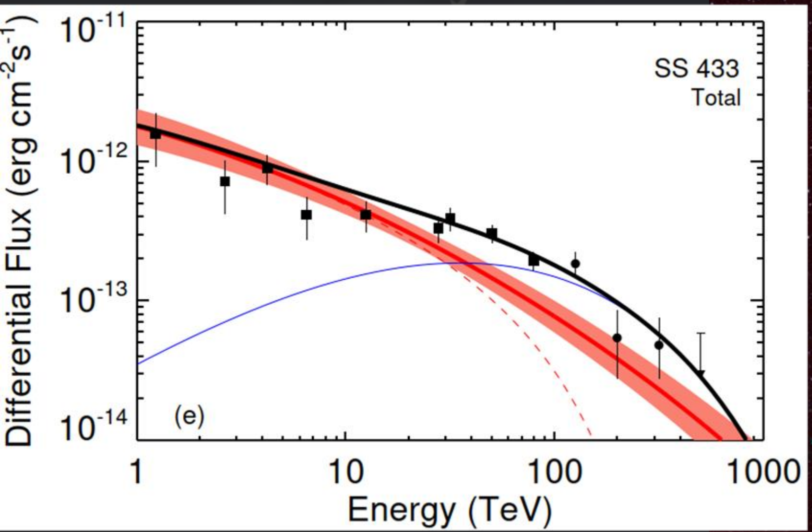
Six μ-Quasars are identified to be PeVatrons

