TeV Halos:

Three Findings

And ~~Three~~ Five! Puzzles

TIM LINDEN

Stockholm University

EARLY LESSONS

- 1.) Pulsars are highly efficient e^+e^- accelerators.
- 2.) TeV e^+e^- are not confined in the source.

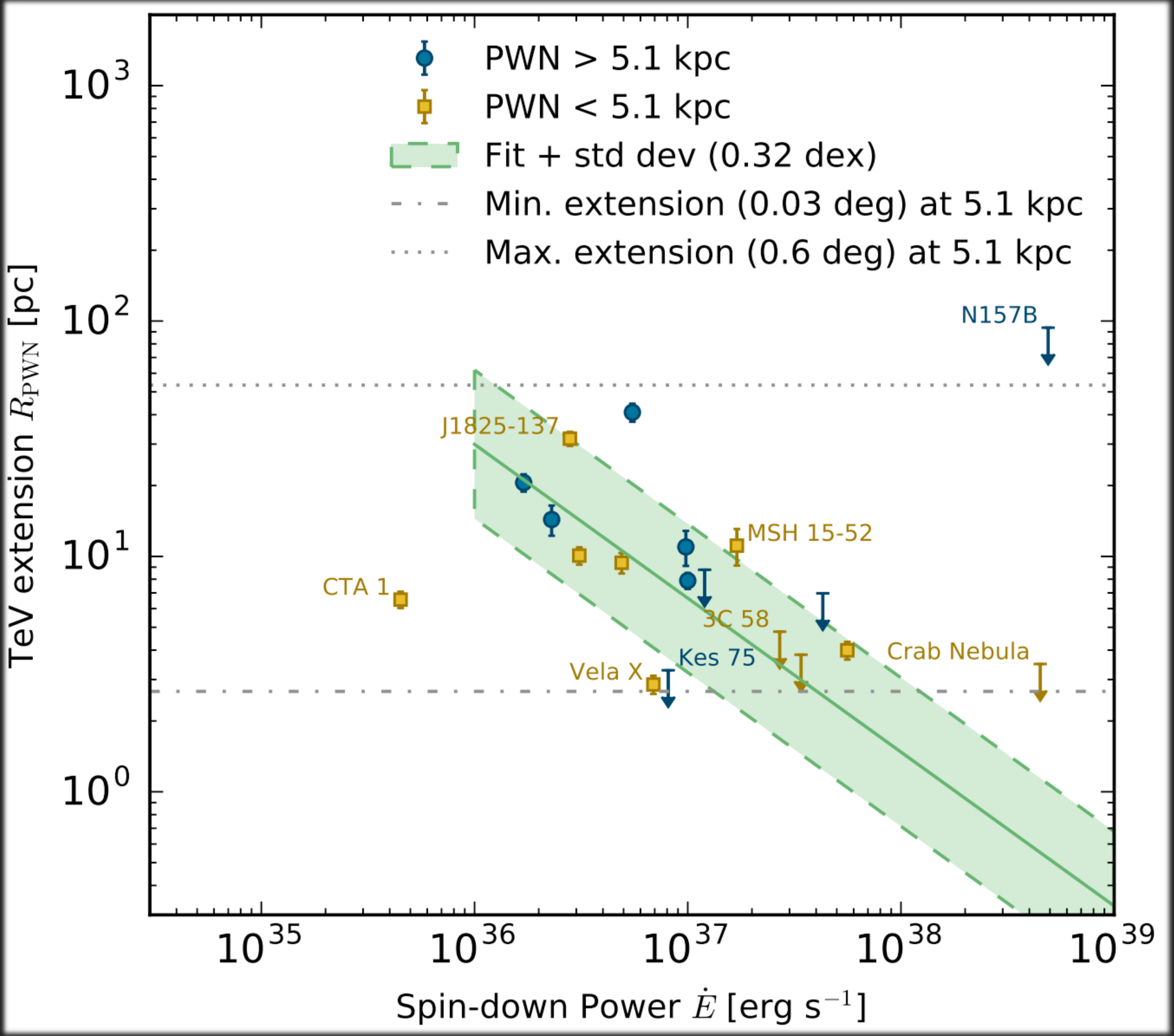
- 3.) Regions near pulsar sources have unusually low diffusion coefficients.

TEV HALOS: A NEW SOURCE CLASS

TeV Halos are much larger than PWN, especially at low spin down power and large ages.

NOTE: The size of halos has the opposite time- dependence as the X-Ray PWN.

$$R_{\mathrm{PWN}} \simeq 1.5 \left(\frac{\dot{E}}{10^{35}\,\mathrm{erg/s}} \right)^{1/2} \times \left(\frac{n_{\mathrm{gas}}}{1\,\mathrm{cm}^{-3}} \right)^{-1/2} \left(\frac{v}{100\,\mathrm{km/s}} \right)^{-3/2} \mathrm{pc}$$



TEV HALOS: THE GEMINGA-CENTRIC MODEL

- **Make One Key Assumption:**

ATNF Name	Dec. (°)	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	—

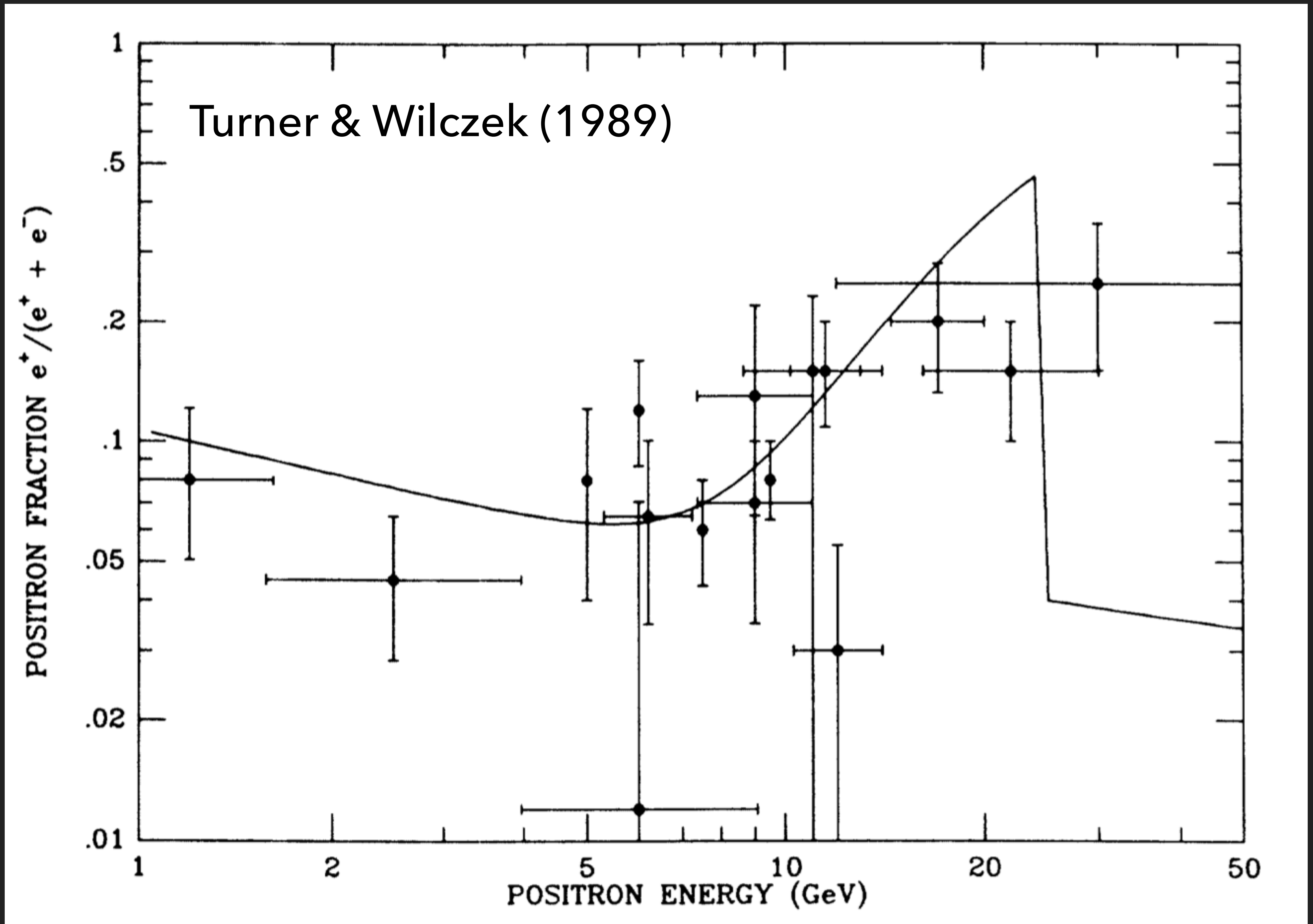
- **The following correlation is consistent with the data.**

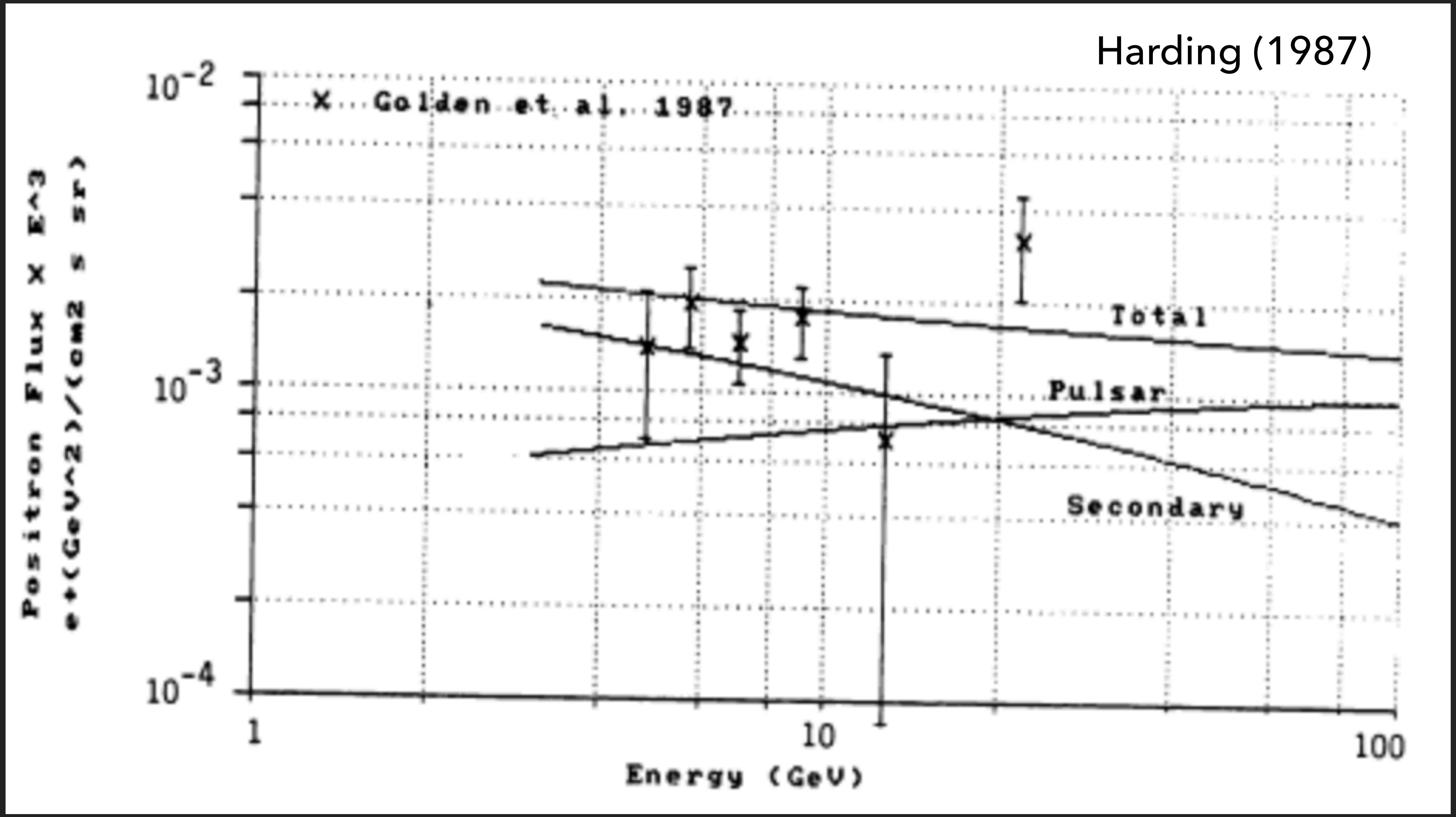
$$\phi_{\mathrm{TeV\ halo}} = \left(\frac{\dot{E}_{\mathrm{psr}}}{\dot{E}_{\mathrm{Geminga}}}\right)\left(\frac{d^2_{\mathrm{Geminga}}}{d^2_{\mathrm{psr}}}\right)\phi_{\mathrm{Geminga}}$$

IMPLICATION 1: THE POSITRON EXCESS

EARLY LESSONS

- **1.) Pulsars are highly efficient e^+e^- accelerators.**





IMPLICATION 1: THE POSITRON EXCESS

- **What were the uncertainties in pulsar scenarios of the positron excess?**

  - **I: The e^+e^- production efficiency?**

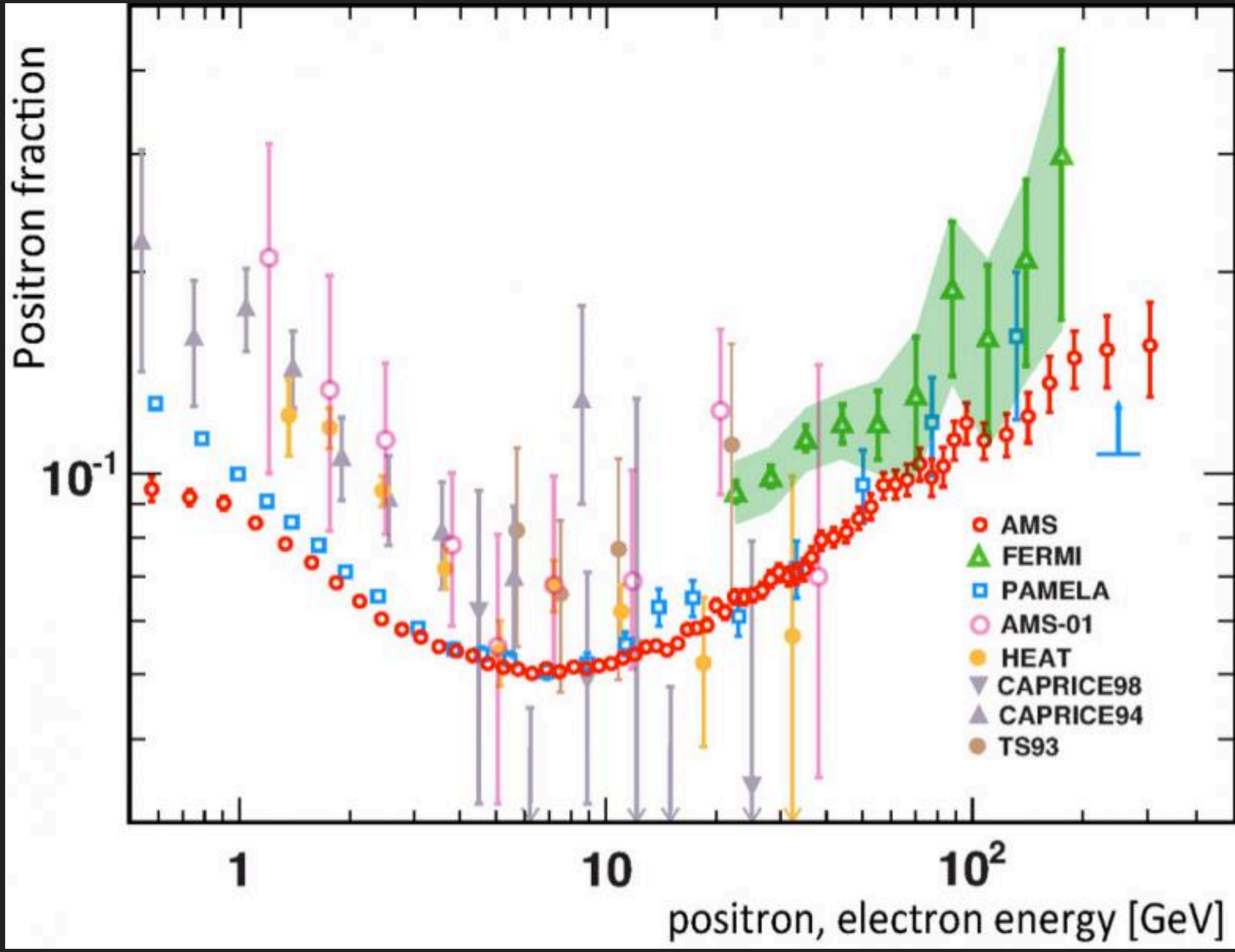
Profumo (0812.4457); Malyshev et al. (0903.1310)

%. A quantitative discussion of plausible values for $f_{e^\pm}$ was recently given in Ref. [38]. We shall not review their discussion here, but Ref. [38] argues (see in particular their very informative App. B and C) that in the context of a standard model for the pulsar wind nebulae, a reasonable range for $f_{e^\pm}$ falls between 1% and 30%.

  - **II: The e^+e^- spectrum.**

Hooper et al. (0810.1527)

part of their energy adiabatically because of the expansion of the wind. The energy spectrum injected by a single pulsar depends on the environmental parameters of the pulsar, but some attempts to calculate the average spectrum injected by a population of mature pulsars suggest that the spectrum may be relatively hard, having a slope of ~1.5-1.6 [18]. This spectrum, however, results from a complex interplay of individual pulsar spectra, of the spatial and age distributions of pulsars in the Galaxy, and on the assumption that the chief channel for pulsar spin down is magnetic dipole radiation. Due to the related uncertainties, variations from this injection spectra cannot be ruled out. Typically, one concentrates the attention on pulsars of age $\sim 10^5$ years because younger pulsars are likely to still

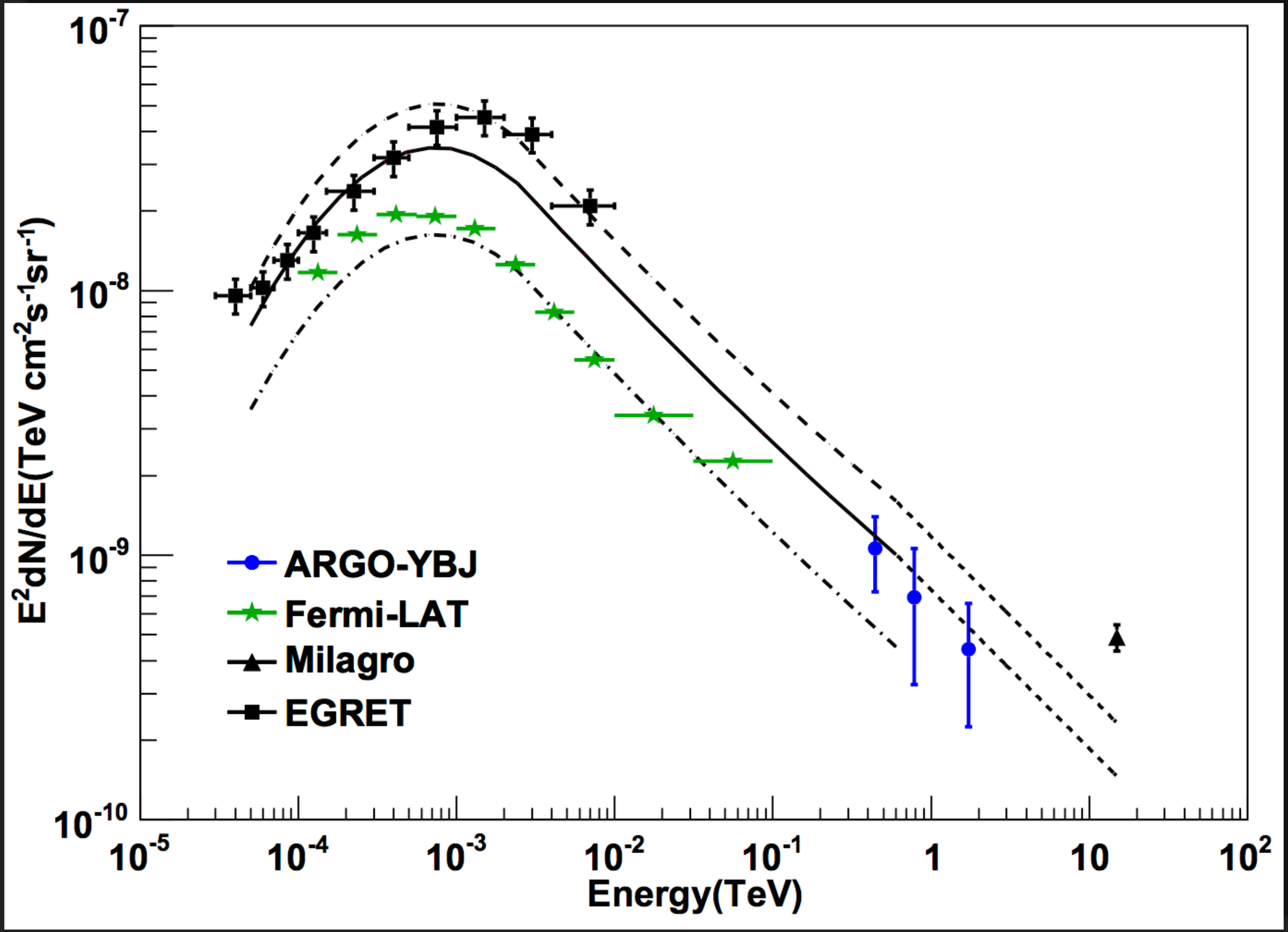


IMPLICATION 2: DIFFUSE TEV GAMMA-RAYS

EARLY LESSONS

- 1.) Pulsars are highly efficient e^+e^- accelerators.
- 2.) TeV e^+e^- are not confined in the source.

IMPLICATION 3: DIFFUSE TEV GAMMA-RAYS

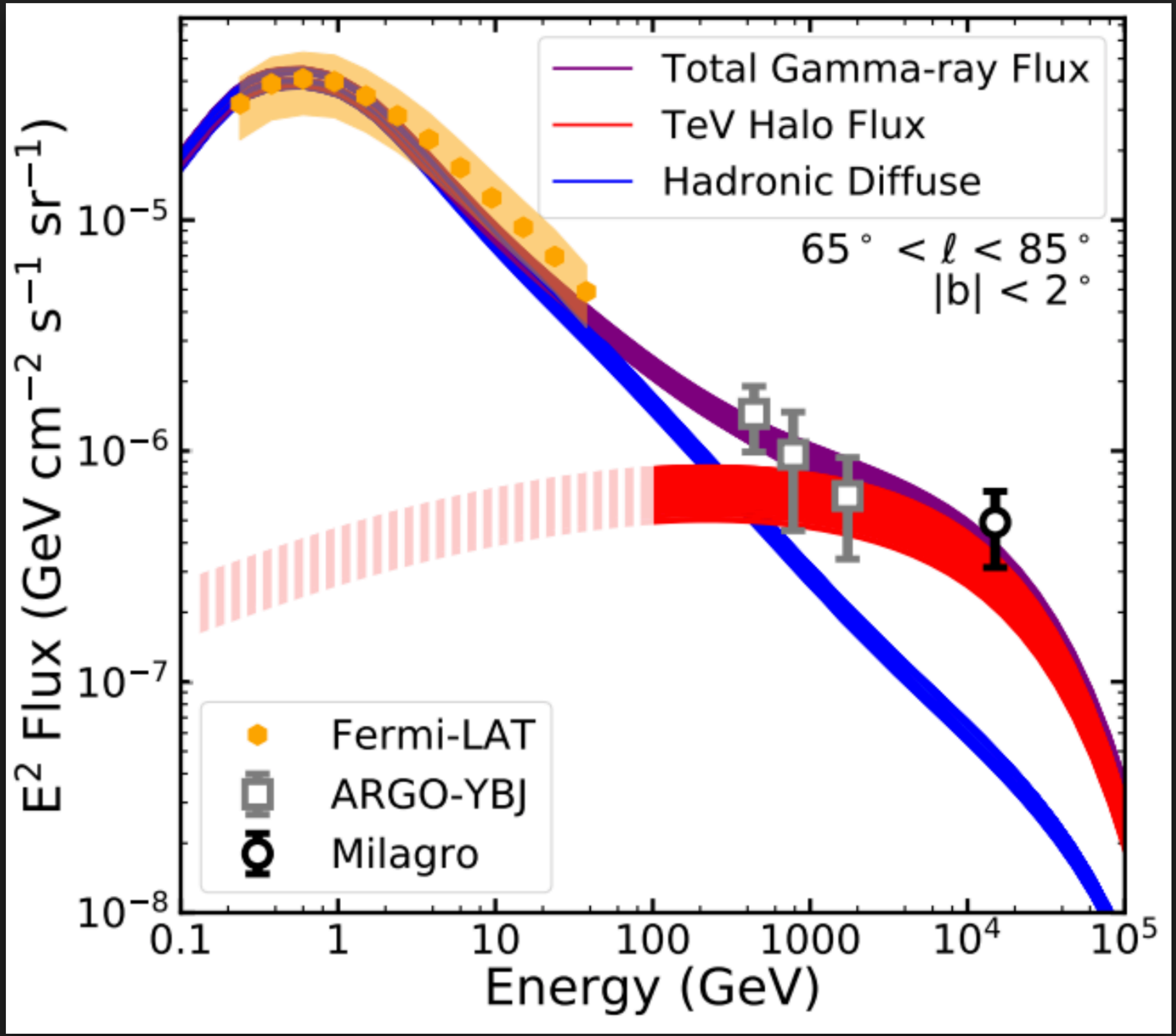


IMPLICATION 3: DIFFUSE TEV GAMMA-RAYS

- TeV halos naturally explain the spectrum and intensity of this emission.
- Multiple halos observed with $E^{-2.0}$ spectra.

