

LHAASO, 拉索, @2021-08

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

# Cosmic Ray Origin and Supernova Remnants

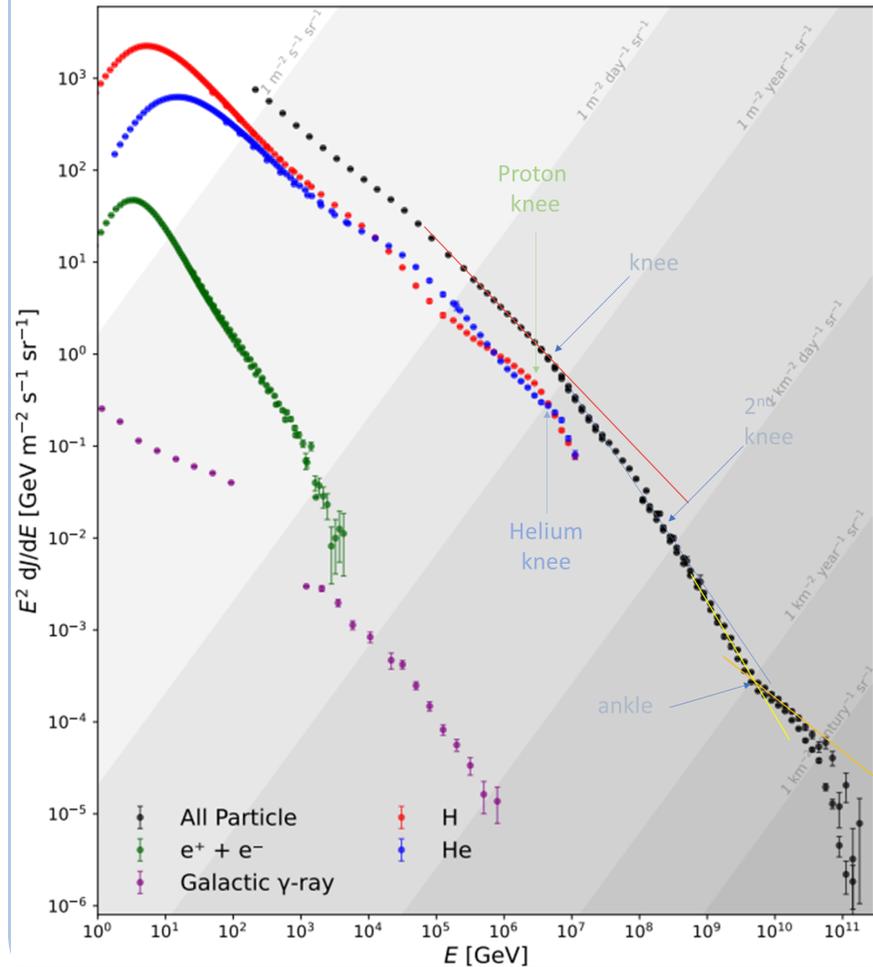
by Zhen Cao 曹臻, IHEP, CRRC, China

Symposium of UHE  $\gamma$ -ray from SNR and CR Origin, Yuxi, China, Feb. 2026



# LHAASO has done tree important measurements

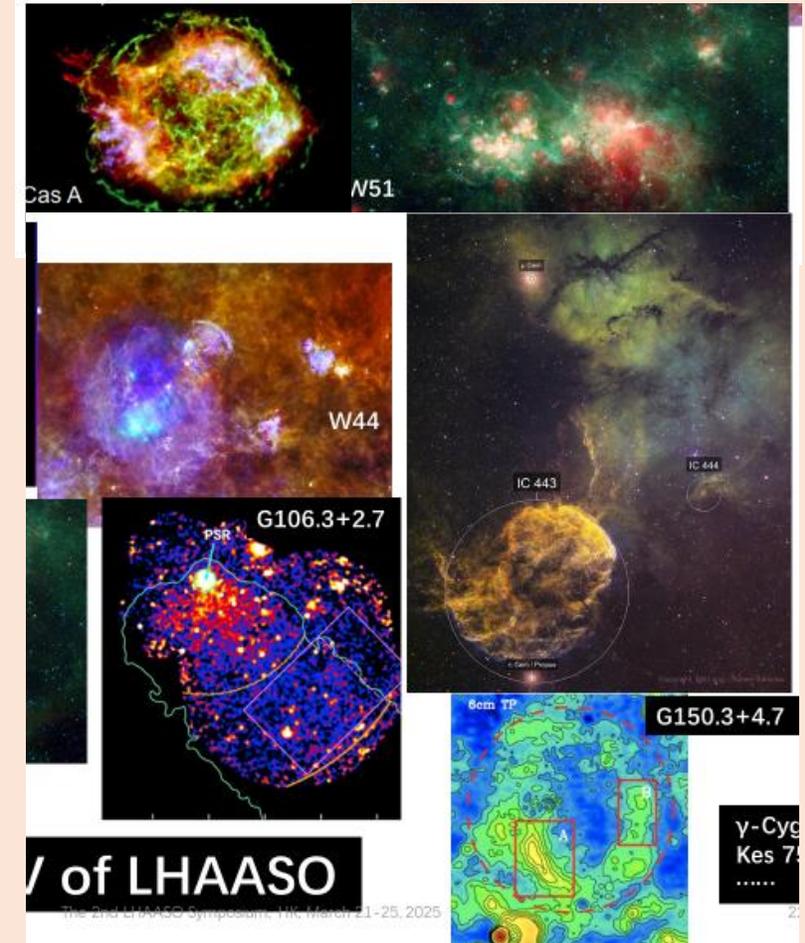
## 1. Measures knees of CR H & He



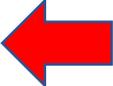
## 2. Discovers $\mu$ Qs being UHE emitters

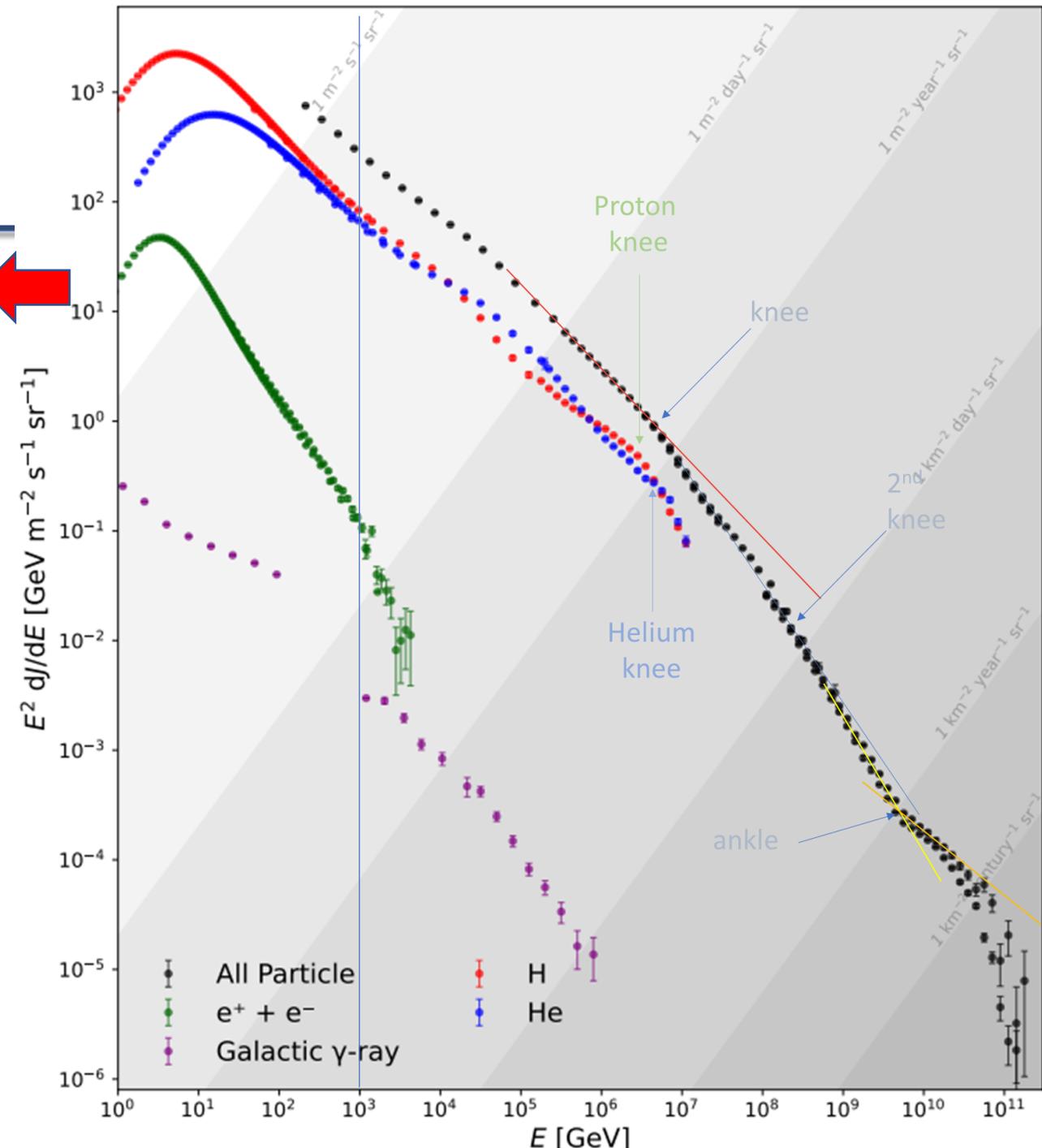


## 3. Observes SNRs in VHE band



# Content

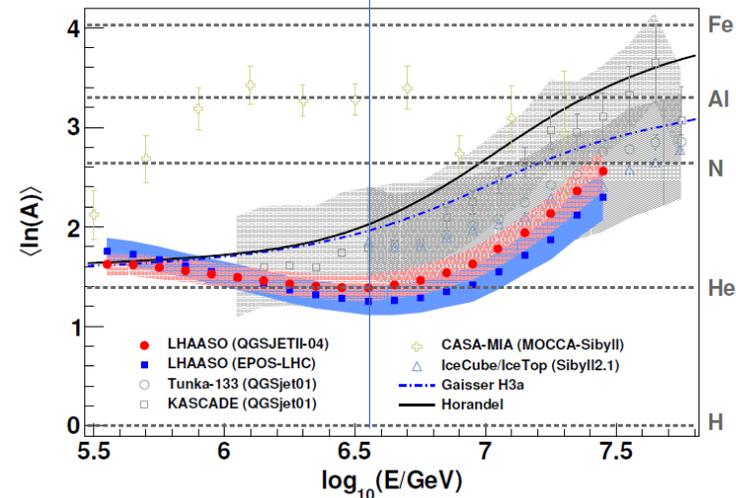
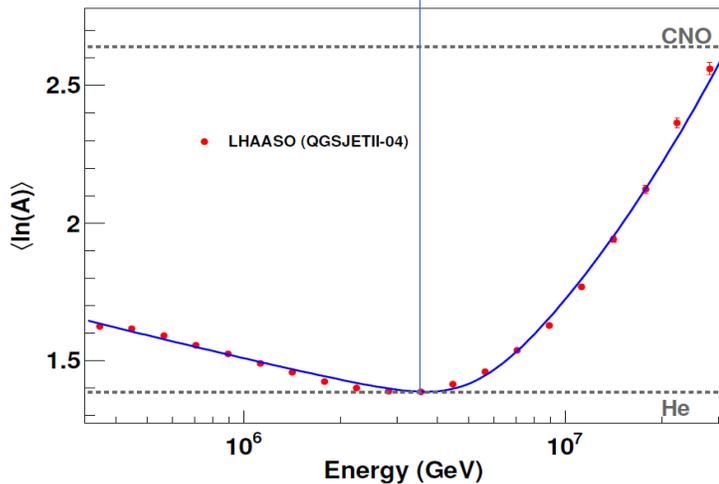
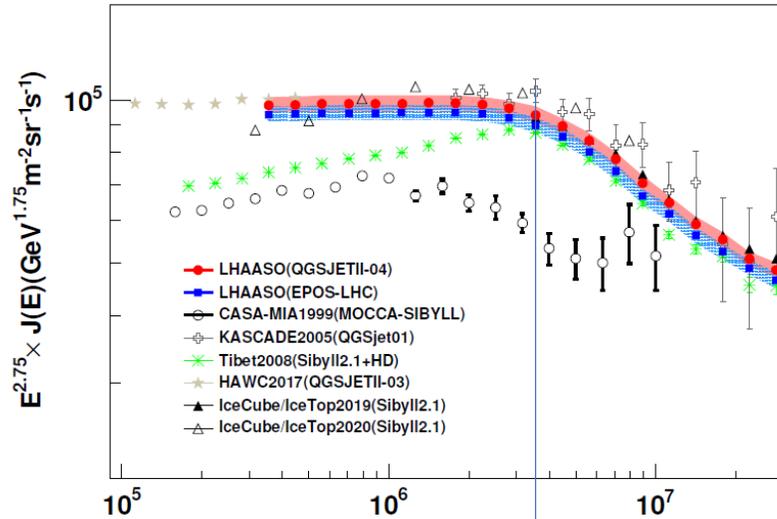
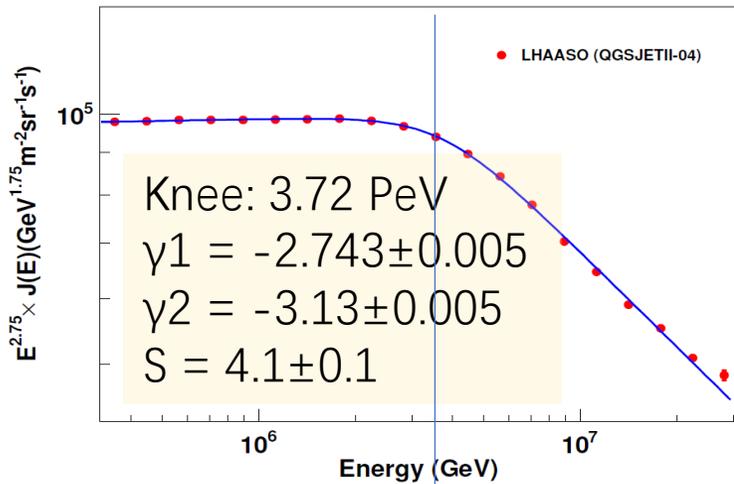
- CR measured at the solar system 
- SNRs as the candidates of CR Accelerator
  - The assumption
  - 1<sup>st</sup> observational evidence around 1 GeV energy band
- Observations in VHE  $\gamma$ -ray band and the discoveries
  - SNRs in dense media
  - SNRs in the environment with few targets
  - A SNR in a cavity
- New component at HE
- Conclusion and discussion



# All-particle energy spectrum & composition by LHAASO



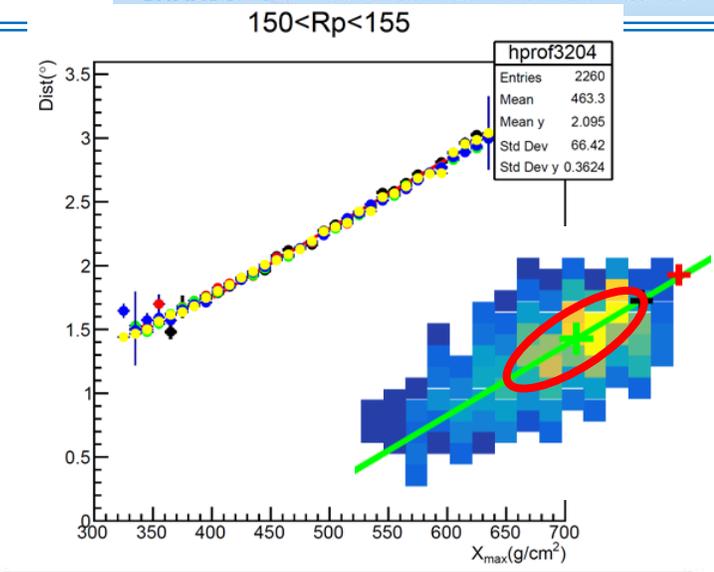
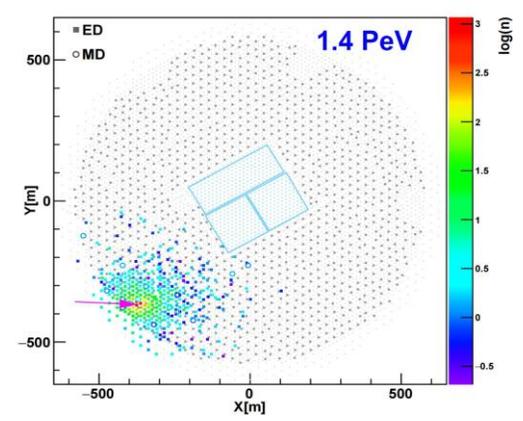
(from 0.3 to 30 PeV)



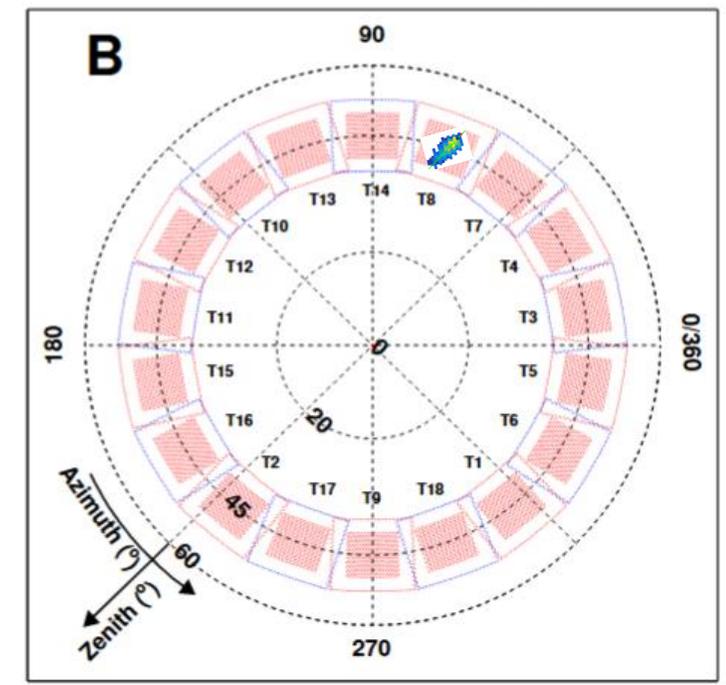
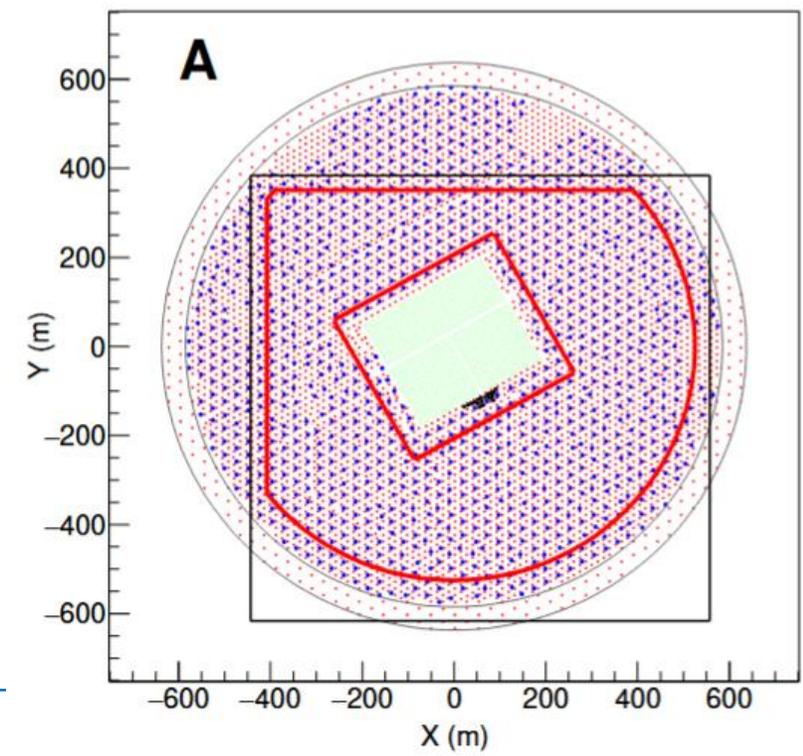
- Systematic uncertainties are sufficiently small
- This unveils a clear correlation between the flux and the composition at the knee

