A Multi-Messenger View of the Milky Way

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Searching for the Sources of Galactic Cosmic Rays Workshop

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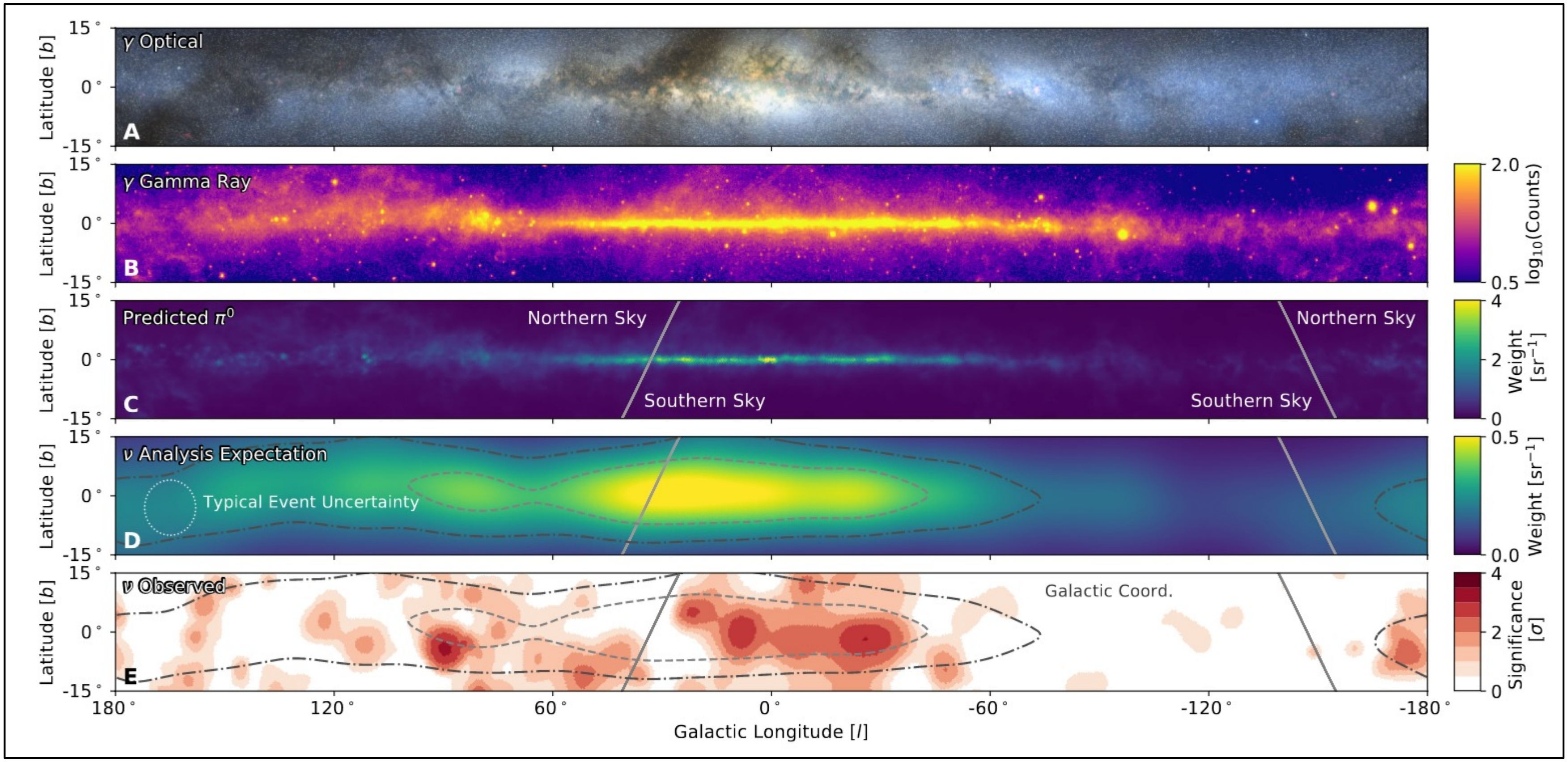
High-Energy Neutrinos From the Galactic Plane

- Last summer, the IceCube Collaboration announced that they had detected neutrino emission from the Galactic Plane (at 4.5σ significance)



IceCube, *Science*, 2307.04427

High-Energy Neutrinos From the Galactic Plane

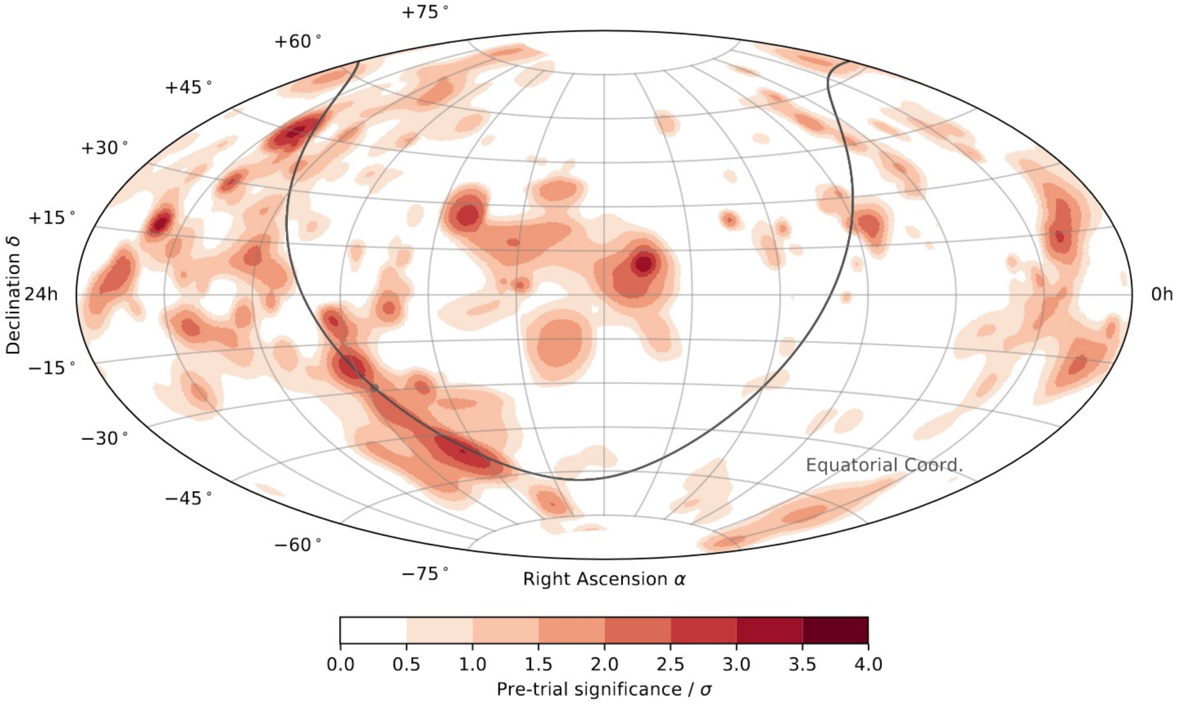
- What is the origin (or more likely, origins) of these neutrinos?
  -Cosmic rays scattering with gas in the ISM?
  -Cosmic ray accelerators? (supernova remnants, pulsar wind nebulae,…)

High-Energy Neutrinos From the Galactic Plane

- What is the origin (or more likely, origins) of these neutrinos?

  -Cosmic rays scattering with gas in the ISM?

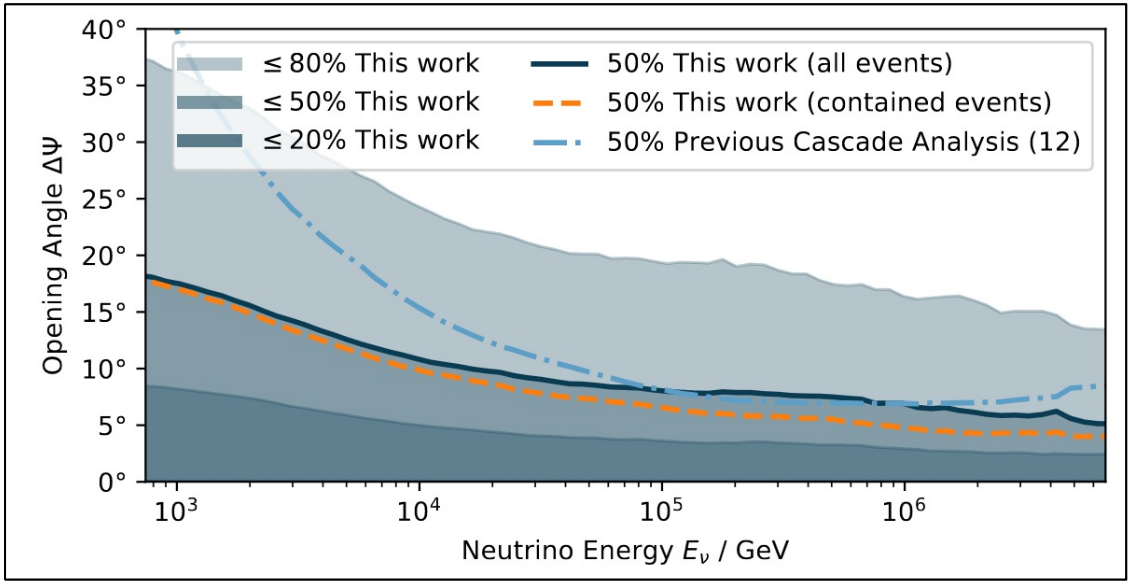
  -Cosmic ray accelerators? (supernova remnants, pulsar wind nebulae,…)
- There are some hints of individual neutrino point sources along the Galactic Plane, but with a statistical significance that does not overcome the trials factor
- Catalog stacking analyses (SNR, PWN) yield ~3.2**σ**, but the data is also consistent with arising entirely from diffuse processes in the Galactic Plane



IceCube, 2307.04427

The Challenge of Resolving Neutrino Sources

- The Galactic Plane (and especially the Inner Galaxy) resides largely within the Southern sky, where cosmic-ray muon backgrounds are large; this forces IceCube to rely on cascades and contained muon tracks
- At ~TeV-scale energies, the background from atmospheric neutrinos is large, limiting the utility of contained muons
- Compared to tracks, cascades have poor angular resolution (although this has been mitigated to some degree by machine learning techniques), making it difficult to resolve any sources that might produce the observed the emission from the Galactic Plane

