Measurement of diffuse gamma-ray emission from Galactic plane with LHAASO

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on behalf of the LHAASO collaboration

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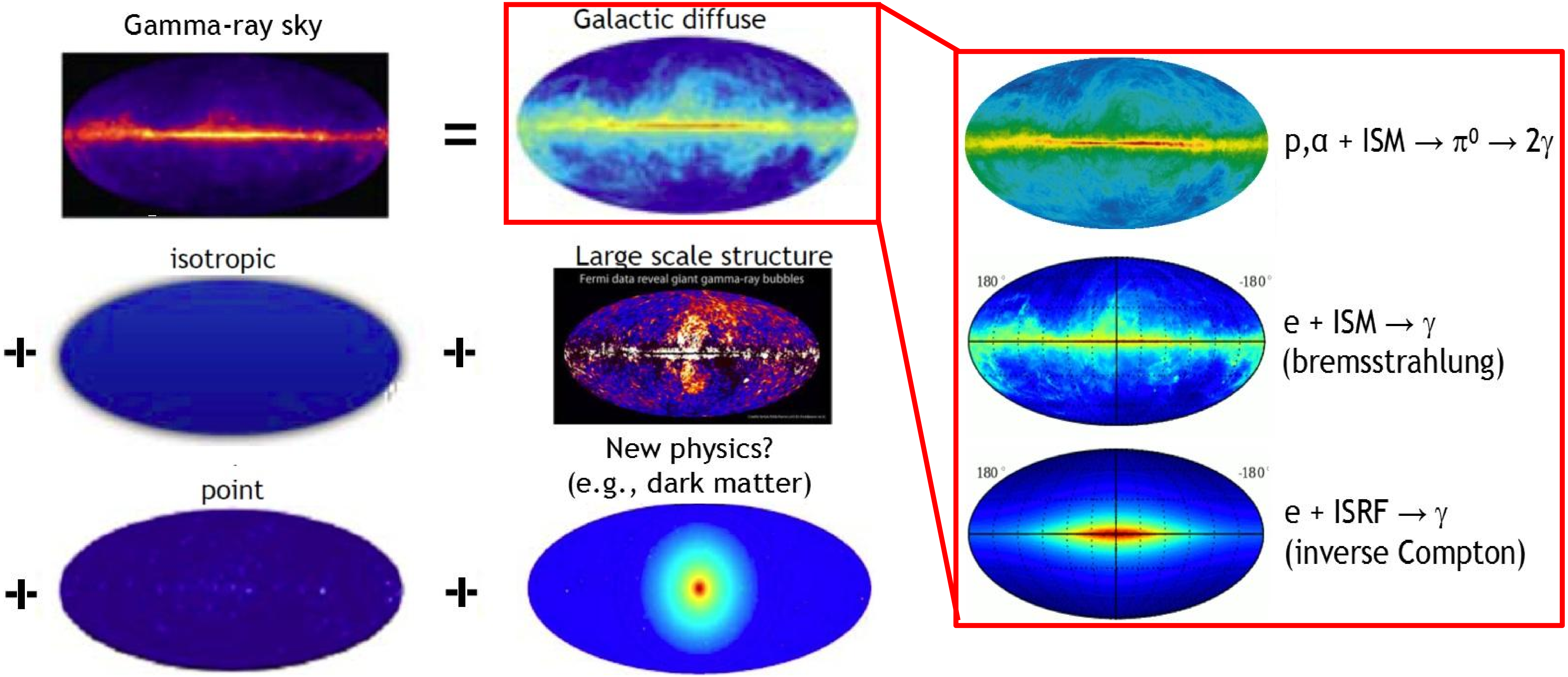
(2023, PRL, 131, 151001; 2025, PRL, 134, 081002)

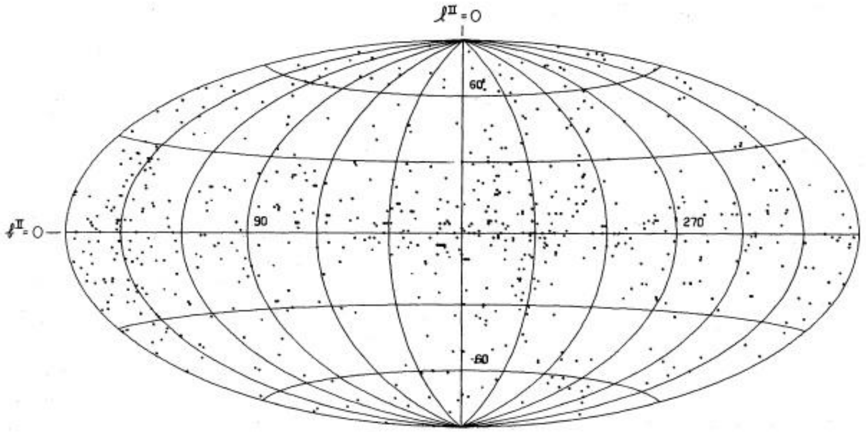
The 2nd LHAASO Symposium, Hongkong, China, Mar. 21-25, 2025

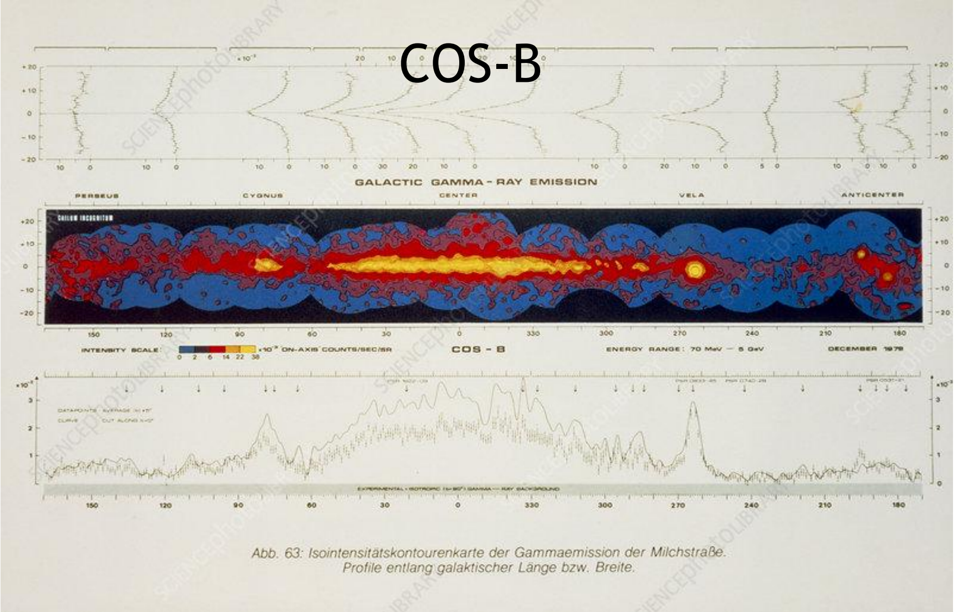
The gamma-ray sky

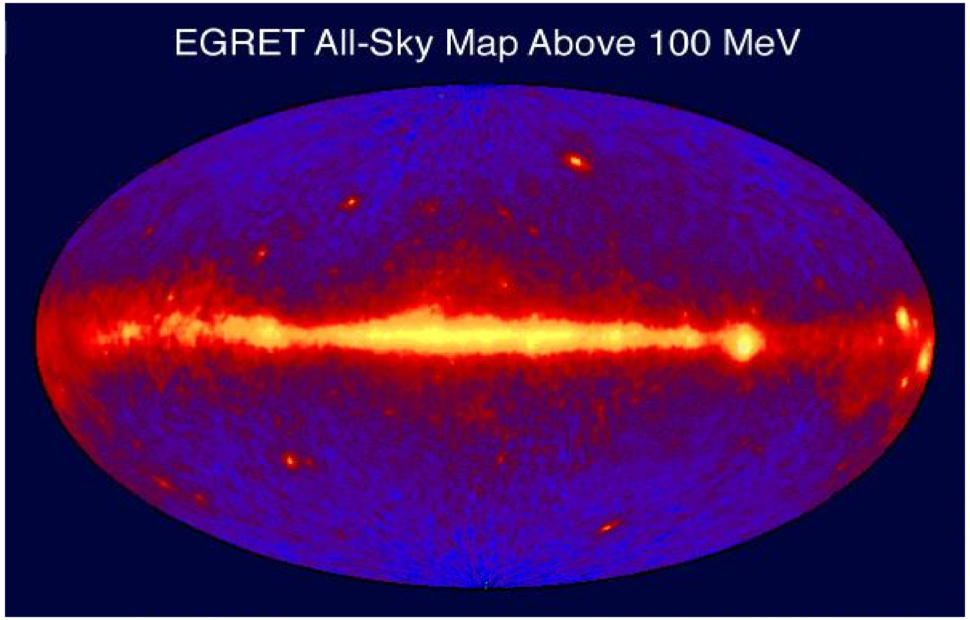


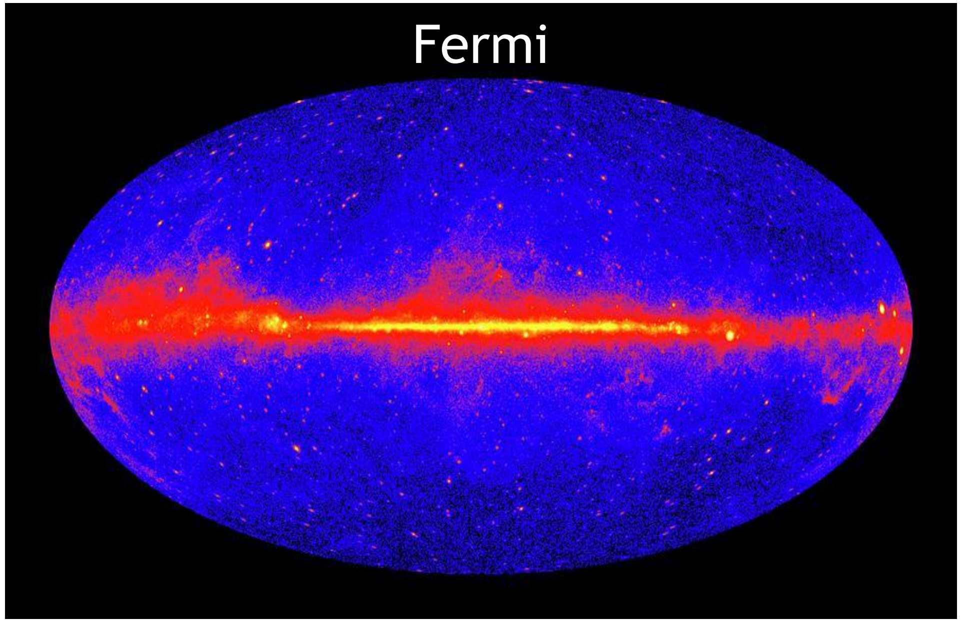
Diffuse γ-ray observations from space (<TeV)

OSO-3: 621 gamma-rays

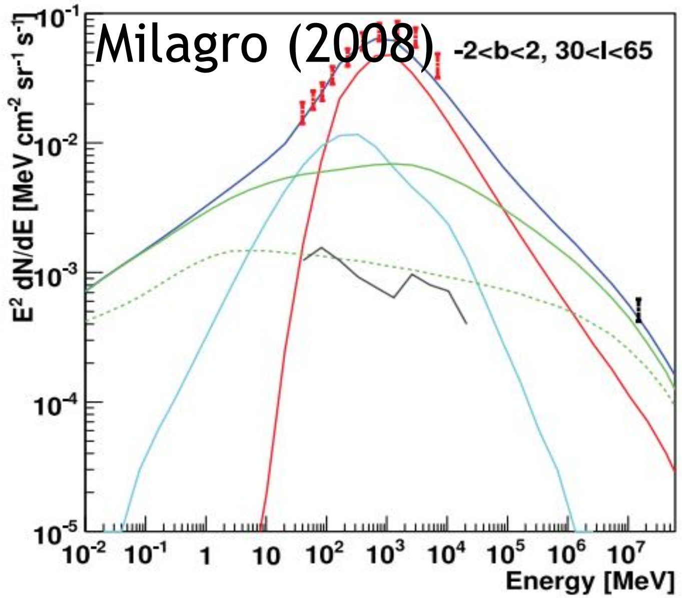


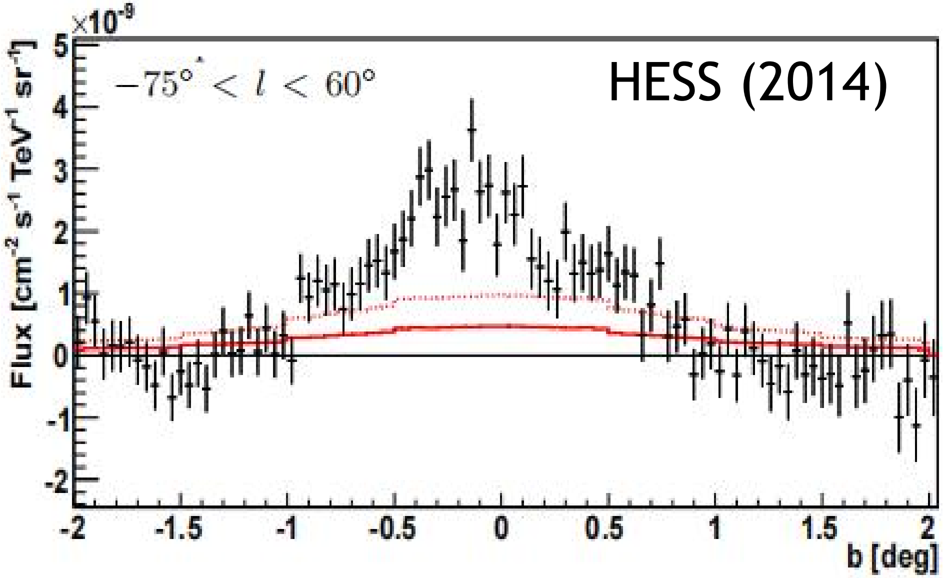


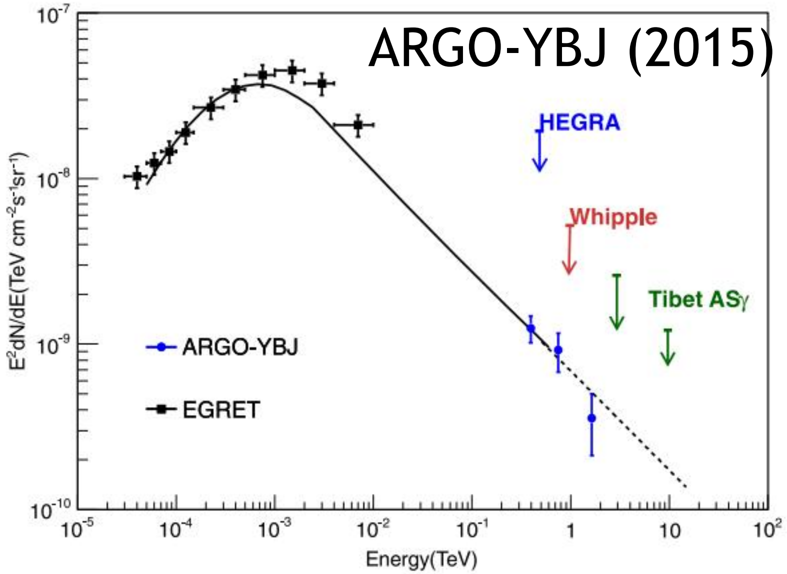


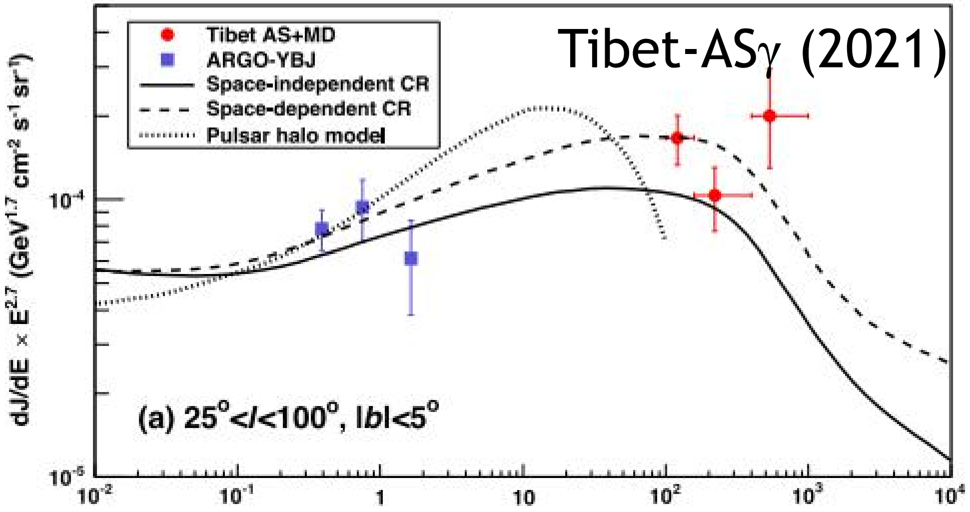


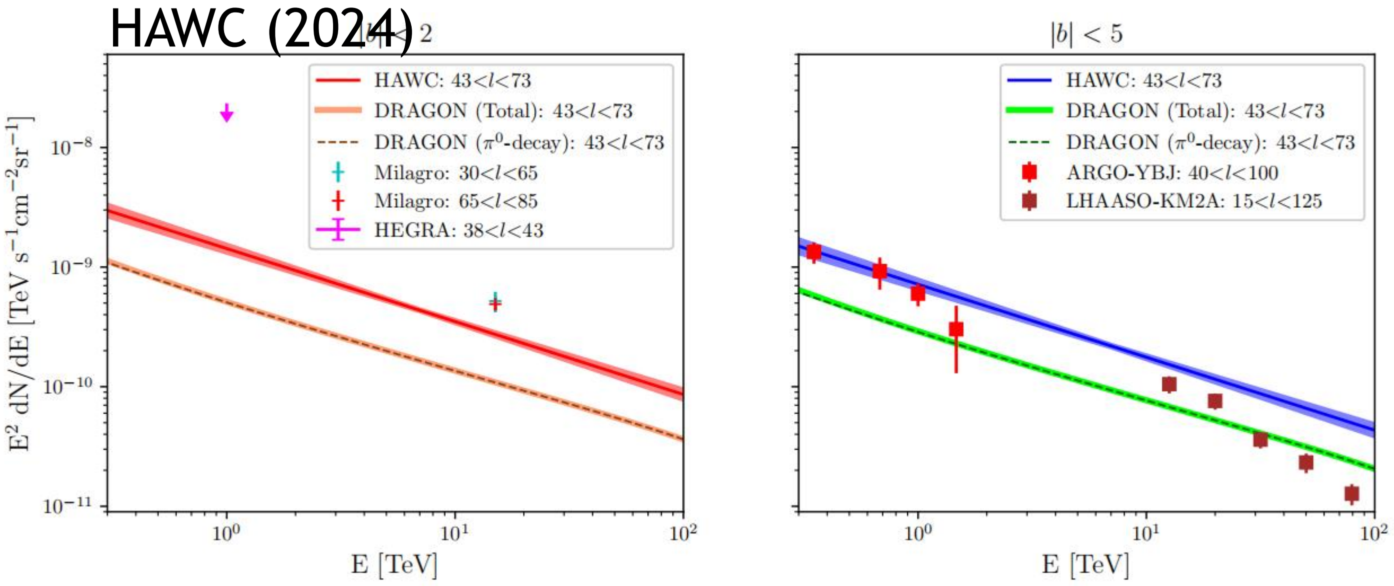
VHE diffuse measurement on ground (>TeV)



