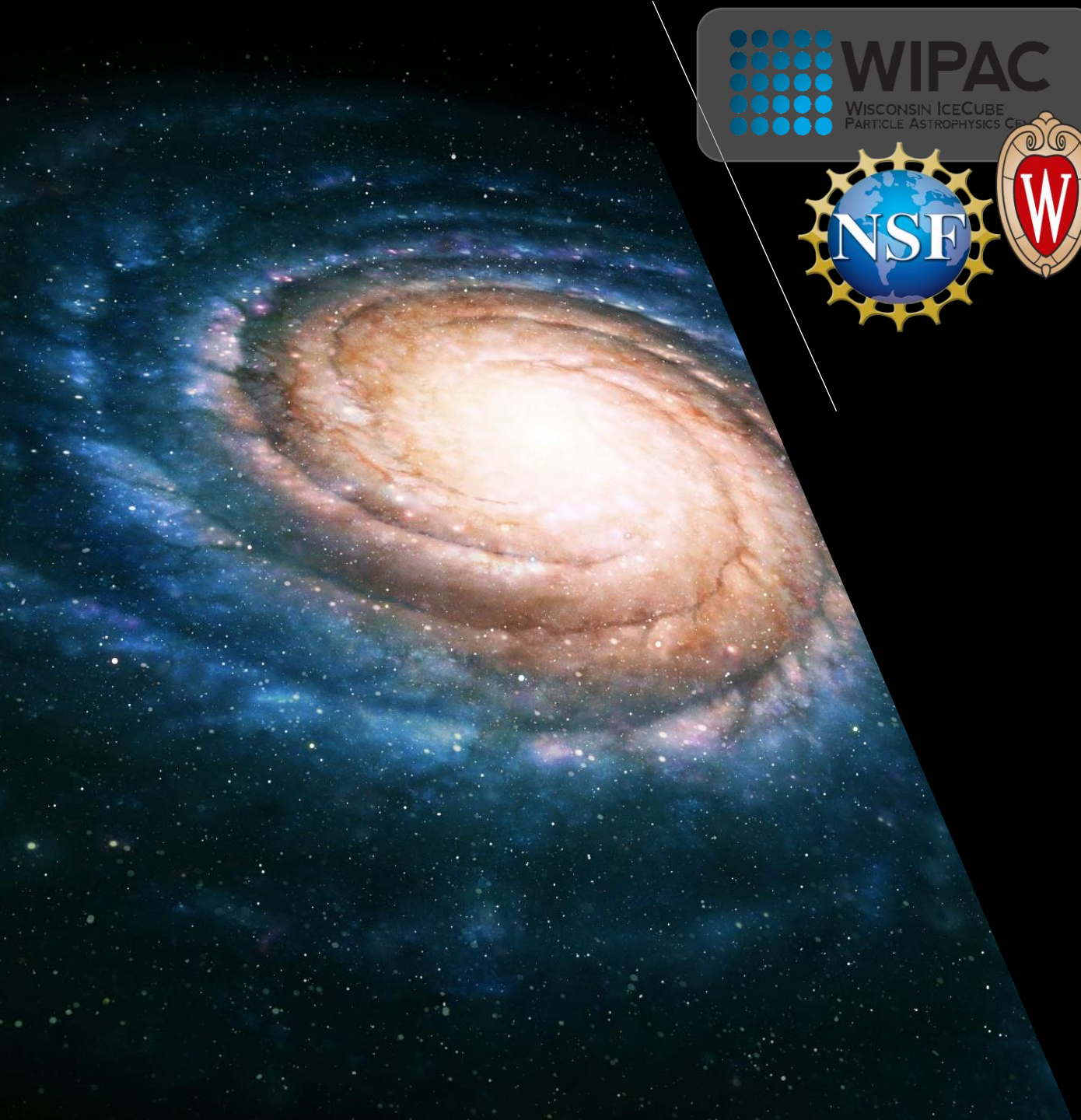
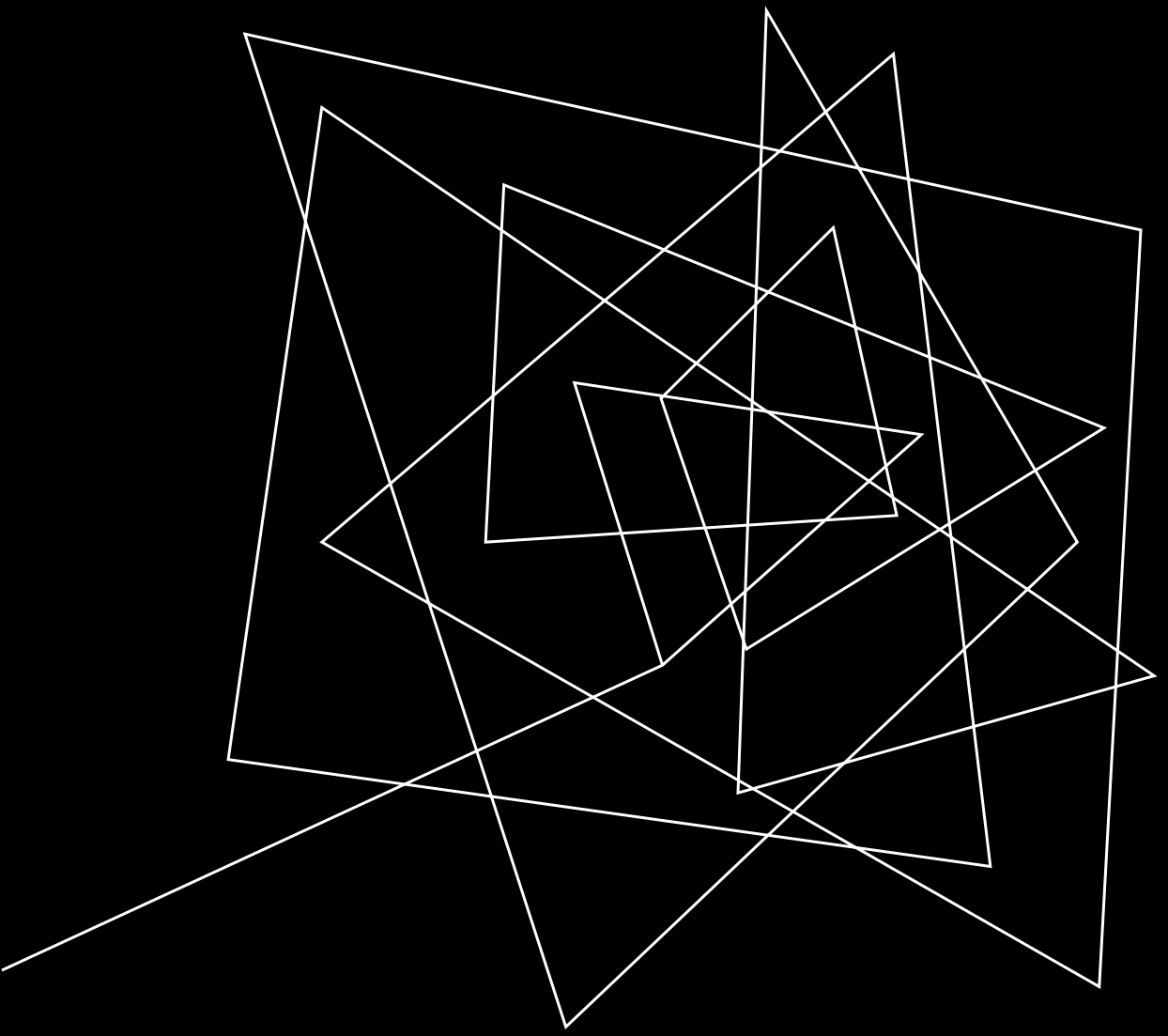


CONSTRAINING GALACTIC COSMIC RAY MODELS WITH A MULTI-MESSENGER ANALYSIS OF DIFFUSE EMISSION

Alisha Roberts[1], Dan Hooper[1], Ilias Cholis[2], Samyak Jain[1]

[1]University of Wisconsin-Madison, [2]Oakland University



BACKGROUND

Cosmic Rays

Highly energetic particles

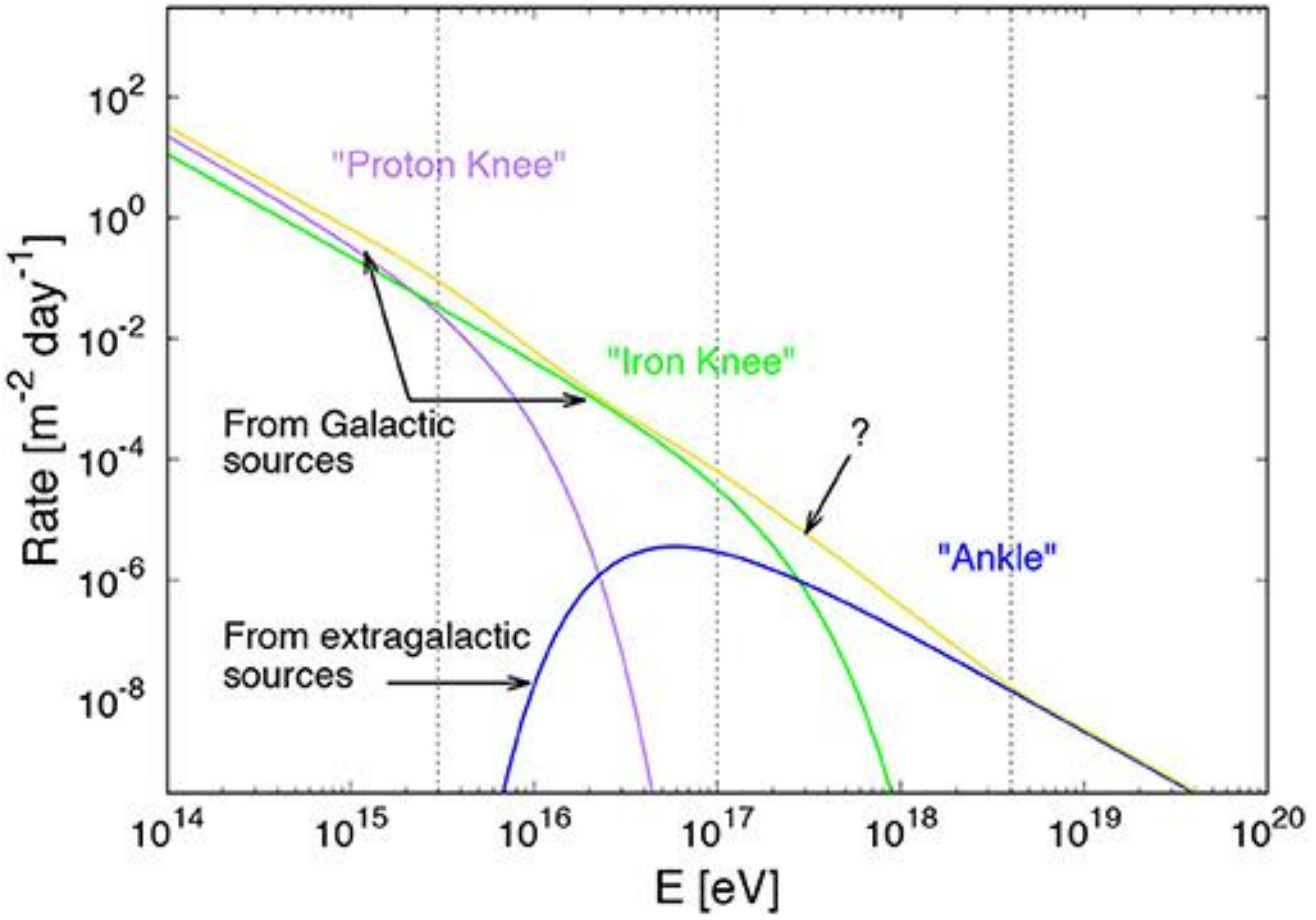
IceCube Collaboration (2012). *Rendering of cosmic rays hitting Earth.*

