Evidence of cosmic-ray acceleration up to sub-PeV energies in the supernova remnant IC 443

arXiv: 2510.26112

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(on behalf of the LHAASO collaboration)

Institute : 1. IHEP 2. PMO 3. SWJTU

Yuxi, Feb, 27, 2026

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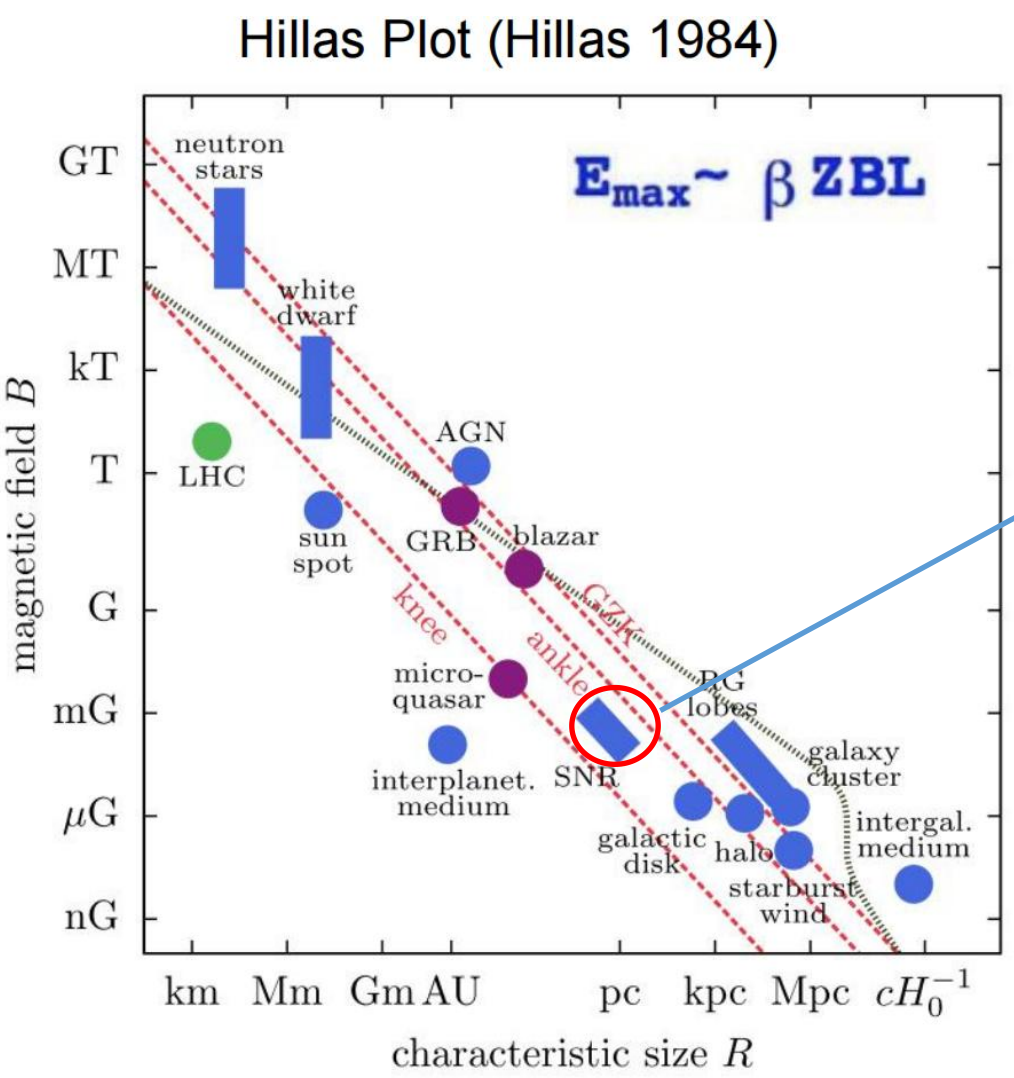
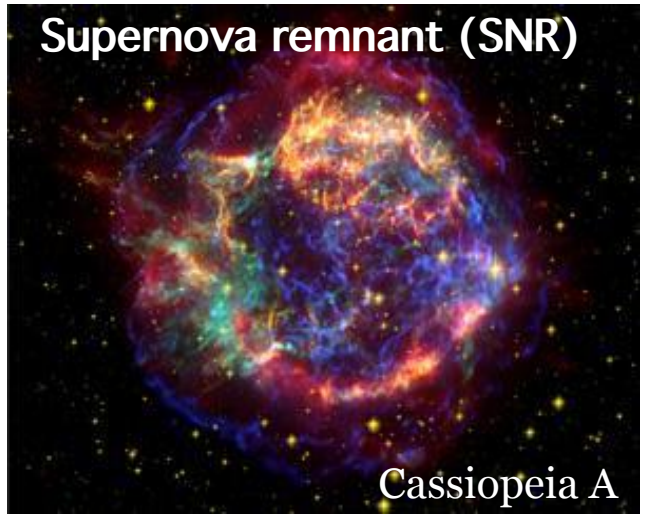
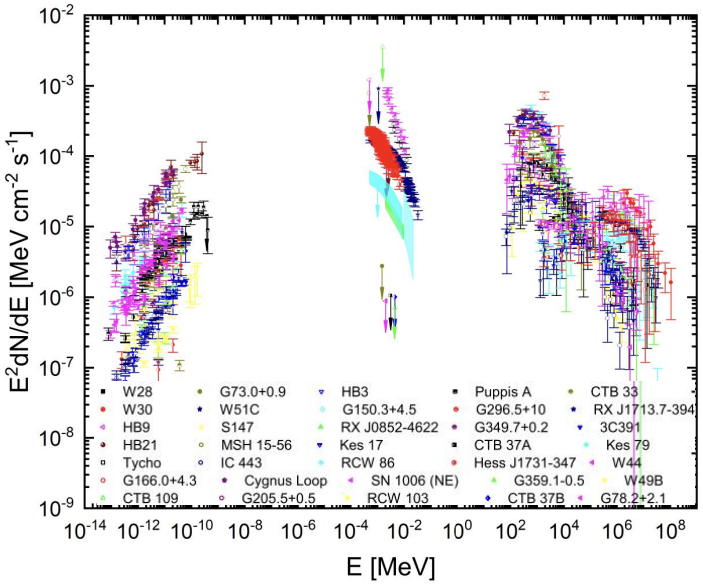
Introduction



Aartsen et al. 2018, AdSpR

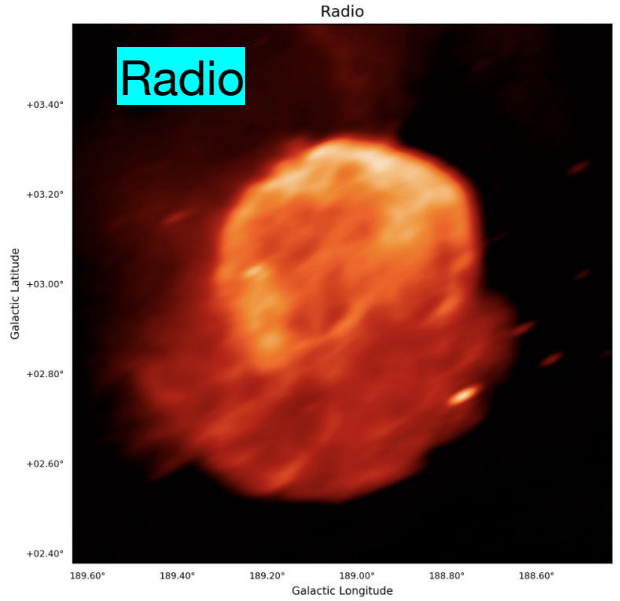


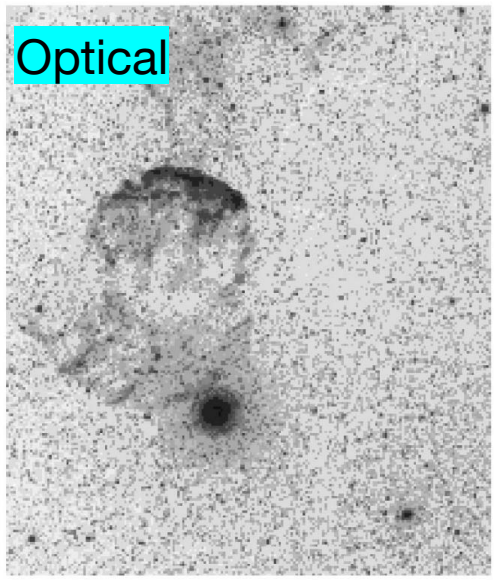


Zeng et al. 2019

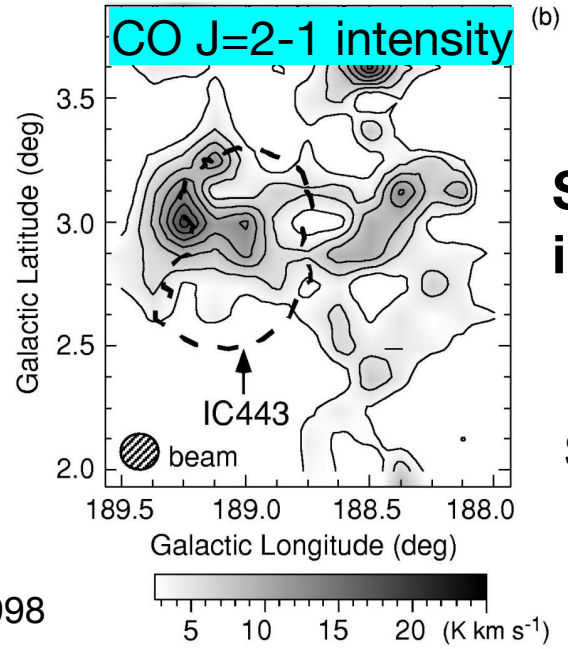
What is the maximum energy of particles accelerated by SNR shocks?