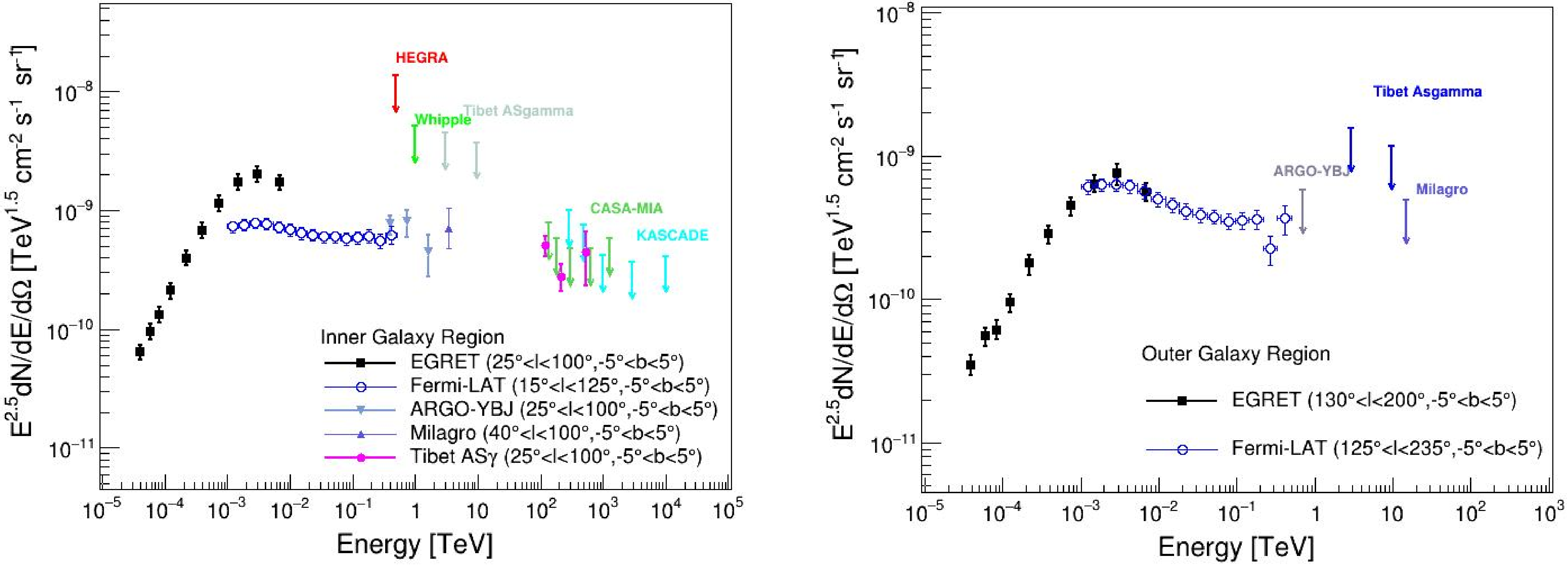






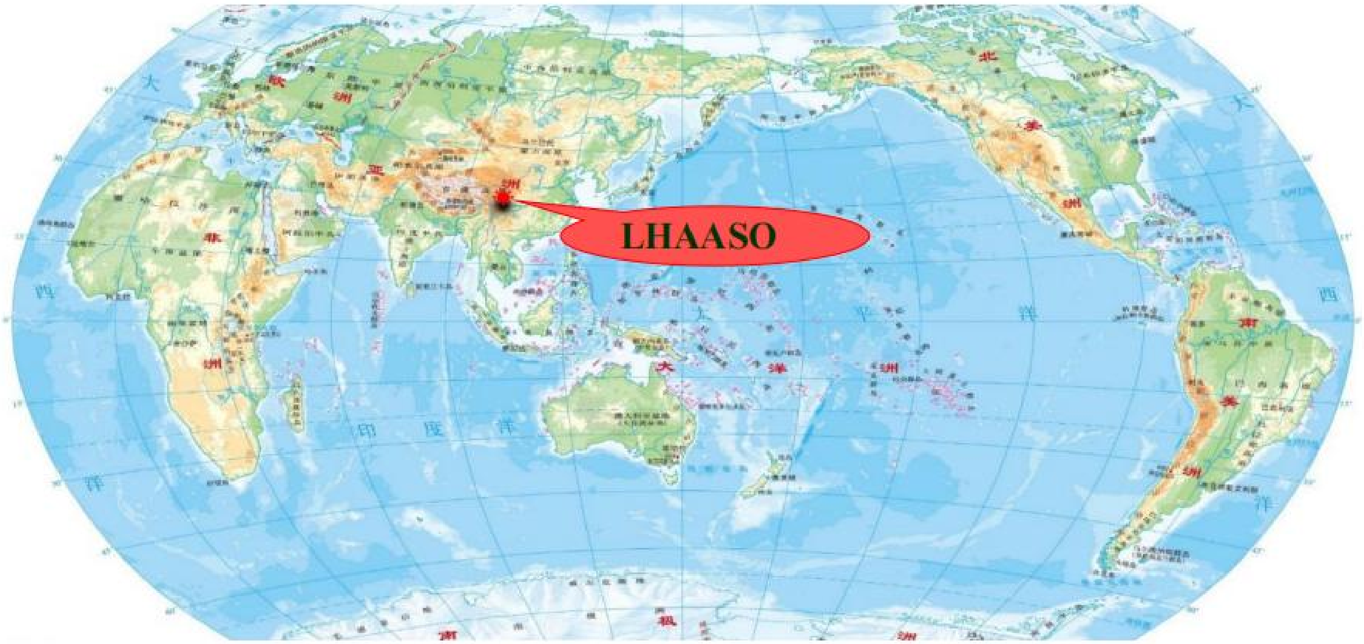


Wide-band diffuse emission measurements



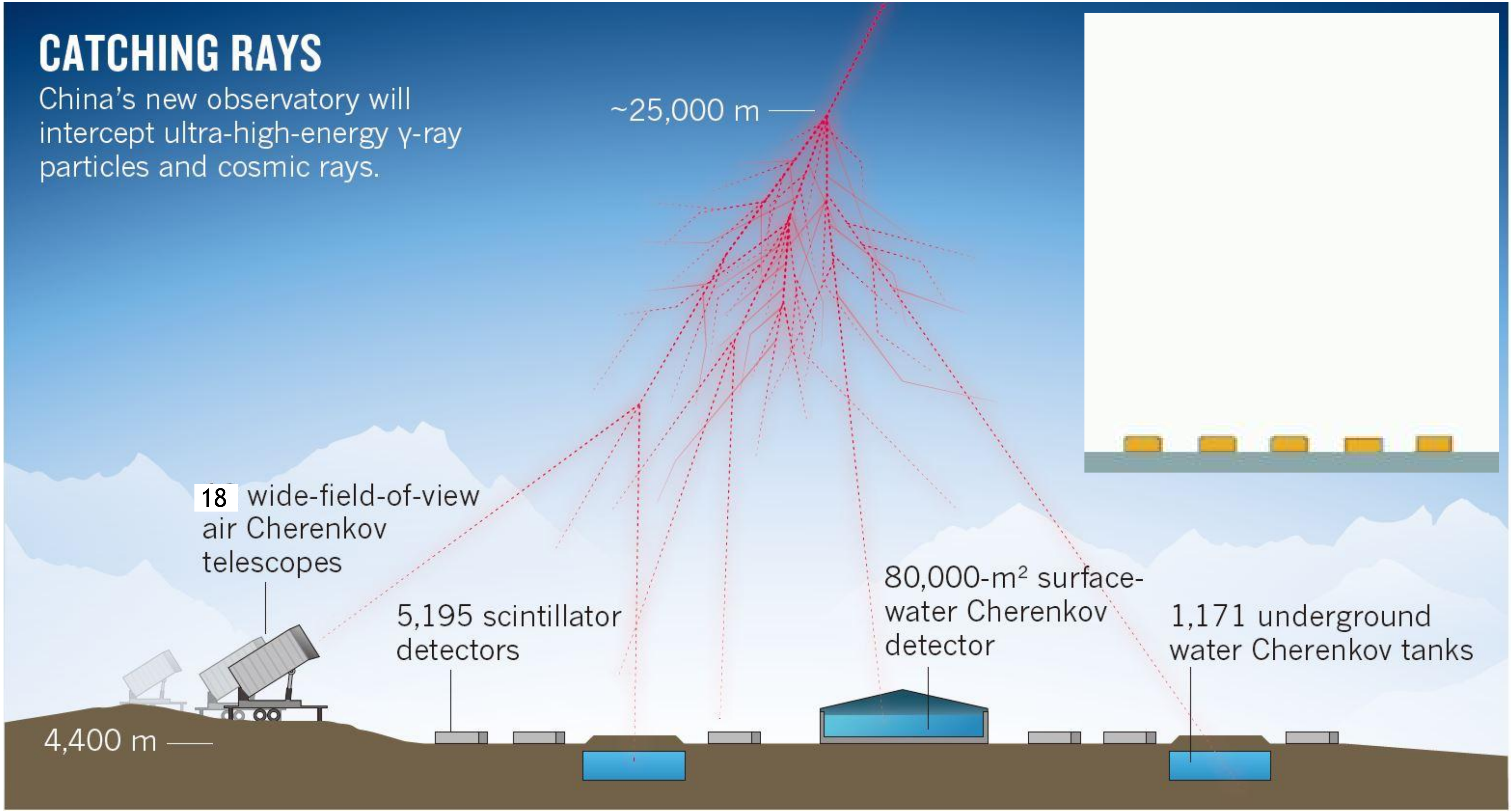
Above TeV, the energy and sky coverage is limited, especially in the outer Galactic plane region where only upper limits were given

Large High Altitude Air Shower Observatory——LHAASO

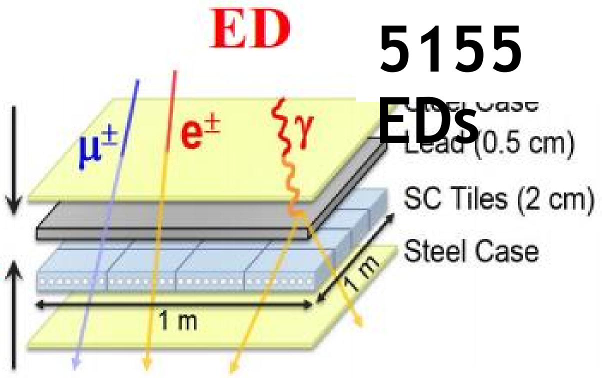


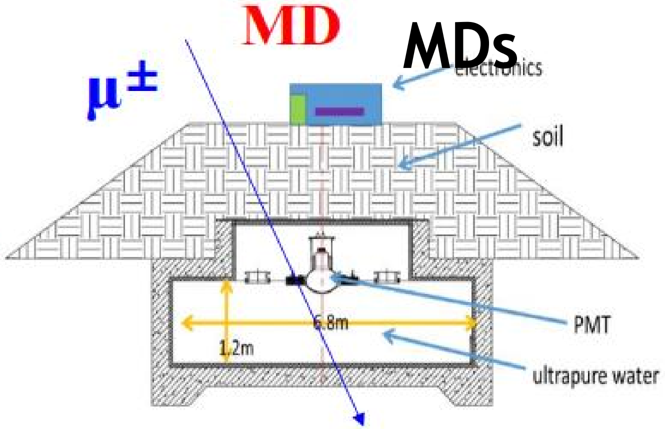
- Haizi mountain, Sichuan, China, 4410 m above the sea level
- LHAASO uses hybrid detector arrays: the square kilometer array (KM2A), the water Cherenkov detector array (WCDA), and the wide field-of-view Cherenkov telescope array (WFCTA)
- Full operation since July 2021

