TeV Halos:
Three Findings
And ~~Three~~ Five! Puzzles

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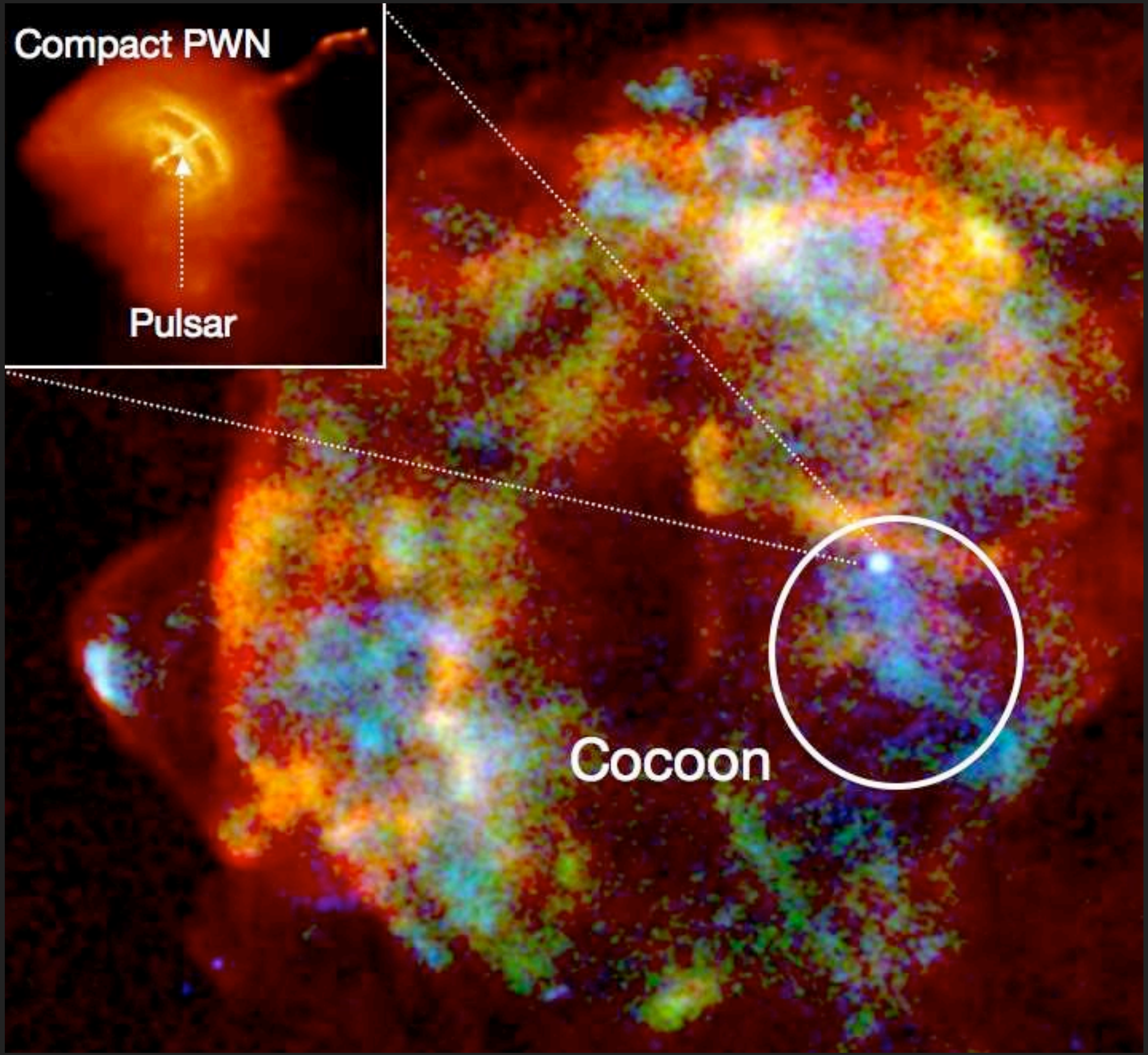
SUPERNOVA REMNANTS AND PULSAR WIND NEBULAE

- Supernova Energetics:
- 10^{53} erg of neutrinos
  - Prompt emission
- 10^{51} erg of electromagnetic energy
  - Powers the supernova remnant
  - Primarily hadronic (0.1-1% leptonic)
- 10^{49} erg of rotational energy in the pulsar
  - Released as the pulsar slows via dipole radiation
  - Primarily leptonic, also magnetic turbulence

$$\dot{E} = -\frac{8\pi^4 B^2 R^6}{3c^3 P(t)^4}$$
$$\approx 1.0 \times 10^{35}\,\mathrm{erg/s} \times \left(\frac{B}{1.6\times 10^{12}\,\mathrm{G}}\right)^2 \left(\frac{R}{15\,\mathrm{km}}\right)^6 \left(\frac{0.23\,\mathrm{s}}{P(t)}\right)^4$$

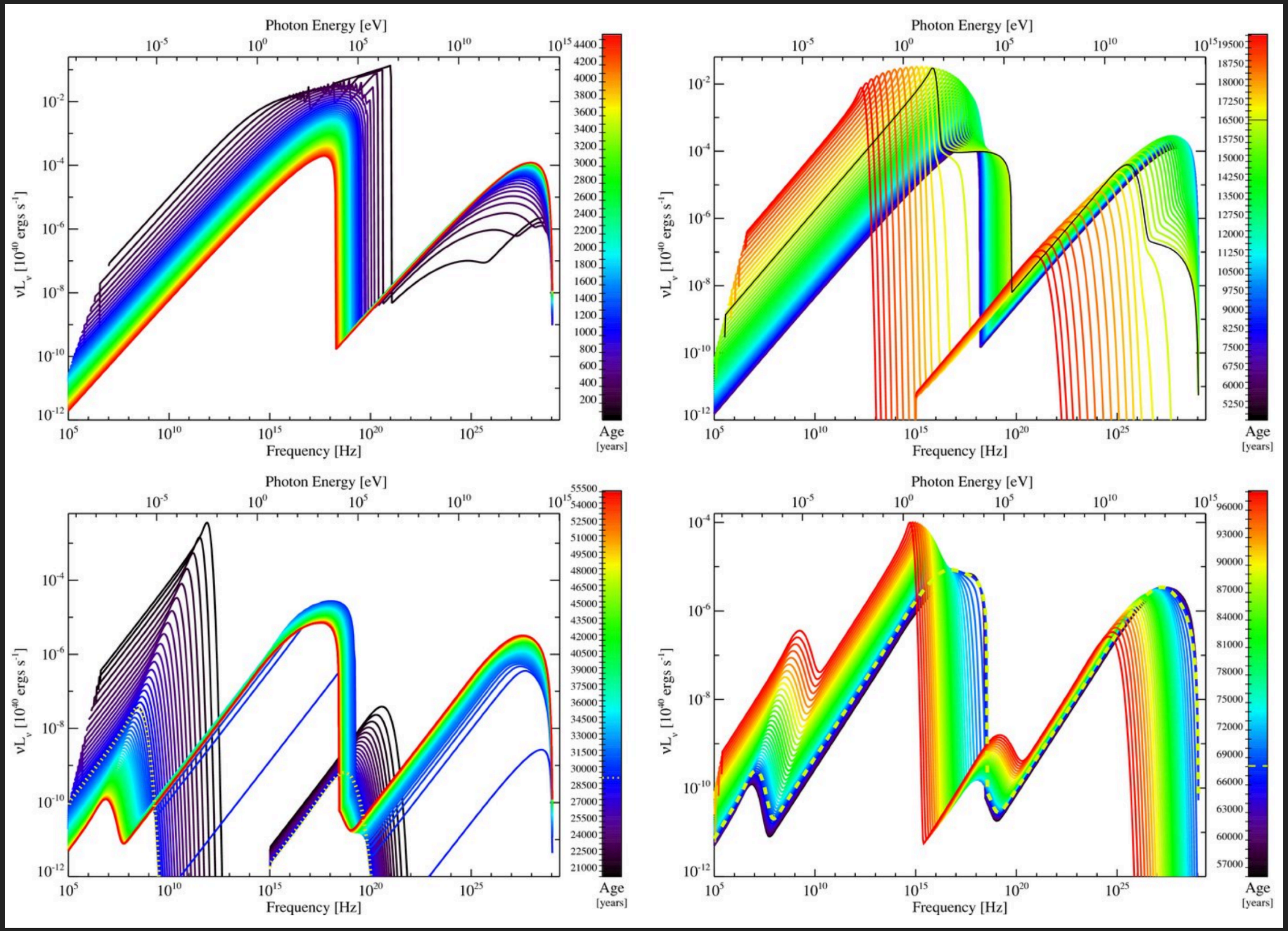


SUPERNOVA REMNANTS AND PULSAR WIND NEBULAE

Mitchell & Gelfand (2208.11026)

- Pulsar Wind Nebulae are bright multi-wavelength sources.
- This implies the continuous acceleration of electrons from GeV - PeV energies.
- What happens to these electrons after the PWN is gone?

$$t^e_{\rm synch} \simeq 1.3 \times 10^6 \text{ yr} \left(\frac{E}{\rm GeV}\right)^{-1} \left(\frac{B}{100\ \mu{\rm G}}\right)^{-2}$$



SUPERNOVA REMNANTS AND PULSAR WIND NEBULAE

Aharonian (1995)

- If the efficiency of diffusion were similar to the standard ISM, the electrons would fill ~kpc regions of the ISM, making their gamma-ray emission invisible.

- Would have a large effect on local e+e-.

N·H
ELSEVIER

Nuclear Physics B (Proc. Suppl.) 39A (1995) 193–206

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

Very high energy gamma-ray astronomy and the origin of cosmic rays

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The paper highlights the status and motivations of very high energy ($E \geq 100\,\mathrm{GeV}$) γ-ray astronomy in the era of the Compton GRO. I discuss the potential of future ground-based γ-ray observations with emphasis on objectives connected with the general problem of the origin of galactic cosmic rays.

1. INTRODUCTION

It is difficult to overestimate the significance of the study of primary cosmic γ-rays by ground-based detectors. The outstanding success of the Compton Gamma-Ray Observatory, in particular the results obtained by the Energetic Gamma-Ray Experiment Telescope (EGRET) [1], indicate an obvious necessity for a new generation of satellite-borne high energy γ-ray detectors. The primary aim of this activity seems to be in performing deep sky surveys in γ-rays at energies $E \leq 10\,\mathrm{GeV}$. Furthermore, since most of the EGRET sources do not exhibit spectral cutoffs in the 1-10 GeV region, the extension of investigations into the unexplored region beyond 10 GeV seems to be the second important issue. However, for any practicable effective area of space-based γ-ray telescopes ($S \leq 10\,\mathrm{m}^2$) the very high energy (VHE) region above 100 GeV will remain, at least

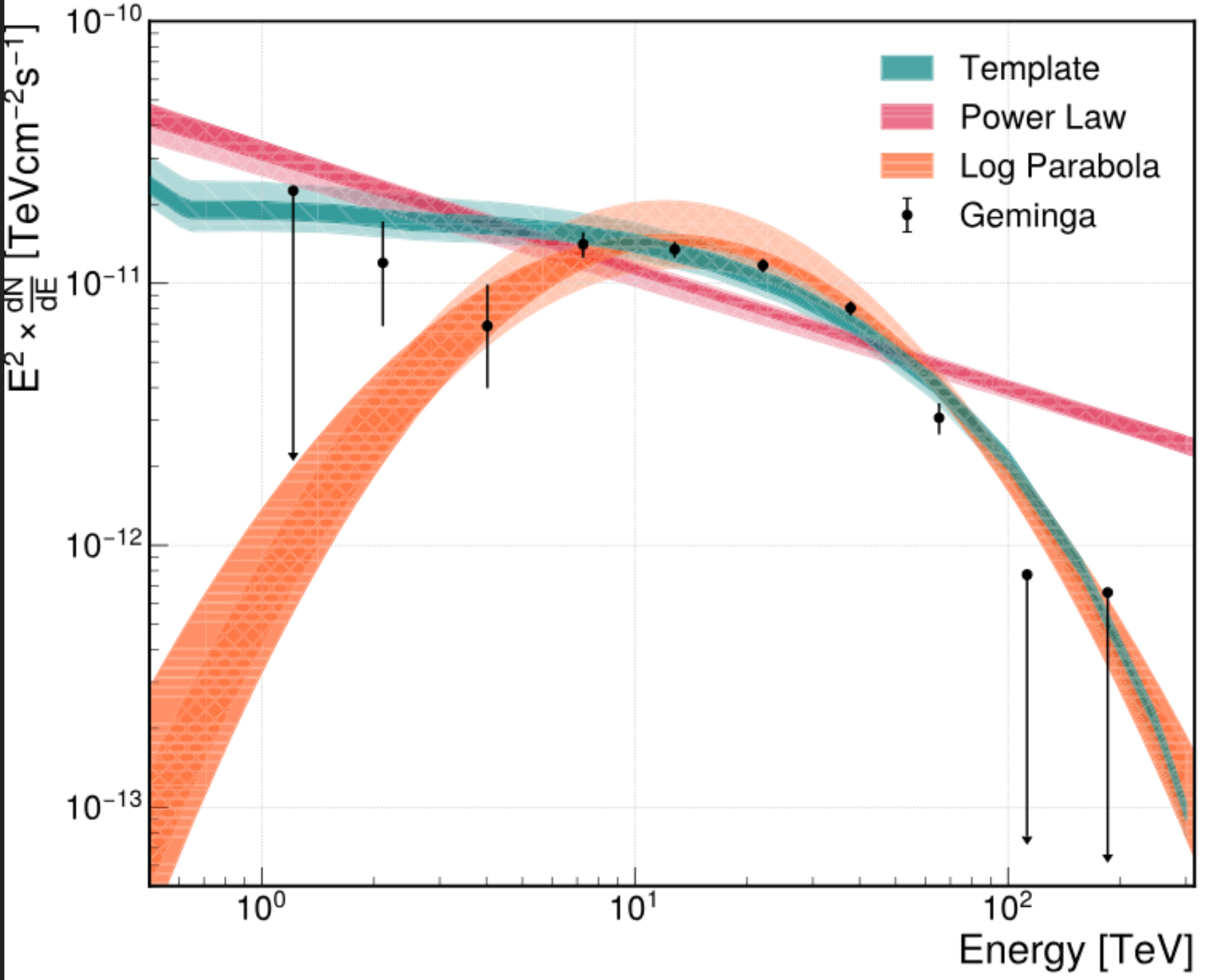
at TeV and/or PeV energies. At first sight, the picture seems rather impressive. However, closer examination of these results shows that most of them have marginal statistical significance [2]. In fact, there are only 3 undisputed DC sources of VHE γ-rays associated with the Crab Nebula, the active galaxy Markarian 421, and the pulsar PSR B1706-44 (see e.g. [3]). Also, tens of episodic events reported by several groups from X-ray binaries and cataclysmic variables like Her X-1, Vela X-1 and AE Aq (for review see [2],[4]) perhaps could be added to this "list" of VHE γ-ray emitters. And finally, it should be also mentioned that Cyg X-3 has been claimed by many groups as an emitter of neutral particles at GeV, TeV, PeV and EeV energies (for review see [2],[5]). Cyg X-3 has played perhaps the most important role in the 80s in the renewed interest in ground based γ-ray observations, but ironically this very source

- Geminga
  - 4.9×10^{-14} TeV^{-1} cm^{-2} s^{-1} (7 TeV)
  - 1.4×10^{31} TeV s^{-1} (7 TeV)
  - 25 pc extension
  - 300 kyr

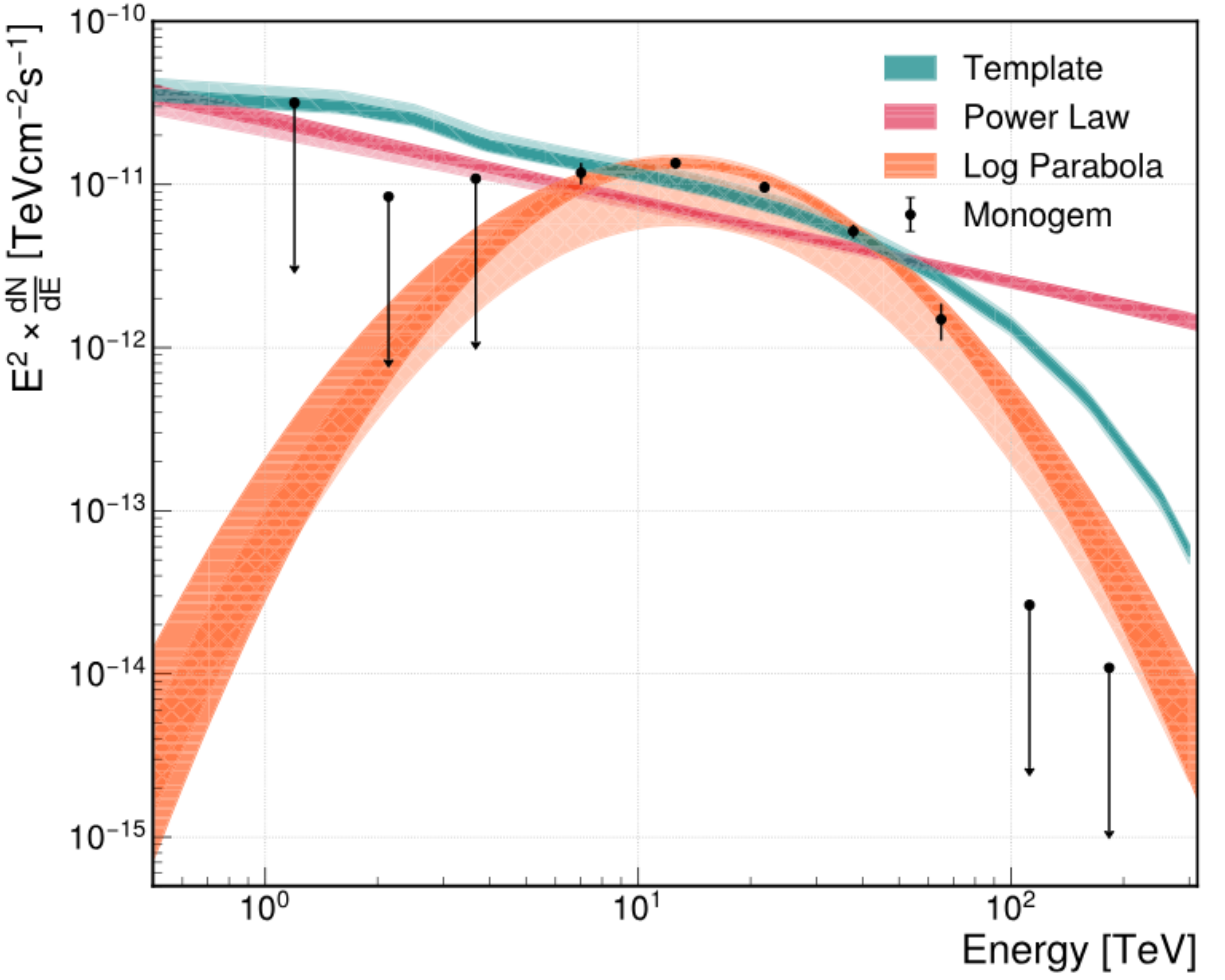
- Monogem
  - 2.3×10^{-14} TeV^{-1} cm^{-2} s^{-1} (7 TeV)
  - 1.1×10^{31} TeV s^{-1} (7 TeV)
  - 25 pc extension
  - 110 kyr

THESE ARE BRIGHT MULTI-TEV SOURCES

Geminga

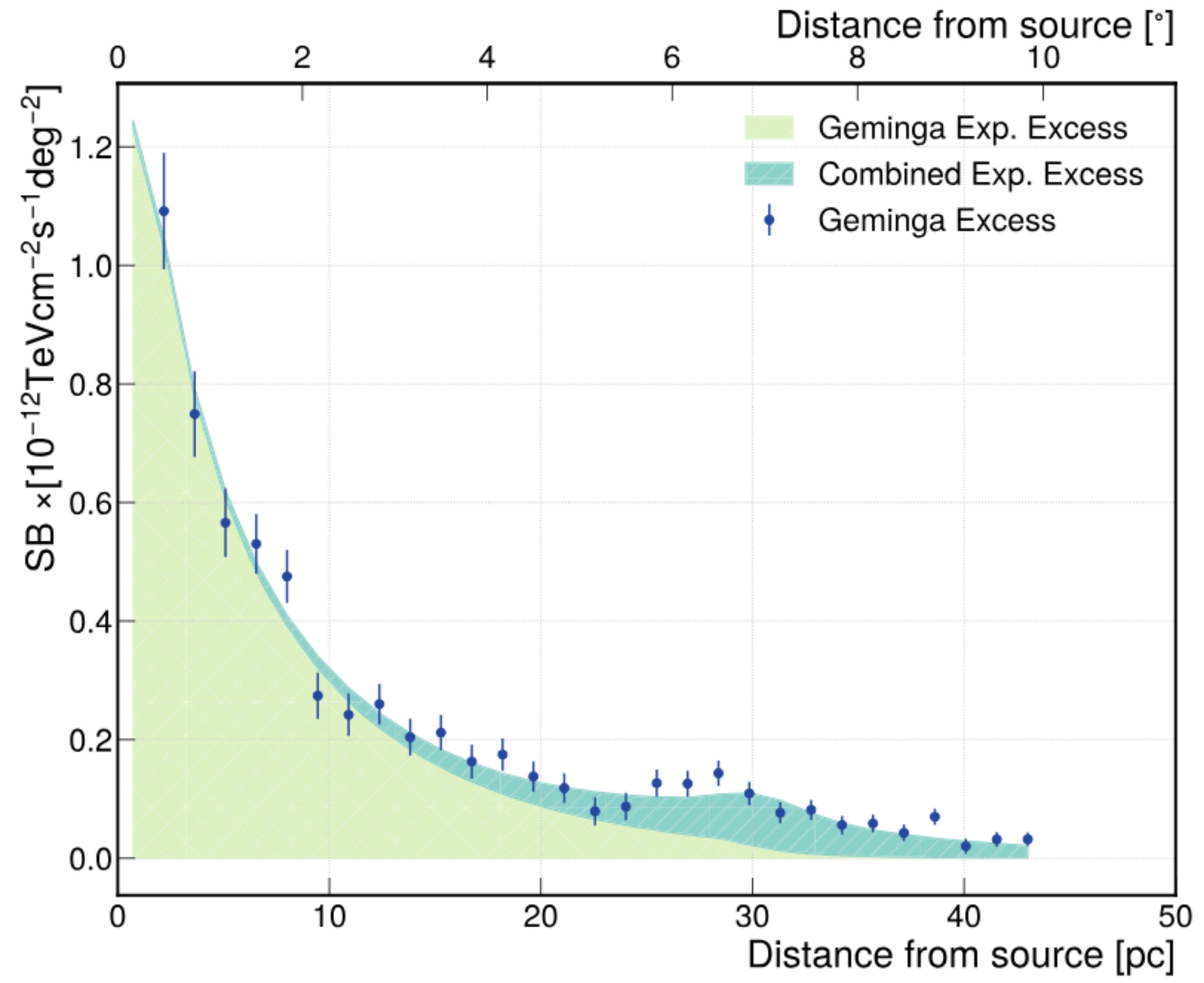


Monogem

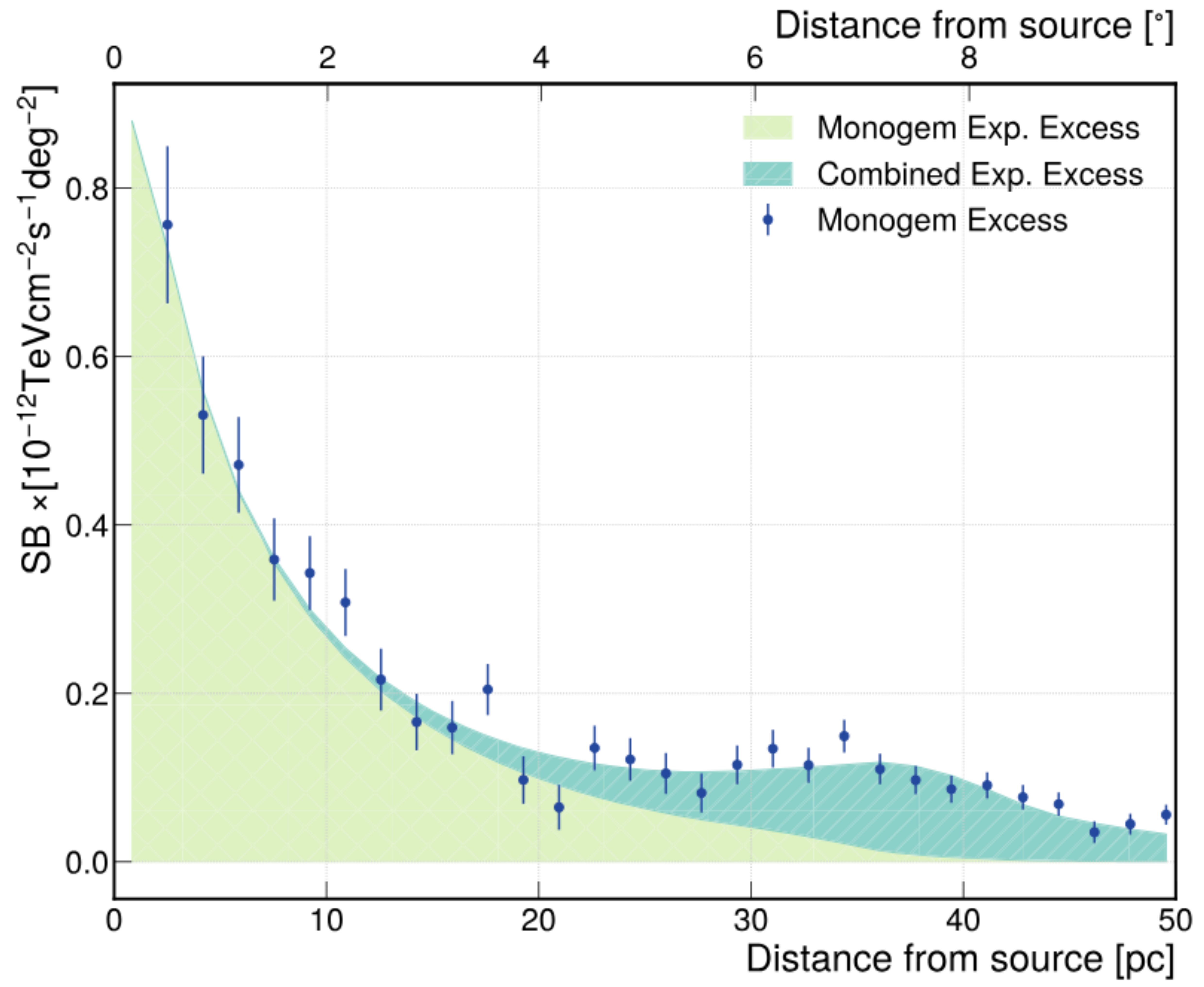


THESE ARE HIGHLY EXTENDED SOURCES

Geminga



Monogem



TEV HALOS: A NEW SOURCE CLASS

RegExp Search

× TeVHalo × TeVHaloCand AND

Filter by Observer AND

Reset | Table Columns | Sync To Map | Filter Selected

Name	RA	Dec	Type Tags	Distance	Catalog
PSR J0359+5414	03 59 19.2	+54 13 12	TeVHaloCand,Gal	3.45 kpc	Default Catalog
HAWC J0543+233	05 43 07.2	+23 24 00	TeVHalo,Gal,PeV		Default Catalog
LHAASO J0621+3755	06 21 52.8	+37 55 12	TeVHalo,PWN,Gal		Default Catalog
Geminga	06 32 28	+17 22 00	TeVHalo,PWN,Gal,PeV,SNR	0.25 kpc	Default Catalog
HAWC J0635+070	06 34 50.4	+07 00 00	TeVHalo,Gal,UNID		Default Catalog
2HWC J0700+143	07 00 28.8	+14 19 12	TeVHalo,Gal		Default Catalog
Vela X	08 35 00	-45 36 00	Gal,SNR,PWN,TeVHalo	0.29 kpc	Default Catalog
Vela Pulsar	08 35 20.7	-45 10 35.2	Gal,PSR,SNR,TeVHaloCand	0.29 kpc	Default Catalog
HESS J1825-137	18 25 49	-13 46 35	TeVHalo,PWN,Gal,PeV,SNR	3.9 kpc	Default Catalog
HESS J1831-098	18 31 25	-09 54 00	TeVHaloCand,PWN,Gal,PeV,...		Newly Announced
HESS J1912+101	19 12 49	+10 09 06	TeVHaloCand,Shell,Gal,PeV,...		Default Catalog
2HWC J1955+285	19 55 19.2	+28 35 24	TeVHaloCand,UNID,PeV		Default Catalog
TeV J2032+4130	20 31 33	+41 34 38	TeVHaloCand,PWN,Gal,PeV	1.8 kpc	Default Catalog

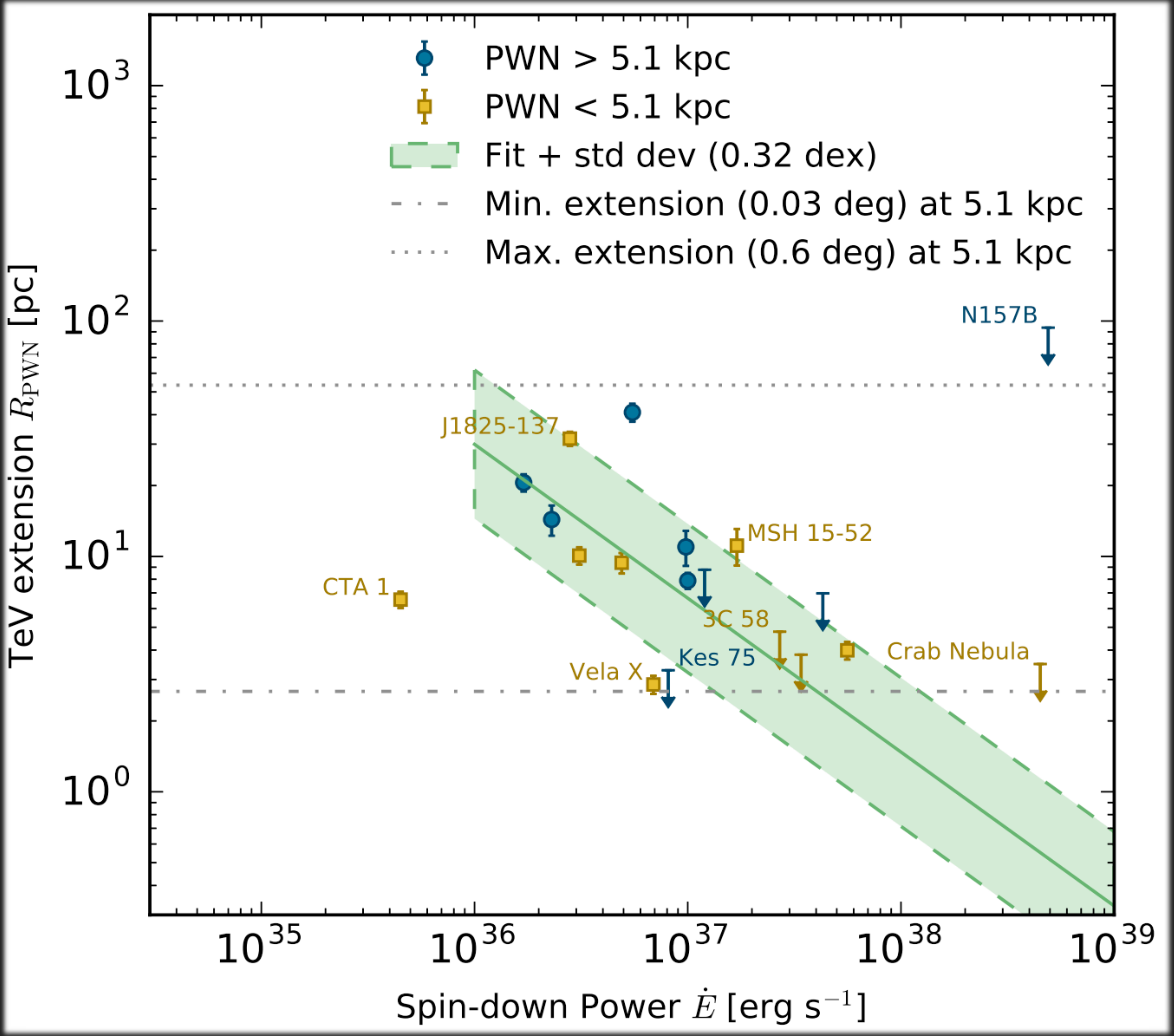
TEV HALOS: A NEW SOURCE CLASS

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.

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



TEV HALOS: THE GEMINGA-CENTRIC MODEL

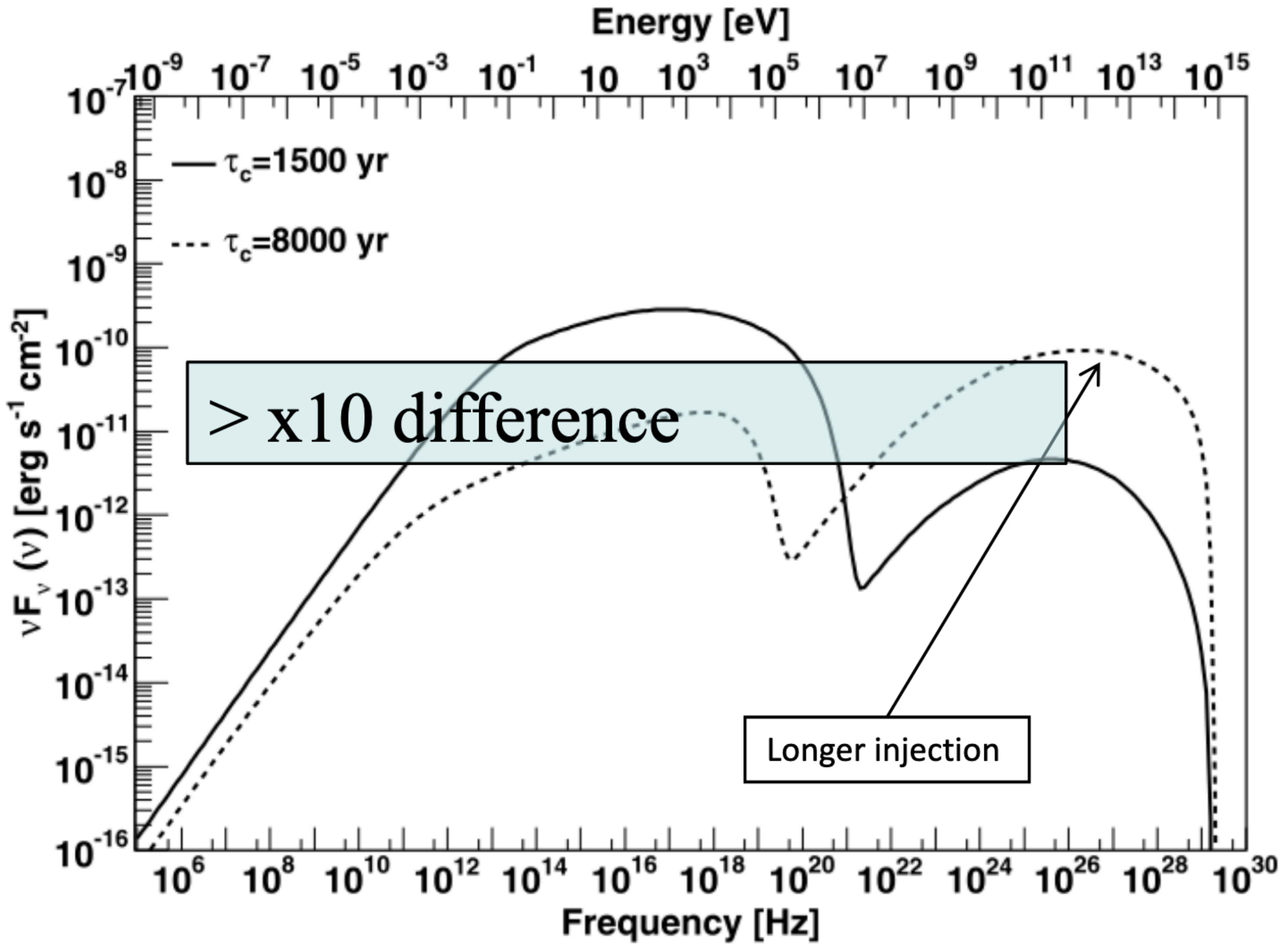
- **Make One Key Assumption:**

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.**

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

Spin-down does not tell the whole story
An example



These are PWN spectra from pulsars with the same

- spin-down evolution,
- spin-down power (1.7×10^{37} erg s^{-1})
- magnetic fraction,
- injection spectrum,
- photon background parameters than Crab,

but two different characteristic ages of 1500 and 8000 years

Detectability estimations based on spin-down power (or spin-down power/D^2) are naive; history counts.

TEV HALOS: A NEW SOURCE CLASS

FERMILAB-PUB-17-080-A

Using HAWC to Discover Invisible Pulsars

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Observations by HAWC and Milagro have detected bright and spatially extended TeV γ-ray sources surrounding the Geminga and Monogem pulsars. We argue that these observations, along with a substantial population of other extended TeV sources coincident with pulsar wind nebulae, constitute a new morphological class of spatially extended TeV halos. We show that HAWCs wide field-of-view unlocks an expansive parameter space of TeV halos not observable by atmospheric Cherenkov telescopes. Under the assumption that Geminga and Monogem are typical middle-aged pulsars, we show that ten-year HAWC observations should eventually observe 37^{+17}_{-13} middle-aged TeV halos that correspond to pulsars whose radio emission is not beamed towards Earth. Depending on the extrapolation of the TeV halo efficiency to young pulsars, HAWC could detect more than 100 TeV halos from mis-aligned pulsars. These pulsars have historically been difficult to detect with existing multiwavelength observations. TeV halos will constitute a significant fraction of all HAWC sources, allowing follow-up observations to efficiently find pulsar wind nebulae and thermal pulsar emission. The observation and subsequent multi-wavelength follow-up of TeV halos will have significant implications for our understanding of pulsar beam geometries, the evolution of PWN, the diffusion of cosmic-rays near energetic pulsars, and the contribution of pulsars to the cosmic-ray positron excess.

I. INTRODUCTION

Recent observations by the High Altitude Water Cherenkov Observatory (HAWC) [1], along with earlier results from Milagro [2], have detected diffuse TeV emission surrounding the Geminga and B0656+14 (hereafter referred to as Monogem [3]) pulsars. While it is difficult to constrain the exact morphology of this emission, both systems are well-fit by Gaussian distributions with an angular extension of $\sim 2°$. These observations are intriguing for several reasons. First, the short cooling times of very high energy electrons imply that even middle-aged pulsars accelerate e^+e^- to energies exceeding $\sim$50 TeV. Second, the angular size of these "TeV halos" indicates that the propagation of cosmic rays near pulsars is significantly more constrained than typical for the interstellar medium [4, 5]. Third, the intensity of this emission indicates that a significant fraction of the total pulsar spin-down luminosity is converted into e^+e^- pairs, providing evidence

positron fraction observed by PAMELA and AMS-02 [4, 6–8].