Galactic

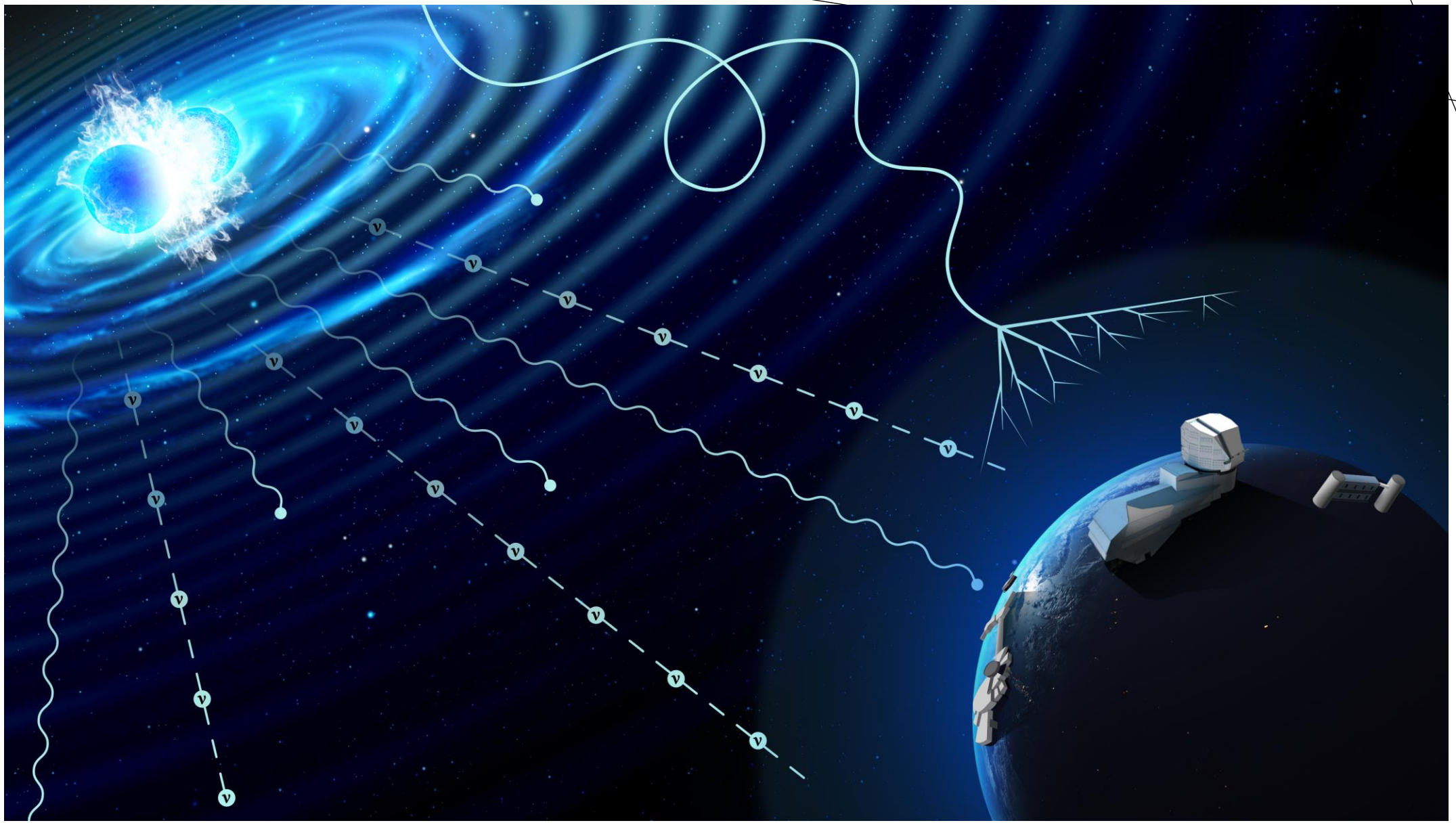
Cosmic Rays

Highly energetic particles

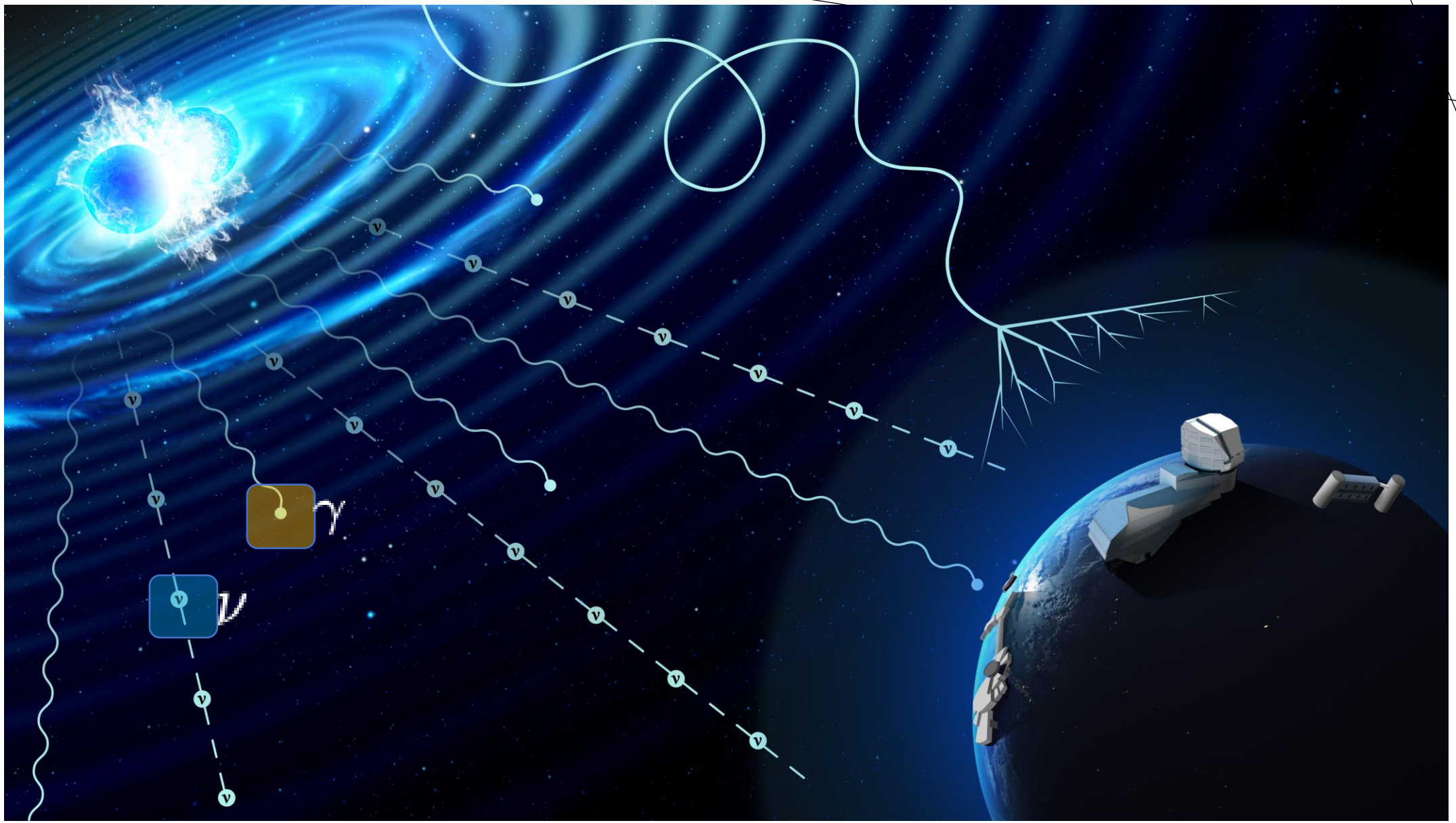
Spectrum by galactic sources generally defined by power-law



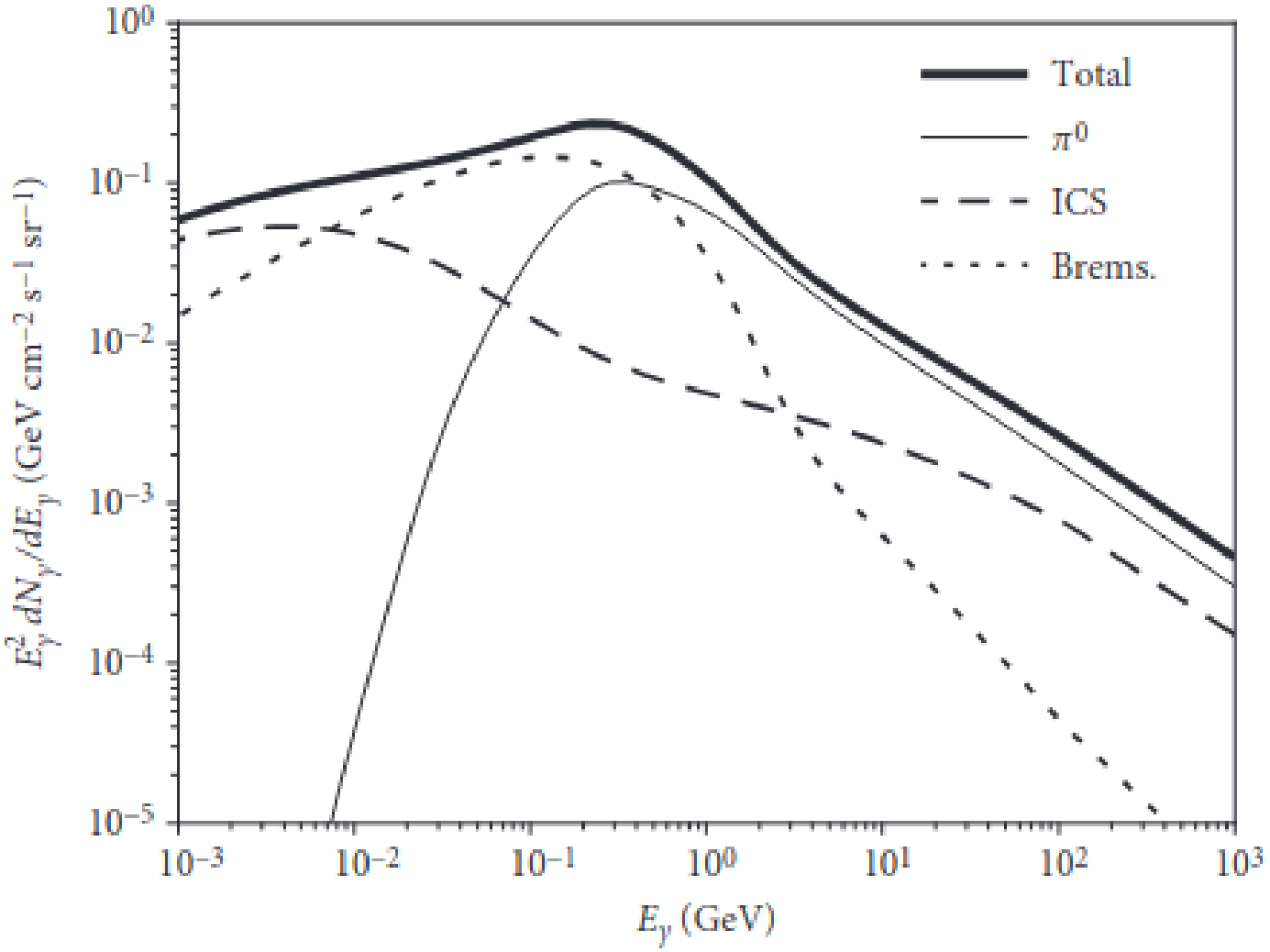
Rafael, R., et. Al. (2019). *Open Questions in Cosmic-Ray Research at Ultrahigh Energies*. Frontiers in Astronomy and Space Sciences.