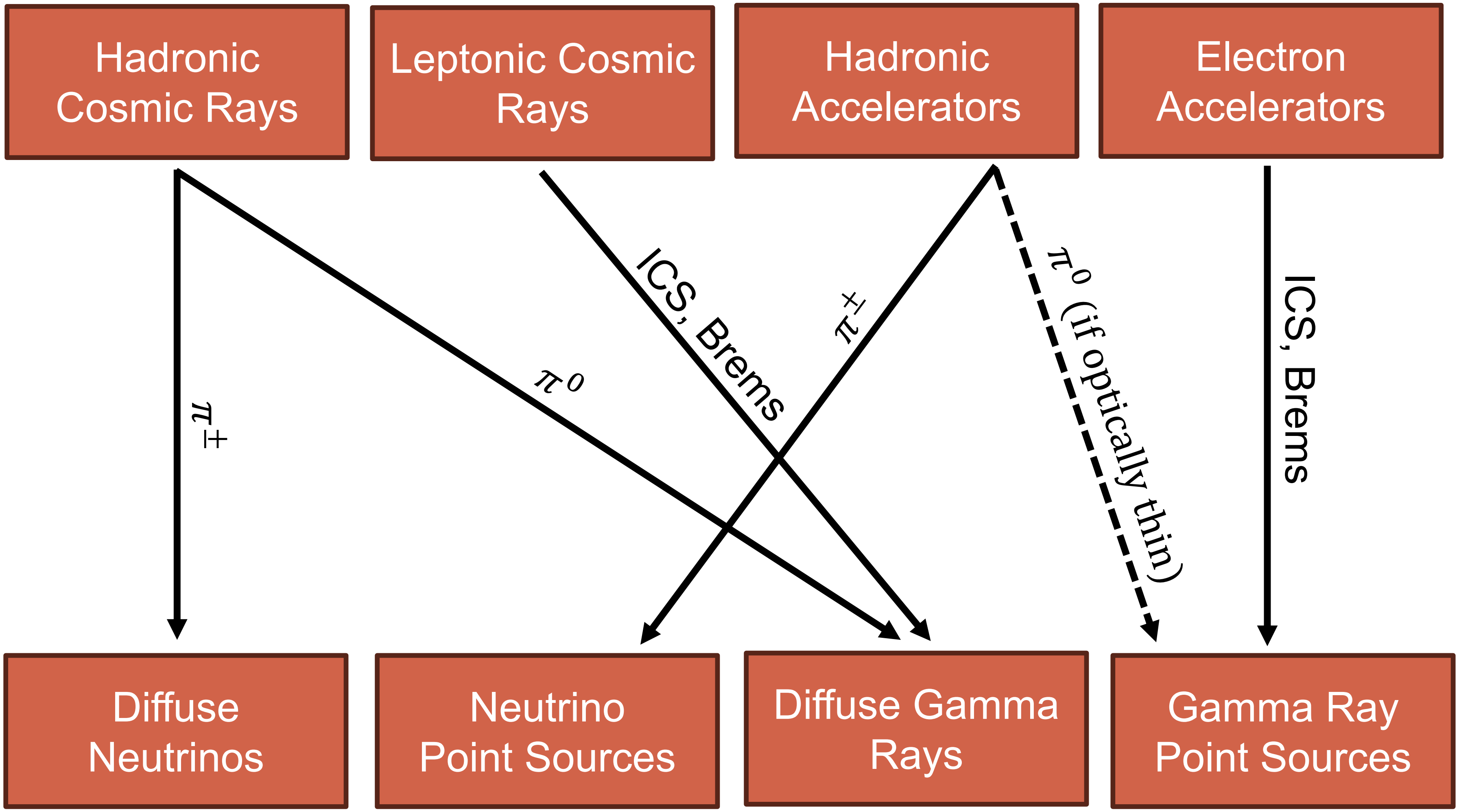


IceCube,
2307.04427

A Task for Multi-Messenger Astrophysics

- Neutrinos, gamma rays, and cosmic rays each provide complementary information that can be used to answer the question of where the neutrinos observed by IceCube originate, and on the related question of the origin of the Galactic cosmic rays
- None of these signals will answer these questions on their own

A Task for Multi-Messenger Astrophysics



Hadronic Cosmic Rays

Leptonic Cosmic Rays

Hadronic Accelerators

Electron Accelerators

$\pi^{\pm}$

π^{0}

ICS, Brems

$\pi^{\pm}$

π^{0} (if optically thin)

ICS, Brems

Diffuse Neutrinos

Neutrino Point Sources

Diffuse Gamma Rays

Gamma Ray Point Sources

*In addition to information derived from measurements of the local cosmic-ray spectrum

Galactic Cosmic-Ray Propagation

- The propagation of cosmic rays through the Milky Way is often modelled using the following transport equation:

$$\begin{aligned}\frac{\partial\psi(\vec{x},p,t)}{\partial t} &= q(\vec{x},p) \ + \ \vec{\nabla}\cdot[D_{xx}\vec{\nabla}\psi(\vec{x},p,t) - \vec{V_c}\psi(\vec{x},p,t)] + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi(\vec{x},p,t) \\ &- \ \frac{\partial}{\partial p}[\dot{p}\psi(\vec{x},p,t) - \frac{p}{3}(\vec{\nabla}\cdot\vec{V_c})\psi(\vec{x},p,t)] - \frac{1}{\tau_f}\psi(\vec{x},p,t) - \frac{1}{\tau_r}\psi(\vec{x},p,t)\end{aligned}$$

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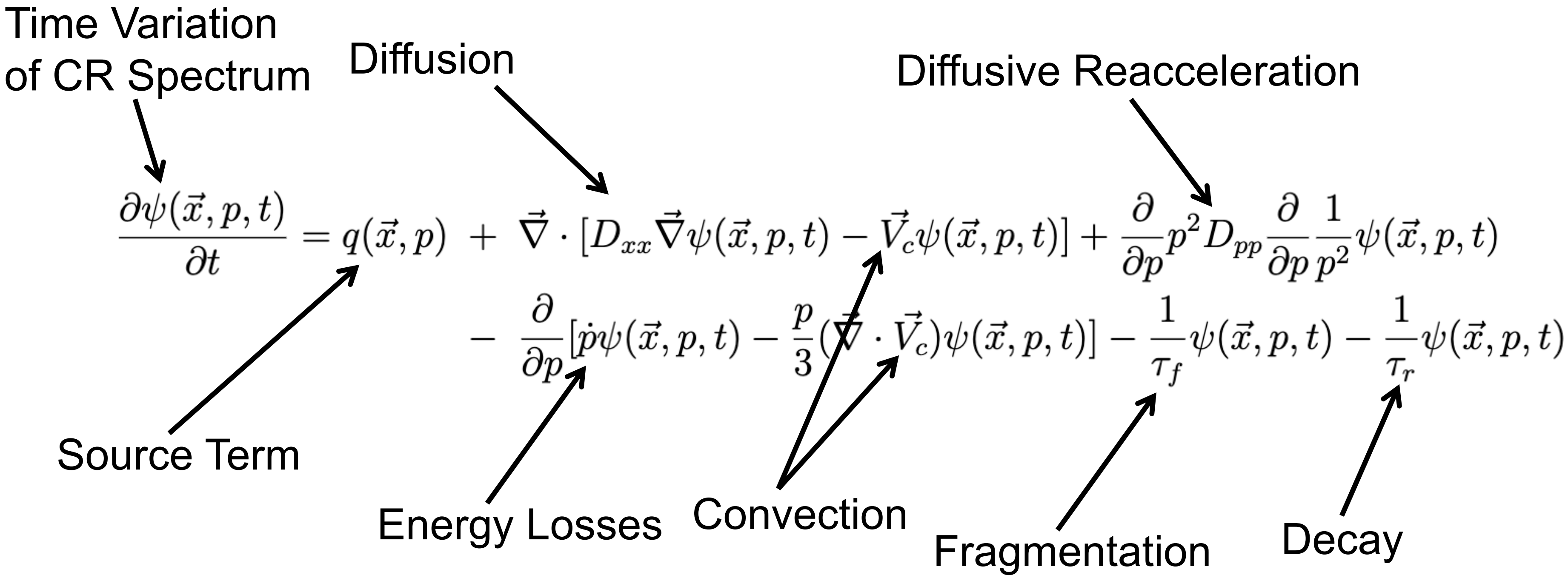


Time Variation of CR Spectrum

Diffusion

Diffusive Reacceleration

$$\frac{\partial\psi(\vec{x},p,t)}{\partial t} = q(\vec{x},p) + \vec{\nabla}\cdot[D_{xx}\vec{\nabla}\psi(\vec{x},p,t) - \vec{V}_c\psi(\vec{x},p,t)] + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi(\vec{x},p,t)$$
$$- \frac{\partial}{\partial p}[\dot{p}\psi(\vec{x},p,t) - \frac{p}{3}(\vec{\nabla}\cdot\vec{V}_c)\psi(\vec{x},p,t)] - \frac{1}{\tau_f}\psi(\vec{x},p,t) - \frac{1}{\tau_r}\psi(\vec{x},p,t)$$

Source Term

Energy Losses

Convection

Fragmentation

Decay

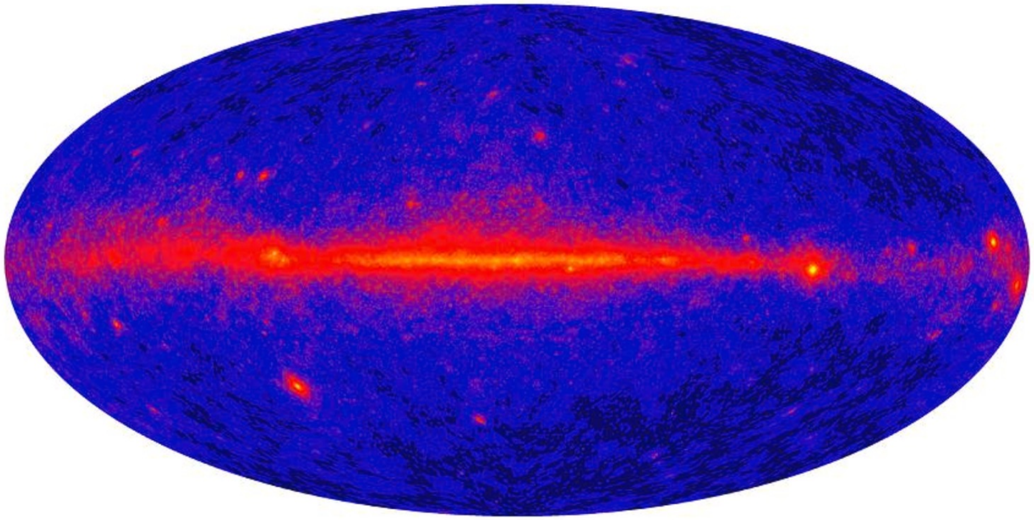
- This approach involves *a lot* of free parameters

Galactic Cosmic-Ray Propagation

- To make this problem tractable, one has to make some simplifying assumptions (steady state, spatially uniform diffusion, etc.)
- At some point, these assumptions will cause the model to break down (to some degree, this is probably happening already)
- We can use *stable* secondary-to-primary ratios in the cosmic-ray spectrum (such as boron-to-carbon) to constrain the typical column depth encountered by cosmic rays, as a function of energy
- We can use *unstable* secondary-to-primary ratios (^{10}Be-to-^{9}Be, ^{27}Al-to-^{26}Al) to constrain the length of time over which cosmic rays propagate, as a function of energy
- This information can be used to constrain the diffusion coefficient (and its energy dependence), the extent of the diffusion zone, and other propagation parameters

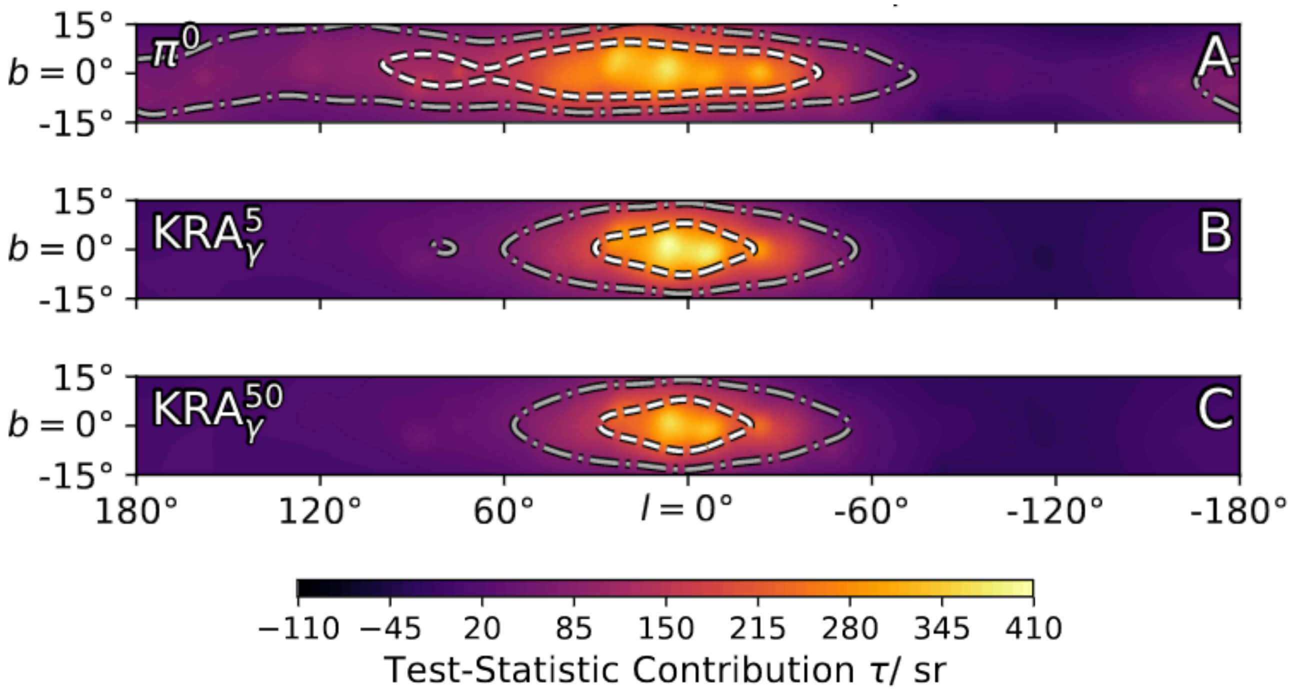
Galactic Cosmic-Ray Propagation

- From an ensemble of cosmic-ray transport models (selected to match observed cosmic-ray ratios), we can predict the flux, spectrum, and angular distribution of the diffuse gamma rays and neutrinos
- We can compare the predicted gamma ray map to that measured by Fermi, ruling out those models that don’t provide reasonable agreement
- Many cosmic ray models are more-or-less consistent with all of the currently available data



