Diffuse TeV-PeV gamma rays and interpretations

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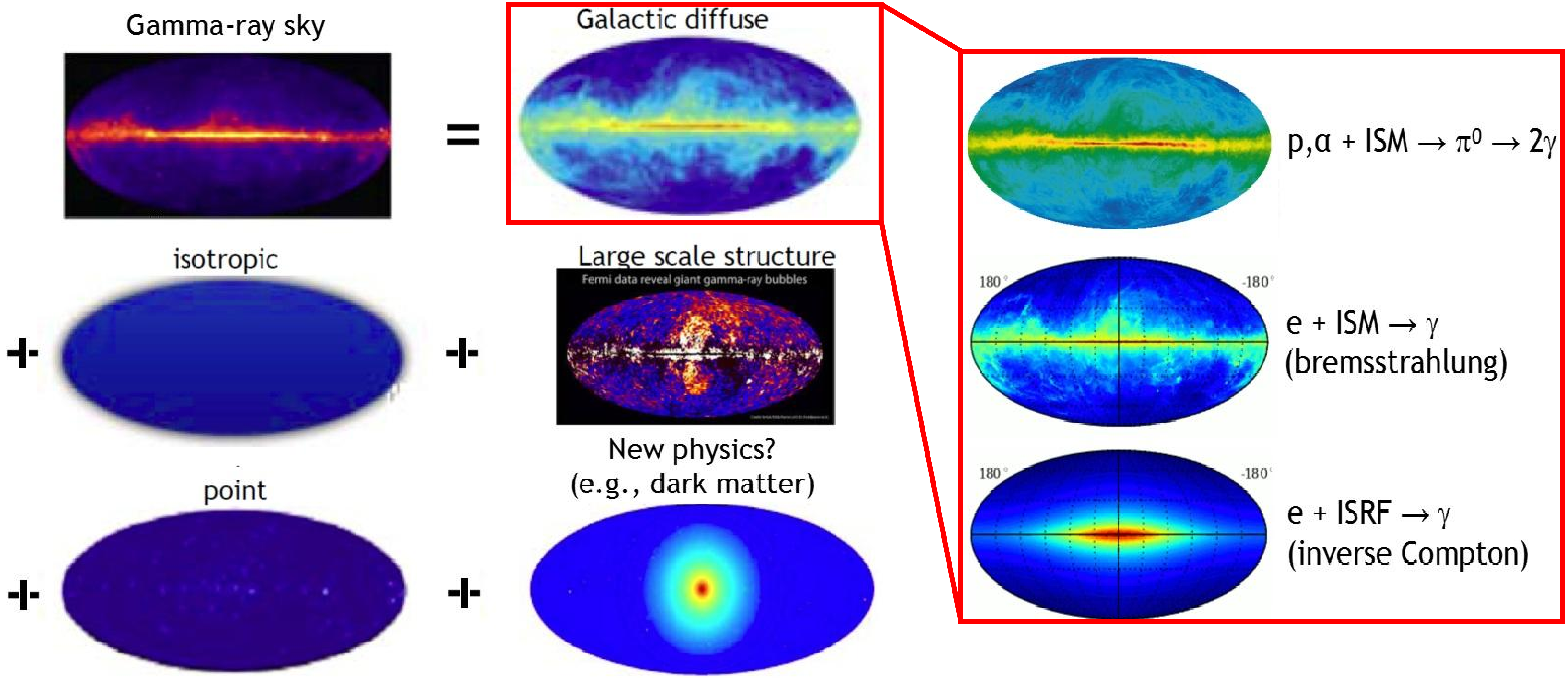
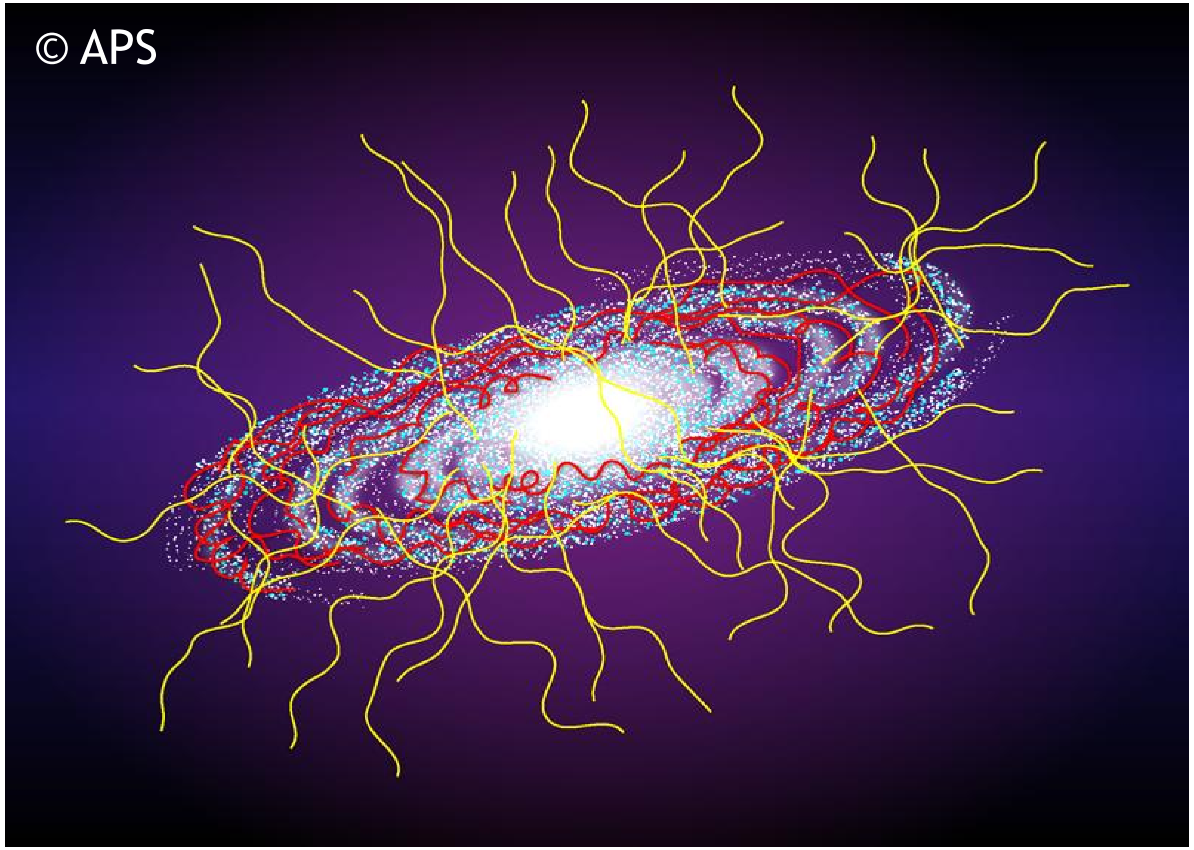
The γ-ray sky

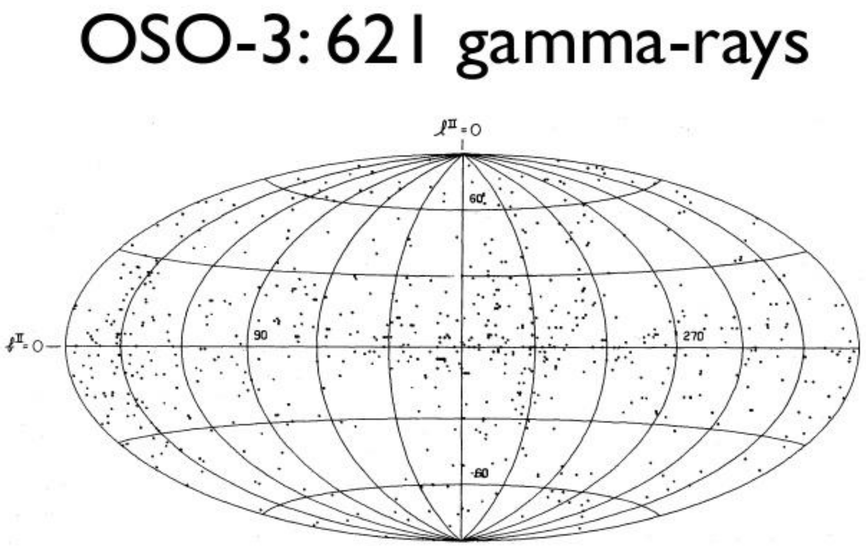


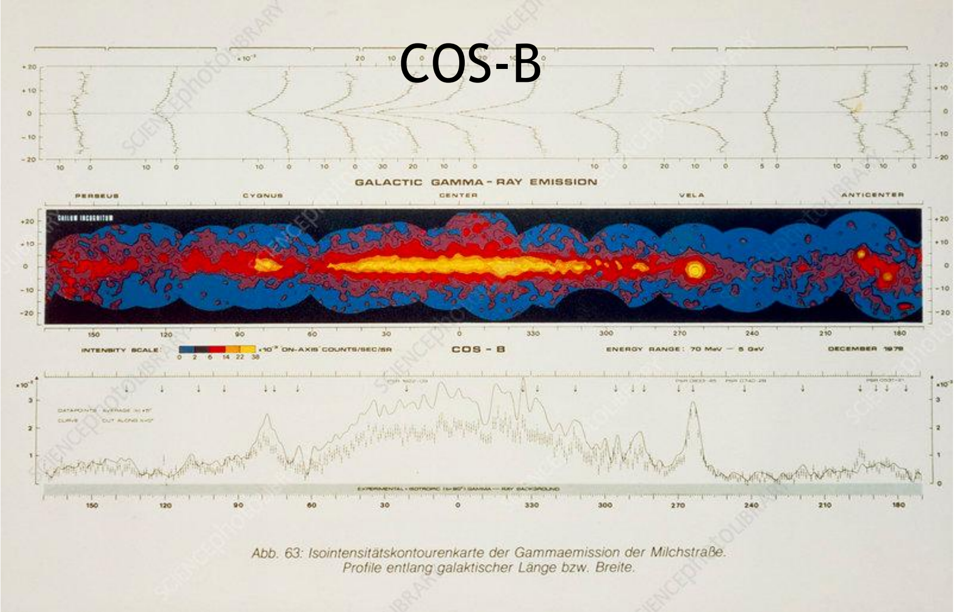
Origin of diffuse γ rays: CR interaction

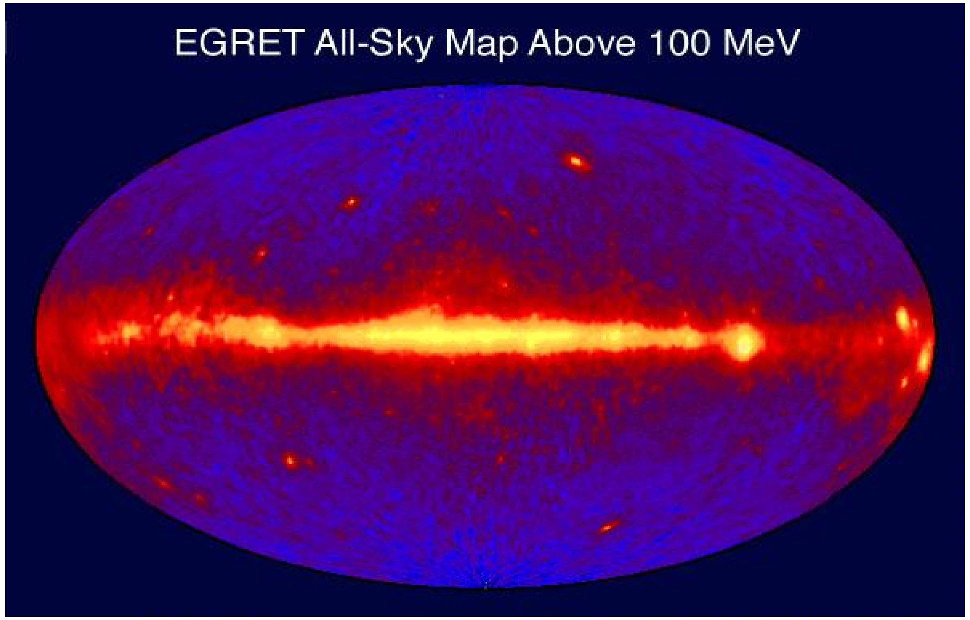


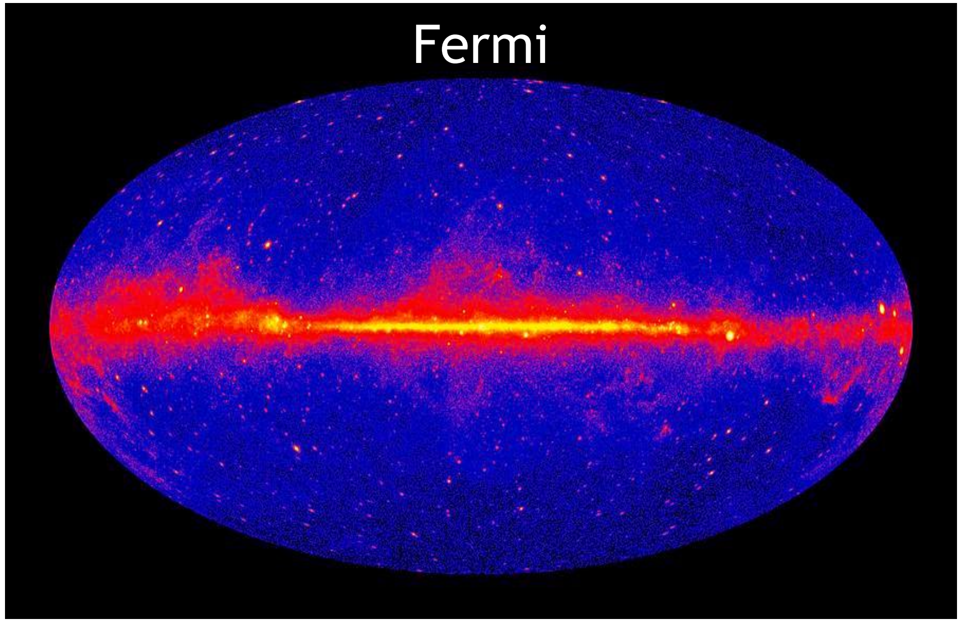
Diffuse γ rays are expected *a priori* to be produced by CR interactions during the propagation, and are thus powerful probe of CR propagation