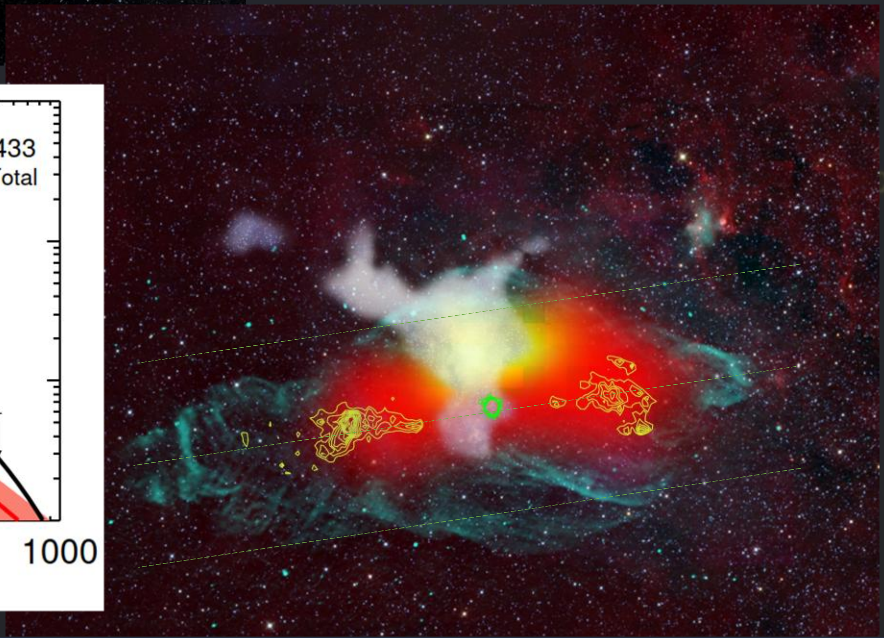


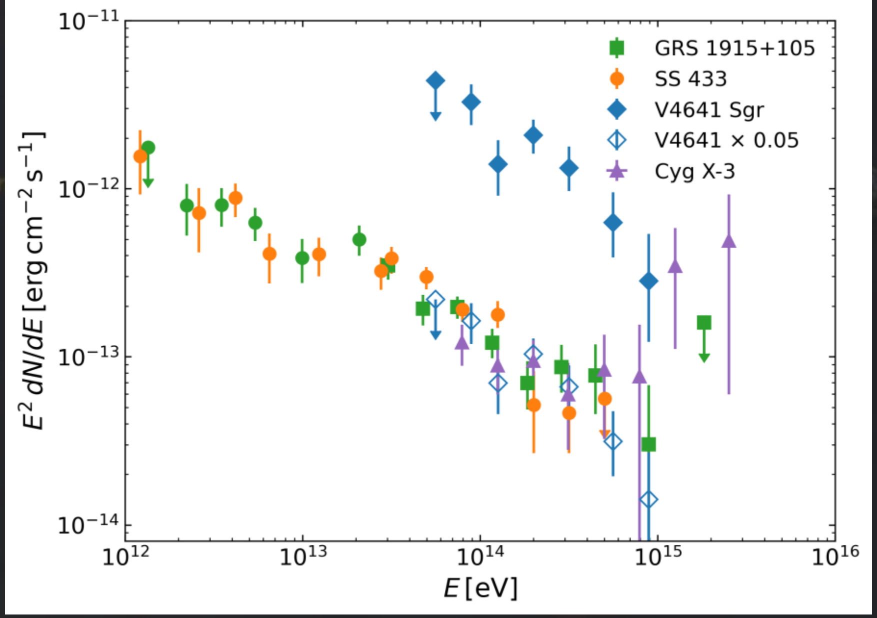






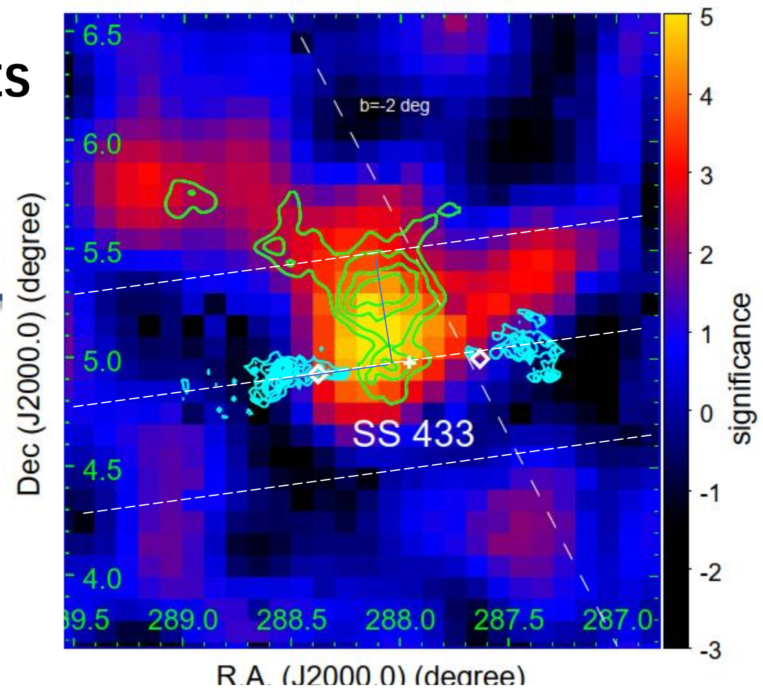




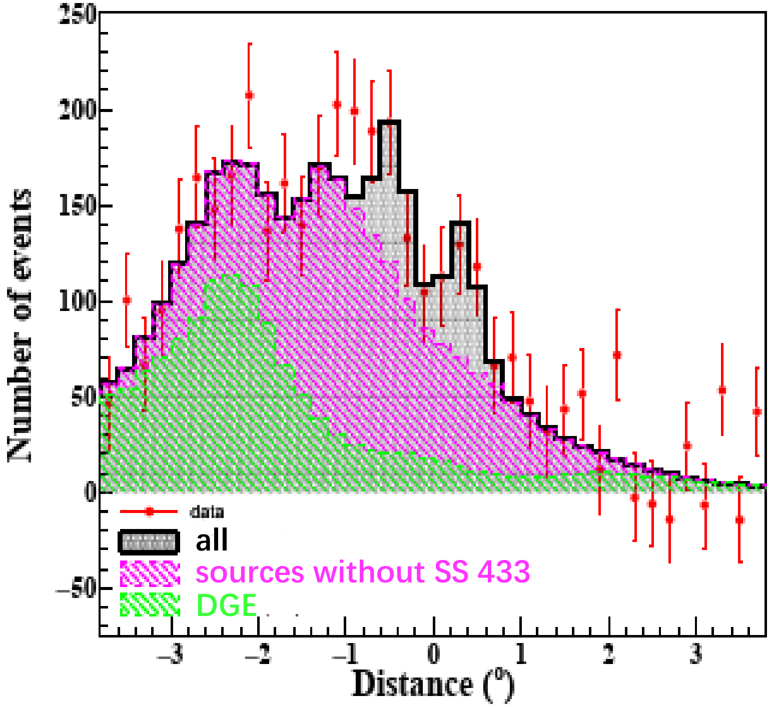


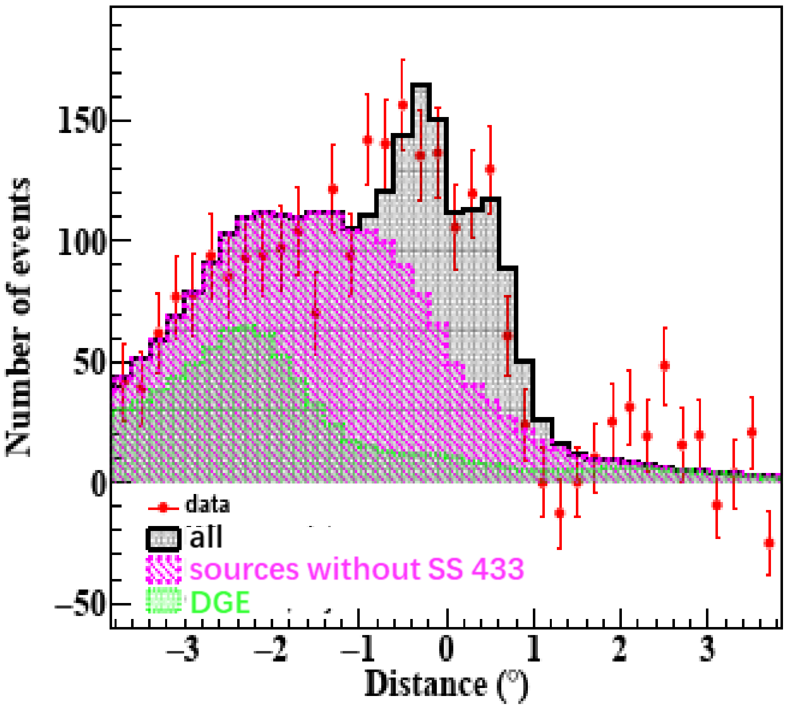
- Subtracting the jet-components

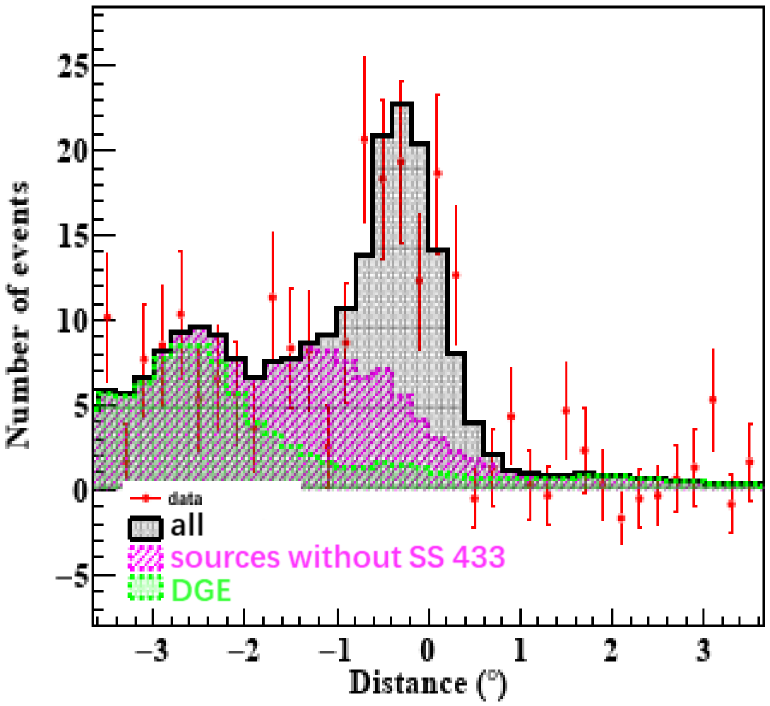
High energy radiation at the central region

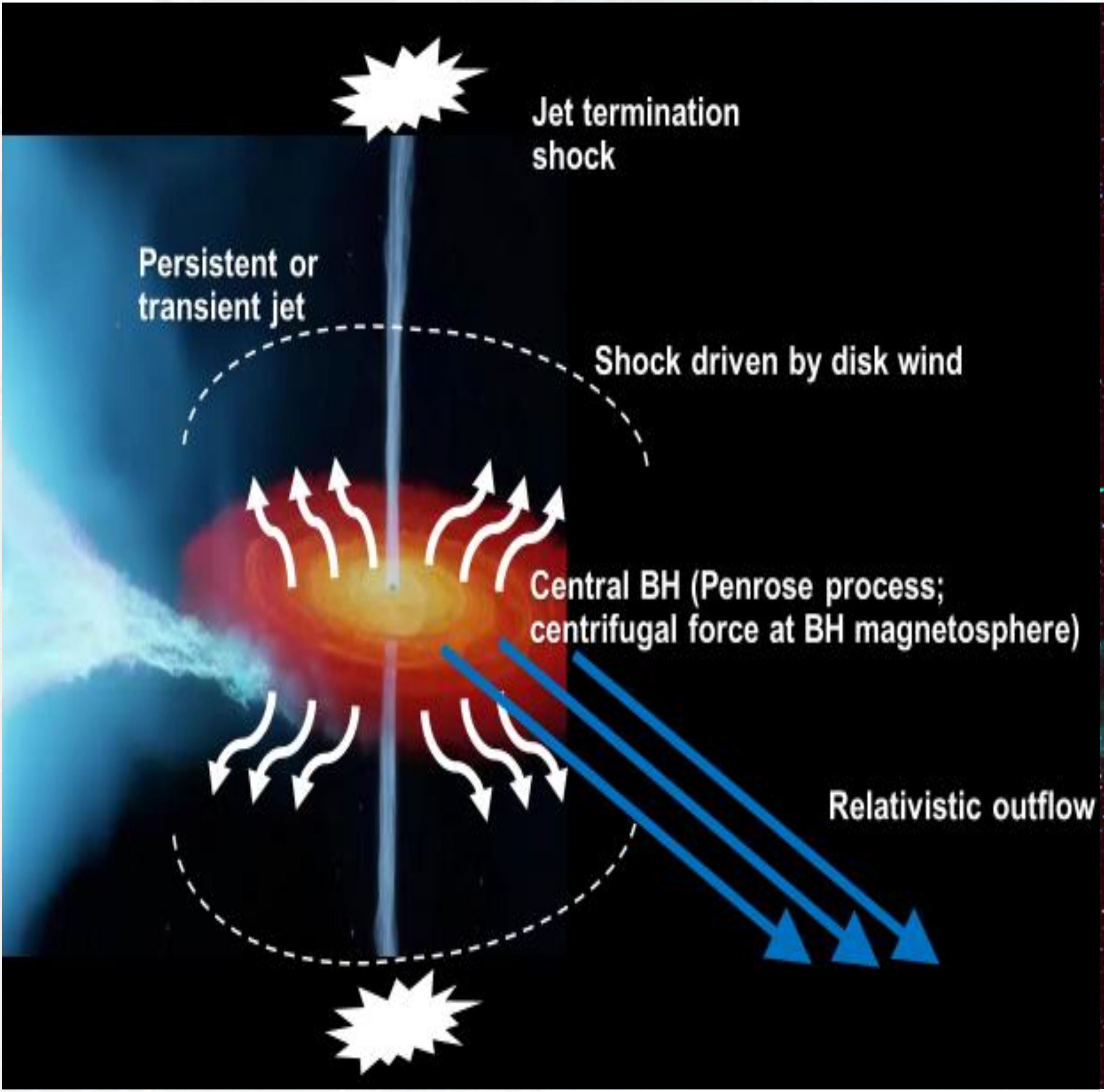


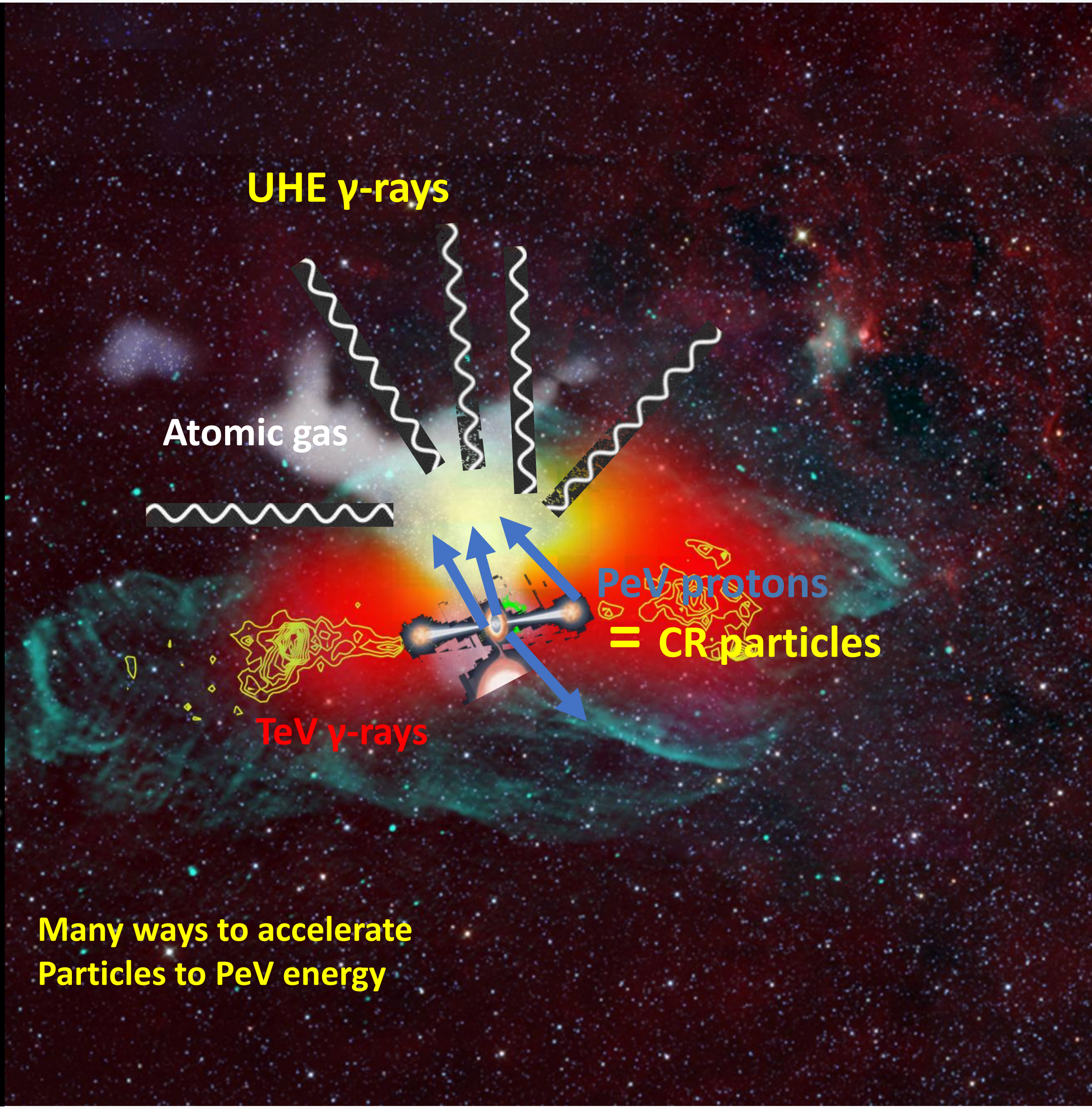
- 1-D #-of-photon distribution: extra central component