RubinObs/NOIRLab/SLAC/NSF/DOE/AURA/P. Marenfeld (2024). *Artist's Illustration of Multi-Messenger Event*



RubinObs/NOIRLab/SLAC/NSF/DOE/AURA/P. Marenfeld (2024). *Artist's Illustration of Multi-Messenger Event*



Hooper, D. (2024). *Particle Cosmology and Astrophysics.* Princeton University Press.

Gamma-rays

Produced in high-energy interactions, often linked with the decay of neutral pions from interacting cosmic rays

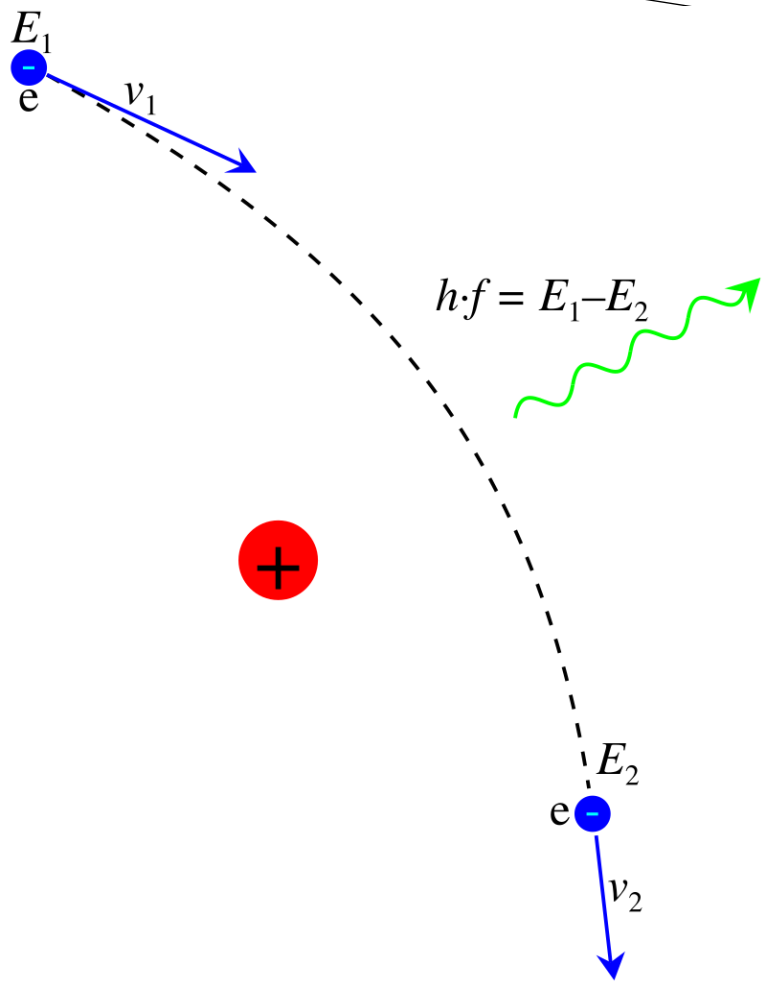
Trace regions where high energy particles are interacting

Produced both leptonically and hadronically

Gamma-rays

via Bremsstrahlung

traces high-energy
electrons in dense gas

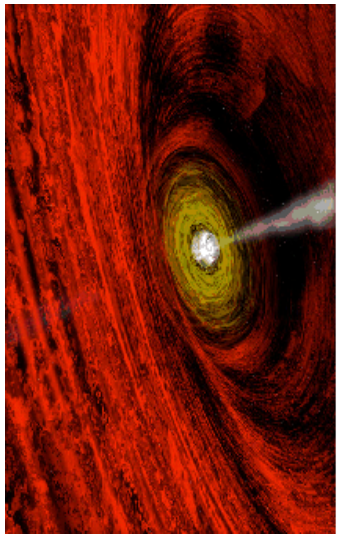


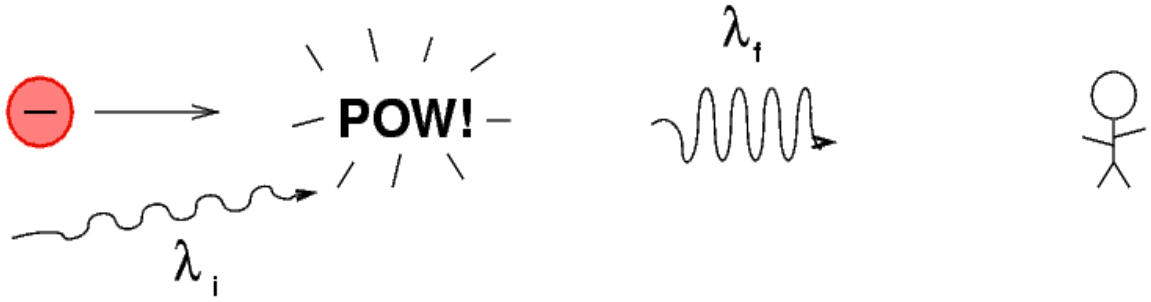
Martin, Dylan (2005). *X-Ray Detection*. University of Arizona Optical Sciences Center

Gamma-rays

Leptonic

- via Bremsstrahlung
- via Inverse Compton Scattering





high-energy (relativistic) electron (e.g., supernovae remnant) transfers energy to low-energy photon (CMB/starlight)

Richmond, M. (2005) *PHYS 314 Lecture on ICS*. Rochester Institute of Technology

Gamma-rays

Leptonic

via Bremsstrahlung

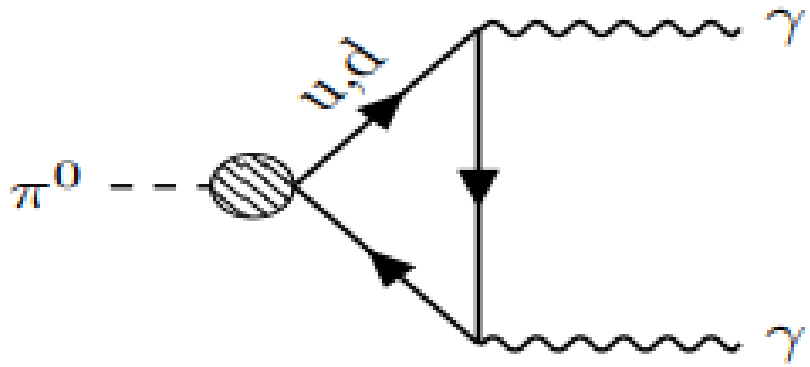
via Inverse Compton Scattering

Hadronic

via Neutral Pion Decay

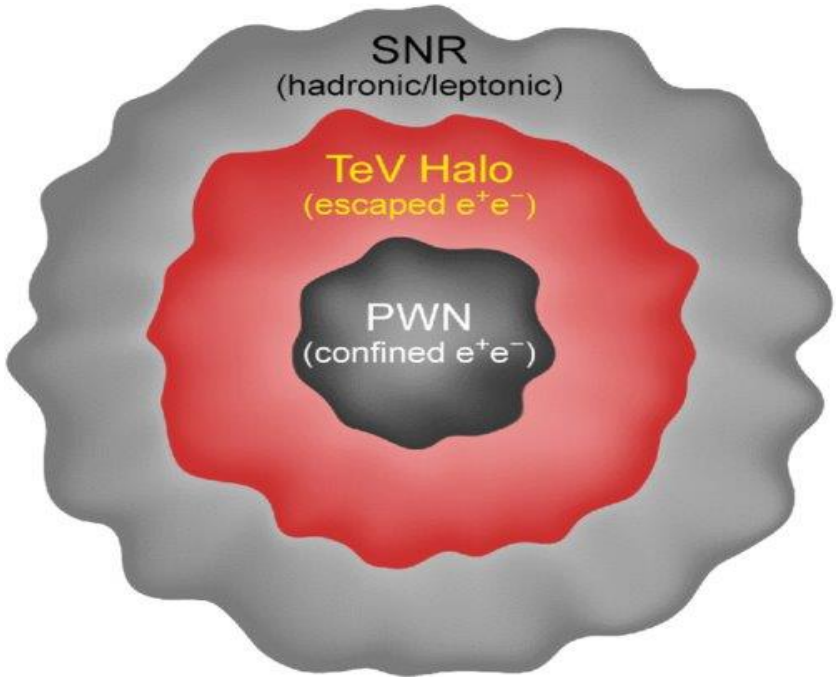
$$p + p_{\mathrm{ISM}} \rightarrow p + p + \pi^0 \rightarrow p + p + \gamma\gamma$$

Main channel of production



Bryman, D., Shrock, R. (2025) *Feynman Diagram of Neutral Pion Decay*. arXiv:2502.18384