The observation of extended "TeV halos" surrounding Geminga and Monogem augment a growing class of TeV sources coincident with pulsars and pulsar wind nebulae (PWN). To date, Atmospheric Cherenkov Telescopes (ACTs), such as H.E.S.S. and VERITAS, have discovered a population of at least 32 such sources [9–12][1]. H.E.S.S. refers to these sources as "TeV PWN", noting that the TeV emission is correlated with pulsars that have visible PWN. However, results from the H.E.S.S. collaboration indicate that the TeV emission is significantly more extended than the X-ray PWN [13]. Thus, these systems may have a unique origin, morphology, and dynamical evolution.

H.E.S.S. observations indicate two important features of TeV halos. First, there is a close correlation between the pulsar spin-down luminosity and the luminosity of the TeV halo. Second, the physical size of the TeV halo is correlated to the

TeV Halos are Everywhere: Prospects for New Discoveries

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(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 escaped from the PWN, but which remain trapped in a larger region where diffusion is inhibited compared to the interstellar medium. Many theoretical properties of TeV halos remain mysterious, but empirical arguments suggest that they are ubiquitous. The key to progress is finding more halos. We outline prospects for new discoveries and calculate their expectations and uncertainties. We predict, using models normalized to current data, that future HAWC and CTA observations will detect in total $\sim$50–240 TeV halos, though we note that multiple systematic uncertainties still exist. Further, the existing HESS source catalog could contain $\sim$10–50 TeV halos that are presently classified as unidentified sources or PWN candidates. We quantify the importance of these detections for new probes of the evolution of TeV halos, pulsar properties, and the sources of high-energy gamma rays and cosmic rays.

I. INTRODUCTION

Milagro observations revealed extended TeV γ-ray emission surrounding the nearby Geminga pulsar, now confirmed by the High Altitude Water Cherenkov (HAWC) observatory [2–4]. Additionally, HAWC has detected similar emission surrounding another nearby pulsar, PSR B0656+14, commonly associated with the Monogem ring [5], and which we refer to as the "Monogem pulsar." These sources are bright ($\sim 10^{32}$ erg s^{-1}), have hard spectra ($\sim E^{-2.2}$), and are spatially extended ($\sim$ 25 pc). In addition, the High Energy Stereoscopic System (HESS) has detected a number of TeV γ-ray sources coincident with pulsars or pulsar wind nebulae (PWNe) [6, 7]. Though they refer to these as "TeV PWN," they find that many are significantly larger than expected from PWN theory [1, 8, 9]. The sources noted above appear morphologically and dynamically distinct from PWNe detected in X-ray and radio observations.

Linden *et al.* [1] identified these sources as a new γ-ray source class ("TeV Halos") and interpreted their emission as the result of electrons and positrons interacting with

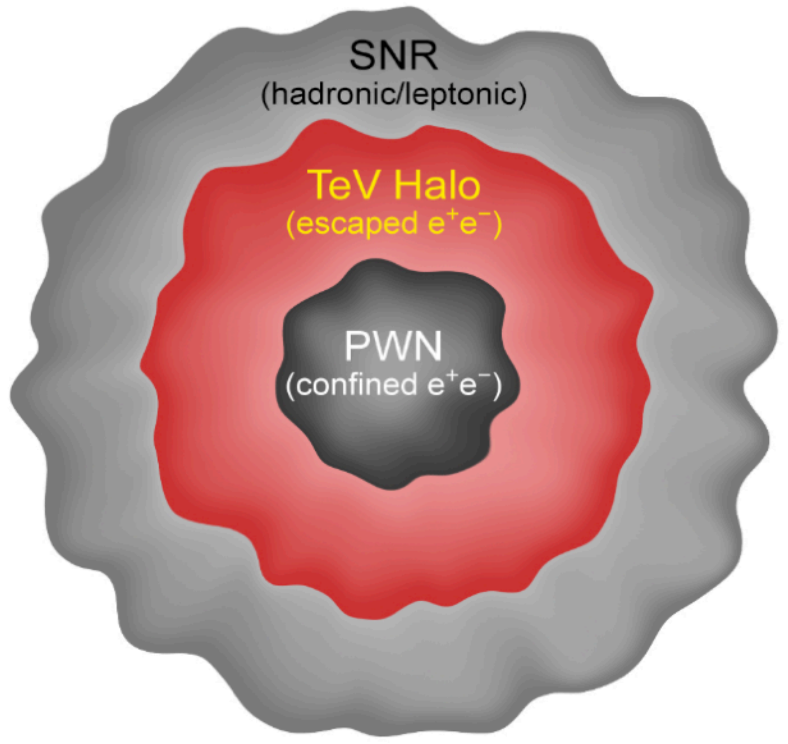

FIG. 1. Schematic illustration of a TeV halo in relation to the more familiar PWN and supernova remnant (SNR). A TeV halo may not form early, and the SNR may be fading when the halo appears.

TEV HALOS: A NEW SOURCE CLASS

Physical Review Letters

ACCEPTED PAPER

Extended TeV halos may commonly exist around middle-aged pulsars

A. Albert et al.

Phys. Rev. Lett. - **Accepted** 11 March, 2025

Abstract

Extended gamma-ray emission around isolated pulsars at TeV energies, also known as TeV halos, have been found around a handful of middle-aged pulsars. The halos are significantly more extended than their pulsar wind nebulae but much smaller than the particle diffusion length in the interstellar medium. The origin of TeV halos is unknown. Interpretations invoke either local effects related to the environment of a pulsar or generic particle transport behaviors. The latter scenario predicts that TeV halos would be a universal phenomena for all pulsars. We searched for extended gamma-ray emission around 36 isolated middle-aged pulsars identified by radio and gamma-ray facilities using 2321 days of data from the High-Altitude Water Cherenkov (HAWC) Observatory. Through a stacking analysis comparing TeV flux models against a background-only hypothesis, we identified TeV halo-like emission at a significance level of $5.10\,\sigma$. Our results imply that extended TeV gamma-ray halos may commonly exist around middle-aged pulsars. This reveals a previously unknown feature about pulsars and opens a new window to identify the pulsar population that are invisible to radio, X-ray, and GeV gamma-ray observations due to magnetospheric configurations.

TEV HALOS: AN ESSENTIAL SOURCE CLASS

Every Nearby Energetic Pulsar Is Surrounded by a Region of Inhibited Diffusion

Isabelle John[1,2,*] and Tim Linden[3,4,†]

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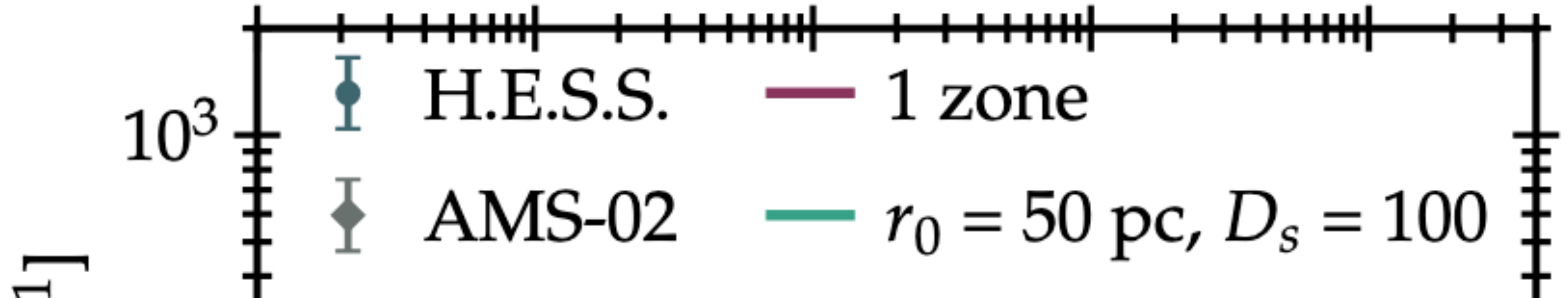
The H.E.S.S. telescope has recently detected the total electron-plus-positron (e^+e^-) flux up to 40 TeV, finding it to be a featureless and steeply-falling power-law above 1 TeV. This result is in stark tension with standard one-zone models of pulsar e^+e^- injection and diffusion, which predict a hard-spectrum signal above ∼10 TeV. We model the local pulsar population, and find 20 sources that would each *individually* overproduce the H.E.S.S. e^+e^- flux in a one-zone diffusion model. We conclude that *every* energetic pulsar younger than ∼500 kyr must be surrounded by a region of inhibited diffusion (*e.g.*, a supernova remnant, pulsar wind nebula, or TeV halo) that prevents the transport of these e^+e^- to Earth. Because the high-electron density in these regions produces bright synchrotron and inverse-Compton emission, we conclude that all nearby pulsars are detectable as (potentially unassociated) radio, x-ray or γ-ray sources.

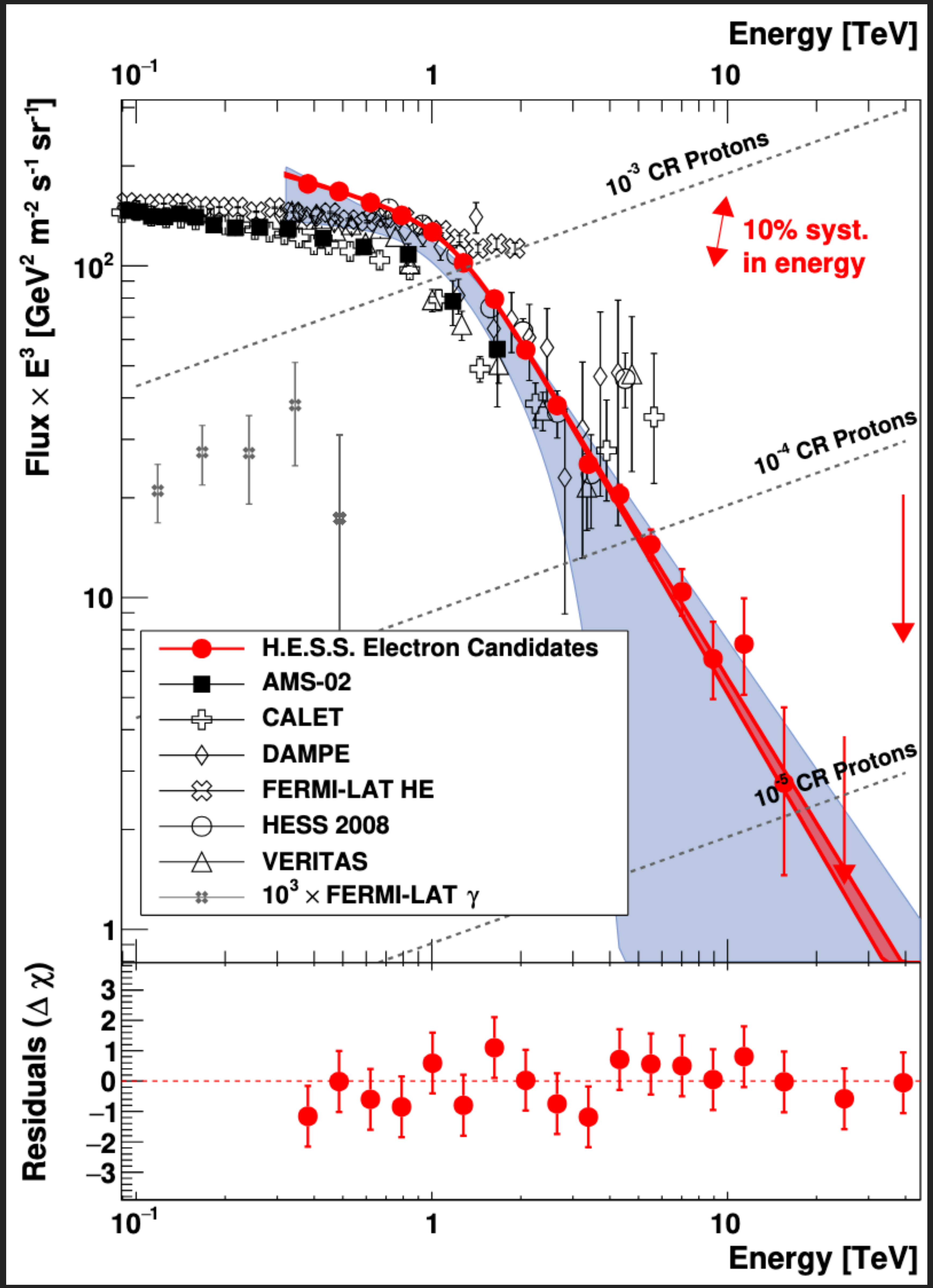
Observations by the High-Energy Stereoscopic System (H.E.S.S.) have recently extended our detection of the combined electron-plus-positron (hereafter, e^+e^-) flux up to an energy of 40 TeV. The e^+e^- flux has a sharp



TEV HALOS: AN ESSENTIAL SOURCE CLASS

- H.E.S.S. e+e- flux falls off rapidly above a TeV.
- Strongly constrains contribution of nearby pulsars.
- No spectral features – no evidence of a cutoff from a single dominant pulsar source.

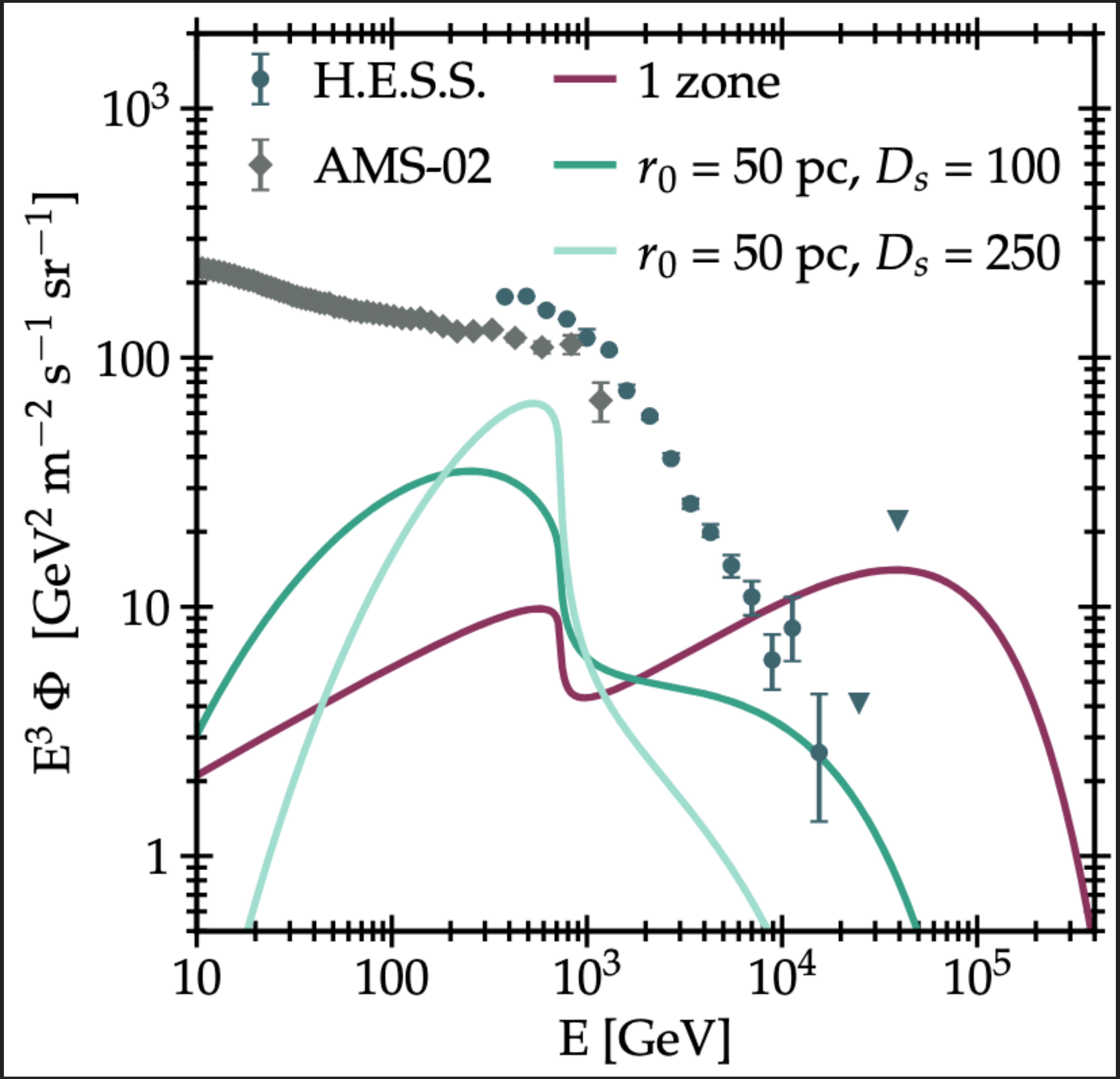
H.E.S.S.. Collaboration (2024; 2411.08981)



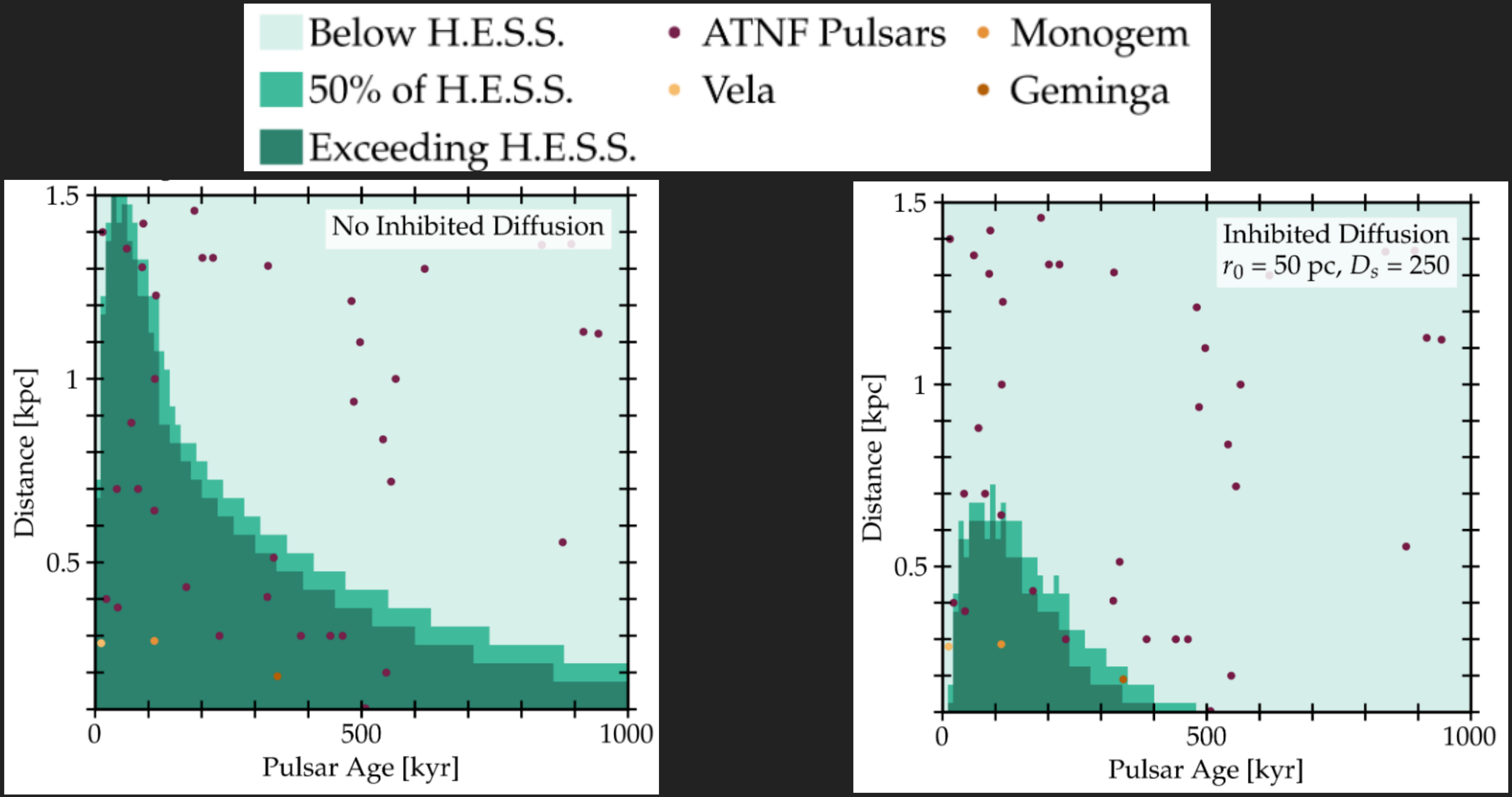
TEV HALOS: AN ESSENTIAL SOURCE CLASS

- Any "Geminga-like" pulsar near the Earth would overproduce H.E.S.S. data by itself.

- Inhibiting diffusion moves the flux to lower energies, where it does not exceed AMS-02 data.



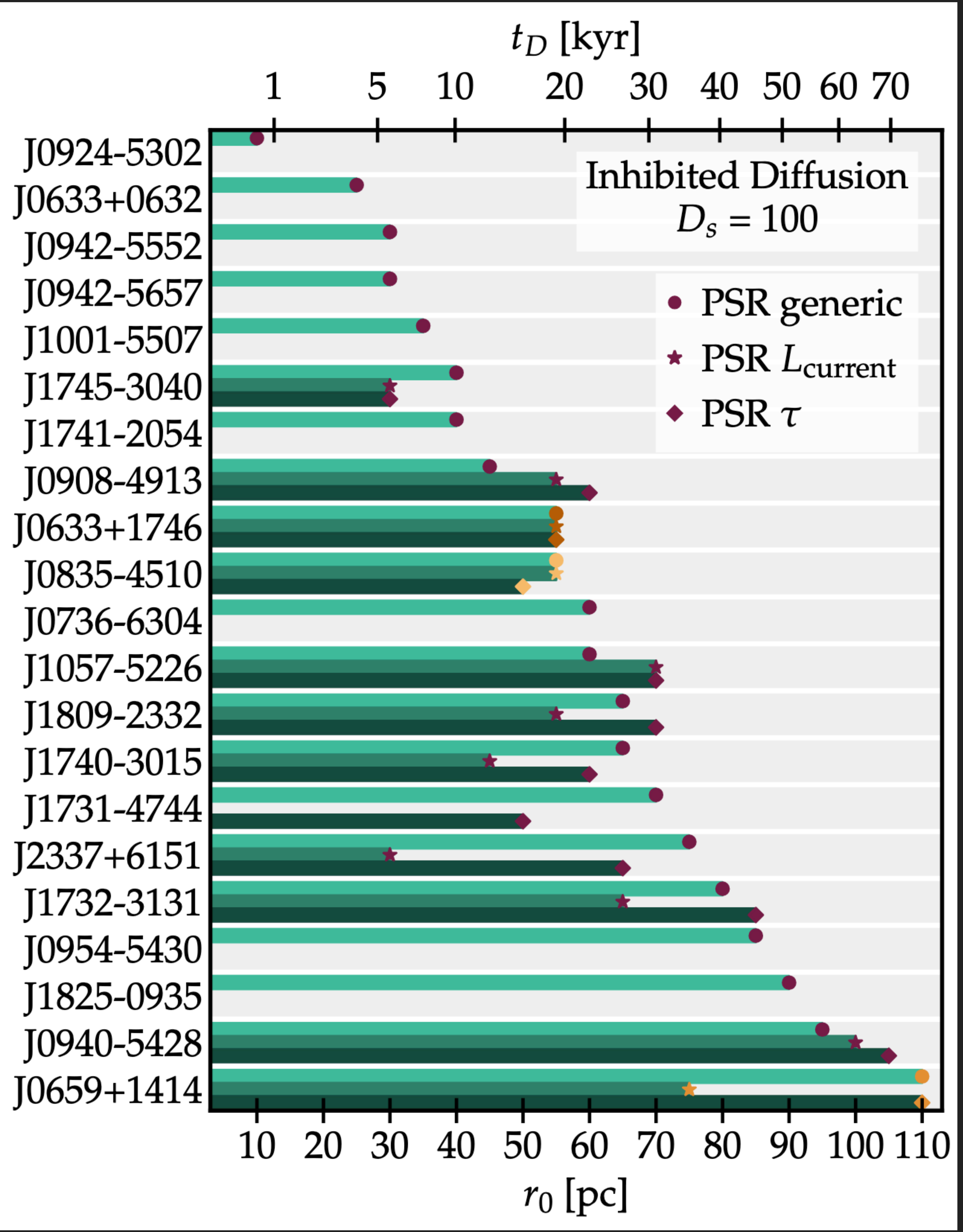
TEV HALOS: AN ESSENTIAL SOURCE CLASS



TEV HALOS: AN ESSENTIAL SOURCE CLASS

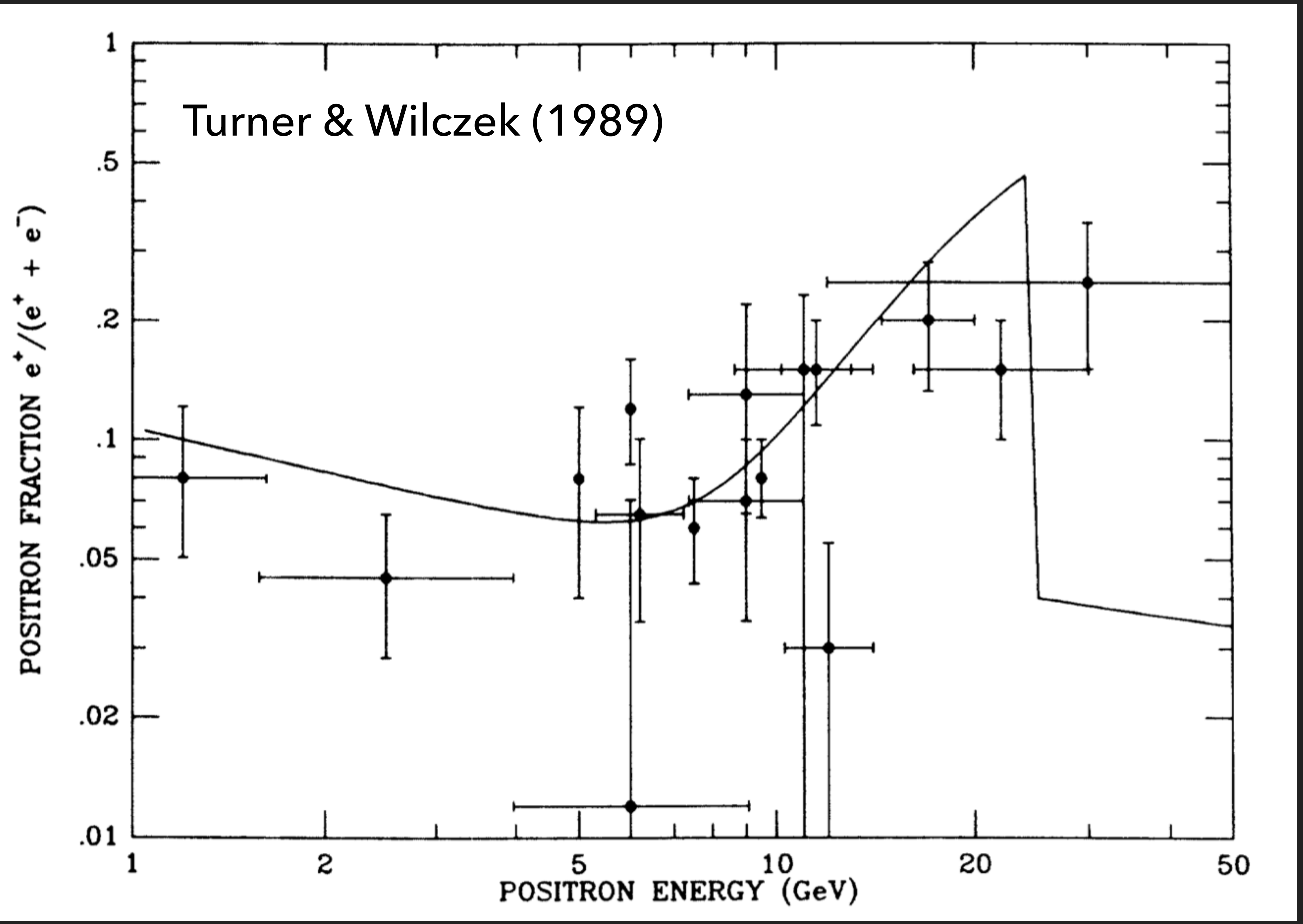
- This is somewhat optimistic, as Geminga has a relatively high spin-down power for its age.

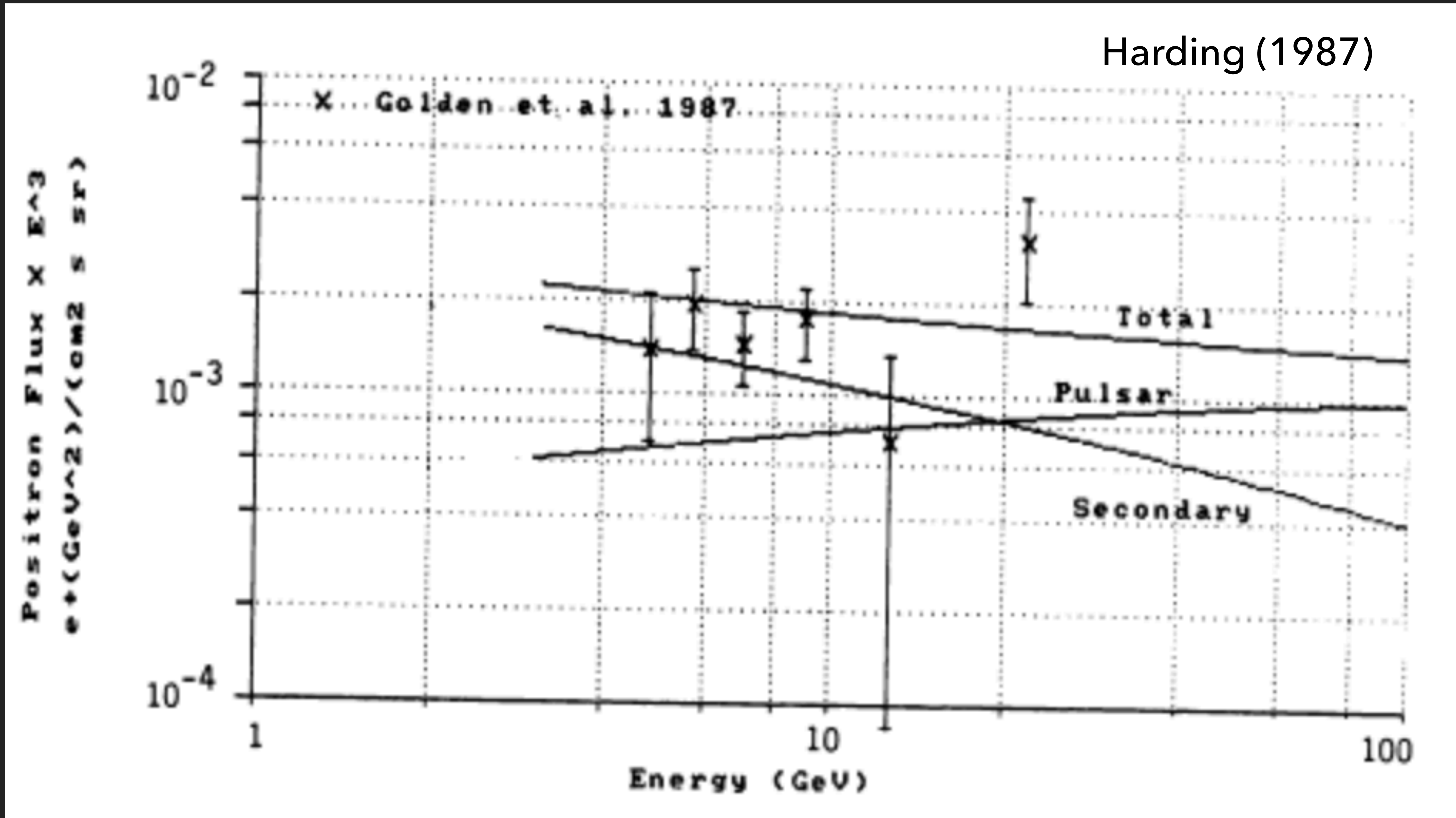
- However, re-scaling the results to the individual spin down power of each pulsar still leaves 11 systems that individually overproduce H.E.S.S. data.




OPPORTUNITY
AHEAD

IMPLICATION 1: THE POSITRON EXCESS





IMPLICATION 1: THE POSITRON EXCESS

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

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

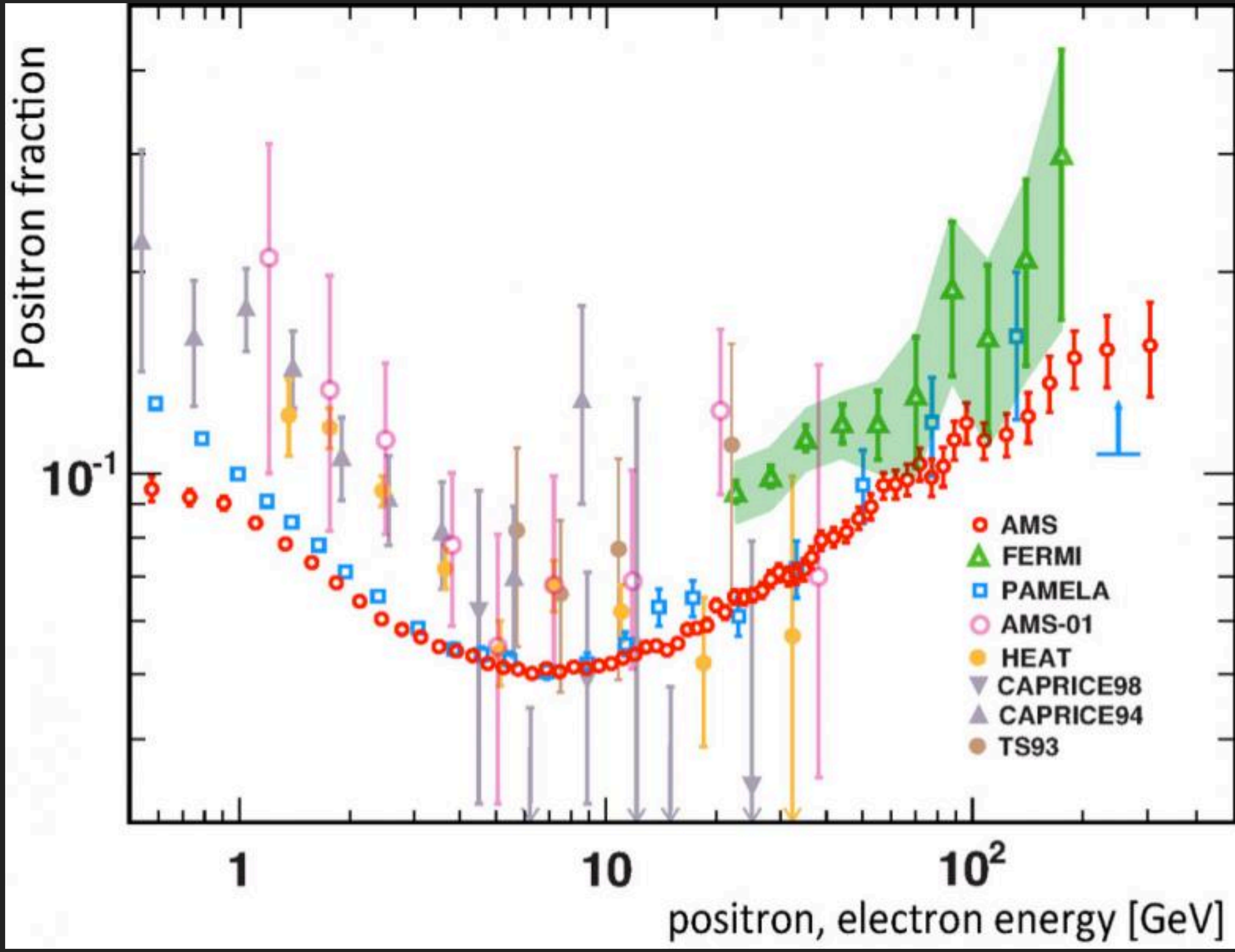
Profumo (0812.4457); Malyshev et al. (0903.1310)

%. 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)

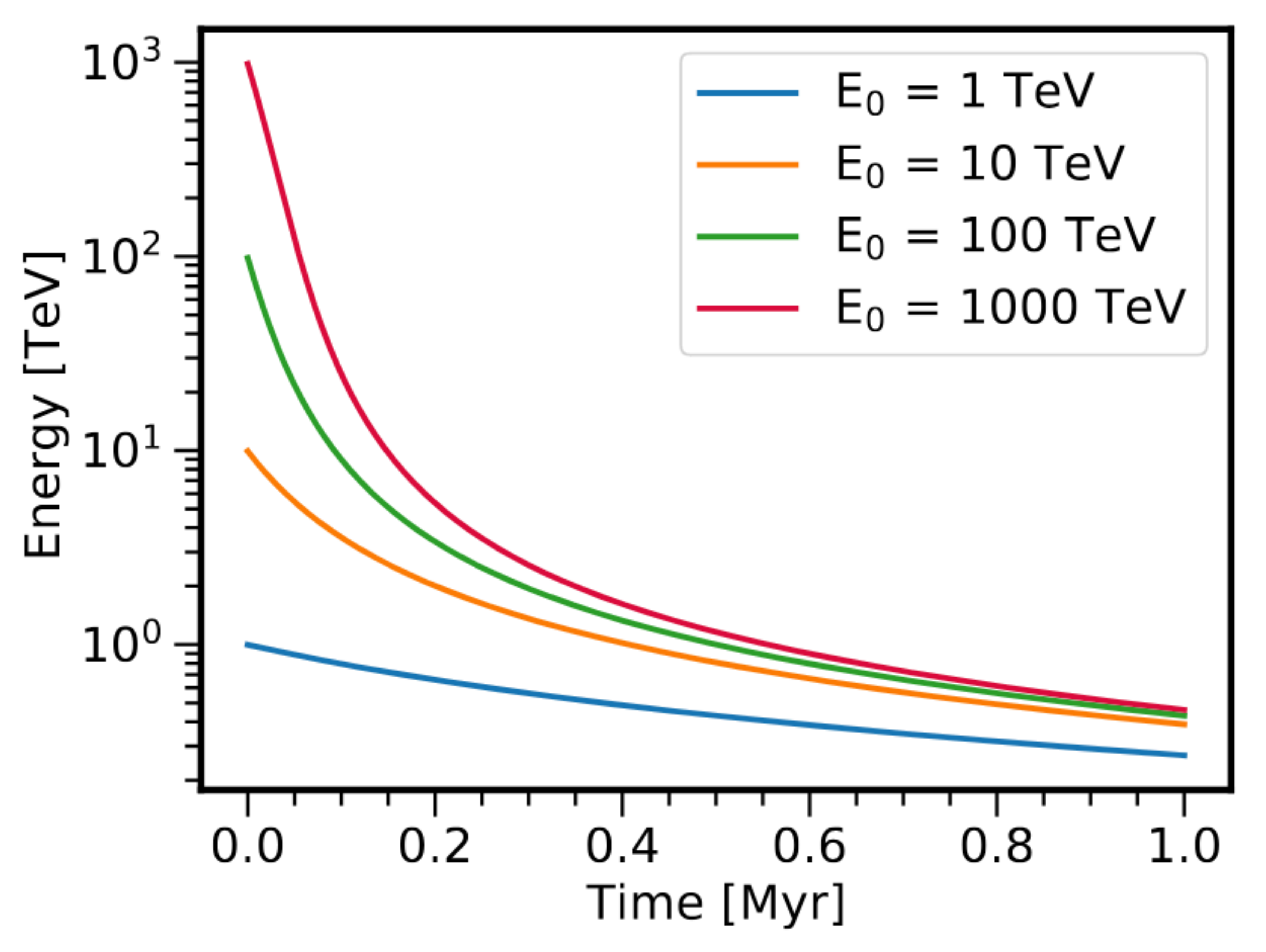
part of their energy adiabatically because of the expansion of the wind. The energy spectrum injected by a single pulsar depends on the environmental parameters of the pulsar, but some attempts to calculate the average spectrum injected by a population of mature pulsars suggest that the spectrum may 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 1: THE POSITRON EXCESS