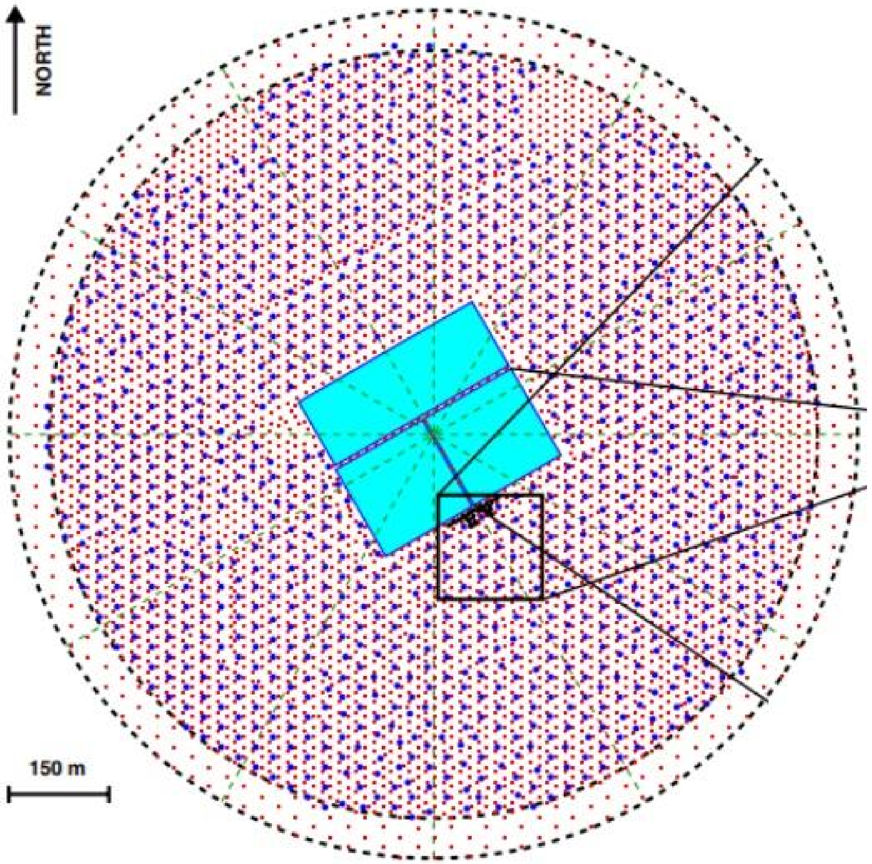
Air shower detection of cosmic rays



KM2A: Square Kilometer Array

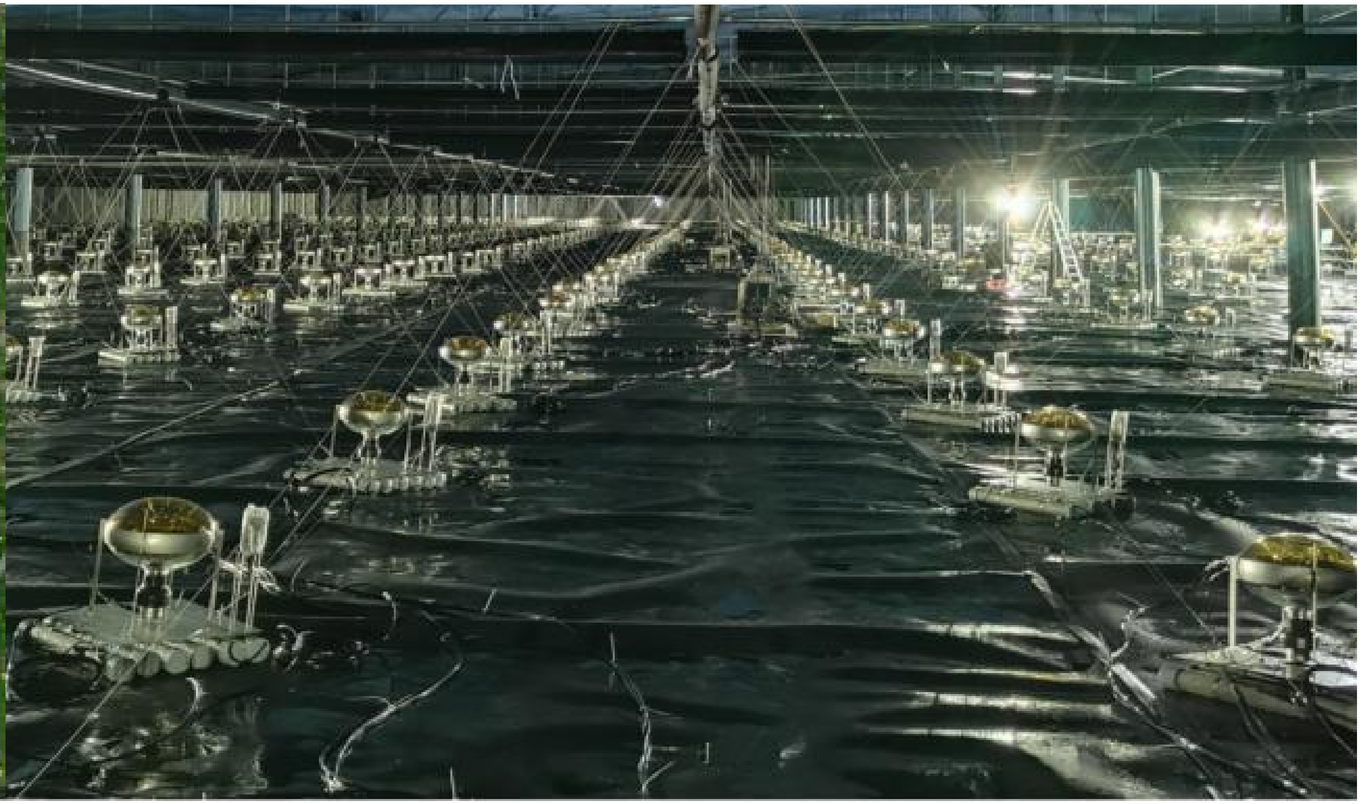






- 1.3 km² area covered by 5155 electromagnetic detectors, used for energy and direction reconstruction
- 1188 muon detectors used for gamma/hadron distinguish
- Energy coverage: 10 TeV - 100 PeV

WCDA: Water Cherenkov Detector Array



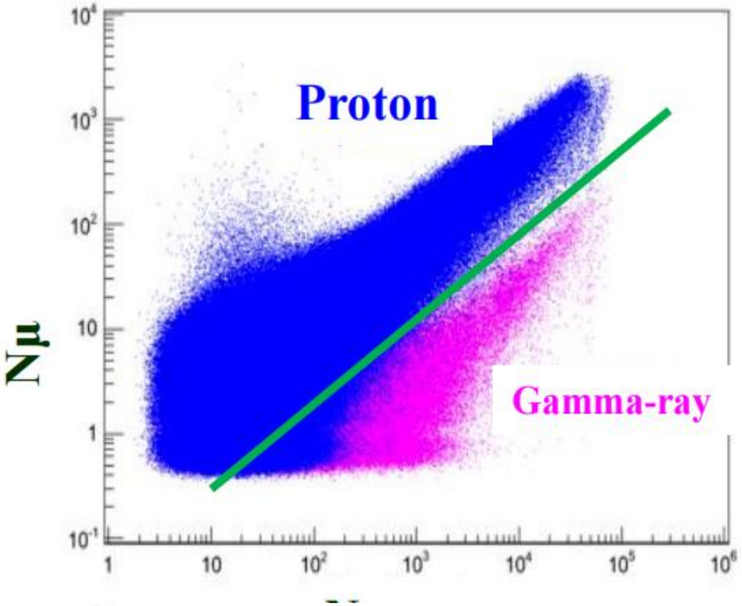
- 78000 m^2 water tank to detect Cherenkov light produced by air shower particles in water
- Energy coverage: 0.3 TeV - PeV

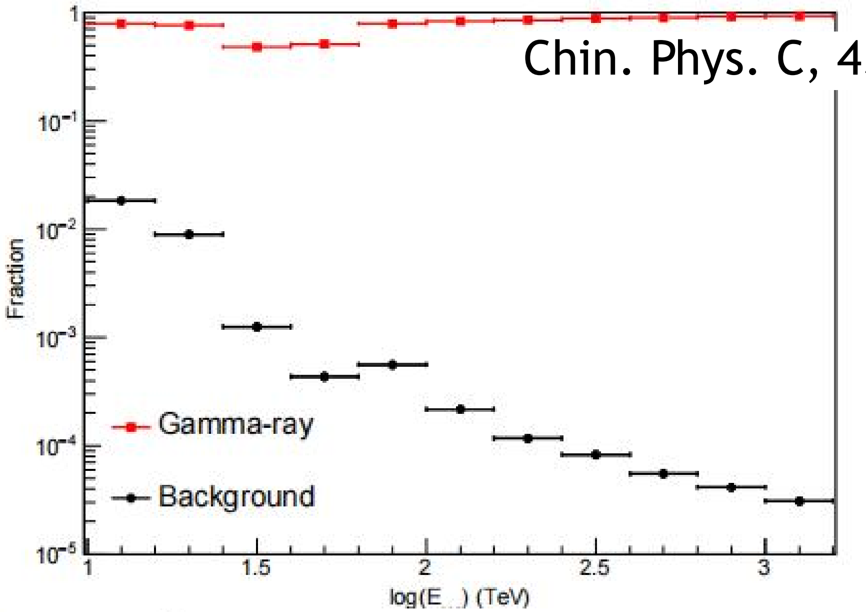
WFCTA: Wide Field Cherenkov Telescope Array

- 18 WFCTA used to distinguish particles with different mass, each one has an area of 4.7 m^2 each and covers a square sky with area 16°×16°
- Energy coverage: 10 TeV - 100 PeV

Gamma-CR discrimination

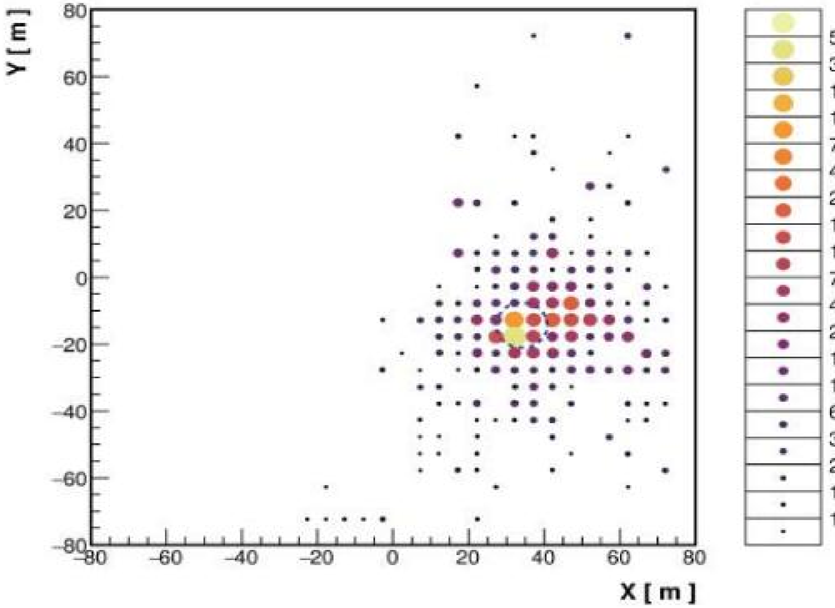
KM2A

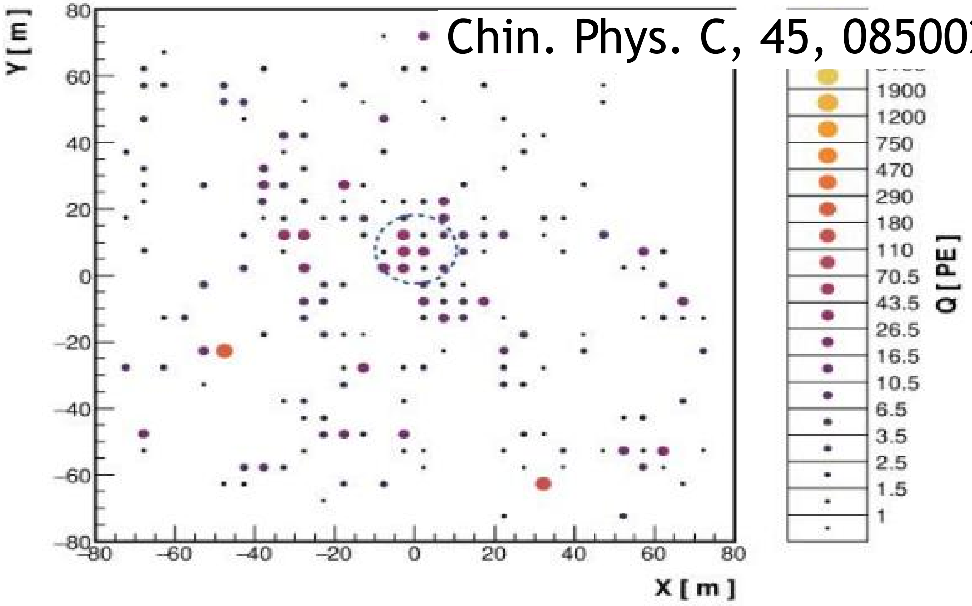




Chin. Phys. C, 45, 025002 (2021)

WCDA

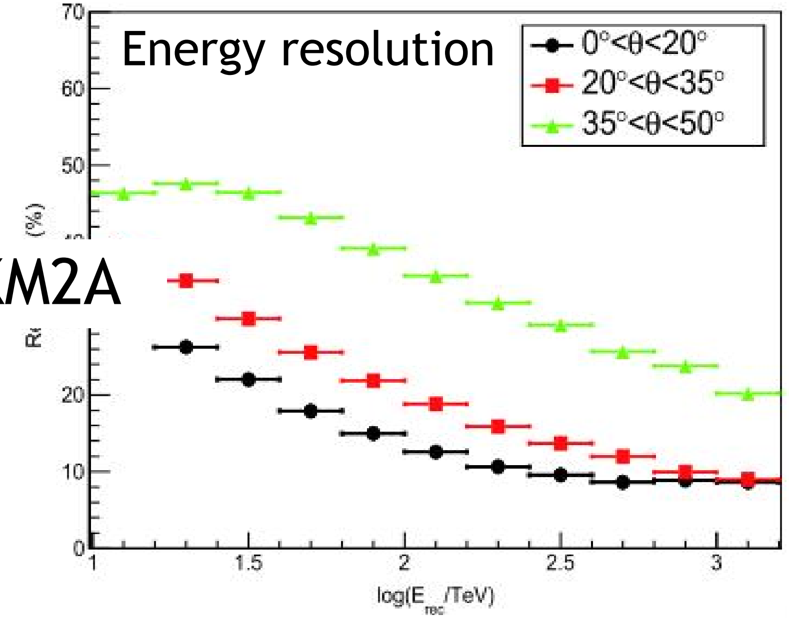


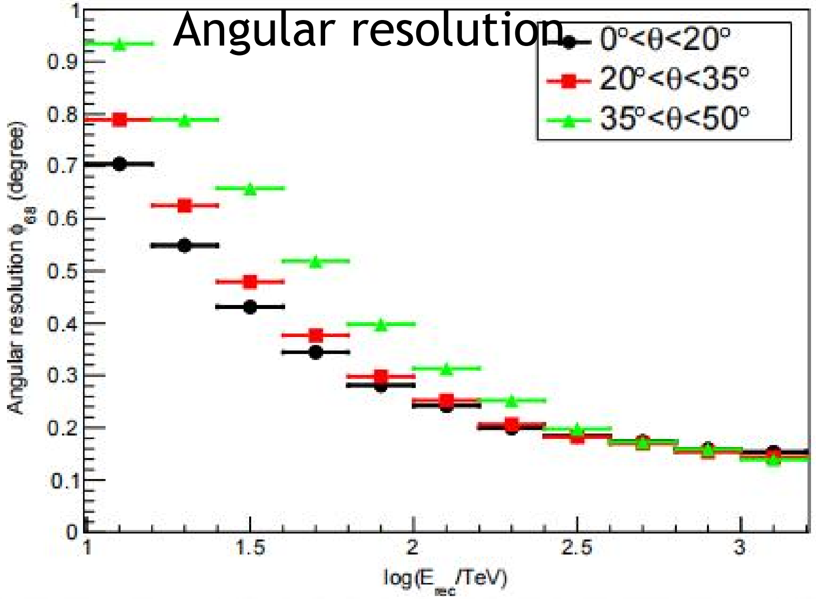


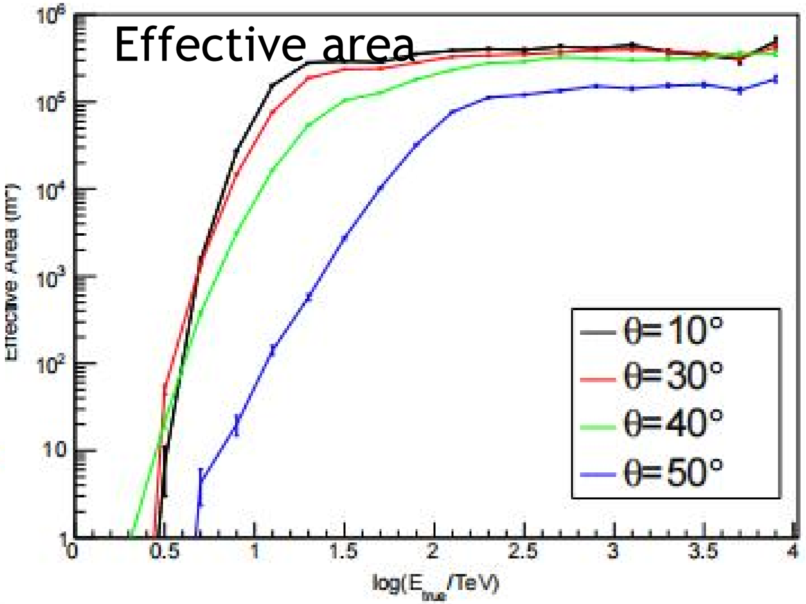
Chin. Phys. C, 45, 085002 (2021)