TeV Halos: young and middle-aged pulsars glow brightly in TeV gamma rays



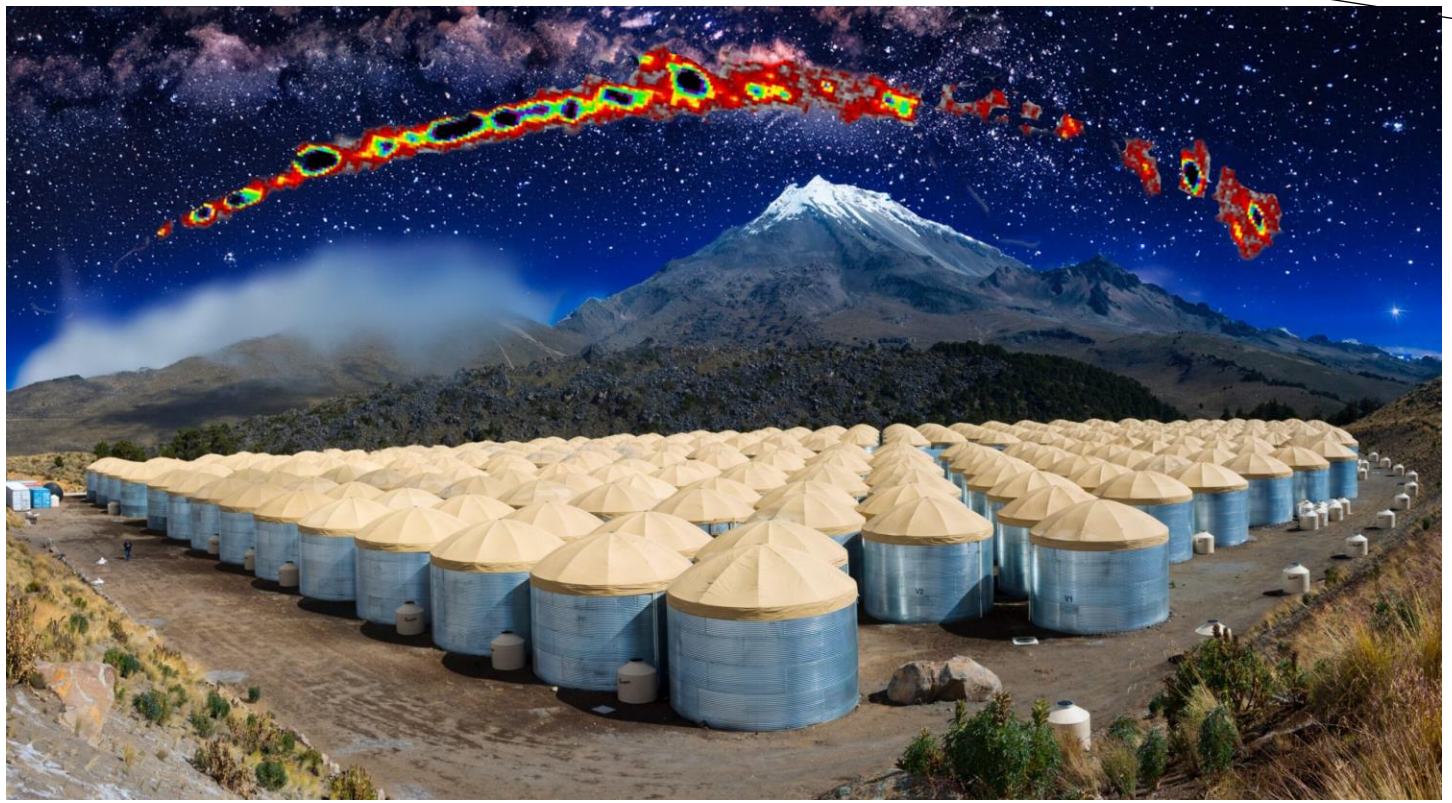
Sudoh, T., Linden, T., Beacom, J. (2019) *Feynman Diagram of Neutral Pion Decay*. arXiv:2502.18384

TeV Halos

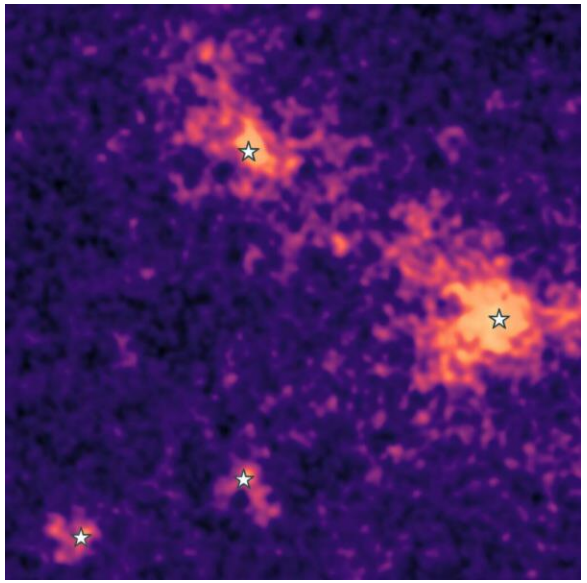
Explain the Positron Excess?

For years, satellites (Pamela, AMS) detected more high-energy positrons near Earth than our standard models can explain.

TeV halos, acting as local factories for positrons, could explain this anomaly (Dekker, A., Holst, I., Simon, E. et al., 2024, arxiv:2306.00051)



Goodman, J. (2023). *HAWC site with superposition of Milky Way's plane as seen in gamma-rays*



Coutiño, S. (2023). *HAWC significance map of some of TeV halos included in the analysis (marked with white stars).*

TeV Halos

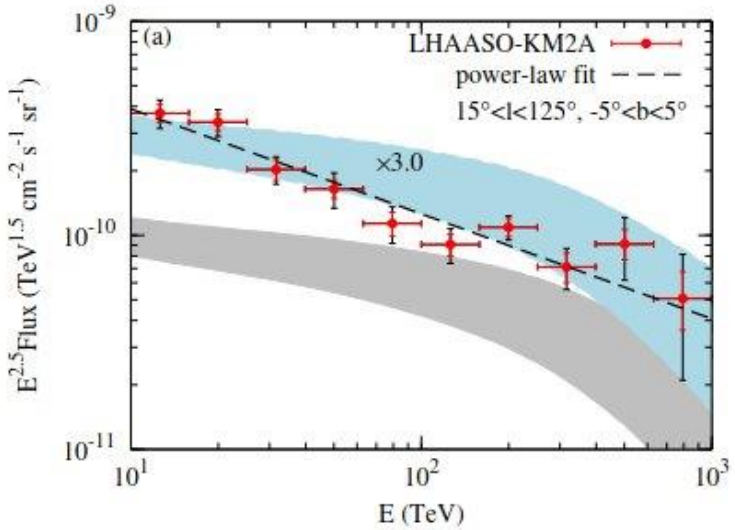
Contribute to diffuse glow?

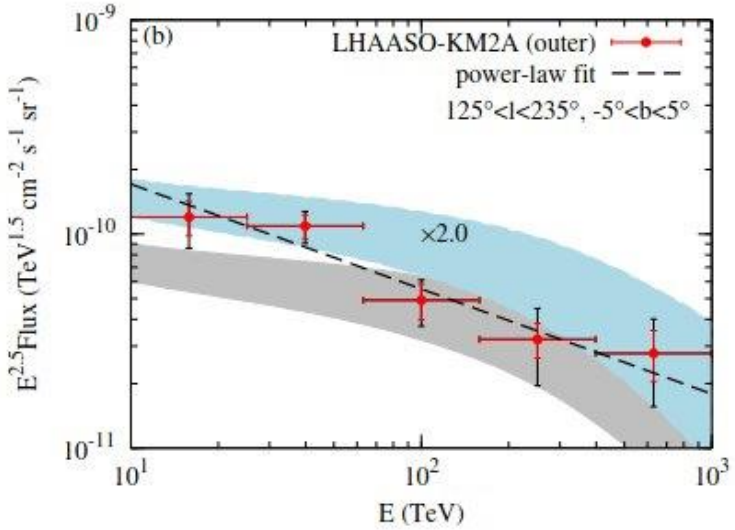
The combined, overlapping glow from thousands of unresolved TeV halos throughout the galaxy could be a significant contributor to the diffuse gamma-ray background that LHAASO is measuring

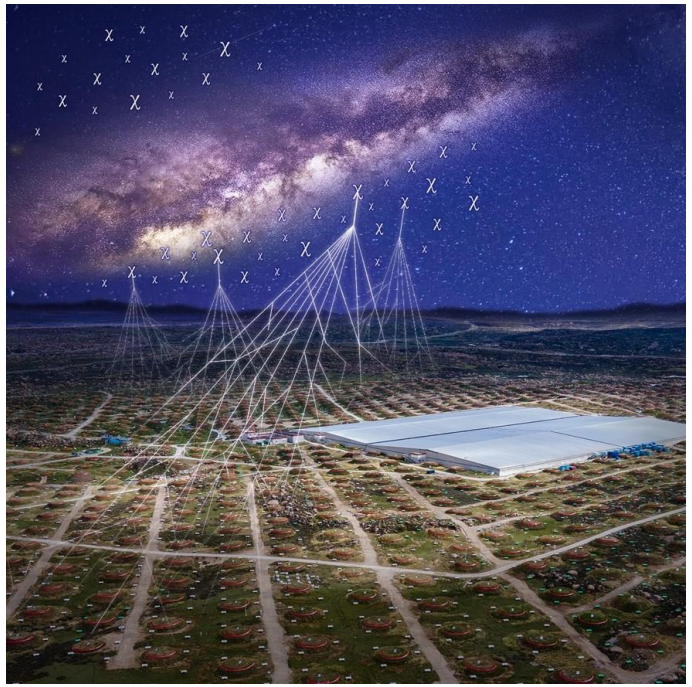
The Gamma-Ray Eye: LHAASO

Large High Altitude Air Shower Observatory (Daocheng, China)

Designed for cosmic-ray and γ-ray studies at TeV and PeV energies







LHAASO (2022). *Artist rendition of cosmic rays being detected at LHAASO.*

LHAASO Collaboration (2023). *Measured fluxes of diffuse γ-ray emission in the inner and outer Galaxy regions.* arXiv:2305.05372v2