- **While >10 TeV e+e- can be trapped in the halo, GeV electrons live too long:**

$$t_{loss} \approx 320 \text{ kyr} \left(\frac{E}{1 \text{ TeV}}\right)^{-1} \left(\frac{\rho_{\text{tot}}\, S_{\text{eff}}(E)}{1 \text{ eV cm}^{-3}}\right)$$



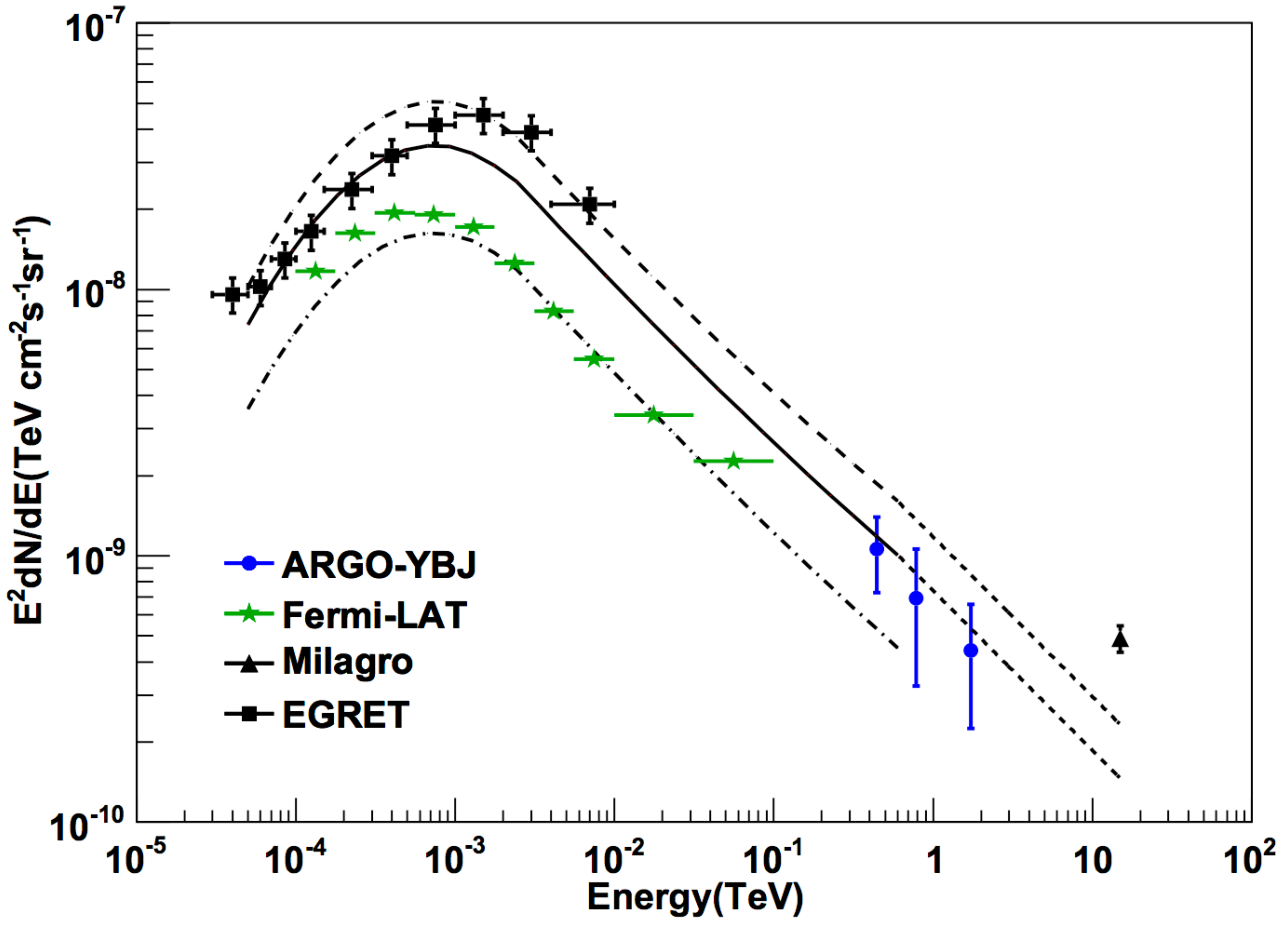
- **These e+e- pairs escape from the source and contribute to the positron flux at Earth.**

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 2: DIFFUSE TEV GAMMA-RAYS

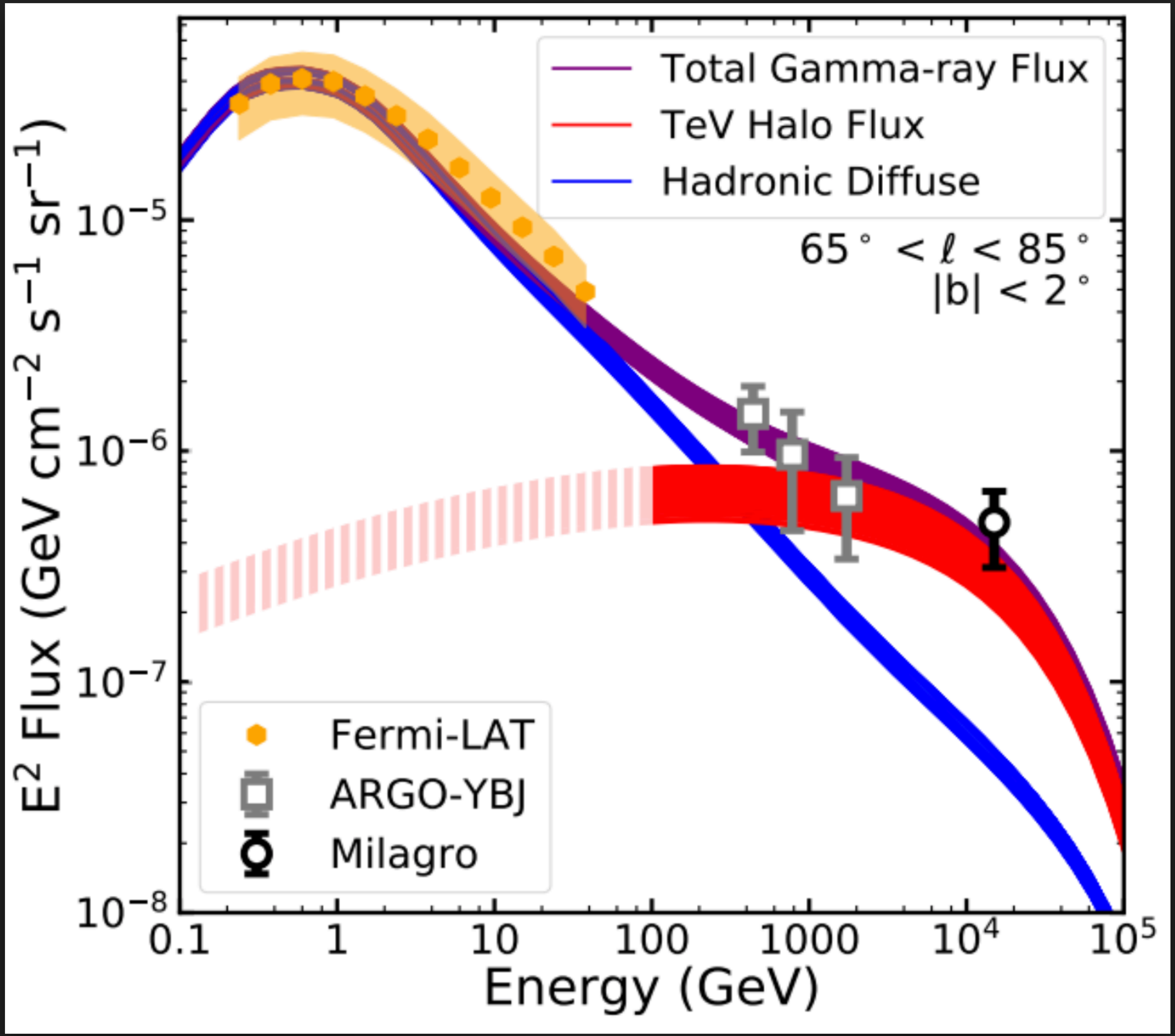


IMPLICATION 2: DIFFUSE TEV GAMMA-RAYS

Linden & Buckman (2017; 1707.01905)

- 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



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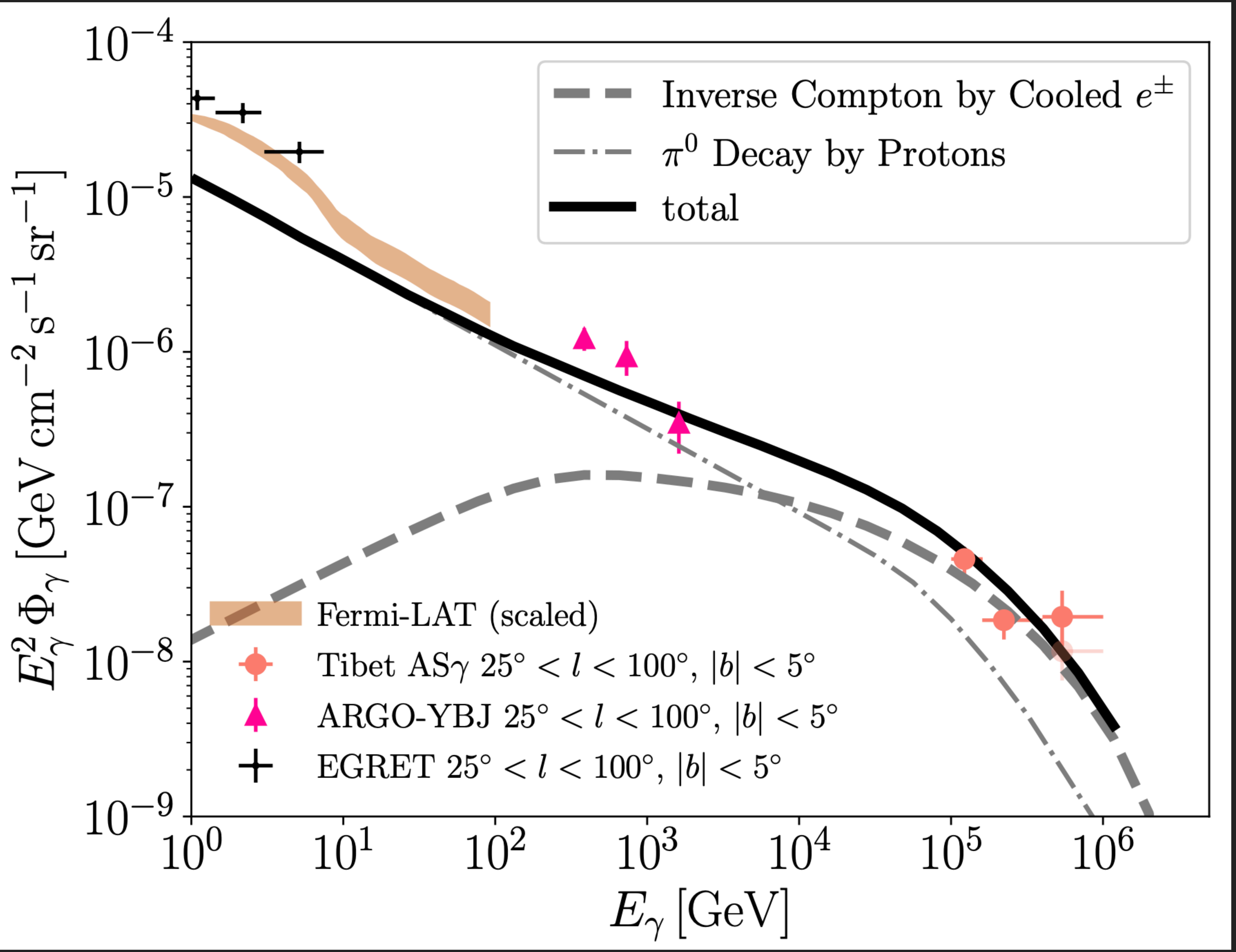
Fang & Murase (2021; 2104.09491)



Tibet ASγ data

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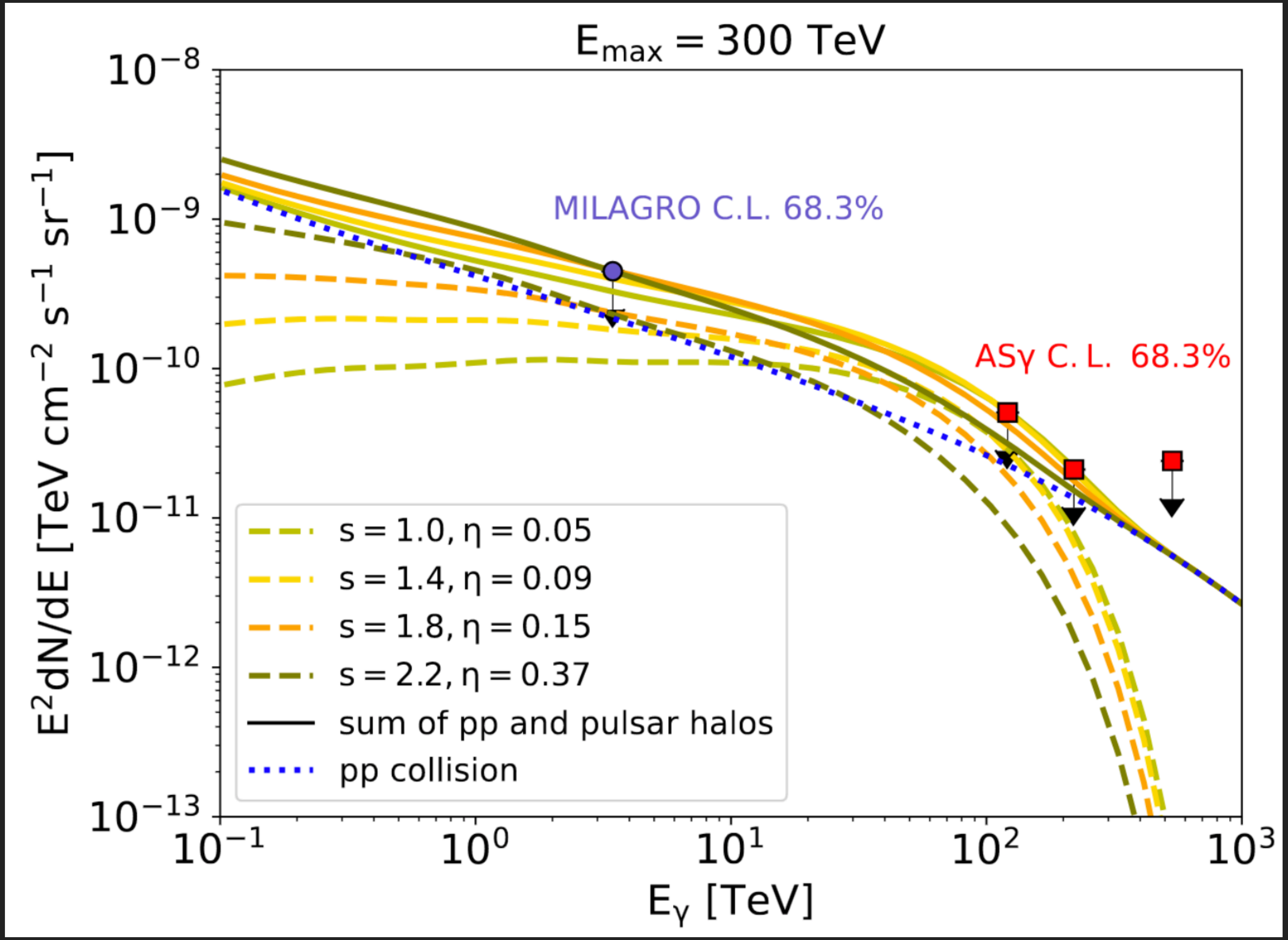
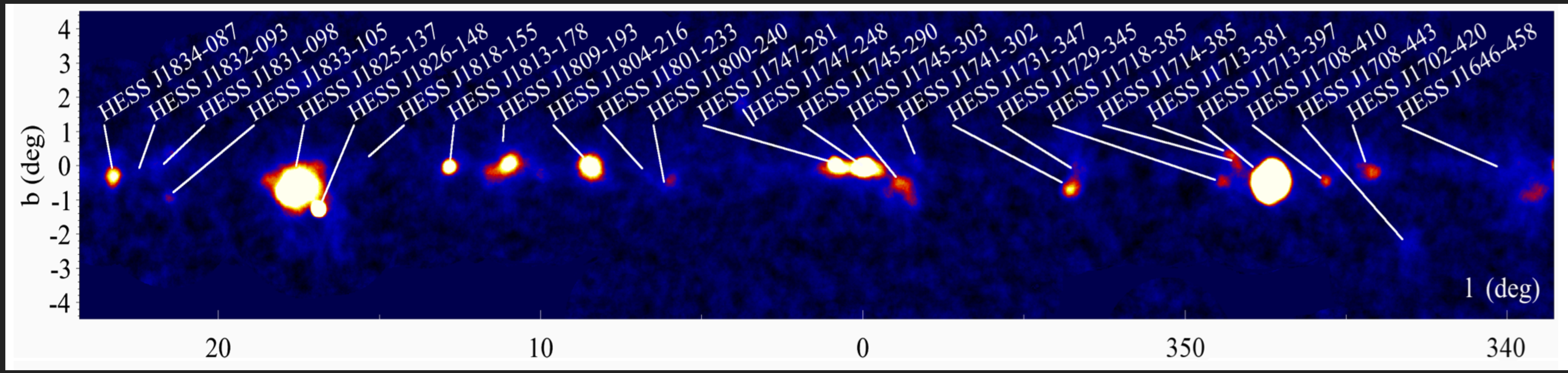
Yan & Liu (2023; 2304.12574)



LHAASO Data

IMPLICATION 3: MOST TEV SOURCES ARE POWERED BY PULSARS

- Radio pulsars are beamed!



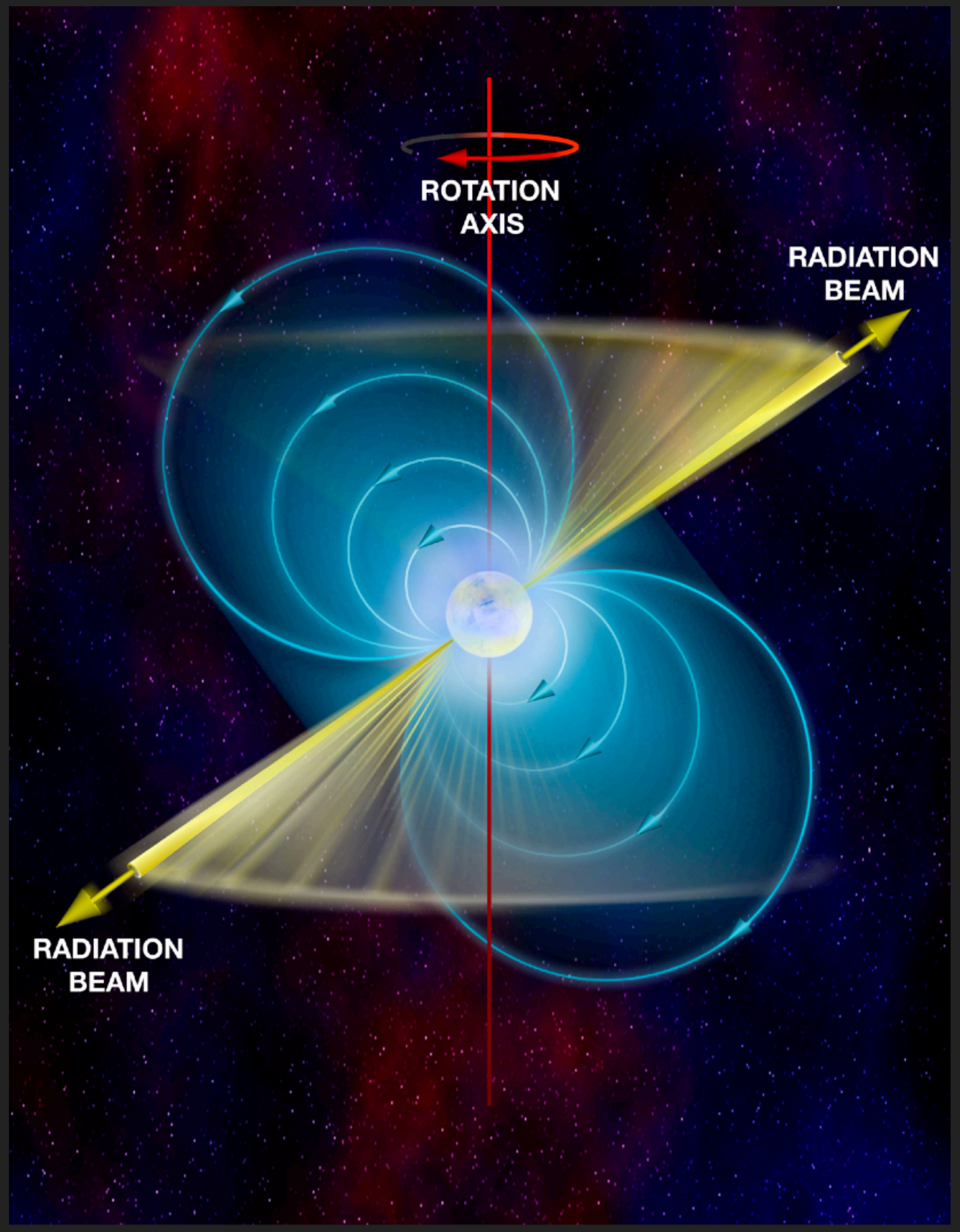
- Beaming fraction is small

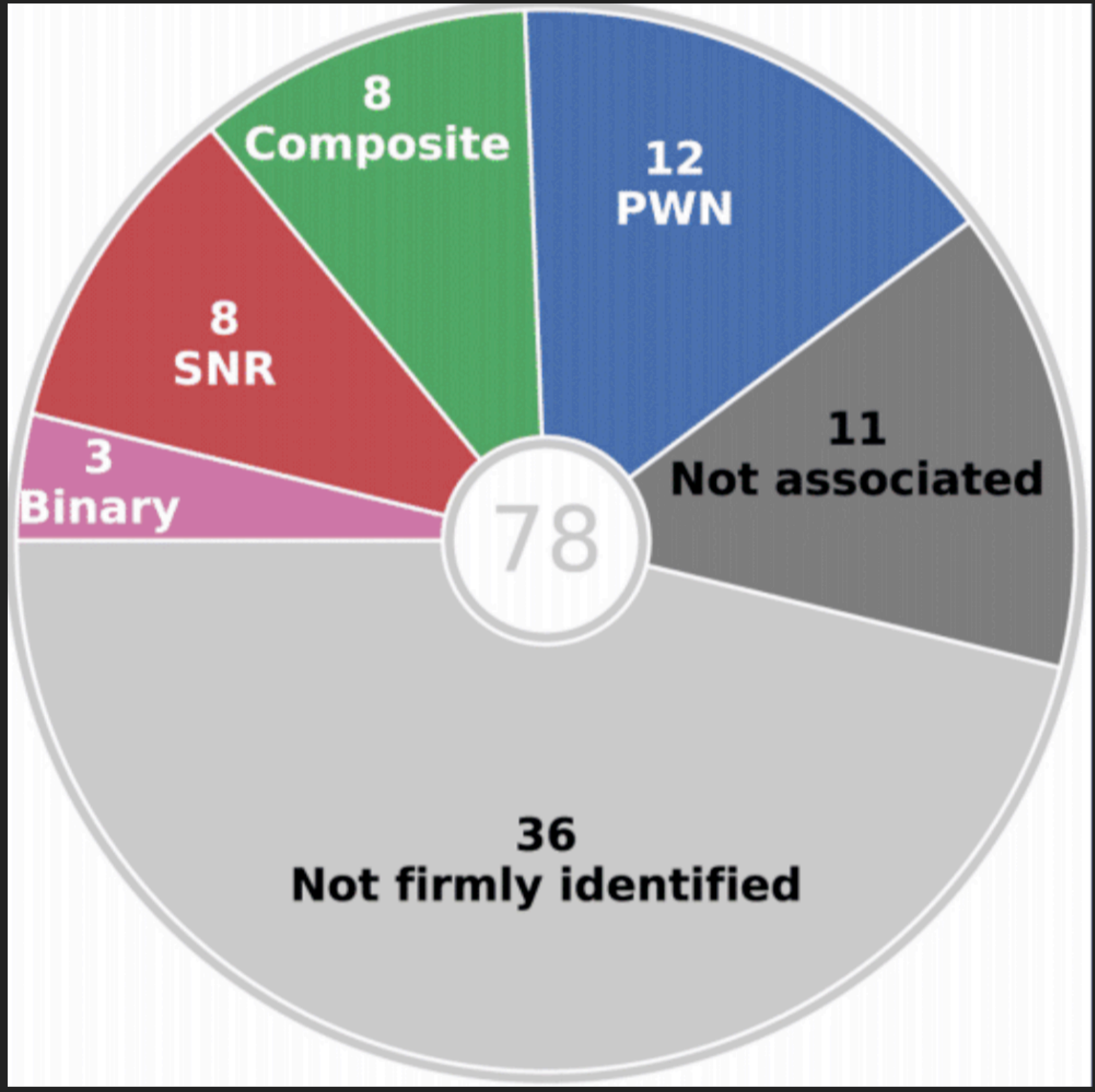
Tauris & Manchester (1998)

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

- This varies between 15-30%.

- Most pulsars are unseen in radio!





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.

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,§]

[1] *Department of Physics, University of California, 1156 High St. Santa Cruz, CA 95060, United States of America*

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

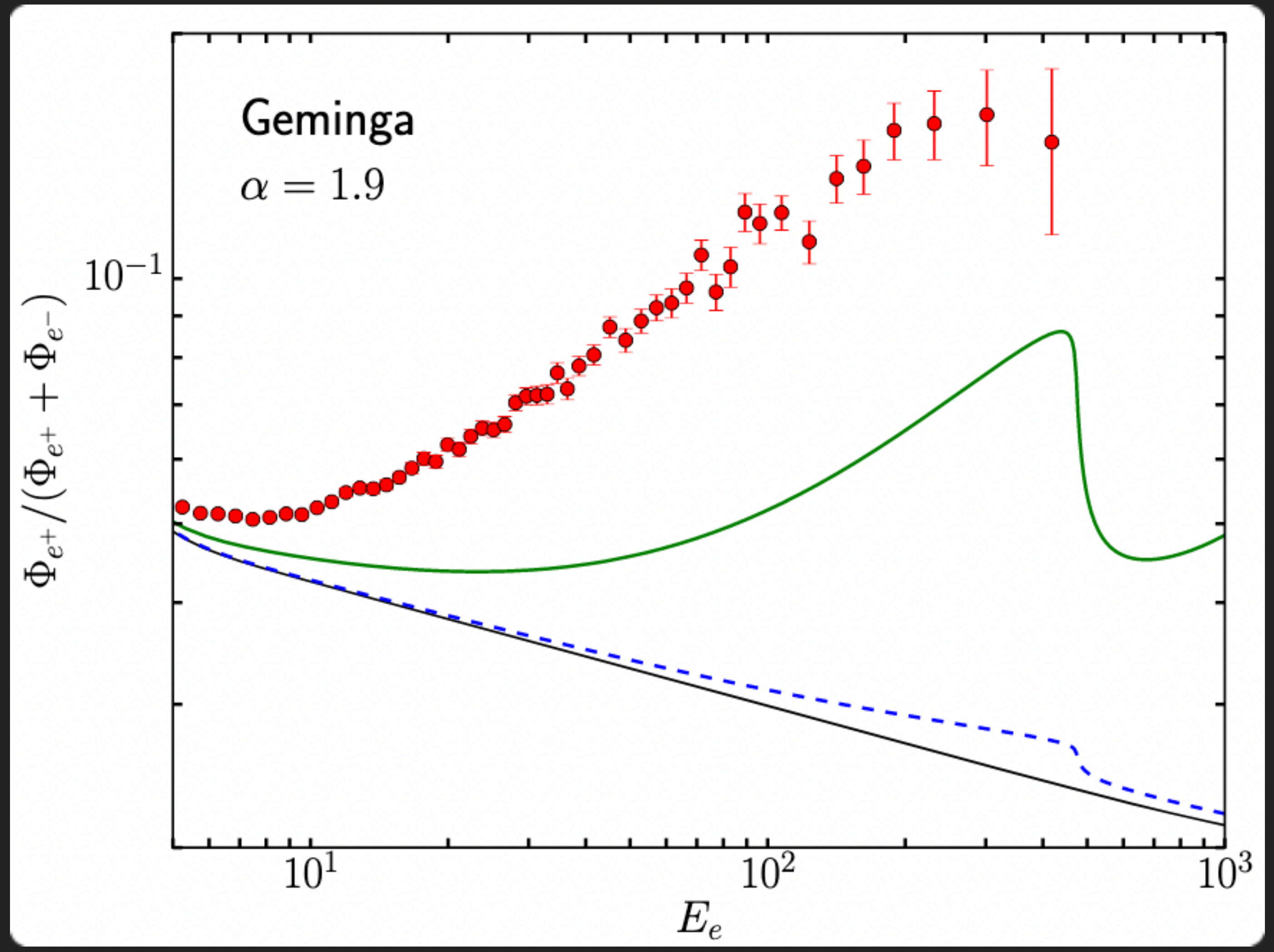
[3] *Departamento de Física, DCI, Campus León, Universidad de Guanajuato, 37150, León, Guanajuato, México*

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.

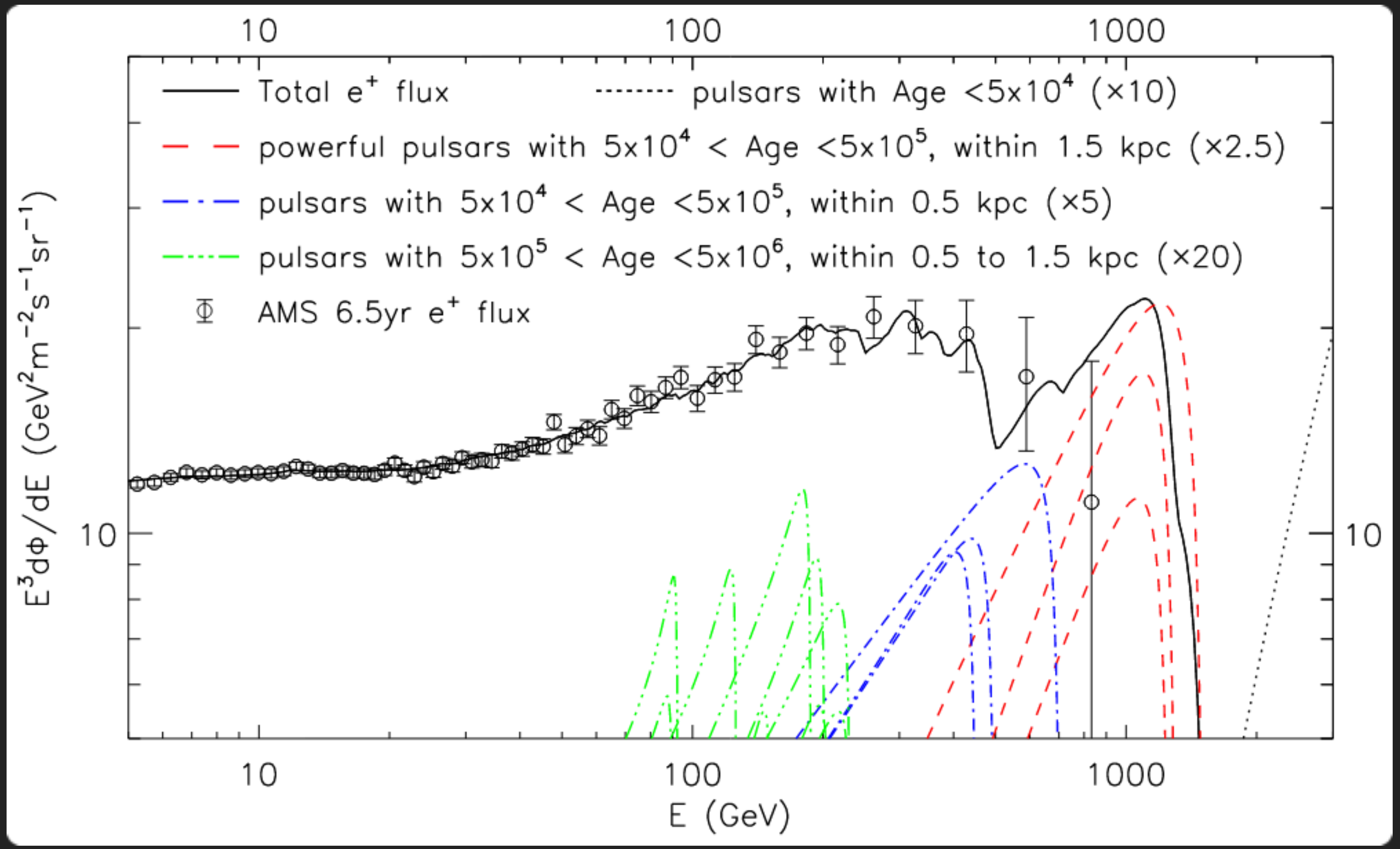
PACS numbers:


BetterCo.