Gamma-ray performance

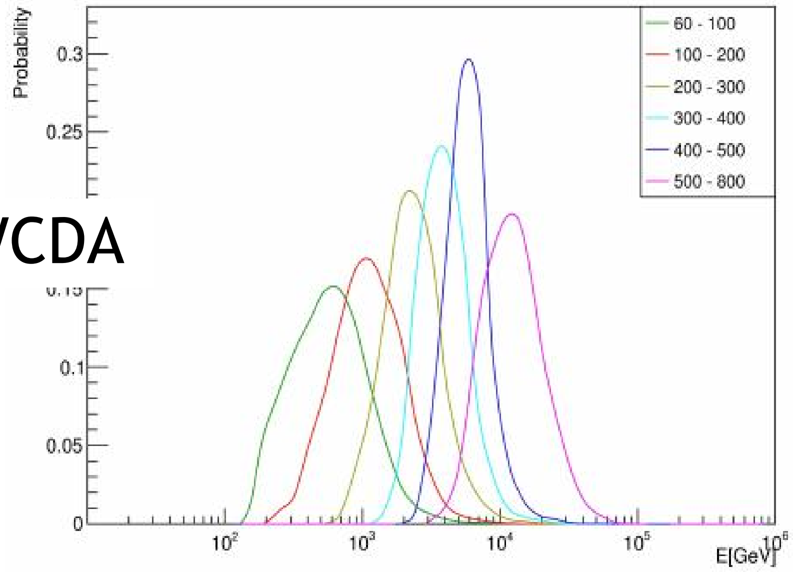
KM2A

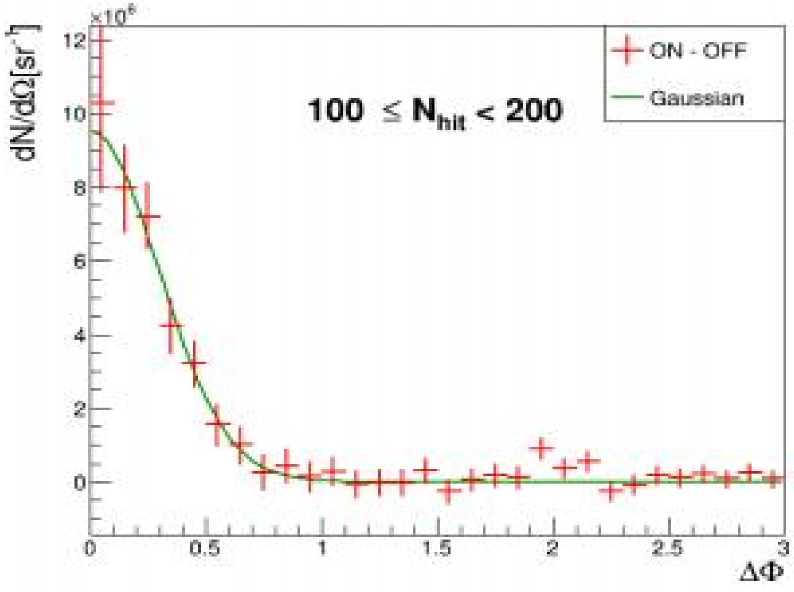


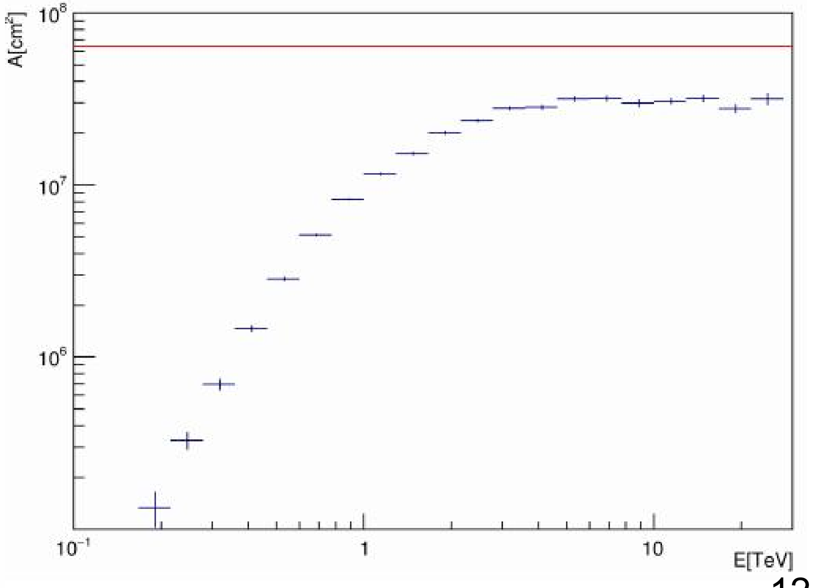




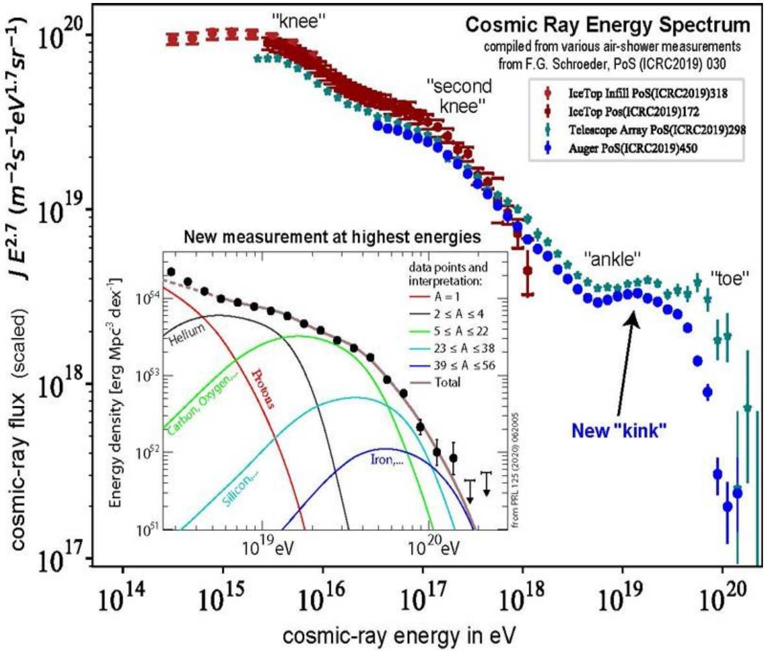
WCDA

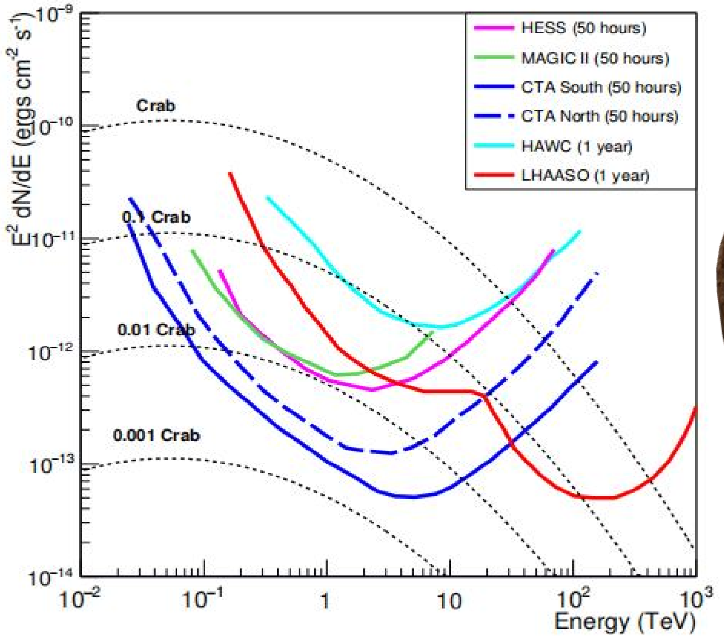


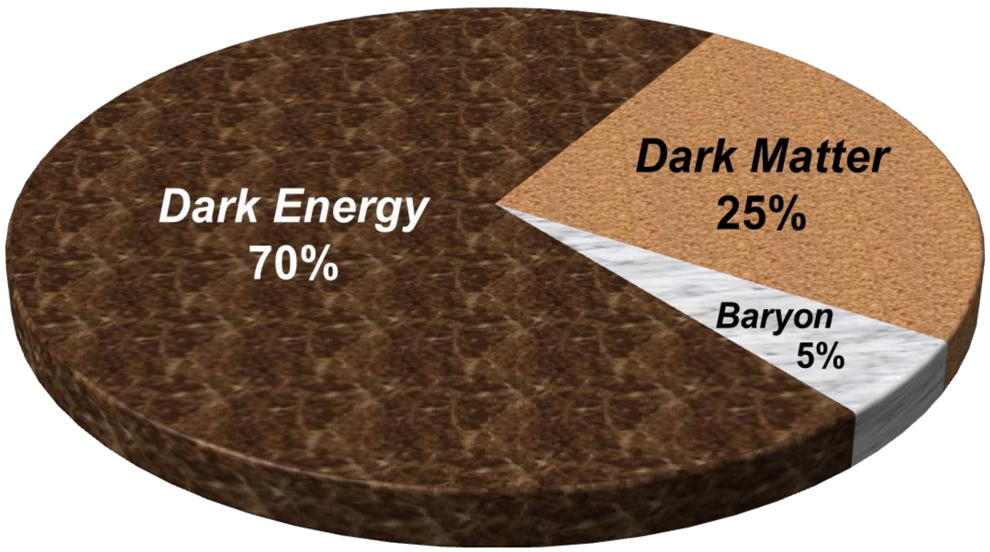




Objectives of LHAASO

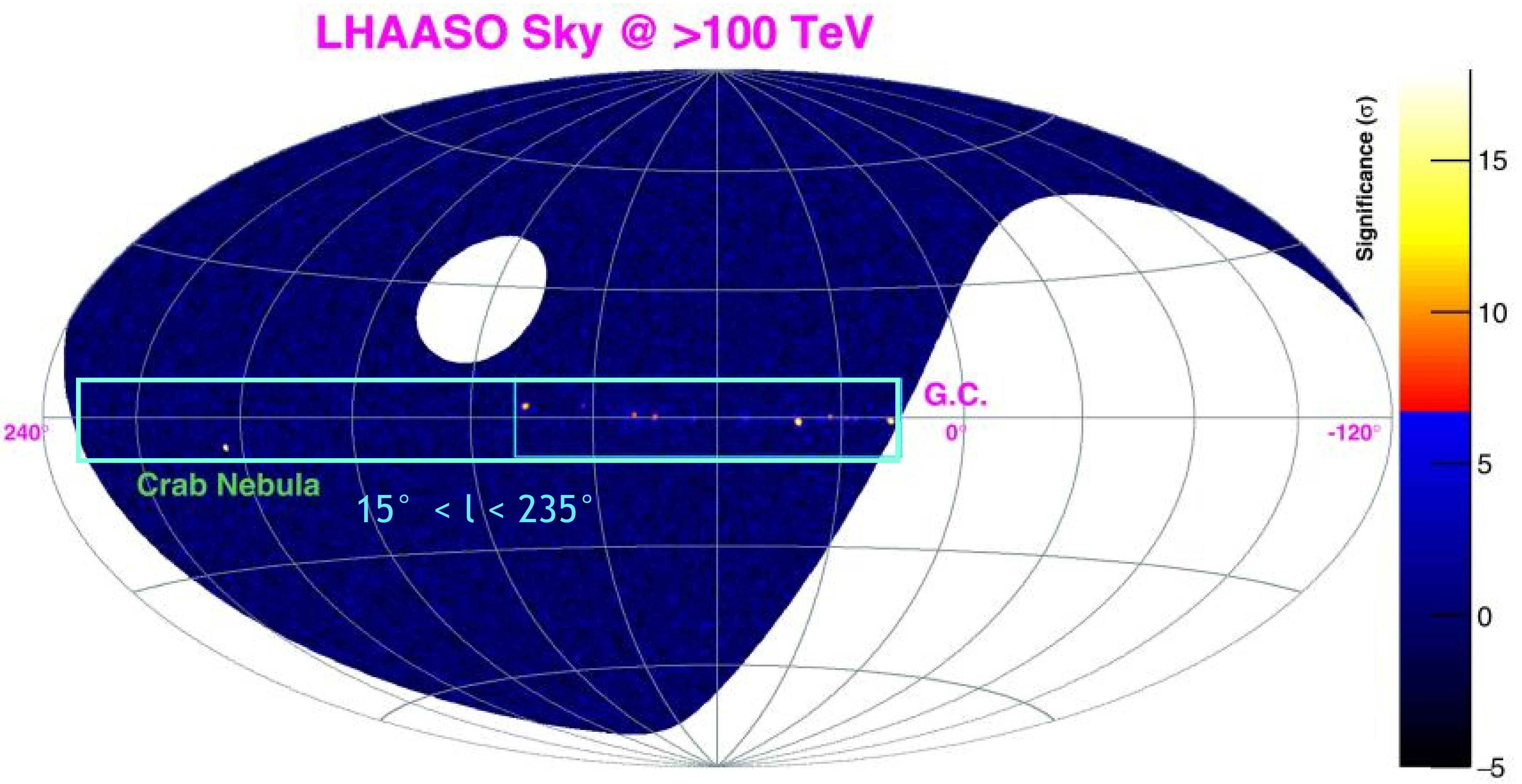






- ➢ **Probe the origin of CRs, via precise measurements of spectra and anisotropies**
- ➢ **Survey the ultra-high-energy gamma-ray sky with unprecedented sensitivity**
- ➢ **Search for new physics**

LHAASO sky coverage

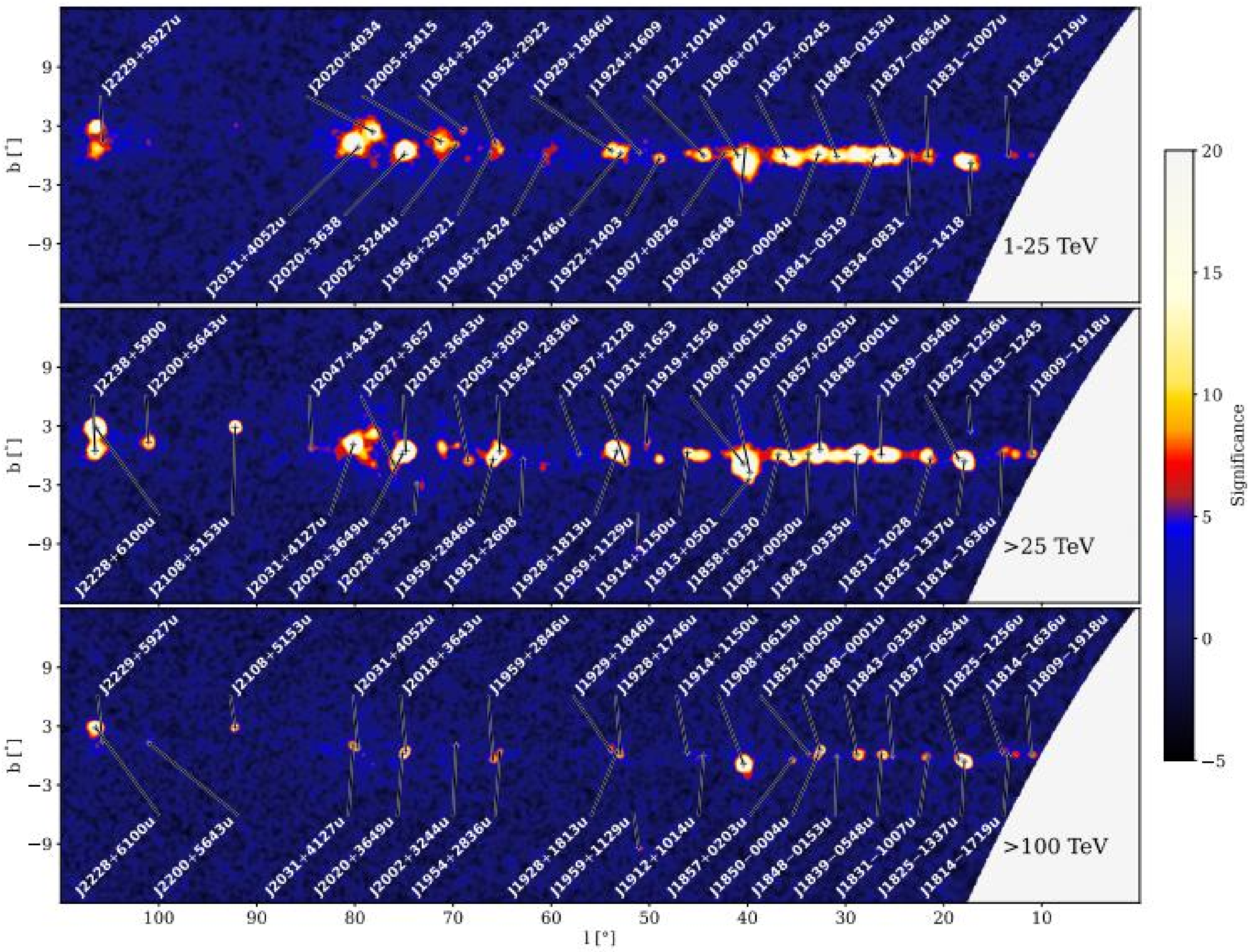


Resolved source masks

$$R_{\rm mask} = n \cdot \sqrt{\sigma_{\rm psf}^2 + \sigma_{\rm ext}^2},$$

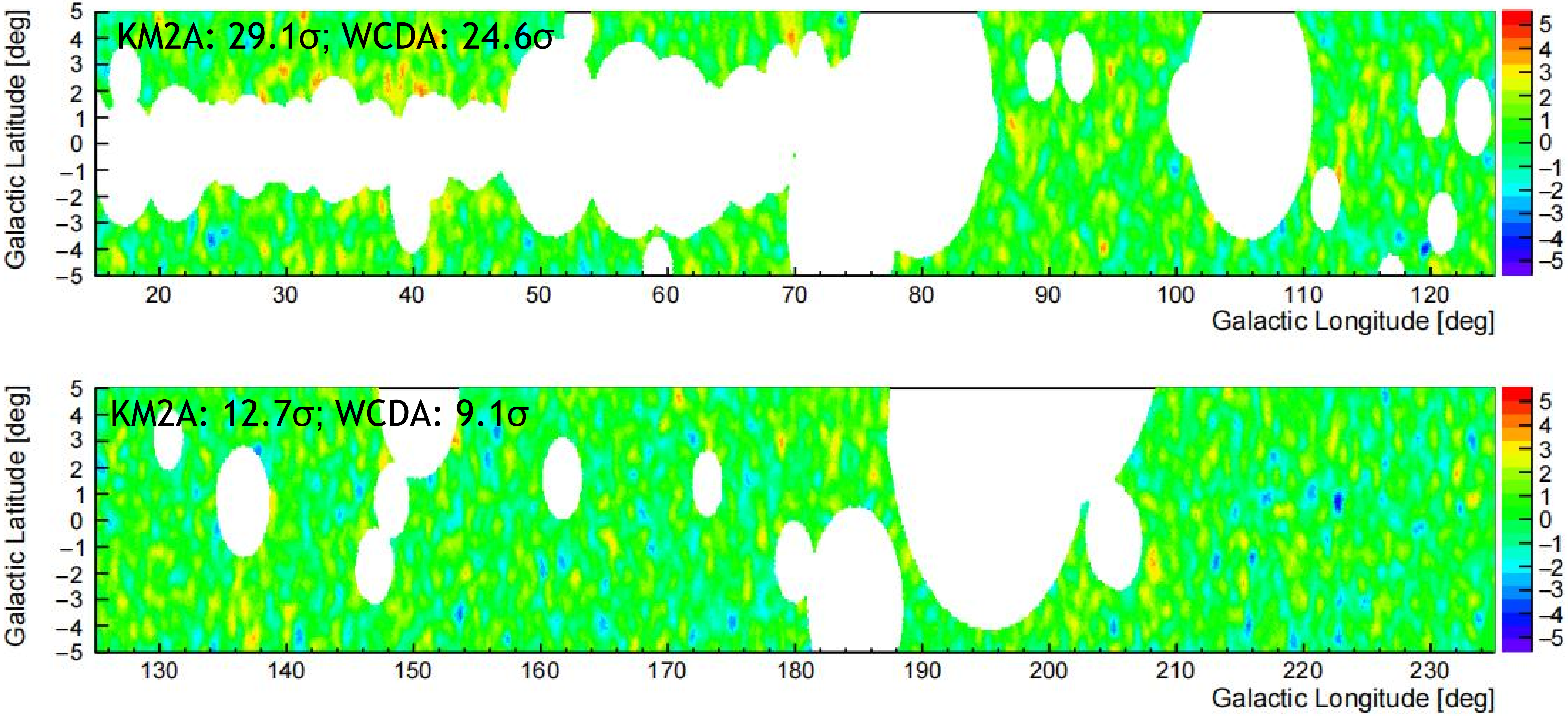
- Assumption: source morphology is Gaussian
- n=2.5 is chosen