# Hybrid Measurement of Cosmic Rays @ knee

WFCTA: 18



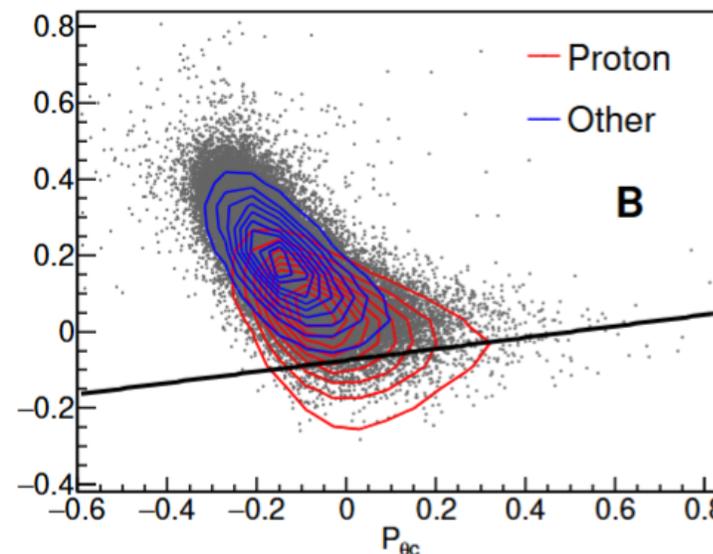
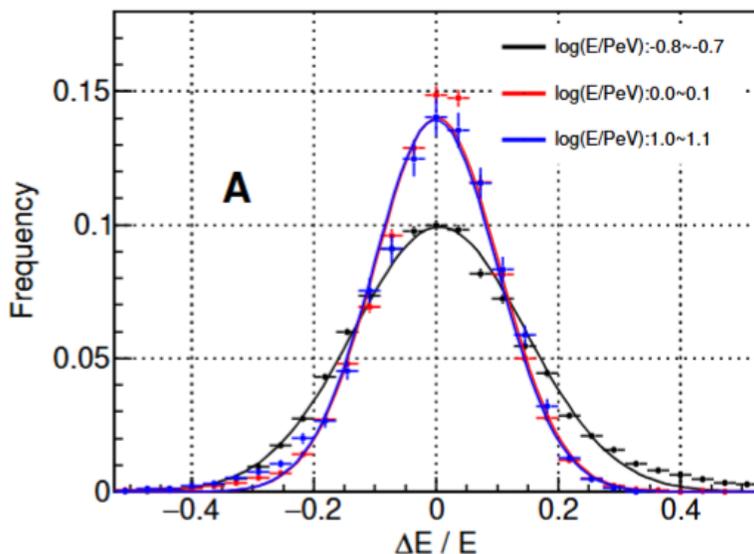
KM2A: (ED, MD, 1 km<sup>2</sup>)  
ED: 5195  
MD: 1188



# Reconstruction and Proton shower selection

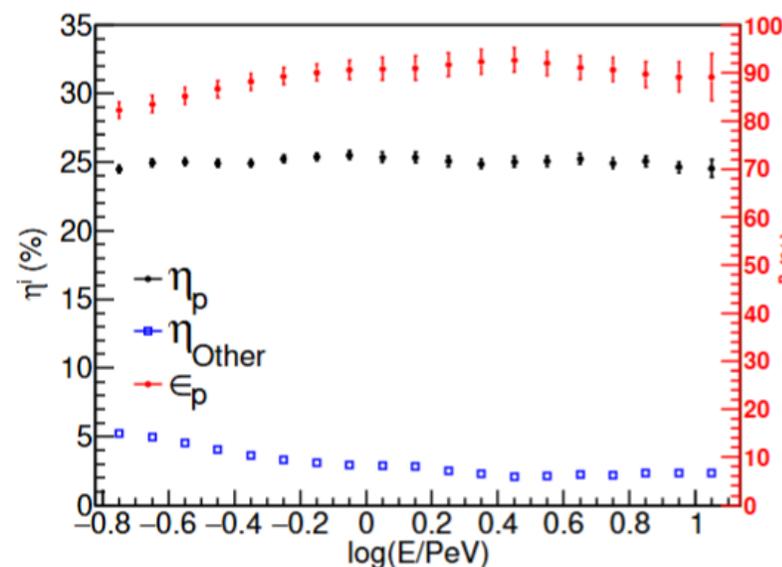
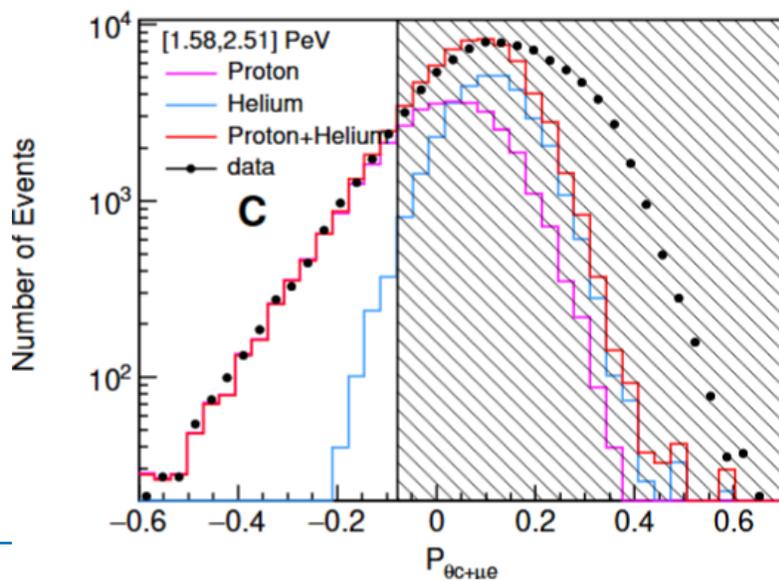
Energy reconstruction

Gaussian energy resolution function



$\mu$ -content Vs. Shower maximum depth  $X_{\text{max}}$

Combined species-sensitive Parameter  
Simulated vs data  
Parameter



Selection purity & efficiency for protons and other nuclei

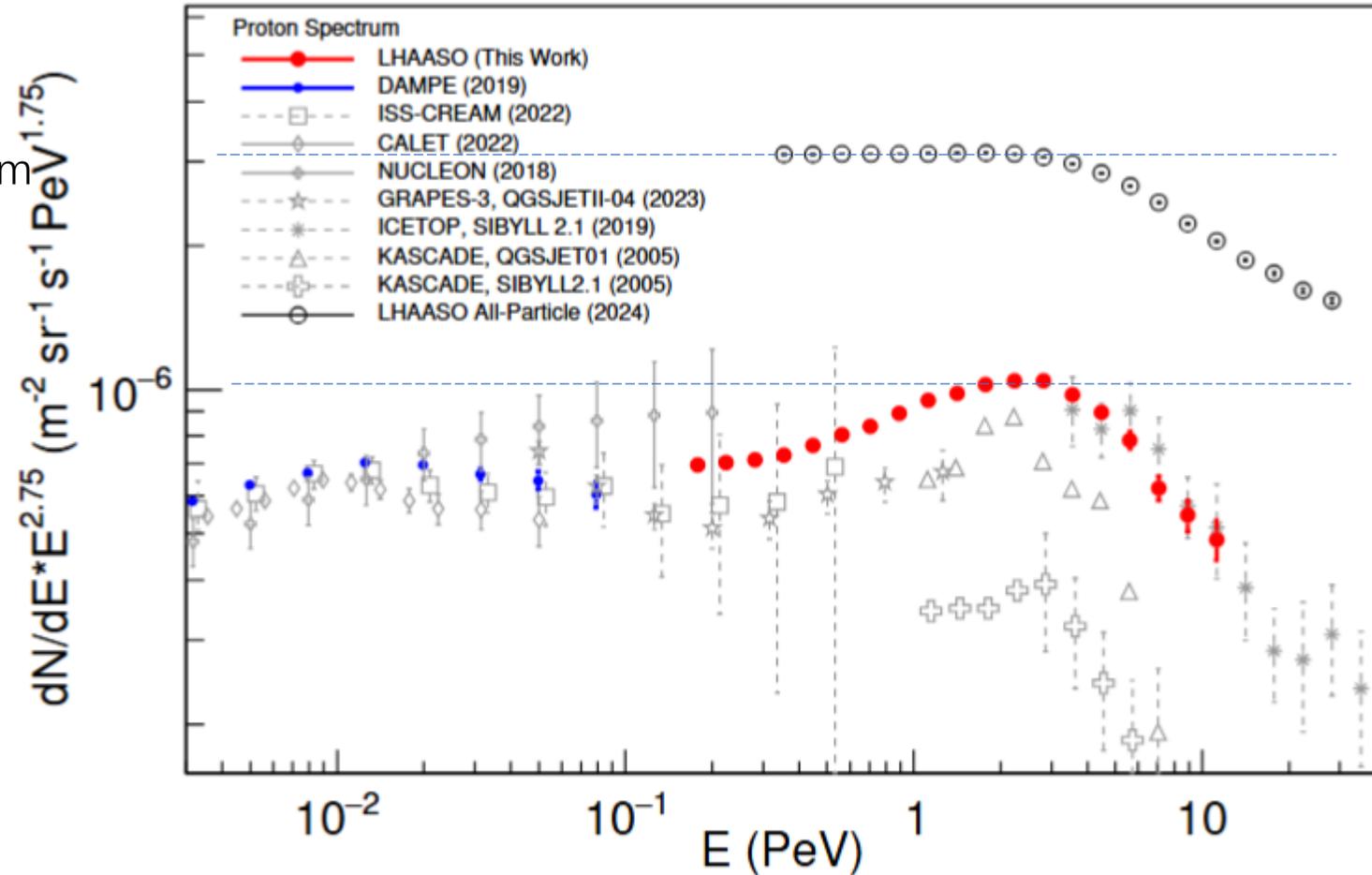
Hardening above 100 TeV

Knee @ knee of all-particle spectrum

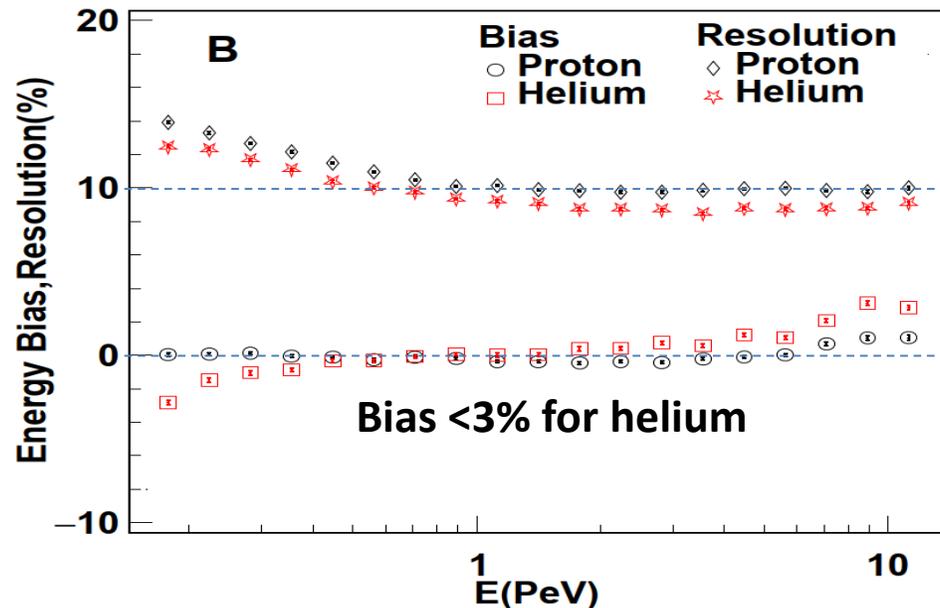
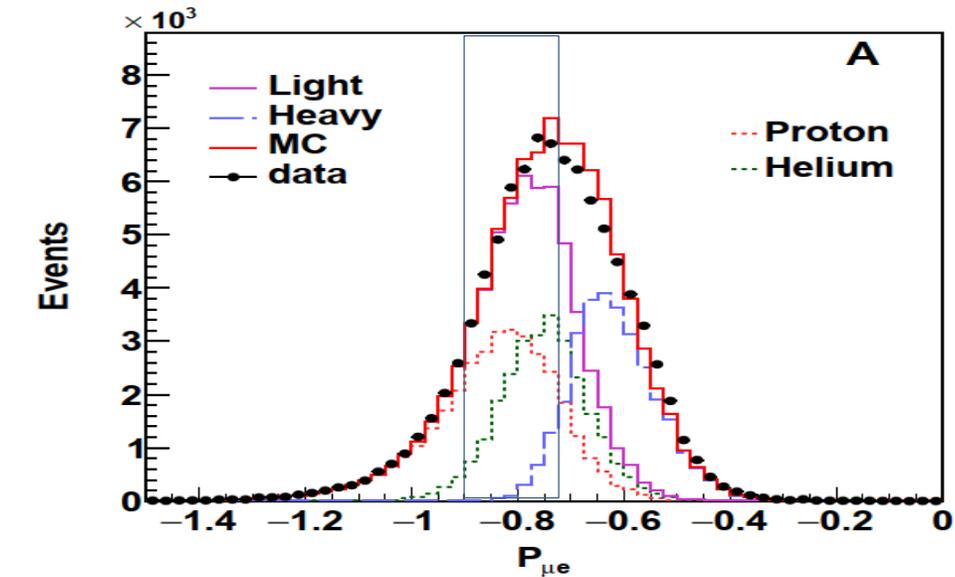
Steeper spectrum than all-particle

~1/3 fraction

New population of sources?



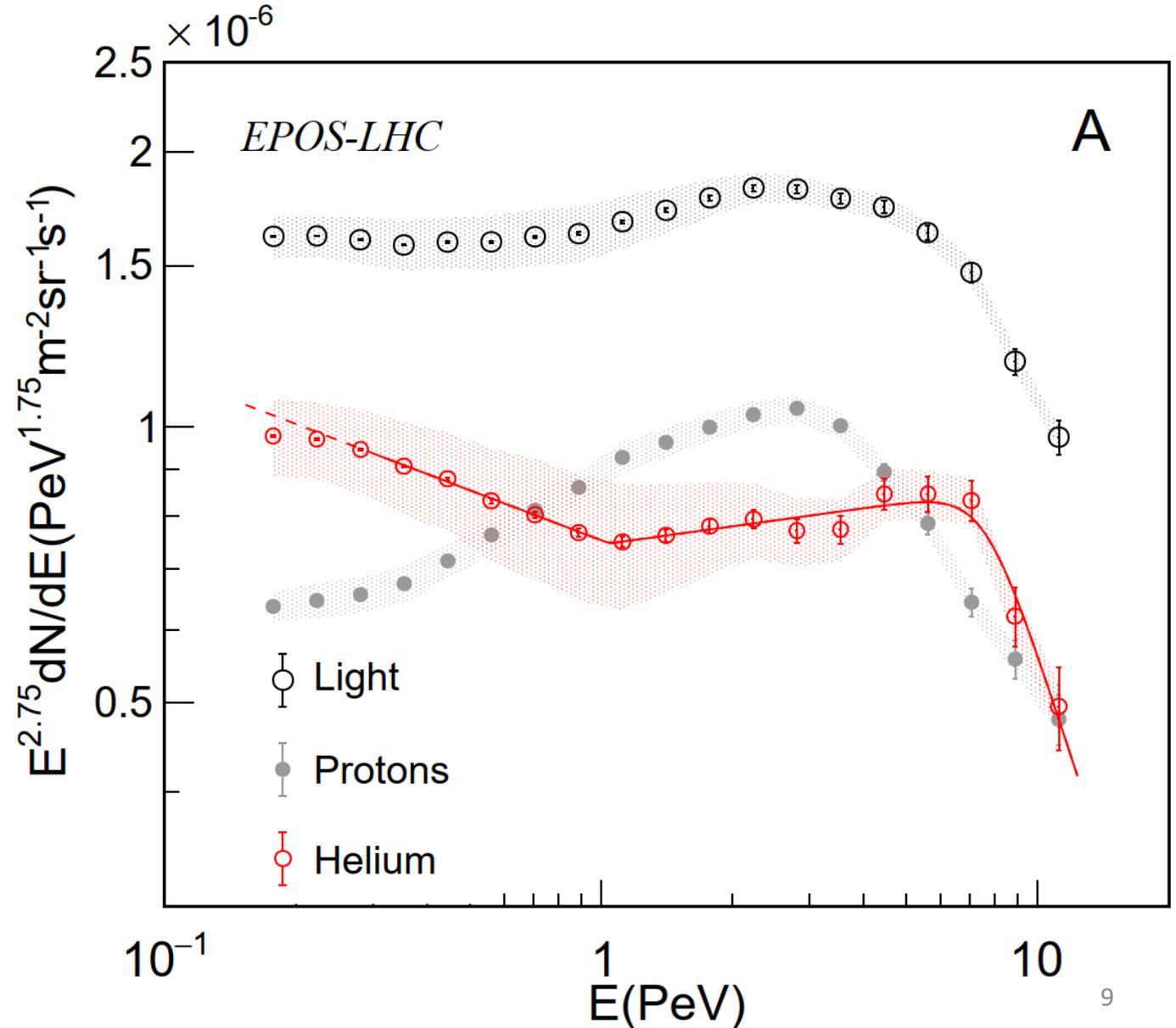
# Light component (H+He) Selection



- 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

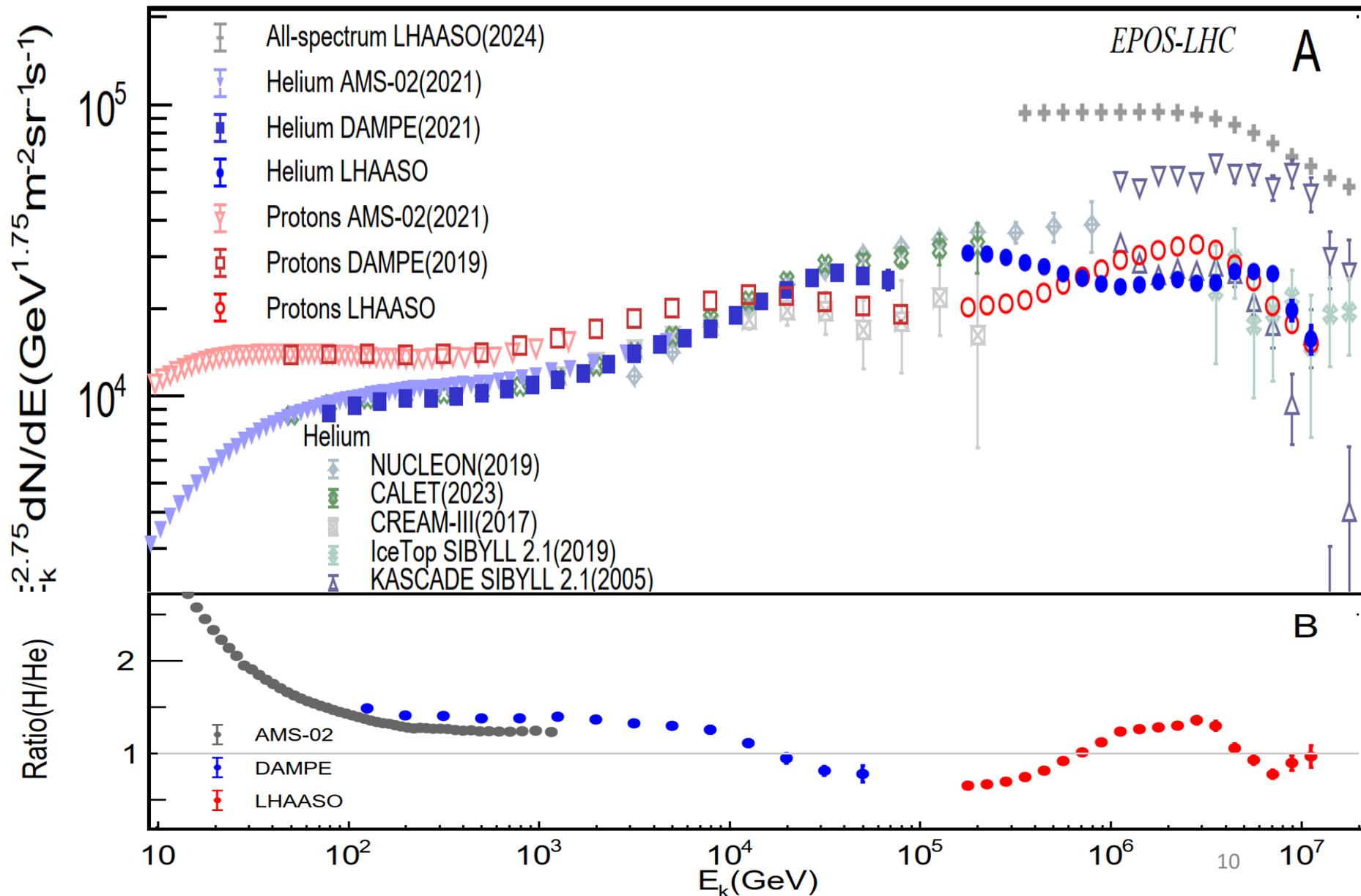
# Spectra of Light CRs and Helium Nuclei

- High Precision  $J_{\text{Light}}(E)$  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:  $6\sigma$
  - 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