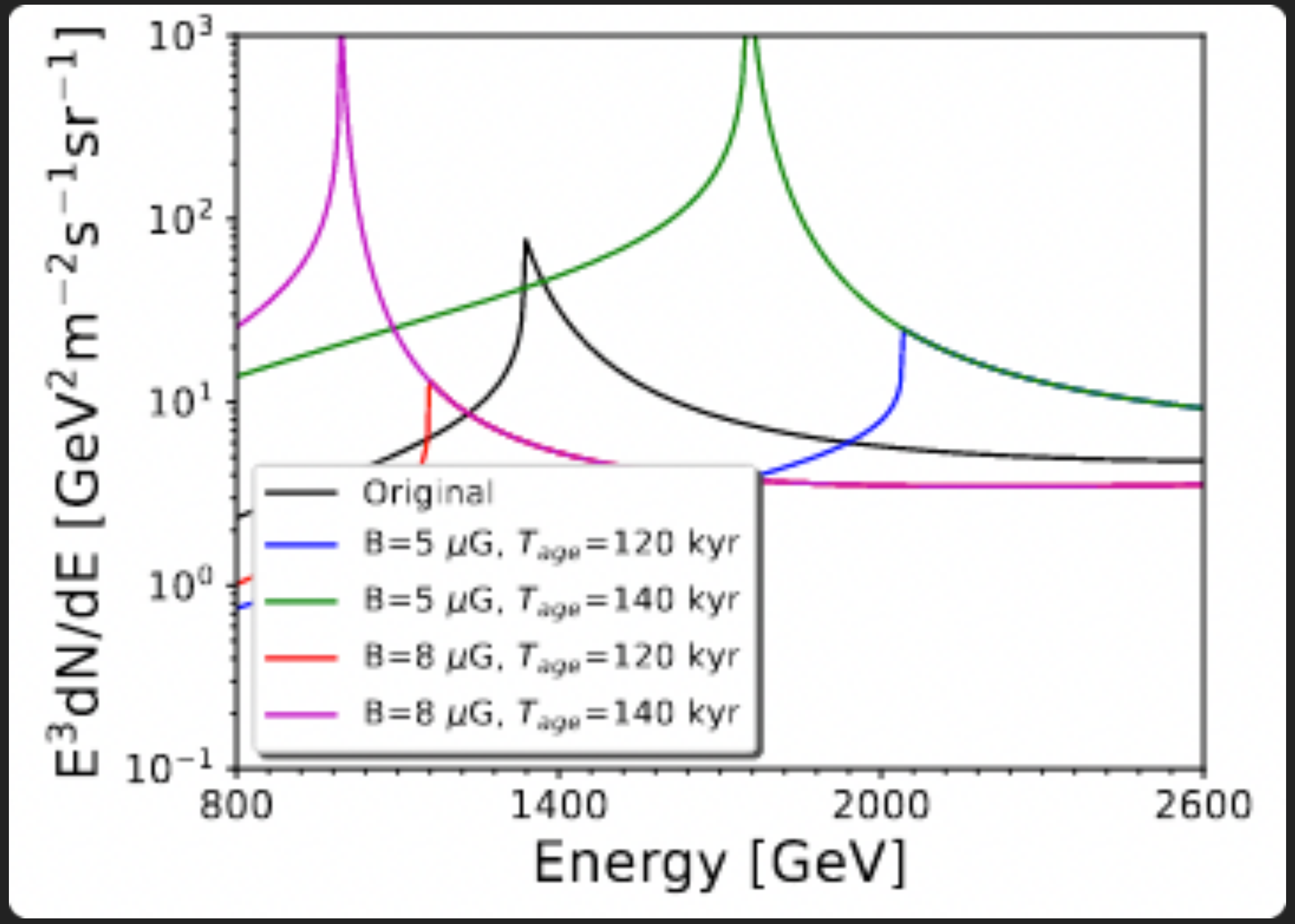
PUZZLE I: THE NUMBER OF PULSARS IN THE POSITRON DATA



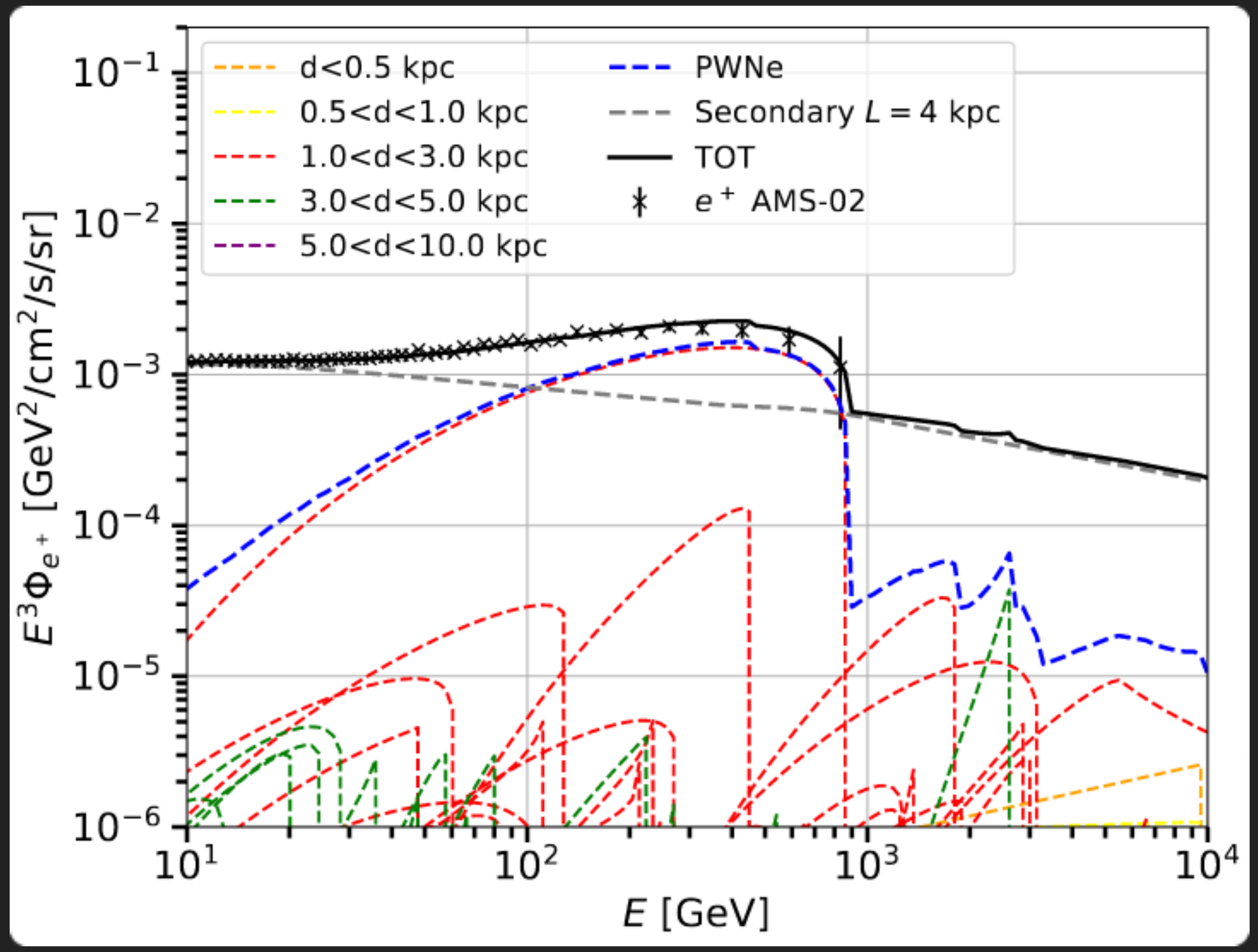
Hooper et al., arXiv:1702.08436



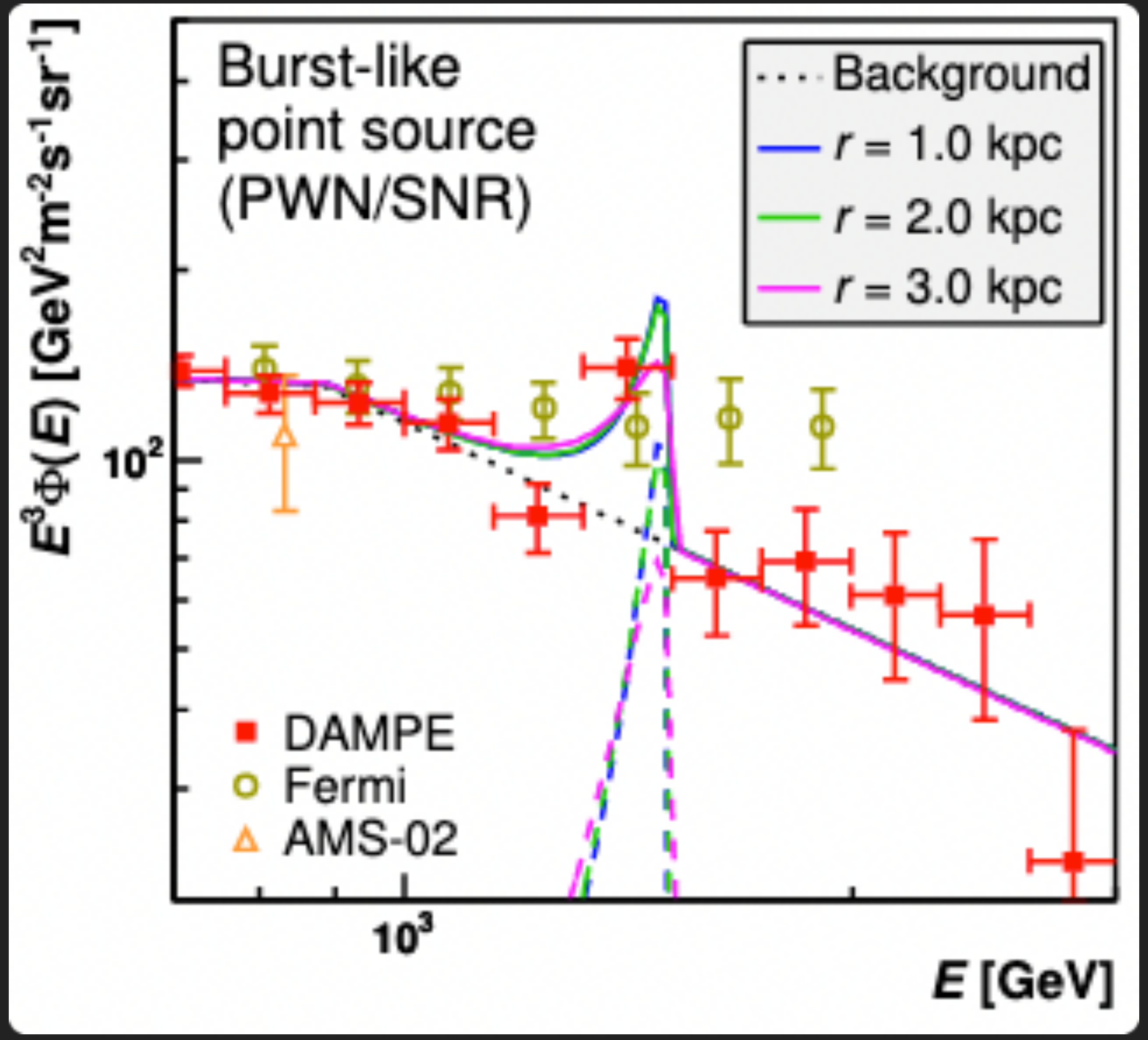
Cholis & Krommydas, arXiv:2111.05864



Bao et al., arXiv:2010.12170



Orusa et al., arXiv:2107.06300

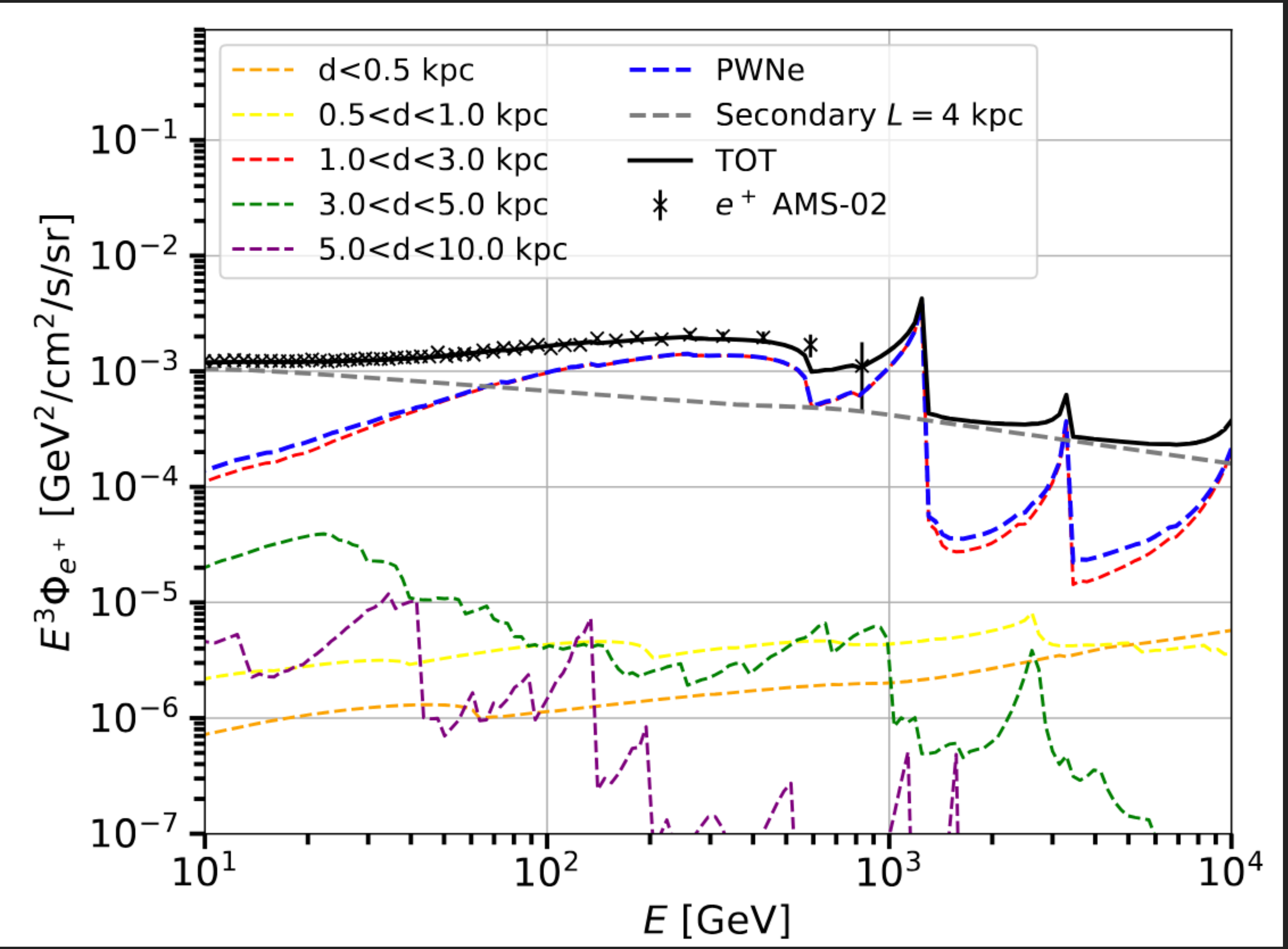


Huang et al., arXiv:1712.00005

Slide courtesy of Isabelle John

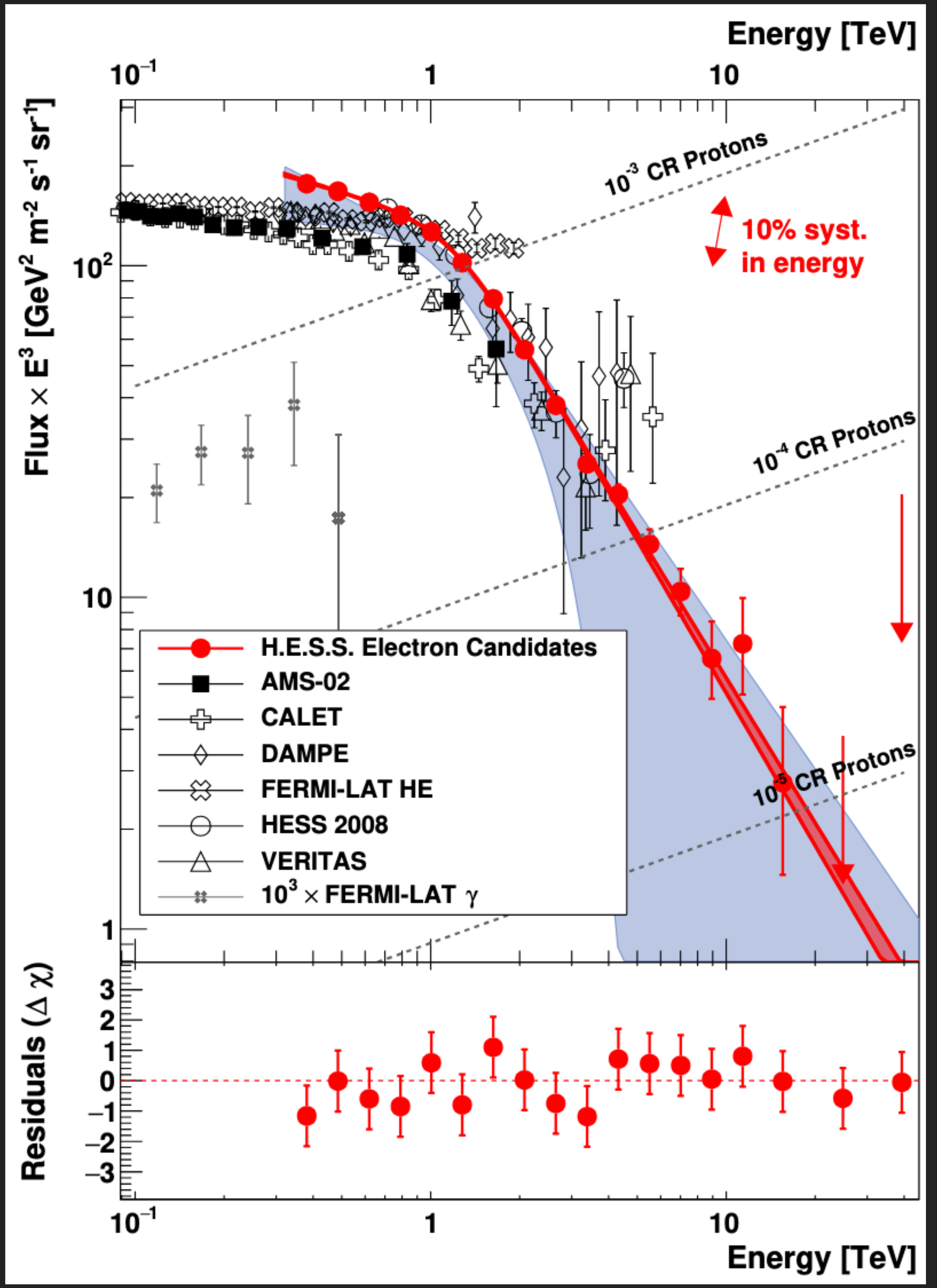
PUZZLE I: THE NUMBER OF PULSARS IN THE POSITRON DATA

- **Debates on the Number of Pulsars**



Orusa et al. (2021; 2107.06300)

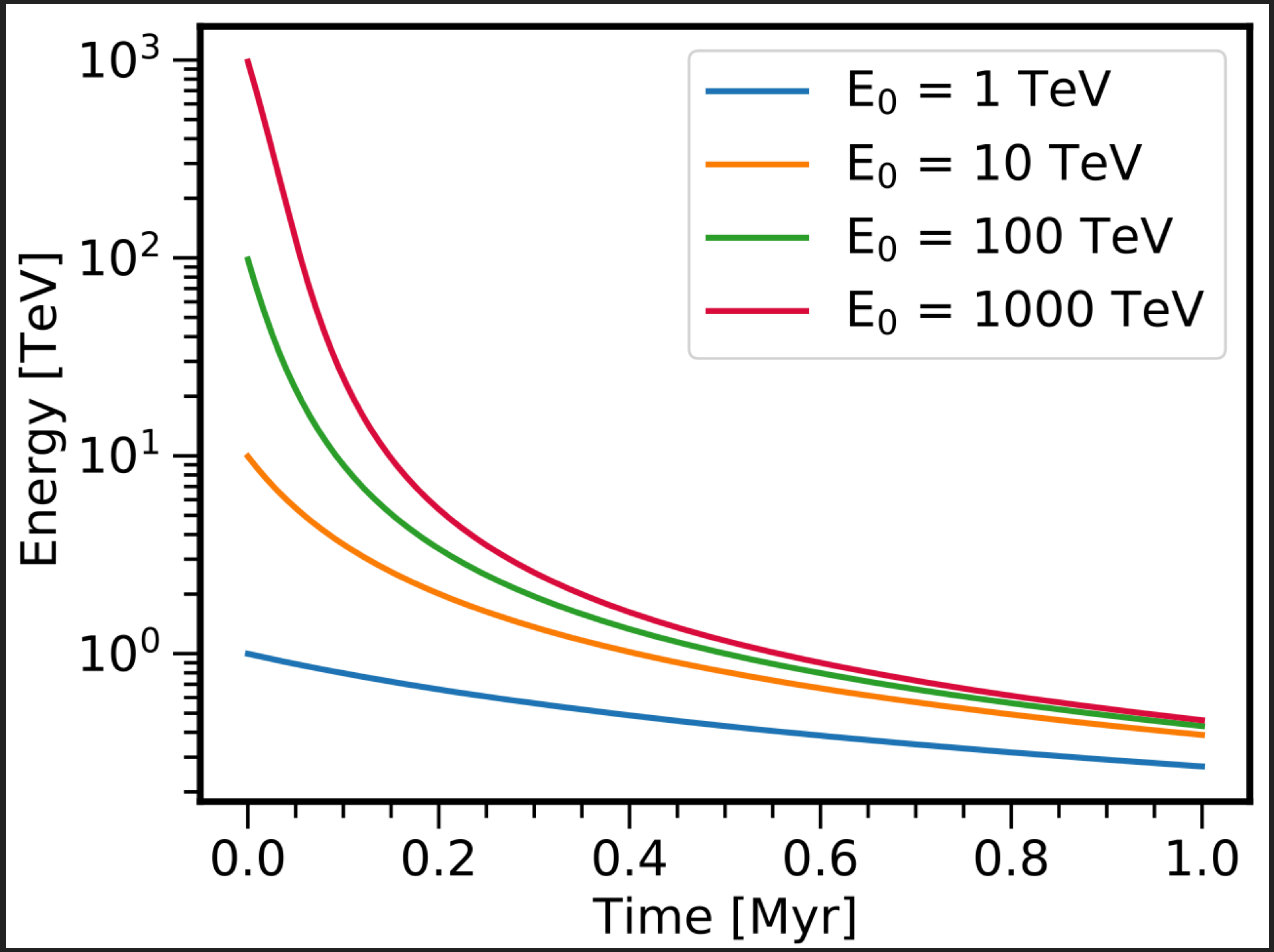
H.E.S.S.. Collaboration (2024; 2411.08981)

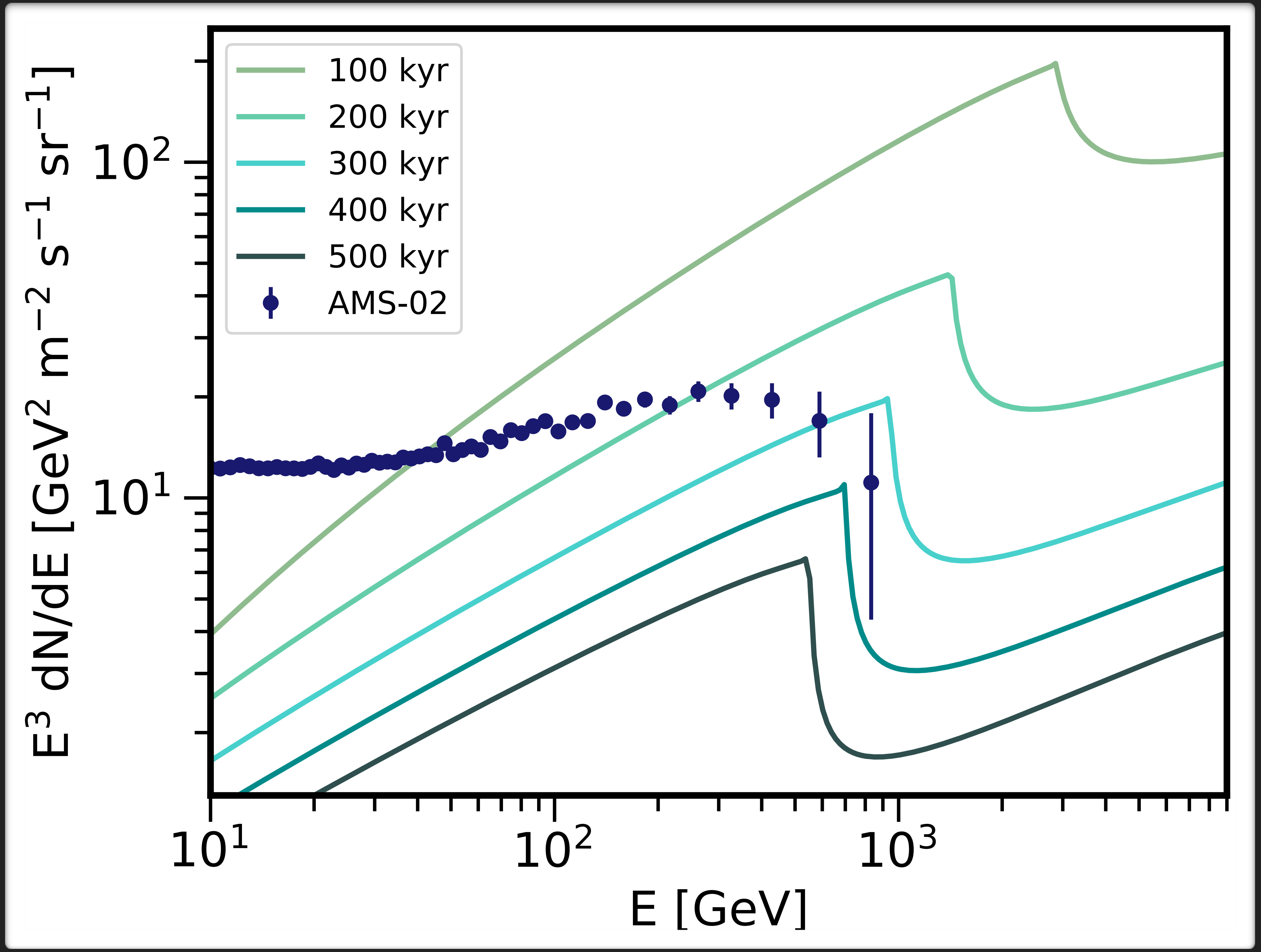


PUZZLE I: THE NUMBER OF PULSARS IN THE POSITRON DATA

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

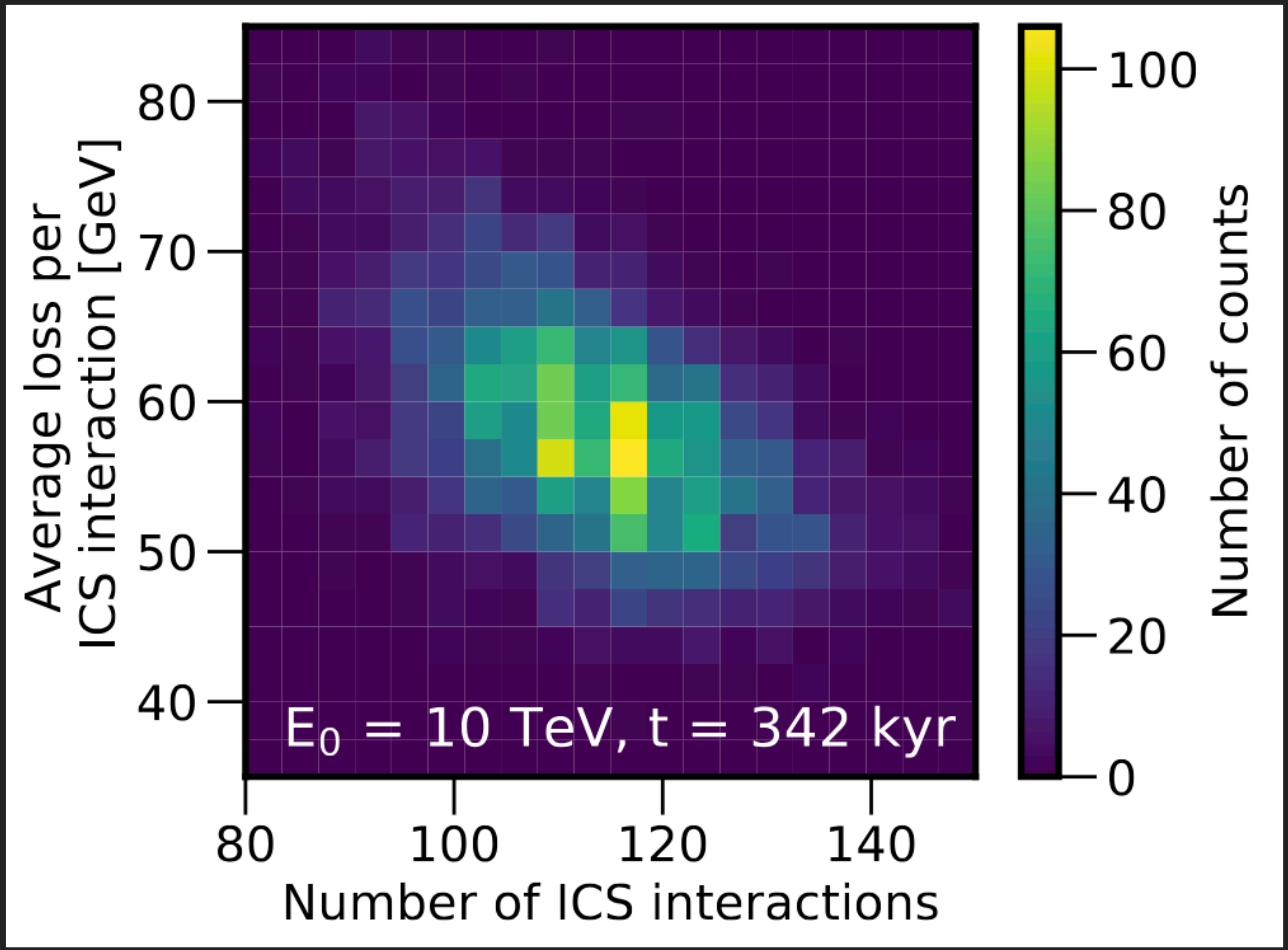
$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T c \left(\frac{E}{m_e}\right)^2 \left[\rho_B + \sum_i \rho_i(\nu_i) S(E,\nu_i)\right]$$

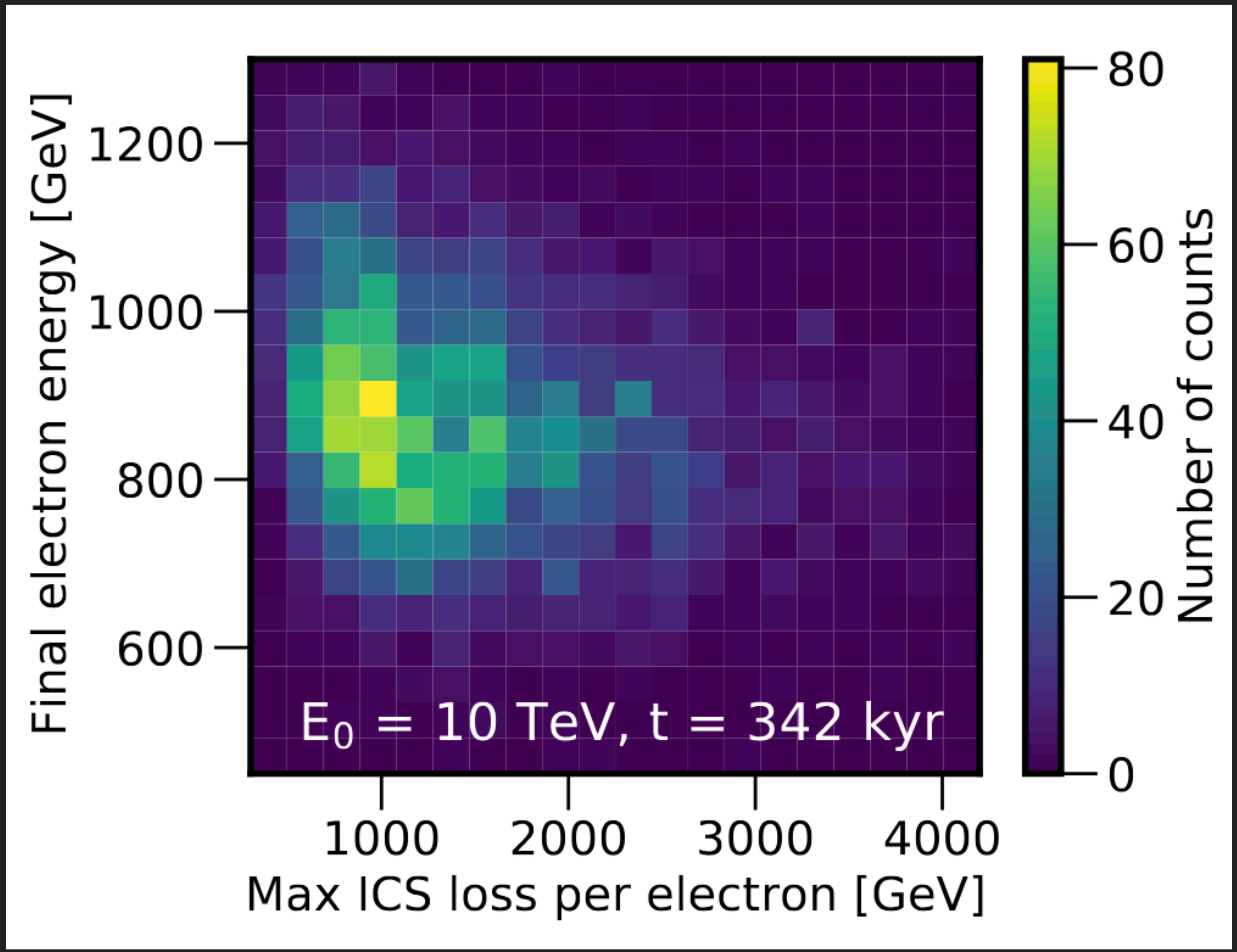




John & Linden (2022; 2206.04699)

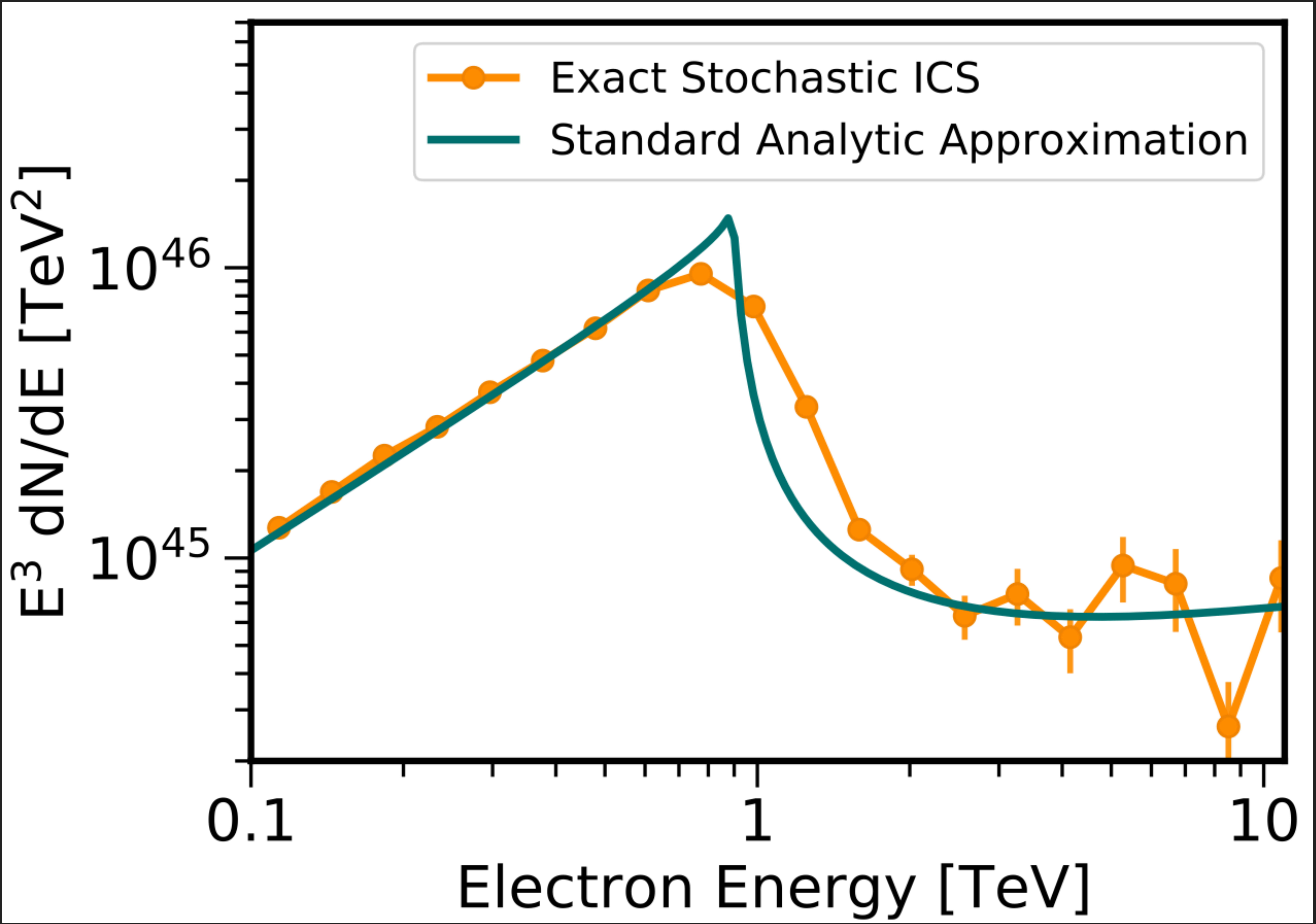
PUZZLE I: THE NUMBER OF PULSARS IN THE POSITRON DATA





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

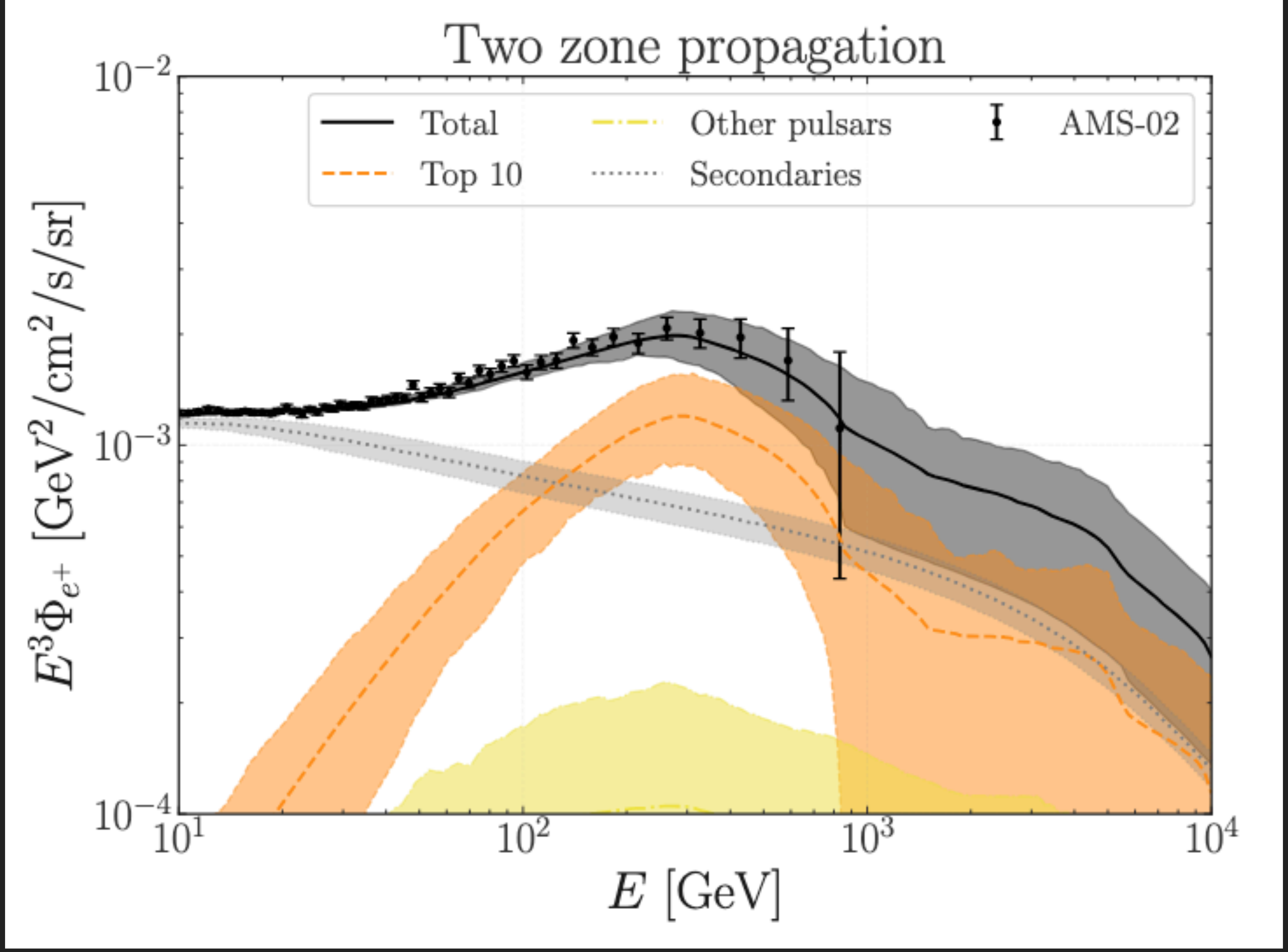
John & Linden (2022; 2206.04699)

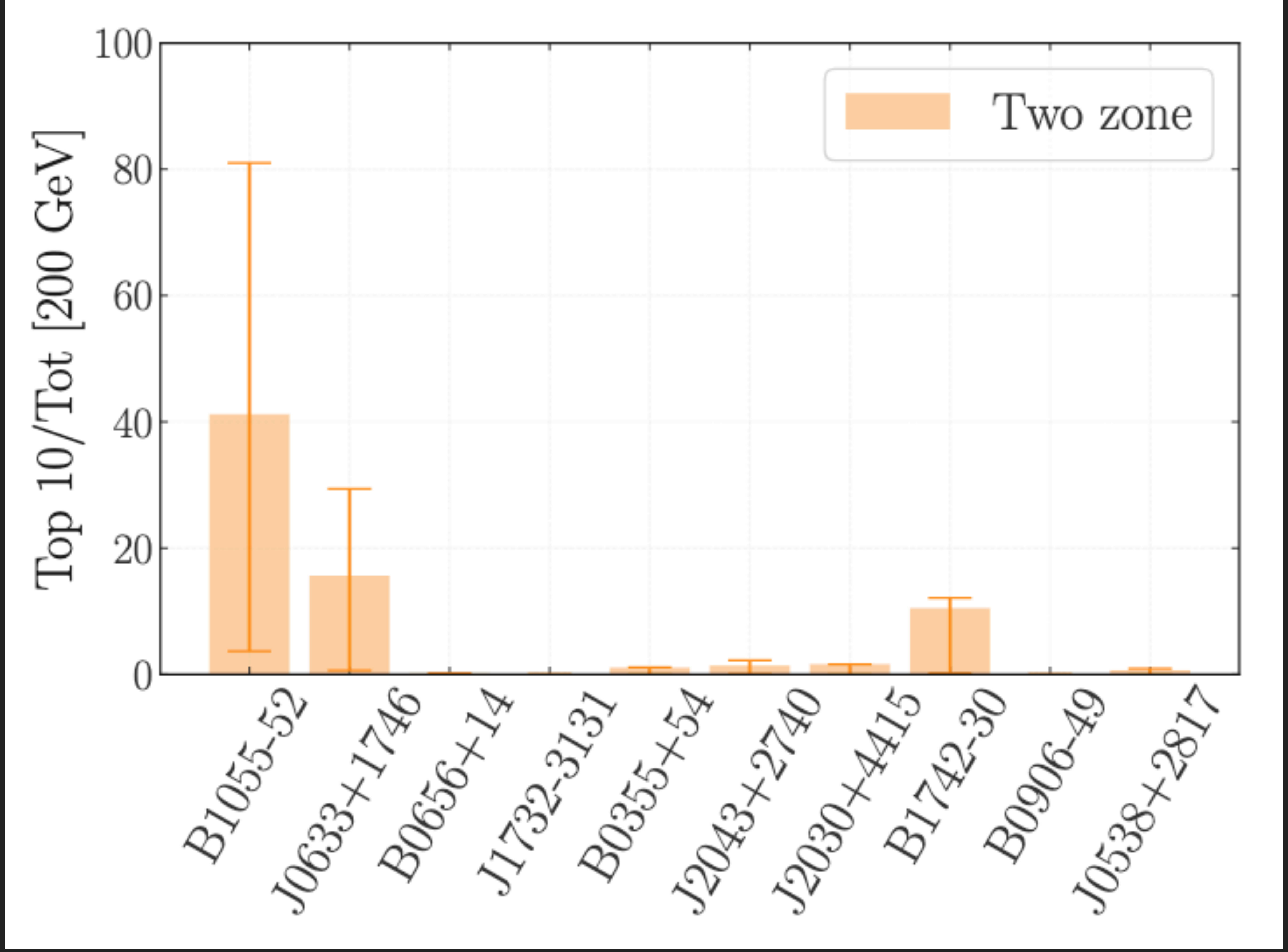


Exact Stochastic ICS
Standard Analytic Approximation
10^{46}
10^{45}
E^3 dN/dE [TeV^2]
0.1
1
10
Electron Energy [TeV]

PUZZLE I: THE NUMBER OF PULSARS IN THE POSITRON DATA

Orusa et al. (2410.10951)



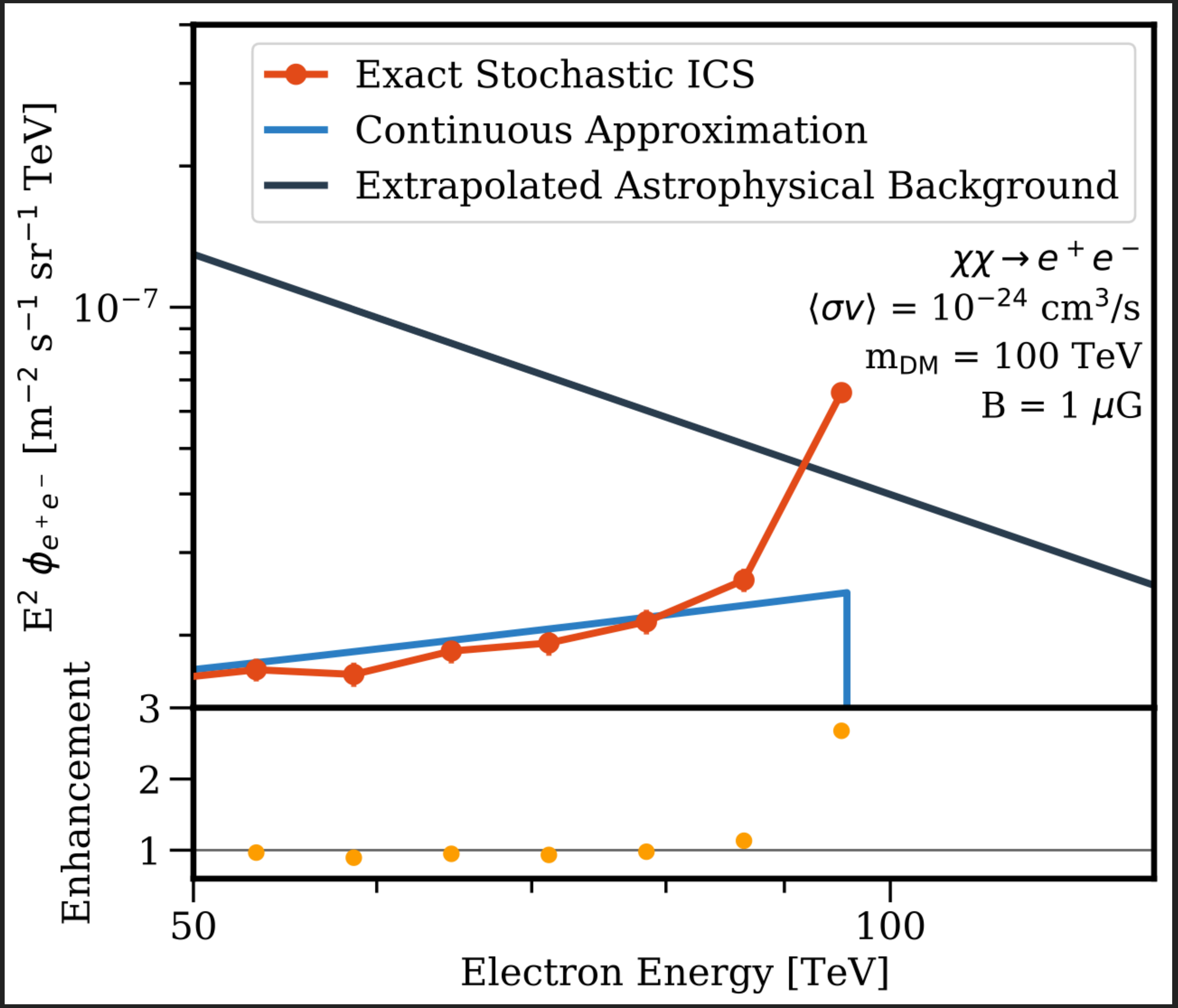


- Energetic models indicate that only a few nearby pulsars dominate the total e+e- flux.