- Source catalogs: LHAASO catalog + TeVCat
- For overlapping sources, LHAASO parameters are used



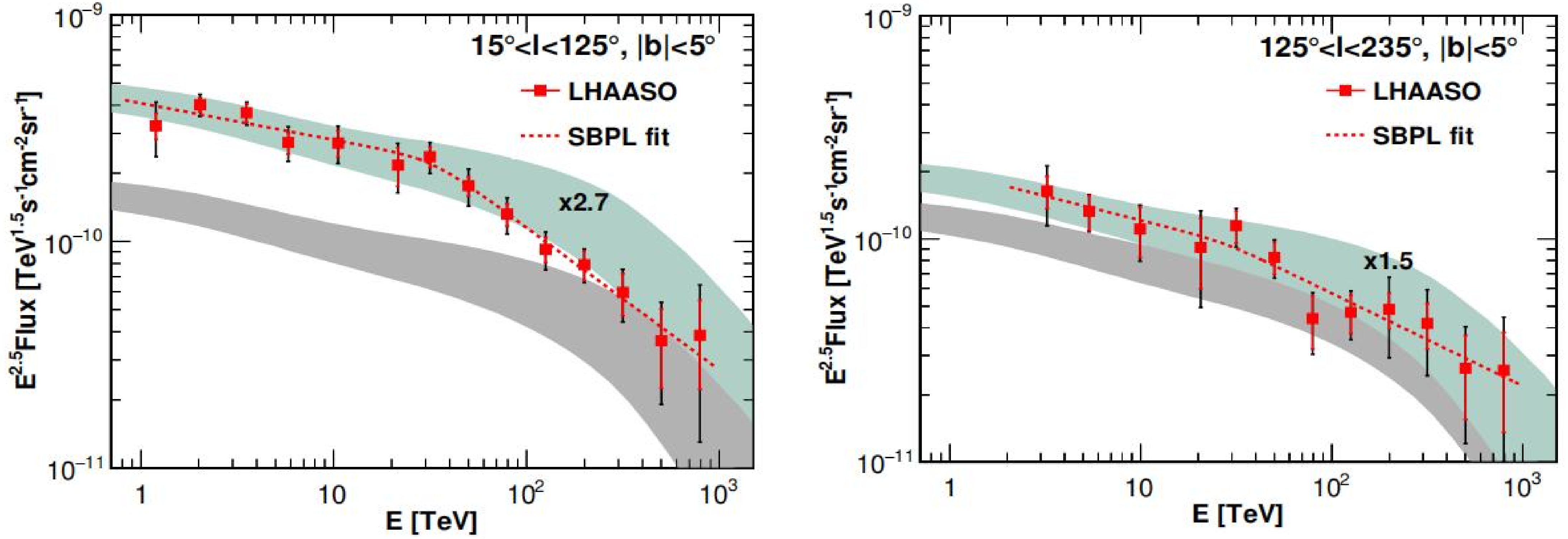
LHAASO first catalog (2024, ApJS)

LHAASO diffuse results



LHAASO (2025, PRL)

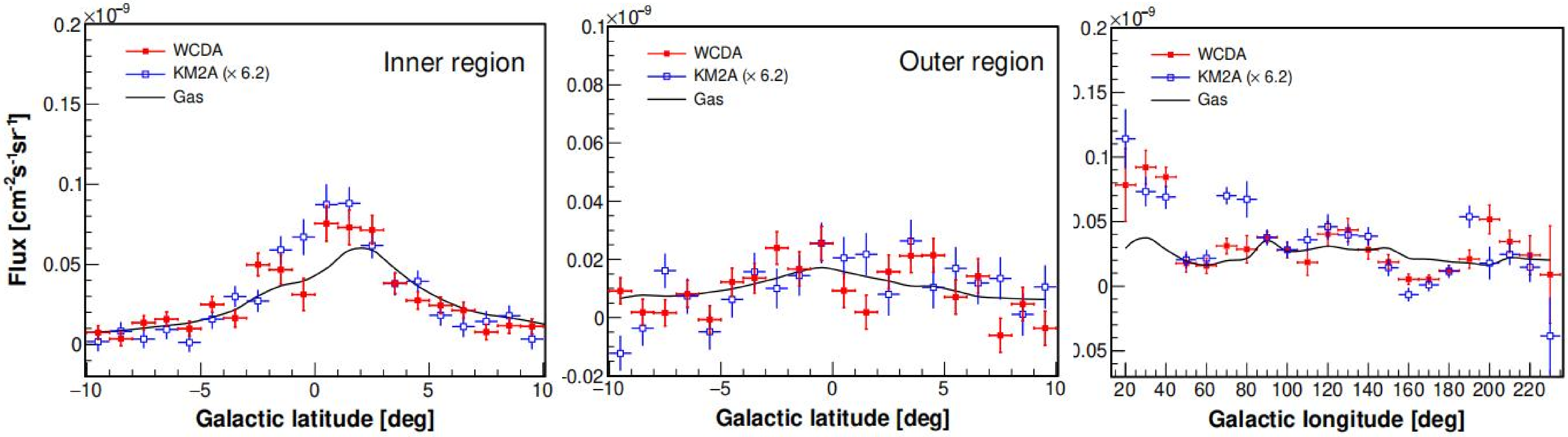
LHAASO diffuse results



Region	ϕ_0 at 10 TeV (10^{-13} TeV^{-1} cm^{-2} s^{-1} sr^{-1})	α	β	E_{br} (TeV)
$15° < l < 125°$ (inner)	$8.88 \pm 0.53_{stat}$	$-2.66 \pm 0.05_{stat}$	$-3.13 \pm 0.08_{stat}$	$32.84 \pm 11.16_{stat}$
$125° < l < 235°$ (outer)	$3.84 \pm 0.37_{stat}$	$-2.72 \pm 0.10_{stat}$	$-2.92 \pm 0.10_{stat}$	$27.86 \pm 22.49_{stat}$

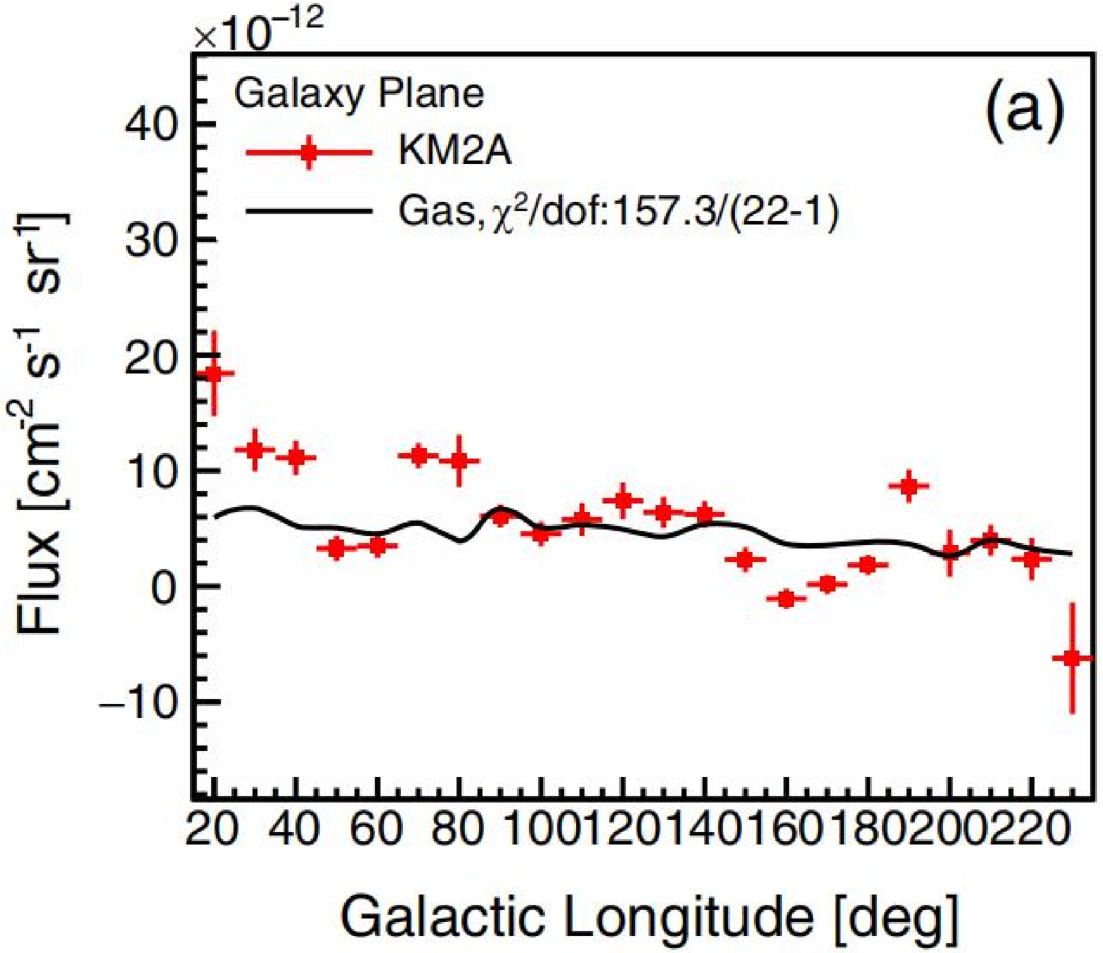
- LHAASO measures diffuse emission from 1 TeV to 1 PeV with high significnace, and gives the first detection from the outer Galactic plane
- A spectral break around 30 TeV is revealed in the inner Galactic plane

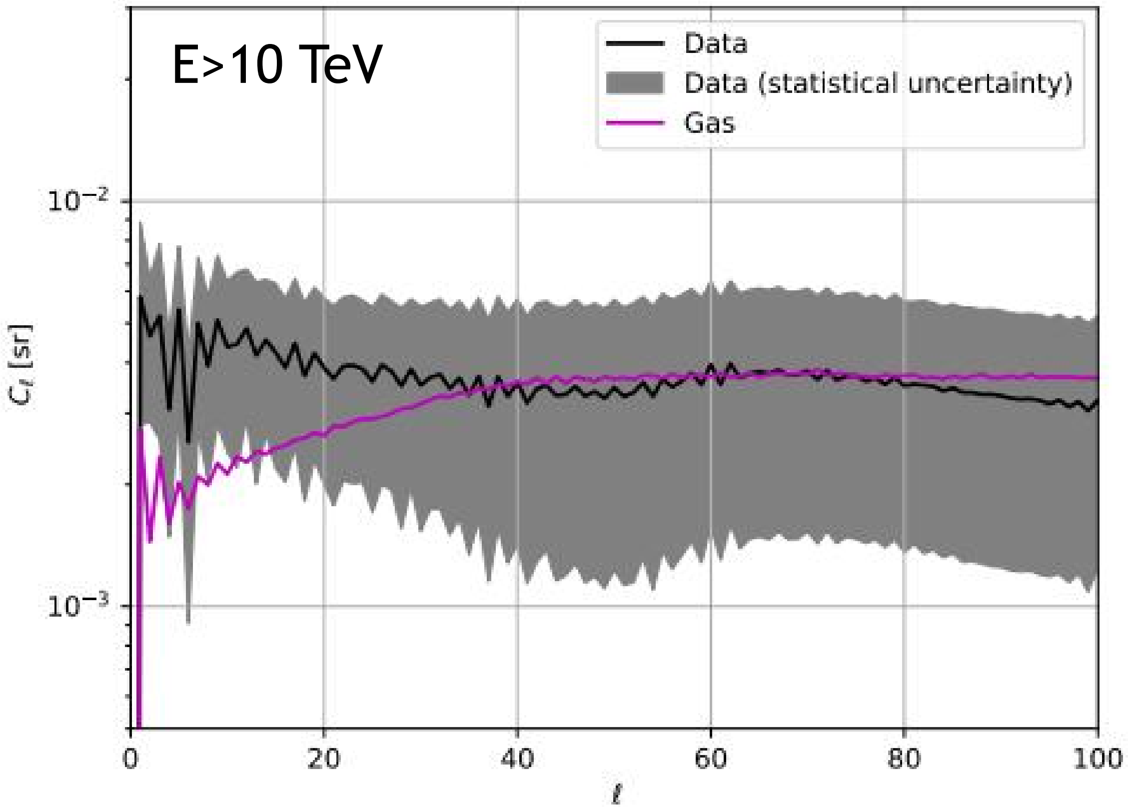
Longitude and latitude profiles



Roughly consistent with gas distributions for *b*, but show significant deviation for *l*

Spatial distribution





Difference between data and gas is also shown in the angular spectra at low-l

Possible spatial variation of spectra

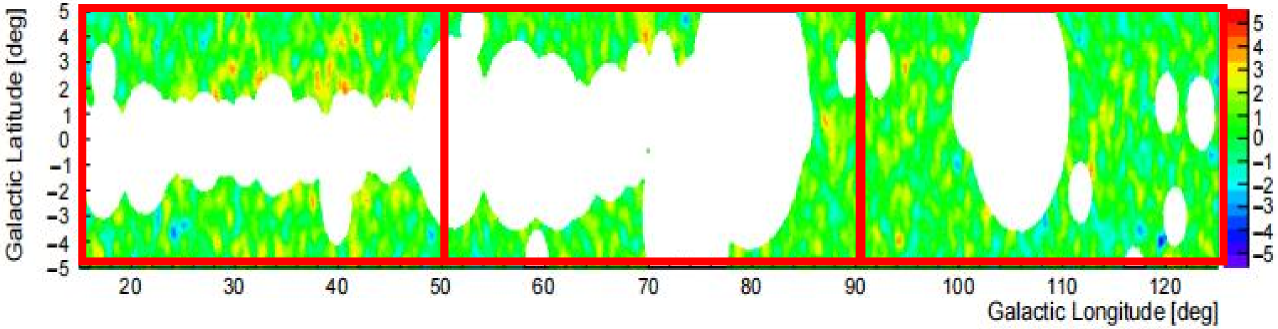
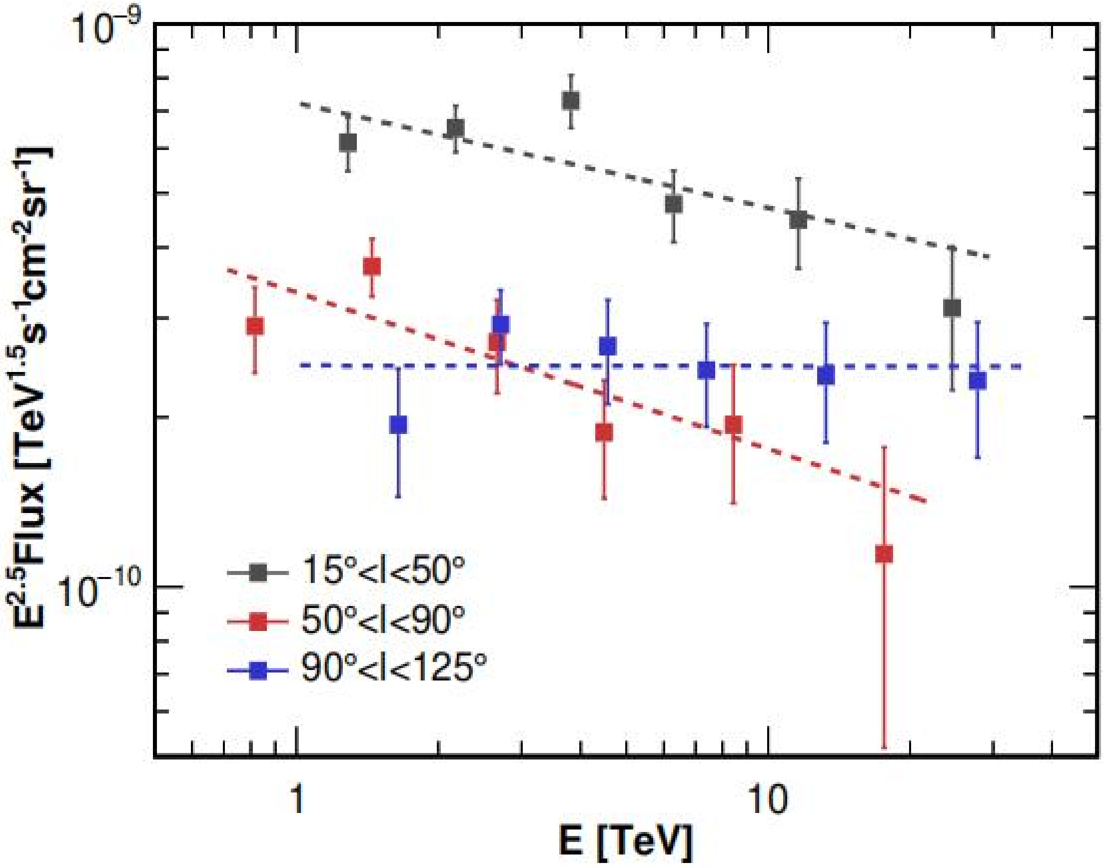