SNR IC 443



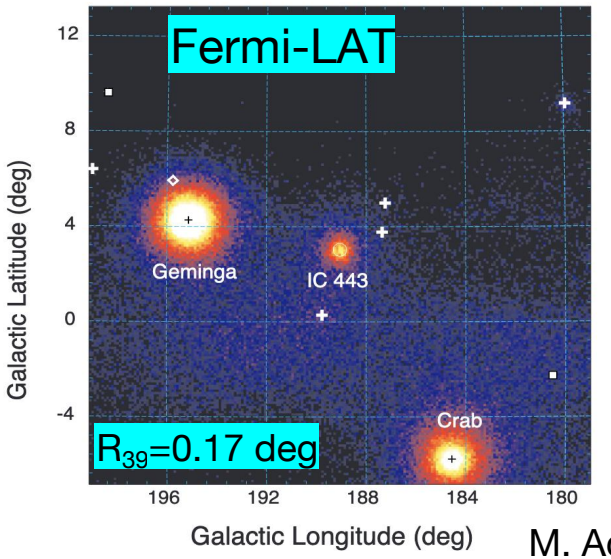


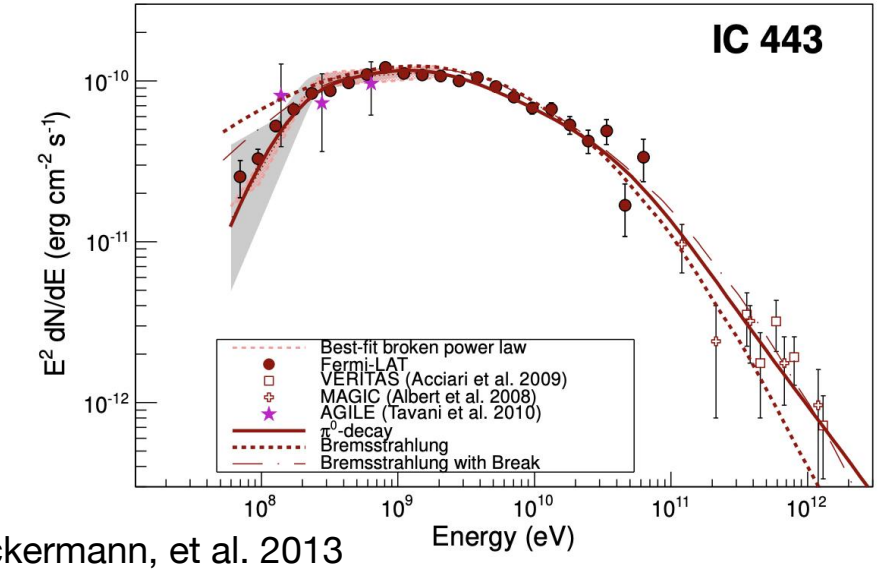
M. Seta, et al. 1998



SNR IC 443 - cloud interactions

SNR age: 3 - 30 kyr
dist: ~1.5 kpc

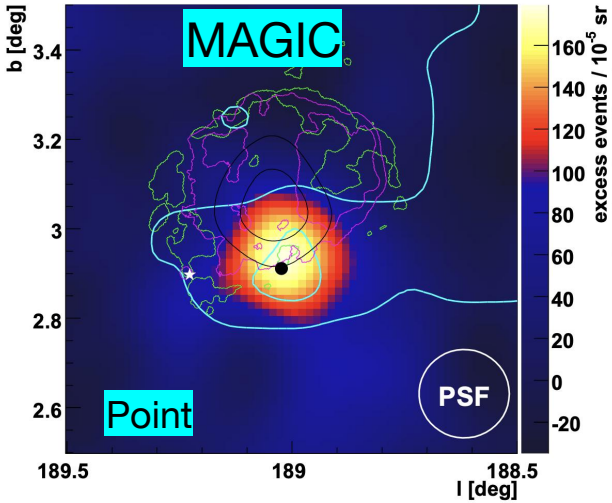




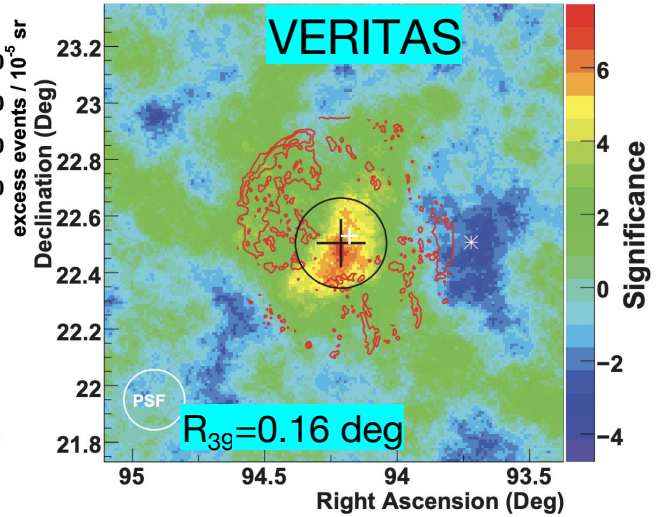
M. Ackermann, et al. 2013

- π^0-decay bump in the sub-GeV spectrum provides clear evidence of hadronic CR acceleration.
- IC 443 is a ideal target for probing hadronic CR acceleration in SNR shocks.

