Measurements and implications of ultra-high energy diffuse γ-ray emission from the Galactic plane

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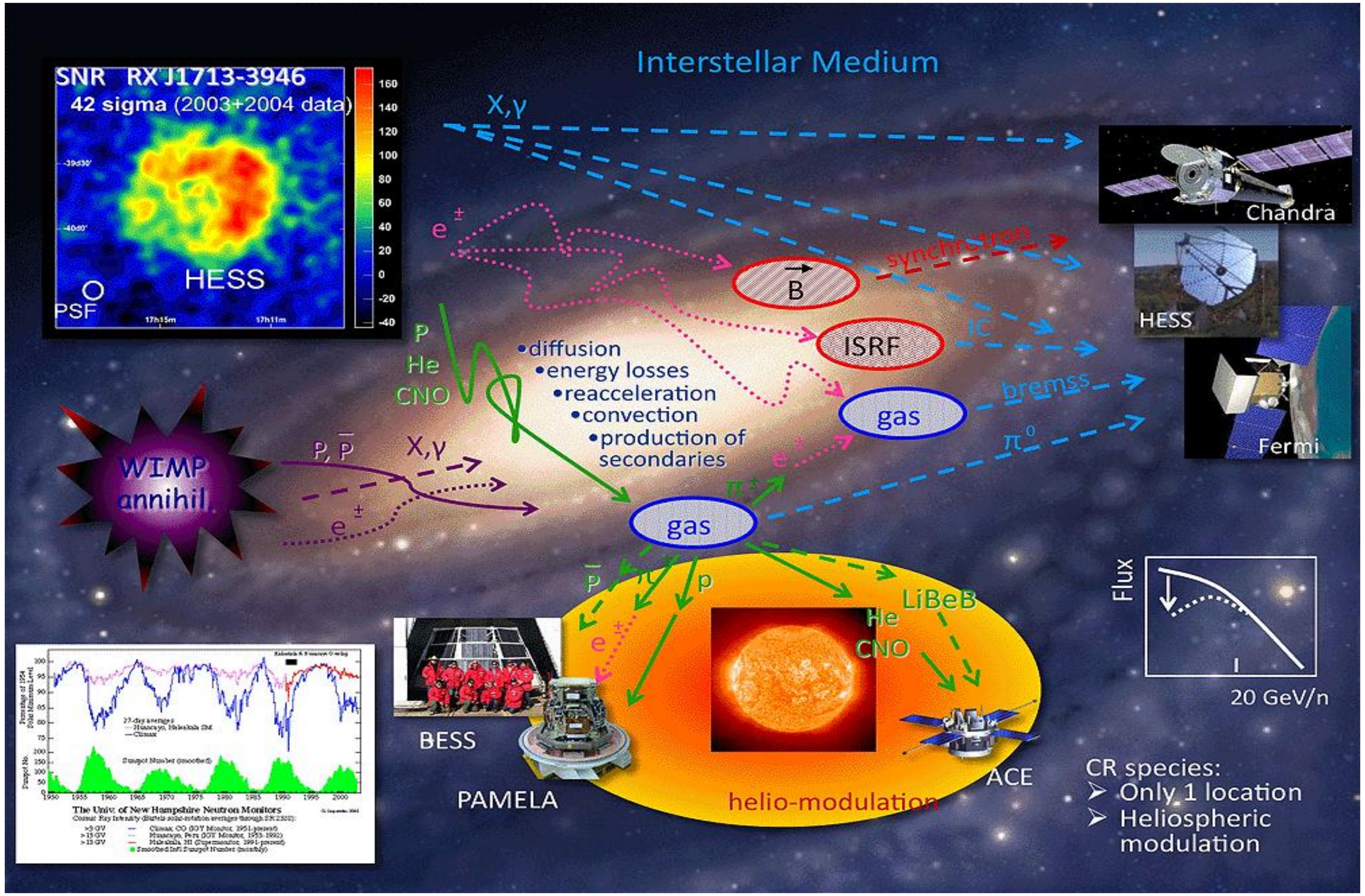
CDY seminar, April 3, 2024

General picture of Galactic cosmic rays



Acceleration at source

↓

Diffusion and Interaction

↓

Helio-sphere propagation

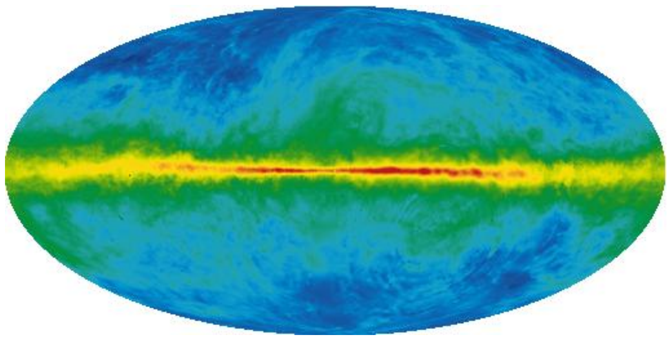
↓

Detection at the Earth

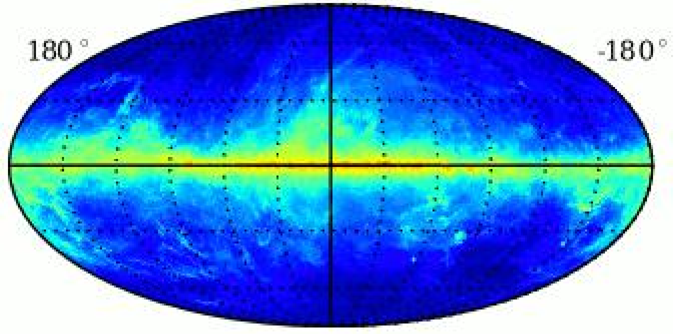
Diffuse γ rays are expected *a priori* to be produced by CR interactions during the propagation, and are thus powerful probe of CR propagation

Origins of Galactic diffuse γ rays

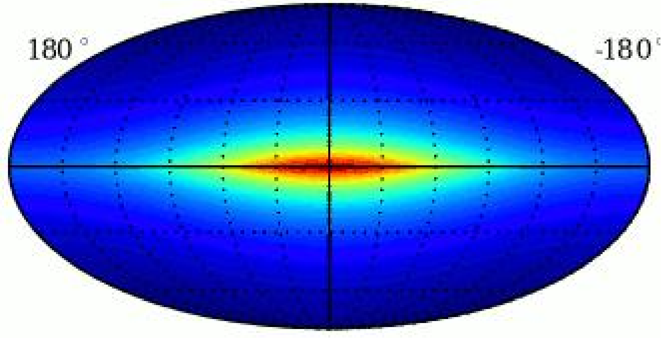
$p,\alpha + ISM \rightarrow \pi^0 \rightarrow 2\gamma$



$e + ISM \rightarrow \gamma$ (bremsstrahlung)

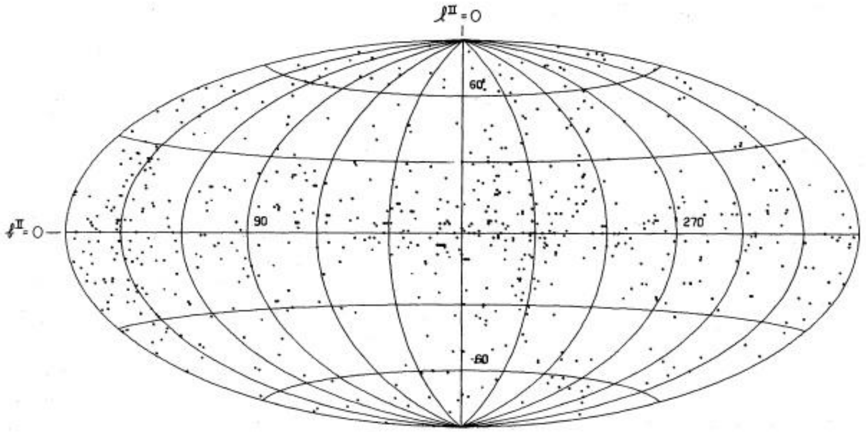


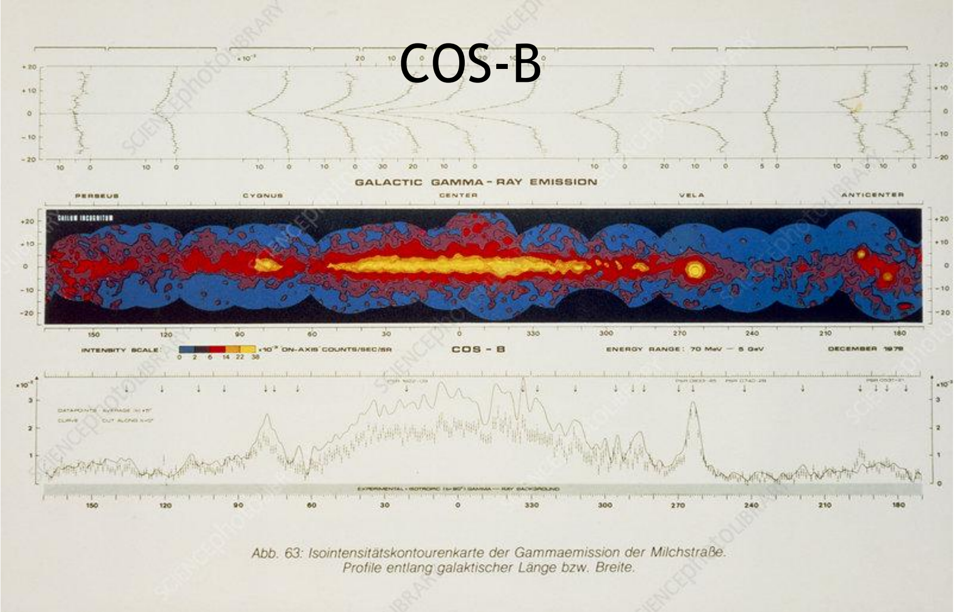
$e + ISRF \rightarrow \gamma$ (inverse Compton)