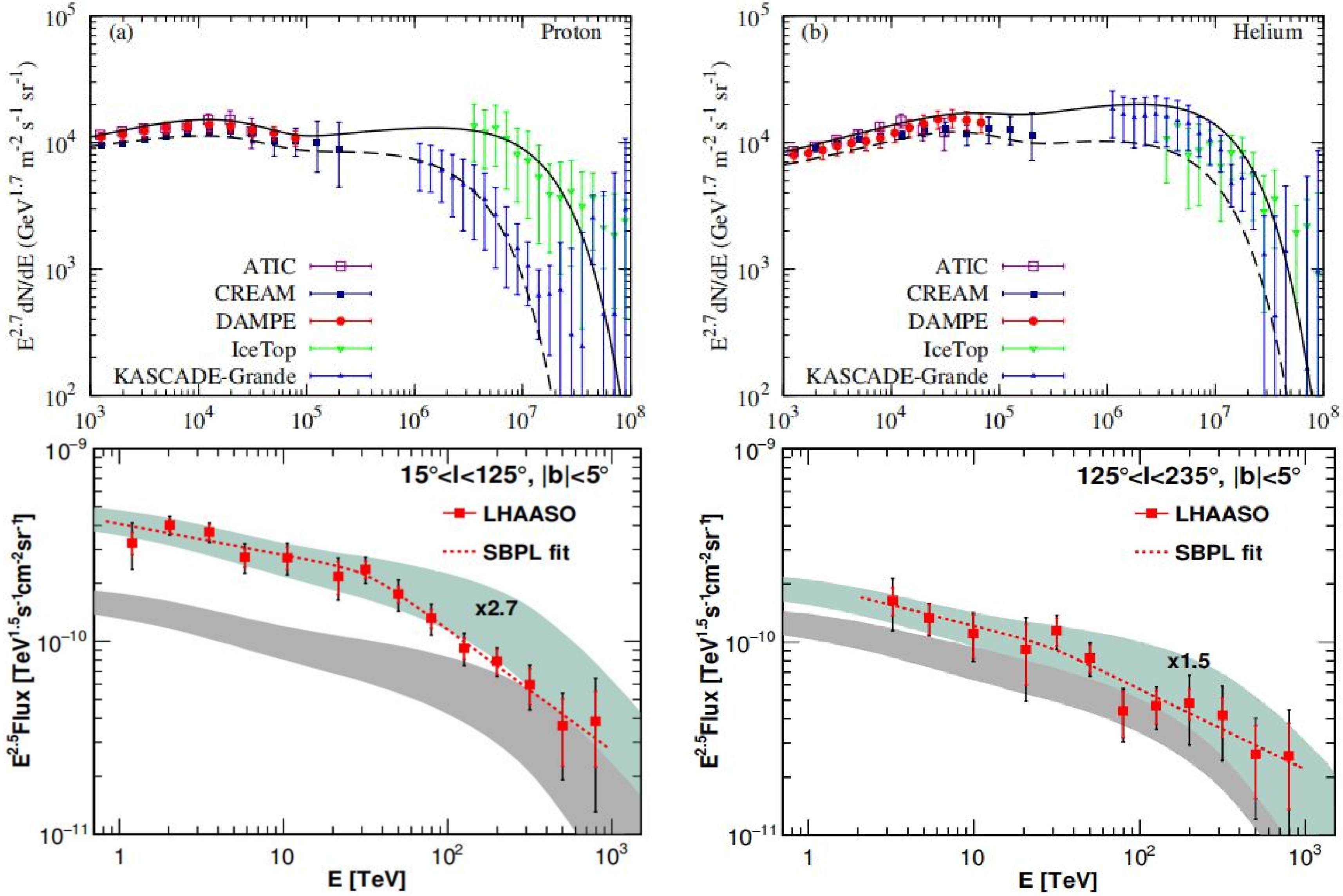
TABLE II. Power-law fitting results of the LHAASO-WCDA diffuse emission.

Region	ϕ_0 at 10 TeV (10^{-13} TeV^{-1} cm^{-2} s^{-1} sr^{-1})	α
$15° < l < 125°$ (inner)	$8.50 \pm 0.58_{stat}$	$-2.67 \pm 0.05_{stat}$
$125° < l < 235°$ (outer)	$3.49 \pm 0.55_{stat}$	$-2.83 \pm 0.19_{stat}$
$15° < l < 50°$	$14.88 \pm 1.26_{stat}$	$-2.69 \pm 0.06_{stat}$
$50° < l < 90°$	$5.55 \pm 0.91_{stat}$	$-2.78 \pm 0.09_{stat}$
$90° < l < 125°$	$7.79 \pm 0.81_{stat}$	$-2.50 \pm 0.09_{stat}$



Hints of spectral variations aross the Galactic plane (~2σ)

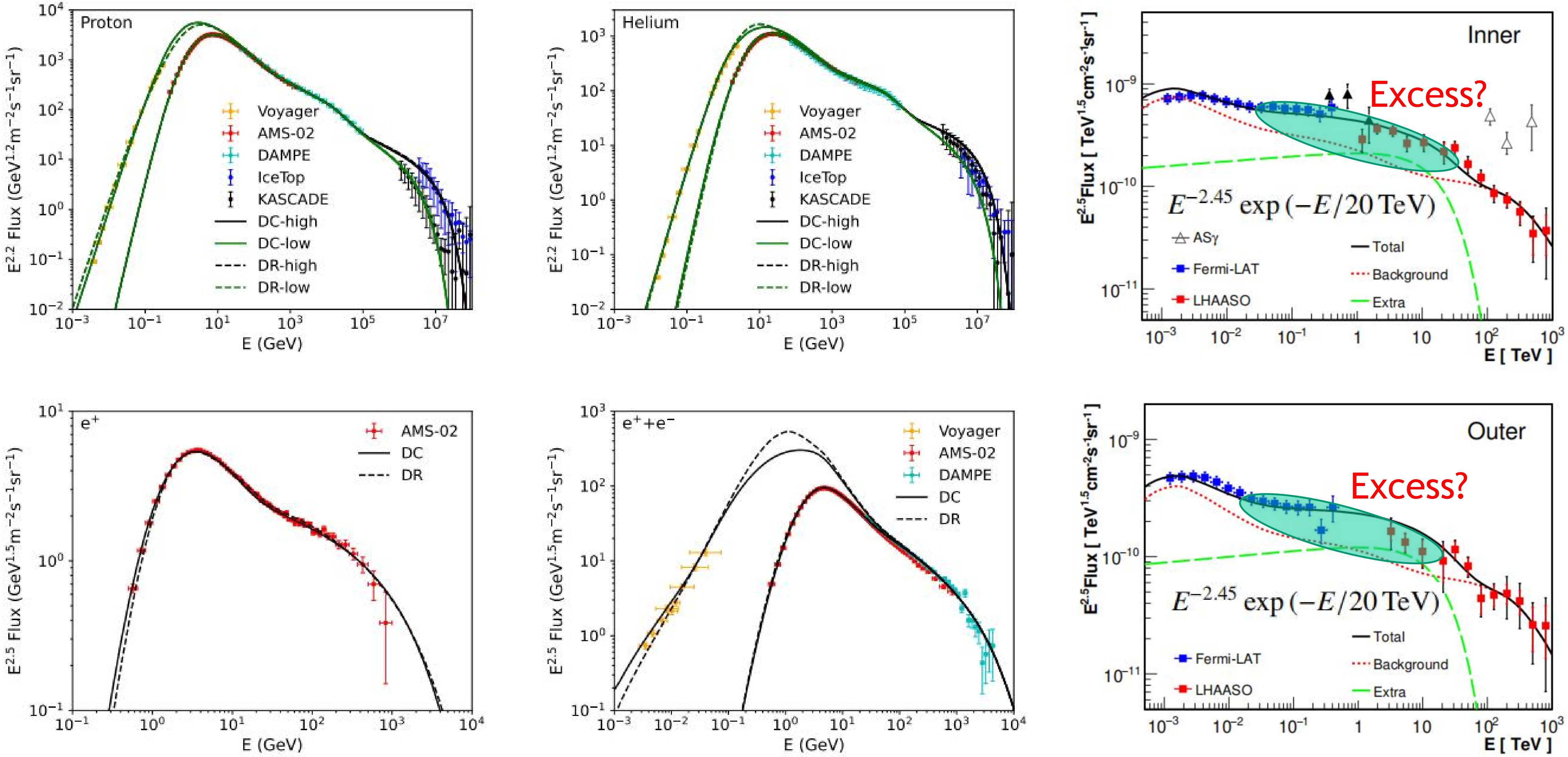
Confront LHAASO data with a toy model



- Toy model prediction: local CR × gas column
- Measured fluxes are higher by a factor of 1.5~2.7 than predictions
- Spectra are slightly different from the prediction

Expectation could be improved significantly with LHAASO CR measurement!

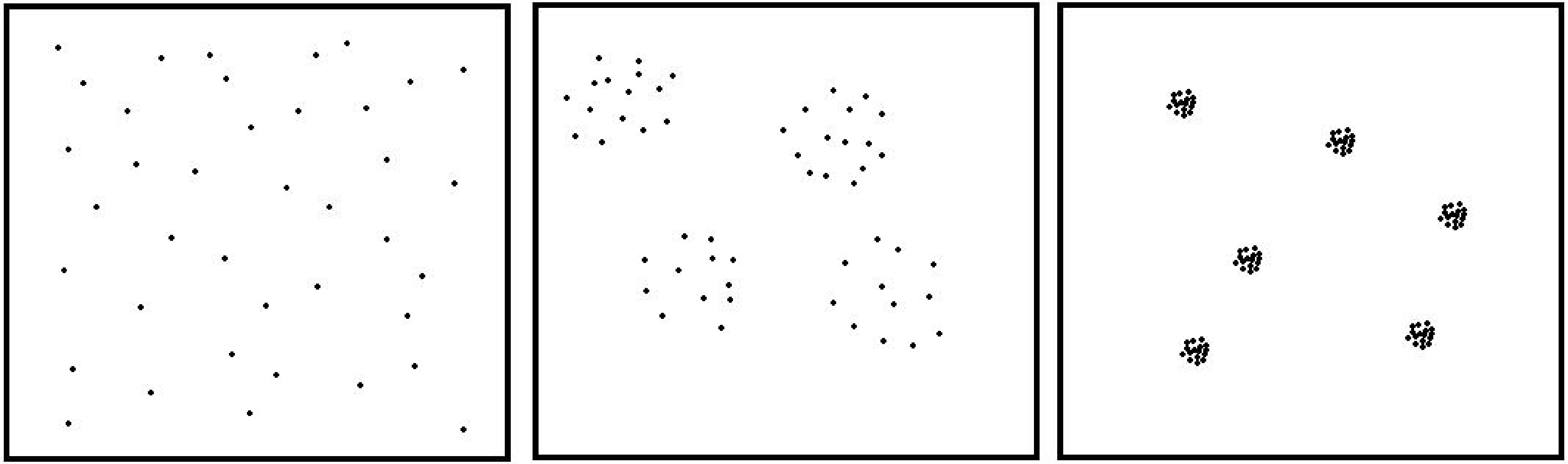
Confront LHAASO data with a GALPROP model

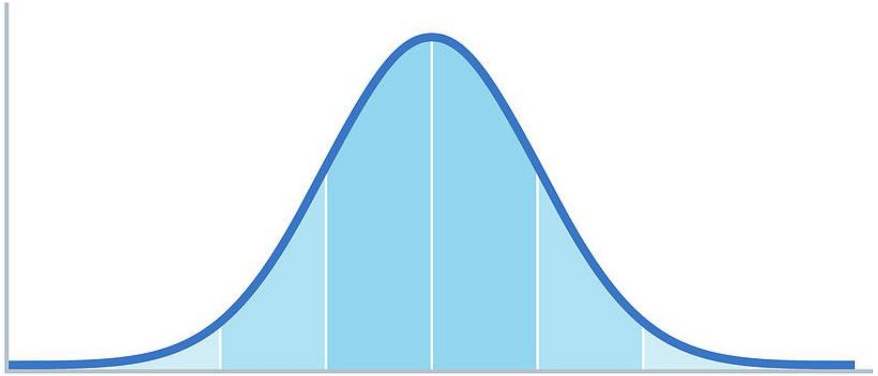


Zhang et al. (2023, ApJ, 957, 43)

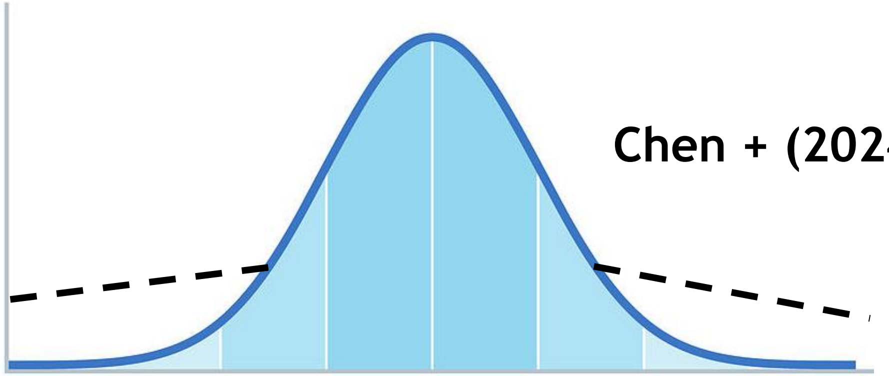
Caveat: no distinct definition between sources and diffuse

Truly diffuse (adequate prop.) | large extended source (non-adequate prop.) | pointlike sources (freshly accelerated)



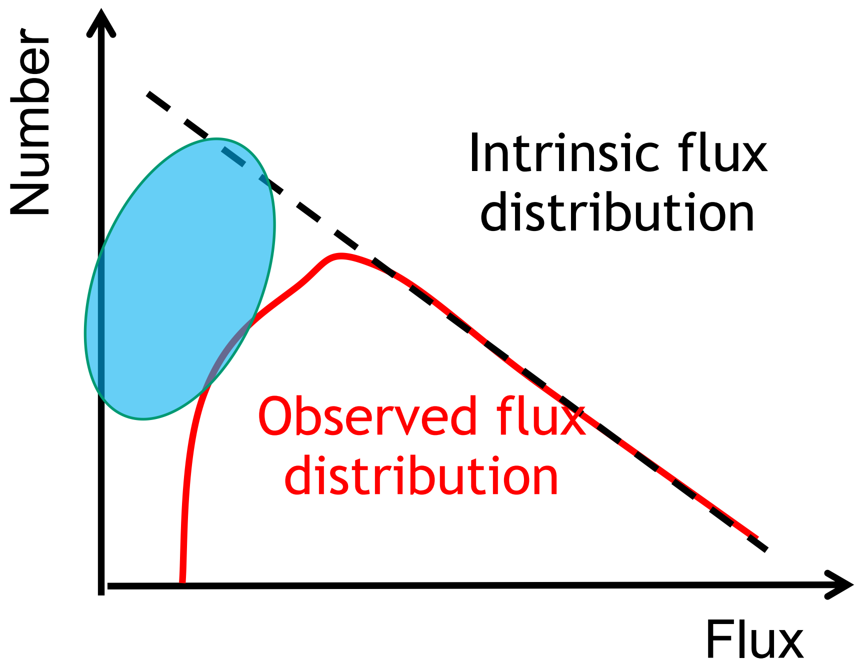


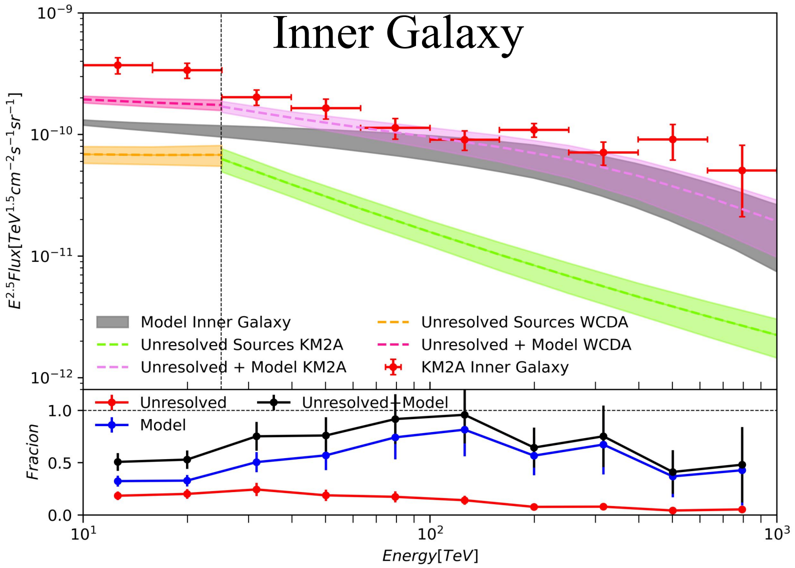
VS.