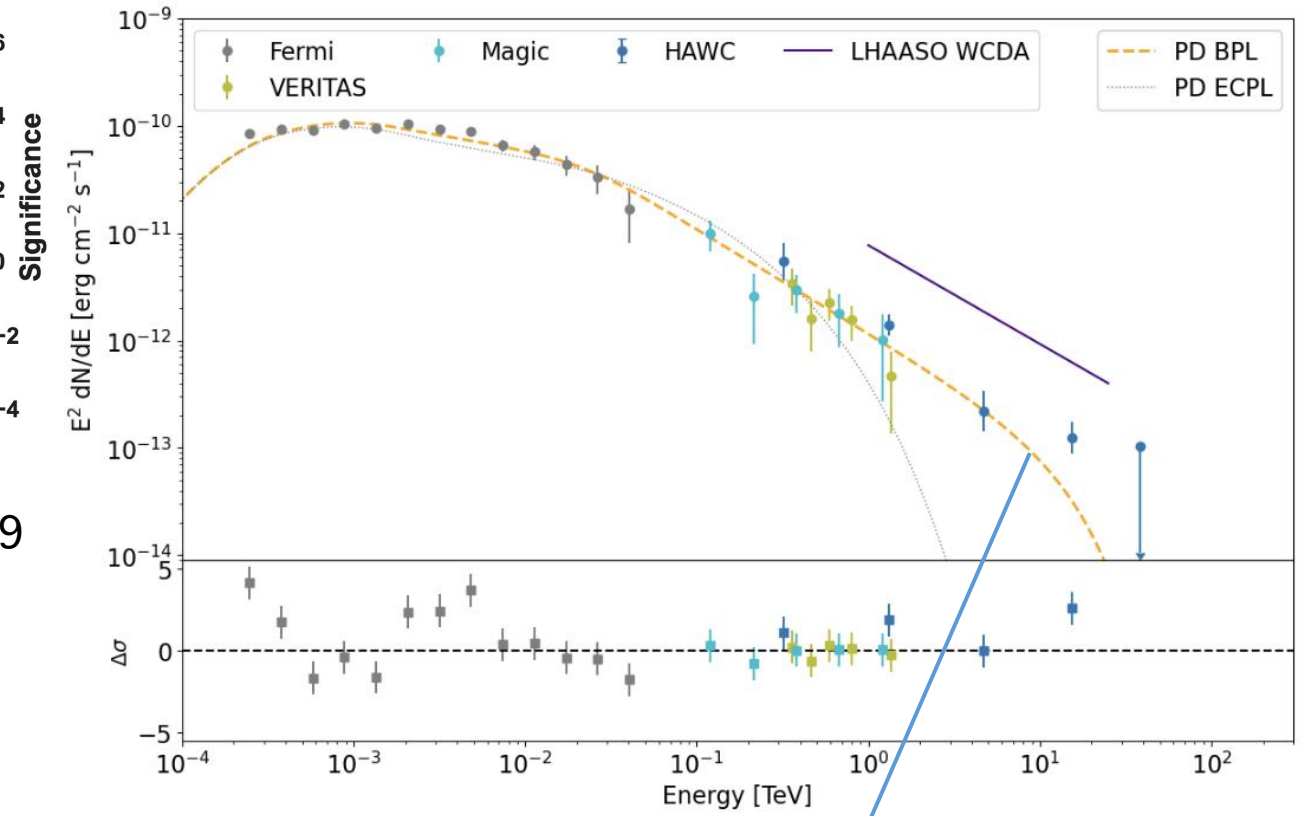
VHE γ-Ray Observations of IC 443



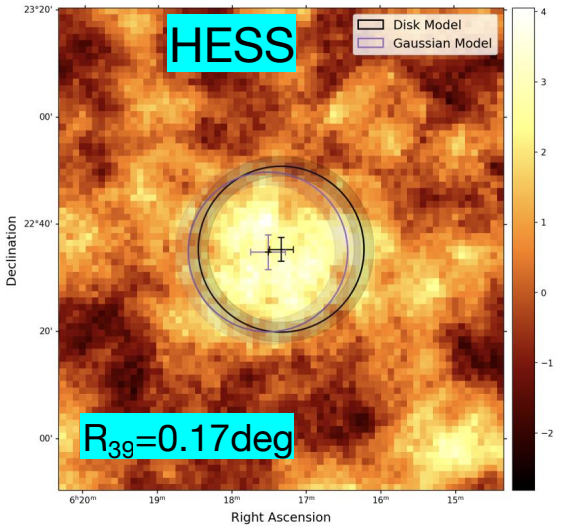
J. Albert,et al. 2007



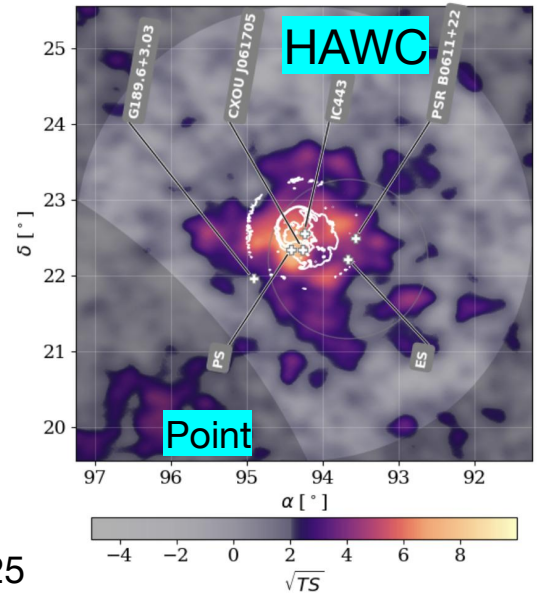
V. A. Acciari, et al. 2009



R. Alfaro, et al. 2025



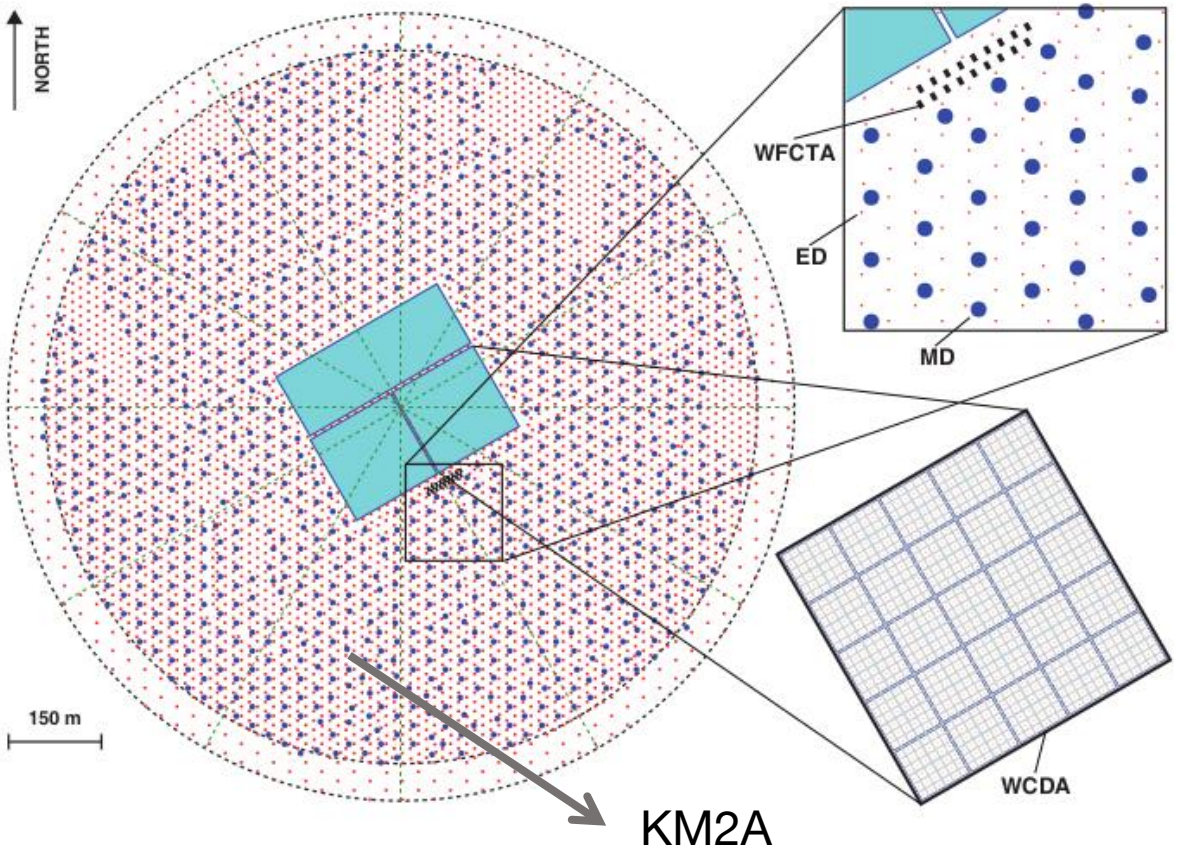
Alison M. W. Mitchell, et al. ICRC2025



The maximum proton energy is constrained to be **above 65 TeV.**

LHAASO Data analysis

■ Large High Altitude Air Shower Observatory (LHAASO)



Cao Z, et al. 2019

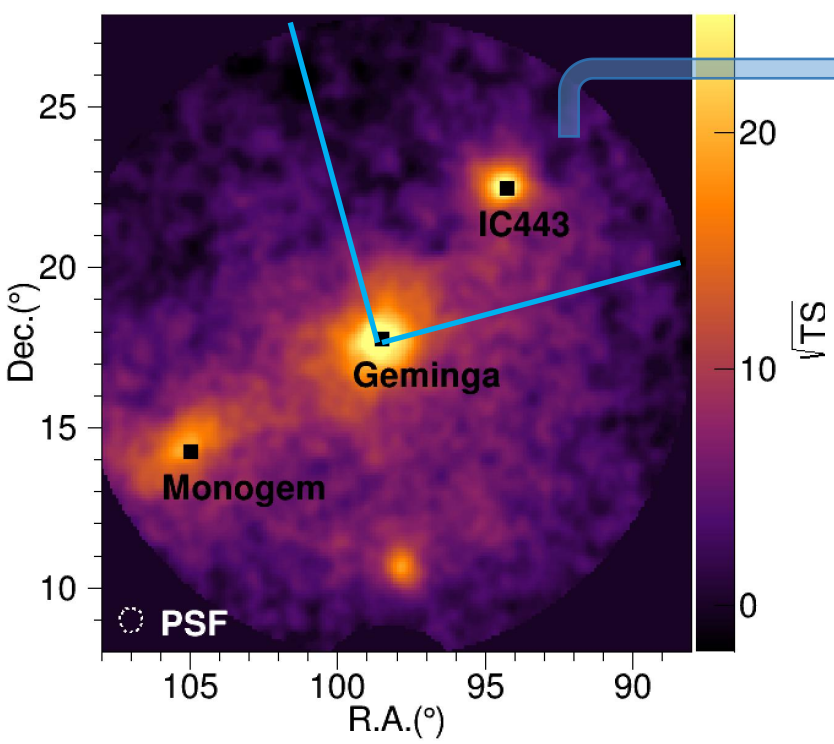
◆ Water Cherenkov Detector Array (WCDA)

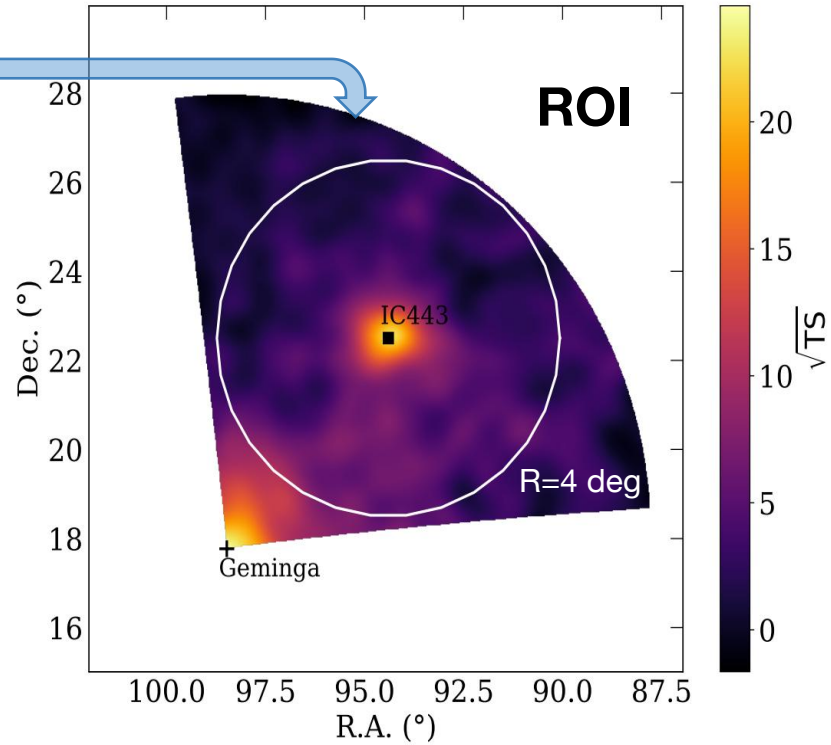
- N_{hit}>100 (>0.6 TeV)
- March 5, 2021 - July 31, 2024 (1136 days)
- Zenith angle < 50 deg

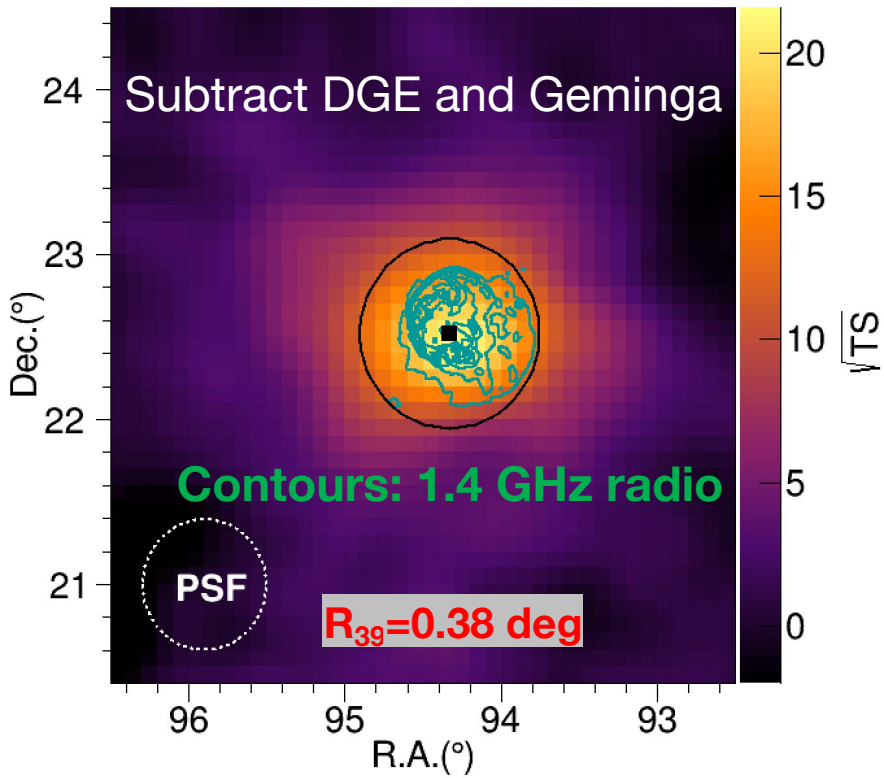
◆ Square Kilometer Array (KM2A)

- Erec: >10 TeV
- July 20, 2021- December 31, 2024 (1228 days)
- Zenith angle < 50 deg

Significance map







3-D likelihood fitting:

$$\phi(E) = \phi_0 (E/3\ \mathrm{TeV})^{-\alpha} e^{-E/E_{\mathrm{cut}}}$$

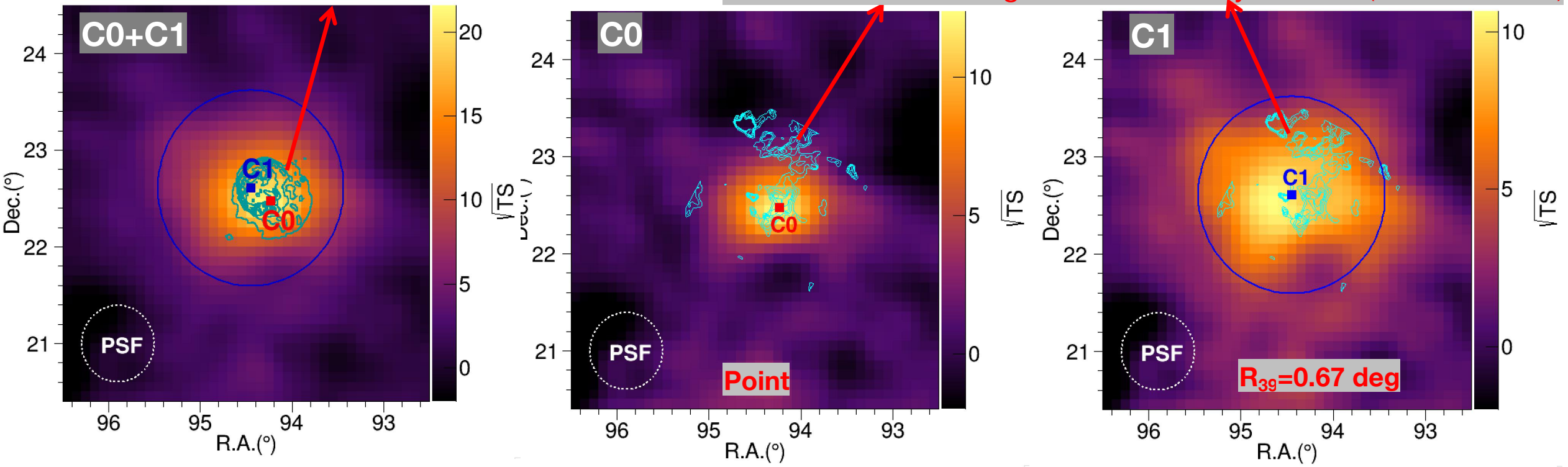
Model	TS	Name	R.A. (°)	Dec. (°)	R_{39} (°)	ϕ_0 (10^{-14} TeV^{-1}cm^{-2}s^{-1})	α	E_{cut} (TeV)
One Component	5581.5	...	94.33±0.03	22.52±0.02	0.38±0.03	15.13±1.56	2.68±0.08	34.22±14.62

Larger than the compact source(R_{39}=0.17 deg**)** detected by Fermi-LAT.

