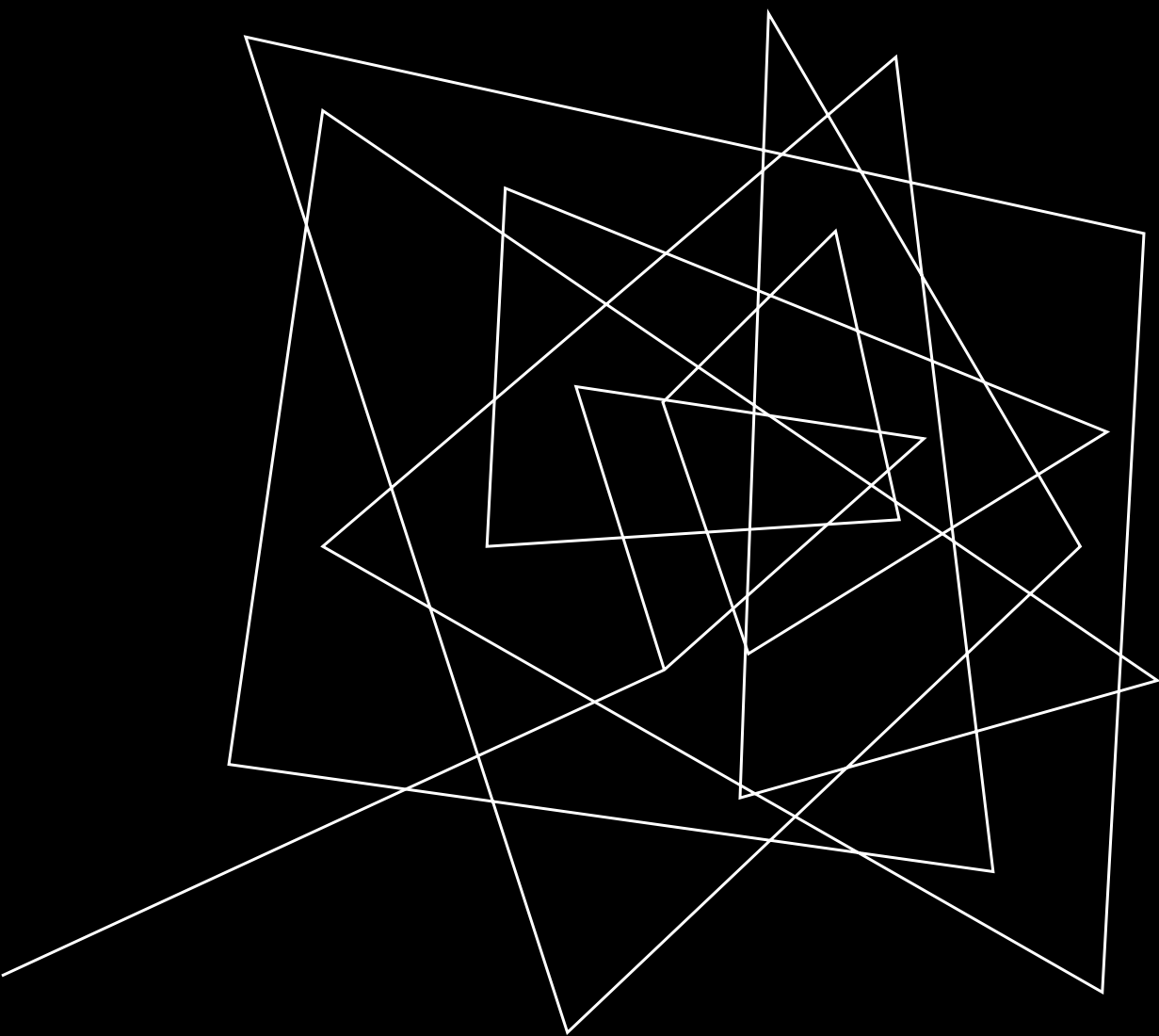




A MULTIMESSENGER ANALYSIS OF THE HIGH- ENERGY MILKY WAY: SOURCE POPULATIONS CONTRIBUTE SIGNIFICANTLY TO ICECUBE'S GALACTIC NEUTRINO FLUX

Alisha Roberts¹, Dan Hooper¹,
Ilias Cholis², Samyak Jain¹



BACKGROUND

Cosmic Rays

Highly energetic particles



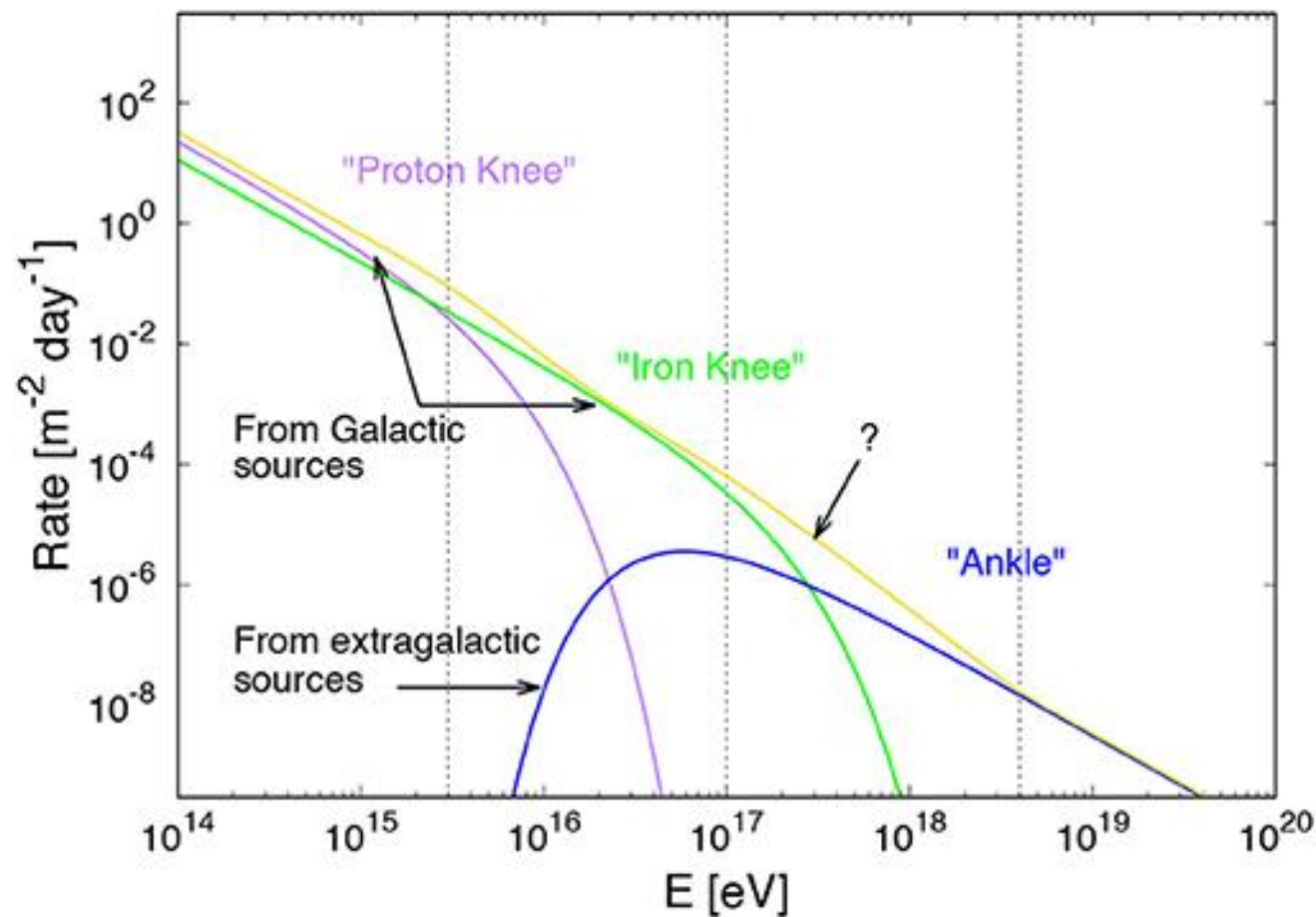
IceCube Collaboration (2012). *Rendering of cosmic rays hitting Earth.*

Galactic

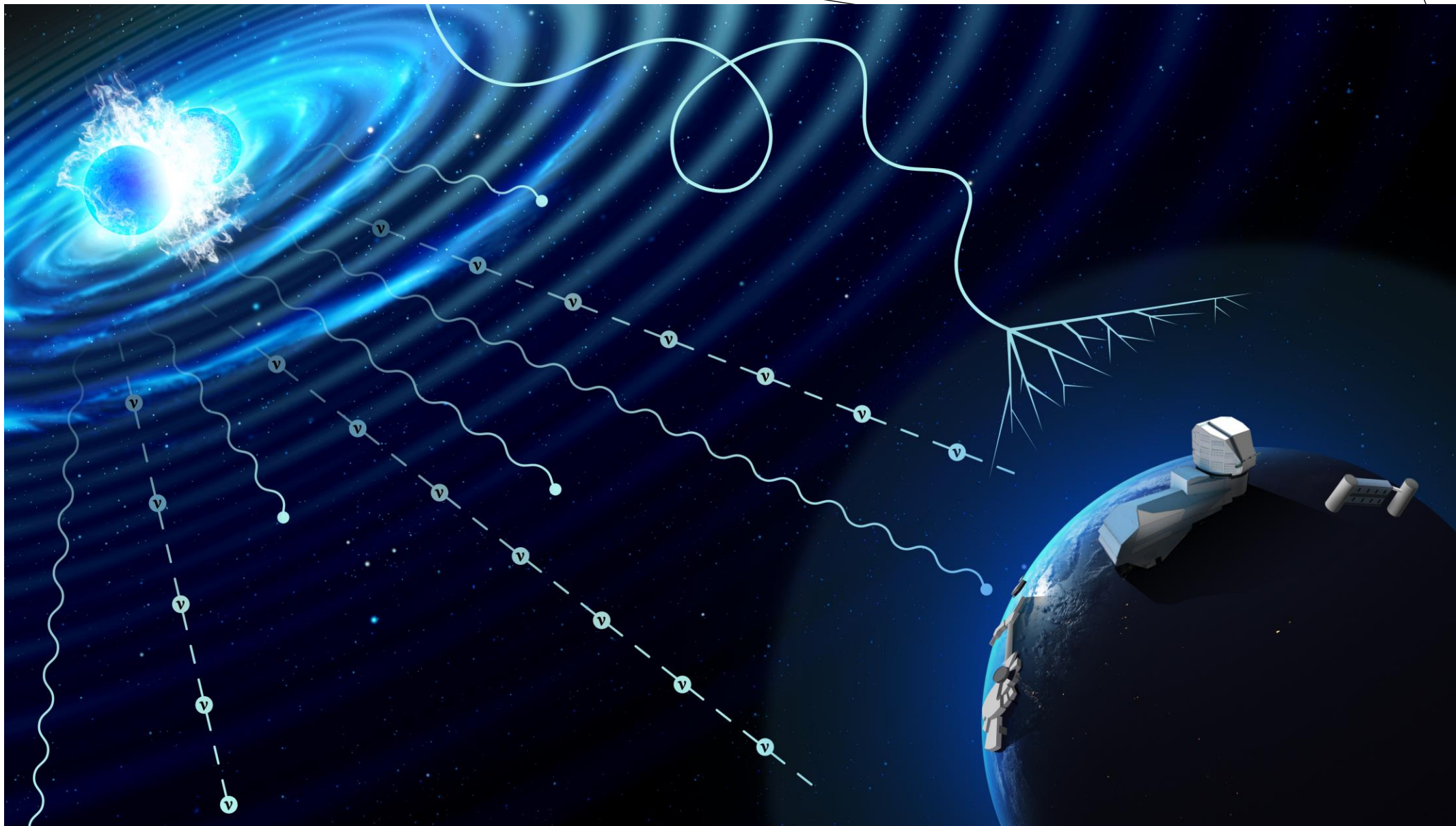
Cosmic Rays

Highly energetic particles

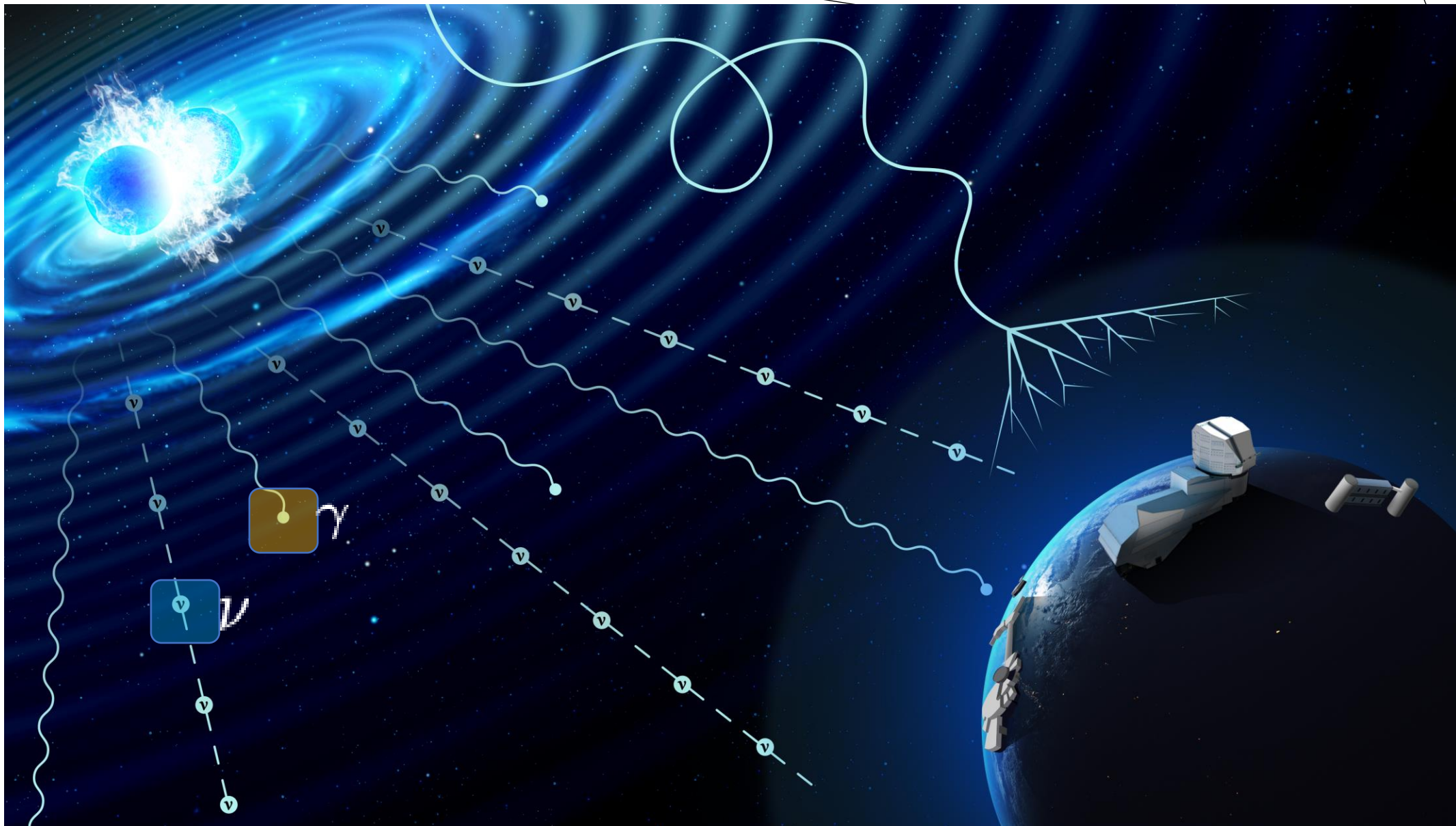
Spectrum by galactic sources generally defined by power-law