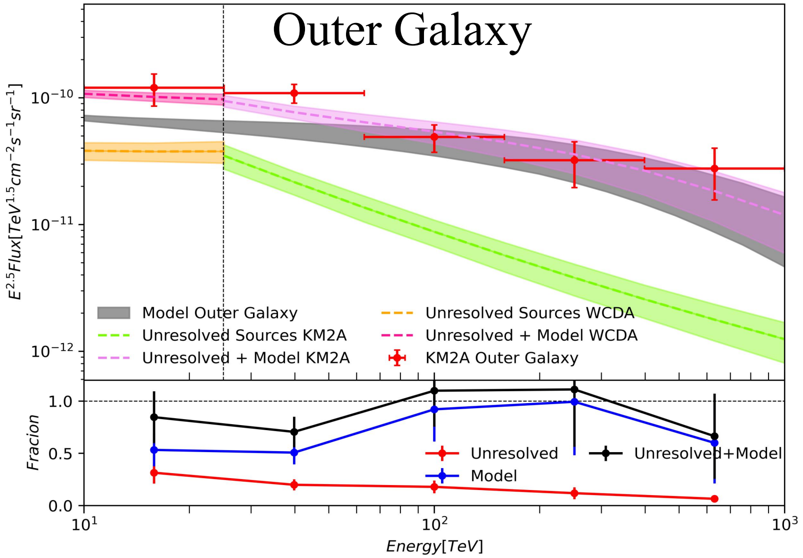


Chen + (2024, CPC)

Unresolved source contribution?



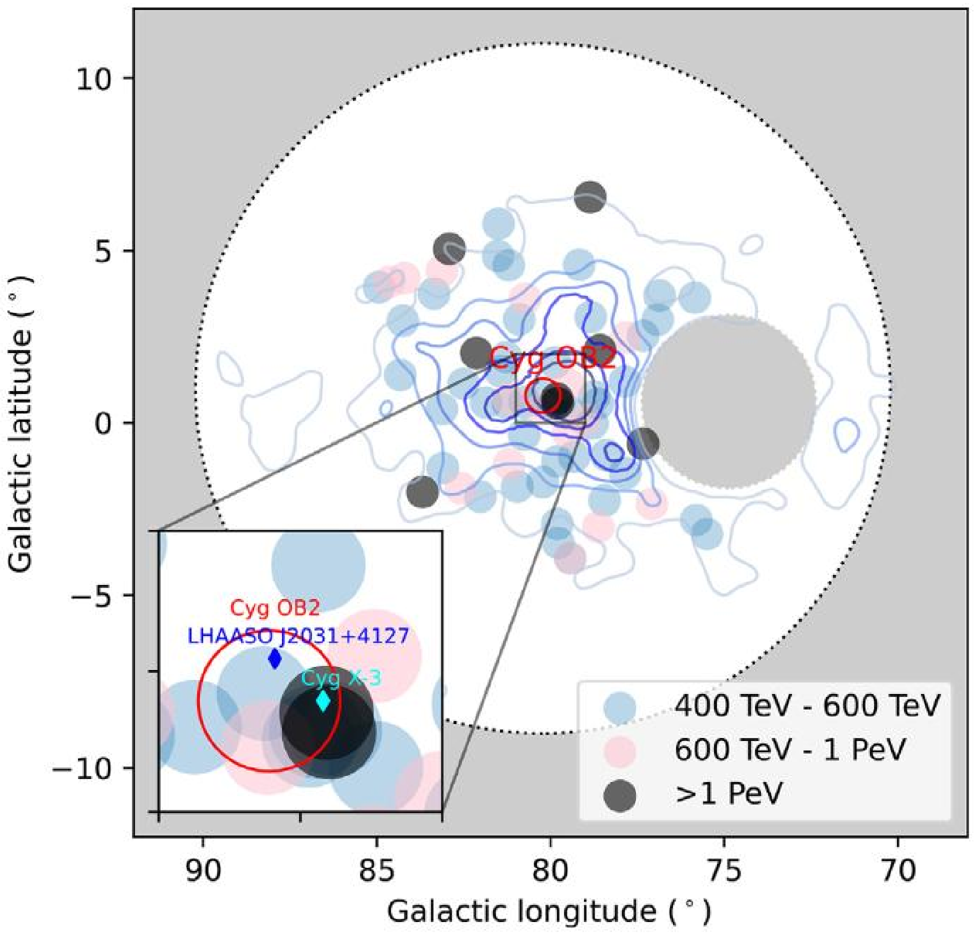


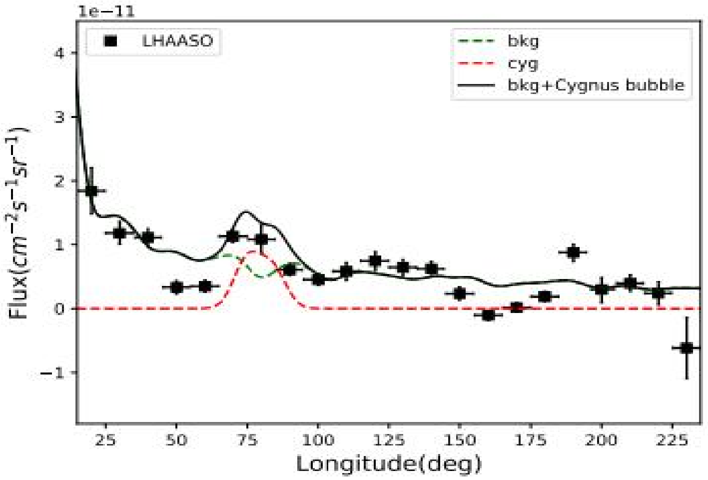


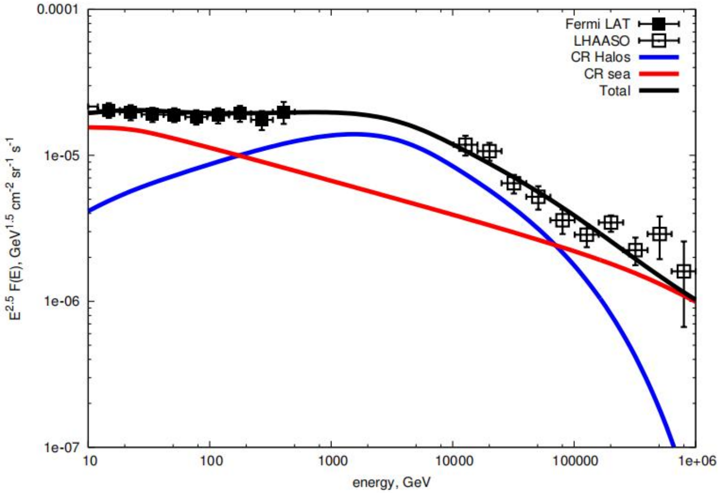
- ✓ The contribution of unresolved sources is able to describe the exta component for Outer Galaxy region, while it is insufficient for Inner Galaxy region.
- ✓ Larger extended sources were not included
- ✓ Additional contributions from unknown mechanisms

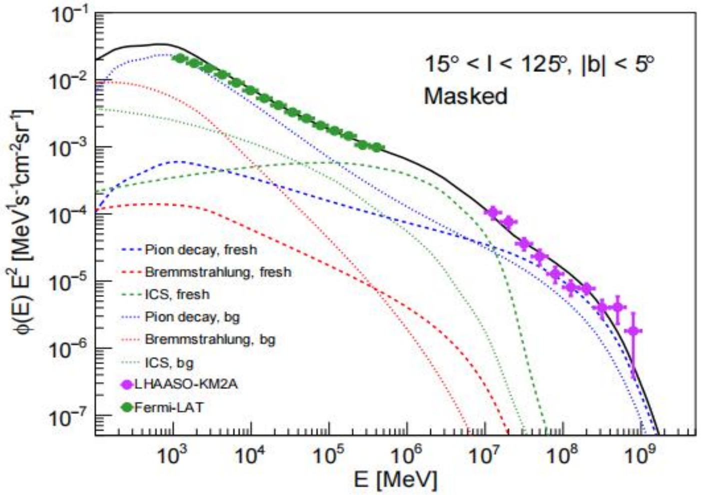
He + (2025, ApJ); Kaci + (2024, ApJ)

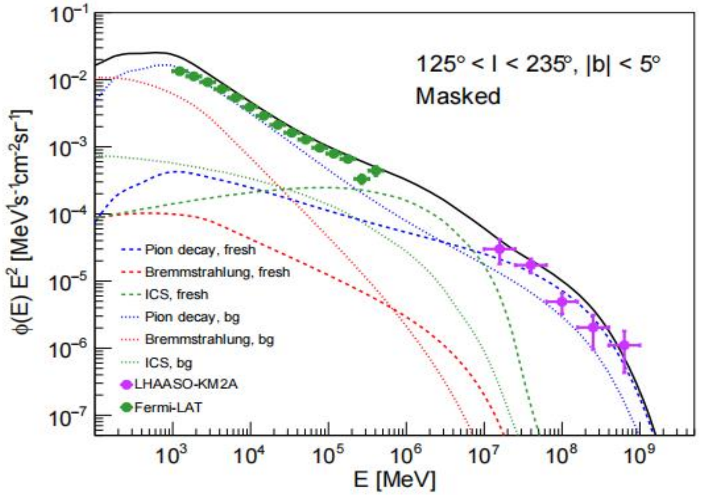
Confinement and interaction around sources











Cygnus bubble: super accelerator as extended as 10 degrees (LHAASO 2024, Sci. Bull.)

Nie + ApJ (2024); He + ApJ (2024); Yang & Aharonian (2024); Ambrosone + (2025)

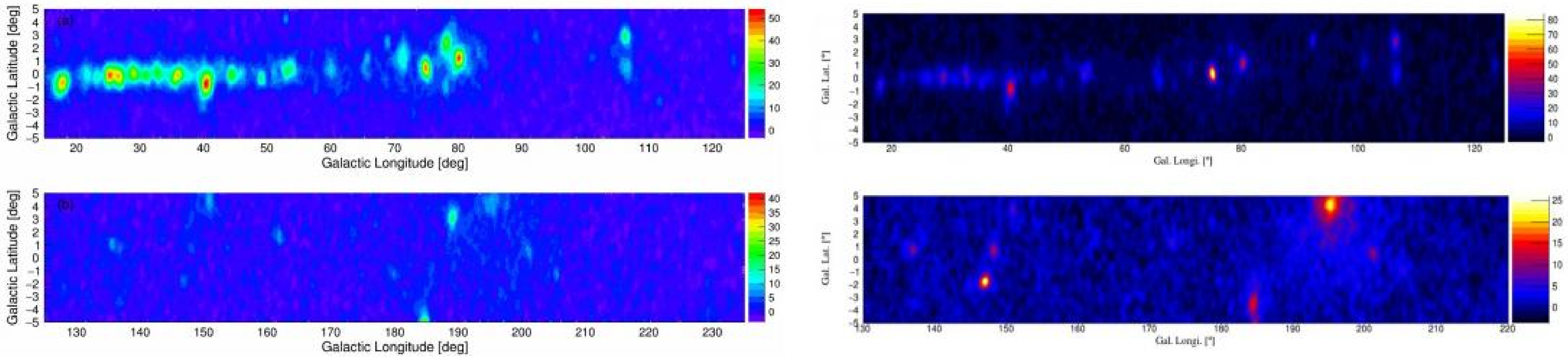
Other interpretations

- Various types of unresolved sources: pulsar halo/PWN (Pagliaroli + 2023 Universe; Yan + 2024 Nat. Astron.; Dekker + 2024 PRD; Chen + 2024 CPC), X-ray binaries (Yue + 2024; Kuze + 2025), massive star clusters (Menchiari + 2024) ...

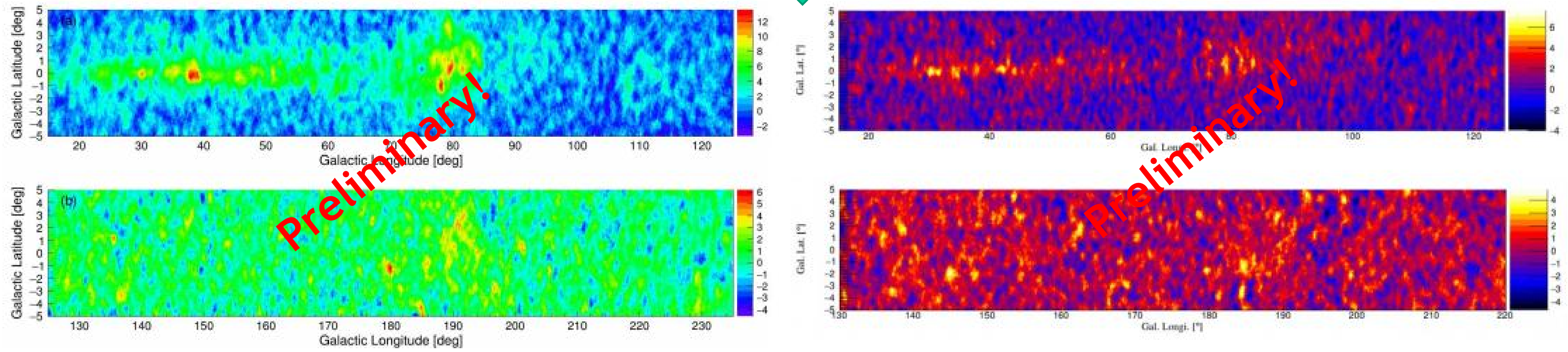
- Cosmic ray sea interaction with alternative propagation setup (Giacinti + 2023; Vecchiotti + 2024; De La Torre Luque + 2025)

- Time-dependent model of discrete sources (Marinos + 2024)