Diffuse γ-ray observations from space

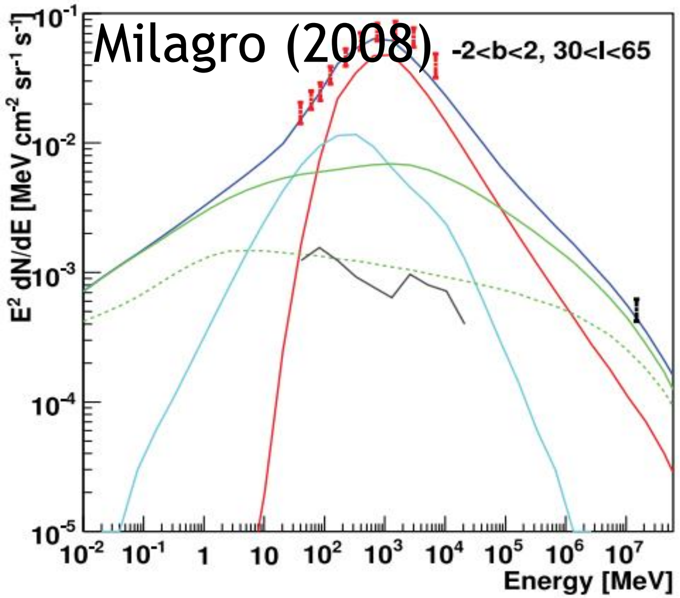


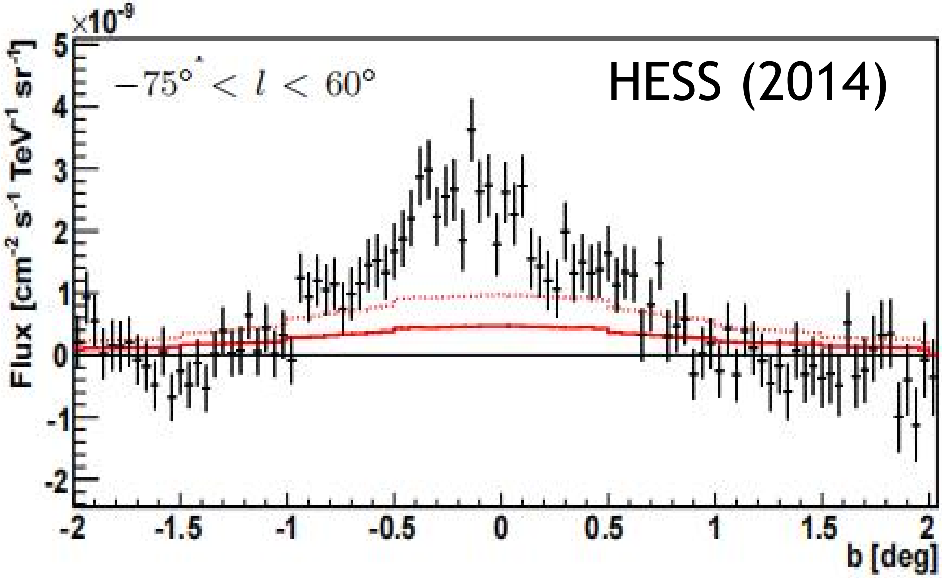


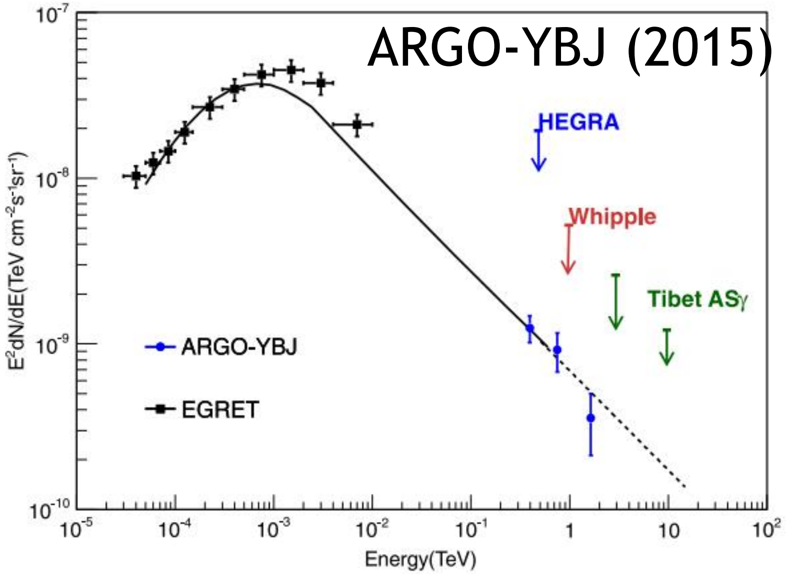


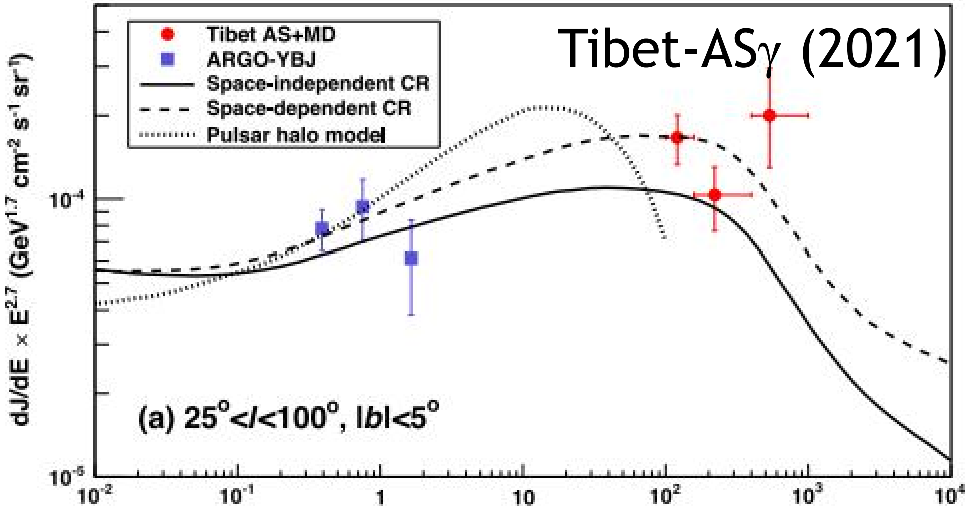


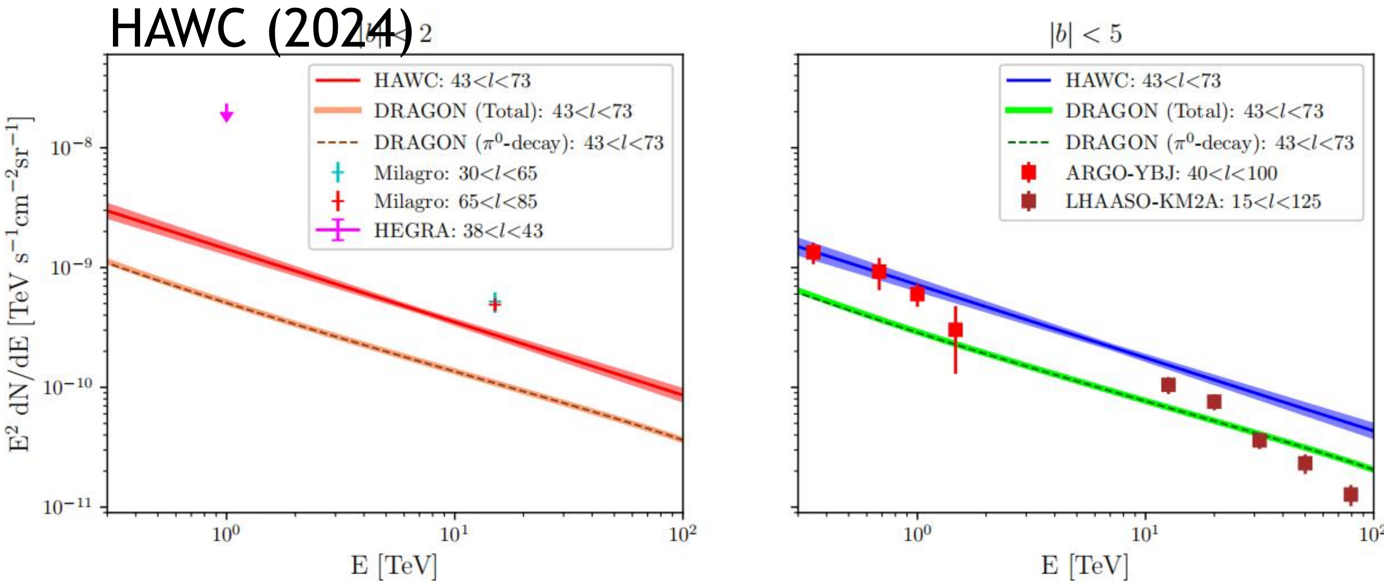
VHE diffuse measurement on ground (>TeV)



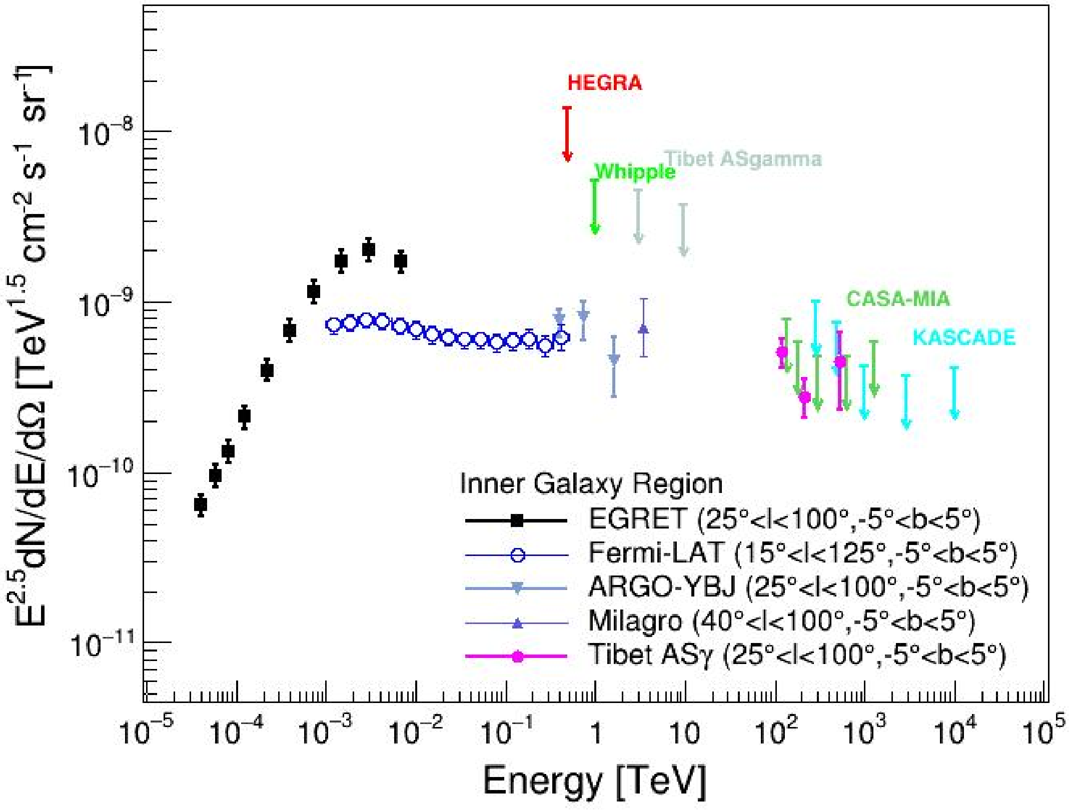


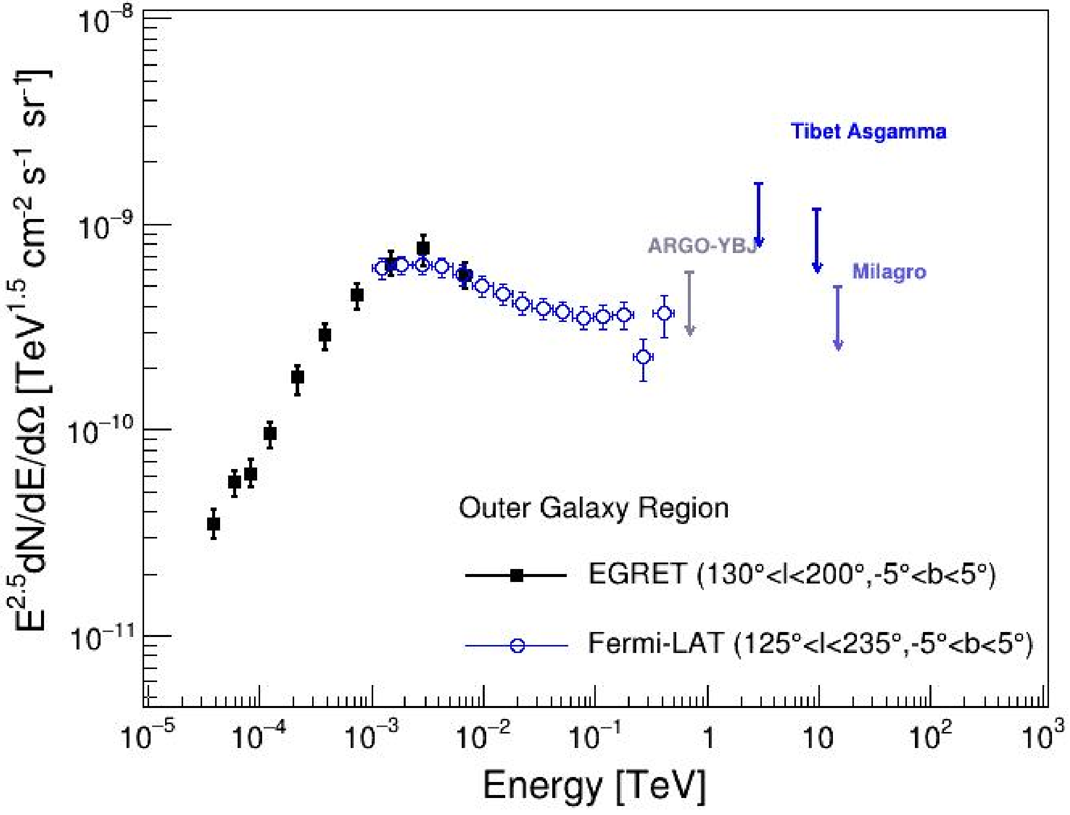






Wide-band diffuse emission measurements

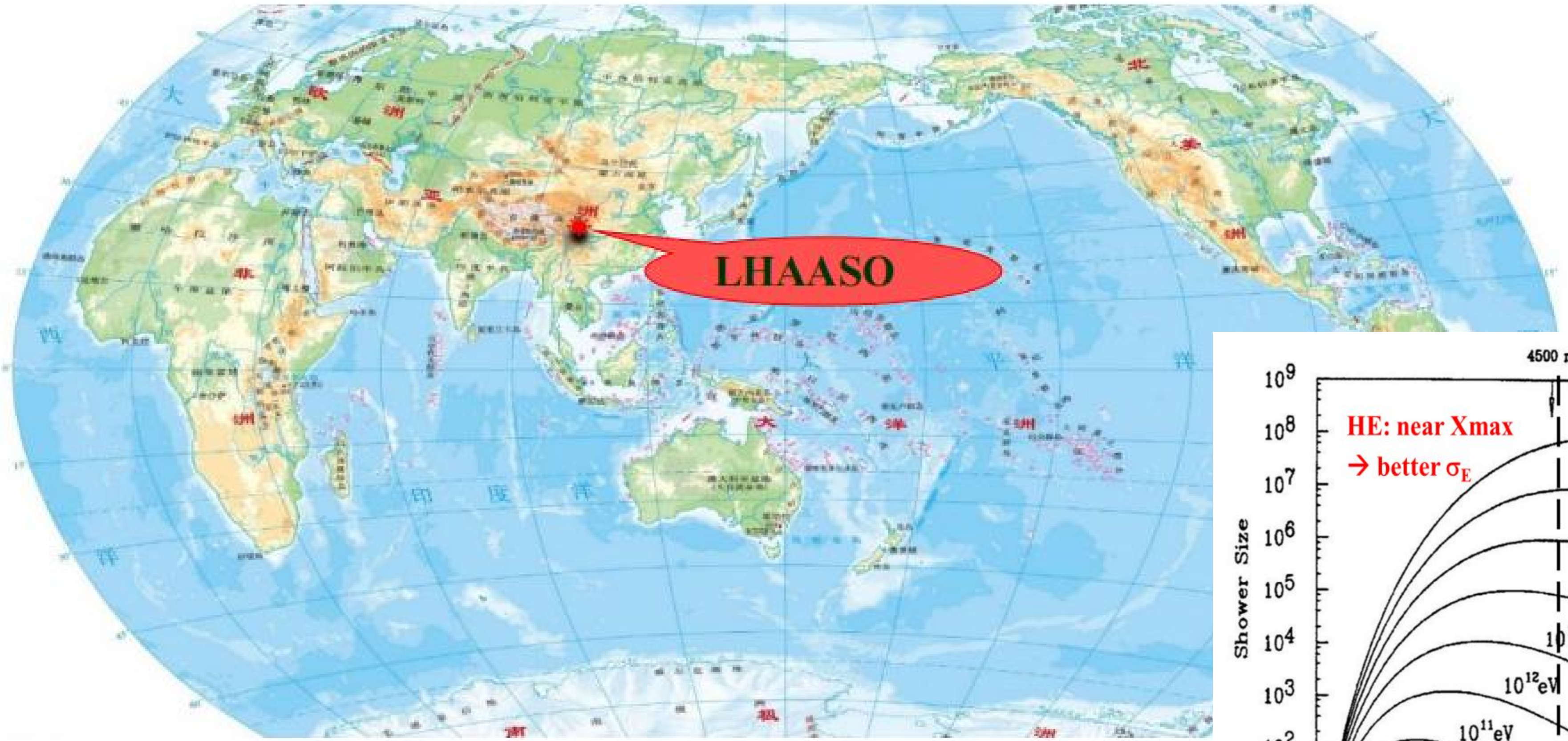


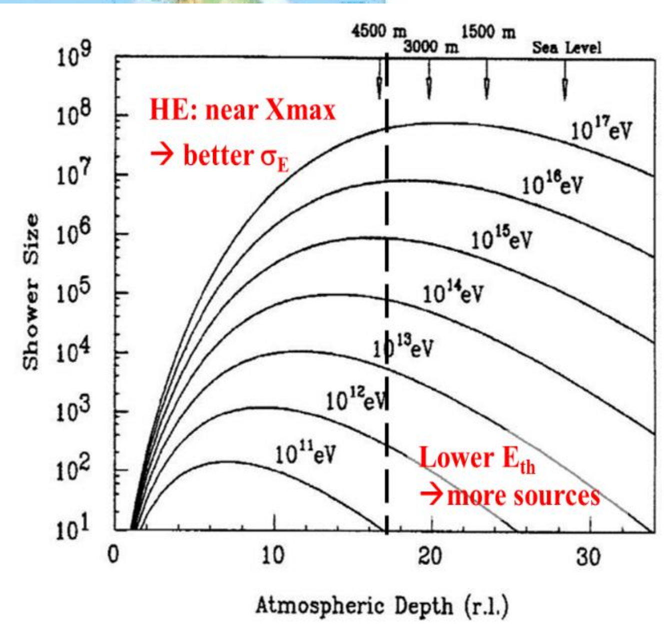


Above TeV, the energy and sky coverage is limited, especially in the outer Galactic plane region where only upper limits were given