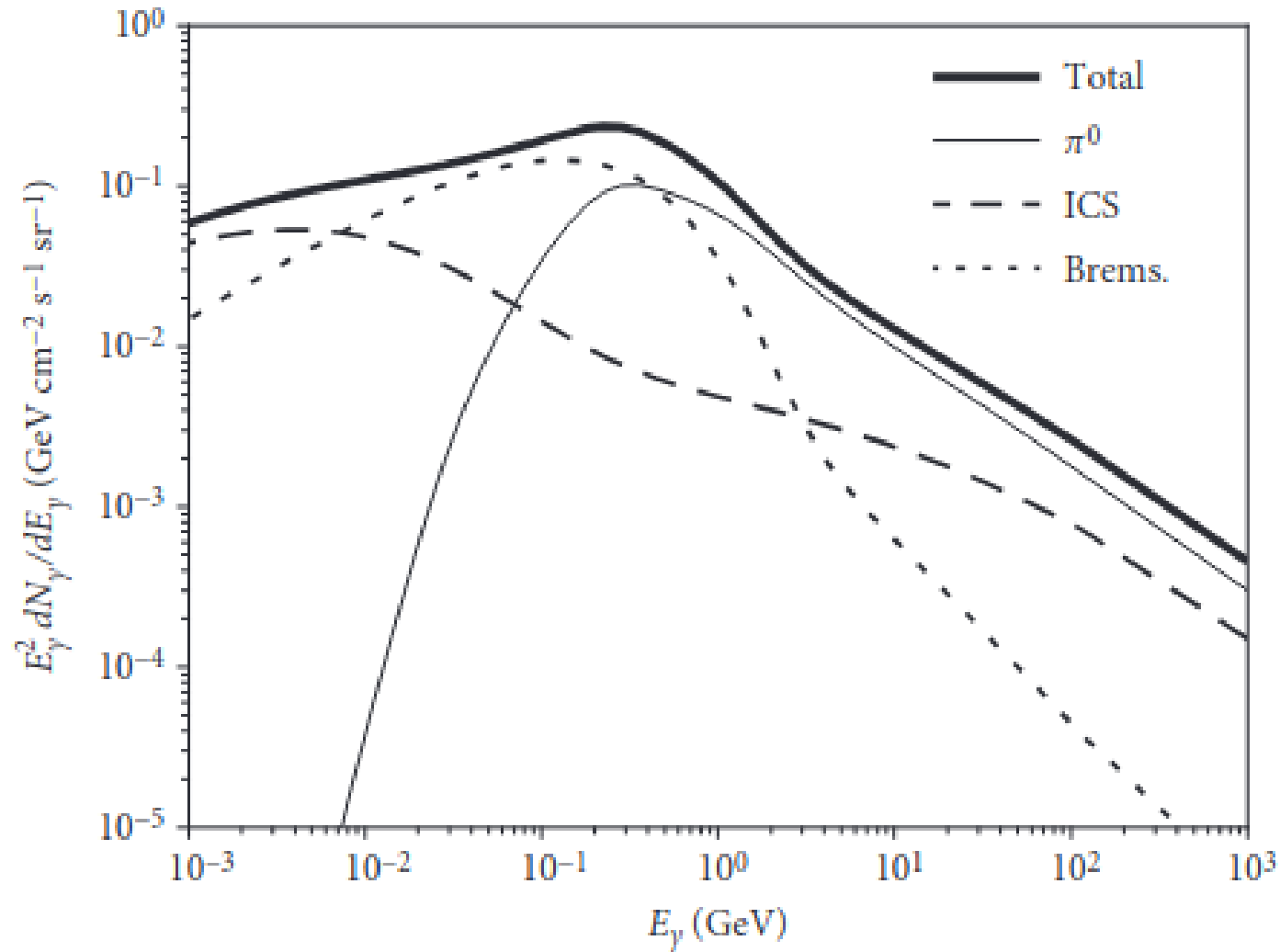
Alves Batista, R., et al. (2019). *Open Questions in Cosmic-Ray Research at Ultrahigh Energies*. Frontiers in Astronomy and Space Sciences.



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



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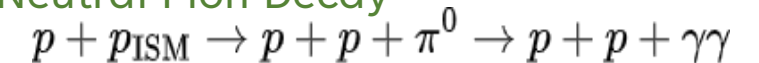
Gamma-rays

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

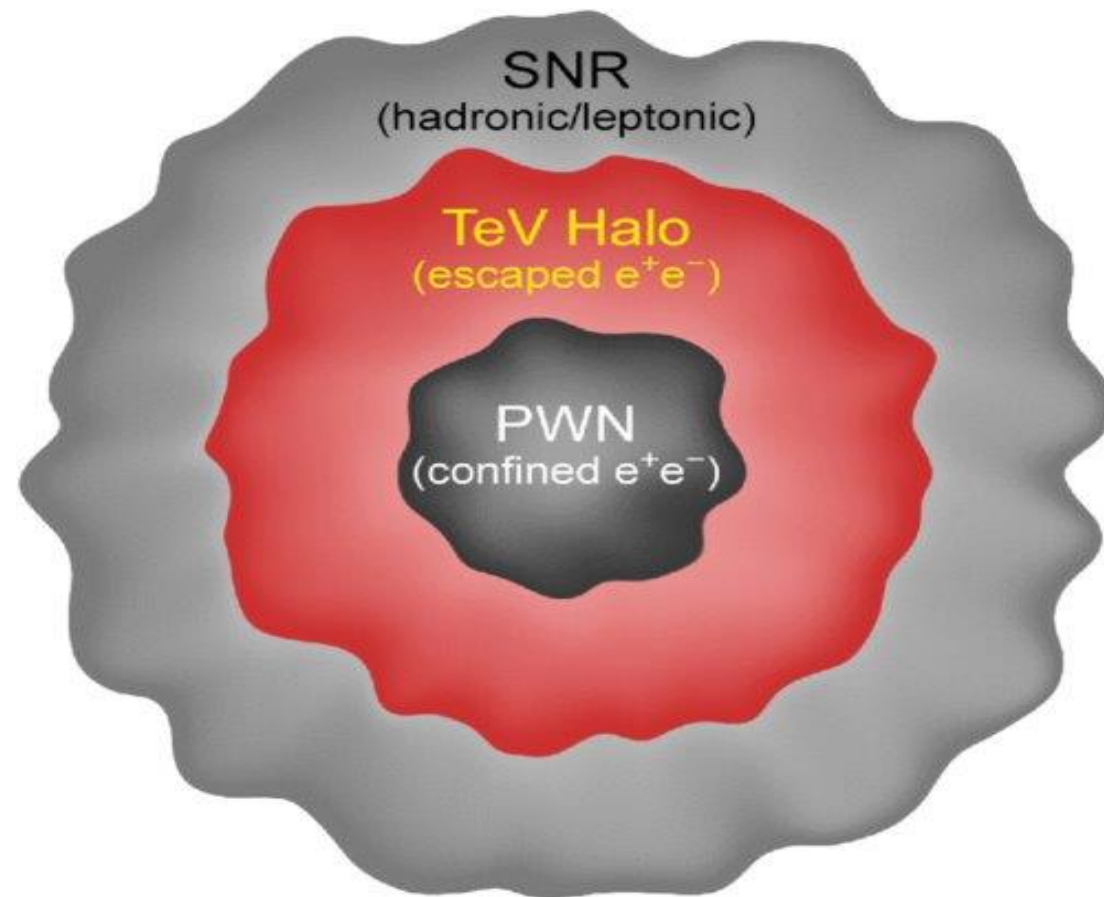
✚ Trace regions where high energy particles are interacting

■ Produced both **leptonically** and **hadronically**:

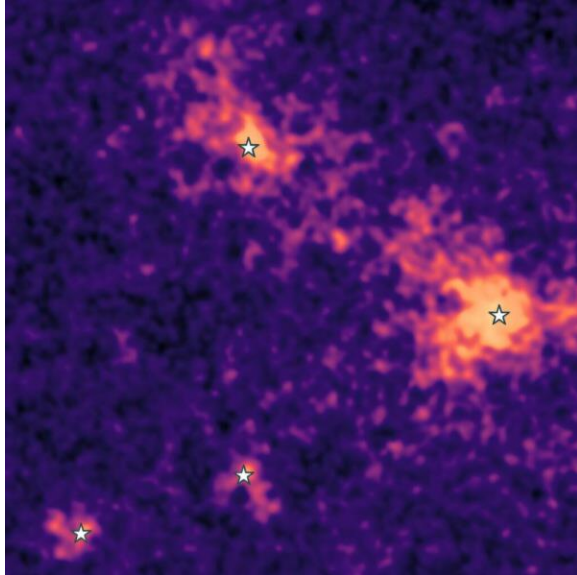
- Inverse Compton Scattering
- Bremsstrahlung
- Neutral Pion Decay



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



Sudoh, T., Linden, T., Beacom, J. (2019) *TeV Halos are Everywhere: Prospects for New Discoveries*. arXiv:1902.08203



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?

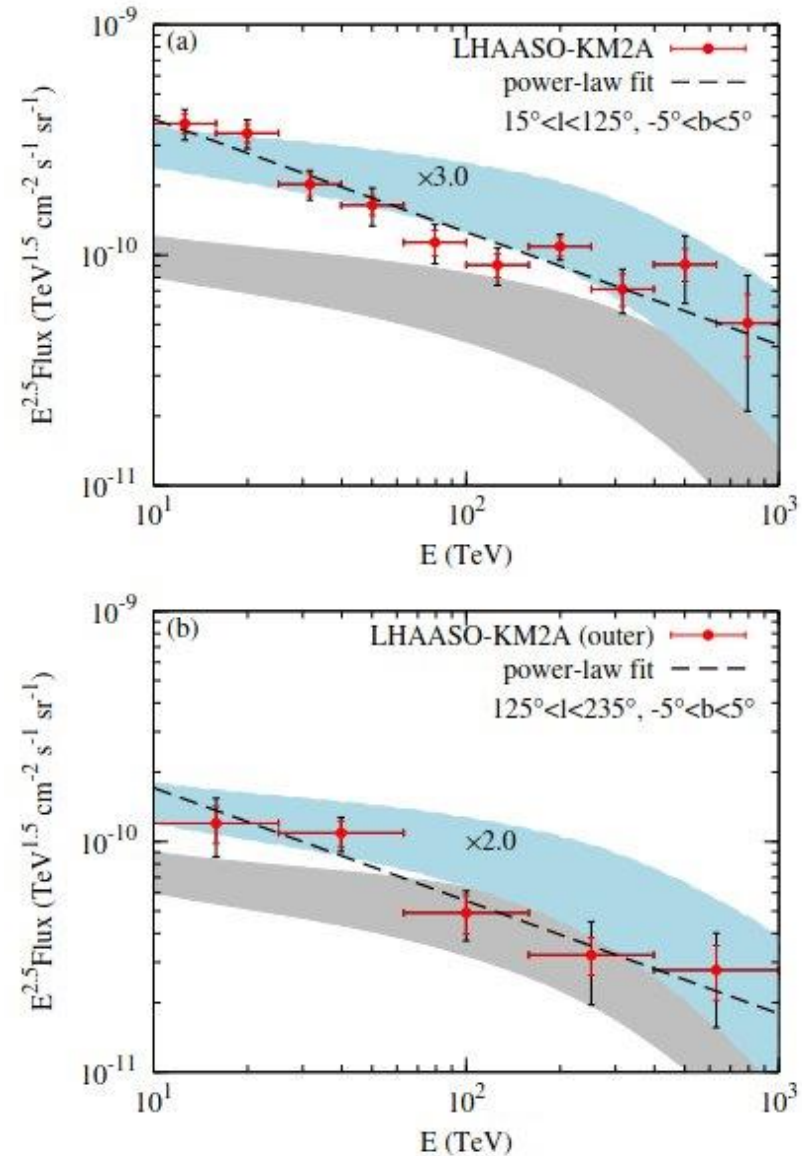
The combined, overlapping glow from thousands of unresolved TeV halos throughout the galaxy could be a significant contributor to the diffuse gamma-ray background that LHAASO is measuring

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.