Improved measurement is important

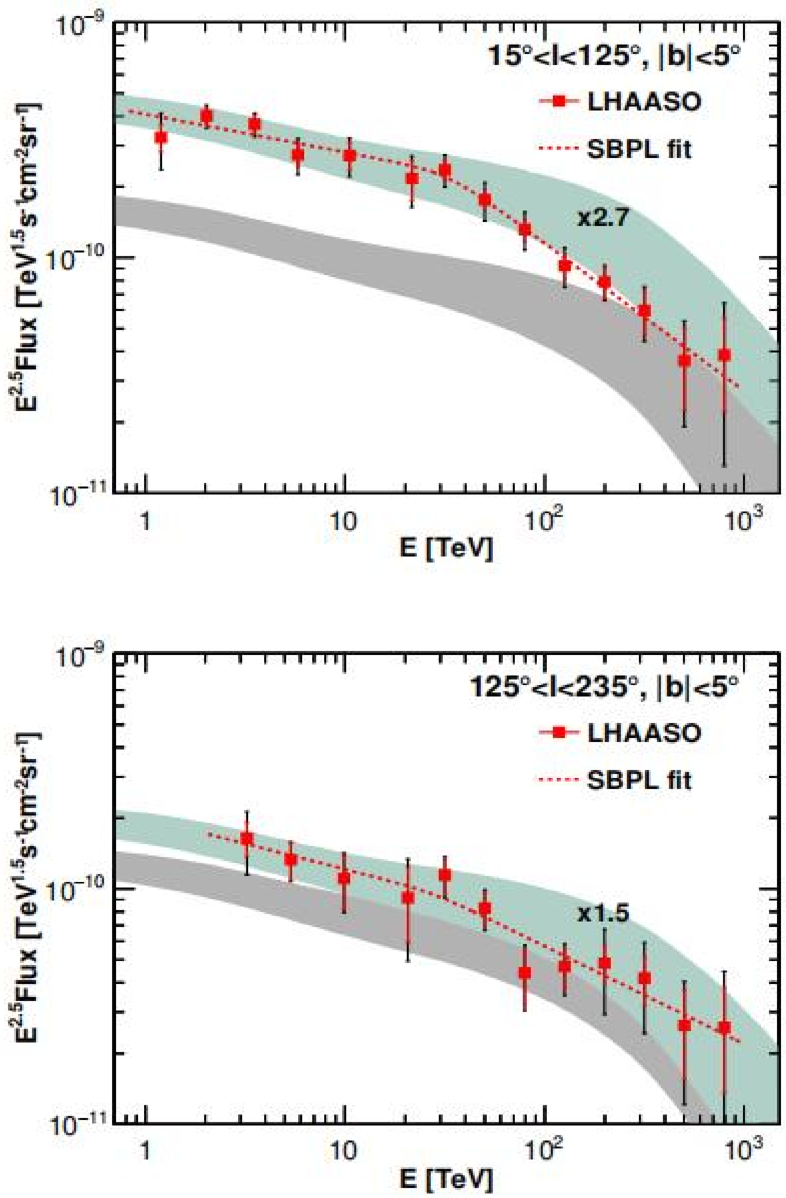


source subtraction



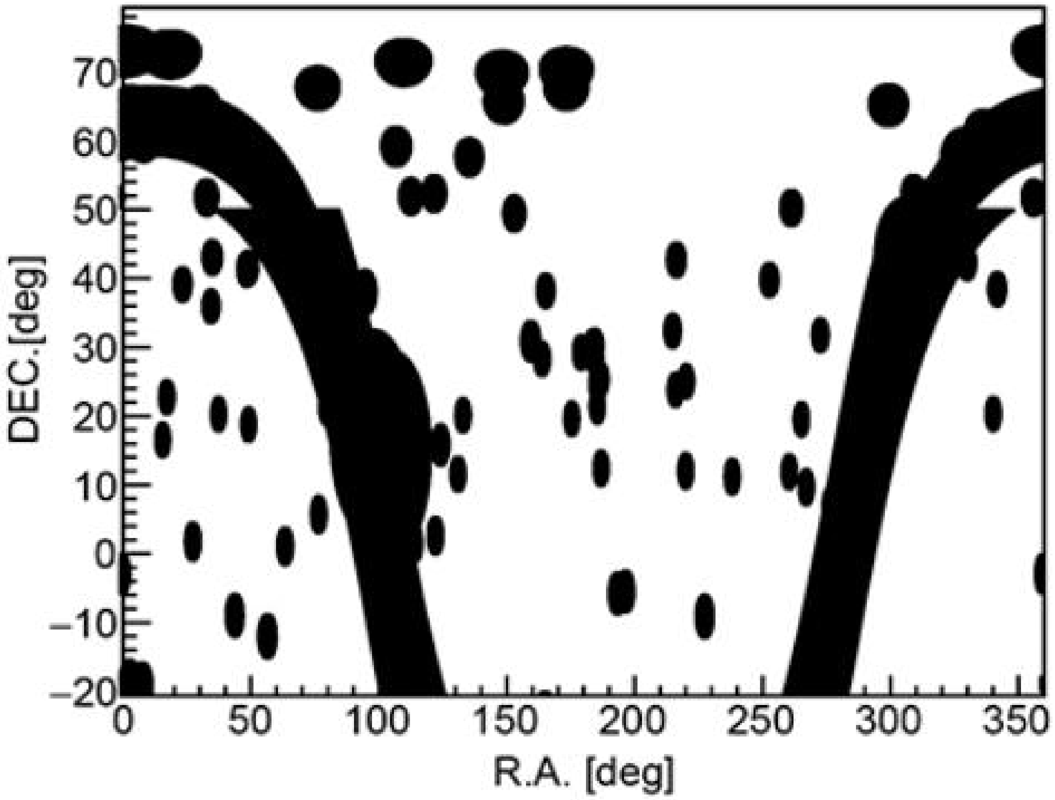
Summary

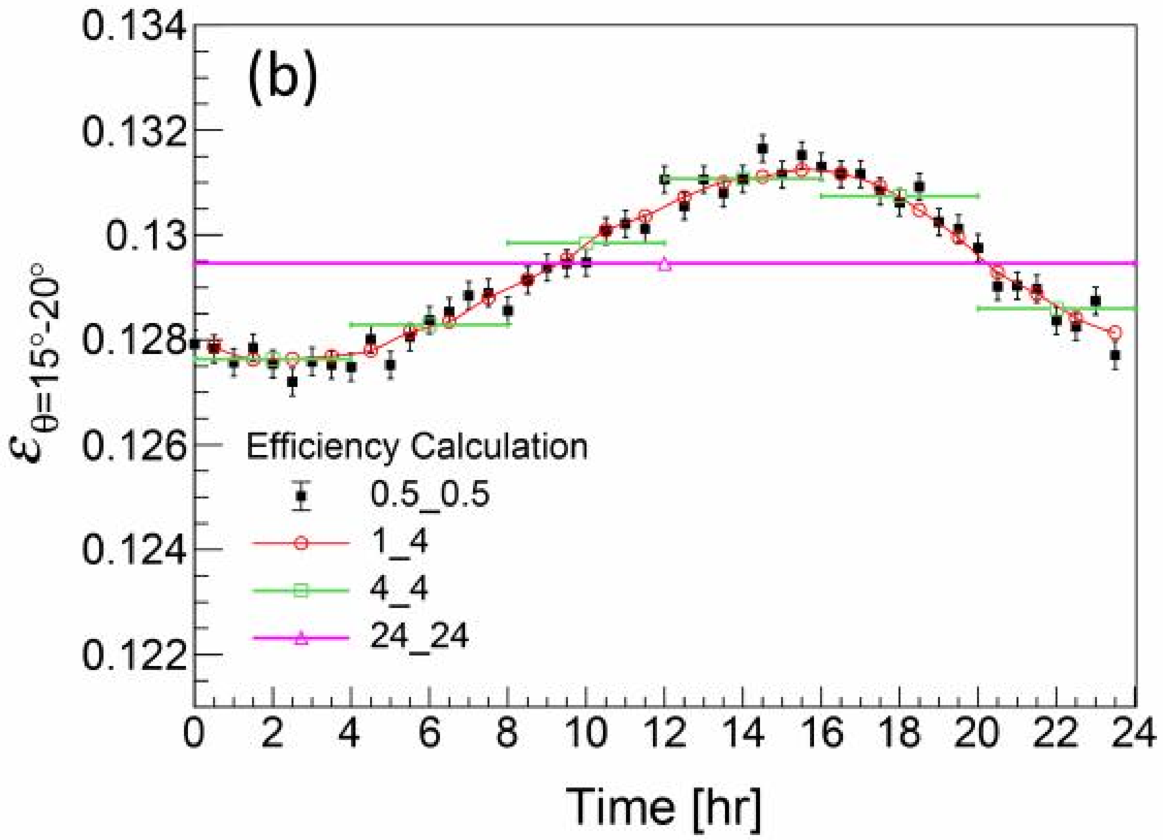
- The diffuse emission from 1 TeV to 1 PeV from the Galactic plane was observed with high significance; Firstly detected in the outer Galaxy region!
- A spectral break around 30 TeV is found in the inner region, with a change of indices by ~0.5
- The longitude distribution deviates from gas distribution; there is possible spectral variation of the spectra across the Galactic plane
- Together with Fermi-LAT, the wide-band data show excesses from several GeV to 10s TeV compared with a traditional CR propagation model, which could be explained by a population of unresolved sources (pulsar halos or secondary interaction at source)



Thank you!

Background estimate





- Direct integral method: assuming the spatial distribution in detector coordinate is stable in a reasonably short time bin
- Efficiencies do vary slightly with time, and thus a sliding window method is adopted (1_10 is used as benchmark, 1 hr step and +/-5 hr window)

Residual source contamination

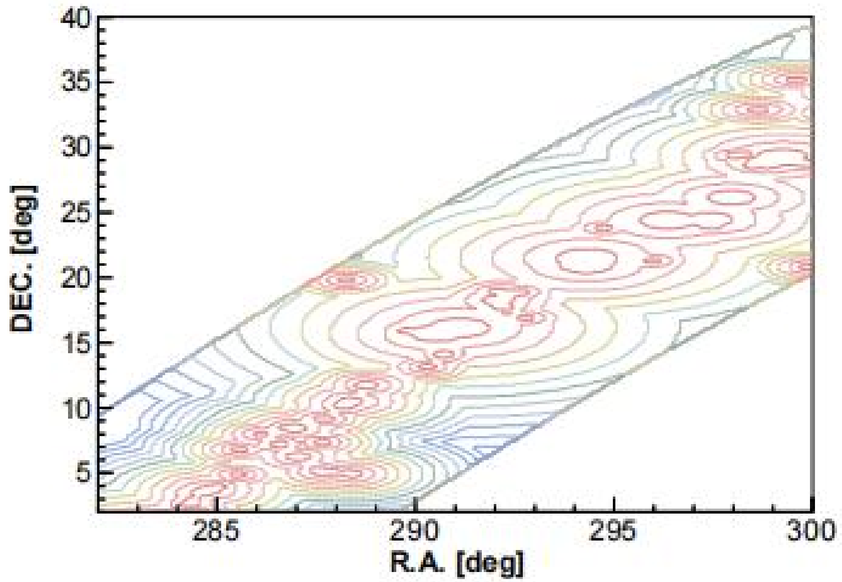


TABLE S1. Residual fractions of resolved sources to the total signal in different hit bins.

N_{hit}	Inner Galaxy (%)	Outer Galaxy (%)
60-100	11.12 ± 0.19	
100-200	4.97 ± 0.12	
200-300	3.76 ± 0.18	1.57 ± 0.10
300-500	3.36 ± 0.21	1.10 ± 0.09
500-800	3.07 ± 0.31	1.18 ± 0.20
>800	2.75 ± 0.49	1.86 ± 0.33

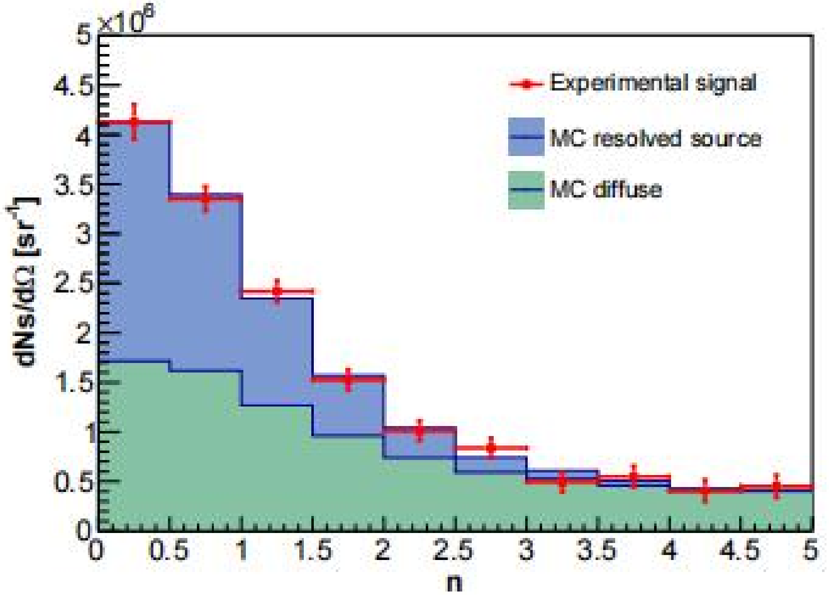


Table 5: Proportion (%) of contamination (f_{cont}) of residual sources (LHAASOCat+TeVCat) to the DGE.

$\log_{10}\left(\frac{E_{rec}}{\mathrm{TeV}}\right)$	Inner Galaxy region			Outer Galaxy region		
	$n = 2.0$	$n = 2.5$	$n = 3.0$	$n = 2.0$	$n = 2.5$	$n = 3.0$
1.0-1.2	11.37 ± 1.09	5.97 ± 0.67	3.56 ± 0.51	9.55 ± 3.03	4.58 ± 1.63	2.65 ± 1.22
1.2-1.4	8.77 ± 0.71	4.26 ± 0.43	2.42 ± 0.31	5.45 ± 1.00	2.25 ± 0.44	0.98 ± 0.20
1.4-1.6	8.14 ± 0.73	2.97 ± 0.36	1.37 ± 0.22	4.32 ± 0.66	1.39 ± 0.23	0.49 ± 0.09
1.6-1.8	6.66 ± 0.56	1.95 ± 0.21	0.76 ± 0.11	6.07 ± 1.30	1.88 ± 0.45	0.58 ± 0.15
1.8-2.0	6.56 ± 0.70	1.97 ± 0.27	0.87 ± 0.16	2.44 ± 0.45	0.77 ± 0.16	0.22 ± 0.05
>2.0	3.26 ± 0.23	0.76 ± 0.06	0.20 ± 0.02	1.47 ± 0.34	0.39 ± 0.09	0.10 ± 0.03

At 100 GeV, the data is about 4e-3, when subtracting sources (yellow) and IGRB (brown), the result is about 3e-4, which is about 2 times of the GDE model (blue) of 1.5e-3

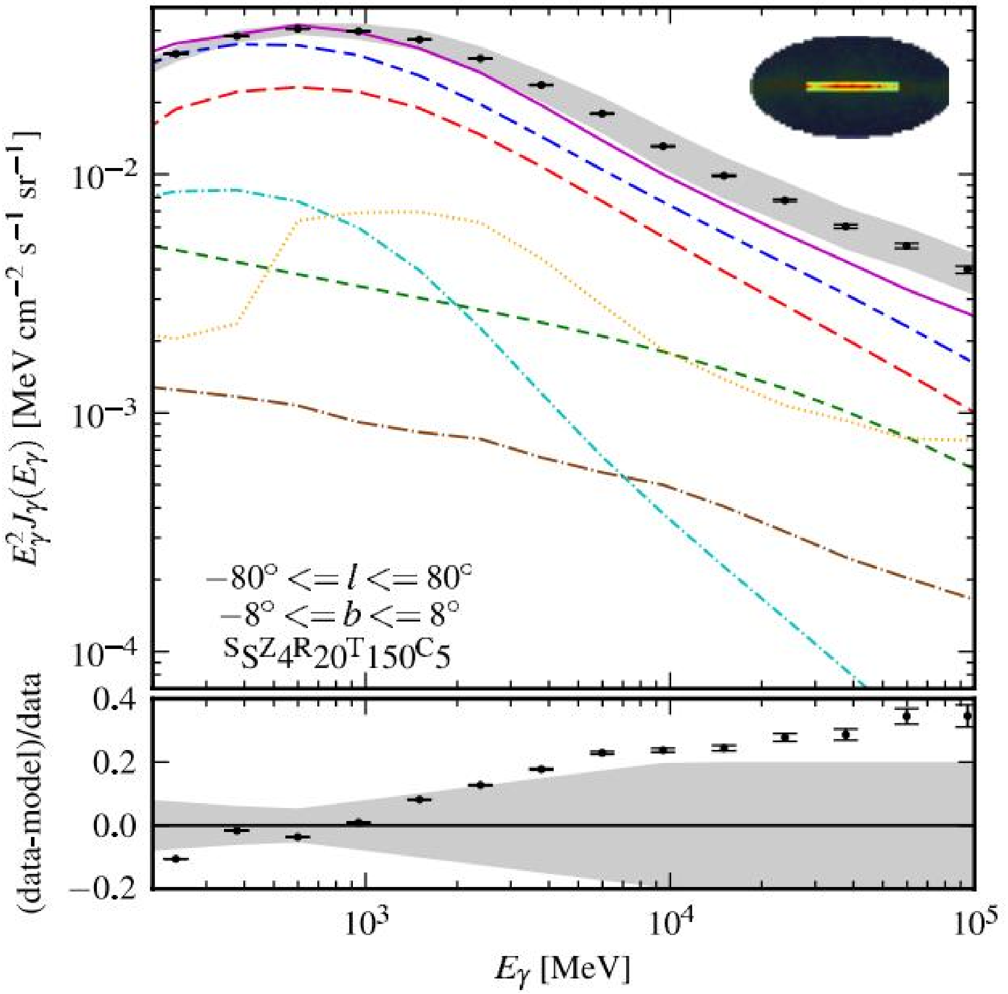
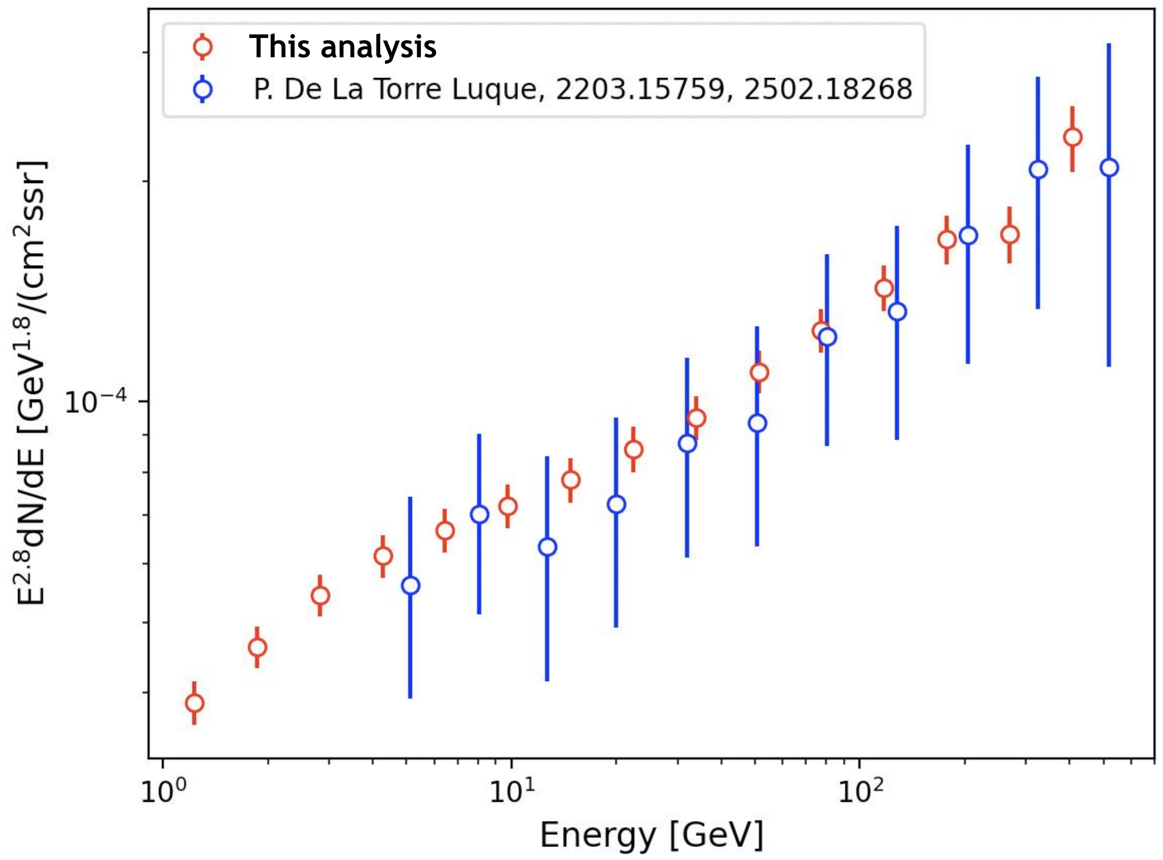


Fig. 17 of Ackermann et al. (2012)



25<l<100, -5<b<5, no mask