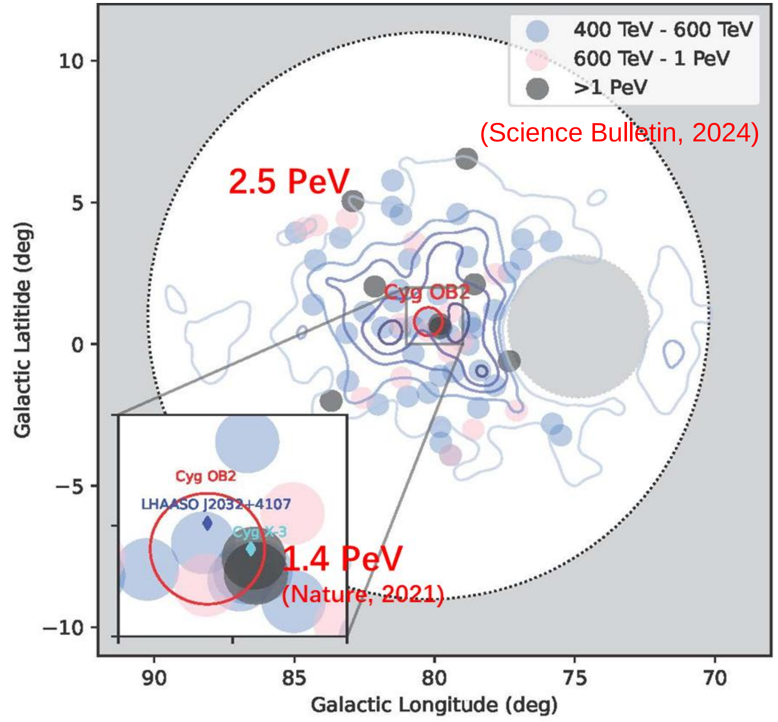




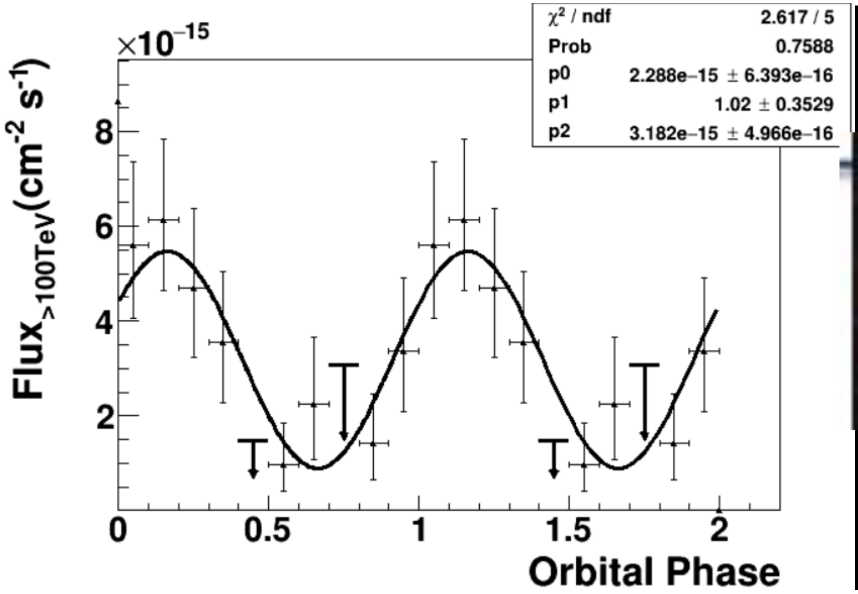

Jet termination shock
Persistent or transient jet
Shock driven by disk wind
Central BH (Penrose process; centrifugal force at BH magnetosphere)
Relativistic outflow


UHE γ-rays
Atomic gas
PeV protons
= CR particles
TeV γ-rays
Many ways to accelerate
Particles to PeV energy

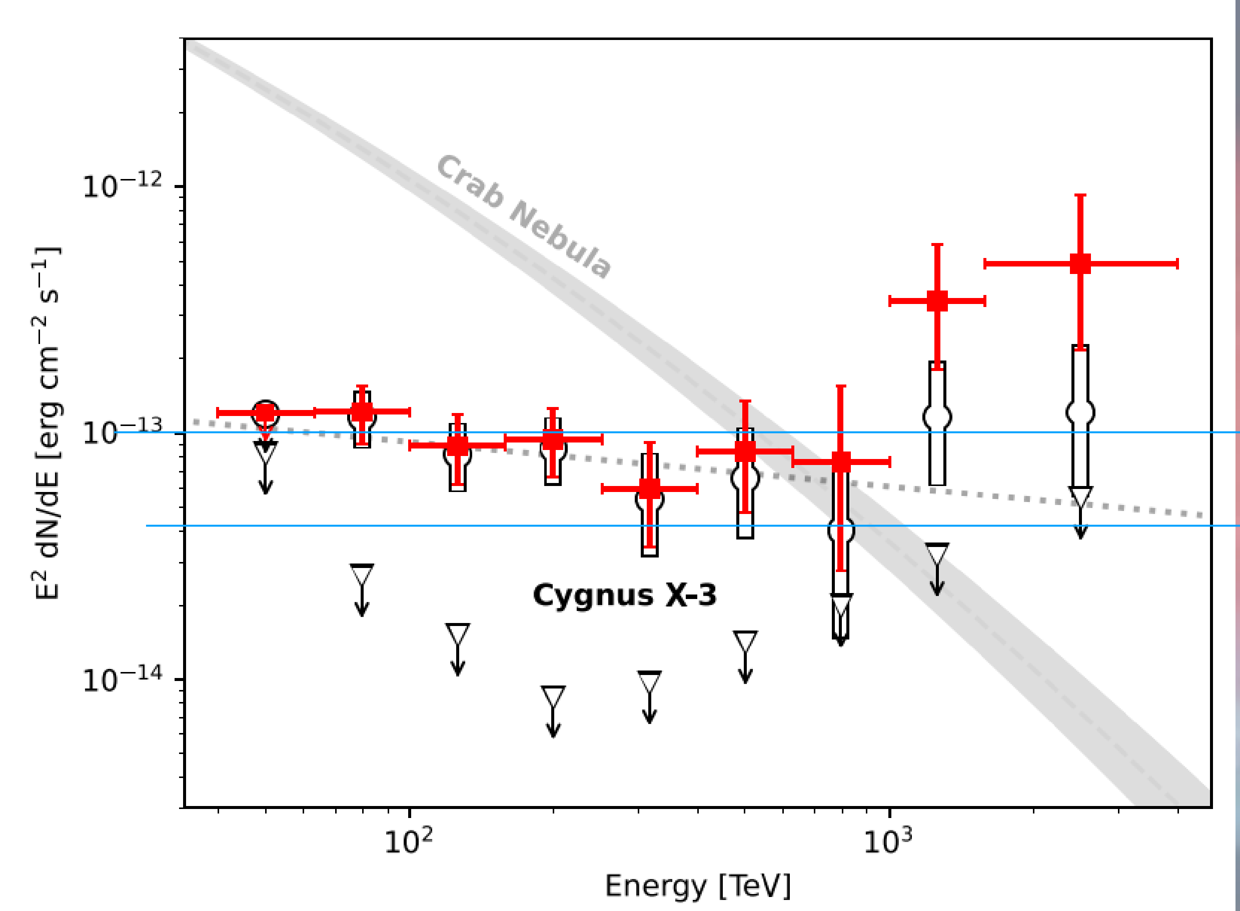
Cyg X-3： 4.8 hour orbiting

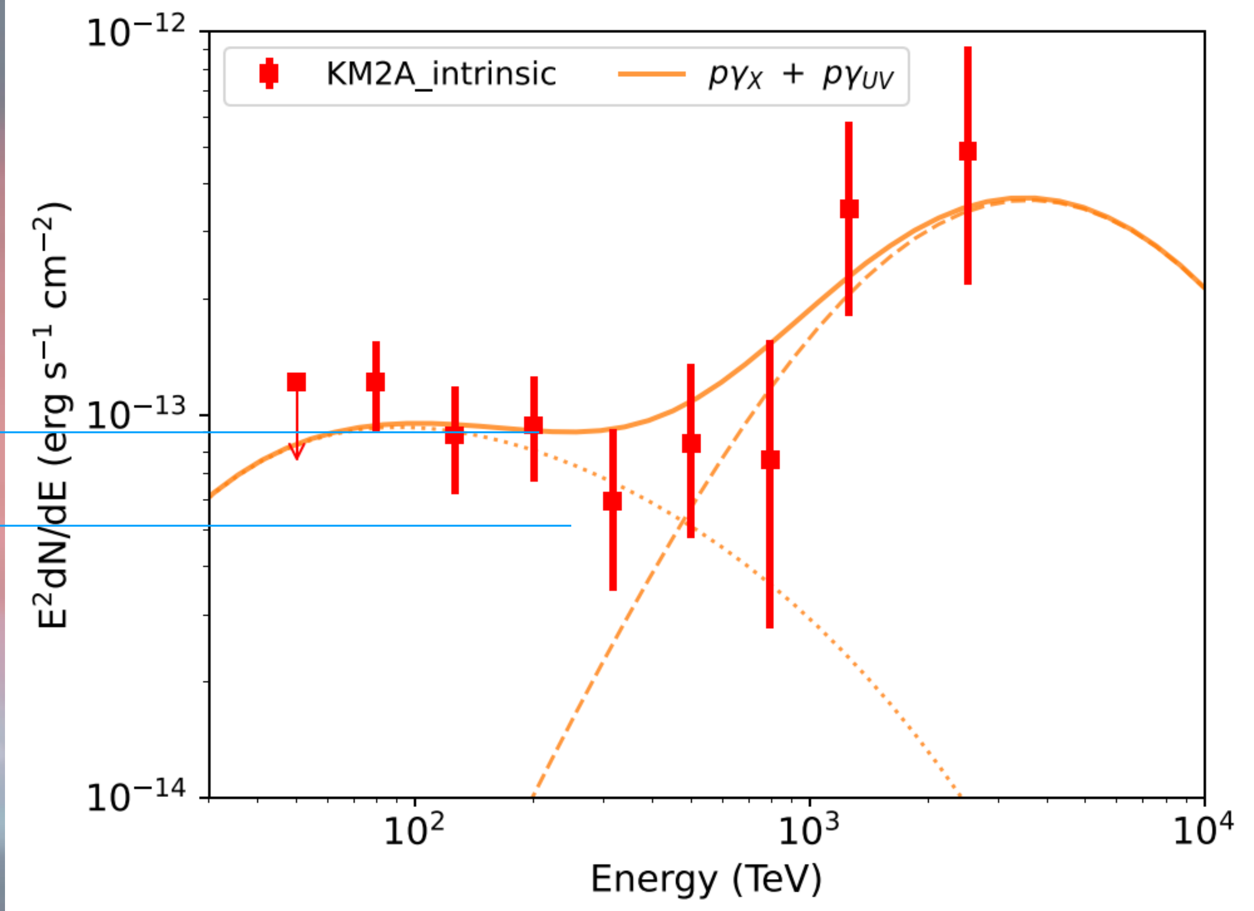


- This guarantees the proton accelerator
- ~4 PeV photons implies
  the super-PeVatron: 40 PeV protons
- For Protons >40 PeV, only
  radiation mechanism:
  proton-γ scattering