+ Points directly to source

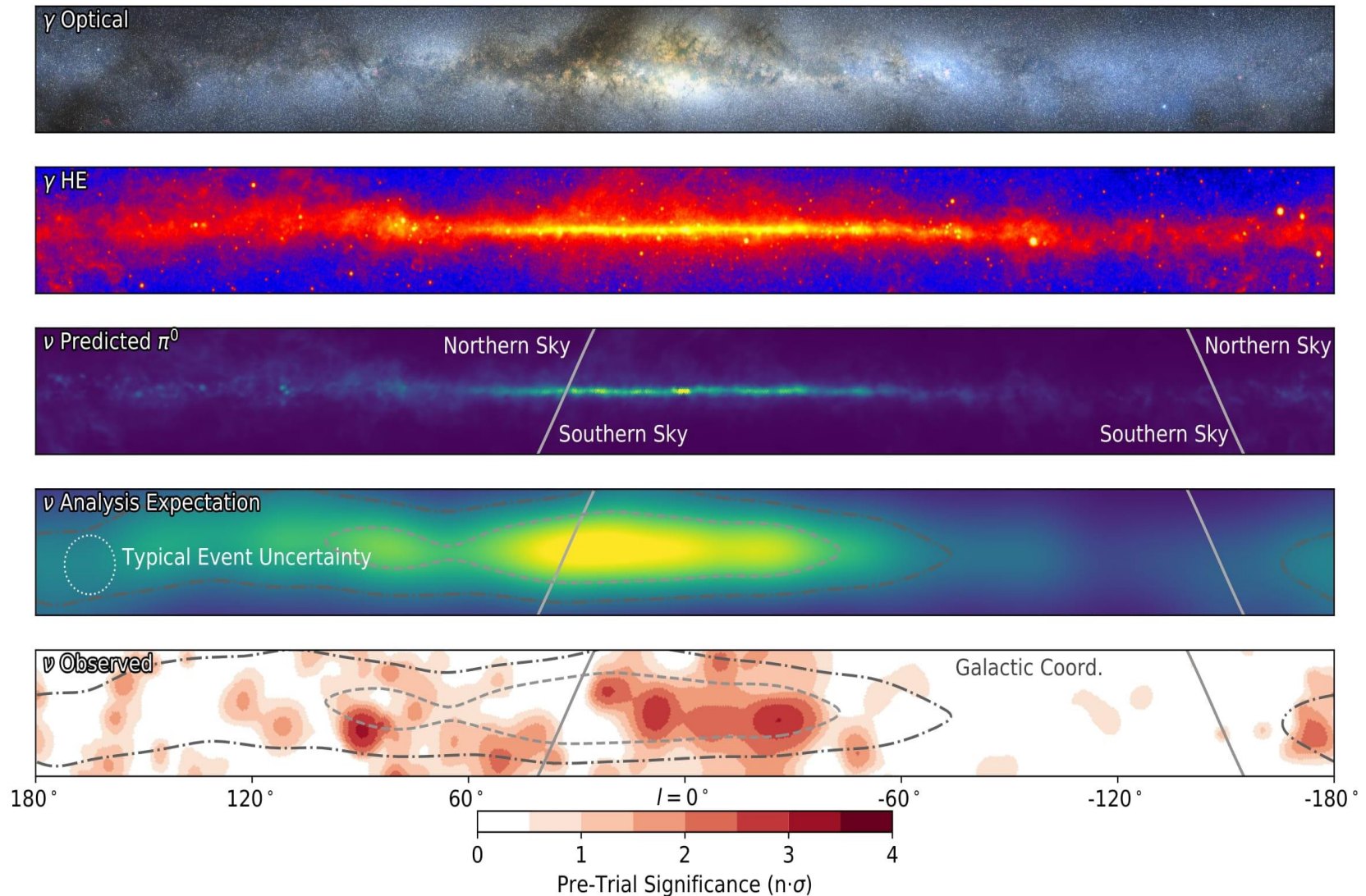
- Difficult to detect due to neutral charge and small cross section

Neutrinos

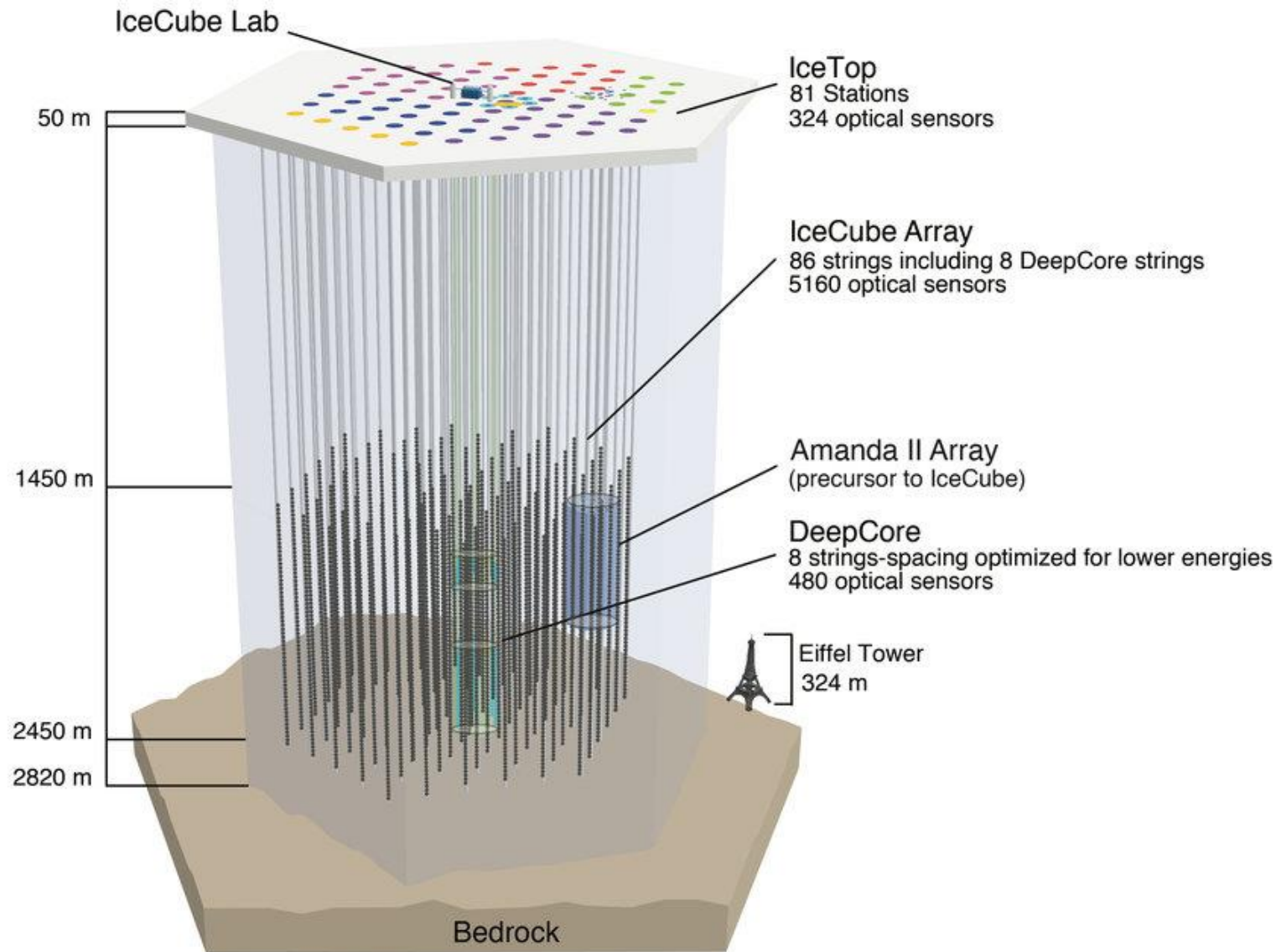
Produced through hadronic interactions (smoking gun!)

Charged and neutral pions are produced together ($\pi^+ : \pi^- : \pi^0 \approx 1 : 1 : 1$), so hadronic ν emission tracks hadronic γ emission, with $E_\nu \approx E_\gamma/2$

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



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 Cherenkov 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.*

The Neutrino Eye: IceCube

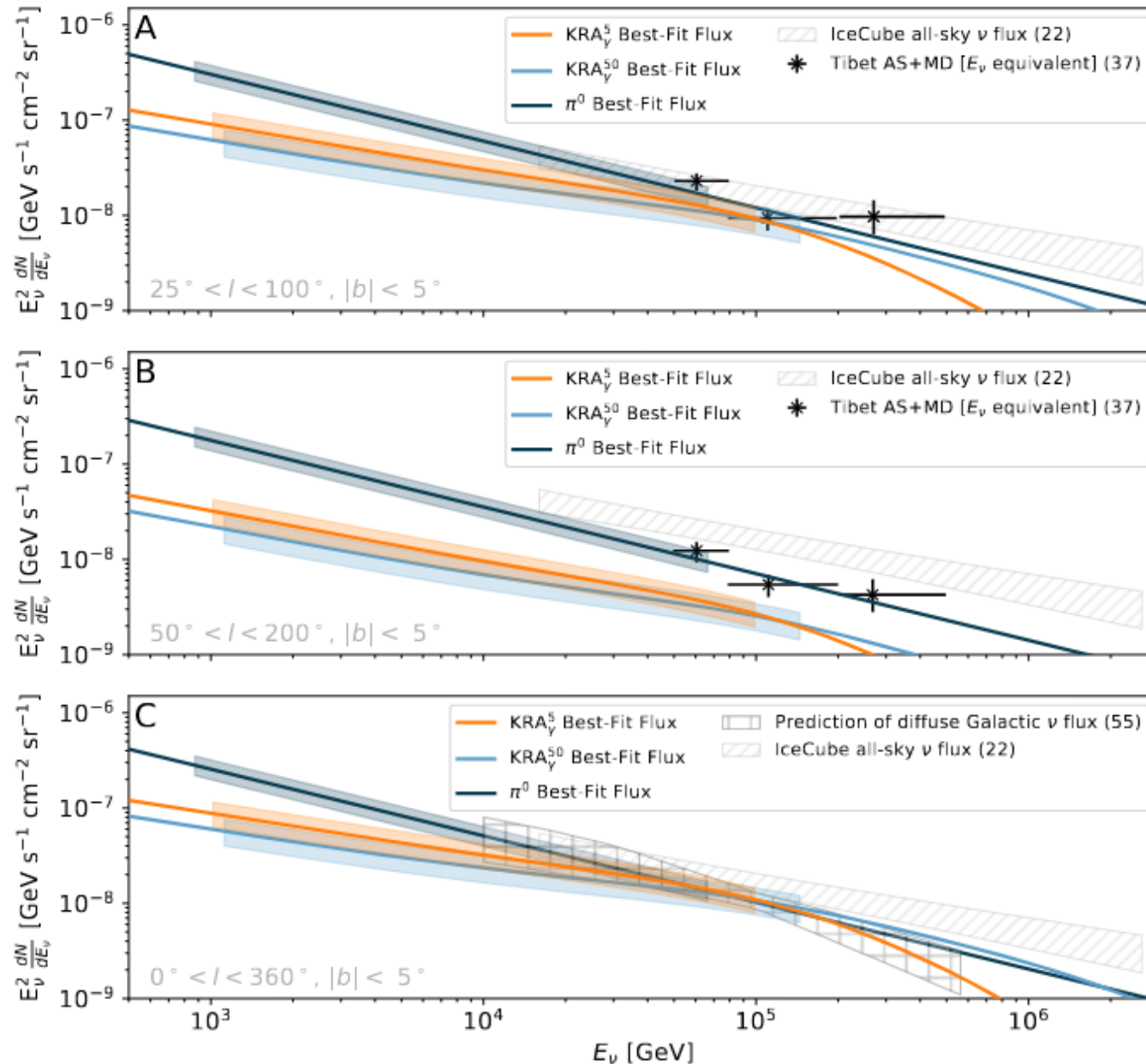
Cubic-kilometer neutrino telescope at the South Pole

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

π° : spatial probability template based on Fermi-LAT gamma-ray sky

KRA_γ^5 : KRA_γ^5 : spectral index varies across the sky (avg. $\approx E^{-2.5}$), 5 PeV cutoff

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



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

TeV Halo MC

Apply proportionality between the pulsar's luminosity to its efficiency and spindown power

- Spindown power relates to the pulsar's period, moment of inertia, spindown timescale, etc.

$$L_{\gamma} = \eta \dot{E}_{\text{rot}}$$

Assign each pulsar an age and spindown power

- Normalize the MW's pulsar population and draw from spatial distribution

$$n_{\text{pulsar}} \propto R^{2.35} e^{-R/1.53 \text{ kpc}} e^{-|z|/z_s}$$

Account for gamma rays being attenuated and apply mask to brightest of simulated TeV Halos

- Masking found to have significant impact on fits and varies as a function of the efficiency

Gamma Rays

Diffuse (hadronic)

- GALPROP, six CR models
- Free A_G :
 - Overall CR density, accounts for calibration uncertainties

TeV Halos (leptonic)

- Monte Carlo pulsar population
- Free η :
 - Spindown power to gamma rays
- Free α_γ :
 - Halo spectral index

Neutrinos

Point Sources (hadronic)

- SNRs, PWNe, microquasars, ...?
- Free A_ν, α_ν :
 - Normalization, index

Fit jointly to LHAASO (gamma ray) and IceCube (neutrino)
- χ^2 over all parameter space, repeated for all six cosmic-ray models

A series of white, thin, overlapping geometric lines on a black background, forming a complex, abstract pattern on the left side of the slide.

RESULTS

Cosmic-Ray Model	GALPROP Normalization A_G	TeV Halos			Neutrino Sources				Total $\sum \chi^2$
		η (%)	α_γ	χ_γ^2	A_ν	α_ν	χ_ν^2	$\Delta\chi_\nu^2$	
A	$1.62^{+0.35}_{-0.12}$	$6.4^{+2.4}_{-6.1}$	$3.50^{+0.00}_{-0.11}$	22.06	$9.95^{+4.91}_{-3.90} \times 10^{-9}$	$2.72^{+0.15}_{-0.15}$	3.72	38.23	25.78
B	$1.98^{+0.19}_{-0.30}$	$0.5^{+7.0}_{-0.3}$	$3.50^{+0.00}_{-0.13}$	23.50	$9.41^{+5.04}_{-3.85} \times 10^{-9}$	$2.72^{+0.16}_{-0.16}$	3.32	33.89	26.83
C	$2.55^{+0.20}_{-0.25}$	$0.4^{+0.4}_{-0.2}$	$3.50^{+0.00}_{-0.16}$	23.48	$9.41^{+5.24}_{-4.00} \times 10^{-9}$	$2.71^{+0.17}_{-0.16}$	3.10	31.80	26.58
D	$2.97^{+0.27}_{-0.27}$	$0.3^{+0.3}_{-0.2}$	$3.50^{+0.00}_{-0.23}$	25.41	$9.41^{+5.44}_{-4.00} \times 10^{-9}$	$2.70^{+0.17}_{-0.17}$	2.95	29.87	28.35
E	$4.00^{+0.00}_{-0.20}$	$0.1^{+0.1}_{-0.0}$	$2.68^{+0.36}_{-0.06}$	28.37	$1.05^{+0.56}_{-0.42} \times 10^{-8}$	$2.68^{+0.16}_{-0.17}$	3.22	32.10	31.59
F	$3.72^{+0.28}_{-0.31}$	$0.3^{+0.3}_{-0.2}$	$3.50^{+0.00}_{-0.18}$	22.24	$9.68^{+5.60}_{-4.03} \times 10^{-9}$	$2.69^{+0.17}_{-0.17}$	3.17	30.39	25.41
E'	$5.08^{+0.45}_{-0.78}$	$0.2^{+0.2}_{-0.1}$	$3.50^{+0.00}_{-0.77}$	26.30	$9.68^{+6.02}_{-4.26} \times 10^{-9}$	$2.66^{+0.18}_{-0.19}$	2.53	25.52	28.82

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Accounts for the fact that the CR spectrum in other parts of the MW might be higher or lower than the measurement of the CR spectrum used to calibrate GALPROP

Change in $\Delta\chi^2$ with and without neutrino point source contribution

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TeV halos possess soft spectra of $3.0 \lesssim \alpha \leq 3.5$, with averaged efficiency η up to roughly 10% within 1σ