Two Components: LHAASO-C0 and LHAASO-C1

Contours:1.4 GHz radio (J.-J. Lee, et al. 2008)

Contours: Molecular gas distribution by MWISP (Y. Su, et al 2014)



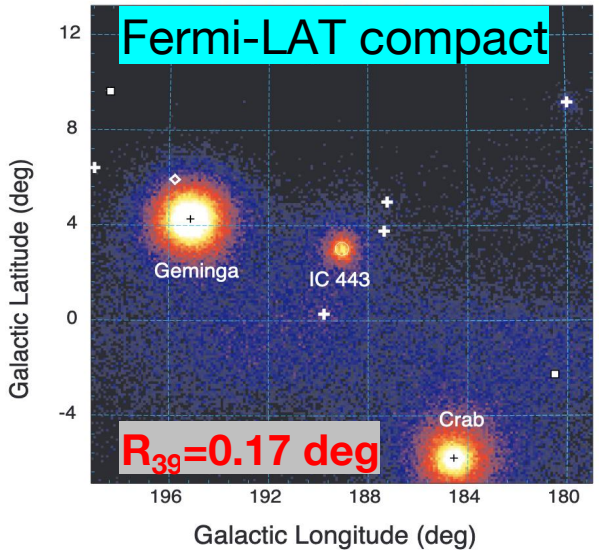
3-D likelihood fitting:

$$\phi(E) = \phi_0(E/3\ \mathrm{TeV})^{-\alpha} e^{-E/E_{\mathrm{cut}}}$$

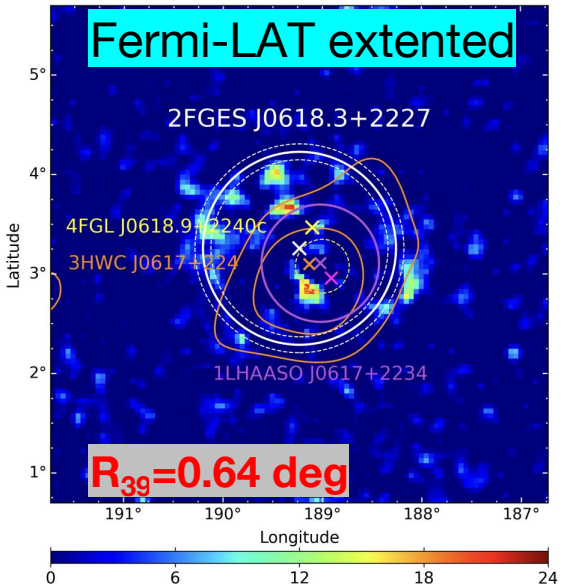
Model	TS	Name	R.A. (°)	Dec. (°)	R_{39} (°)	ϕ_0 (10^{-14} TeV^{-1}cm^{-2}s^{-1})	α	E_{cut} (TeV)
Two Components	5630.5	C0	94.27±0.03	22.44±0.02	Point	3.51±0.43	2.95±0.07	-
		C1	94.45±0.07	22.61±0.06	0.67±0.07	17.20±2.74	2.53±0.14	19.65 ± 8.67
One Component	5581.5	...	94.33±0.03	22.52±0.02	0.38±0.03	15.13±1.56	2.68±0.08	34.22±14.62

~6.0σ

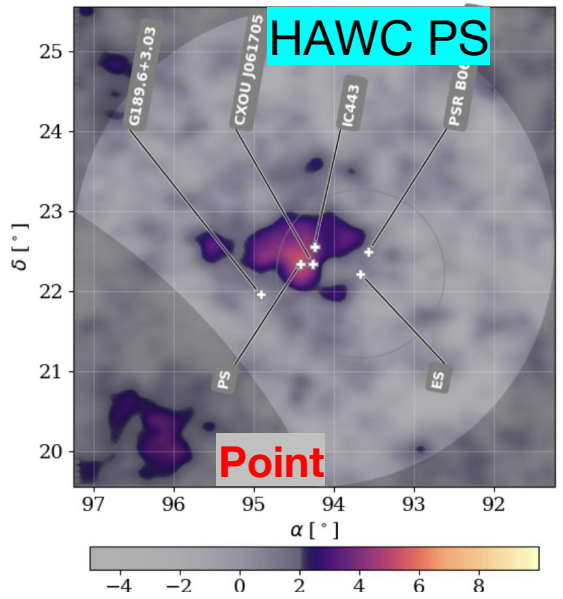
Two Components: LHAASO-C0 and LHAASO-C1

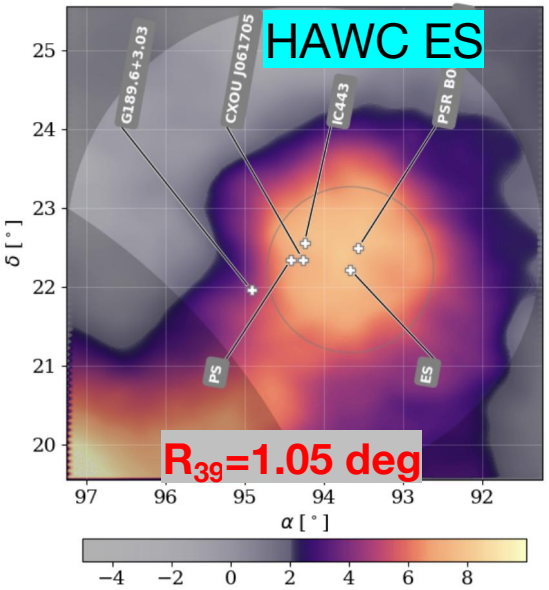


M. Ackermann, et al. 2013

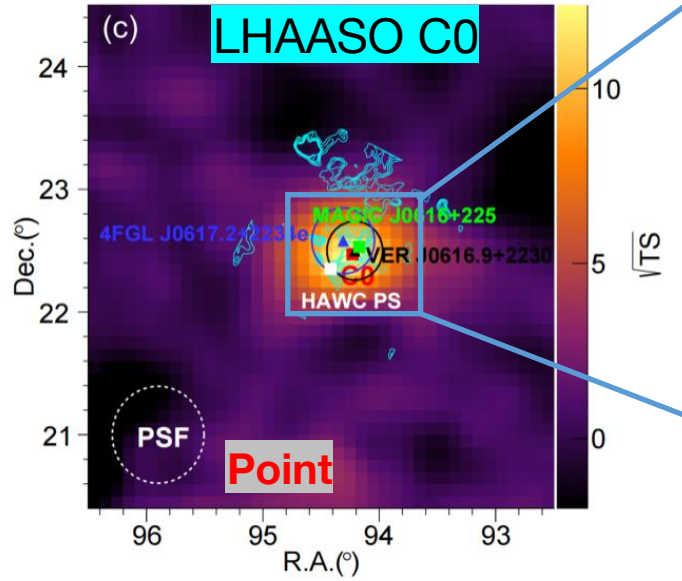


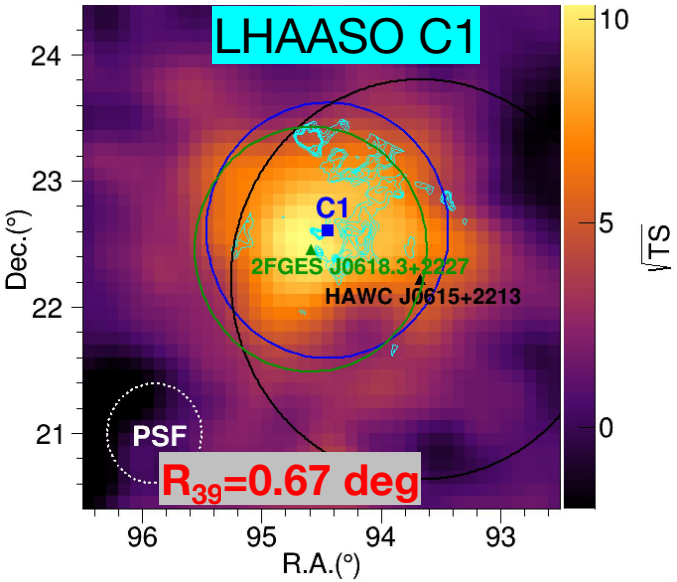
S. Abdollahi, et al. 2024





R. Alfaro, et al. 2025





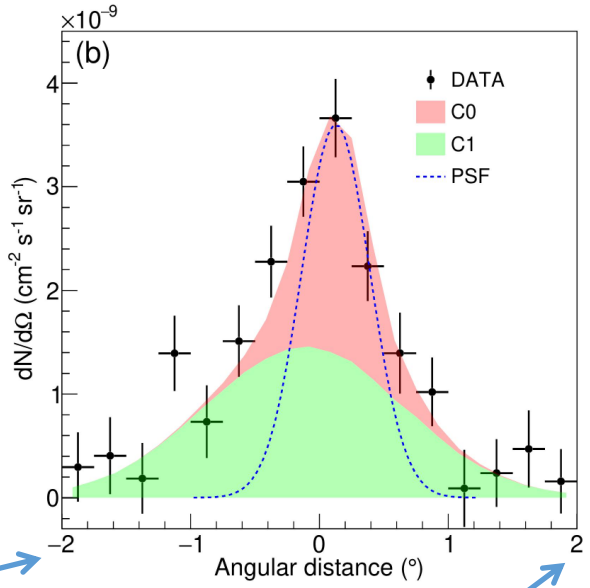
Fermi-LAT:
compact source (IC 443)
+ extended source

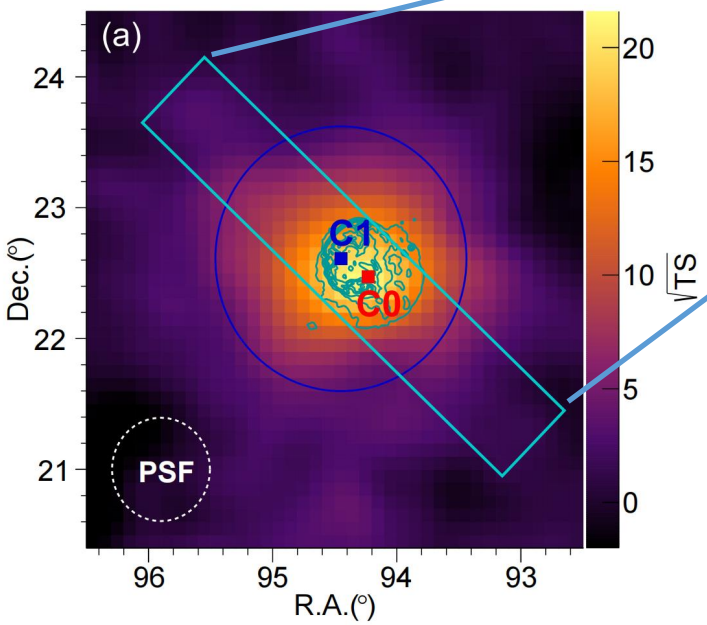
HAWC:
point source (IC 443)
+ extended source