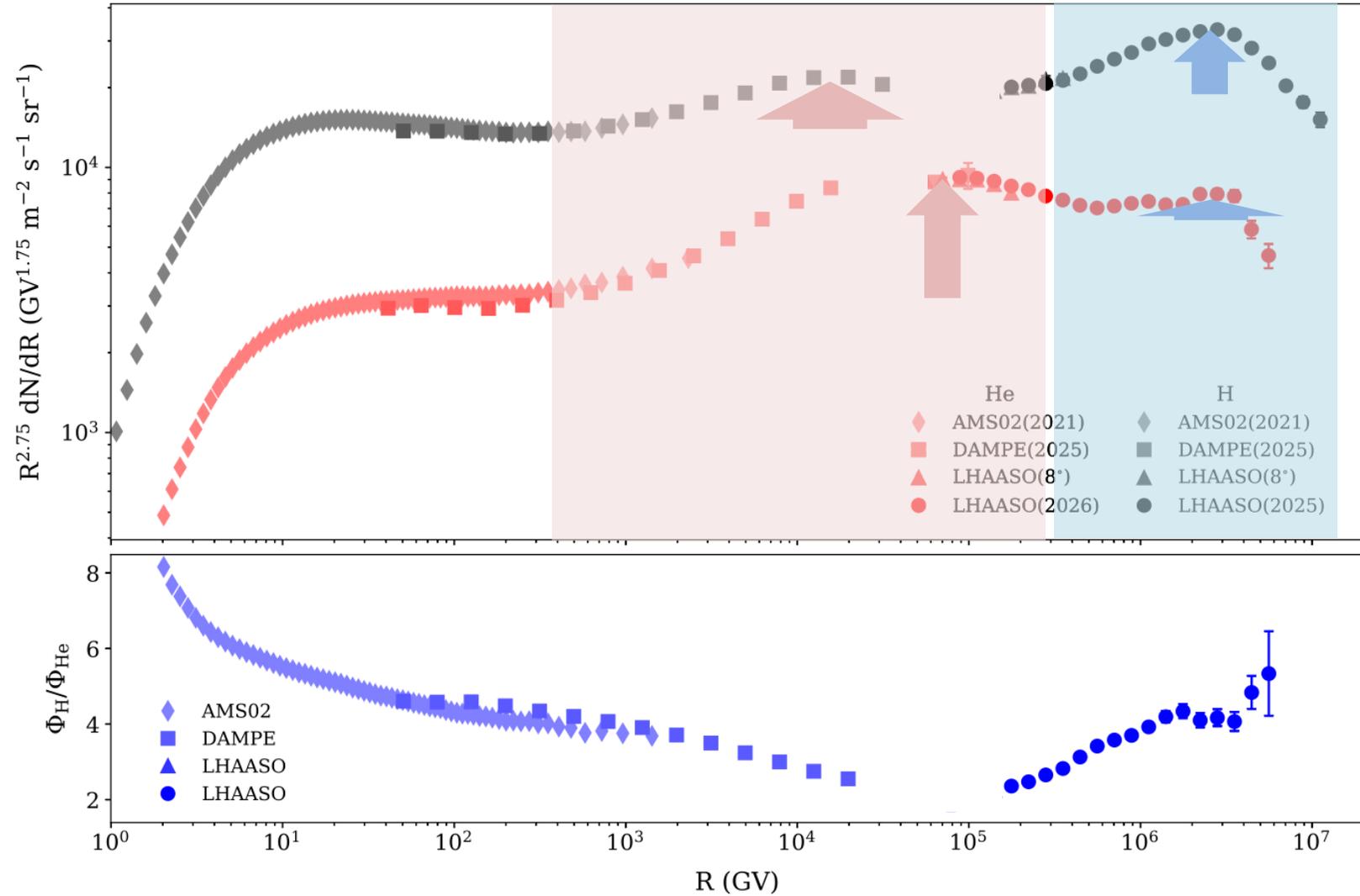
# Helium Spectrum and p/He ratio

- 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

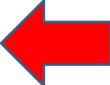


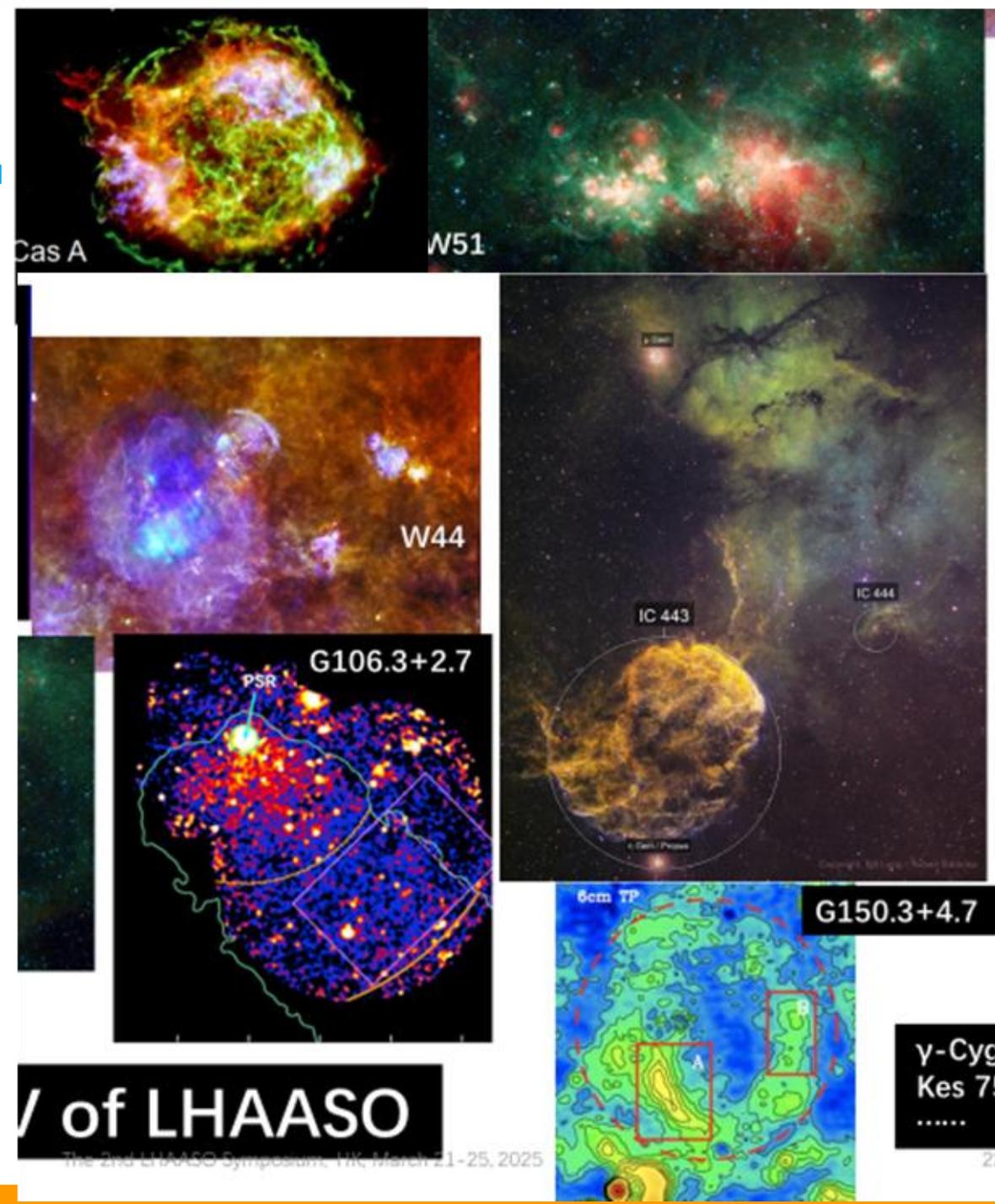
# Spectra of Rigidity of protons and helium nuclei

- 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



# Content

- CR measured at the solar system
- SNRs as the candidates of CR Accelerator 
  - The assumption
  - 1<sup>st</sup> observational evidence around 1 GeV energy band
- Observations in VHE  $\gamma$ -ray band and the discoveries
  - SNRs in dense media
  - SNRs in the environment with few targets
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# Known for 90 years as a hypothesis .....



Baade & Zwicky (1934) :  
SN → 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

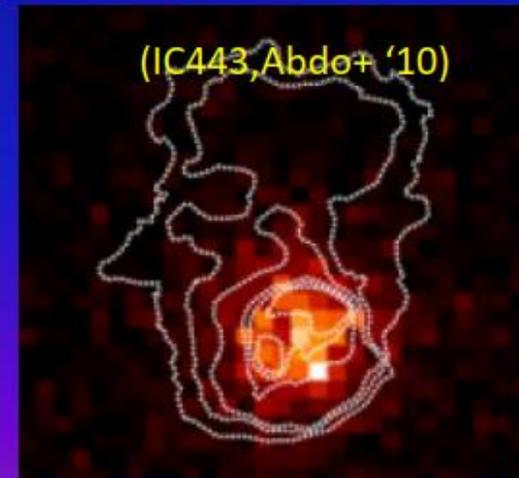
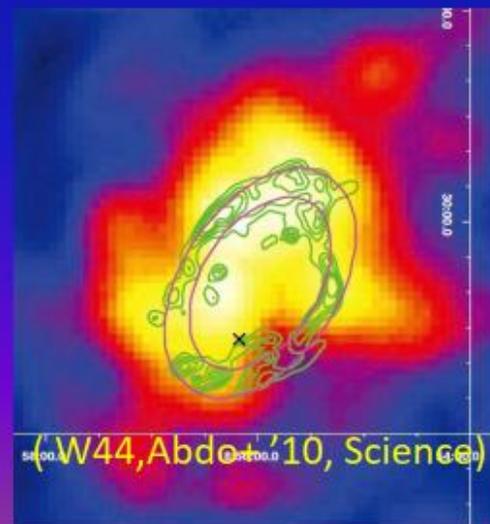
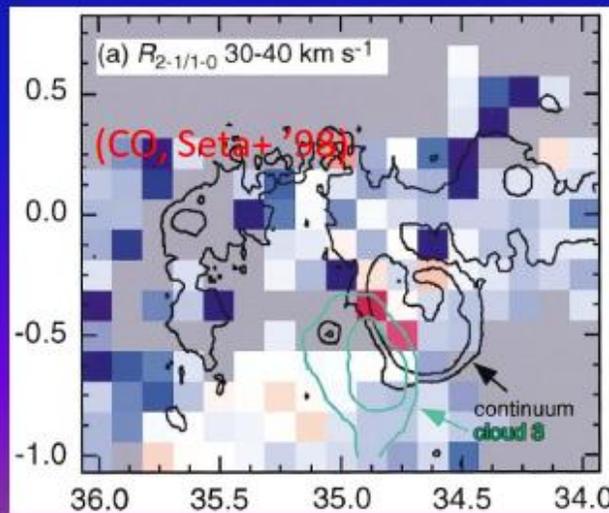
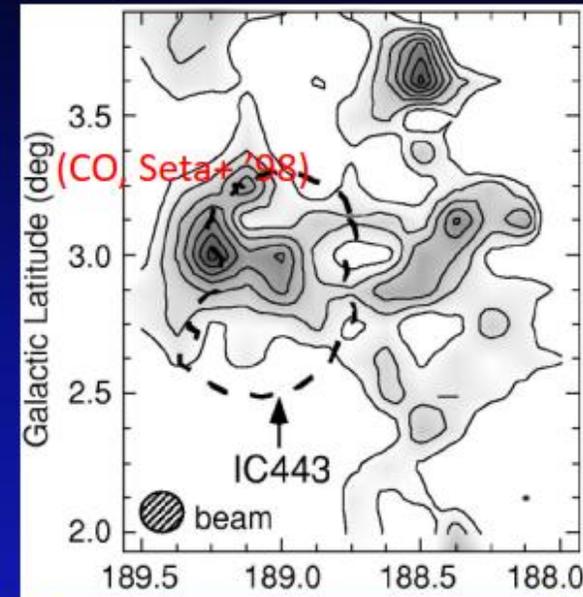
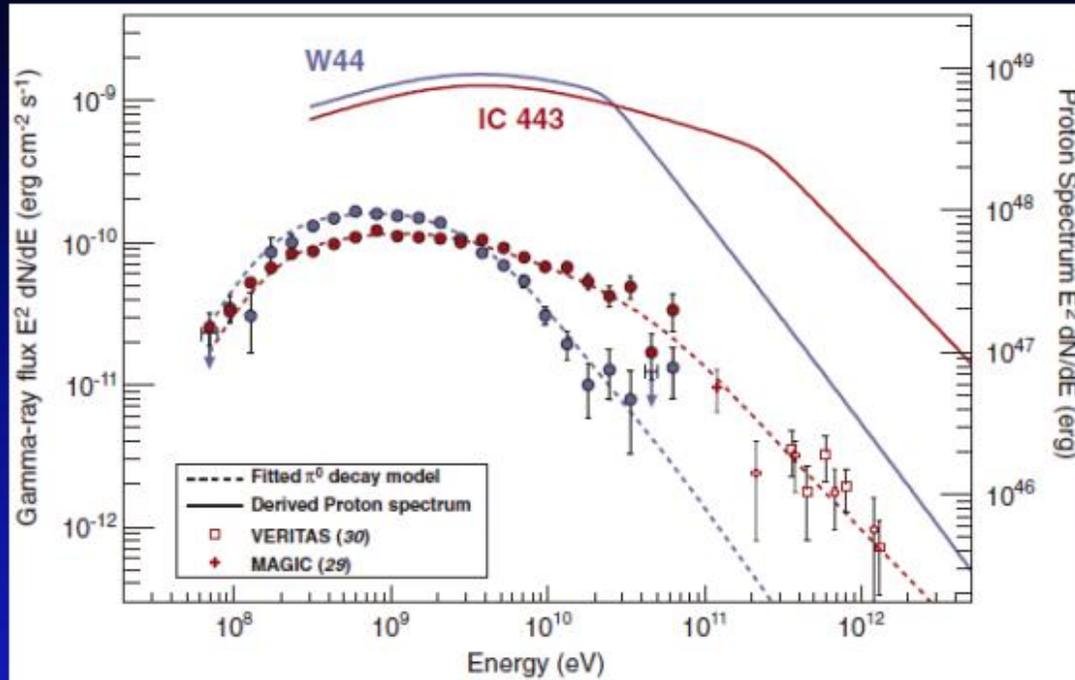
happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a **neutron star**, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed 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.

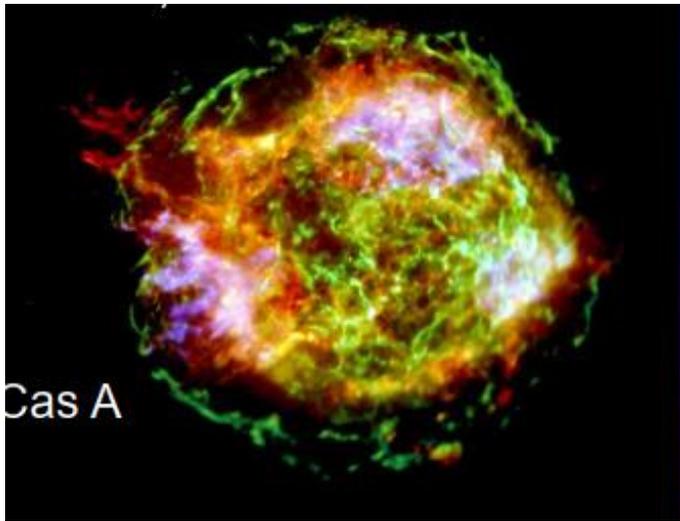
*D. Conclusions.*—From the data available on super-novae we conclude (1) Mass may be *annihilated* in bulk. By this we mean that an assembly of atoms whose total mass is  $M$  may lose in the form of electromagnetic radiation and kinetic energy an amount of energy  $E_T$  which probably cannot be accounted 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.

Fermi-LAT (Ackermann, M. et al. 2013, Science): W44 & IC443

AGILE (Giuliani, A. et al. 2011, ApJ, 742, L30): W44

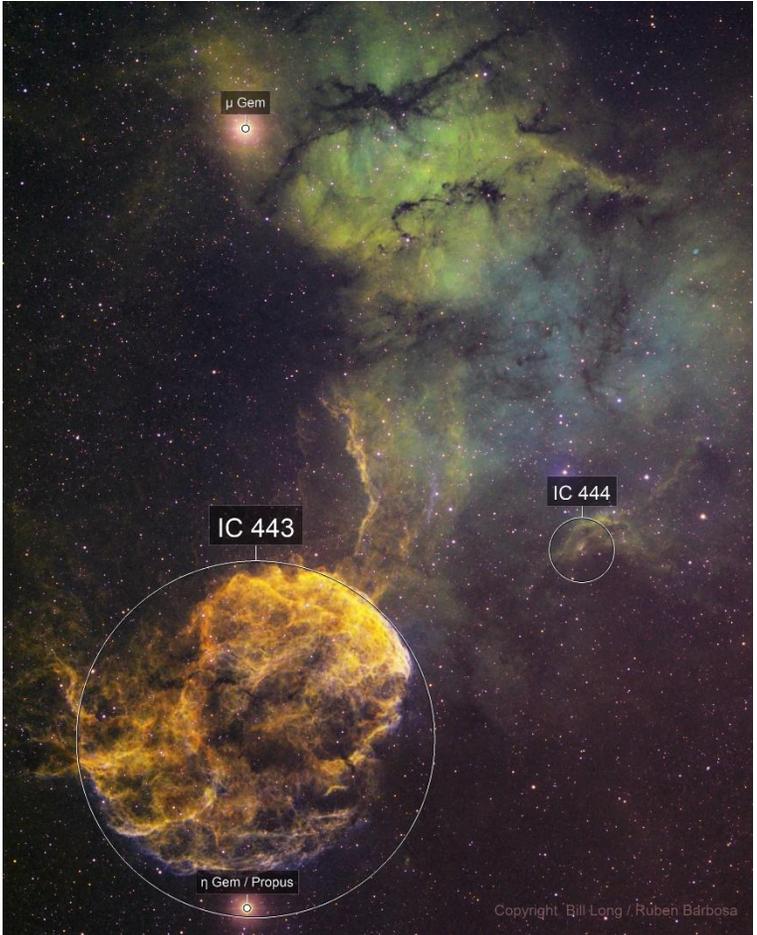




Cas A



W44



IC 443

IC 444

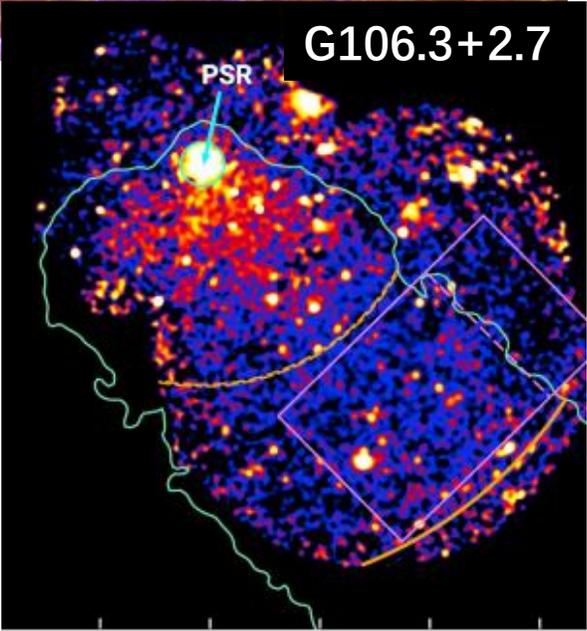
$\mu$  Gem

$\eta$  Gem / Propus

Copyright Bill Long / Ruben Barbosa



W51



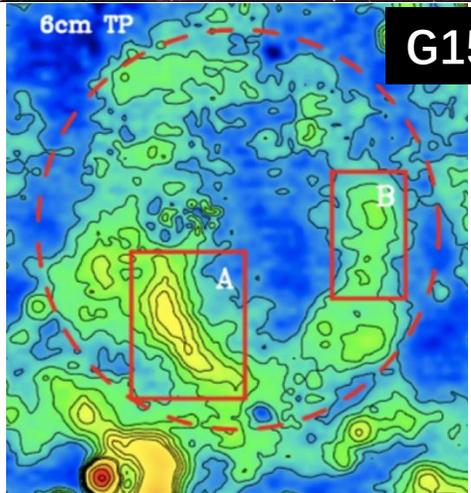
G106.3+2.7

PSR

# SNRs in the FoV of LHAASO

2025/3/21

The 2nd LHAASO Symposium, IHK, March 21-25, 2025



6cm TP

G150.3+4.7

A

B

$\gamma$ -Cygni  
Kes 75  
.....