Galactic Cosmic-Ray Propagation

- Here are a few examples of the neutrino sky map predicted from cosmic-ray interactions in the ISM (this traces the hadronic part of the gamma-ray map):

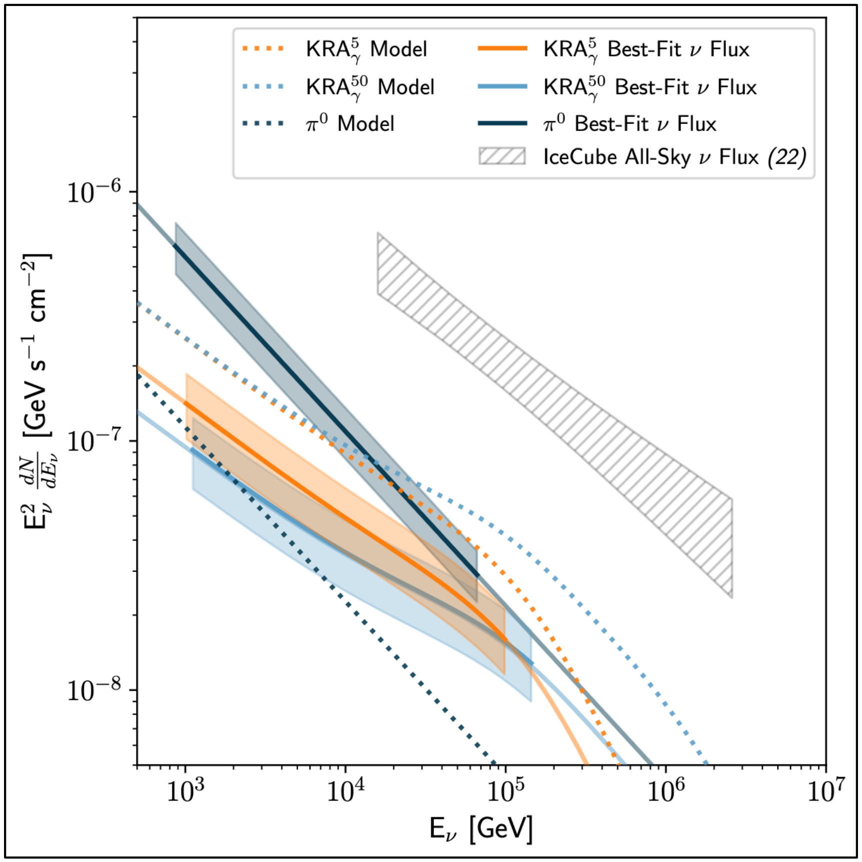


- The gray (white) contours contain 50% (20%) of the predicted flux
- The color scale scale represents the contribution to the test statistic in IceCube's Galactic Plane analysis, per solid angle

IceCube, *Science*, 2307.04427

Galactic Cosmic-Ray Propagation

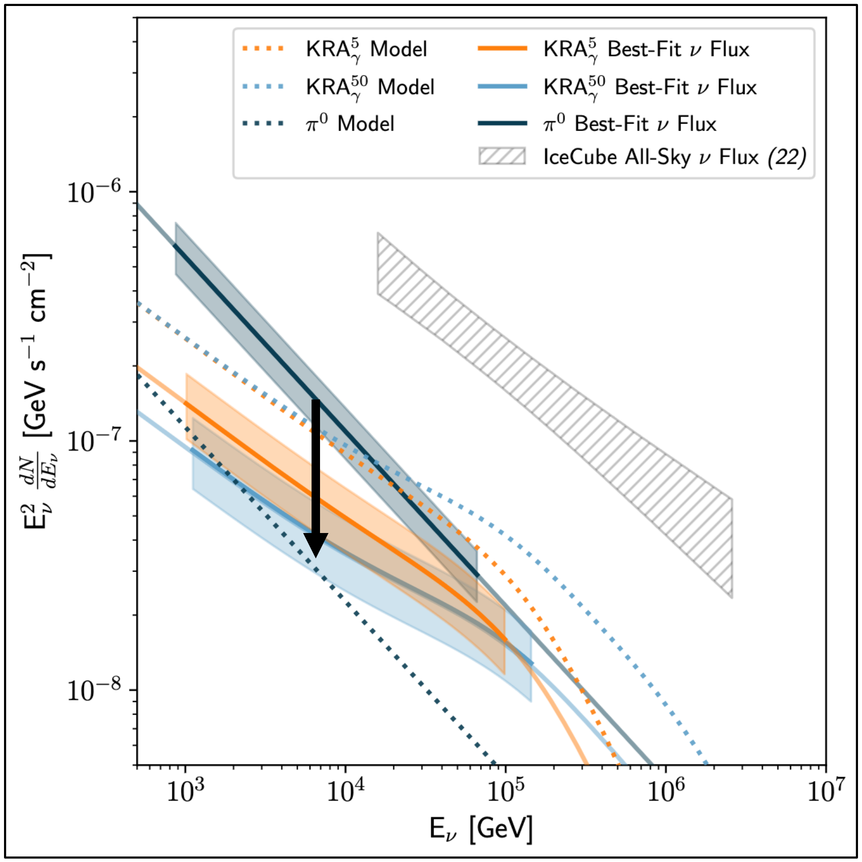
- Here is the neutrino spectrum predicted by the same three models, normalized to fit the IceCube data:



IceCube, *Science*, 2307.04427

Galactic Cosmic-Ray Propagation

- Here is the neutrino spectrum predicted by the same three models, normalized to fit the IceCube data:
- For the π^0 model, the predicted emission accounts for only ~20% of that measured by IceCube



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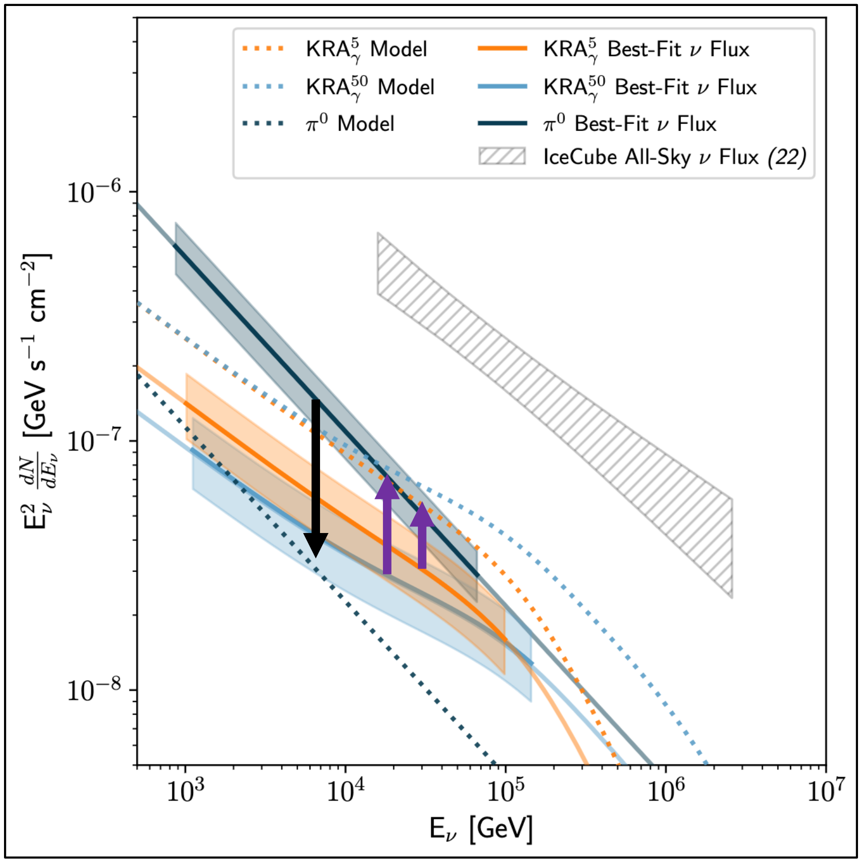
Galactic Cosmic-Ray Propagation

- Here is the neutrino spectrum predicted by the same three models, normalized to fit the IceCube data:
- For the π^0 model, the predicted emission accounts for only ~20% of that measured by IceCube
- In contrast, the KRA models *overshoot* the observed neutrino flux by a factor of ~2-3
- While these three models are far from exhaustive, they are reasonably representative of models that provide a good fit to cosmic-ray data



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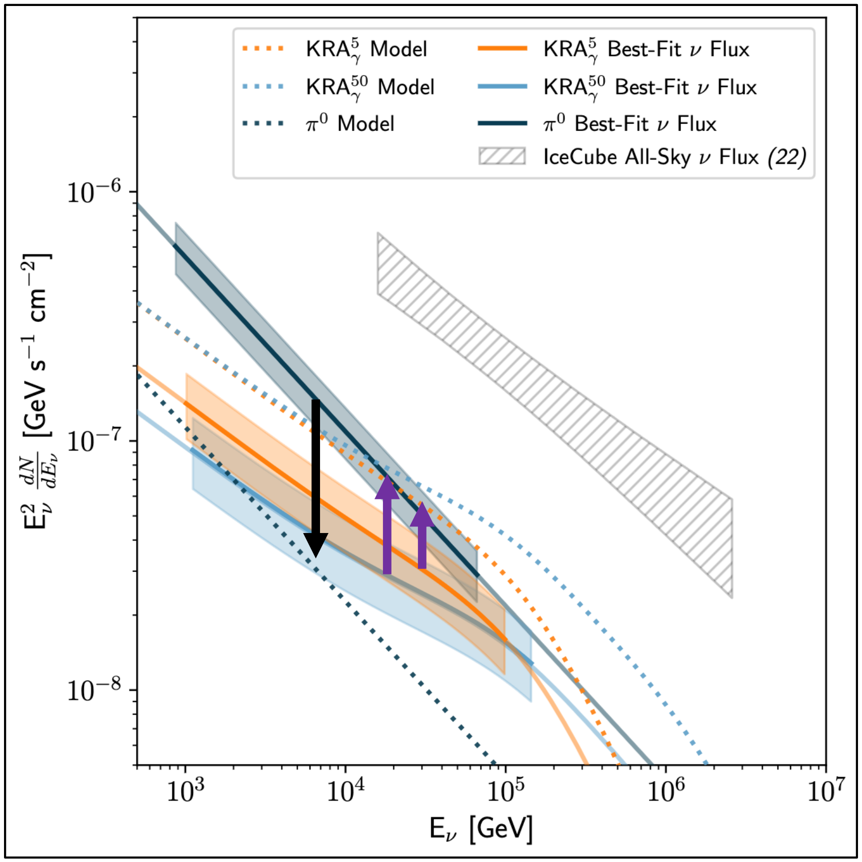
Bottom Line:

- Diffuse cosmic ray interactions likely contribute significantly to the Galactic neutrino flux
- Bonus: IceCube's observations can be used to constrain cosmic-ray transport models