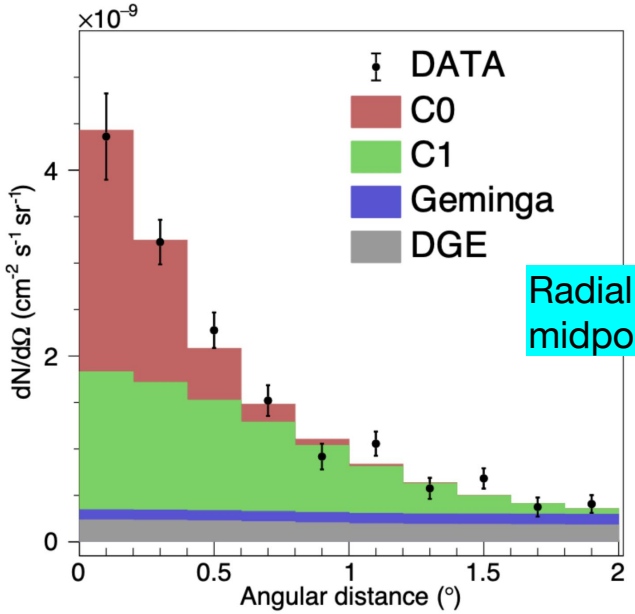
LHAASO:
point source (IC 443)
+ extended source

One-dimensional distribution and residual map

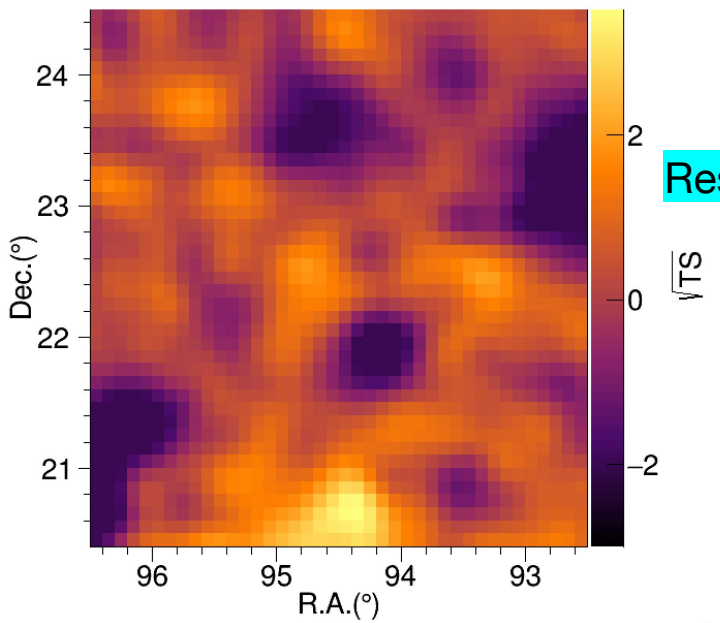
1D distribution of γ-ray flux within the rectangular box.





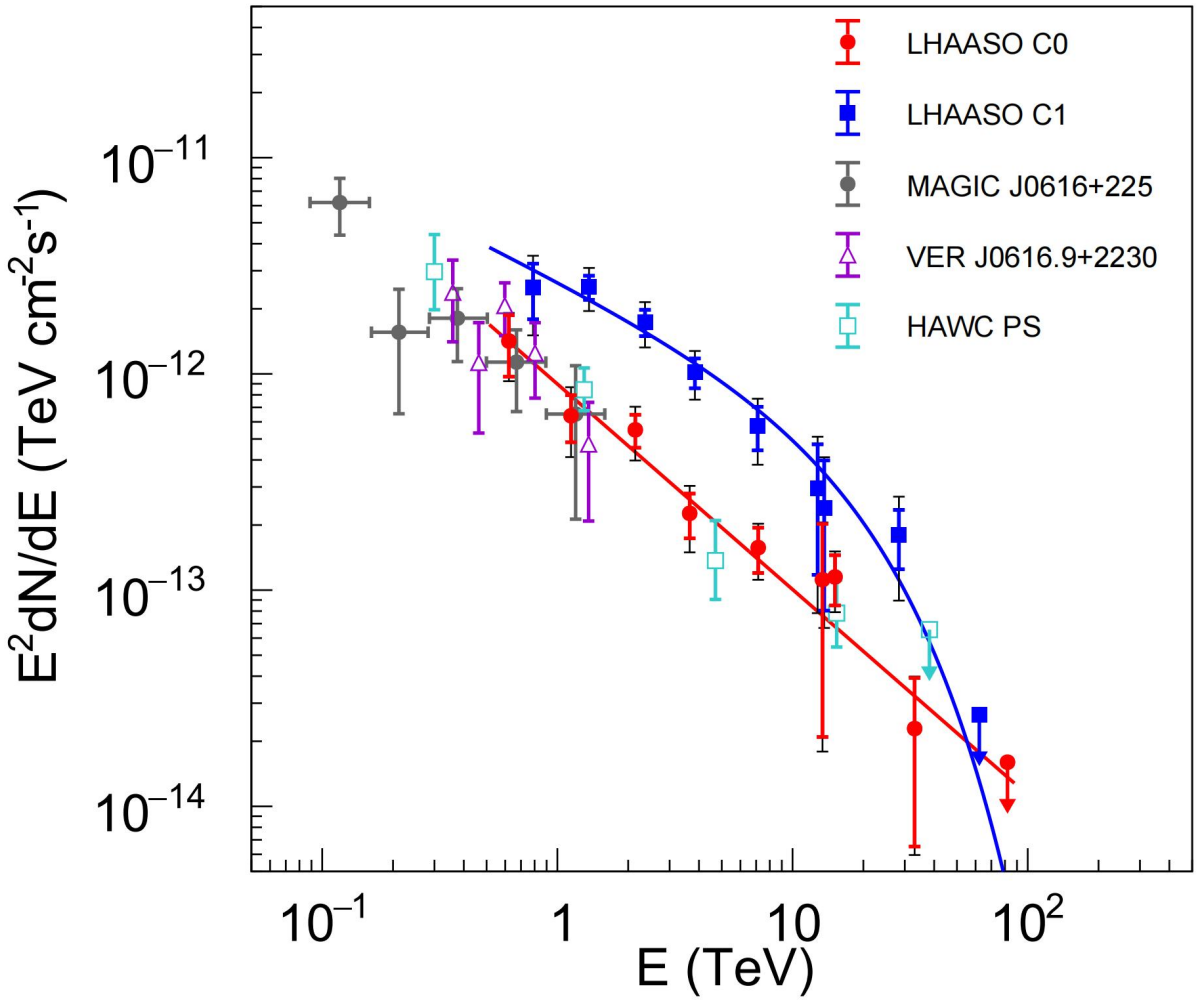


Radial profile centered at the midpoint between C0 and C1.



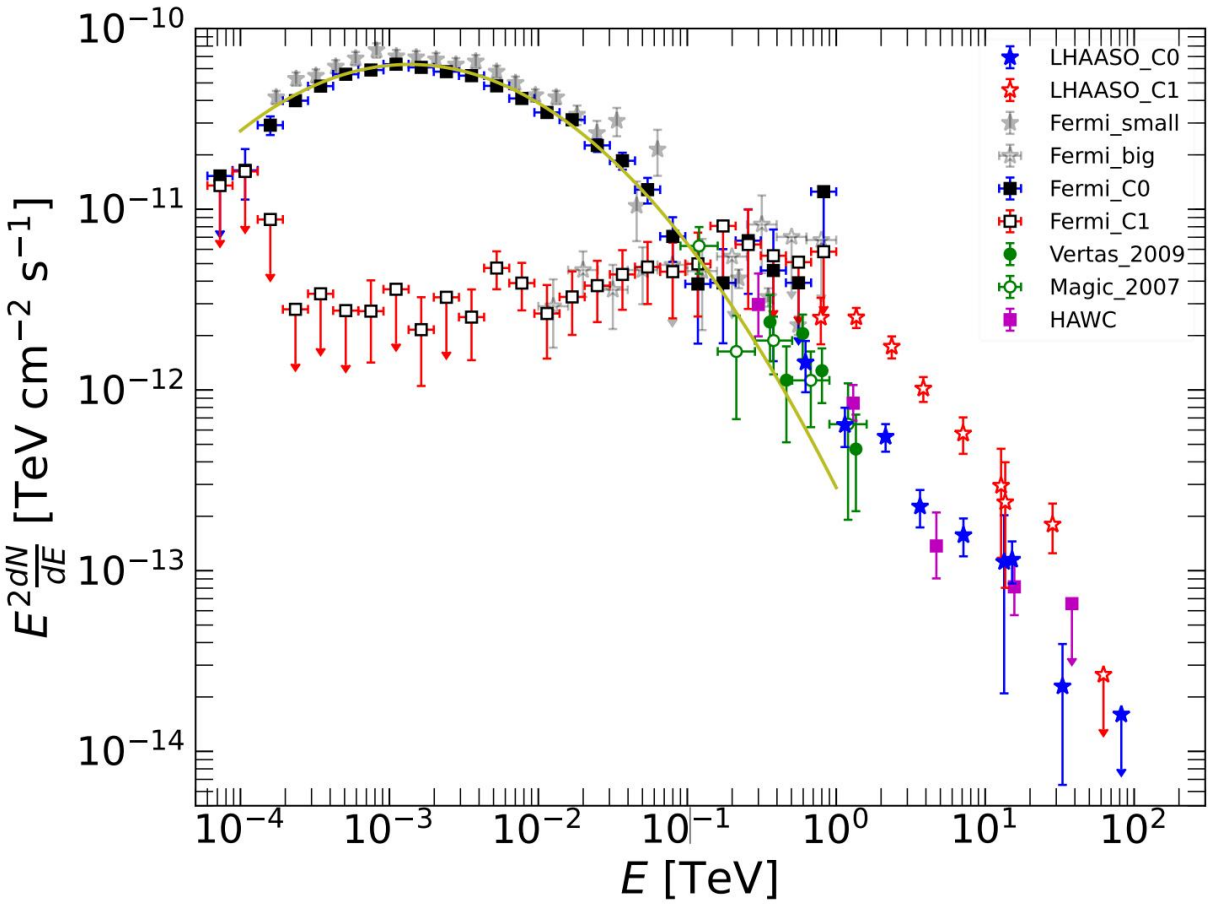
Residual map

Spectral energy distributions (SED)