**In dense cloudy environment**

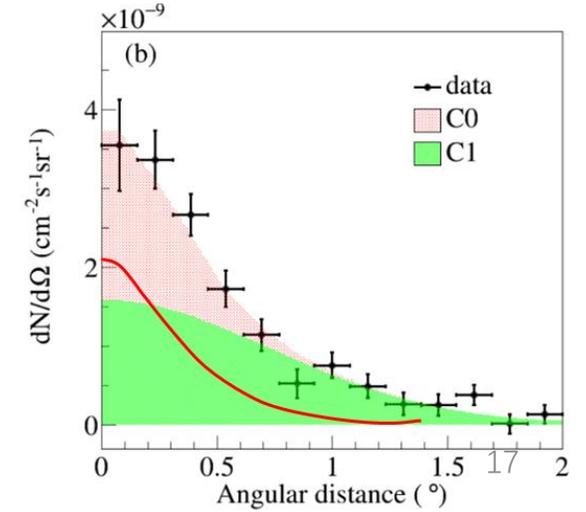
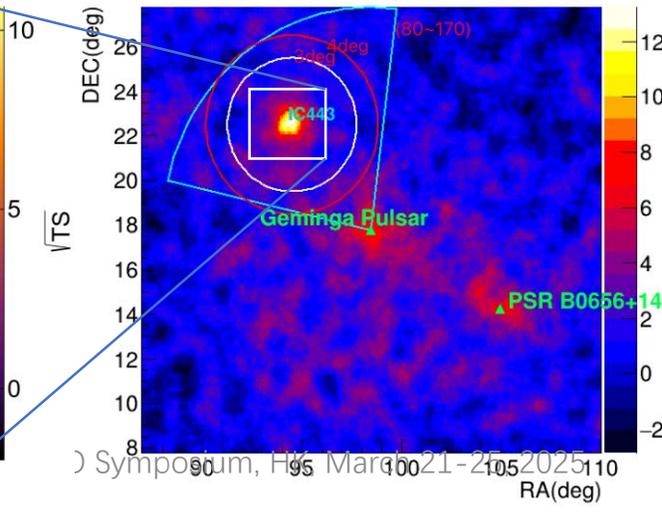
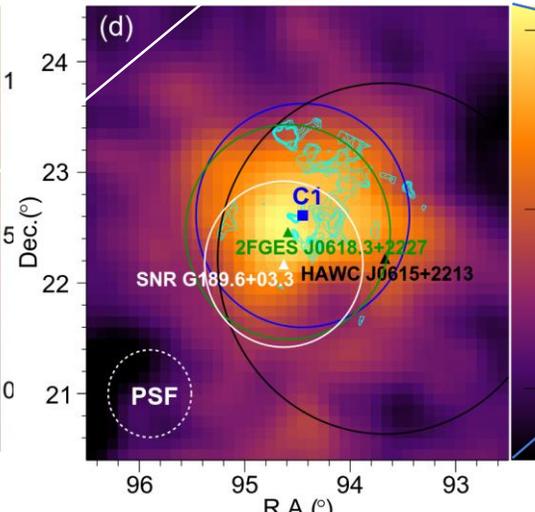
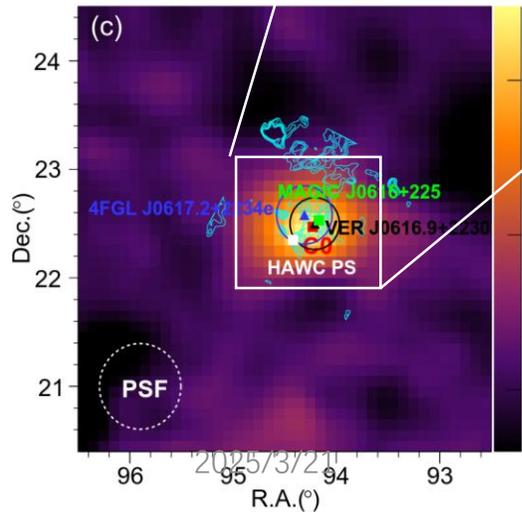
# IC 433 by LHAASO: Morphology

- The total significance of IC 443.
- Two Gaussian components: 1 Gauss VS 2 Gauss

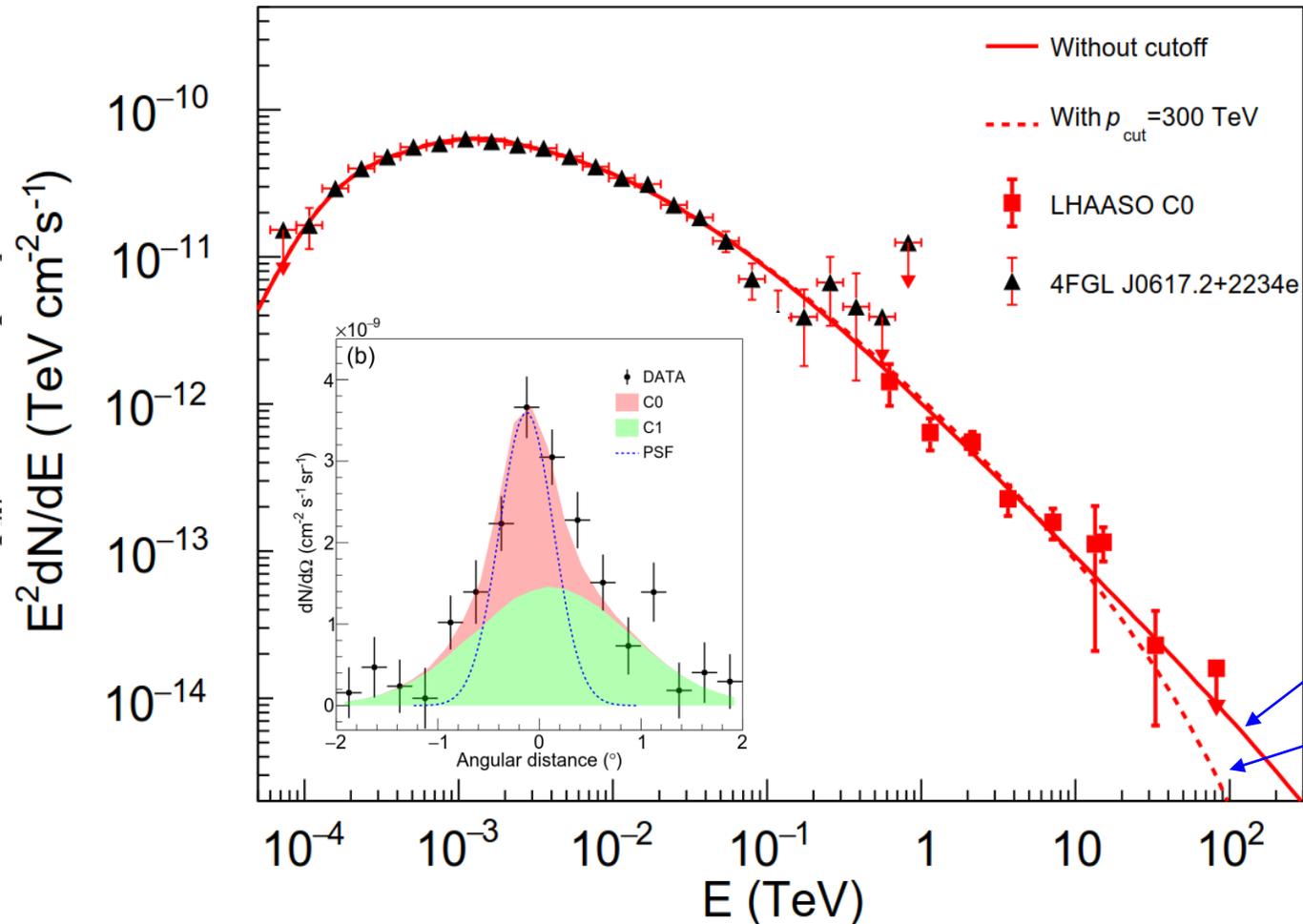


Model	$\Delta TS$	Name	R.A. ( $^{\circ}$ )	Dec. ( $^{\circ}$ )	Extension ( $^{\circ}$ )
Two Components	40	C0	$94.24 \pm 0.03$	$22.43 \pm 0.02$	Pt
		C1	$94.40 \pm 0.07$	$22.58 \pm 0.06$	$1.00 \pm 0.11$
One Component	-	-	$94.30 \pm 0.03$	$22.52 \pm 0.03$	$0.58 \pm 0.05$

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



# Interpretation: nice extension of the proton spectrum



## Hadronic origin of C0:

- $N(H) = 20/\text{cm}^3$
- Particle distribution inside SNR:

$$Q(P_i) = Q_0 e^{-\frac{P_i}{P_{i,\text{cut}}}} P_i^{-s_1} \left[ 1 + \left( \frac{P_i}{P_{i,\text{br}}} \right)^{s_2 - s_1} \right]^{-1}$$

$$s_1 = 2.12^{+0.10}_{-0.14}, s_2 = 3.10^{+0.11}_{-0.11}, E_{\text{br}} = 125^{+121}_{-72} \text{ GeV}$$

$$E_{\text{cut}}^p = 10 \text{ PeV}$$

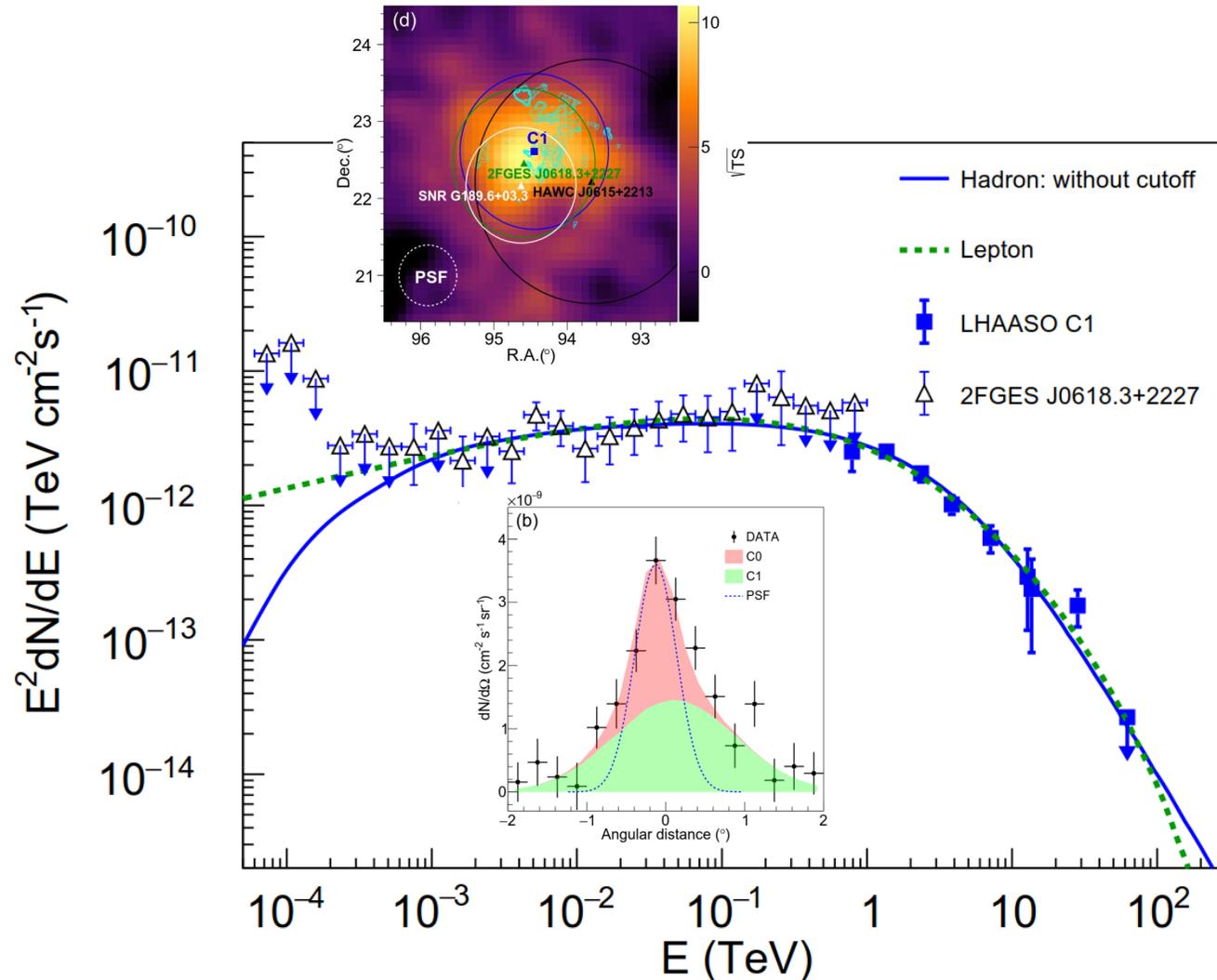
$$E_{\text{cut}}^p (68\%) = 1 \text{ PeV}$$

Interesting to see that the extension seems not to stop at even very high energies!  
We'll see...

# Escaping protons?

Hybrid model:

- C1 : the pp process of **escaping** CRs, resulting in a hardening of the proton energy spectrum ( $s_2' = s_2 + 1$ )
- C1 : IC emission of electrons, with the electron and proton sharing consistent shapes



Parameters:

Dist=1.5k pc

Age=10k year

Particle injection:

Proton:  $s_1 = 1.72, s_2 = 3.0, E_b = 30 \text{ GeV}$

$D_0 = 1.0 \times 10^{27} \text{ cm}^2 \text{ s}^{-1}$  at 100 TeV

$E_{cut}^p = 10 \text{ PeV}$

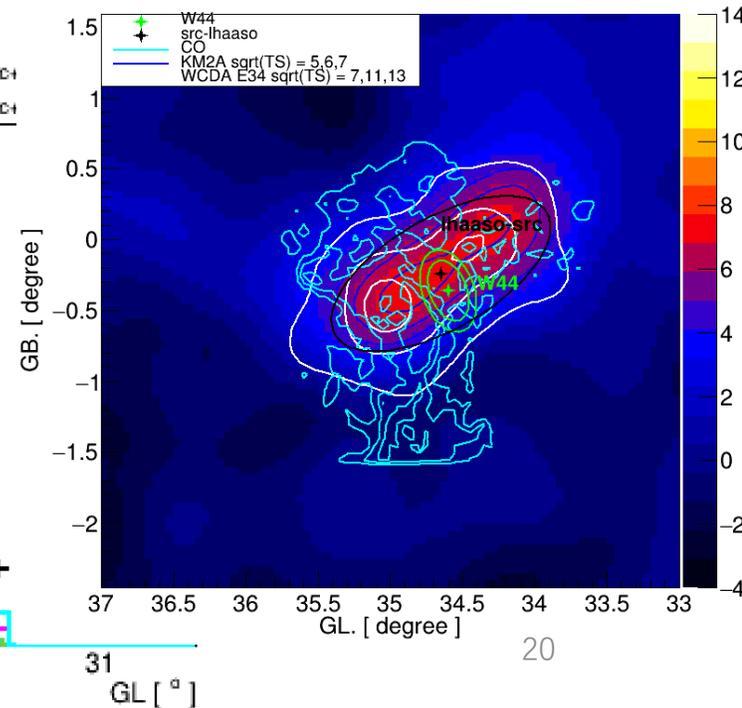
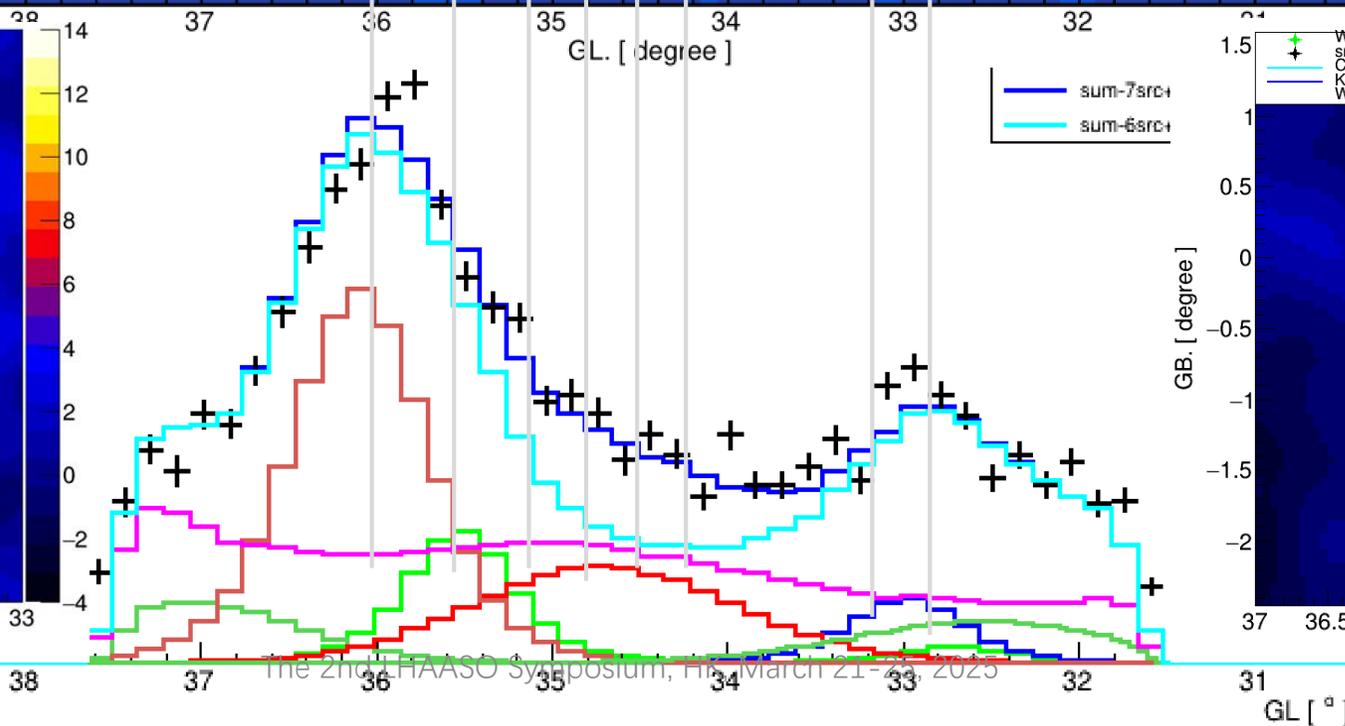
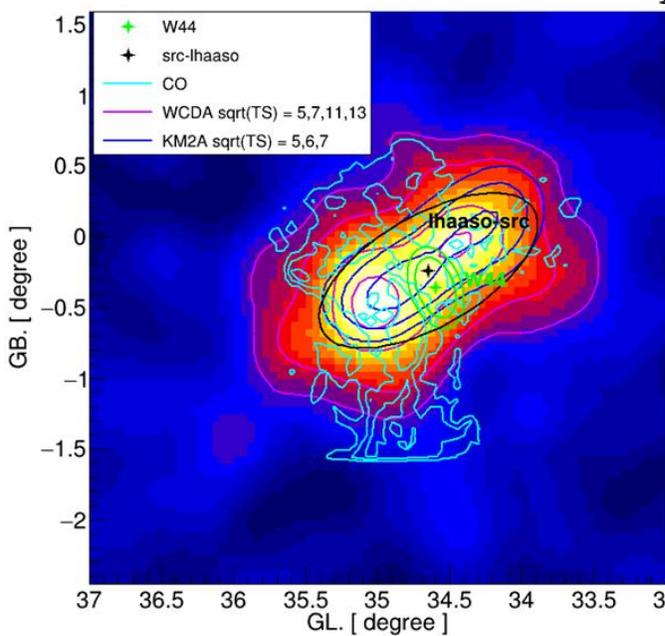
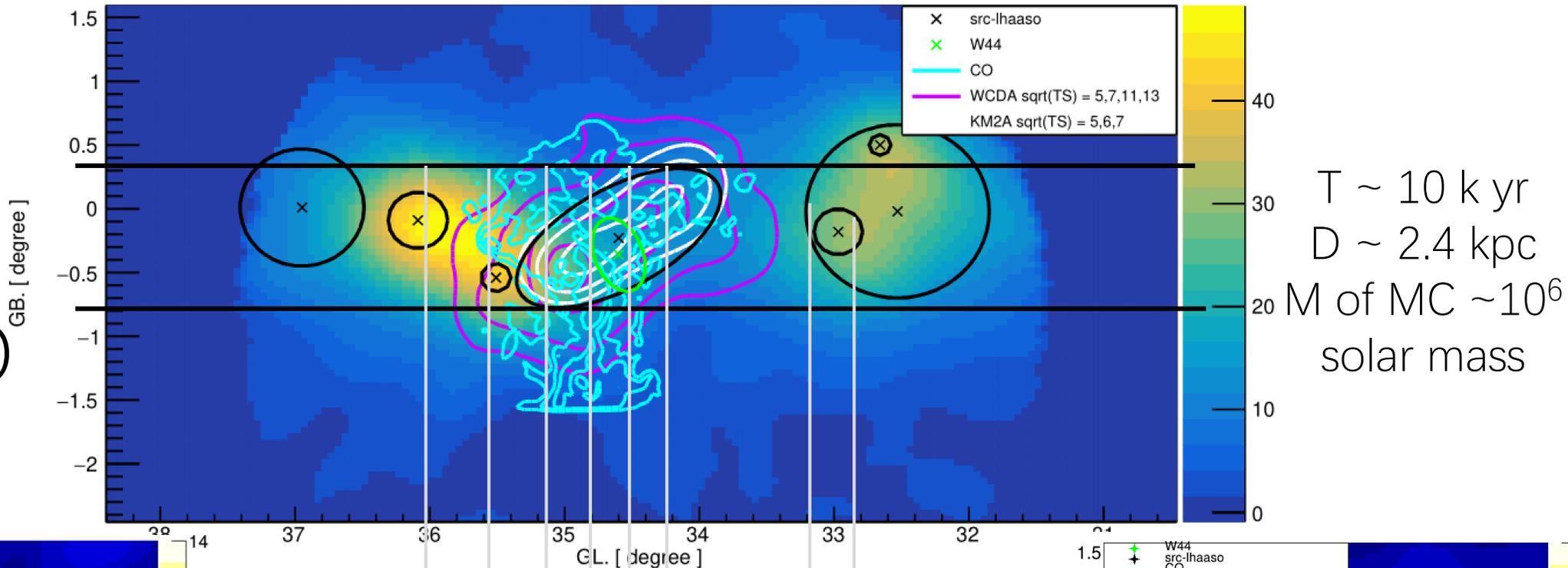
Electron:

$D_0 = 2.0 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$  at 100 TeV and  $K_{ep} = 0.04$