BIG PICTURE

- **Test hypothesis of TeV halo contribution to Positron Excess**

Points directly to source

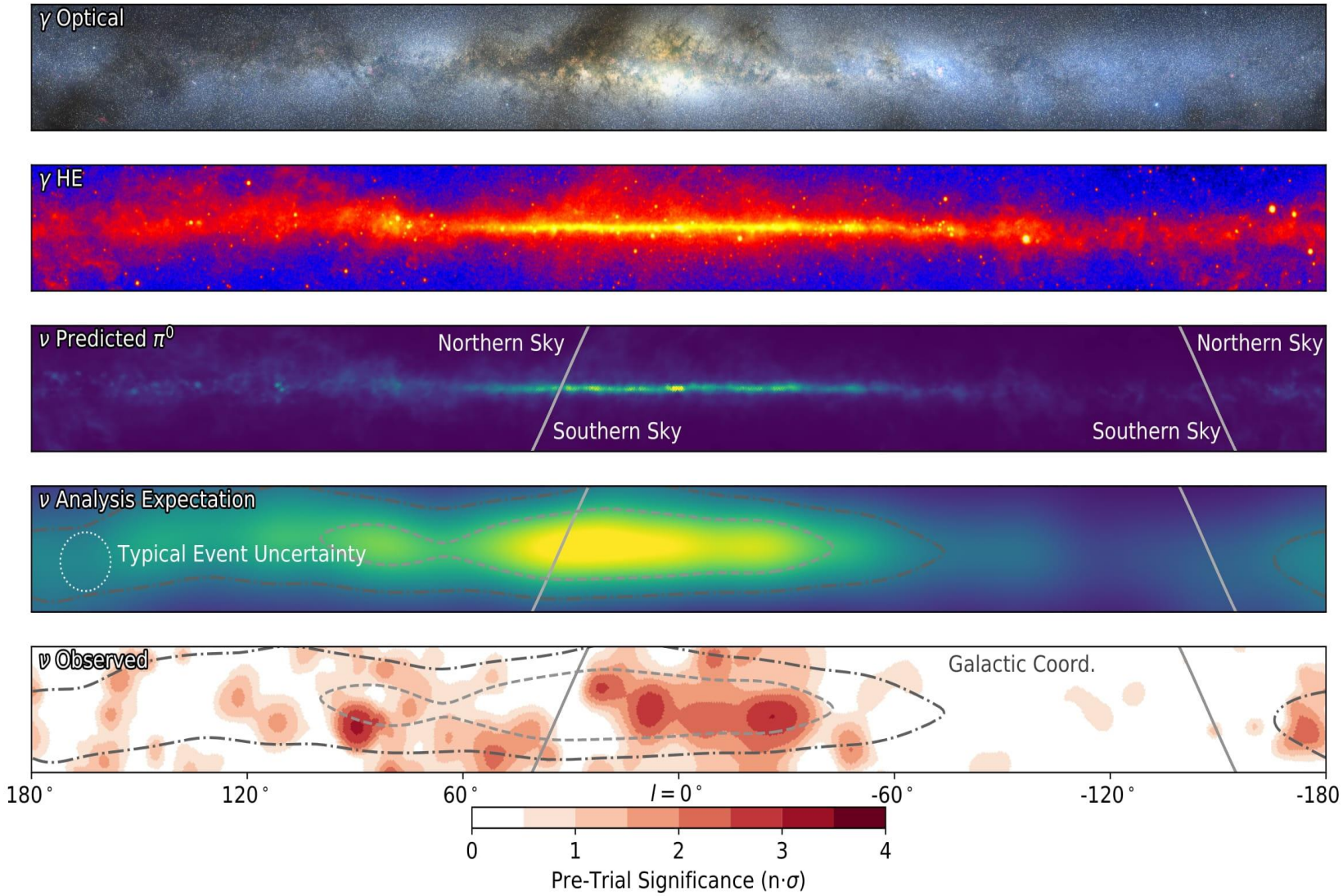
Difficult to detect due to neutral charge and small cross section

Neutrinos

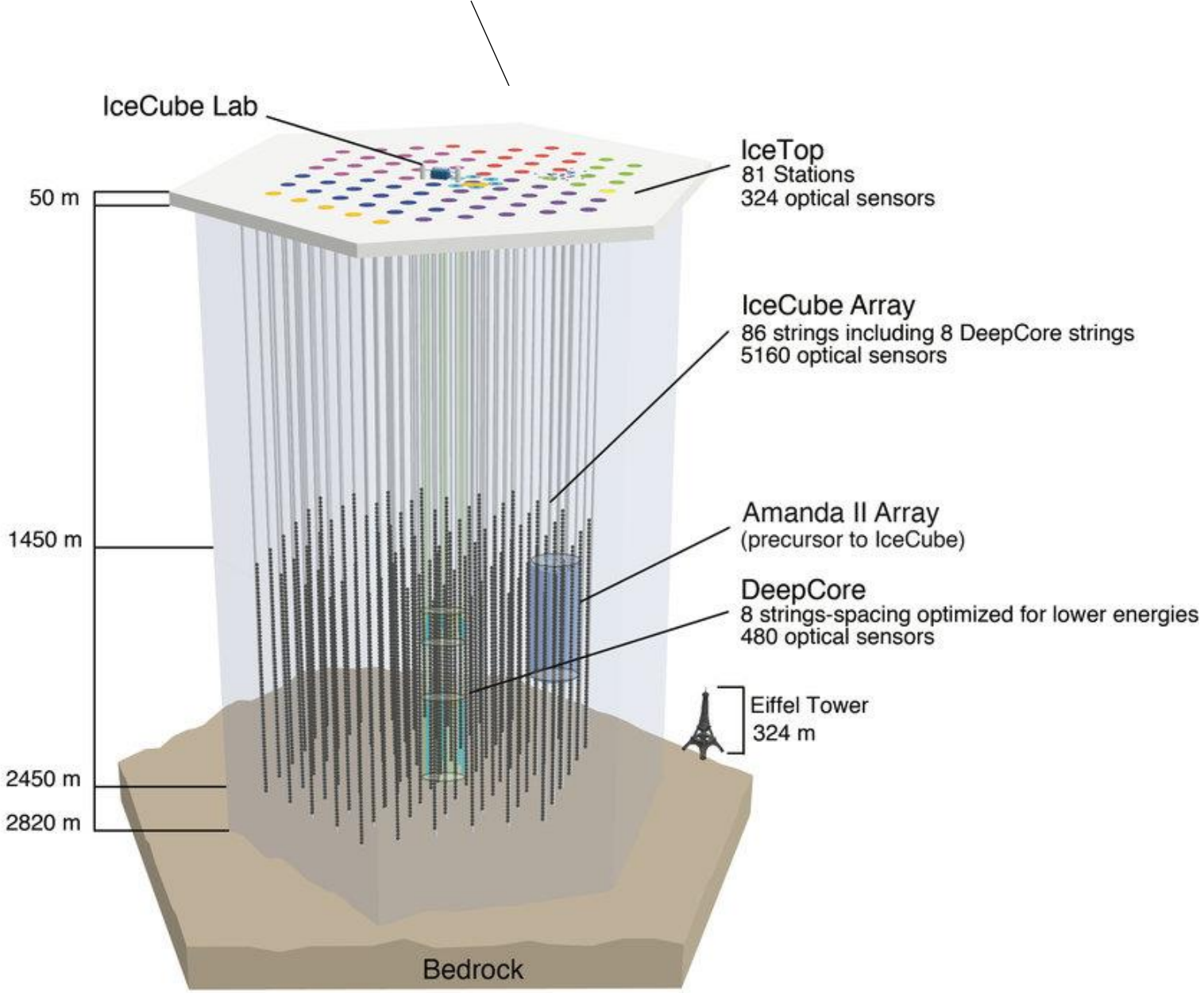
Produced through hadronic interactions

Should approximately parallel gamma-ray emission in high energies in pion 1:1:1 ratio

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ \bar{\nu}_\mu \nu_e \nu_\mu,$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- \nu_\mu \bar{\nu}_e \bar{\nu}_\mu$$



IceCube Collaboration. (2023). *Observation of high-energy neutrinos from the Galactic plane*. Science.

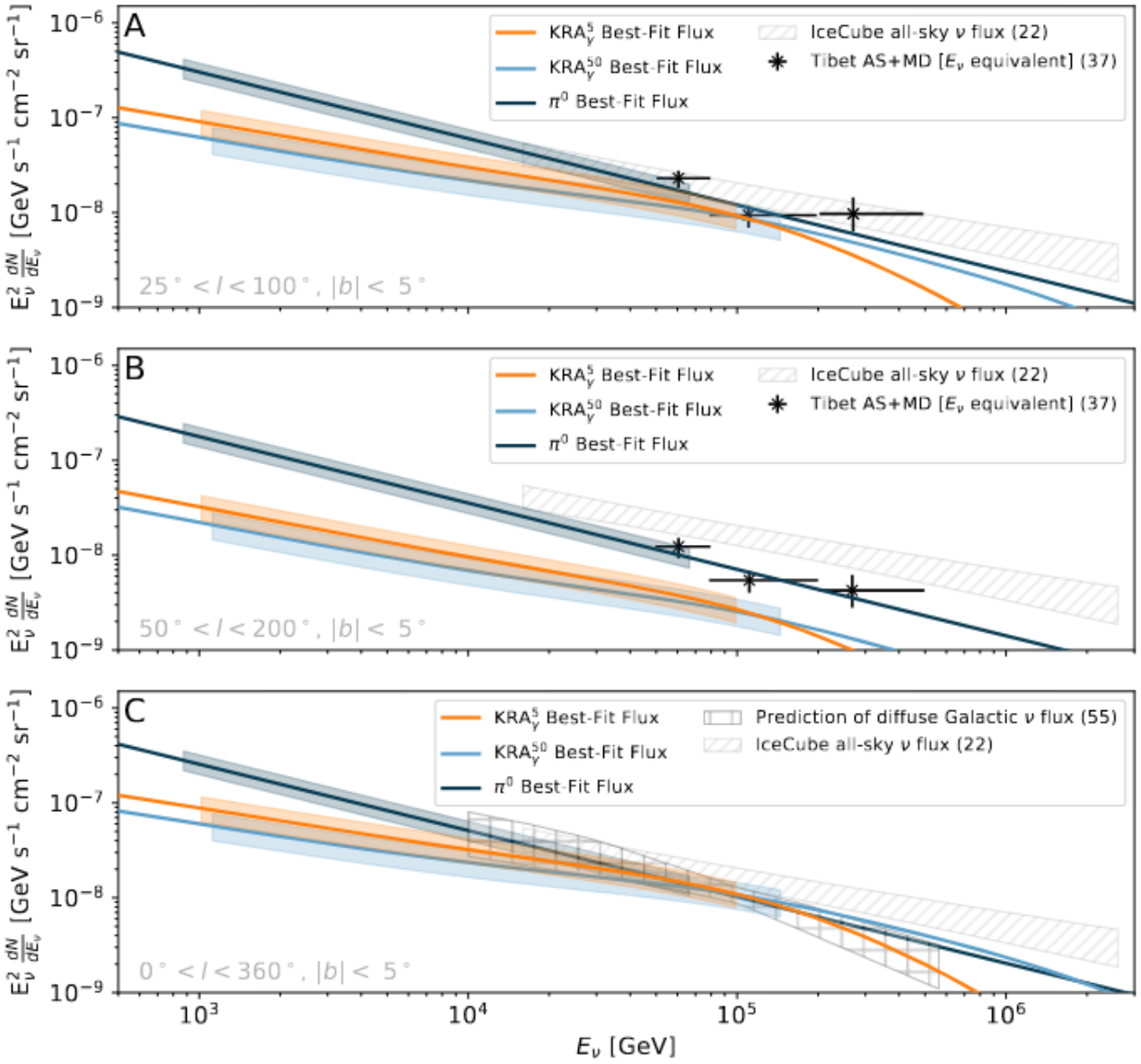


The Neutrino Eye: IceCube

Cubic-kilometer neutrino telescope at the geographic South Pole

Digital Optical Modules detect Cherekov light from charged lepton resulting from neutrino-ice interaction

Karen Andeen and Matthias Plum for the IceCube Collaboration. (2019). *Three-dimensional layout of the neutrino detector.*



IceCube Collaboration. (2023). *Observation of high-energy neutrinos from the Galactic plane.* Science.