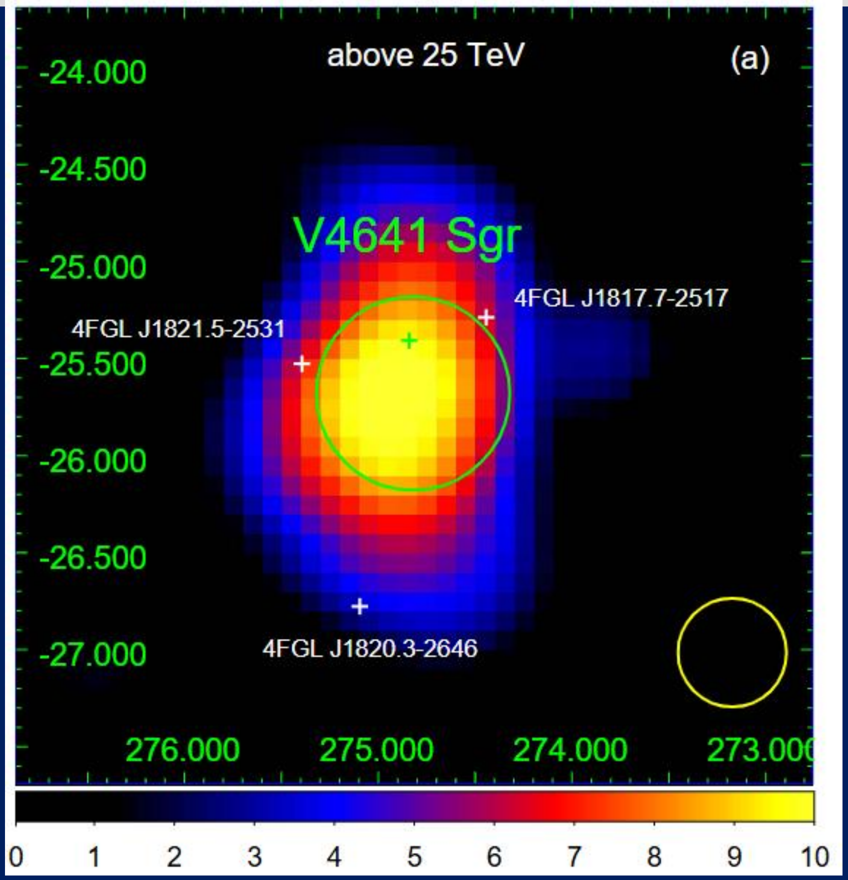
SED of a source of proton-photon scattering

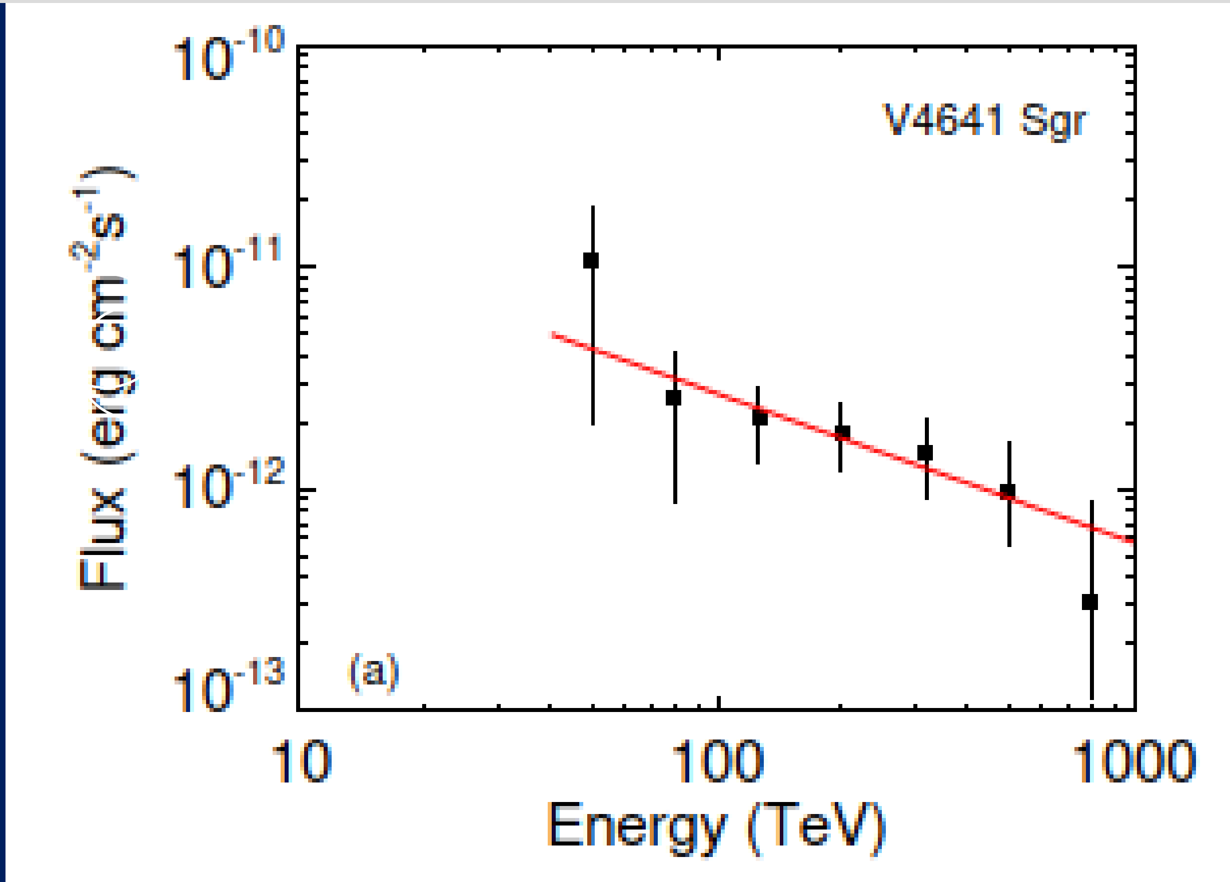




Black Hole as a super-PeVatron?

Very difficult to detect: not only due to the distant: ~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
- Future expectations
- Summary