- Note - “Halo” is not needed
  - Pulsar efficiency ~10%
  - Power must escape PWN

Linden & Buckman (2017; 1707.01905)



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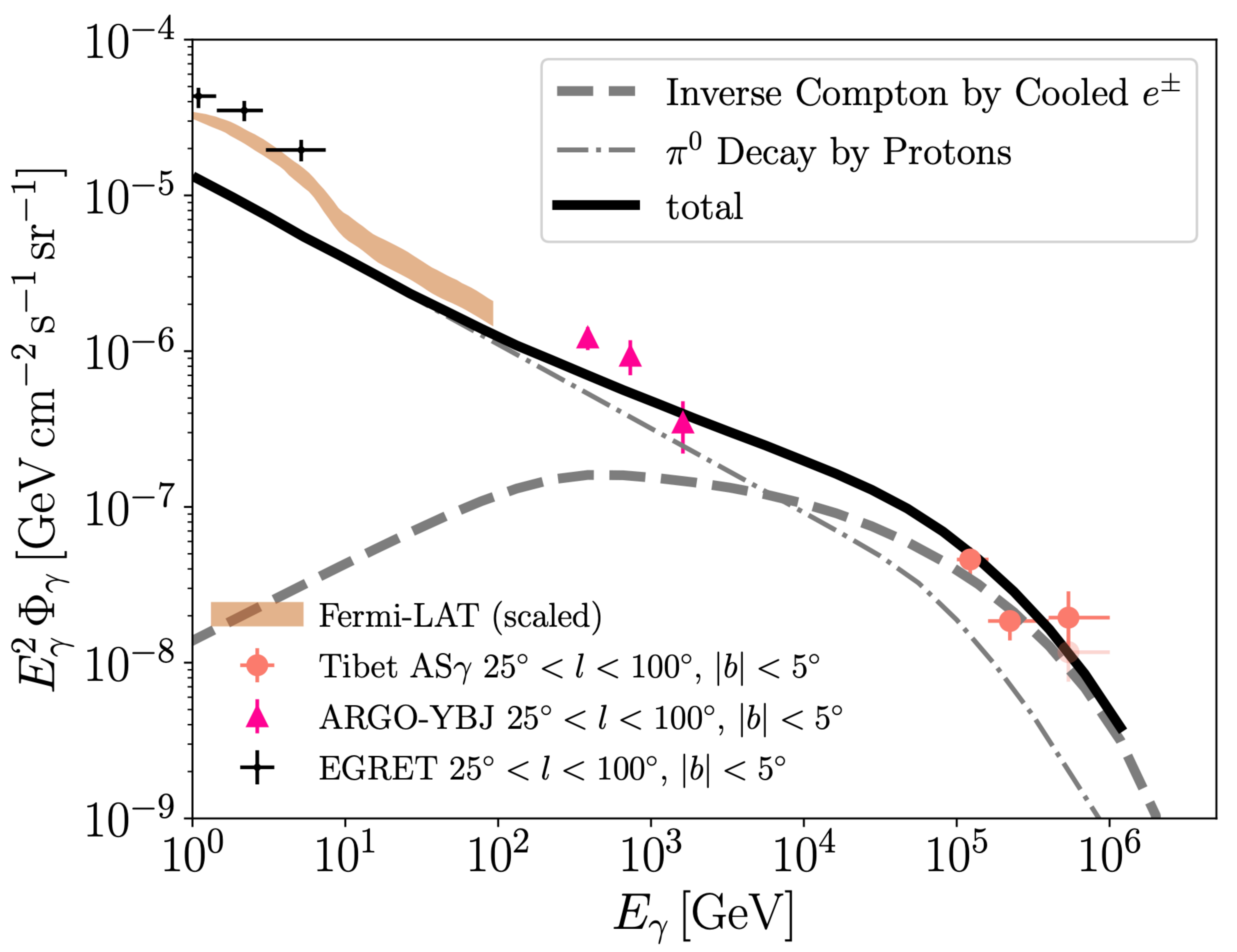
Fang & Murase (2021; 2104.09491)



Tibet ASγ data

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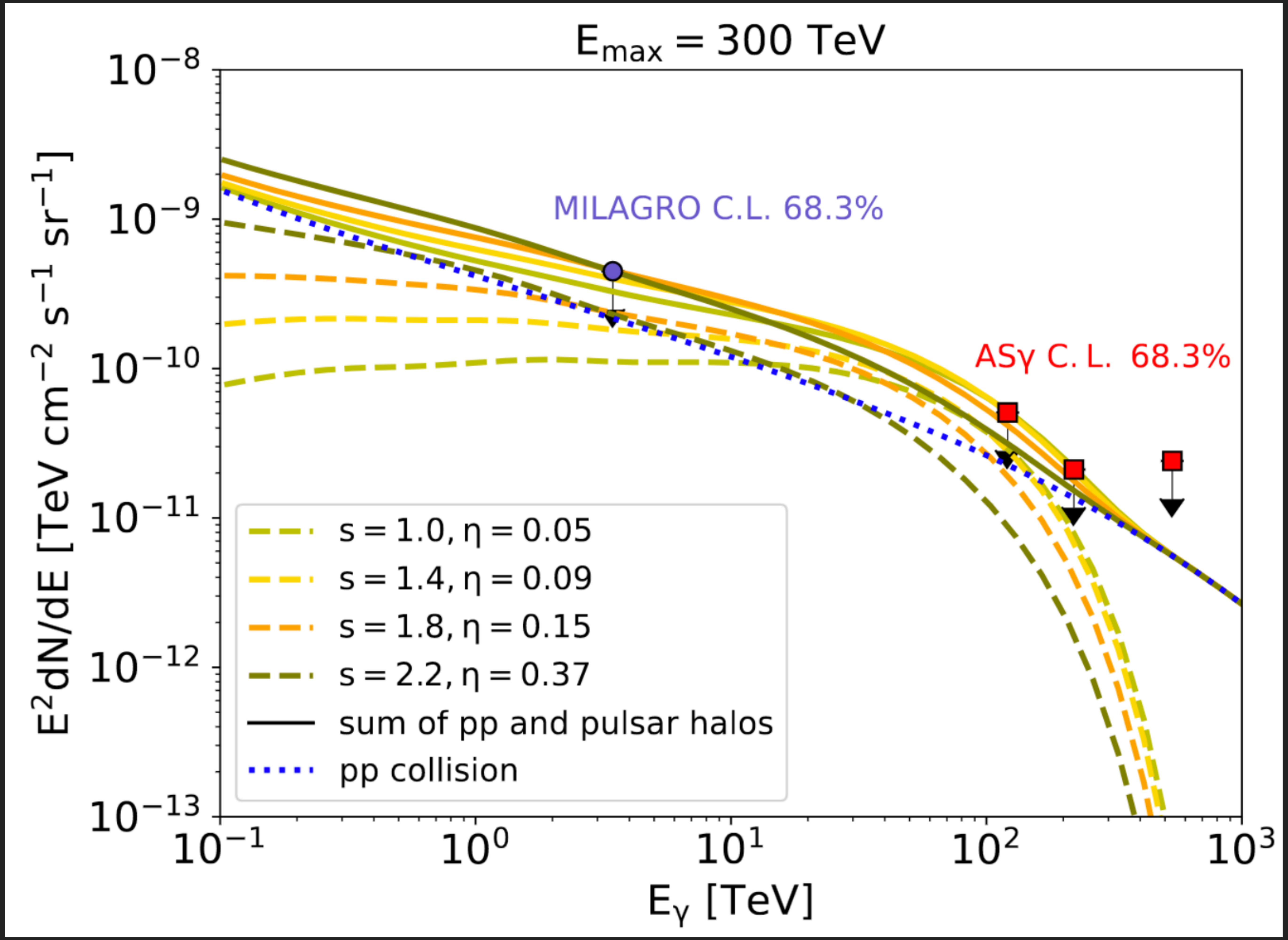
Yan & Liu (2023; 2304.12574)



LHAASO Data

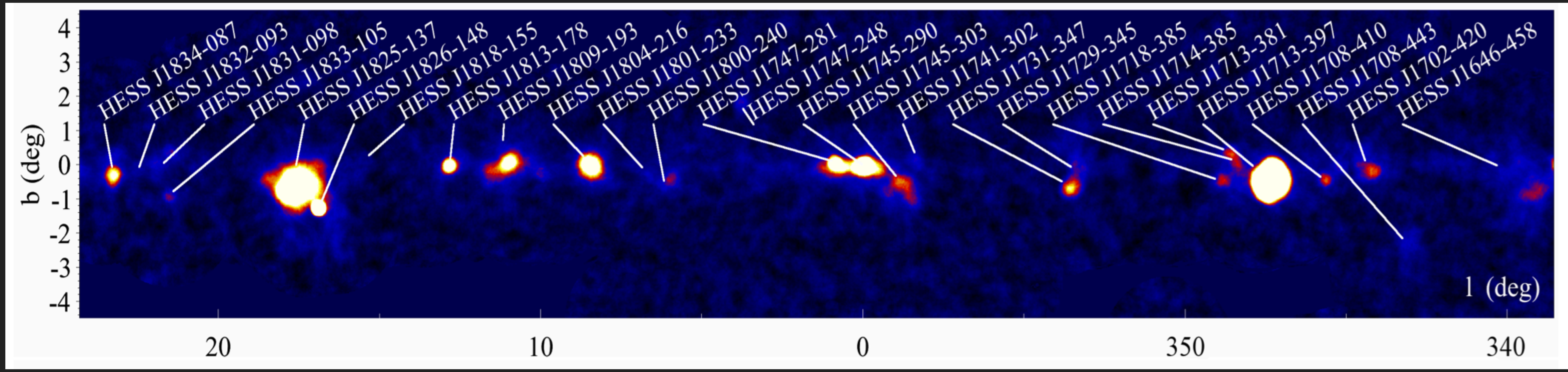
EARLY LESSONS

- 1.) Pulsars are highly efficient e^+e^- accelerators.
- 2.) TeV e^+e^- are not confined in the source.

- 3.) Regions near pulsar sources have unusually low diffusion coefficients.

IMPLICATION 3: MOST TEV SOURCES ARE POWERED BY PULSARS

- Radio pulsars are beamed!



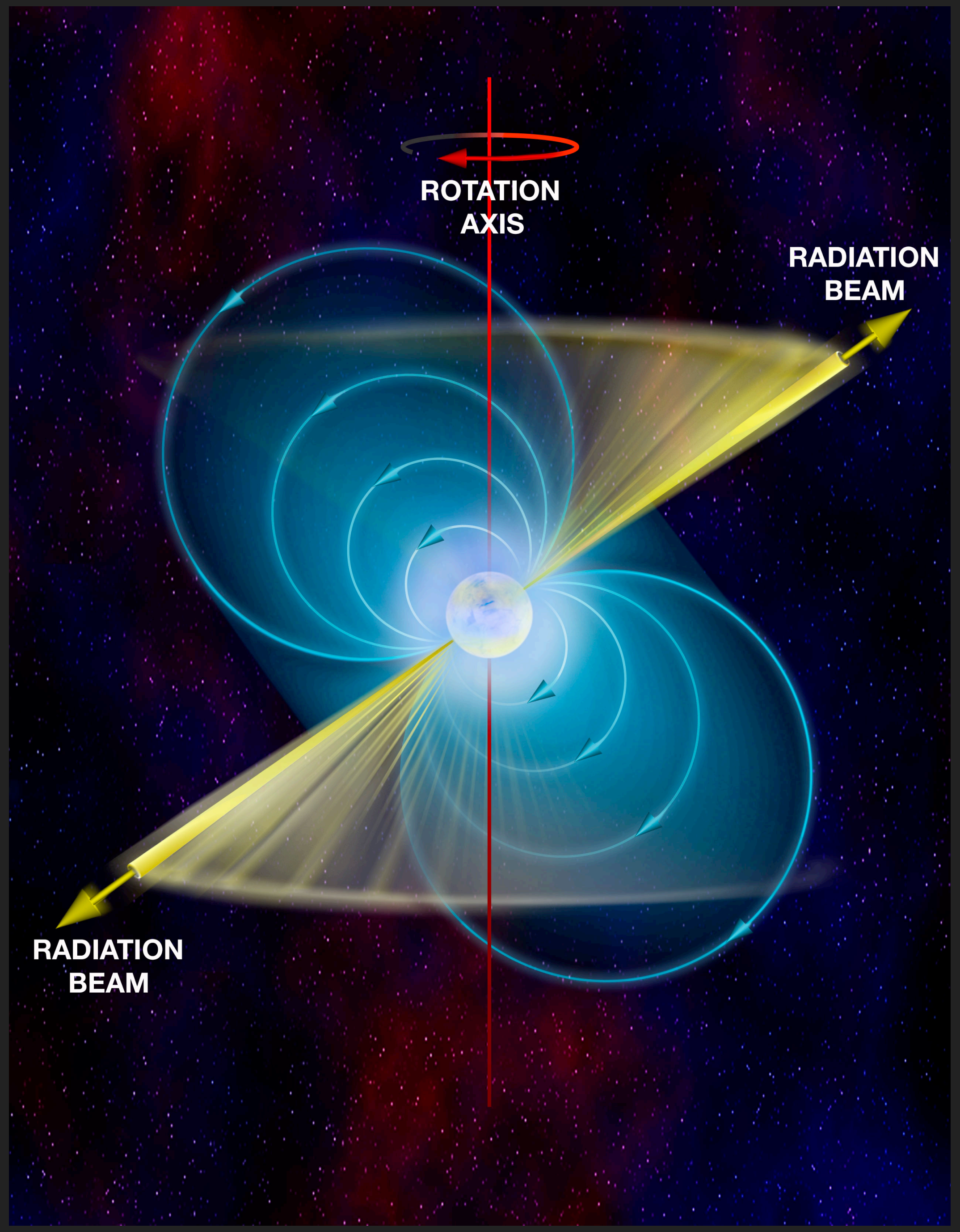
- Beaming fraction is small

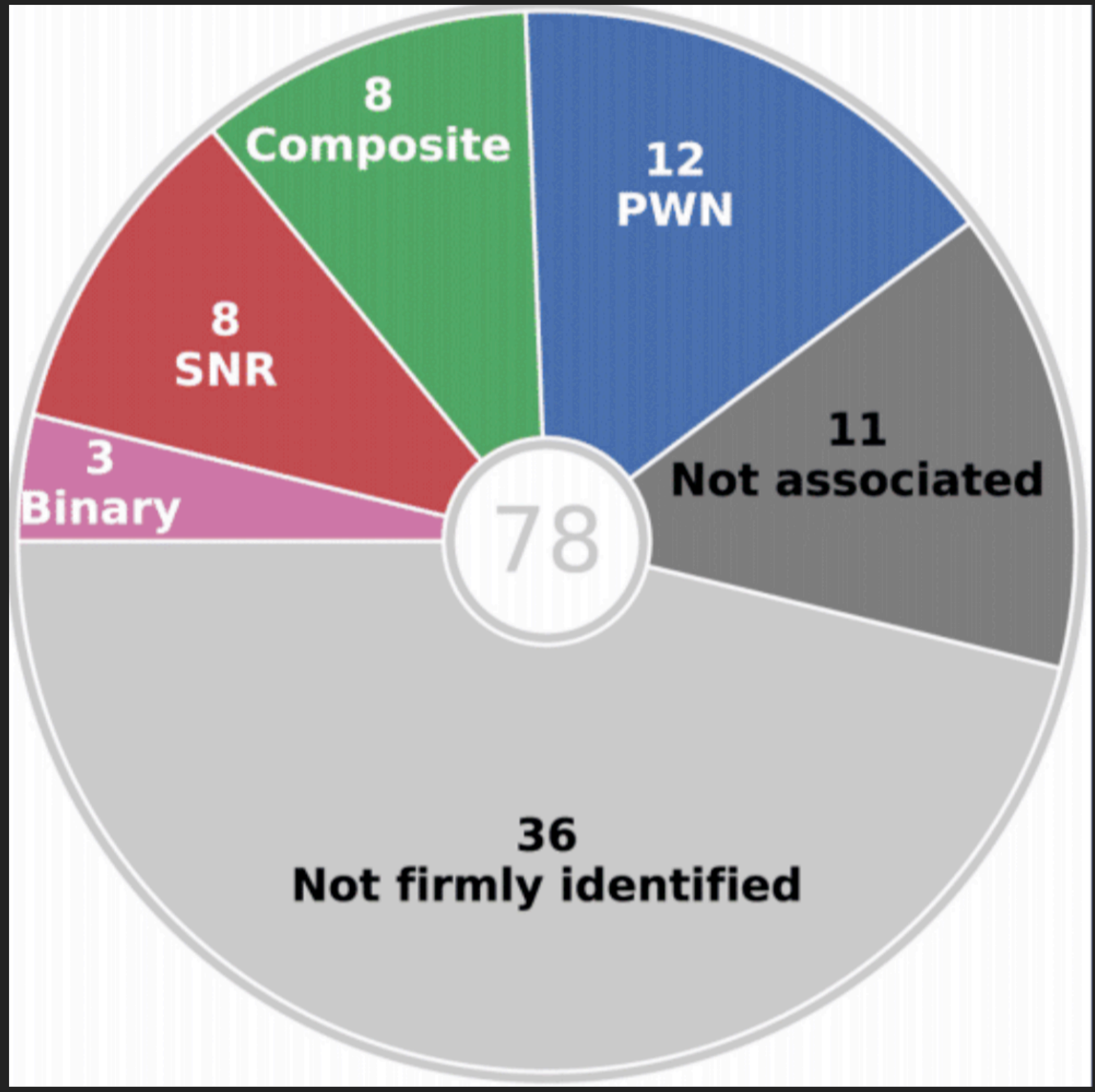
Tauris & Manchester (1998)

$$f = \left[1.1\left(\log_{10}\left(\frac{\tau}{100\ \mathrm{Myr}}\right)\right)^2 + 15\right]\%$$

- This varies between 15-30%.

- Most pulsars are unseen in radio!





Lessons from HAWC PWNe observations: the diffusion constant is not a constant; Pulsars remain the likeliest sources of the anomalous positron fraction; Cosmic rays are trapped for long periods of time in pockets of inefficient diffusion

Stefano Profumo,[1,2,*] Javier Reynoso-Cordova,[2,3,†] Nicholas Kaaz,[1,‡] and Maya Silverman[1,§]

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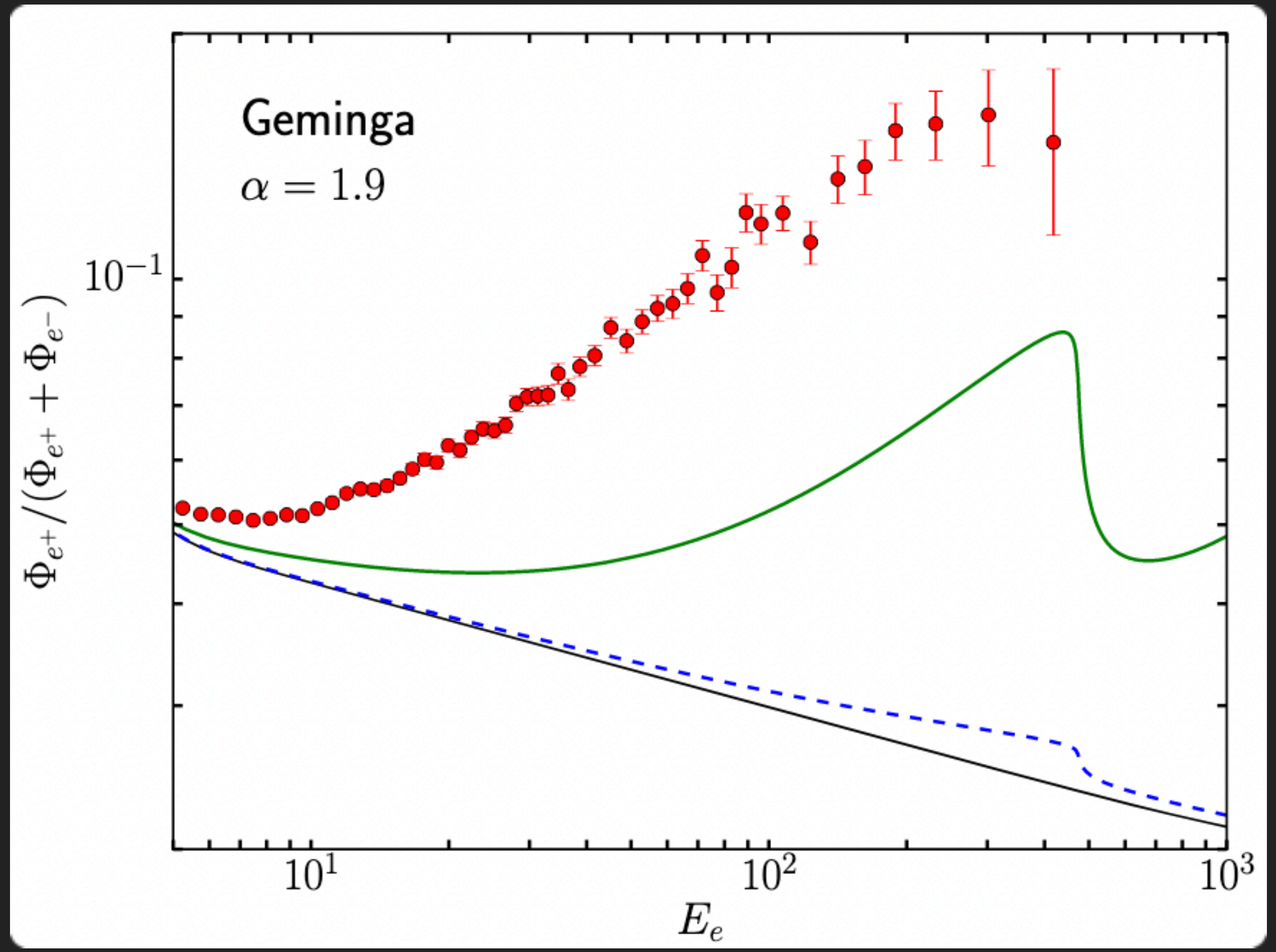
[2] *Santa Cruz Institute for Particle Physics, 1156 High St. Santa Cruz, CA 95060, United States of America*

[3] *Departamento de Física, DCI, Campus León, Universidad de Guanajuato, 37150, León, Guanajuato, México*

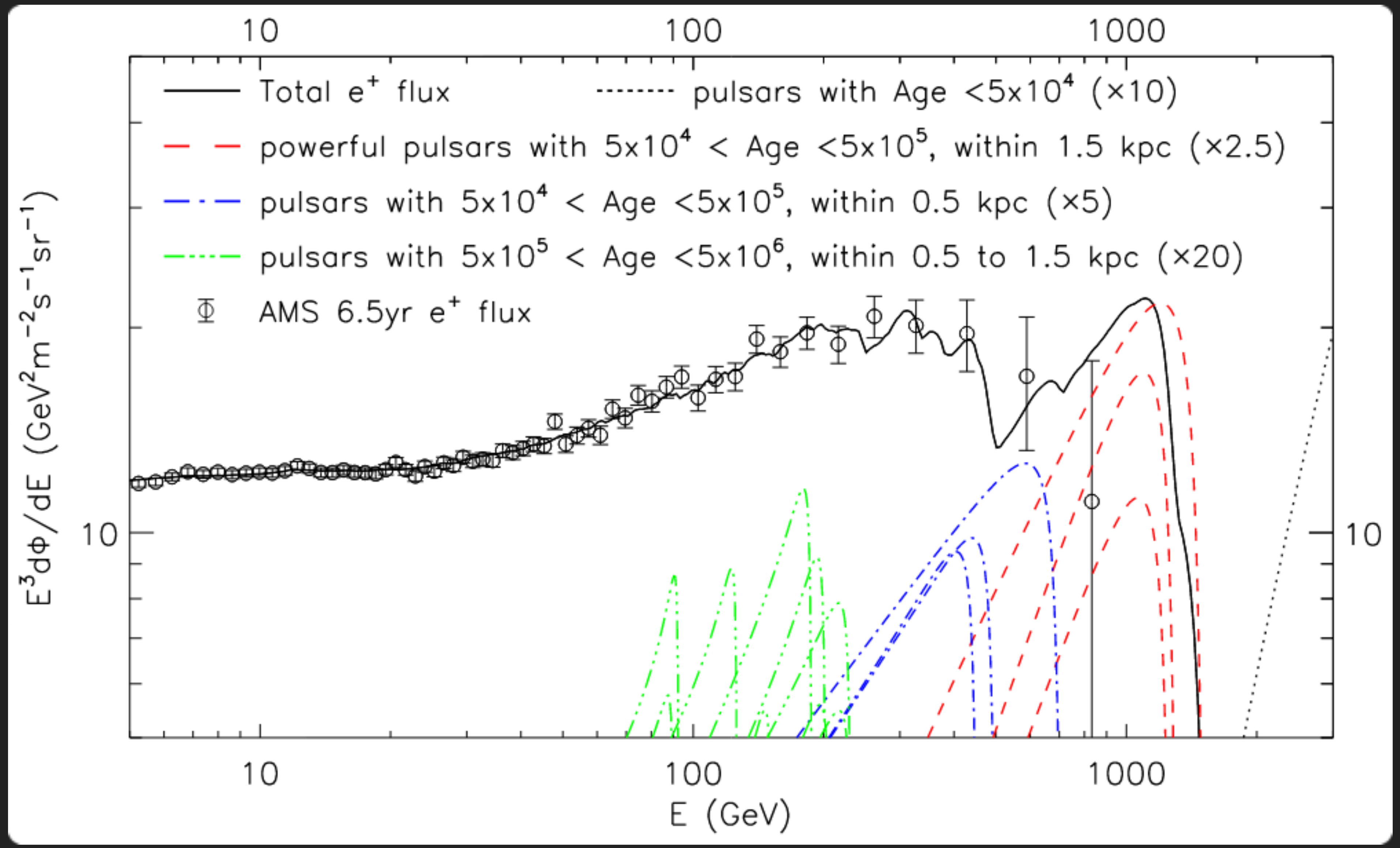
Recent TeV observations of nearby pulsars with the HAWC telescope have been interpreted as evidence that diffusion of high-energy electrons and positrons within pulsar wind nebulae is highly inefficient compared to the rest of the interstellar medium. If the diffusion coefficient well outside the nebula is close to the value inferred for the region inside the nebula, high-energy electrons and positrons produced by the two observed pulsars could not contribute significantly to the local measured cosmic-ray flux. The HAWC collaboration thus concluded that, under the assumption of isotropic and homogeneous diffusion, the two pulsars are ruled out as sources of the anomalous high-energy positron flux. Here, we argue that since the diffusion coefficient is likely *not* spatially homogeneous, the assumption leading to such conclusion is flawed. We solve the diffusion equation with a radially dependent diffusion coefficient, and show that the pulsars observed by HAWC produce potentially perfect matches to the observed high-energy positron fluxes. We also study the implications of inefficient diffusion within pulsar wind nebulae on Galactic scales, and show that cosmic rays are likely to have very long residence times in regions of inefficient diffusion. We describe how this prediction can be tested with studies of the diffuse Galactic emission.