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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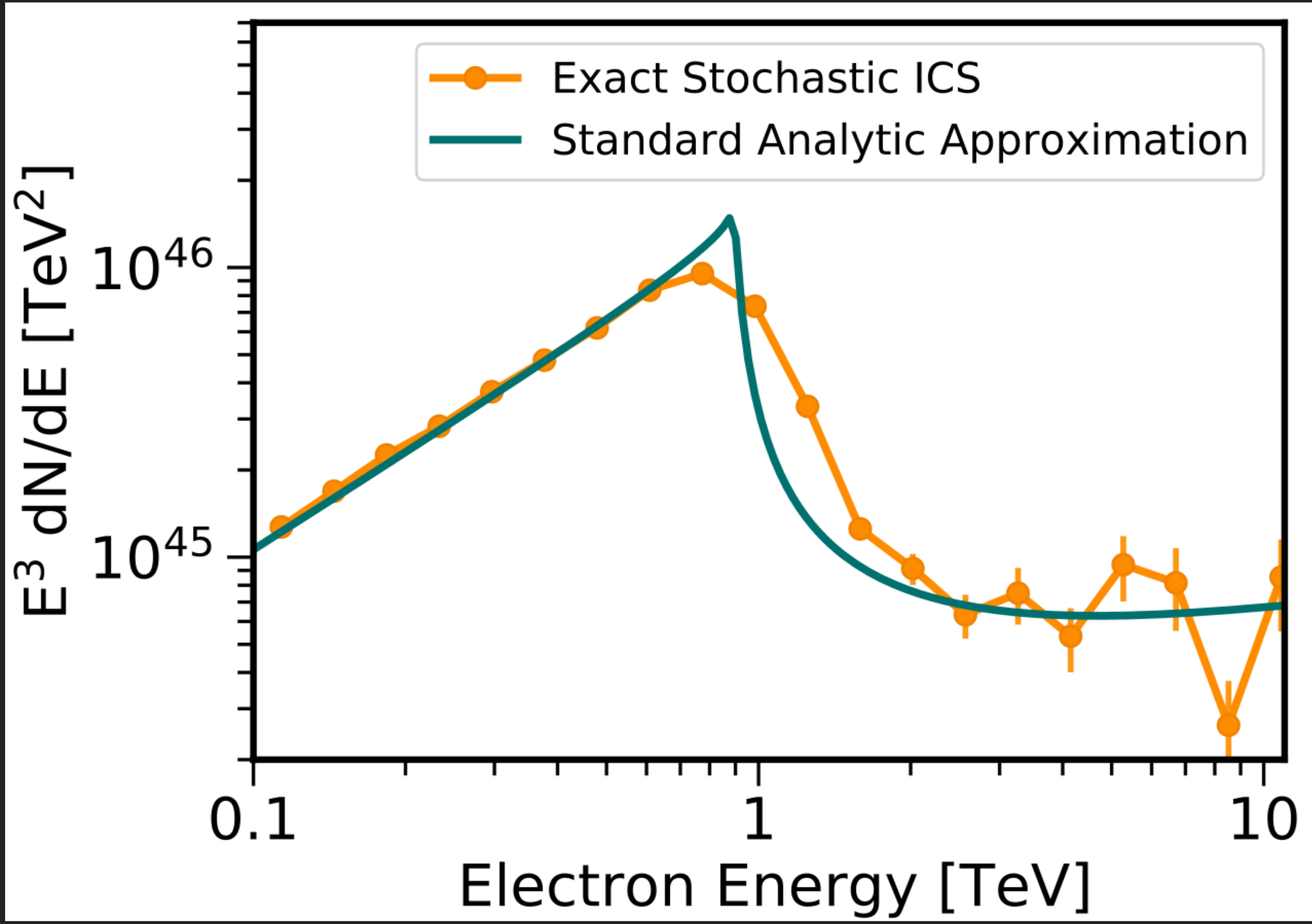

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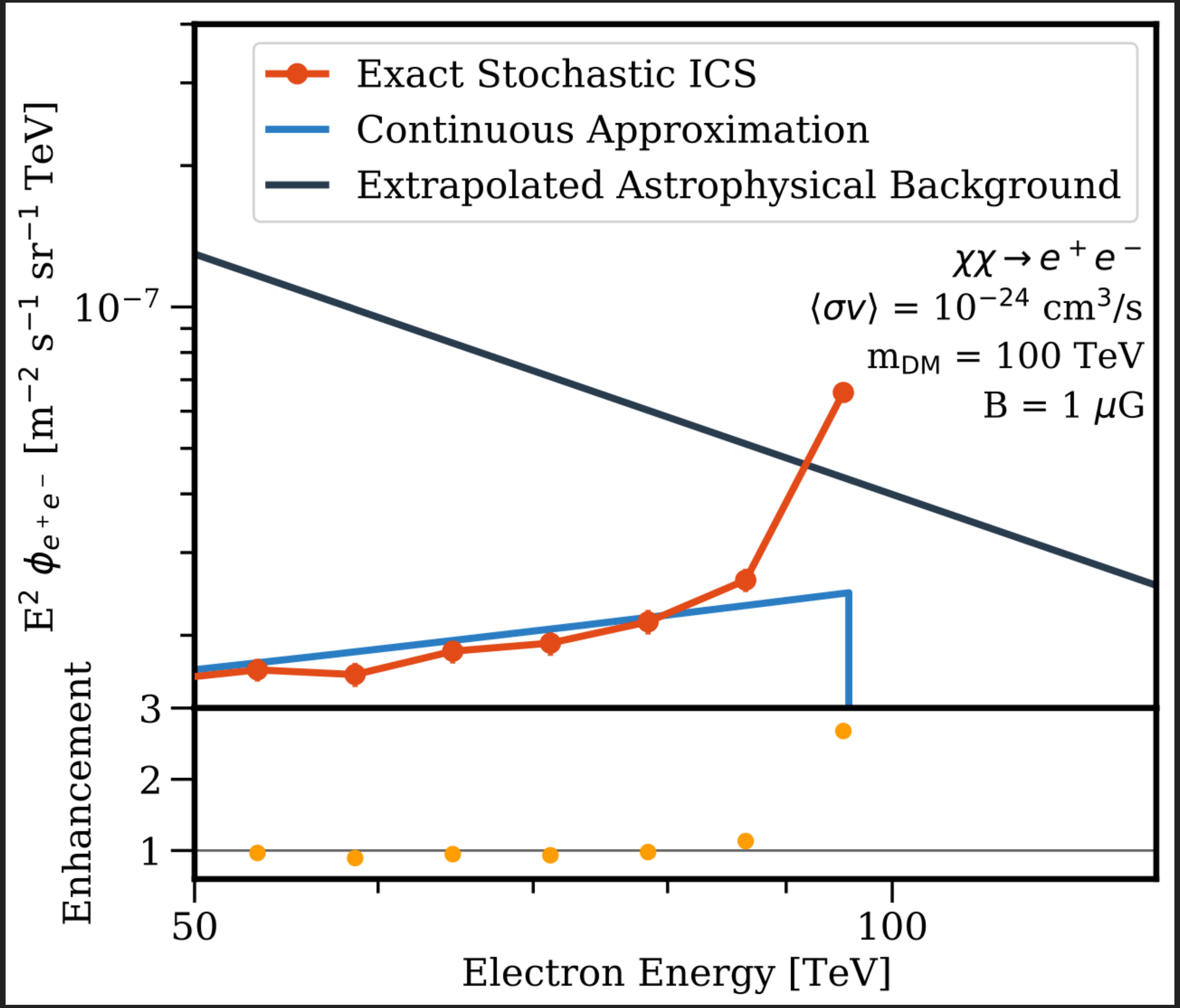
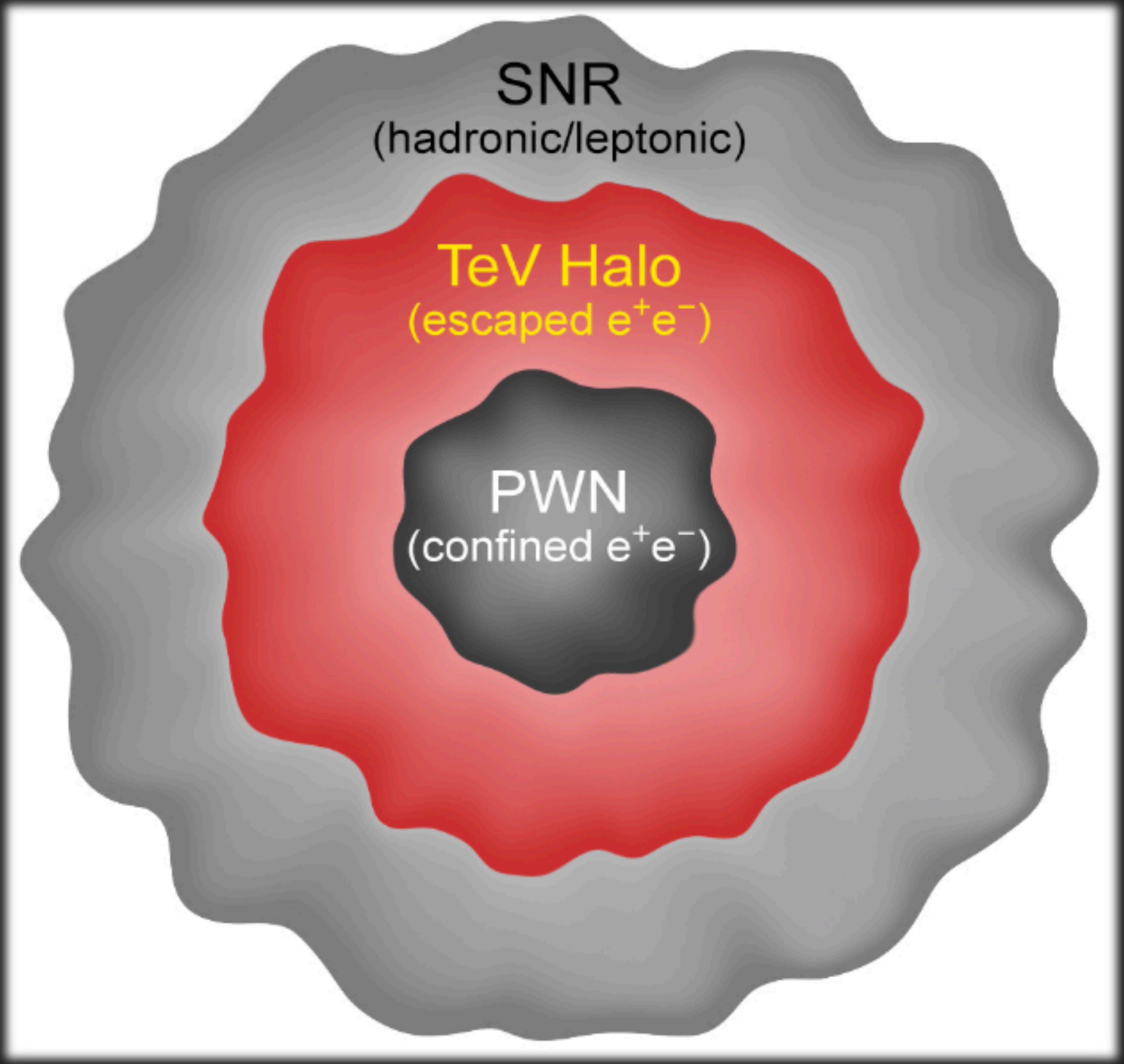
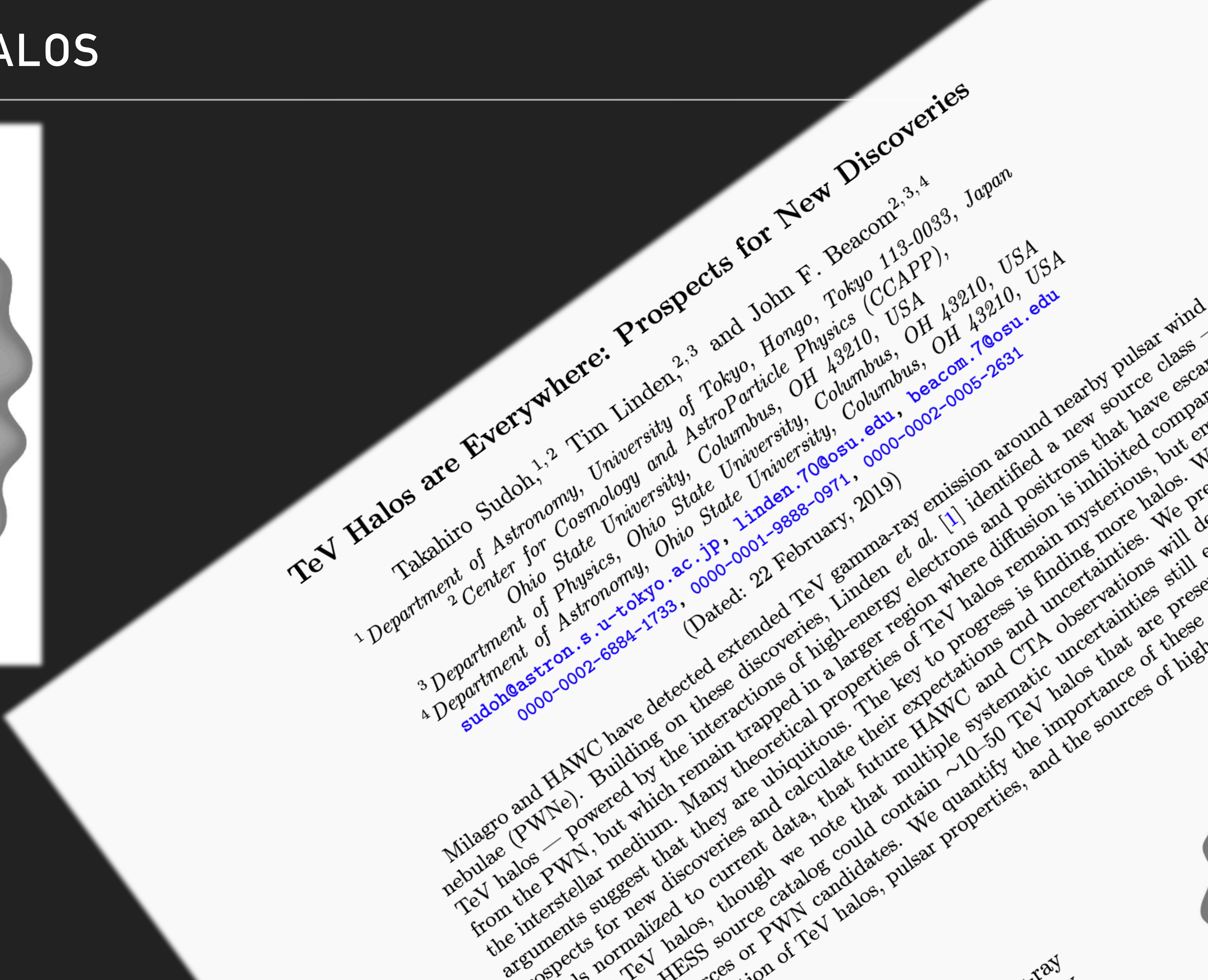


John & Linden (2023; 2304.07317)

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]

[1] Department of Astronomy, University of Tokyo, Hongo, Tokyo 113-0033, Japan
[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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sudoh@astron.s.u-tokyo.ac.jp, linden.70@osu.edu, beacom.7@osu.edu
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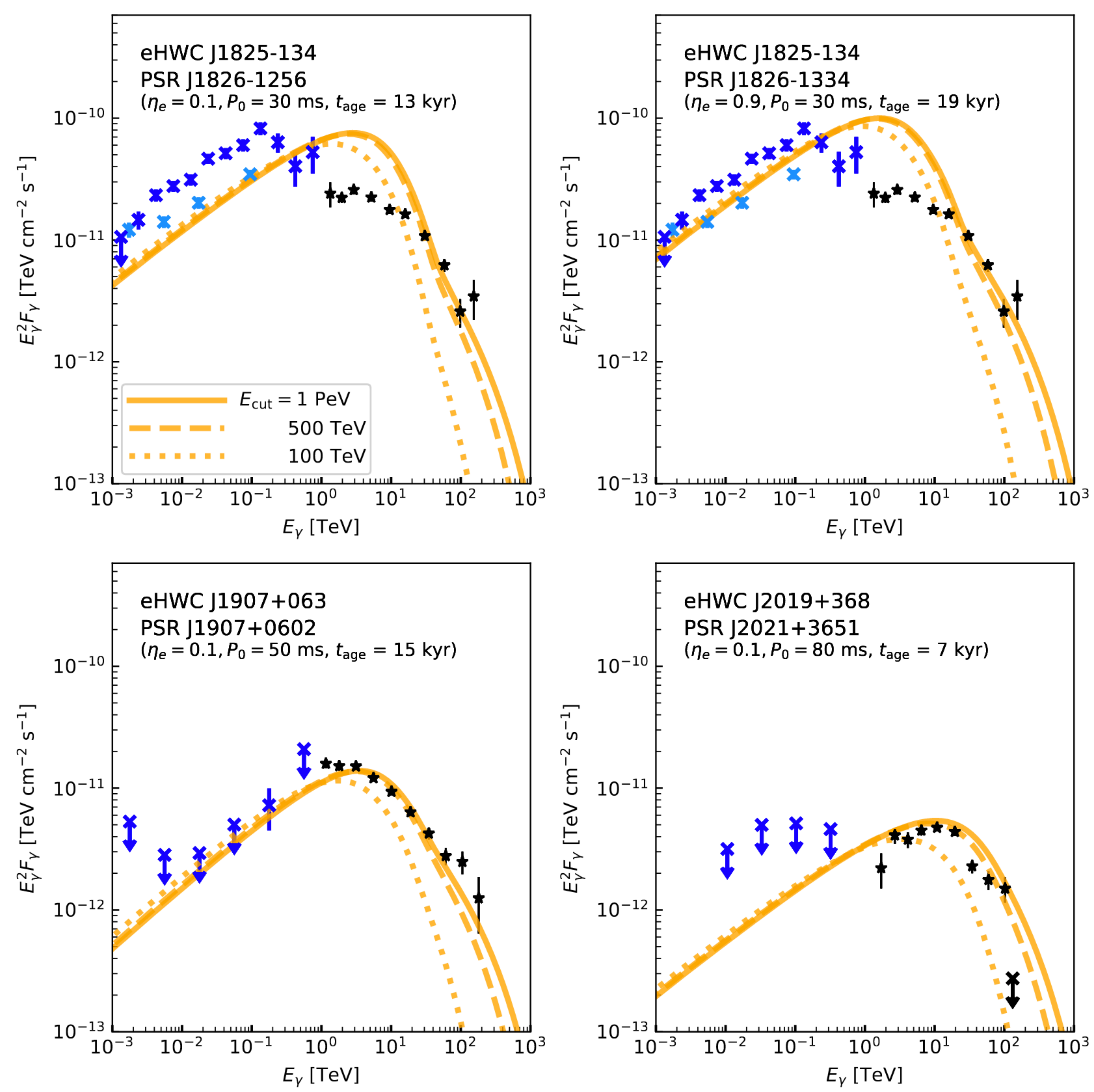
(Dated: 22 February, 2019)

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 em
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

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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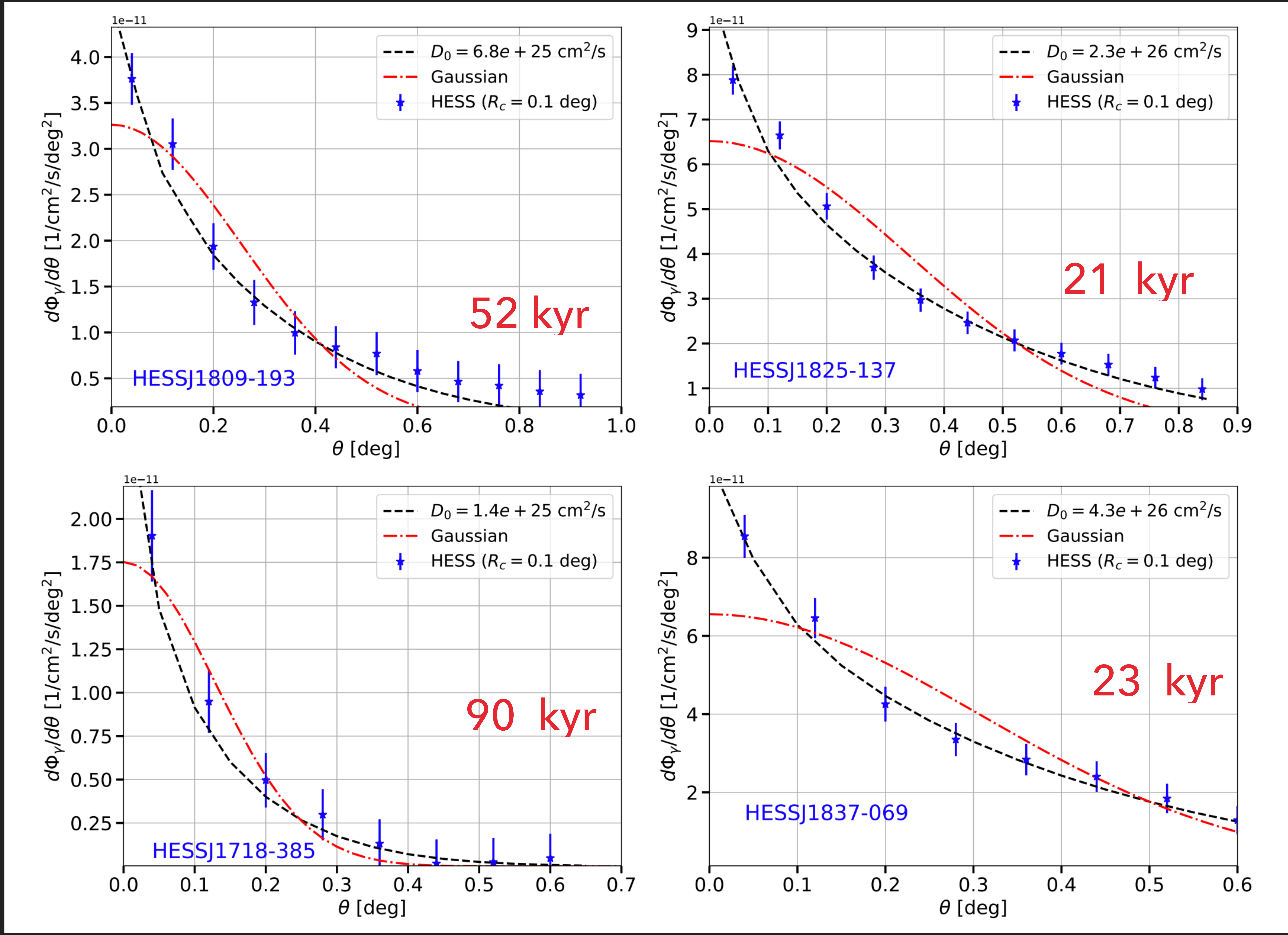


Property of the pulsars: Kick velocity

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 $w = 0.90$.

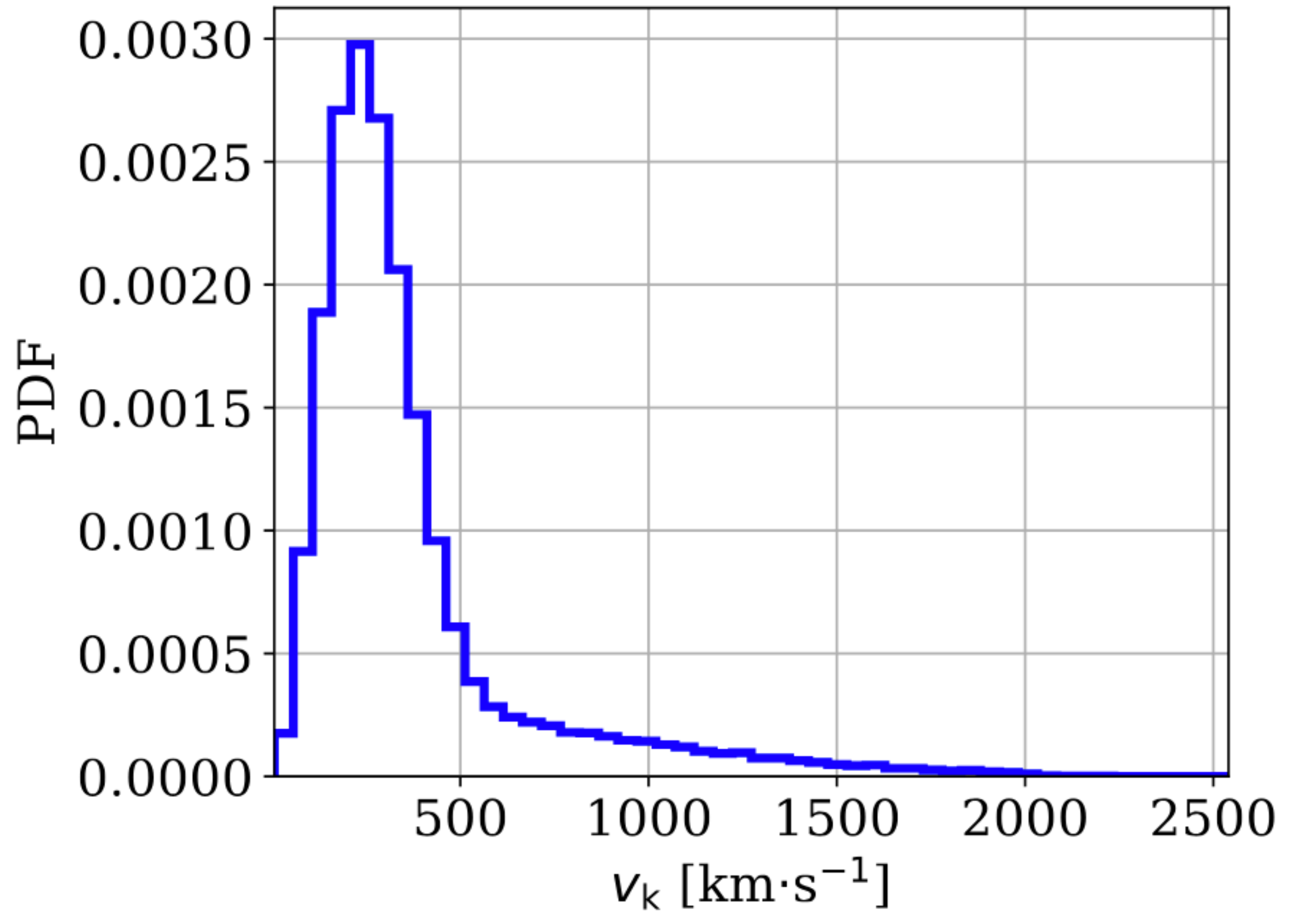


Figure: PDF of the kick velocity of pulsars.

PUZZLE IIIB: MIRAGE HALOS

PUZZLE IIIB: MIRAGE HALOS

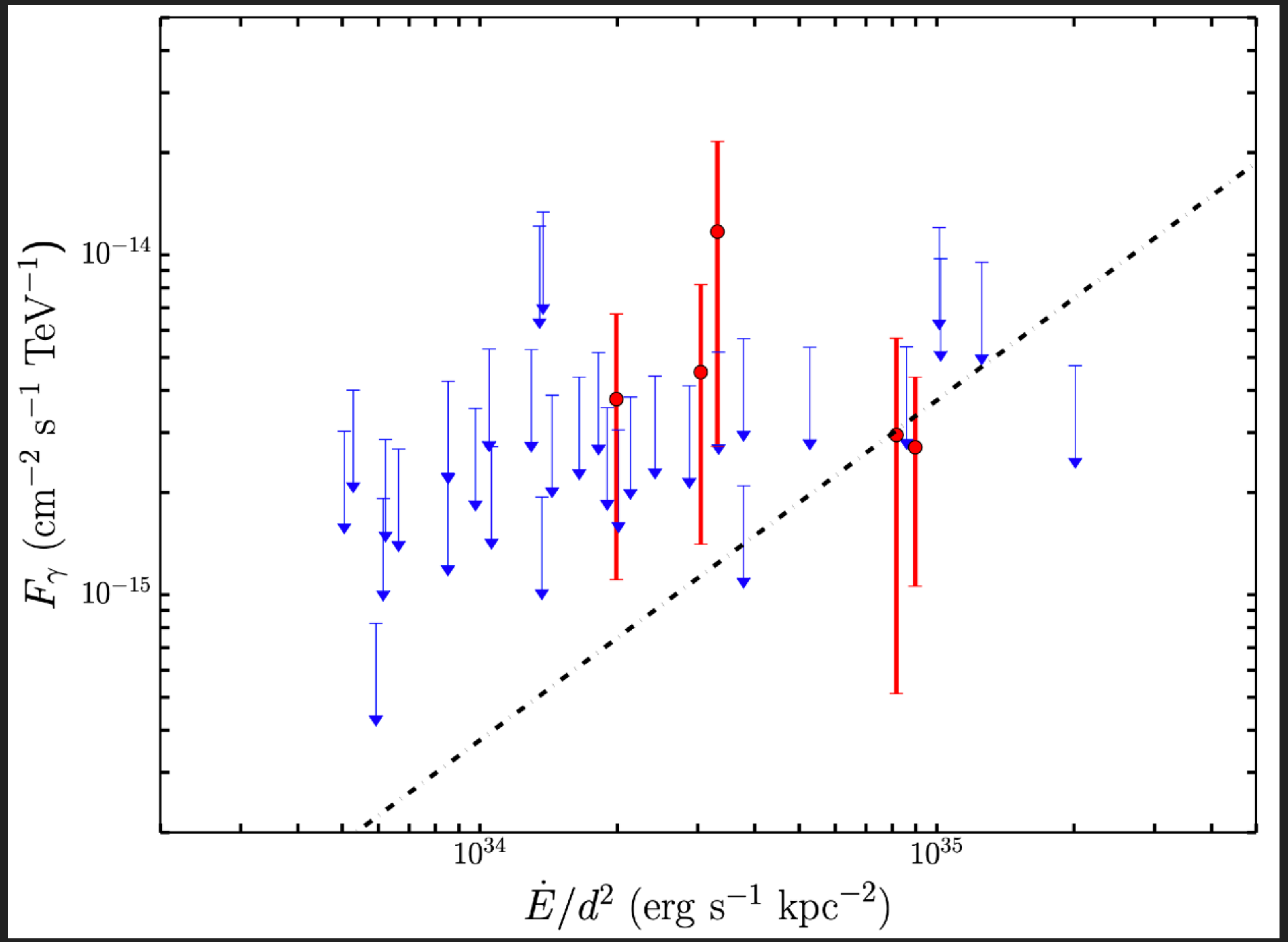
Bao et al. (2407.02478)

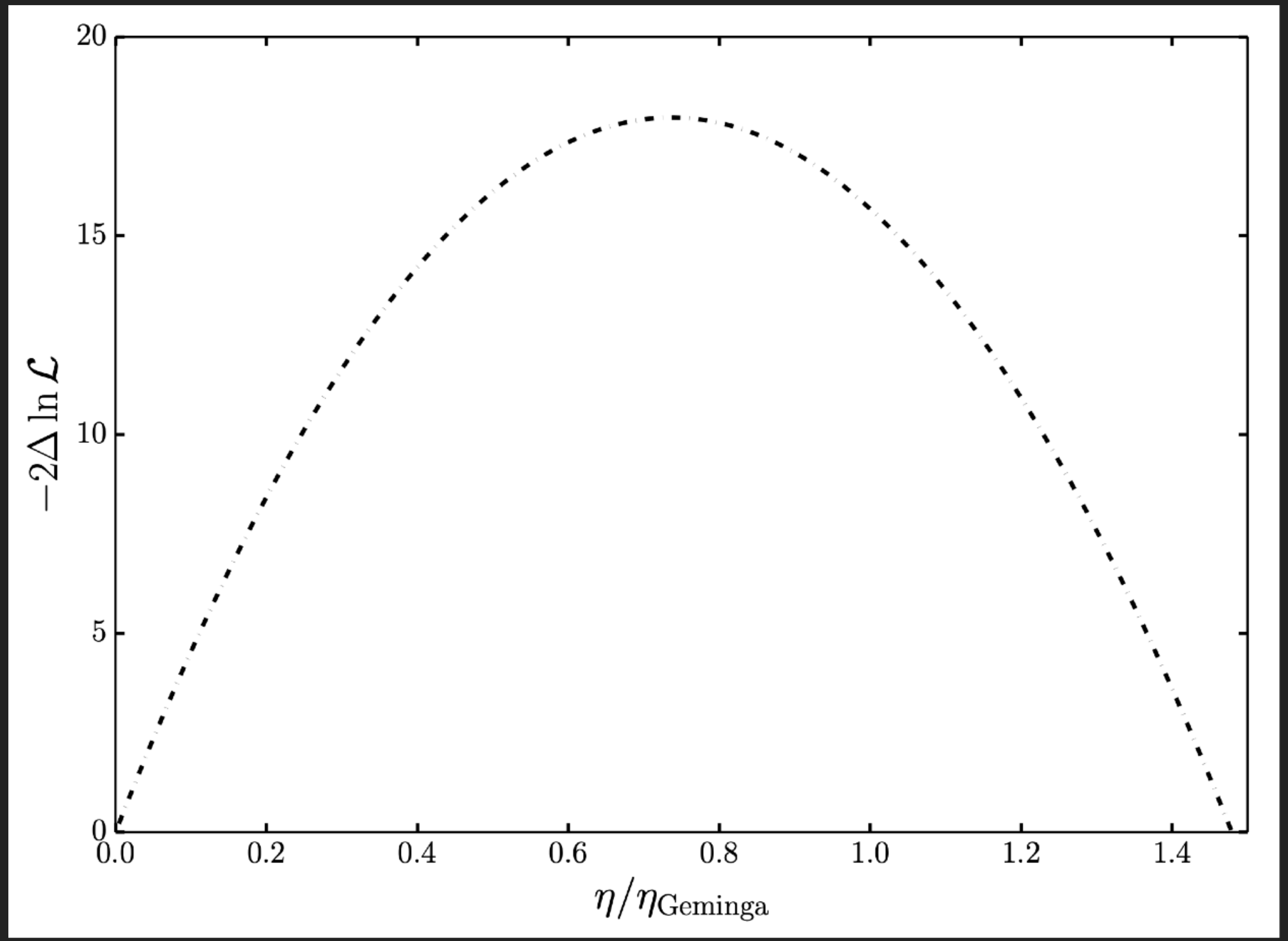
- “Mirage” TeV halos - Many more systems may be difficult to detect or analyze, because they break the modeling assumption of spherical symmetry.