Note: the regions of interest are not identical for these observations

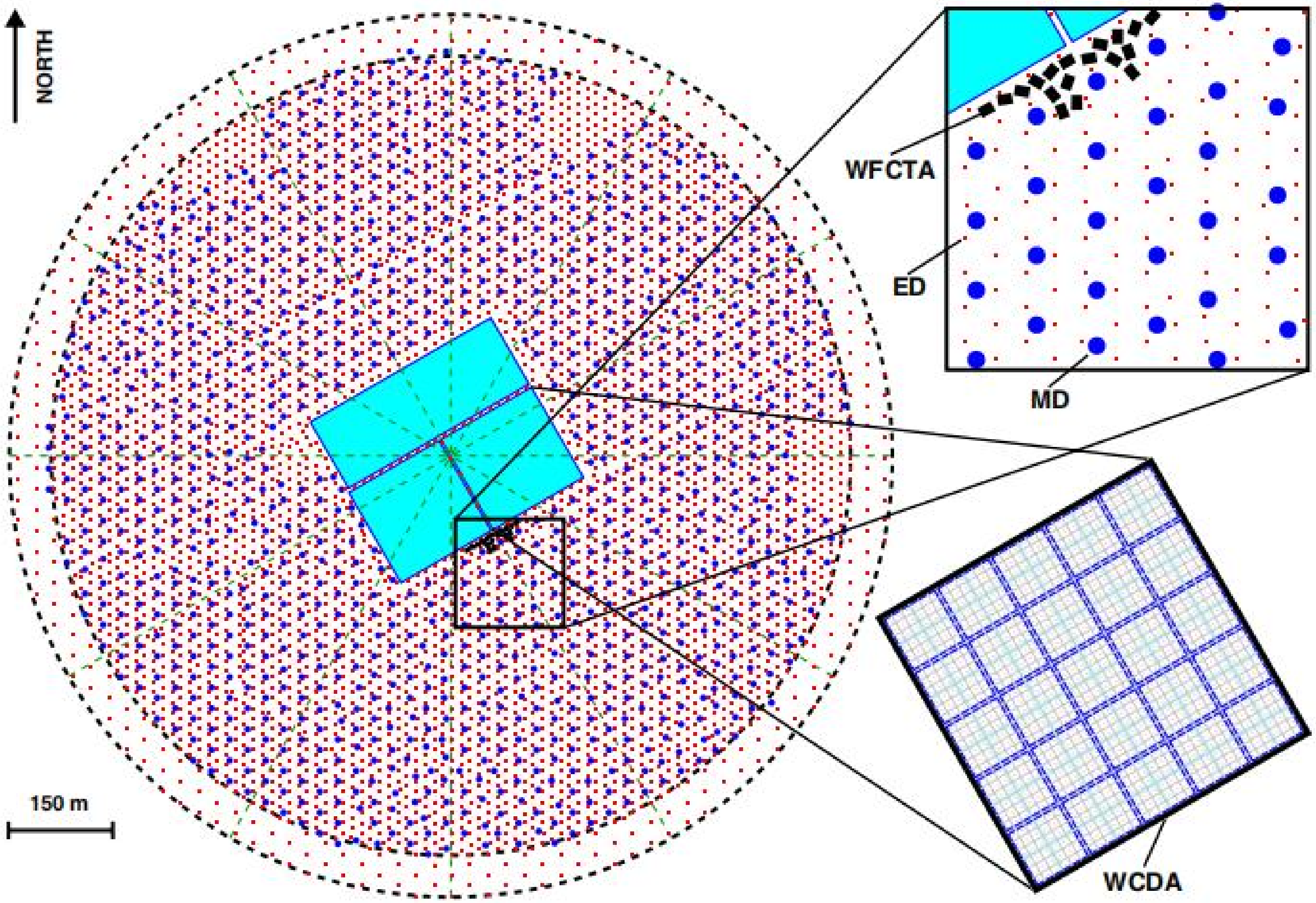
Large High Altitude Air Shower Observatory (LHAASO)





- Haizi mountain, Sichuan, China
- 4410 m above the sea level

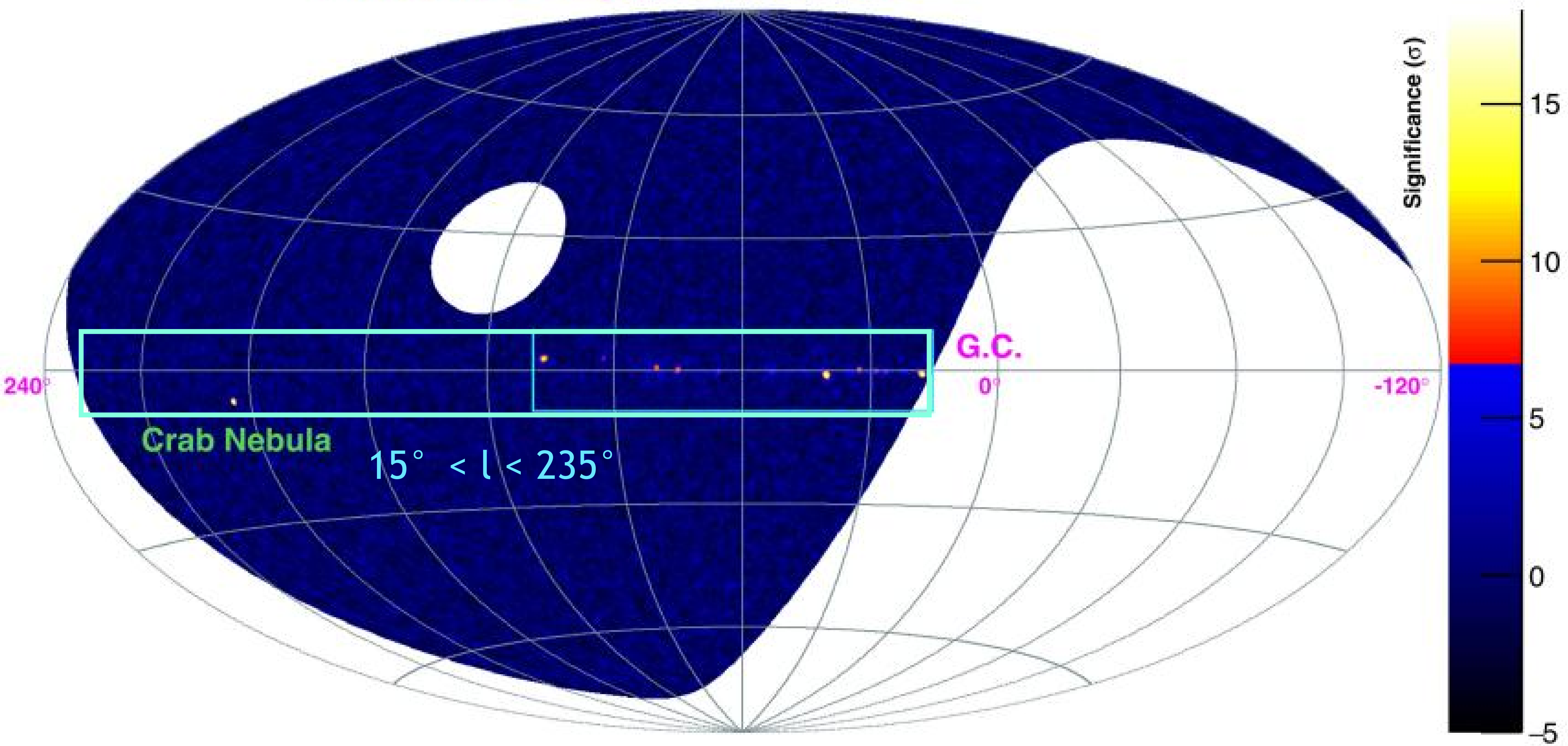
LHAASO detector layout



- 5195 EDs
  - 1 m² each
  - 15 m spacing
- 1188 MDs
  - 36 m² each
  - 30 m spacing
- 3120 WCDs
  - 25 m² each
- 18 WFCTs

The large area and hybrid detection technique makes LHAASO a powerful facility for cosmic ray and gamma-ray observations in a wide energy range.

LHAASO sky coverage

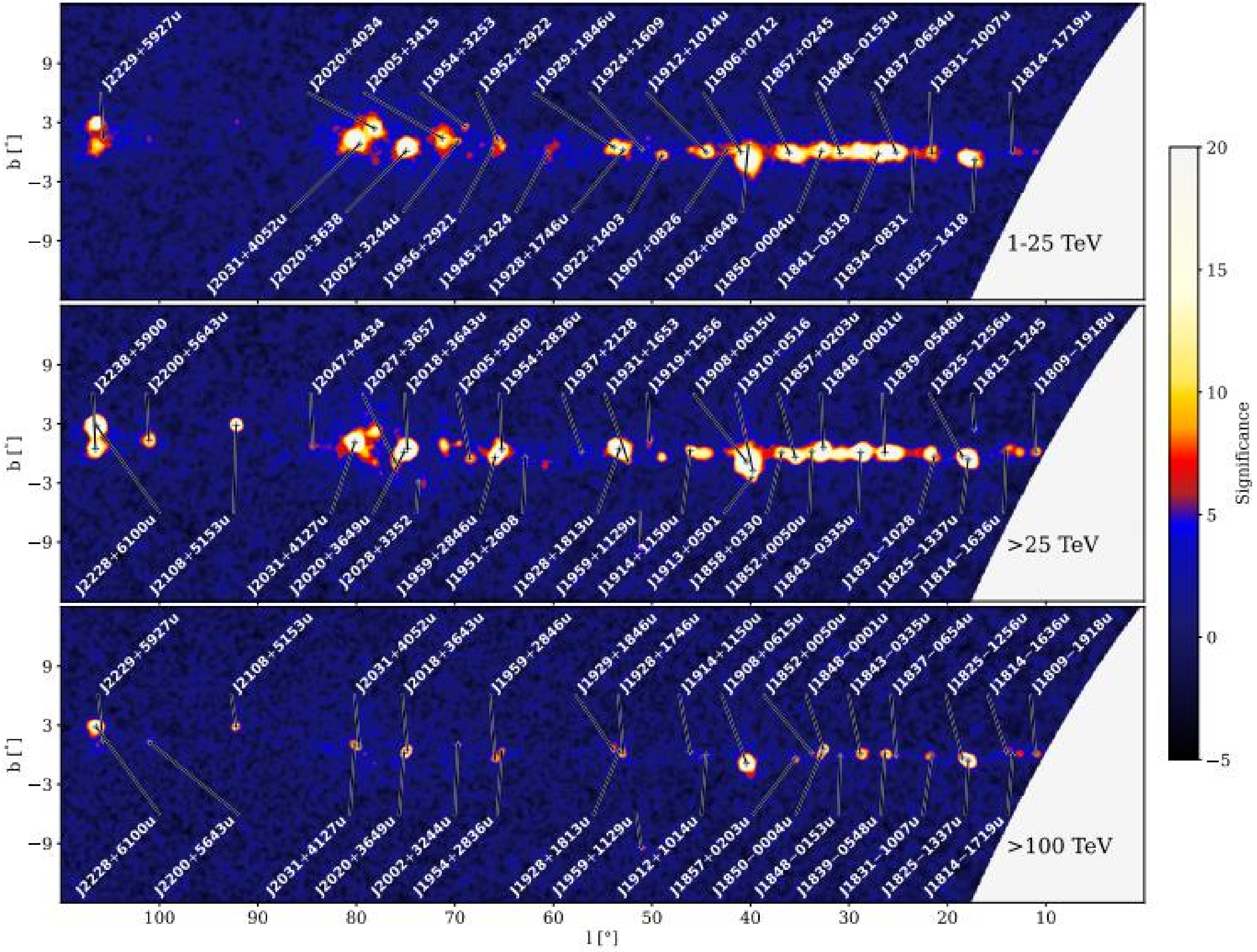


Resolved source mask

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

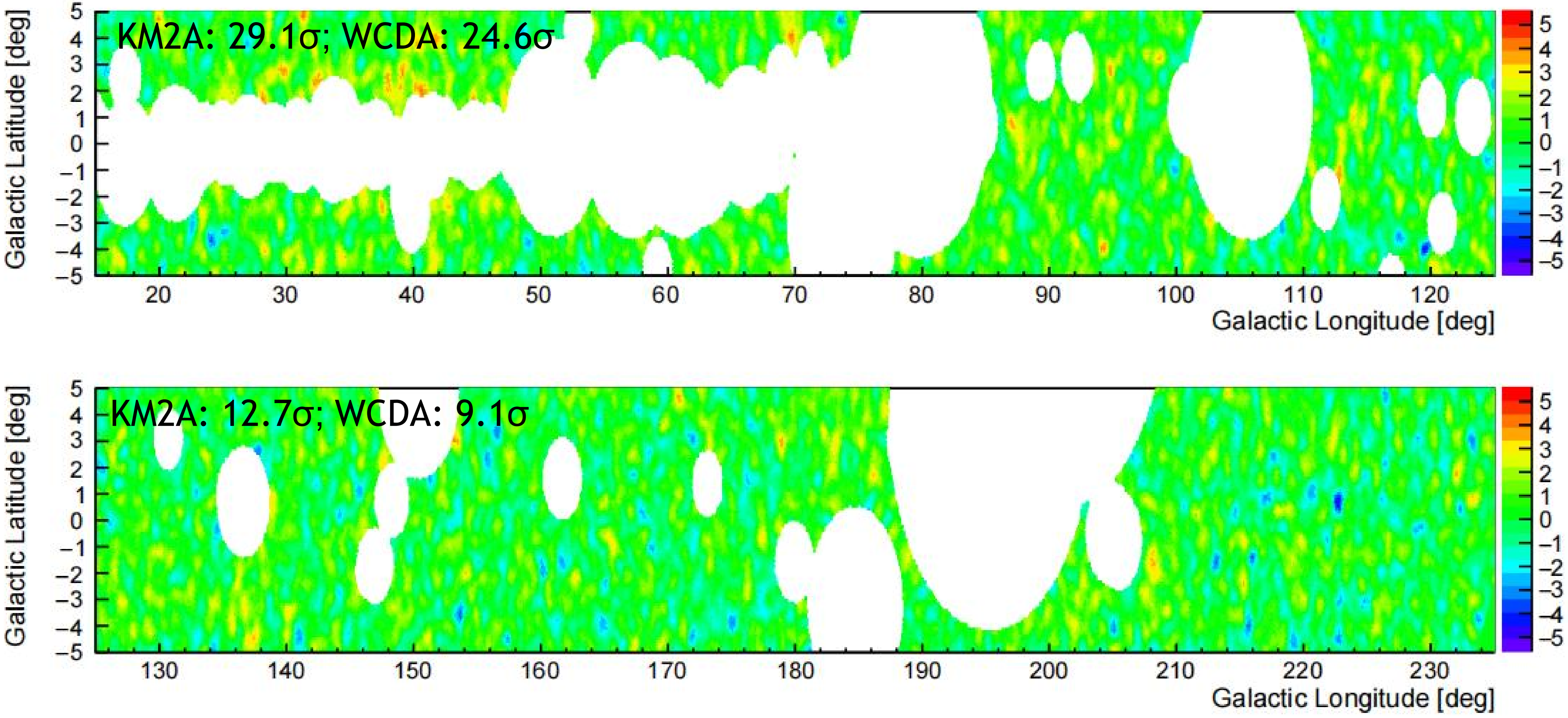
- n=2.5 is chosen
- PSF of the lowest energy bin is used