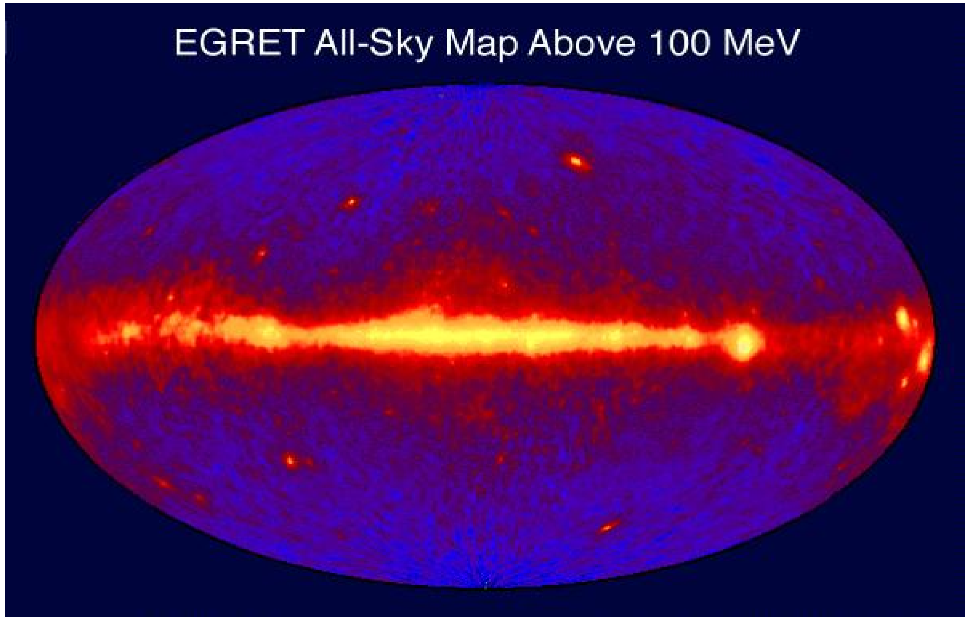


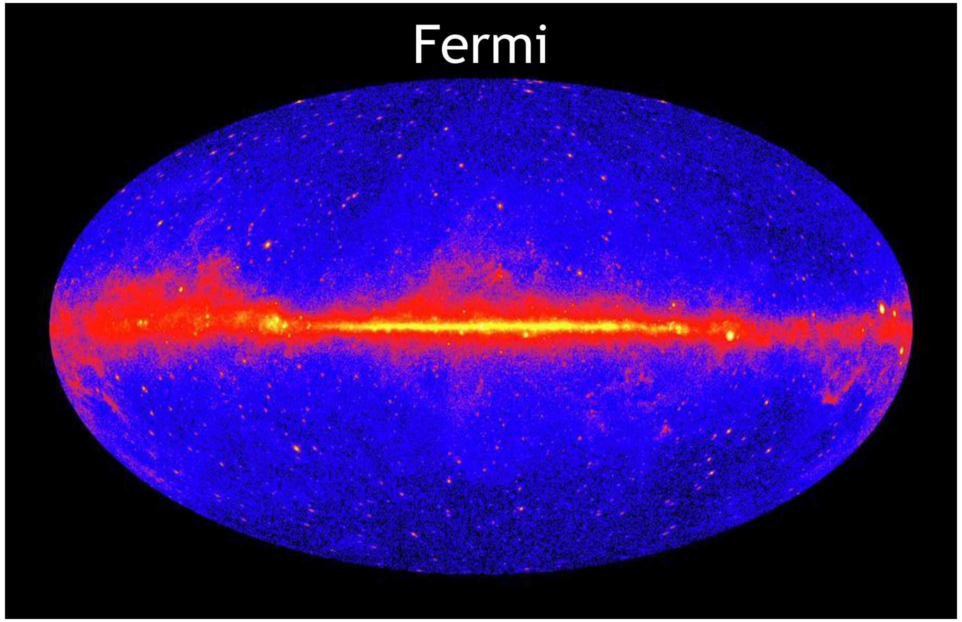
Diffuse γ-ray observations from space

OSO-3: 621 gamma-rays







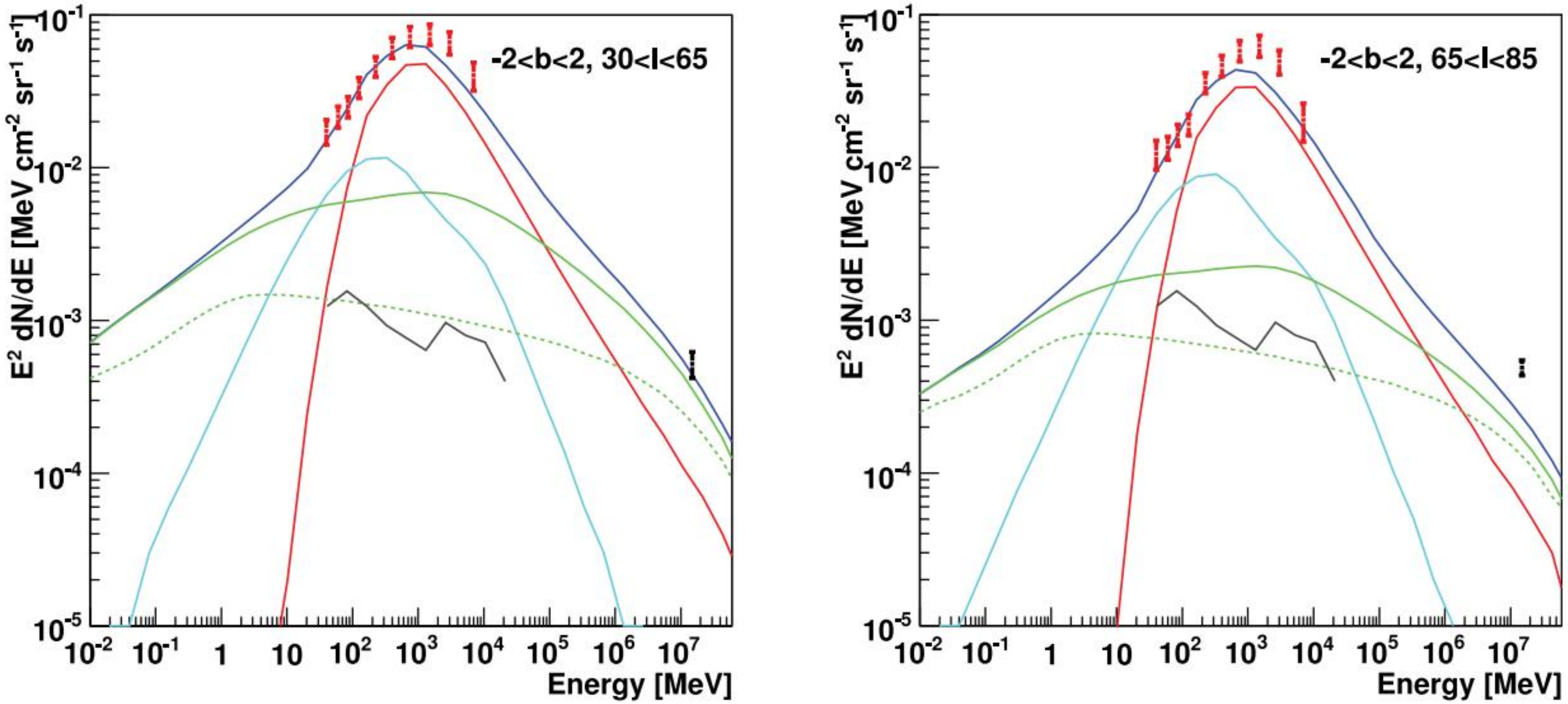


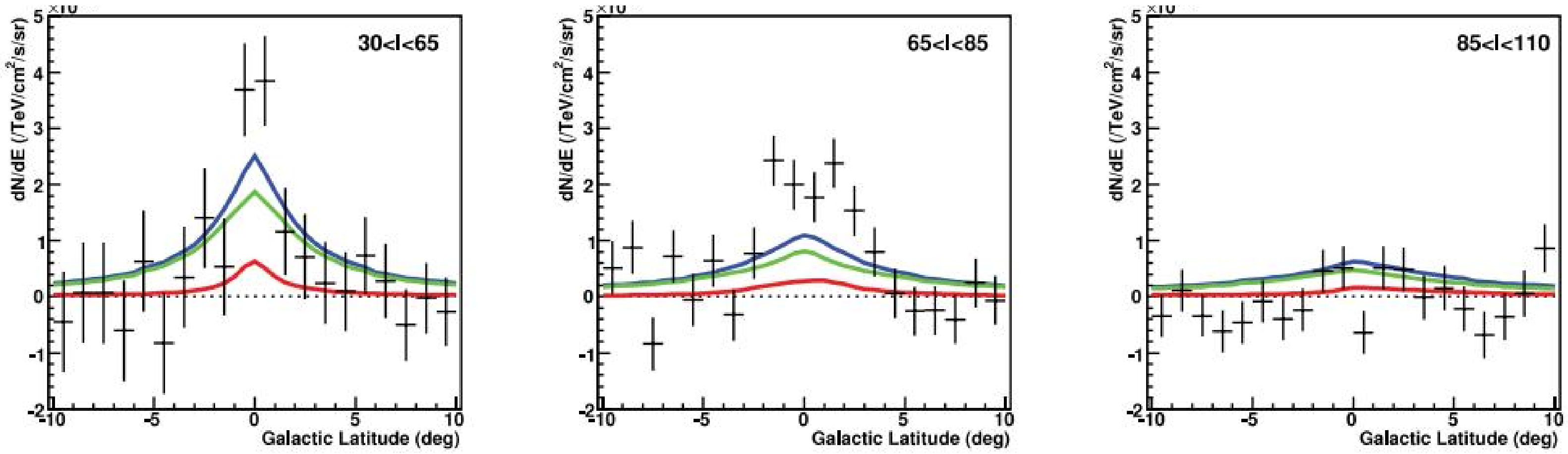
VHE diffuse emission by Milagro

- Milagro measured diffuse emission in the Galactic plane around ~10 TeV

- Found excesses in the Cygnus region

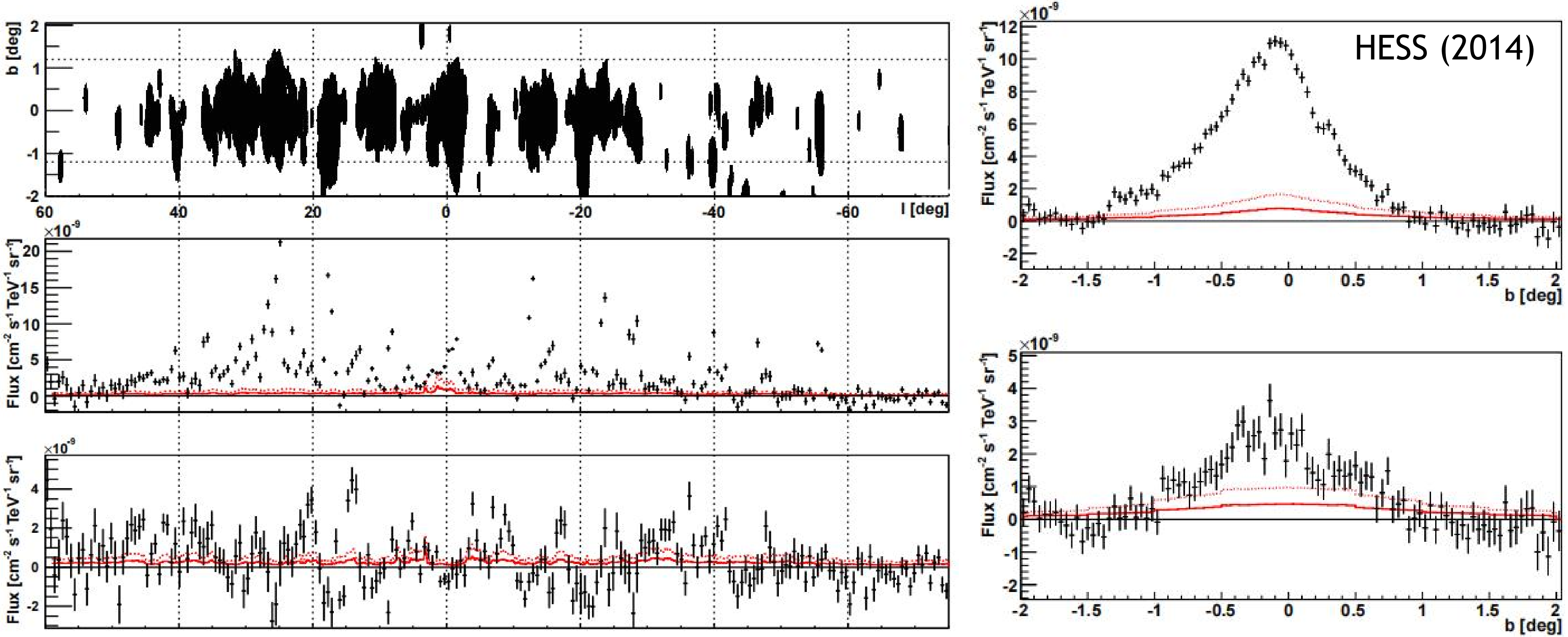
- Source subtraction of Milagro is very limited





Milagro (2008)

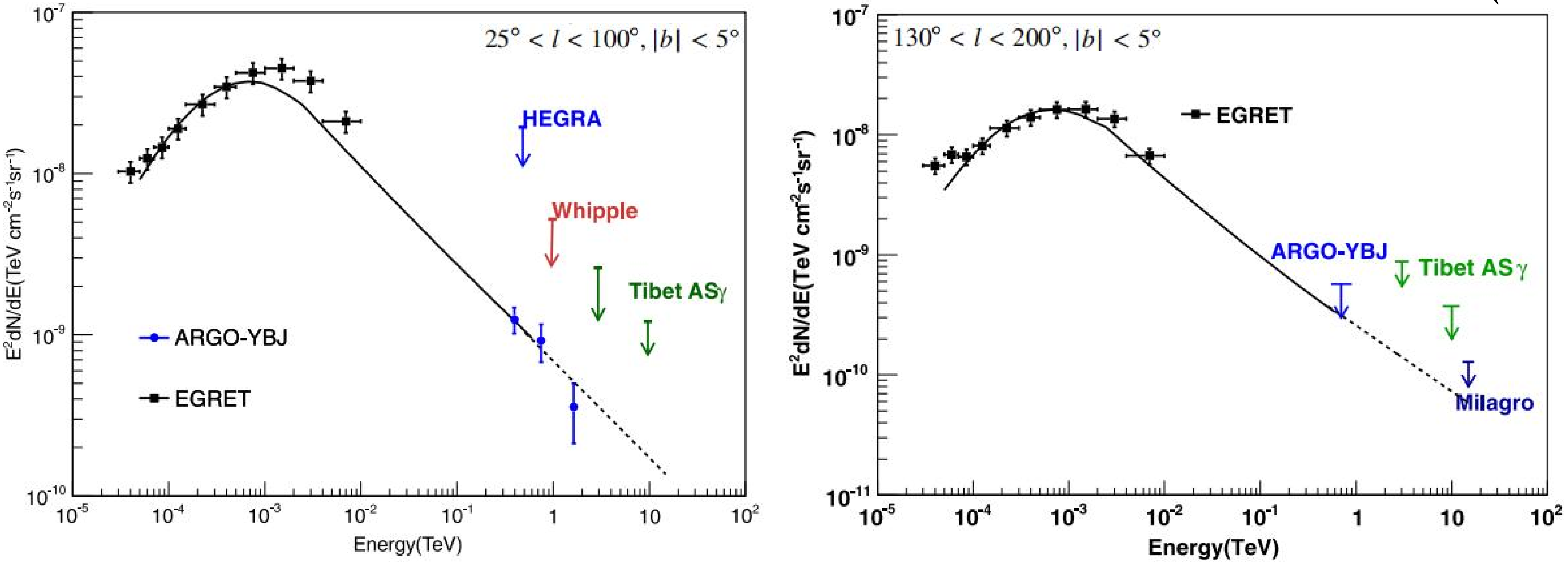
VHE diffuse emission by HESS



ray flux measurements were made over an extensive grid of celestial locations. Longitudinal and latitudinal profiles of the observed γ-ray fluxes show characteristic excess emission not attributable to known γ-ray sources. For the first time large-scale γ-ray emission along the

VHE diffuse emission by ARGO-YBJ

ARGO-YBJ (2015)



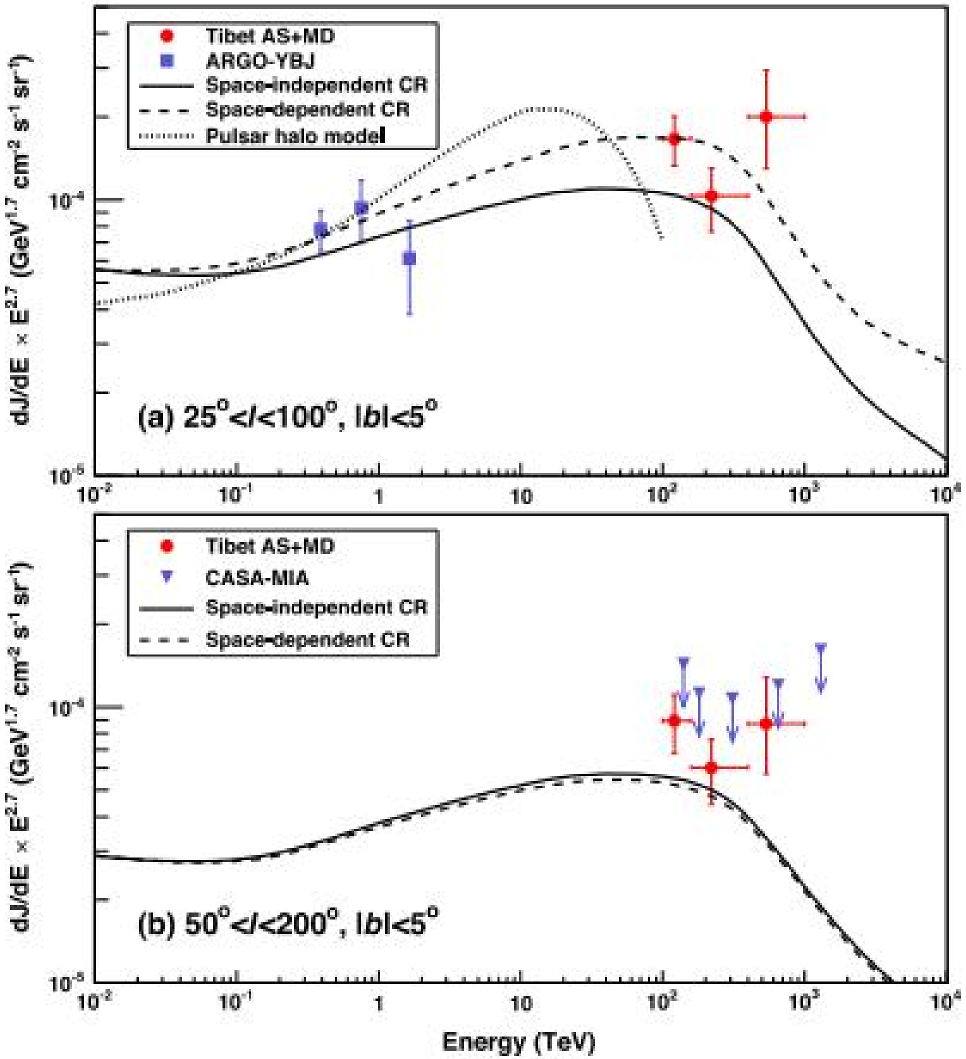
ARGO-YBJ measured diffuse emission from the inner Galaxy region, which is consistent with the extrapolation of Fermi-tuned model prediction

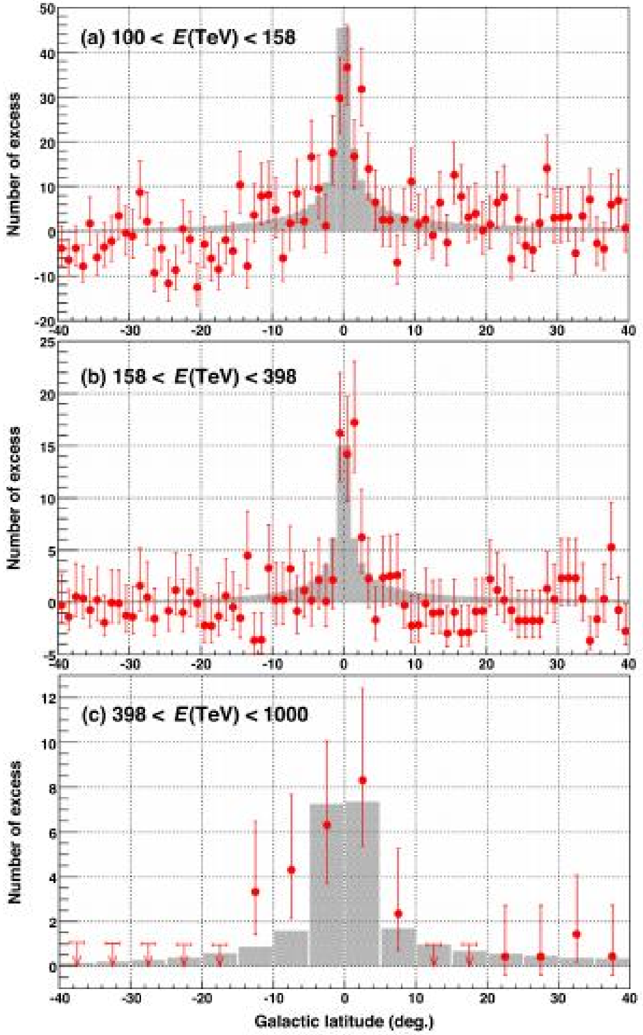
UHE diffuse measurements by Tibet-ASγ

- Tibet-ASγ measured diffuse emission above 100 TeV, and found excess compared with the conventional model prediction