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.



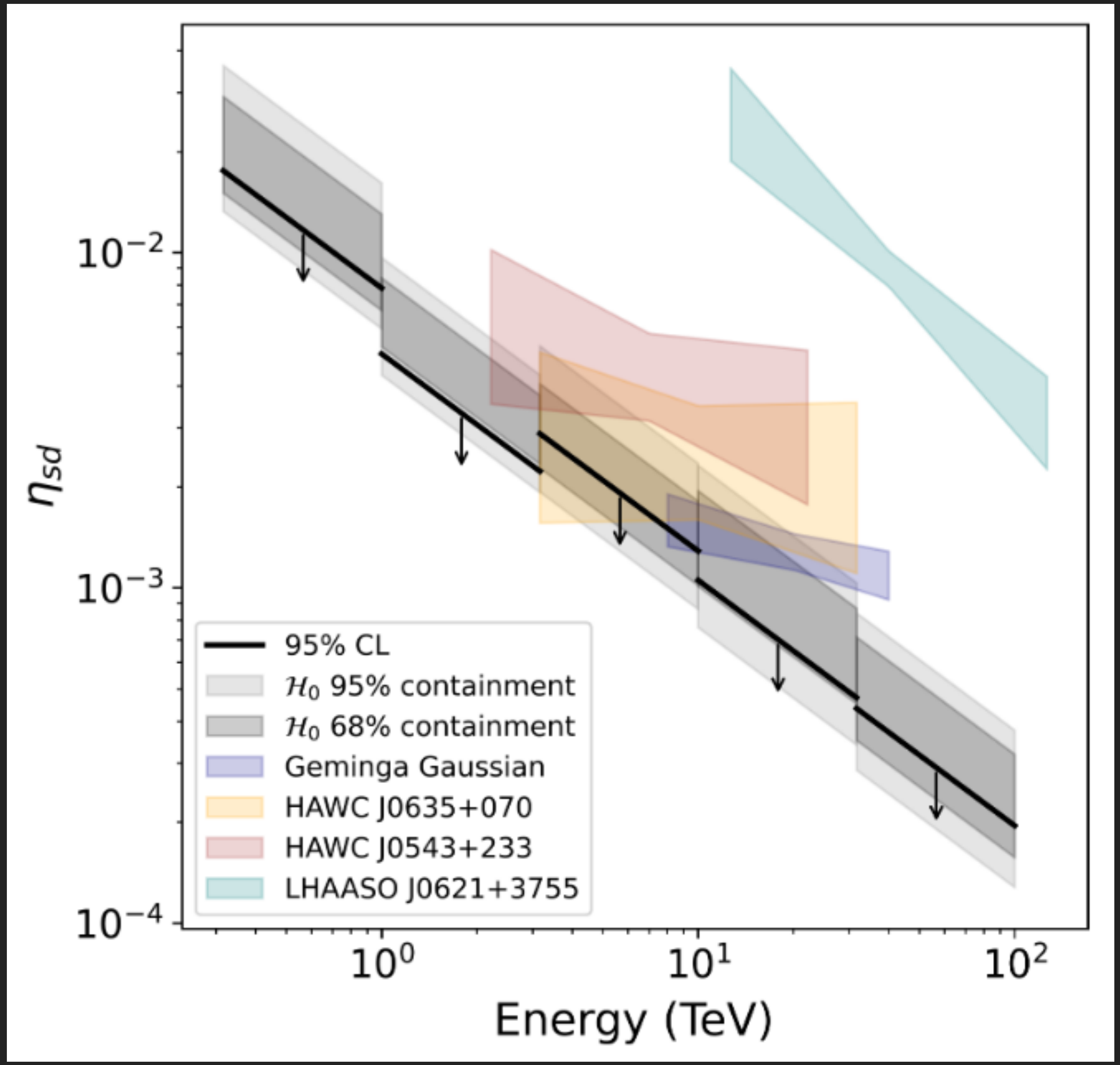


LHAASO Collaboration (2023; 2305.17030)

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

PUZZLE IIIC: TEV HALOS POWERED BY MILLISECOND PULSARS?

- HAWC Collaboration produced a new analysis of 57 MSPs with 5 years of data.
- Found no evidence for MSP-powered TeV halos.



HAWC Collaboration (2505.00184)

Name	RA [°]	Dec [°]	$TS^{1/2}$ (this work)	$TS^{1/2}$ (HL22)
PSRJ0023+0923	5.82	9.39	1.34	1.33
PSRJ0030+0451	7.61	4.86	0.94	2.55
PSRJ0034-0534	8.59	−5.58	1.92	0.10
PSRJ0218+4232	34.53	42.54	1.52	1.56
PSRJ0337+1715	54.43	17.25	1.54	0.25
PSRJ0557+1550	89.38	15.84	−0.15	0.14
PSRJ0605+3757	91.27	37.96	-8.20×10^{-2}	−1.02
PSRJ0613-0200	93.43	−2.01	1.73	6.00×10^{-2}
PSRJ0621+2514	95.30	25.23	−0.10	1.62
PSRJ0751+1807	117.79	18.13	-1.44×10^{-2}	−2.09
PSRJ1023+0038	155.95	0.64	0.83	2.56
PSRJ1231-1411	187.80	−14.20	-4.99×10^{-2}	-2.00×10^{-2}
PSRJ1300+1240	13.00	12.68	−0.14	−0.59
PSRJ1400-1431	210.15	−14.53	0.12	−1.04
PSRJ1622-0315	245.75	−3.26	0.88	−0.51
PSRJ1630+3734	247.65	37.58	1.40	−0.59
PSRJ1643-1224	250.91	−12.42	-4.29×10^{-2}	0.66
PSRJ1710+4923	257.52	49.39	0.66	−0.62
PSRJ1719-1438	259.79	−14.63	-4.61×10^{-2}	−0.56
PSRJ1737-0811	264.45	−8.19	-9.14×10^{-2}	−0.16
PSRJ1741+1351	265.38	13.86	-7.93×10^{-2}	2.64
PSRJ1744-1134	266.12	−11.58	-6.74×10^{-2}	−0.95
PSRJ1745-0952	266.29	−9.88	1.23	−1.97
PSRJ1843-1113	280.92	−11.23	1.76	0.15
PSRJ1911-1114	287.96	−11.24	-6.82×10^{-2}	-2.00×10^{-2}
PSRJ1921+1929	290.35	19.49	3.38×10^{-3}	0.62
PSRJ1939+2134	19.66	21.58	0.83	3.34
PSRJ1959+2048	19.99	20.80	0.95	2.12
PSRJ2017+0603	304.34	6.05	0.13	−0.37
PSRJ2042+0246	310.55	2.77	0.40	−0.67
PSRJ2043+1711	310.84	17.19	-8.46×10^{-3}	−0.72
PSRJ2214+3000	333.66	30.01	1.98	0.33
PSRJ2234+0611	338.60	6.19	−0.11	−0.23
PSRJ2234+0944	338.70	9.74	1.34	0.80
PSRJ2256-1024	344.23	−10.41	1.21	0.45
PSRJ2302+4442	345.70	44.71	-9.28×10^{-2}	-1.00×10^{-2}
PSRJ2339-0533	354.91	−5.55	0.63	−0.35

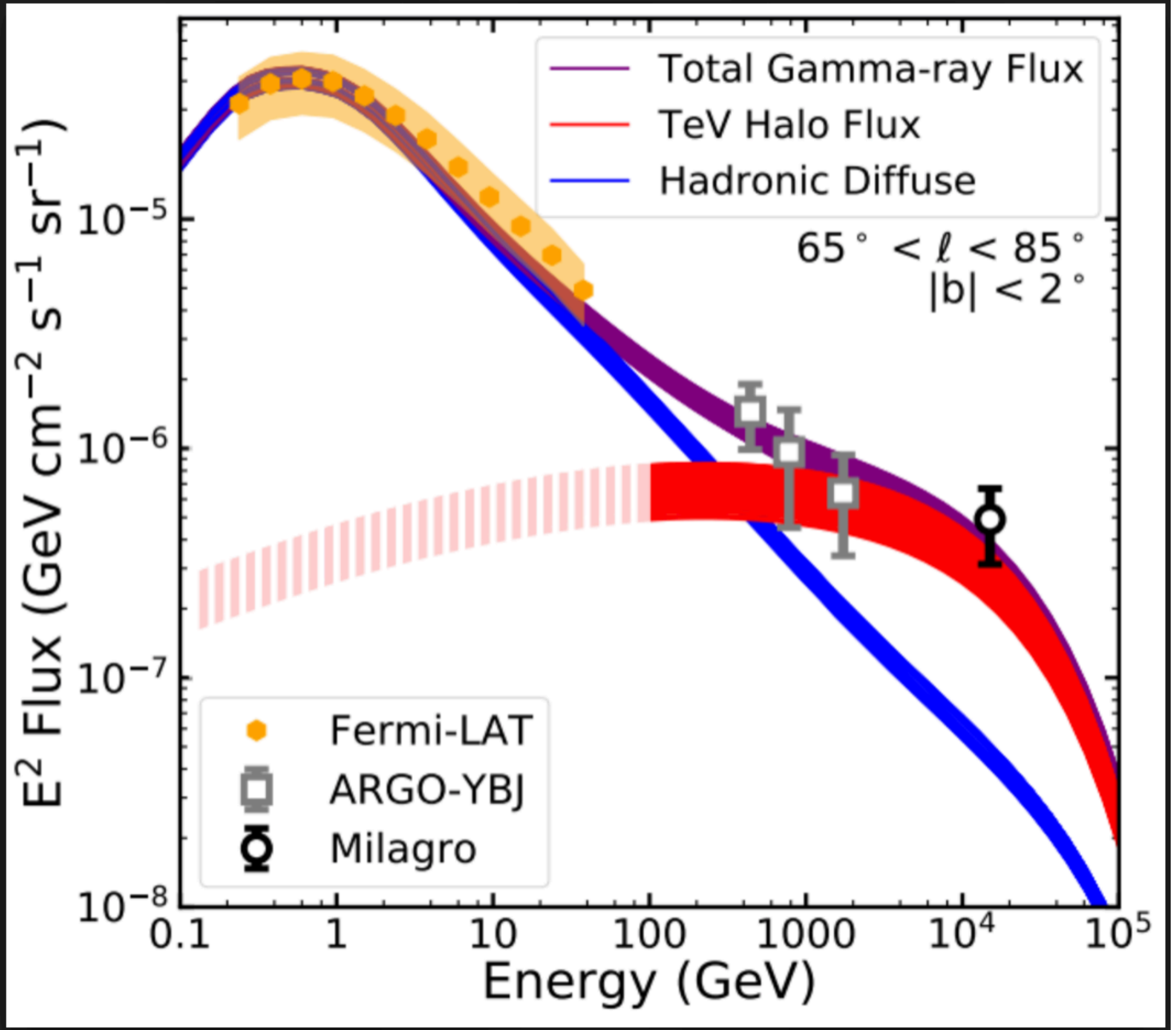
PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

IceCube Collaboration (2023)

IMPLICATION 2: DIFFUSE TEV GAMMA-RAYS

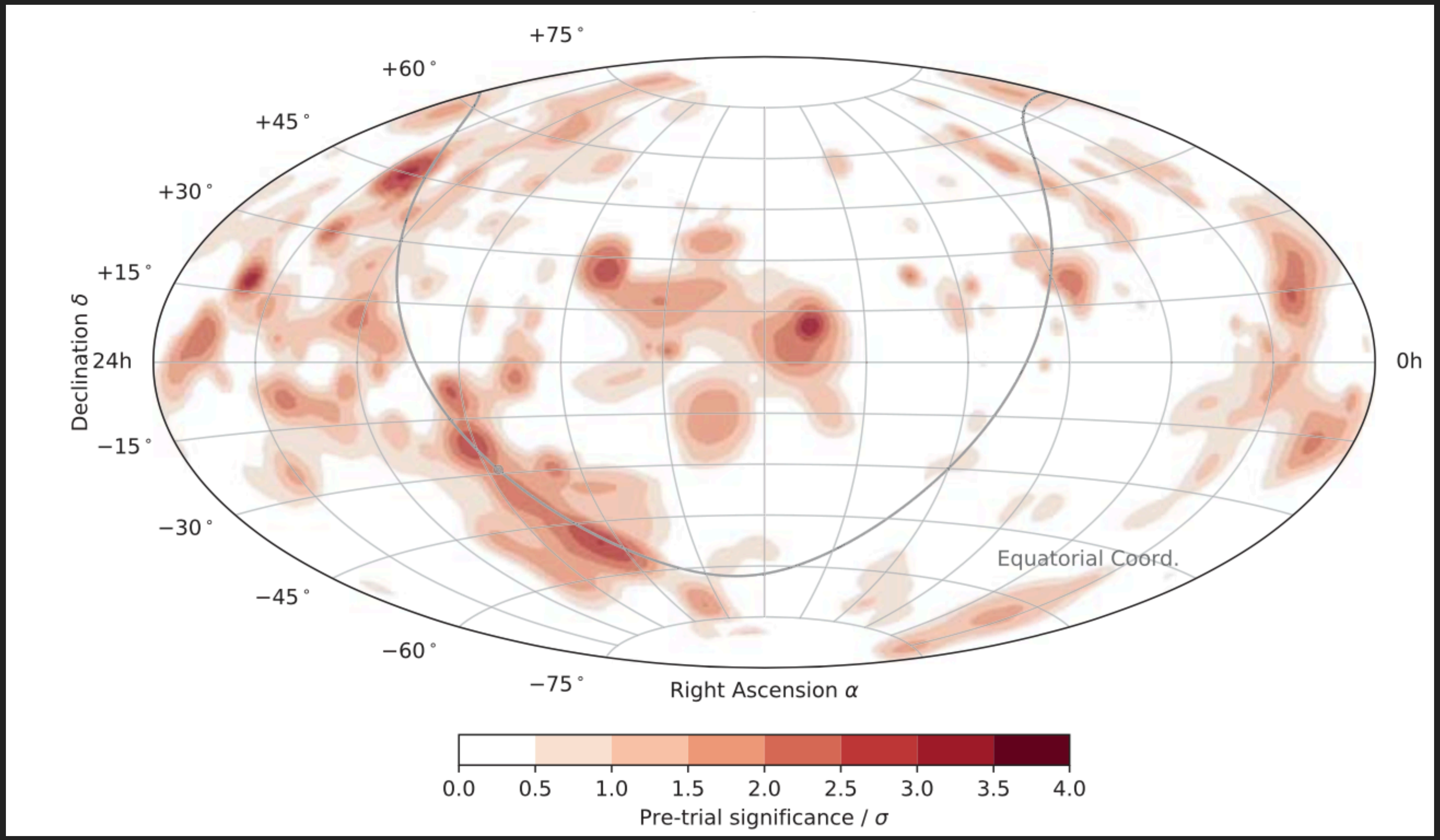
- TeV halos naturally explain the spectrum and intensity of this emission.
- Multiple halos observed with $E^{-2.0}$ spectra.
- Note - "Halo" is not needed
  - Pulsar efficiency ~10%
  - Power must escape PWN

Linden & Buckman (2017; 1707.01905)



PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

IceCube Collaboration (2023)



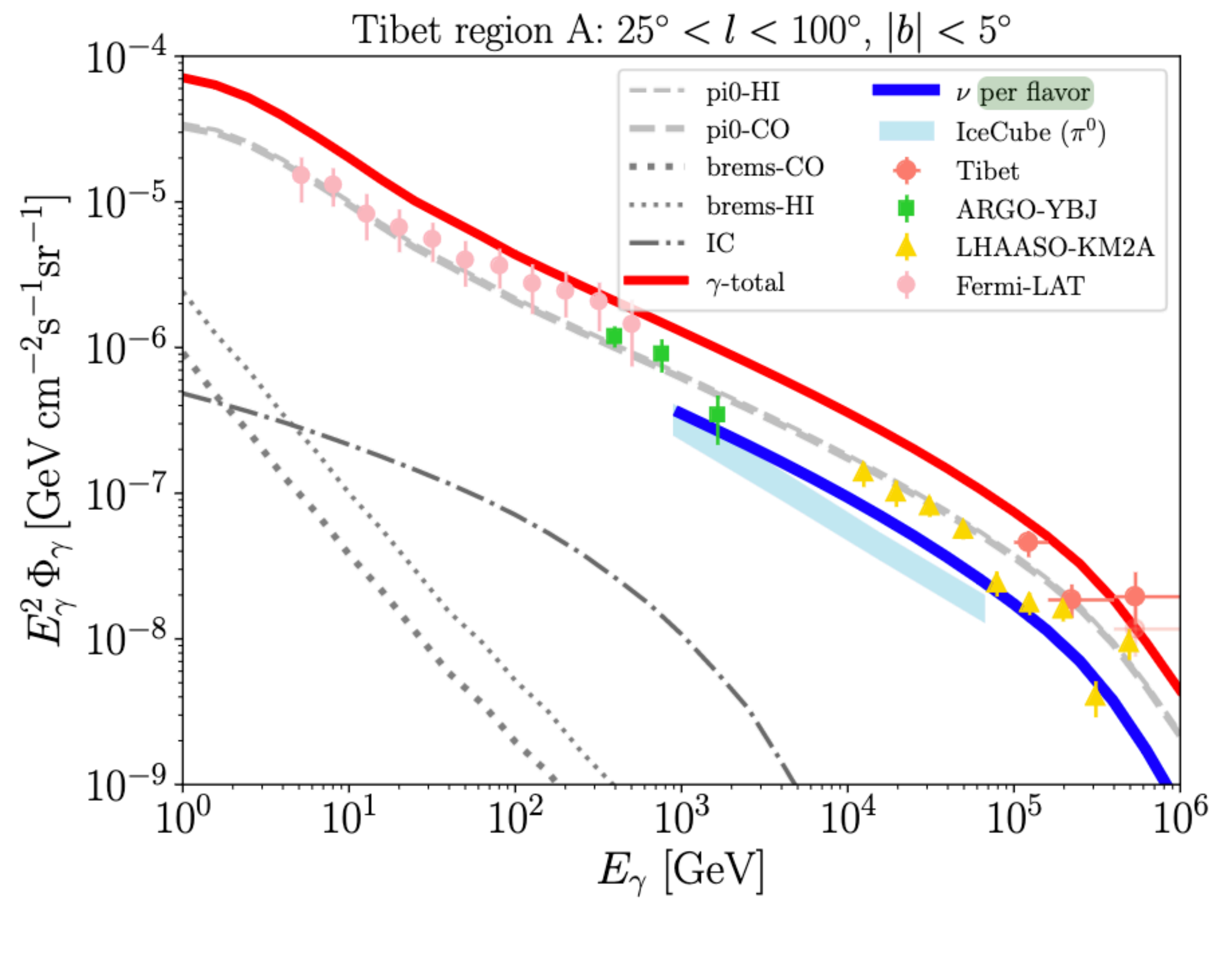
- IceCube detection of a galactic neutrino flux – with a normalization that is ~4x brighter than expectations from the Fermi-LAT extrapolation.

PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

Fang et al. (2023; 2306.17275)

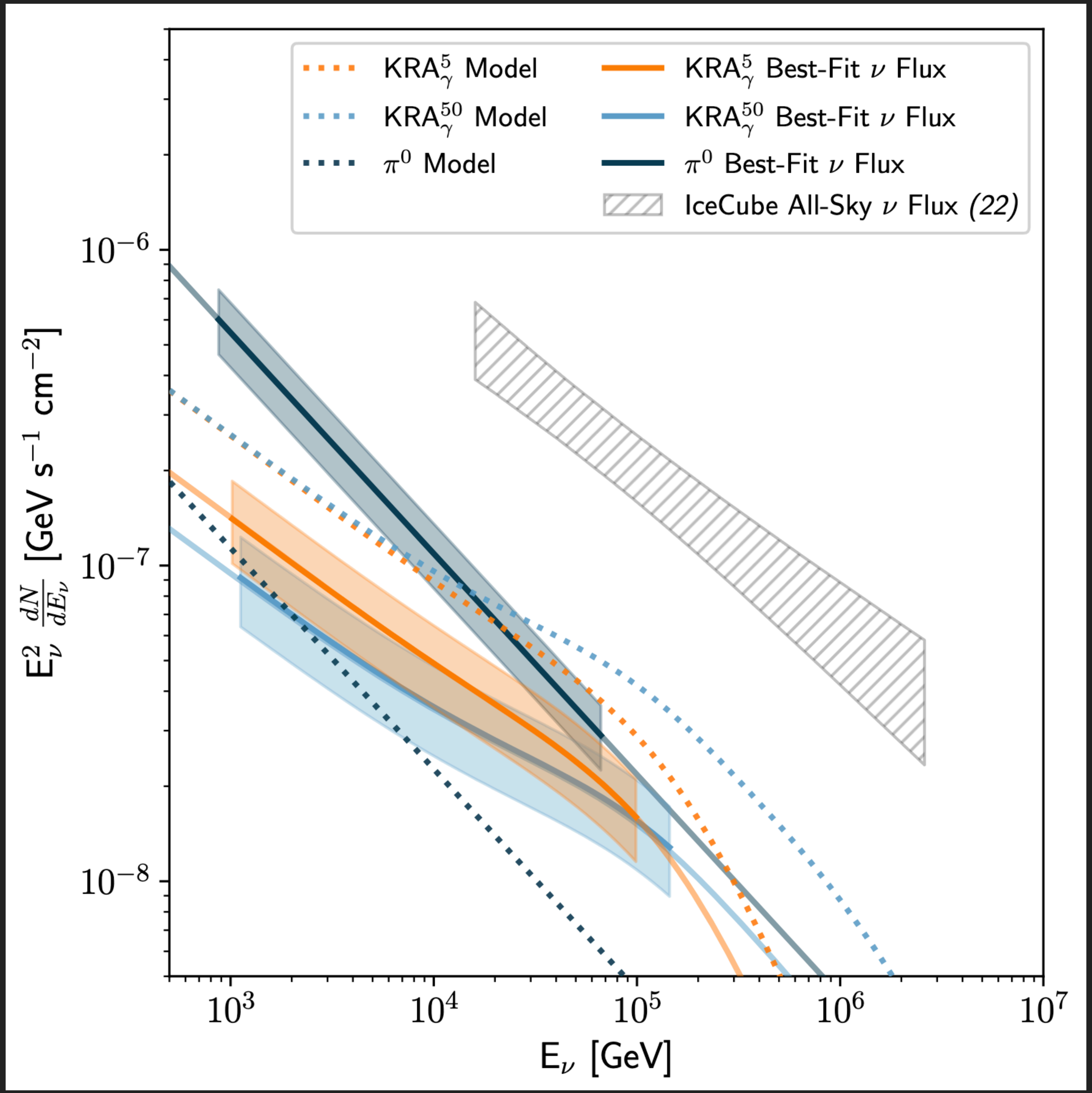
- If the IceCube neutrino flux from the galaxy is higher, then the gamma-ray flux from hadronic processes (i.e., not halos) could also be higher.

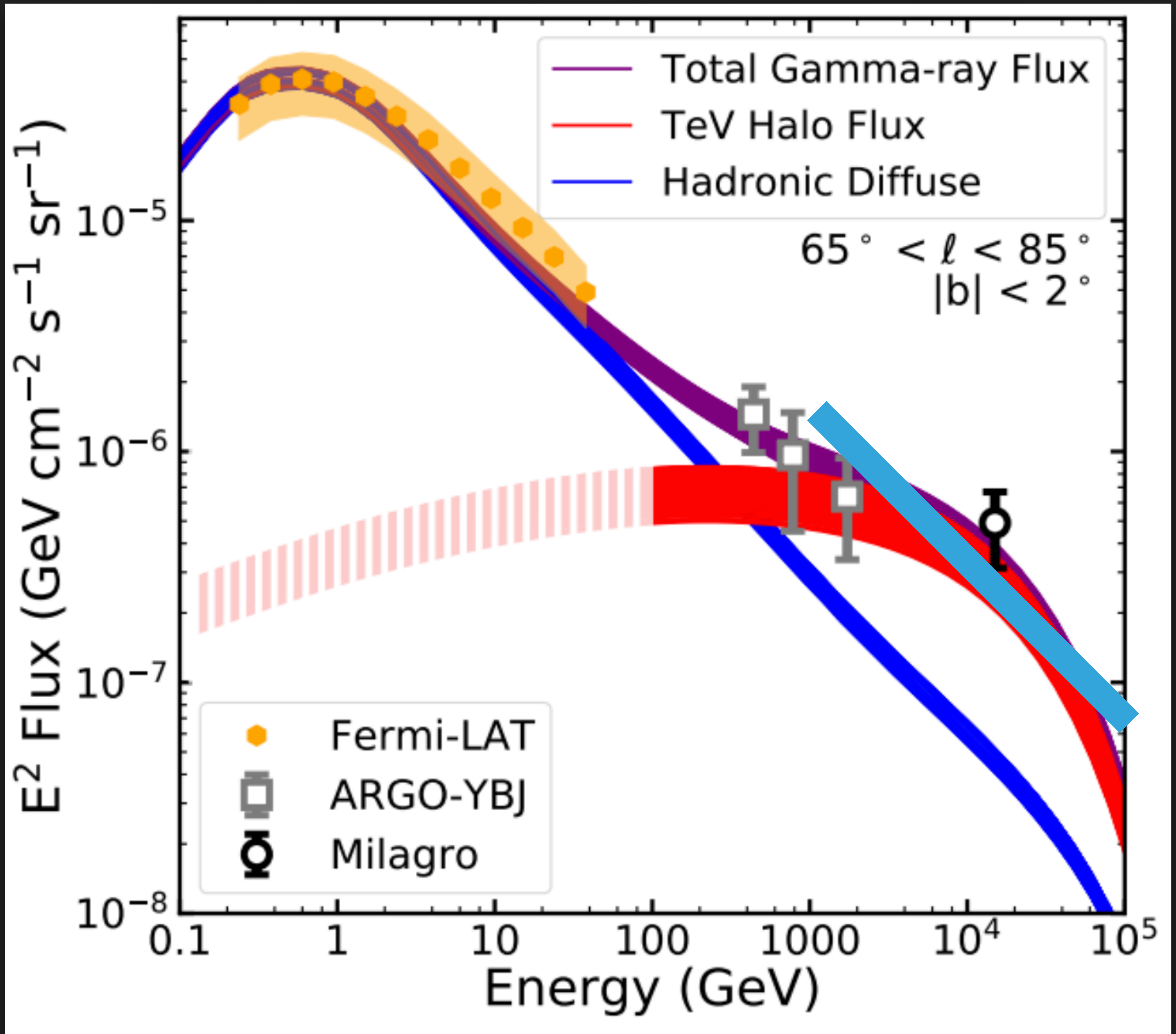
- In Fang et al. this is capable of producing the diffuse galactic gamma-ray emission



PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

IceCube Collaboration (2023)





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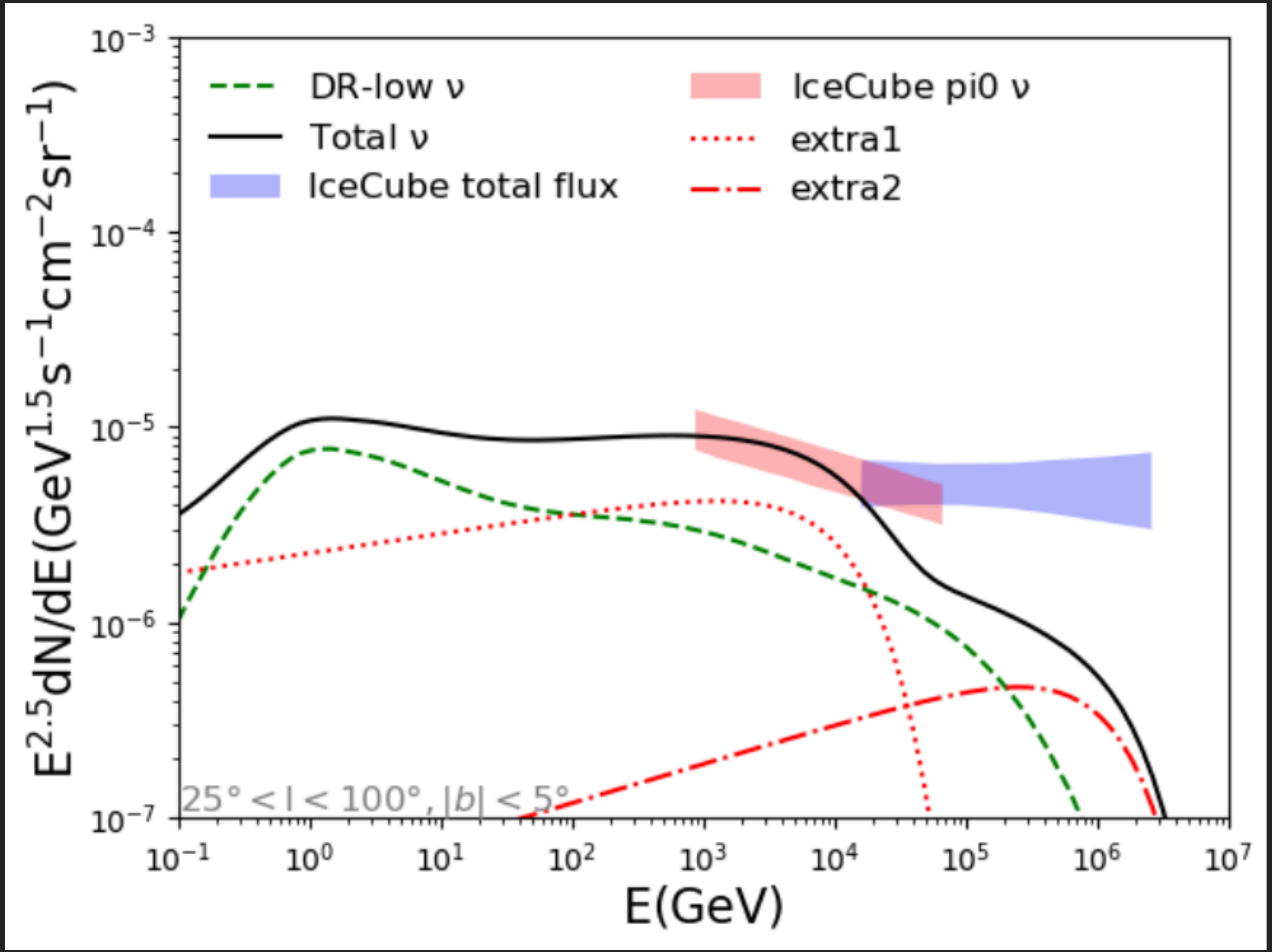
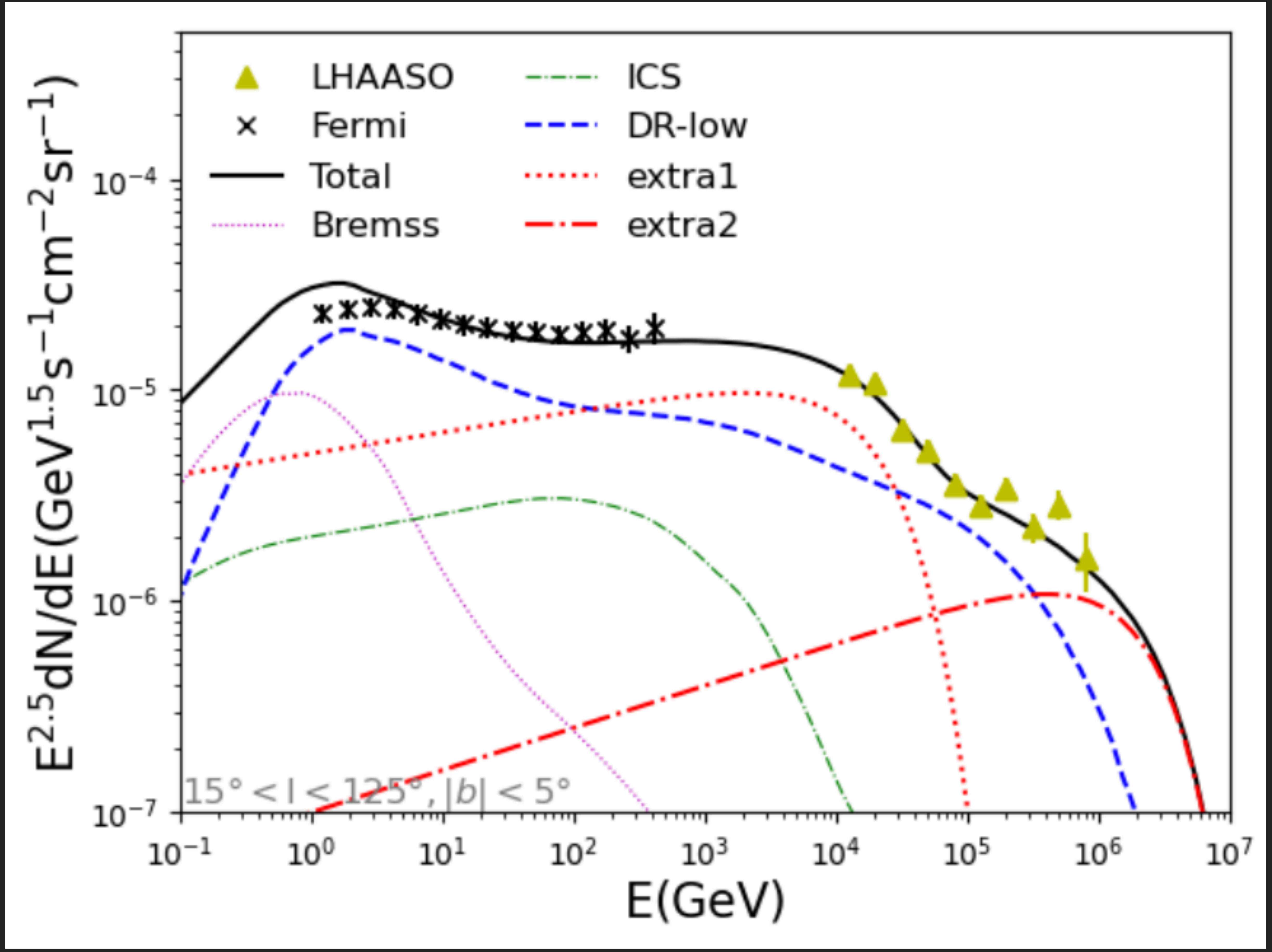
PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

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.