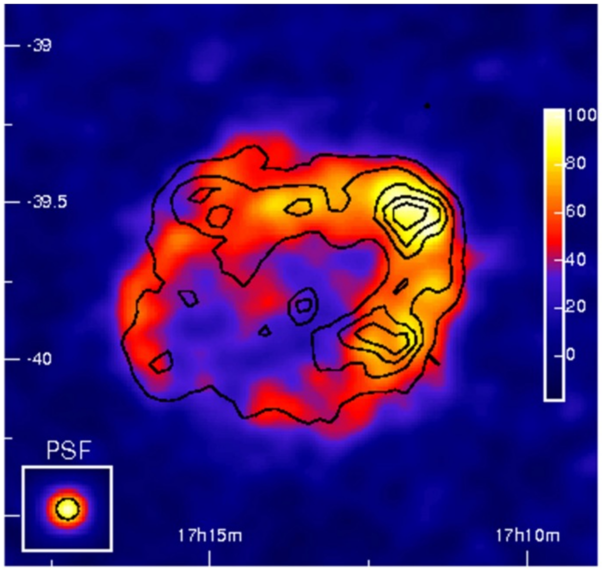


IceCube, *Science*, 2307.04427

Galactic Gamma-Ray Point Sources

Gamma ray catalogs contain hundreds of Galactic sources, including:

- Supernova remnants
- Pulsar wind nebulae
- Pulsars/TeV halos (including globular clusters)
- Novae, high-mass/low-mass binaries



HESS, RX 1713.7-3946

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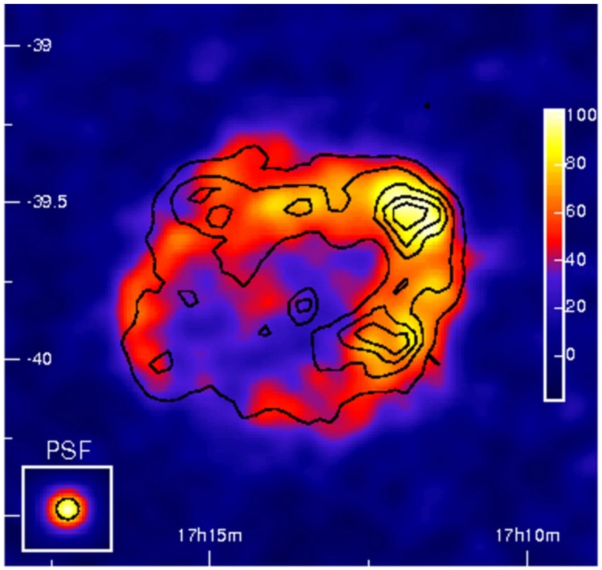
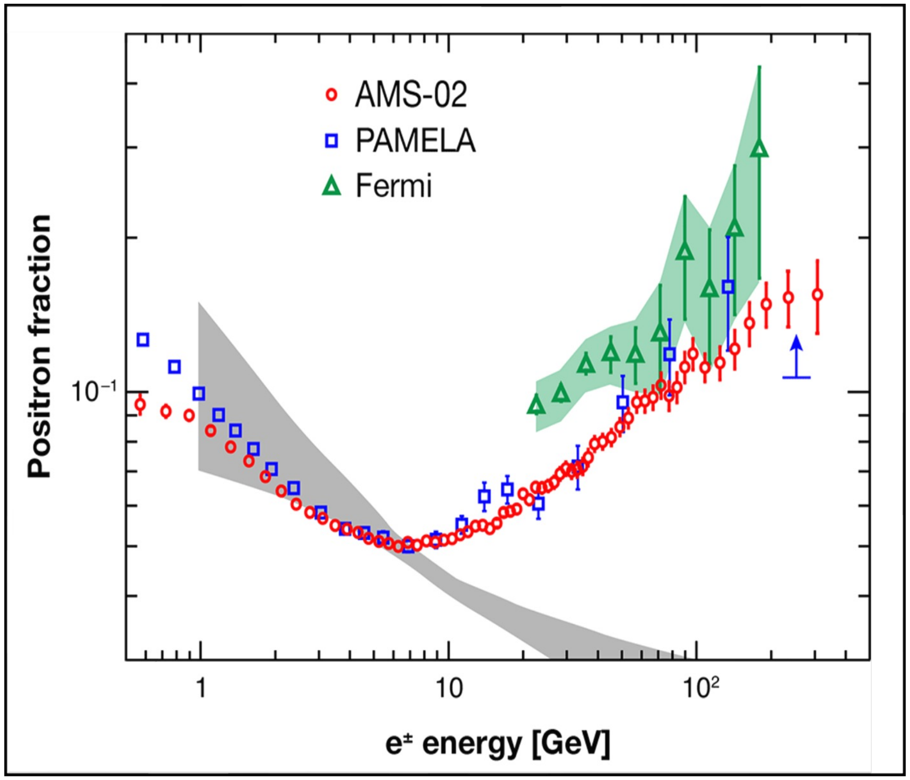


HESS, RX 1713.7-3946

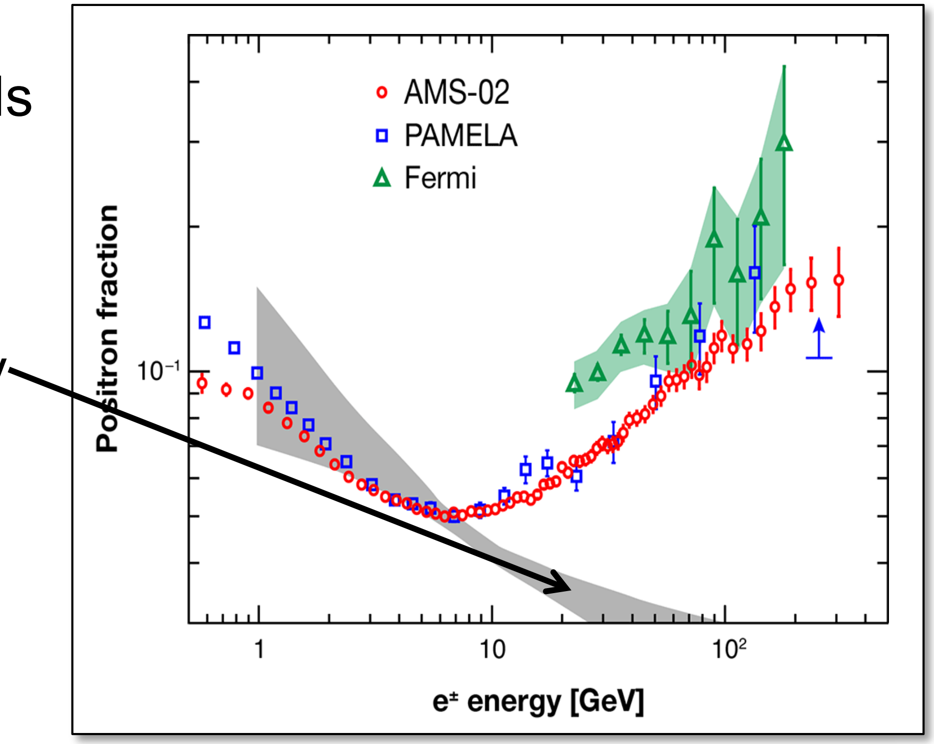
The Cosmic Ray Positron Excess

- I started thinking about very-high energy gamma-ray emission from pulsars in 2009, when PAMELA reported that the cosmic-ray positron fraction increases with energy
- Earlier hints of this had been reported by HEAT, AMS-01, and this has since been confirmed by AMS-02, which extended this measurement to energies of ~400 GeV

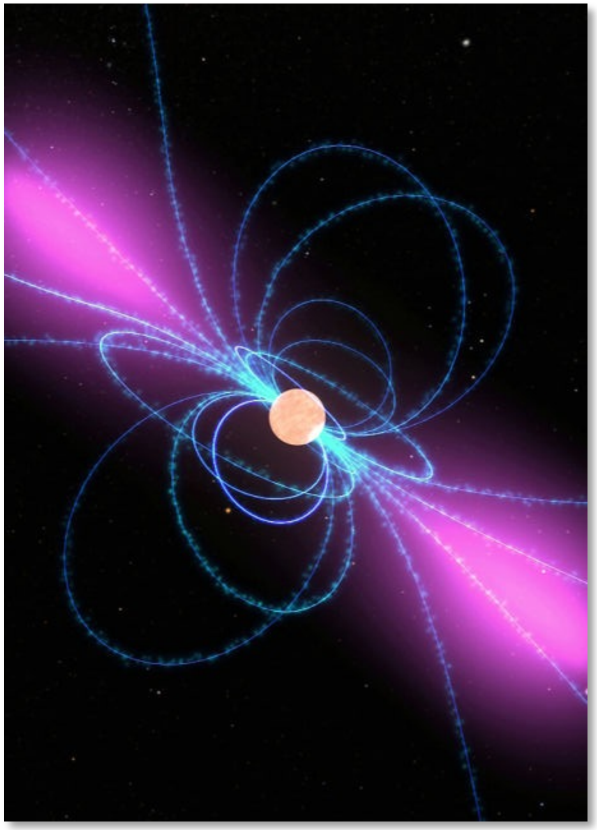


Where Do These Positrons Come From?

- Prior to these measurements, we expected cosmic-ray positrons to be produced largely through cosmic-ray interactions with gas, producing these particles through charged pion decay (*ie*. “*secondary” positrons*)
- Although the precise shape of the secondary positron spectrum depends on the details of the cosmic-ray transport model that is adopted, this mechanism generically predicts a positron fraction that falls with energy
- This observation thus requires the existence of nearby, *primary* sources of energetic positrons
- The possibility that these positrons might arise from dark matter annihilations received an enormous amount of attention, but this class of scenarios is now ruled out



Cosmic Ray Positrons From Pulsars



- It was quickly appreciated that if pulsars produce a hard spectrum of high-energy electron-positron pairs, these sources could be responsible for the observed positron excess
- Two known pulsars stood out as the promising potential sources of ~100 GeV positrons:

  Geminga: age~370,000 yrs, distance~250 pc

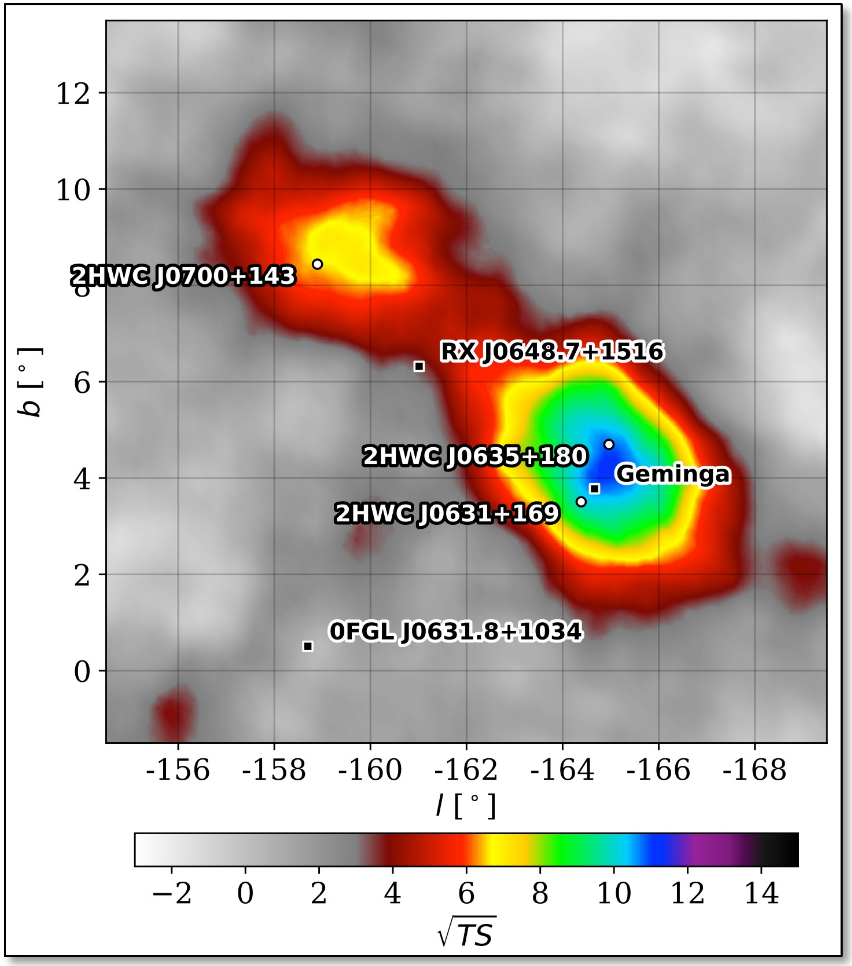
  Monogem: age~110,000 yrs, distance~280 pc