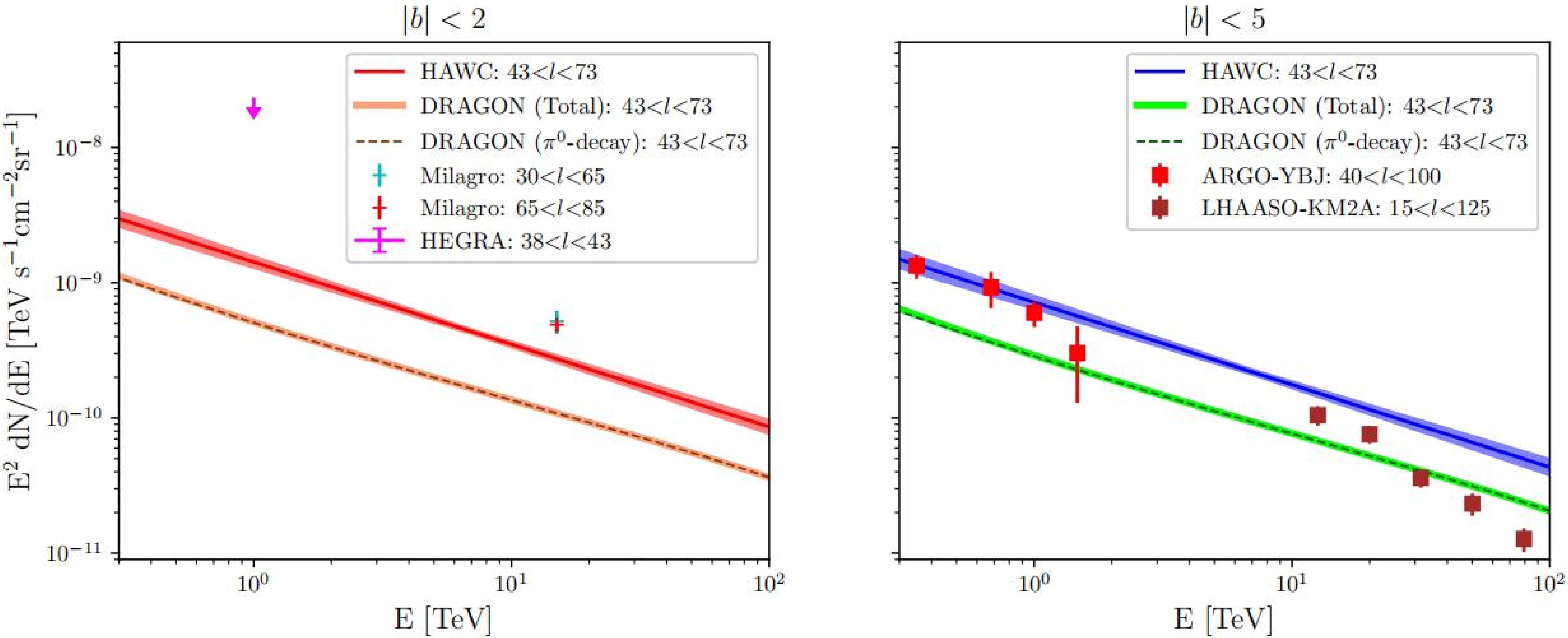
- Source subtraction radius is 0.5 degree

Tibet-ASγ (2021)





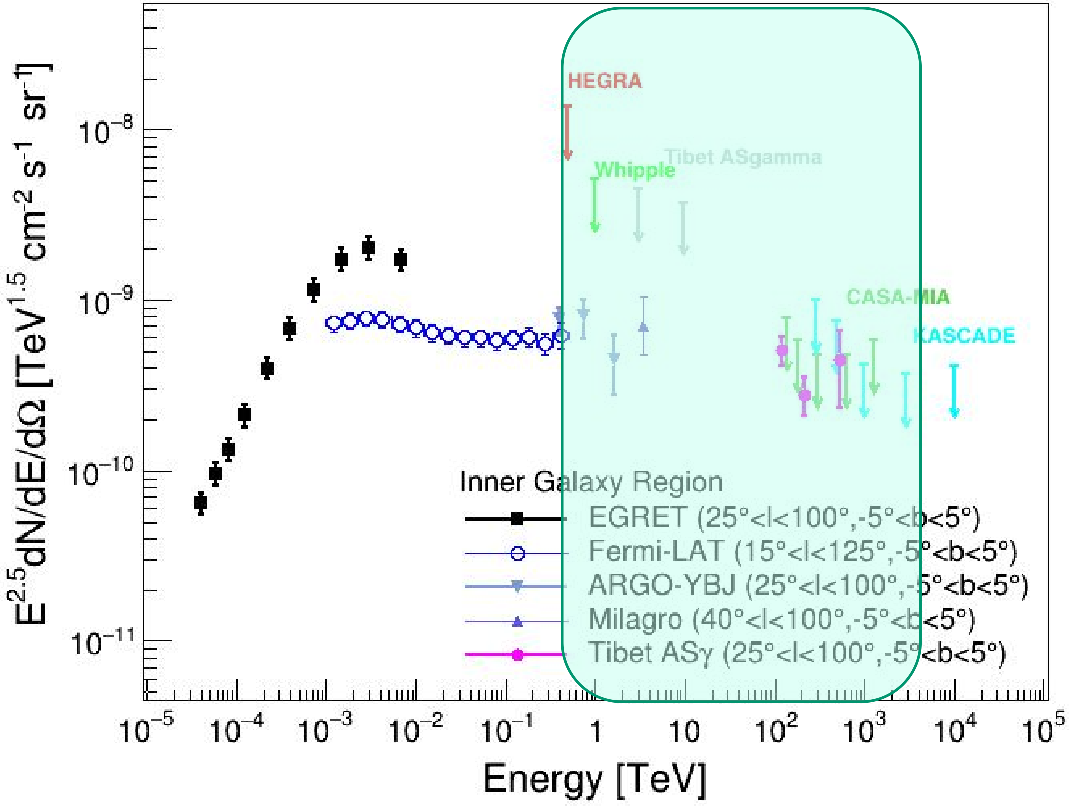
VHE diffuse emission by HAWC

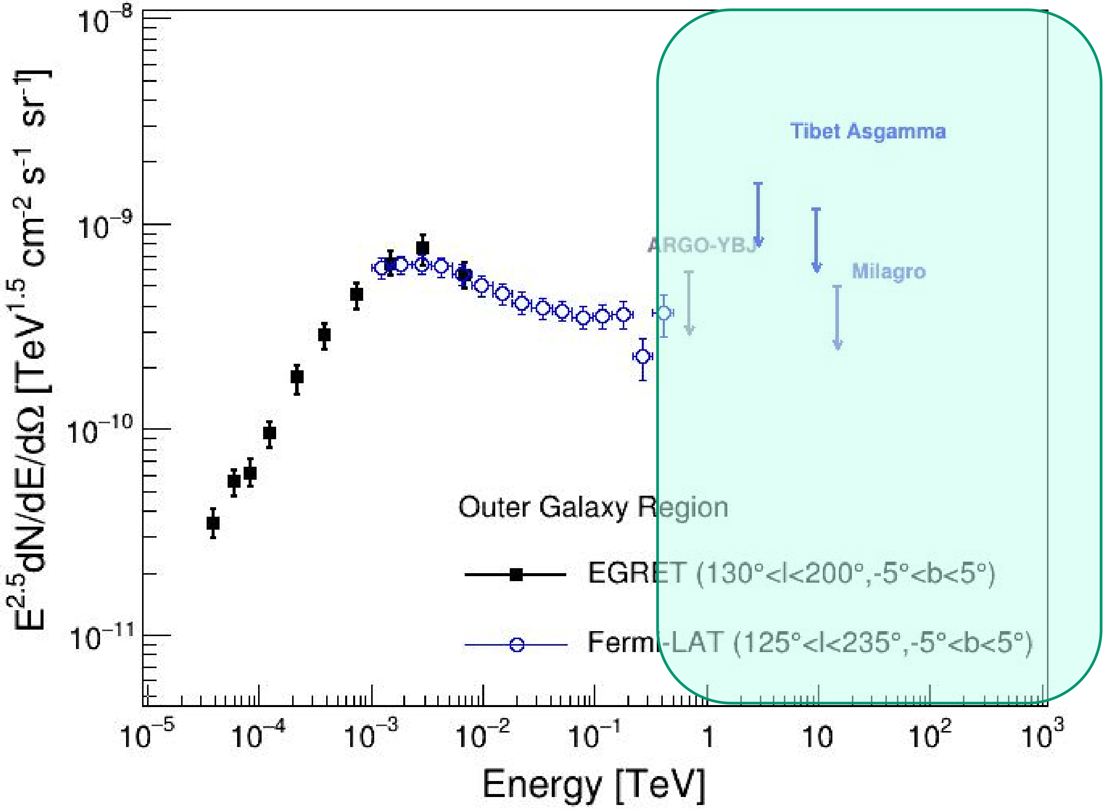


spectrum is compatible with the spectrum of the emission arising from a CR population with an *index* similar to that of the observed CRs. When comparing with the DRAGON *base model*, the HAWC GDE flux is higher by about a factor of 2. Unresolved sources such as pulsar wind nebulae and teraelectronvolt halos could explain the excess

HAWC 2024, ApJ, 961, 104

Wide-band diffuse emission measurements



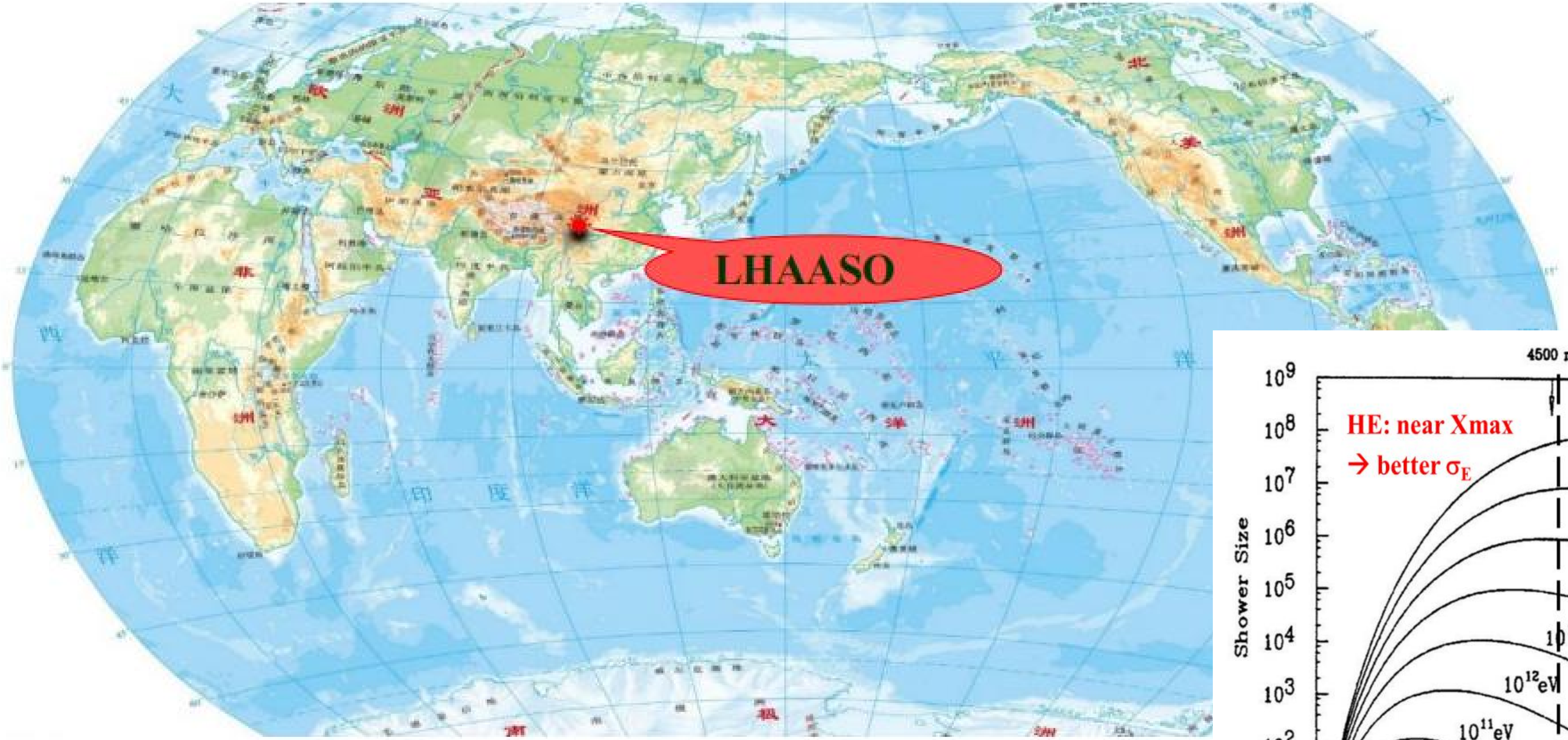


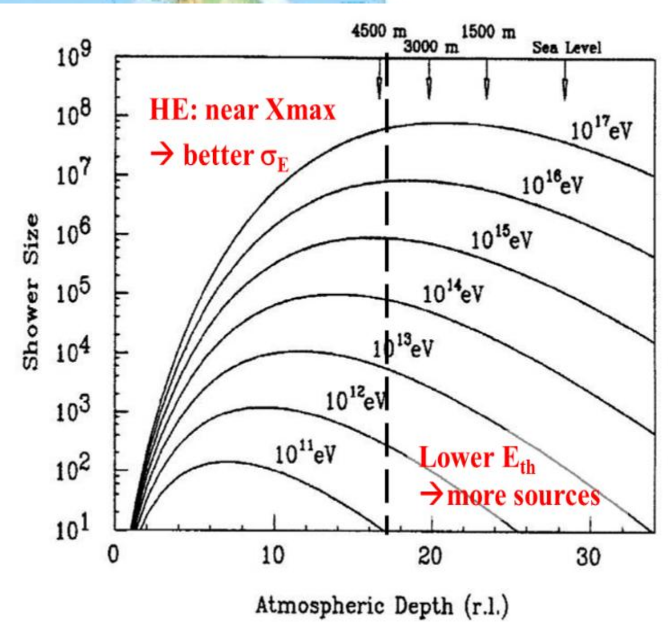
Upper limits:

HEGRA (99% C.L., 38° < l < 43°, |b| < 2°),
Whipple (99.9% C.L., 38.5° < l < 41.5°, |b| < 2°)
Tibet ASγ (99%C.L., 20° < l < 55°, |b| < 2°)
CASA-MIA (90%.C.L., 50° < l < 200°, |b| < 5°)

ARGO-YBJ（99% C.L., 130°< l < 200°, |b| < 5°）
Milagro (95%C.L., 136° < l < 216°, |b| < 2°)
Tibet ASγ (99% C.L., 140° < l < 225°, |b| < 2°)

