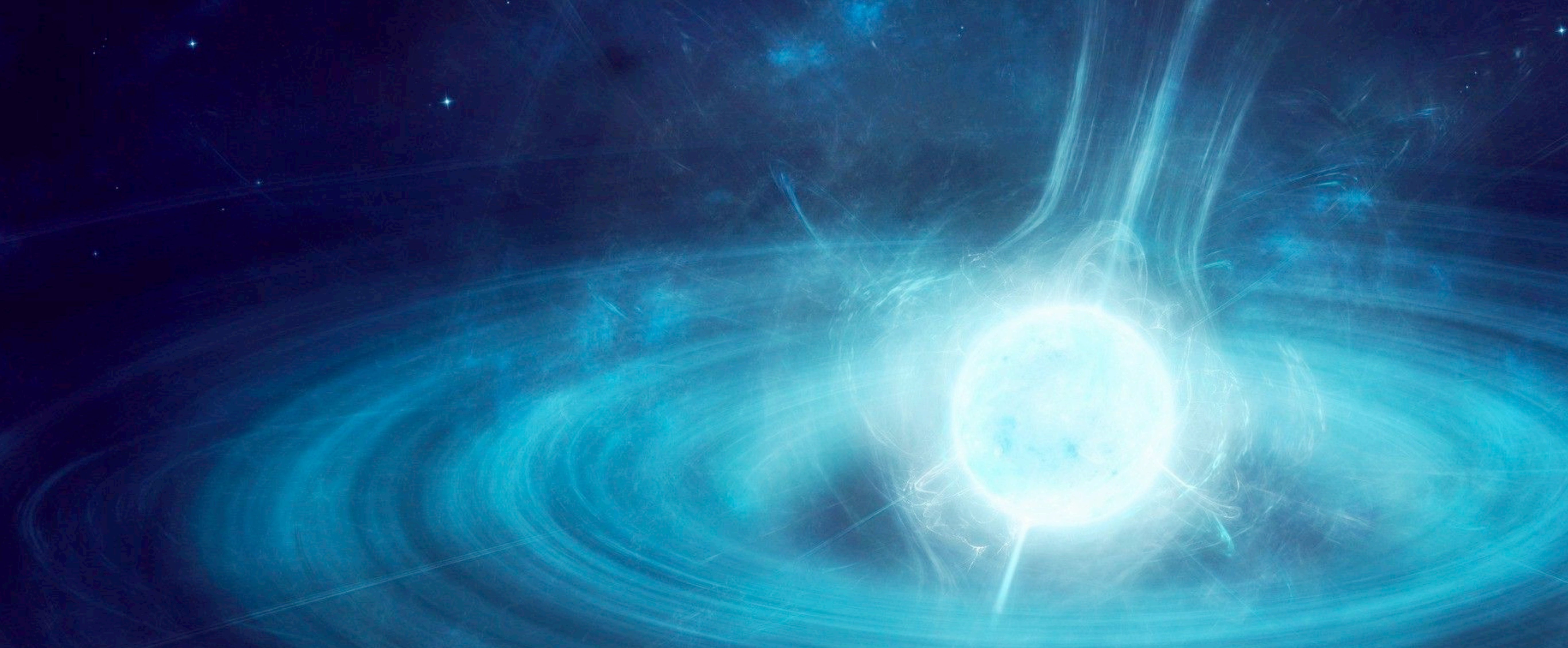


TIM LINDEN

THE RISE OF THE LEPTONS

PULSAR EMISSION DOMINATES THE TEV GAMMA-RAY SKY

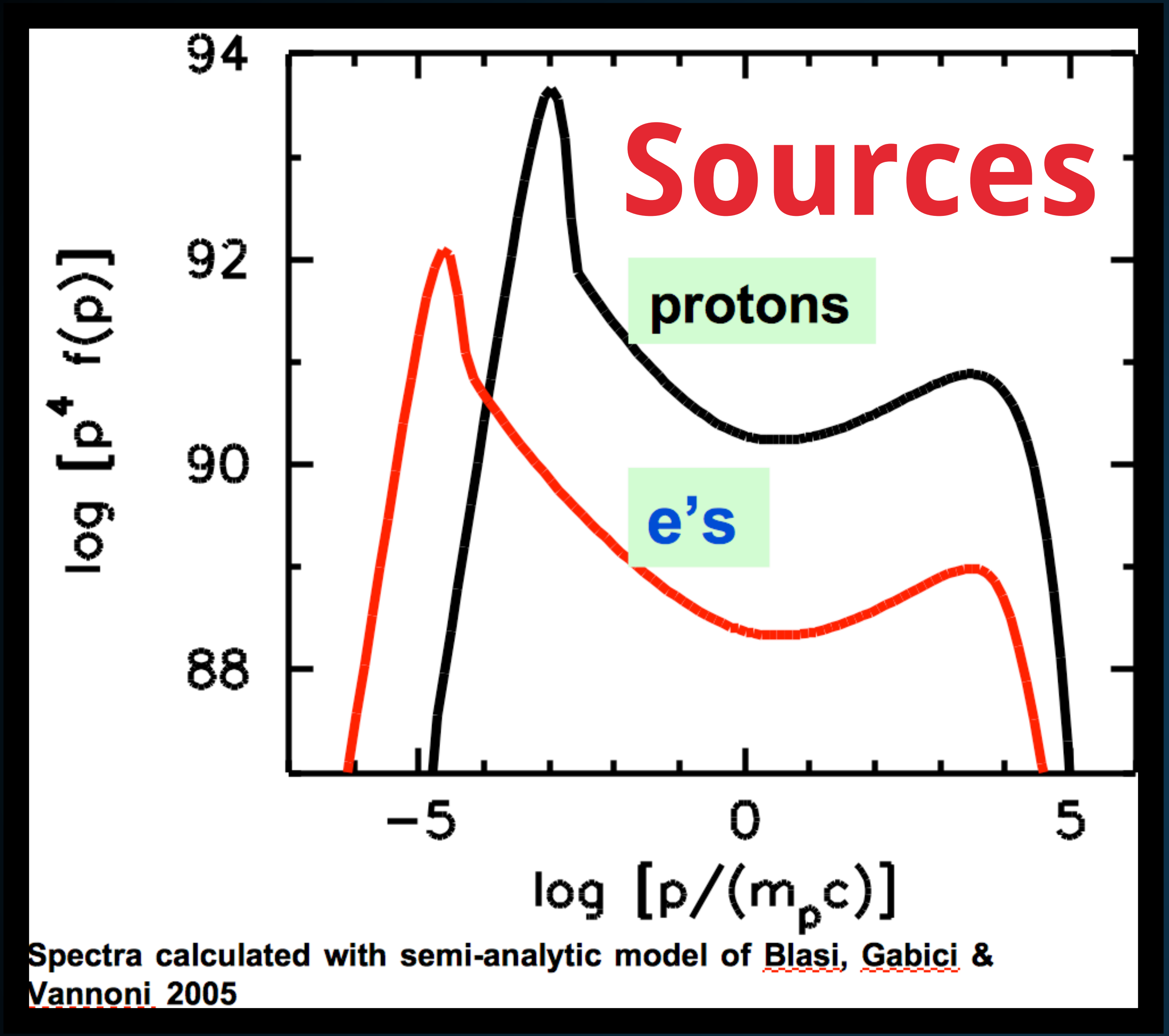
Michelson Postdoctoral Prize Lectures
Case Western Reserve University
October 2, 2018

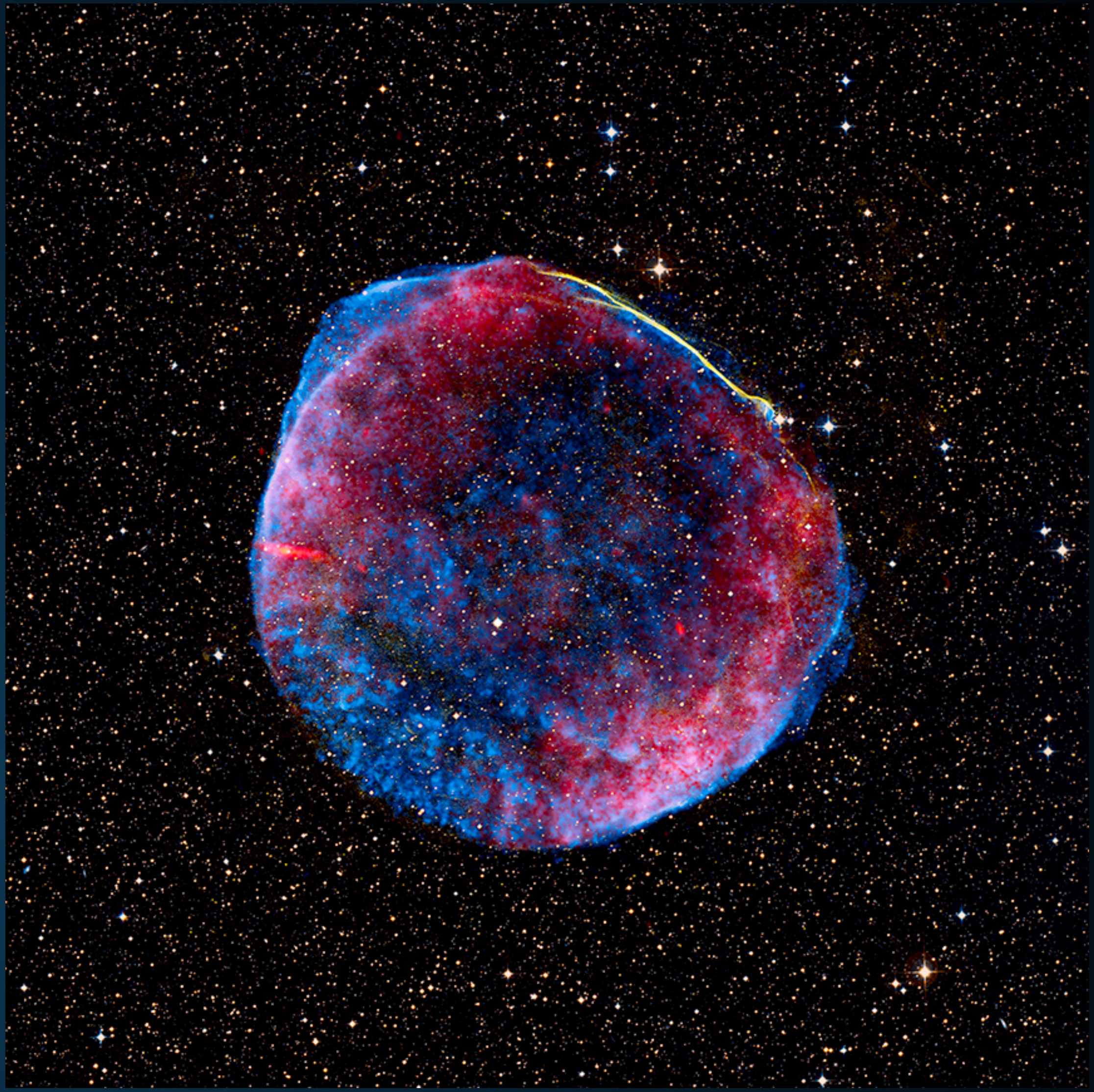
The Ohio State University
Center for Cosmology and Astroparticle Physics

A UNIVERSE DOMINATED BY PROTONS

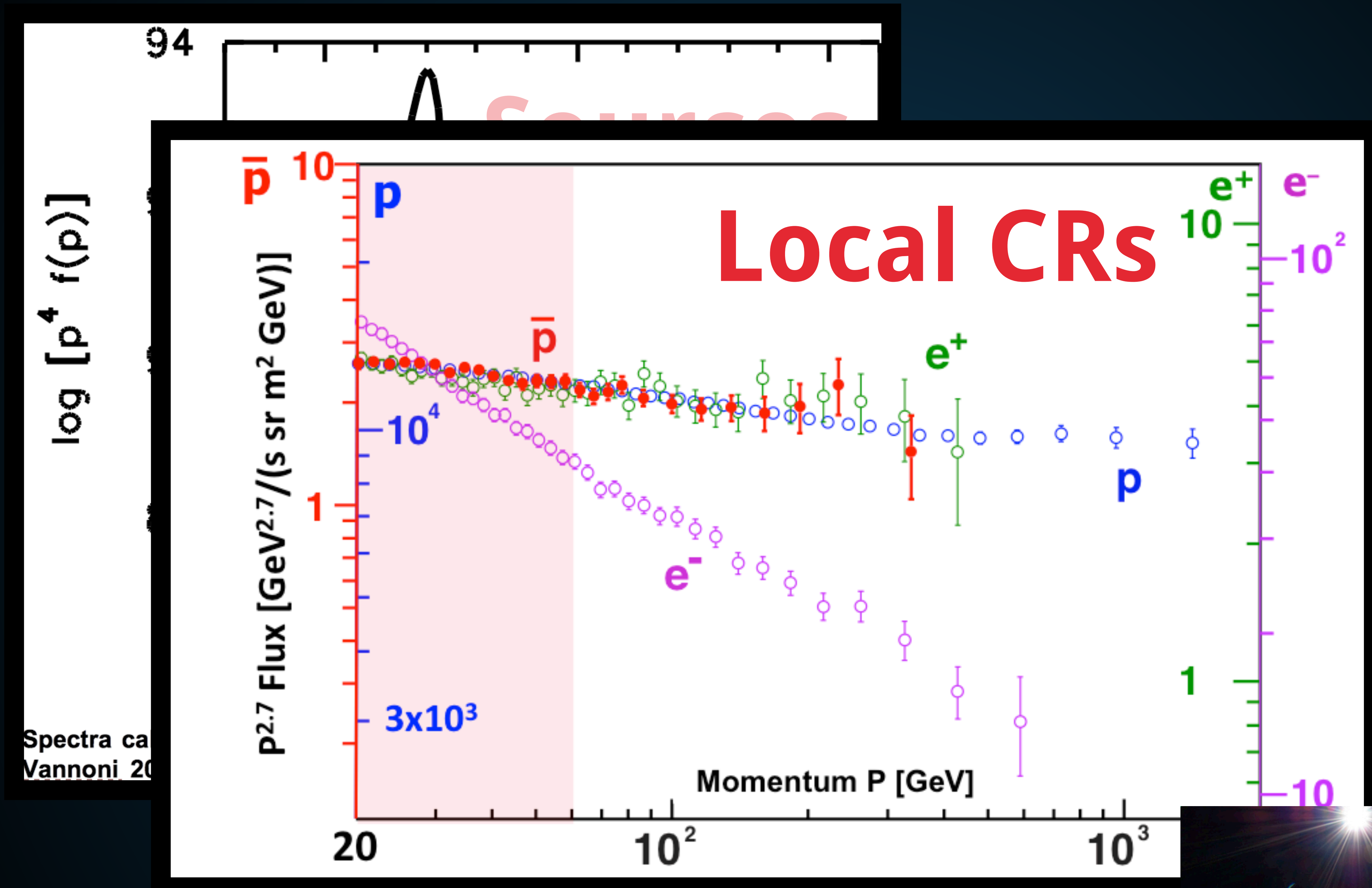
We normally think that the Milky Way cosmic-ray energy budget is dominated by protons.

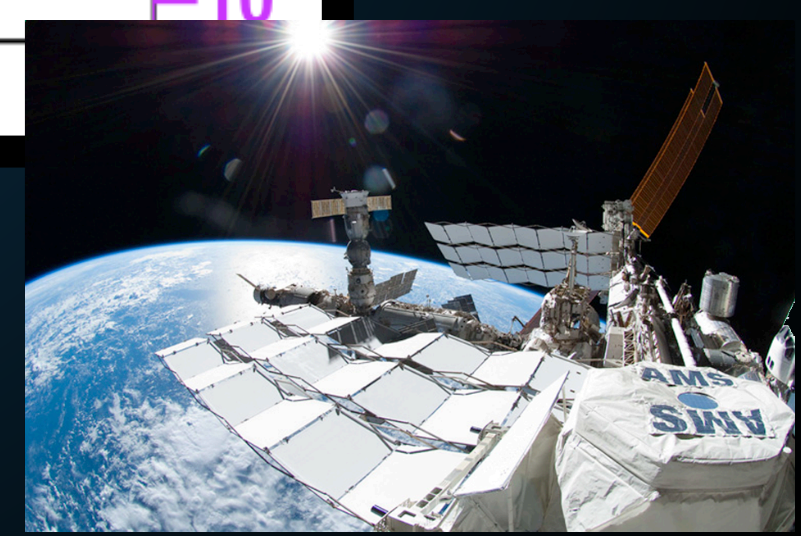
A UNIVERSE DOMINATED BY PROTONS



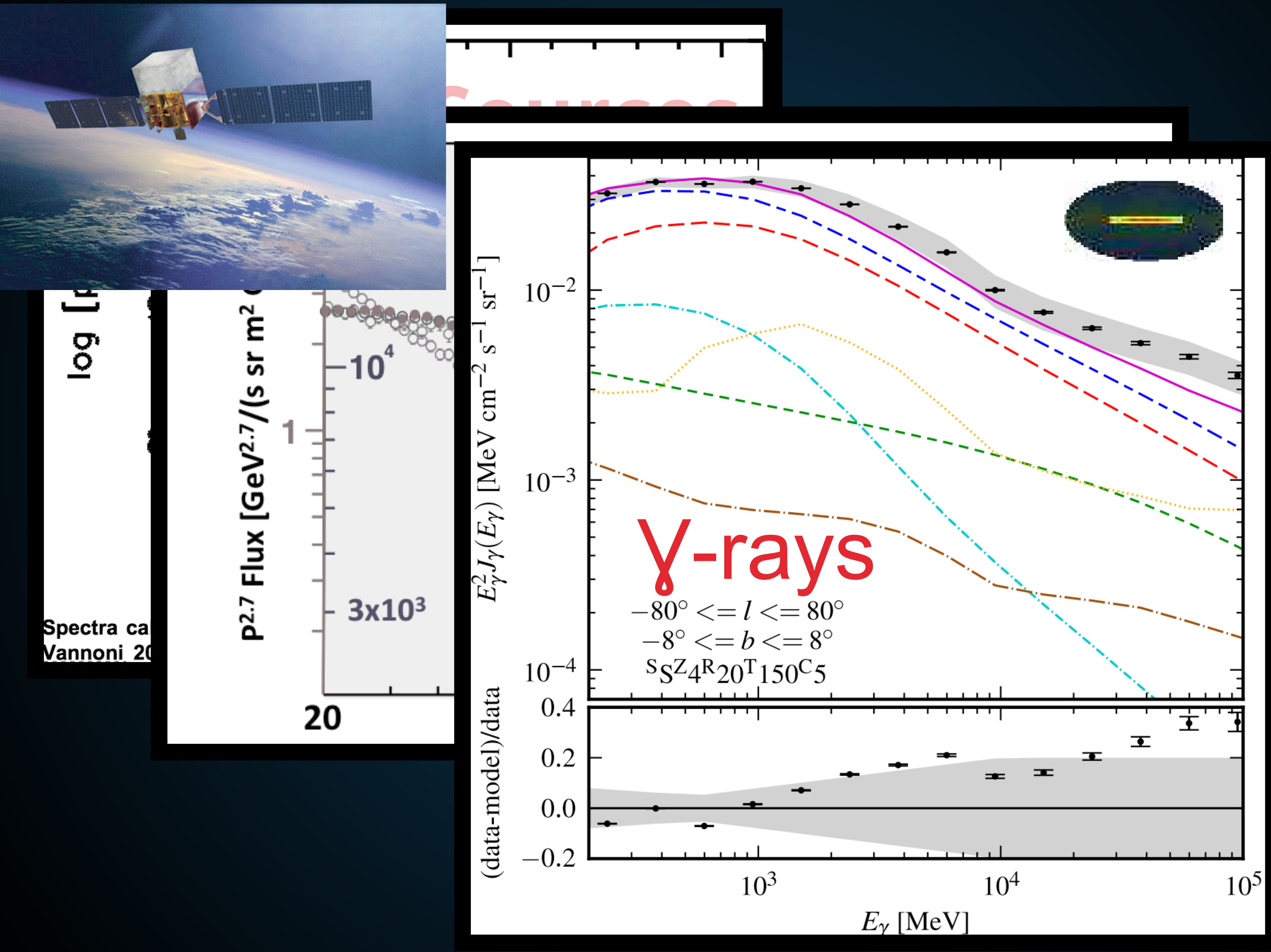


A UNIVERSE DOMINATED BY PROTONS



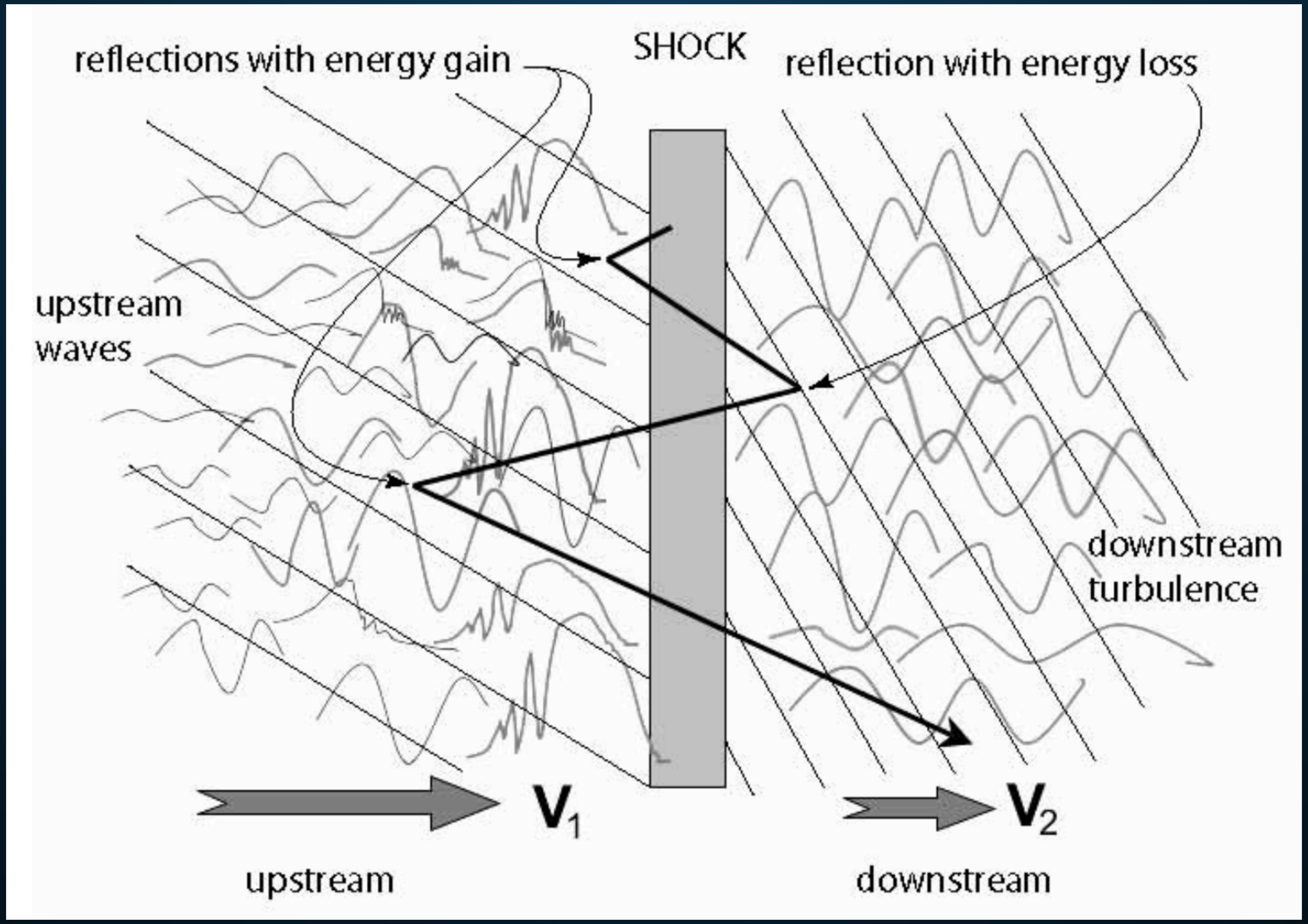


A UNIVERSE DOMINATED BY PROTONS

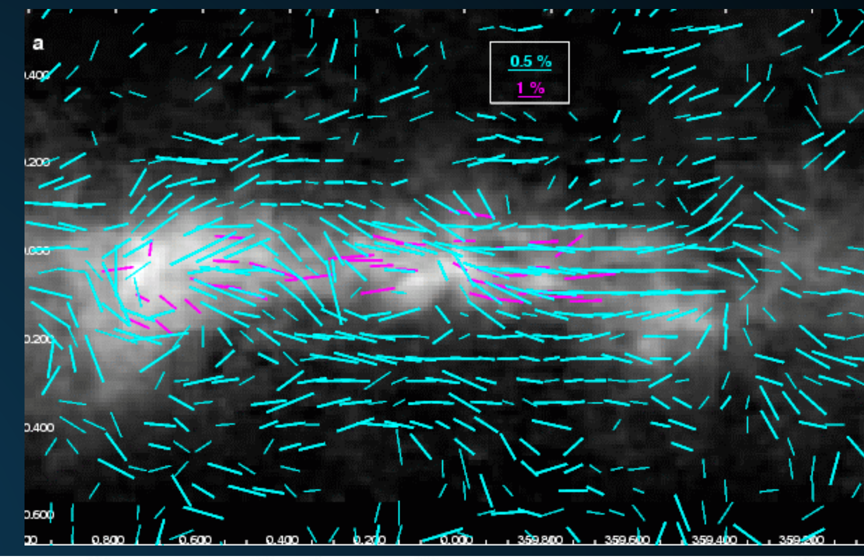


Start with a source of relativistic cosmic-rays

- Supernova Explosions
- Supernova Remnants
- Shocks/Mergers



Start with a source of relativistic cosmic-rays



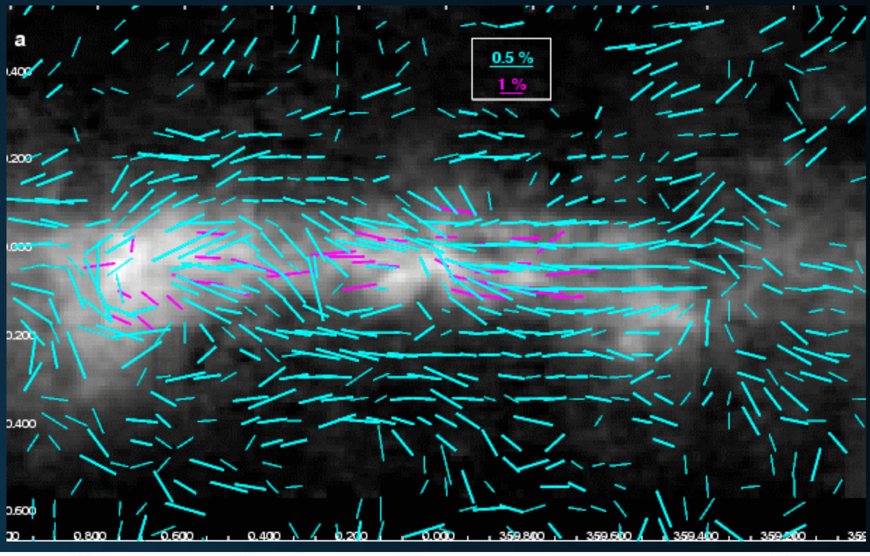
cosmic rays propagate

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

Solved Numerically:
e.g. Galprop

- **If they propagate to Earth, can be detected:**
  - **AMS-02/PAMELA**
  - **CREAM/HEAT/CAPRICE**