$E_{cut}^e = 50 \text{ TeV}$

$B = 5.0 \mu\text{G}$

# W44 by LHAASO

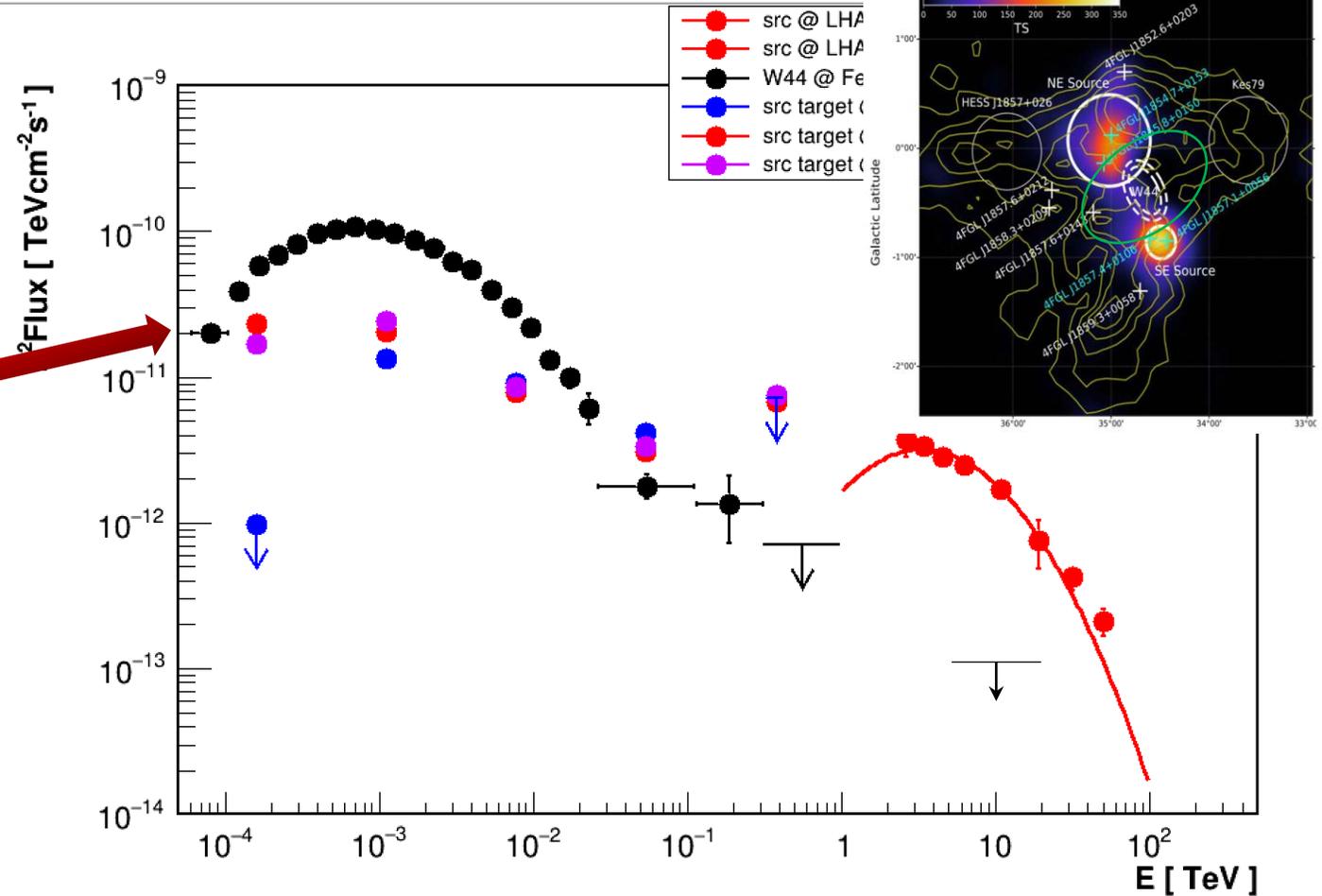
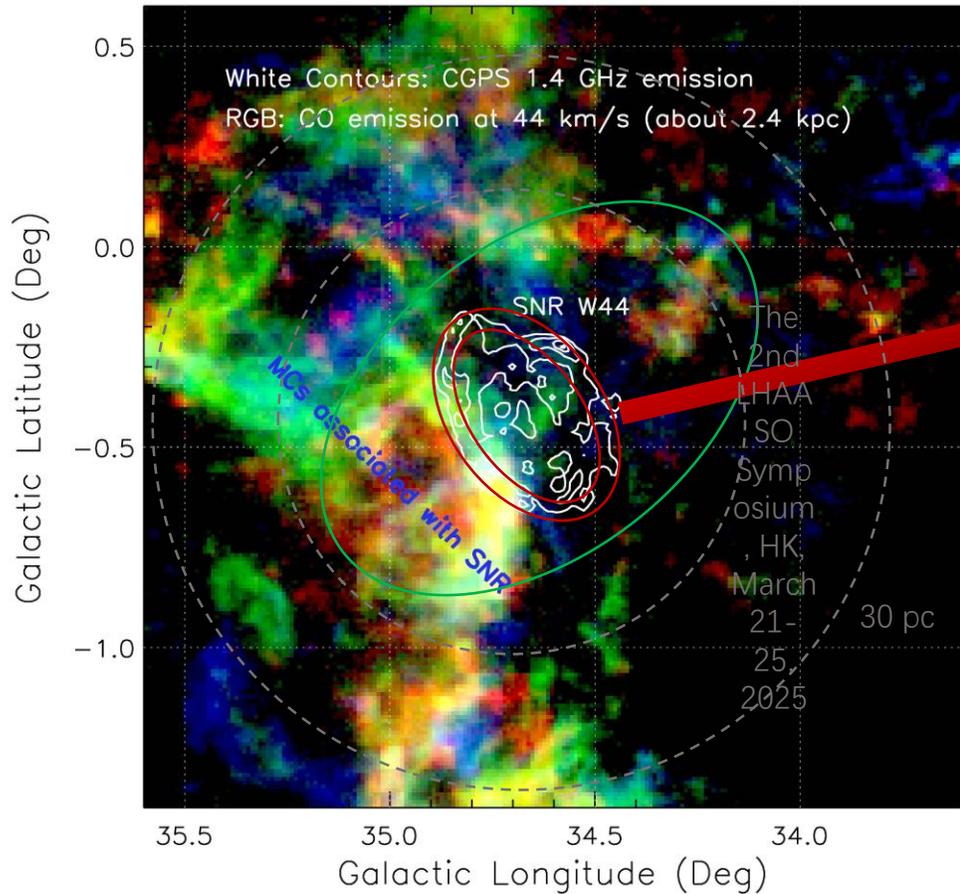


2025/3/21

The 2nd LHAASO Symposium, 19-24 March 2025

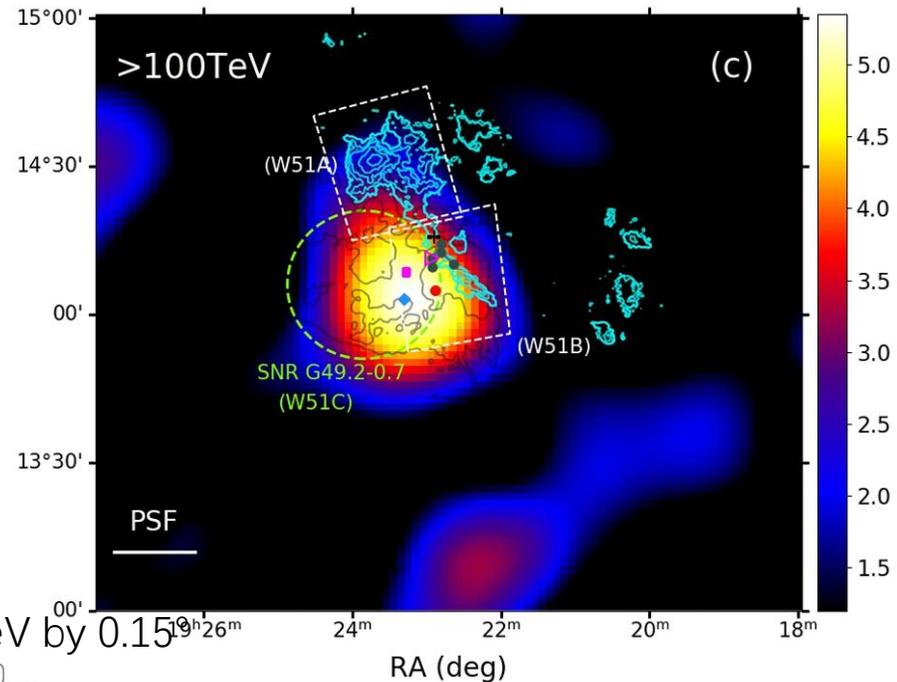
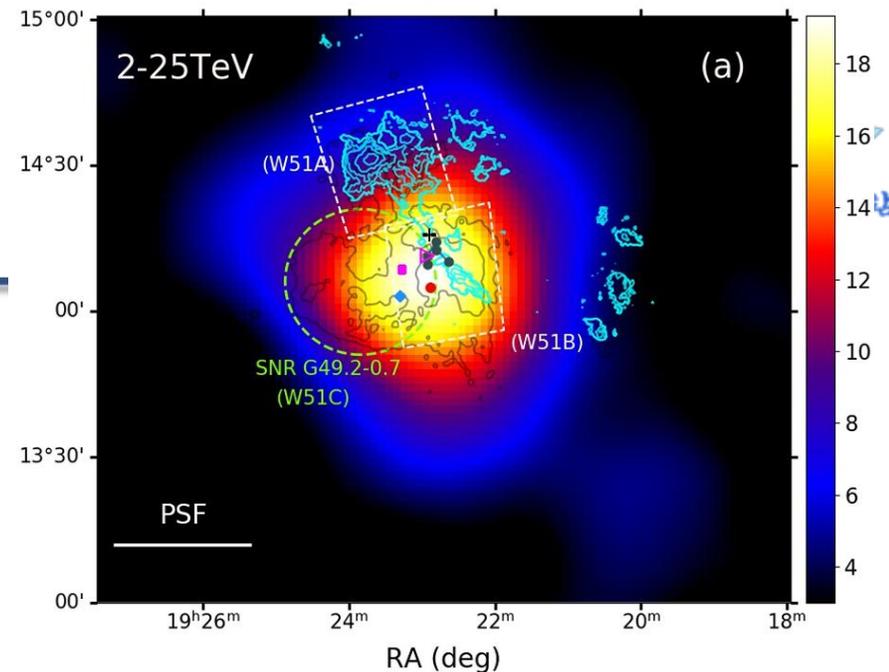
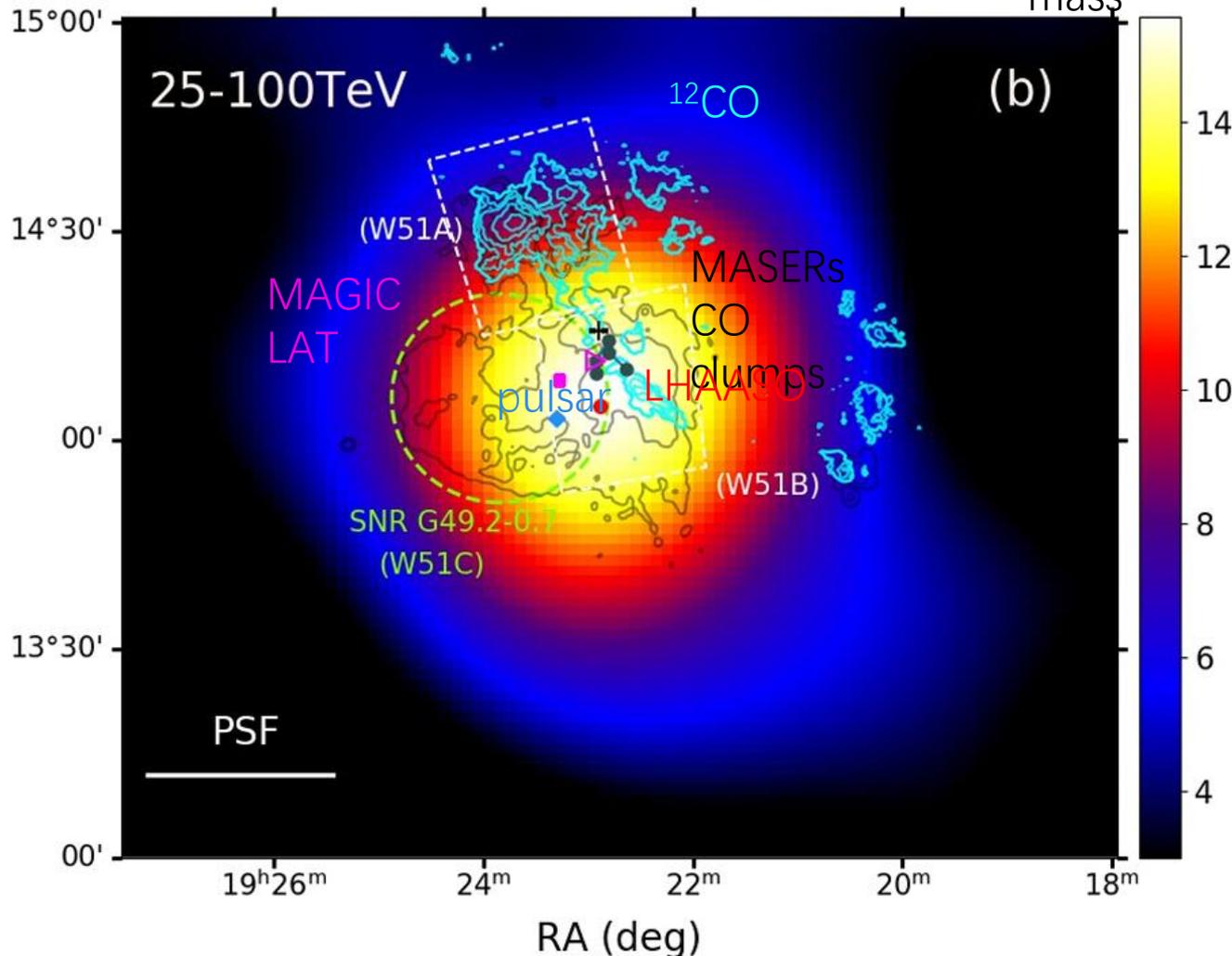
20

# Very Clear Molecular Clouds and SNR Interaction



# W51 in LHAASO FoV

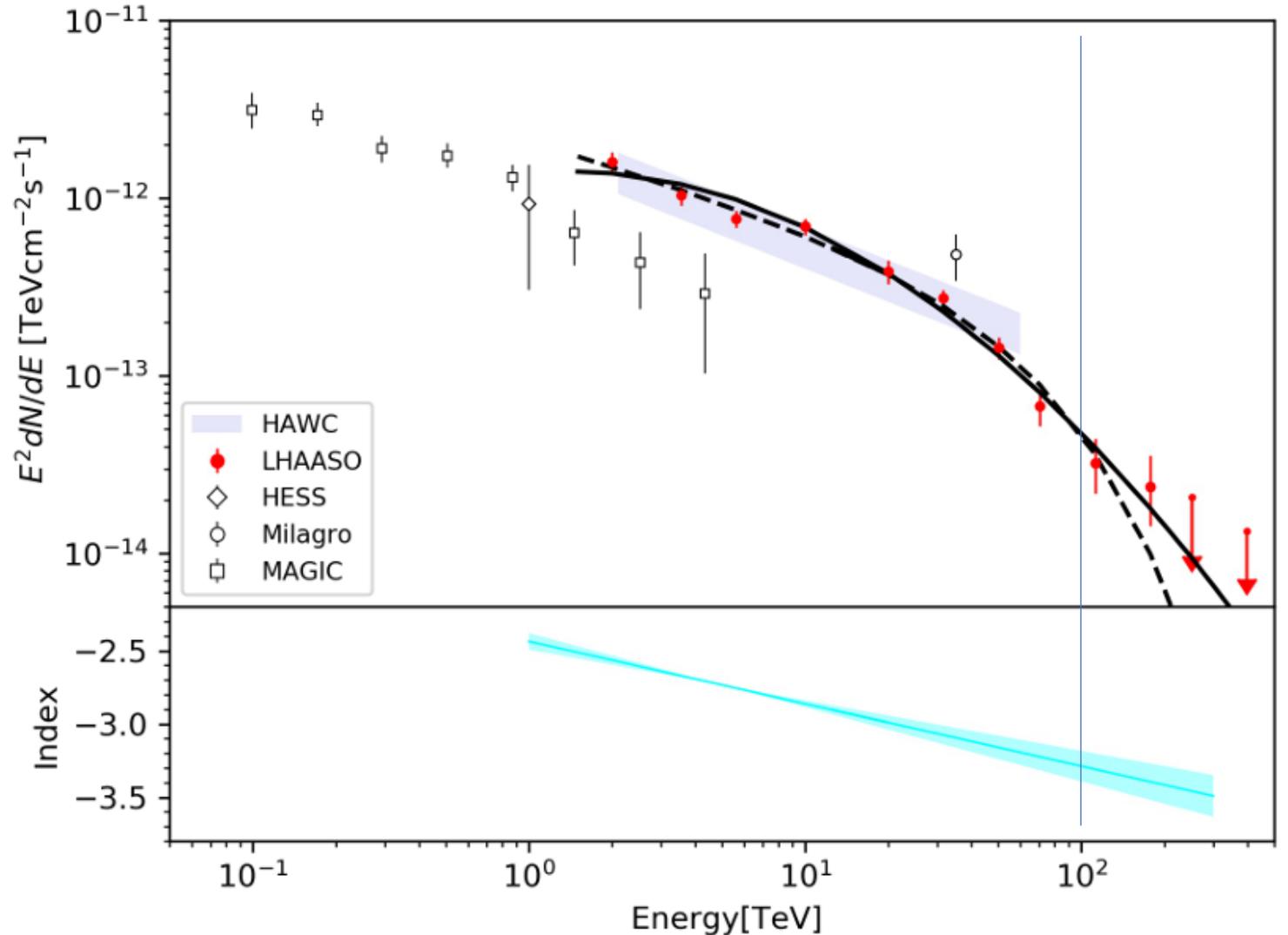
$D \sim 4.3$  kpc  
 $T \sim 18$  kyr  
 $MC \sim 10^5$  solar  
 mass



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

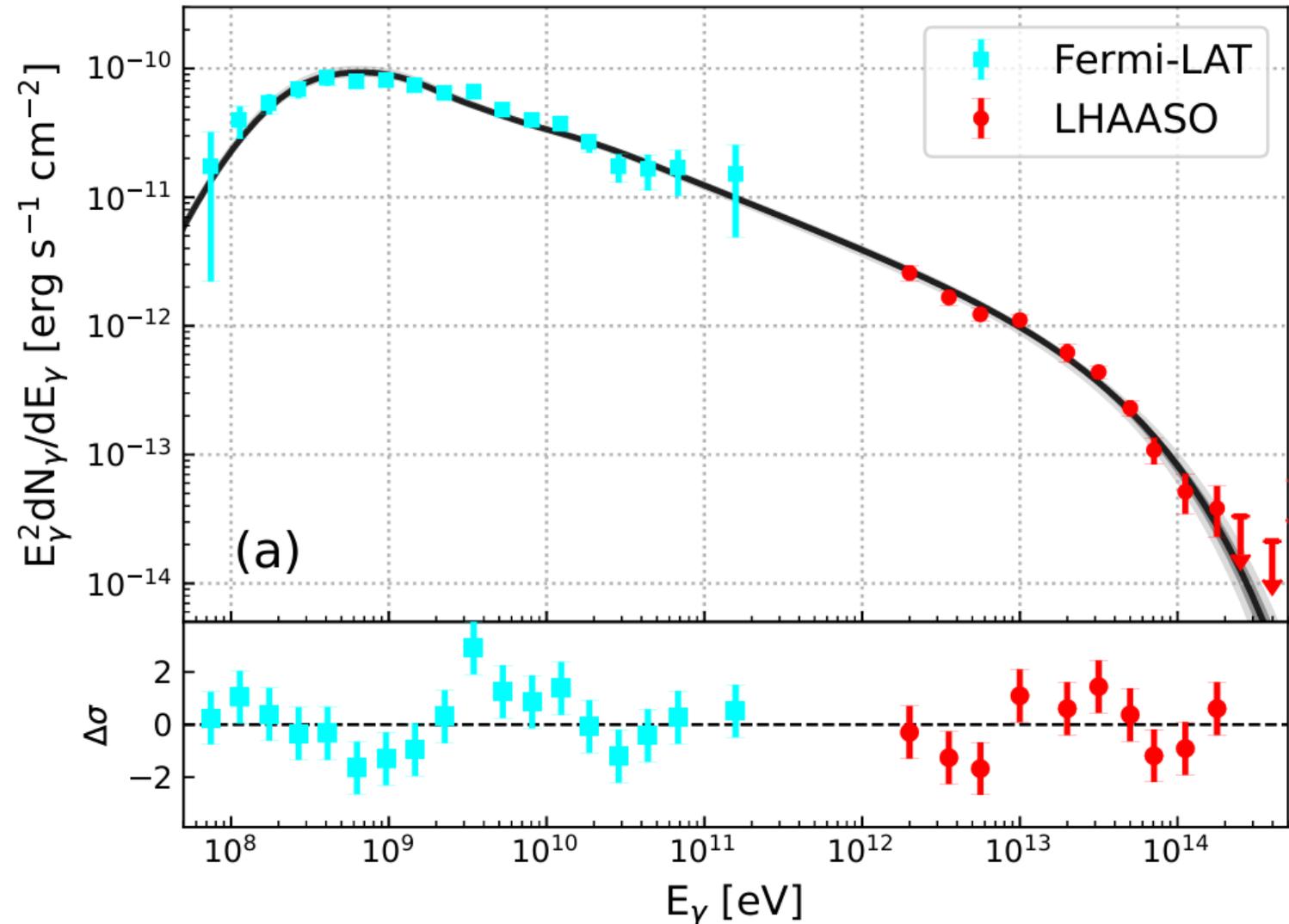
# W51 LHAASO SED

- 2-100 TeV, photons are concentrated at the contact region between the shell and molecular clouds indicated by the OH masers and CO distribution and the clumps
- It may not be easy to rule out the photons at higher energies (>100 TeV) possibly associated with the pulsar OCX J192318.5+140305 ( $E=10^{36}$  erg/s), since the centroid sifted by  $1\sigma$  of the PSF
- MAGIC flux is lower by a factor of 3! That indicates only peak part has been measured