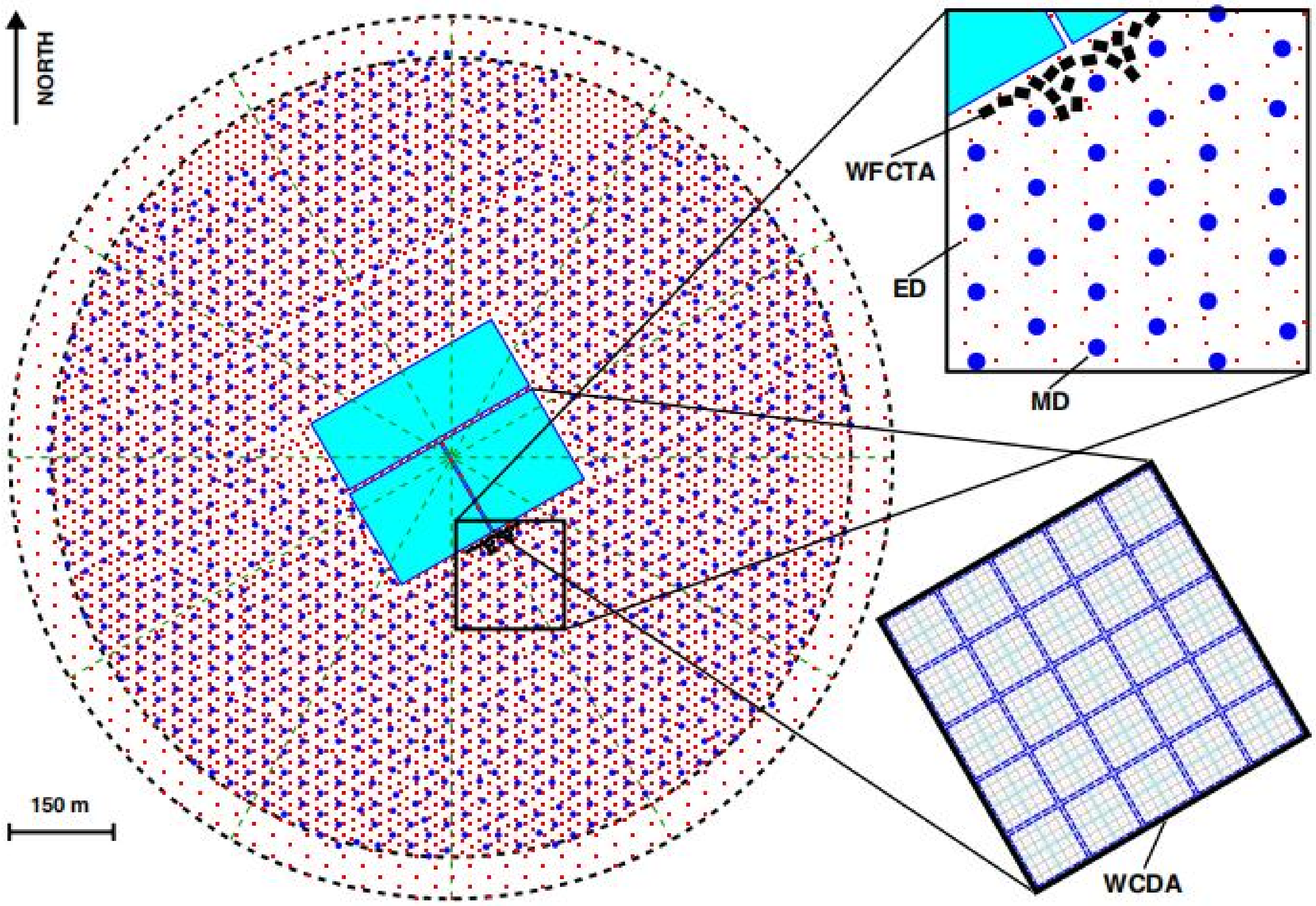
Large High Altitude Air Shower Observatory (LHAASO)





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

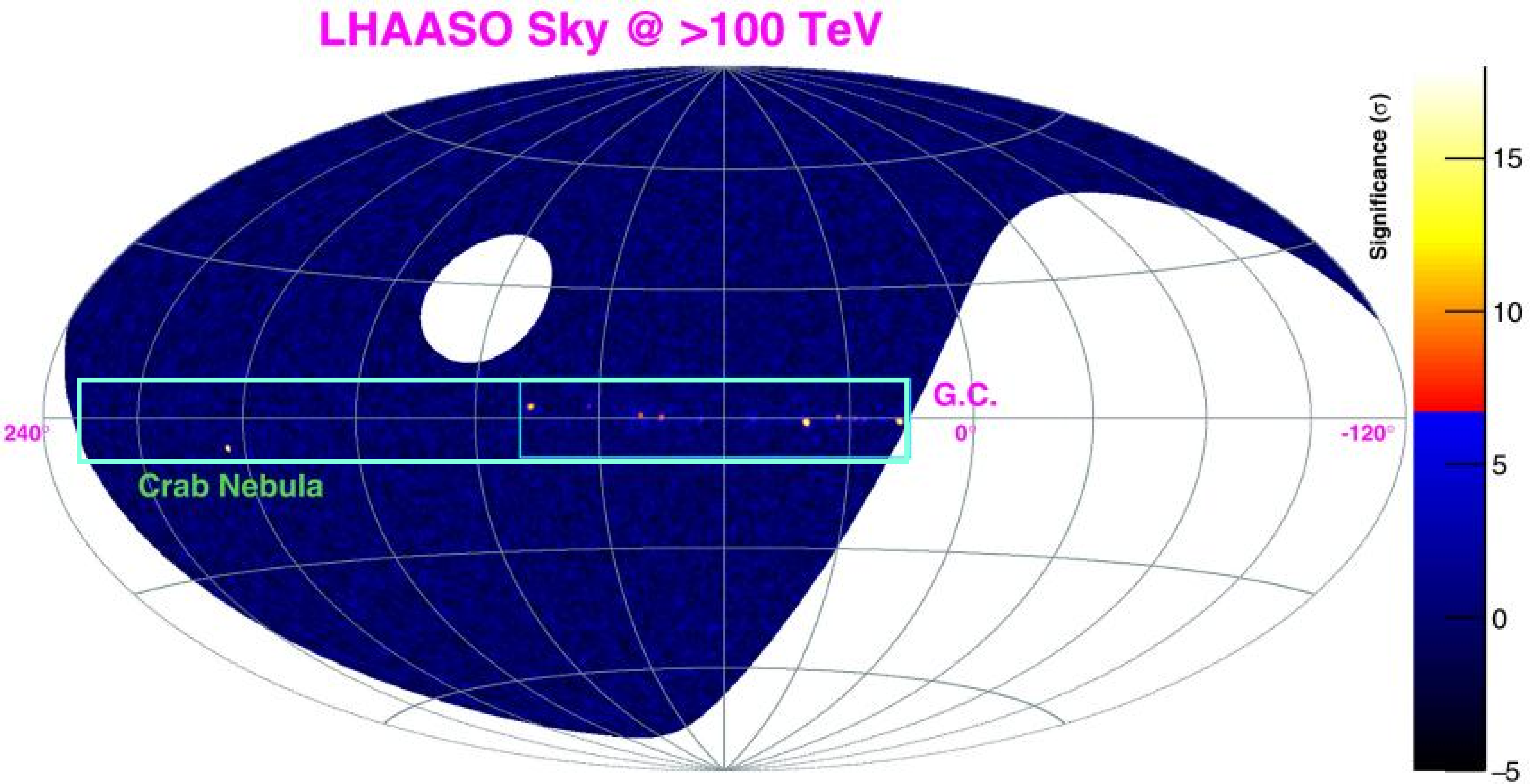
LHAASO detector layout



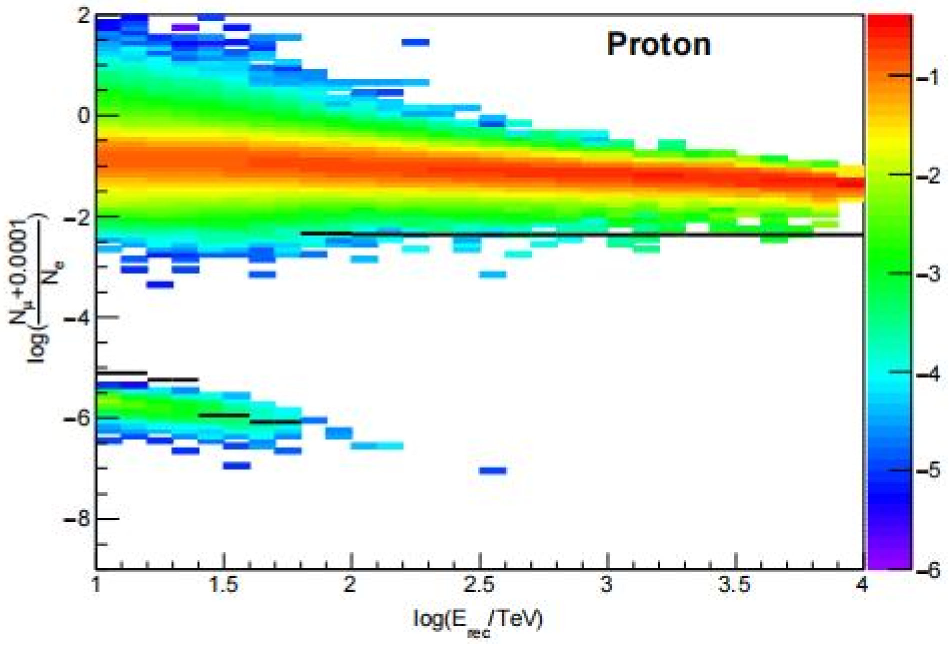
- 5195 EDs
  - 1 m^2 each
  - 15 m spacing
- 1188 MDs
  - 36 m^2 each
  - 30 m spacing
- 3120 WCDs
  - 25 m^2 each
- 18 WFCTs

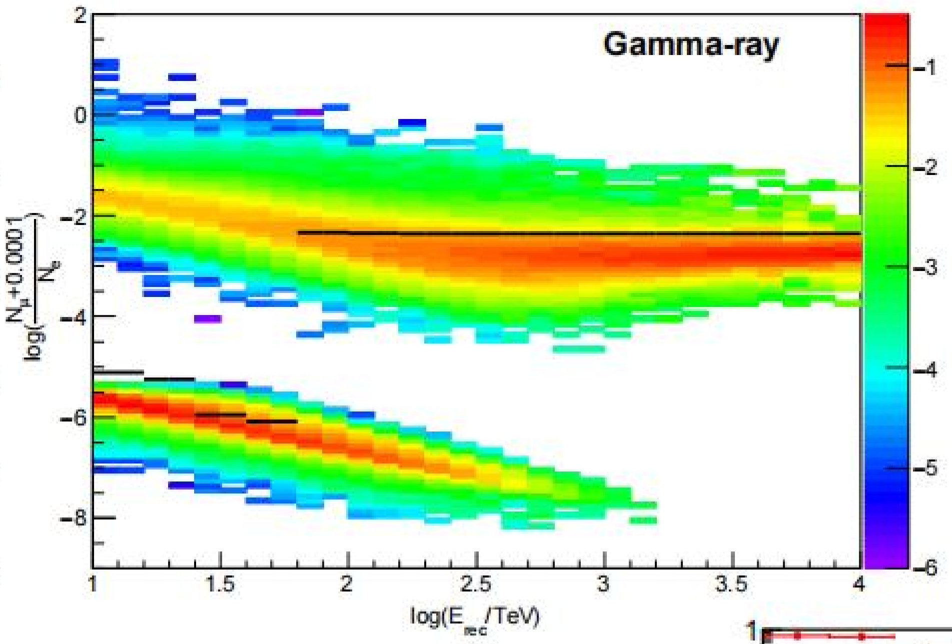
The large area and hybrid detection technique makes LHAASO a powerful facility for cosmic ray and gamma-ray observations in a wide energy range.