Start with a source of relativistic cosmic-rays

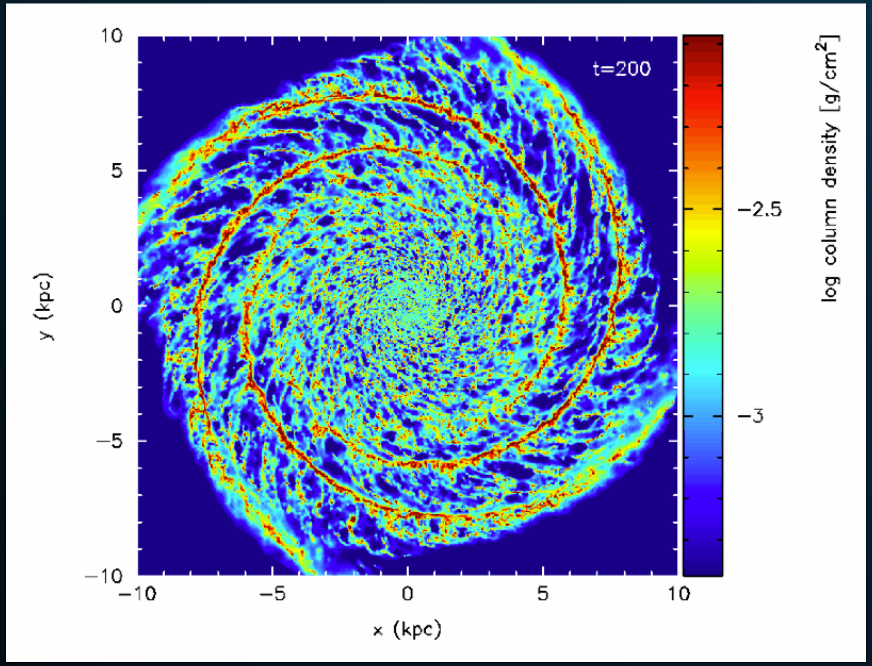


cosmic rays propagate

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

Solved Numerically:
e.g. Galprop

Gas/ISRF

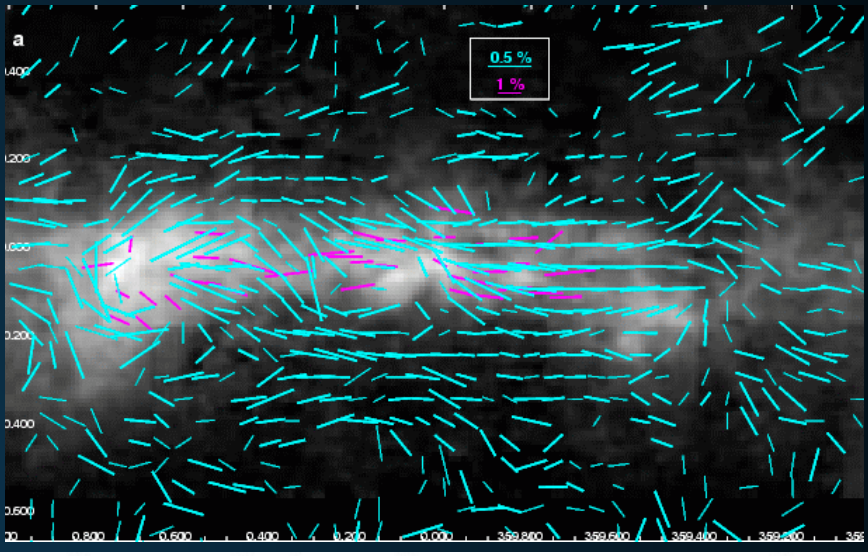


- **Alternatively can collide with Galactic gas or the interstellar radiation field.**

COSMIC-RAY ACCELERATION AND PROPAGATION

Start with a source of relativistic cosmic-rays

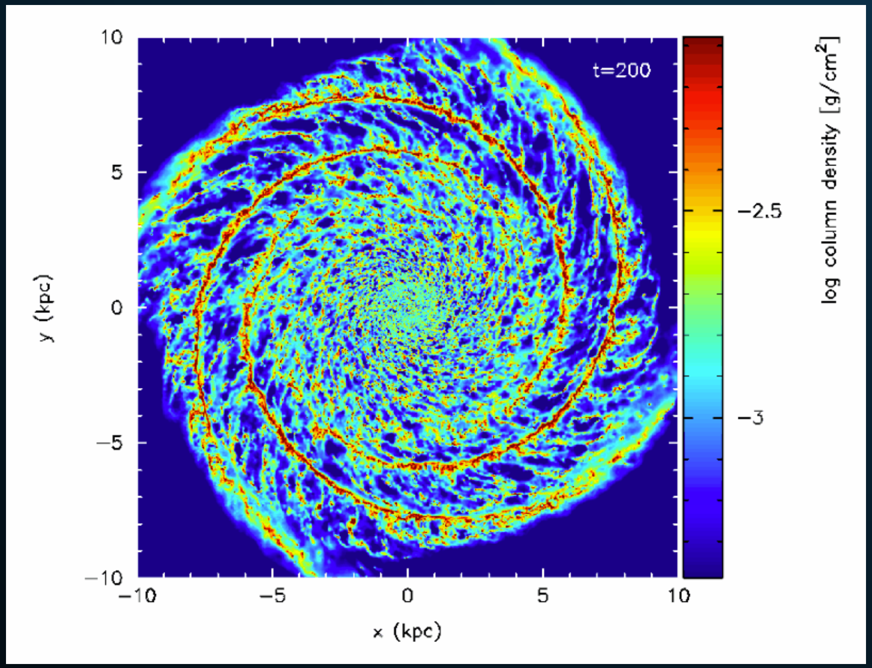
cosmic rays propagate

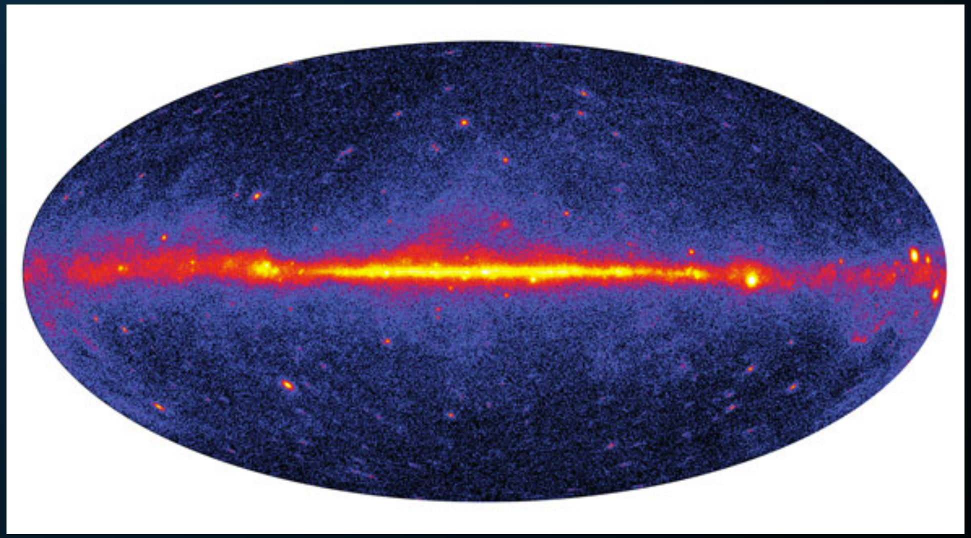


$$\frac{\partial \psi}{\partial t} = q(\vec{r},p) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi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

Solved Numerically:
e.g. Galprop

Gas/ISRF





A NEW PICTURE

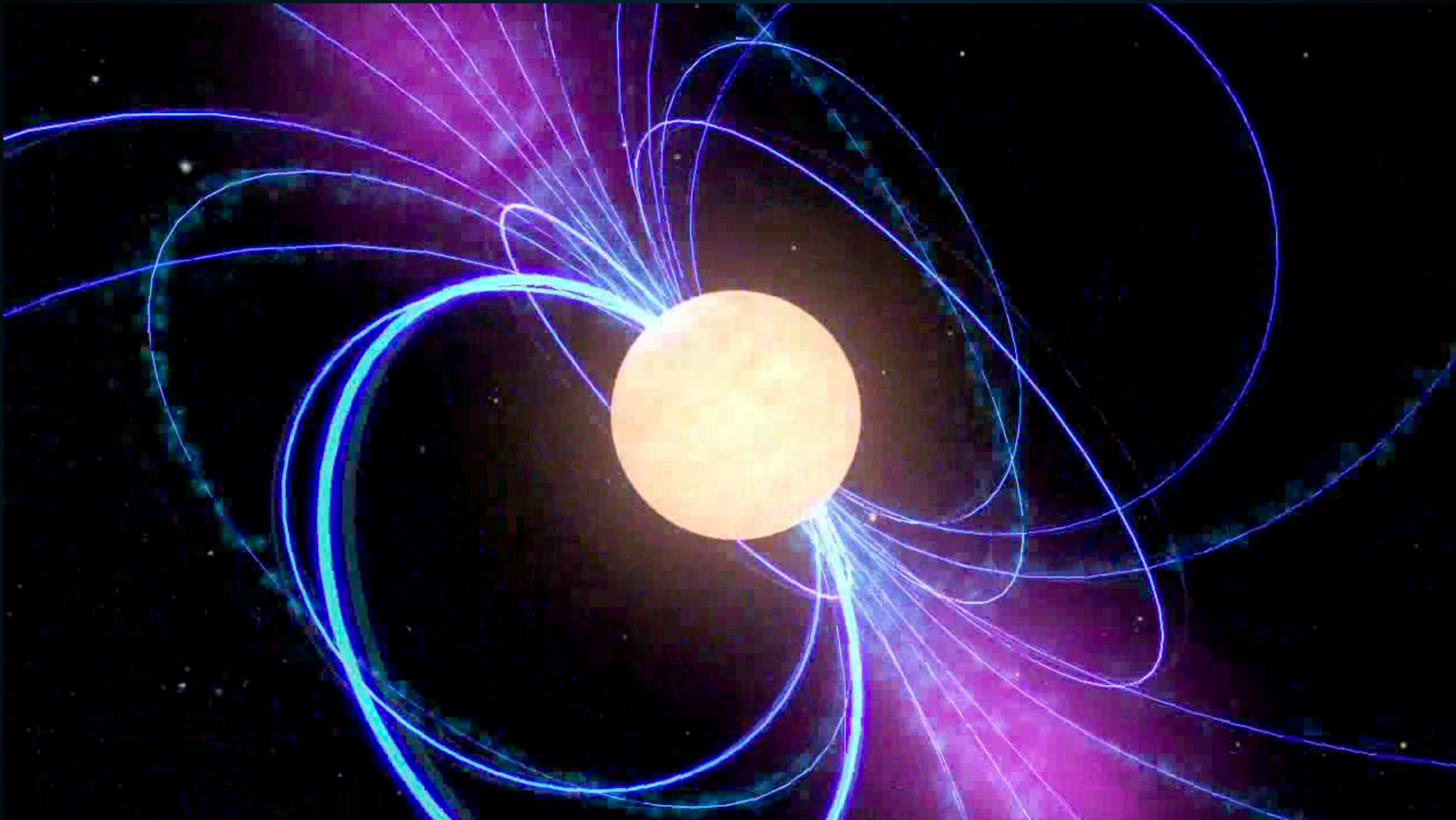
- **In this talk, I will argue that electrons and positrons dominate the Milky Way's energetics at TeV energies:**
  - **1.) Pulsars produce the majority of the TeV gamma-ray emission observed from the Milky Way**
  - **2.) Pulsars produce the majority of the bright TeV sources observed by CTA/HAWC/HESS etc.**
  - **3.) Pulsars are responsible for the rising positron fraction observed by PAMELA/AMS-02**

A NEW PICTURE

- **Always worry about the assumptions behind bold statements:**
    - **Observations necessitate these results.**
    - **Very few (and reasonable) modeling assumptions**

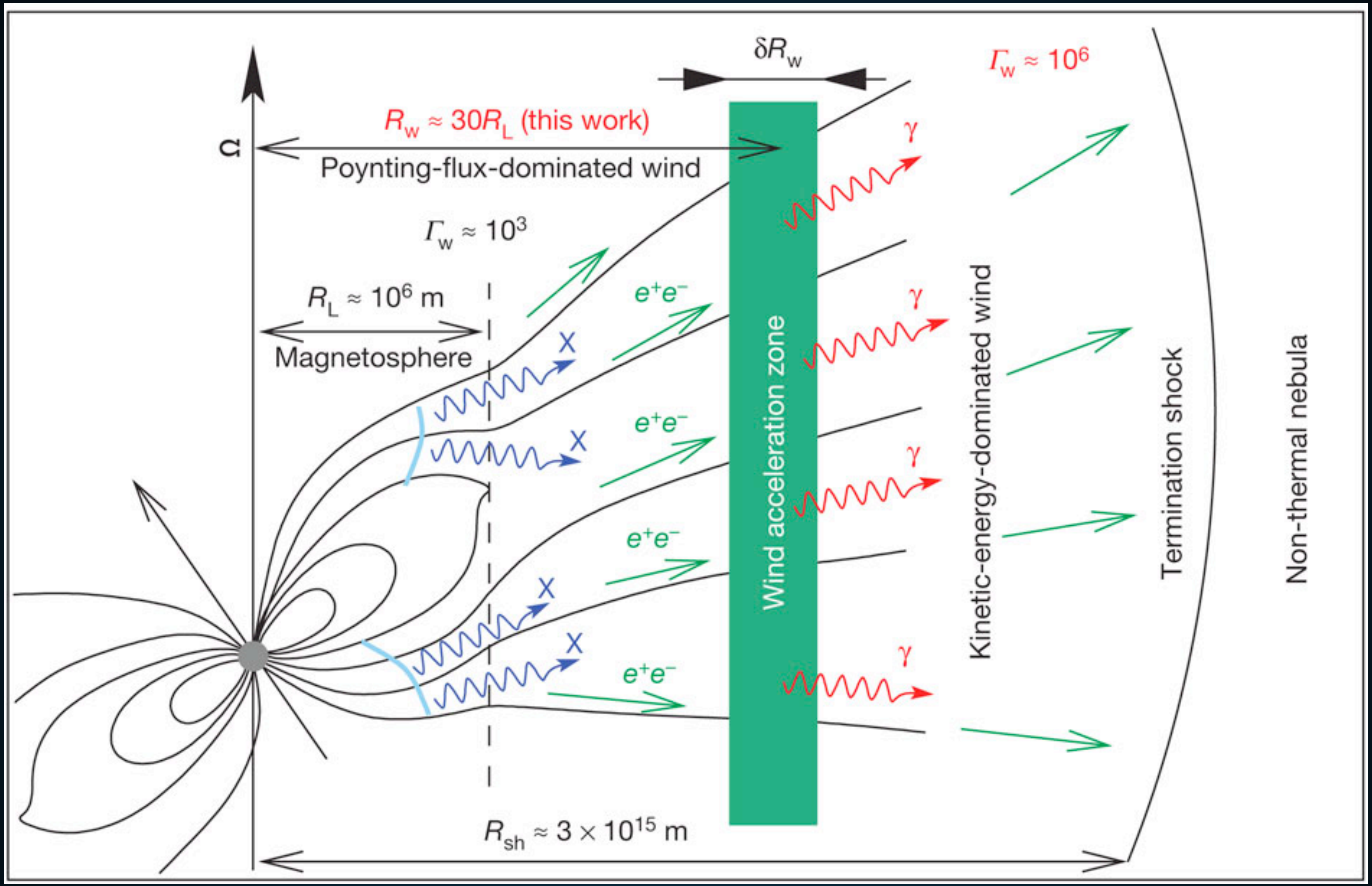
What do we know about pulsars?

PULSARS AS ASTROPHYSICAL ACCELERATORS



- **Rotational Kinetic Energy of the neutron star is the <u>ultimate power source</u> of all emission in this problem.**

PRODUCTION OF ELECTRON AND POSITRON PAIRS



- Electrons boiled off the pulsar surface produce e^+e^- pairs.
- Final e+e- Spectrum is model dependent.

REACCELERATION IN THE PULSAR WIND NEBULA

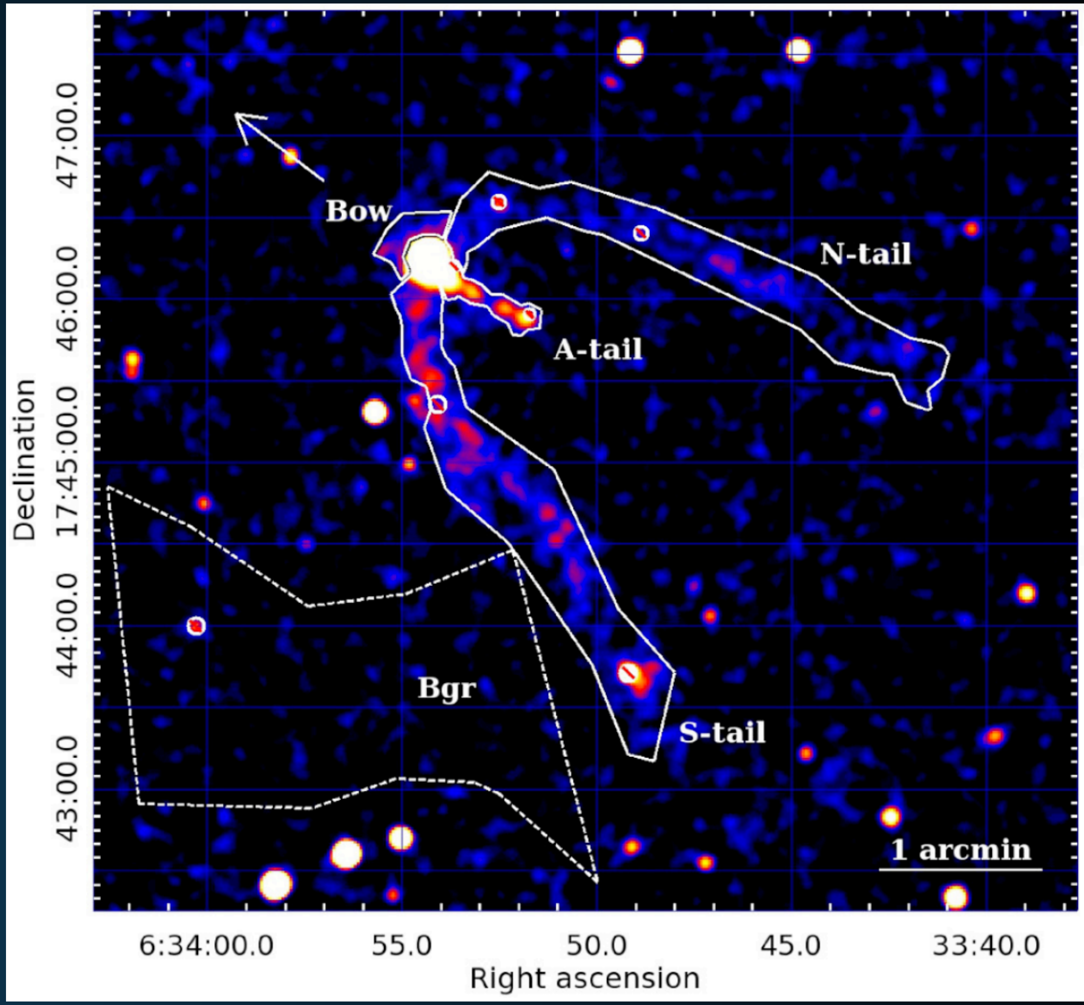
- **PWN termination shock:**
  - **Voltage Drop > 30 PV**
  - **e^+e^- energy > 1 PeV (known from synchrotron)**
- **Resets e^+e^- spectrum.**
- **Many Possible Models:**
  - **1st Order Fermi-Acceleration**
  - **Magnetic Reconnection**
  - **Shock-Driven Reconnection**

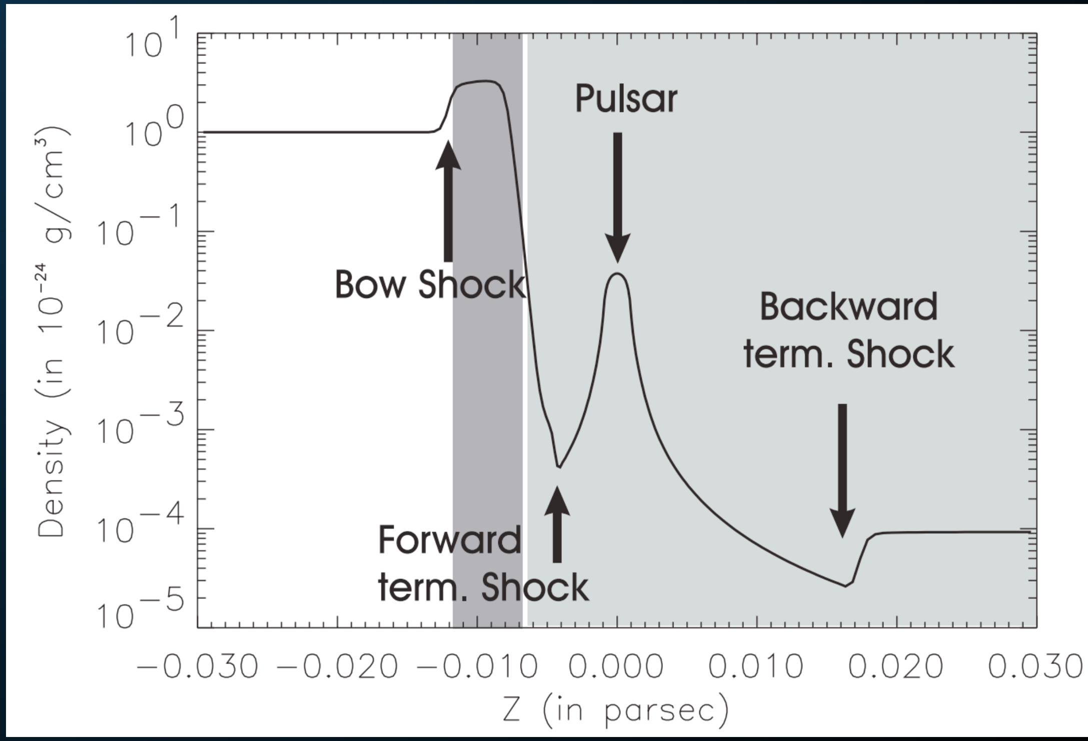
LOW-ENERGY OBSERVATIONS OF PULSAR WIND NEBULAE

- **Extent of radio and X-Ray PWN is approximately 1 pc.**
- **Termination shock produced when ISM energy density stops the relativistic pulsar wind.**

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

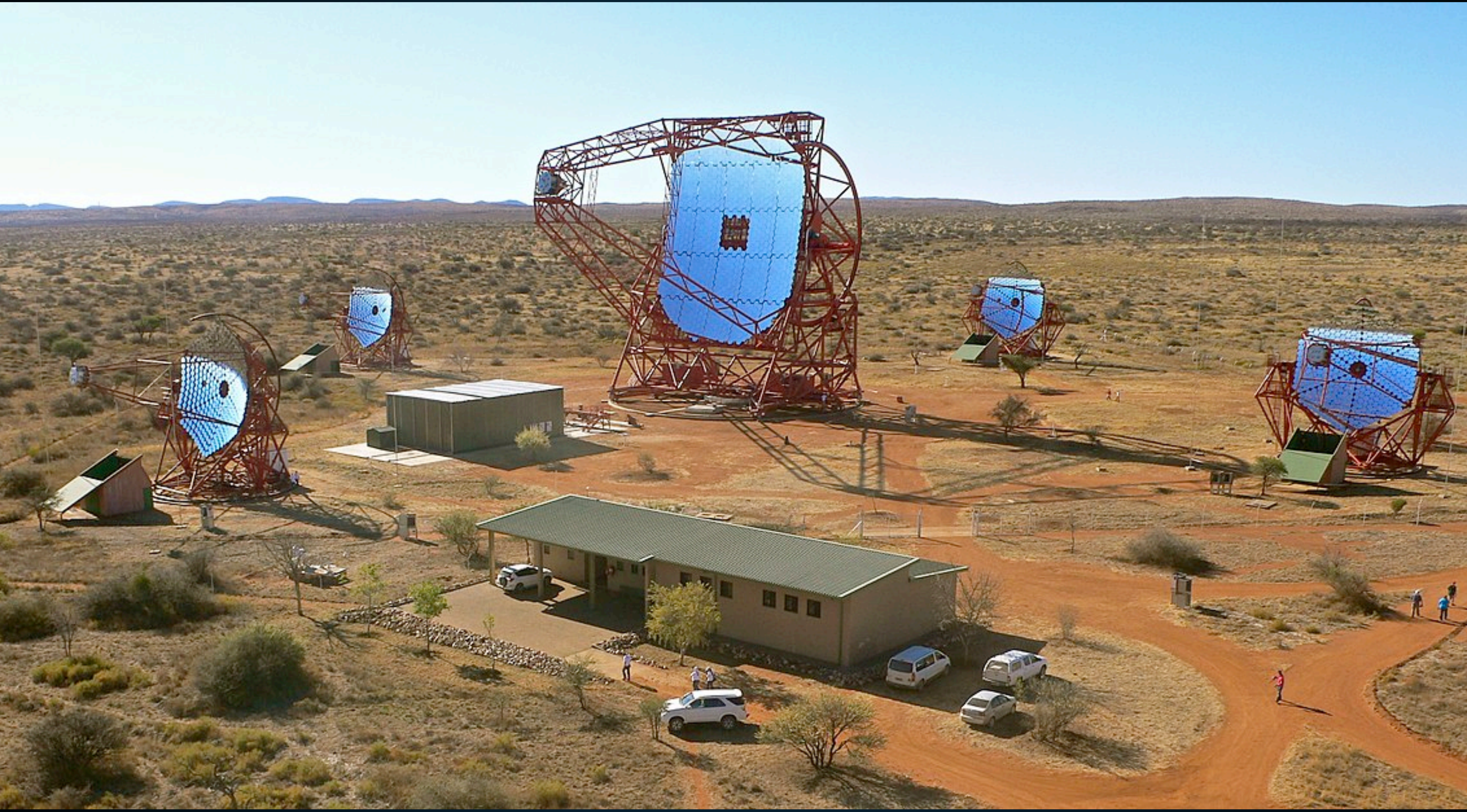
- **NOTE: The radial extent of PWN is explained by a known physical mechanism.**