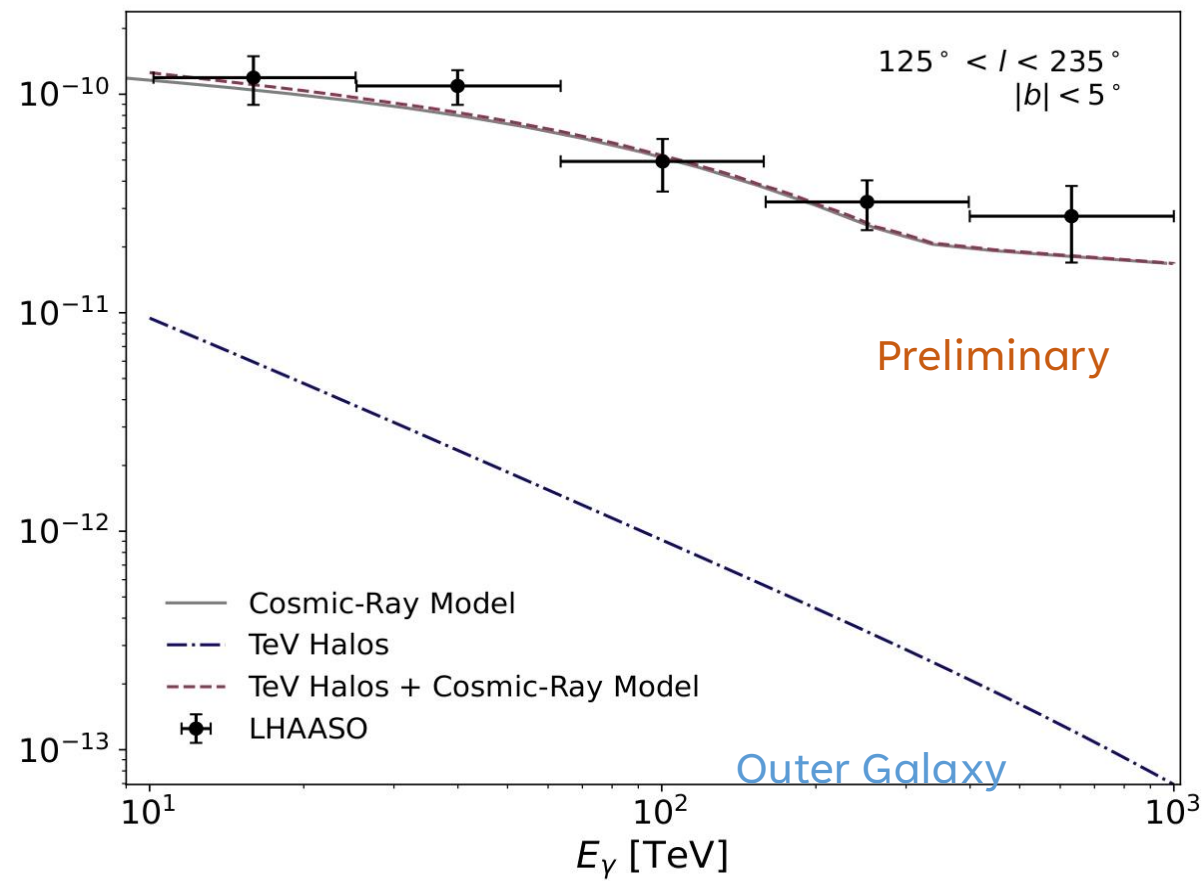
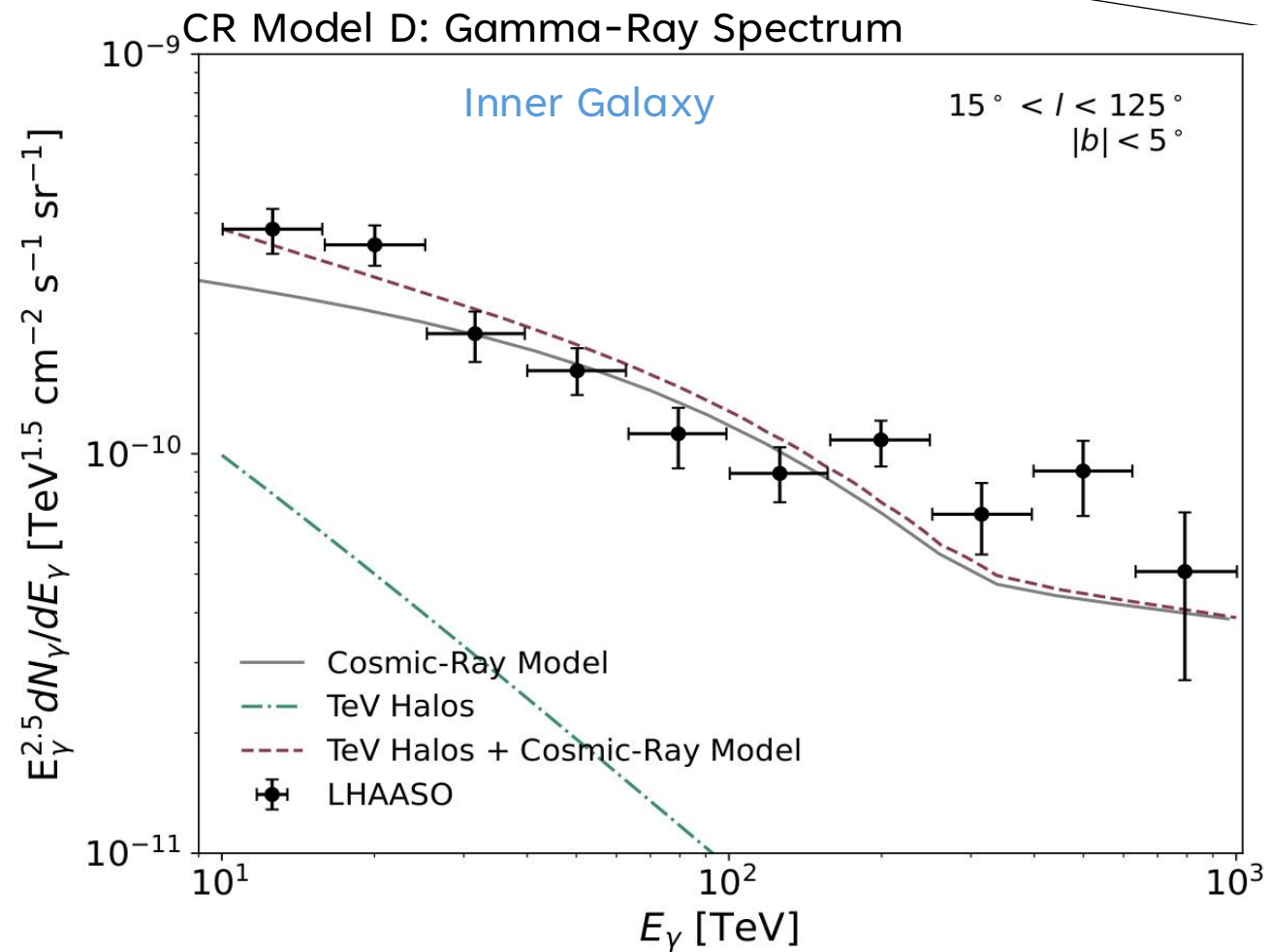
With higher AG limit, there is dominant diffuse emission, which makes the emission from the TeV halos prefer spectral index of 3.5.

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Fits generally favor CR interactions with ISM; unresolved TeV halos can contribute significantly, but are not required
 -> The γ -ray decomposition depends on the CR transport model; the need for neutrino sources does not.

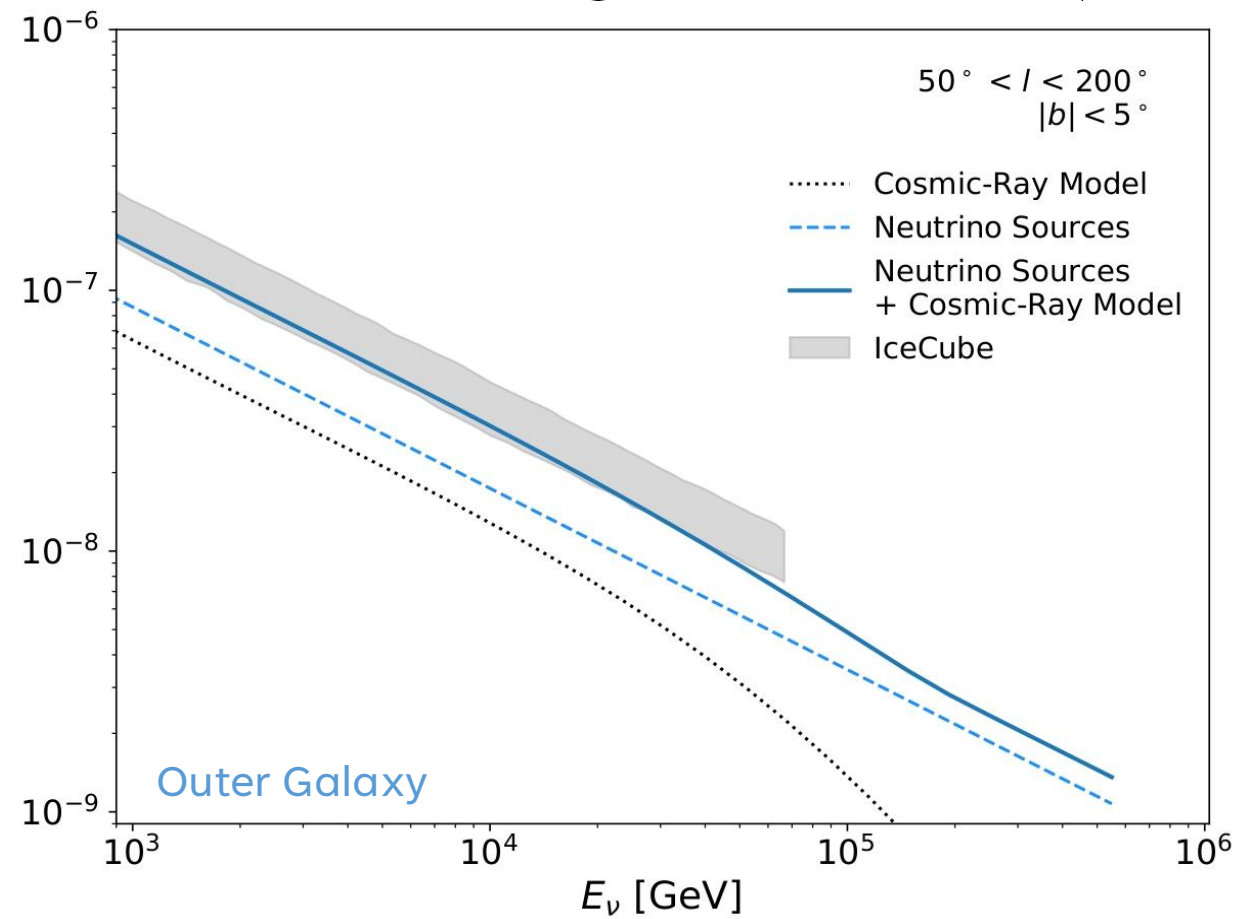
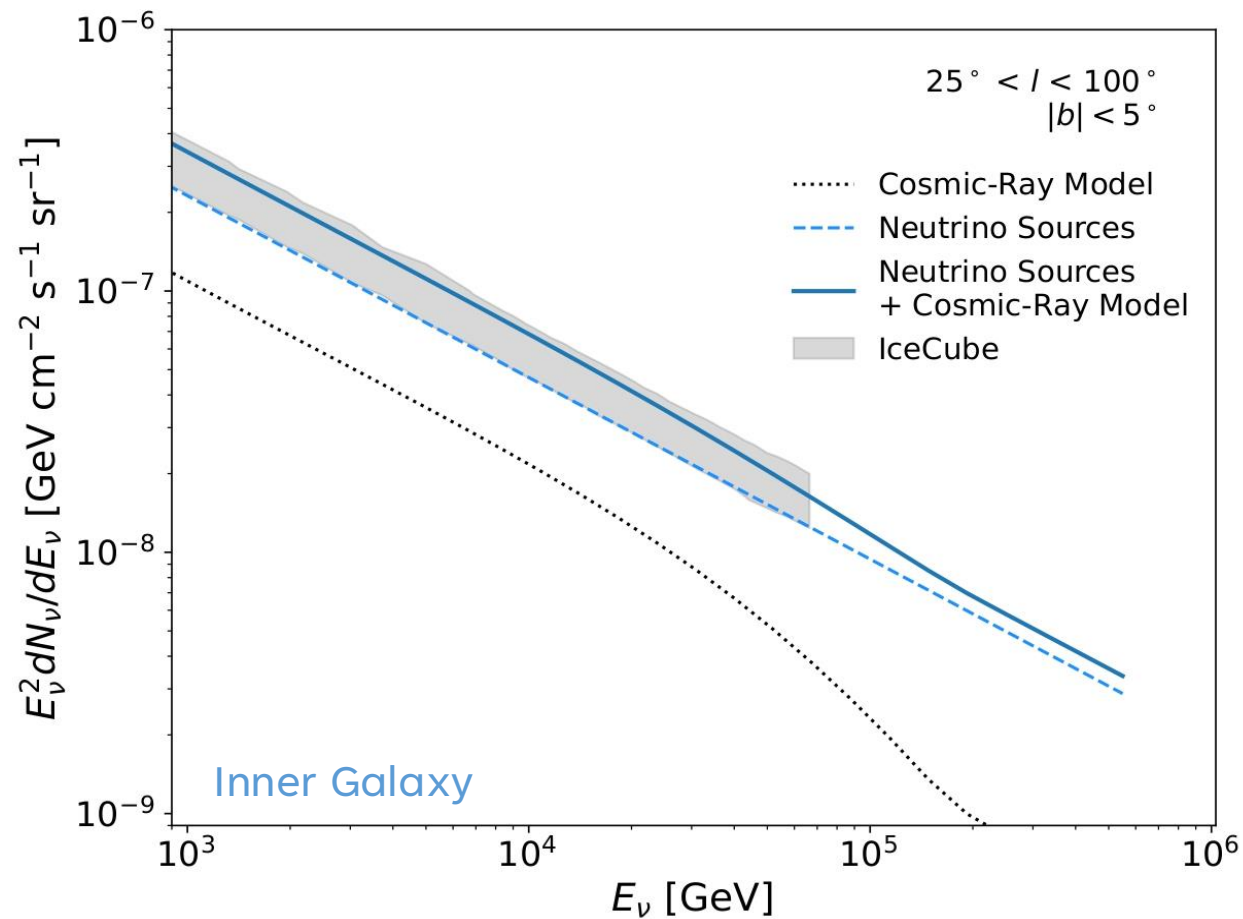
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High statistical significance for one or more neutrino source populations