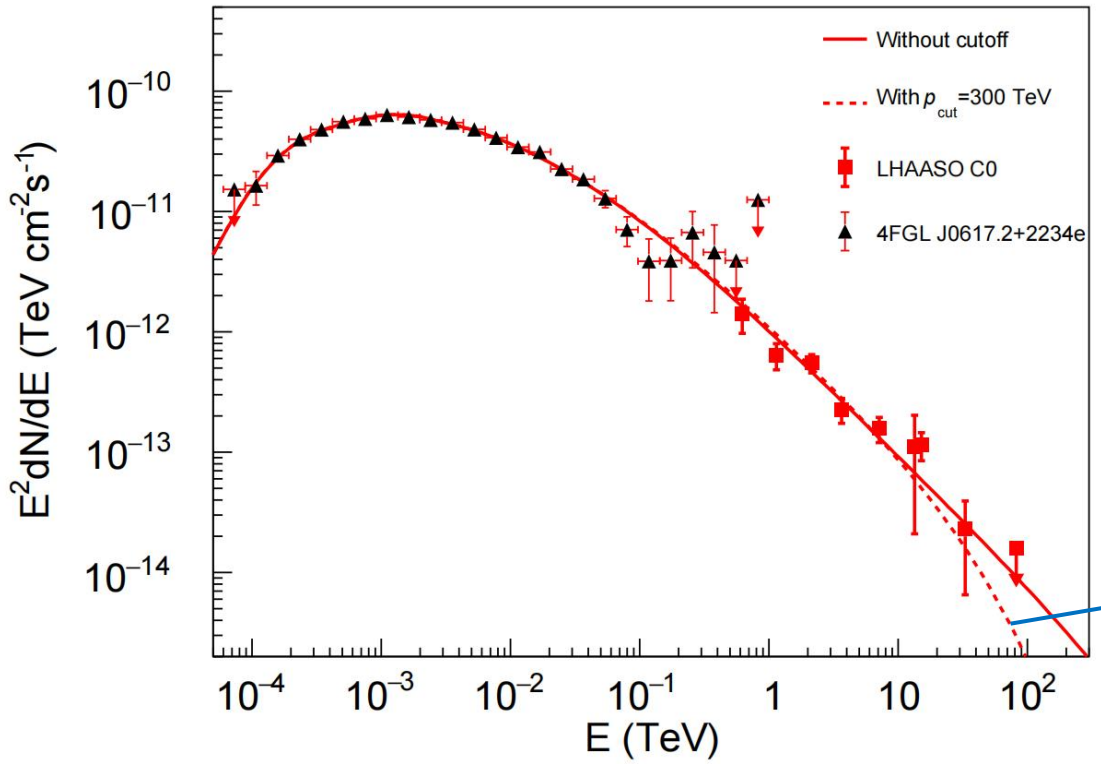
Blue line: $17.20 \times 10^{-14}(E/3\mathrm{TeV})^{-2.53}e^{-E/19.65\mathrm{TeV}}E^2$

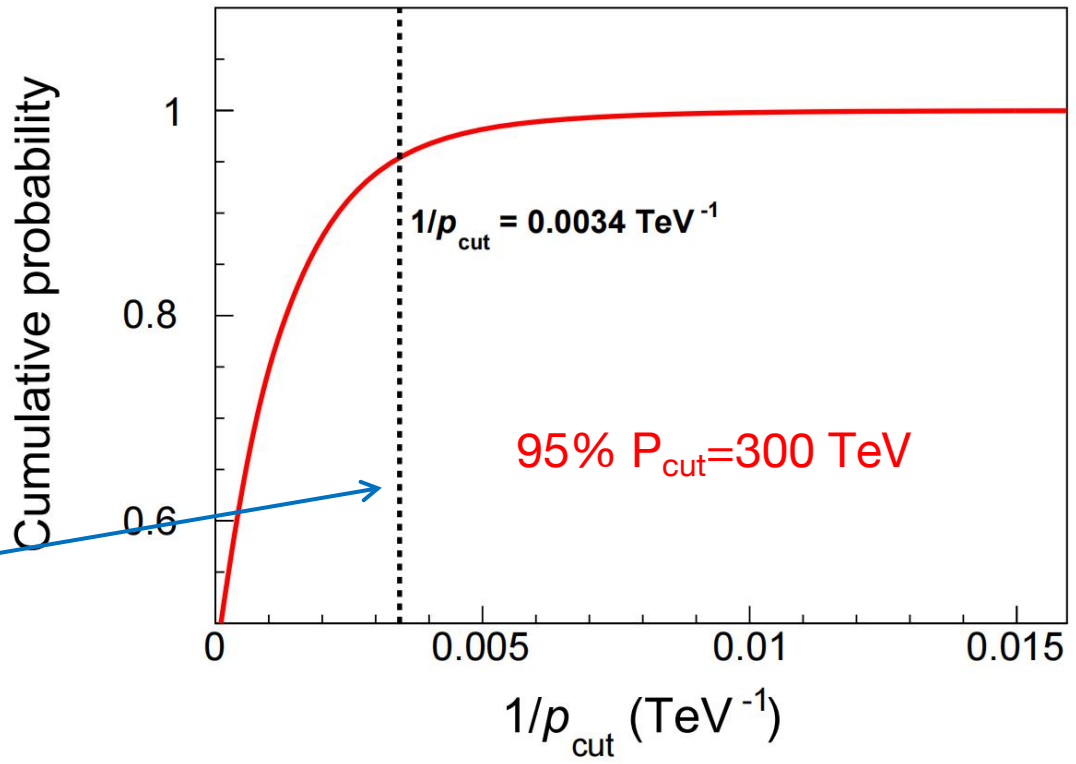
Red line: $3.51 \times 10^{-14}(E/3\mathrm{TeV})^{-2.95}E^2$



Fermi-LAT points: Reanalyzed data from August 4, 2008 to February 5, 2025 (870 weeks).

Physical interpretation for LHAASO C0 (IC443)





Hadronic model: Accelerated protons collided with molecular gas.

Proton spectrum: $Q(p) = Q_0 p^{-s_1} \left[1 + (p/p_{\rm br})^{s_2 - s_1}\right]^{-1} {\rm e}^{-p/p_{\rm cut}}$,

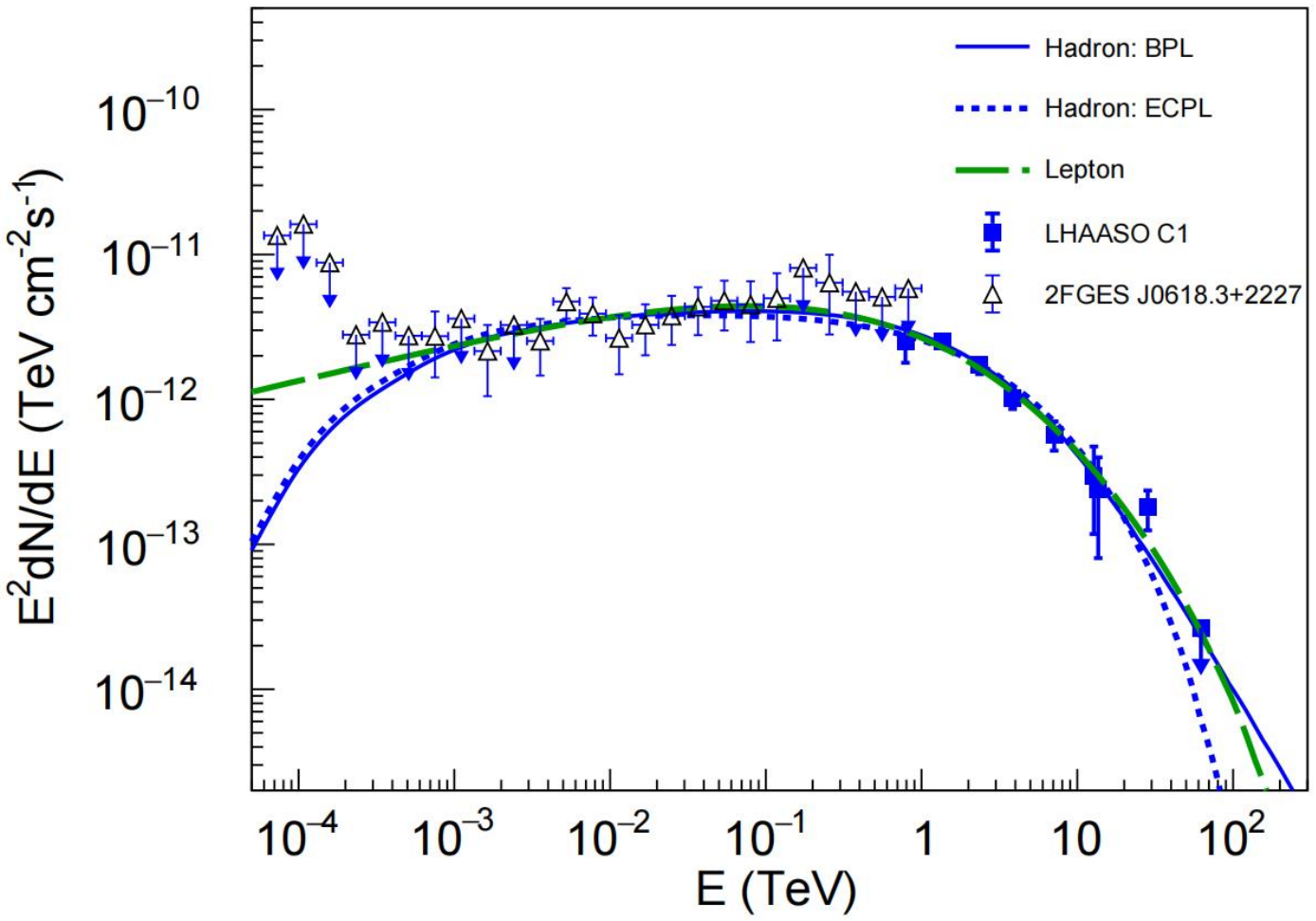
No significant spectral cutoff is found.

Best fit: $p_{\rm cut} = \infty$,

$s_1 = 2.28^{+0.03}_{-0.02}$, $s_2 = 3.13^{+0.05}_{-0.06}$, $p_{\rm br} = 0.38^{+0.16}_{-0.13}$ TeV,

$W_p = 5.67^{+0.57}_{-0.57} \times 10^{49} (n/20\ {\rm cm}^{-3})^{-1}$ erg (Total energy)

Physical interpretation for LHAASO C1



Hadronic model: Accelerated protons collided with molecular gas.