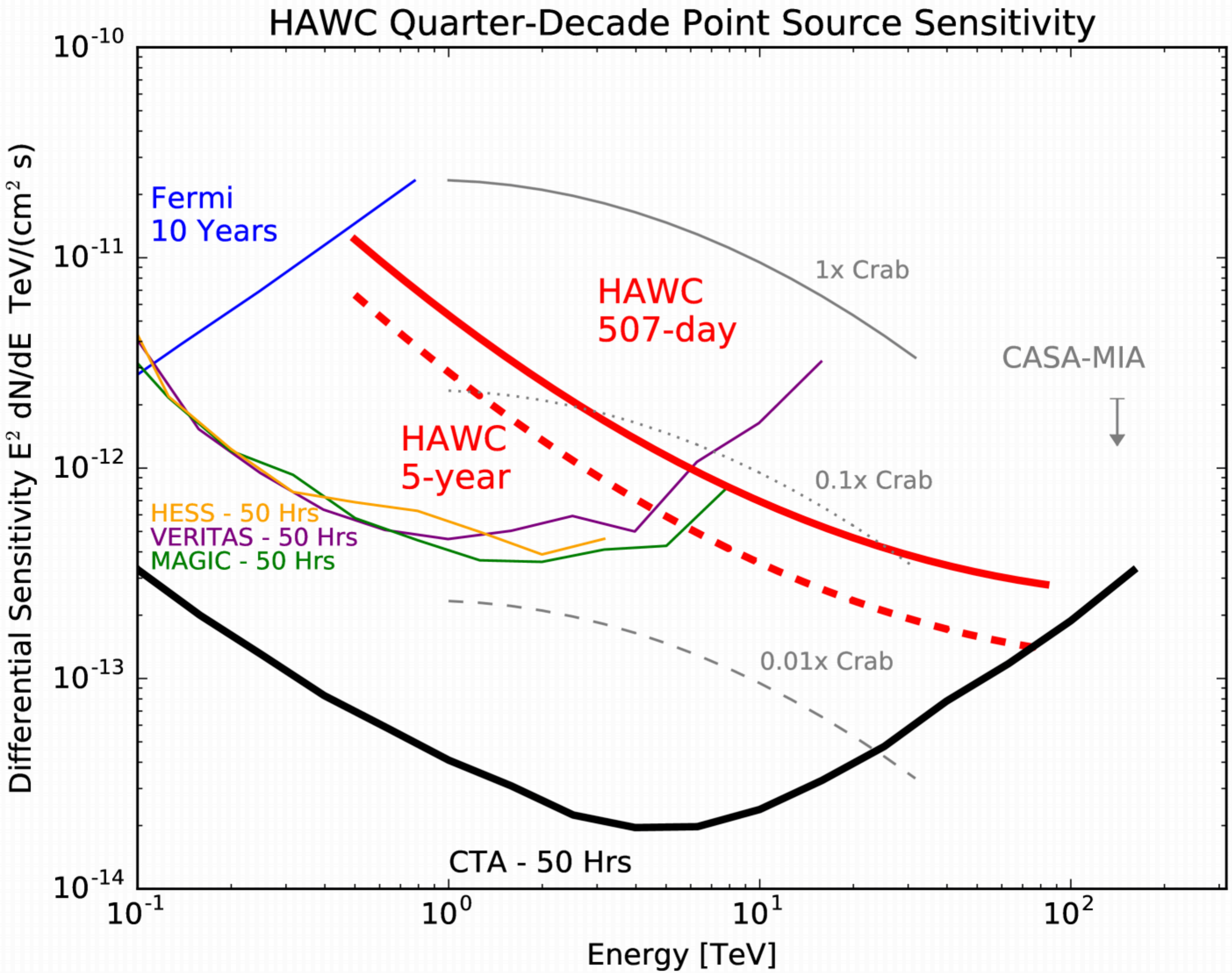




HIGH ALTITUDE WATER CHERENKOV TELESCOPE

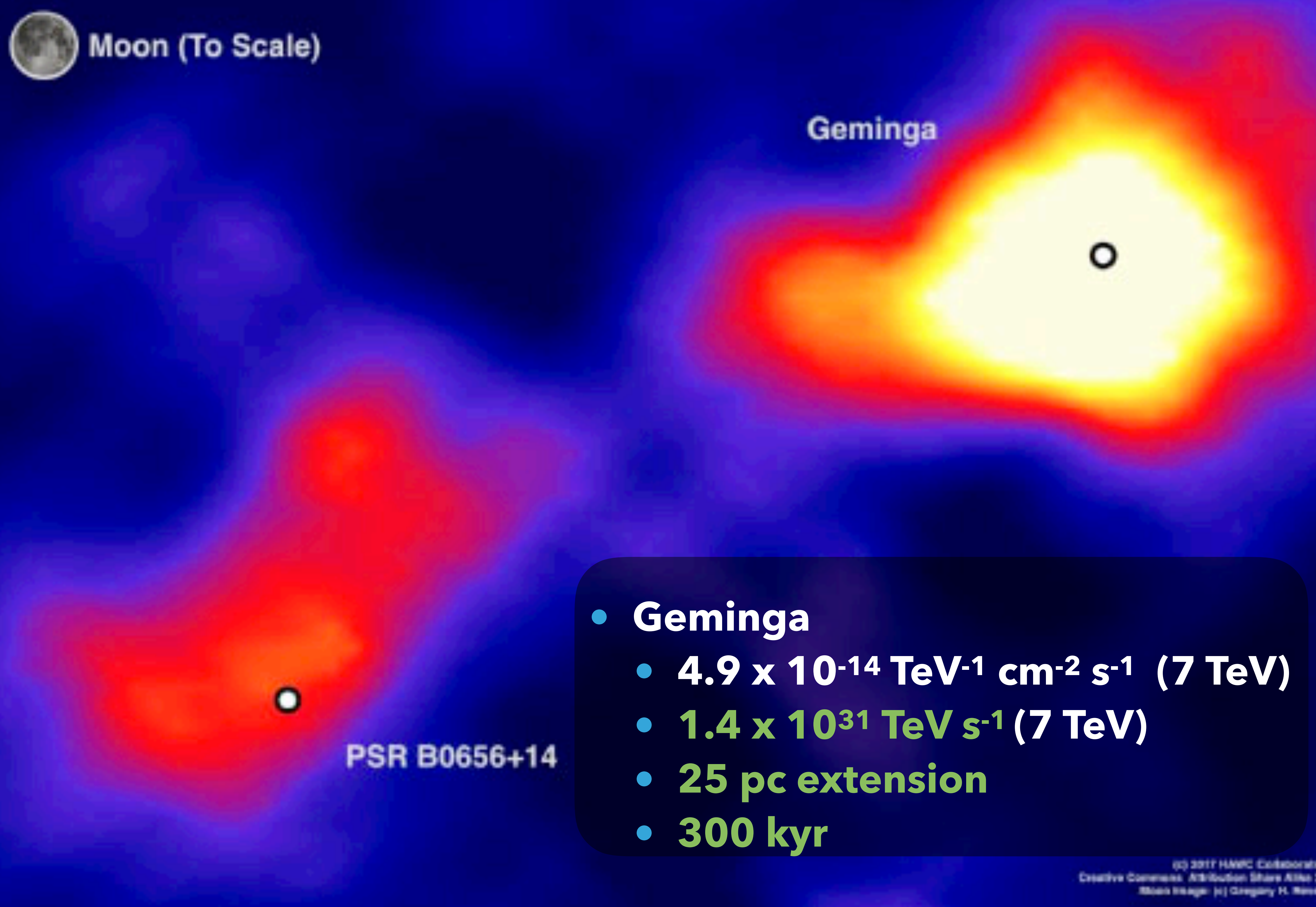
HIGH ENERGY SPECTROSCOPIC SYSTEM





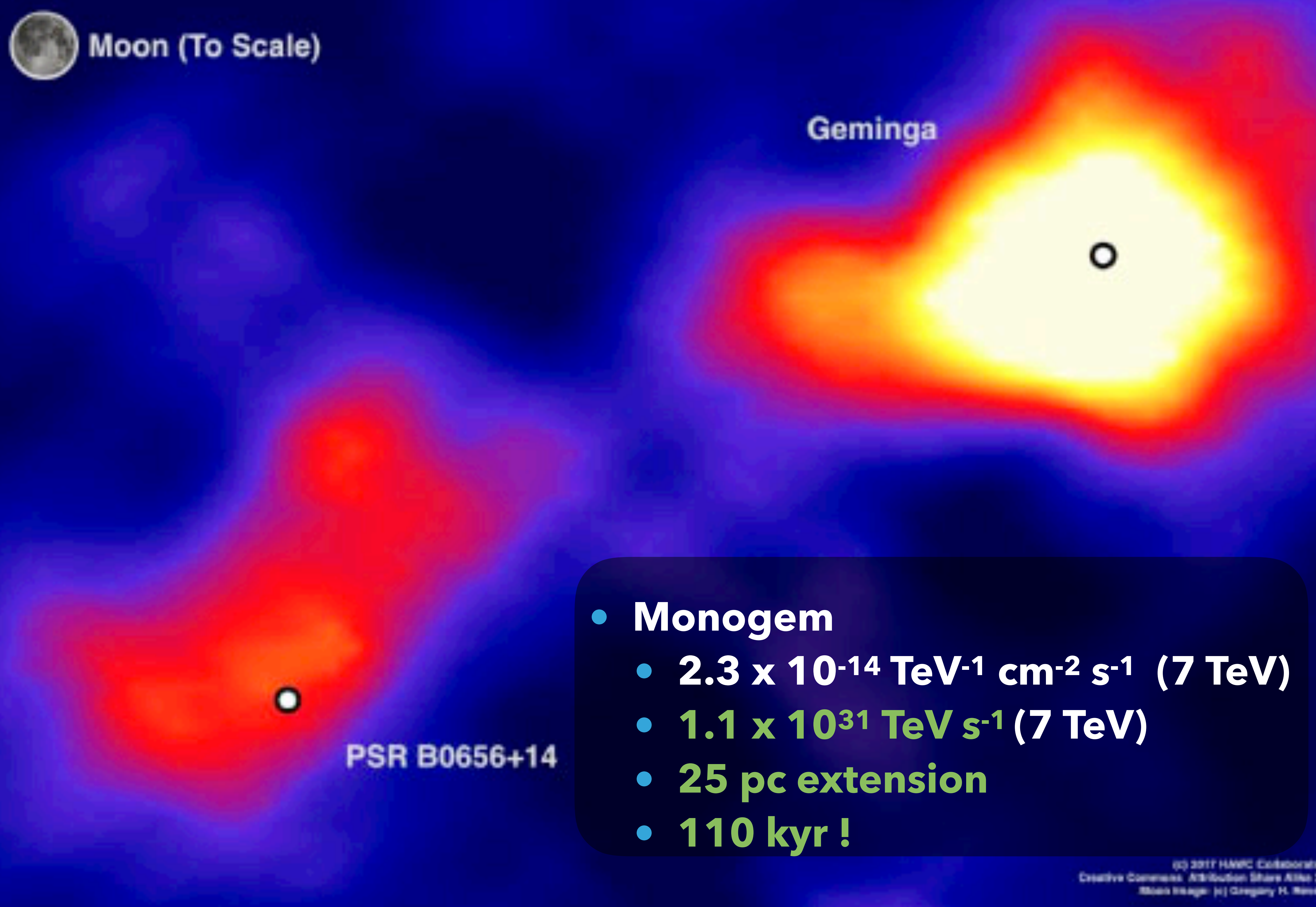
HAWC Quarter-Decade Point Source Sensitivity
Differential Sensitivity E² dN/dE TeV/(cm² s)
Energy [TeV]
Fermi
10 Years
HAWC
507-day
HAWC
5-year
1x Crab
0.1x Crab
0.01x Crab
CASA-MIA
HESS - 50 Hrs
VERITAS - 50 Hrs
MAGIC - 50 Hrs
CTA - 50 Hrs

HAWC OBSERVATIONS OF GEMINGA AND MONOGEM



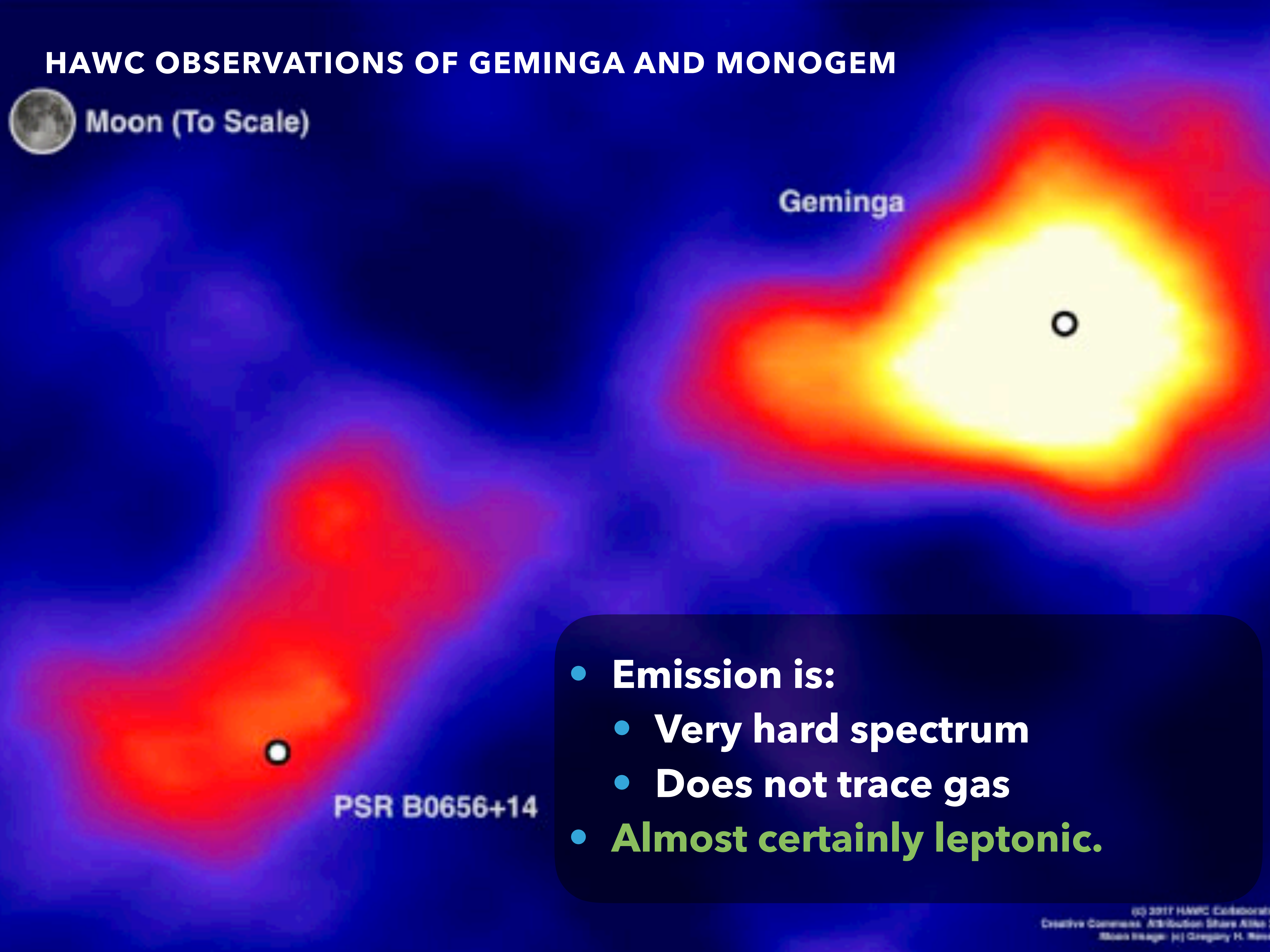
- **Geminga**
  - **4.9 x 10^{-14} TeV^{-1} cm^{-2} s^{-1} (7 TeV)**
  - **1.4 x 10^{31} TeV s^{-1} (7 TeV)**
  - **25 pc extension**
  - **300 kyr**

HAWC OBSERVATIONS OF GEMINGA AND MONOGEM



- **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 !**

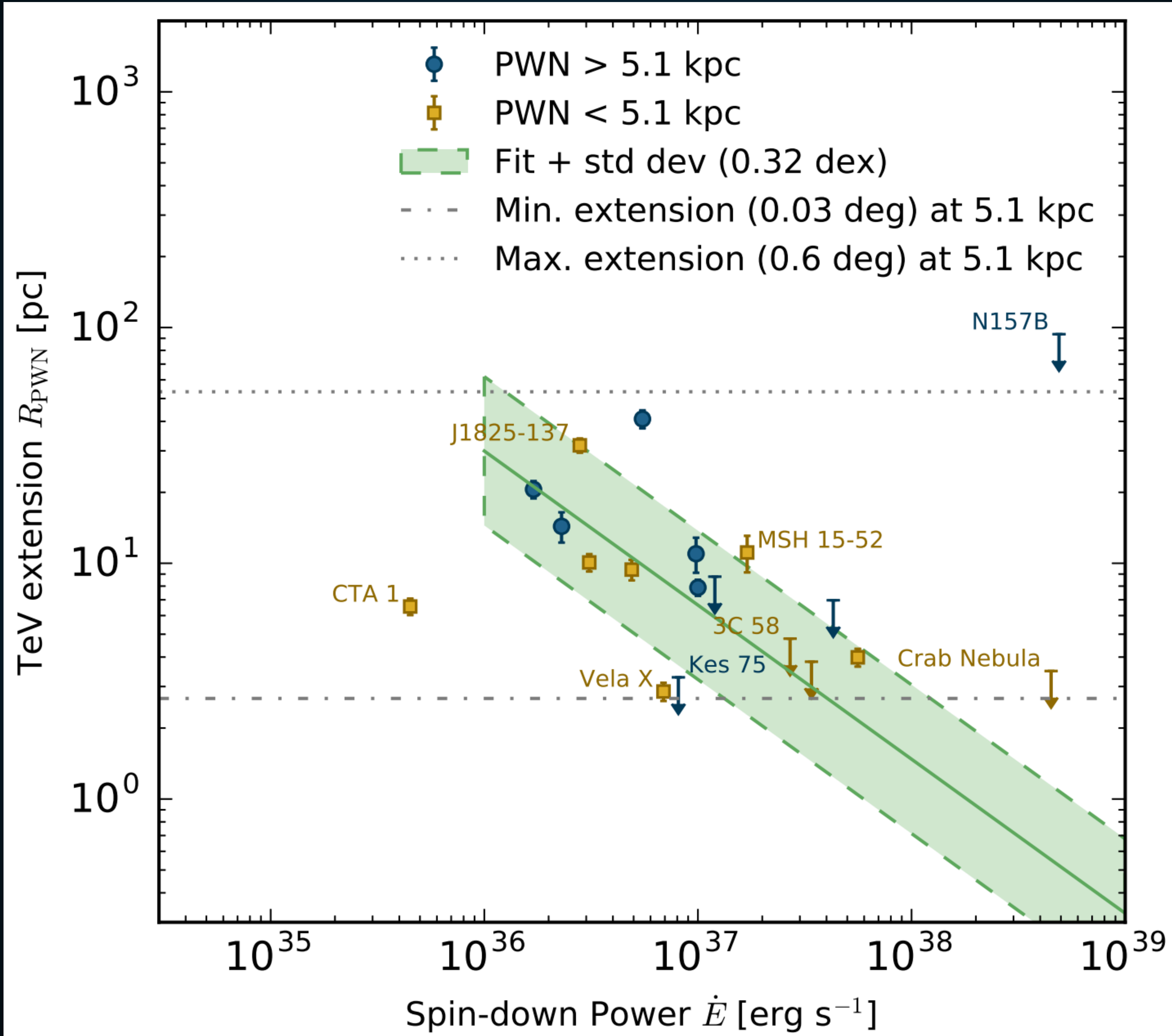
HAWC OBSERVATIONS OF GEMINGA AND MONOGEM



- **Emission is:**
  - **Very hard spectrum**
  - **Does not trace gas**
- **Almost certainly leptonic.**

HESS OBSERVATIONS OF PULSAR WIND NEBULAE

1702.08280



HESS OBSERVATIONS OF PULSAR WIND NEBULAE

1702.08280

Table 4 Candidate pulsar wind nebulae from the pre-selection.

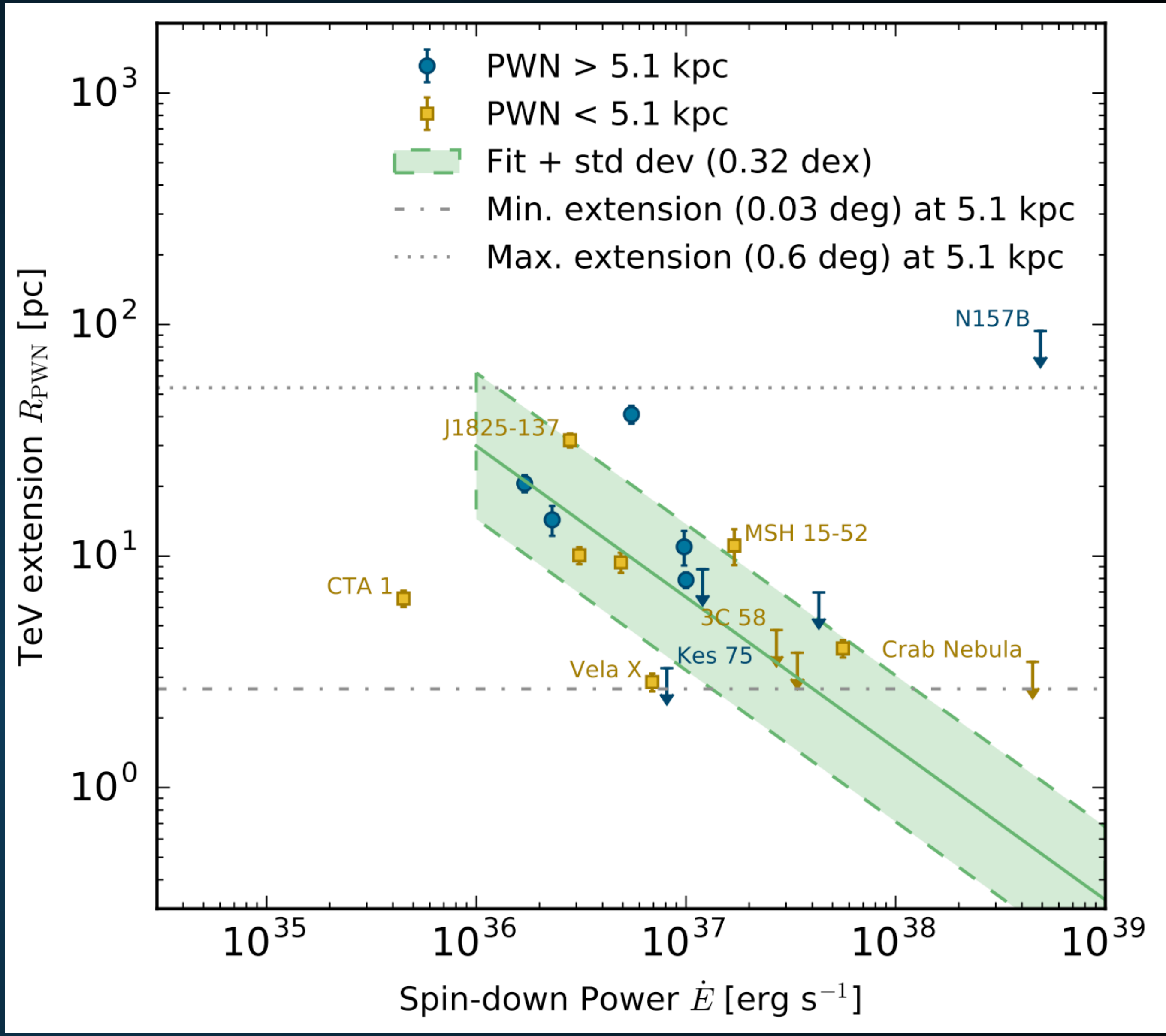
HGPS name	ATNF name	lg $\dot{E}$	τ_c (kyr)	d (kpc)	PSR offset (pc)	Γ	R_{PWN} (pc)	$L_{1-10\,TeV}$ (10^{33} erg s^{-1})
J1616−508 (1)	J1617−5055	37.20	8.13	6.82	< 26	2.34 ± 0.06	28 ± 4	162 ± 9
J1023−575	J1023−5746	37.04	4.60	8.00	< 9	2.36 ± 0.05	23.2 ± 1.2	67 ± 5
J1809−193 (1)	J1811−1925	36.81	23.3	5.00	29 ± 7	2.38 ± 0.07	35 ± 4	53 ± 3
J1857+026	J1856+0245	36.66	20.6	9.01	21 ± 6	2.57 ± 0.06	41 ± 9	118 ± 13
J1640−465	J1640−4631 (1)	36.64	3.35	12.8	< 20	2.55 ± 0.04	25 ± 8	210 ± 12
J1641−462	J1640−4631 (2)	36.64	3.35	12.8	50 ± 5	2.50 ± 0.11	< 14	17 ± 4
J1708−443	B1706−44	36.53	17.5	2.60	17 ± 3	2.17 ± 0.08	12.7 ± 1.4	6.6 ± 0.9
J1908+063	J1907+0602	36.45	19.5	3.21	21 ± 3	2.26 ± 0.06	27.2 ± 1.5	28 ± 2
J1018−589A	J1016−5857 (1)	36.41	21.0	8.00	47.5 ± 1.6	2.24 ± 0.13	< 4	8.1 ± 1.4
J1018−589B	J1016−5857 (2)	36.41	21.0	8.00	25 ± 7	2.20 ± 0.09	21 ± 4	23 ± 5
J1804−216	B1800−21	36.34	15.8	4.40	18 ± 5	2.69 ± 0.04	19 ± 3	42.5 ± 2.0
J1809−193 (2)	J1809−1917	36.26	51.3	3.55	< 17	2.38 ± 0.07	25 ± 3	26.9 ± 1.5
J1616−508 (2)	B1610−50	36.20	7.42	7.94	60 ± 7	2.34 ± 0.06	32 ± 5	220 ± 12
J1718−385	J1718−3825	36.11	89.5	3.60	5.4 ± 1.6	1.77 ± 0.06	7.2 ± 0.9	4.6 ± 0.8
J1026−582	J1028−5819	35.92	90.0	2.33	9 ± 2	1.81 ± 0.10	5.3 ± 1.6	1.7 ± 0.5
J1832−085	B1830−08 (1)	35.76	147	4.50	23.3 ± 1.5	2.38 ± 0.14	< 4	1.7 ± 0.4
J1834−087	B1830−08 (2)	35.76	147	4.50	32.3 ± 1.9	2.61 ± 0.07	17 ± 3	25.8 ± 2.0
J1858+020	J1857+0143	35.65	71.0	5.75	38 ± 3	2.39 ± 0.12	7.9 ± 1.6	7.1 ± 1.5
J1745−303	B1742−30 (1)	33.93	546	0.200	1.42 ± 0.15	2.57 ± 0.06	0.62 ± 0.07	0.014 ± 0.003
J1746−308	B1742−30 (2)	33.93	546	0.200	< 1.1	3.3 ± 0.2	0.56 ± 0.12	0.009 ± 0.003

- **HESS systems have a higher spin down power, but are more distant.**

WE CALL THESE SYSTEMS TEV HALOS

1702.08280

- **They are much larger than the PWN.**
  - **Especially at low-energies.**



NOTE: This has the opposite energy dependence as the X-Ray PWN.