LHAASO sky coverage



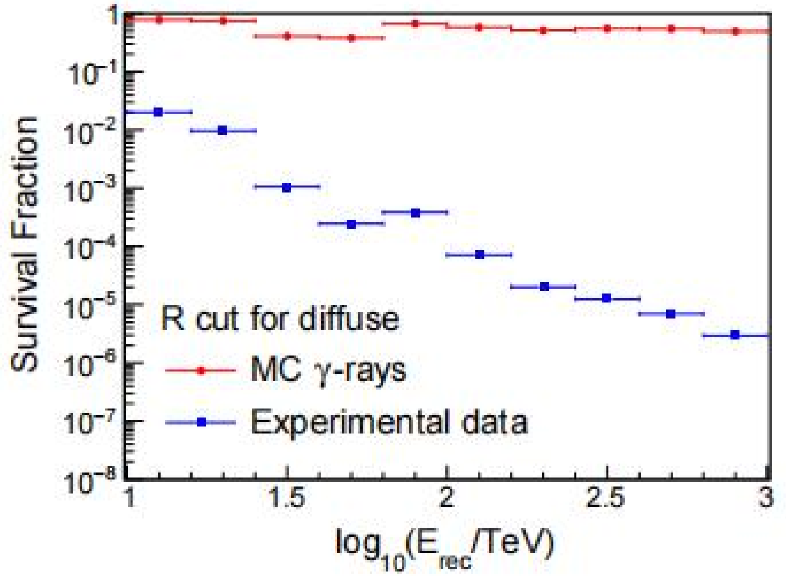
Gamma/CR discrimination



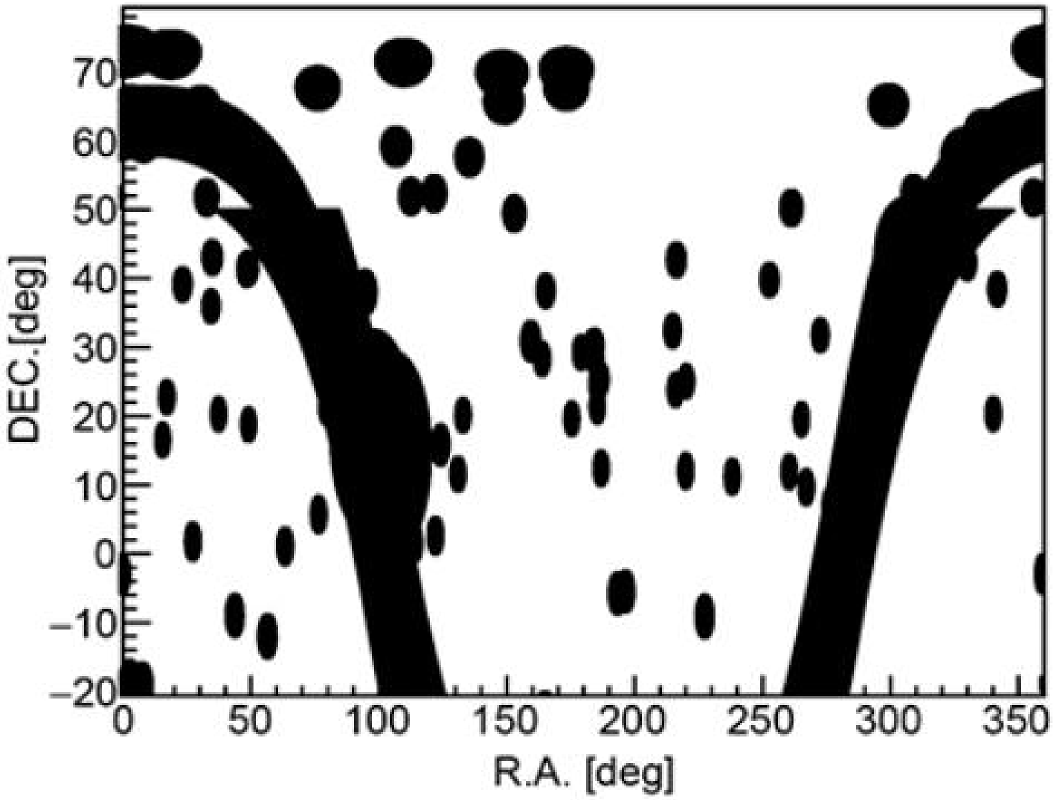


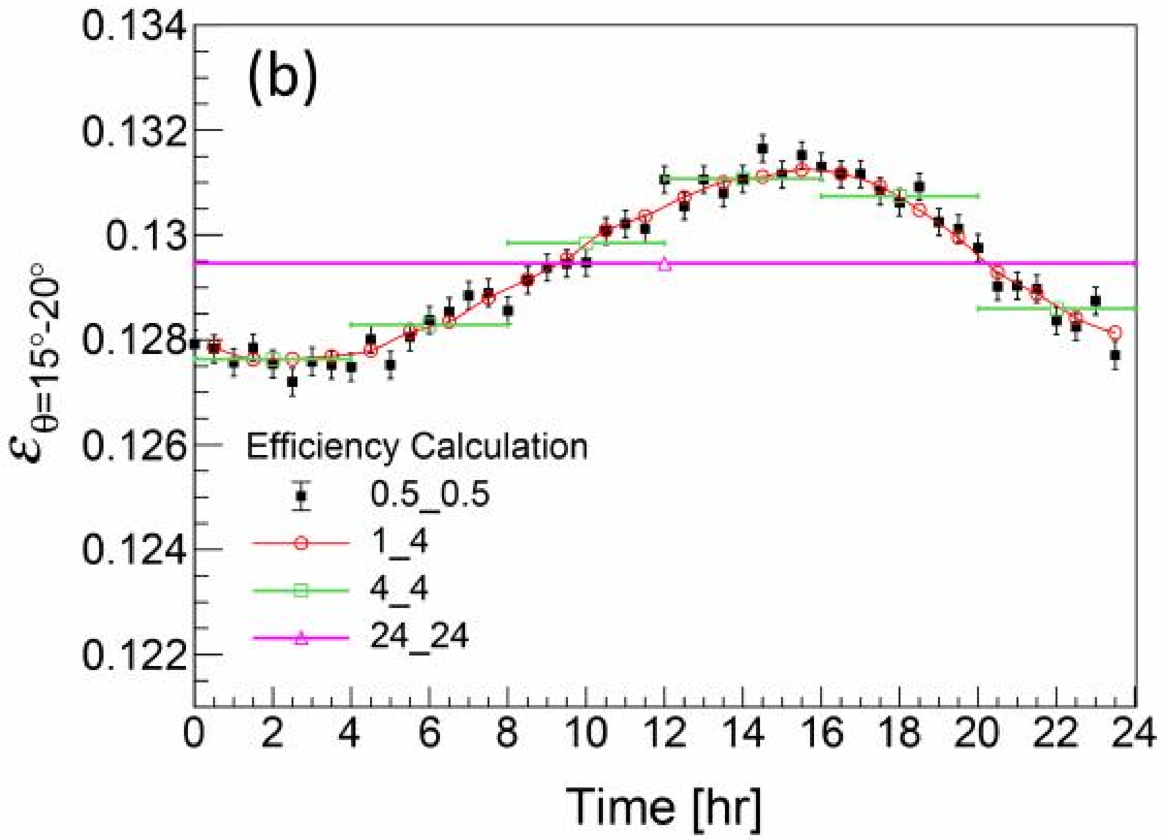
$$R = \log\left(\frac{N_\mu + 0.0001}{N_e}\right)$$

- ➢ Optimize R cuts from the standard point source analysis to enable a higher $Q=S/B^{1/2}$ factor
- ➢ Efficiencies change from ~90% to ~60%



Background estimate





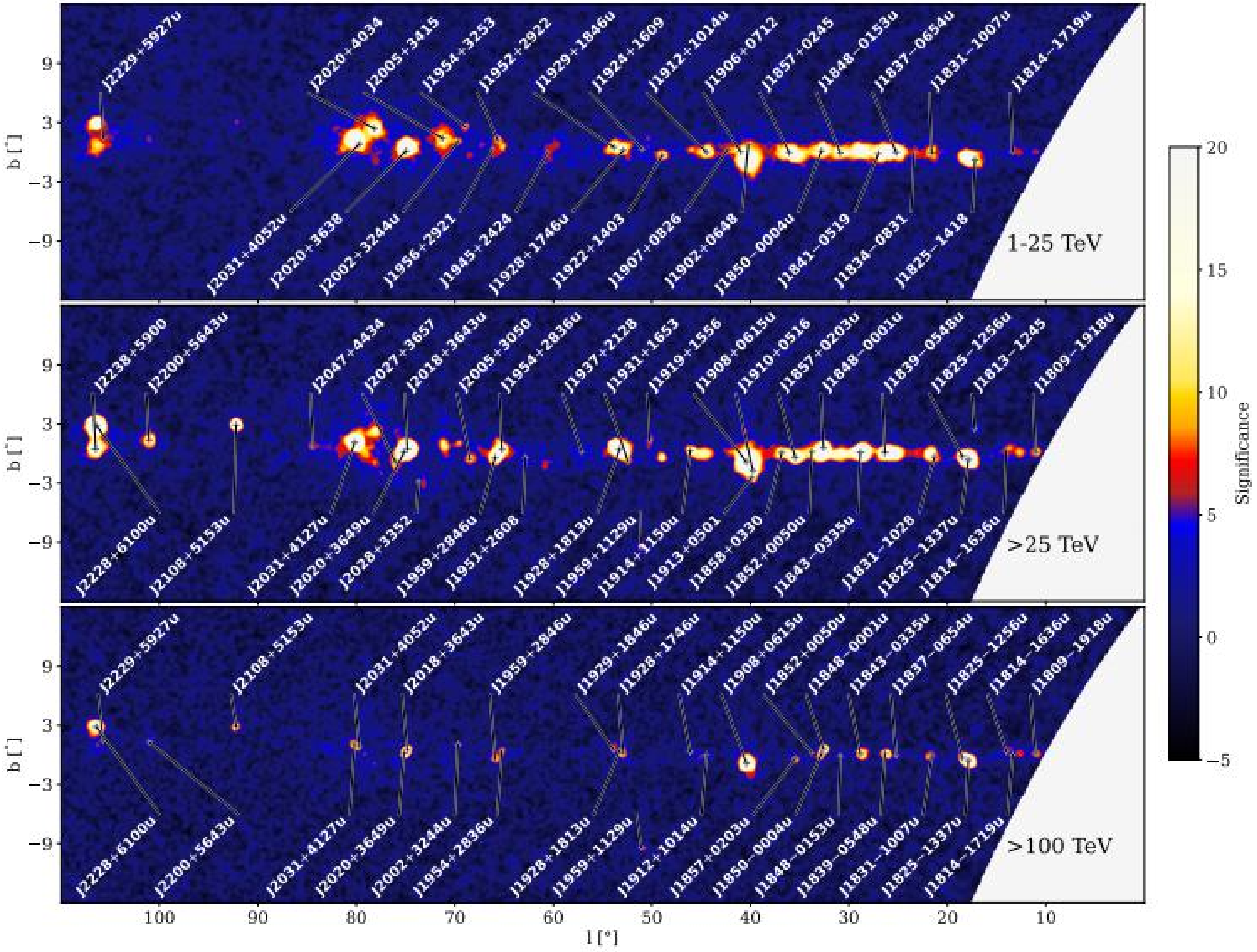
- Direct integral method: assuming the spatial distribution in detector coordinate is stable in a reasonably short time bin
- Efficiencies do vary slightly with time, and thus a sliding window method is adopted (1_10 is used as benchmark, 1 hr step and +/-5 hr window)

Resolved source mask

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

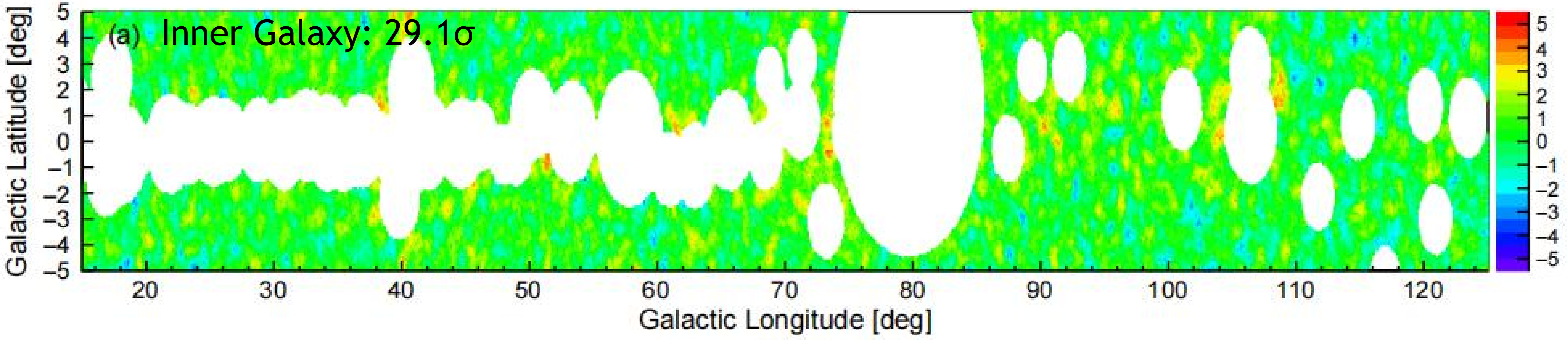
- n=2.5 is chosen
- PSF of the lowest energy bin is used

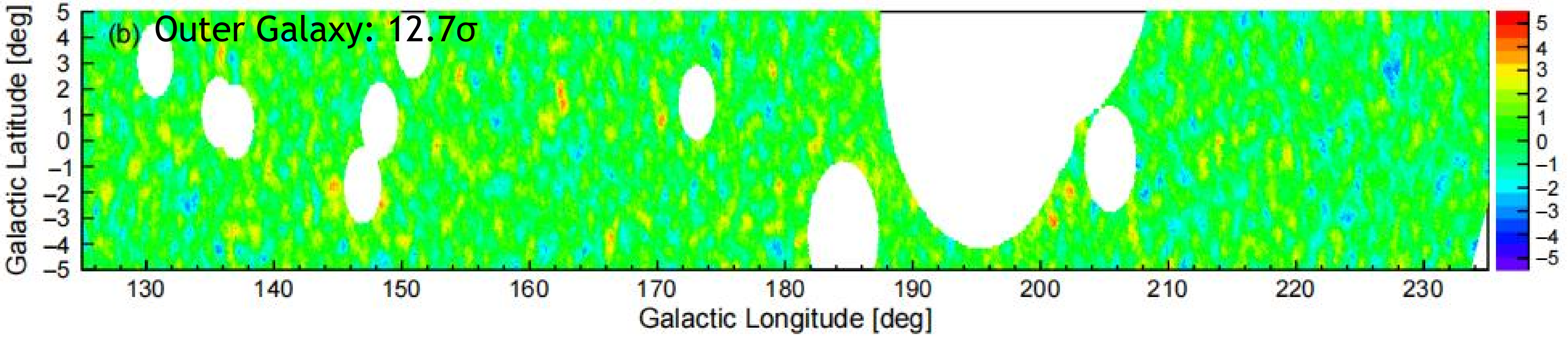
- Source catalogs: KM2A catalog + TeVCat
- For overlapping sources, KM2A parameters are used



LHAASO first catalog (2024, ApJS)