Diffuse model makes up majority of data

- Limited TeV halo contribution at all energies

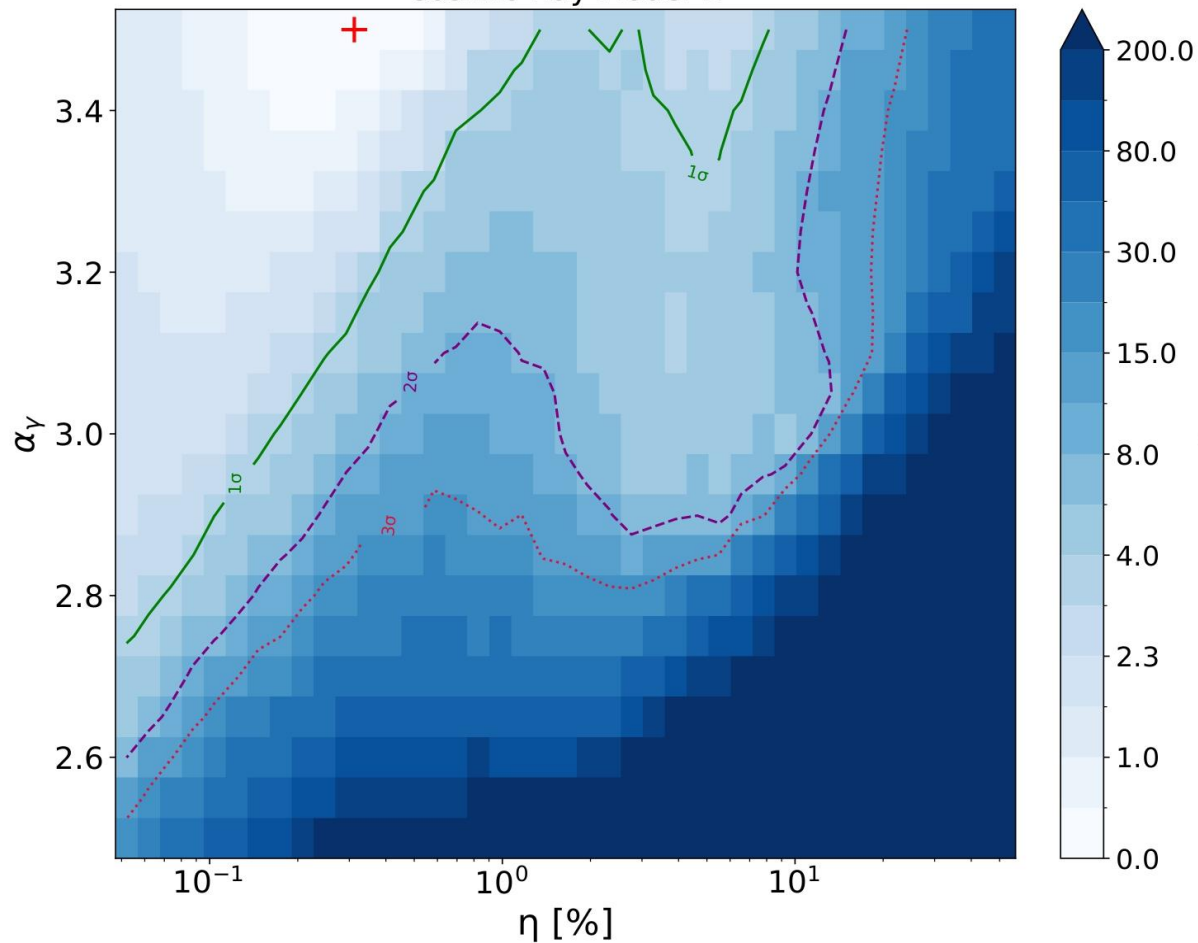


Neutrino point sources account for more than half of emission seen by IceCube

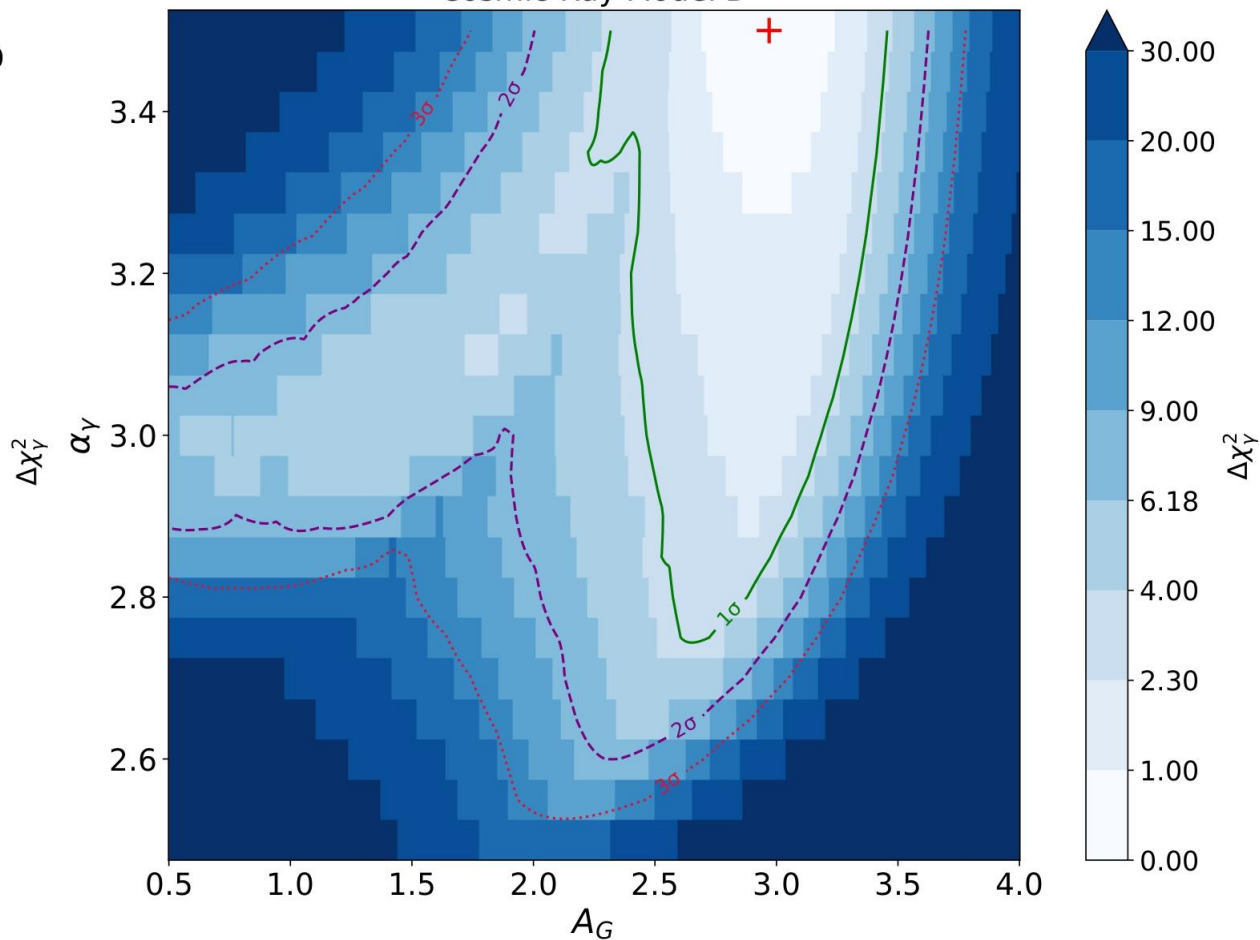
- 60-90% of total flux from unresolved sources (upper limit)
- $\gtrsim 20\%$ at 95% CL (lower limit)

Parameter Landscape

Cosmic-Ray Model D



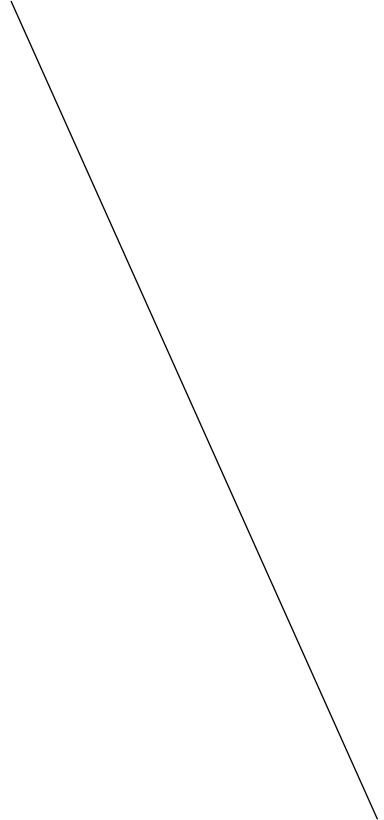
Cosmic-Ray Model D



TeV halos possess soft spectra of $3.0 \lesssim \alpha \leq 3.5$, with averaged efficiency η up to roughly 10% within 1σ

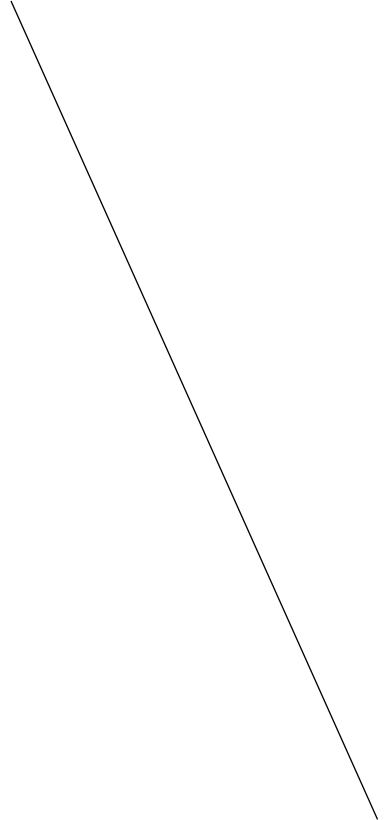
CONCLUSION

- **A multi-messenger framework** to combine baseline cosmic-ray models, new source populations like TeV Halos and Point Source models, and observational data from LHAASO and IceCube
- Our results across six CR models demonstrate the following:
 - In gamma-ray channel, the LHAASO flux is primarily recovered by the diffuse hadronic model, leaving a subdominant role for unresolved leptonic TeV halos
 - Diffuse CR–ISM emission, normalized to LHAASO, underpredicts IceCube in every model: $\Delta\chi^2 = 25.5\text{--}38.2$ in favor of adding source populations ($\alpha_v \approx 2.7$), which supply $\sim 60\text{--}90\%$ of the Galactic Plane v flux ($\gtrsim 20\%$ at 95% CL)



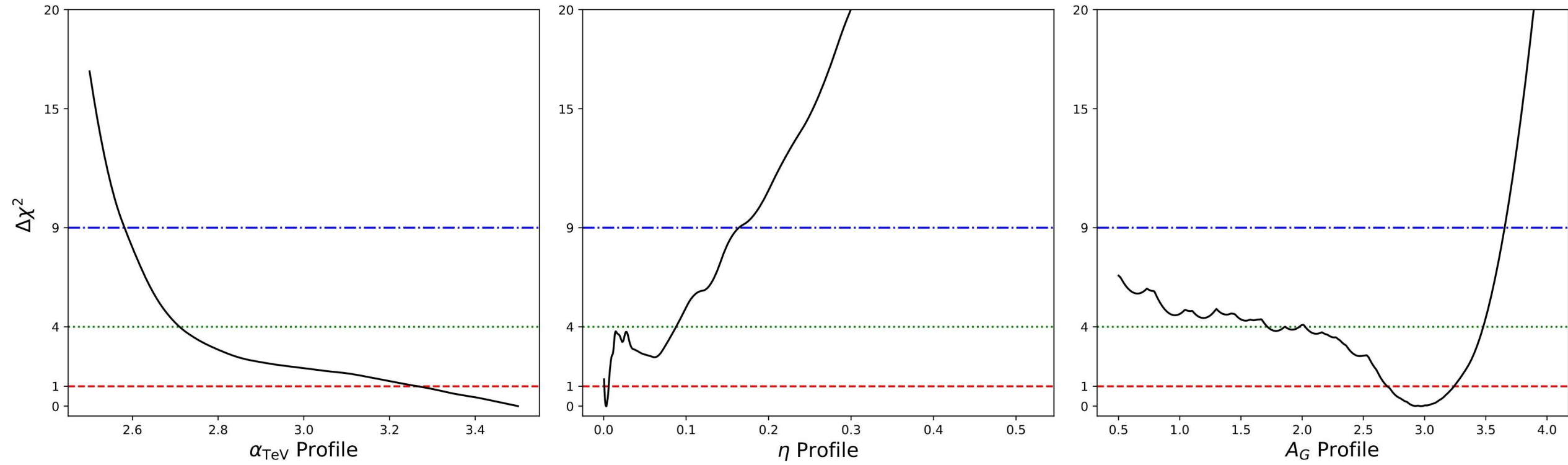
QUESTIONS?

Thank you!