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



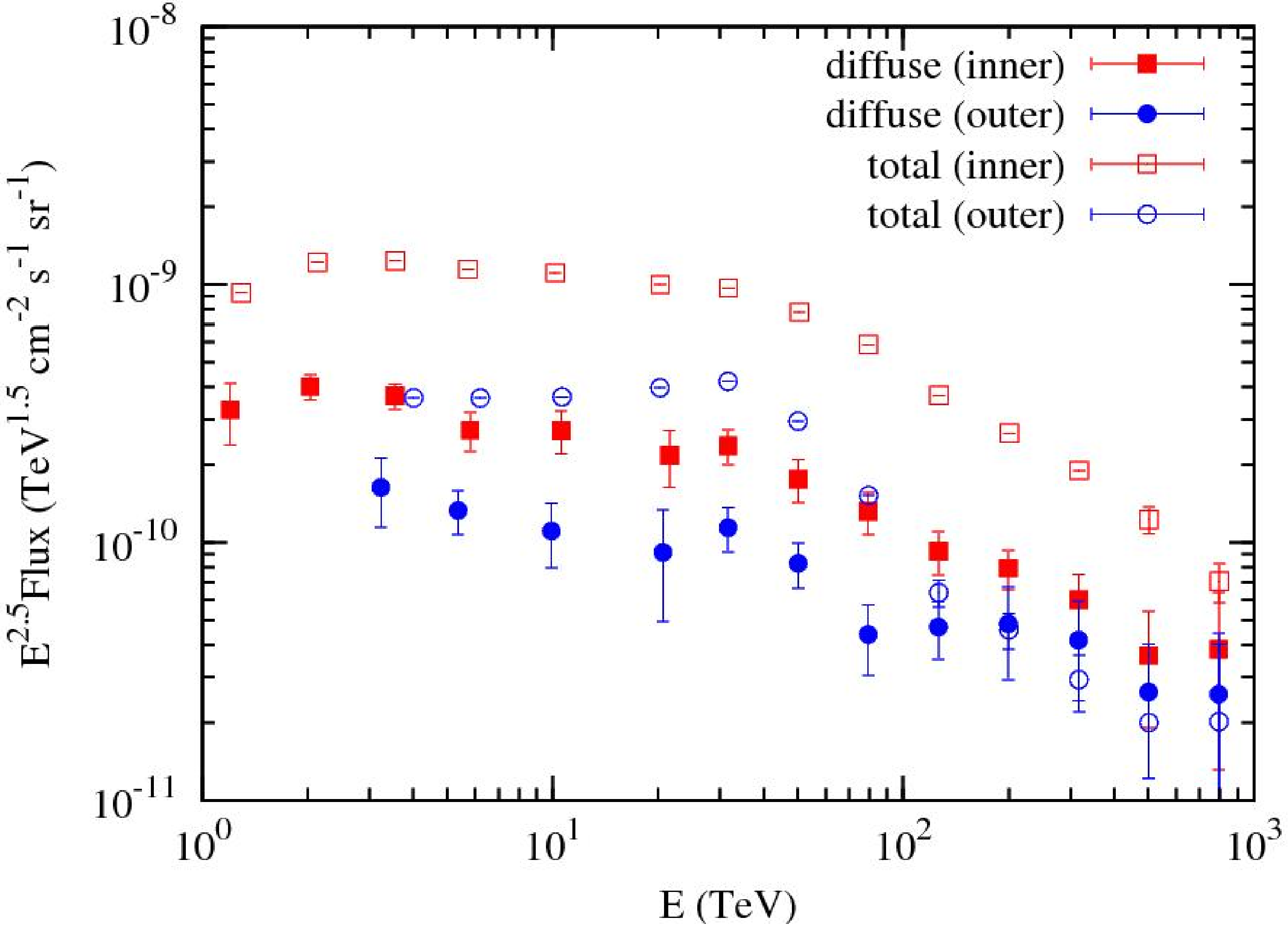
LHAASO first catalog (2024, ApJS)

Diffuse map



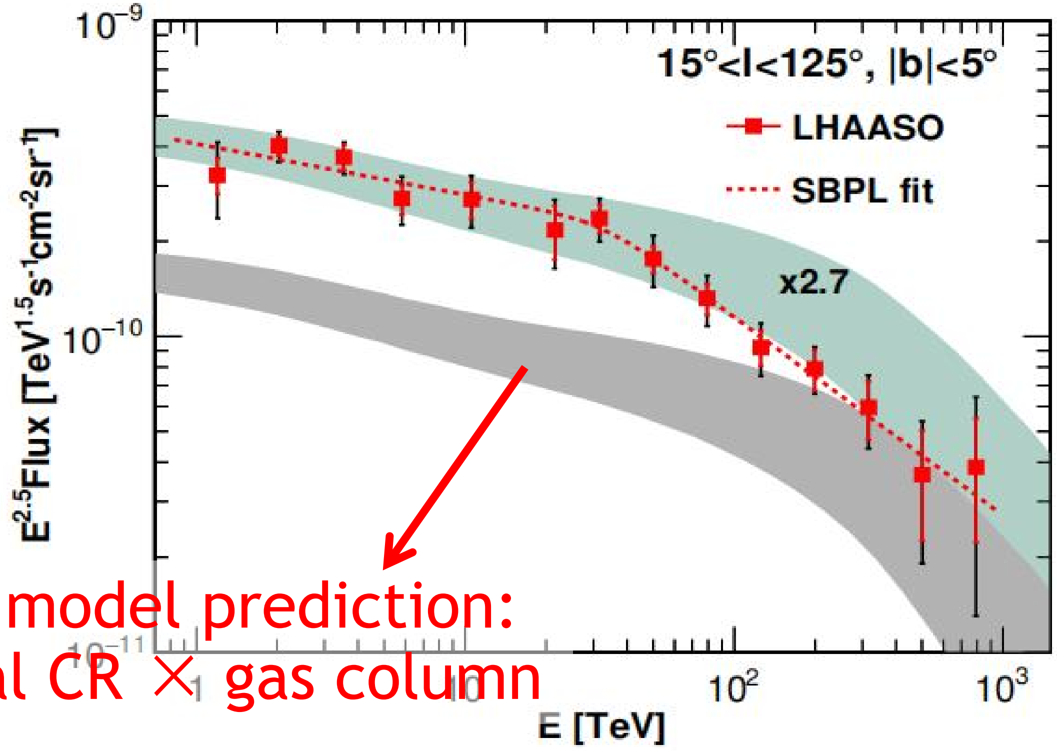
LHAASO (2023, PRL; 2025, PRL)

Diffuse vs. total emission

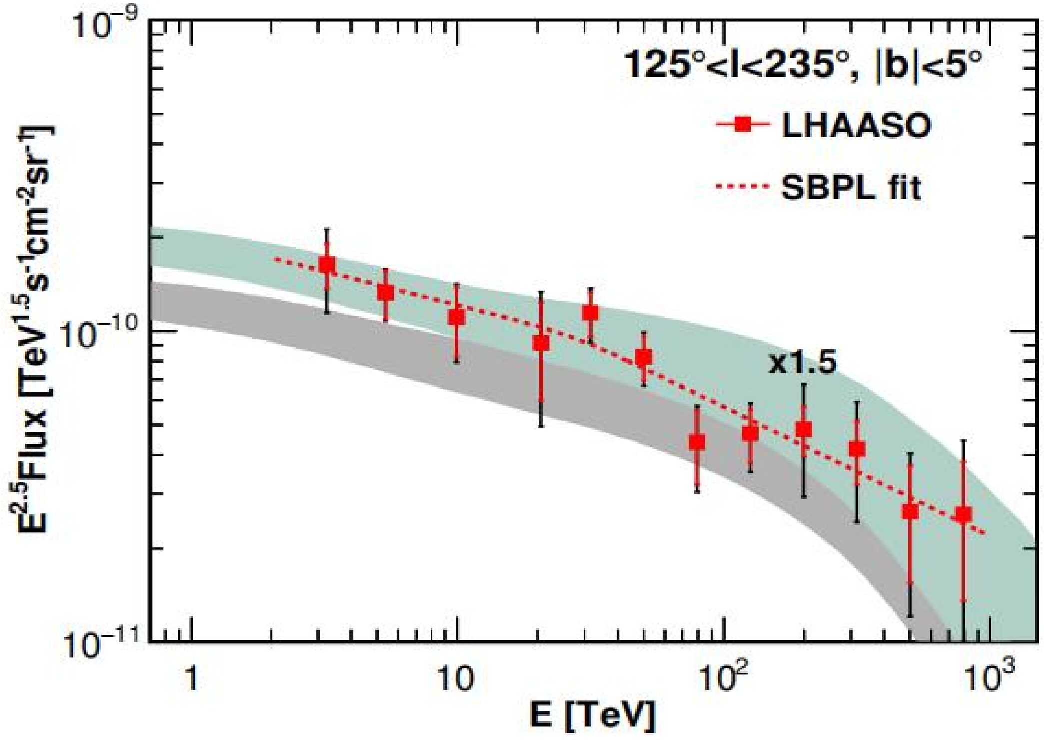


LHAASO (2025, PRL)

Diffuse SED



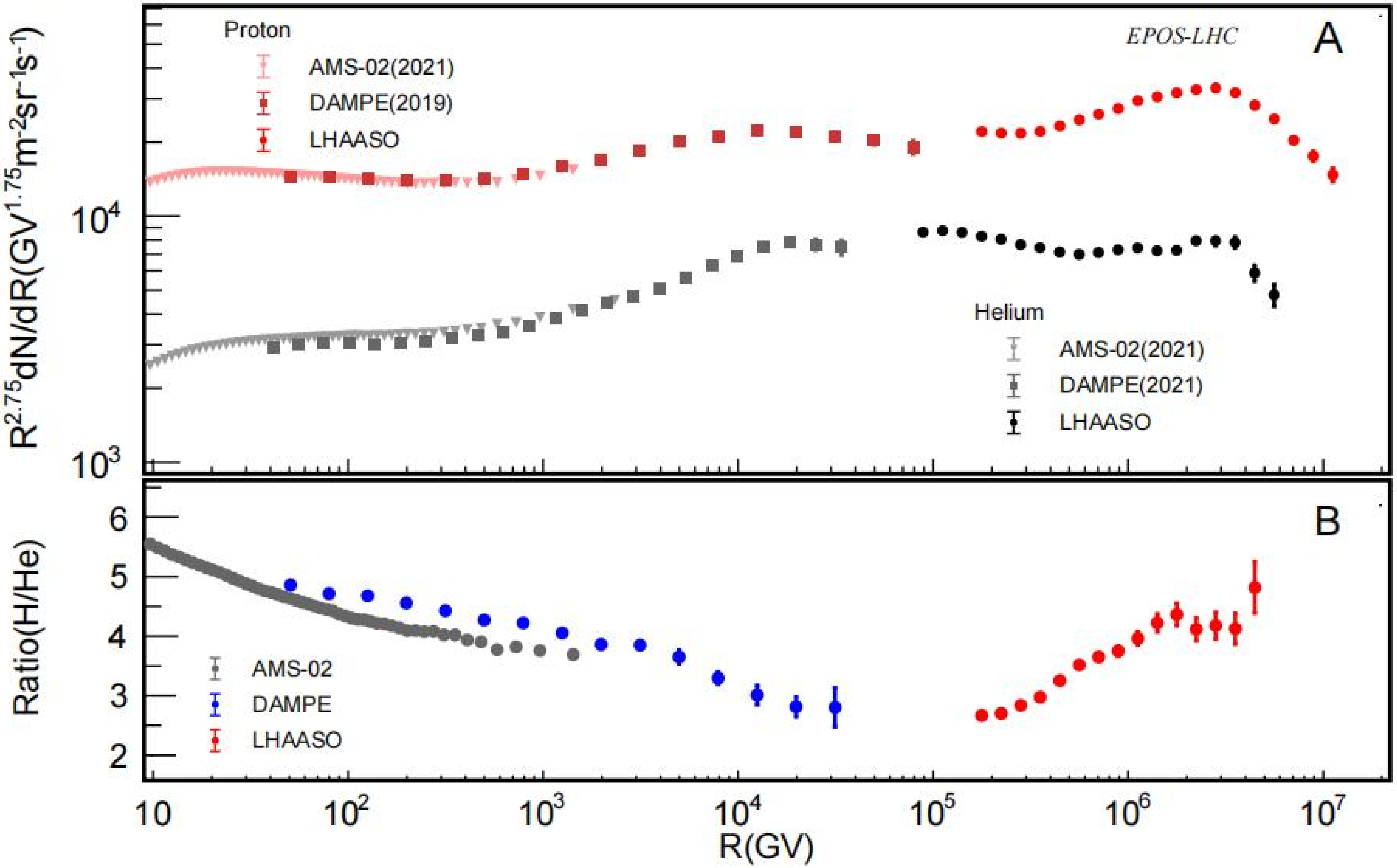
Toy model prediction:
local CR × gas column



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)	$3.84 \pm 0.37_{stat}$	$-2.72 \pm 0.10_{stat}$	$-2.92 \pm 0.10_{stat}$	$27.86 \pm 22.49_{stat}$

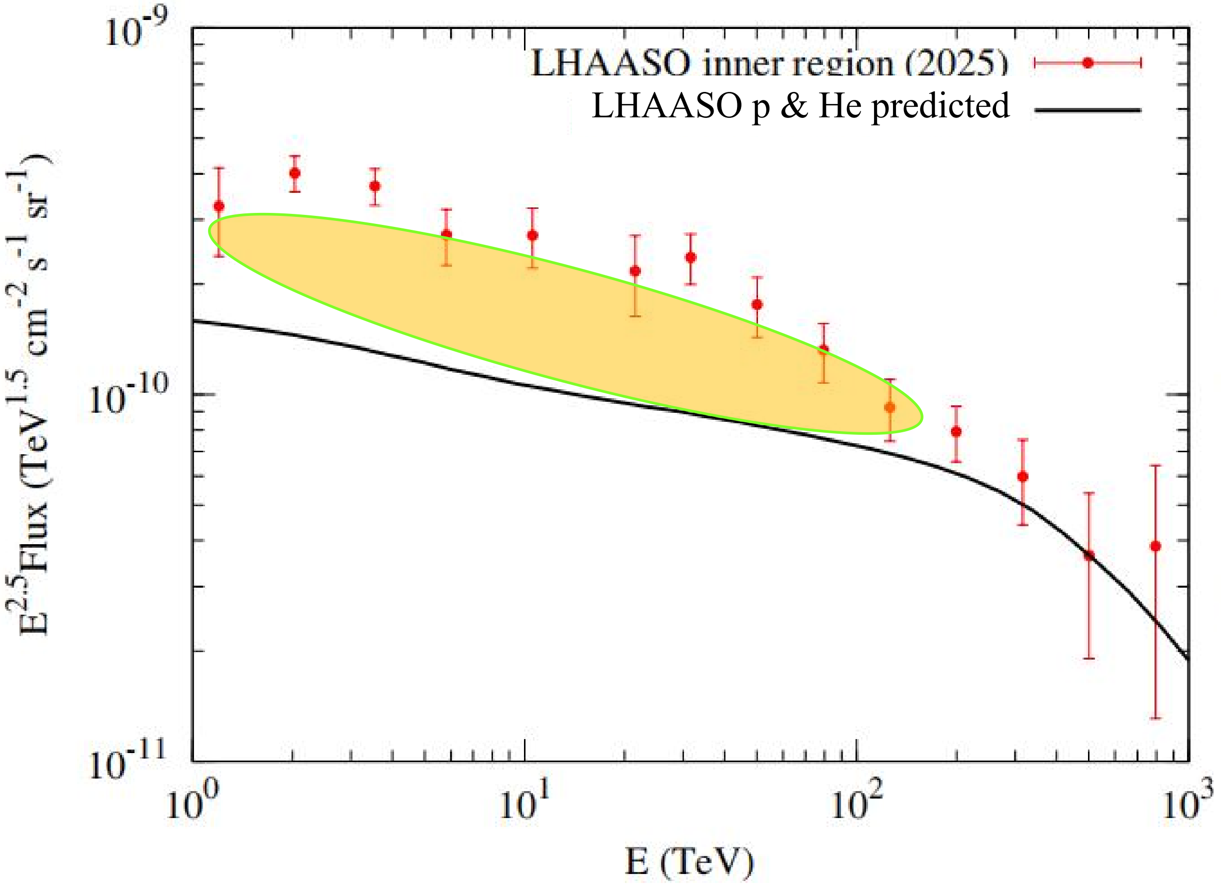
- **LHAASO measures diffuse emission from 1 TeV to 1 PeV with high significnace, and gives the first detection from the outer Galactic plane**
- **A spectral break around 30 TeV is revealed in the inner Galactic plane**