The Neutrino Eye: IceCube

Cubic-kilometer neutrino telescope at the South Pole

Digital Optical Modules (DOMs) detect Cherekov light from charged lepton resulting from neutrino-ice interaction

π^0: spatial probability template based on gamma-ray emission

KRA_γ^5: constant, model-averaged spectrum over the sky with 5 PeV cosmic-ray energy cutoff

KRA_γ^{50}: 50 PeV cosmic-ray energy cutoff

BIG PICTURE

- **Test hypothesis of TeV halo contribution to Positron Excess**

- **Bridge gap between the predicted neutrino flux from cosmic ray propagation models and IceCube data**

BIG PICTURE

- **Test hypothesis of TeV halo contribution to Positron Excess**
- **Bridge gap between the predicted neutrino flux from cosmic-ray propagation models and IceCube data**

RESEARCH FOCUS:

Determine whether for some cosmic ray model, how much emission from unresolved sources are needed to explain diffuse gamma-ray and neutrino flux.

METHODS

1. Take diffuse gamma-ray model from **GALPROP** (including pion decay, IC, and Bremsstrahlung) for inner and outer galaxy

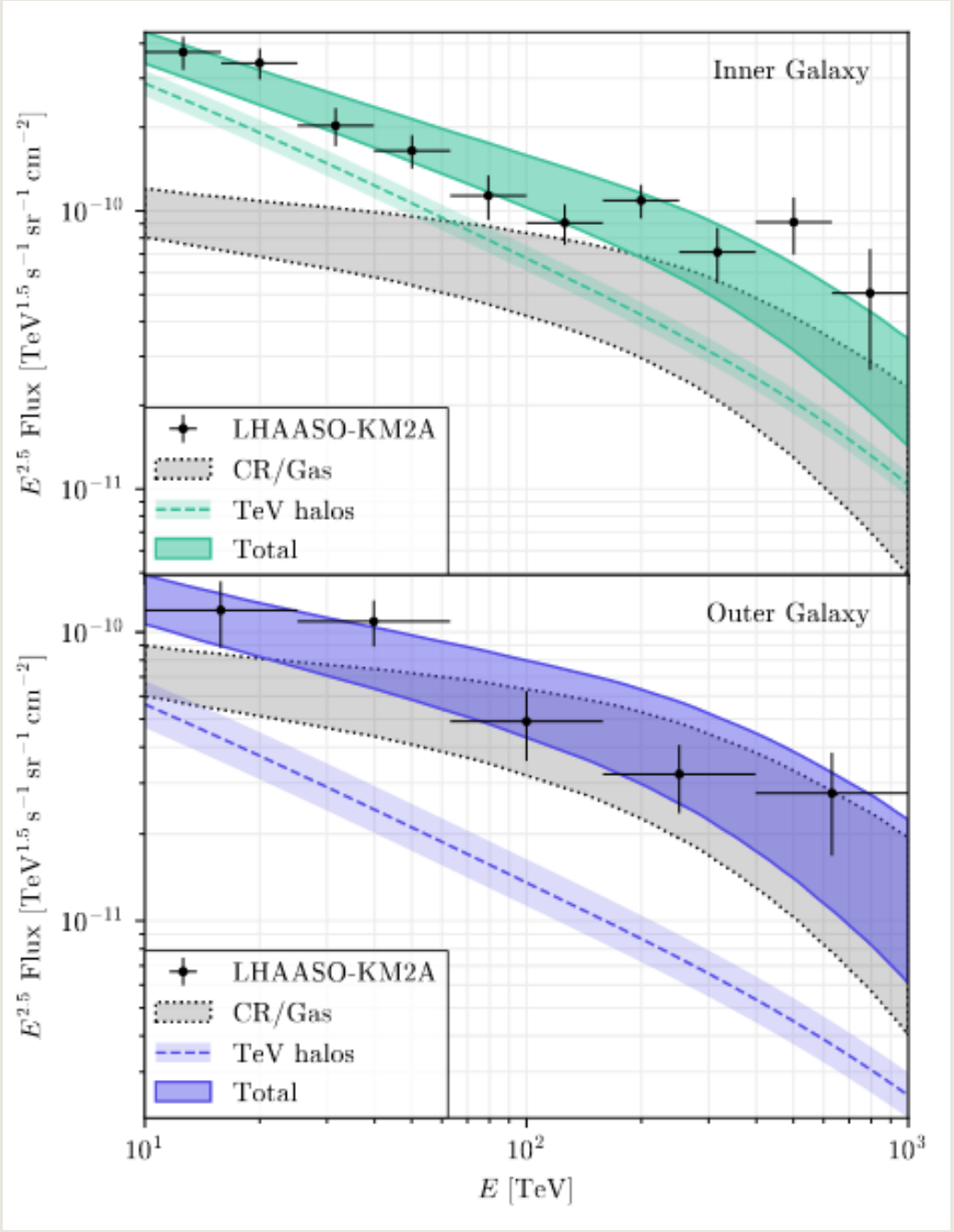
Moskalenko, I. et al. (2017).

GALPROP:

Numerical code for modeling propagation of relativistic charged particles and their respective diffuse emission in the Milky Way

1. Take diffuse gamma-ray model from GALPROP (including pion decay, IC, and Bremsstrahlung) for inner and outer galaxy

2. Add a model for the unresolved **TeV Halo** population

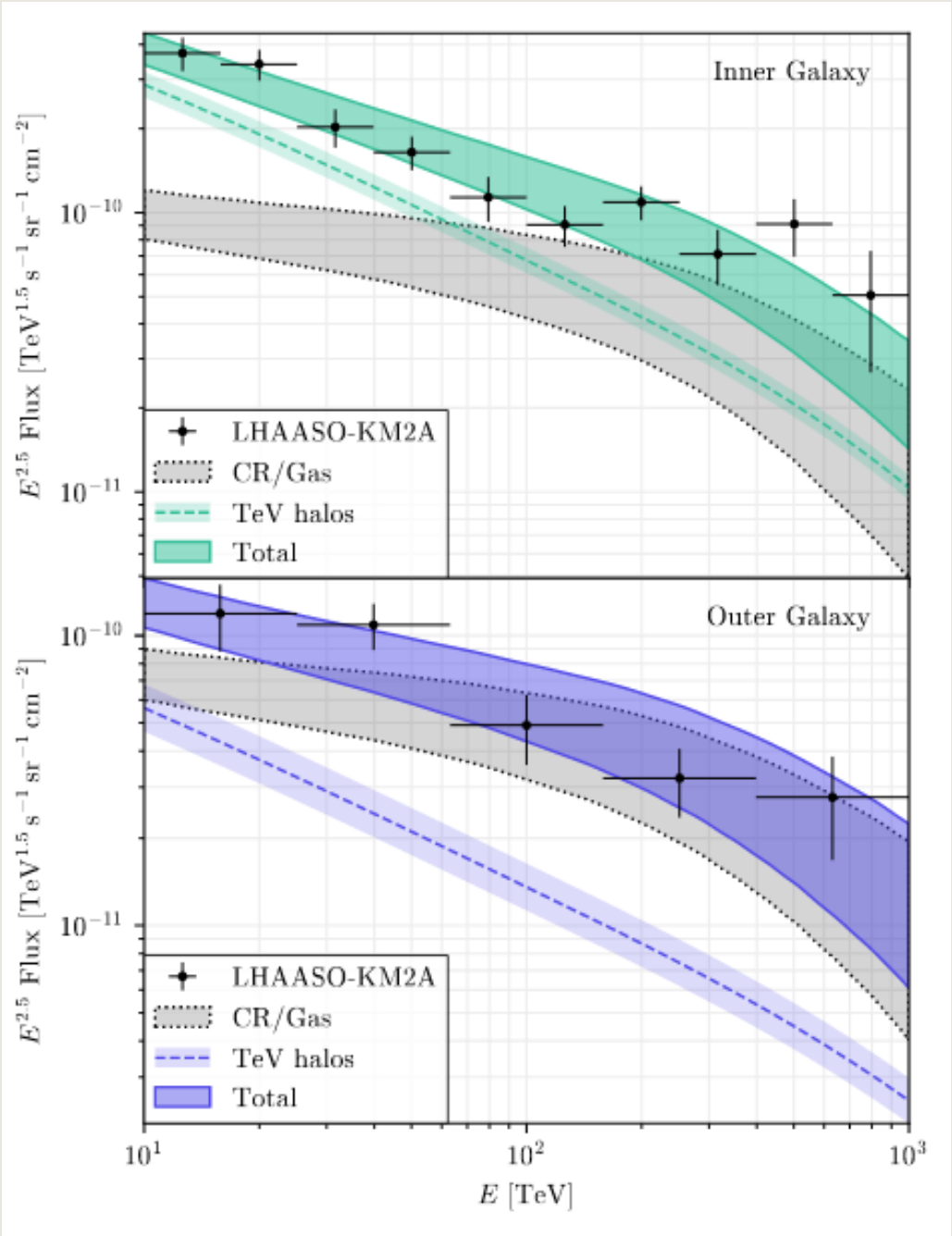


Dekker, A., Holst, I., Simon, E., etc.. (2024). *Diffuse Ultra-High-Energy Gamma-Ray Emission From TeV Halos.*

1. Take diffuse gamma-ray model from GALPROP (including pion decay, IC, and Bremsstrahlung) for inner and outer galaxy

2. Add a model for the unresolved TeV Halo population

3. Sum GALPROP and TeV Halo fluxes to create total predicted gamma-ray spectrum



Dekker, A., Holst, I., Simon, E., etc.. (2024). *Diffuse Ultra-High-Energy Gamma-Ray Emission From TeV Halos.*