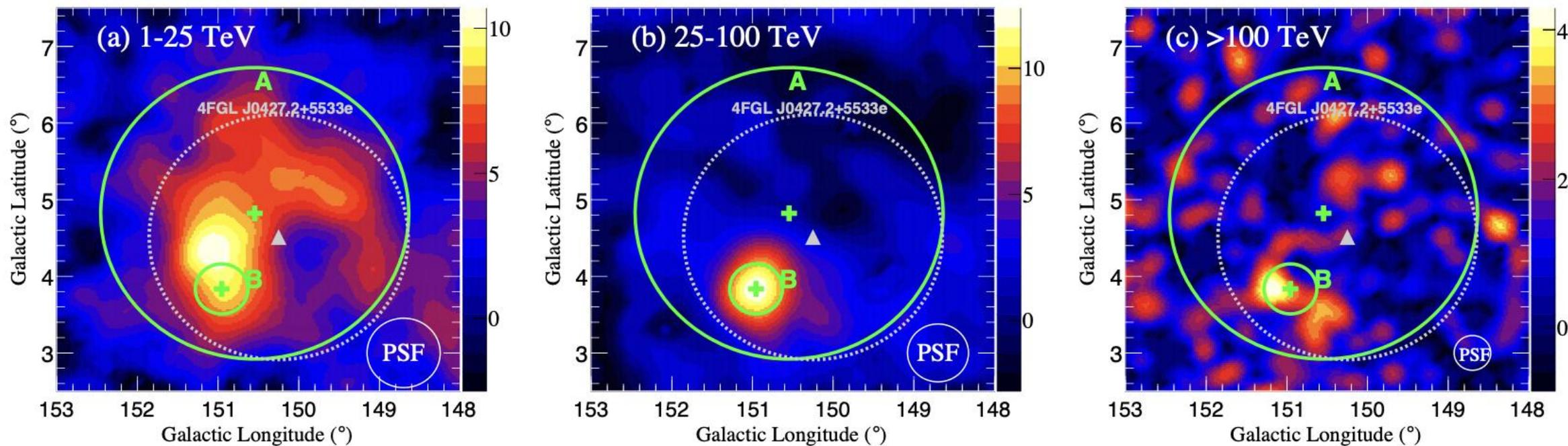
# Protons may be same originated as those generated the LAT measured $\pi^0$ -bump

- 1<sup>st</sup> clear evidence about the SNRs are generating CR protons up to 1 PeV
- Cut-off feature is rather evident with the  $E_{\text{cut}} \sim 500$  TeV for the accelerator
- Exponential cut-off vs. broken power-law SEDs, there is no sufficient statistics to distinguish between the two scenarios



**In an environment with fewer targets**

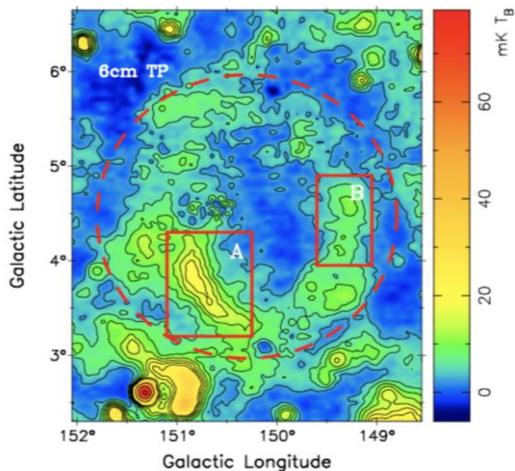
# G150.3+4.5 is found clear two sources



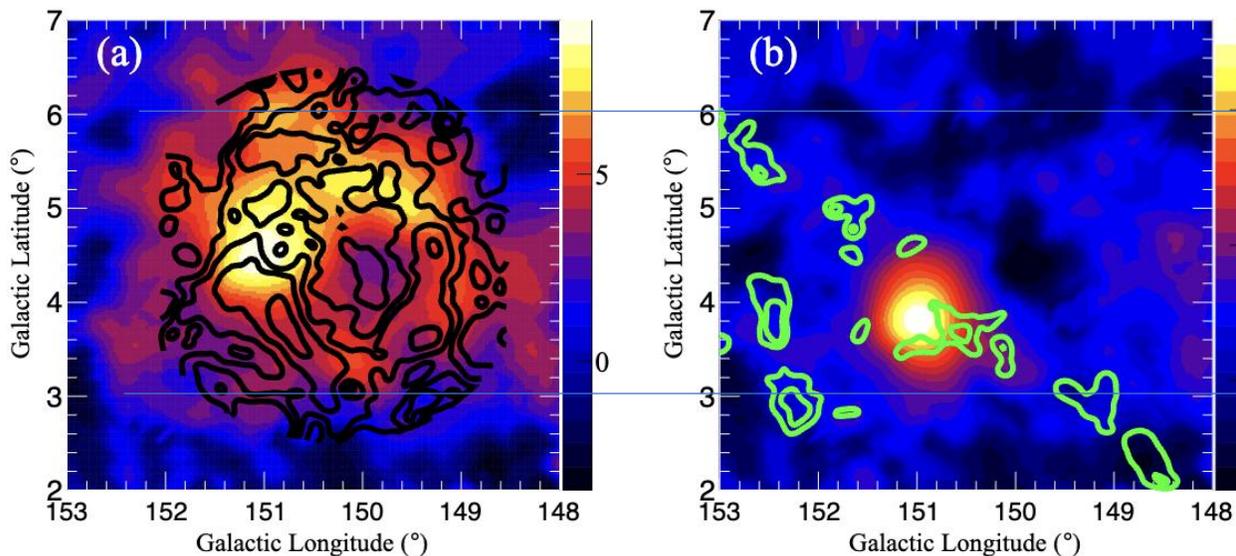
Source	Component	R.A. ( $^{\circ}$ )	Dec. ( $^{\circ}$ )	$R_{39}$ ( $^{\circ}$ )
G150.3+4.5	A	$67.15 \pm 0.17$	$55.51 \pm 0.09$	$1.26 \pm 0.07$
	B	$66.73 \pm 0.07$	$54.52 \pm 0.04$	$0.22 \pm 0.04$

# 1LHAASO J0428+5531-SNR

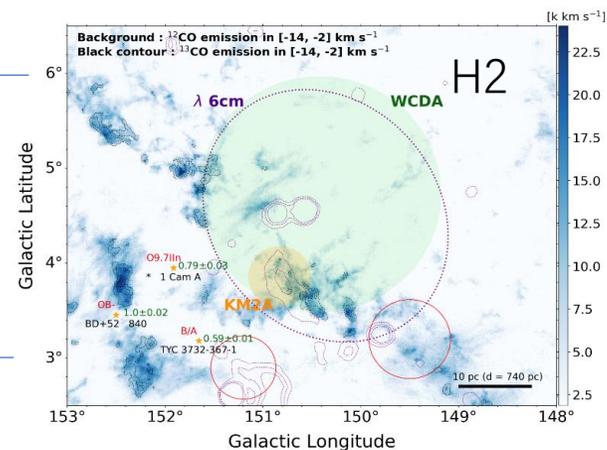
Gao&Han (2014) Radio (6cm)



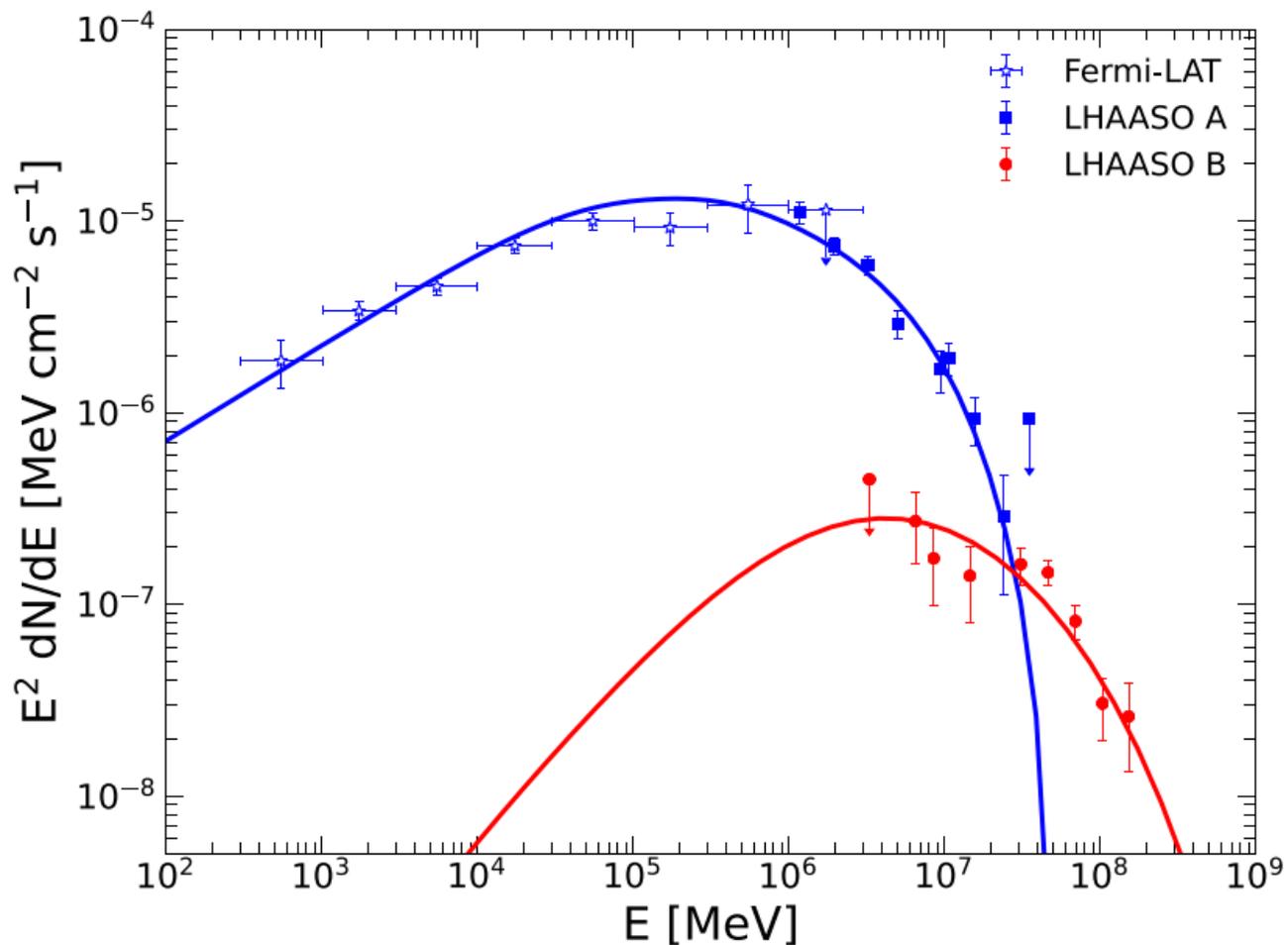
- Discovery: 2014
- Age: 1-160 kyr
- Shell Distance: 0.5 - 4.5 kpc
- Pulsar: no
- Radio Size:  $3^\circ \times 2.5^\circ$



Jian-Cheng Feng et al . (2014)



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

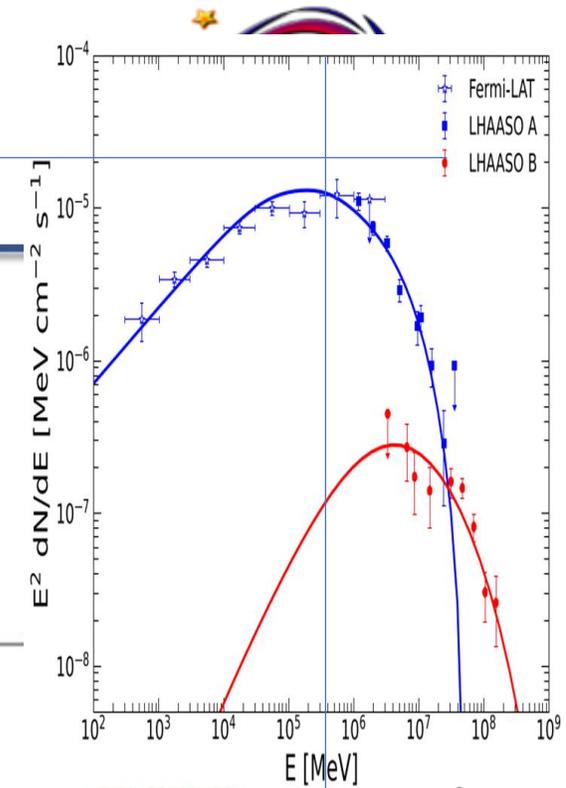
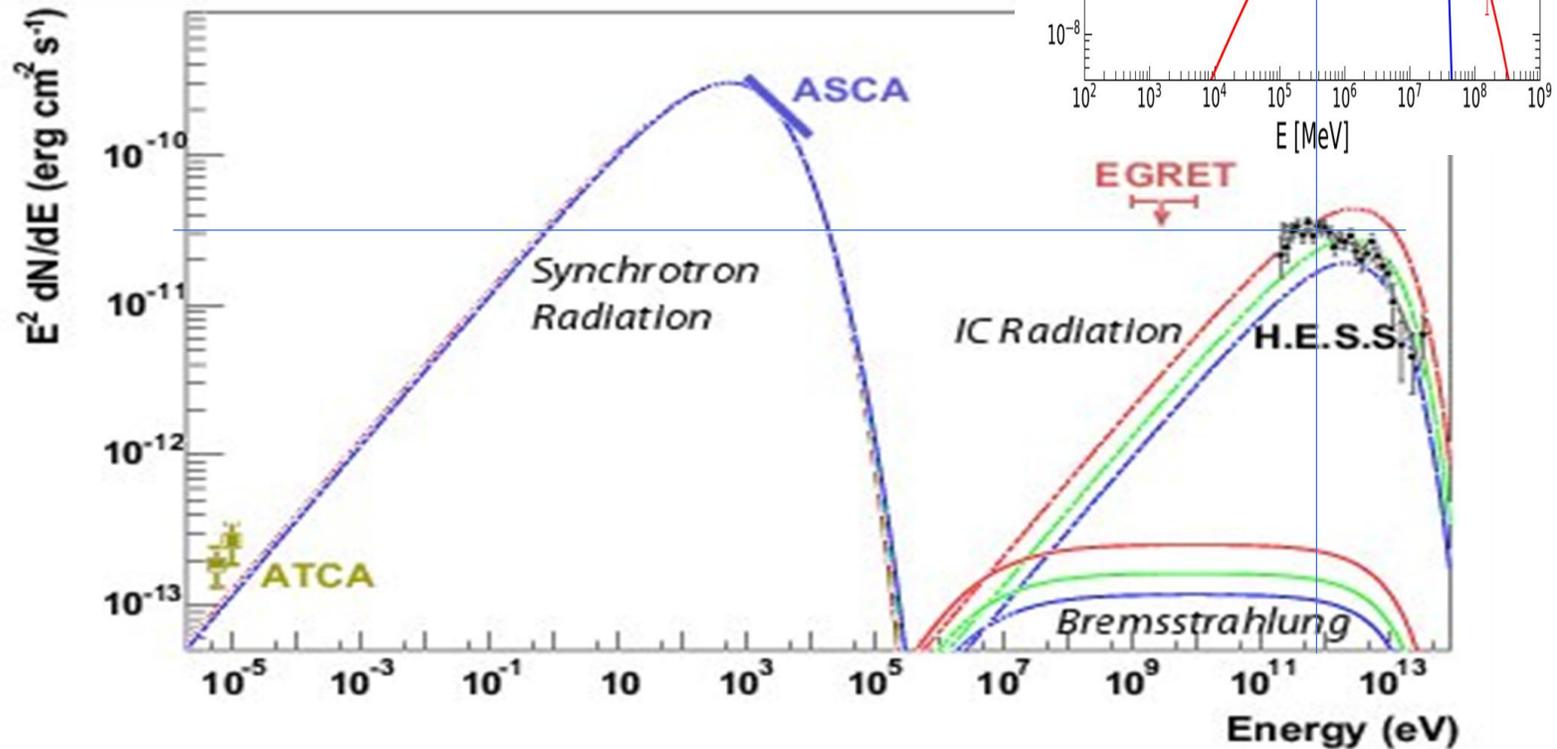
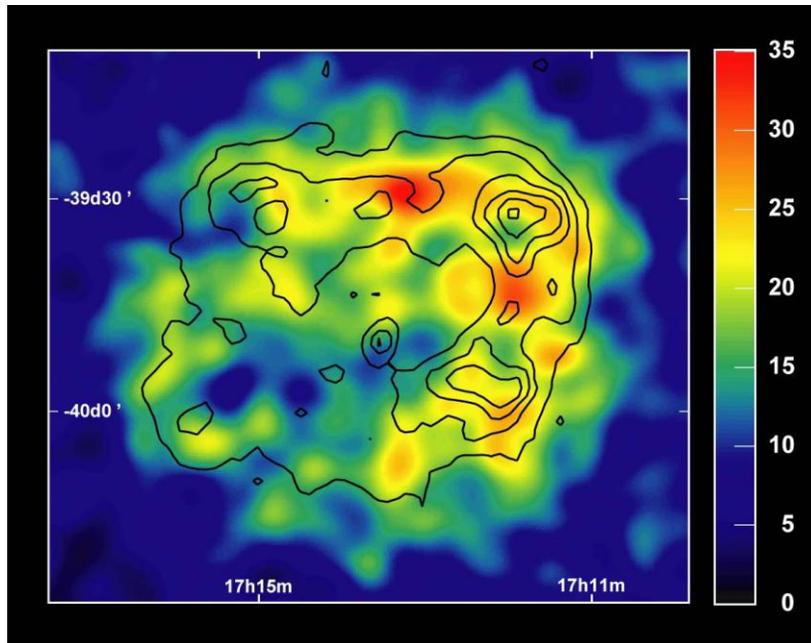


- The more concentrated radiation seems from the interaction with the clumpy MC
- It might represent the escaped high energy protons, could be as high as 1 PeV

# RXJ1713.7-3946

ASCA data: synchrotron X rays

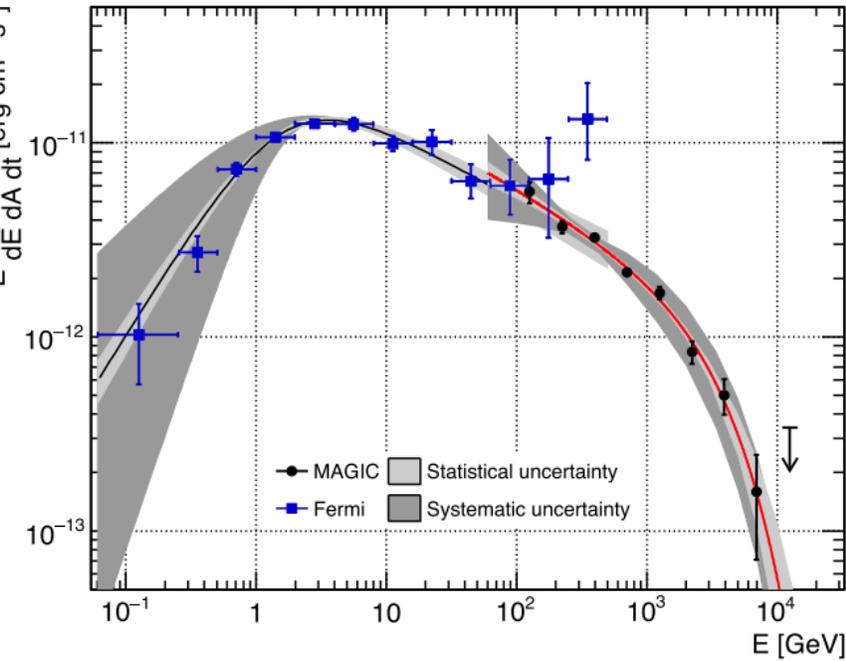
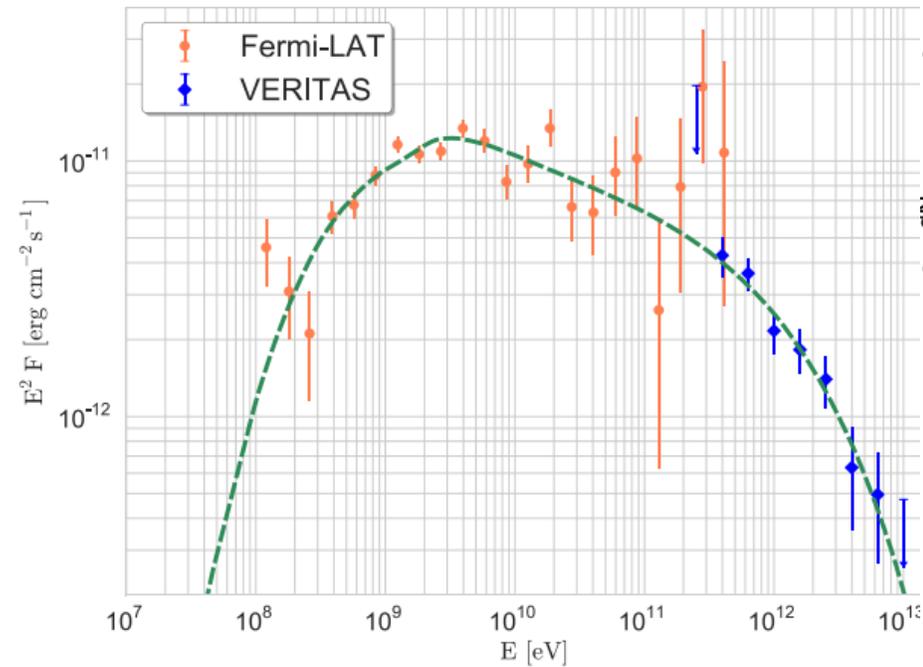
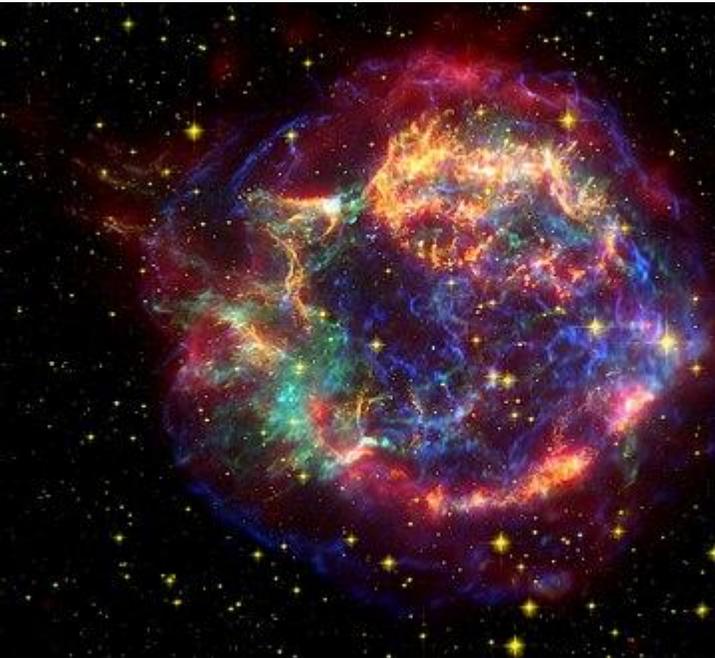
- Fine structures in the radiation morphology points to  $B > 100 \mu\text{G}$
- If leptonic, **X/TeV ratio** requires  $B \sim 10 \mu\text{G}$  (with  $\sigma_{\text{IC}}/\sigma_{\text{Synch}} \propto B^{-2}$ )