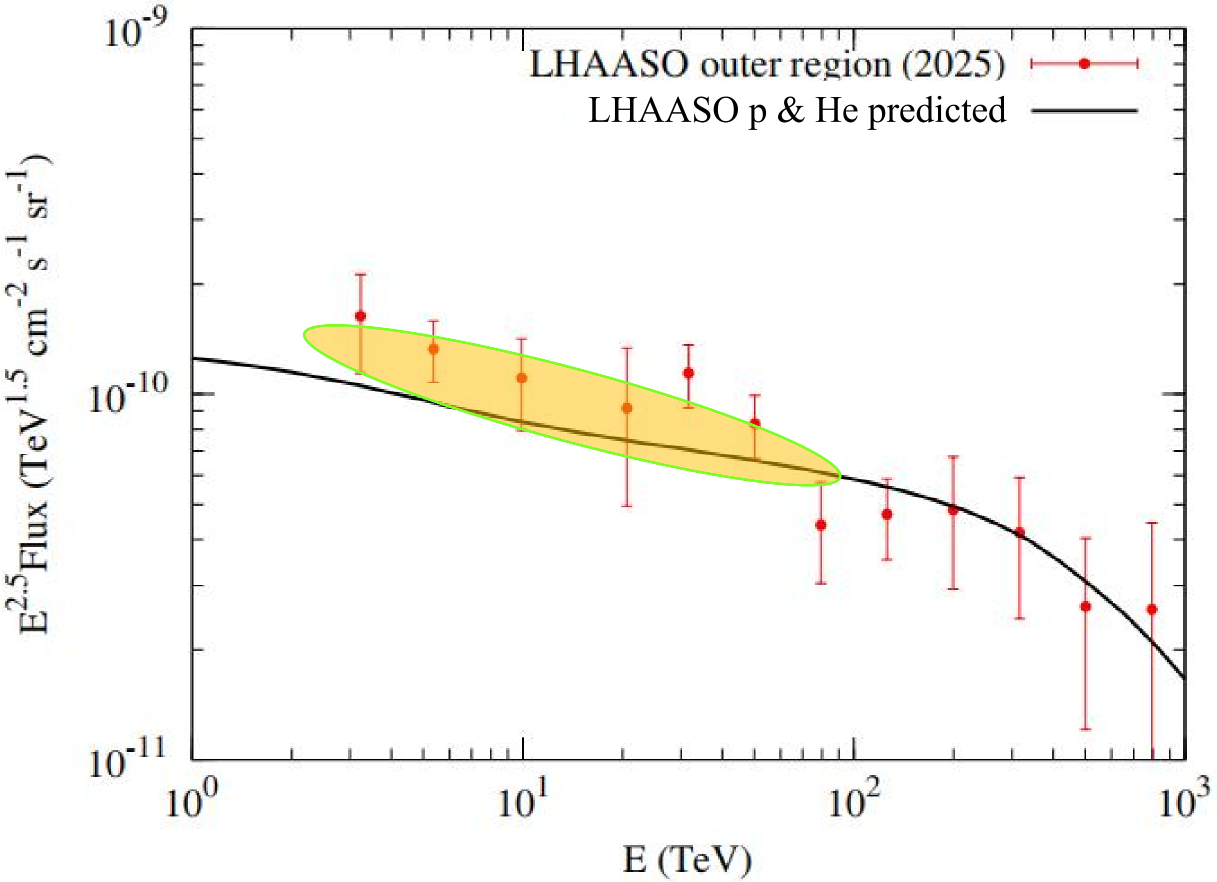
LHAASO proton and He spectra



LHAASO 2025, Sci. Bull., 70, 4173
LHAASO 2026, PRL, 136, 121001

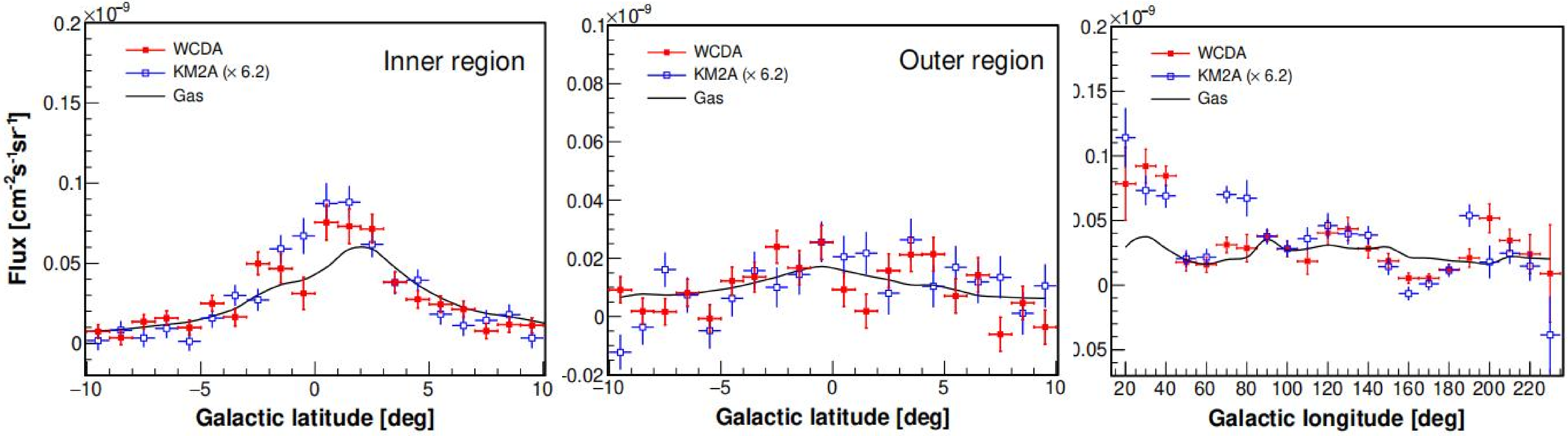
Updated model prediction with LHAASO CR spectra





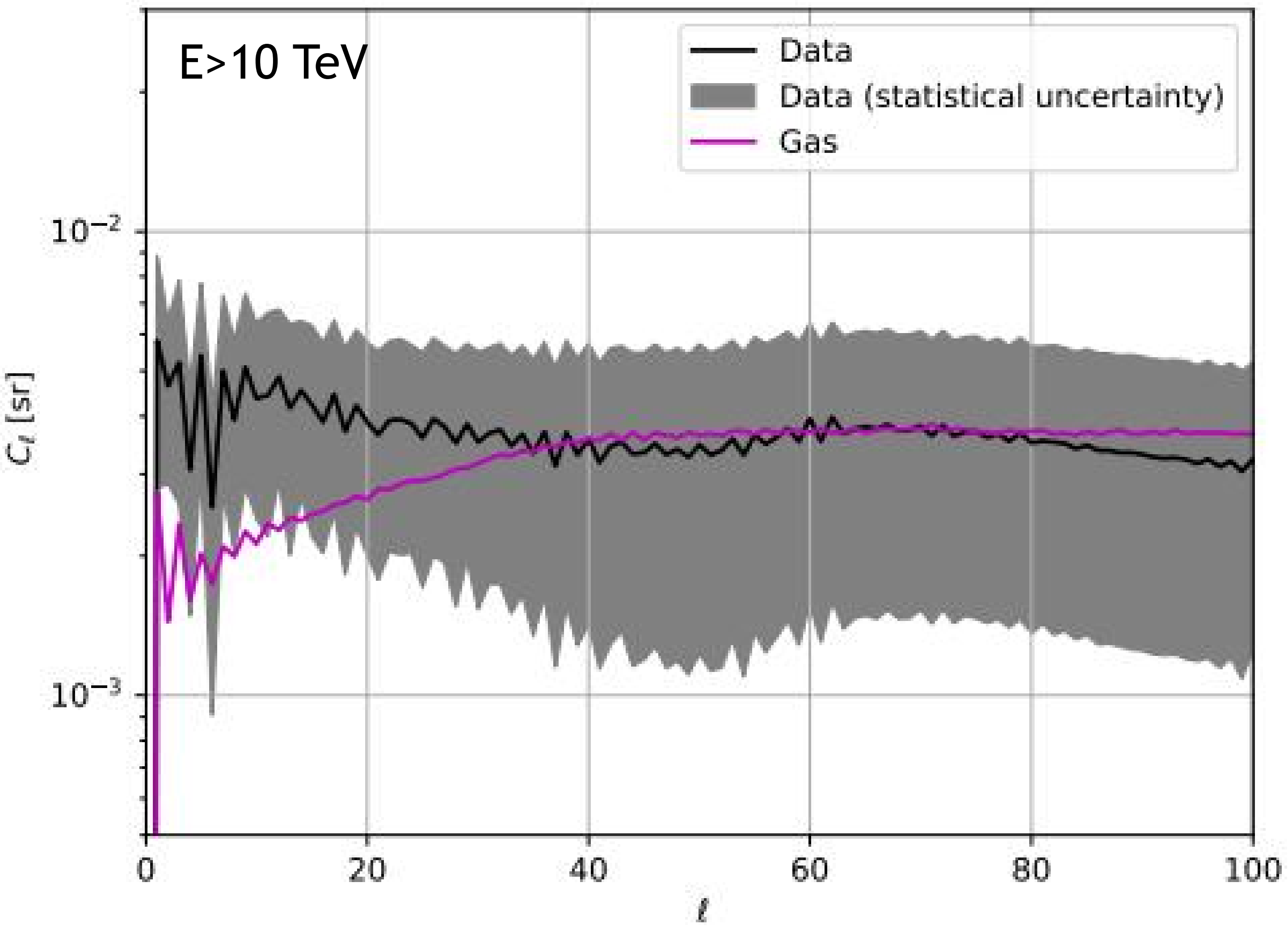
- The diffuse fluxes in the Galactic plane below ~100 TeV are higher than the prediction of cormic ray interactions
- Uncertainties of gas density may not affect this conclusion

Longitude and latitude profiles



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

Angular spectrum



Difference between data and gas is also shown in the angular spectrum at low-l (may correspond to difference at O(10) degrees)

Possible spatial variation of spectra

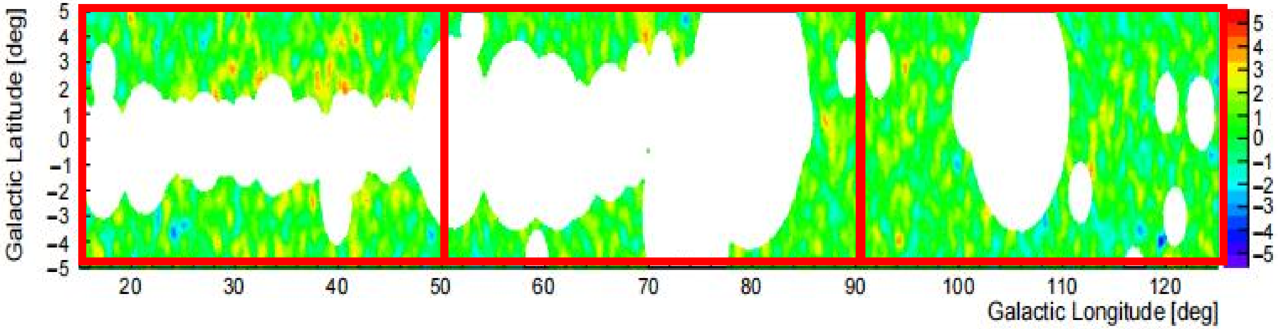
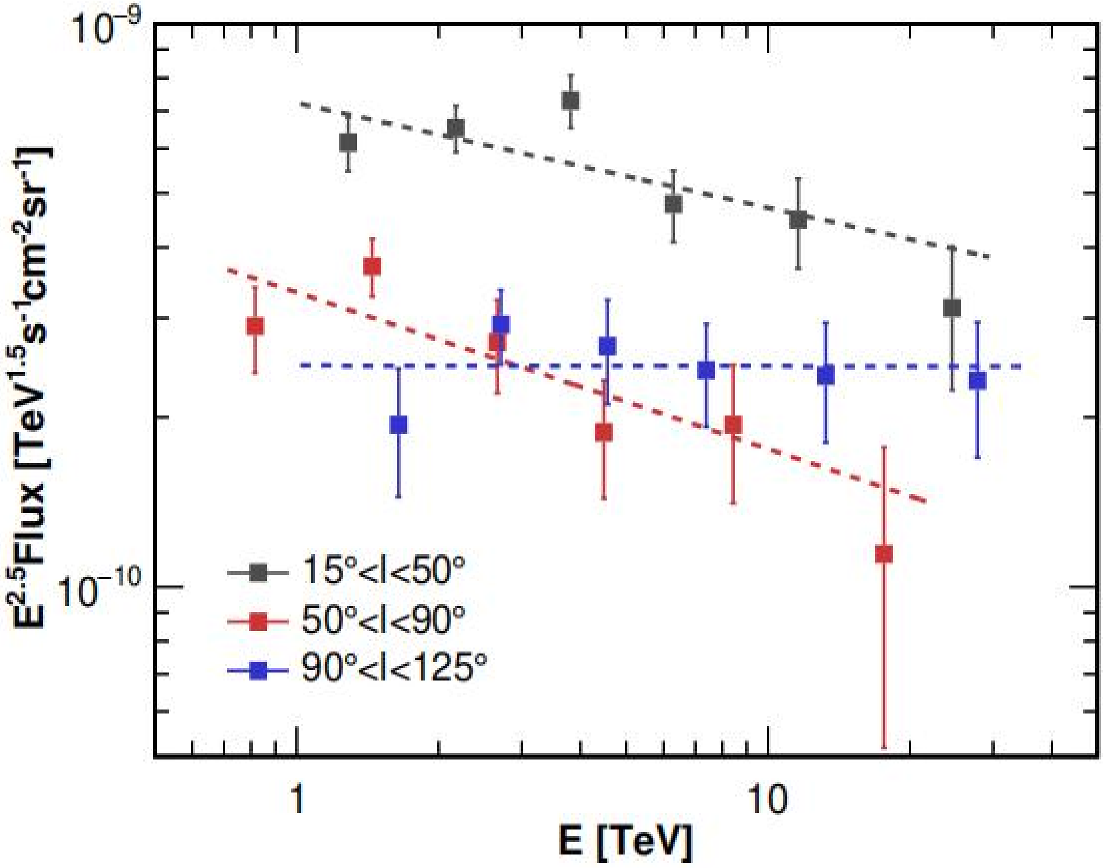


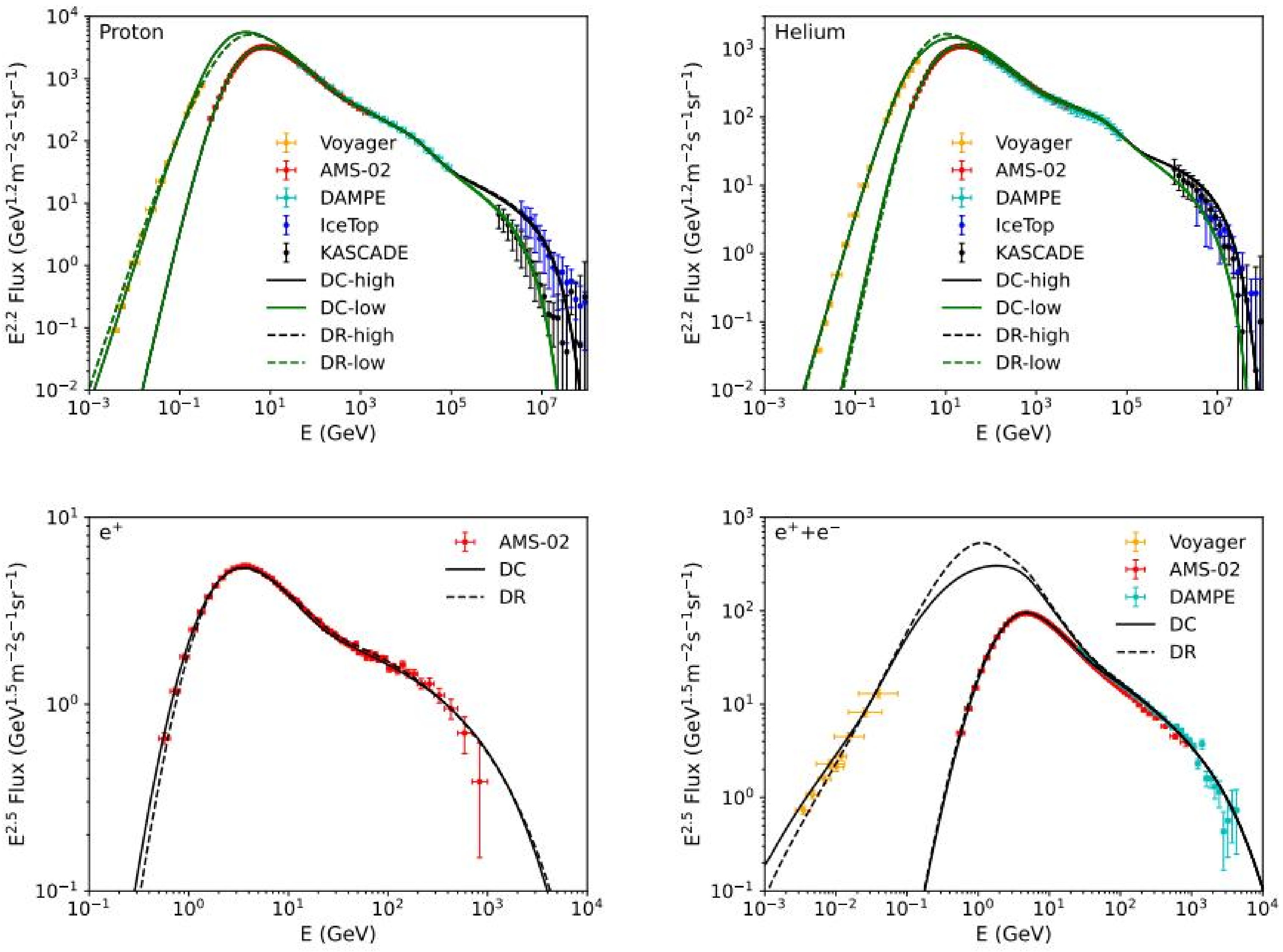
TABLE II. Power-law fitting results of the LHAASO-WCDA diffuse emission.