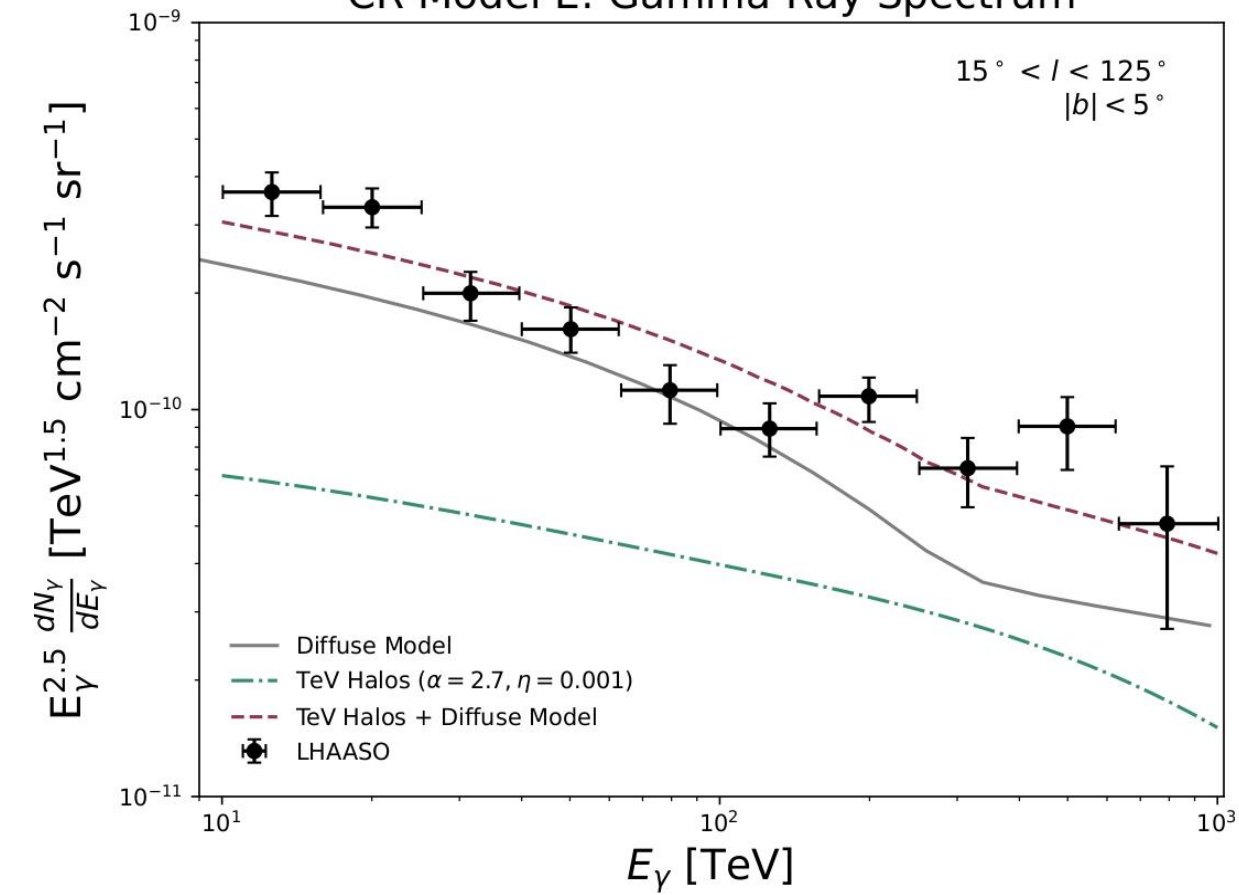


BACKUP SLIDES

CR Model D Profile Likelihoods



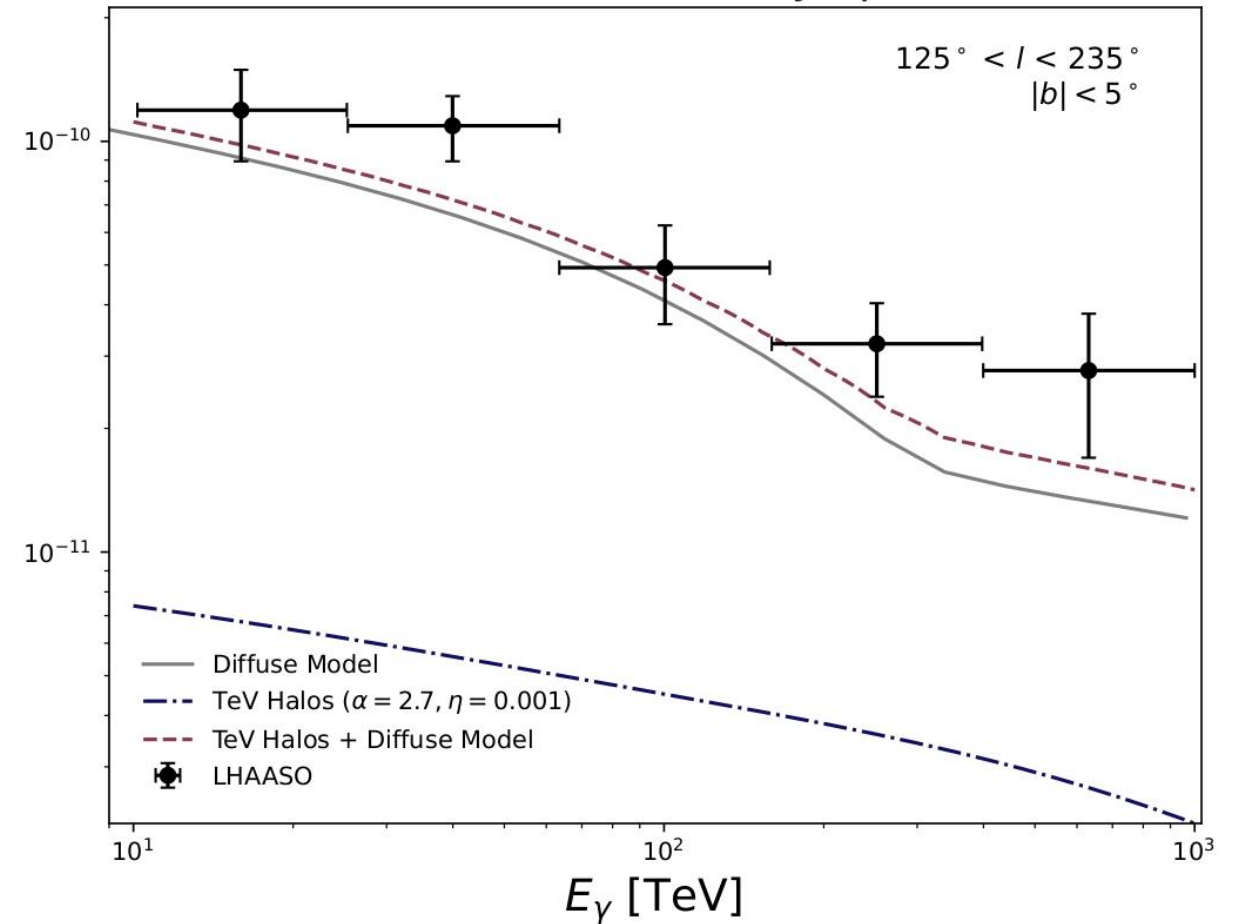
CR Model E: Gamma-Ray Spectrum

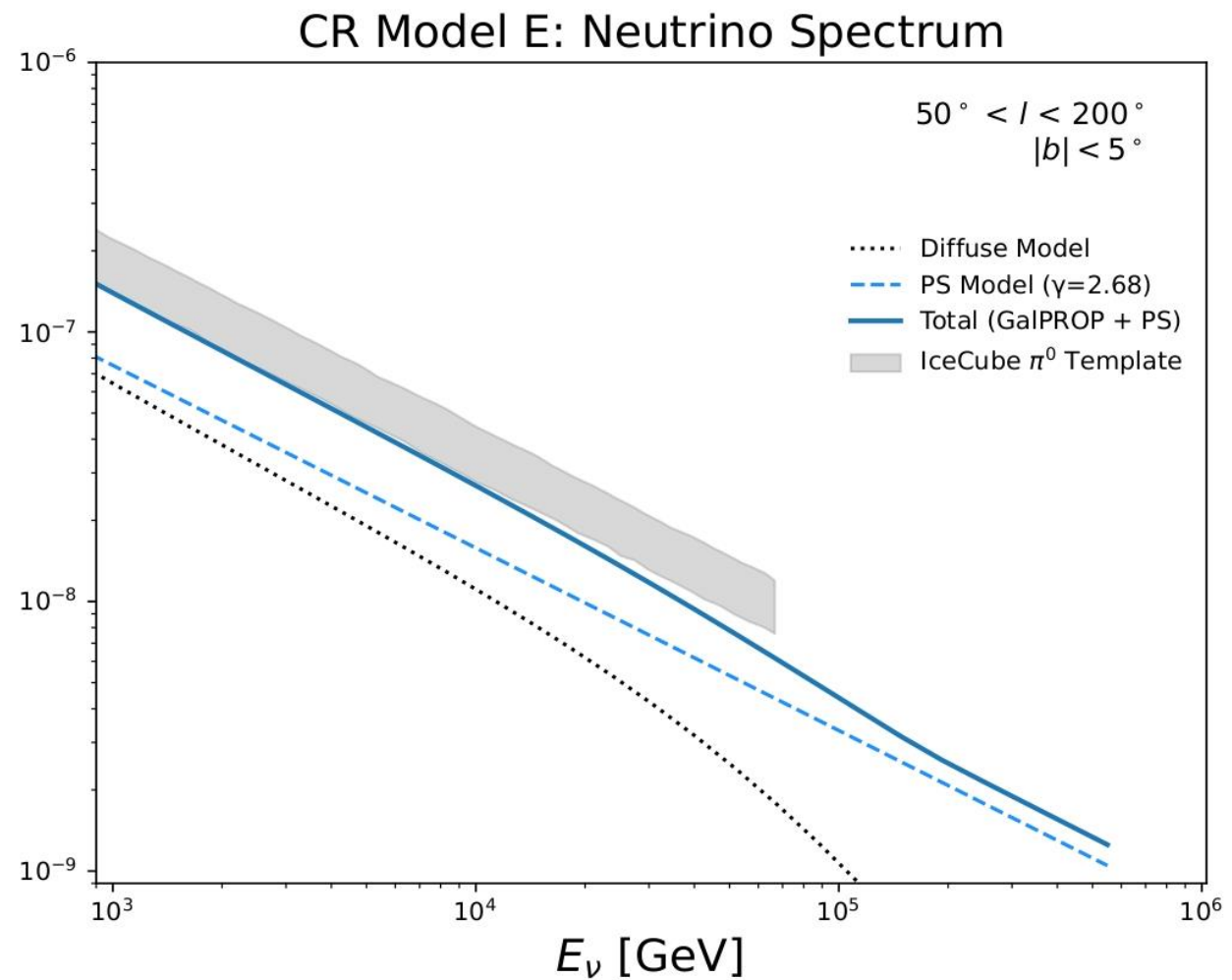
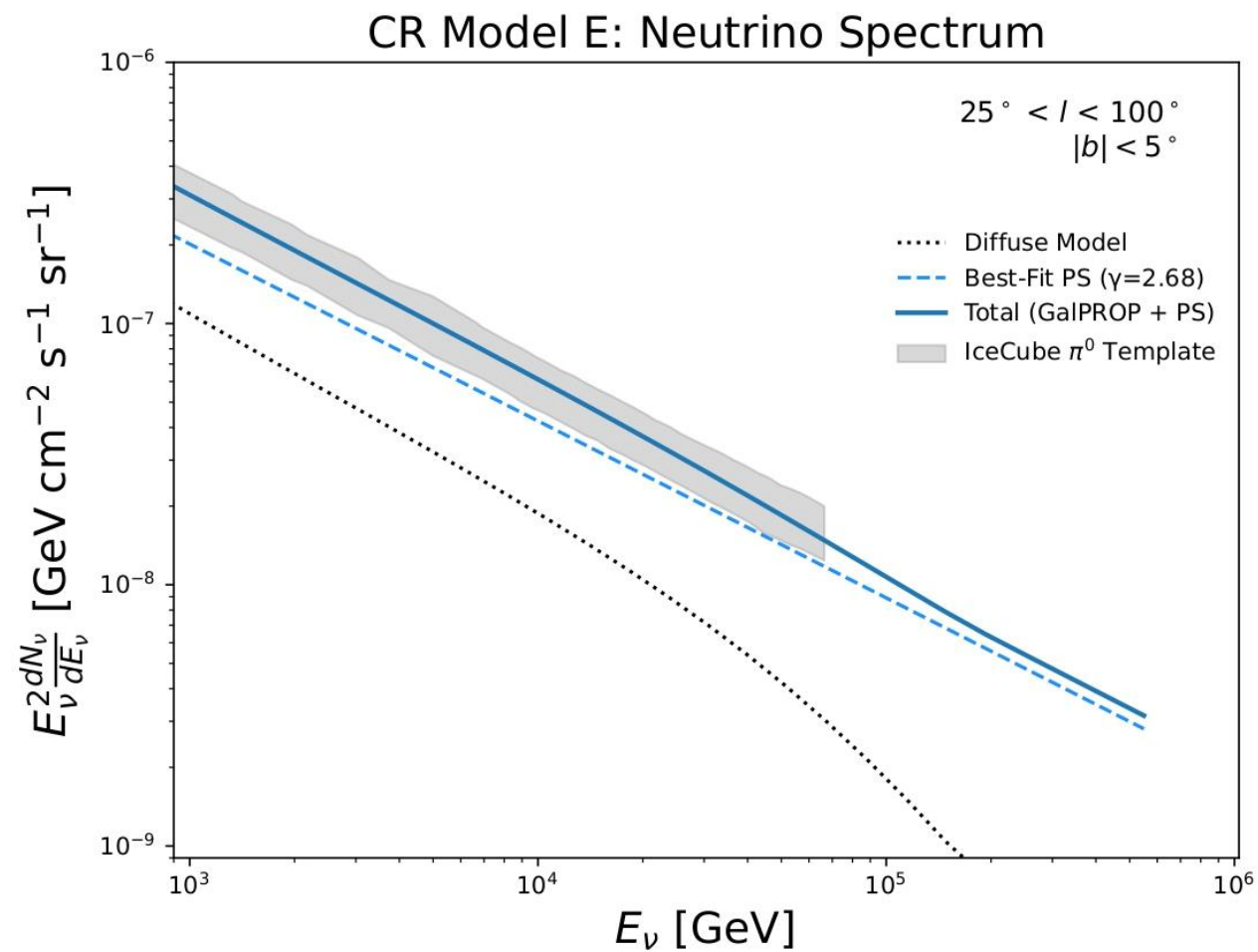


Model E prefers harder halo spectra ($\alpha_\gamma \approx 2.7$),
with A_G at the prior boundary ($\rightarrow$ motivates E')