PACS numbers:

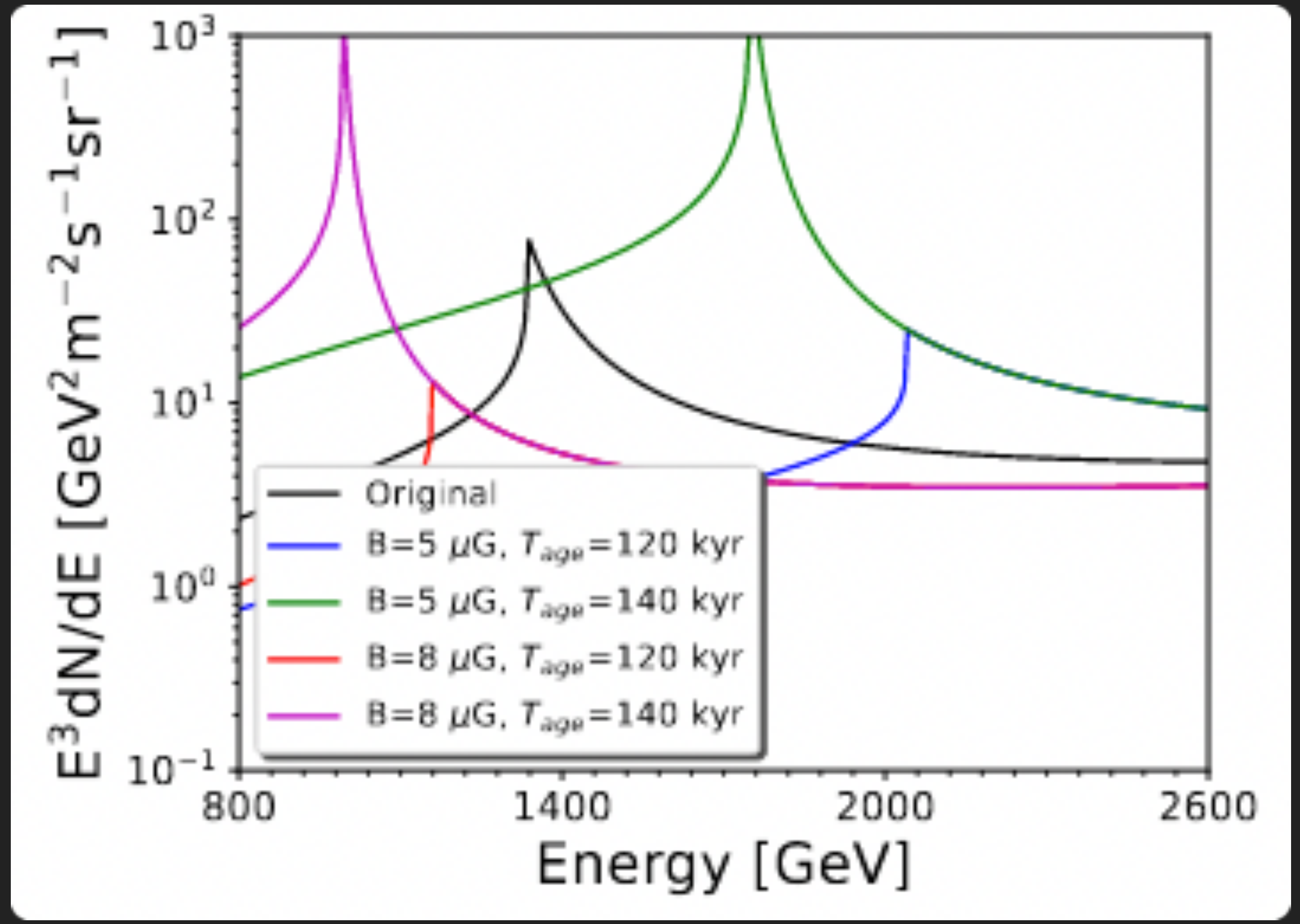
PUZZLE I: THE NUMBER OF PULSARS IN THE POSITRON DATA



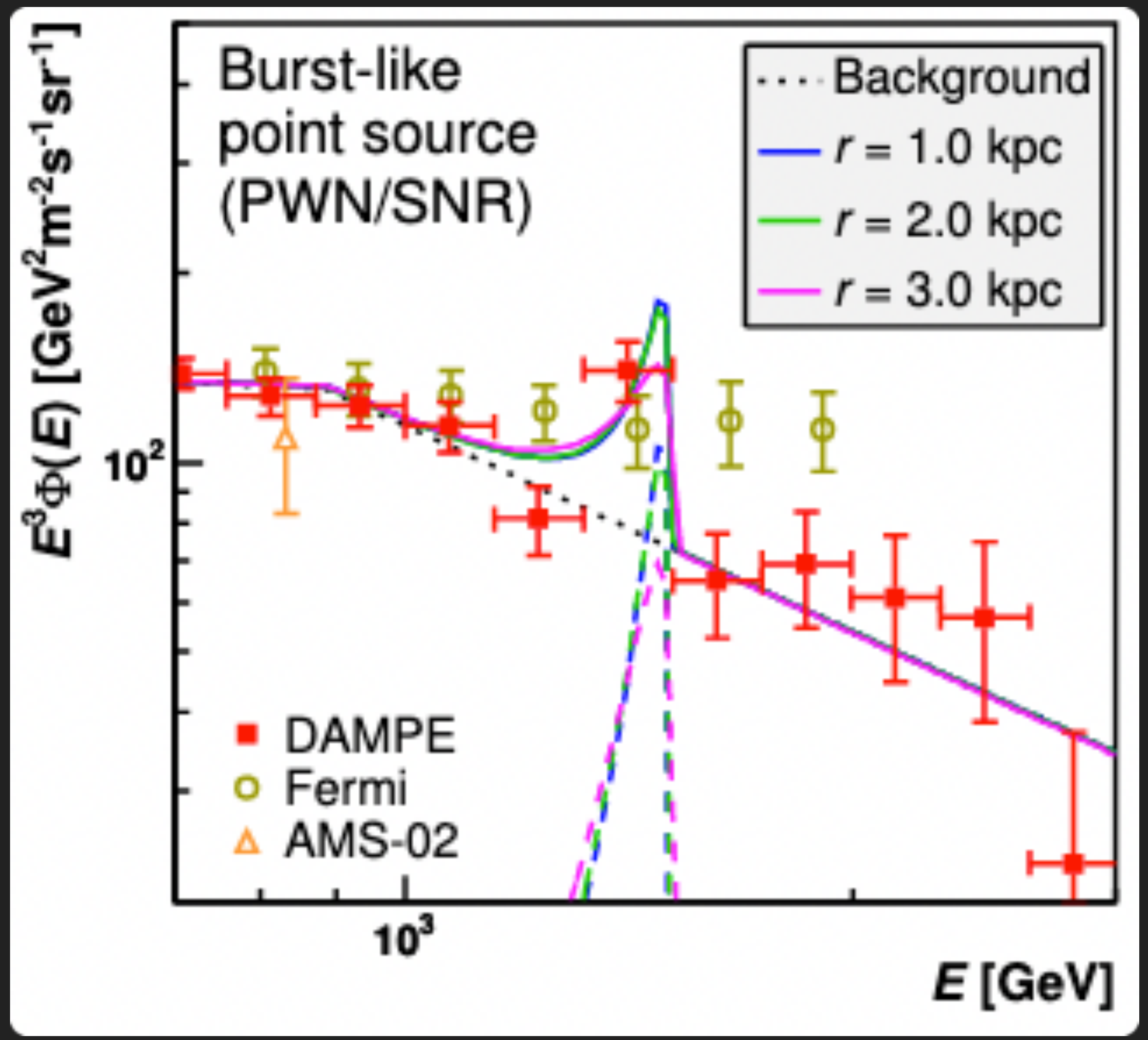
Hooper et al., arXiv:1702.08436



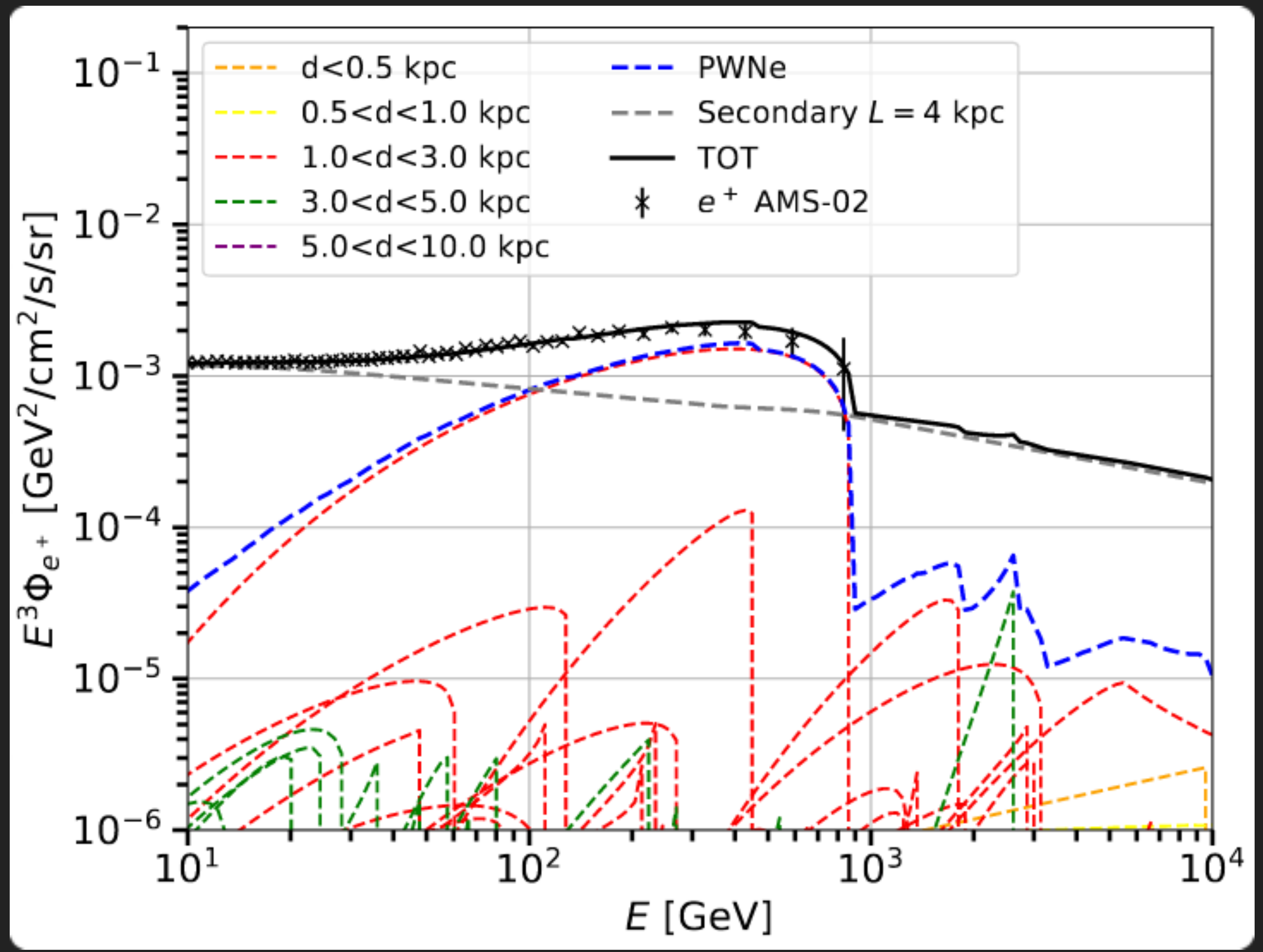
Cholis & Krommydas, arXiv:2111.05864



Bao et al., arXiv:2010.12170



Huang et al., arXiv:1712.00005



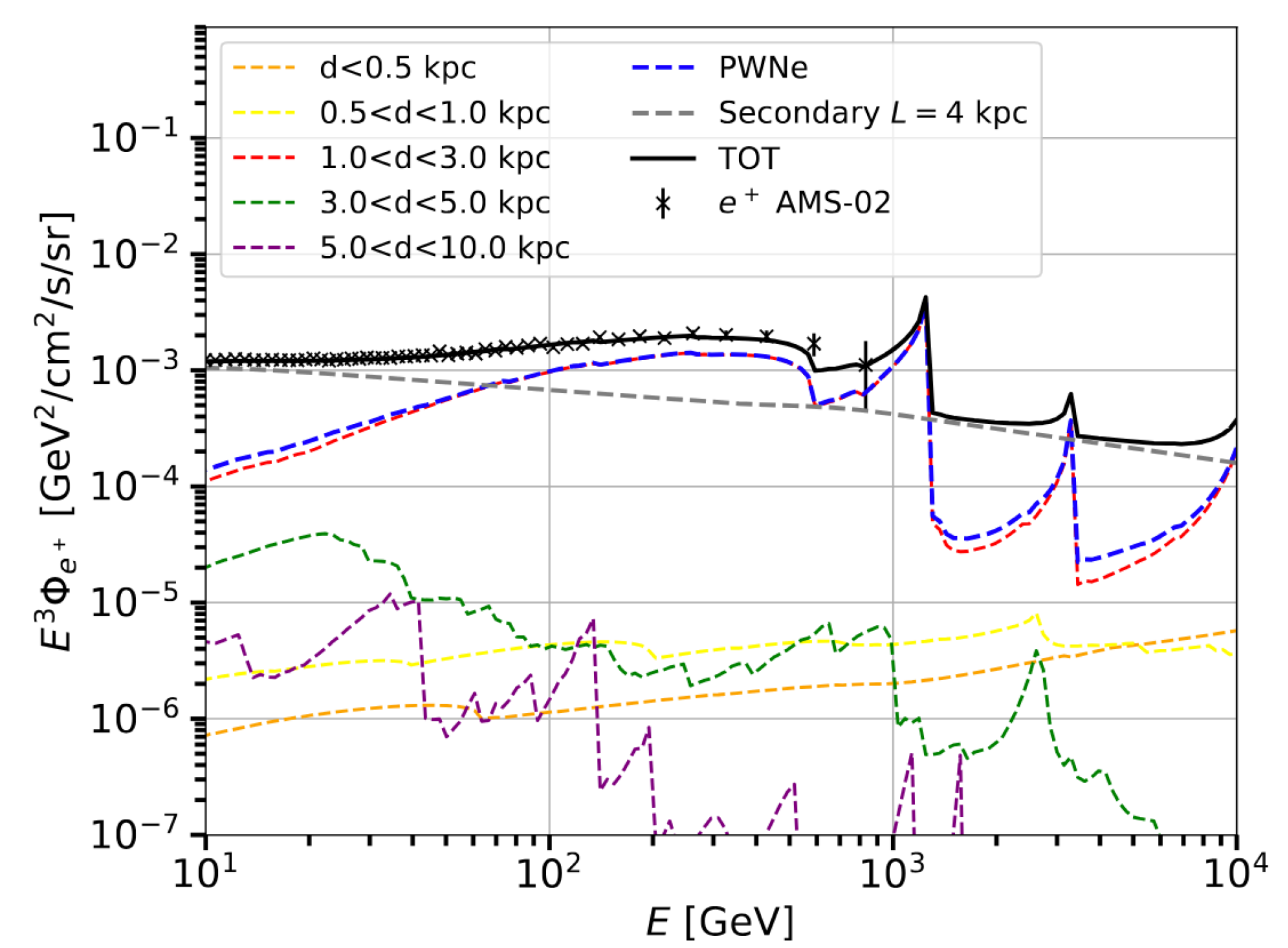
Orusa et al., arXiv:2107.06300

Slide courtesy of Isabelle John

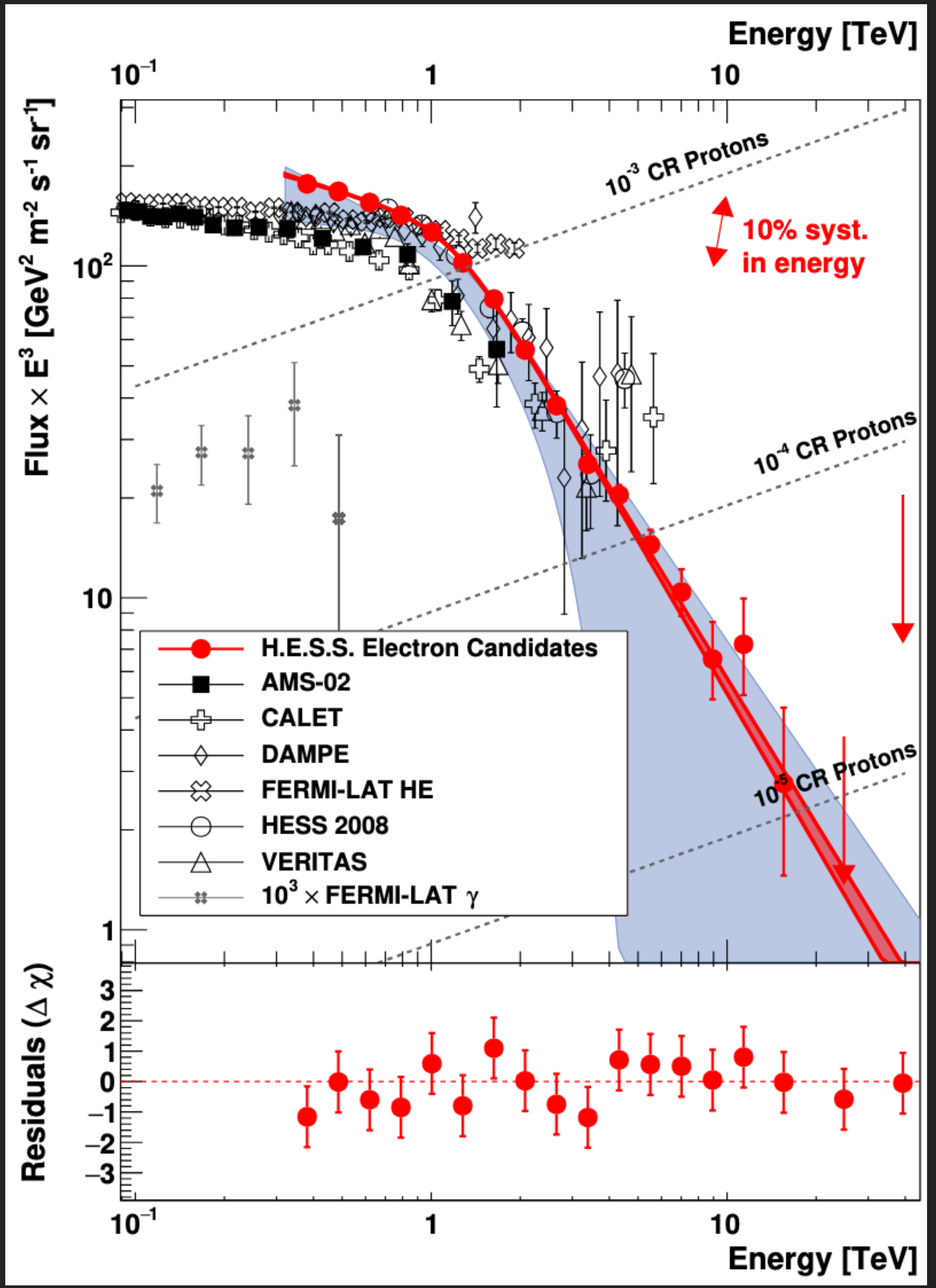
PUZZLE I: THE NUMBER OF PULSARS IN THE POSITRON DATA

H.E.S.S.. Collaboration (2024; 2411.08981)

- **Debates on the Number of Pulsars**



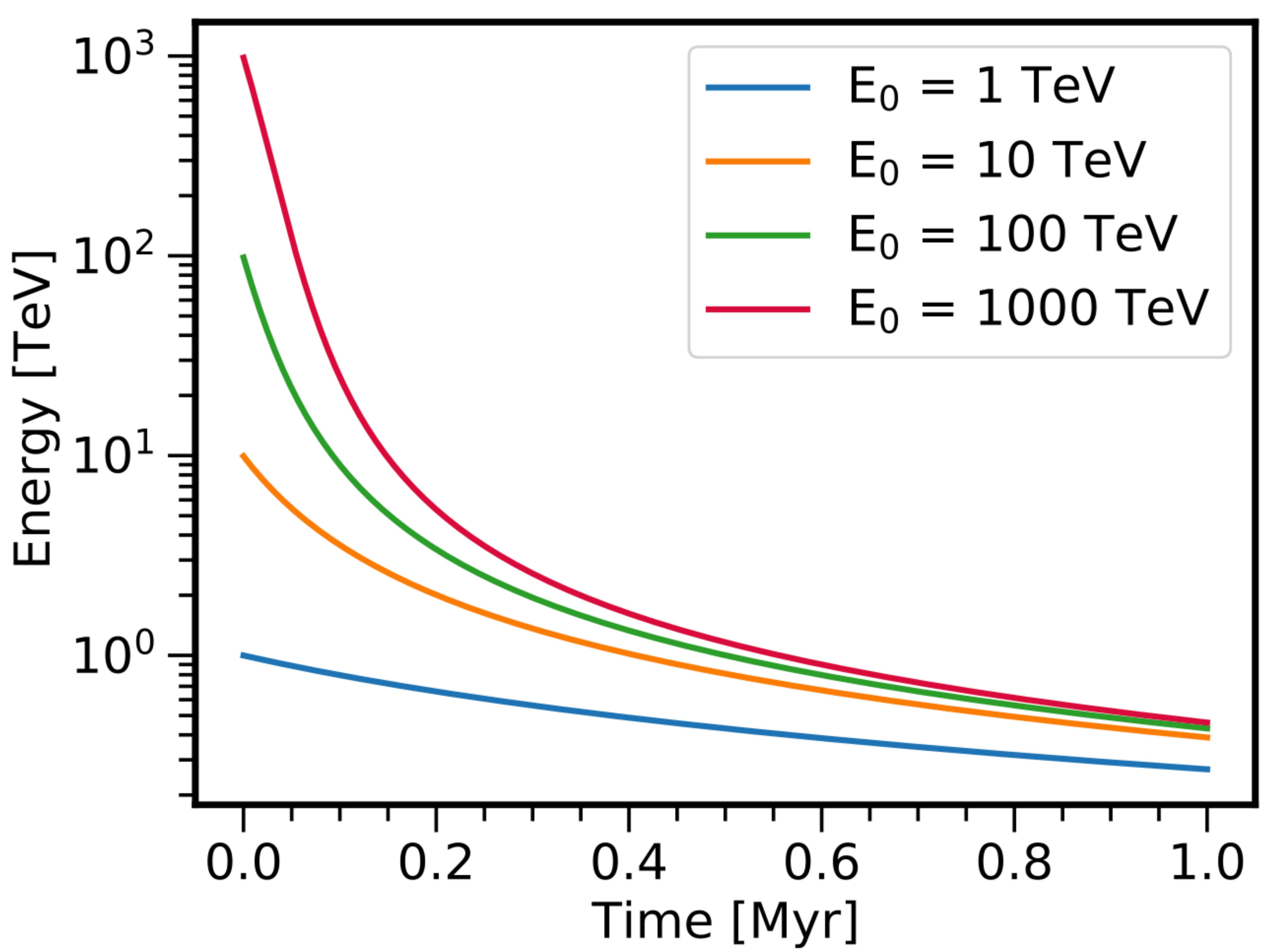
Orusa et al. (2021; 2107.06300)

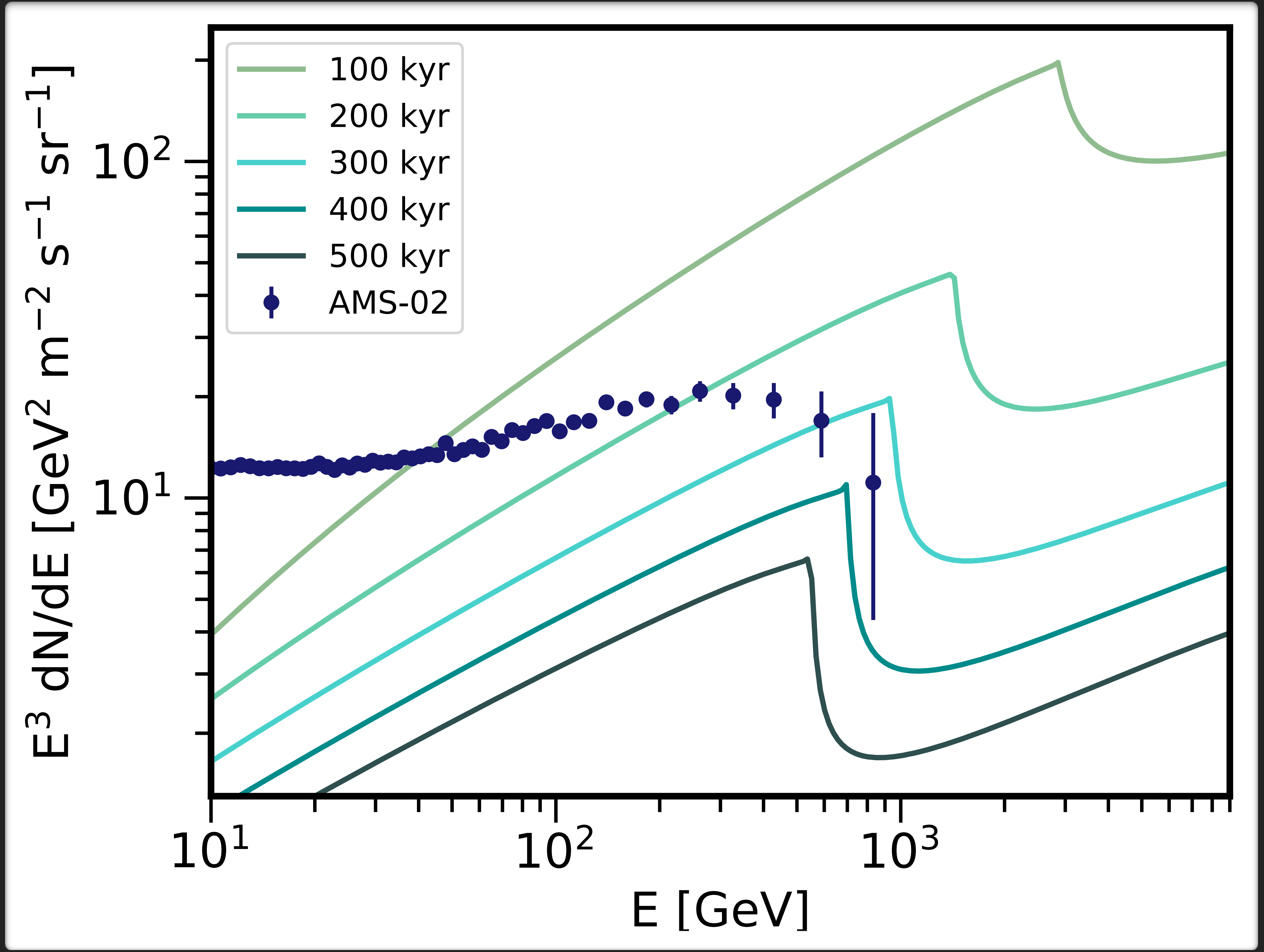


PUZZLE I: THE NUMBER OF PULSARS IN THE POSITRON DATA

- For pulsars, there is a key error: Studies generally use a continuous approximation for electron energy losses:

$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T c \left(\frac{E}{m_e}\right)^2 \left[\rho_B + \sum_i \rho_i(\nu_i) S(E, \nu_i)\right]$$



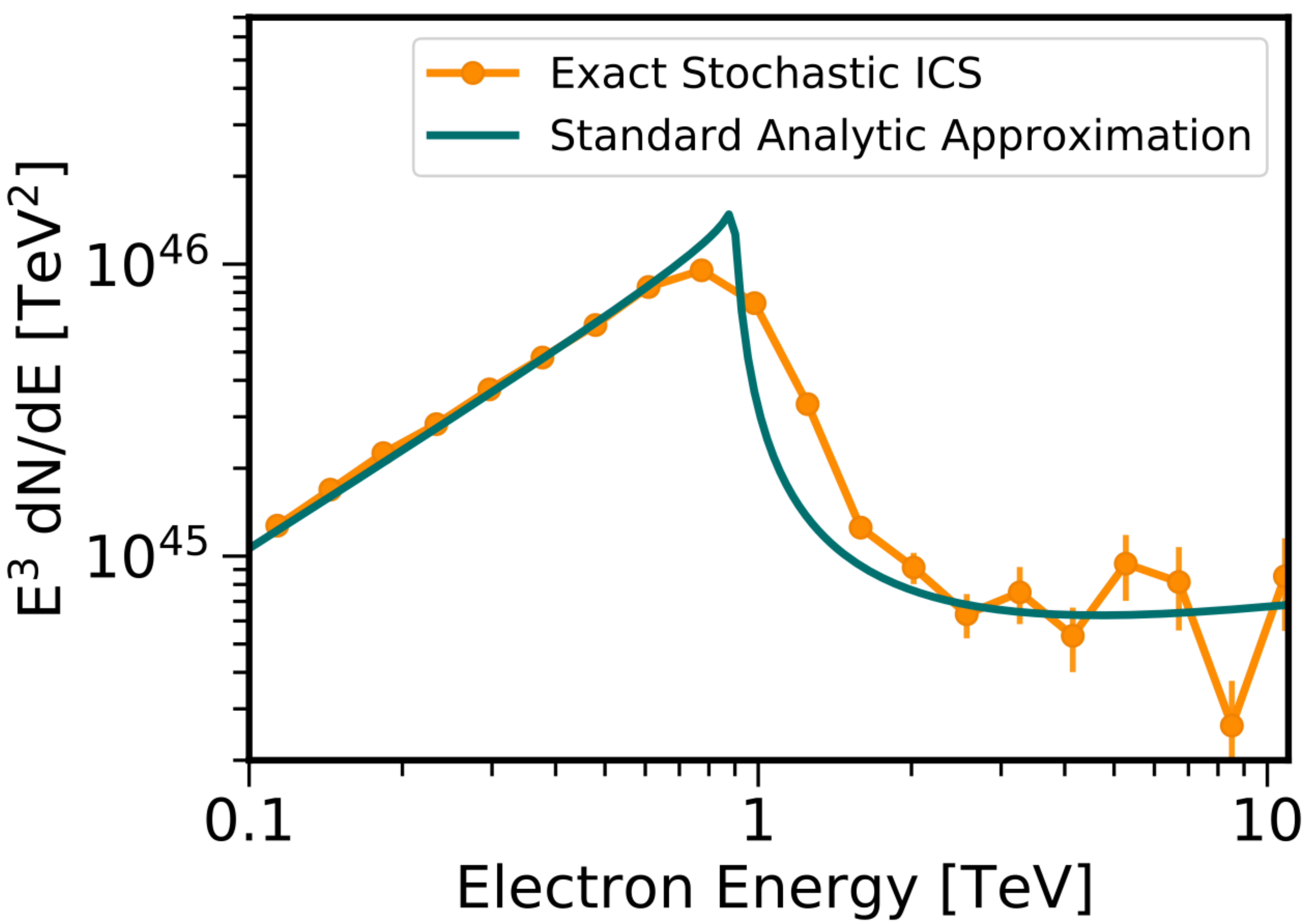


John & Linden (2022; 2206.04699)

PUZZLE I: THE NUMBER OF PULSARS IN THE POSITRON DATA

- But ICS interactions are very rare and stochastic. The energy after a given time is not determined by the initial energy.

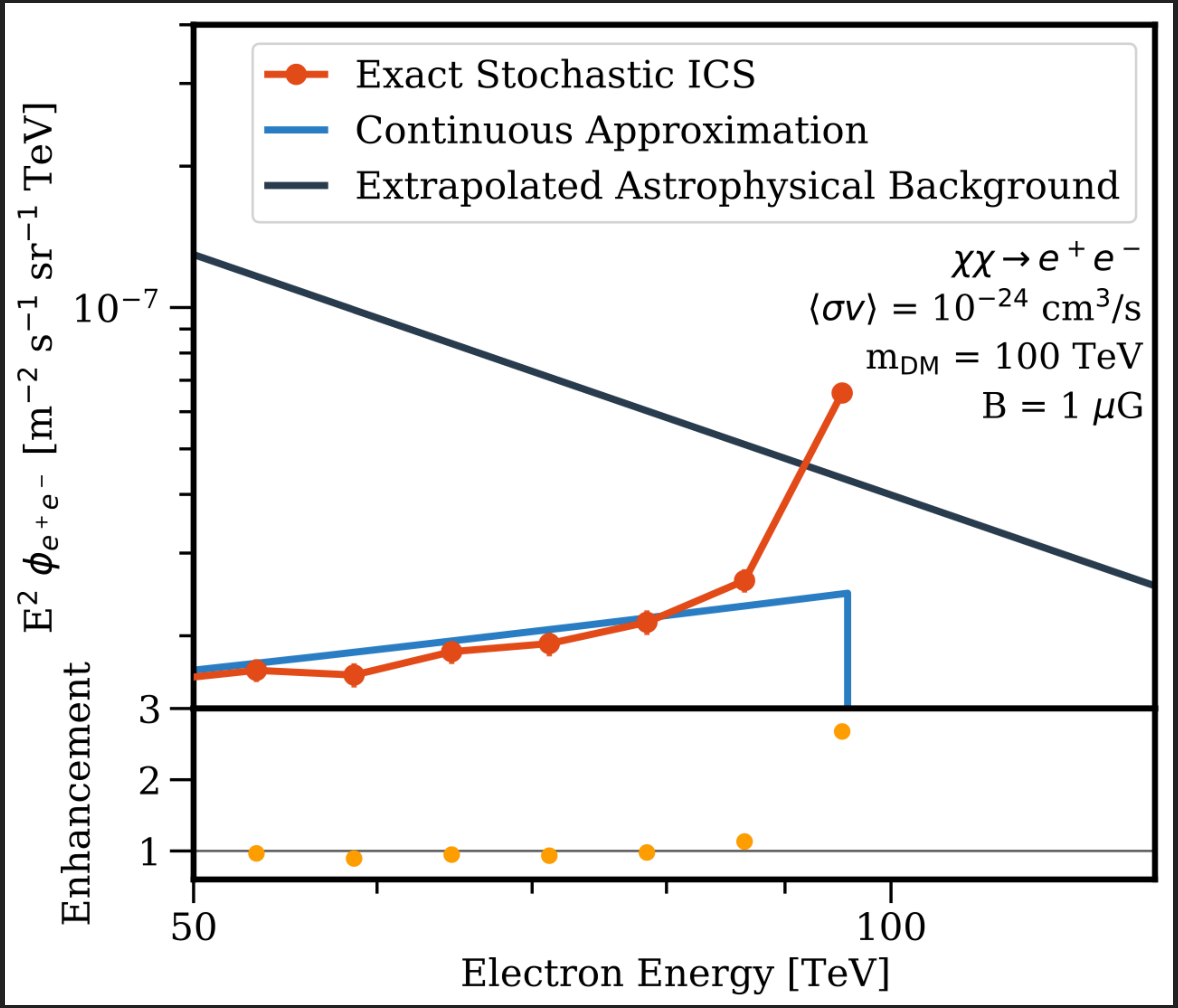
John & Linden (2022; 2206.04699)


Exact Stochastic ICS
Standard Analytic Approximation
E^3 dN/dE [TeV^2]
10^{46}
10^{45}
0.1
1
10
Electron Energy [TeV]

PUZZLE II: DARK MATTER VS. PULSARS IN THE POSITRON DATA

John & Linden (2023; 2304.07317)

- For dark matter, the spectral cutoff is not produced by ICS cooling, but from the dark matter mass.
- The stochasticity of cooling instead means that some particles don't cool at all, enhancing the peak.
- Correctly accounting for ICS energy losses makes it possible to differentiate dark matter and pulsars via their positron spectrum.



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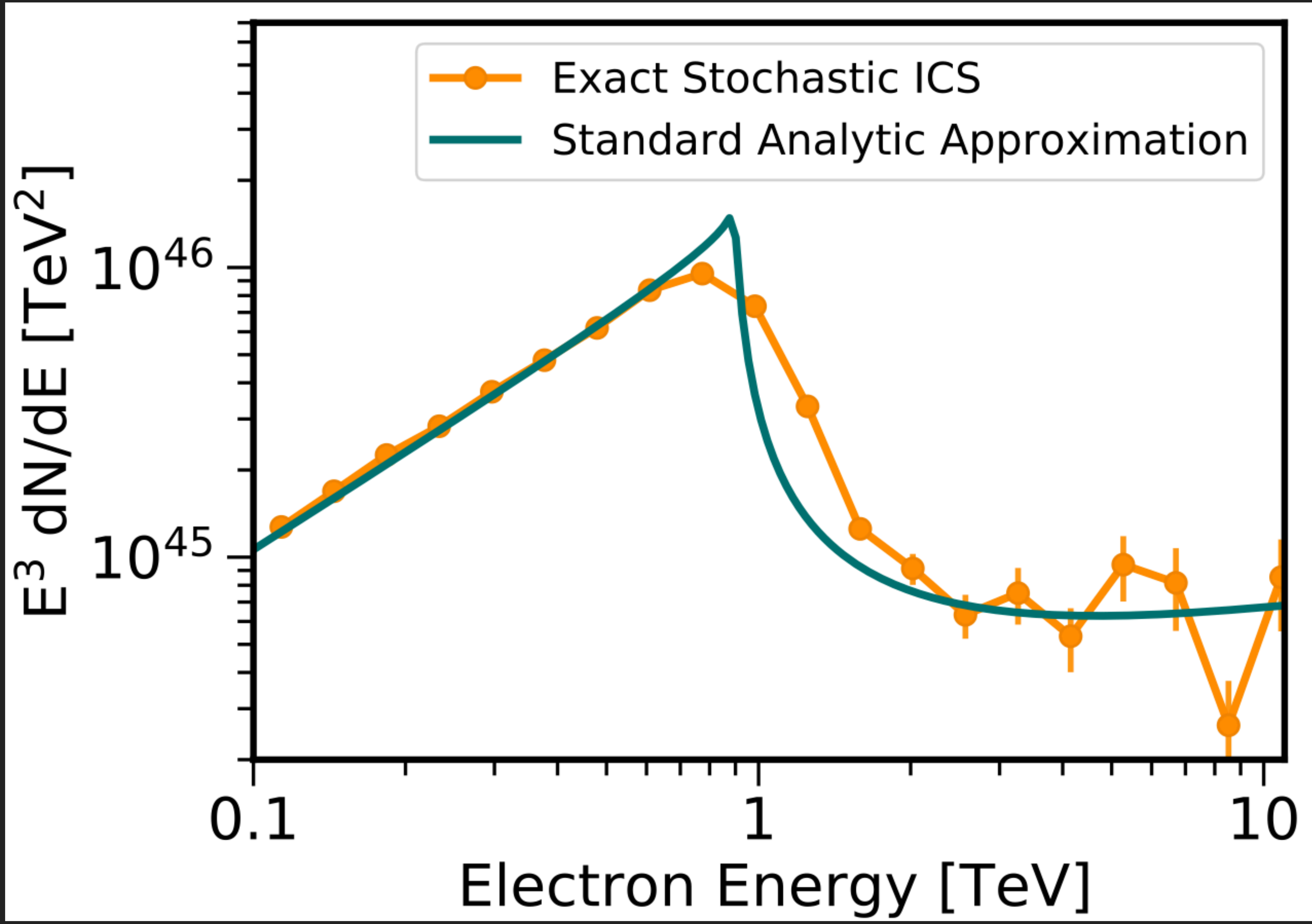

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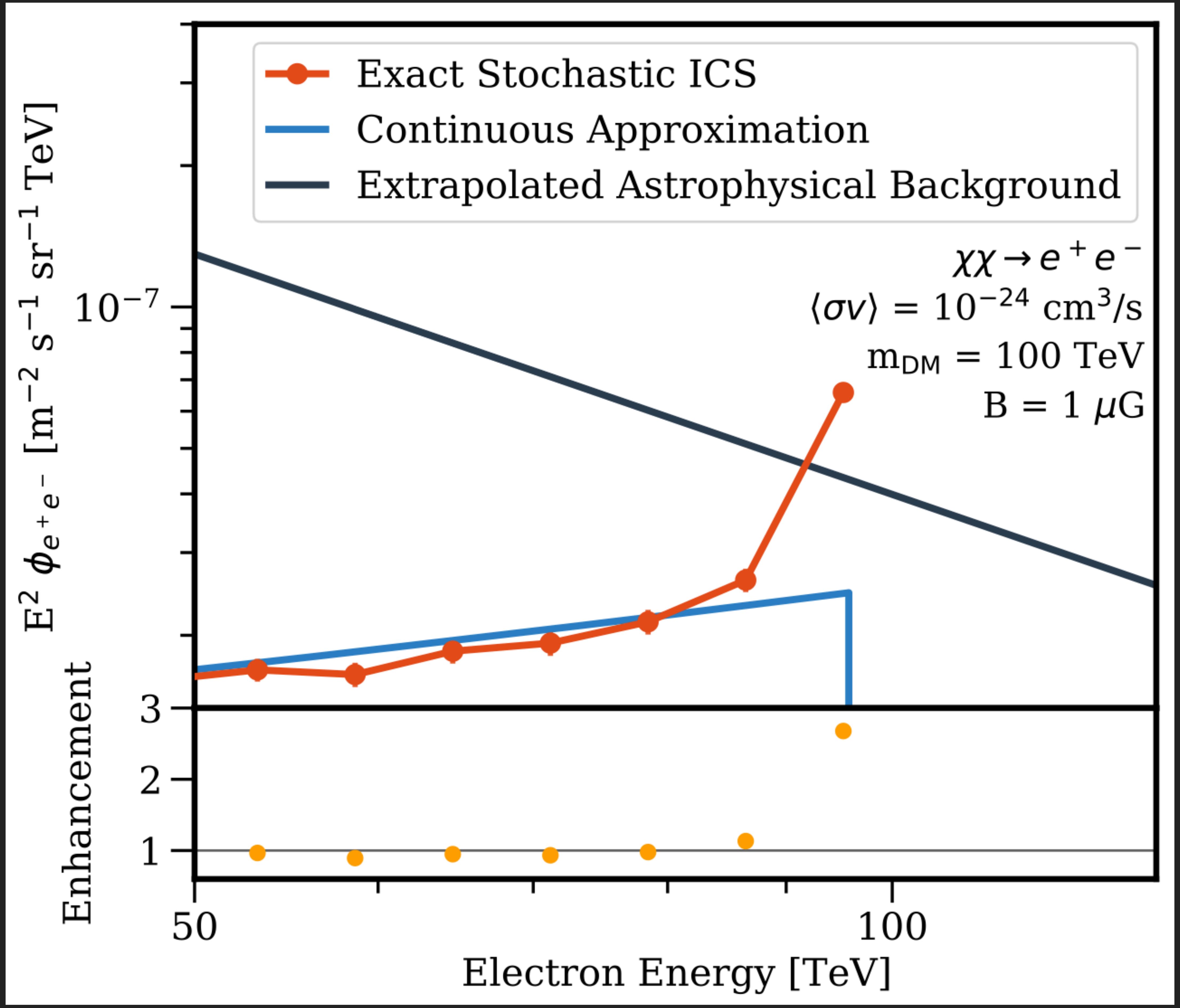
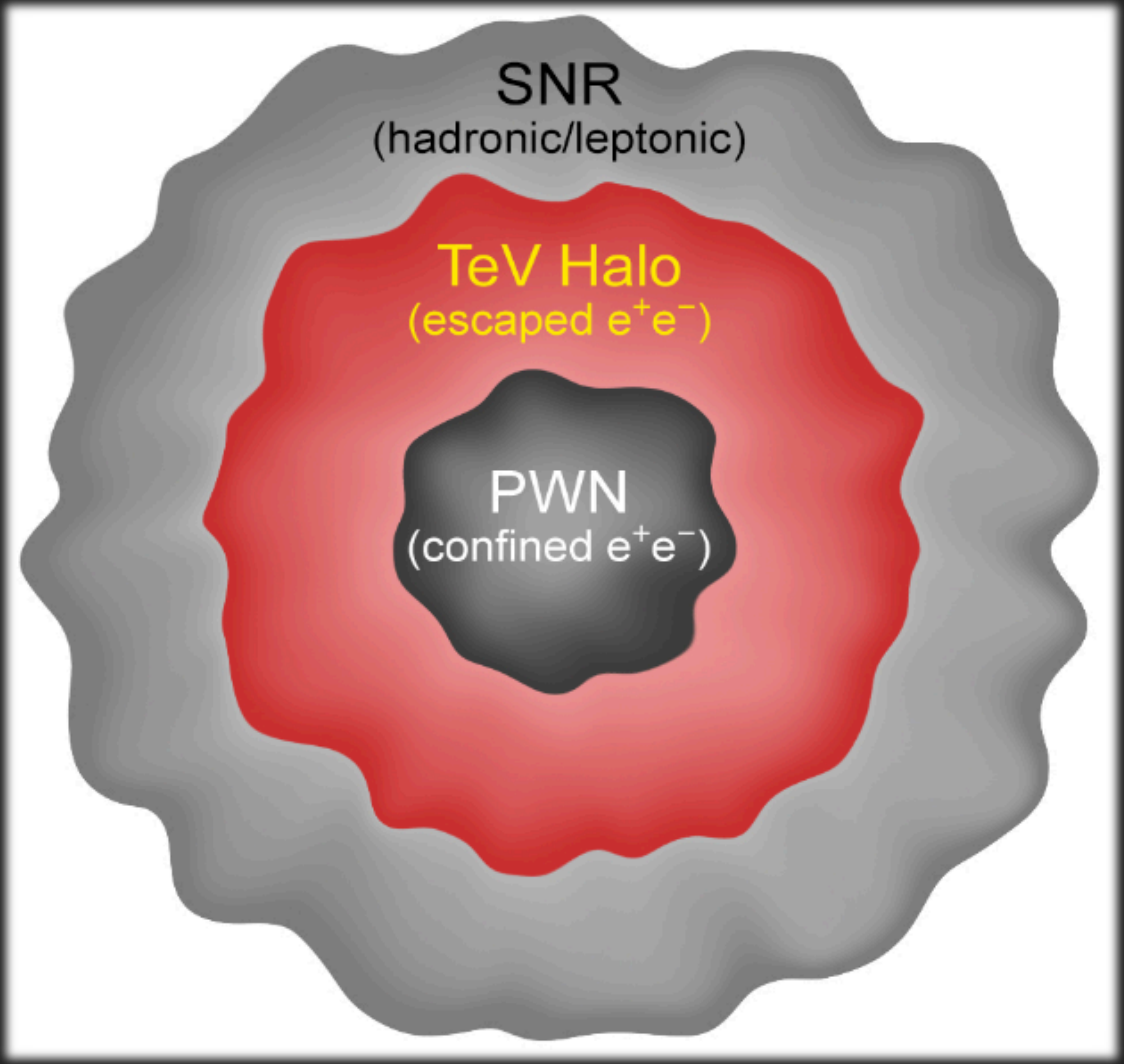
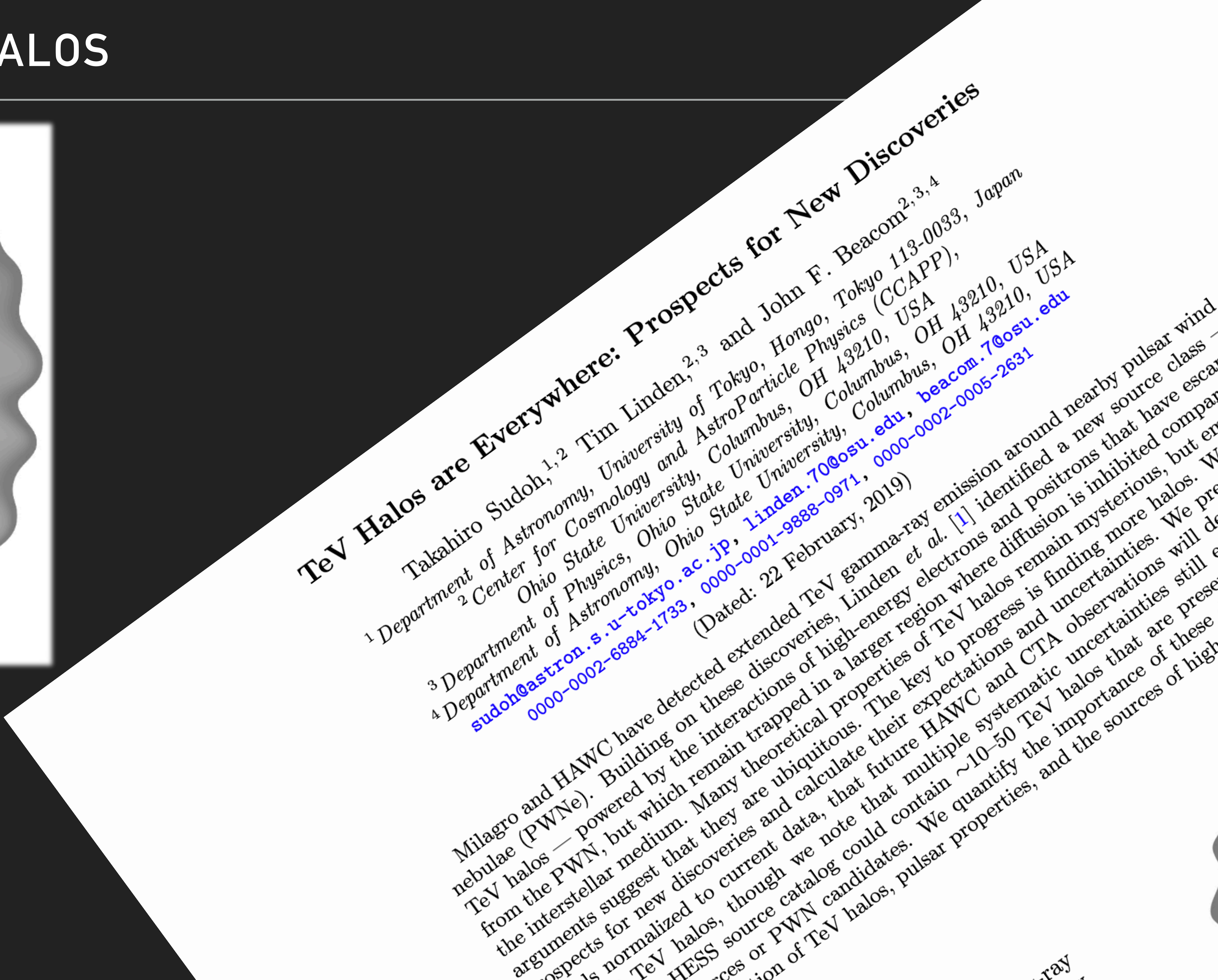


John & Linden (2023; 2304.07317)

ONLY DARK MATTER CAN PRODUCE SHARP SPECTRA IN THE POSITRON DATA!