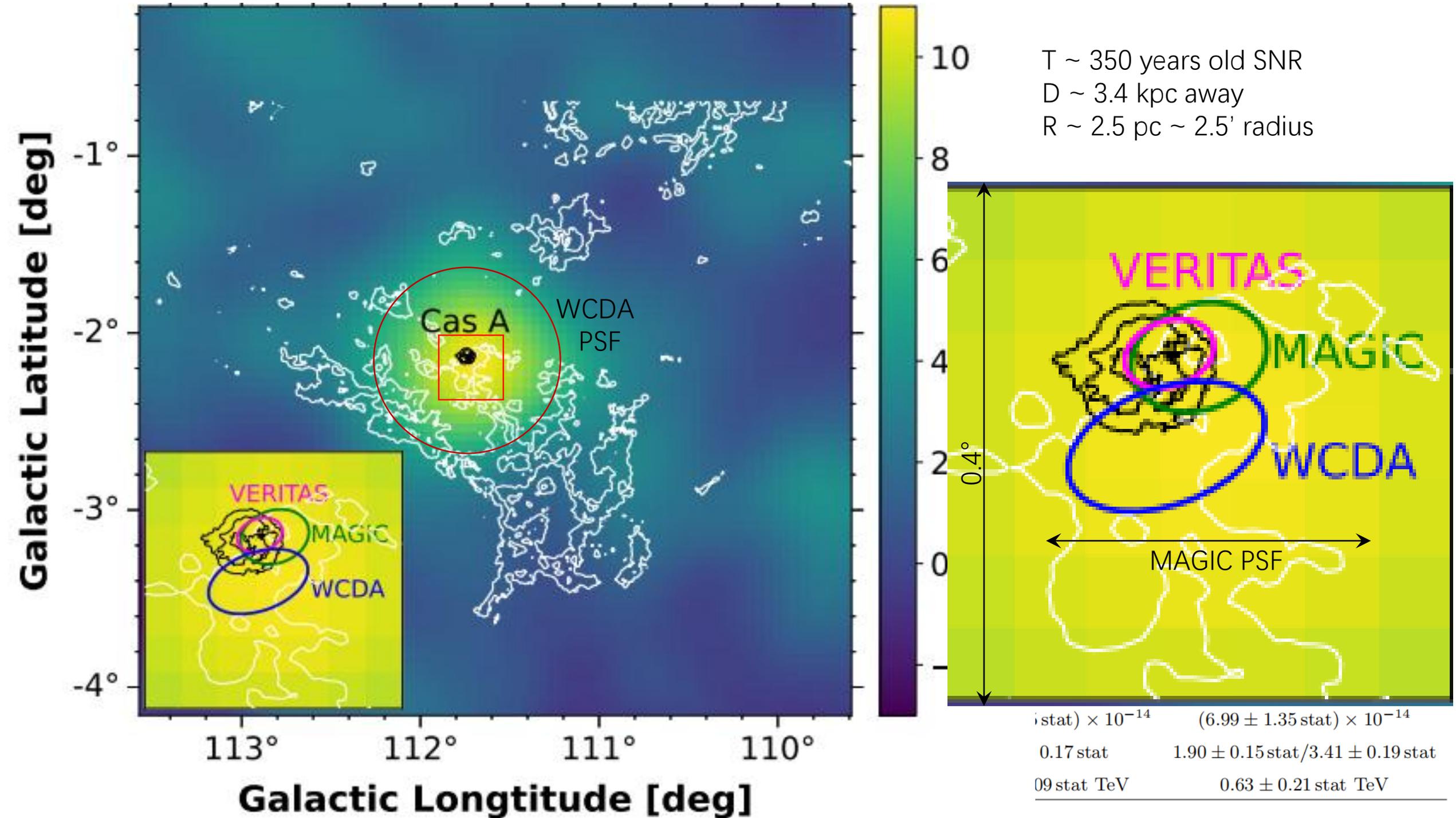
Yong SNR as a PeVatron?



# Does or Did the Supernova Remnant Cassiopeia A Operate as a PeVatron?



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



ms34

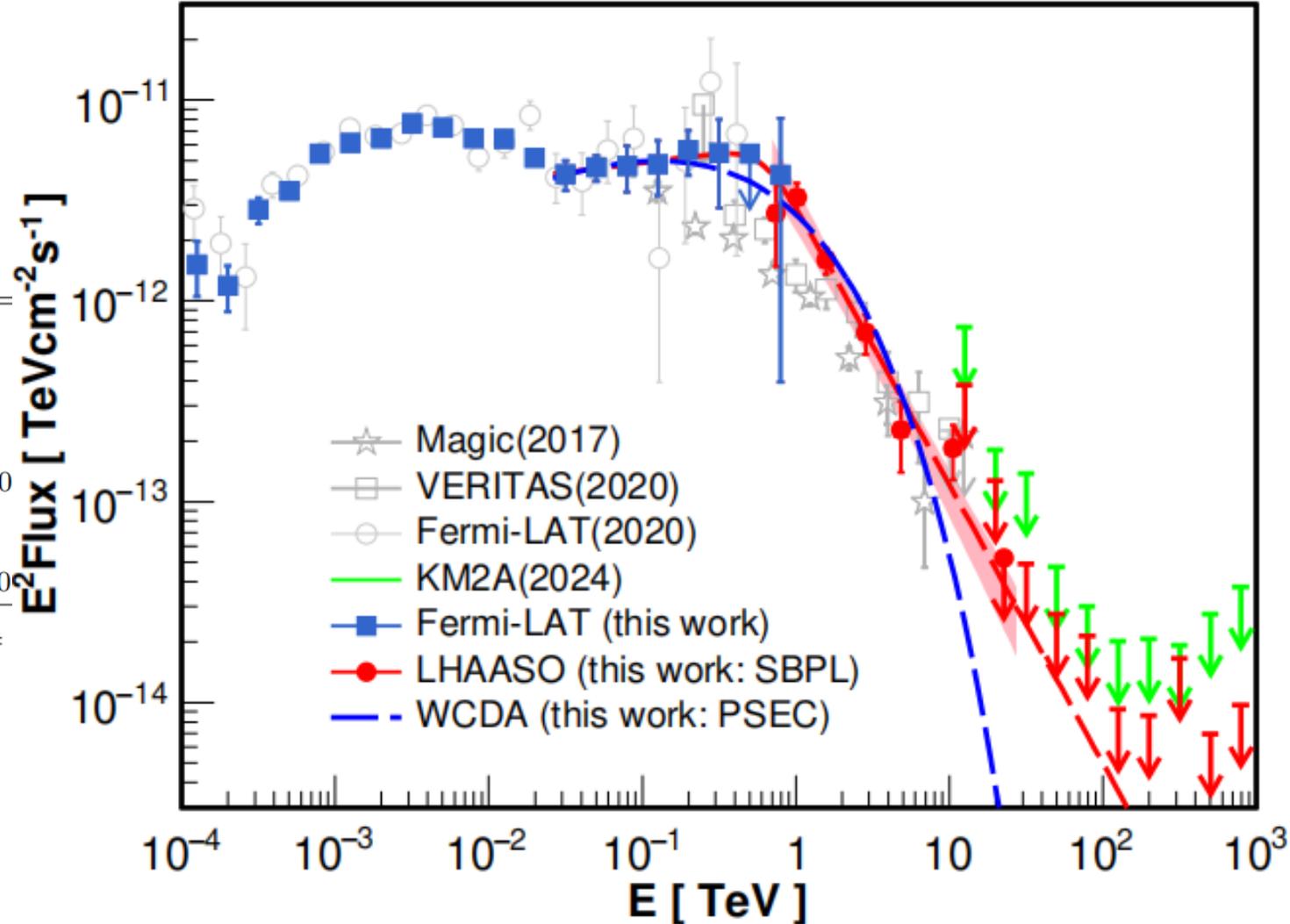
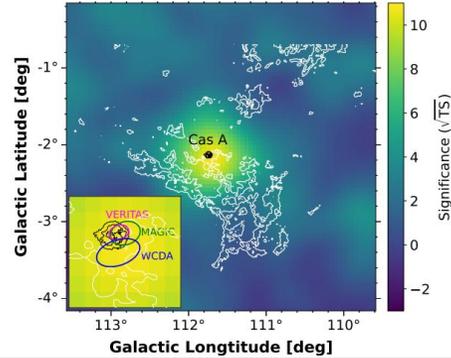
ms59



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

# Does or Did the Supernova Remnant Cassiopeia A Operate as a PeVatron?

## Broadband $\gamma$ -ray spectrum of supernova remnant Cassiopeia A

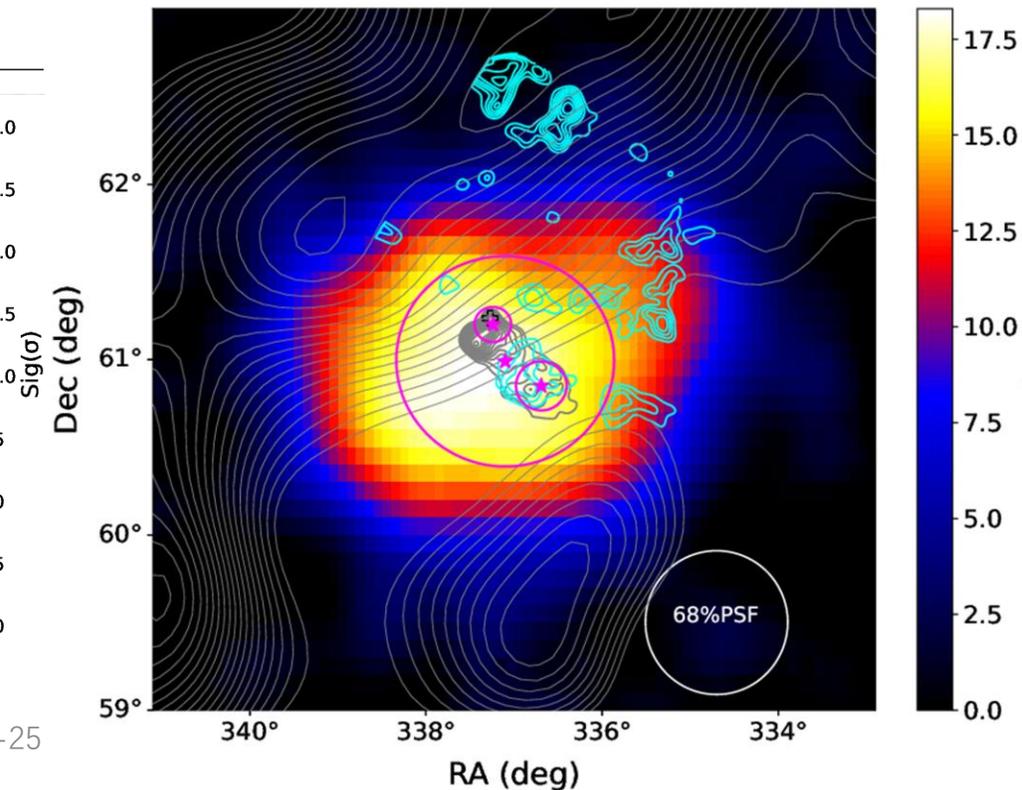
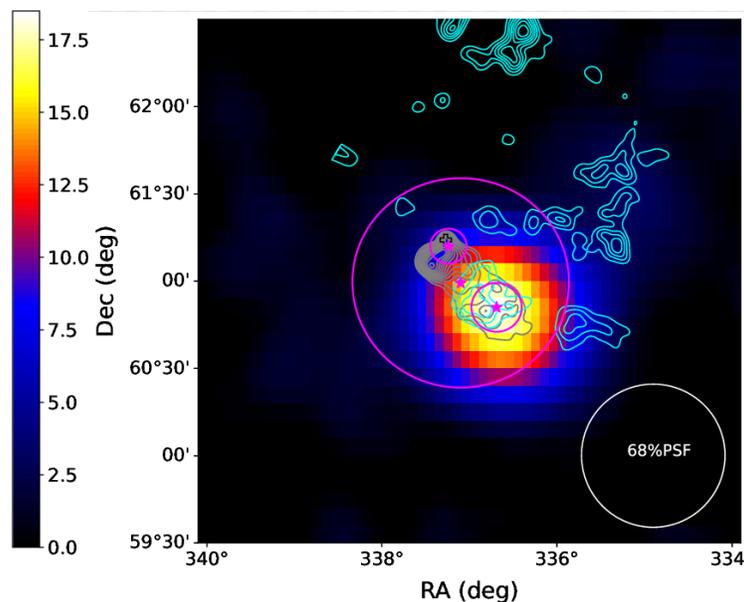
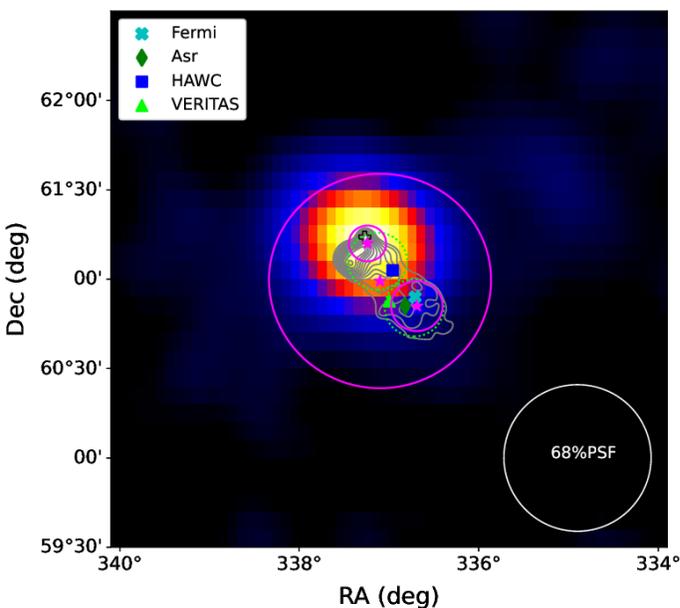
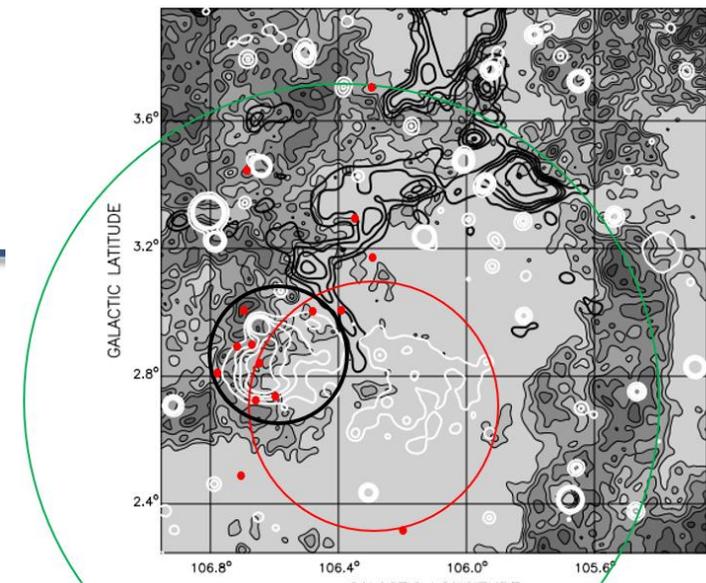


Spectral Types	PL <sup>a</sup>
RA	$350.87^\circ \pm 0.07^\circ_{stat}$
Dec	$58.75^\circ \pm 0.04^\circ_{stat}$
Flux@3 TeV/TeV <sup>-1</sup> cm <sup>-2</sup> s <sup>-1</sup>	$(6.64 \pm 0.84 stat) \times 10^{-14}$ (9.0)
$\Gamma$ or $\Gamma_1/\Gamma_2$	$3.30 \pm 0.08 stat$
$E_{cut}$ or $E_{br}$	
PSEC	SBPL
$350.87^\circ$	$350.87^\circ$
$58.75^\circ$	$58.75^\circ$
$(9.01 \pm 0.85 stat) \times 10^{-14}$	$(6.99 \pm 1.35 stat) \times 10^{-14}$
$1.60 \pm 0.17 stat$	$1.90 \pm 0.15 stat/3.41 \pm 0.19 stat$
$0.20 \pm 0.09 stat$ TeV	$0.63 \pm 0.21 stat$ TeV

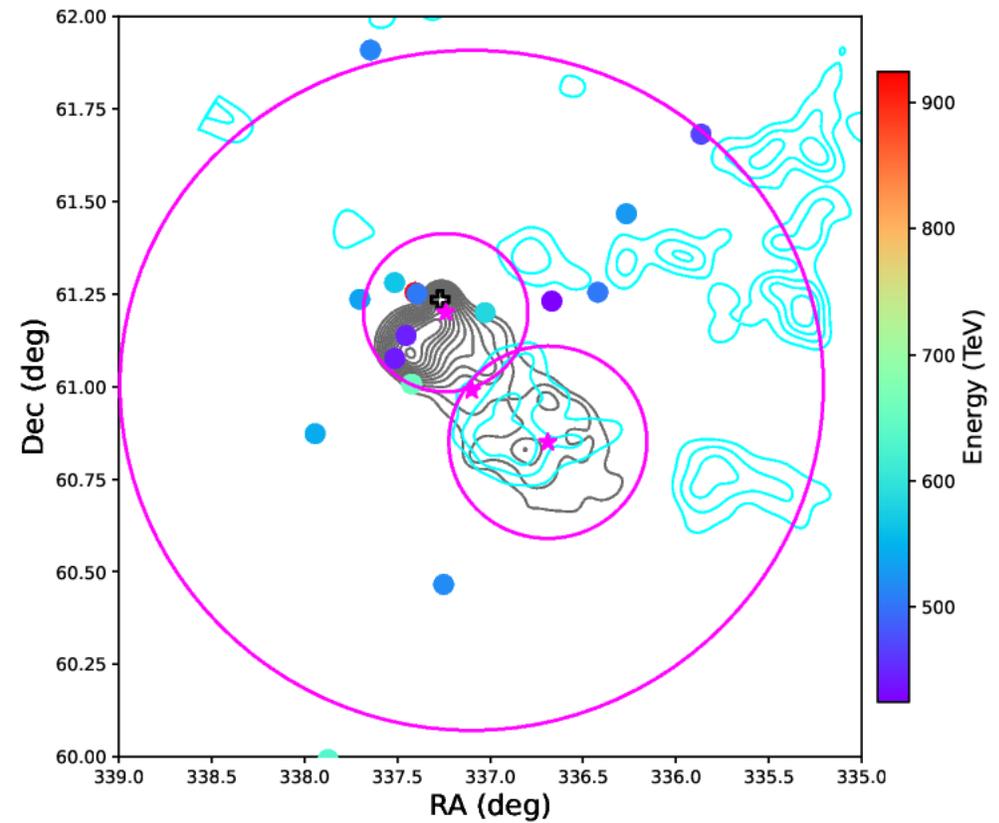
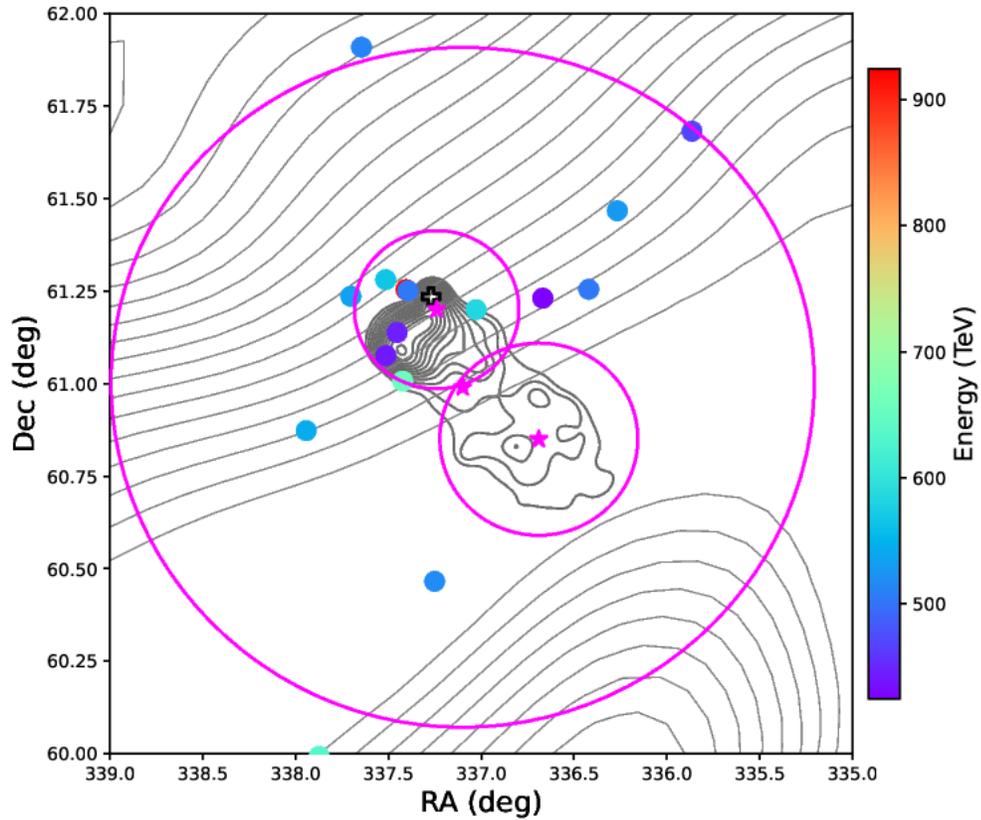
# Particle escaping from the SNR?