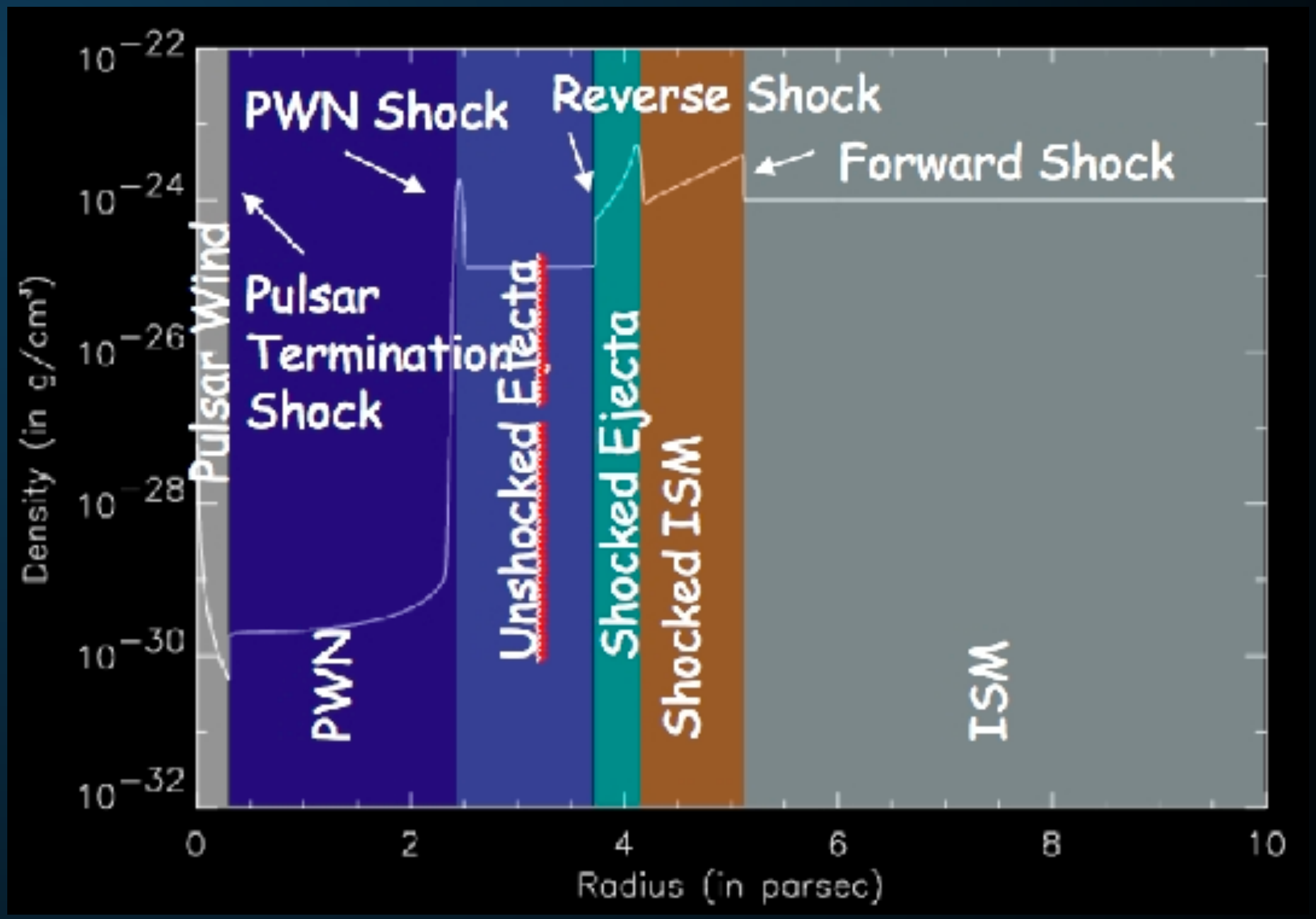
$$R_{\rm PWN} \simeq 1.5 \left(\frac{\dot{E}}{10^{35}\,{\rm erg/s}}\right)^{1/2} \times \left(\frac{n_{\rm gas}}{1\,{\rm cm}^{-3}}\right)^{-1/2} \left(\frac{v}{100\,{\rm km/s}}\right)^{-3/2} {\rm pc}$$

WHAT ARE TEV HALOS

- TeV halos are a new feature
  - 3 orders of magnitude larger than PWN in volume
  - Opposite energy dependence

- PWN are morphologically connected to the physics of the termination shock

- TeV halos need a similar morphological description.



We’ll go back to the model later…

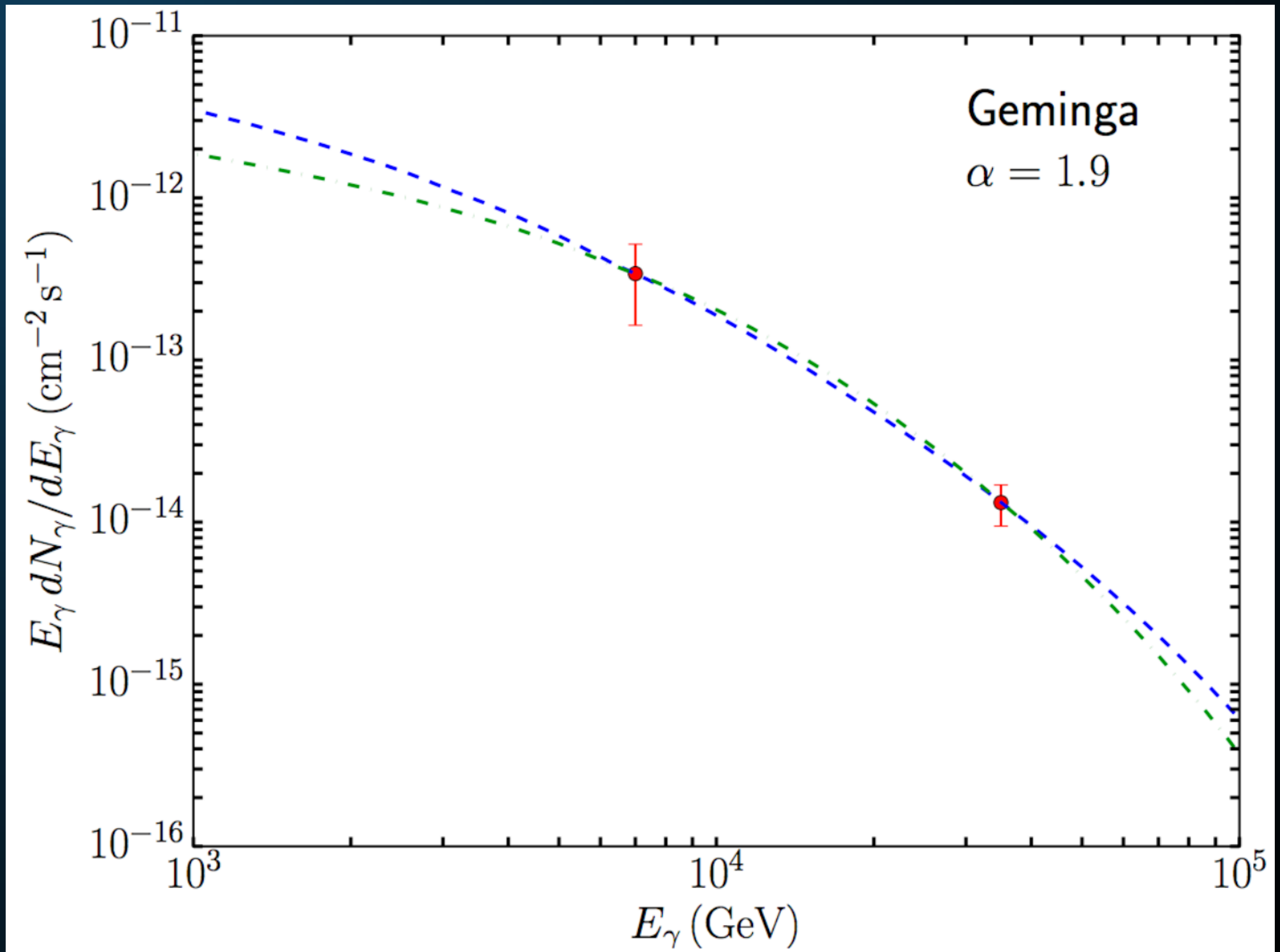
What do TeV observations tell us about pulsars?

GEMINGA GAMMA-RAY SPECTRUM

Name	Tested radius	Index	$F_7 \times 10^{15}$	TeVCat
	[°]		$[\mathrm{TeV^{-1}cm^{-2}s^{-1}}]$	
2HWC J0631+169	-	-2.57 ± 0.15	6.7 ± 1.5	Geminga
”	2.0	-2.23 ± 0.08	48.7 ± 6.9	Geminga
2HWC J0635+180	-	-2.56 ± 0.16	6.5 ± 1.5	Geminga

- **We assume an electron injection spectrum following a power-law with an exponential cutoff.**

- **Best Fit:**
    - **$-1.9 < \alpha < -1.5$**
    - **$E_{cut} \cong 50$ TeV**



Geminga Electron Power is:

~ 3–9 x 10^{33} erg s^{-1} !

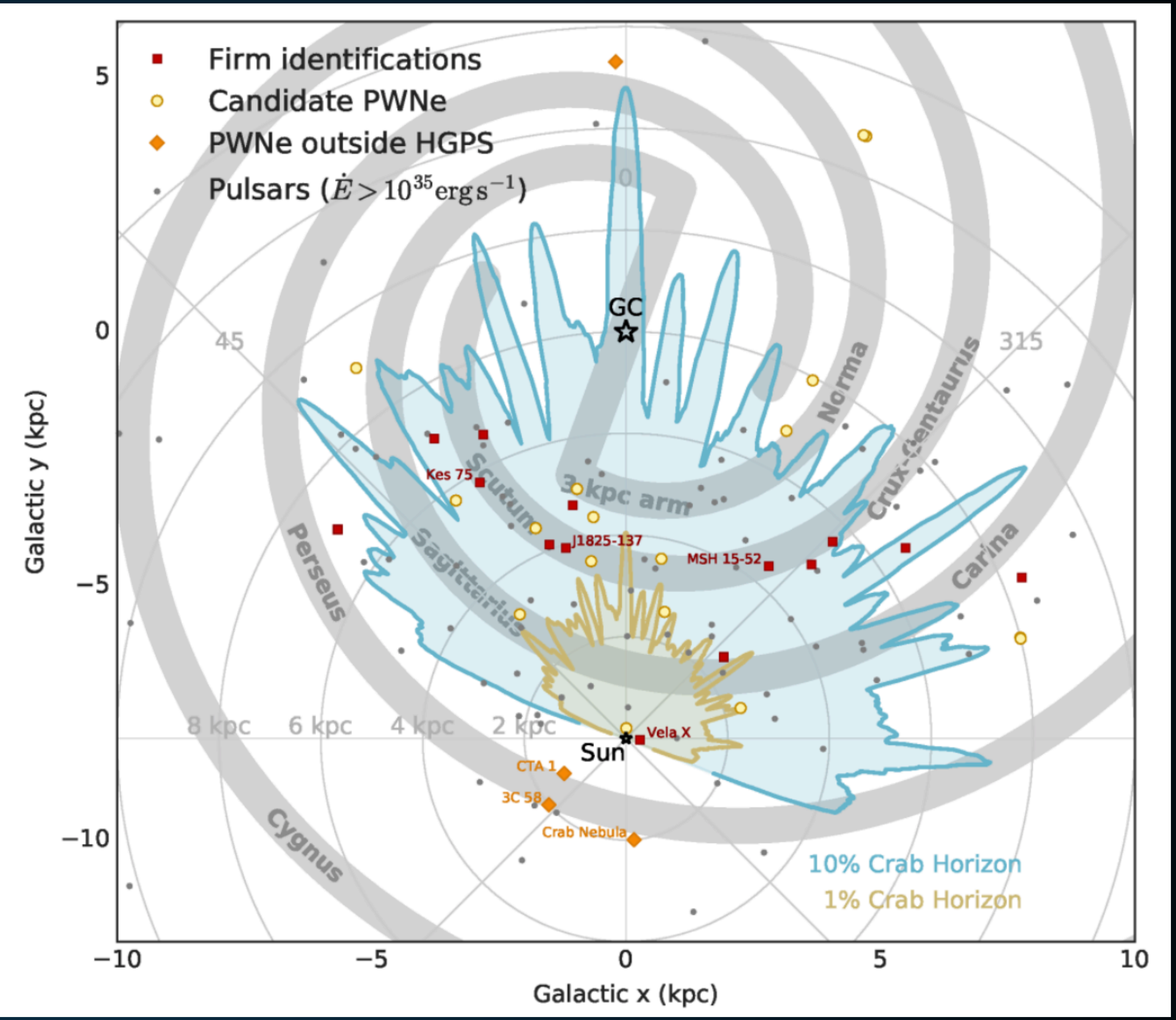
9-27% of the total pulsar spin-down power!

A NON-MODEL OF TEV HALOS

1702.08280

- **Assumption: Geminga (and Monogem) are typical pulsars.**

- **This statement is well supported:**
  - **Observed because they are the two closest sources.**
  - **Many similar HESS Sources.**



THE FIRST-ORDER MODEL OF TEV HALOS

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

$$\theta_{\mathrm{TeV\ halo}} = \left(\frac{d_{\mathrm{Geminga}}}{d_{\mathrm{psr}}}\right)\theta_{\mathrm{Geminga}}$$

- **Assume that every pulsar converts an equivalent fraction of its spin-down power into the TeV halo flux.**

Note: Using Monogem would increases fluxes by nearly a factor of 2.

Overview:

Assume that pulsars convert an the same fraction of their spindown power to e^+e^- as Geminga.

Assume that the e^+e^- spectrum is the same as Geminga.

ASSUMPTION: PULSAR POPULATION MODELS

Linden & Buckman (1707.01905)

- **Use a generic model for pulsar luminosities**

- $B_0 = 10^{12.5}$ G (+/- $10^{0.3}$ G)
- $P_0 = 0.3$ s (+/- 0.15 s)
- Spindown Timescale of ~10^4 yr (depends on B_0)
- Galprop model for supernova distances


PsrPopPy: An open-source package for pulsar population simulations

D. Bates[1,2], D. R. Lorimer[1,3], A. Rane[1] and J. Swiggum[1]

Department of Physics and Astronomy, West Virginia University, Morgantown, WV, 26506 USA

Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Manchester M

Astronomy Observatory, PO Box 2, Green Bank, WV 24944, USA

software package for the simulation of

PSRPOP package. The codebase h

which remain in their

language, and improvi

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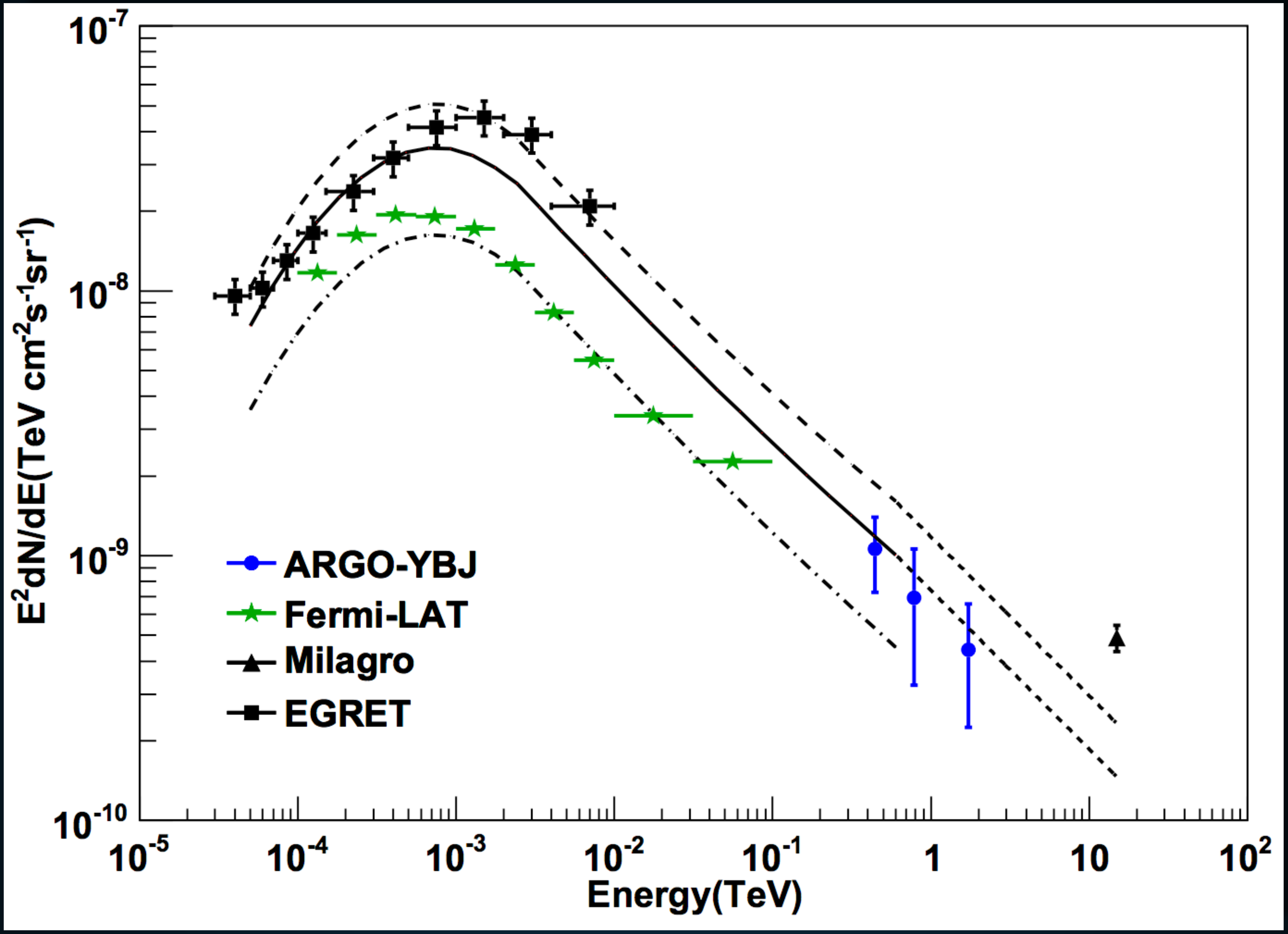
Implication I:

Most diffuse TeV emission is powered by pulsars

IMPLICATION I: THE TEV EXCESS

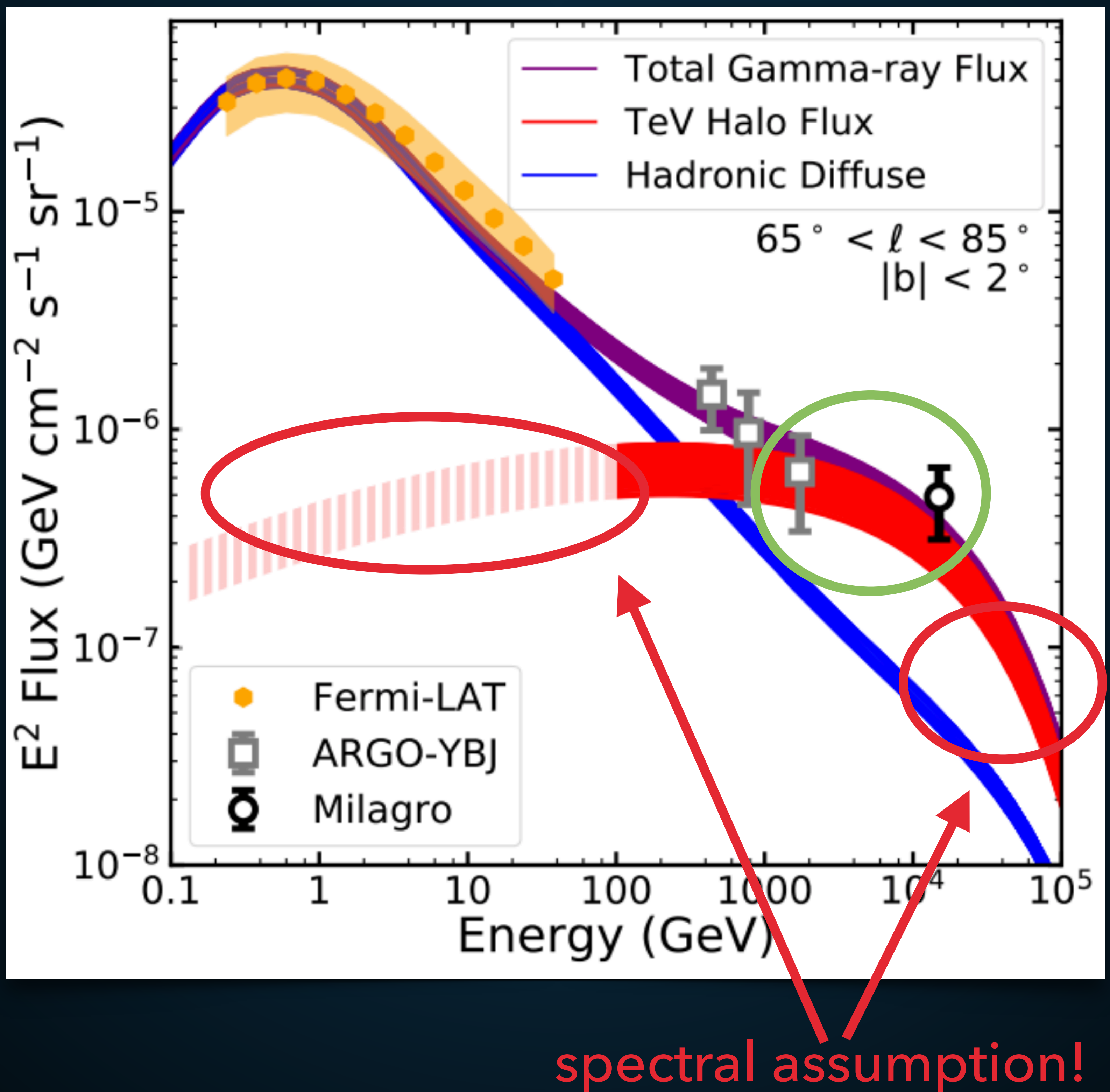
Bartoli et al. (2015; 1507.06758)



- **Milagro had previously detected an excess in 10 TeV emission from the Milky Way.**