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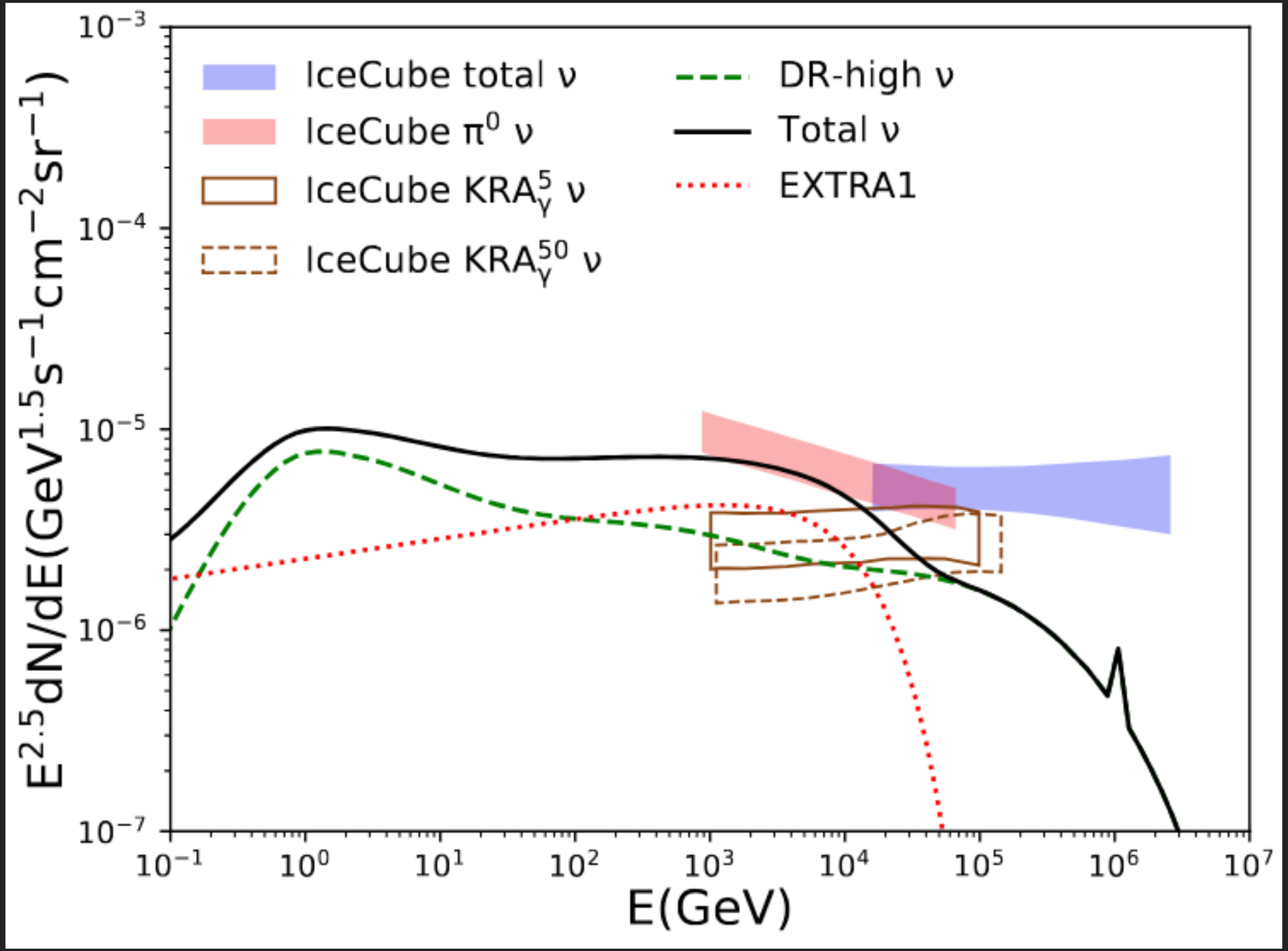
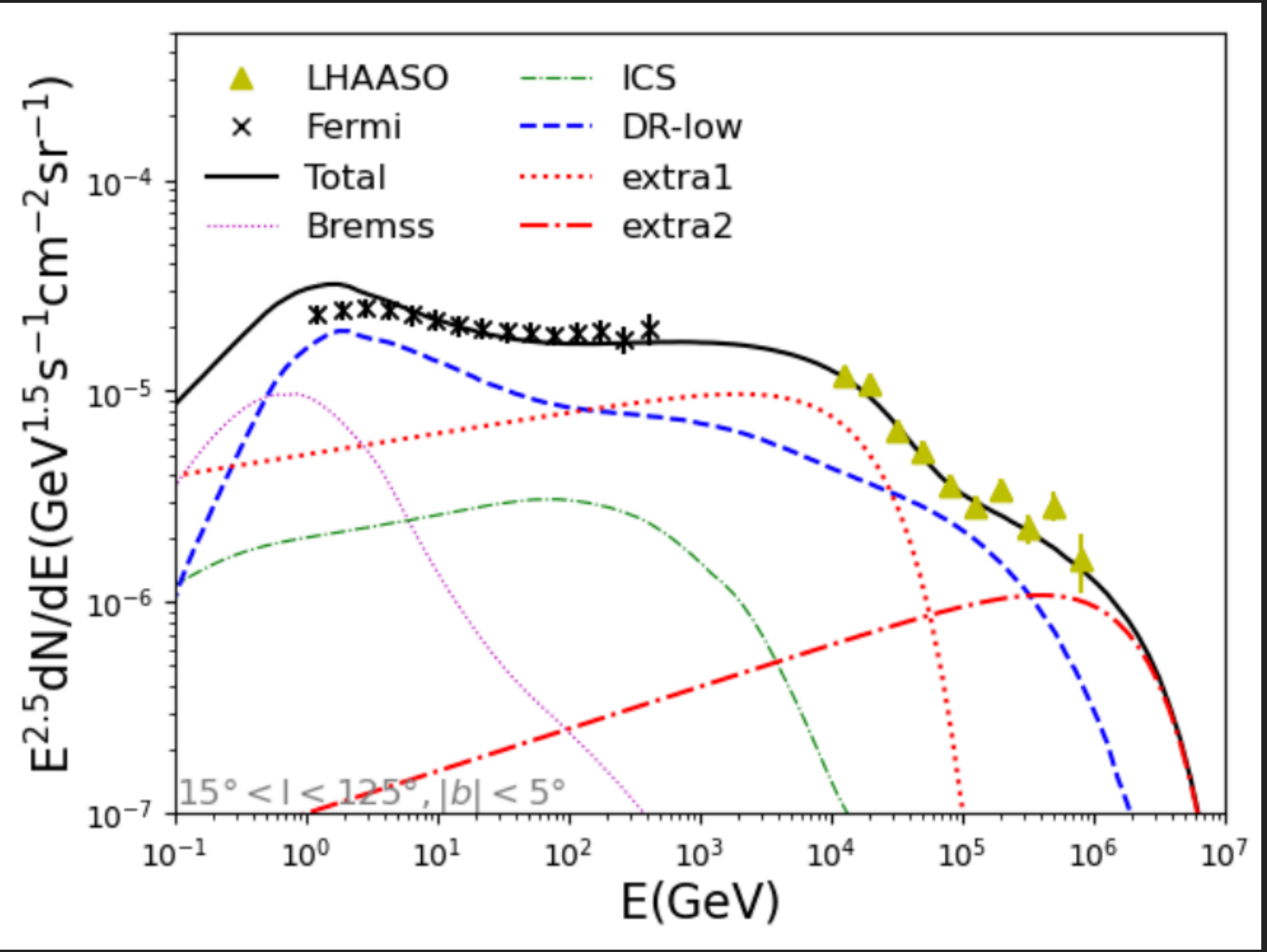
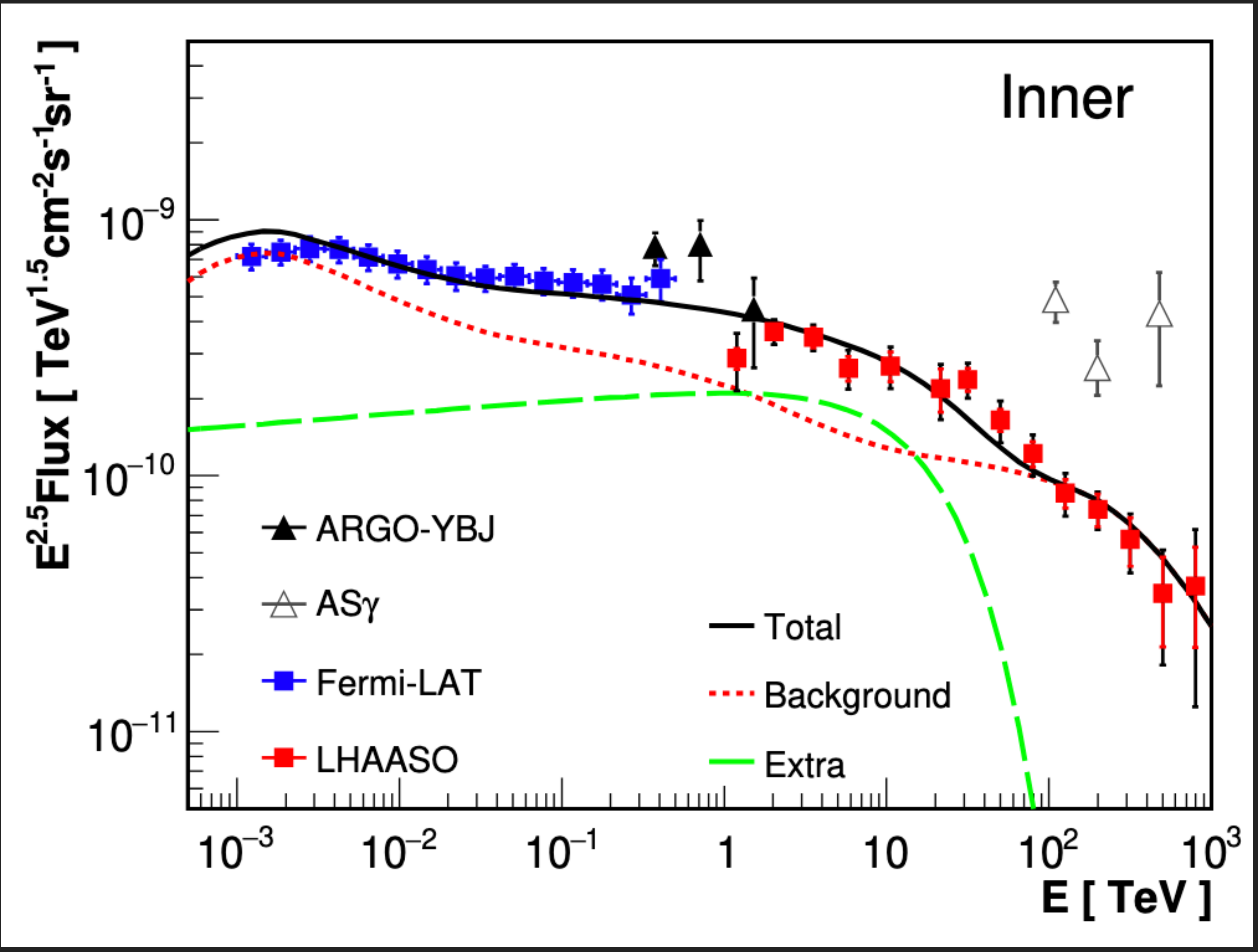


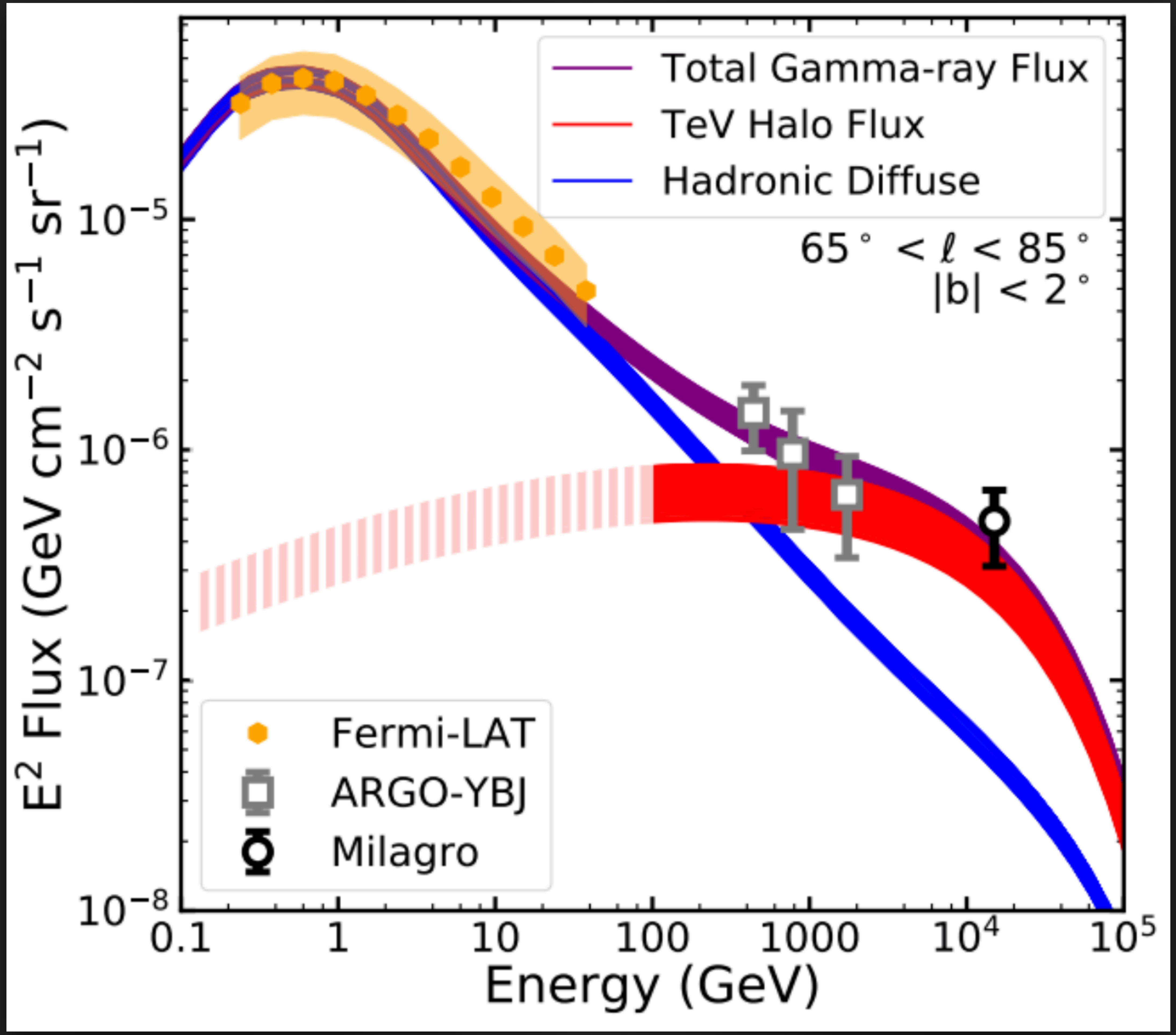


- Models that explain the IceCube neutrino flux still require an additional gamma-ray component (here: “Extra1 and Extra2”).
    - In this model it is likely leptonic.

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.

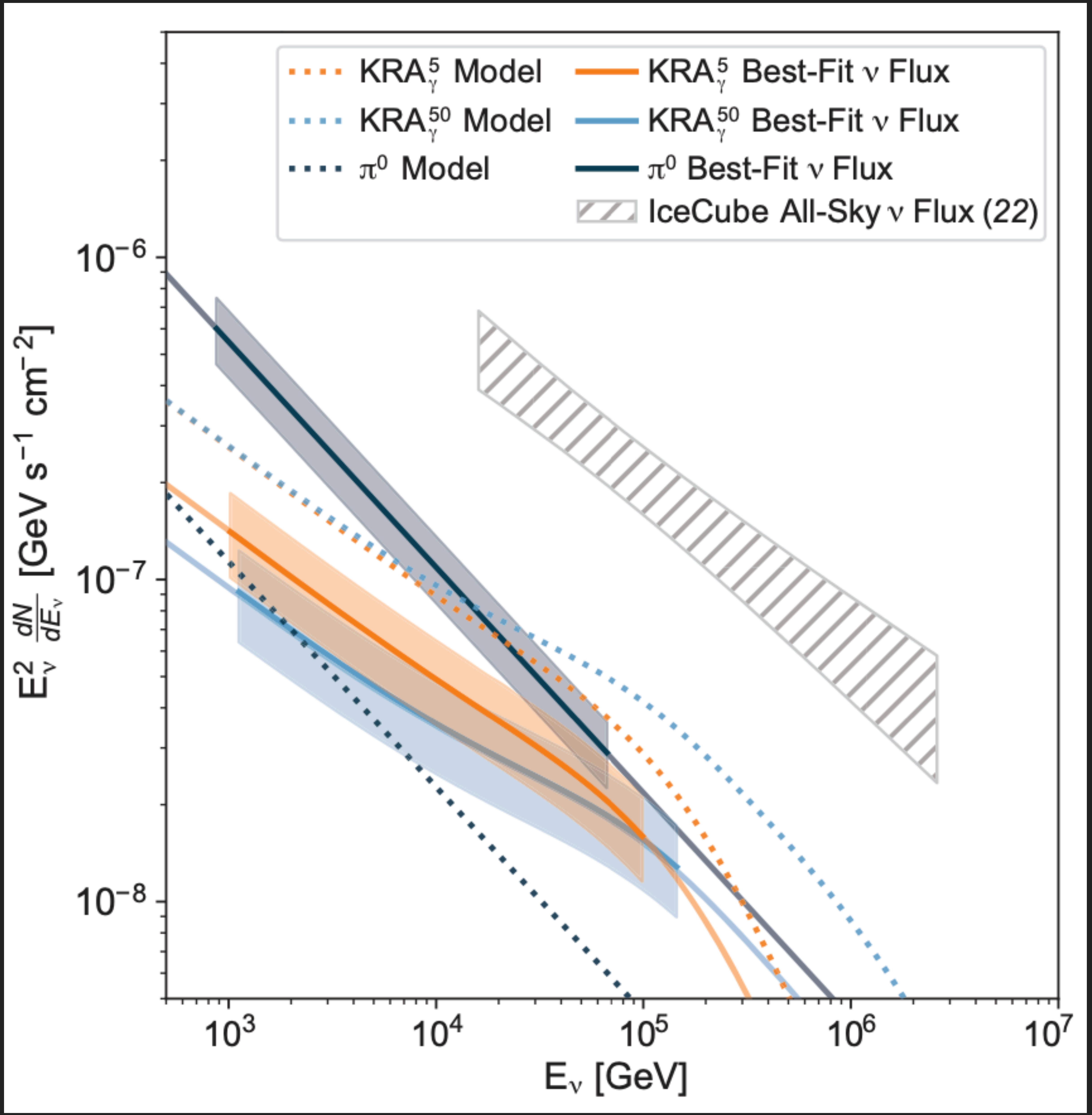
PUZZLE IV: HADRONIC VS. LEPTONIC DIFFUSE TEV EMISSION

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

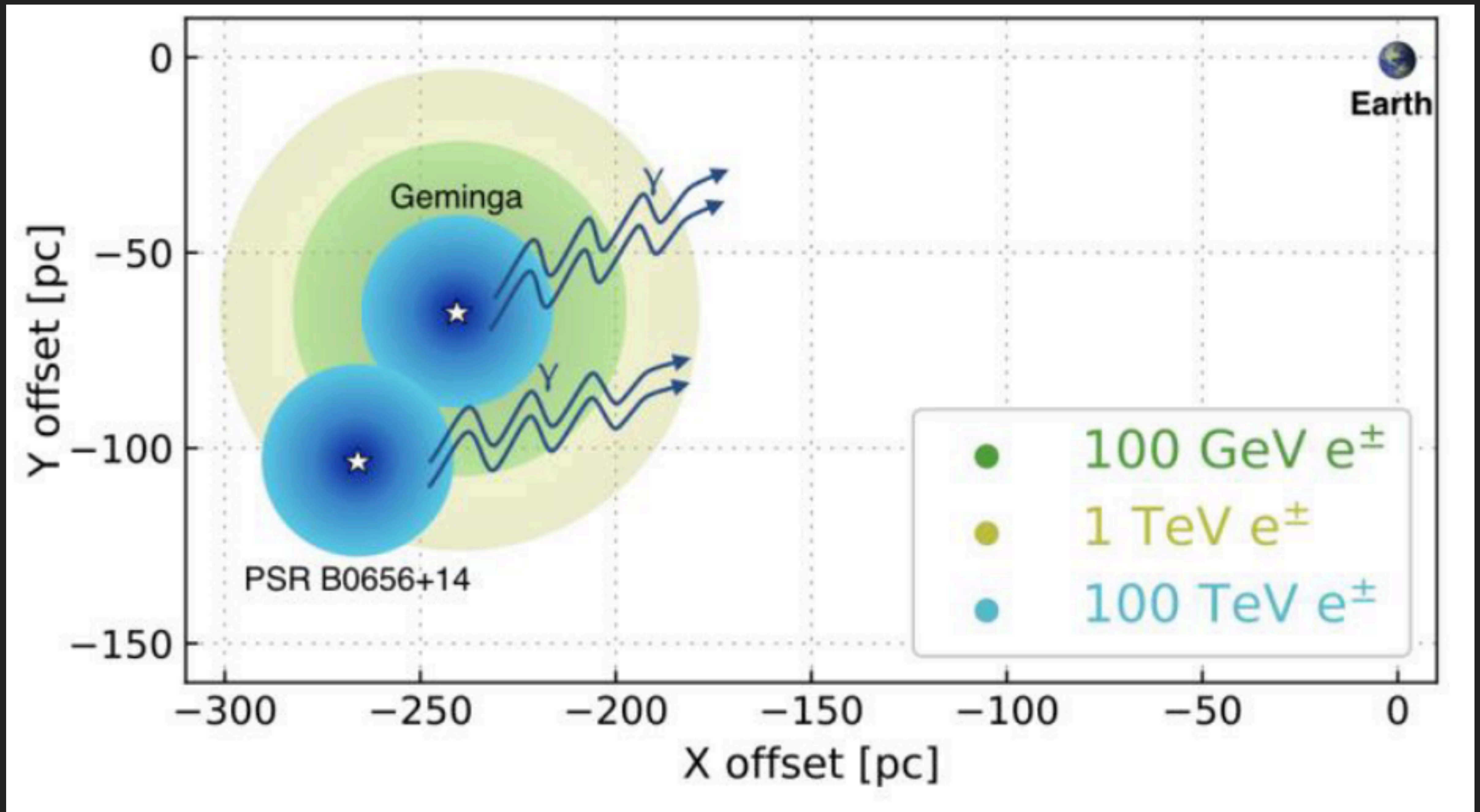


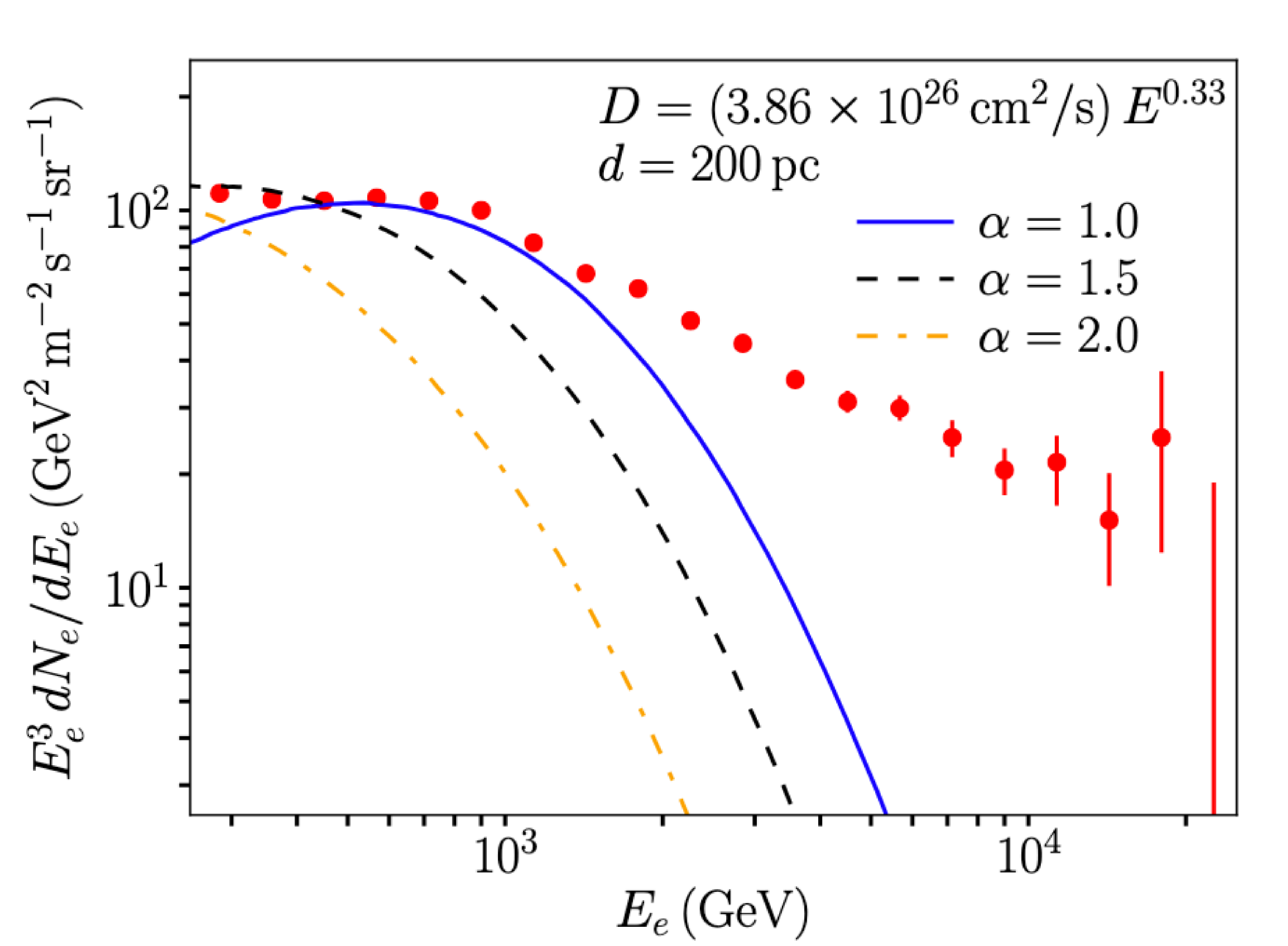
PUZZLE V: WHAT ARE TEV HALOS?

- Failed Model 1: One zone models

Hooper & Linden (1711.07482)

HAWC Collaboration (1711.06223)

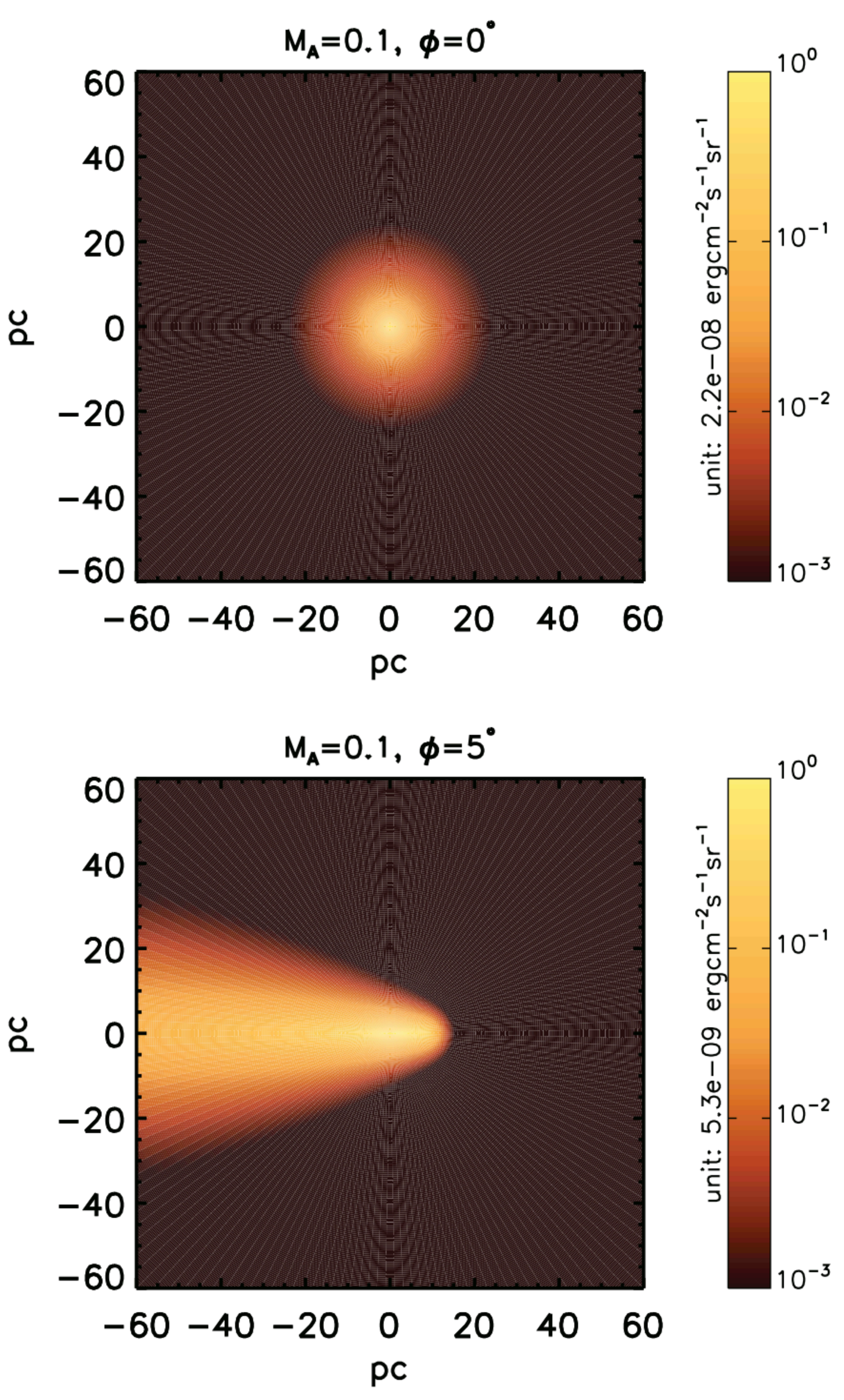




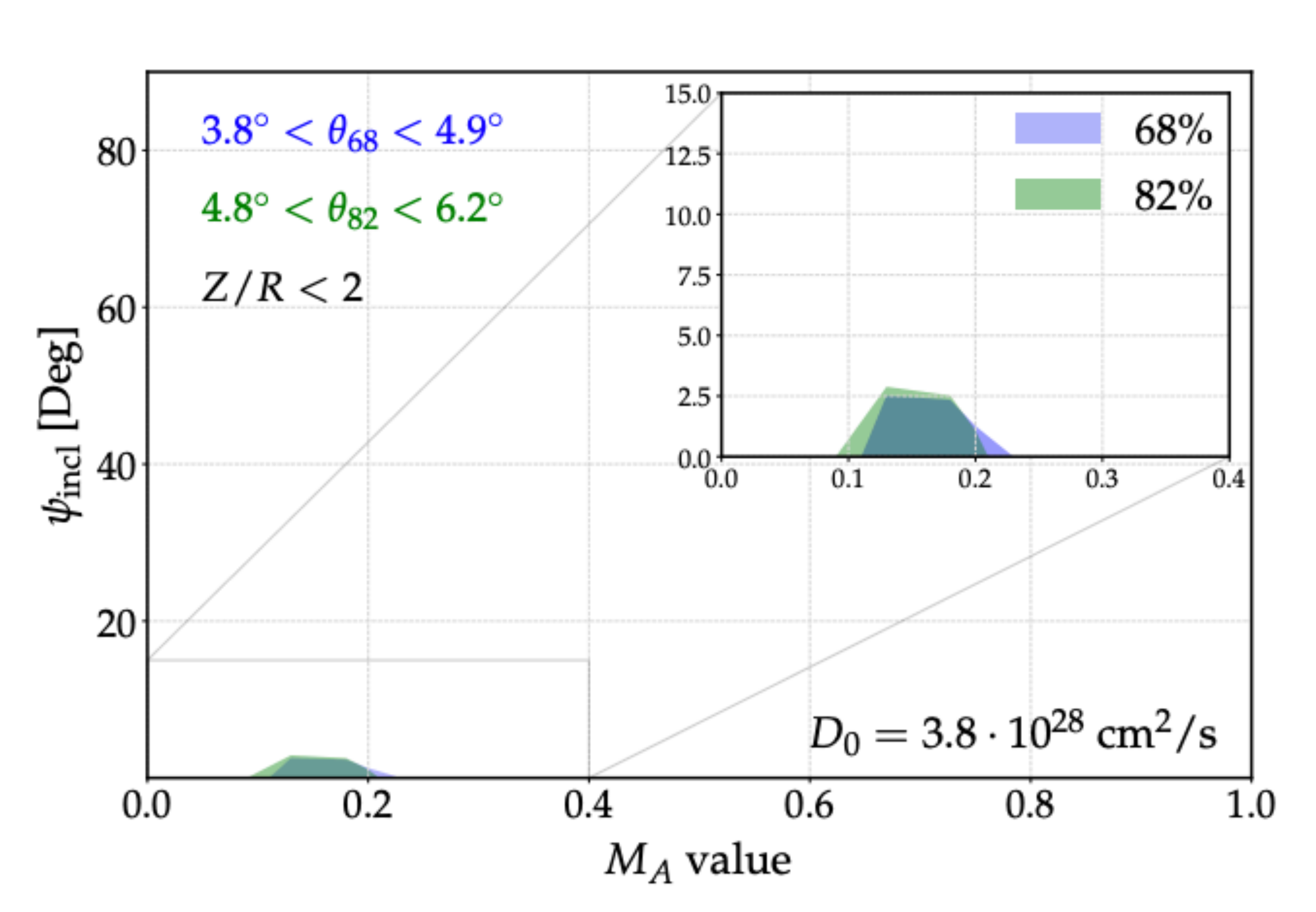
PUZZLE V: WHAT ARE TEV HALOS?

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

Liu, Yan, Zhang (2019; 1904.11536)



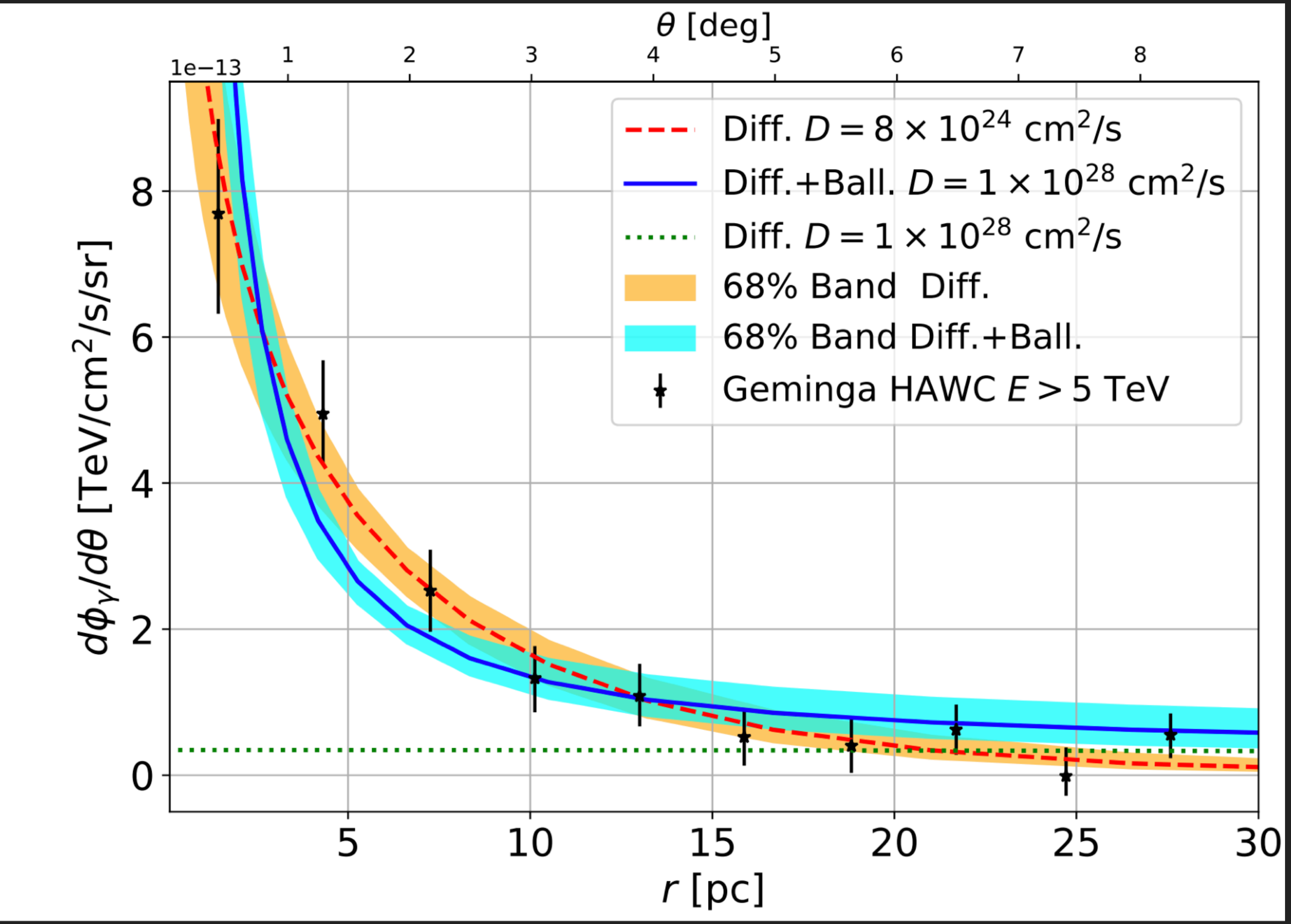
De la Torre Luque et al. (2022; 2205.08544)



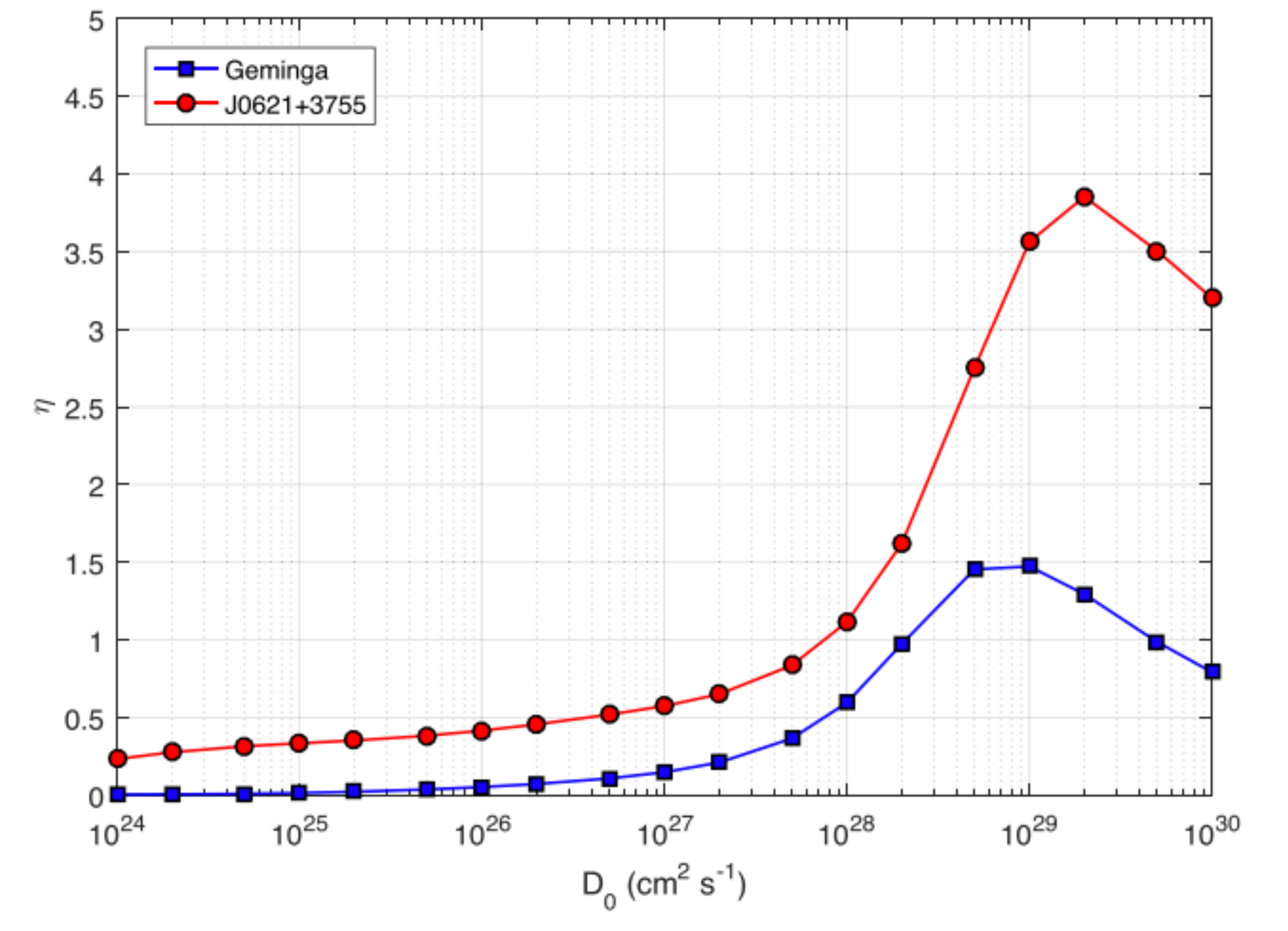
PUZZLE V: WHAT ARE TEV HALOS?