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)

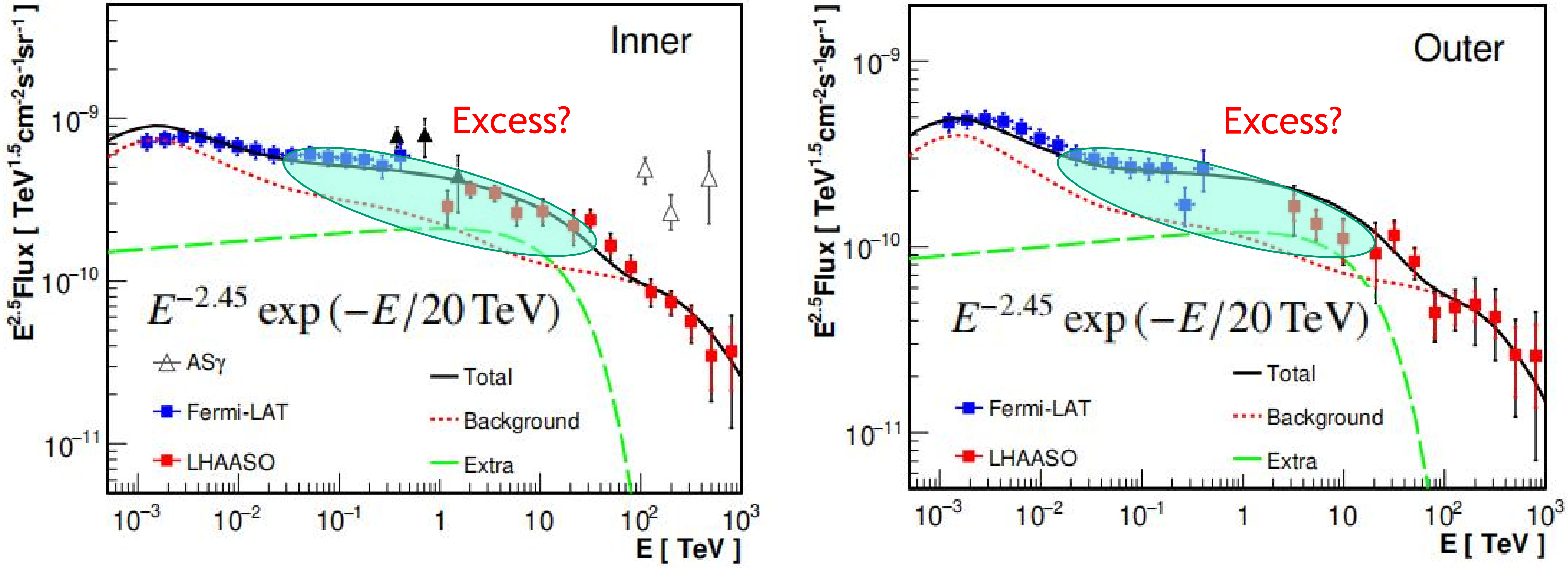
Comparison with a GALPROP model



Homogeneous, isotropic propagation setup

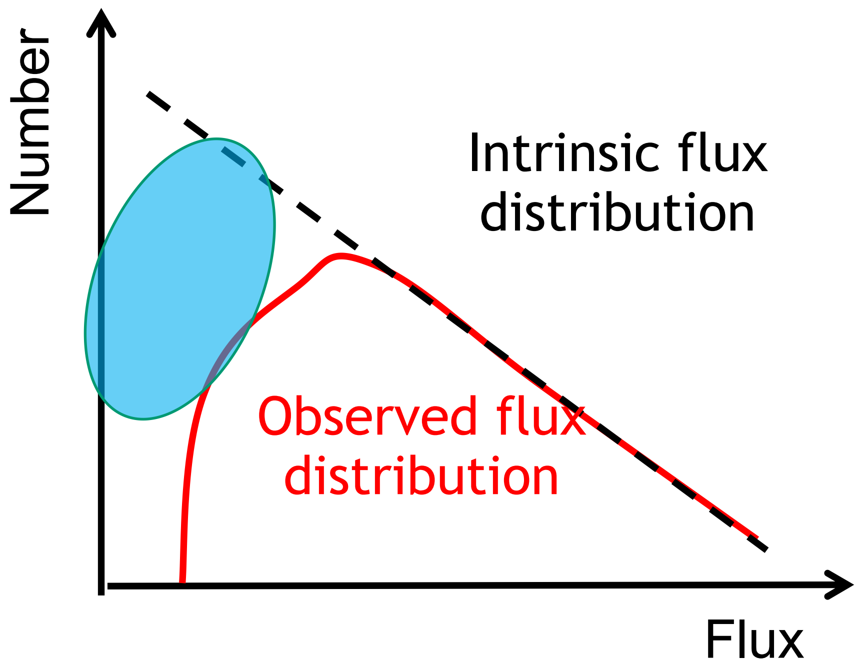
Zhang et al. (2023, ApJ, 957, 43)

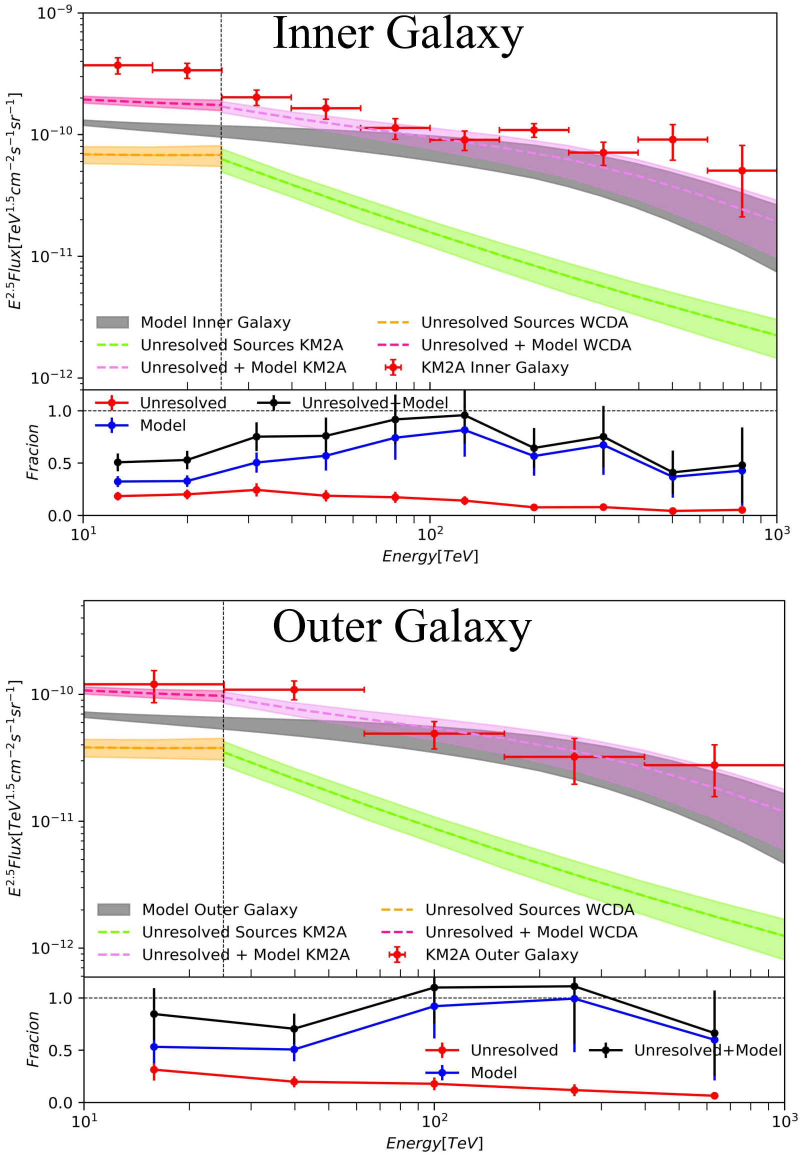
Comparison with a GALPROP model



Intermediate energy excesses may come from an unresolved source component?

Unresolved source contribution?

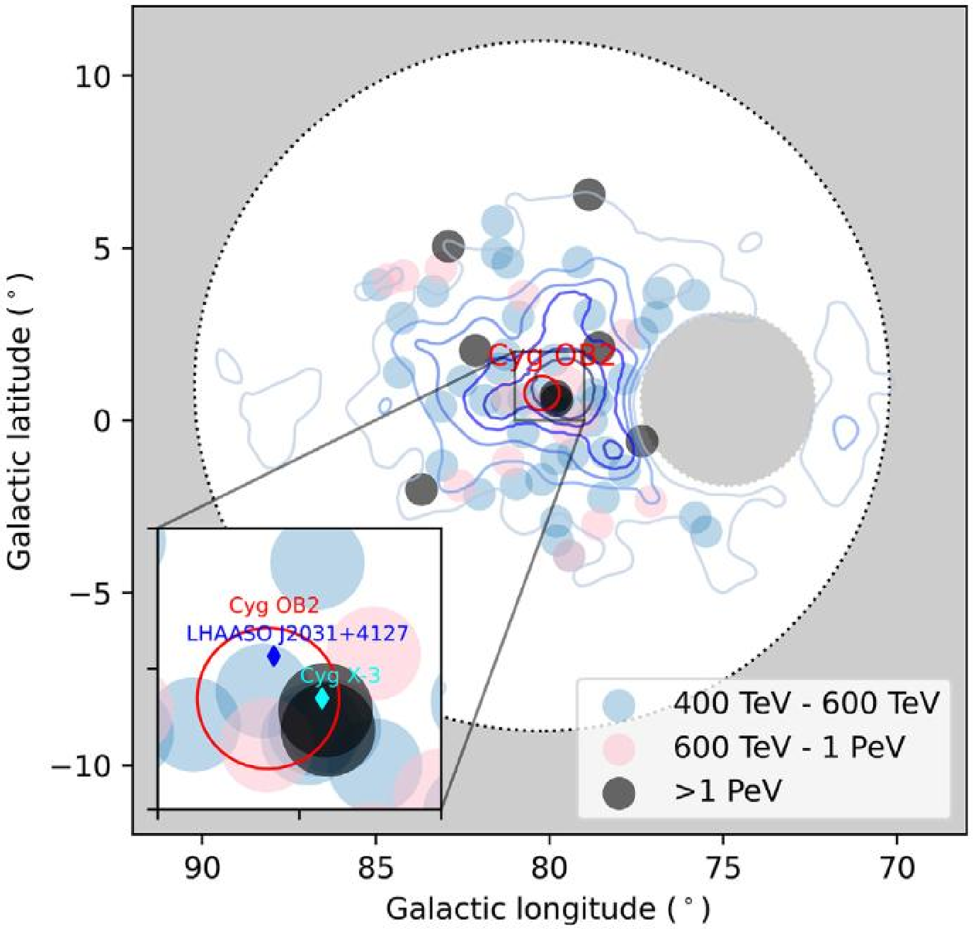


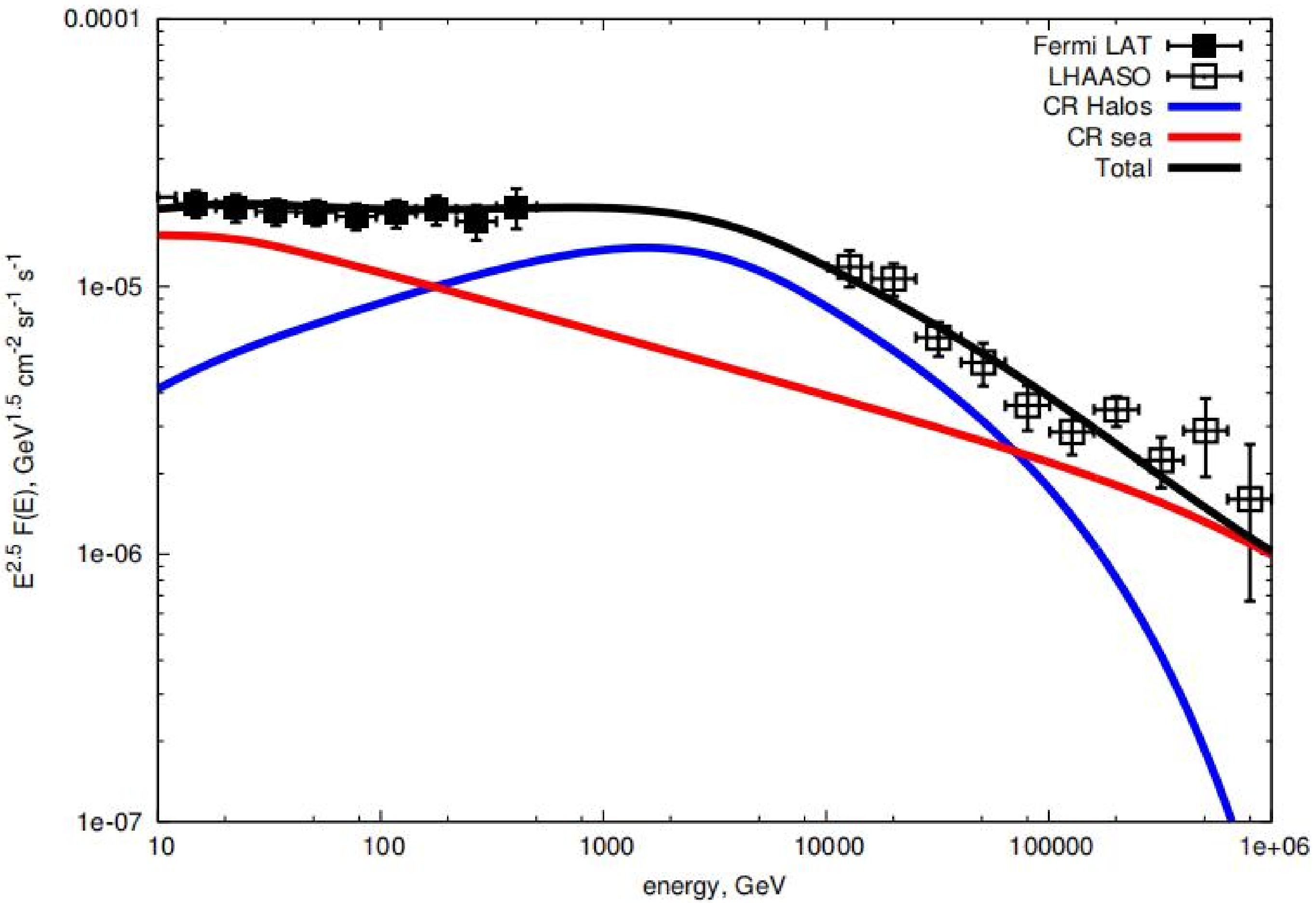


- ✓ The contribution of unresolved sources based on extrapolation of LHAASO catalog can partly account for the excesses
- ✓ Larger extended sources were not included
- ✓ Additional contributions from unknown mechanisms

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

Confinement and interaction around sources

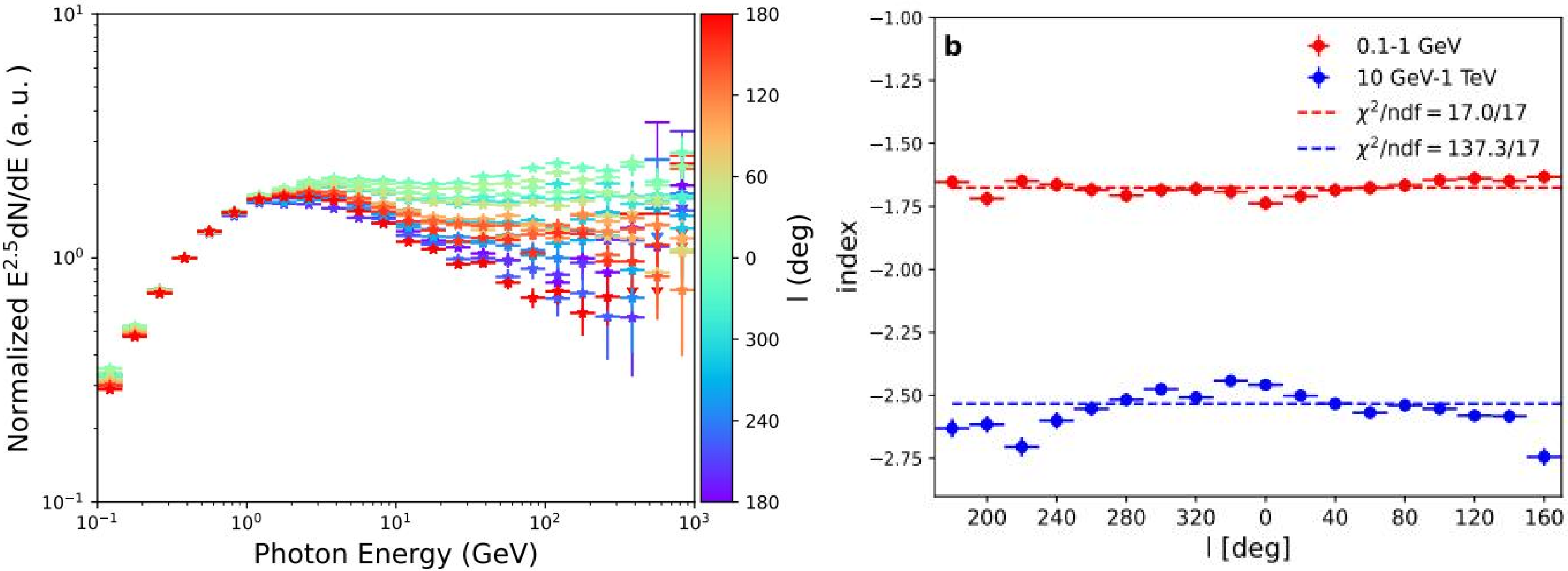




Cygnus bubble: super accelerator as extended as 10 degrees (LHAASO 2024, Sci. Bull.)