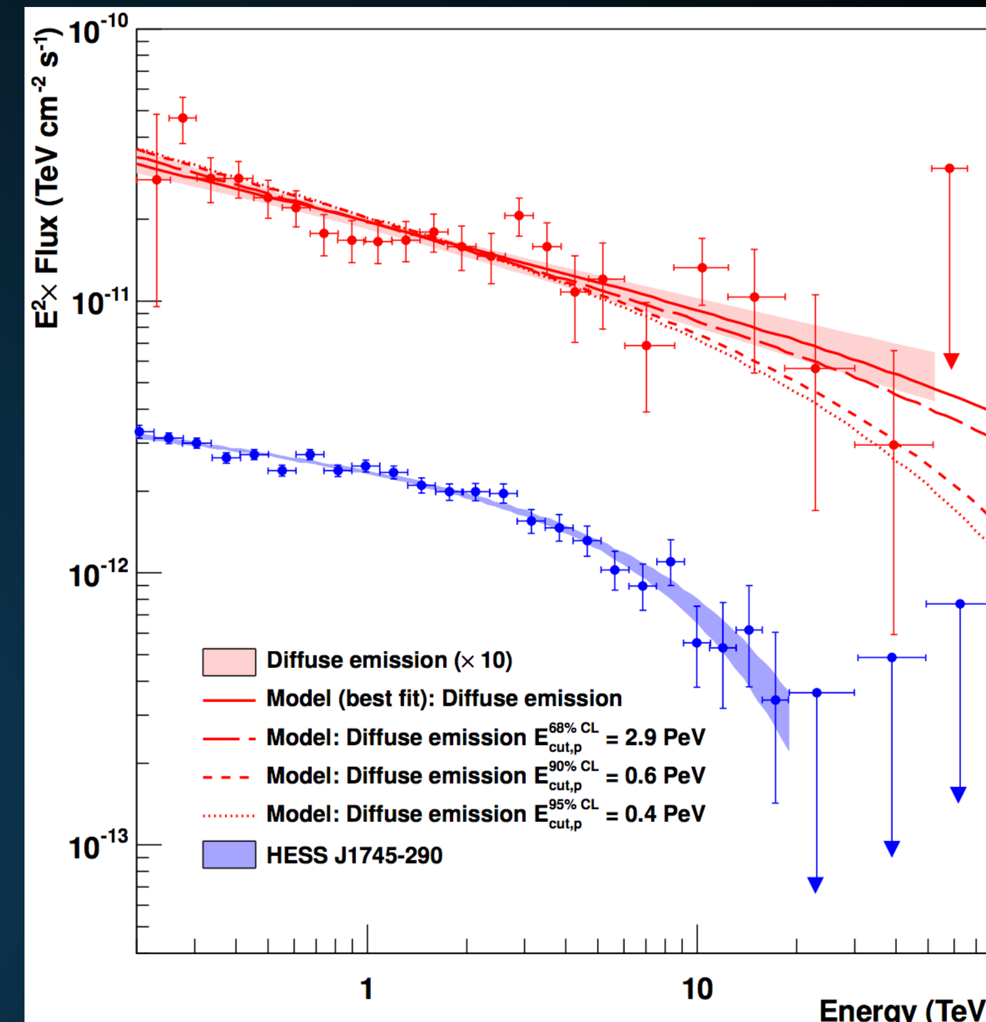
Linden & Buckman (1707.01905)

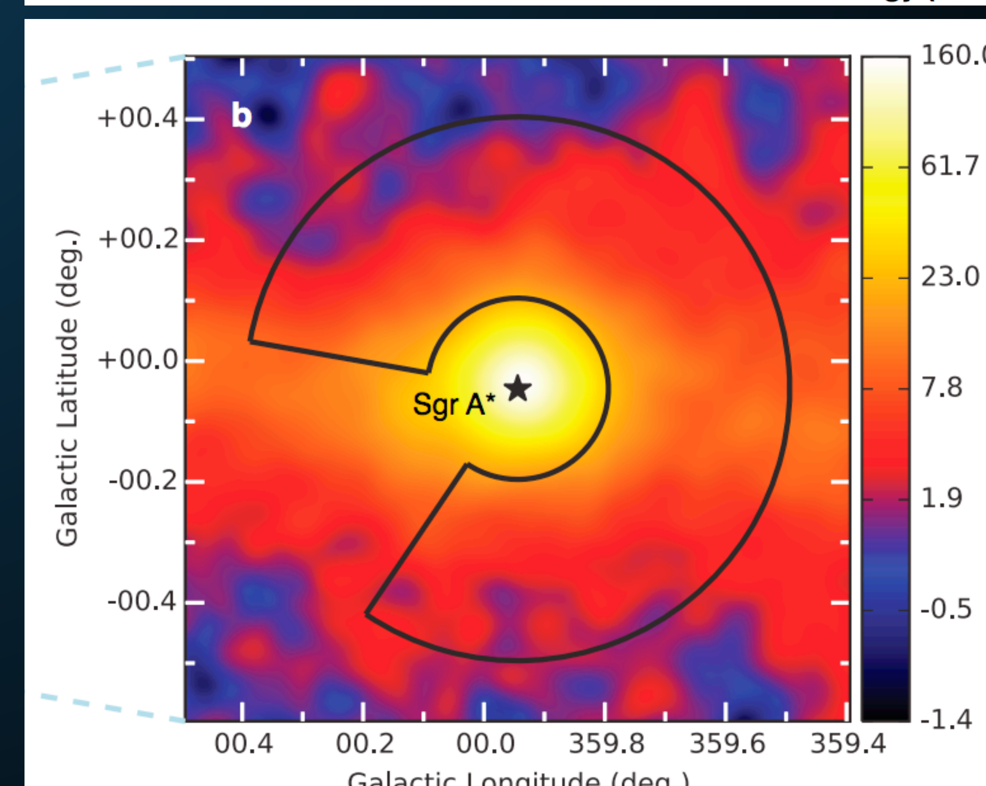
- **TeV halos naturally explain the TeV excess!**



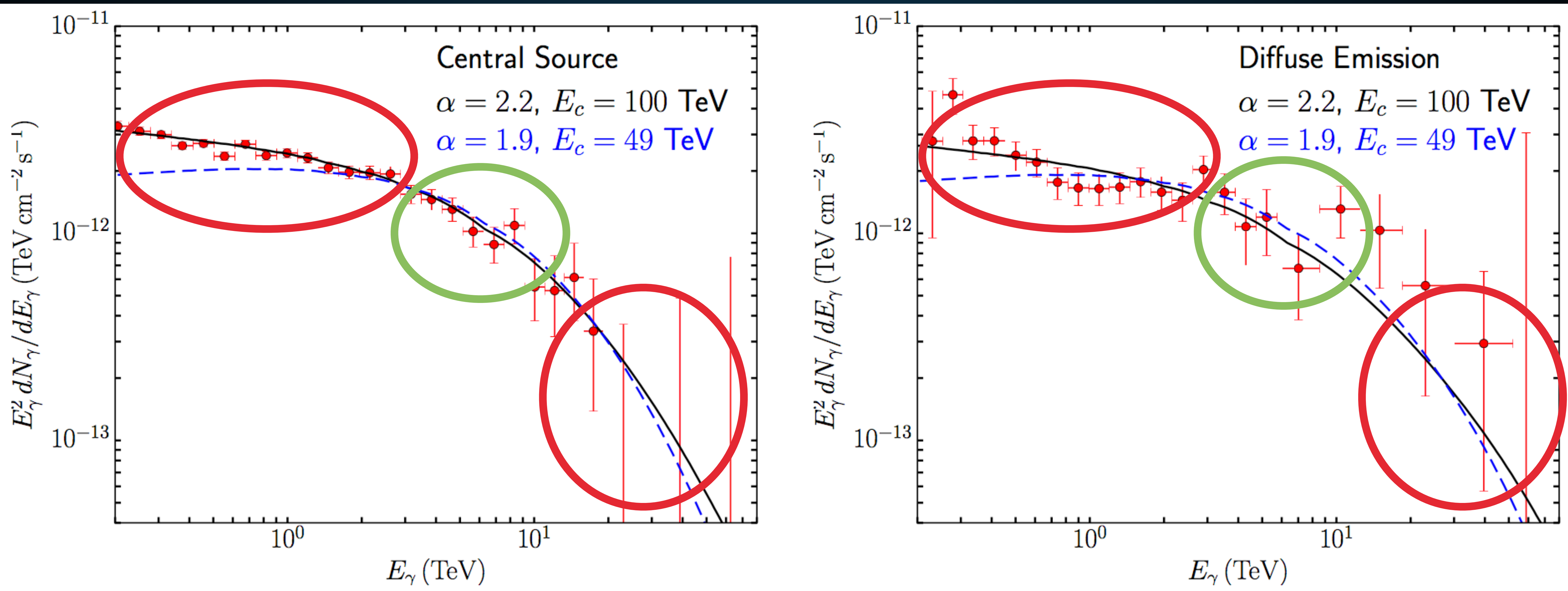
IMPLICATION IB: THE GALACTIC CENTER PEVATRON

- **HESS observed diffuse ~50 TeV emission from the Galactic center.**
- **If this emission is hadronic, it indicates PeV particle acceleration in the GC**
- **Spherical symmetry hints at Galactic Center source.**





- **TeV halos naturally explain the data!**



Implication II:

Most TeV gamma-ray sources are TeV halos.

TEV HALOS ARE A GENERIC FEATURE OF PULSARS

- **5 / 39 sources in the 2HWC catalog are correlated with bright, middle-aged (100 – 400 kyr) pulsars.**

2HWC Name	ATNF Name	Distance (kpc)	Angular Separation	Projected Separation	Expected Flux ($\times 10^{-15}$)	Actual Flux ($\times 10^{-15}$)	Flux Ratio	Expected Extension	Actual Extension	Age (kyr)	Chance Overlap
J0700+143	B0656+14	0.29	0.18°	0.91 pc	43.0	23.0	1.87	2.0°	1.73°	111	0.0
J0631+169	J0633+1746	0.25	0.89°	3.88 pc	48.7	48.7	1.0	2.0°	2.0°	342	0.0
J1912+099	J1913+1011	4.61	0.34°	27.36 pc	13.0	36.6	0.36	0.11°	0.7°	169	0.30
J2031+415	J2032+4127	1.70	0.11°	3.26 pc	5.59	61.6	0.091	0.29°	0.7°	181	0.002
J1831-098	J1831-0952	3.68	0.04°	2.57 pc	7.70	95.8	0.080	0.14°	0.9°	128	0.006

- **12 others with young pulsars**
  - **2.3 chance overlaps**
  - **TeV emission may be contaminated by SNR**

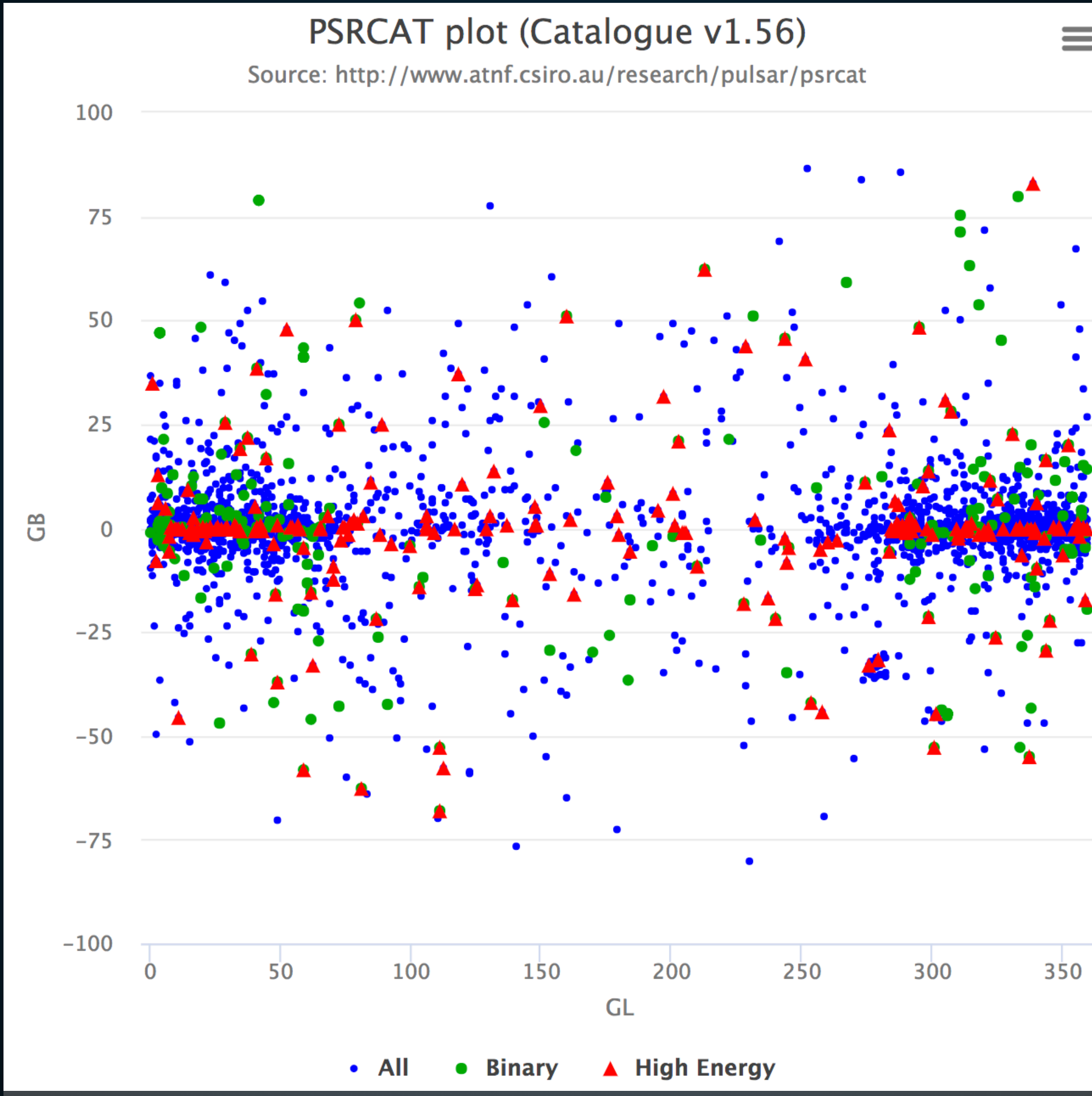
2HWC Name	ATNF Name	Distance (kpc)	Angular Separation	Projected Separation	Expected Flux ($\times 10^{-15}$)	Actual Flux ($\times 10^{-15}$)	Flux Ratio	Expected Extension	Actual Extension	Age (kyr)	Chance Overlap
J1930+188	J1930+1852	7.0	0.03°	3.67 pc	23.2	9.8	2.37	0.07°	0.0°	2.89	0.002
J1814-173	J1813-1749	4.7	0.54°	44.30 pc	243	152	1.60	0.11°	1.0°	5.6	0.61
J2019+367	J2021+3651	1.8	0.27°	8.48 pc	99.8	58.2	1.71	0.28°	0.7°	17.2	0.04
J1928+177	J1928+1746	4.34	0.03°	2.27 pc	8.08	10.0	0.81	0.11°	0.0°	82.6	0.002
J1908+063	J1907+0602	2.58	0.36°	16.21 pc	40.0	85.0	0.47	0.2°	0.8°	19.5	0.26
J2020+403	J2021+4026	2.15	0.18°	6.75 pc	2.48	18.5	0.134	0.23°	0.0°	77	0.01
J1857+027	J1856+0245	6.32	0.12°	13.24 pc	11.0	97.0	0.11	0.08°	0.9°	20.6	0.06
J1825-134	J1826-1334	3.61	0.20°	12.66 pc	20.5	249	0.082	0.14°	0.9°	21.4	0.14
J1837-065	J1838-0655	6.60	0.38°	43.77 pc	12.0	341	0.035	0.08°	2.0°	22.7	0.48
J1837-065	J1837-0604	4.78	0.50°	41.71 pc	8.3	341	0.024	0.10°	2.0°	33.8	0.68
J2006+341	J2004+3429	10.8	0.42°	80.07 pc	0.48	24.5	0.019	0.04°	0.9°	18.5	0.08

STEP I: TEV HALOS ARE A GENERIC FEATURE OF PULSARS

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	—

- **Can produce a ranked list of the 57 ATNF pulsars in the HAWC field of view – these are the brightest 11.**
- **10 year HAWC observations should detect:**
  - **TeV halos from a dozen middle-aged ATNF pulsars.**
  - **TeV halos from ~40 additional young pulsars.**

WHY DO WE CARE?

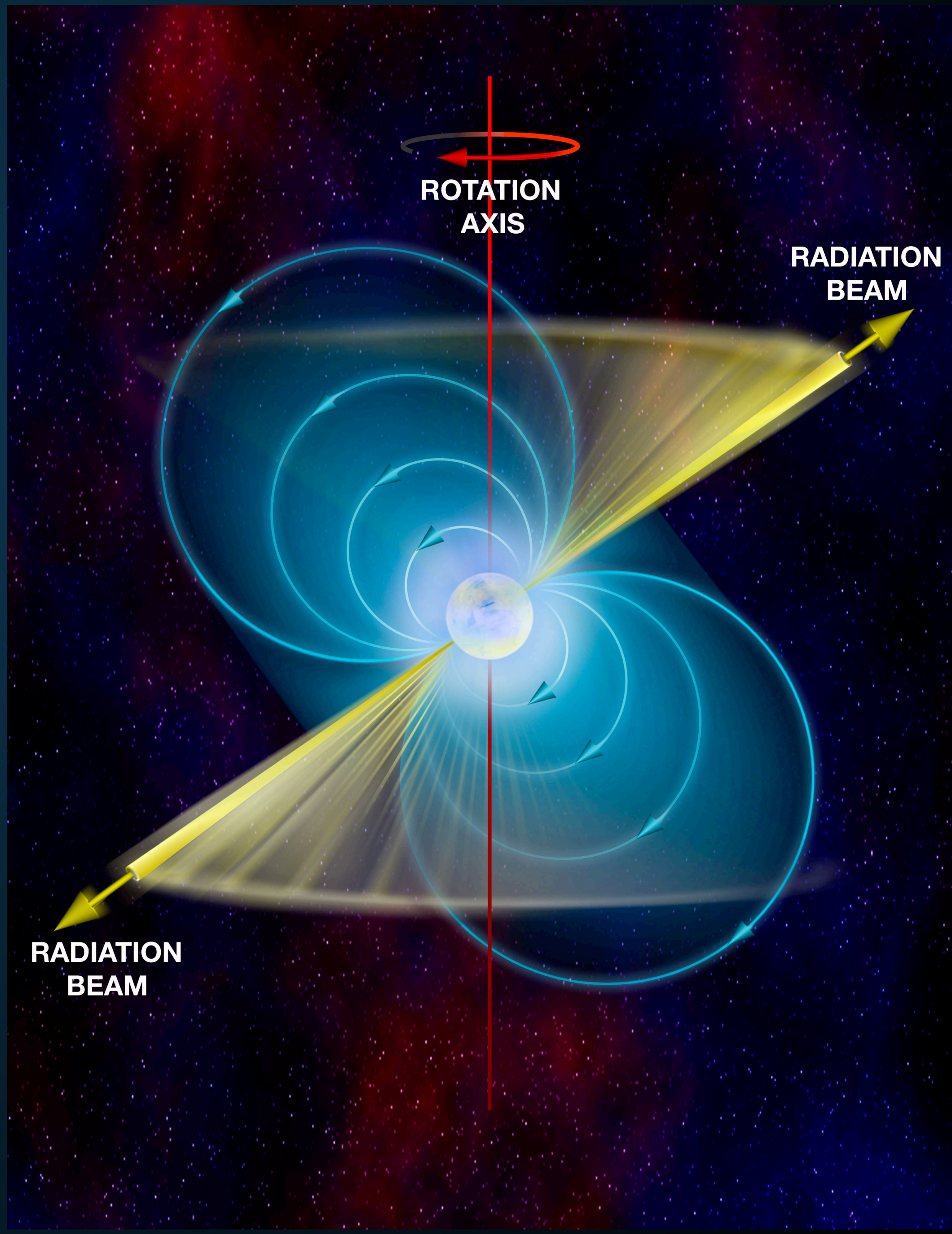


- **Tauris and Manchester (1998) calculated the beaming angle from a population of young and middle-aged pulsars.**

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

- **This varies between 15-30%.**

- **Most pulsars are unseen in radio!**



MISSING TEV HALOS

TL et. al (2017; 1703.09704)

2HWC Name	ATNF Name	Distance (kpc)	Angular Separation	Projected Separation	Expected Flux ($\times 10^{-15}$)	Actual Flux ($\times 10^{-15}$)	Flux Ratio	Expected Extension	Actual Extension	Age (kyr)	Chance Overlap
J0700+143	B0656+14	0.29	0.18°	0.91 pc	43.0	23.0	1.87	2.0°	1.73°	111	0.0
J0631+169	J0633+1746	0.25	0.89°	3.88 pc	48.7	48.7	1.0	2.0°	2.0°	342	0.0
J1912+099	J1913+1011	4.61	0.34°	27.36 pc	13.0	36.6	0.36	0.11°	0.7°	169	0.30
J2031+415	J2032+4127	1.70	0.11°	3.26 pc	5.59	61.6	0.091	0.29°	0.7°	181	0.002
J1831-098	J1831-0952	3.68	0.04°	2.57 pc	7.70	95.8	0.080	0.14°	0.9°	128	0.006

2HWC Name	ATNF Name	Distance (kpc)	Angular Separation	Projected Separation	Expected Flux ($\times 10^{-15}$)	Actual Flux ($\times 10^{-15}$)	Flux Ratio	Expected Extension	Actual Extension	Age (kyr)	Chance Overlap
J1930+188	J1930+1852	7.0	0.03°	3.67 pc	23.2	9.8	2.37	0.07°	0.0°	2.89	0.002
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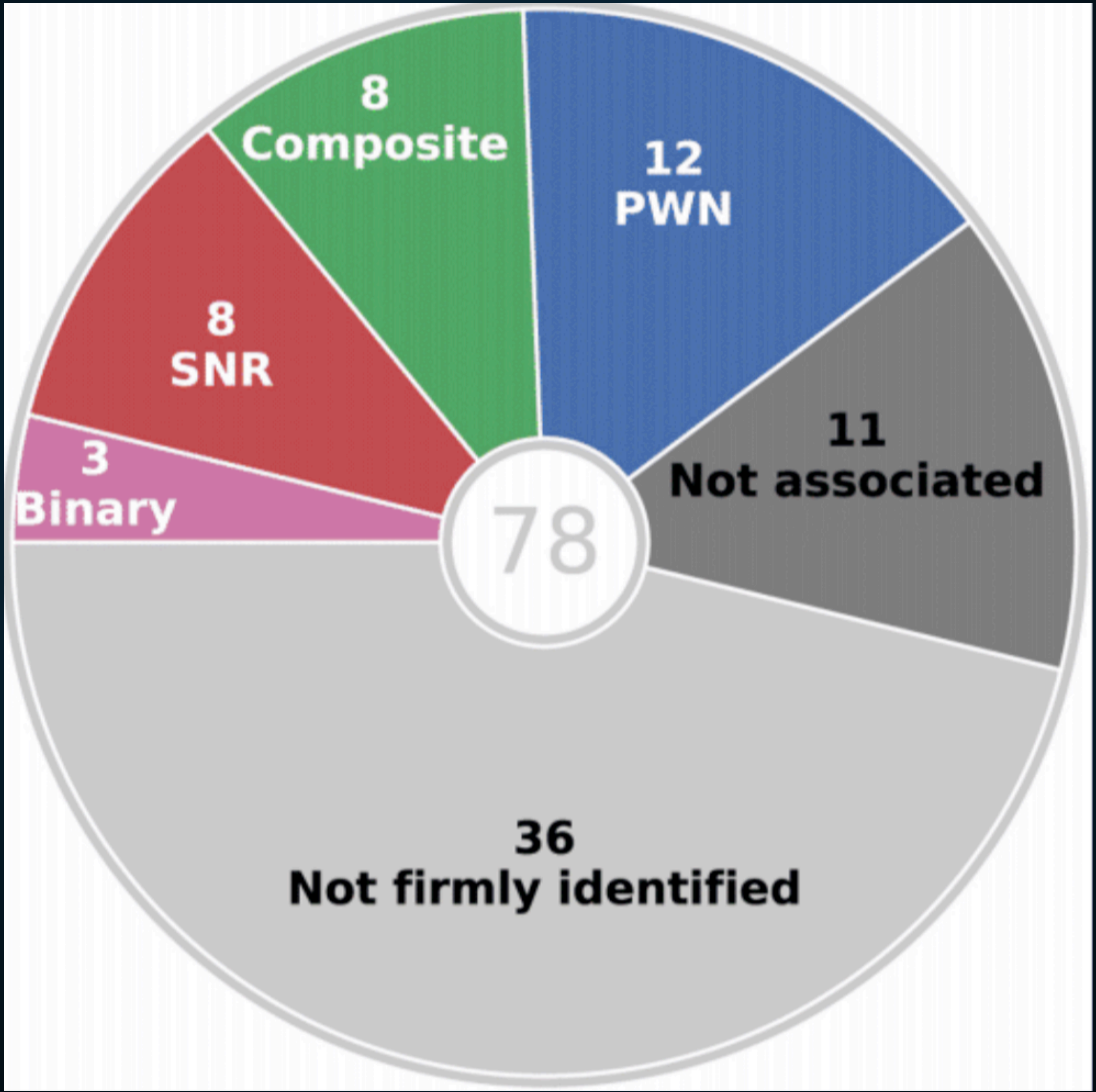
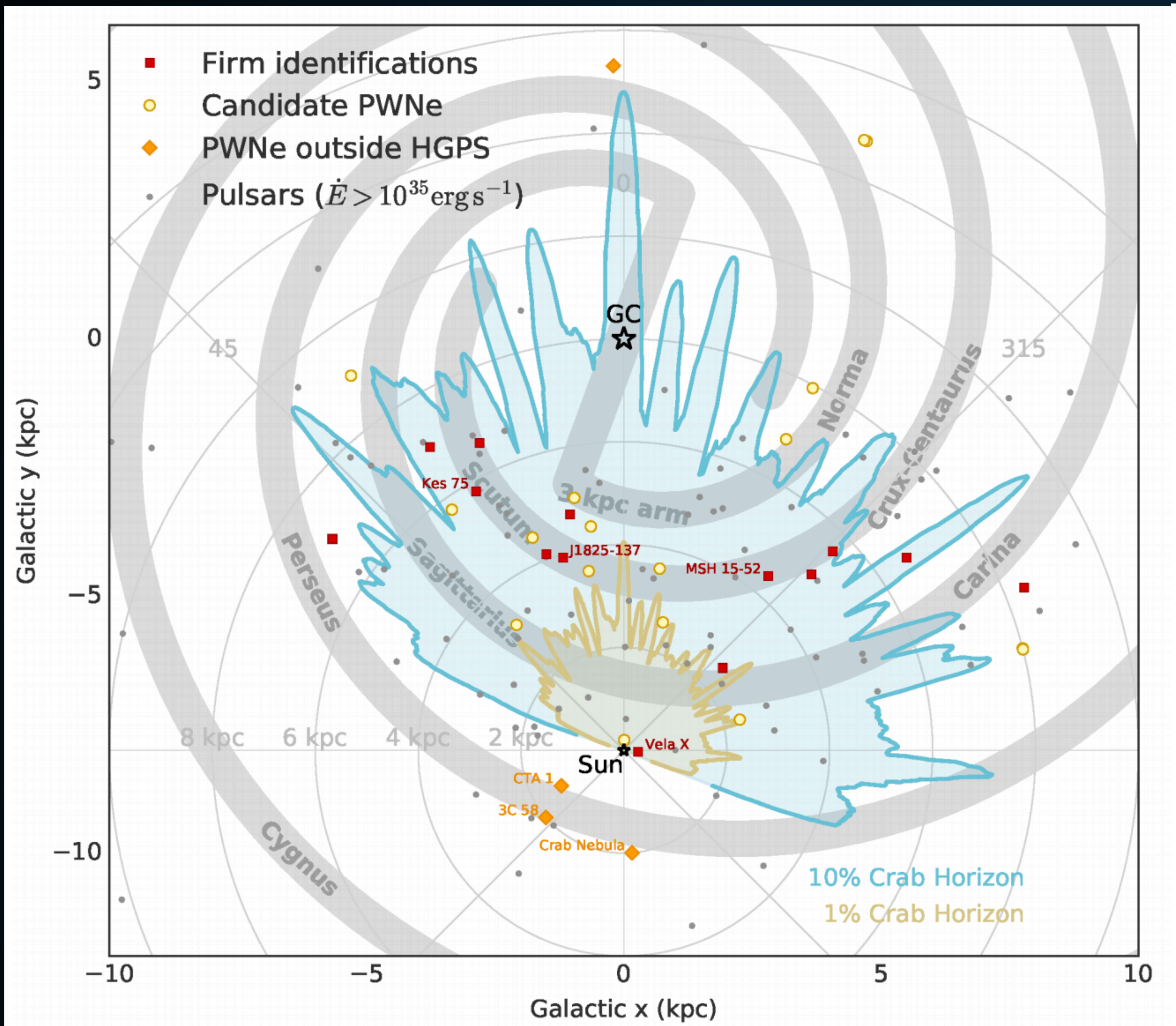
- **Correcting for the beaming fraction implies that 56^{+15}_{-11} TeV halos are currently observed by HAWC.**
- **However, only 39 total HAWC sources.**
- **Chance overlaps, SNR contamination must be taken into account.**