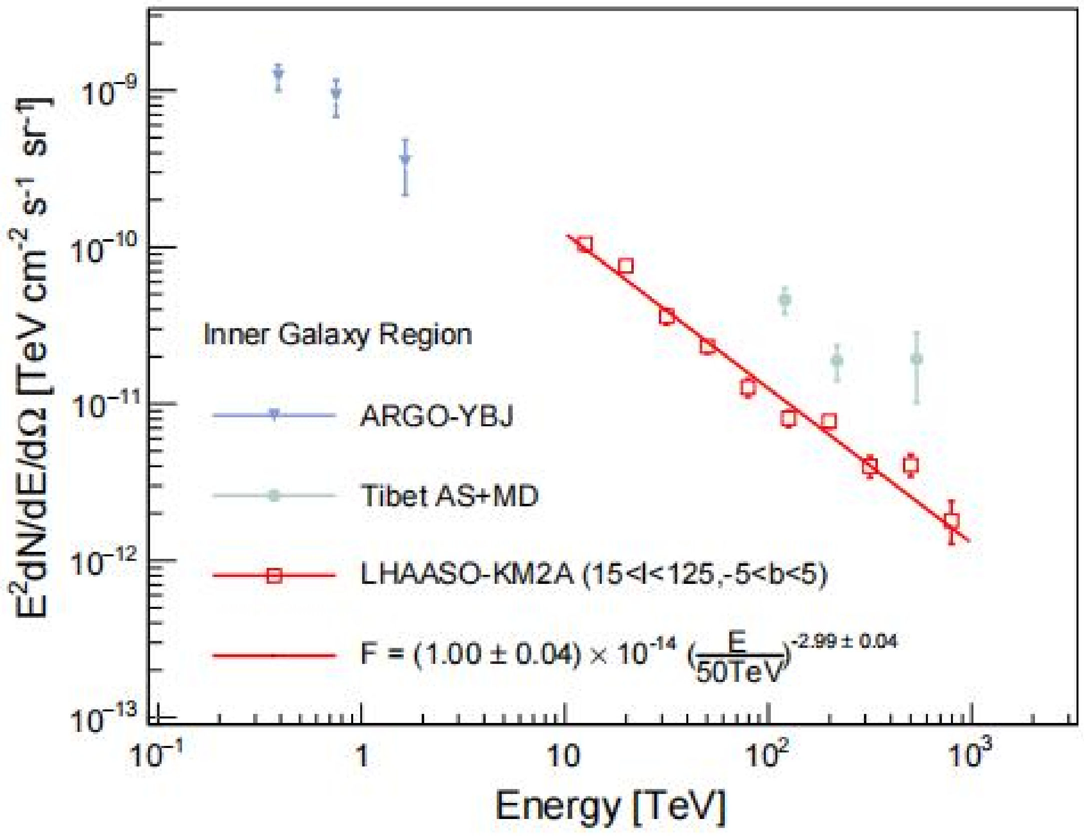
LHAASO diffuse results

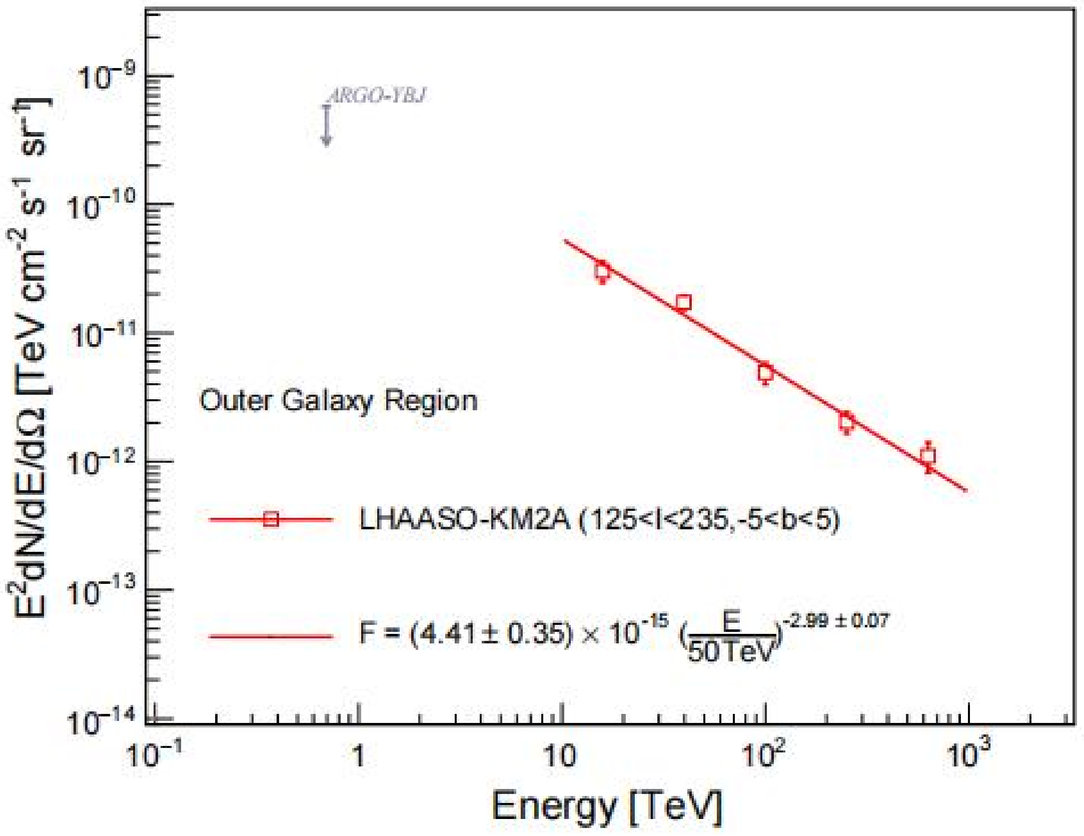




LHAASO, 2023, PRL, 131, 151001

LHAASO diffuse results



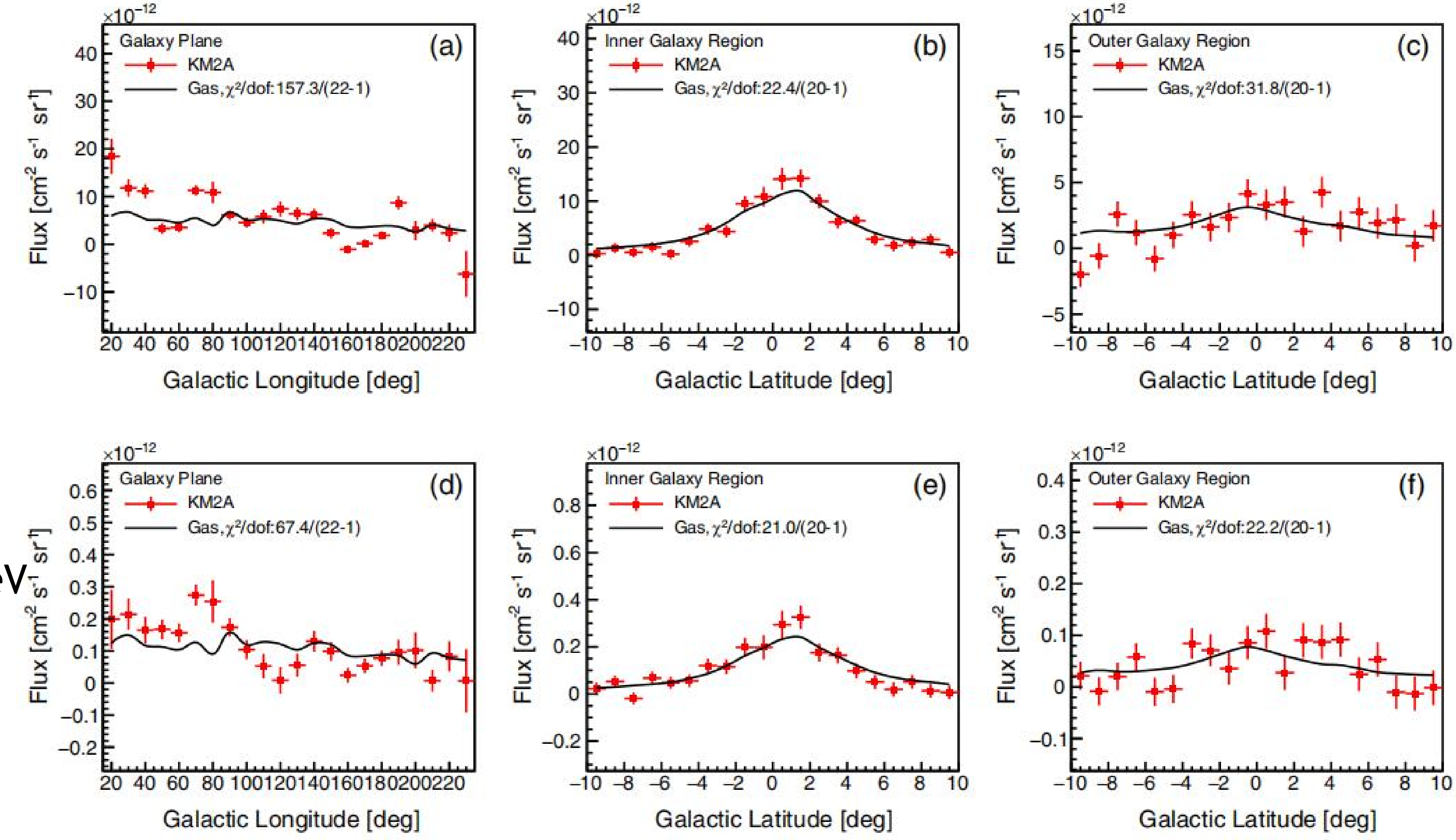


- First detection of VHE diffuse emission from outer Galactic plane
- Spectra follow power-law forms with an index of ~3