- If ~20% of the spin-down power of these pulsars goes into the production of high-energy pairs, they could plausibly dominate the observed positron spectrum
- Prior to HAWC, it was almost entirely unknown what fraction of a given pulsar’s spindown power goes into the production of high-energy pairs

DH, Blasi, Serpico, PRD, arXiv:0810.1527;
Yuksel, Kistler, PRL, arXiv:0810.2784

VHE Gamma-Ray Observations of Geminga

- In 2017, the HAWC Collaboration reported the detection of very high-energy gamma ray emission from the regions surrounding the Geminga and Monogem pulsars
- Surprisingly, the emission observed from these sources extends to a radius of ~2°
- This emission does not originate from the pulsar itself, and is dominated by the inverse Compton scattering of very high-energy electrons/positrons
- These extended regions of multi-TeV emission surrounding pulsars are known as “TeV Halos”

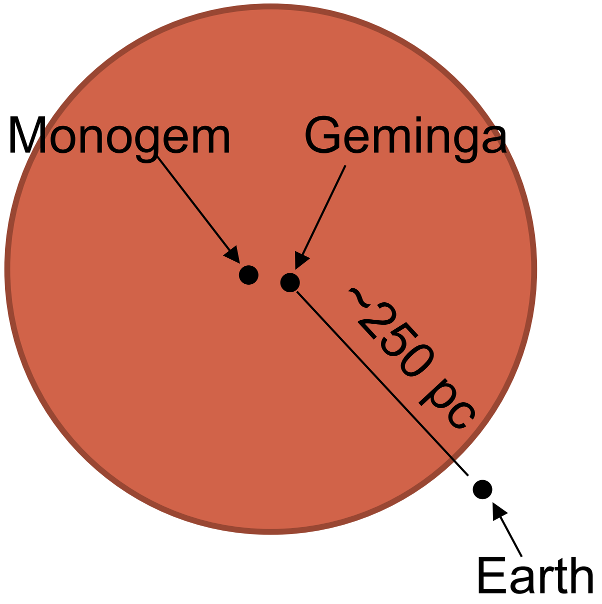


(Modeled as a 2° Radius Disk)

HAWC, arXiv:1702.02992; 1711.06223
Milagro, ApJ, arXiv:0904.1018

Cosmic Ray Diffusion and TeV Halos

- 10 TeV electrons cool via ICS and synchrotron on a timescale of $t \sim 2\text{x}10^4$ yr
- Using the diffusion coefficient that is implied by measurements of B/C and other secondary-to-primary ratios, these particles should diffuse a distance of $L_{dif} \sim (D\,t)^{1/2} \sim 200$ pc over this cooling time
- If this were realized in nature, the very high-energy gamma rays from Geminga and Monogem should come from a large fraction of the sky



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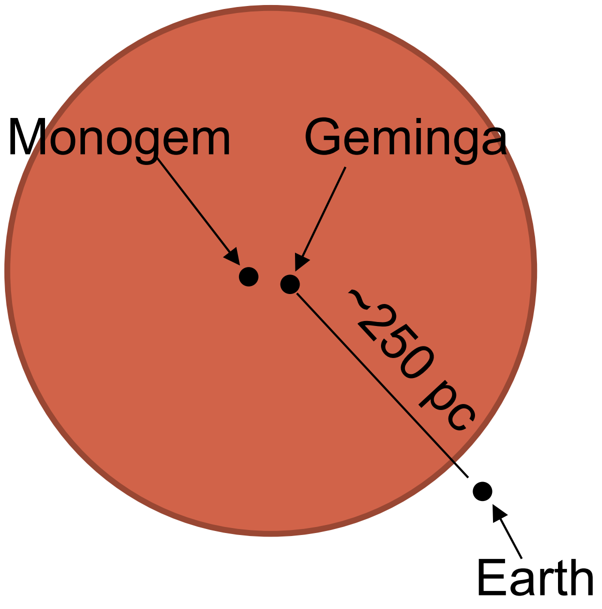
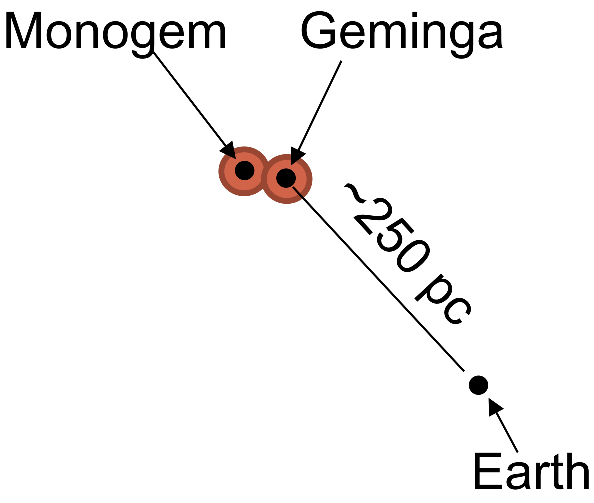
- If this were realized in nature, the very high-energy gamma rays from Geminga and Monogem should come from a large fraction of the sky
- The ~2° extension of these sources indicates that they are surrounded by regions of highly suppressed diffusion, relative to elsewhere in the ISM





The Efficiency of TeV Halos

- If diffusion had been not been suppressed in the regions surrounding these pulsars, their ICS emission would have been distributed across much of the sky, and very difficult to identify
- The surprising compactness of this emission allowed us to measure the intensity of TeV halos, and to calculate the fraction of these pulsars' spindown power that goes into the production of energetic electron-positron pairs
- This fraction appears to be significant, on the order of ~10%

DH, I. Cholis, T. Linden, K. Feng, arXiv:1702.08436

What About Other Pulsars?

To date, roughly ~3700 Milky Way pulsars have been detected at radio wavelengths and ~300 at GeV energies; many others remain undetected

How many pulsars should HAWC or LHAASO be able to detect?

Associations with Radio Pulsars?

- Even early on, the answer to this question was clearly *many*
- Of the 39 sources in the 2HWC catalog, 16 were potentially associated with known radio pulsars (compared to an expected ~2.7 chance associations)

2HWC Name	ATNF Name	Distance (kpc)	Angular Separation	Projected Separation	Expected Flux ($\times10^{-15}$)	Actual Flux ($\times10^{-15}$)	Flux Ratio
J0700+143	B0656+14	0.29	0.18°	0.91 pc	43.0	23.0	1.87
J0631+169	J0633+1746	0.25	0.89°	3.88 pc	48.7	48.7	1.0
J1912+099	J1913+1011	4.61	0.34°	27.36 pc	13.0	36.6	0.36
J2031+415	J2032+4127	1.70	0.11°	3.26 pc	5.59	61.6	0.091
J1831-098	J1831-0952	3.68	0.04°	2.57 pc	7.70	95.8	0.080
J1930+188	J1930+1852	7.0	0.03°	3.67 pc	23.2	9.8	2.37
J1814-173	J1813-1749	4.7	0.54°	44.30 pc	243	152	1.60
J2019+367	J2021+3651	1.8	0.27°	8.48 pc	99.8	58.2	1.71
J1928+177	J1928+1746	4.34	0.03°	2.27 pc	8.08	10.0	0.81
J1908+063	J1907+0602	2.58	0.36°	16.21 pc	40.0	85.0	0.47
J2020+403	J2021+4026	2.15	0.18°	6.75 pc	2.48	18.5	0.134
J1857+027	J1856+0245	6.32	0.12°	13.24 pc	11.0	97.0	0.11
J1825-134	J1826-1334	3.61	0.20°	12.66 pc	20.5	249	0.082
J1837-065	J1838-0655	6.60	0.38°	43.77 pc	12.0	341	0.035
J1837-065	J1837-0604	4.78	0.50°	41.71 pc	8.3	341	0.024
J2006+341	J2004+3429	10.8	0.42°	80.07 pc	0.48	24.5	0.019

Similar efficiencies as Geminga!

- This trend continued in the 3HWC catalog and the first LHAASO catalog, demonstrating that they are dominated by TeV halos (and perhaps PWN)

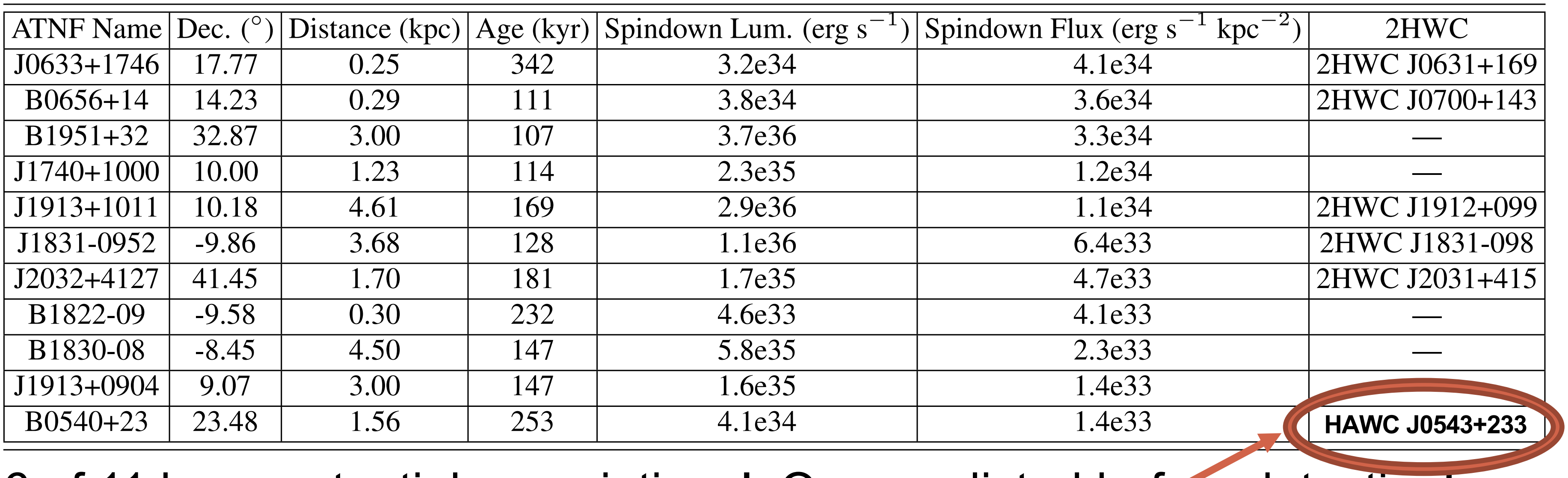
T. Linden, K. Auchettl, J. Bramante, I. Cholis, K. Fang, DH, T. Karwal, S. Li, arXiv:1703.09704

Associations with Radio Pulsars?

- Many of the sources detected by HAWC and LHAASO are powered by pulsars, but are most radio pulsars also TeV gamma-ray sources?

Associations with Radio Pulsars?