Proton spectrum:

(1) BPL: $Q(p) = Q_0 p^{-s_1} [1 + (p/p_{\rm br})^{s_2 - s_1}]^{-1}$,

$$s_1 = 1.94^{+0.06}_{-0.10},\ s_2 = 3.78^{+0.46}_{-0.28},\ p_{\rm br} = 22.6^{+13.6}_{-8.3}\ \text{TeV},$$

$$W_p = 8.18^{+0.85}_{-0.83} \times 10^{49} (n/1\ \text{cm}^{-3})^{-1}\ \text{erg}.$$

(2) ECPL: $Q(p) = Q_0 p^{-s_1} \mathrm{e}^{-p/p_{\rm cut}}$.

$$s = 1.98 \pm 0.06,\ p_{\rm cut} = 41.3 \pm 12.7\ \text{TeV},$$

$$W_p = (8.28 \pm 0.85) \times 10^{49} (n/1\ \text{cm}^{-3})^{-1}\ \text{erg}.$$

Leptonic model: Inverse Compton scattering CMB and infrared photons.

Electron spectrum:

(1) ECBPL: $Q(p) = Q_0 p^{-s_1} [1 + (p/p_{\rm br})^{s_2 - s_1}]^{-1} \mathrm{e}^{-p/p_{\rm cut}}$,

$$s_1 = 2.49^{+0.40}_{-1.12},\ s_2 = 3.84^{+1.12}_{-0.47},\ p_{\rm br} = 3.66^{+16.08}_{-3.00}\ \text{TeV},$$

$$p_{\rm cut} = 125\ \text{TeV (fixed)}\quad W_e = 2.12^{+12.04}_{-1.96} \times 10^{48}\ \text{erg}$$

Conclusion

- SNR–MC interacting systems are ideal laboratories to probe hadronic cosmic-ray acceleration.

- Using LHAASO data, we resolve two VHE γ-ray sources in the IC 443 region: **a point source (C0) and an extended source (C1).**

- **LHAASO C0** connects smoothly with the **Fermi-LAT compact source** and is well described by a hadronic model. We derive a 95% lower limit on the proton cutoff momentum of ~300 TeV, providing strong evidence for sub-PeV proton acceleration by the SNR shock.

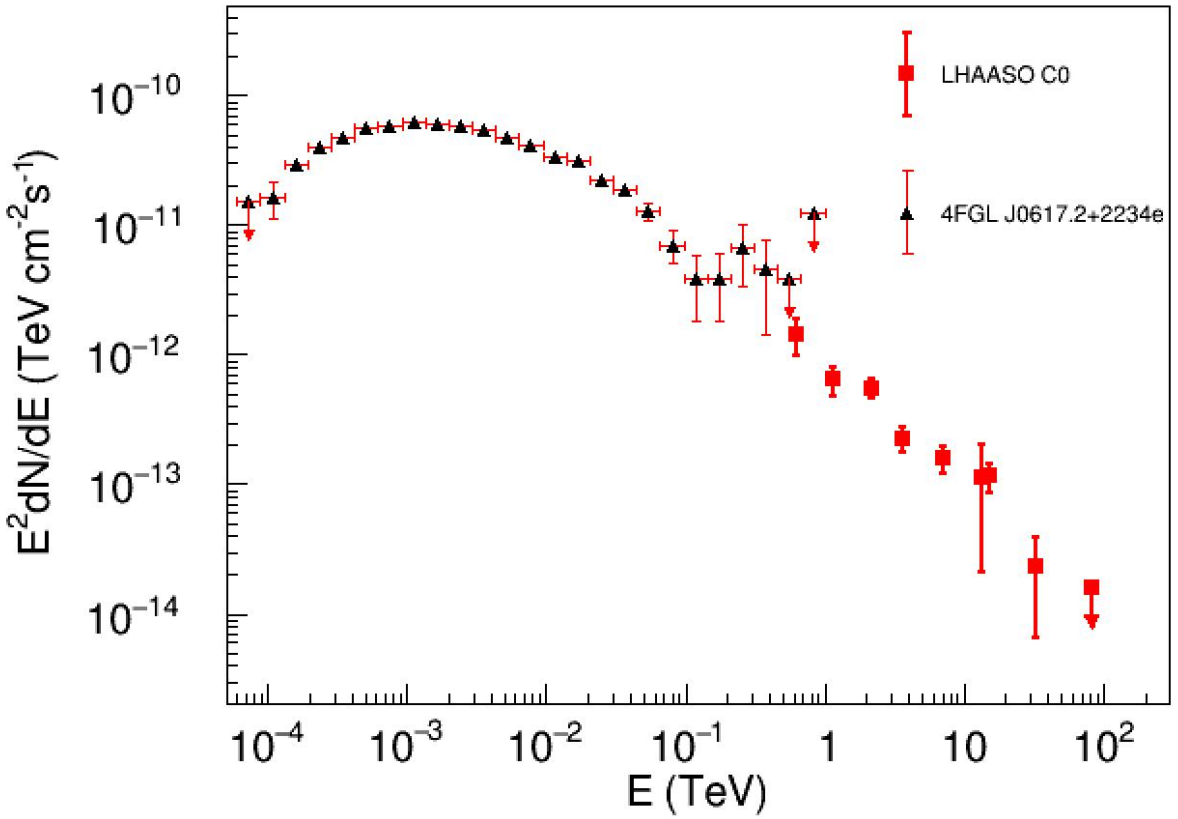
- **LHAASO C1** is consistent with the **Fermi-LAT extended source** in both morphology and spectrum. Its γ-ray emission can be explained either by interactions of escaping protons with molecular gas (hadronic scenario) or by leptonic processes.

Thank you !!!

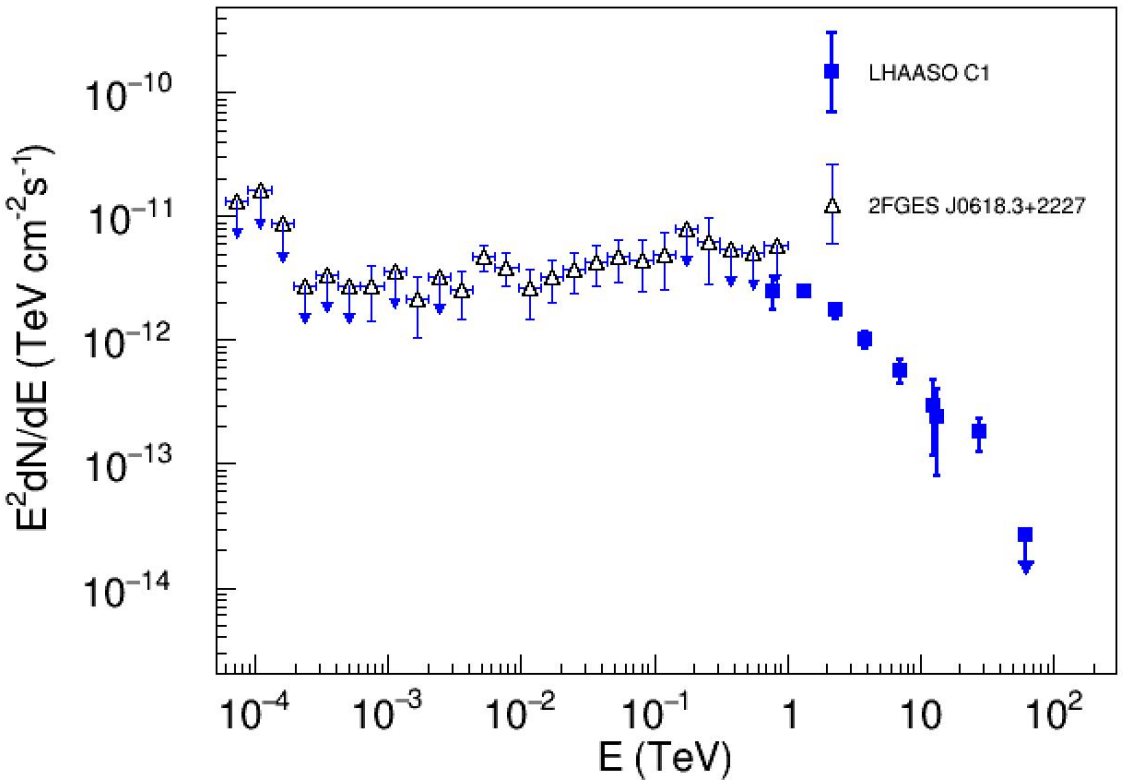
Back Up

Fermi-LAT Data Re-analysis

- August 4, 2008 to February 5, 2025 (870 weeks)
- P8R3 SOURCE Fermi-LAT data
- 60 MeV to 1 TeV
- Galactic diffuse model gll_iem_v07.fits and the isotropic background spectrum iso_P8R3_SOURCE_V3_v1.txt



Gaussian extension (R_{39}): 0.17 deg



R_{39}: 0.64 deg

Systematic uncertainties

- DGE free or fixed
  - The diffuse γ-ray flux is either fixed to the LHAASO outer Galactic region measurement or treated as a free parameter in the fit.
- DGE template
  - The spatial template is constructed from gas survey maps or from Planck dust emission data.
- Geminga model in ROI
  - The Geminga halo morphology within the ROI is modeled using either a symmetric or an asymmetric assumption.

	C0
E (TeV)	$E^2dN/dE \pm \sigma_{stat} \pm \sigma_{sys}$ (TeV cm^{-2} s^{-1})
0.62	$(1.42 \pm 0.45 \pm 0.21) \times 10^{-12}$
1.14	$(6.40 \pm 1.57 \pm 1.65) \times 10^{-13}$
2.14	$(5.51 \pm 0.96 \pm 1.20) \times 10^{-13}$
3.65	$(2.26 \pm 0.53 \pm 0.56) \times 10^{-13}$
7.14	$(1.57 \pm 0.37 \pm 0.26) \times 10^{-13}$
15.15	$(1.15 \pm 0.30 \pm 0.20) \times 10^{-13}$
13.40	$(1.12 \pm 0.91 \pm 0.24) \times 10^{-13}$
33.04	$(2.29 \pm 1.64 \pm 0.43) \times 10^{-14}$
82.20	$< 1.60 \times 10^{-14}$

σ_{sys} ~ 20%

Model	ΔTS	R.A. (°)	Dec. (°)	R_{39} (°)	Flux @ 3 TeV (10^{-14} TeV^{-1}cm^{-2}s^{-1})	α	E_{cut} (TeV)	Φ_0 (DGE) (TeV^{-1}cm^{-2}s^{-1})	Comment
C0		94.27±0.03	22.44±0.02	0.01±0.20	3.51±0.43	2.95±0.07	–	5.35±0.37	Benchmark
C1		94.45±0.07	22.61±0.06	0.67±0.07	17.20±2.74	2.53±0.14	19.65±8.67	(Planck)	
C0	−15.3	94.28±0.03	22.45±0.02	0.07±0.21	4.09±0.39	2.97±0.06	–	3.84	DGE fixed
C1		94.43±0.06	22.59±0.07	0.82±0.08	19.98 ±2.15	2.53±0.10	22.01 ± 8.11	(Planck)	
C0	+0.6	94.27±0.03	22.44±0.02	0.01±0.20	3.45±0.40	2.95±0.07	–	6.32± 0.44	DGE template
C1		94.42±0.06	22.60±0.06	0.66±0.06	16.98 ±2.18	2.52±0.12	22.01 ± 6.86	(gas survey)	from gas survey
C0	−1.2	94.27±0.03	22.44±0.02	0.01±0.20	3.48±0.34	2.96±0.07	–	6.50±0.45	Symmetric Geminga
C1		94.42±0.07	22.59±0.06	0.67±0.05	16.61 ±2.11	2.49±0.12	21.07 ± 6.80	(Planck)	in the ROI

* DGE spectrum: $\Phi = \Phi_0 \cdot 10^{-14}(E/10\ \text{TeV})^{-2.72}\left[1 + (E/27.86\ \text{TeV})^5\right]^{(2.72-2.92)/5}$ [38].