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

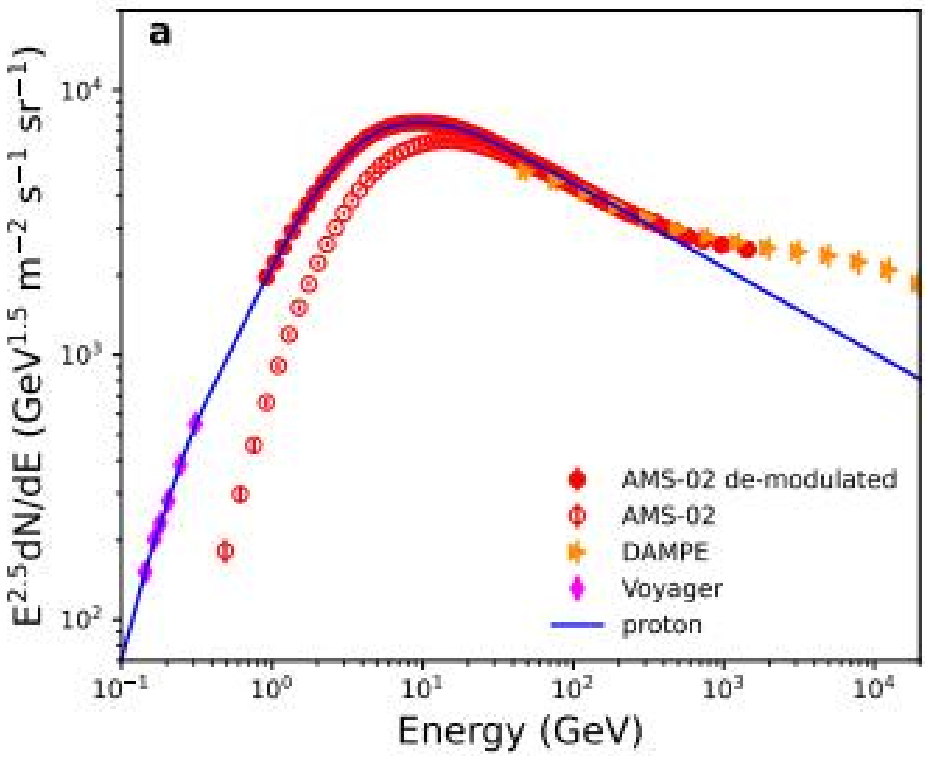
Re-analysis of the Fermi-LAT data

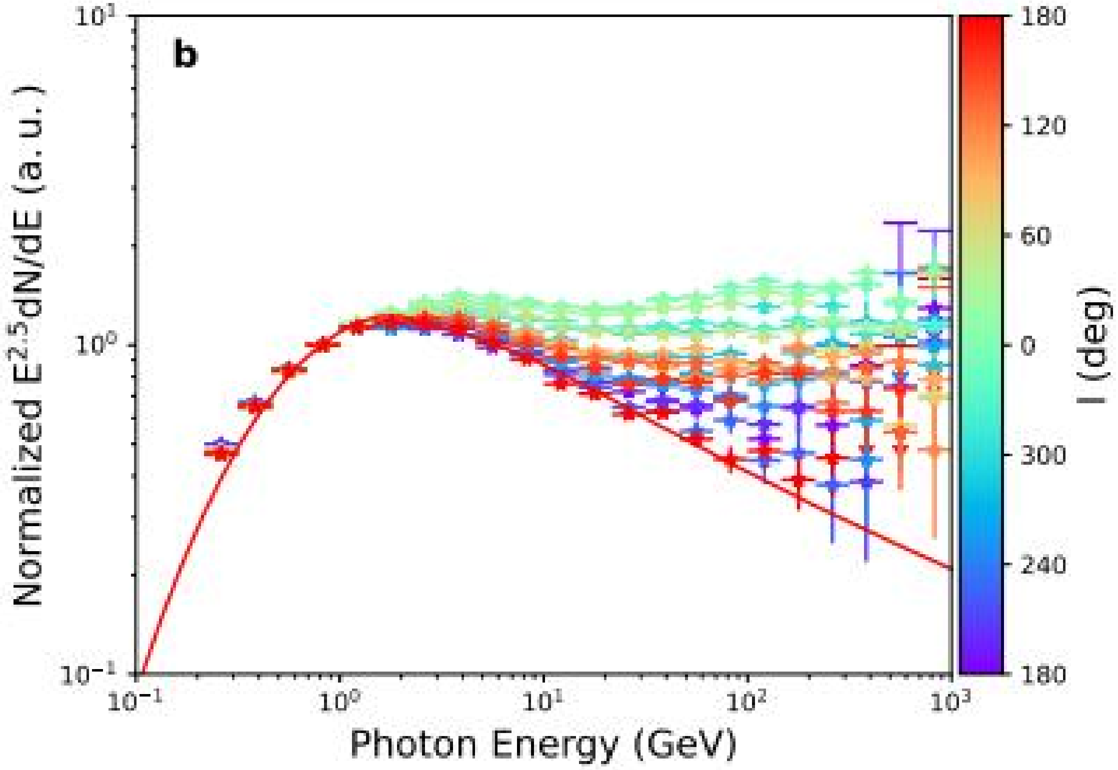


- ➢ **Divide the Galactic plane into 18 regions, each with $20^0 \times 20^0$ size**
- ➢ **The low-energy spectra are uniform, and high-energy spectra show variations**

Chen et al., arXiv:2509.26290; see also Yang et al. (2016, PRD)

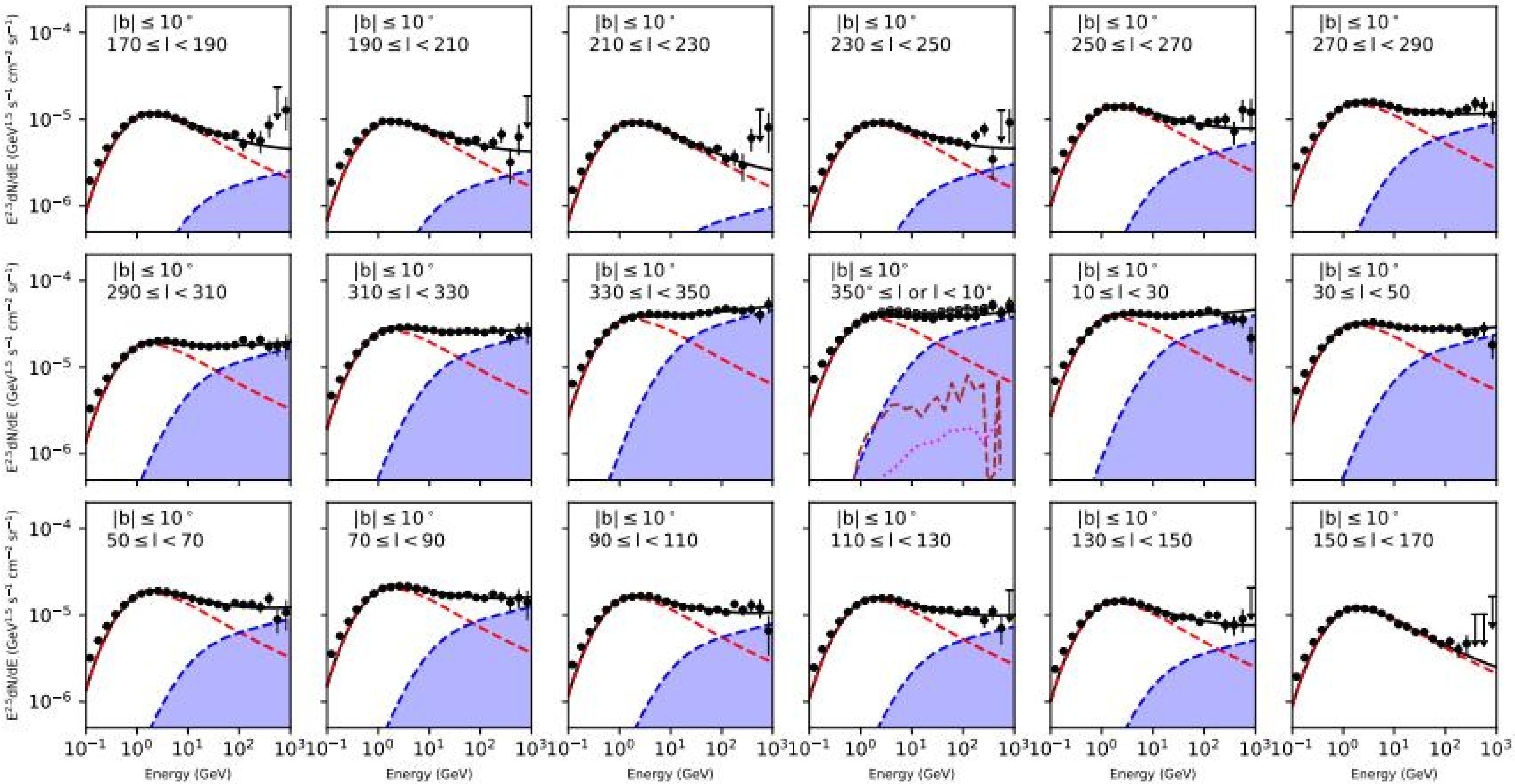
Re-analysis of the Fermi-LAT data





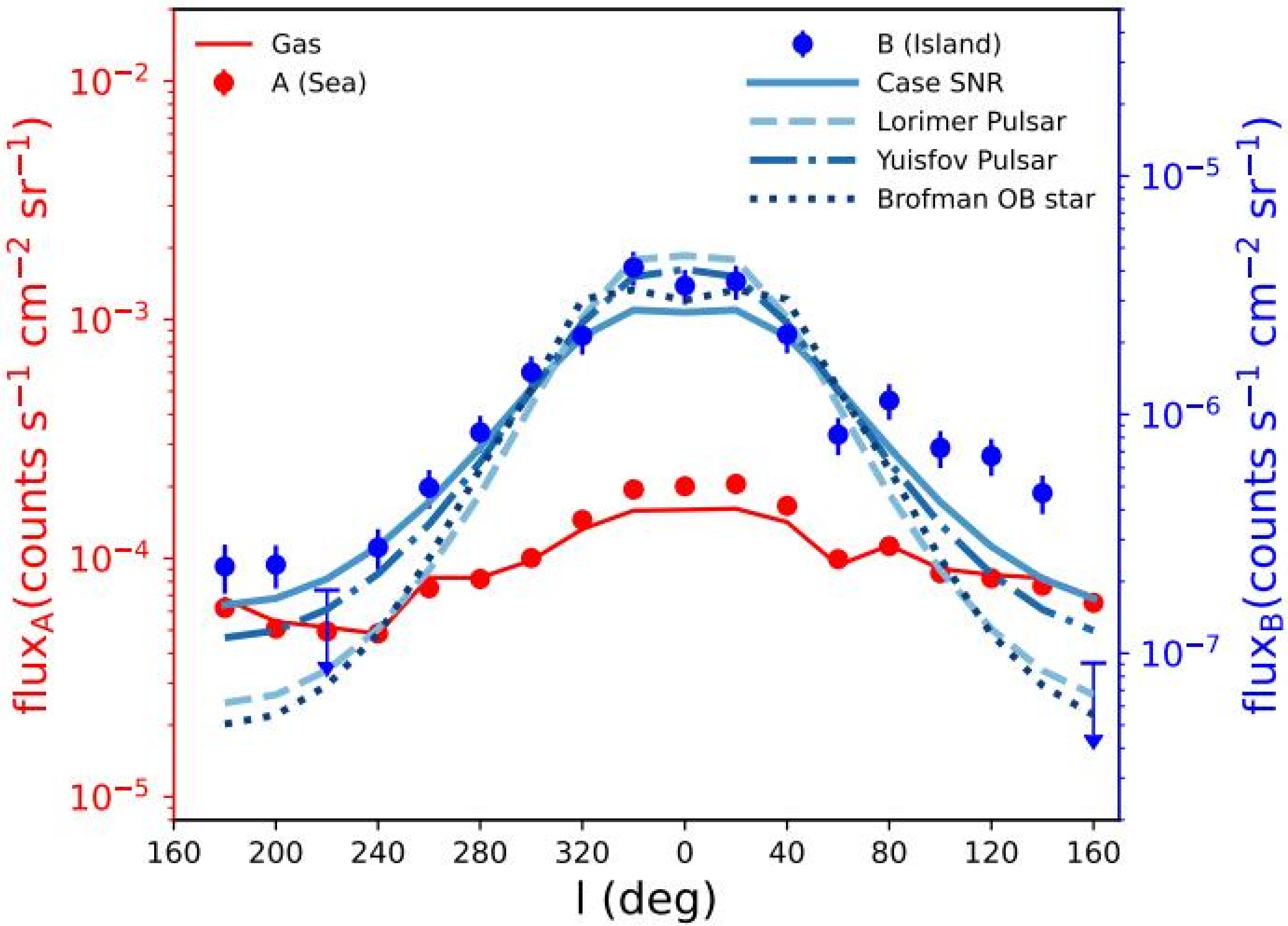
The low-energy spectra are consistent with prediction using locally observed proton spectrum

Two-component de-composition



See also Liu & Yang (2022, A&A) for the Galactic center region

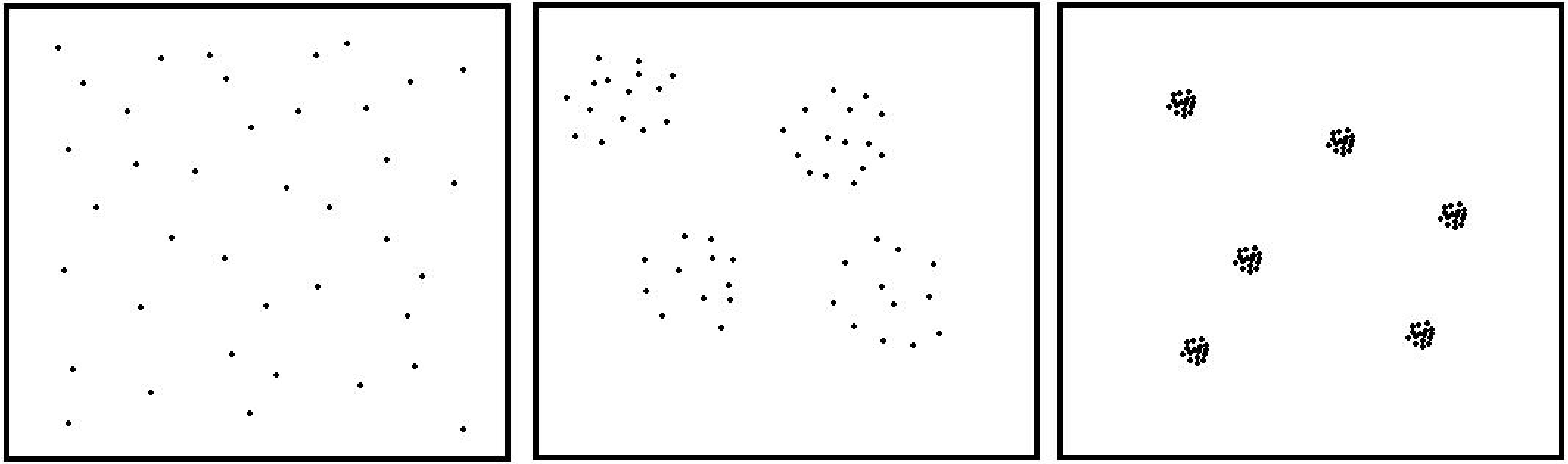
Two-component de-composition



- The A component (dominates in low energy) is consistent with gas distribution
- The B component (dominates at high energy) is correlated with potential source distribution

Implications on CR distribution and propagation

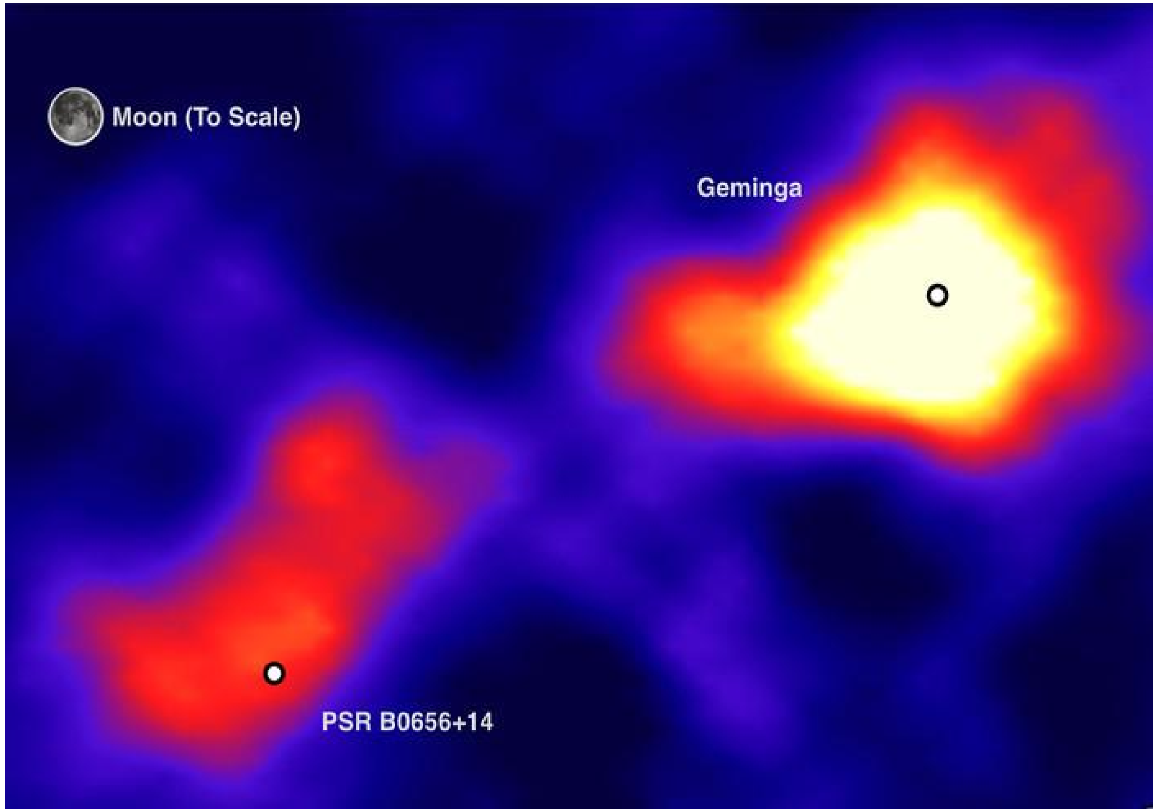
Truly diffuse (adequate prop.) | large extended source (non-adequate prop.) | pointlike sources (freshly accelerated)