- Many of the sources detected by HAWC and LHAASO are powered by pulsars, but are most radio pulsars also TeV gamma-ray sources?
- Here is a list of the young (100-400 kyr) radio pulsars in HAWC's field-of-view, ranked by their predicted gamma-ray flux (assuming a Geminga-like efficiency):



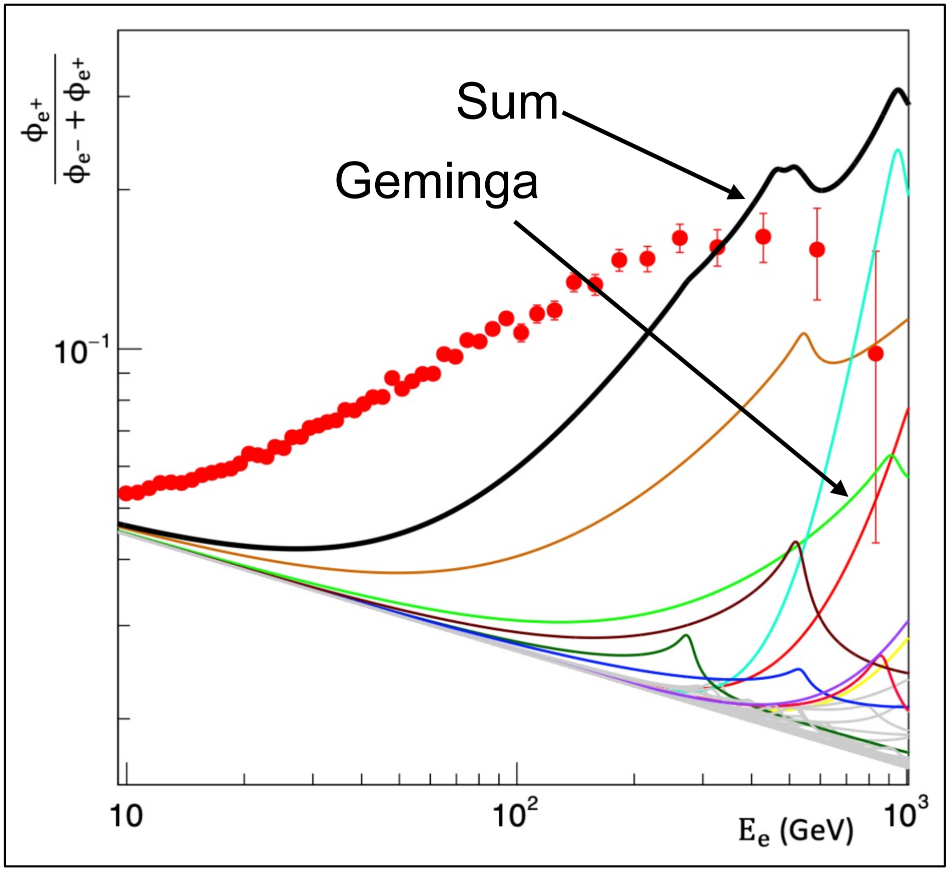
ATNF Name	Dec. ($^\circ$)	Distance (kpc)	Age (kyr)	Spindown Lum. (erg s^{-1})	Spindown Flux (erg s^{-1} kpc^{-2})	2HWC
J0633+1746	17.77	0.25	342	3.2e34	4.1e34	2HWC J0631+169
B0656+14	14.23	0.29	111	3.8e34	3.6e34	2HWC J0700+143
B1951+32	32.87	3.00	107	3.7e36	3.3e34	—
J1740+1000	10.00	1.23	114	2.3e35	1.2e34	—
J1913+1011	10.18	4.61	169	2.9e36	1.1e34	2HWC J1912+099
J1831-0952	-9.86	3.68	128	1.1e36	6.4e33	2HWC J1831-098
J2032+4127	41.45	1.70	181	1.7e35	4.7e33	2HWC J2031+415
B1822-09	-9.58	0.30	232	4.6e33	4.1e33	—
B1830-08	-8.45	4.50	147	5.8e35	2.3e33	—
J1913+0904	9.07	3.00	147	1.6e35	1.4e33	
B0540+23	23.48	1.56	253	4.1e34	1.4e33	**HAWC J0543+233**

- 6 of 11 have potential associations! One predicted <u>before</u> detection! (11/9 ATEL)
- All indications suggest that that TeV halos are present around most (if not all) middle-aged pulsars

T. Linden, K. Auchettl, J. Bramante, I. Cholis, K. Fang, DH, T. Karwal, S. Li, arXiv:1703.09704

TeV Halos and the Positron Excess

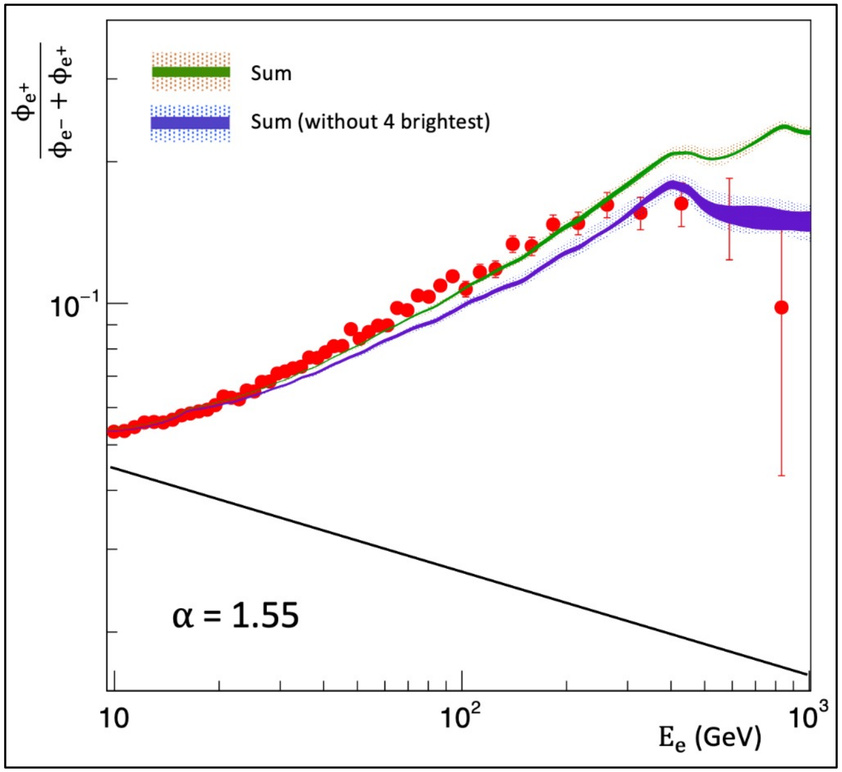
- Although Geminga and Monogem surely contribute to the local positron flux, this signal is expected to receive contributions from *many* pulsars
- Here is the predicted contribution from the 10 known pulsars that are expected to contribute the most to the local positron excess (adopting a 15% efficiency into >10 GeV e^+/e^-)
- At the highest measured energies, the positron fraction is likely dominated by only a handful of TeV halos, making any predictions subject to large uncertainties associated with pulsar-to-pulsar variations
- At lower energies, the observed positron flux is instead dominated by a large number of TeV halos (including many that have not been detected yet), allowing us to make more reliable predictions



M. Bitter, DH, arXiv:2205.05200

TeV Halos and the Positron Excess

- To model the Milky Way's population, we used a Monte Carlo, treating as free parameters the beaming angle, efficiency, spindown timescale, and injected spectral shape of e^+e^- pairs
- We found that we can fit the observed positron flux and pulsar populations for an average radio beaming angle that covers ~30% of the sky, a GeV beaming angle that covers ~70% of the sky, a spectral index of ~1.6, and an efficiency of ~15%
- For these parameter choices, we obtain the following:



M. Bitter, DH, arXiv:2205.05200

Implications for Diffuse Gamma-Ray Backgrounds

- These results have important implications for the diffuse gamma-ray emission that we should expect to see across other parts of the sky
- Last year, for example, LHAASO reported a new measurement of the diffuse gamma-ray emission from the Galactic Plane
- How much of this emission comes from unresolved TeV halos?

Implications for Diffuse Gamma-Ray Backgrounds

- To answer this question, we modeled the Milky Way's pulsar population and their TeV halos, adopting the following spatial distribution:

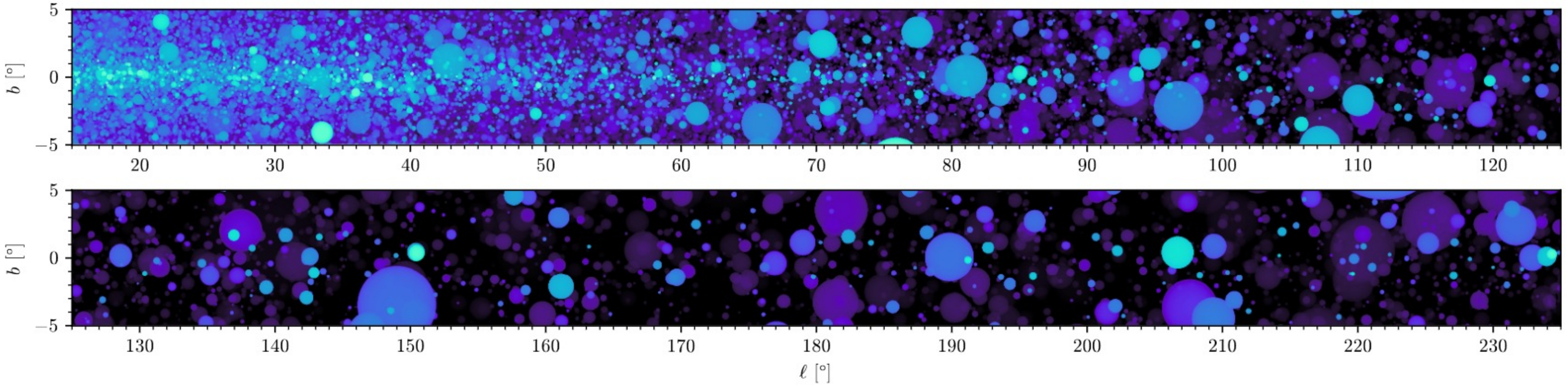
$$n_{\rm pulsar} \propto R^{2.35}\, e^{-R/1530\,{\rm pc}}\, e^{-|z|/z_s},$$

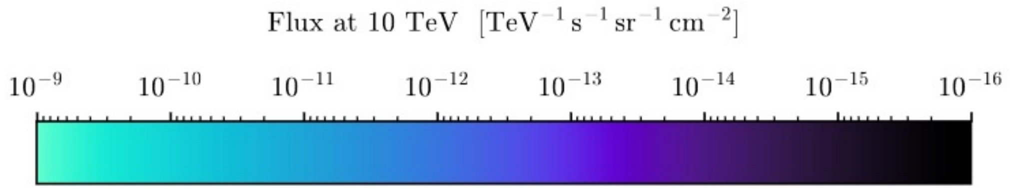
where we account for natal kicks by adopting $z_s = 70\,{\rm pc} + 180\,{\rm pc} \times (t/10^6\,{\rm yr})$, up to a maximum scale height of 1 kpc

- We model the evolution of the TeV halos according to magnetic dipole breaking, adopting a spindown timescale of 10^4 years, a surface magnetic field of $B=1.6\text{x}10^{12}$ G, and an initial period of $P_0=0.04$ s

A. Dekker, I. Holst, DH, G. Leone,
E. Simon, H. Xiao, arXiv:2306.00051

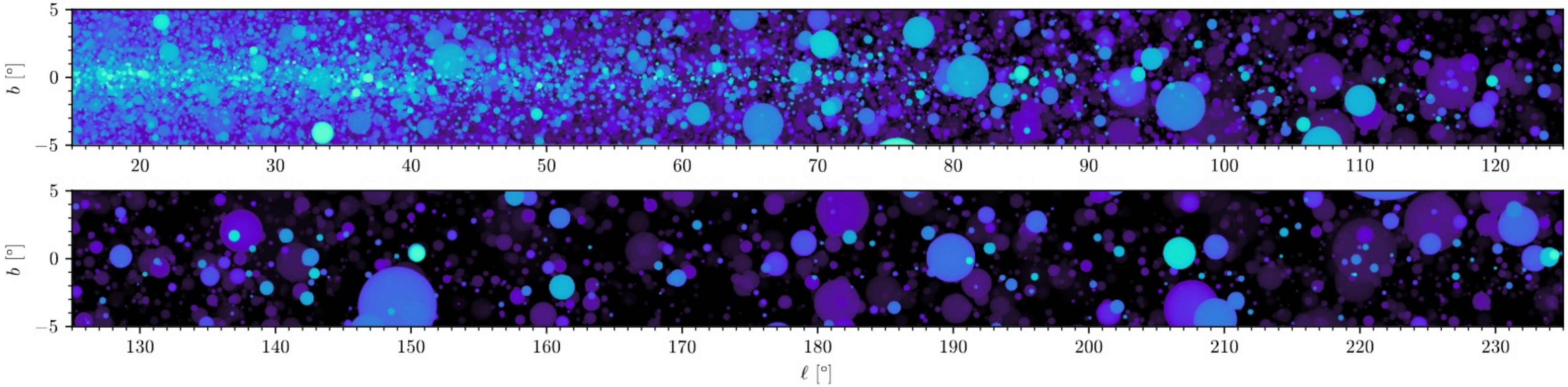
Here’s an example of one realization of our Monte Carlo:



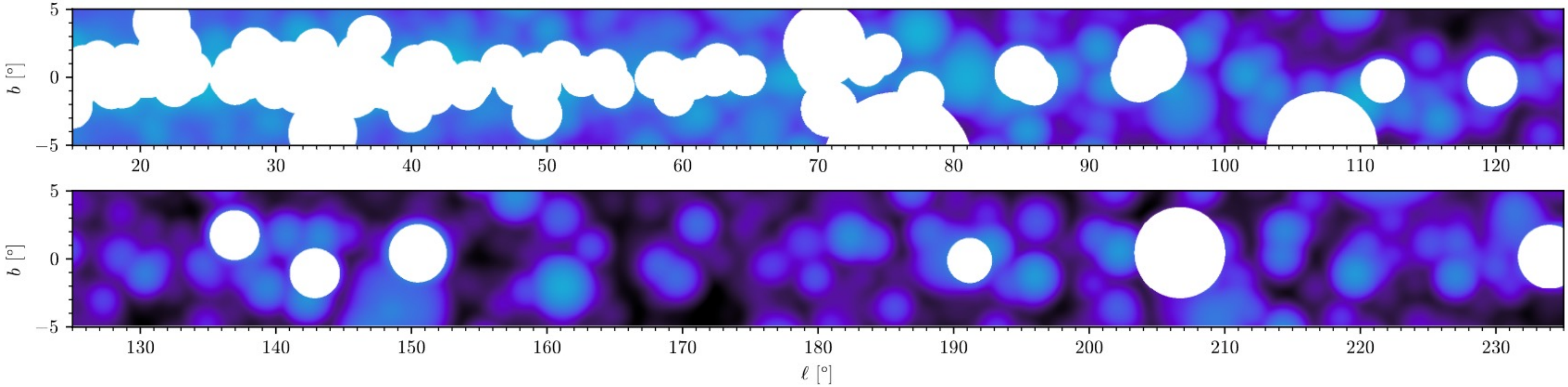


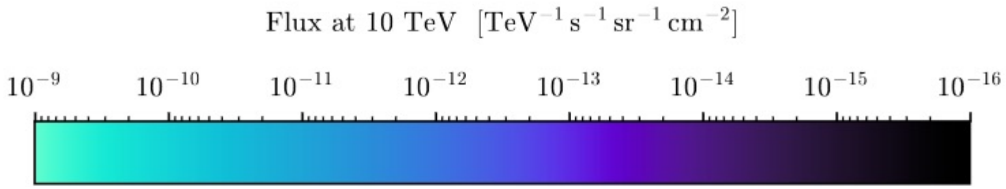
A. Dekker, I. Holst, DH, G. Leone,
E. Simon, H. Xiao, arXiv:2306.00051

Here's an example of one realization of our Monte Carlo:



After accounting for LHAASO's PSF and masking resolved sources:





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E. Simon, H. Xiao, arXiv:2306.00051

Implications for Diffuse Gamma-Ray Backgrounds

- So, how do the results of our pulsar population model compare to the LHAASO data?

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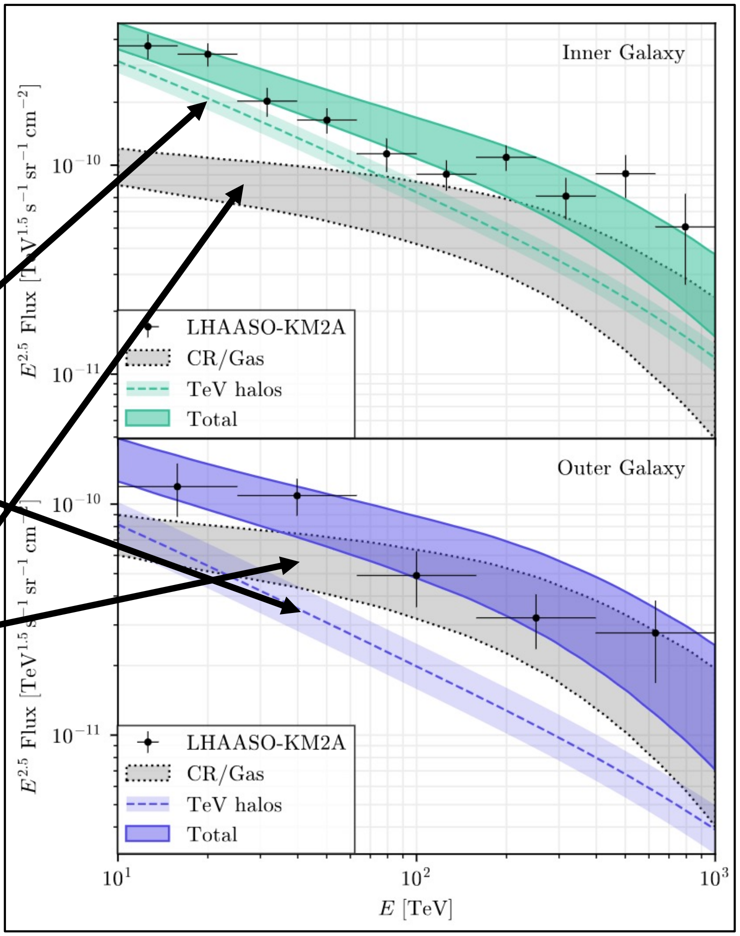
Implications for Diffuse Gamma-Ray Backgrounds

- So, how do the results of our pulsar population model compare to the LHAASO data?
- Normalized such that 5.2%* of the spindown power goes into >TeV gamma rays, we find that TeV halos should dominate the diffuse emission observed from the Inner Galaxy between ~10-100 TeV



Unresolved TeV halos
(across 10 MC realizations)

CR scattering with gas

*5.2% to >TeV gamma rays is consistent with ~15% to >10 GeV electrons/positrons, as required to explain the positron excess

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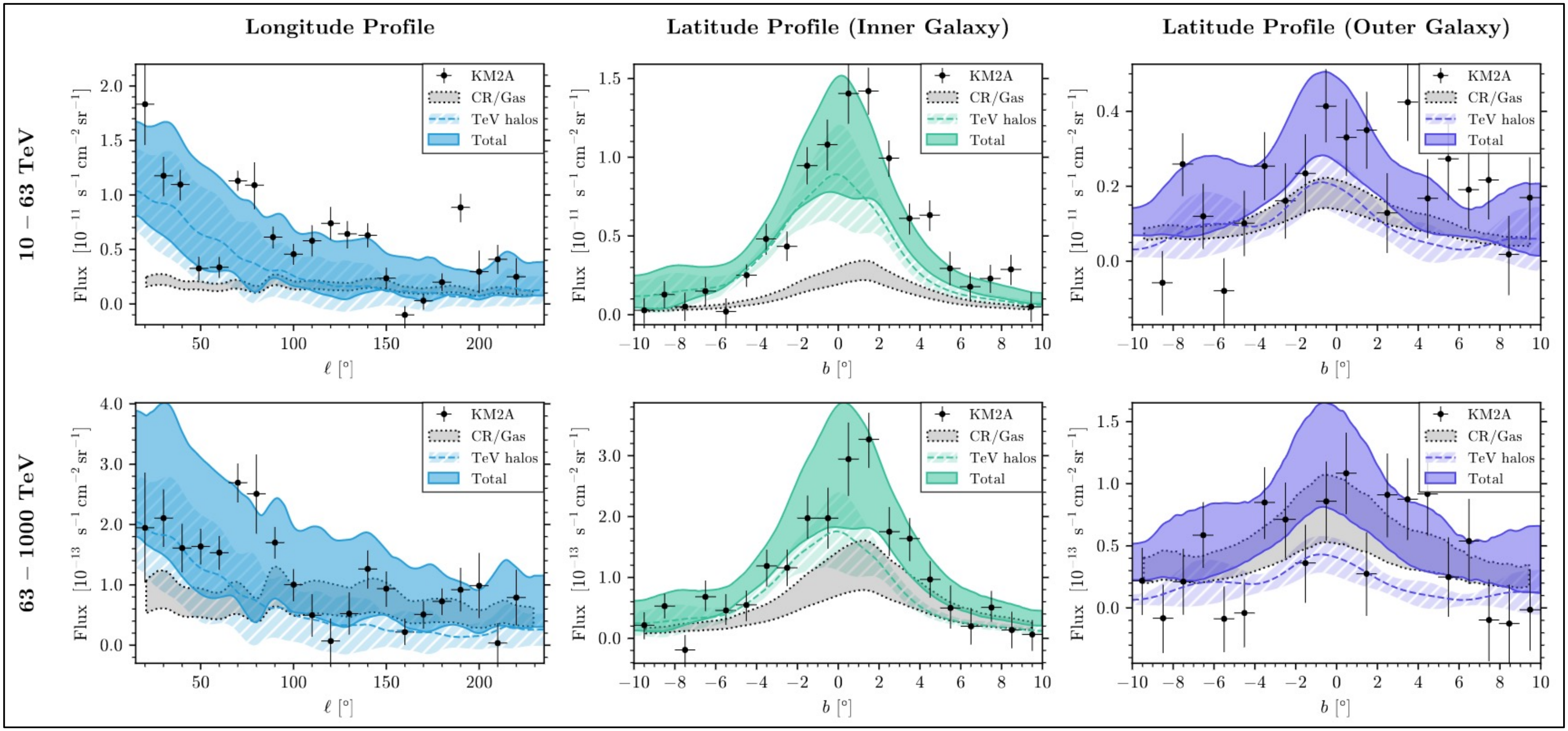
Implications for Diffuse Gamma-Ray Backgrounds

- The observed longitude and latitude profiles of this emission are also in good agreement with the predictions of our model