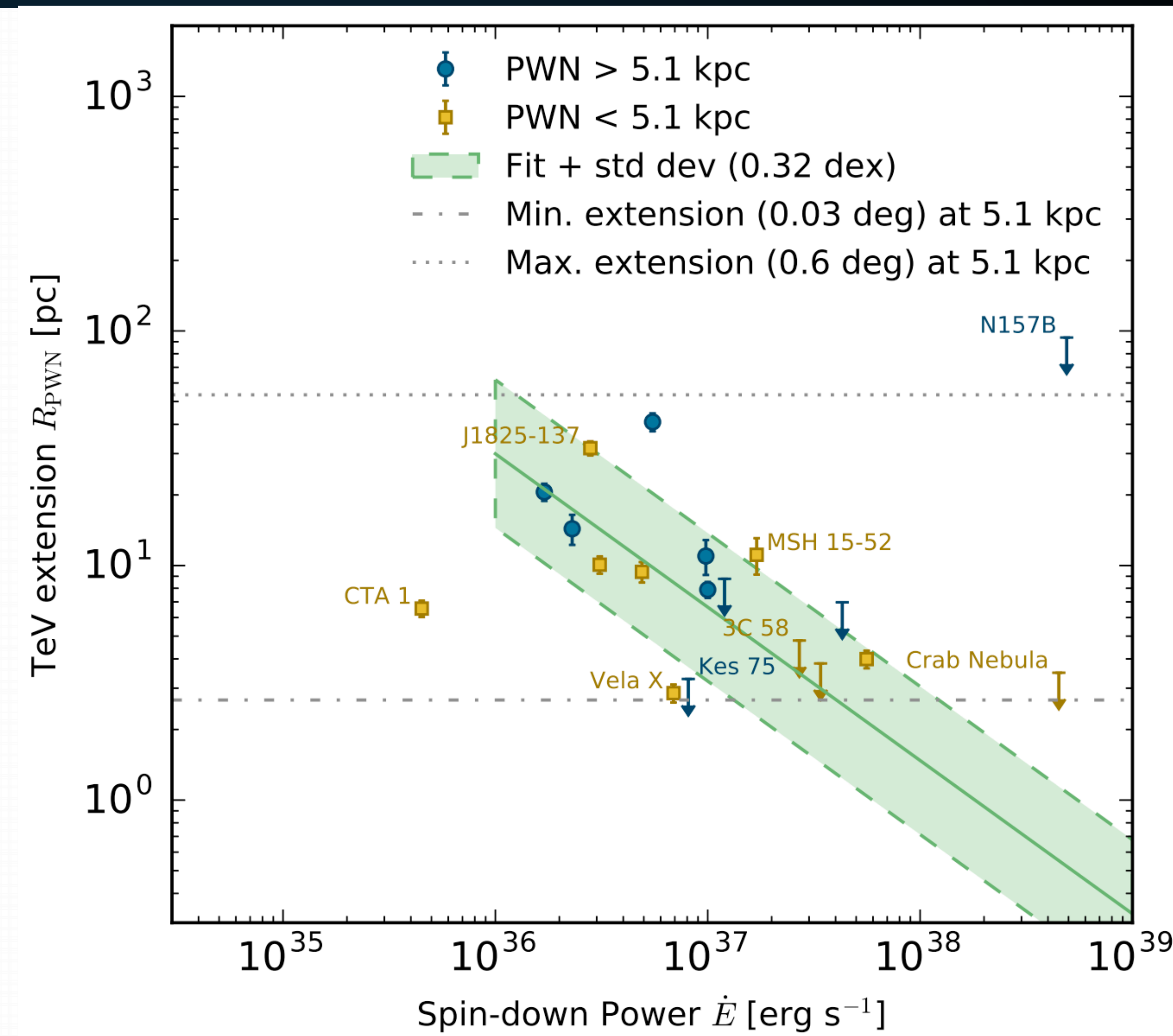
MISSING TEV HALOS

HAWC Collaboration (2018)

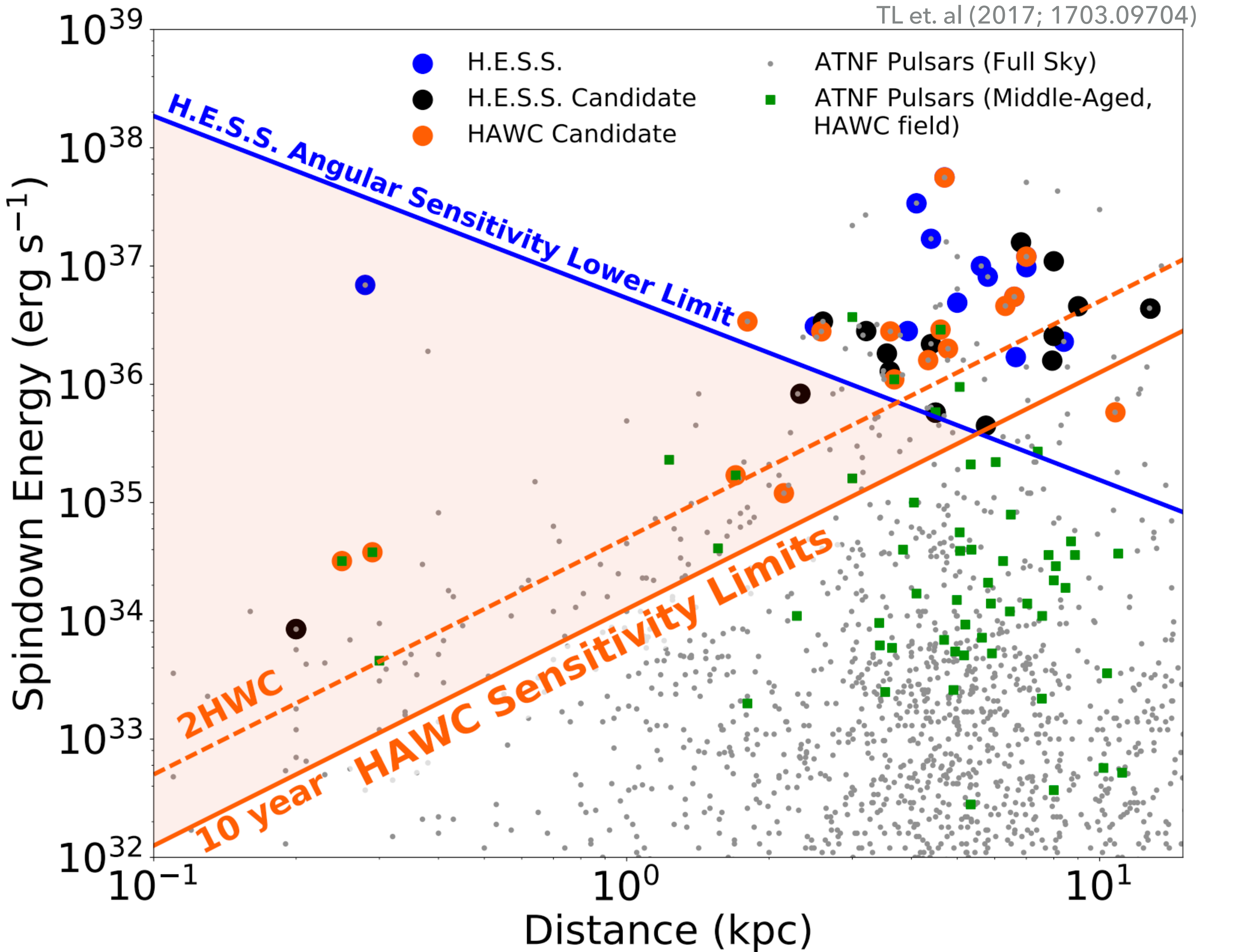


MISSING TEV HALOS





- **Targeted ACTs are sensitive to the flux from TeV halos.**
- **ACTs are not sensitive to sources extended >0.5°.**
- **Large parameter space available only to HAWC.**



TL et. al (2017; 1703.09704)
H.E.S.S.
H.E.S.S. Candidate
HAWC Candidate
ATNF Pulsars (Full Sky)
ATNF Pulsars (Middle-Aged, HAWC field)
H.E.S.S. Angular Sensitivity Lower Limit
2HWC
10 year HAWC Sensitivity Limits
Spindown Energy (erg s^{-1})
Distance (kpc)
10^{39}
10^{38}
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
10^{-1}
10^{0}
10^{1}

FIRST STEPS

[Previous | Next | ADS]

HAWC detection of TeV emission near PSR B0540+23

ATel #10941; *Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration*
on ***9 Nov 2017; 23:11 UT***
Credential Certification: Colas Riviere (riviere@umd.edu)

Subjects: Gamma Ray, TeV, VHE, Pulsar

The High Altitude Water Cherenkov (HAWC) collaboration reports the discovery of a new TeV gamma-ray source HAWC J0543+233. It was discovered in a search for extended sources of radius 0.5° in a dataset of 911 days (ranging from November 2014 to August 2017) with a test statistic value of 36 (6σ pre-trials), following the method presented in Abeysekara et al. 2017, ApJ, 843, 40. The measured J2000.0 equatorial position is RA=85.78°, Dec=23.40° with a statistical uncertainty of 0.2°. HAWC J0543+233 was close to passing the selection criteria of the 2HWC catalog (Abeysekara et al. 2017, ApJ, 843, 40, see HAWC J0543+233 in 2HWC map), which it now fulfills with the additional data.
HAWC J0543+233 is positionally coincident with the pulsar PSR B0540+23 (Edot = 4.1e+34 erg s-1, dist = 1.56 kpc, age = 253 kyr). It is the third low Edot, middle-aged pulsar announced to be detected with a TeV halo, along with Geminga and B0656+14. It was predicted to be one of the next such detection by HAWC by Linden et al., 2017, arXiv:1703.09704.
Using a simple source model consisting of a disk of radius 0.5°, the measured spectral index is -2.3 ± 0.2 and the differential flux at 7 TeV is (7.9 ± 2.3) × 10^-15 TeV-1 cm-2 s-1. The errors are statistical only. Further morphological and spectral analysis as well as studies of the systematic uncertainty are ongoing.

[Previous | Next | ADS]

HAWC detection of TeV source HAWC J0635+070

ATel #12013; *Chad Brisbois (Michigan Technological University), Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andrew Smith (University of Maryland) on behalf of the HAWC collaboration*
on ***6 Sep 2018; 14:47 UT***
Credential Certification: Colas Riviere (riviere@umd.edu)

Subjects: Gamma Ray, TeV, VHE, Pulsar

The High Altitude Water Cherenkov (HAWC) collaboration reports the discovery of a new TeV gamma-ray source HAWC J0635+070. It was discovered in a search for extended sources covering 1128 days of HAWC observations with a test statistic value of 27 (>5σ pre-trials), following the method presented in [Abeysekara et al. 2017, ApJ, 843, 40]. Its significance in the 2HWC data set excluded it from being included in the catalog (~3.5σ pre-trials), but with the addition of ~600 more days of data it now satisfies that criterion. The best-fit J2000.0 equatorial position is RA=98.71±0.20°, Dec=7.00±0.22°, with a Gaussian 1-sigma extent of 0.65°±0.18°.

The spectral energy distribution is well-fit by a power law with spectral index -2.15±0.17. The differential flux at 10 TeV is (8.6 ± 3.2) × 10^-15 TeV-1 cm-2 s-1. All errors are statistical only; further morphological and spectral analysis as well as studies of the systematic uncertainty are ongoing.

Given its spectrum and morphology, we believe HAWC J0635+070 may be the TeV halo of the pulsar PSR J0633+0632 (Edot = 1.2e+35 erg s-1, dist = 1.35 kpc, age = 59 kyr, unknown proper motion [Manchester et al., 2005, AJ, 129]). The gamma-ray spectrum and morphology is compatible with a "Geminga-like" TeV Halo [Abeysekara et al. 2017, Science, 358, 911; Linden et al., 2017, PRD, 96, 103016]. We encourage follow-up observations at other wavelengths.

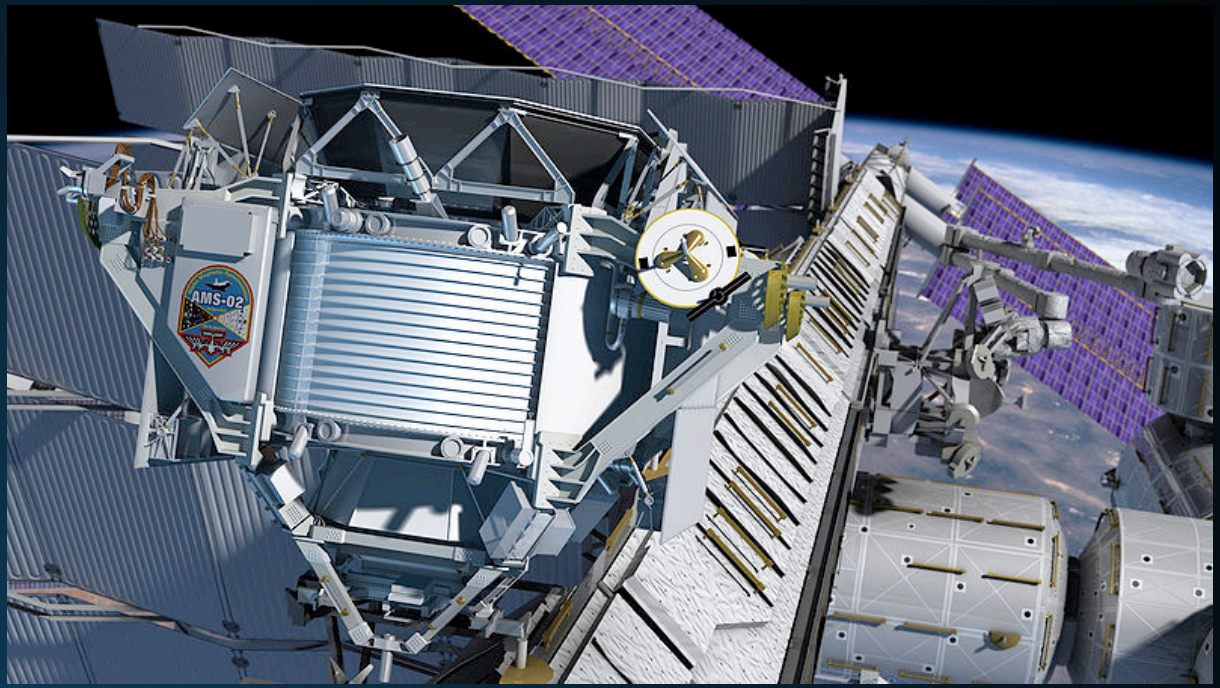
- **HAWC has detected two additional TeV halos**
- **Total Count:**
  - **Middle-Aged: 6**
  - **Younger: 12**

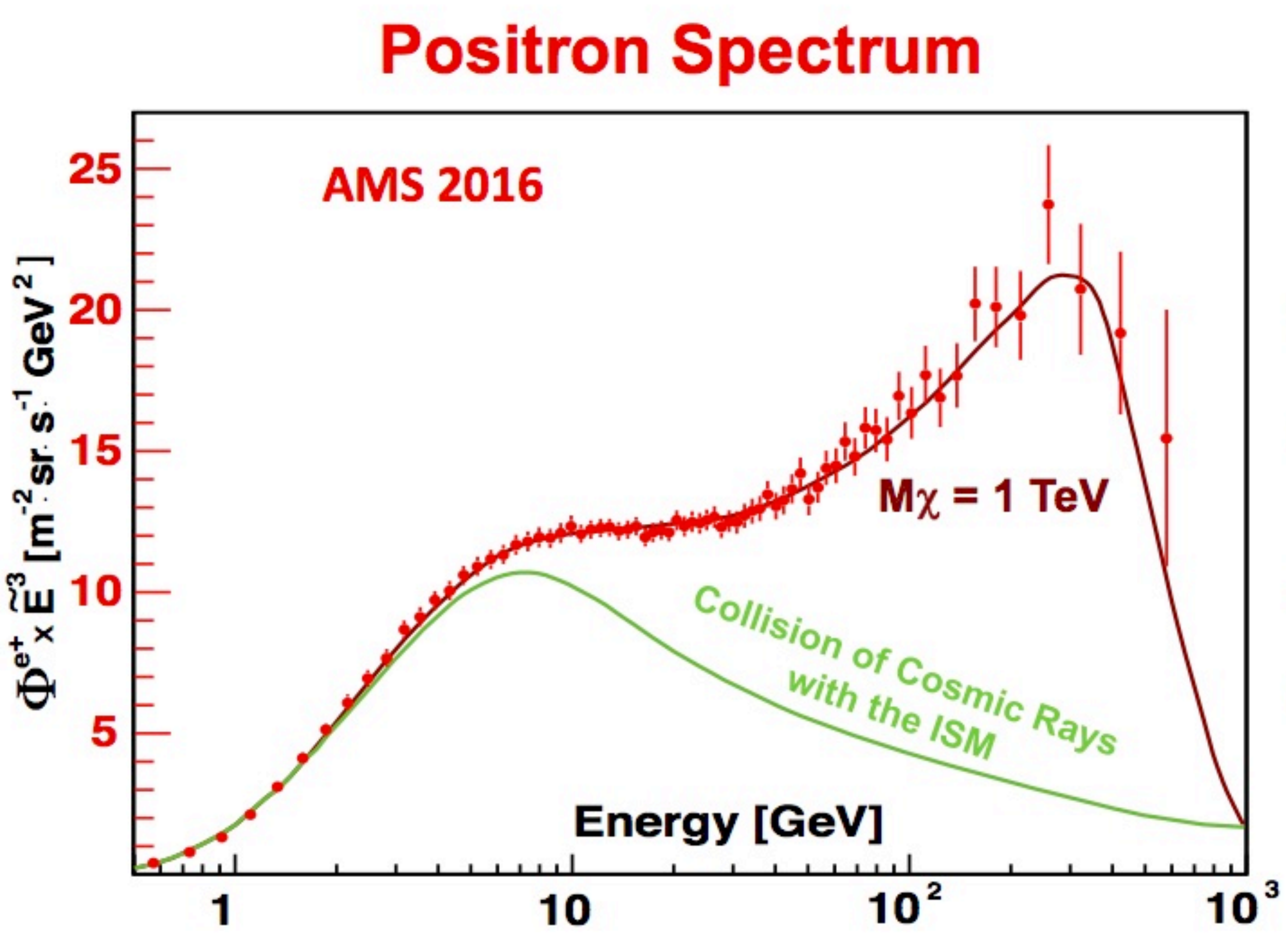
These conclusions stem merely from the existence of these sources.

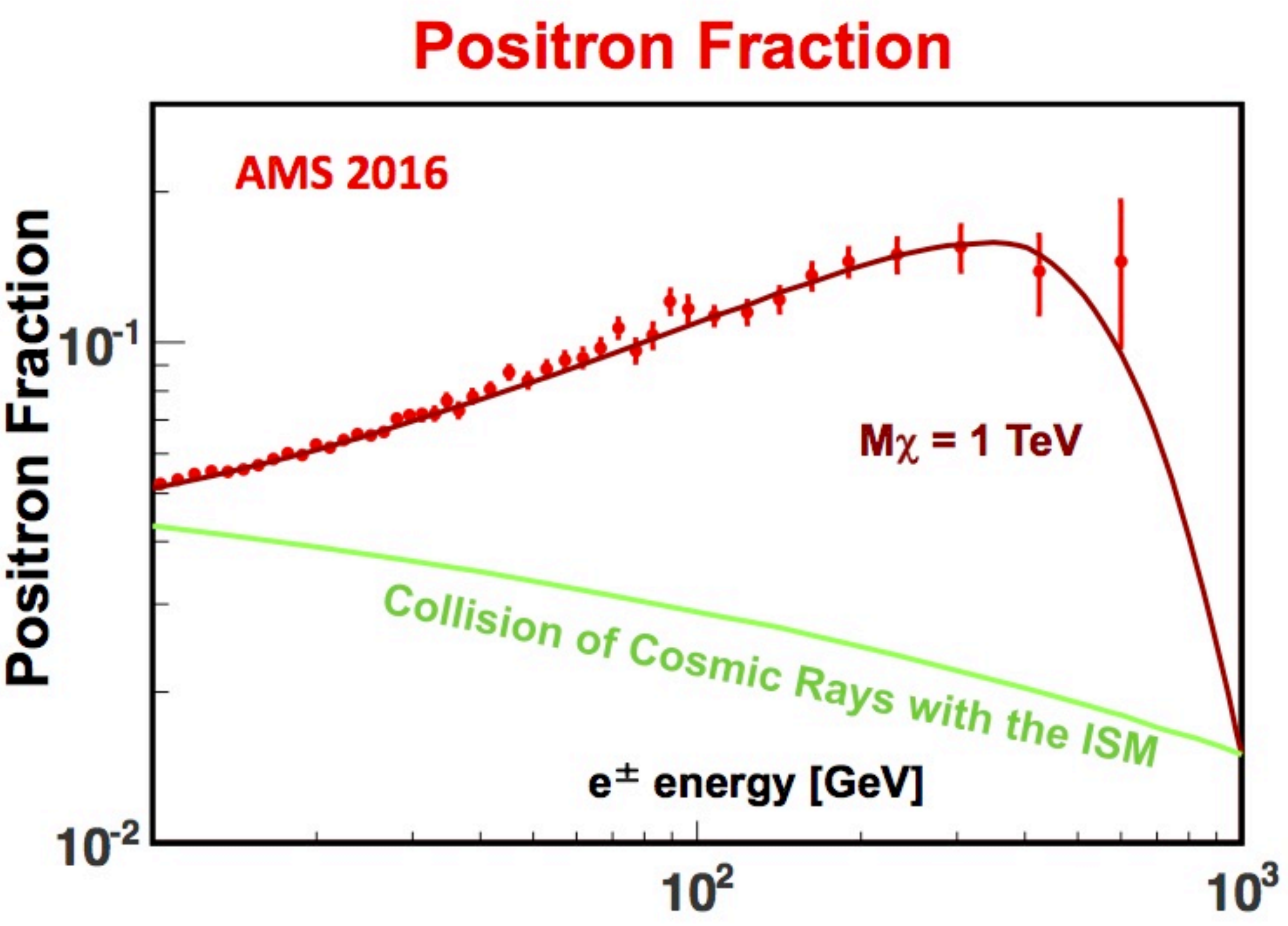
So far - no modeling of what a TeV halo is…

Implication III: The positron excess is due to pulsar activity

THE POSITRON EXCESS







PULSARS PRODUCE THE POSITRON EXCESS

- **What were the uncertainties in pulsar models?**
  - **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.**
  - **III: The propagation of e^+e^- to Earth.**

PULSARS PRODUCE THE POSITRON EXCESS

- **What were the uncertainties in pulsar models?**
  - **I: The e^+e^- production efficiency?**
  - **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 $\sim$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

  - **III: The propagation of e^+e^- to Earth.**

PULSARS PRODUCE THE POSITRON EXCESS

- **What were the uncertainties in pulsar models?**
  - **I: The e^+e^- production efficiency?**
  - **II: The e^+e^- spectrum.**
  - **III: The propagation of e^+e^- to Earth.**

Malyshev et al. (0903.1310)

The observed spectrum on Earth of electrons and positrons injected by pulsars is also strongly dependent on propagation effects. In particular, the observed cutoff in the flux of electrons from a pulsar can be much smaller than the injection cutoff due to energy losses ("cooling") during propagation. We define the cooling break, $E_{\rm br}(t)$, as the maximal energy electrons can have after propagating for time t. Since – as stated above – the typical

Cosmic-ray propagation is the last key.