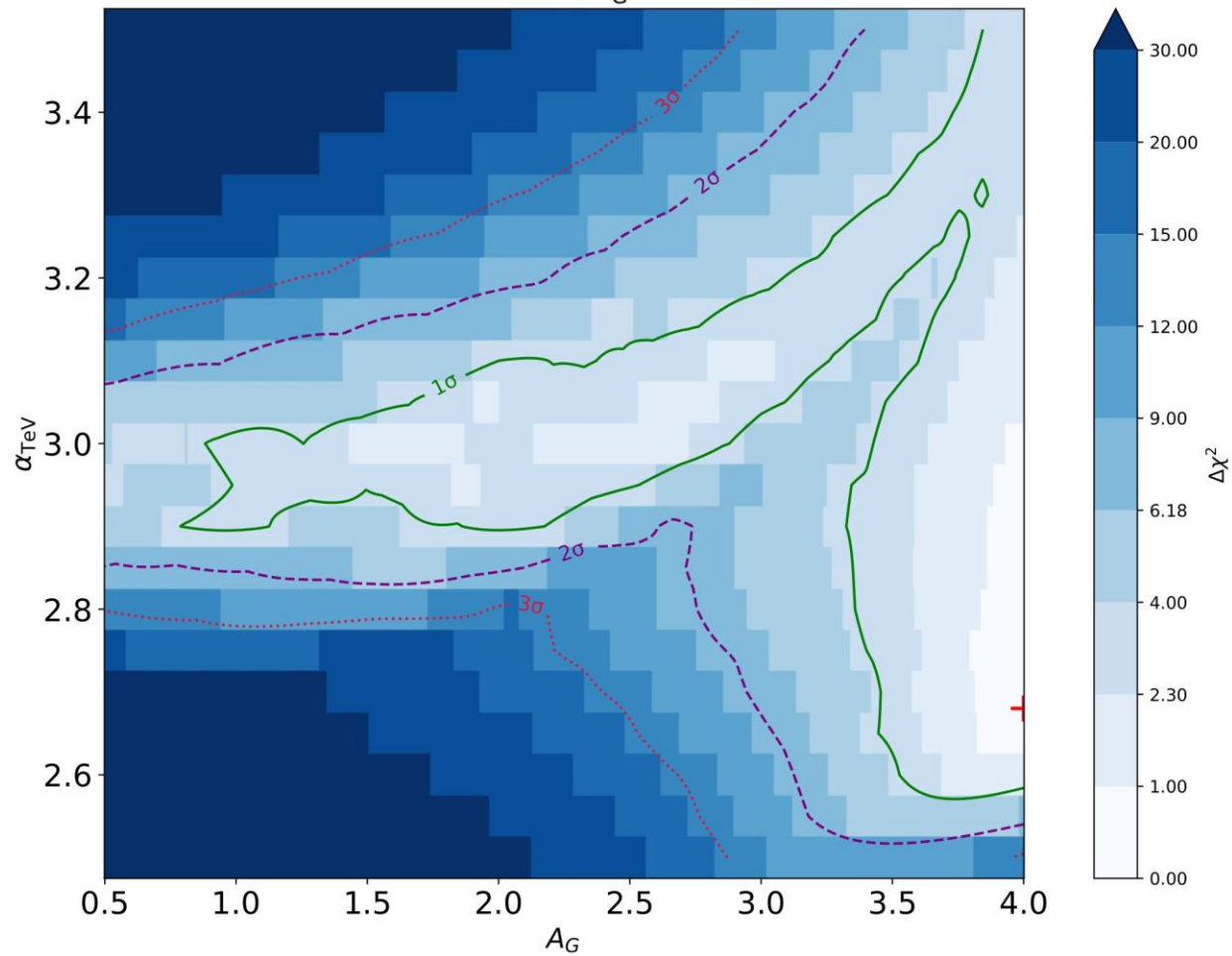
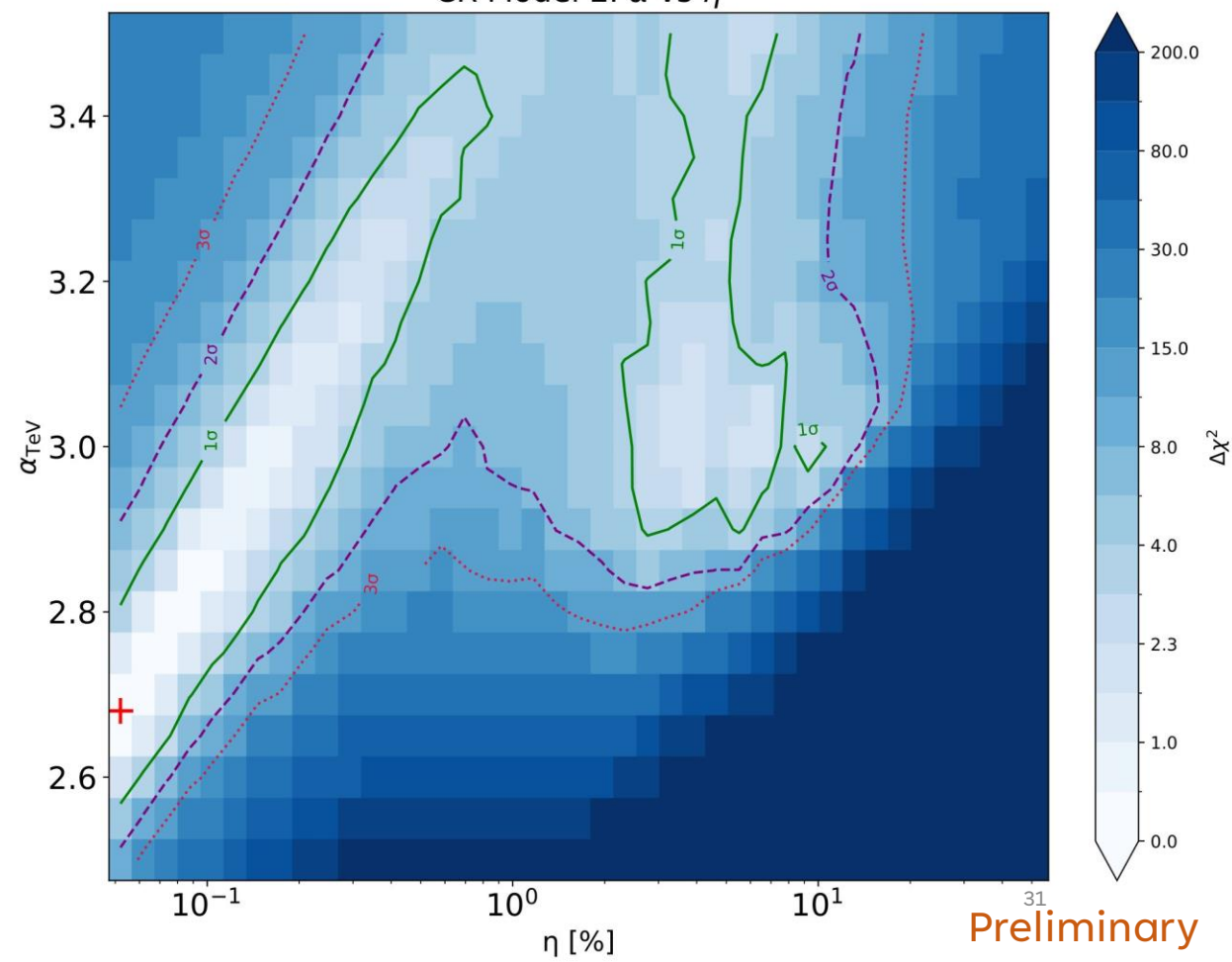
ALTERNATE COSMIC RAY MODEL (E)

CR Model E: Gamma-Ray Spectrum



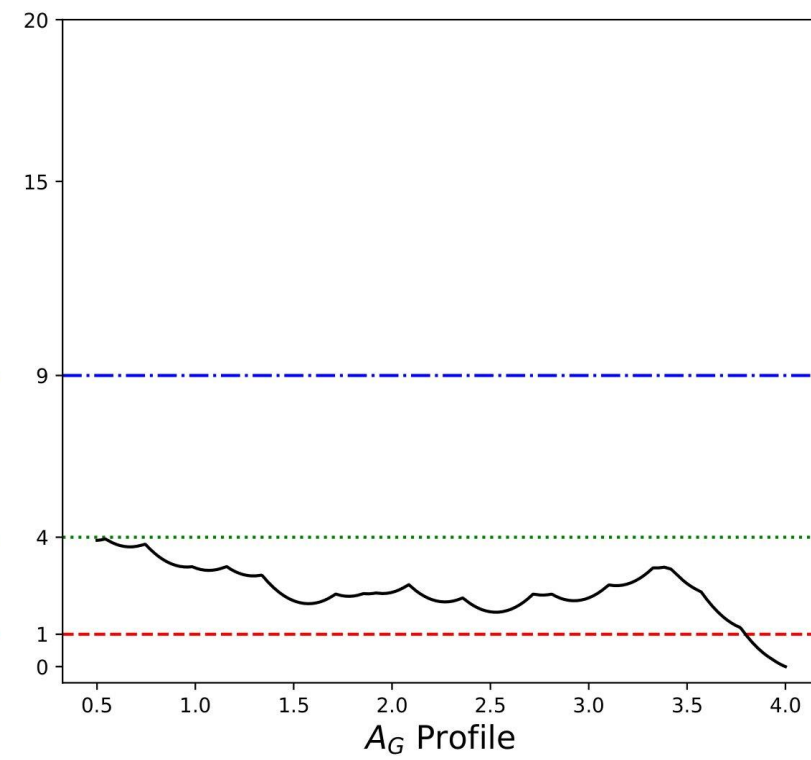
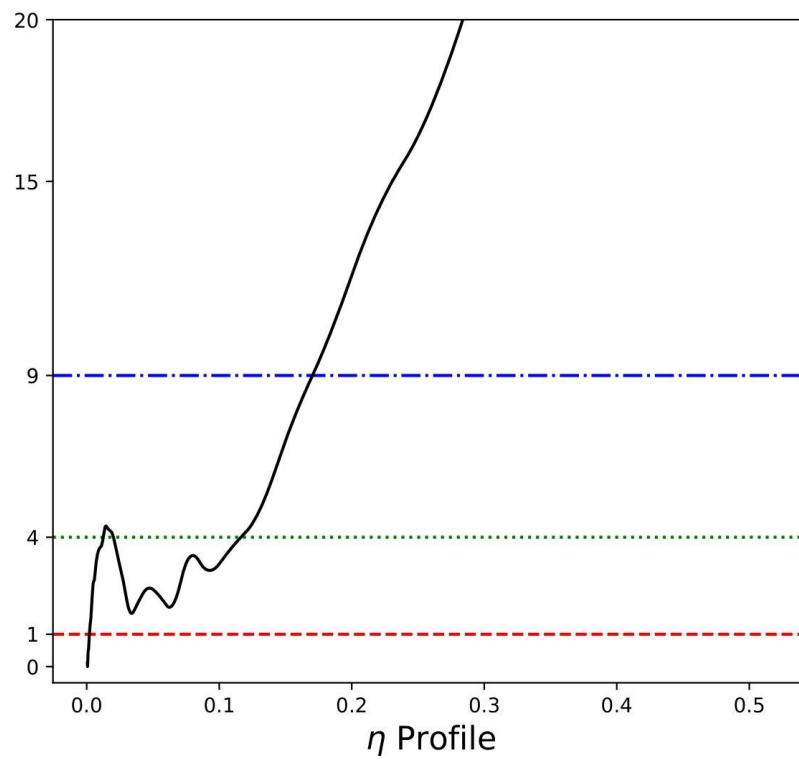
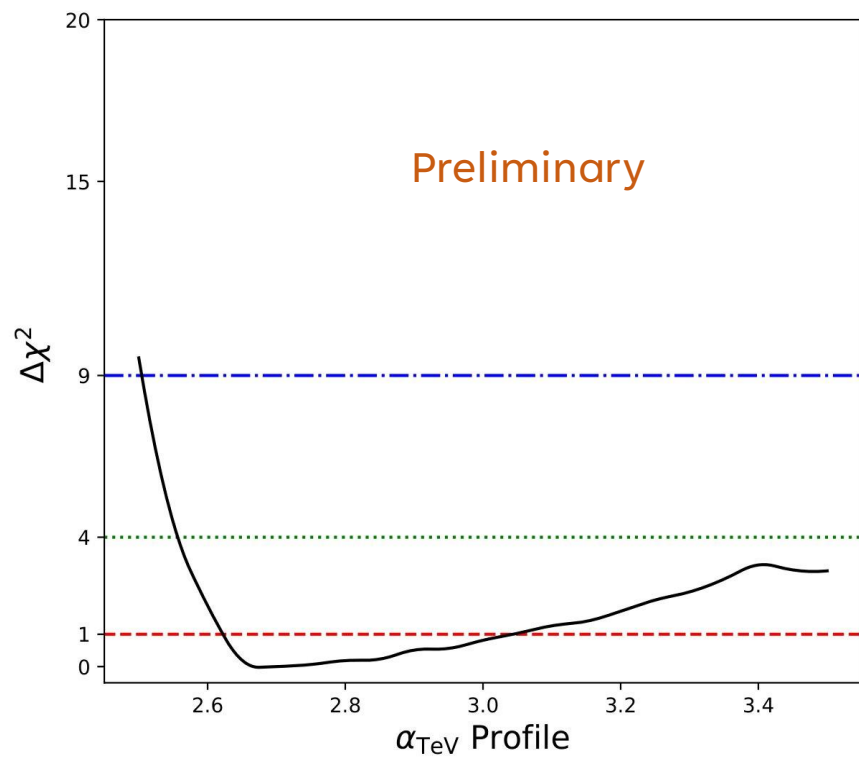


Still: Neutrino point sources account more than half of emission seen by IceCube

CR Mod E: A_G vs α CR Model E: α vs η 

Preliminary

CR Model E Profile Likelihoods

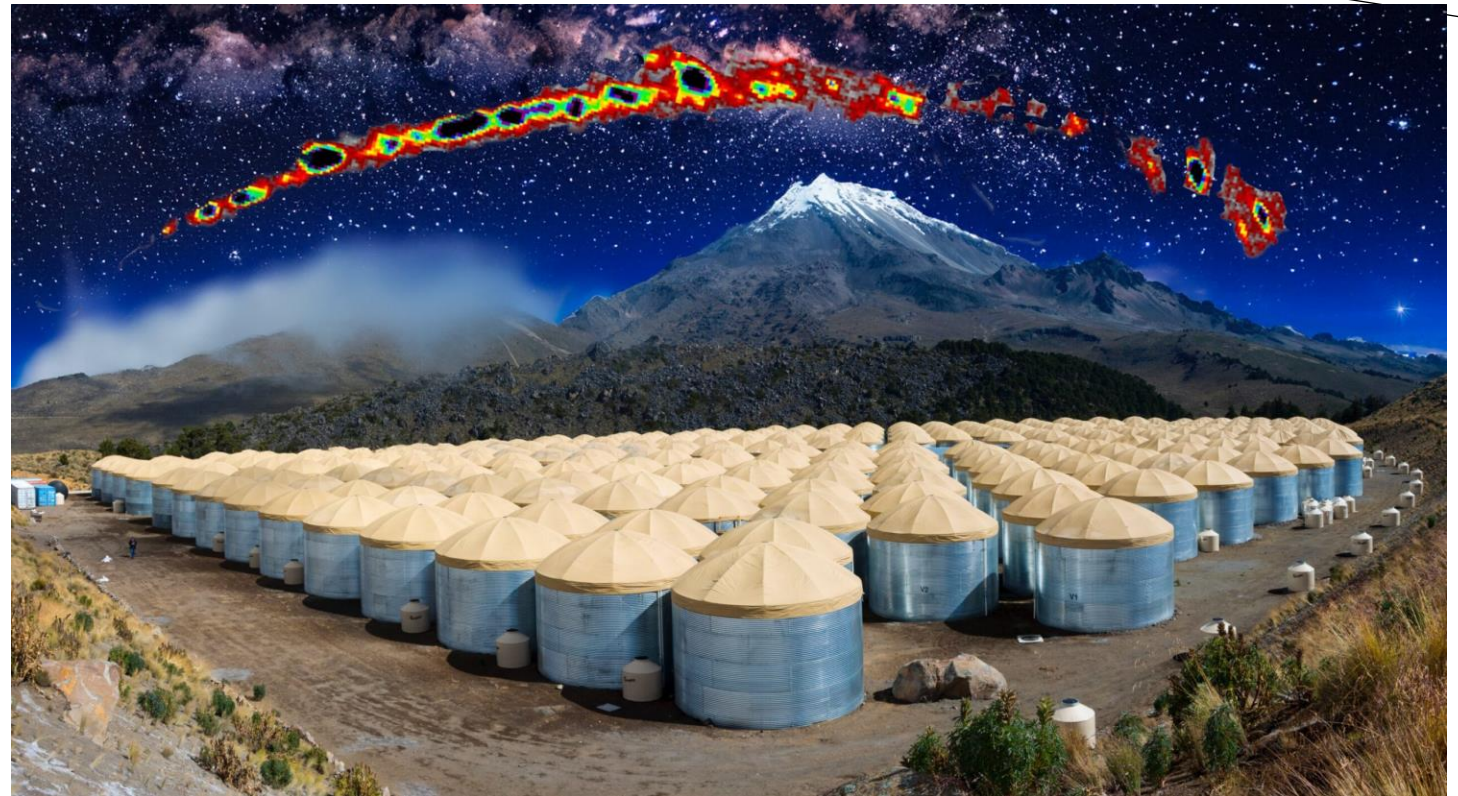


TeV Halos

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 (Hooper, Cholis, Linden & Fang 2017 arXiv:1702.08436)