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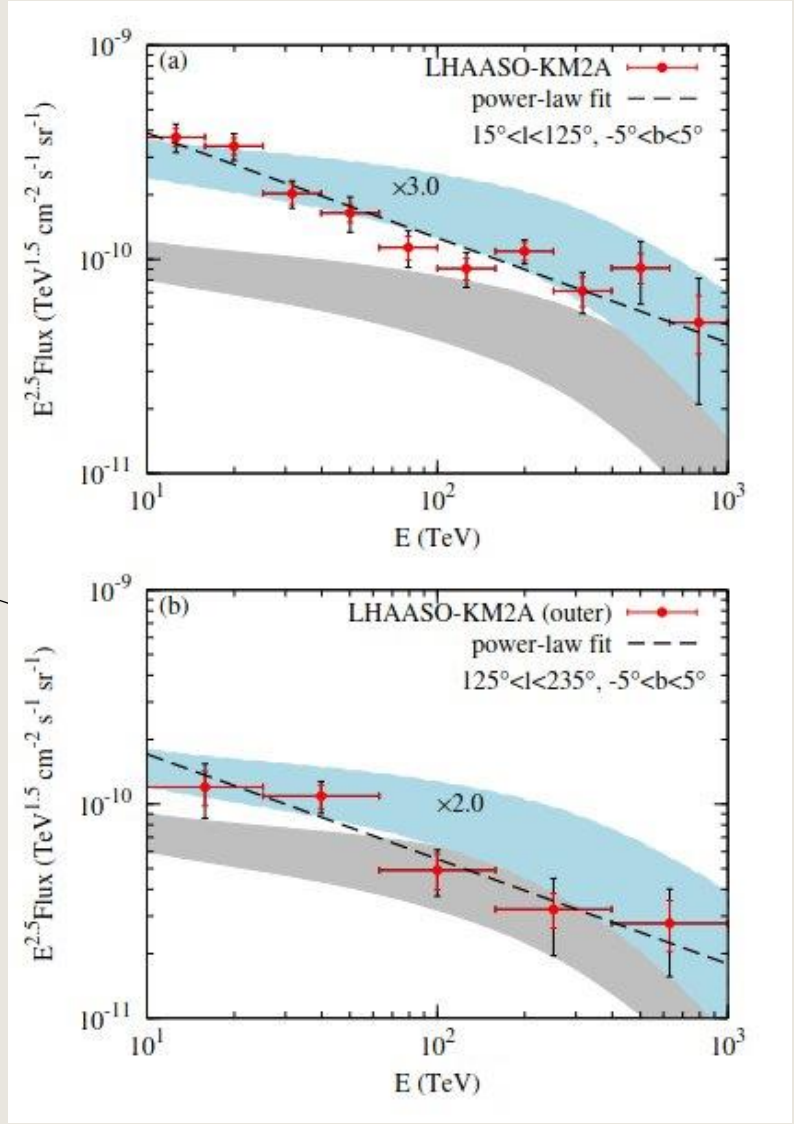
3. Sum GALPROP and TeV Halo fluxes to create total predicted gamma-ray spectrum

4. Compare final model to **LHAASO** data



LHAASO Collaboration (2023). *Measured fluxes of diffuse γ-ray emission in the inner and outer Galaxy regions.* arXiv:2305.05372v2

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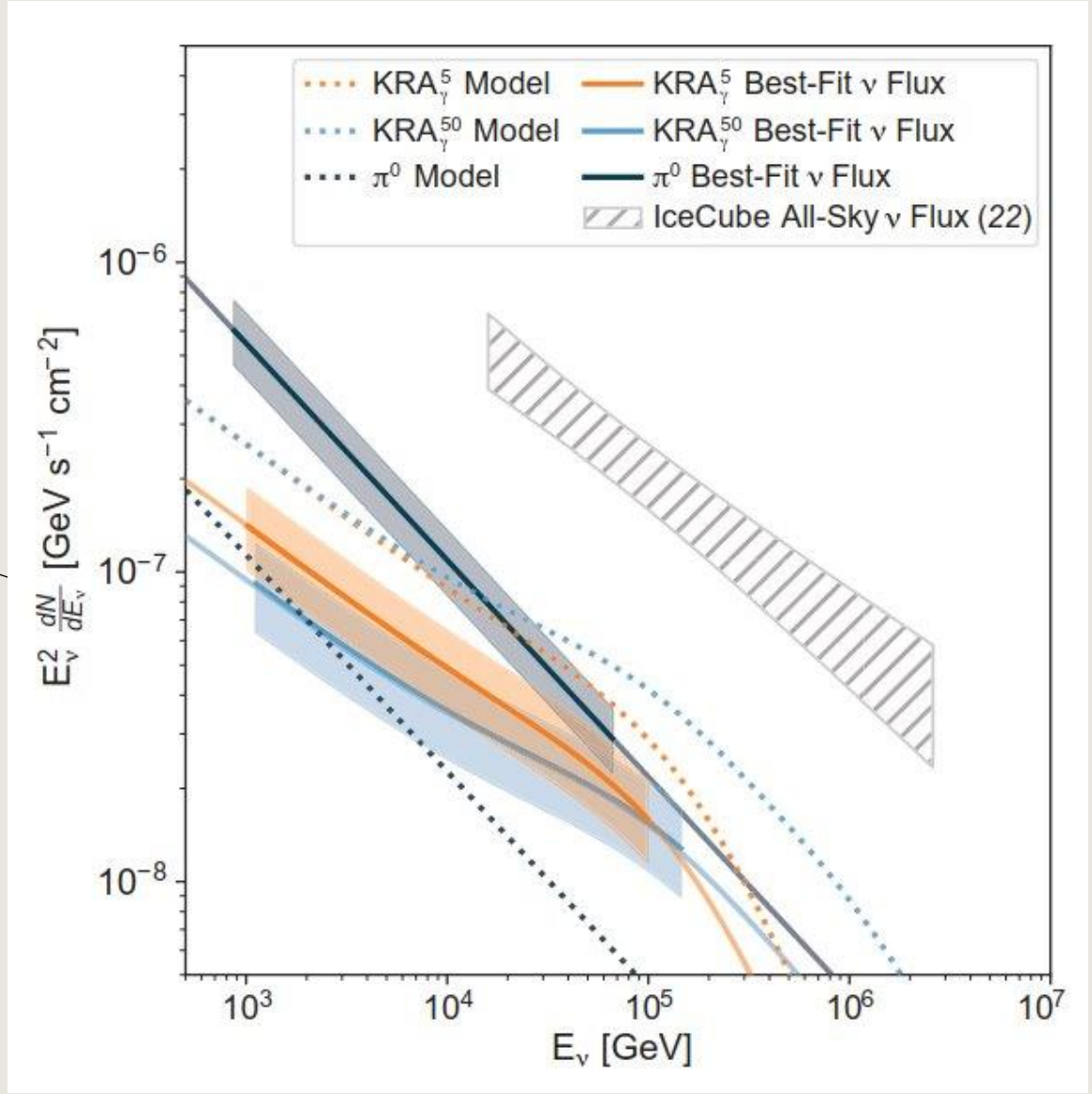
2. Add a model for the unresolved TeV Halo population

3. Sum GALPROP and TeV Halo fluxes to create total predicted gamma-ray spectrum

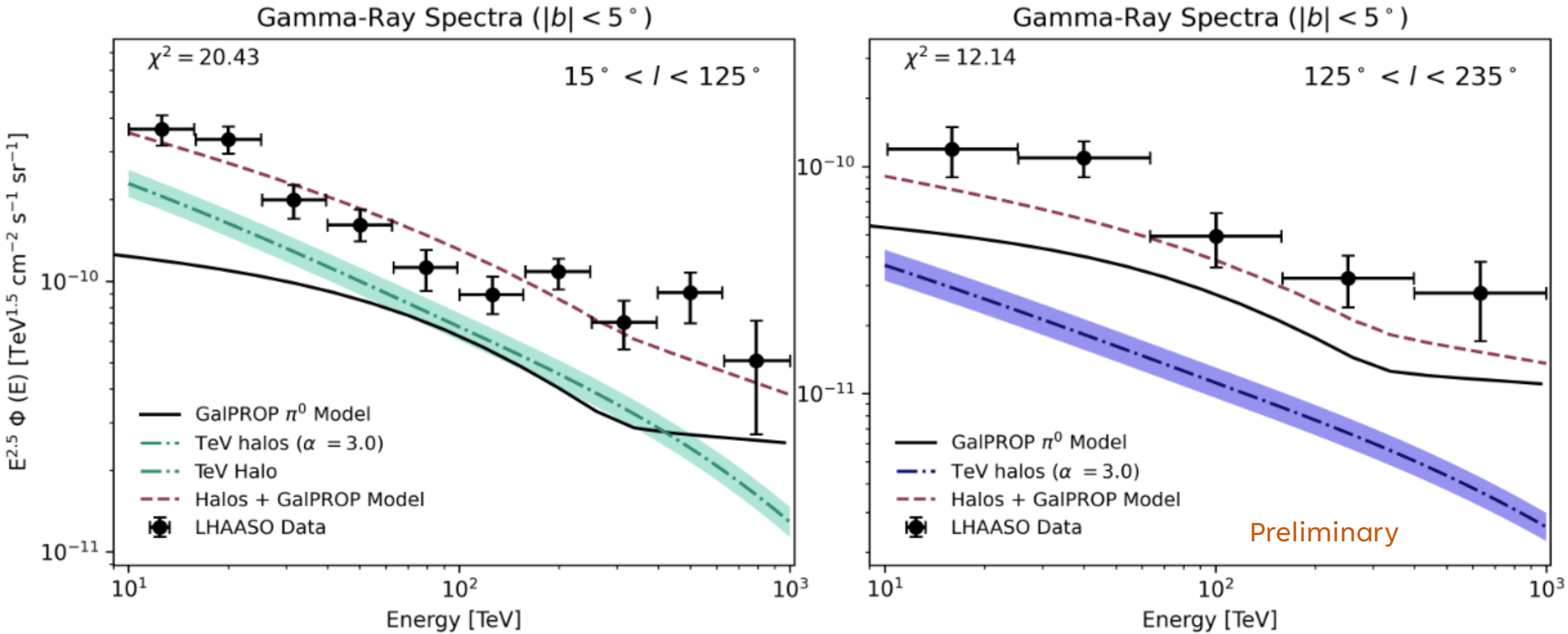
4. Compare final model to LHAASO data

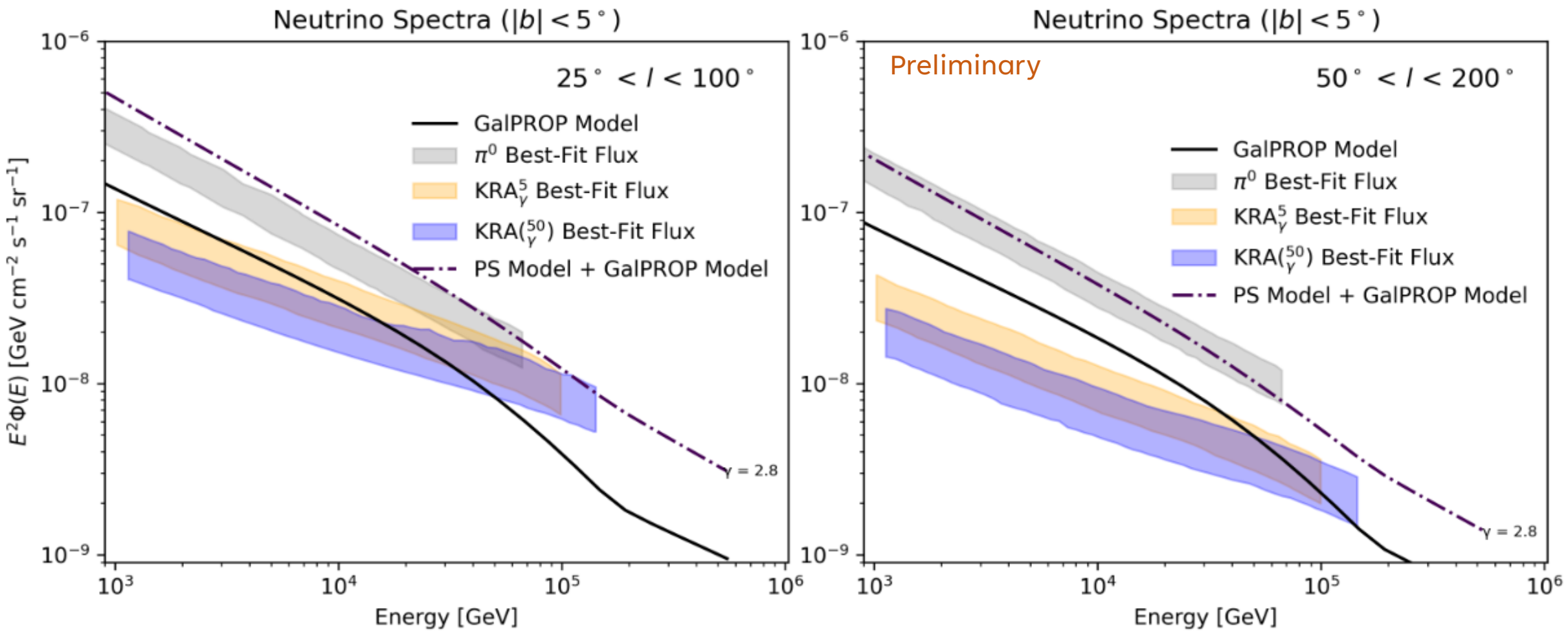
5. Pion-decay component of the gamma-ray model made into direct prediction for the neutrino flux