Longitude and latitude profiles

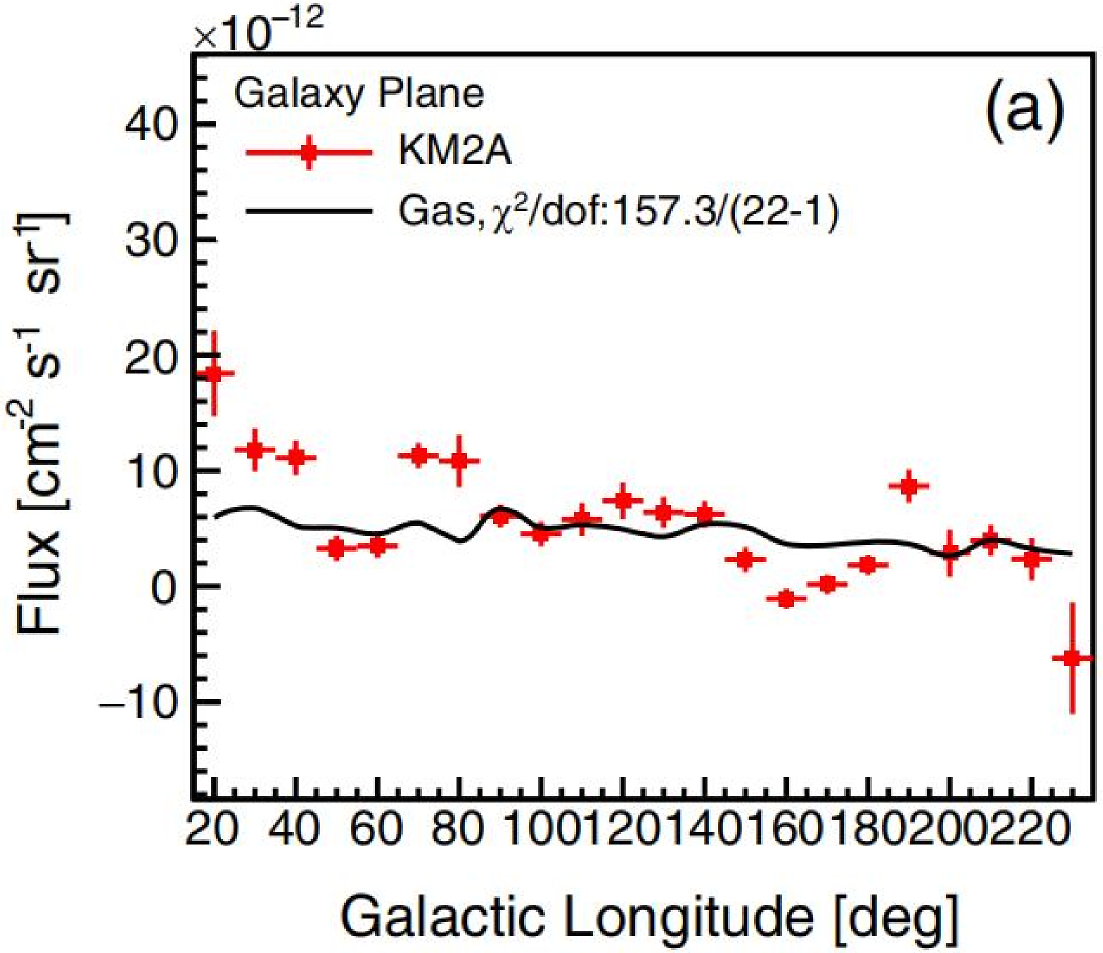
10-63 TeV

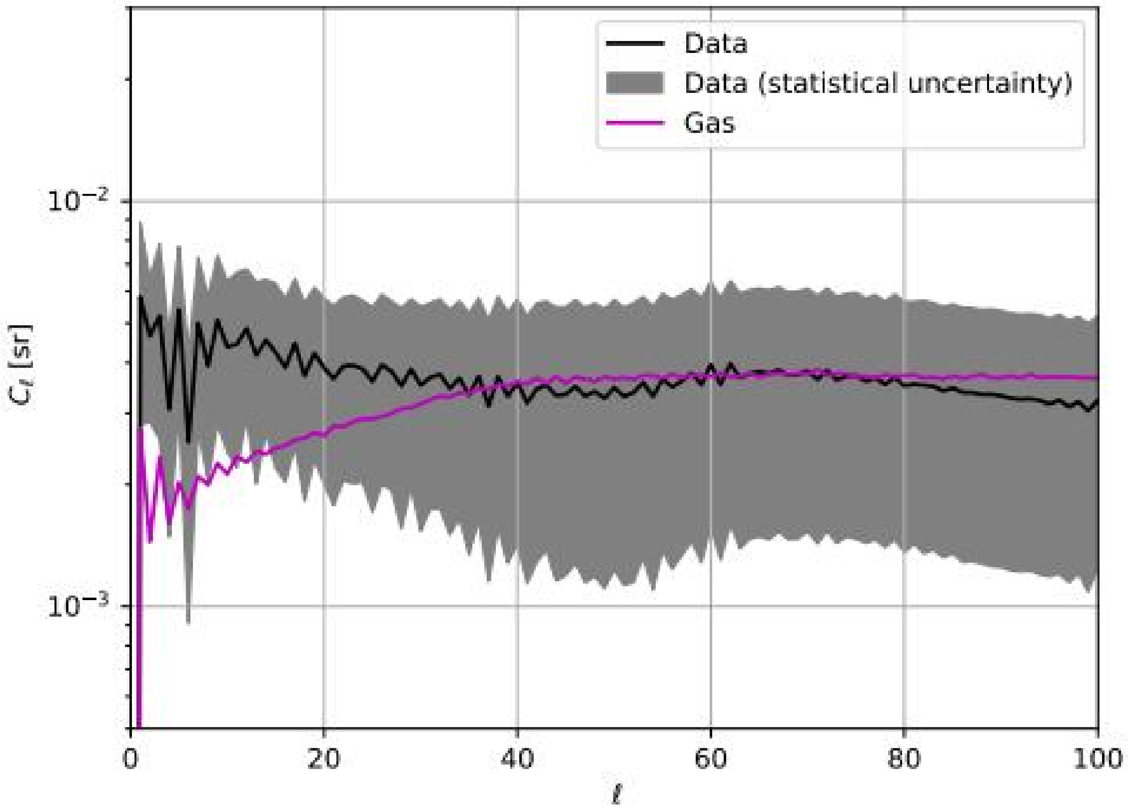
63-1000 TeV



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

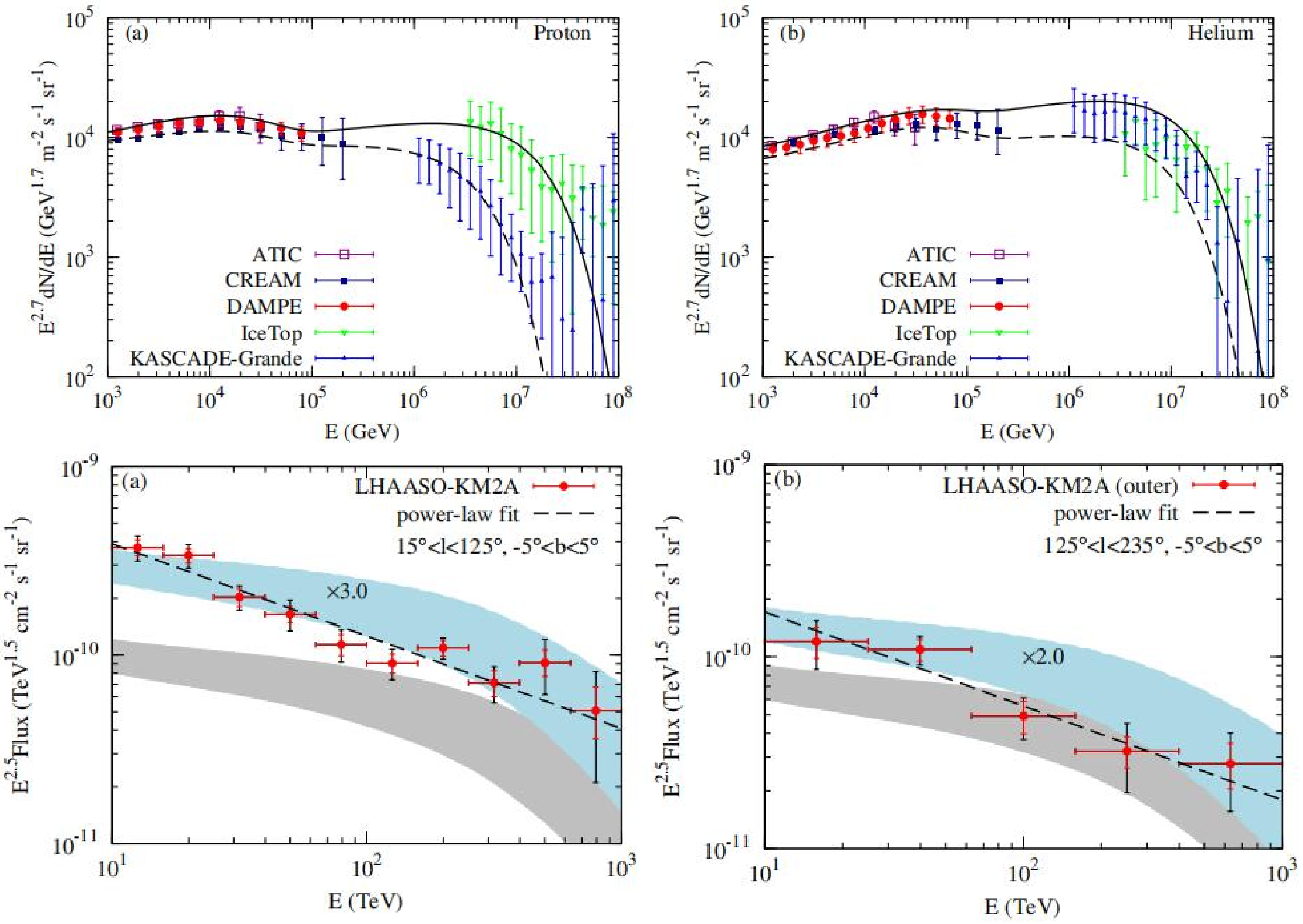
Spatial distribution





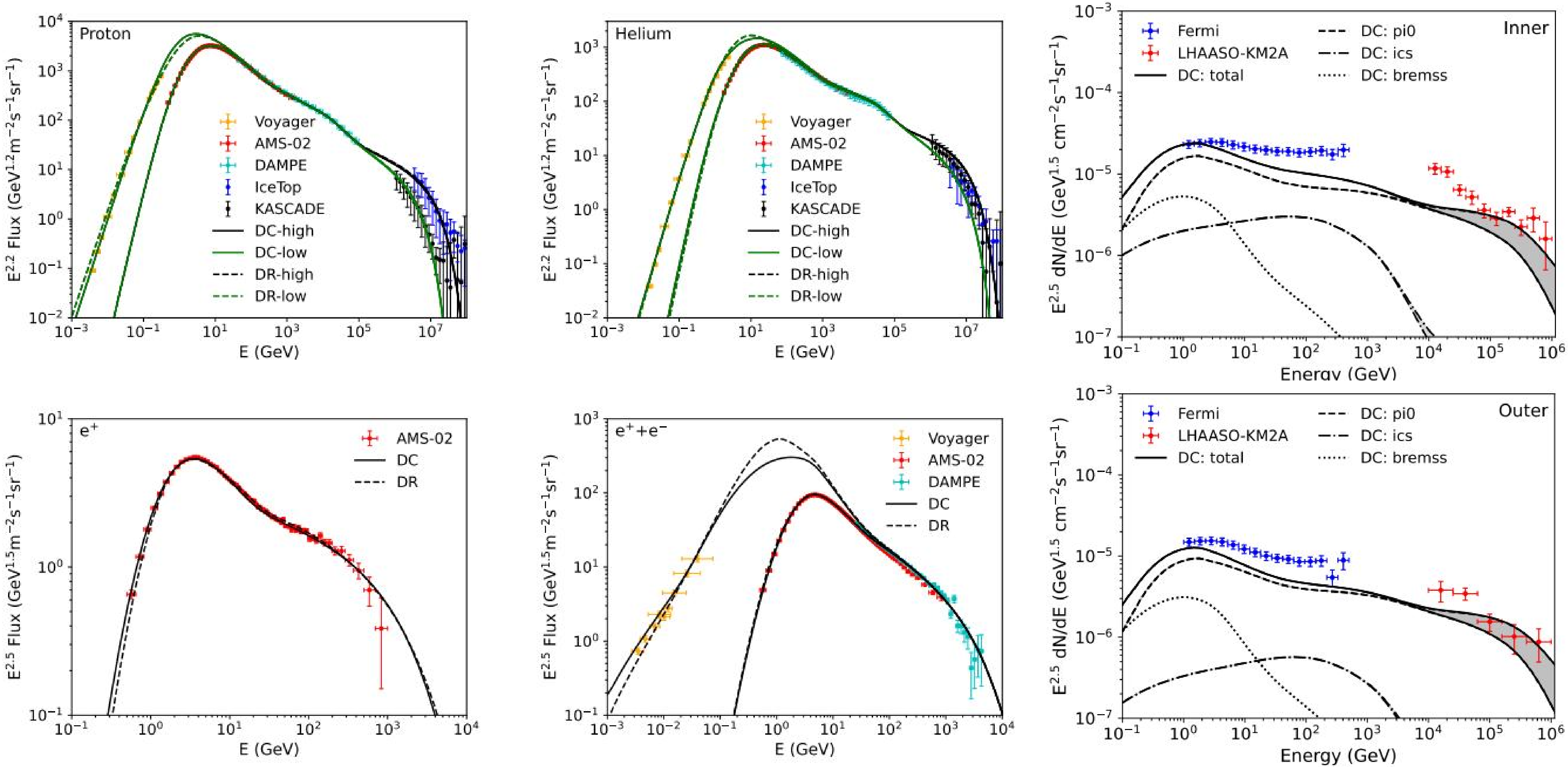
Difference of the longitude distribution between data and gas is also reflected in the angular spectra

Confront LHAASO data with a toy model



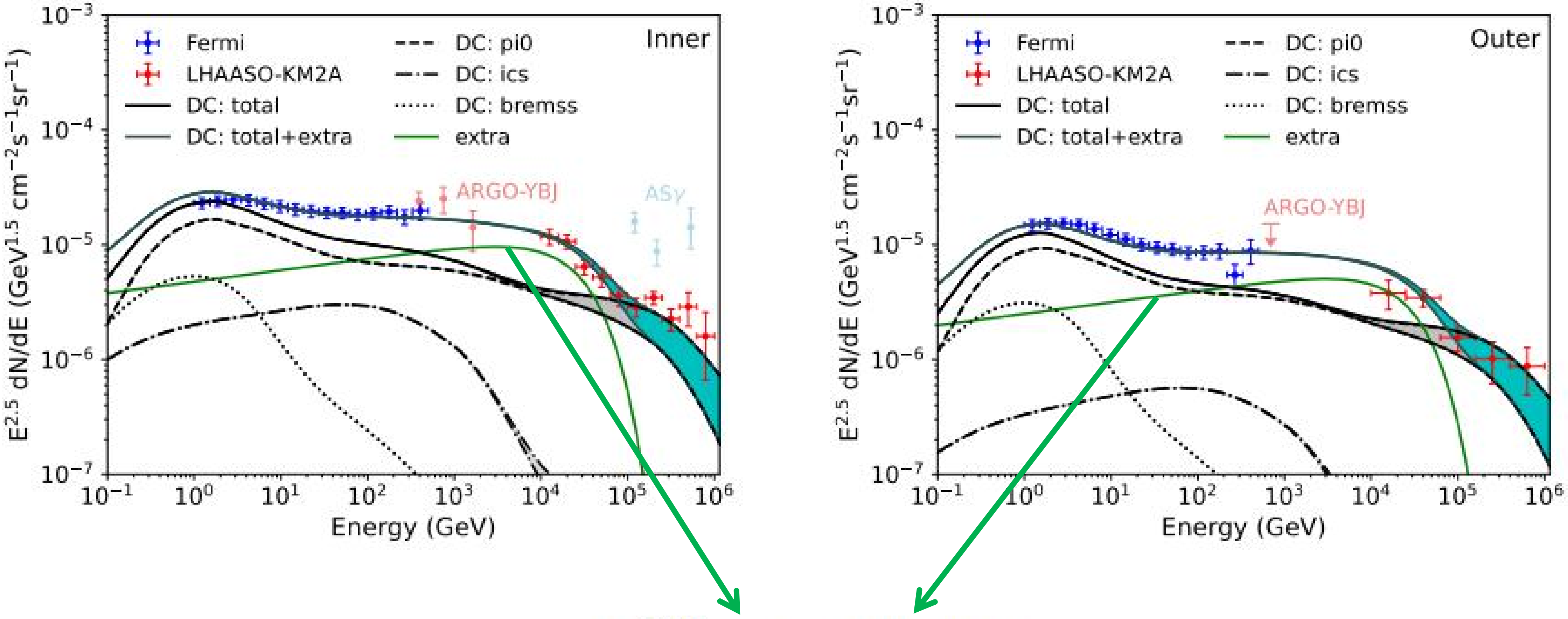
- Toy model prediction: local CR × gas column (PLANCK dust opacity)
- Measured fluxes are higher by a factor of 2~3 than predictions: unresolved sources or propagation effect?
- Spectra are slightly different from the prediction: fitting *p*-values of 10^{-4}~10^{-2} in the inner region

Confront LHAASO data with a GALPROP model



R. Zhang et al. (arXiv:2305.06948)

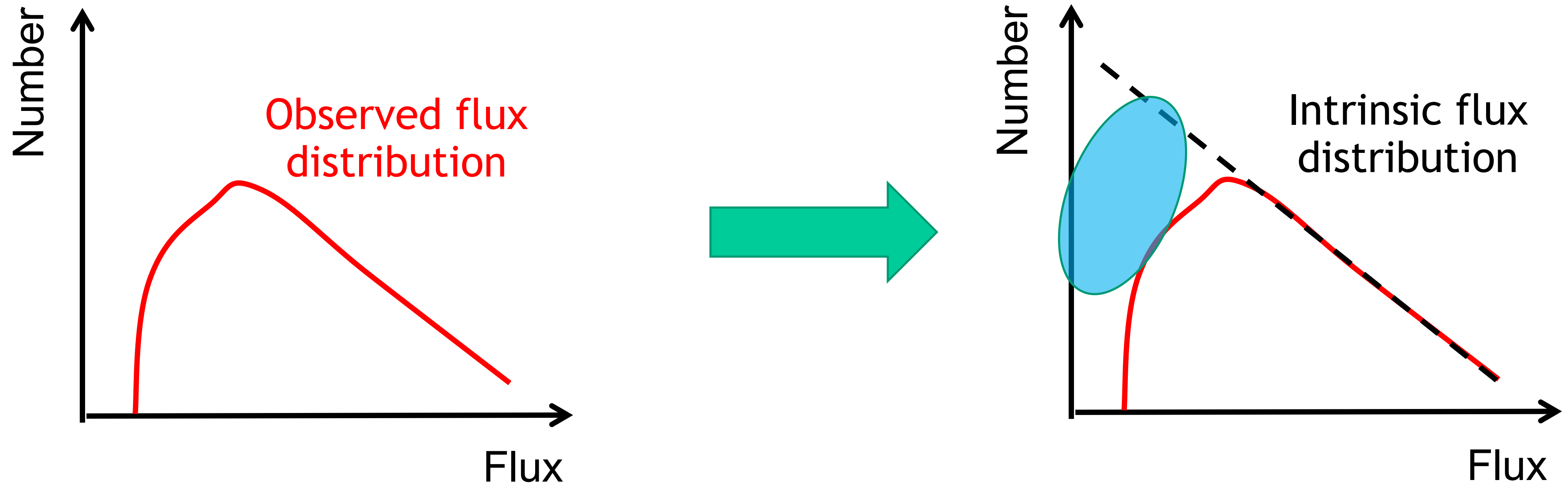
Unresolved source population?



$$\propto E^{-2.40} \exp\left(-E/30\ \mathrm{TeV}\right)$$

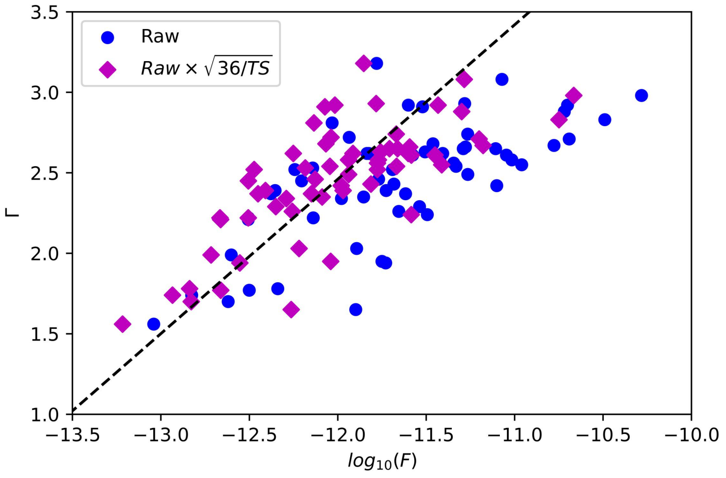
R. Zhang et al. (arXiv:2305.06948)

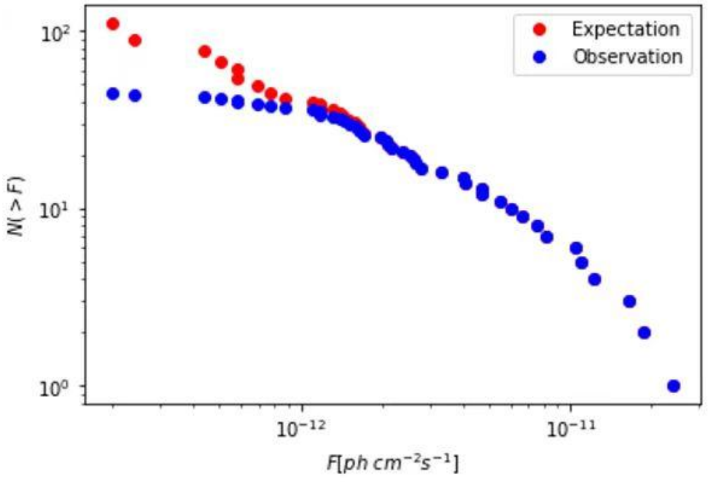
Unresolved source contribution

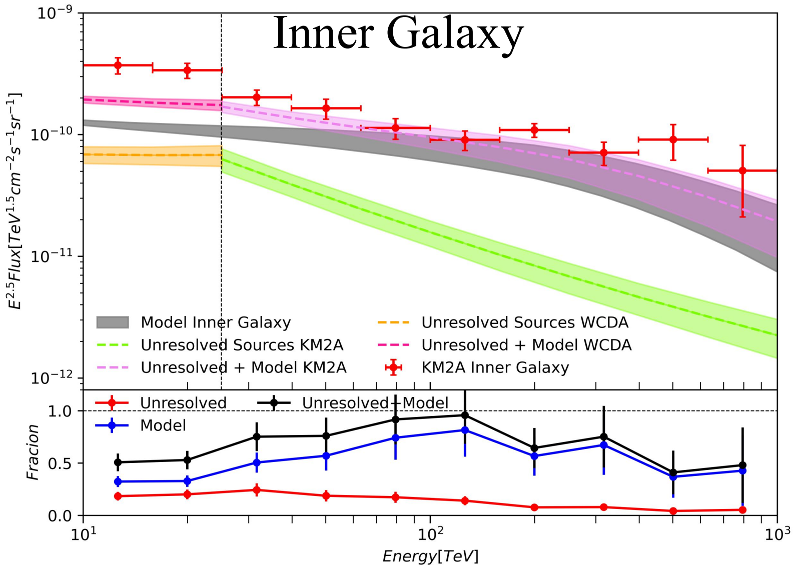


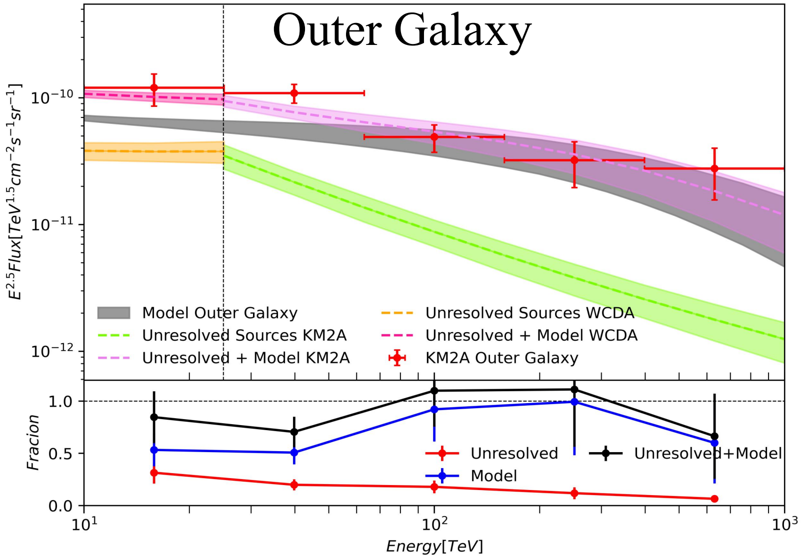
Unresolved source contribution

- ➢ Based on 1st LHAASO Catalog
- ➢ Nonparametric Method: Lynden-Bell Method







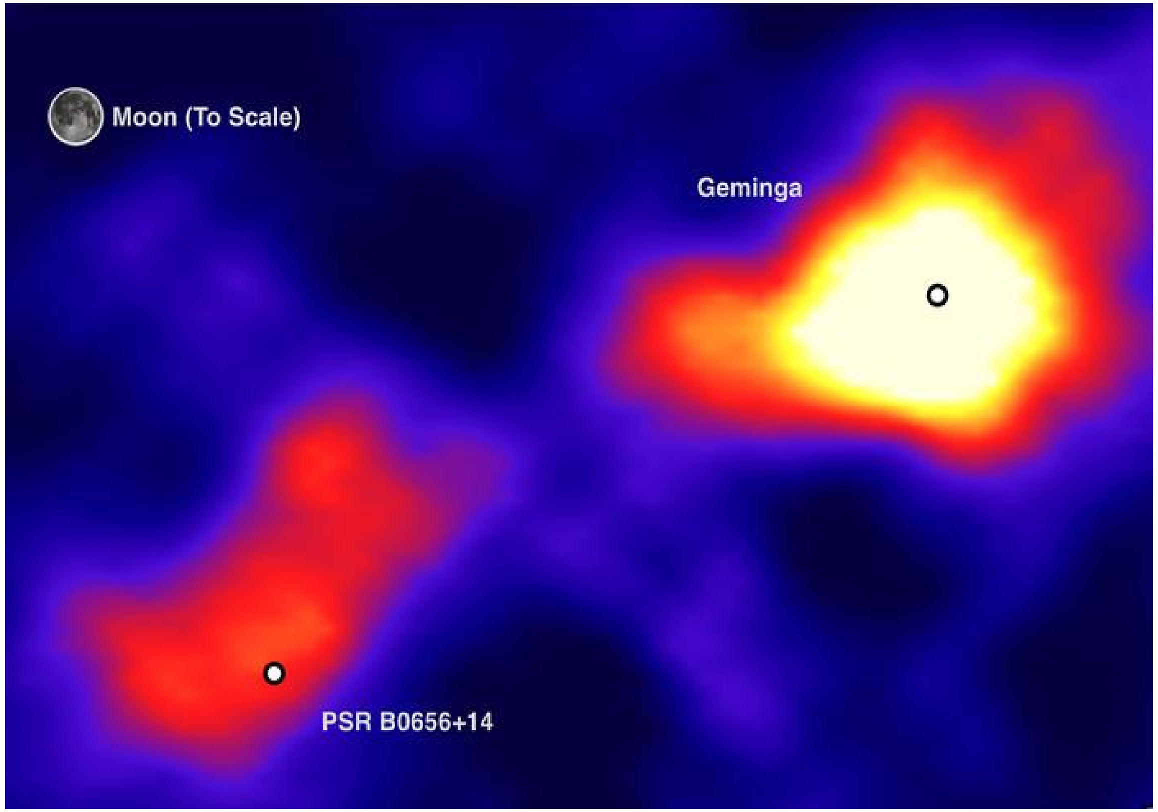


- ✓ The contribution of unresolved sources is able to describe the exta conponent for Outer Galaxy region, while it is insufficient for Inner Galaxy region.
- ✓ Larger extended sources was not considered
- ✓ Additional contributions from unknown mechanisms