Survey power:
AI-aid analysis

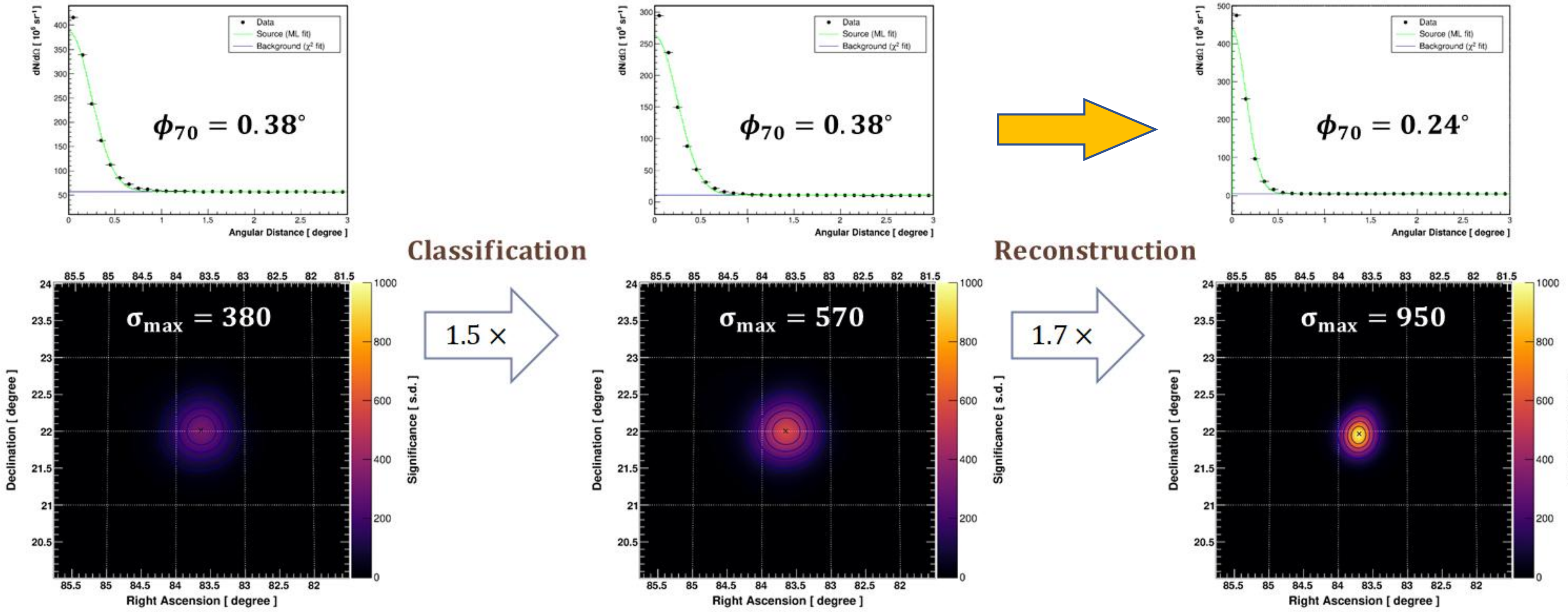
LACT: angular res.~ 3 arcmin

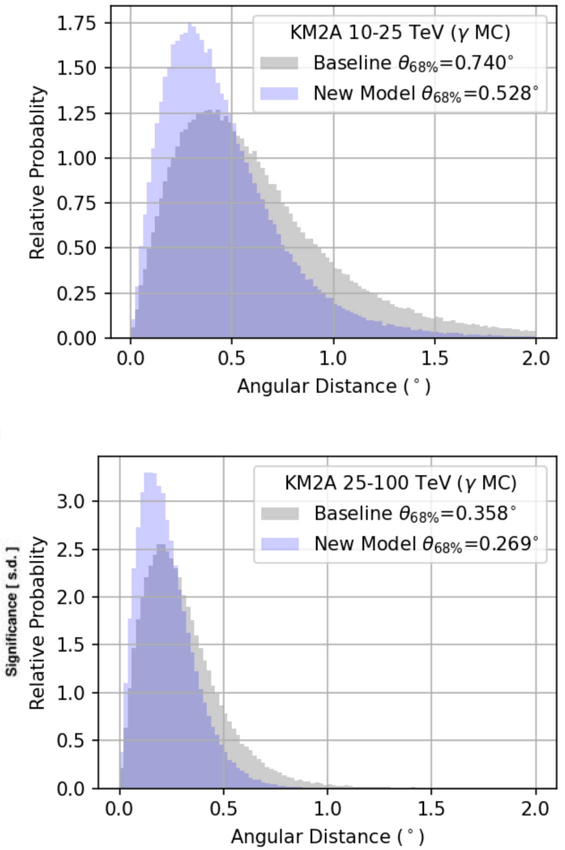
Galactic –source：
30 km^3 detector

AI helps to enhance the discovery power

WCDA was designed with 13 mCU → 5 mCU

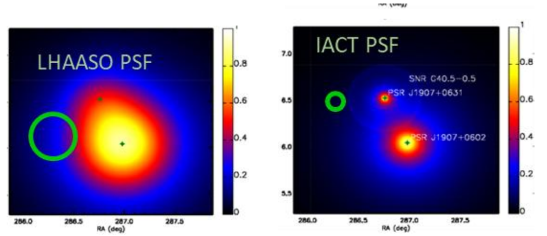
KM2A angular res.~0.36° → 0.27°

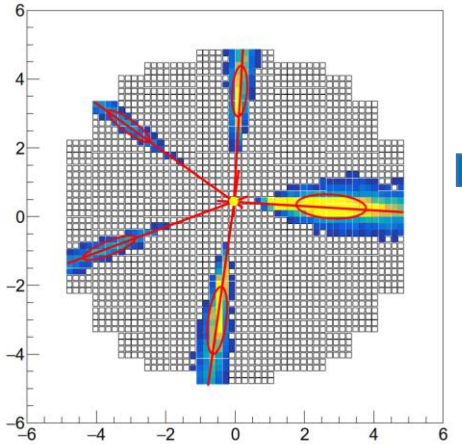


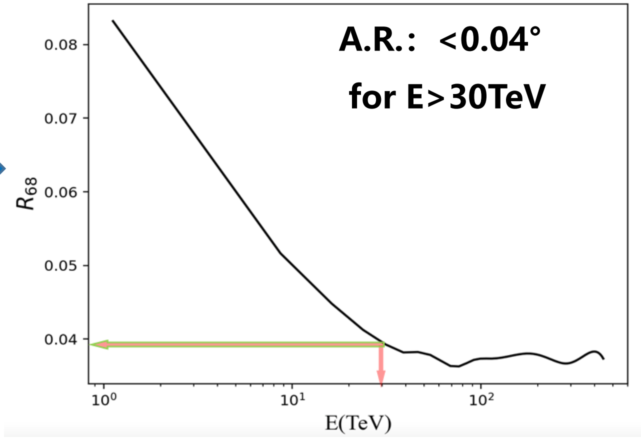


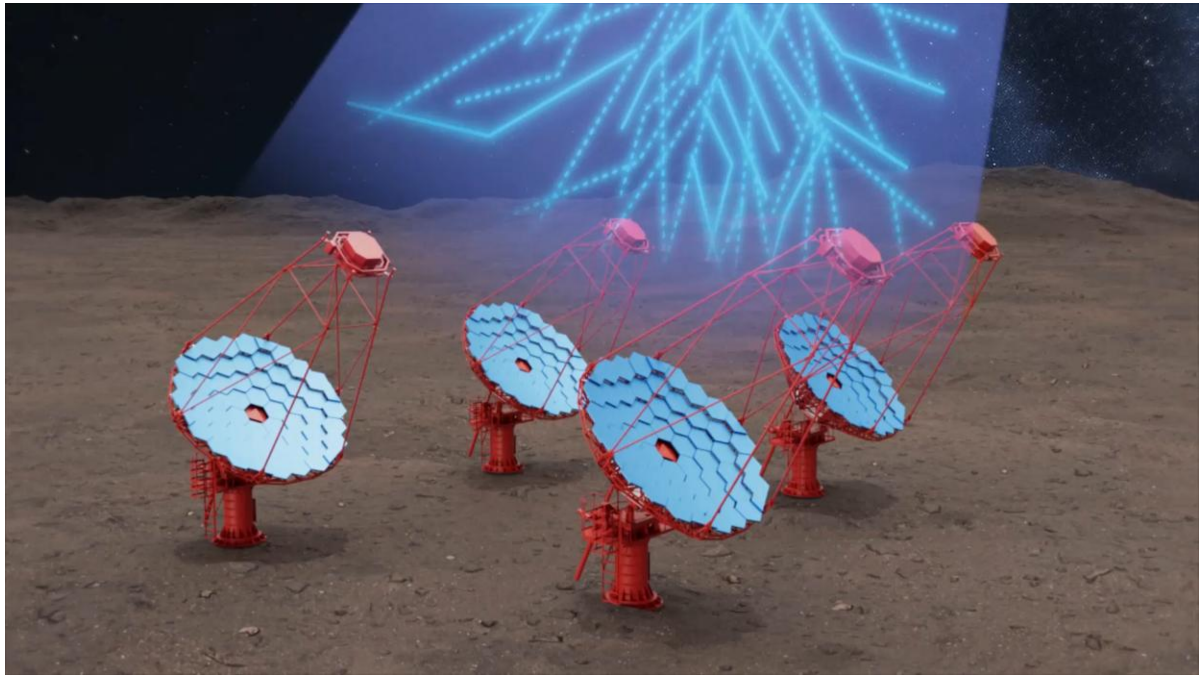
LACT (36 MST) as the upgrading of LHAASO

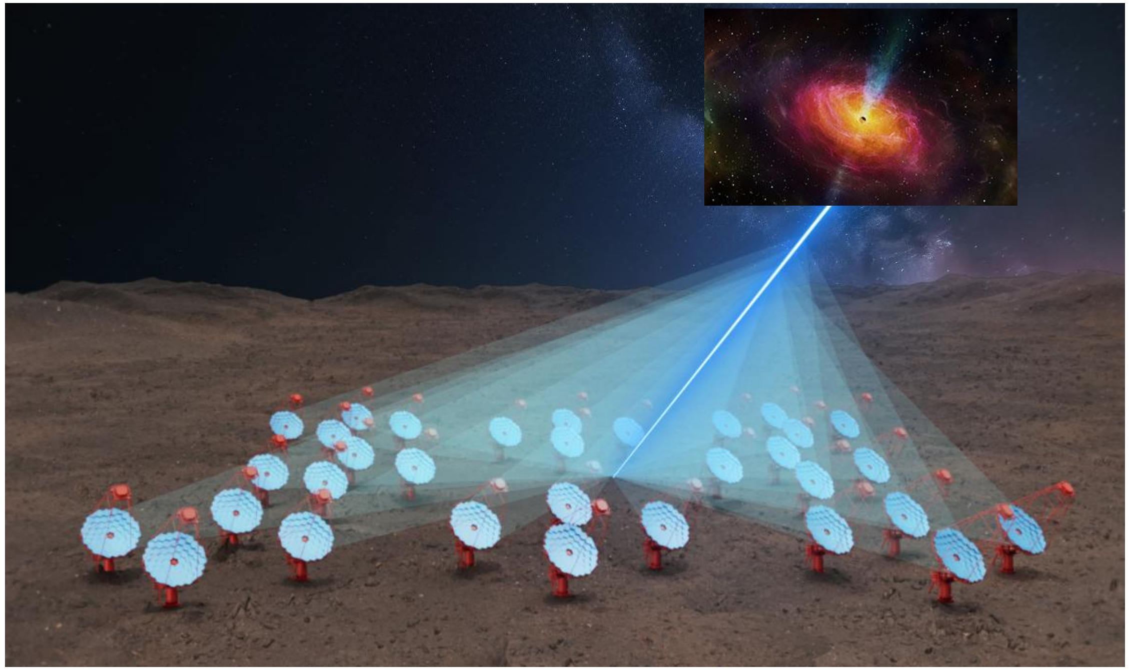
- **Stereo measurement of Cherenkov image**
  - **At least 4 telescopes simultaneously**
- **Reconstruction**
  - Angular resolution **0.04° for E**>30 TeV