HAWC fitting Result

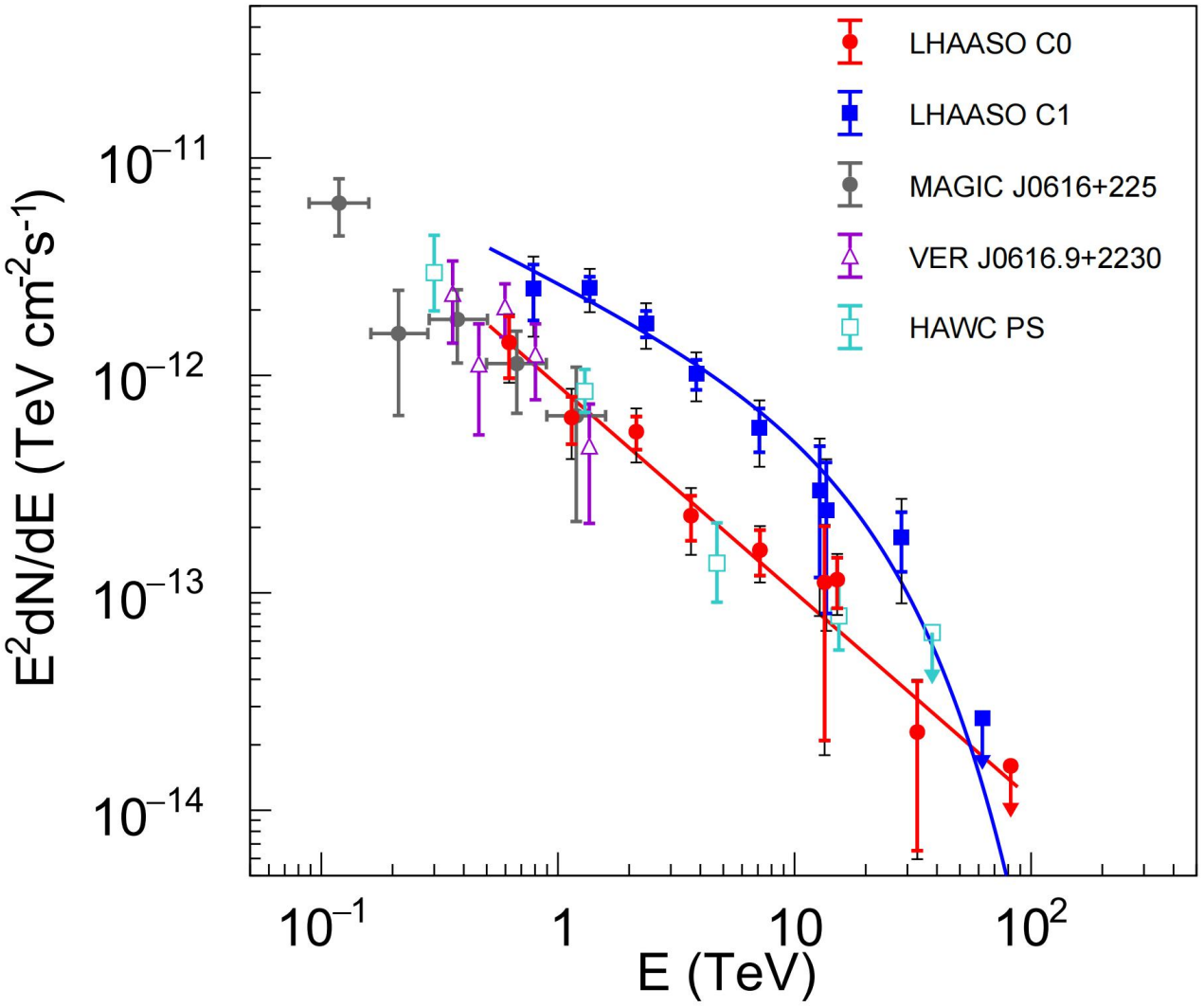
Table 1. Results of the analysis in the region of IC 443 using the $f_{\rm hit}$ scheme.

Source	Φ_0	Index	R.A.	Decl.	σ	$\mathrm{TS_{source}}$
	$[\mathrm{TeV^{-1}\,cm^{-2}\,s^{-1}}]$		[°]	[°]	[°]	
PS	$(5.9 \pm 1.3\,^{+0.35}_{-0.91}) \times 10^{-14}$	$-3.14 \pm 0.18\,^{+0.08}_{-0.09}$	$94.42^{+0.07}_{-0.05} \pm 0.01$	$22.35^{+0.06\ +0.05}_{-0.07\ -0.03}$	–	28.2
ES	$(3.18^{+1.37}_{-0.92} \pm 1.3) \times 10^{-13}$	$-2.49 \pm 0.08\,^{+0.01}_{-0.03}$	$93.67 \pm 0.19 \pm 0.04$	$22.22 \pm 0.20 \pm 0.1$	$1.05^{+0.21}_{-0.18} \pm 0.18$	88.8
GDE model	$2.62 \pm 1.20\,^{+0.07}_{-0.30}$*	–	–	–	–	16.5

NOTE—First set of uncertainties are statistical while the second set are systematic. The normalization of the two sources is at $E_{\rm piv} = 2.3$ TeV. PS is associated with IC 443. ES is the new source HAWC J0615+2213.
*Scale factor: unitless and only includes systematics from detector configuration.

HAWC fitting result

Spectral energy distributions (SED)



Total errors including statistical and systematic ones. (black error bars)

Systematic uncertainties

- DGE free or fixed
- The diffuse γ-ray flux is either fixed to the LHAASO outer Galactic region measurement or treated as a free parameter in the fit.

- DGE template
- The spatial template is constructed from gas survey maps or from Planck dust emission data.

- Geminga model in ROI
- The Geminga halo morphology within the ROI is modeled using either a symmetric or an asymmetric assumption.

LHAASO C0: ECPL

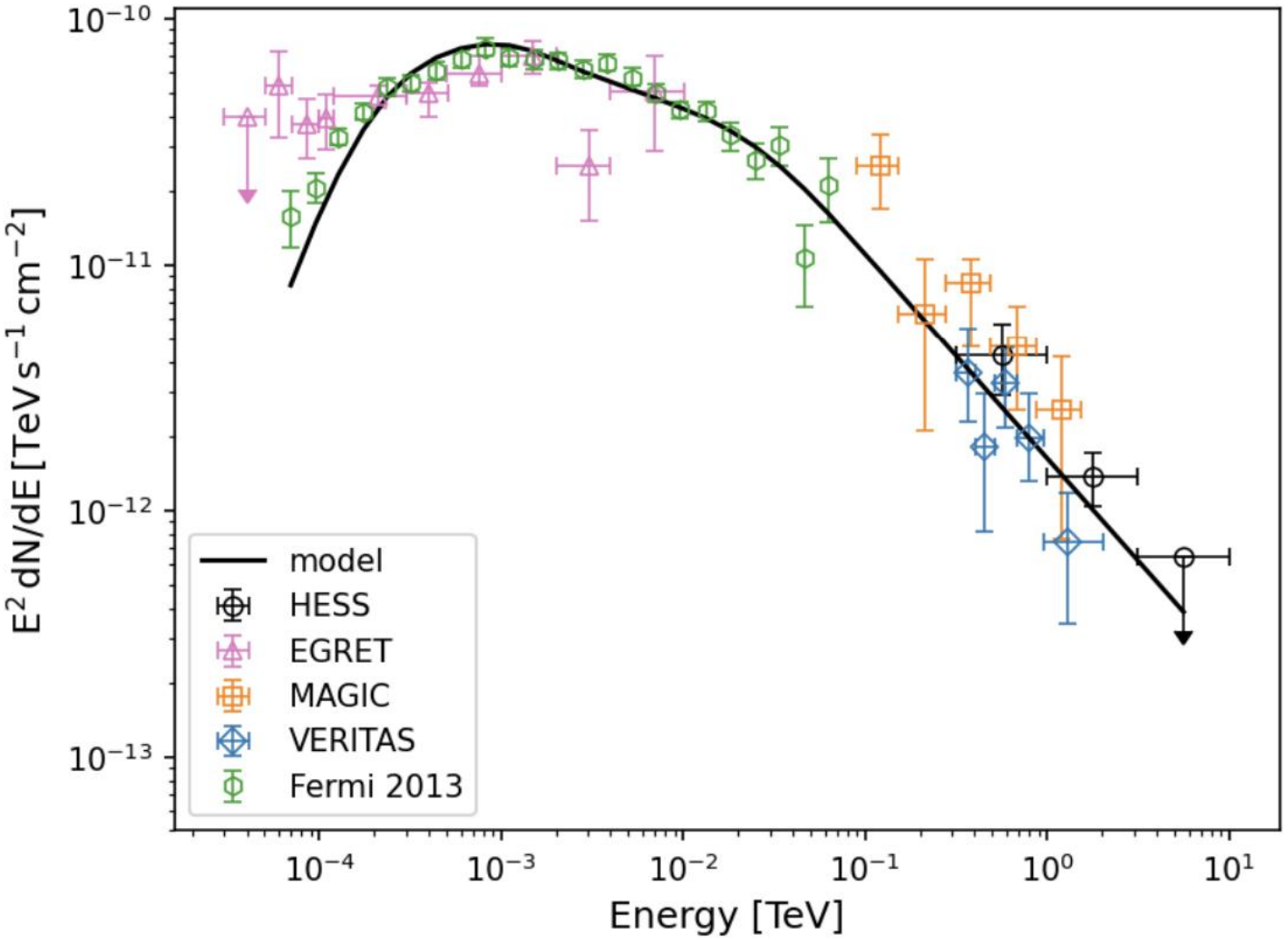
Model	TS	Name	R.A. (°)	Dec. (°)	R_{39} (°)	ϕ_0 (10^{-14} TeV^{-1}cm^{-2}s^{-1})	α	$E_{\rm cut}$ (TeV)
Two Components	5630.5	C0	94.27±0.03	22.44±0.02	Point	3.51±0.43	2.95±0.07	-
		C1	94.45±0.07	22.61±0.06	0.67±0.07	17.20±2.74	2.53±0.14	19.65 ± 8.67
One Component	5581.5	...	94.33±0.03	22.52±0.02	0.38±0.03	15.13±1.56	2.68±0.08	34.22±14.62

C0: ECPL

TS=5634.2 (+3.7)

$$\phi_0 = 4.01 \pm 0.68, \alpha = 2.7 \pm 0.2, E_{cut} = 56.7 \pm 14.5$$

HESS Result



HESS result