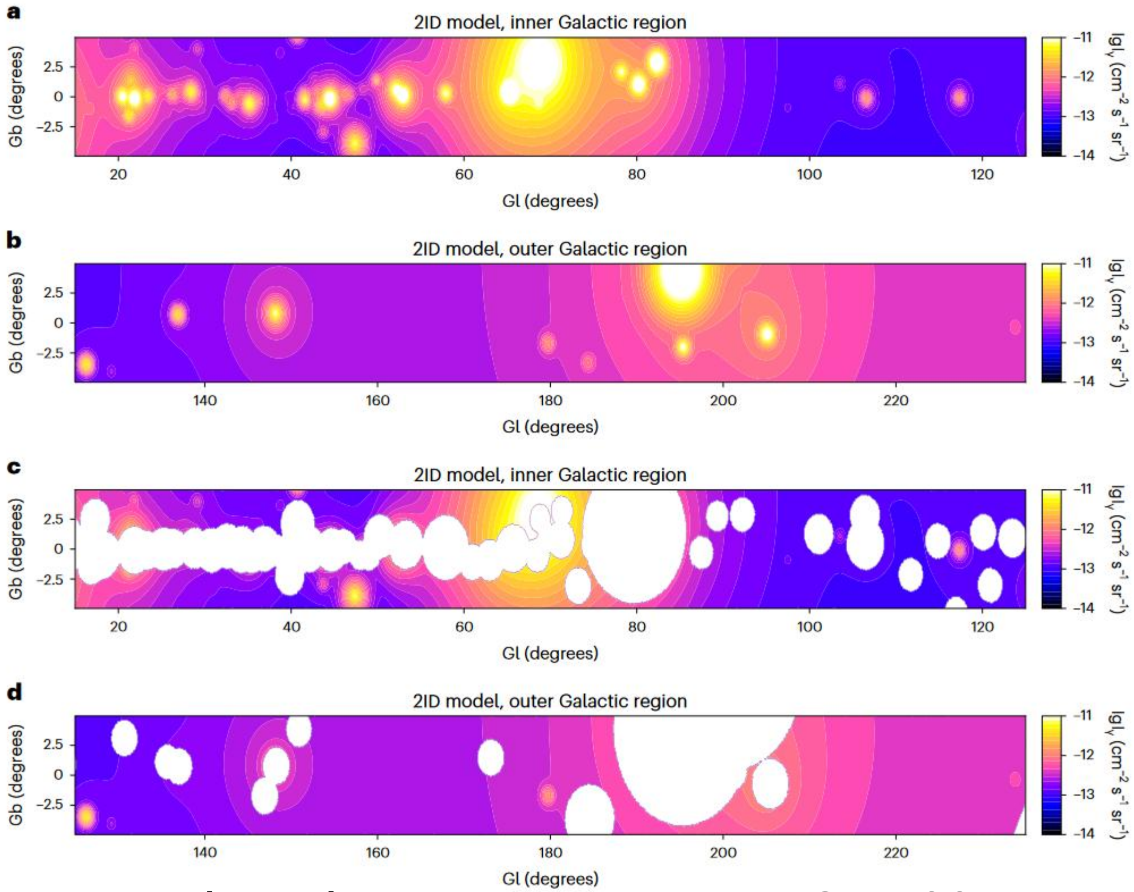
J. He et al. (2024, in preparation)

Pulsar halo interpretation

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).

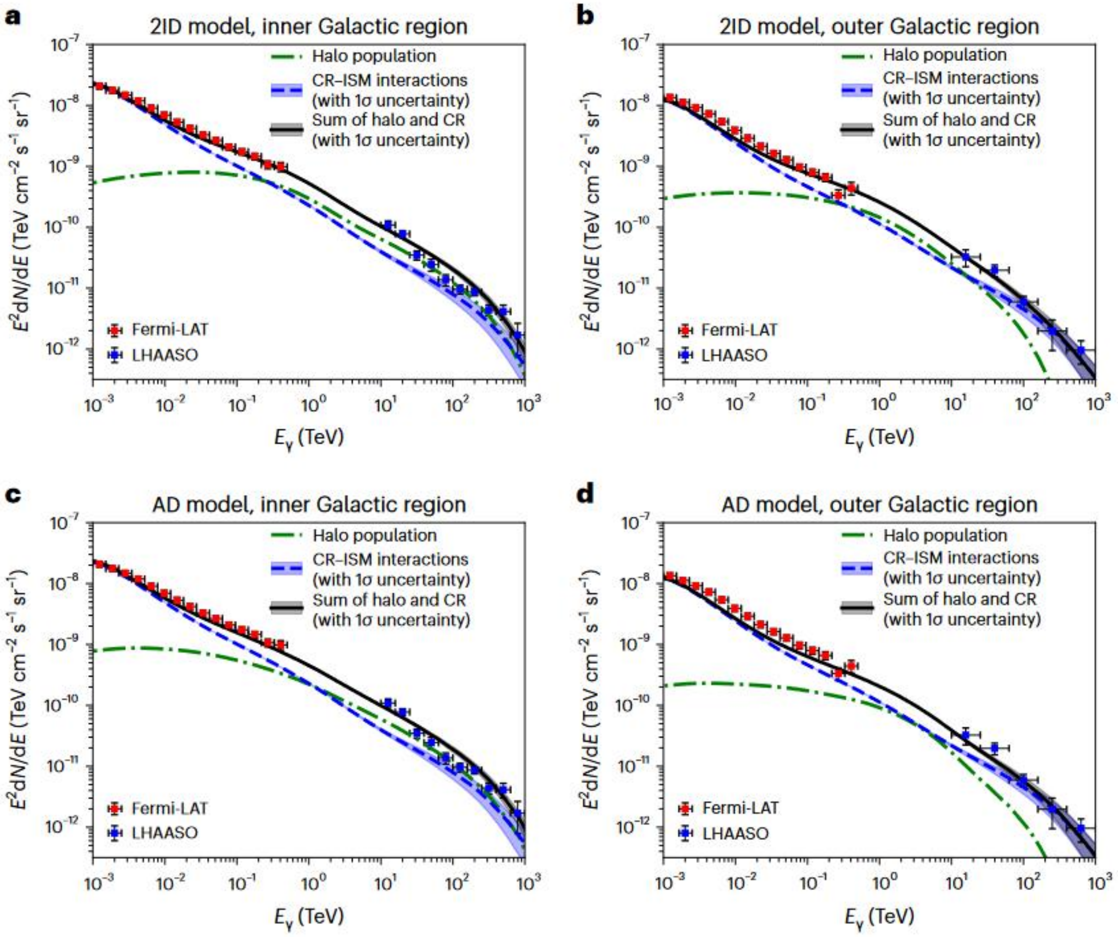


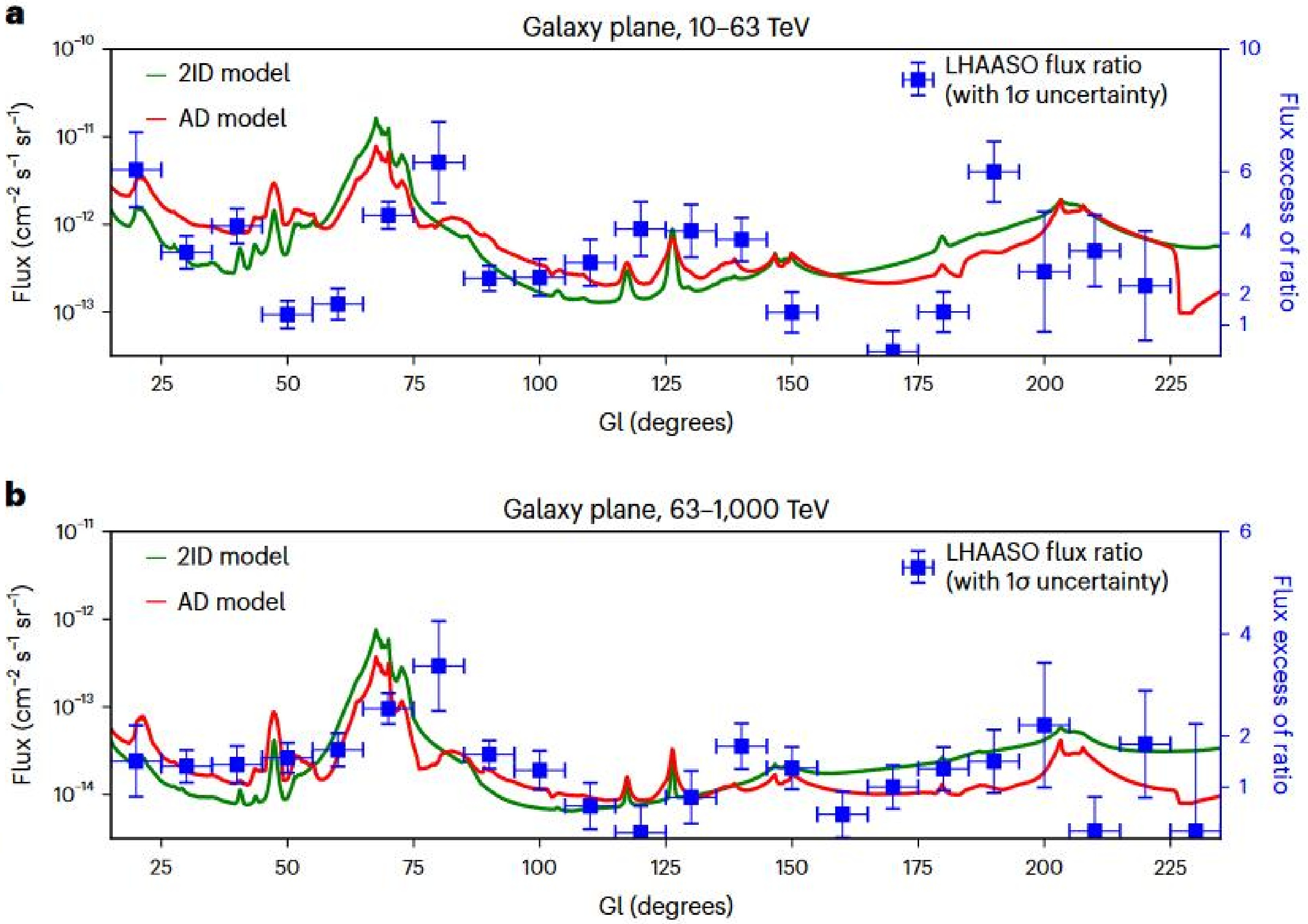
Predicted gamma-ray map in 25-100 TeV from halos of ATNF pulsars

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

See also Dekker et al. 2003

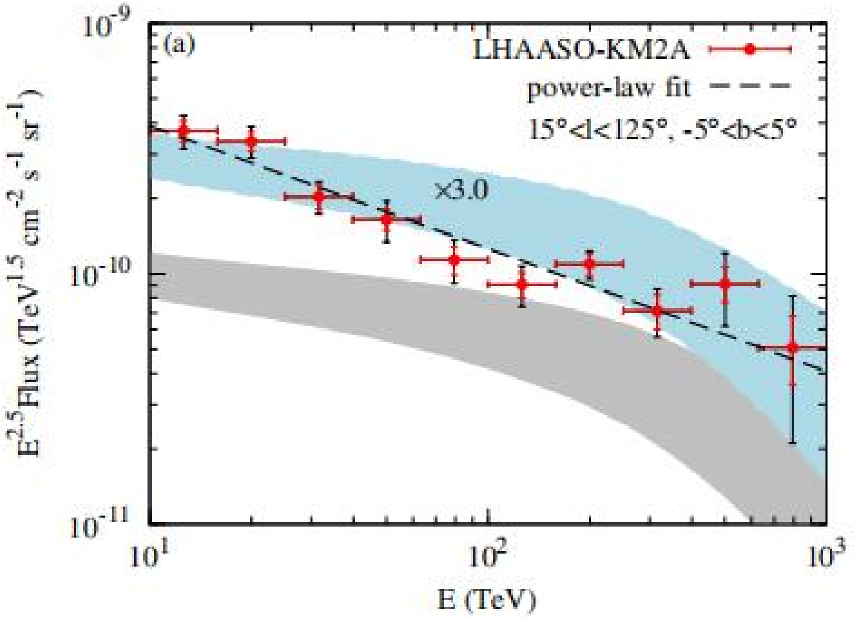
Pulsar halo interpretation

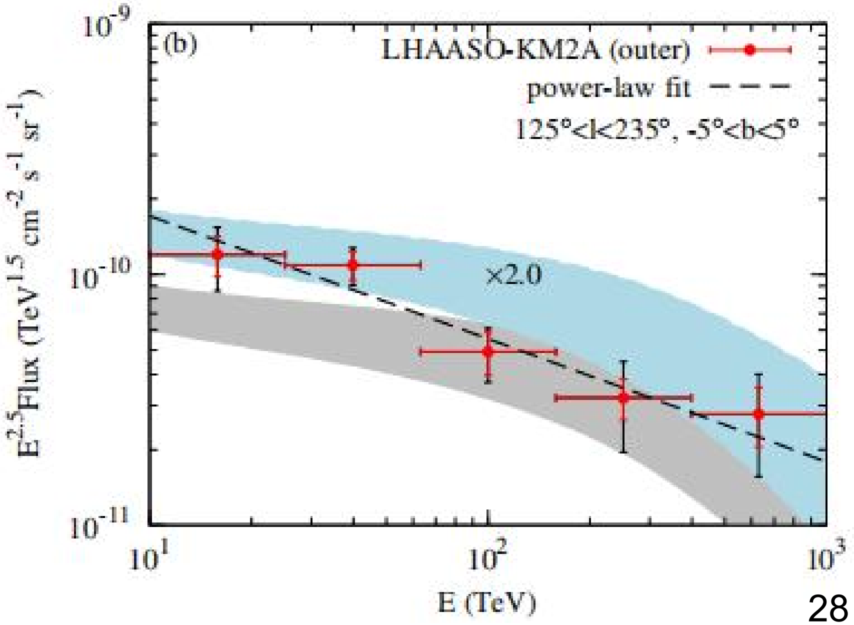




K. Yan et al. (2024, Nat. Astron.)

Summary





- The diffuse emission from two regions of the Galactic plane was observed with high significance; Firstly detected in the outer Galaxy region!
- Spectral indices of both regions are about -3; deviation from single power-law is not evident by the current data
- The latitude distributions are consistent with the gas template, and more complicated structures in the longitude distributions
- Overall fluxes of are higher by a factor of several than the local CR interaction with l.o.s. gas —— unresolved sources or propagation effect?
- A pulsar halo model can properly explain the measurements

Thank you!