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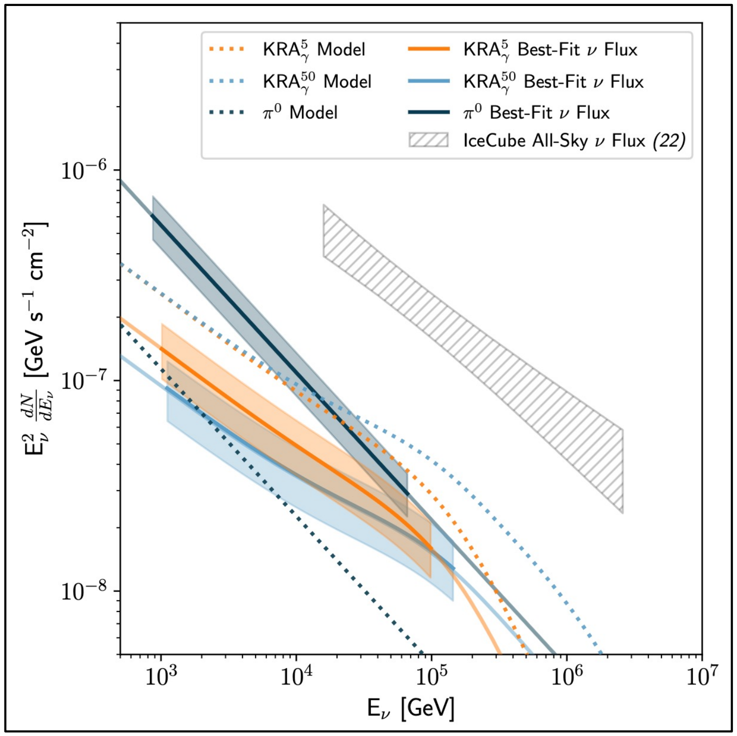
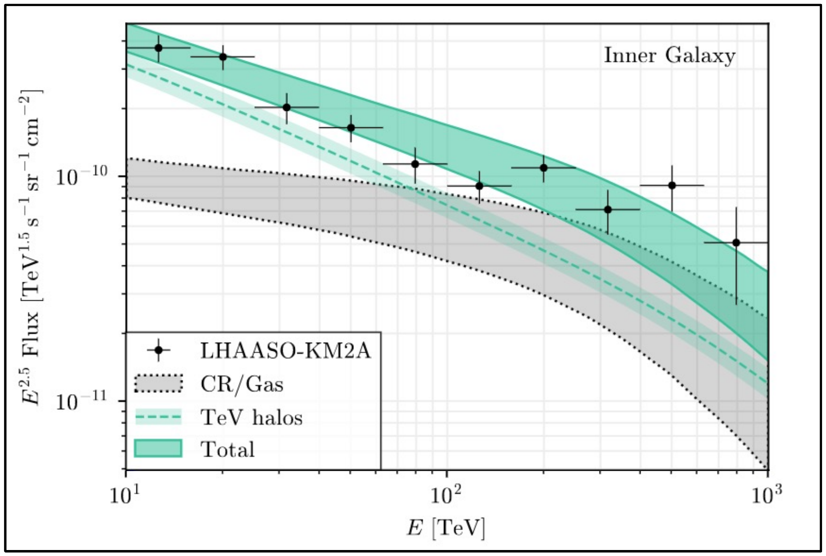
E. Simon, H. Xiao, arXiv:2306.00051

Implications for the Origin of IceCube's Galactic Plane Emission

- Over the range of angles and energies that have been detected by IceCube, the diffuse gamma-ray emission is likely to be dominated by unresolved TeV halos (which are leptonic, and do not produce neutrinos)
- This doesn't leave a lot of room for emission from ICS or bremstraahlung, providing us with an opportunity to further constrain models of cosmic-ray transport



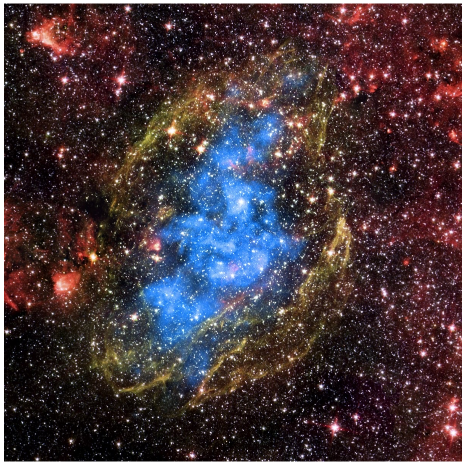


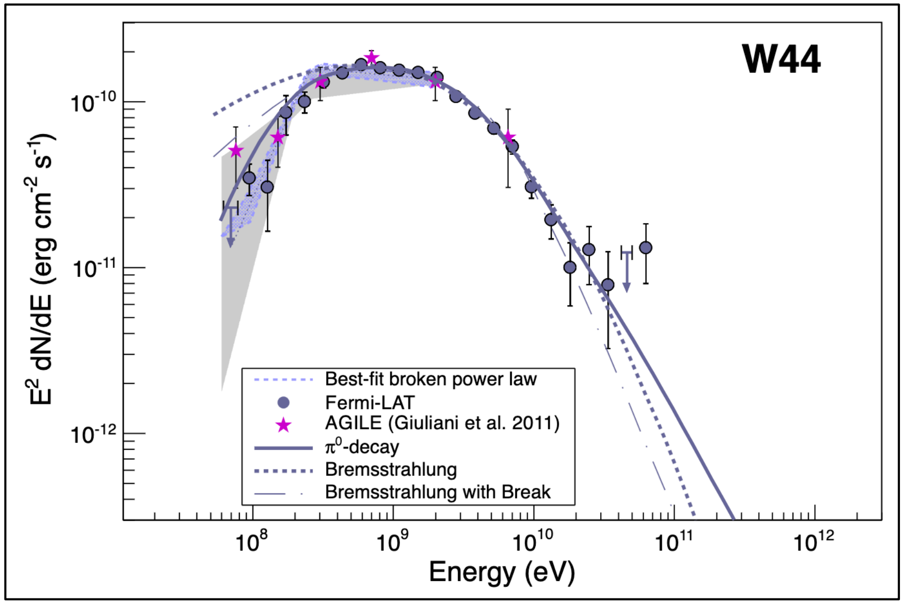
A. Dekker, I. Holst, DH, G. Leone, E. Simon, H. Xiao, arXiv:2306.00051

Neutrinos from Galactic Sources

- Although a significant fraction of the neutrino flux observed from the Galactic Plane is generated by diffuse cosmic rays, there is still room for contributions from point sources
- Supernova remnants and pulsar wind nebulae both seem particularly promising
- Gamma ray observations of several SNRs (W44, IC 443, SNR G106.3+2.7) have identified the characteristic spectral features associated with pion decay
- While its hard to rule out leptonic processes, non-hadronic interpretations of this data seem fine-tuned

Supernova Remnant, W44

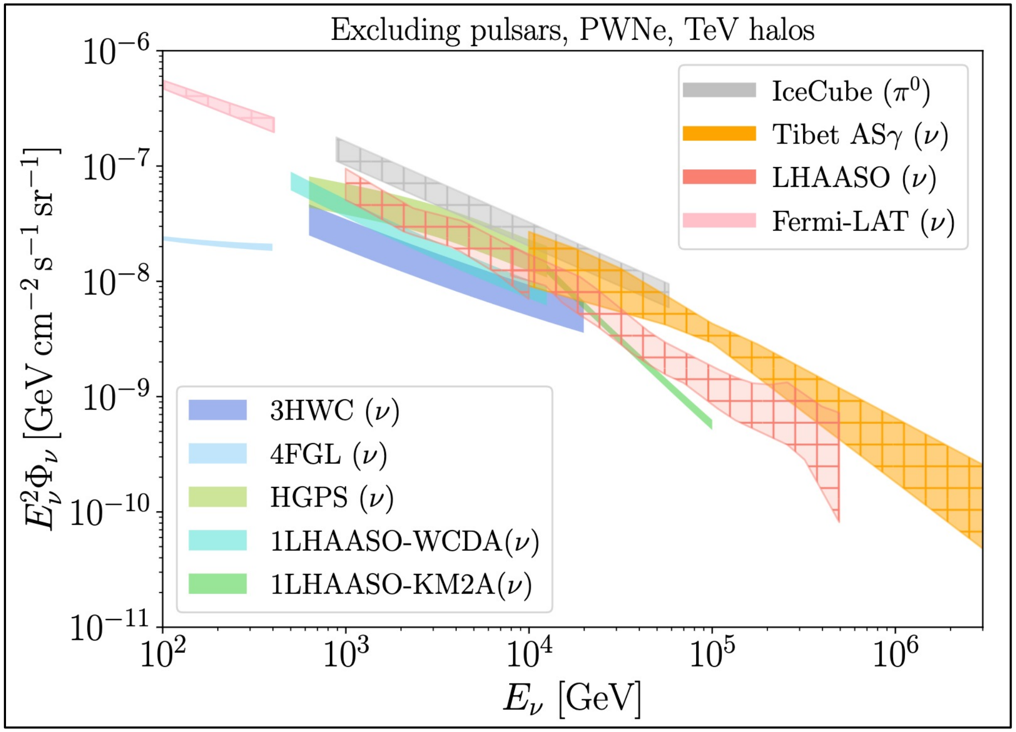




Fermi Collaboration, *Science*, arXiv:1302.3307; Fang, PRL, arXiv:2208.05457

Neutrinos from Galactic Sources

- From gamma-ray source catalogs, one can derive upper limits on the contribution to the neutrino flux from these sources (assuming purely hadronic gamma-ray emission and that the sources are optically thin)
- Even under these highly optimistic assumptions, most the observed neutrino emission cannot arise from *cataloged* gamma-ray sources
- Most of IceCube's flux must arise from a combination of diffuse cosmic-ray interactions and *unresolved* sources



Fang & Murase, arXiv:2307.02905

Neutrinos from Galactic Sources

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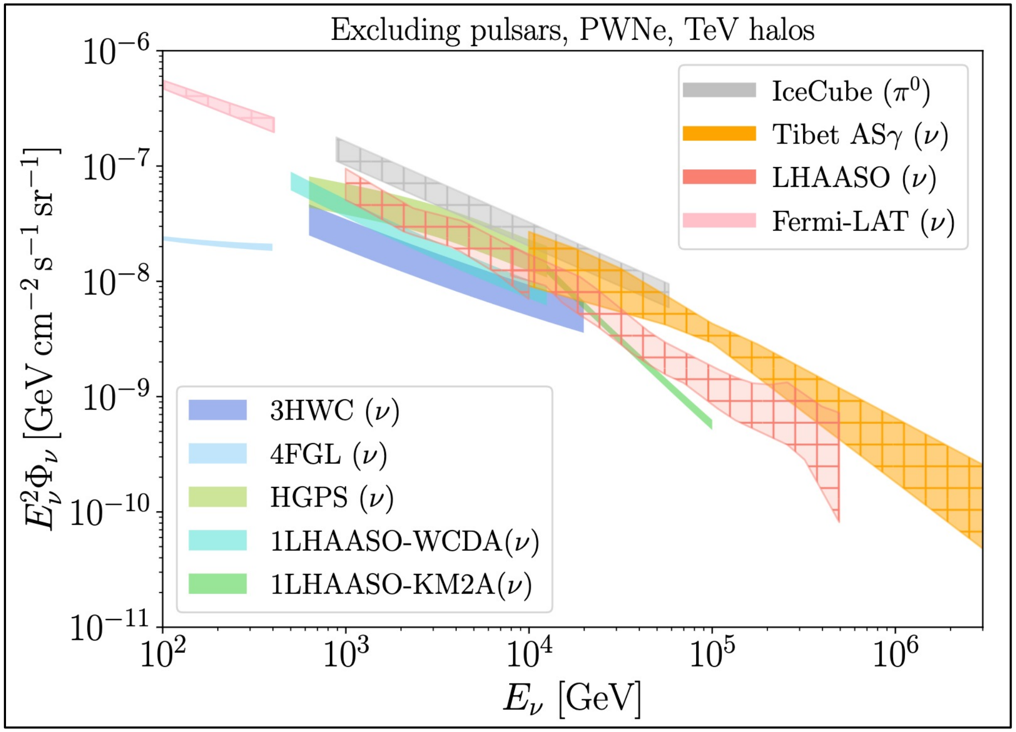
- Even under these highly optimistic assumptions, most the observed neutrino emission cannot arise from *cataloged* gamma-ray sources
- Most of IceCube's flux must arise from a combination of diffuse cosmic-ray interactions and *unresolved* sources
- The flux of the diffuse gamma-ray emission at ~1-30 TeV is comparable to the observed neutrino flux
- Is this in tension with the significant flux of gamma-ray emission that is expected from unresolved TeV halos?
- Maybe, but this depends critically on the cosmic-ray transport model that is adopted
- I think of this as an opportunity to constrain cosmic-ray transport models



Fang & Murase, arXiv:2307.02905

Summary

- The neutrino flux observed by IceCube from the Galactic Plane originates from both individual sources and from cosmic-ray scattering in the ISM
- Resolved gamma-ray sources cannot be responsible for most the observed neutrino emission
- Observations of TeV halos indicate that they are an approximately universal feature of middle-aged pulsars; these sources appear to be responsible for the observed cosmic-ray positron fraction, and for a significant fraction of the diffuse very high-energy gamma-ray emission that has been observed from the Milky Way
- This leaves relatively little room for gamma-ray emission from hadronic sources, such as unresolved supernova remnants or pulsar wind nebulae
- By combining cosmic-ray, gamma-ray, and neutrino data, we can break long-standing degeneracies and begin to constrain models for cosmic-ray acceleration and transport in the Milky Way