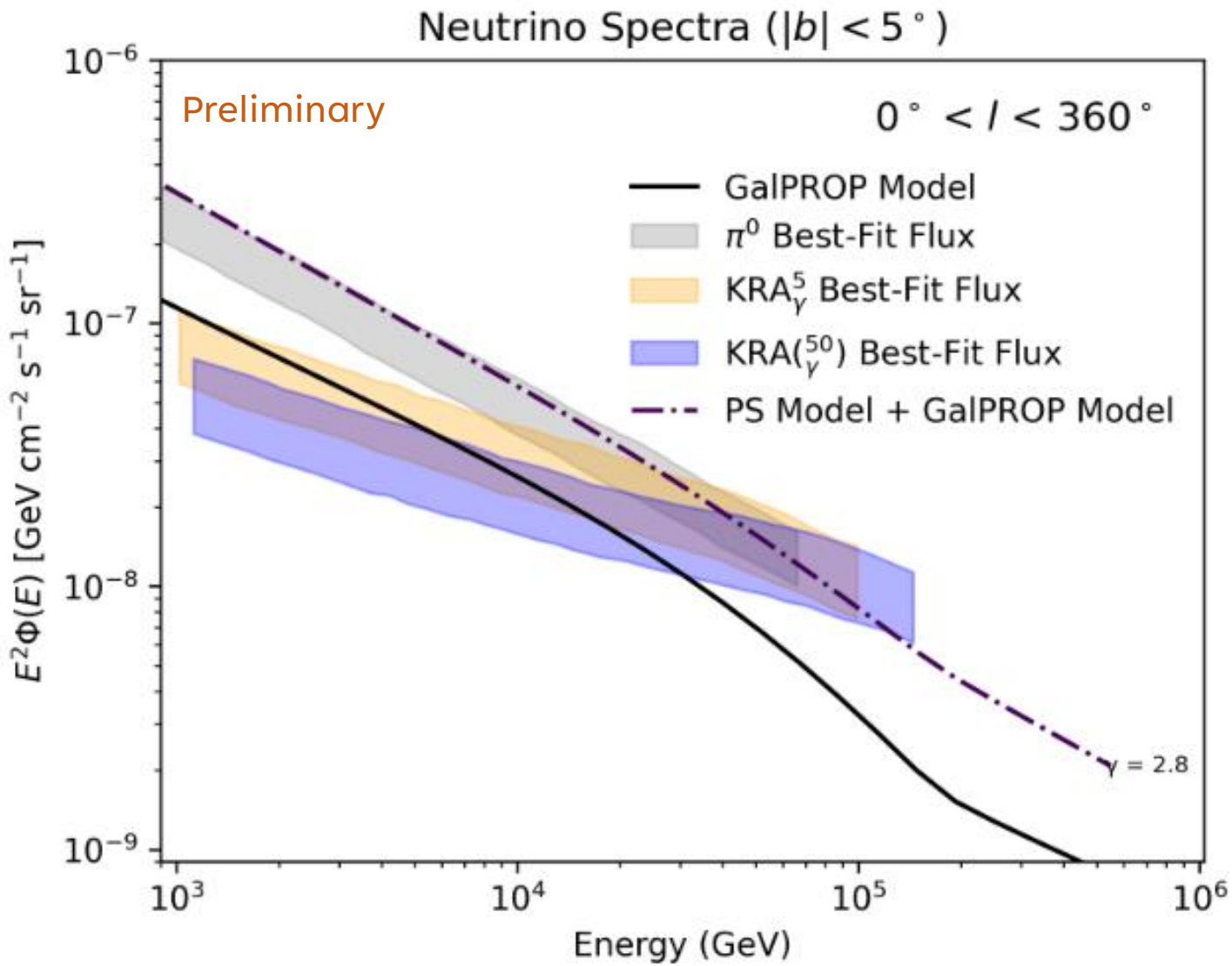


IceCube Collaboration. (2023). *Observation of high-energy neutrinos from the Galactic plane*. Science.

RESULTS


Gamma-Ray Spectra ($|b| < 5^\circ$)
$\chi^2 = 20.43$
$15^\circ < l < 125^\circ$
GalPROP π^0 Model
TeV halos ($\alpha = 3.0$)
TeV Halo
Halos + GalPROP Model
LHAASO Data
$E^{2.5}\,\Phi\,(E)$ [TeV$^{1.5}$ cm^{-2} s^{-1} sr^{-1}]
Energy [TeV]
Gamma-Ray Spectra ($|b| < 5^\circ$)
$\chi^2 = 12.14$
$125^\circ < l < 235^\circ$
GalPROP π^0 Model
TeV halos ($\alpha = 3.0$)
Halos + GalPROP Model
LHAASO Data
Preliminary
Energy [TeV]


Neutrino Spectra (|b| < 5°)
25° < l < 100°
GalPROP Model
π⁰ Best-Fit Flux
KRA$_\gamma^5$ Best-Fit Flux
KRA($_\gamma^{50}$) Best-Fit Flux
PS Model + GalPROP Model
γ = 2.8
$E^2\Phi(E)$ [GeV cm^{-2} s^{-1} sr^{-1}]
Energy [GeV]
Neutrino Spectra (|b| < 5°)
Preliminary
50° < l < 200°
GalPROP Model
π⁰ Best-Fit Flux
KRA$_\gamma^5$ Best-Fit Flux
KRA($_\gamma^{50}$) Best-Fit Flux
PS Model + GalPROP Model
γ = 2.8
Energy [GeV]


Neutrino Spectra (|b| < 5°)
Preliminary
0° < l < 360°
GalPROP Model
π⁰ Best-Fit Flux
KRA$_\gamma^5$ Best-Fit Flux
KRA($_\gamma^{50}$) Best-Fit Flux
PS Model + GalPROP Model
γ = 2.8
$E^2\Phi(E)$ [GeV cm^{-2} s^{-1} sr^{-1}]
Energy (GeV)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^3
10^4
10^5
10^6

CONCLUSION

- **A multi-messenger framework** in development to combine baseline cosmic-ray models, new source populations like TeV Halos and Point Source models, and observational data from LHAASO and IceCube.

- **Preliminary results** show that our baseline models alone are insufficient. Adding a new component like unresolved TeV halos significantly improves the fit to the gamma-ray data. Likewise, PS models improve our neutrino fits to the IceCube benchmarks.

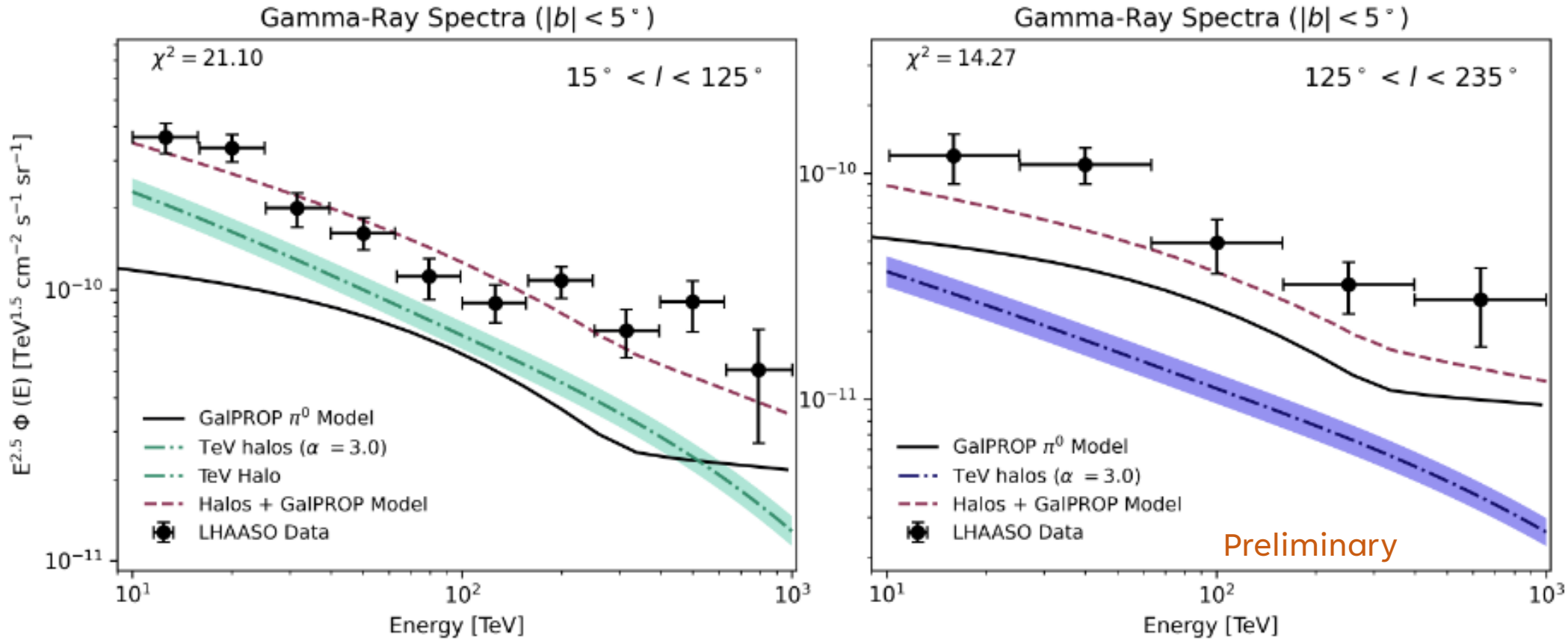
- **The analysis will be running** a full-scale, systematic study across 80 models to provide new constraints on cosmic-ray propagation in our galaxy.

QUESTIONS?

Thank you!

BACKUP SLIDES

ALTERNATE COSMIC RAY MODEL (B)



Best-fit Efficiency (η): 0.0241 (2.41%)
Best-fit Spectral Index (α): 3.00
Minimum Reduced Chi-Squared (χ^2/dof): 2.40