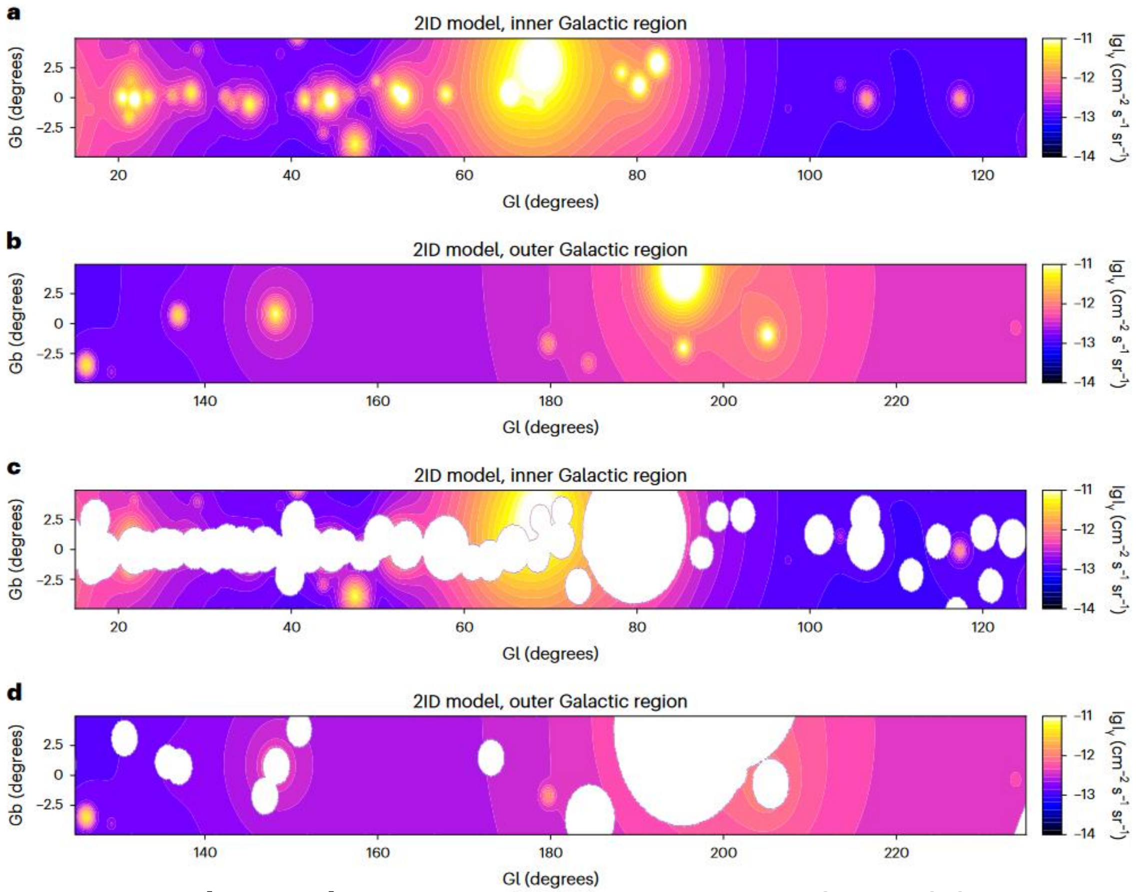
CR sea | **CR islands** (halos/bubbles)

Alternative scenario: pulsar halos

HAWC (2017, Science)



Extended halos around middle-aged pulsars are expected to be common in Milky Way, which could form a diffuse component of gamma-ray background (e.g., Aharonian & Atoyan 2000; Linden & Buckman 2018).

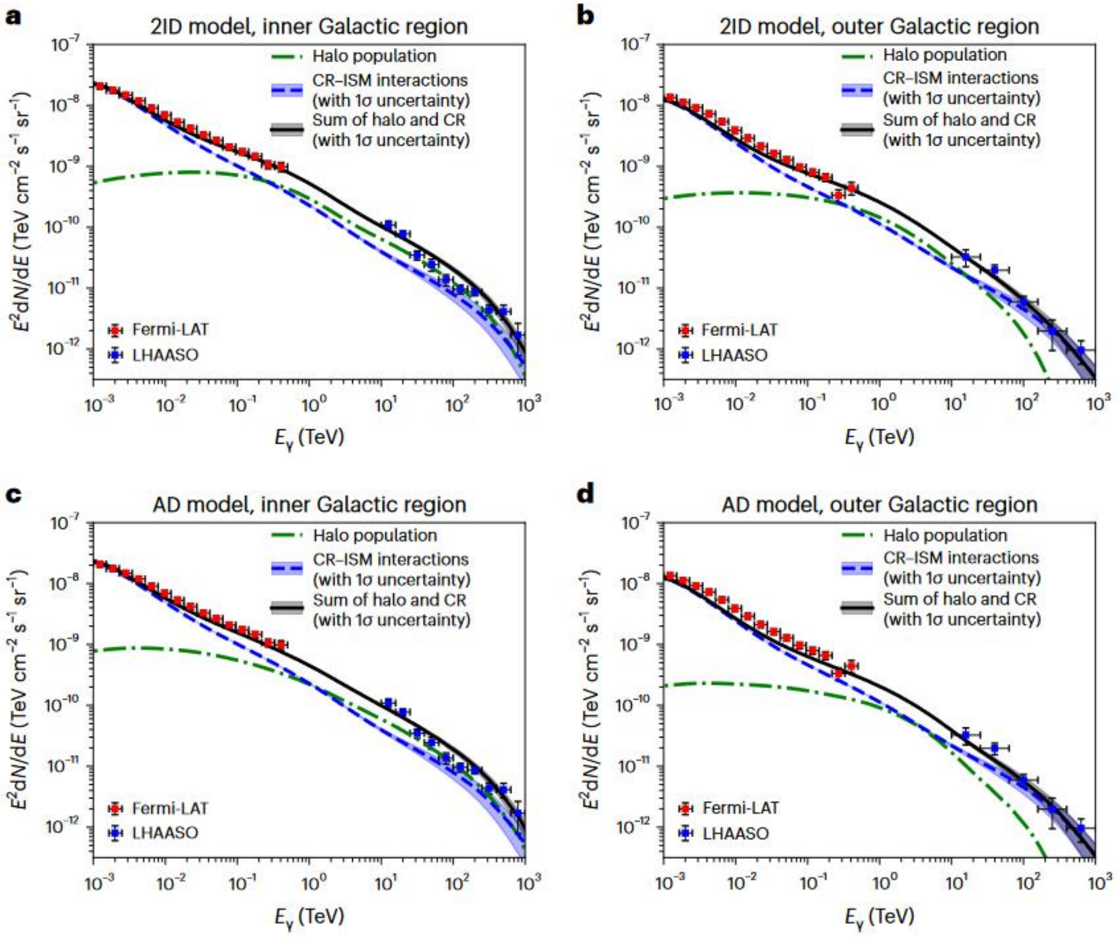


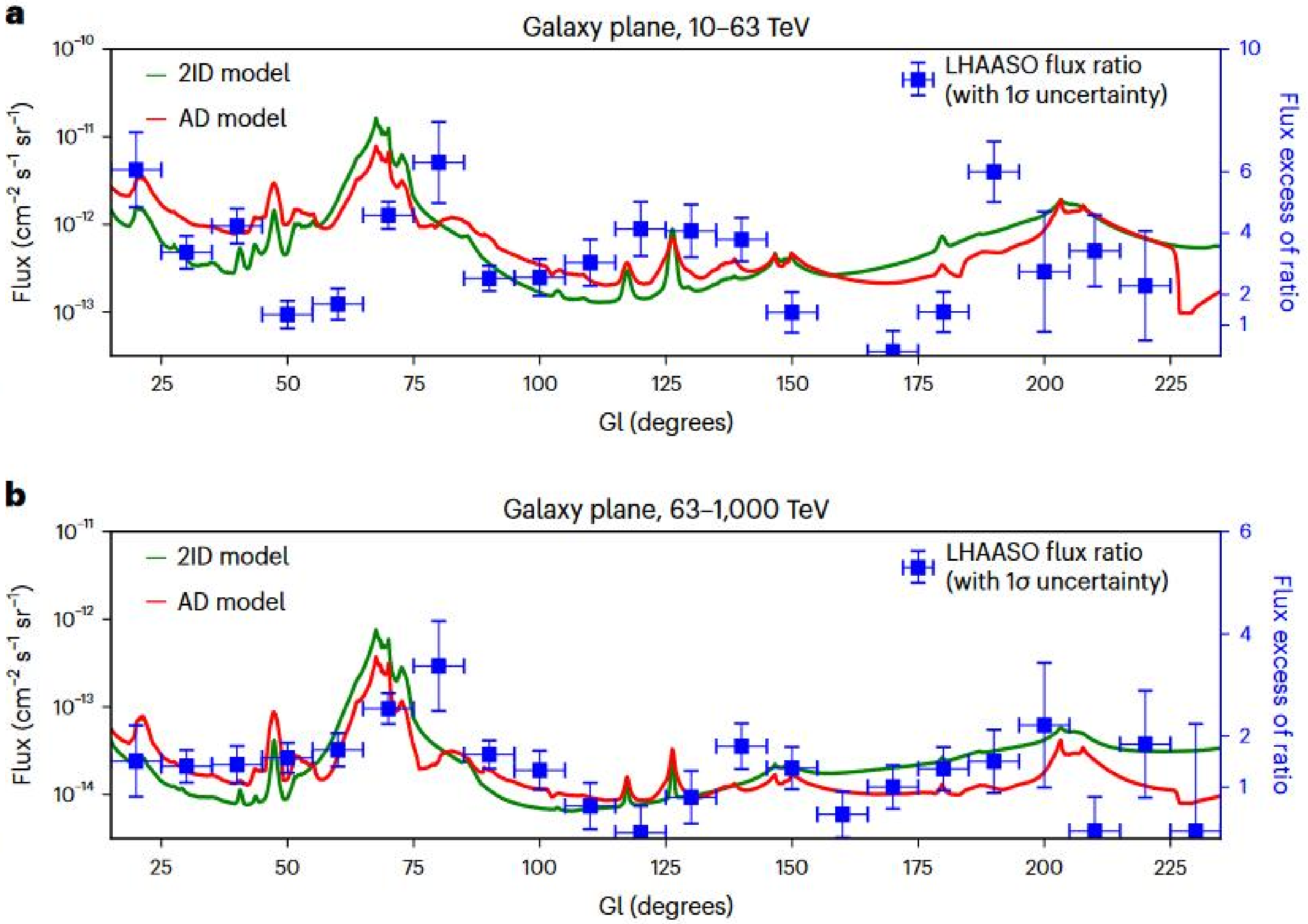
Predicted gamma-ray map in 25–100 TeV from halos of ATNF pulsars

K. Yan et al. (2024, Nat. Astron.)

See also Dekker + (2024, PRD), Chen + (2024, CPC)

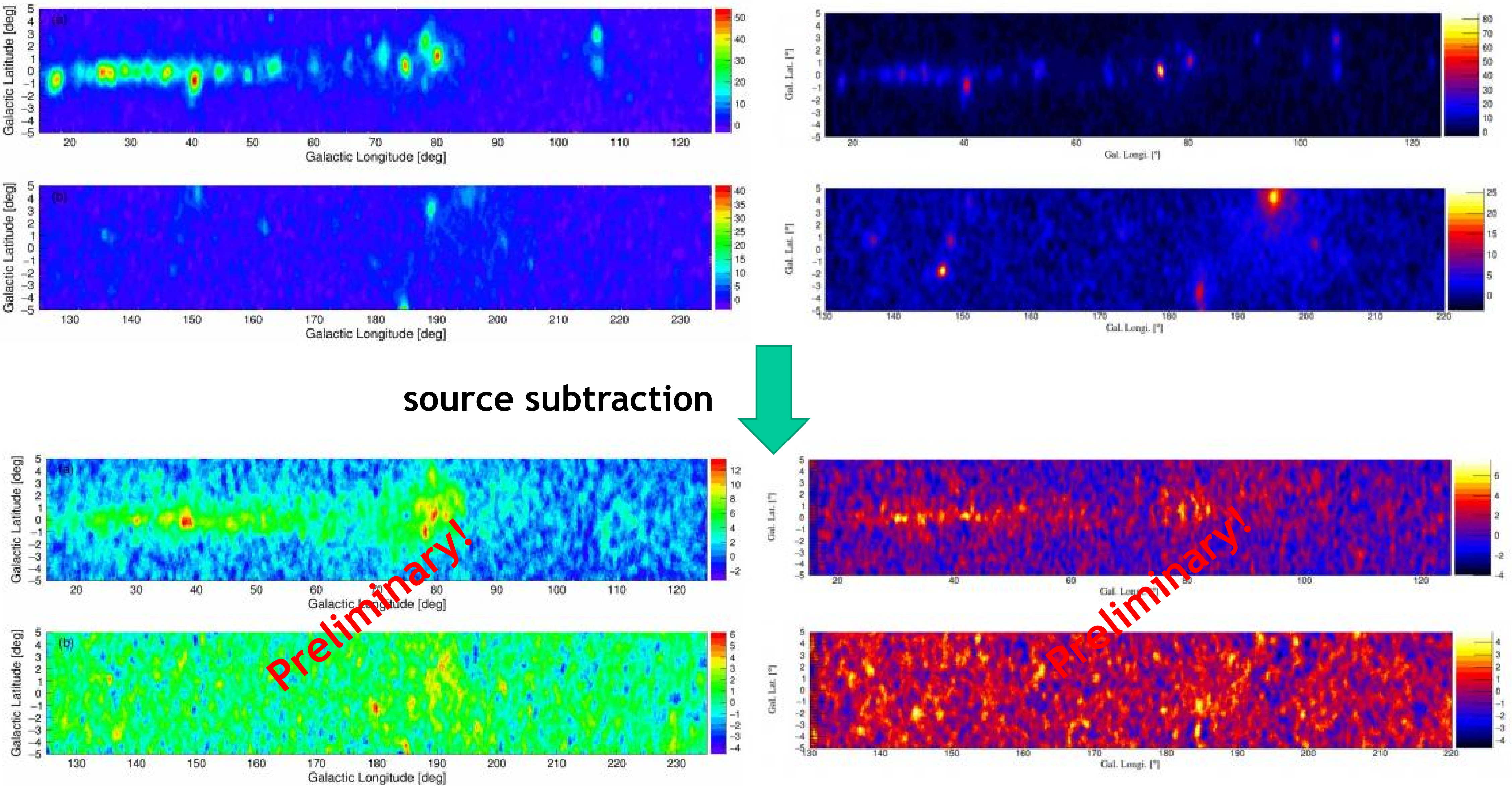
Alternative scenario: pulsar halos





K. Yan et al. (2024, Nat. Astron.)

Next step: improved analysis is on-going



Summary

- **Observational facts:**
  - ✓ Wide-band diffuse emission has been detected (TeV-PeV by LHAASO; sub-GeV-TeV by Fermi)
  - ✓ A break around 30 TeV has been shown in the inner Galaxy region
  - ✓ Longitude distribution deviates from gas profile
  - ✓ Spectral variations across the Galactic plane (Fermi; hint by LHAASO)
- **Confronting data with canonical prediction:**
  - ✓ Excesses of data from several GeV to tens of TeV
  - ✓ Spectral shapes deviate from prediction based on local CR spectra
- **Possible implication:**
  - ✓ A low-surface-brightness, unresolved component may exist in the data
  - ✓ Likely due to confined CRs with inefficient propagation time (CR islands)
  - ✓ Leptonic contribution (e.g., pulsar halos) may also be possible

Thank you!