PUZZLE III: COMPLEX HALOS





TeV Halos are Everywhere: Prospects for New Discoveries

Takahiro Sudoh,[1,2] Tim Linden,[2,3] and John F. Beacom[2,3,4]
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[2] Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, OH 43210, USA
[3] Department of Physics, Ohio State University, Columbus, OH 43210, USA
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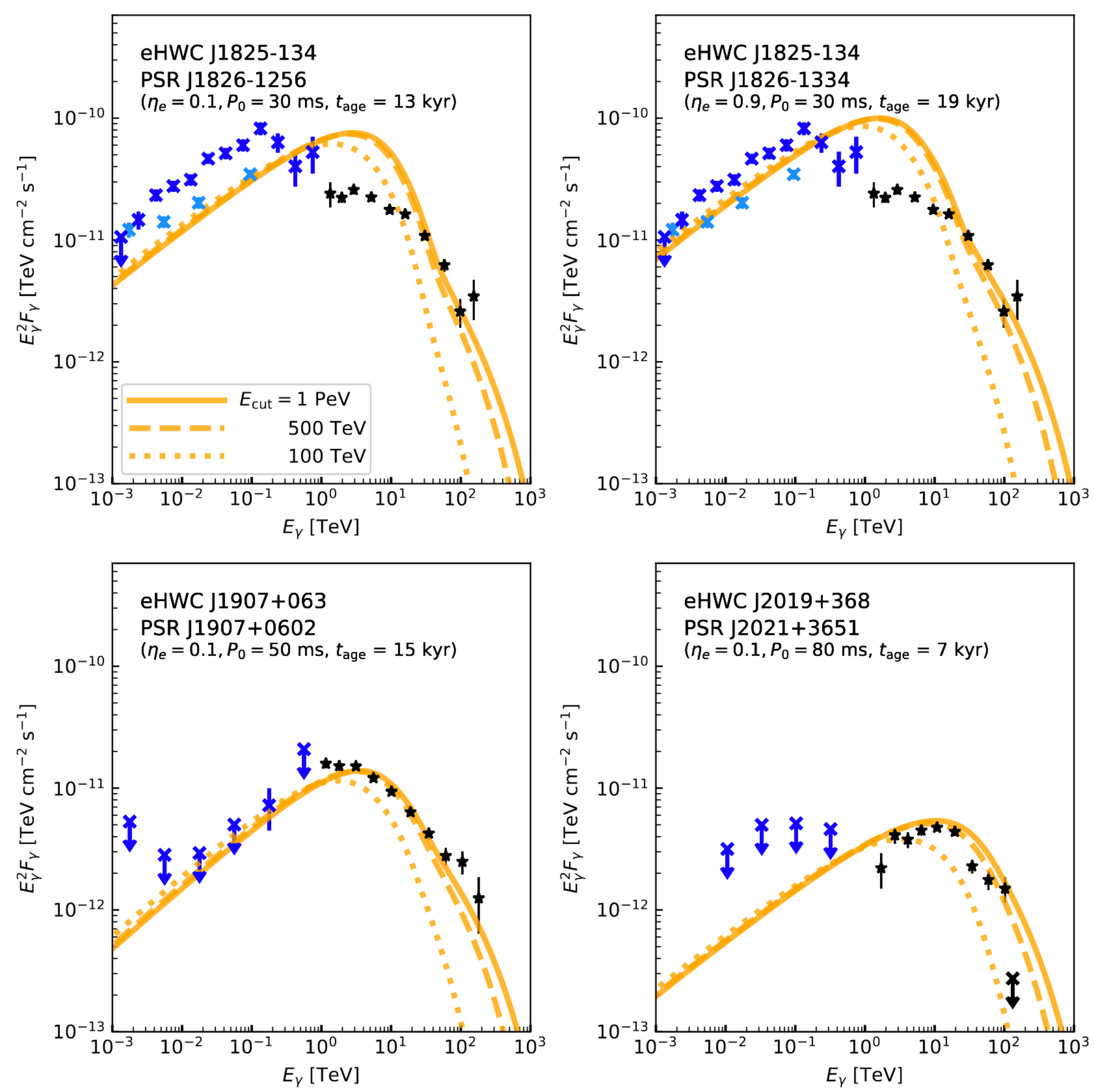
0000-0002-6884-1733, 0000-0001-9888-0971, 0000-0002-0005-2631
(Dated: 22 February, 2019)

Milagro and HAWC have detected extended TeV gamma-ray emission around nearby pulsar wind
nebulae (PWNe). Building on these discoveries, Linden et al. [1] identified a new source class —
TeV halos — powered by the interactions of high-energy electrons and positrons that have escap
from the PWN, but which remain trapped in a larger region where diffusion is inhibited compar
the interstellar medium. Many theoretical properties of TeV halos remain mysterious, but en
arguments suggest that they are ubiquitous. The key to progress is finding more halos. W
ospects for new discoveries and calculate their expectations and uncertainties. We pre
ls normalized to current data, that future HAWC and CTA observations will de
TeV halos, though we note that multiple systematic uncertainties still e
HESS source catalog could contain ~10–50 TeV halos that are prese
ces or PWN candidates. We quantify the importance of these
tion of TeV halos, pulsar properties, and the sources of high
ray

PUZZLE IIIA: COMPOSITE OBJECTS

Sudoh, Linden, Hooper (2101.11026)

- Most of the highest energy HAWC sources have positions consistent with pulsars.
- Ages only 7-20 kyr.
- Interplay between PWN and Halo is of critical importance.



PUZZLE IIIA: COMPOSITE OBJECTS

Di Mauro, Manconi, Donato (2019; 1908.03216)

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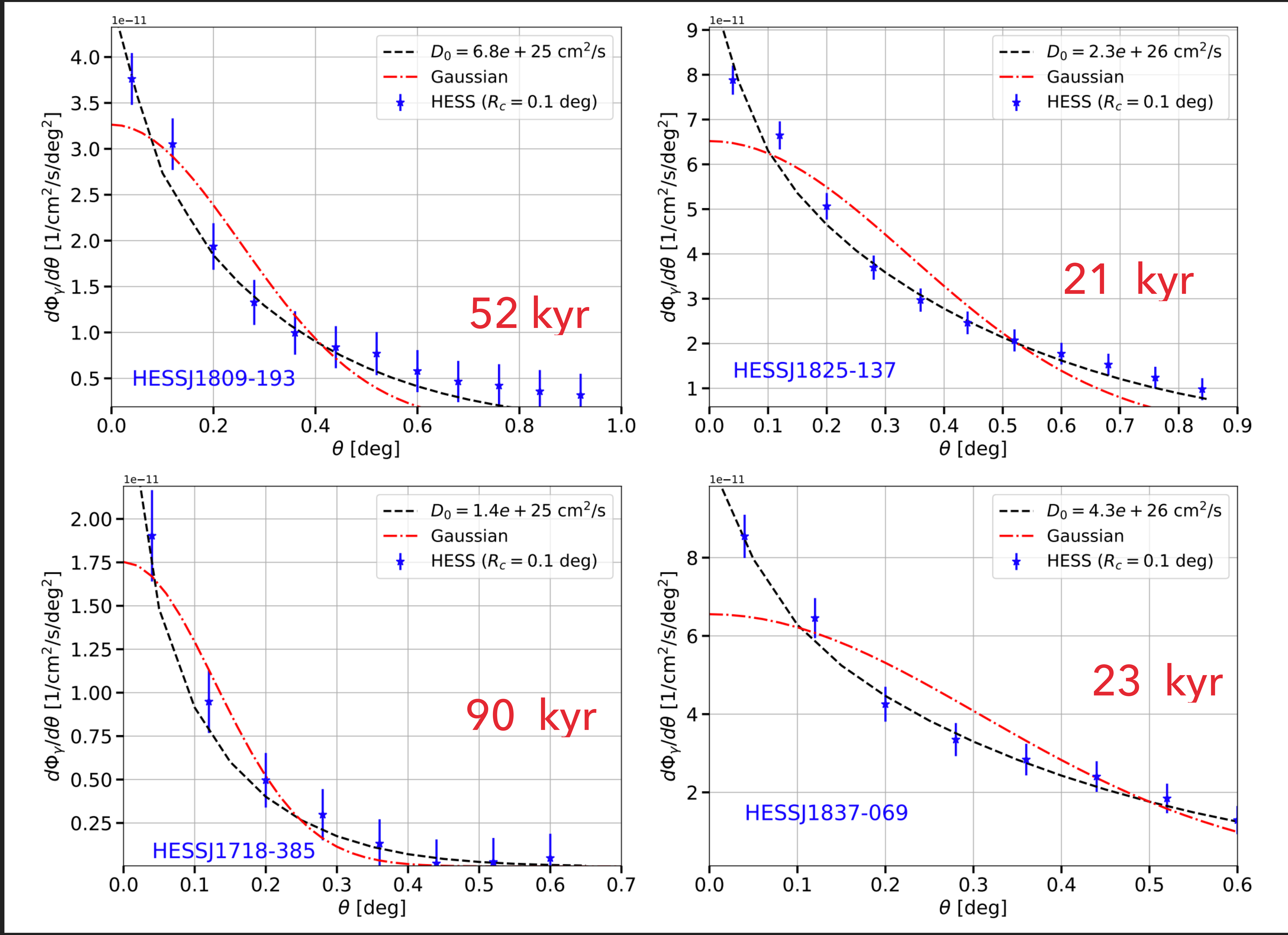


Property of the pulsars: Kick velocity

Kick velocity distribution

Taken from Faucher-Giguère et al. (2006), modulus of all components:

$$f(v_k^{x,y,z}) = w\,\mathcal{N}(v_k, \sigma = 160 \text{ km/s}) + (1-w)\,\mathcal{N}(v_k, \sigma = 780 \text{ km/s}) \quad (1)$$

with $w = 0.90$.

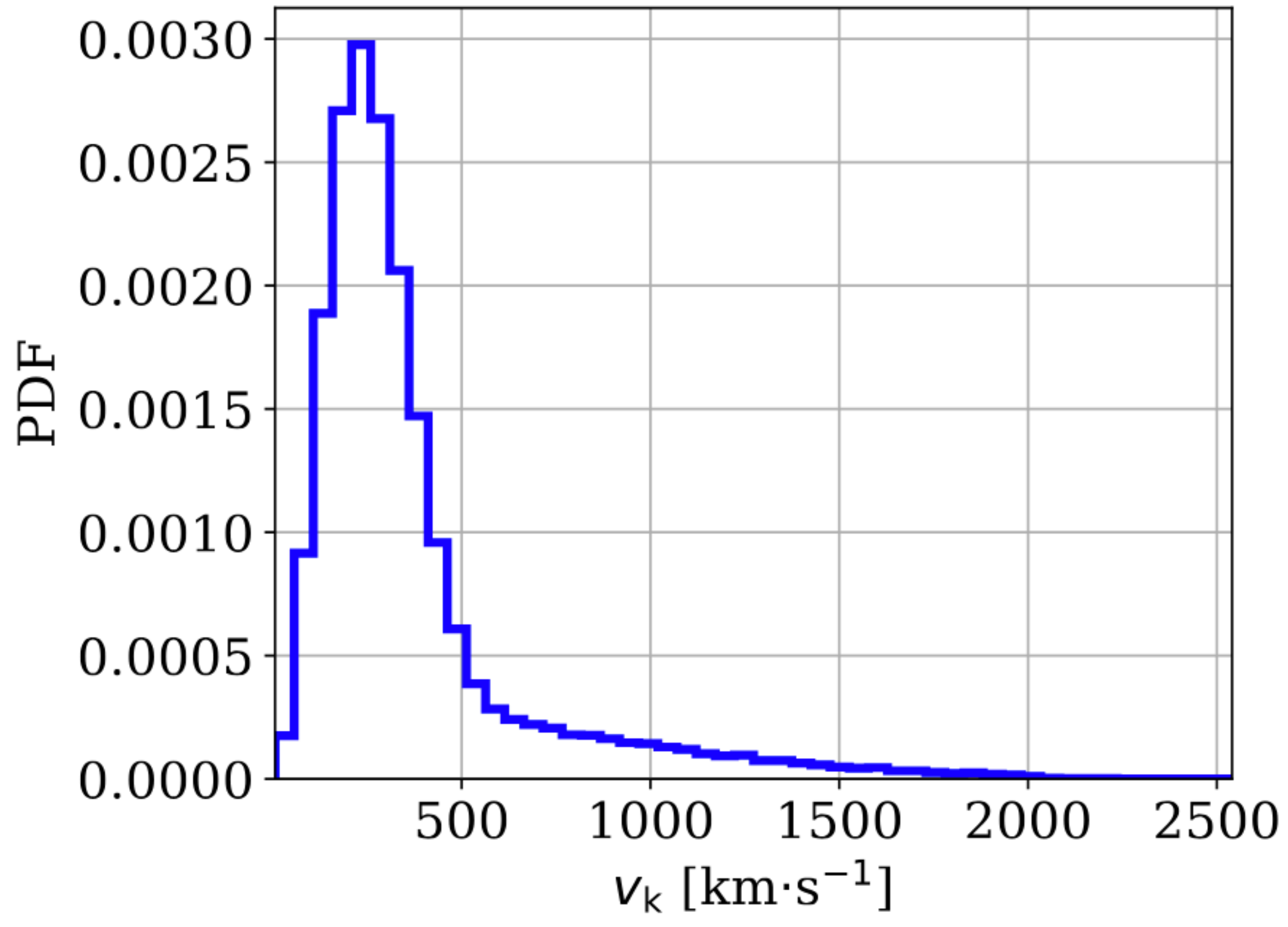


Figure: PDF of the kick velocity of pulsars.

PUZZLE IIIB: MIRAGE HALOS

PUZZLE IIIB: MIRAGE HALOS

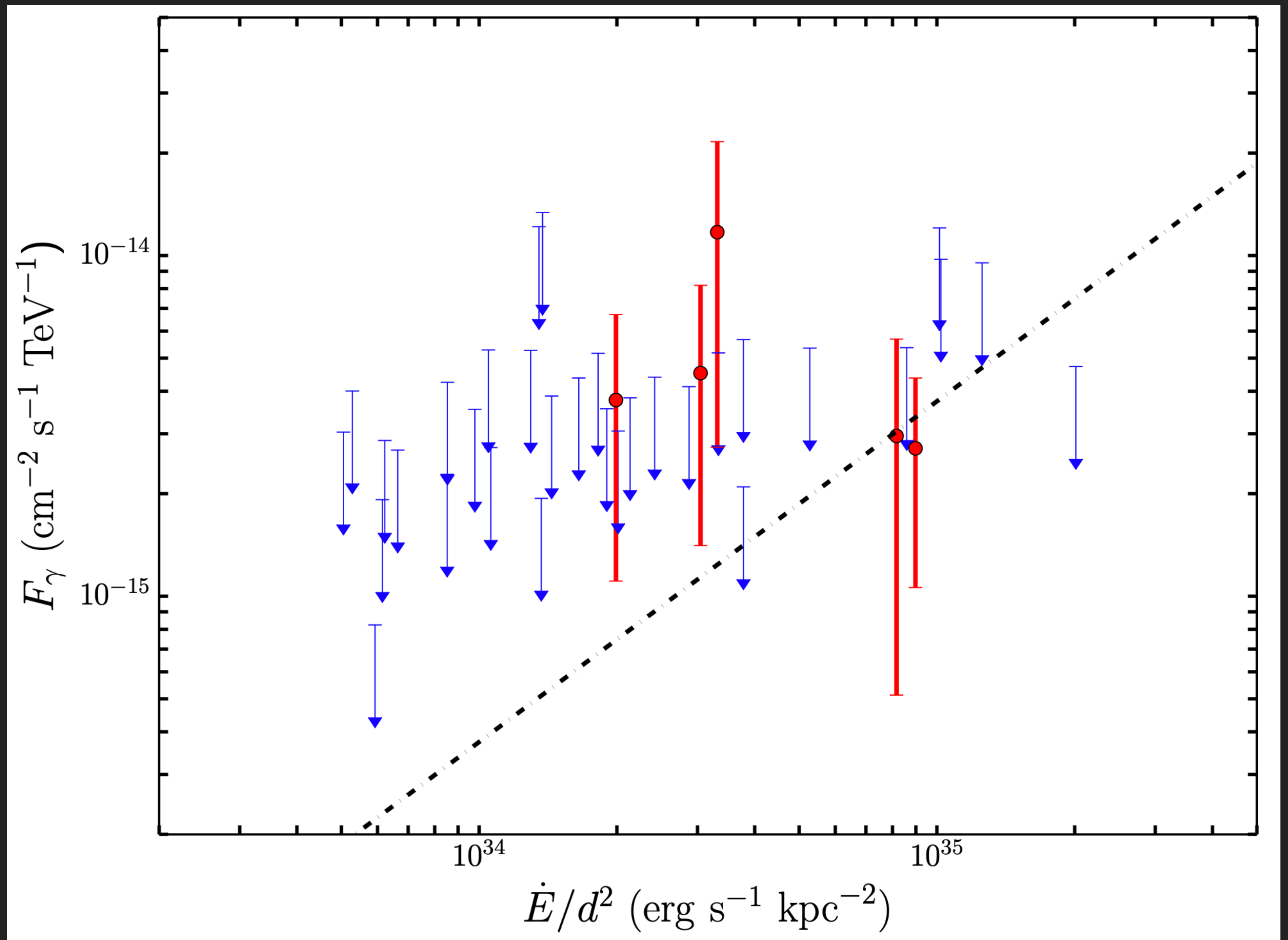
Bao et al. (2407.02478)

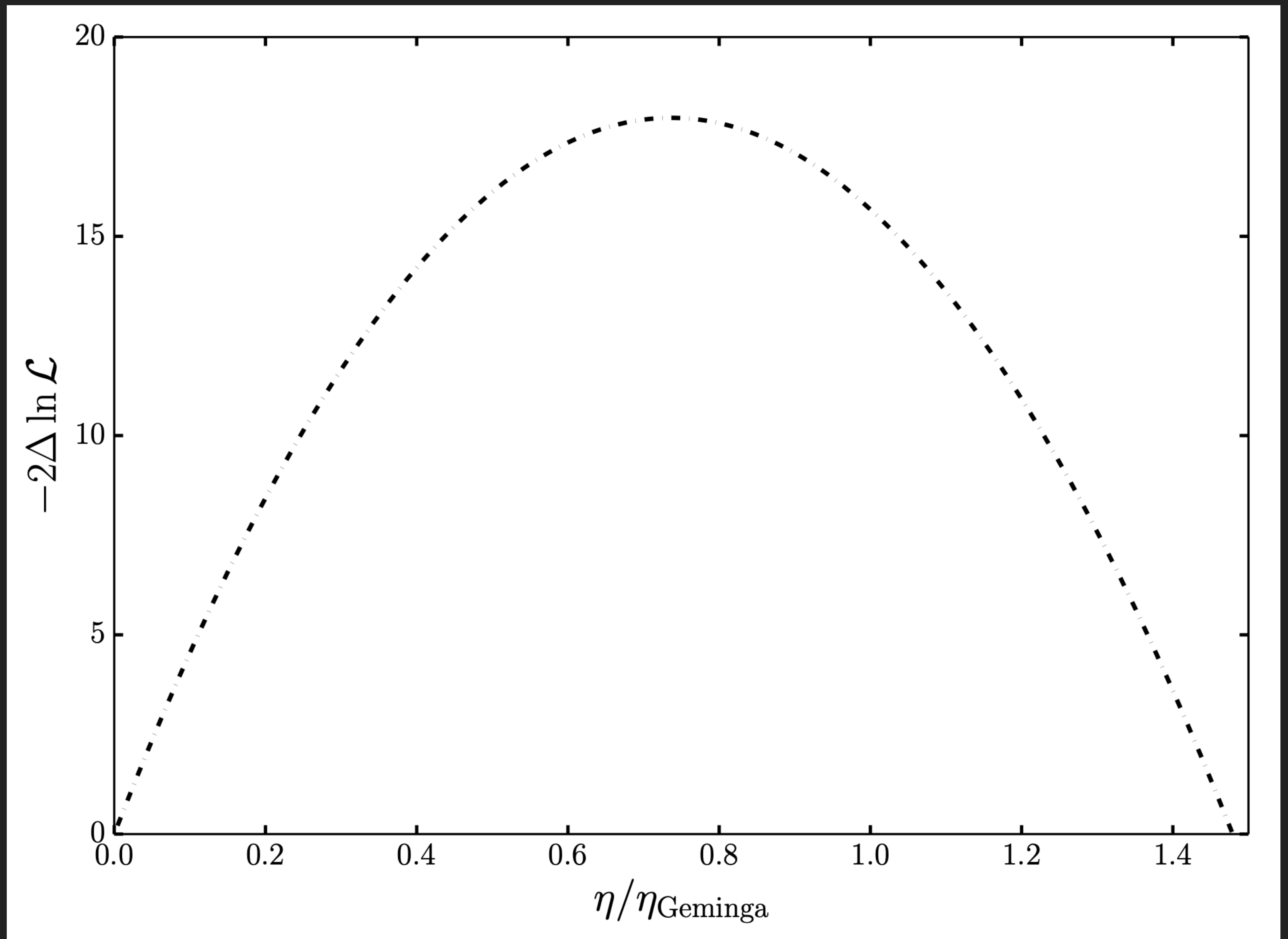
- "Mirage" TeV halos - Many more systems may be difficult to detect or analyze, because they break the modeling assumption of spherical symmetry.

PUZZLE IIIC: TEV HALOS POWERED BY MILLISECOND PULSARS?

Hooper, TL (2021; 2104.00014)

- Do MSPs Have TeV Halos?
- Tentative: 4.24σ Poisson evidence from a HAWC stacking analysis (~2.3σ from blank sky test).
- Possible MSP Detection by LHAASO
- Important theoretical implications:
  - Cosmic-Ray confinement near pulsars?
  - Cosmic-Ray diffusion at high latitudes
  - PWN/Magnetospheric acceleration models.



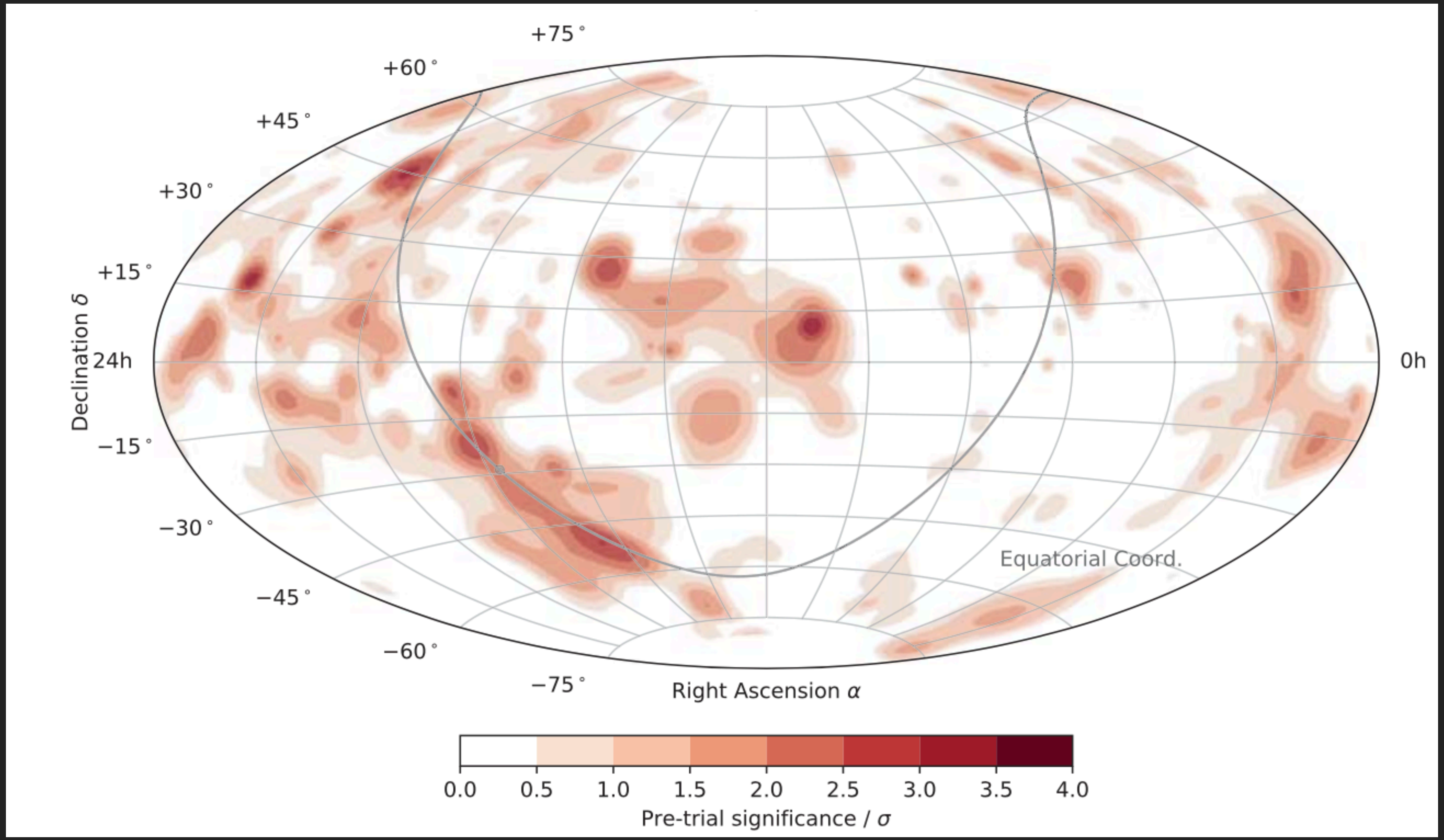


LHAASO Collaboration (2023; 2305.17030)

1LHAASO J0216+4237u	0.33	ATNF PSR J0218+4232	$\dot{E} = 2.44 \times 10^{35}$ erg s^{-1},τ_c = 476000.0 kyr,d = 3.15 kpc
	0.33	4FGL J0218.1+4232	PSR J0218+4232;MSP;

PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

IceCube Collaboration (2023)



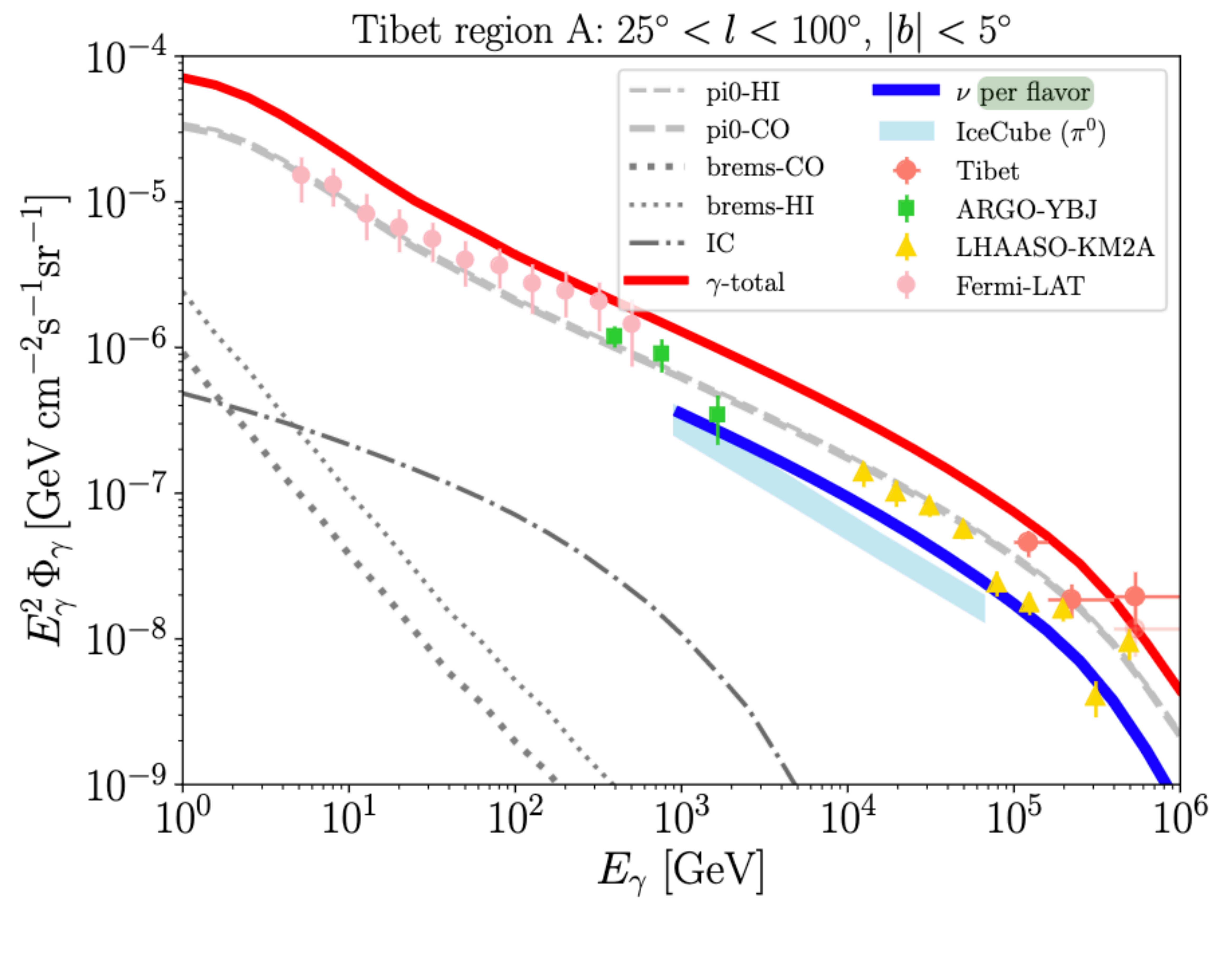
- IceCube detection of a galactic neutrino flux – with a normalization that is ~4x brighter than expectations from the Fermi-LAT extrapolation.

PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

Fang et al. (2023; 2306.17275)

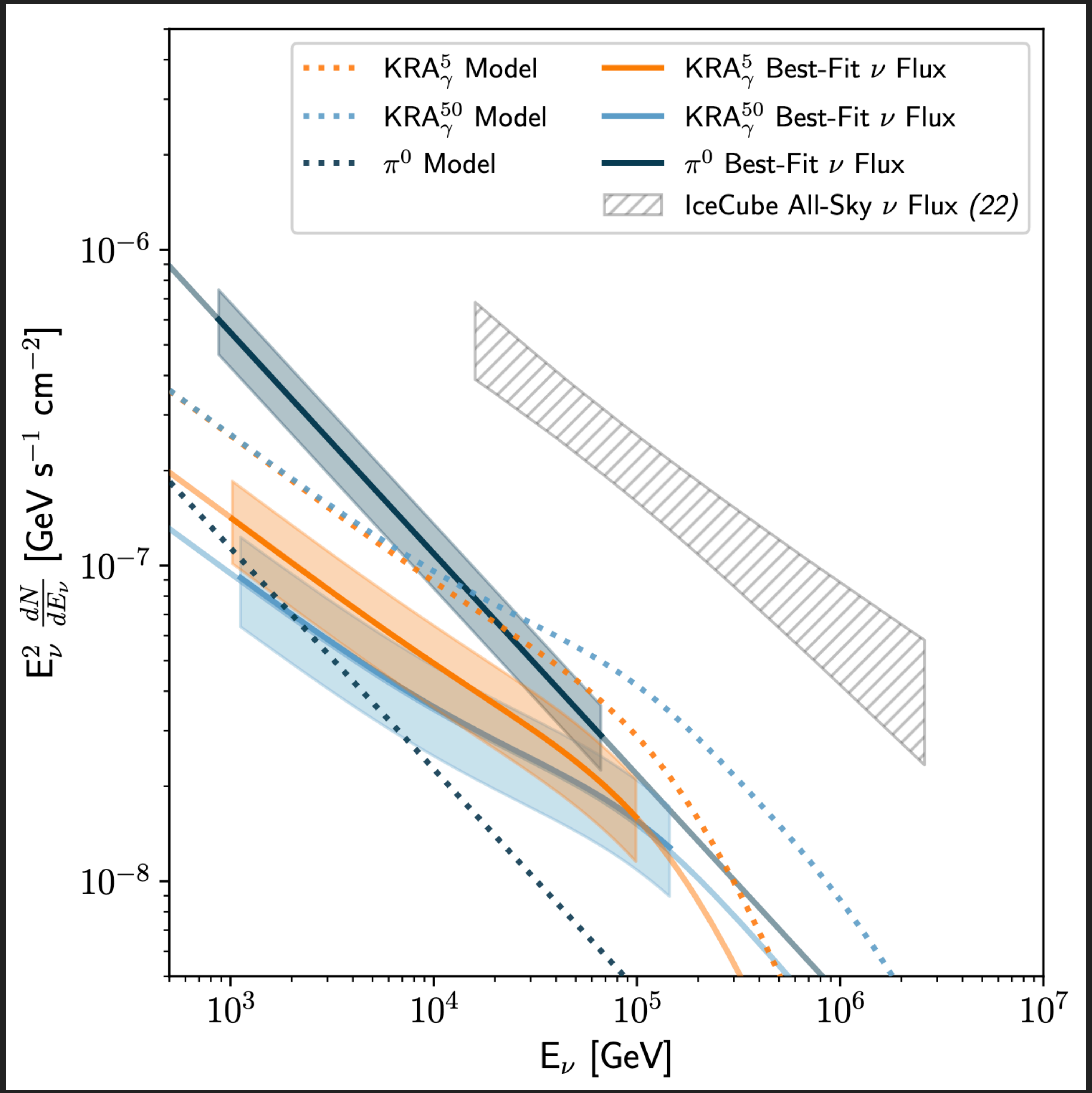
- If the IceCube neutrino flux from the galaxy is higher, then the gamma-ray flux from hadronic processes (i.e., not halos) could also be higher.

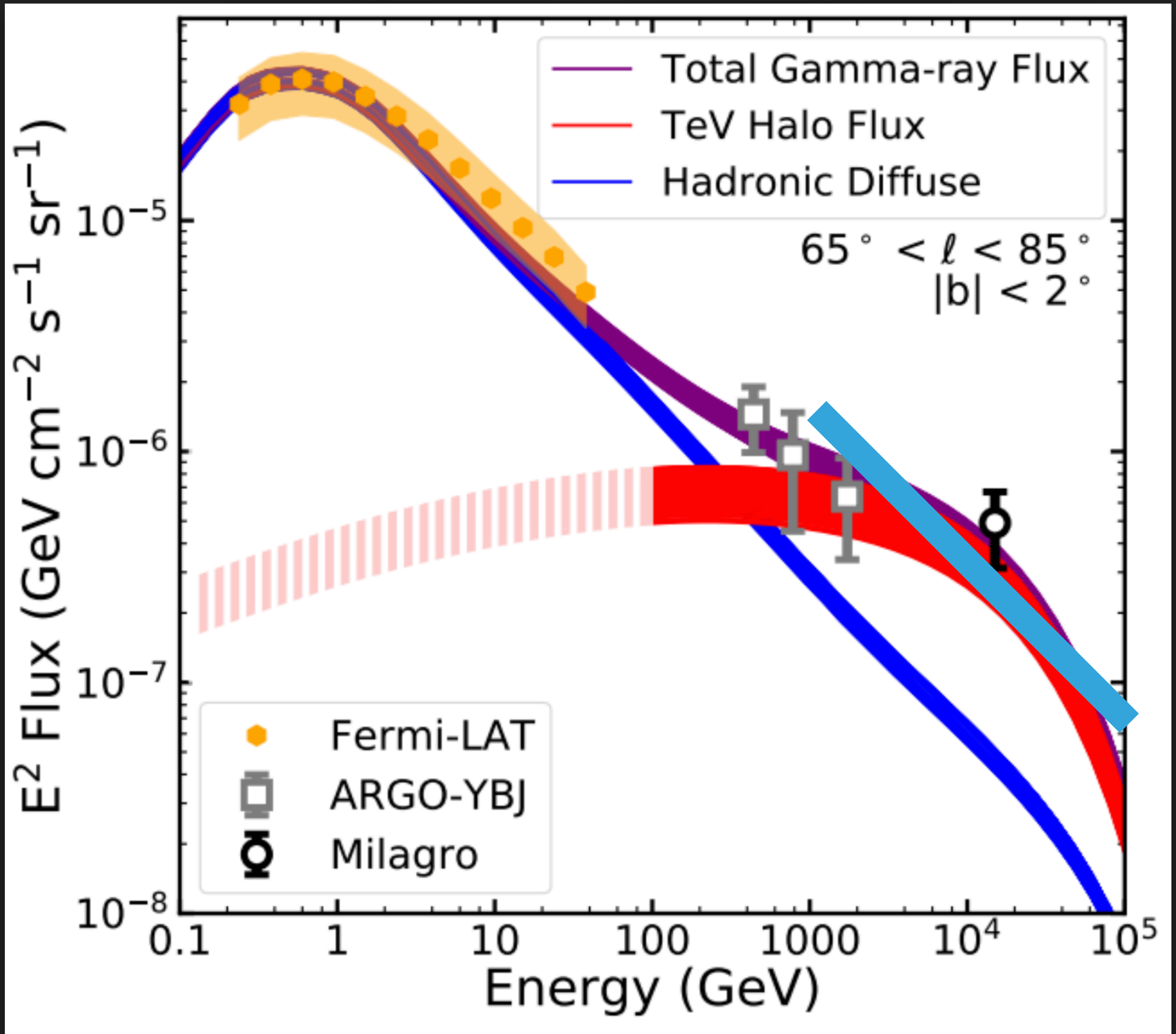
- In Fang et al. this is capable of producing the diffuse galactic gamma-ray emission



PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

IceCube Collaboration (2023)





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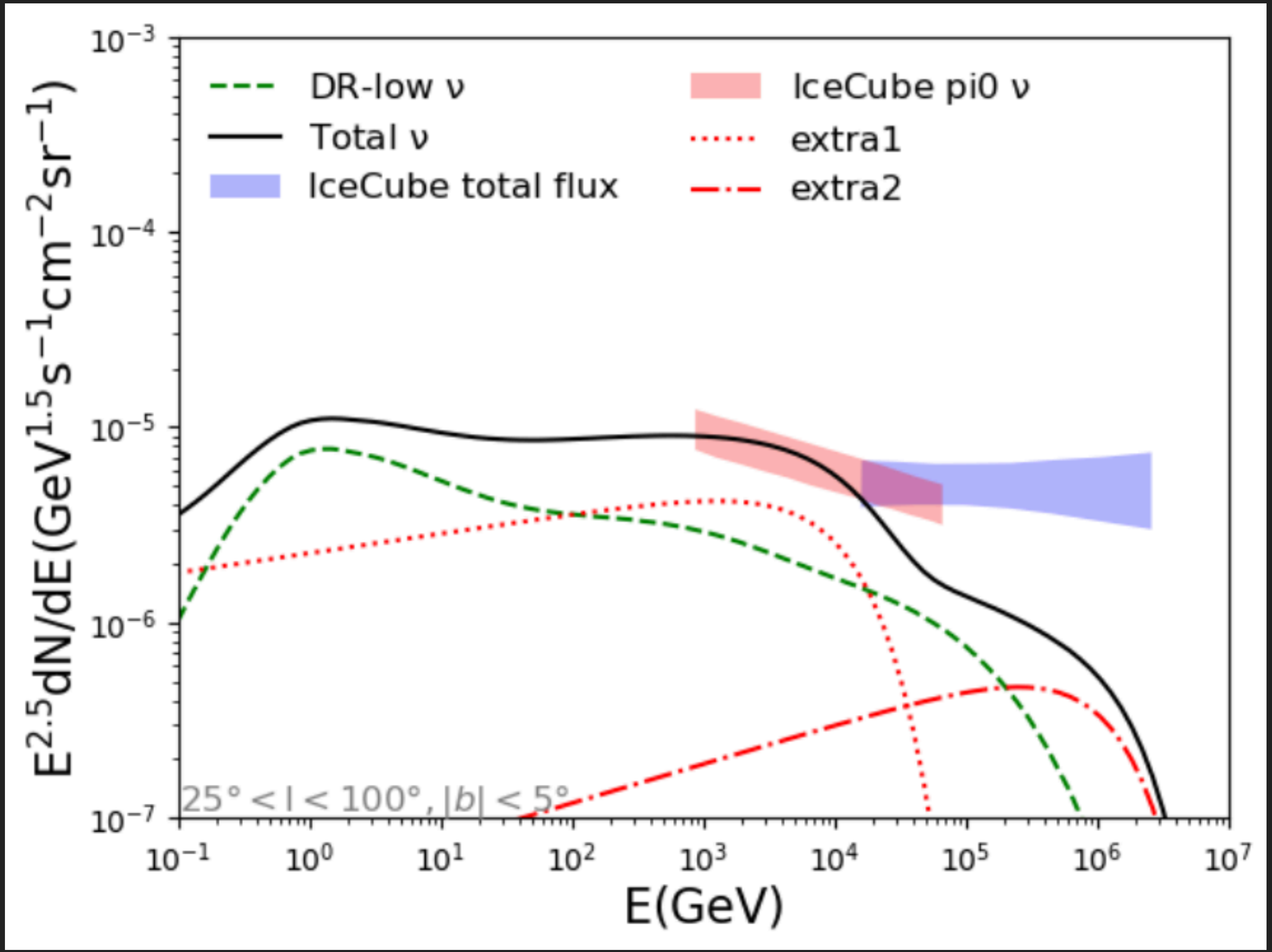
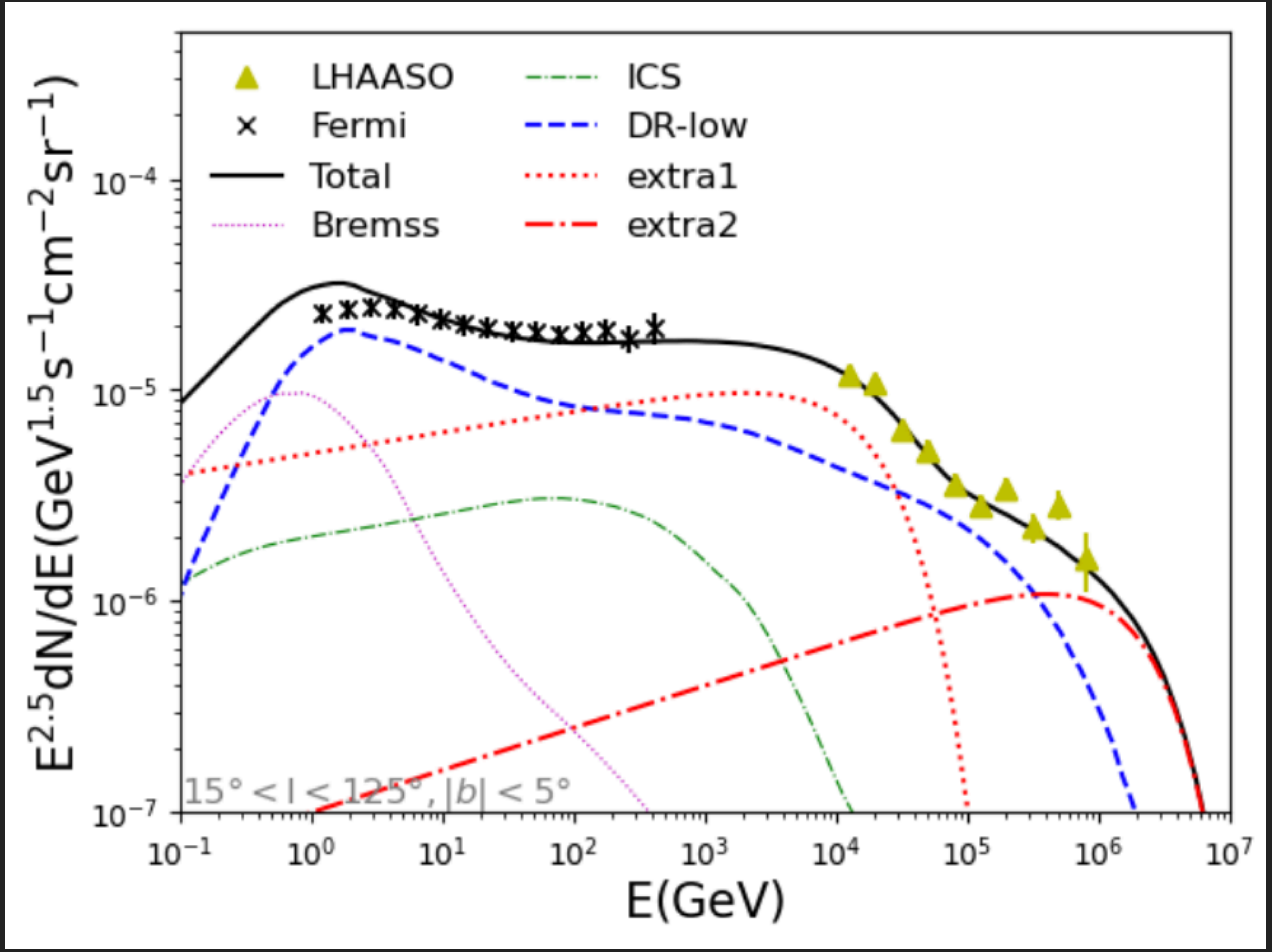
PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

Shao et al. (2023; 2307.01038)

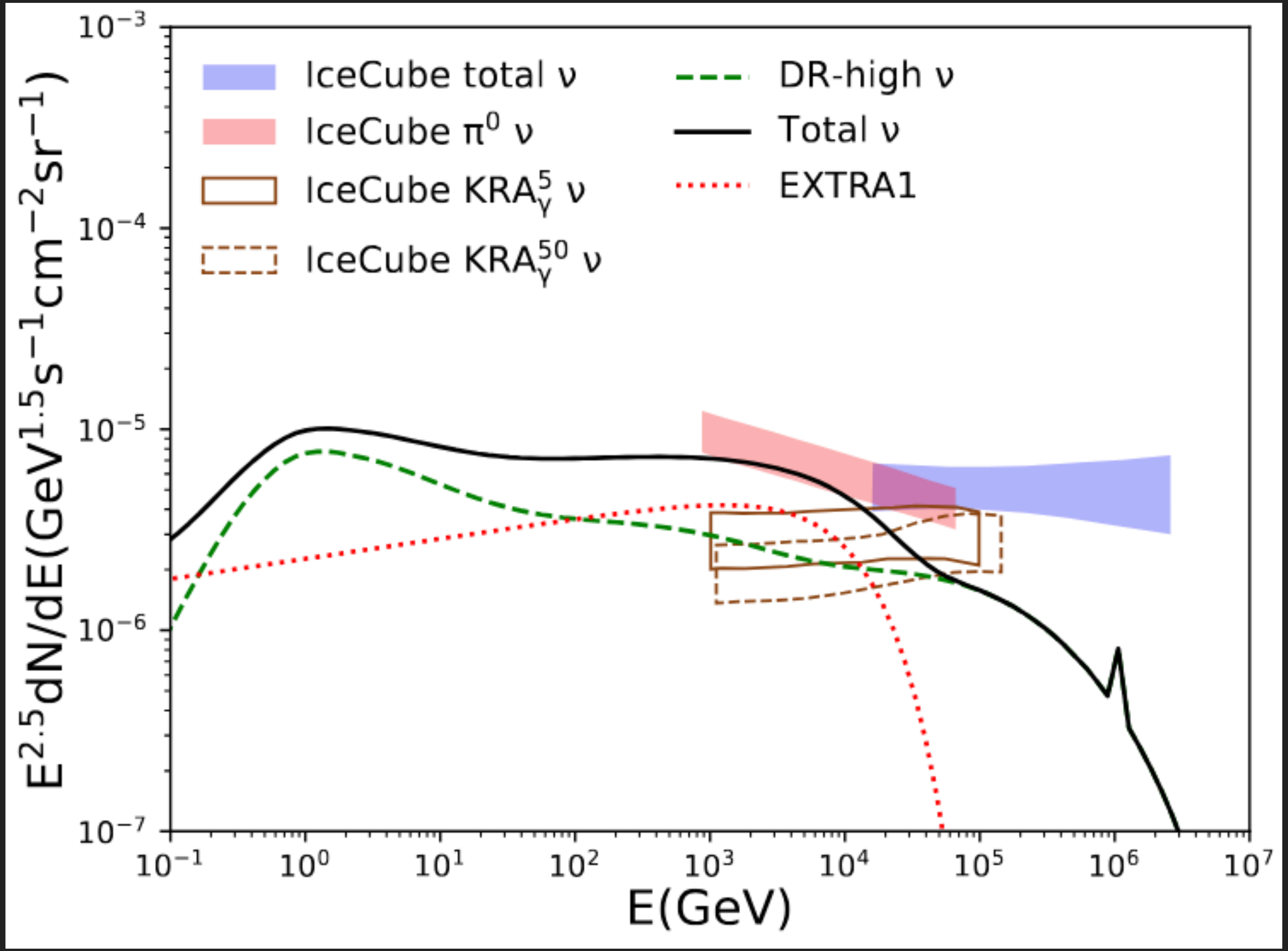


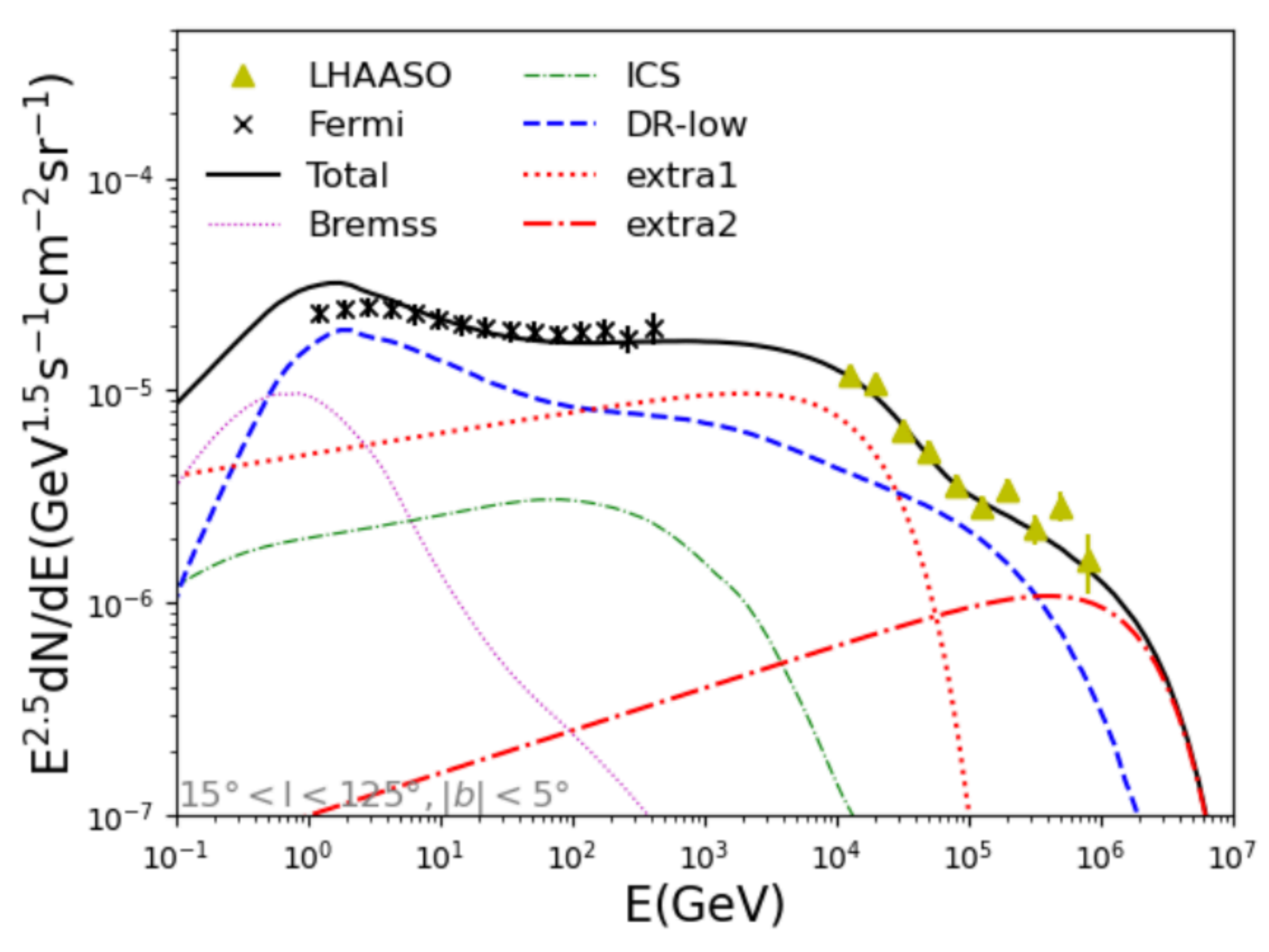


- Models that explain the IceCube neutrino flux still require an additional gamma-ray component (here: "Extra1 and Extra2").
    - In this model it is hadronic.

PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

Shao et al. (2023; 2307.01038)

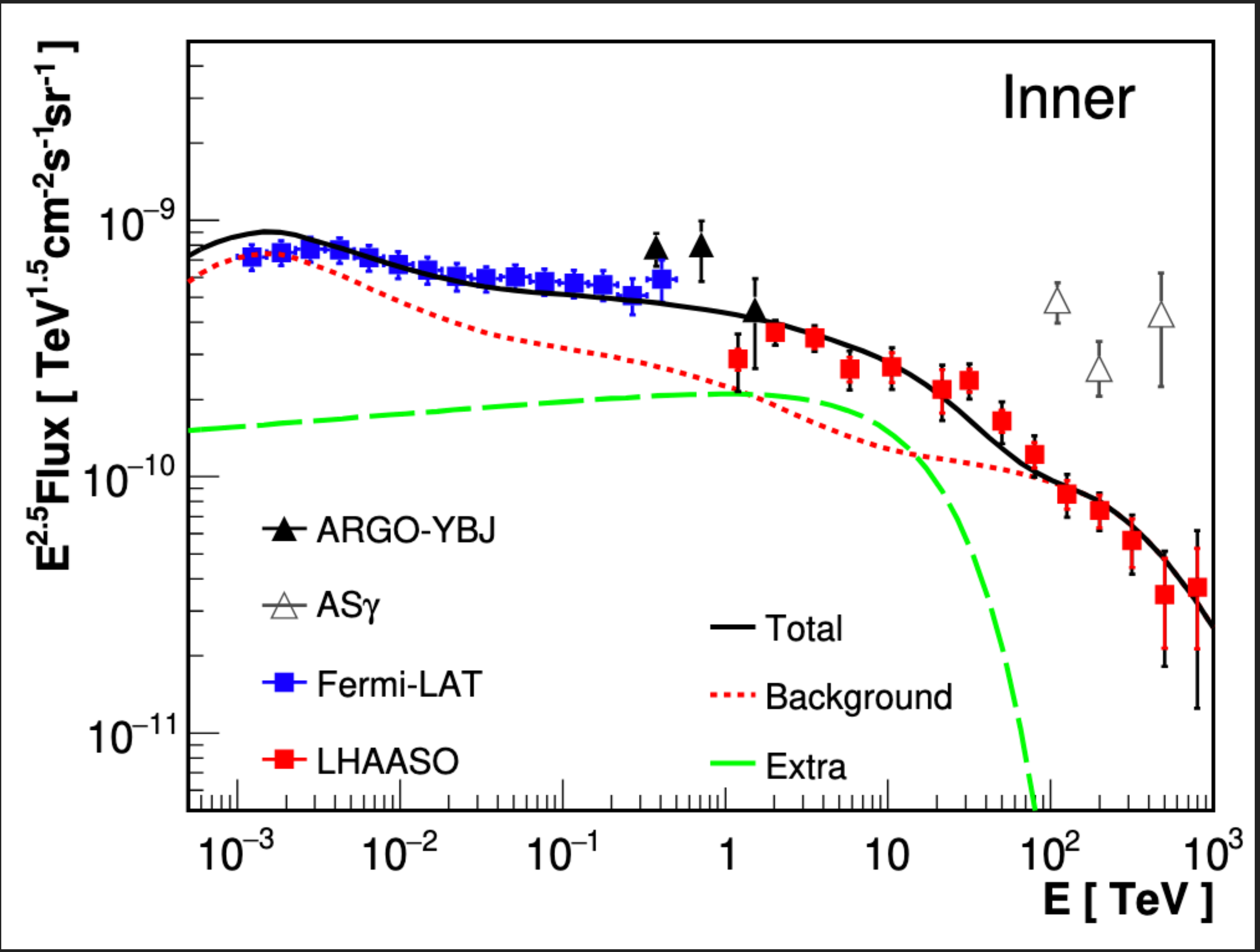


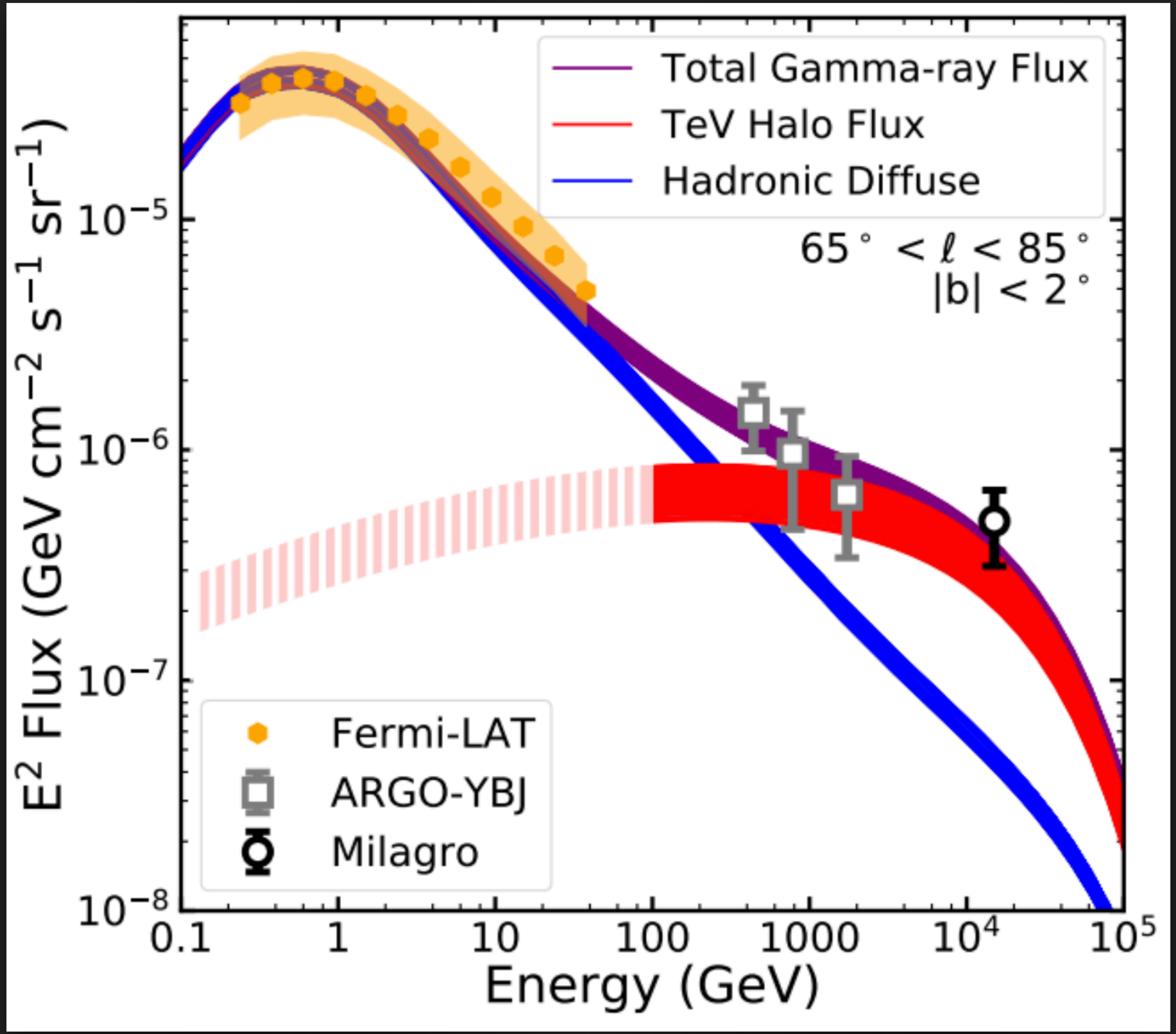


- Models that explain the IceCube neutrino flux still require an additional gamma-ray component (here: "Extra1 and Extra2").
  - In this model it is likely leptonic.

PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

LHAASO Collaboration (2411.16021)



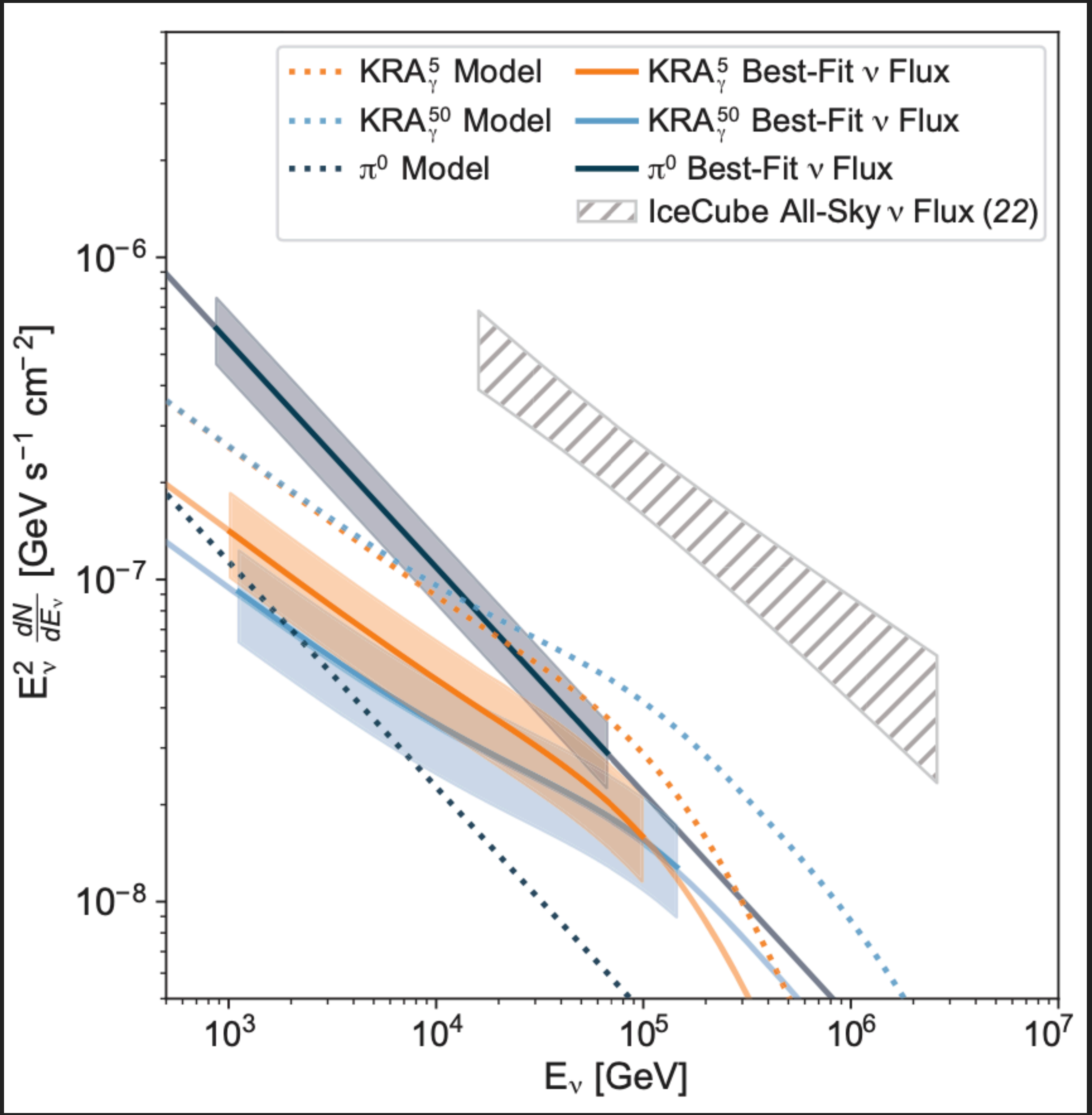


- LHAASO collaboration recently reported a diffuse spectrum requiring an EXTRA component as well, with a very similar spectrum to Geminga.

PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

IceCube Collaboration (2023)

- IceCube neutrino flux is unknown at low energies (nearly order of magnitude uncertainties from models that fit the data to within 1σ.
- On top of this, there is an intrinsic factor of 2 uncertainty in even the IceCube flux measurement.
- There is also a factor of ~2 uncertainty in the TeV halo flux owing to the "Geminga-like" assumption

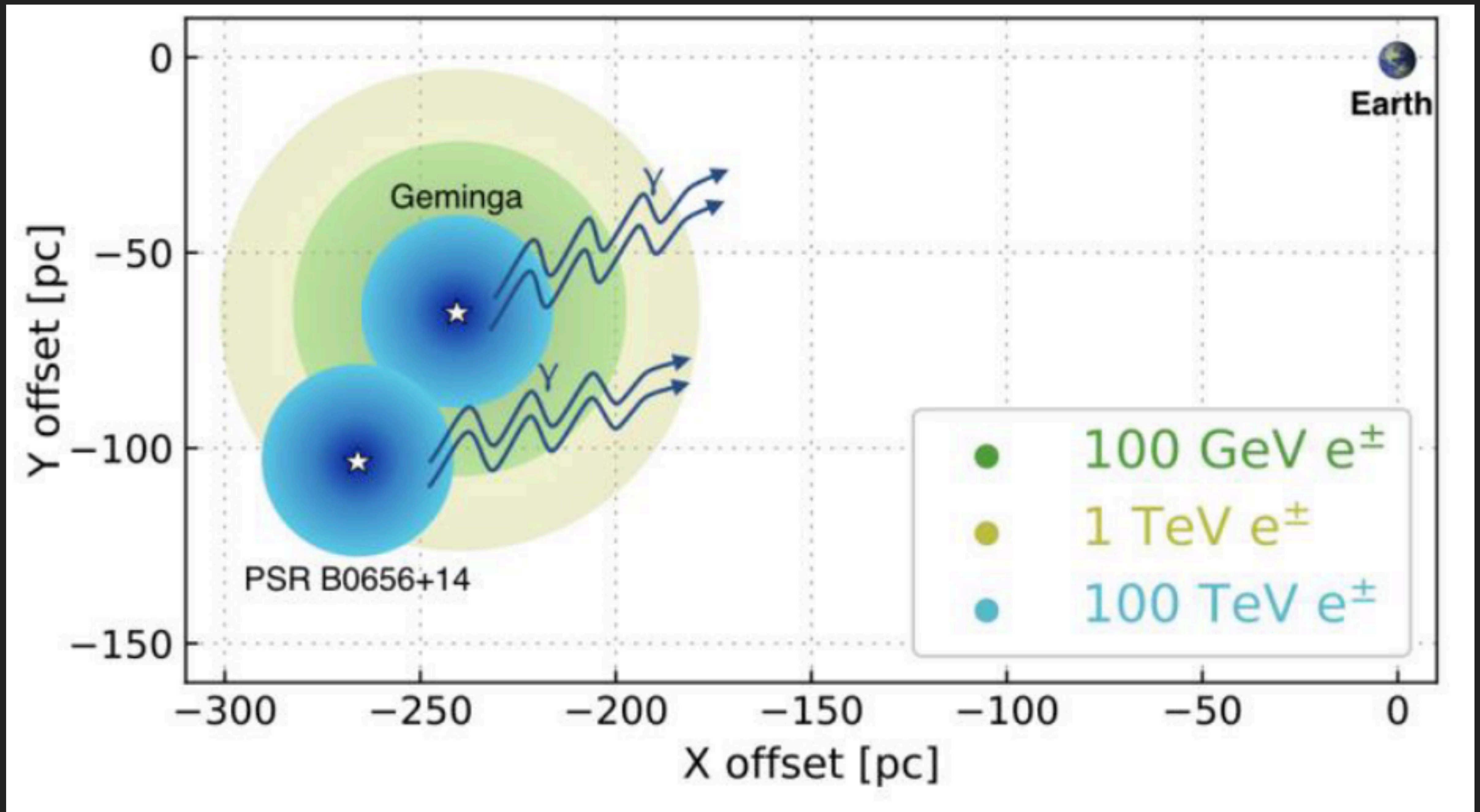


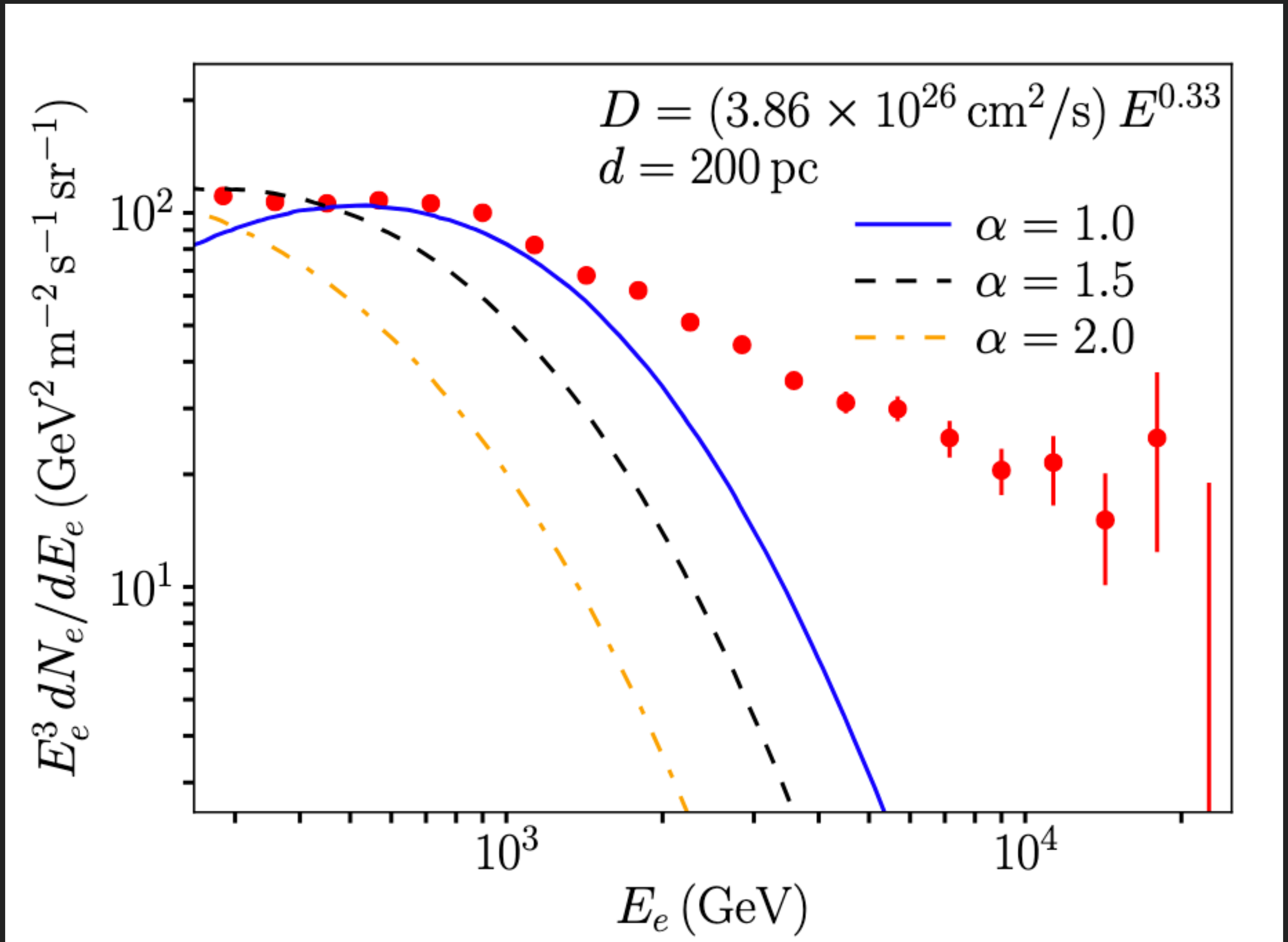
PUZZLE V: WHAT ARE TEV HALOS?

- Failed Model 1: One zone models

Hooper & Linden (1711.07482)

HAWC Collaboration (1711.06223)

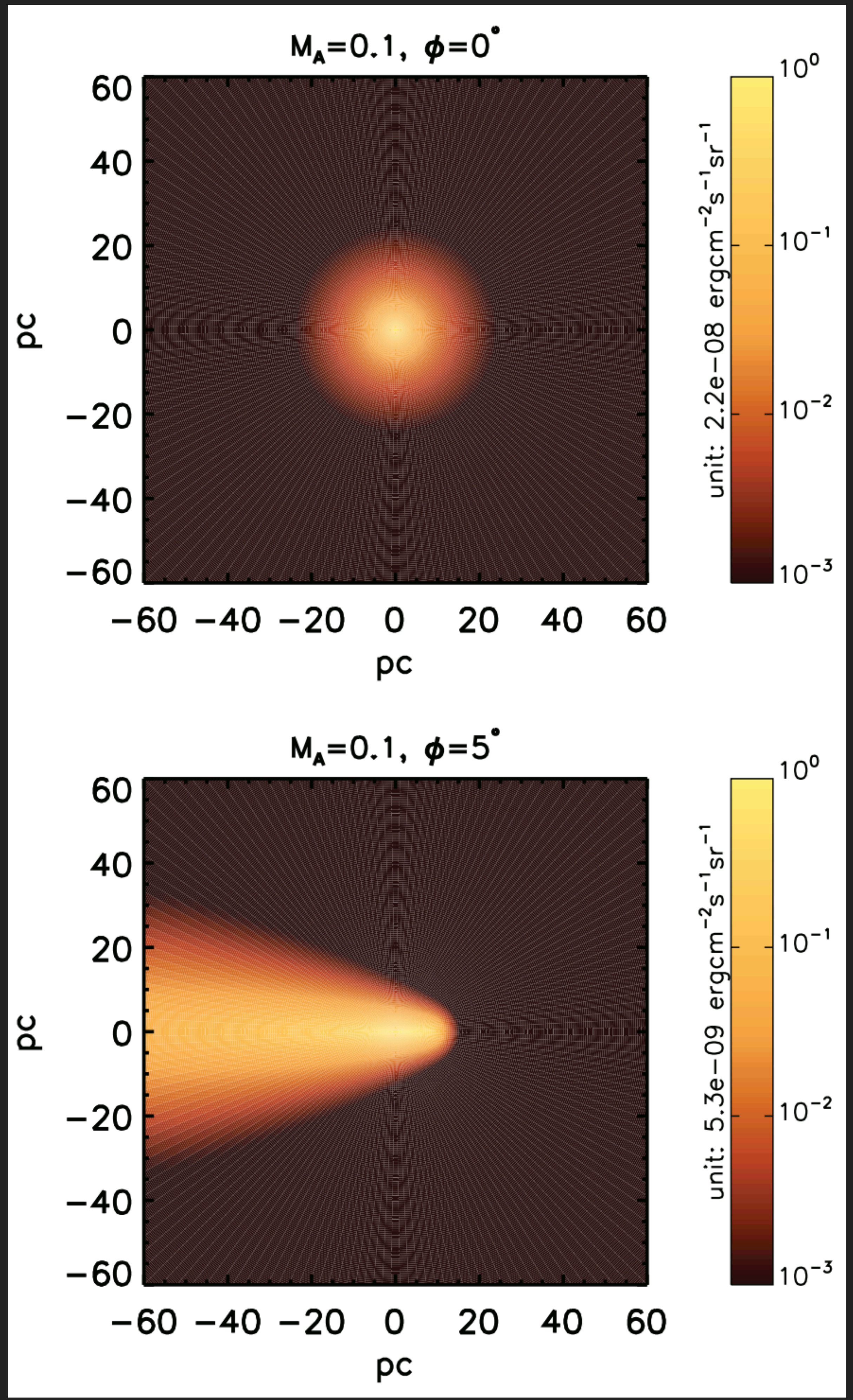




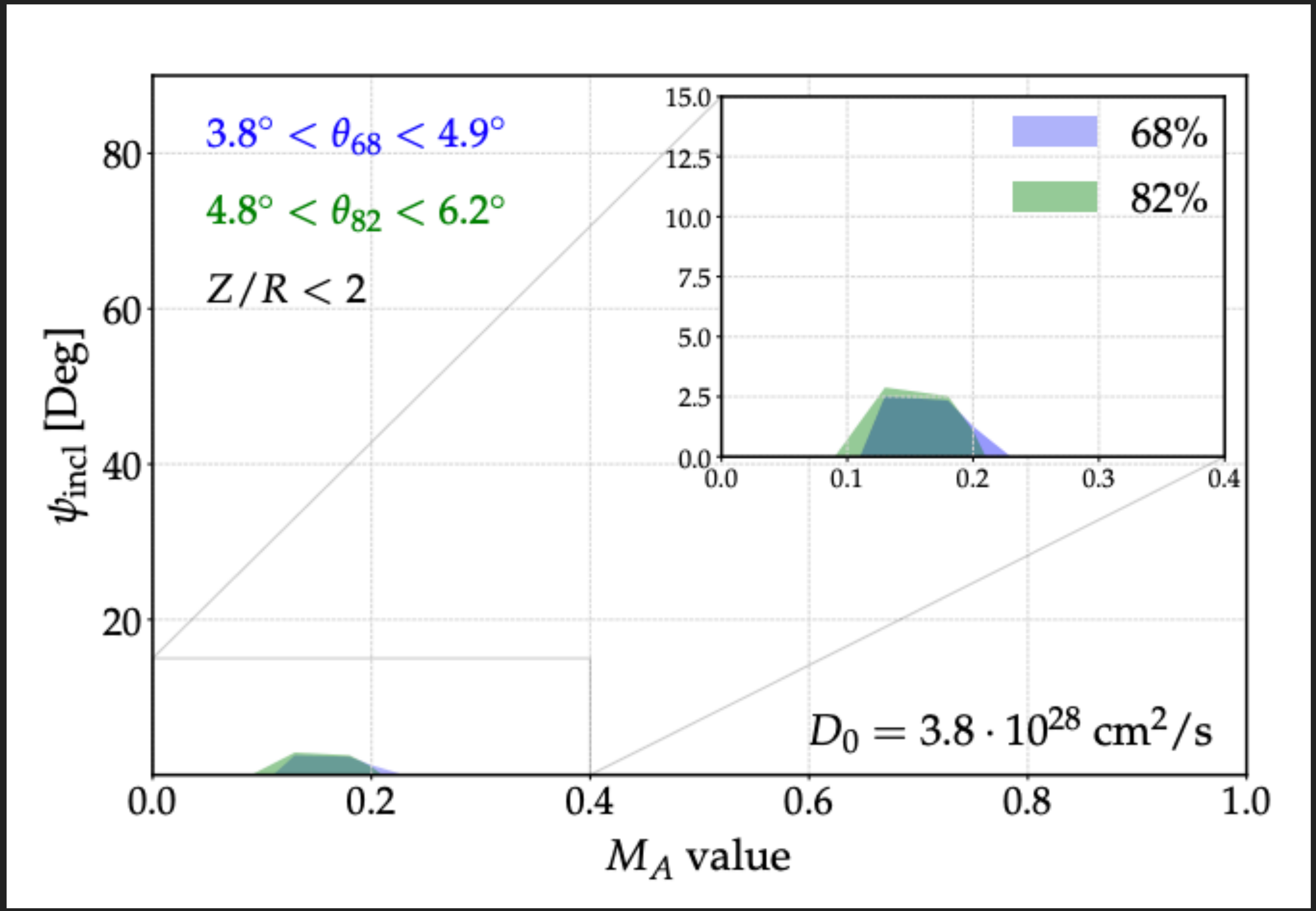
PUZZLE V: WHAT ARE TEV HALOS?