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

Recchia et al. (2021; 2106.02275)



Bao et al. (2021; 2107.07395)



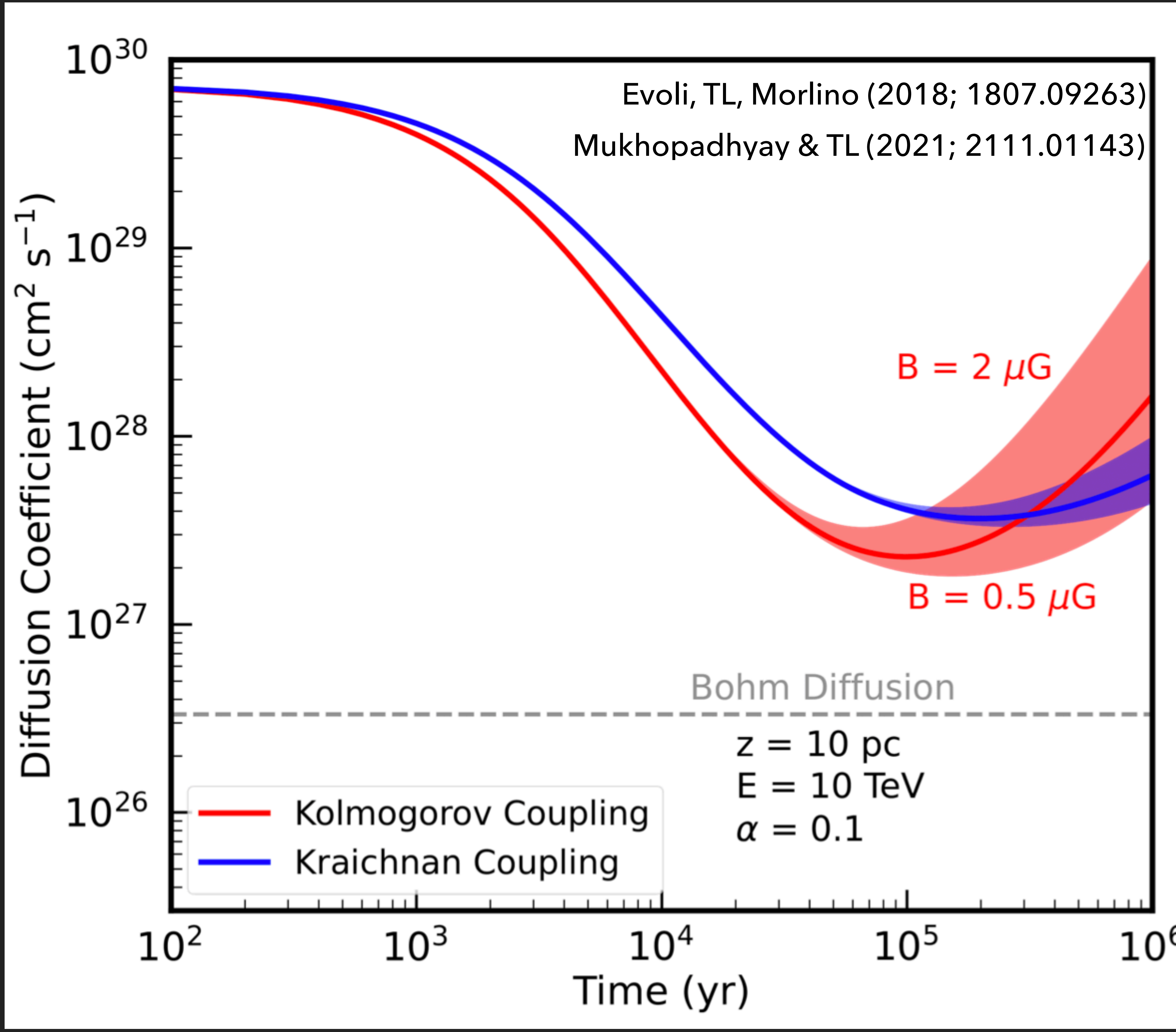
PUZZLE V: WHAT ARE TEV HALOS?

- 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

Kun Fang[1⋆] Xiao-Jun Bi[1,2†] Peng-Fei Yin[1‡]
[1] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[2] *School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*

23 July 2019

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

PUZZLE V: WHAT ARE TEV HALOS?

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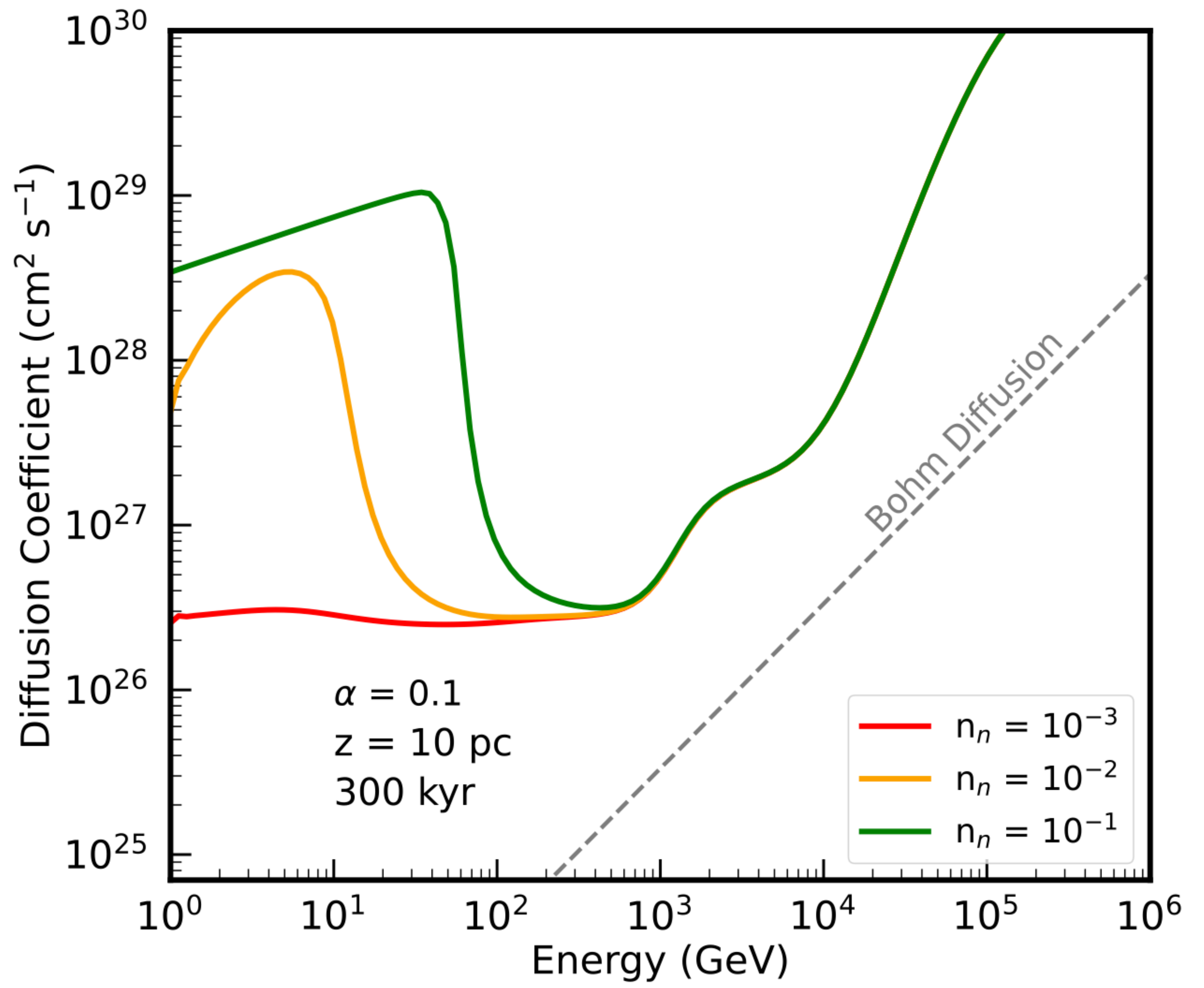

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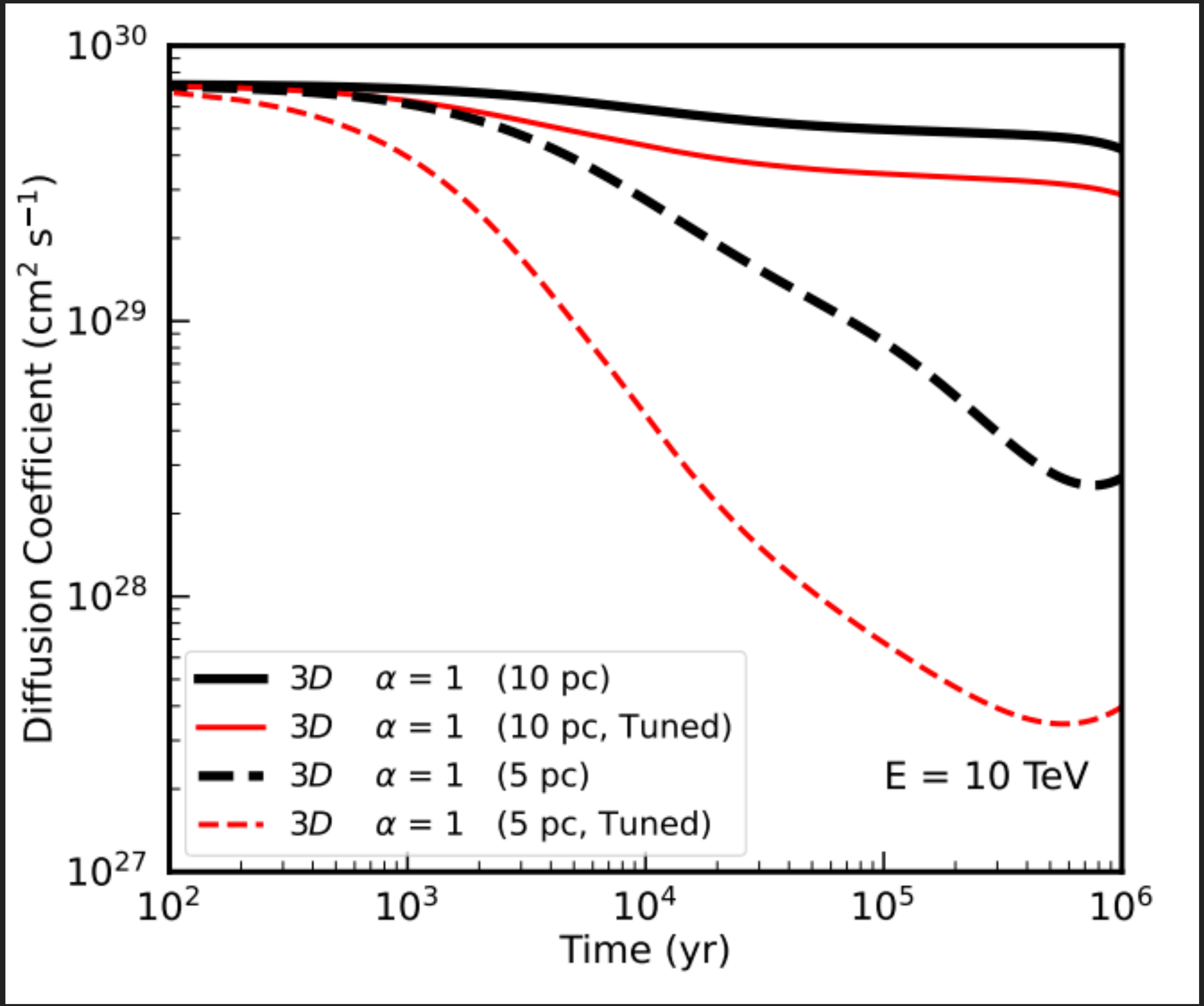

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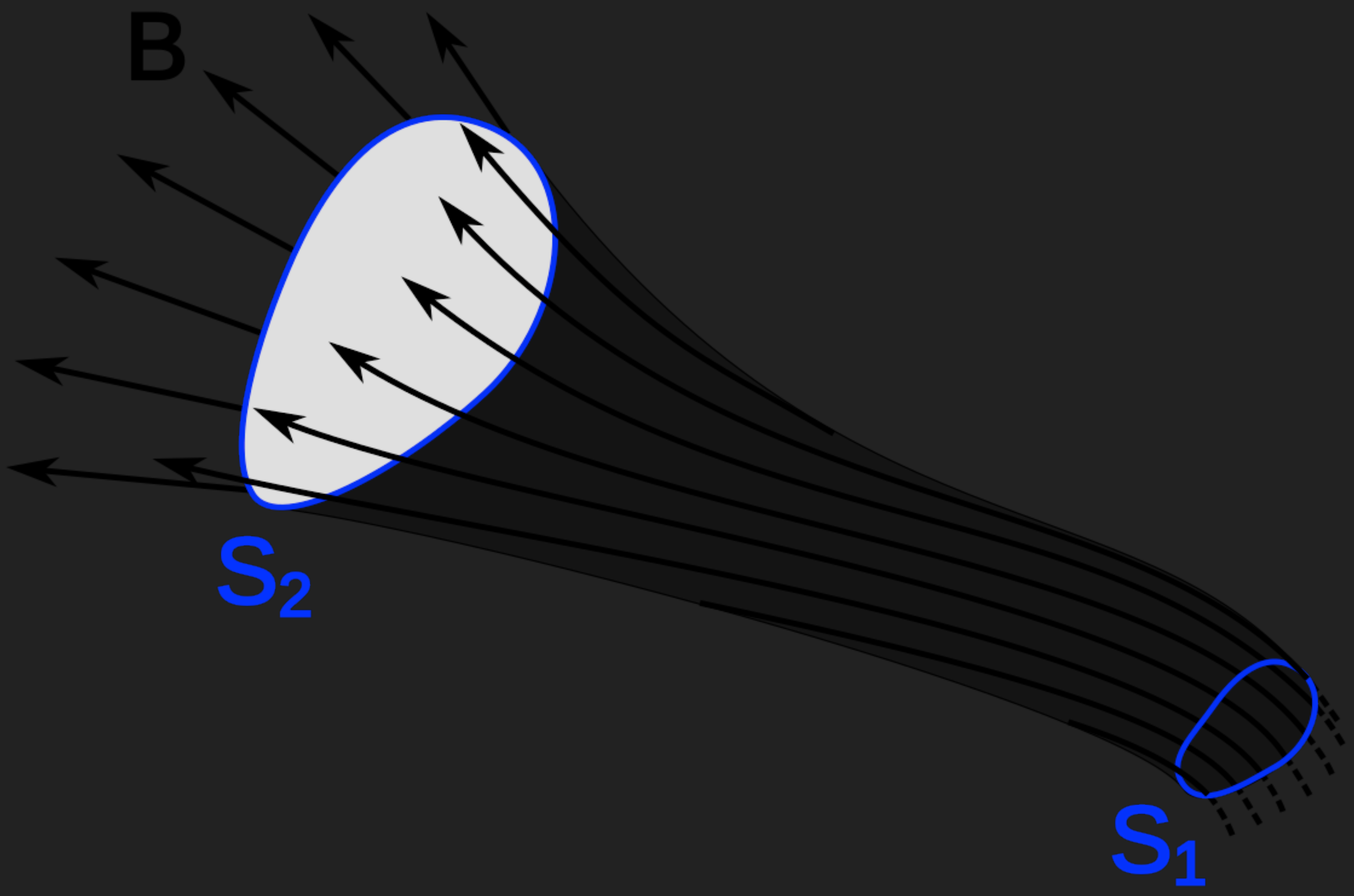

$$\Gamma_{CR} = \frac{16\pi^2}{3B_0^2}\frac{v_A}{kW(k)}\left(p^4 v(p)\frac{\partial f}{\partial z}\right)_{p_{res}}$$

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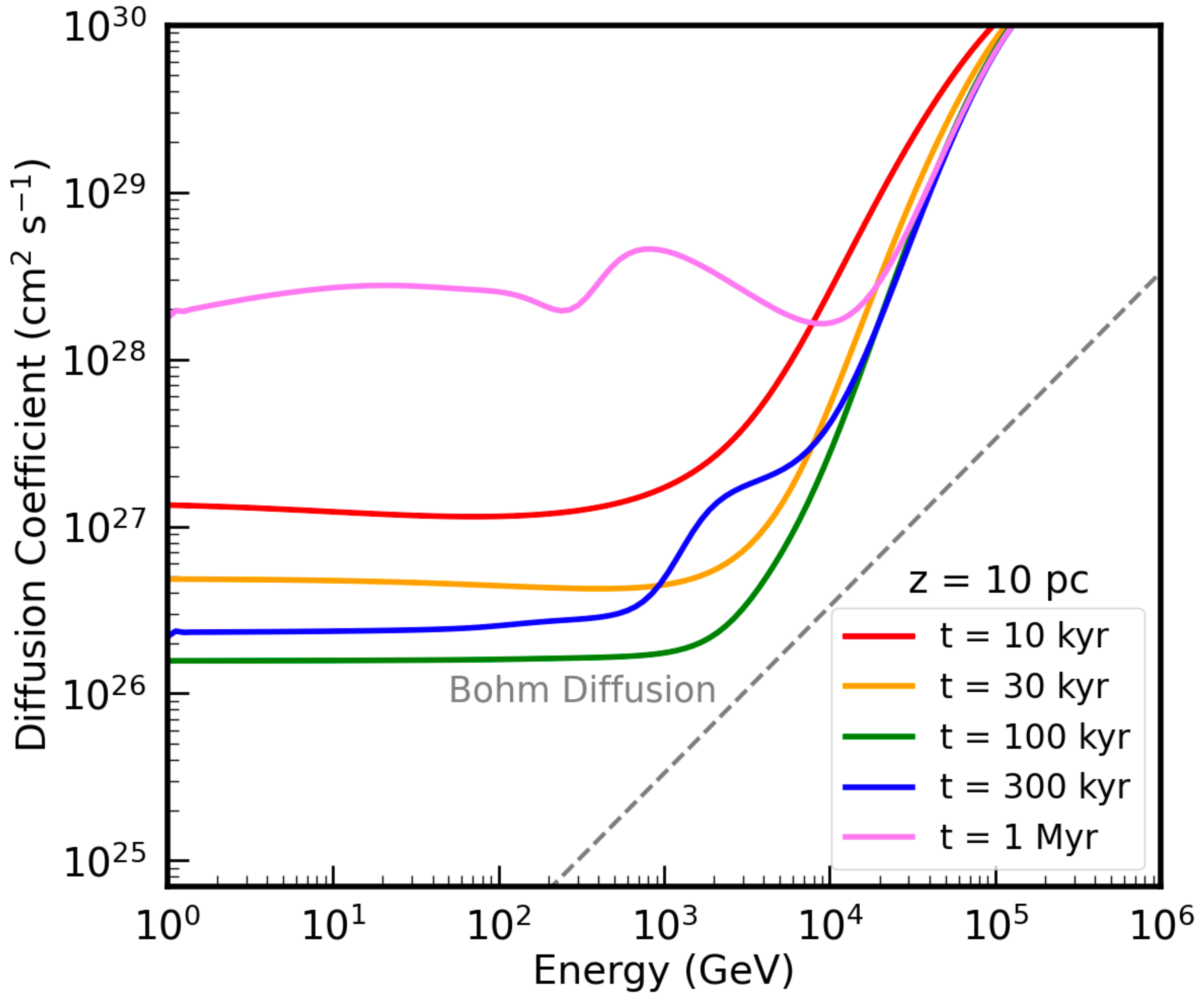
PUZZLE V: WHAT ARE TEV HALOS?

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

- 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!



TeV Halos:

Three Findings

And ~~Three Five!~~ Six! Puzzles

TIM LINDEN

Stockholm University

FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

PUZZLE VI: GLOBAL EFFECTS OF TEV HALOS

Origin of the Cosmic Ray Galactic Halo Driven by Advected Turbulence and Self-Generated Waves

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[1] *Gran Sasso Science Institute, Viale F. Crispi 7, L'Aquila, Italy*
[2] *INFN/Laboratori Nazionali del Gran Sasso, Via G. Acitelli 22, Assergi (AQ), Italy*
[3] *INAF/Osservatorio Astrofico di Arcetri, L.go E. Fermi 5, Firenze, Italy*

The diffusive paradigm for the transport of Galactic cosmic rays is central to our understanding of the origin of these high energy particles. However it is worth recalling that the normalization, energy dependence and spatial extent of the diffusion coefficient in the interstellar medium are fitted to the data and typically are not derived from more basic principles. Here we discuss a scenario in which the diffusion properties of cosmic rays are derived from a combination of wave self-generation and advection from the Galactic disc, where the sources of cosmic rays are assumed to be located. We show for the first time that a halo naturally arises from these phenomena, with a size of a few kpc, compatible with the value that typically best fits observations in simple parametric approaches to cosmic ray diffusion. We also show that transport in such a halo results in a hardening in the spectra of primary cosmic rays at ~ 300 GV.

0 Jul 2018

Introduction – Understanding cosmic-ray (CR) propagation in the Galaxy and its implications for observations at dif-

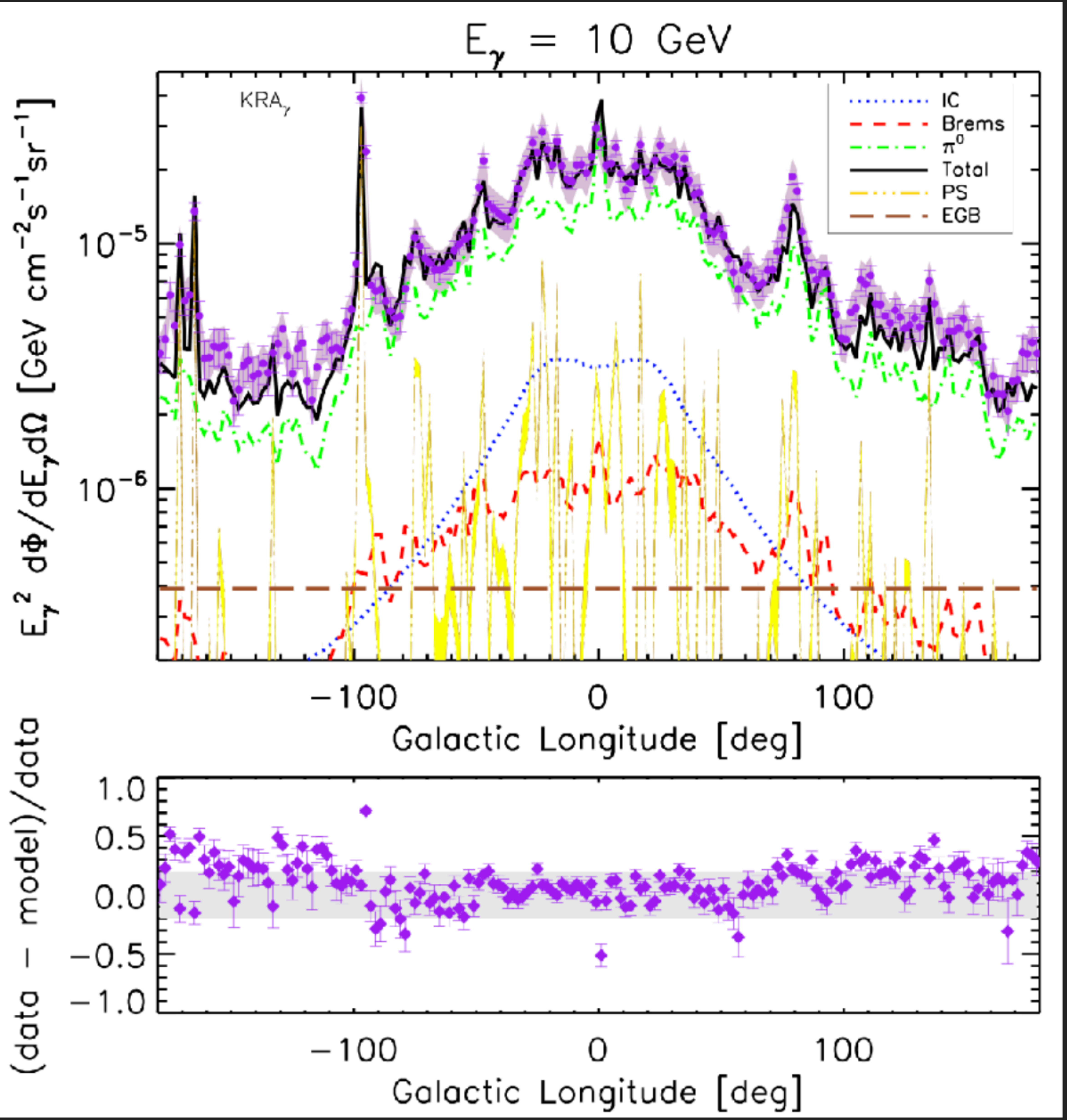
grammage that scales with rigidity as $R^{-1/3}$, that is claimed to be consistent with the diffusion coefficient expected from

PUZZLE VI: GLOBAL EFFECTS OF TEV HALOS

Gaggero et al. 2022 (1411.7623)

- Models of Gamma-Ray data provide better fits to diffuse emission if CR propagation is inhibited near the GC.

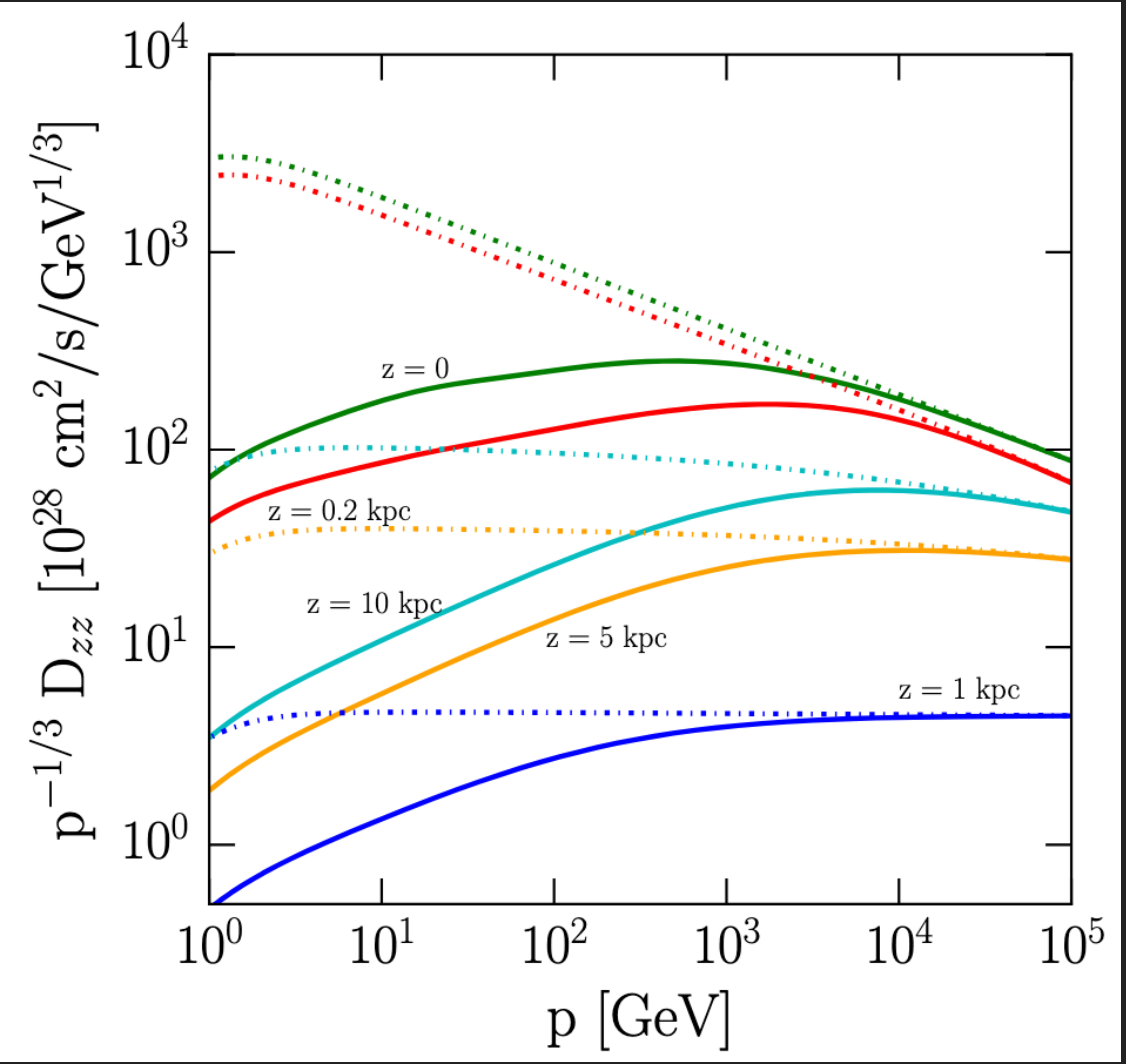
- Indicative of source-produced effects.



PUZZLE VI: GLOBAL EFFECTS OF TEV HALOS

Evoli et al. (2018; 1806.05143)

- These models only use CR protons.
- Dominate global diffusion below 1 TeV, but are subdominant at high energies (need background diffusion).
- Leptons can contribute!

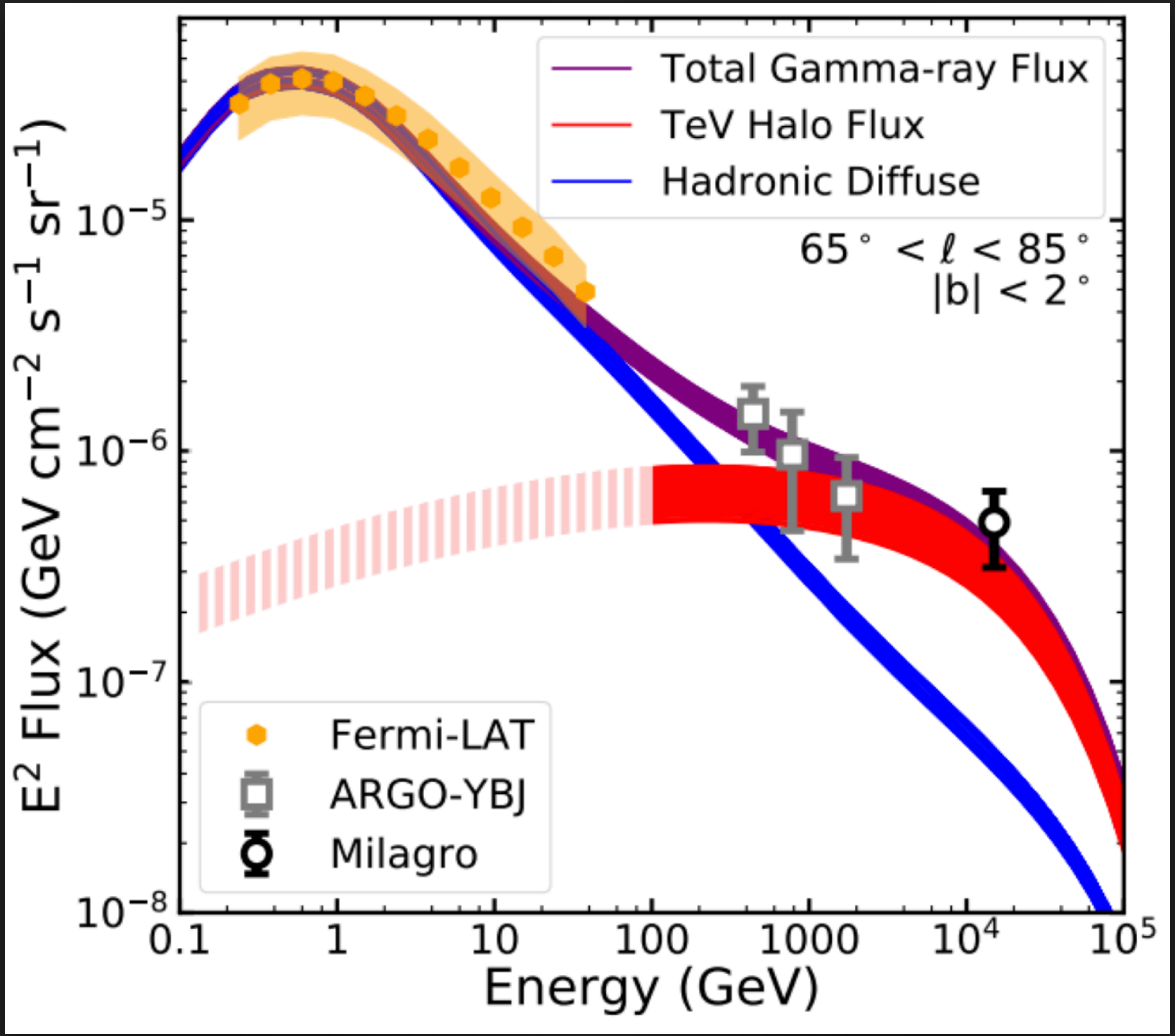


PUZZLE VI: GLOBAL EFFECTS OF TEV HALOS

- While the e+e- density is subdominant, their effects are more local, enhancing the streaming instability.

$$\Gamma_{CR} = \frac{16\pi^2}{3B_0^2}\frac{v_A}{kW(k)}\left(p^4 v(p)\frac{\partial f}{\partial z}\right)_{p_{res}}$$

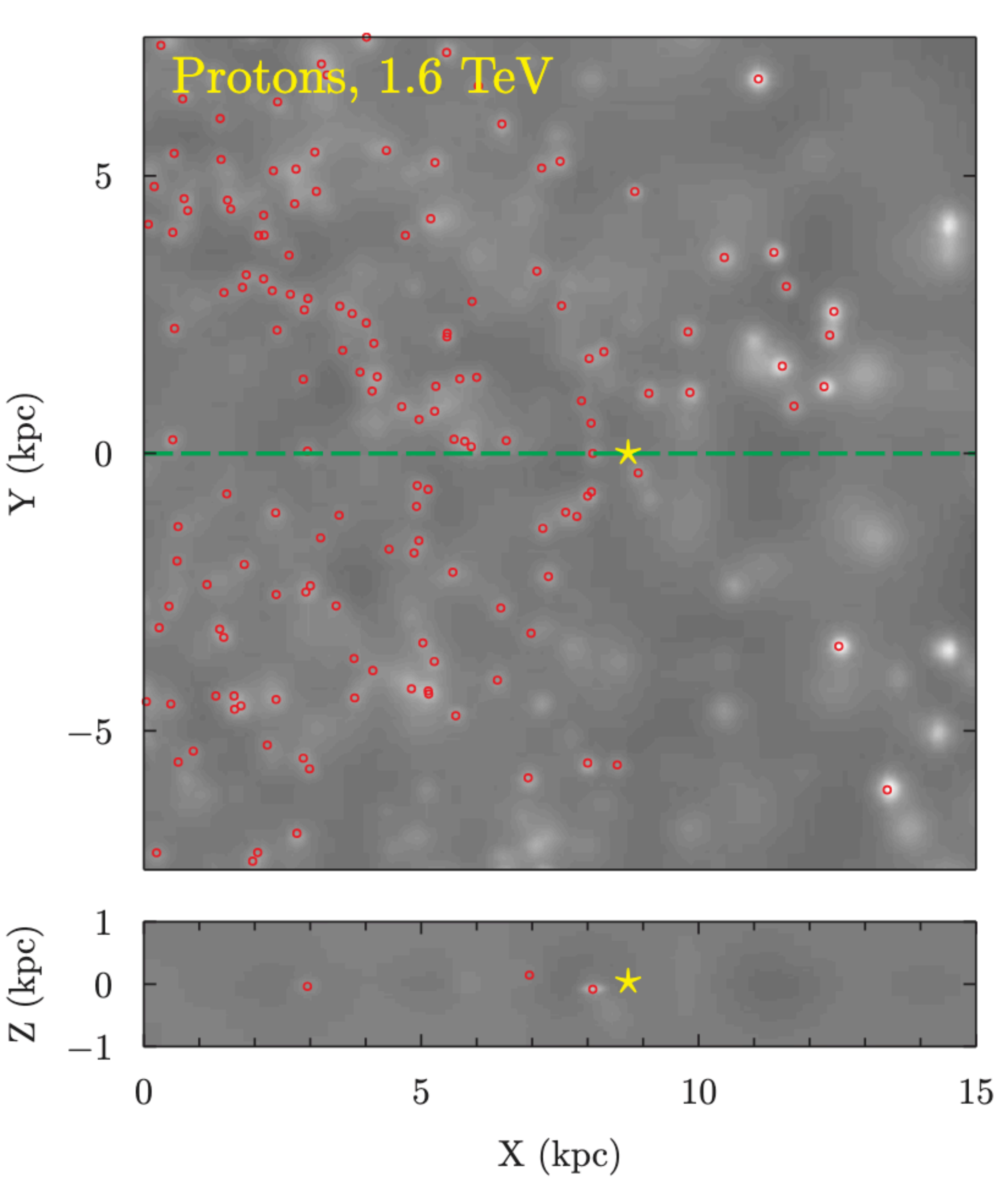
- This is particularly true at high energies!

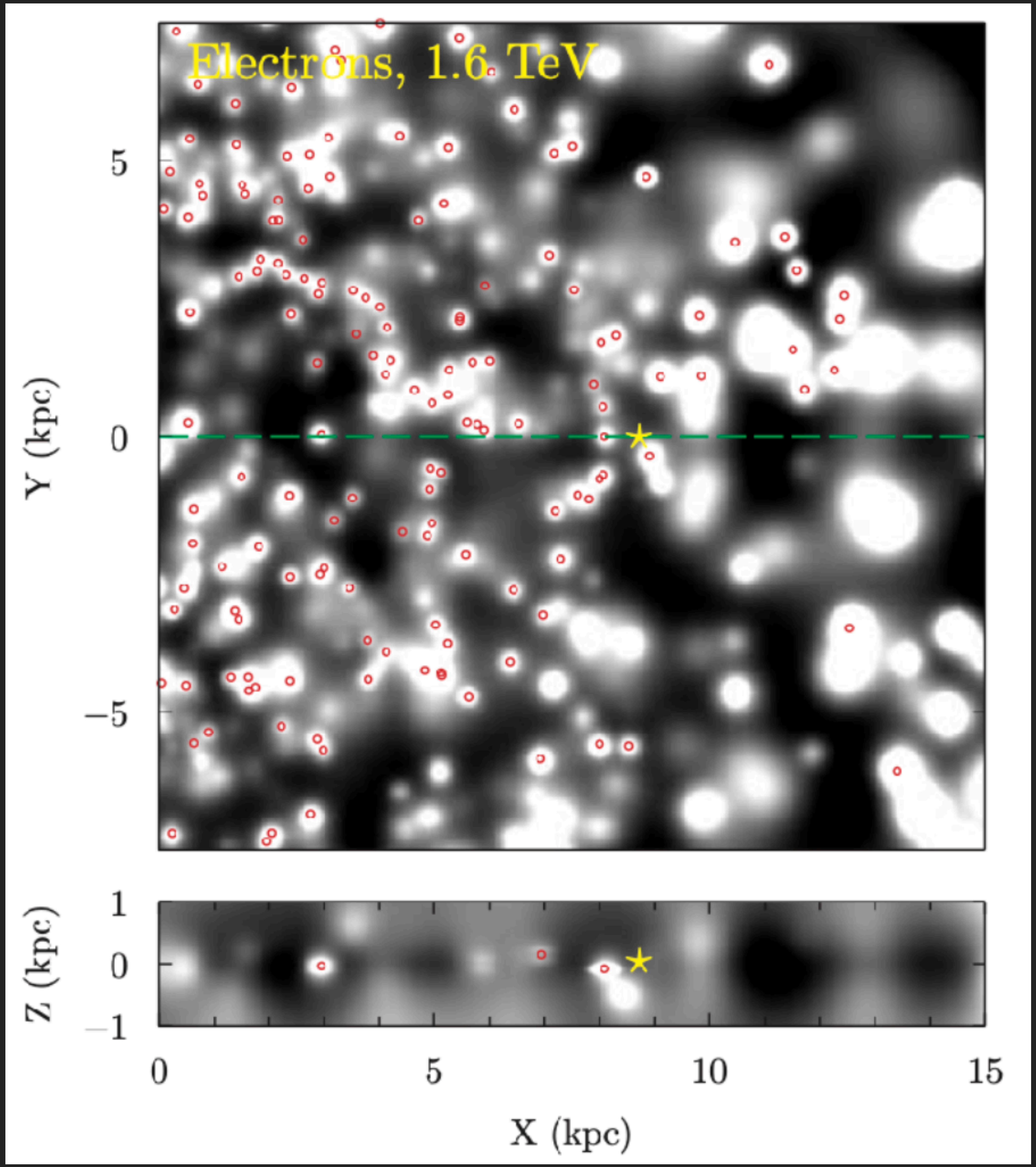


PUZZLE VI: GLOBAL EFFECTS OF TEV HALOS

Porter et al. 2019 (1909.02223)

See also: Thaler et al. 2022 (2209.02295)





TeV Halos:
The Key to a Self-Consistent Model?

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.