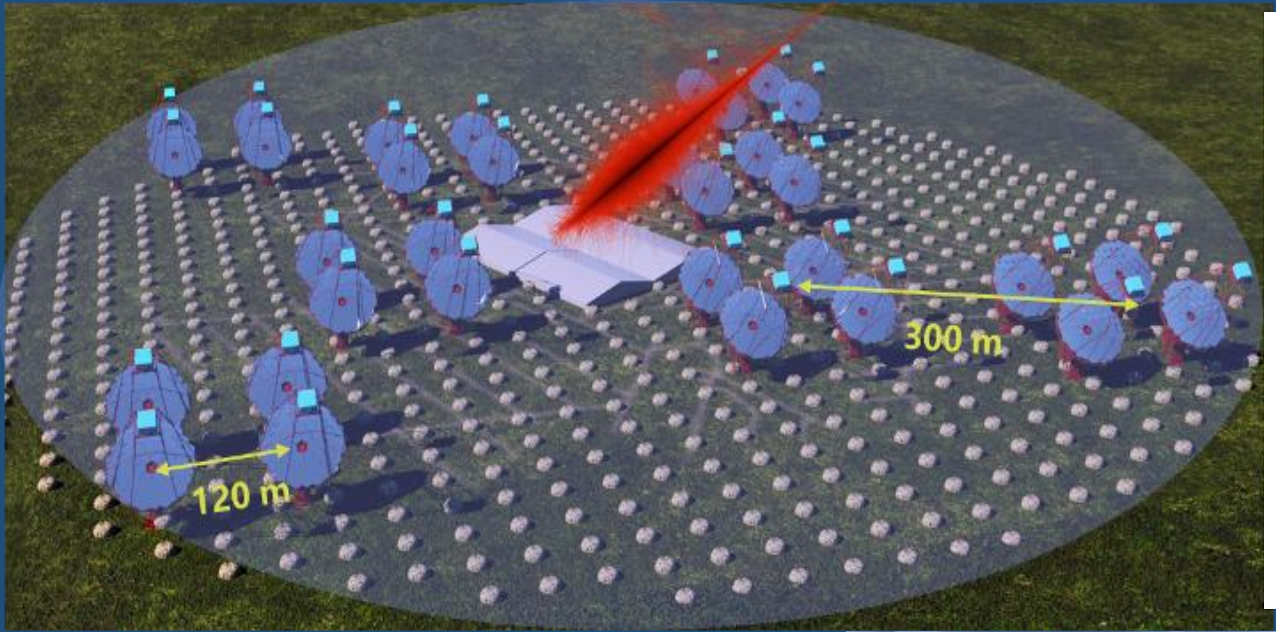


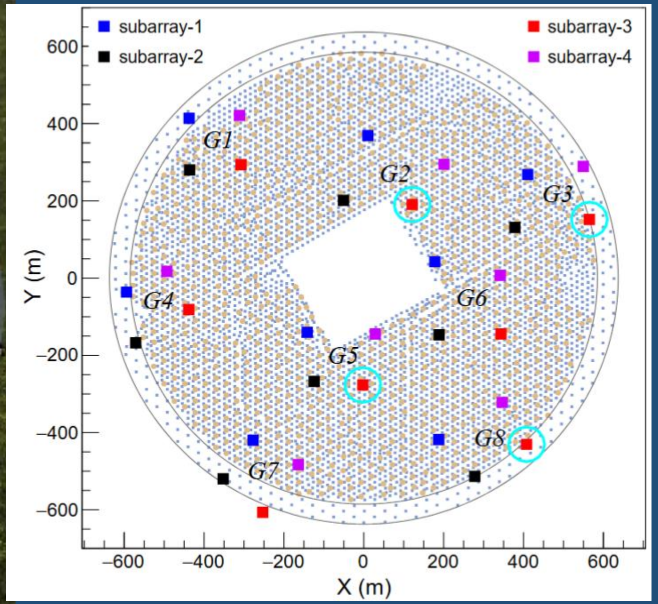






LACT : an IACT array in LHAASO

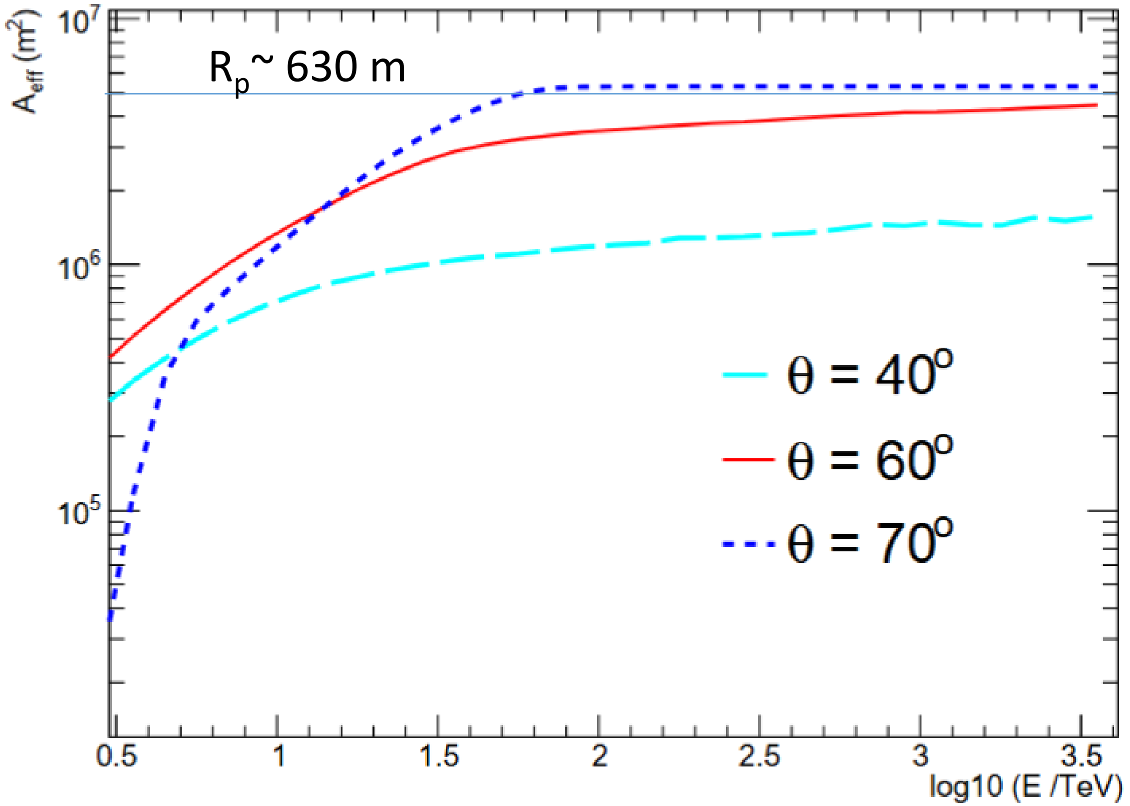


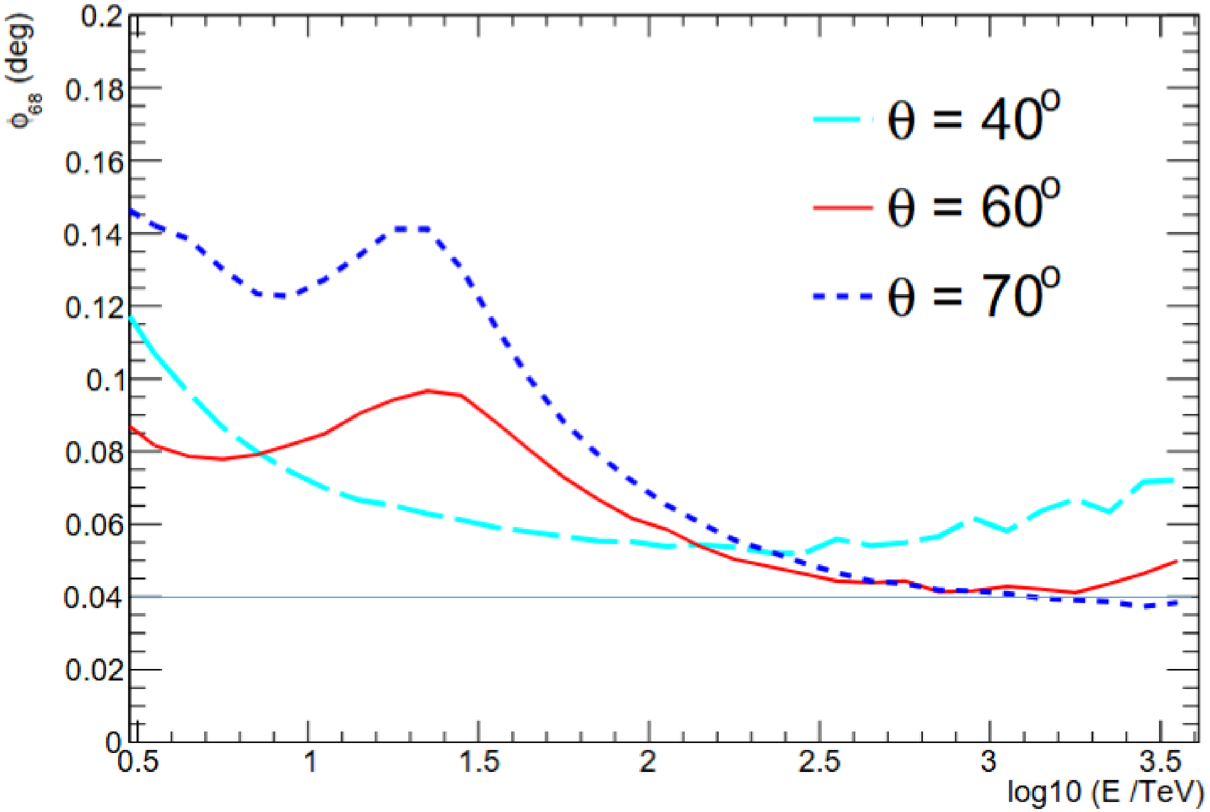


- Funded
- 8X4 array at LHAASO site
- 6-m telescopes
- two proto type telescopes
- First light soon in this year!

4 Telescope Array Performance

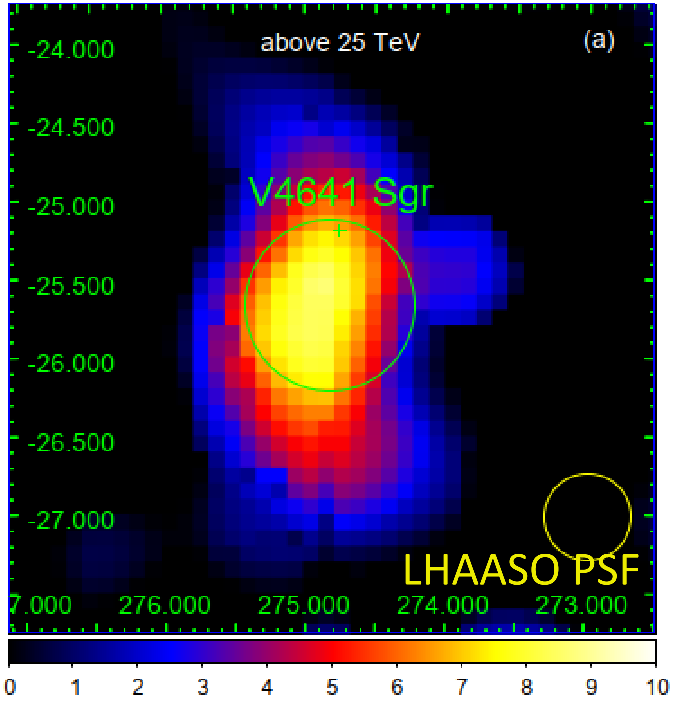
- Effective area for small elevation targets
- Angular resolution