- Failed Model 2: Magnetic fields anomalously pointed towards the Earth

Liu, Yan, Zhang (2019; 1904.11536)



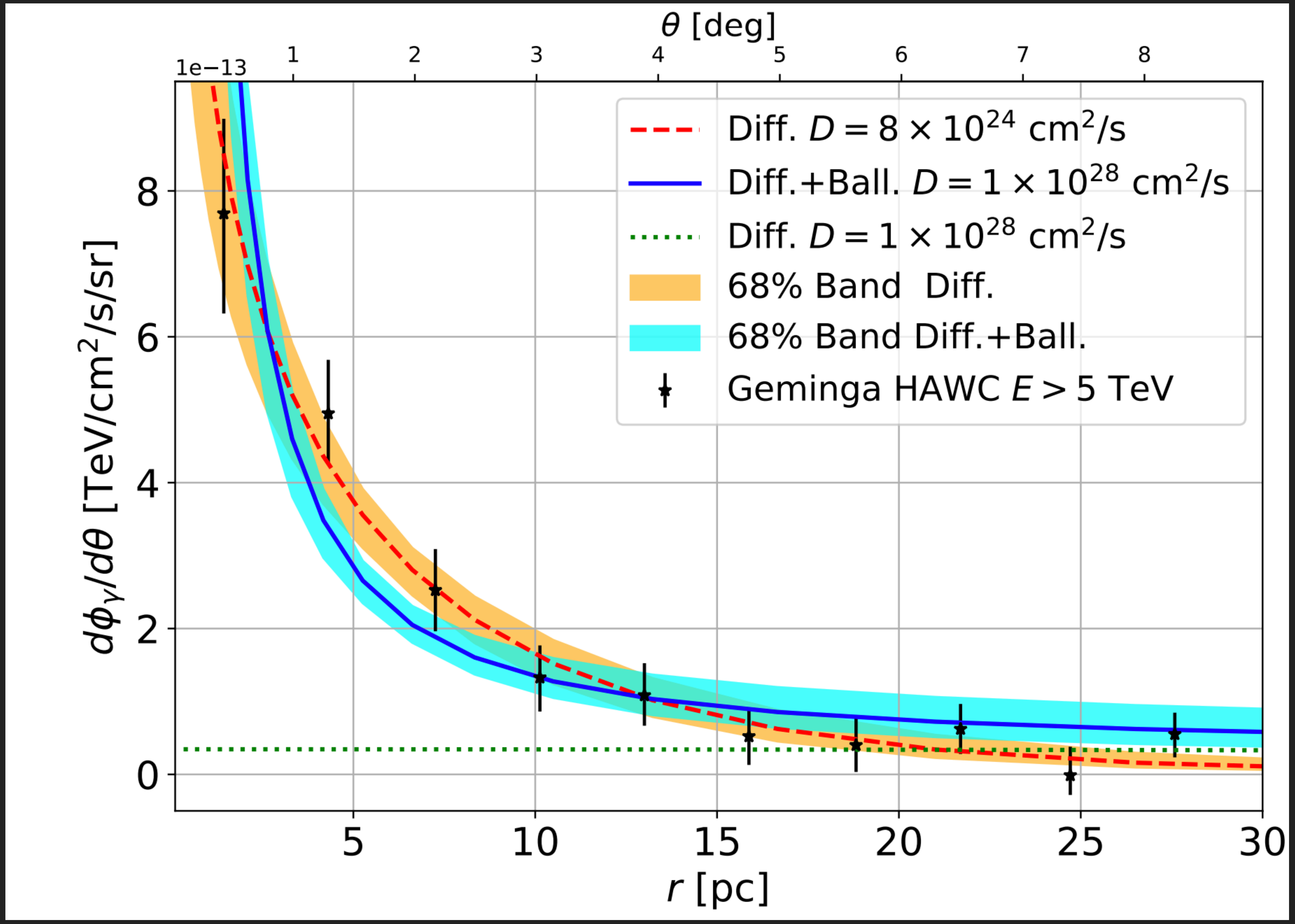
De la Torre Luque et al. (2022; 2205.08544)



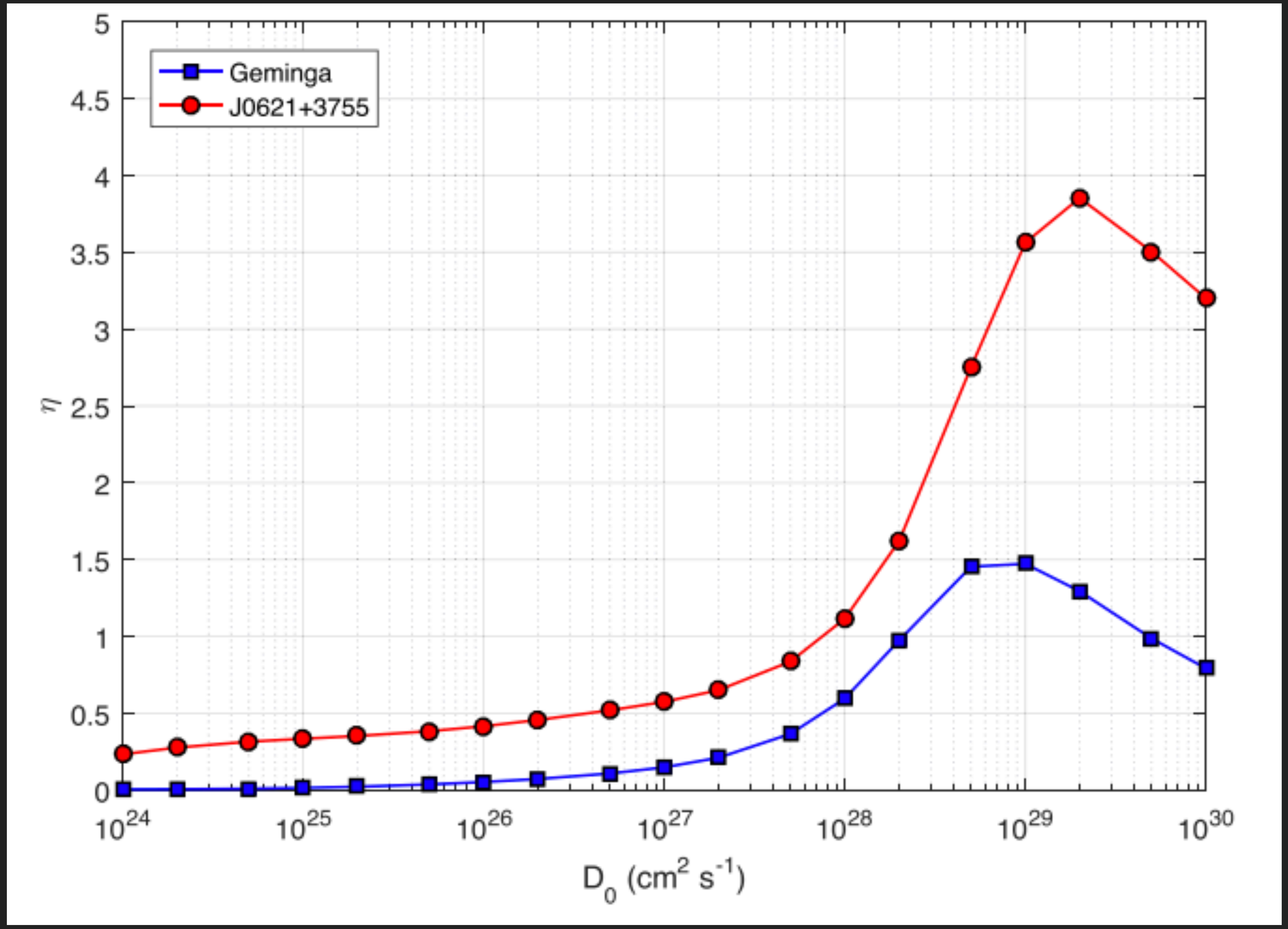
PUZZLE V: WHAT ARE TEV HALOS?

- Failed Model 3: Rectilinear propagation during gamma-ray production.

Recchia et al. (2021; 2106.02275)



Bao et al. (2021; 2107.07395)



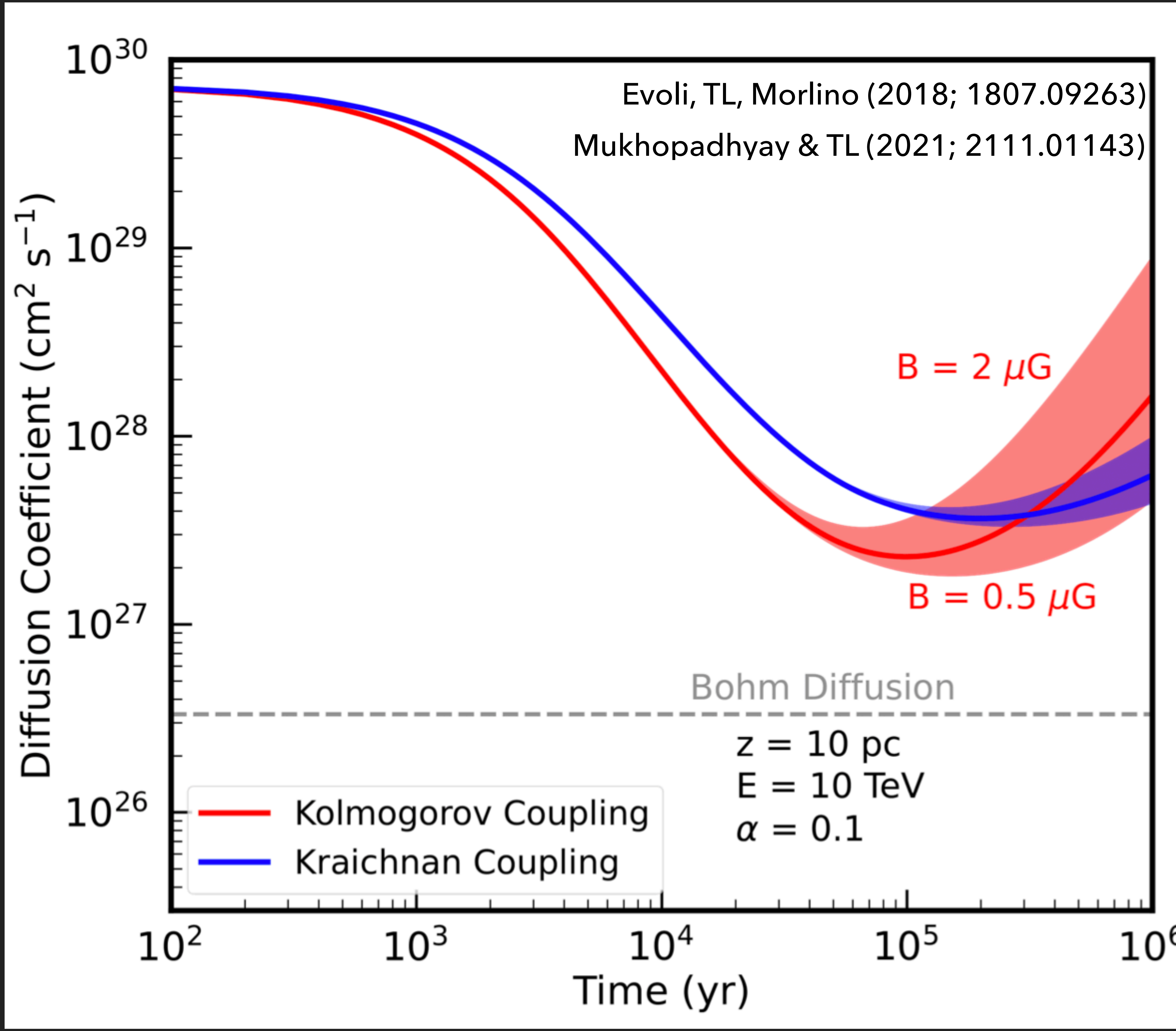
PUZZLE V: WHAT ARE TEV HALOS?

- Self-confinement models (and most other models for inhibited diffusion) - require the high energy of a very young pulsar.

- Probing the diffusion around the youngest systems is critical for understanding TeV halo dynamics.

$$\frac{\partial \mathcal{W}}{\partial t} + v_A \frac{\partial \mathcal{W}}{\partial z} = (\Gamma_{\rm CR} - \Gamma_{\rm D})\mathcal{W}(k, z, t)$$

$$\Gamma_{\rm CR}(k) = \frac{2\pi}{3} \frac{c|v_A|}{k\mathcal{W}(k)\, U_0} \left[p^4 \frac{\partial f}{\partial z}\right]_{p_{\rm res}}$$



PUZZLE V: WHAT ARE TEV HALOS?

Evoli, TL, Morlino (2018; 1807.09263)
Mukhopadhyay & TL (2021; 2111.01143)

$$\frac{\partial W}{\partial t} + v_A \frac{\partial W}{\partial z} = (\Gamma_{CR} + \Gamma_{NLD})\, W(k, z, t)$$

$$\Gamma_{CR}(k) = \frac{2\pi}{3} \frac{c\,|v_\alpha|}{k\; W(k)} \left(\frac{B_0^2}{8\pi}\right)^{-1} \left[p^4 \frac{\partial f}{\partial z}\right]_{p_{\rm res}}$$

$$\Gamma_{NLD}(k) = c_k\, v_\alpha \begin{cases} k^{3/2} W^{1/2} & \text{Kolmogorov} \\ k^2 W & \text{Kraichnan} \end{cases}$$

$$D(p,t) = \frac{4}{3\pi} \frac{c r_L(p))}{k_{\rm res} W(z, k_{\rm res}))}$$

PUZZLE V: WHAT ARE TEV HALOS?

- Many uncertainties in these models:
  - Role of Supernova Remnant
  - Disruption by molecular gas or magnetic fields
  - Pulsar Proper Motion
  - 1D vs. 3D diffusion
  - non-Resonant Terms
  - Halos in close proximity

Possible origin of the slow-diffusion region around Geminga

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ABSTRACT

Geminga pulsar is surrounded by a multi-TeV γ-ray halo radiated by the high energy electrons and positrons accelerated by the central pulsar wind nebula (PWN). The angular profile of the γ-ray emission reported by HAWC indicates an anomalously slow diffusion for the cosmic-ray electrons and positrons in the halo region around Geminga. In the paper we study the possible mechanism for the origin of the slow diffusion. At first, we consider the self-generated Alfvén waves due to the streaming instability of the electrons and positrons released by Geminga. However, even considering a very optimistic scenario for the wave growth, we find this mechanism DOES NOT work to account for the extremely slow diffusion at the present day if taking the proper motion of Geminga pulsar into account. The reason is straightforward as the PWN is too weak to generate enough high energy electrons and positrons to stimulate strong turbulence at the late time. We then propose an assumption that the strong turbulence is generated by the shock wave of the parent supernova remnant (SNR) of Geminga. Geminga may still be inside the SNR, and we find that the SNR can provide enough energy to generate the slow-diffusion circumstance. The TeV halos around PSR B0656+14, Vela X, and PSR J1826-1334 may also be explained under this assumption.

Key words: cosmic rays – ISM: individual objects: Geminga nebula – ISM: supernova remnants – turbulence

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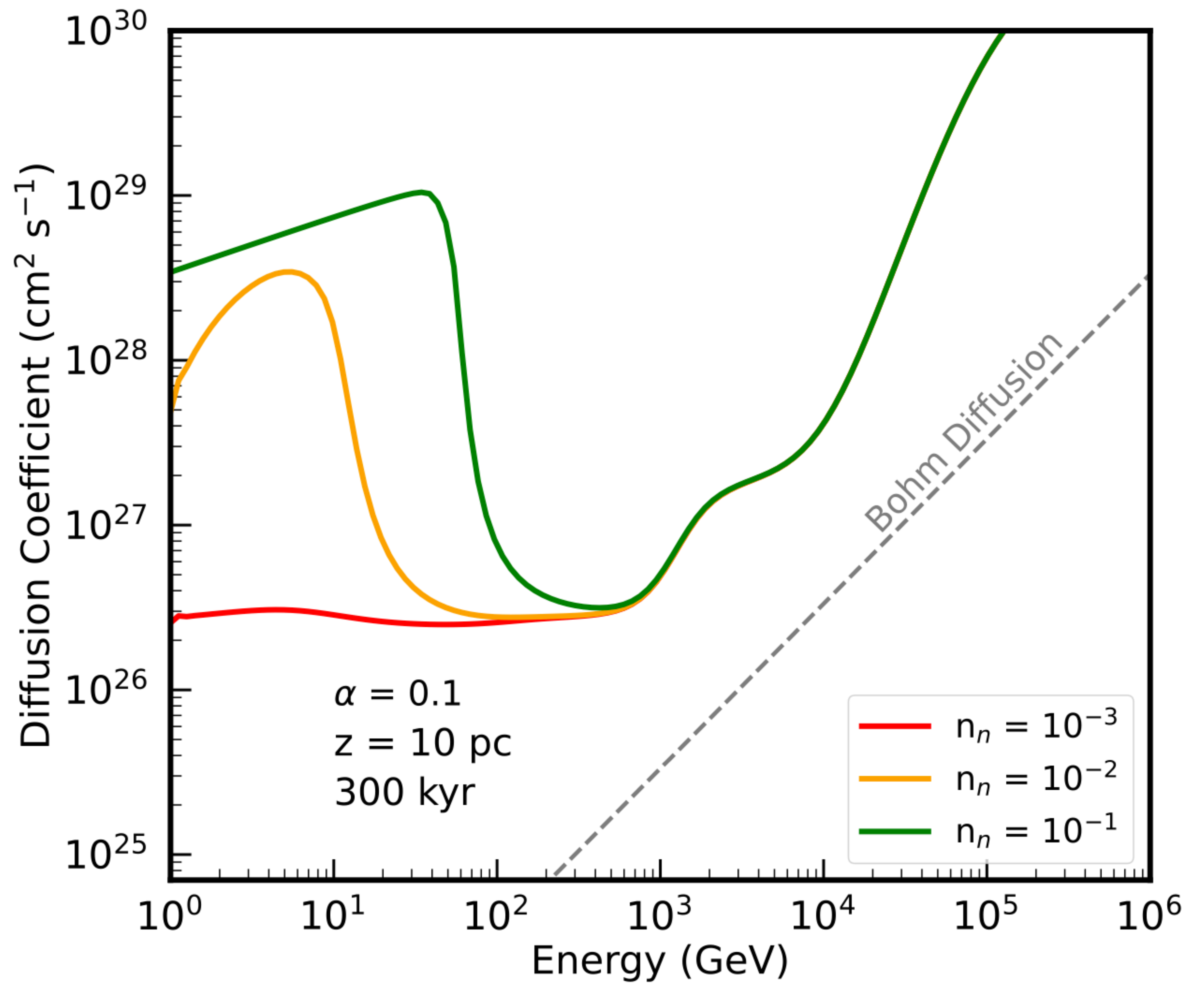

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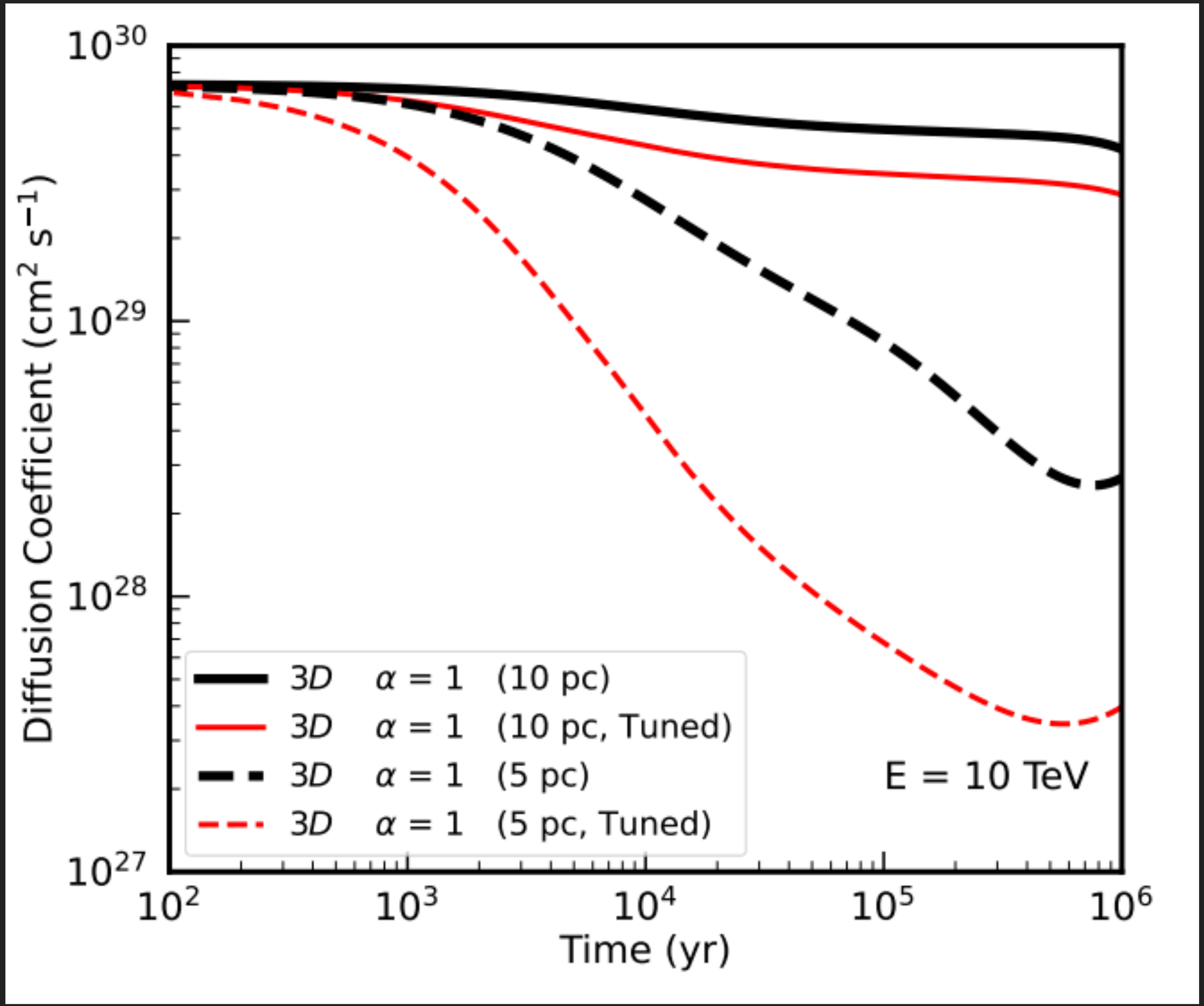

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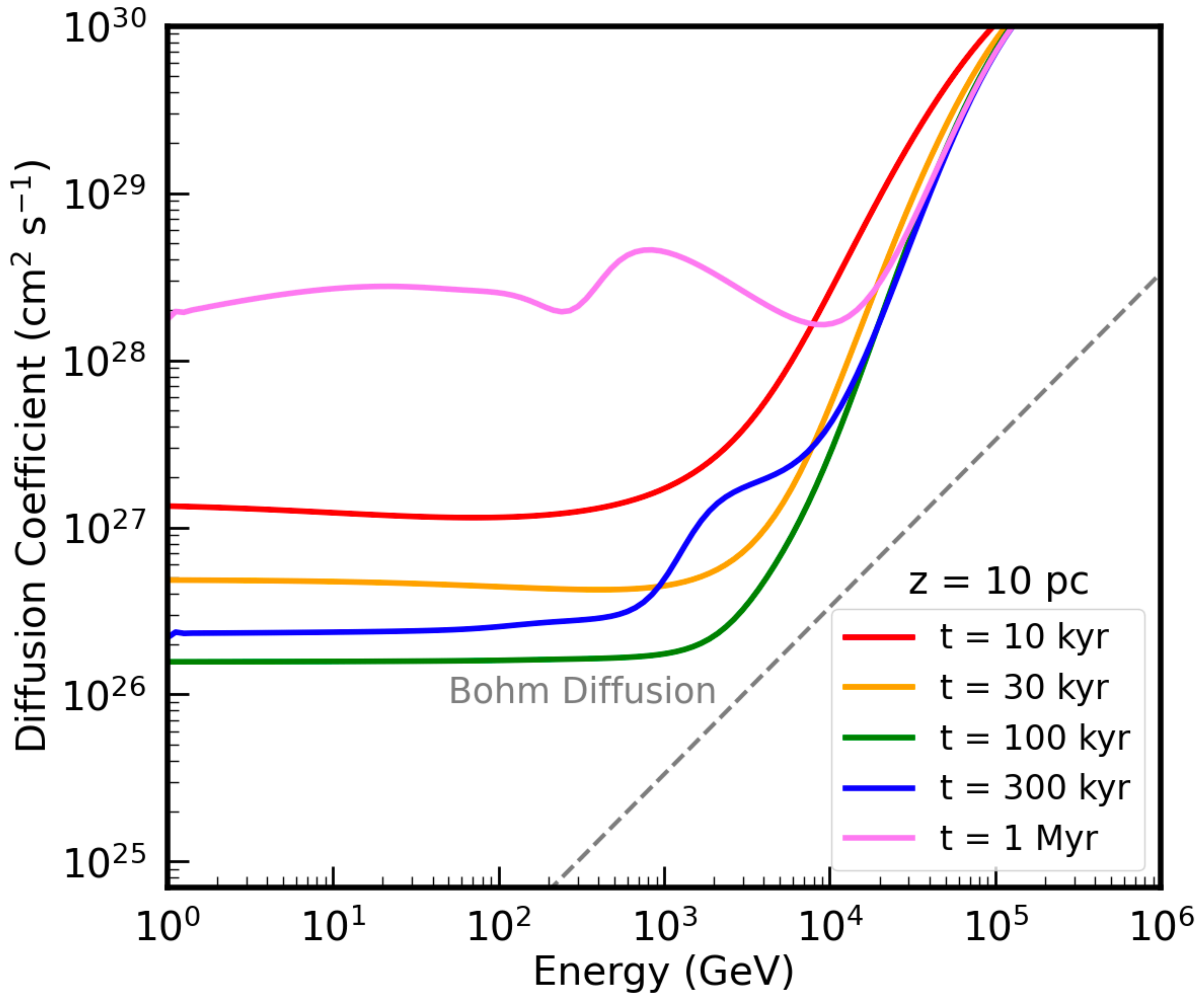
- Several Predictions of these Models:
  - Relatively flat low-energy diffusion coefficient.
  - Highly energy dependent diffusion coefficient at high energies.
    - 100 TeV halo detections challenge this interpretation!



CONCLUSIONS

- TeV halos are a common feature around middle-aged (and possibly young and recycled pulsars).
- The early lessons were easy – TeV halos prove that pulsars produce the positron flux, and clearly provide a significant fraction of the TeV sources and diffuse TeV emission.
- The next-generation lessons are harder:
  - Understand the diversity of sources.
  - Understand fundamentals of halo diffusion.
  - Understand interplay between leptonic and hadronic sources.