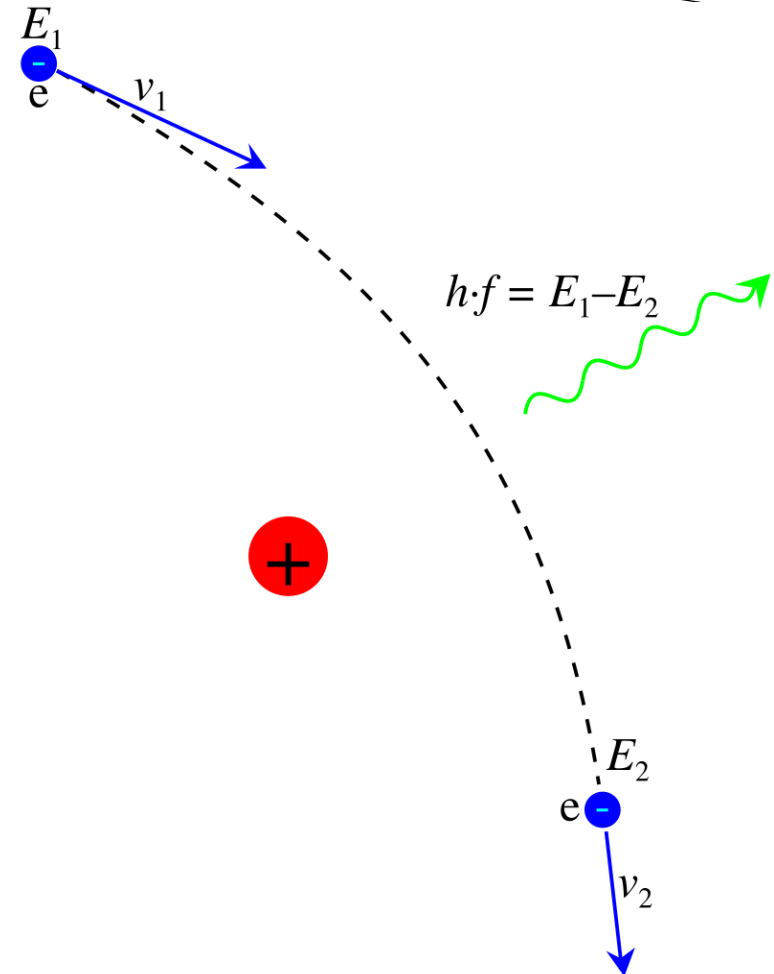


Goodman, J. (2023). *HAWC site with superposition of Milky Way's plane as seen in gamma-rays*

Gamma-rays

via Bremsstrahlung

traces high-energy
electrons in dense gas



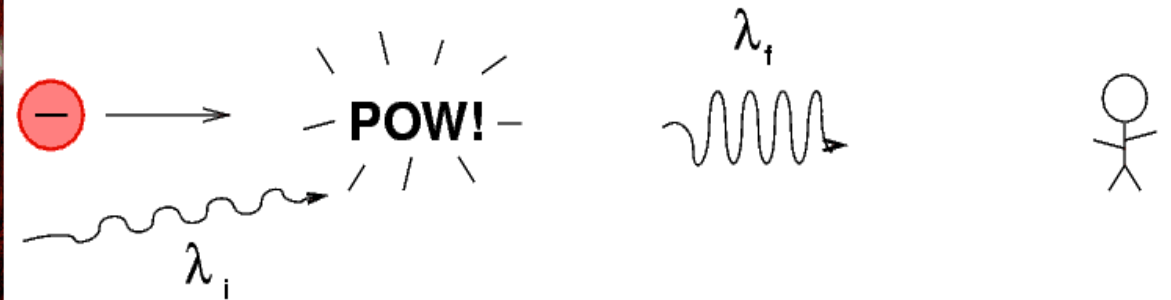
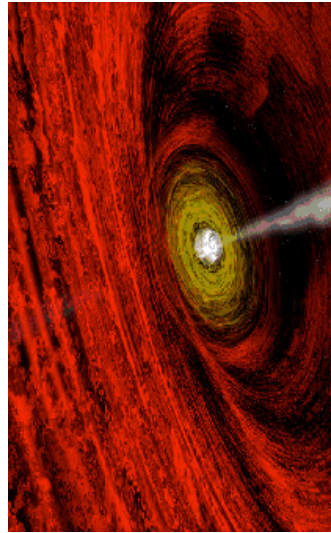
Martin, Dylan (2005). *X-Ray Detection*. University of Arizona Optical Sciences Center

Gamma-rays

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

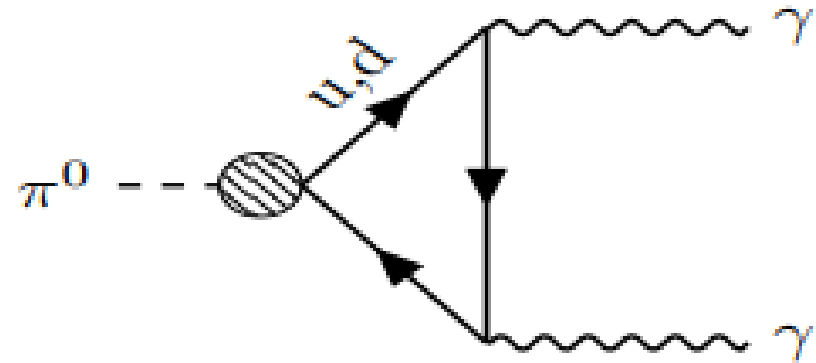
via Inverse Compton Scattering

Hadronic

via Neutral Pion Decay

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

Main channel of production



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

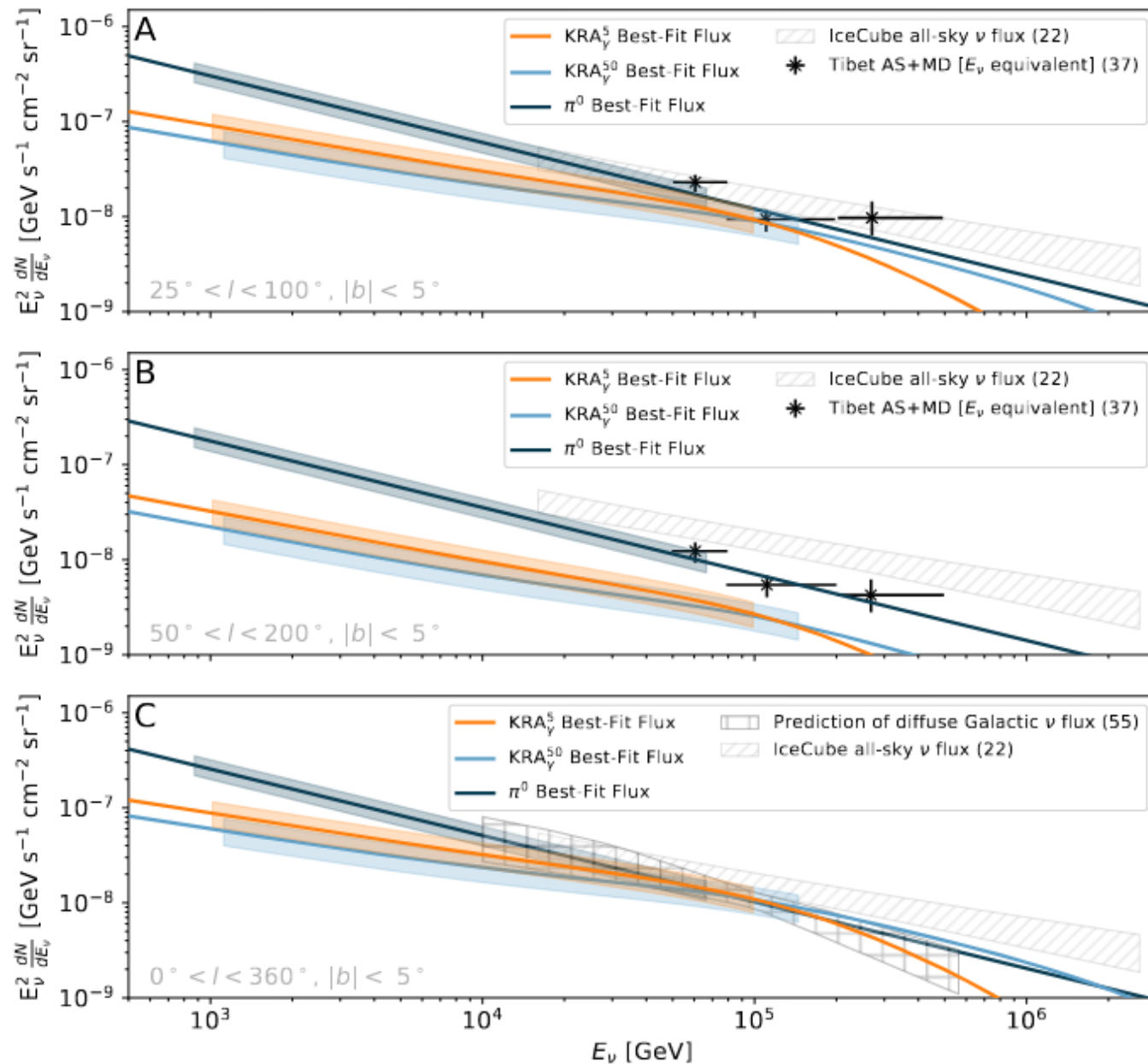
CR Model	δ	z_L (kpc)	$D_0 \times 10^{28}$ (cm ² /s)	v_A (km/s)	$dv_c/d z $ (km/s/kpc)	α_1 H/He	R_{br1} H/He (GV)	α_2 H/He	R_{br2} H/He (GV)	α_3 H/He
A	0.33	5.7	6.70	30.0	0	1.74/1.70	6.0/7.4	2.04/2.16	14.0/21.5	2.41/2.39
B	0.37	5.5	5.50	30.0	2	1.72/1.74	6.0/8.0	2.00/2.14	12.4/21.0	2.38/2.375
C	0.40	5.6	4.85	24.0	1	1.69/1.65	6.0/6.7	2.00/2.13	12.4/20	2.38/2.355
D	0.45	5.7	3.90	24.0	5.5	1.69/1.68	6.0/7.0	1.99/2.12	12.4/18.7	2.355/2.34
E	0.50	6.0	3.10	23.0	9	1.71/1.68	6.0/7.2	2.02/2.14	11.2/17.5	2.38/2.33
F	0.43	3.0	1.85	20.0	2	1.68/1.74	6.0/10.5	2.08/2.09	13.0/21.0	2.41/2.33

TABLE I. The cosmic-ray propagation assumptions (CR Model), determined by the diffusion index δ , the diffusion scale height z_L , the normalization of the diffusion co-efficient D_0 , the Alfvén velocity v_A , the galactic convection gradient dv_c/dv , the injection indices α_1 , α_2 , α_3 , and the rigidity breaks R_{br1} and R_{br2} for cosmic-ray hydrogen and helium isotopes. In the last five columns, the first values refer to hydrogen injection properties and the second values to helium.

Diffusion index
related to the
rigidity/energy
dependence of
cosmic rays

Diffusion
normalization for how
well a CR is
transported by
turbulent Galactic
magnetic fields

Convection term



The Neutrino Eye: IceCube

Cubic-kilometer neutrino telescope at the South Pole

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

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

KRA_γ^5 : KRA_γ^5 : spectral index varies across the sky (avg. $\approx E^{-2.5}$), 5 PeV cutoff

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

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

Model	KRA $^5_\gamma$					KRA $^{50}_\gamma$				
	A_ν	α_ν	χ^2_ν	$\Delta\chi^2_\nu$	$\sum\chi^2$	A_ν	α_ν	χ^2_ν	$\Delta\chi^2_\nu$	$\sum\chi^2$
A	$1.26^{+1.22}_{-1.04} \times 10^{-8}$	$1.31^{+1.07}_{-0.31}$	2.50	3.28	24.56	$6.39^{+4.72}_{-4.99} \times 10^{-9}$	$1.00^{+0.93}_{-0.00}$	6.32	1.77	28.38
B	$1.19^{+0.88}_{-1.04} \times 10^{-8}$	$1.00^{+1.22}_{-0.00}$	3.73	1.78	27.23	$4.05^{+4.74}_{-4.05} \times 10^{-9}$	$1.00^{+2.00}_{-0.00}$	11.95	0.72	35.45
C	$1.05^{+0.88}_{-0.96} \times 10^{-8}$	$1.00^{+1.15}_{-0.00}$	5.15	1.38	28.63	$3.34^{+4.75}_{-3.33} \times 10^{-9}$	$1.00^{+2.00}_{-0.00}$	16.49	0.48	39.97
D	$9.41^{+8.87}_{-9.09} \times 10^{-9}$	$1.00^{+1.15}_{-0.00}$	7.04	1.11	32.45	$2.83^{+4.72}_{-2.82} \times 10^{-9}$	$1.00^{+2.00}_{-0.00}$	21.75	0.35	47.16
E	$1.51^{+0.87}_{-1.09} \times 10^{-8}$	$1.00^{+0.89}_{-0.00}$	5.50	2.85	33.86	$6.13^{+4.68}_{-4.81} \times 10^{-9}$	$1.00^{+0.70}_{-0.00}$	17.26	1.64	45.62
F	$1.08^{+0.88}_{-0.95} \times 10^{-8}$	$1.00^{+1.03}_{-0.00}$	6.34	1.48	28.58	$3.58^{+4.74}_{-3.57} \times 10^{-9}$	$1.00^{+2.00}_{-0.00}$	20.13	0.55	42.37
E'	$7.14^{+8.78}_{-7.14} \times 10^{-9}$	$1.00^{+2.00}_{-0.00}$	14.39	0.63	40.69	$1.74^{+4.74}_{-1.74} \times 10^{-9}$	$1.00^{+2.00}_{-0.00}$	39.17	0.13	65.47

- These fits favor very hard (and seemingly unphysical) spectral indices for the neutrino source population
- Considerably weaker evidence for any contribution from neutrino sources

NEUTRINO MODELING

These factors leave open the possibility that many of the neutrinos detected from the Galactic Plane could originate from unresolved point sources, such as supernova remnants, pulsar wind nebulae, or microquasars.

As we did with the gamma-ray emission from TeV halos, we parameterize the spectrum of the neutrino emission from unresolved point sources as a power-law

$$n \propto e^{-R/3.35 \text{ kpc}} e^{-|z|/0.2 \text{ kpc}}$$

$$\frac{dN_\nu}{dE_\nu} = A_\nu \times \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\alpha_\nu}$$

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Working Assumptions:
assume isotropic and
homogeneous diffusion

- Consider six main cosmic-ray models evaluated in GALPROP for any given direction by integrating along line of sight

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related to the
rigidity/energy
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Diffusion
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$$D(R) = \beta D_0 \left(\frac{R}{4\text{GV}} \right)^\delta$$