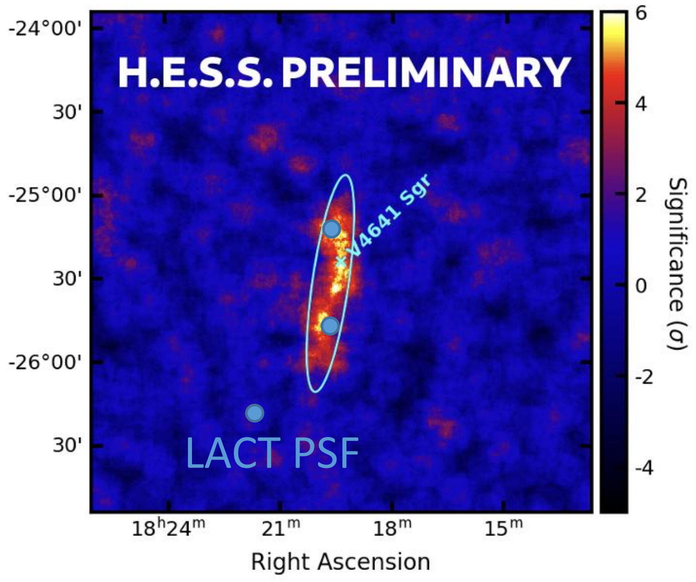


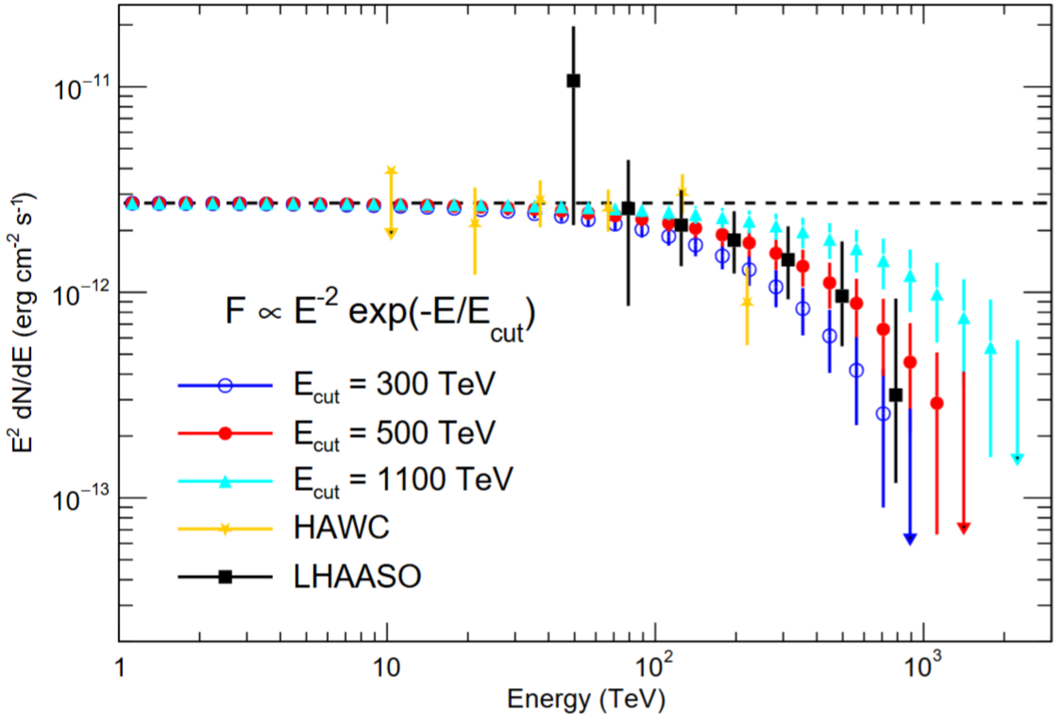


Jet Termination vs central accelerator

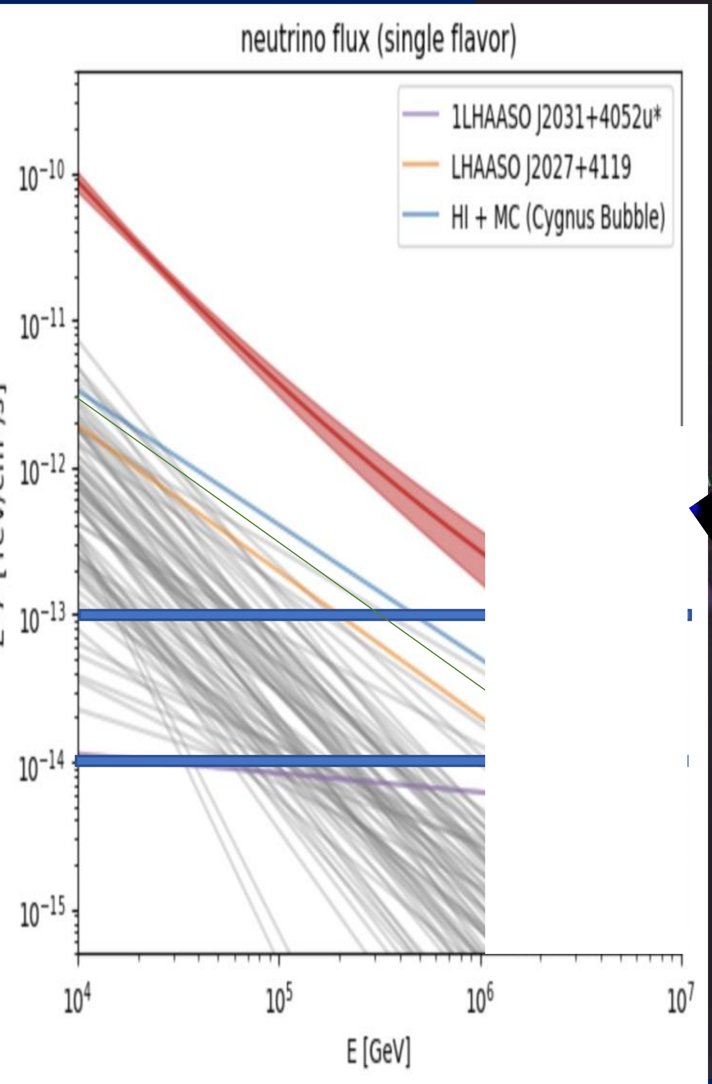
- LHAASO vs. LACT (either two point sources or complex morphology)

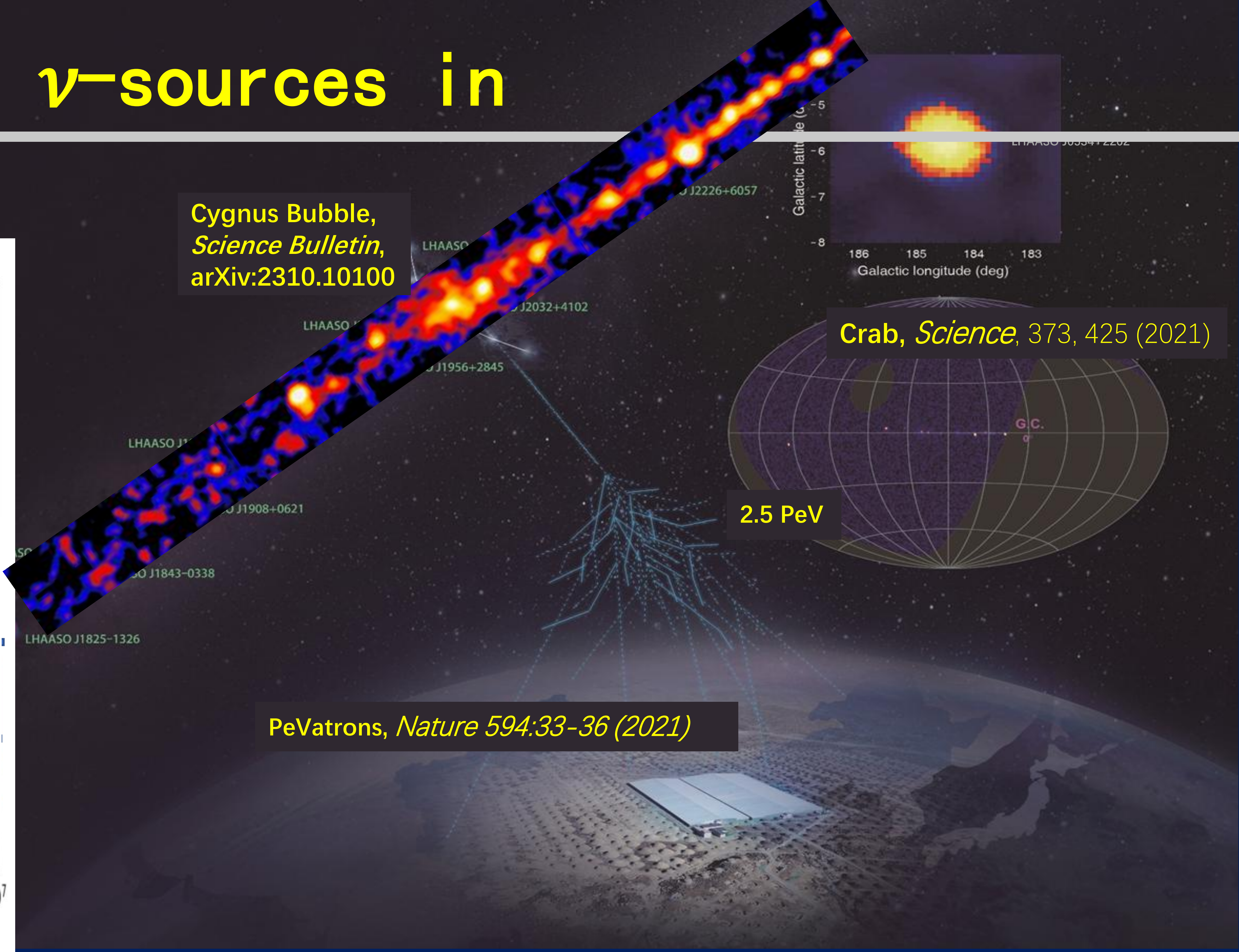






Guaranteed ν-sources in our galaxy





Cygnus Bubble, *Science Bulletin*, arXiv:2310.10100

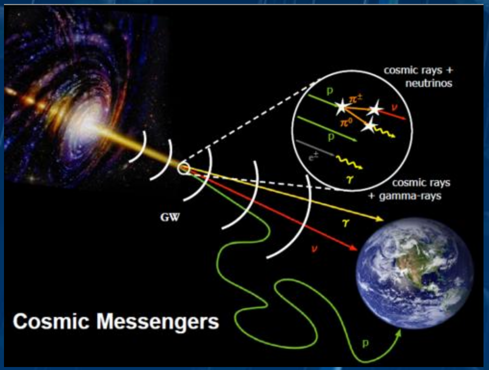
Crab, *Science*, 373, 425 (2021)