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

Templet	Ra(°)	Dec(°)	$\sigma$ (°)	SED	alp1	alp2	Flux*10 <sup>-12</sup> (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	

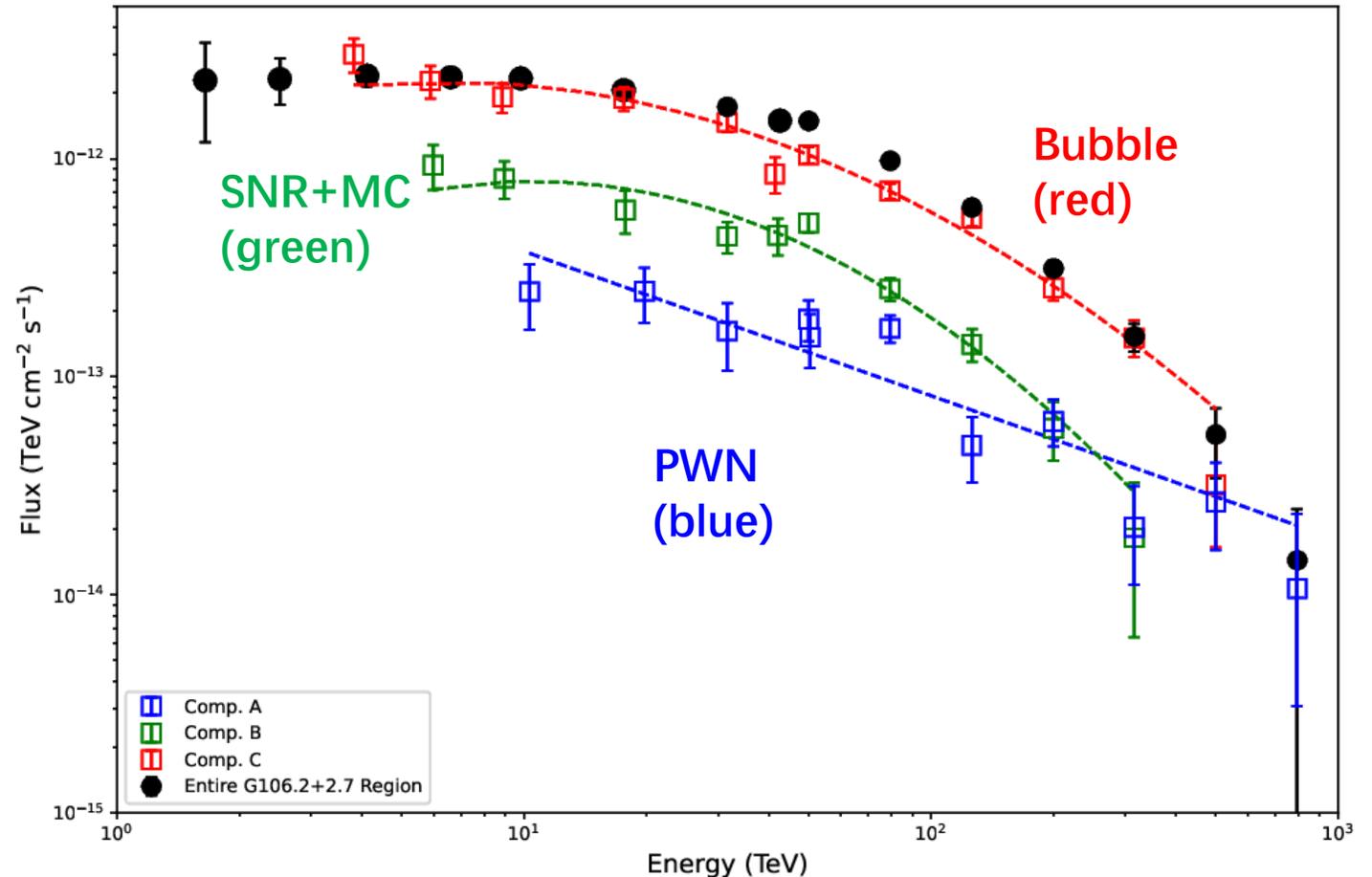


# Photons with $E > 400$ TeV

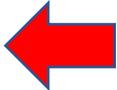


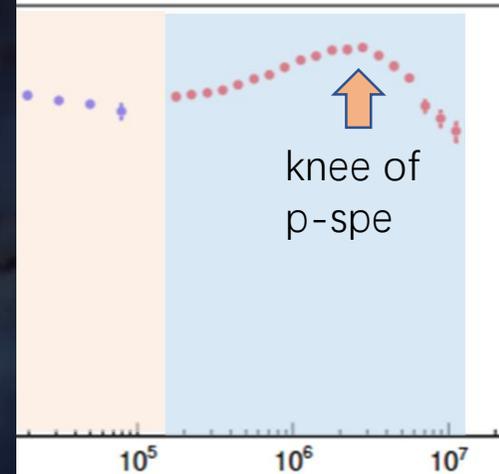
# SEDs of the 3 Components

- 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



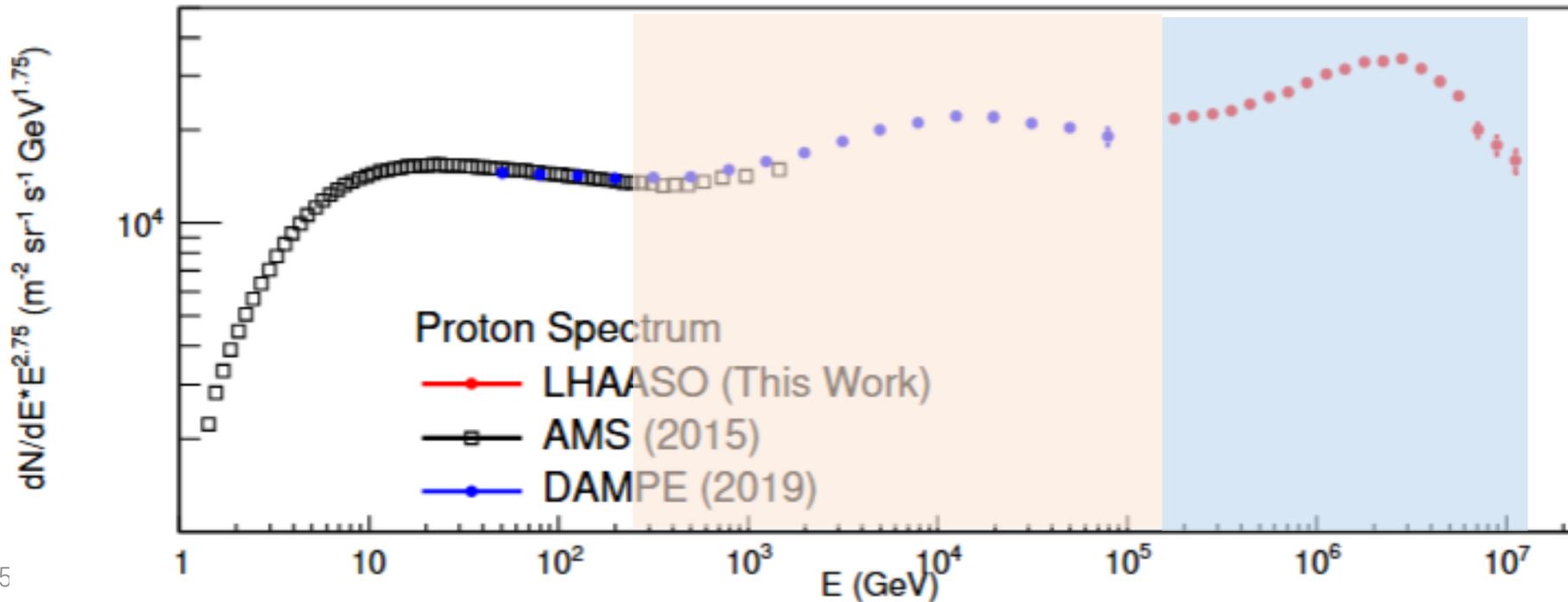
# Content

- CR measured at the solar system
- SNRs as the candidates of CR Accelerator
  - The assumption
  - 1<sup>st</sup> observational evidence around 1 GeV energy band
- Observations in VHE  $\gamma$ -ray band and the discoveries
  - SNRs in dense media
  - SNRs in the environment with few targets
  - A SNR in a cavity
- New component at HE 
- Conclusion and discussion

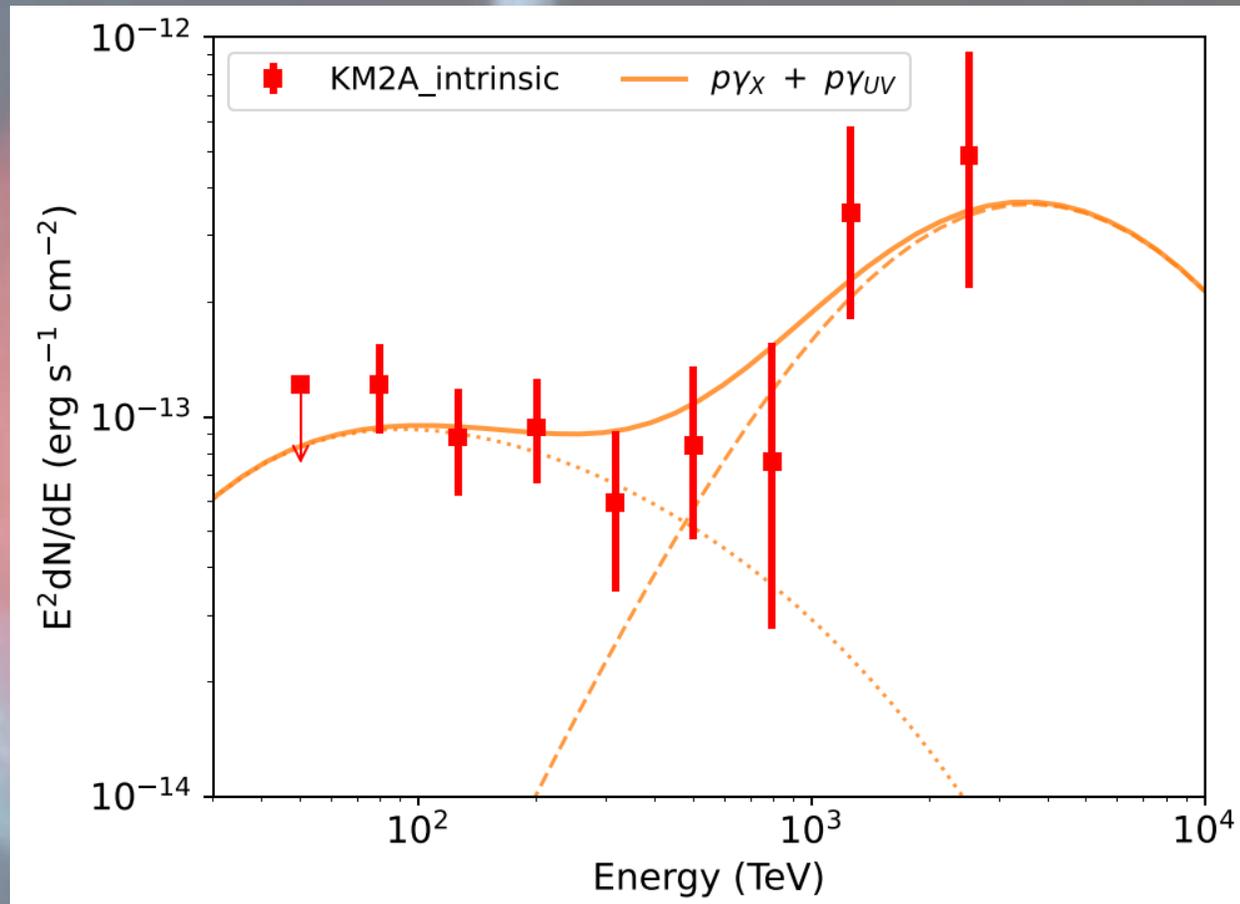
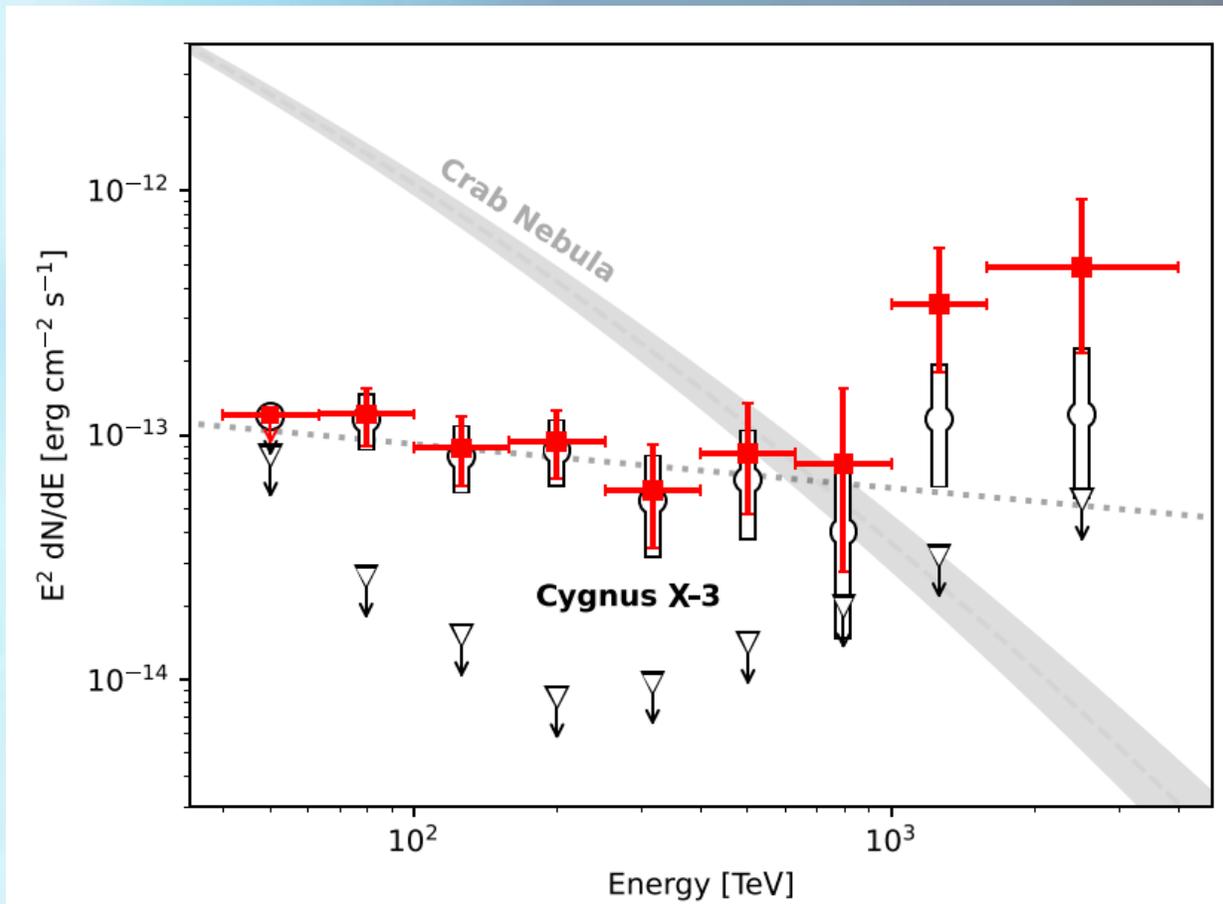


# New Component Responsible to the Knee

- SNRs accelerate CRs to very high energy, W 51, W 44, IC 433, Cas A ...
- IC 433: the  $\pi^0$ -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**



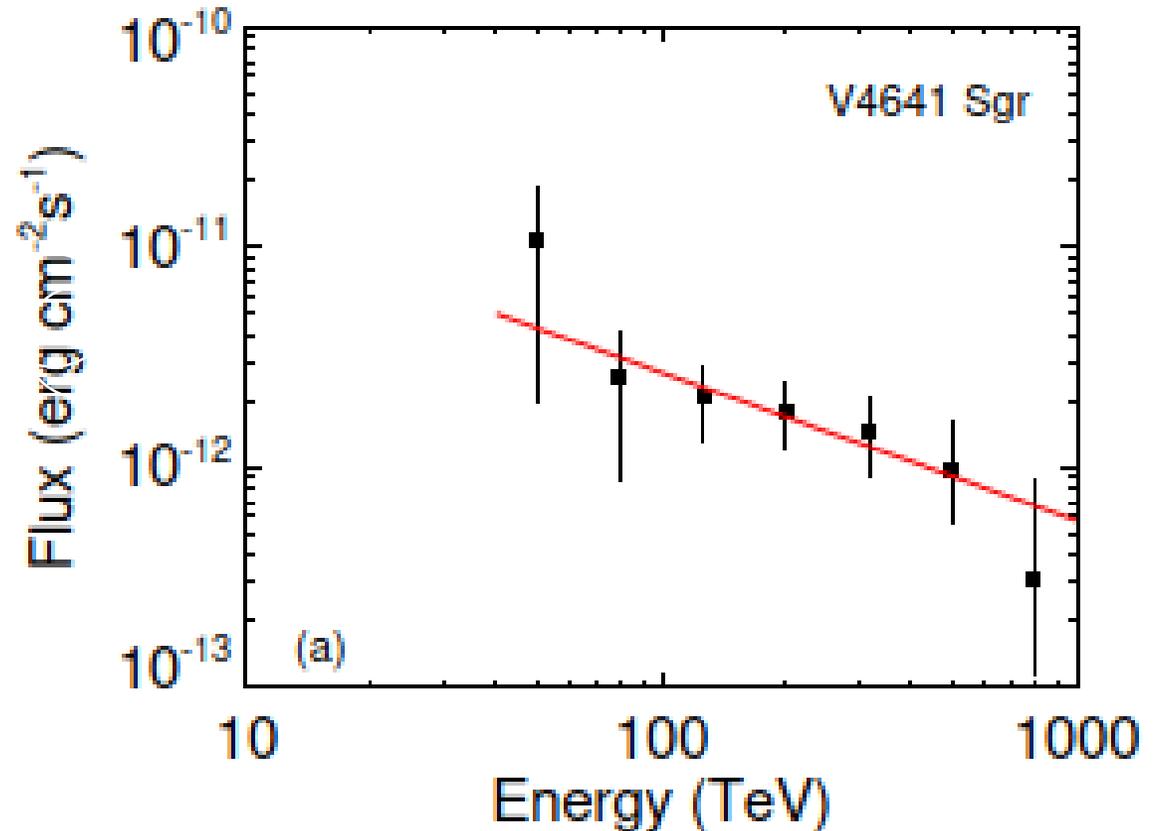
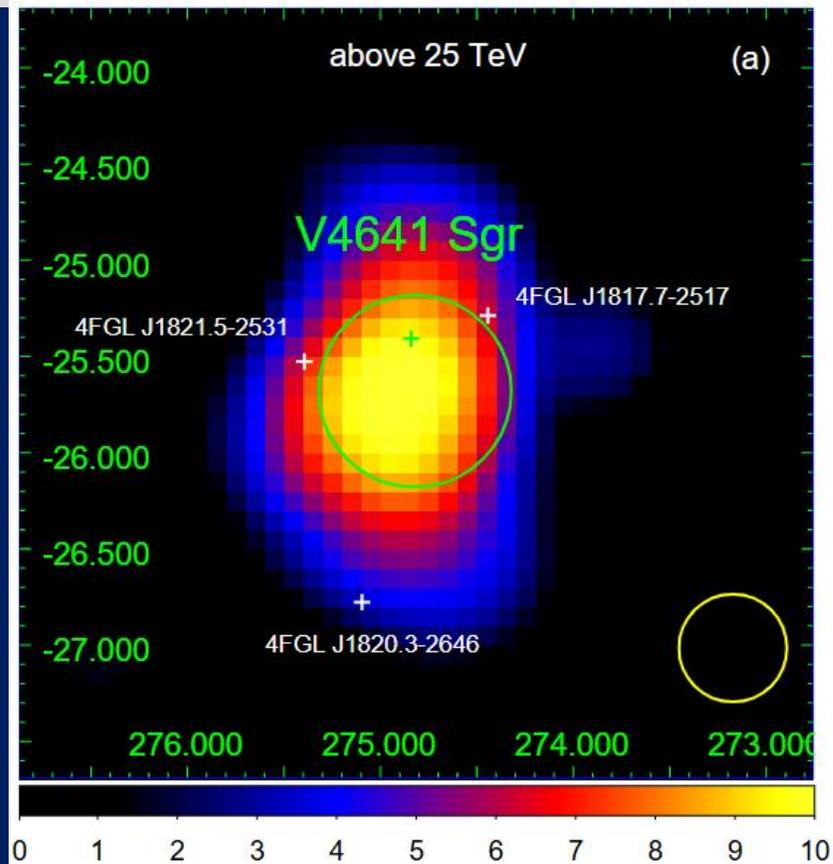
# SED of a source of proton-photon scattering



# 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 !!



# Summary

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- 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 potential CR accelerator population
- 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<sub>41</sub>