2.5 PeV

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

High-energy Underwater Neutrino Telescope

H U N T



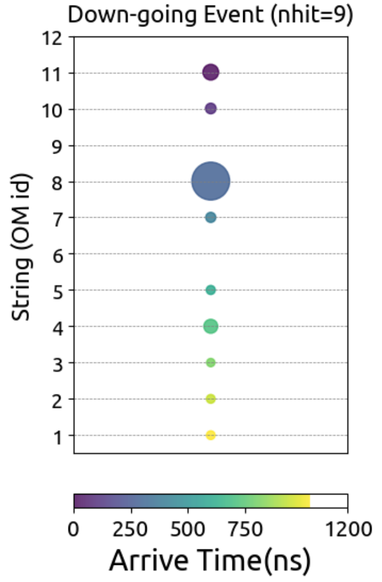
36 m

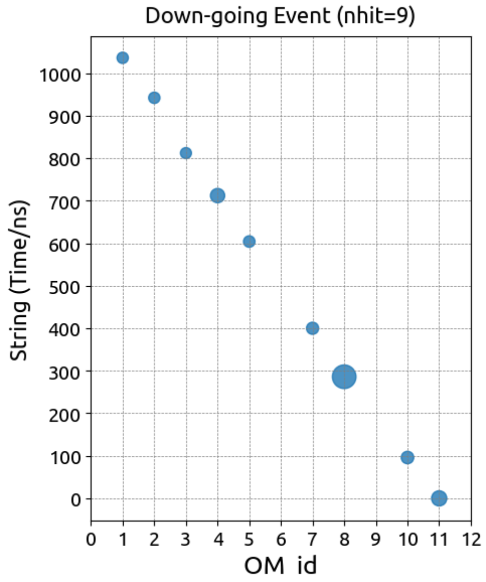
- Resulution ~0.1°(tracks), <3°(cascades)
- Energy resolution: ΔlogE~0.3(tracks)
  ΔE~10-30% (cascades).
- Discovering Neu sources (>100 TeV) at the level of 5σ within several years

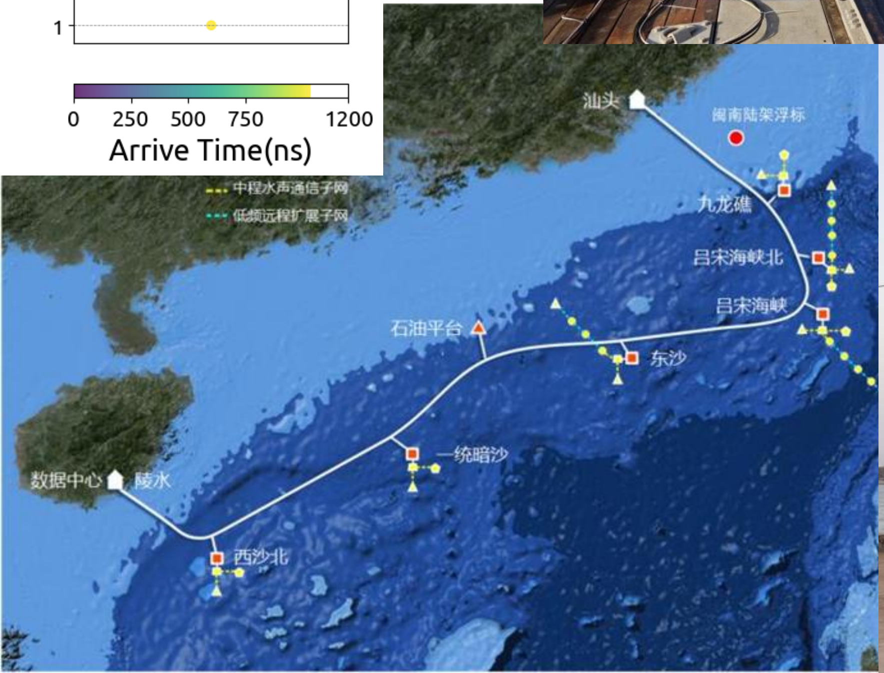
- Volume： 6×6 = 36 km^2, **~30** km^3
- Separations of strings： Dstring ~ 130 m
- Separation of optical modules ： DOM ~36 m
- Length of each string： ~860 m
- ~2,300 strings, 24 OMs in each string， 55000 OMs in total

130 m

Prototype tests at GVD at L. Baikal and in South China sea



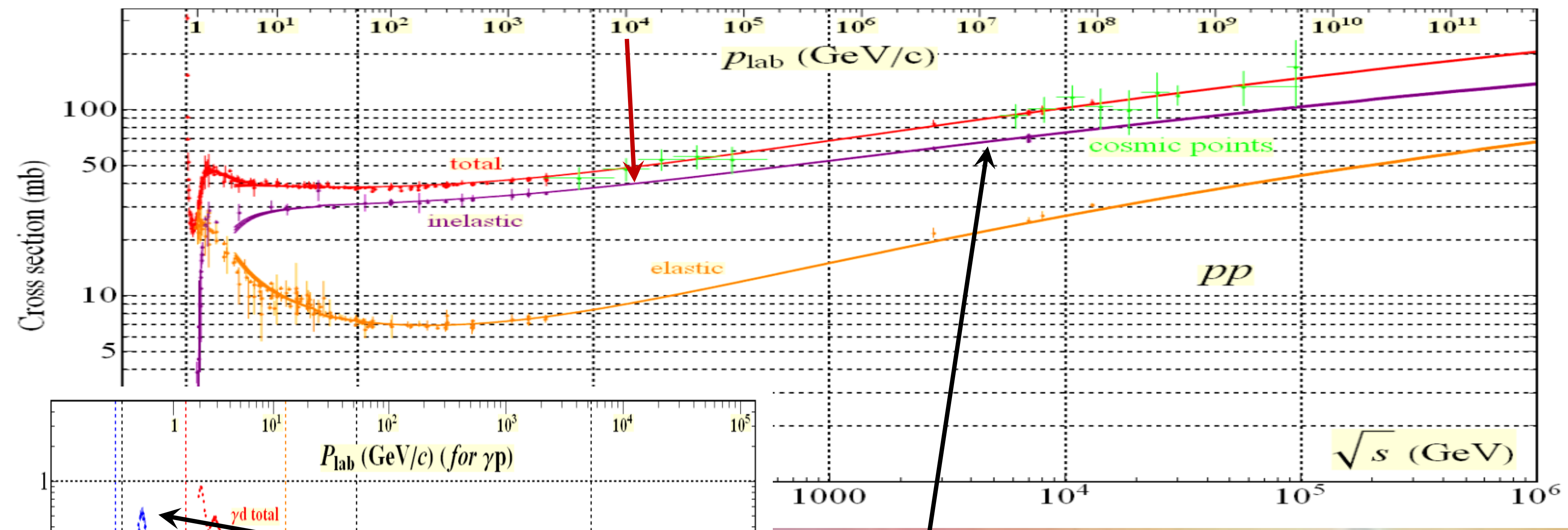


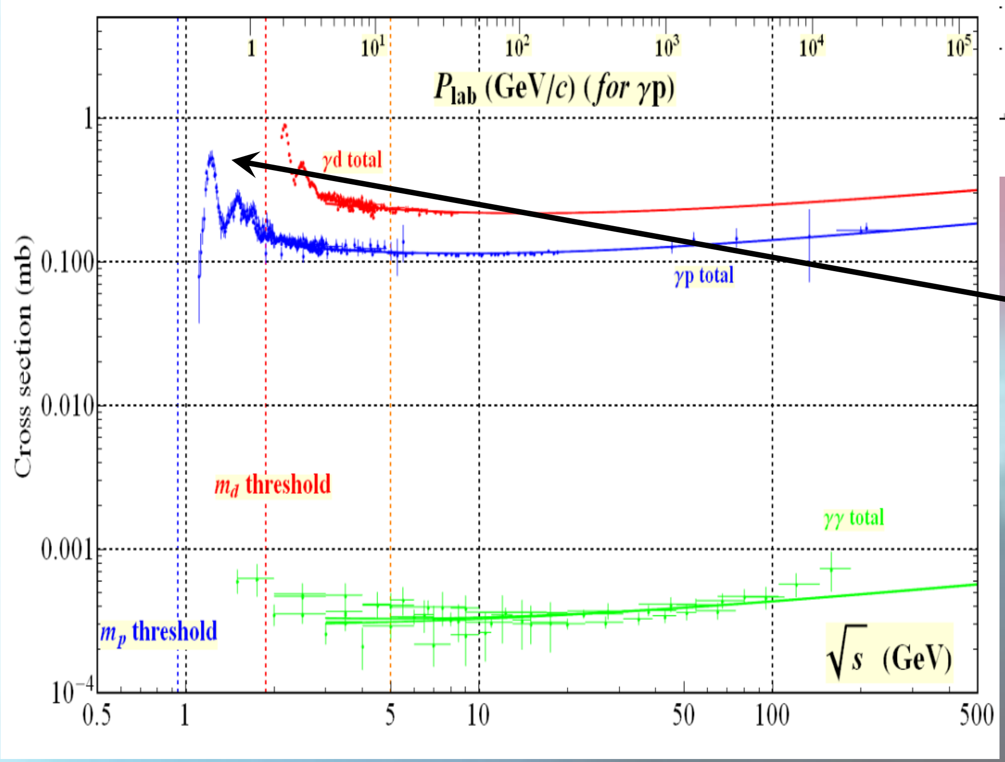


Summary

- Proton spectrum is measured for the first time with a 90% purity sample and provides evidence of the 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 km^3 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

p-p versus γ-p: σ and interaction time scale





- For 10 TeV protons, σ_{pp}~40 mb
- If $n_X >> 70\ n_{gas}$, γ-p would dominate over p-p
- This seems to be a very reasonable assumption at places very close to the accretion disk

- For 10 PeV protons hit on ambient gas (protons in Lab) , inelastic σ~70 mb
- For PeV protons hit on UV photons star light of the companion WR, the Δ resonance σ~0.6 mb
- Interaction time scale $\tau = 1/\sigma n_T c$, σ is the cross section , n_T is the # density of targets, c is the speed of light
- Only if $n_{UV} >> 120\ n_{gas}$, where n_{UV} is the photon density in the star light near the BH and n_{gas} is the particle density of the gas on the WR star surface
- In reality, $n_{UV} > 10{,}000\ n_{gas}$, at the surface of the WR star
- So $\tau_{pUV} << \tau_{pp}$, accelerated proton at ~PeV scattering on UV photons in the WR star light can be dominant over the scattering on the particles in the gas of the star surface