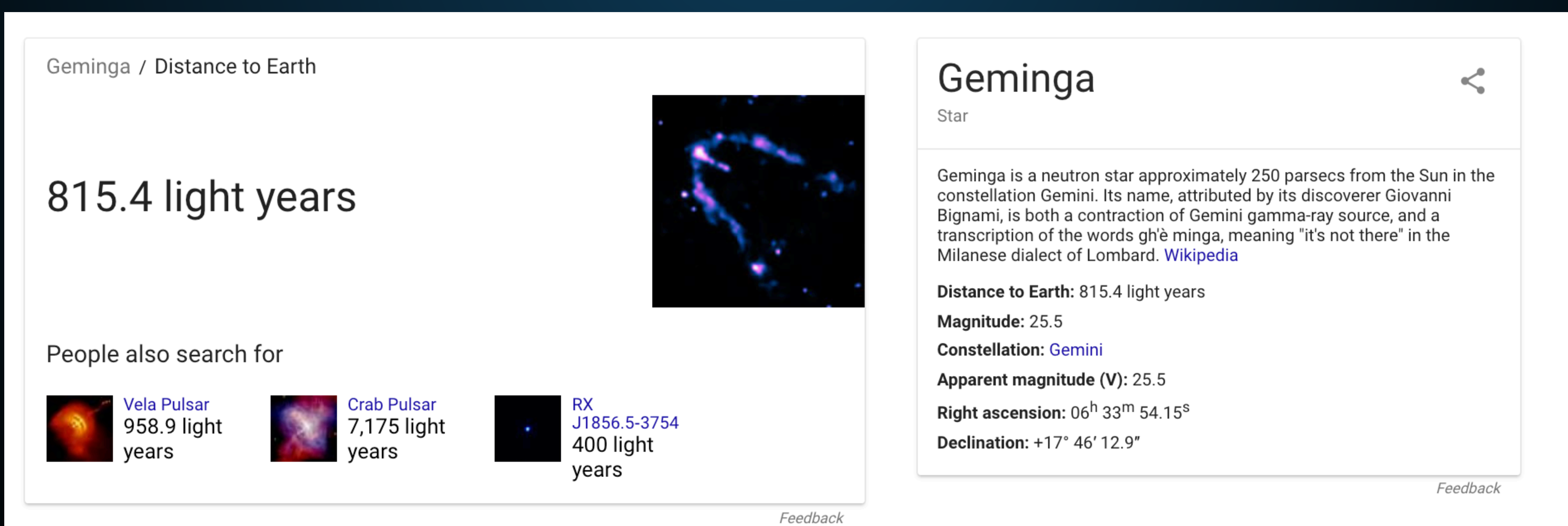
COSMIC-RAY DIFFUSION IN THE ISM

Hooper, Cholis, TL, Fang (2017; 1702.08436)

- **The energy loss timescale in the ISM (5 μG; 1 eV cm^{-3}) is approximately:**

$$\tau_{\rm loss} \approx 2 \times 10^4 \, {\rm yr} \left(\frac{10 \, {\rm TeV}}{E_e} \right)$$

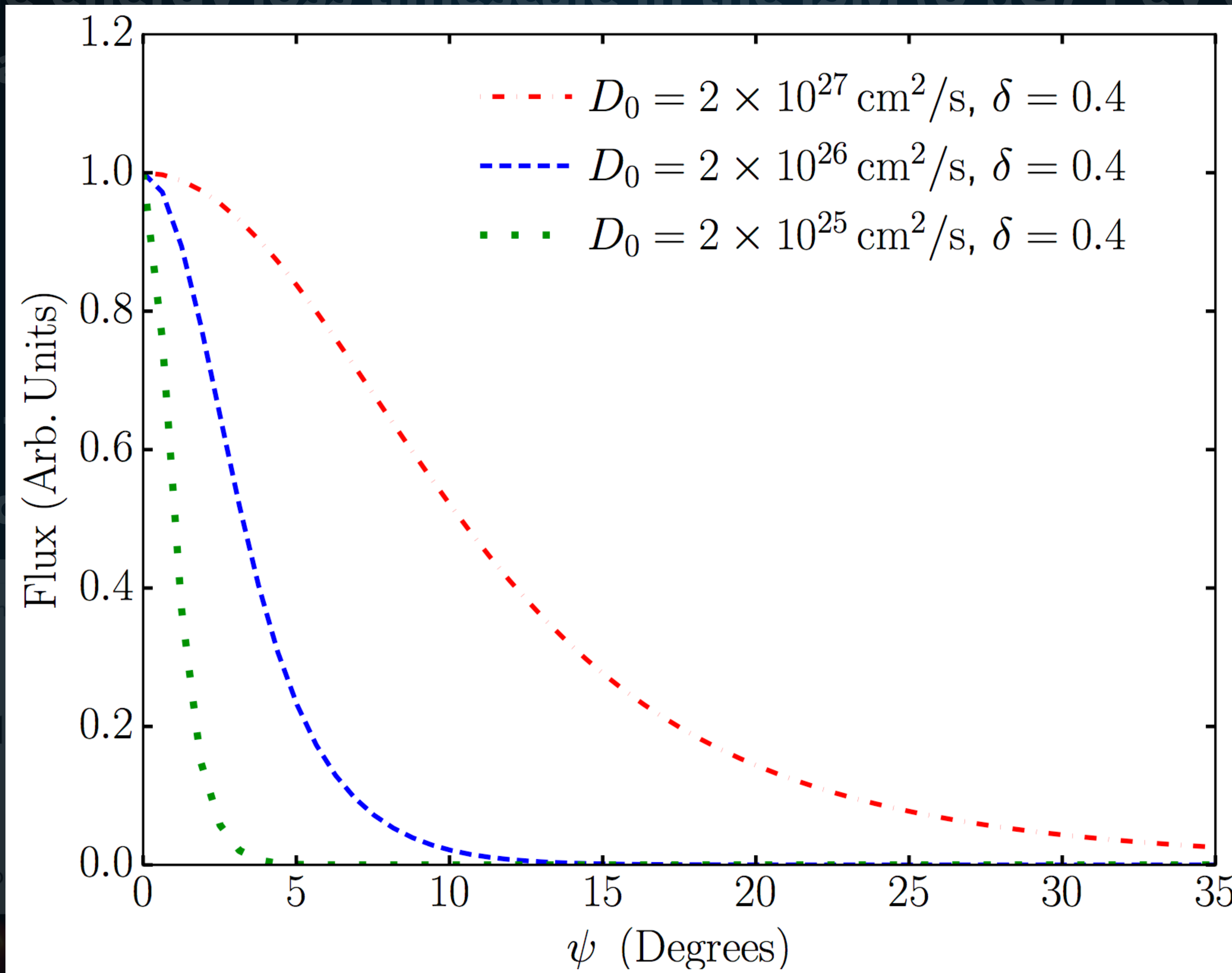
- **In the ISM (D_0 = 5 x 10^{28} cm^{2}s^{-1} δ=0.33), this implies a radial extent of ~250 pc.**



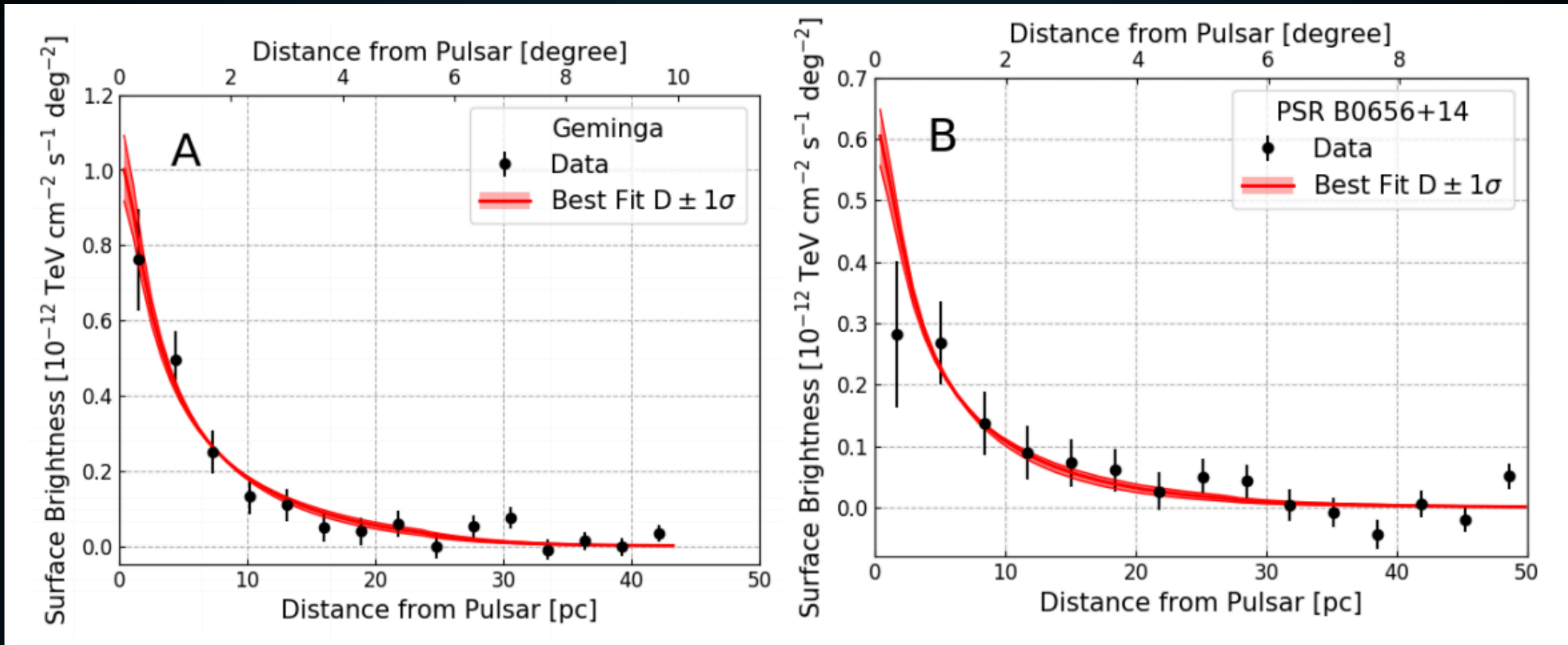
COSMIC-RAY DIFFUSION IN THE ISM

Hooper, Cholis, TL, Fang (2017; 1702.08436)

- The energy loss timescale in the ISM (5 μG; 1 eV cm^{-3}) is a



AN ENERGETICS PROBLEM



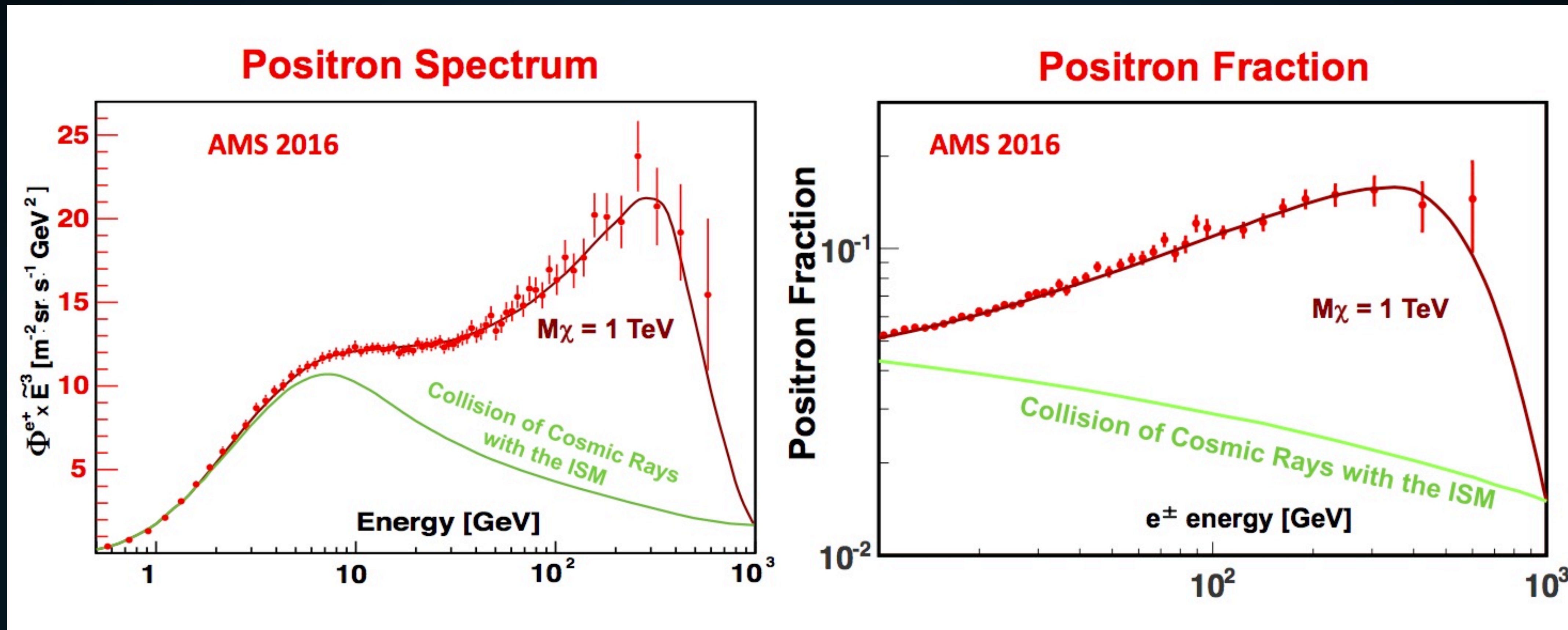
- **Morphology of each pulsar fit by diffusion.**
- **If diffusion continued to 250 pc, would require >100% efficiency.**

AN ENERGETICS PROBLEM

Pulsar Parameters		Geminga	PSR B0656+14
(Right ascension, declination) (J2000 source location)	[degrees]	(98.48, 17.77)	(104.95, 14.24)
τ_c (characteristic age)	[years]	342,000	110,000
D_{100} (Diffusion coefficient of 100TeV electrons from joint fit of two PWNe)	[$\times 10^{27}$ cm^2/sec]	4.5 ± 1.2	4.5 ± 1.2

Abeysekara et al. (2017; 1711.06223)

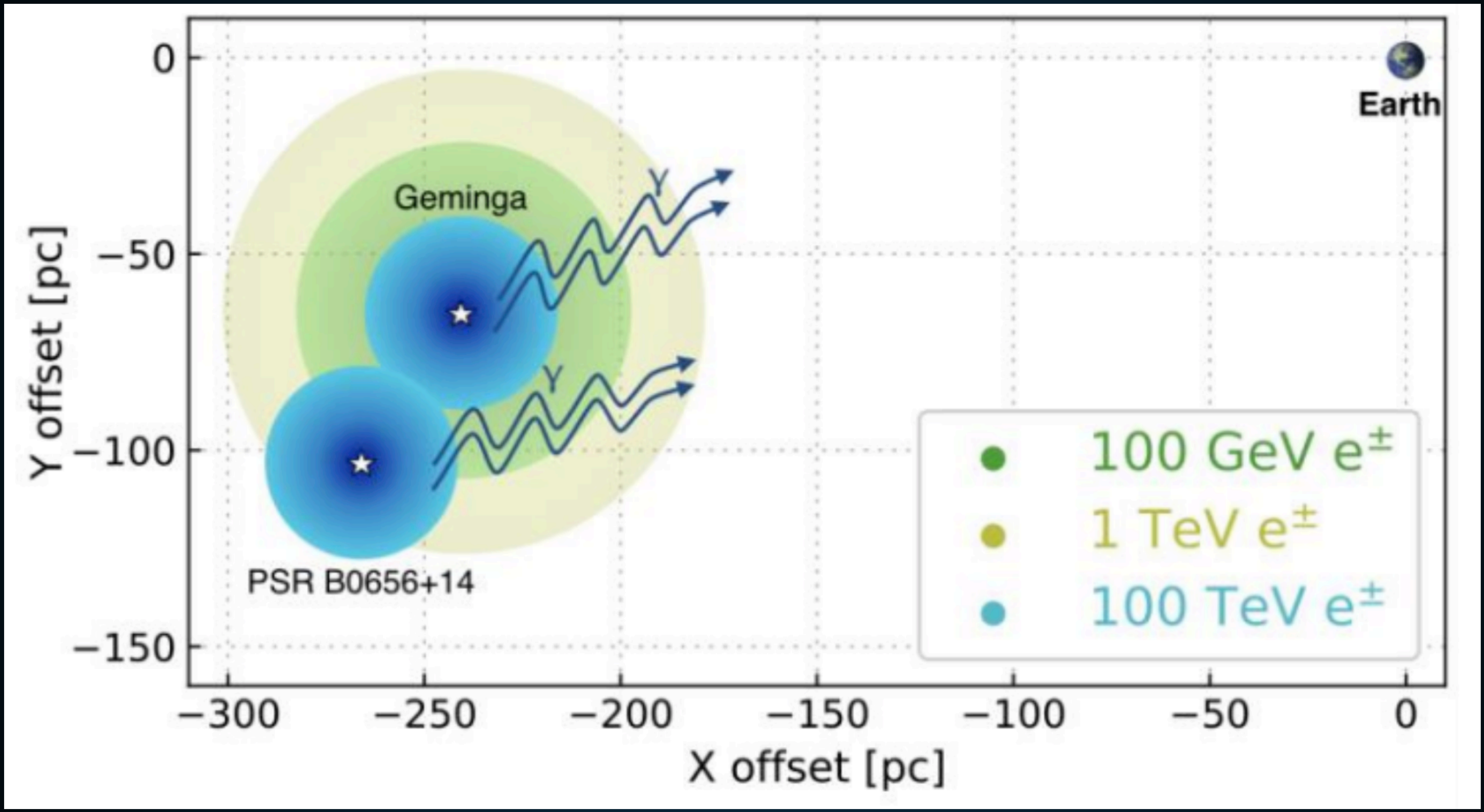
LOW-ENERGY COSMIC-RAY DIFFUSION



$$\tau_{Diff} \propto \frac{L^2}{D_0 E^{\delta}} \qquad \tau_{loss} \propto E^{-1}$$

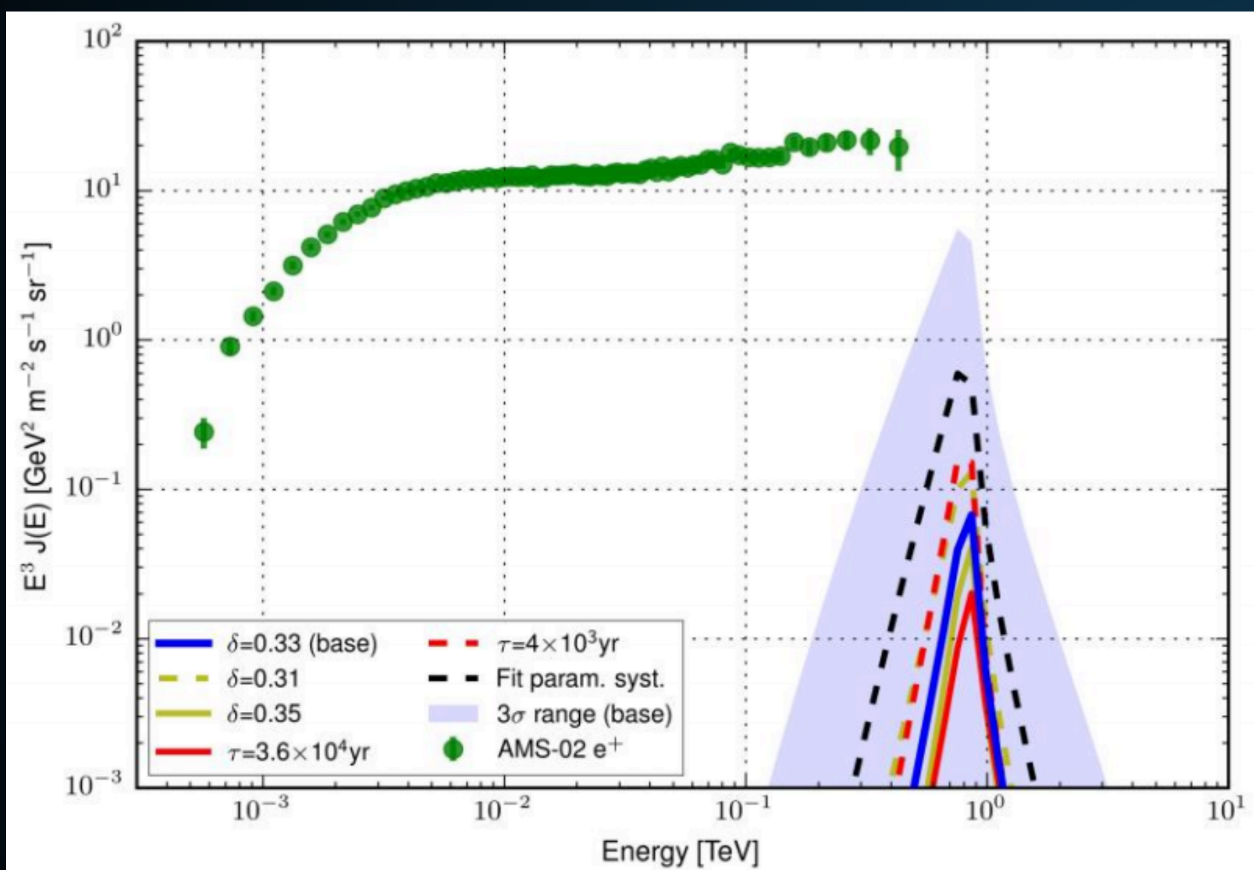
$$\left(\frac{\Delta E}{E}\right) \tilde{\propto} \frac{\tau_{Diff}}{\tau_{loss}} \propto E^{1-\delta}$$

AVERAGE COSMIC-RAY DIFFUSION



TWO POSSIBLE ASSUMPTIONS

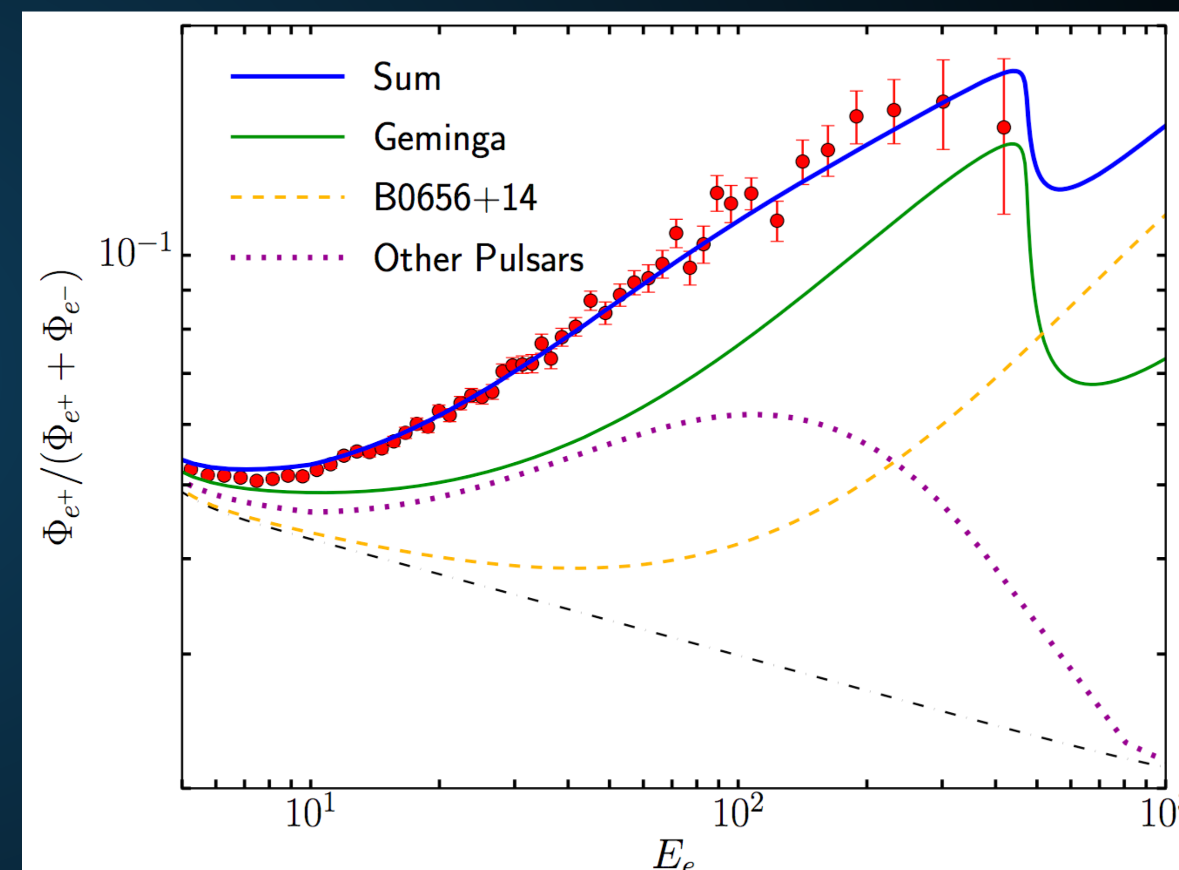
Extrapolate Low-Diffusion Constant UP to Earth:



100 GeV positrons do not make it to Earth

HAWC Collaboration (Science; 1711.06223)

Extrapolate the High Diffusion Constant DOWN to Earth:



100 GeV positrons do make it to Earth

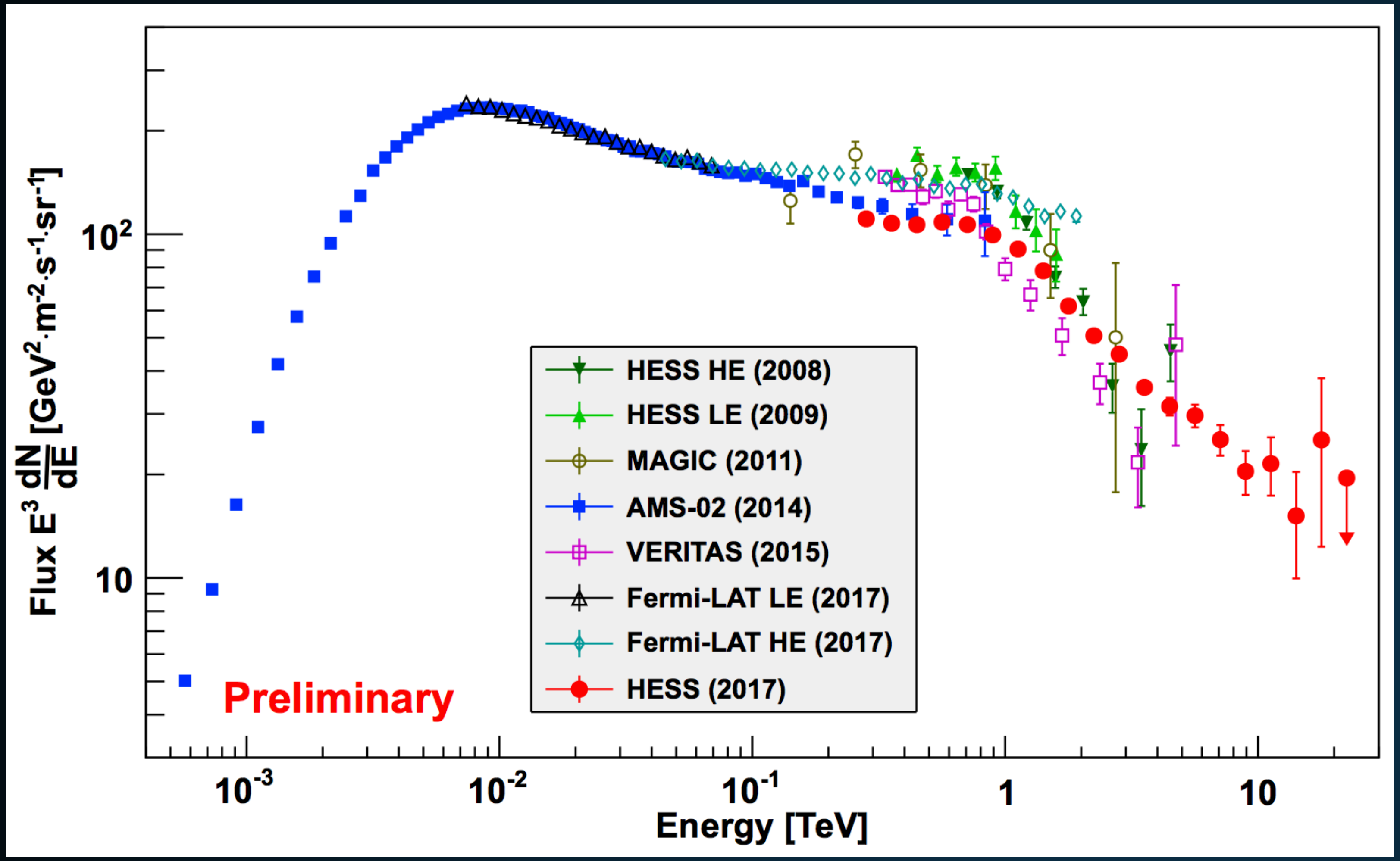
Hooper et al. (1702.08436)

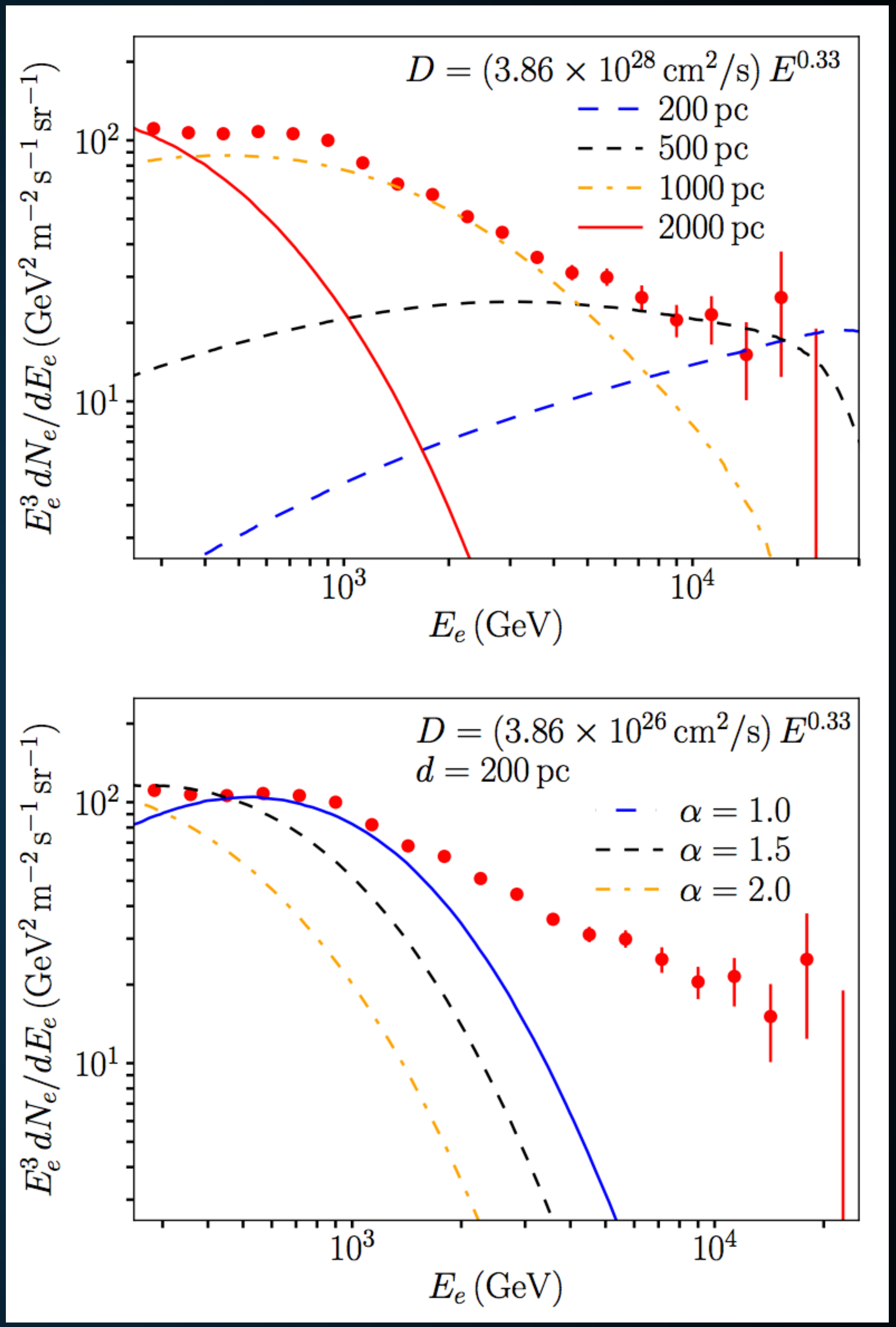
Profumo et al. (1803.09731)

Fang et al. (1803.02640)

CAN THE LOCAL DIFFUSION CONSTANT BE LOW?

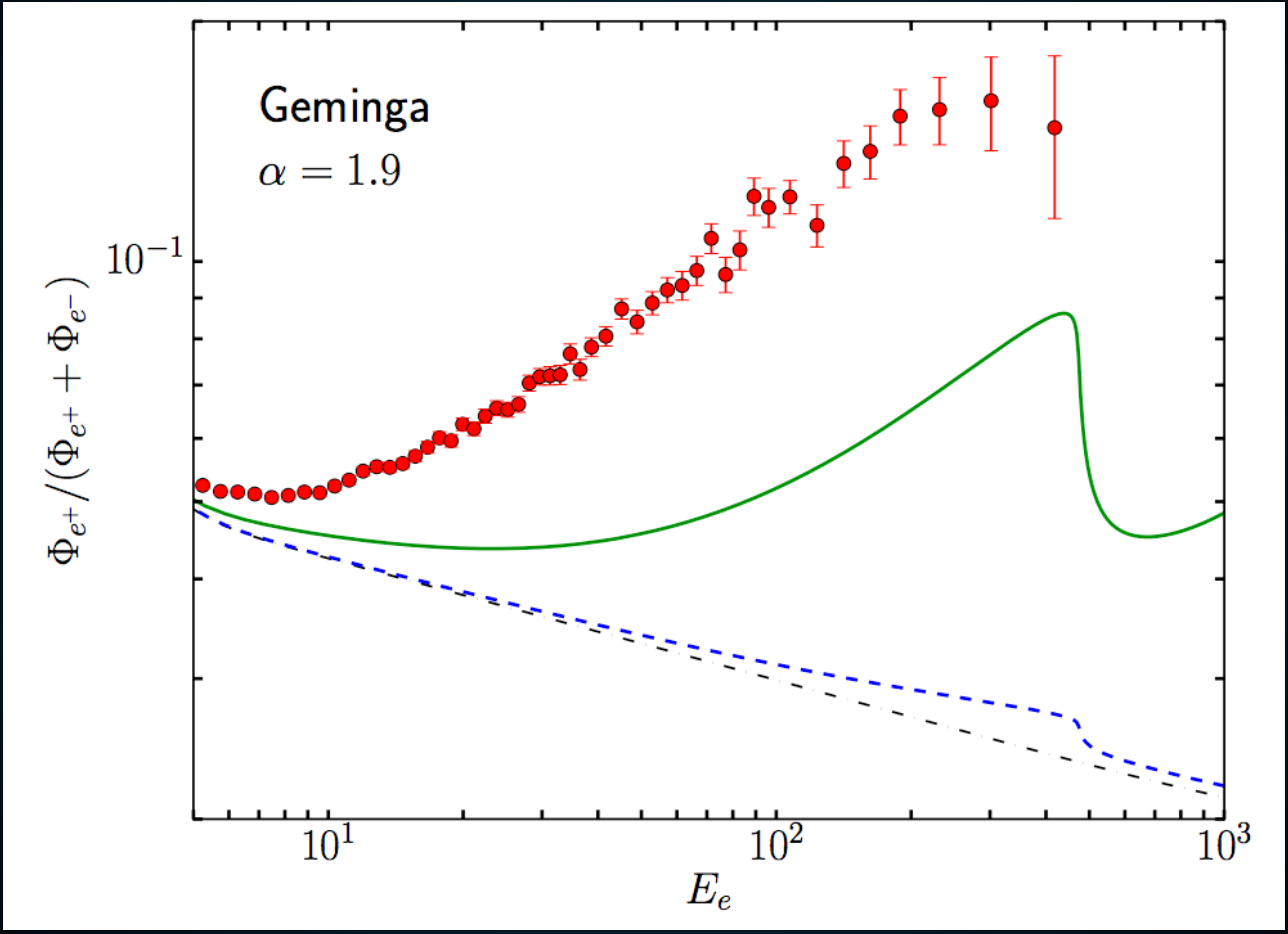
Hooper & Linden (1711.07482)





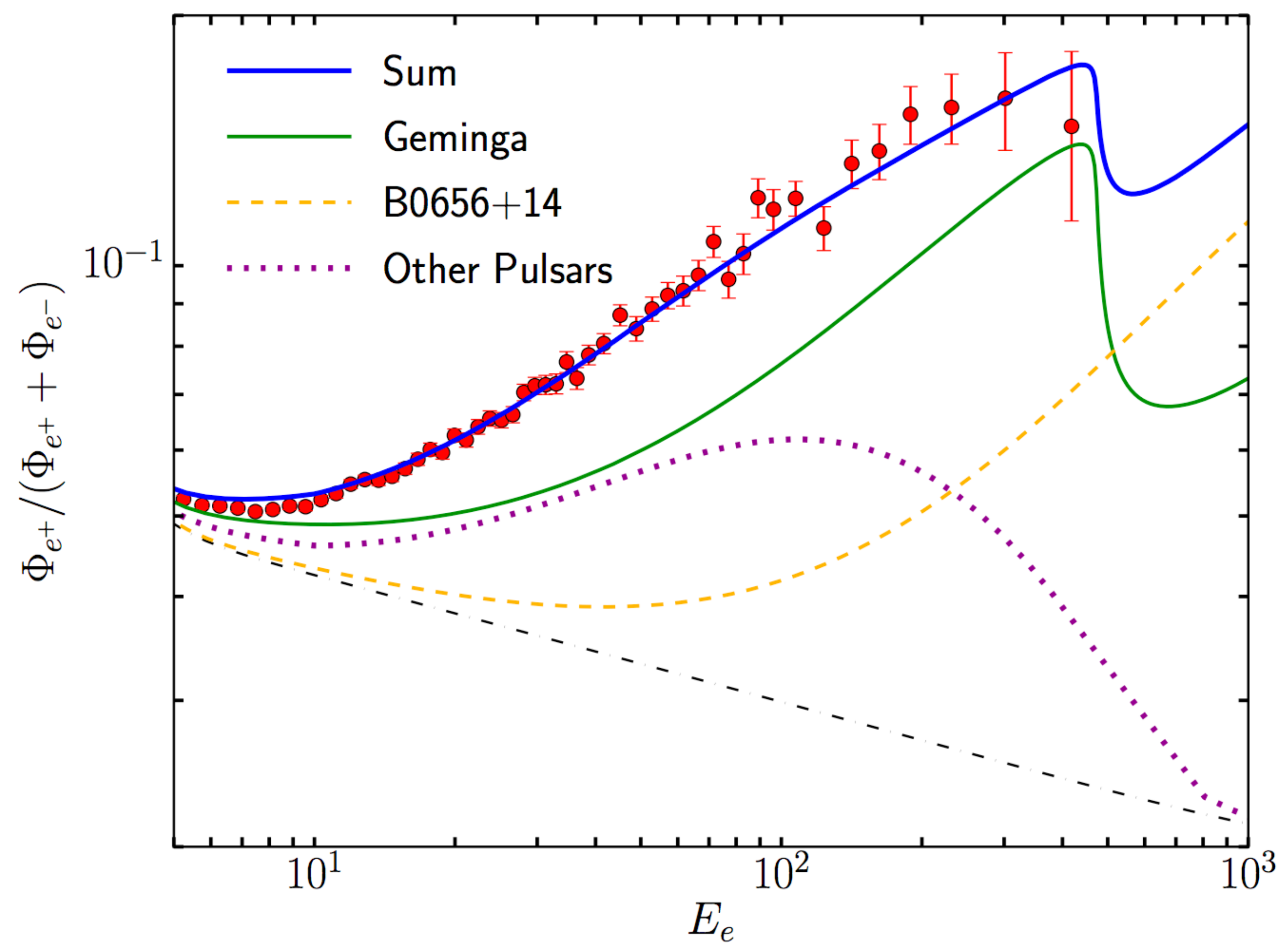
- **HESS Observations of 20 TeV electrons resolve this.**
- **If diffusion near Earth is low, then there is no source for these particles.**

THE POSITRON FRACTION FROM TEV HALOS



Hooper, Cholis, TL, Fang (2017; 1702.08436)

THE POSITRON FRACTION FROM TEV HALOS



*Braking index slightly changed to fit model to data.

- Total Contribution from:
  - Geminga
  - Monogem
  - Average of other young pulsars
- Reasonable models can be exactly fit to the excess.

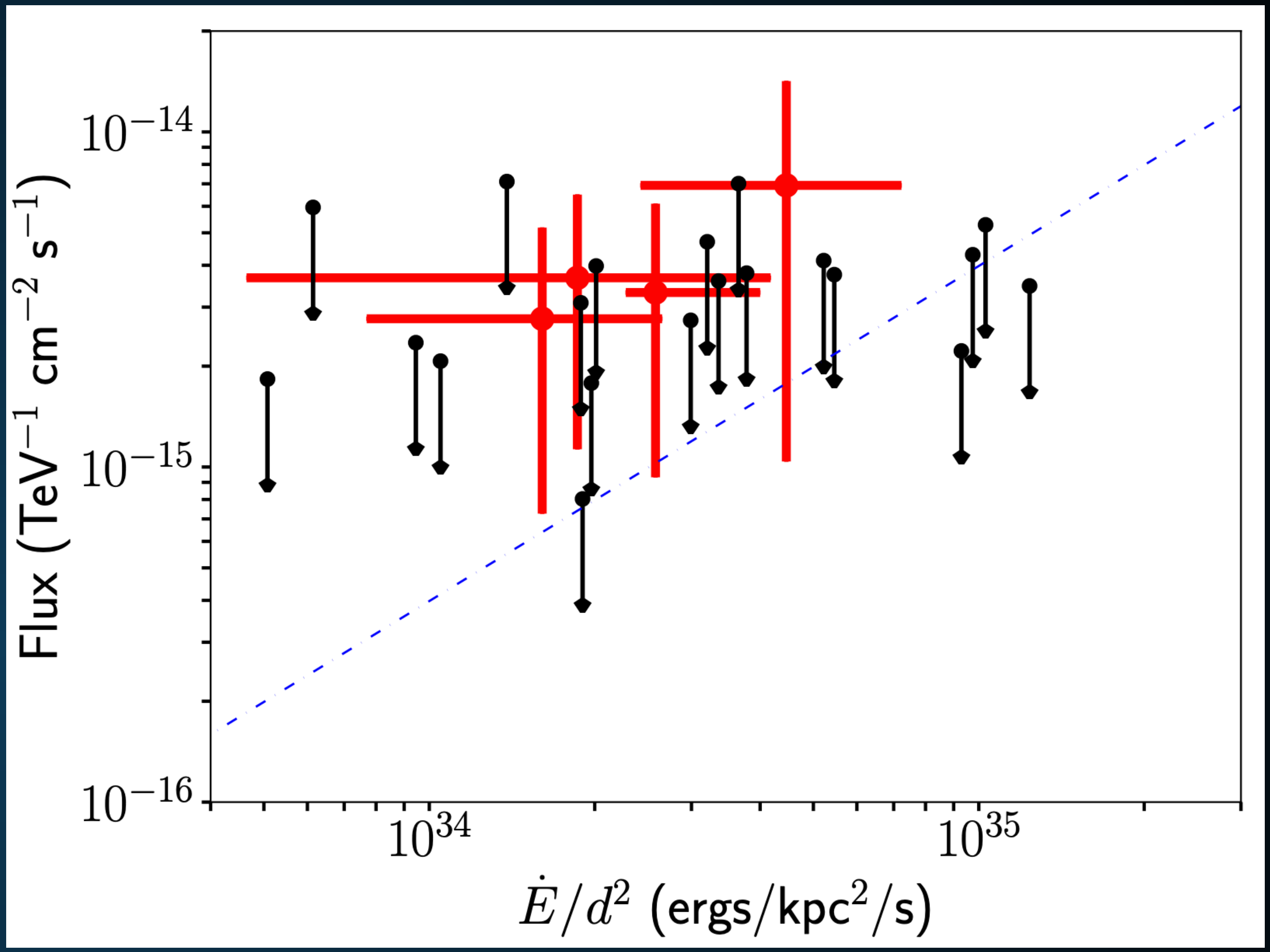
Hooper, Cholis, TL, Fang (2017; 1702.08436)

WHAT ABOUT MILLISECOND PULSARS?

Hooper & TL (2018; 1803.08046)

- **Millisecond Pulsars are the oldest recycled systems.**

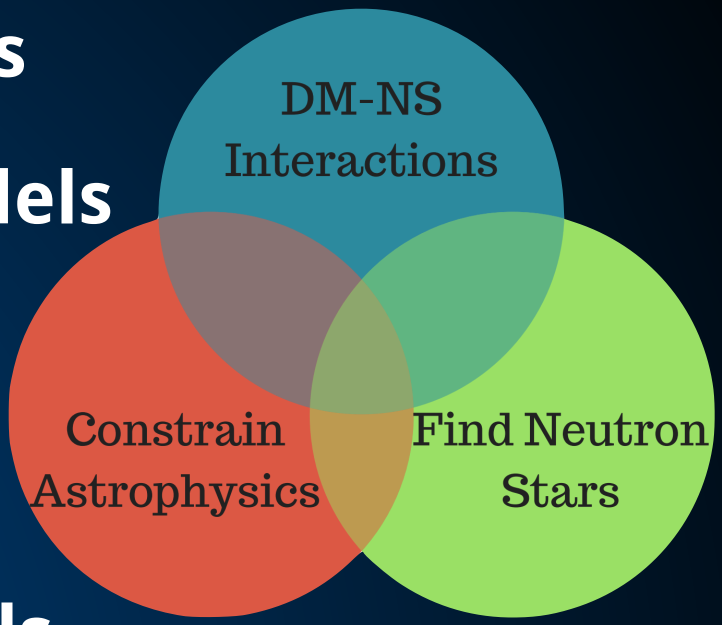
- **Stacked analysis of the nearest millisecond pulsars yields ~2.9σ evidence for gamma-ray emission.**



Why do we care?

The Program (from yesterday)

1. Understand Dark Matter/Neutron Star Interactions
   - Can already set strong constraints on some models
     1. Asymmetric Dark Matter
     2. Axions
   - Can probe extremely generic dark matter models.



2. Differentiate dim dark matter signals from astrophysics
   - Need detailed models of neutron star physics.
   - Requires observations of pulsars with “special” attributes
     1. Nearby
     2. Strong Magnetic Fields
     3. Not Beamed Towards Earth

ASSUMPTIONS

TeV Gamma-Ray Luminosity Roughly Proportional to Spindown Power

= Pulsars explain the Milagro TeV Excess

+ High Energy electrons trapped in TeV halos

= HAWC Sources are TeV halos

+ Low energy electrons escape from TeV halos

= Pulsars explain the positron excess

+ GC pulsars consistent with massive star formation

= TeV halos explain the HESS pevatron

+ MSPs produce TeV halos

= New Population of Blind Search TeV MSPs

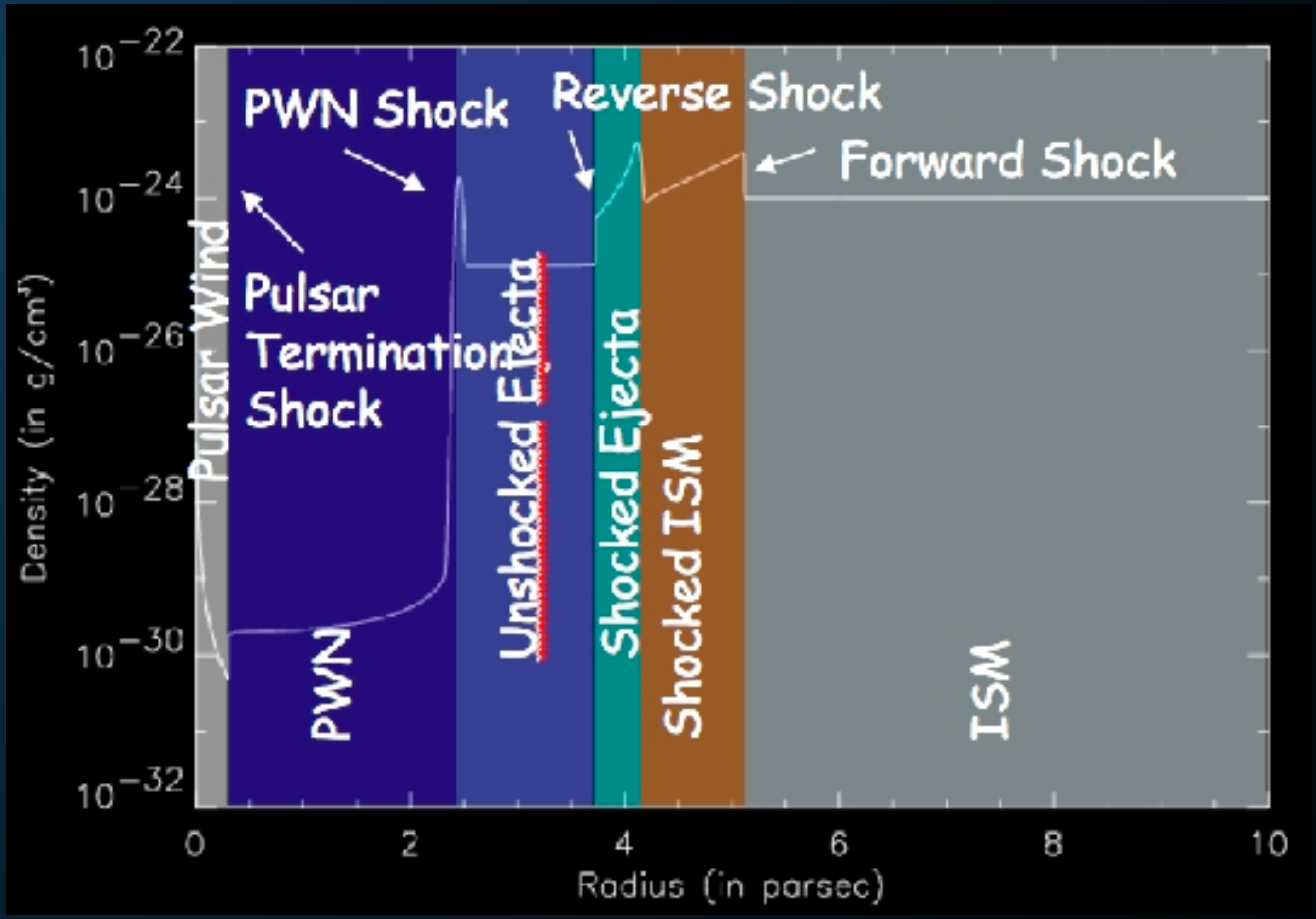
What is a TeV halo?

WHAT ARE TEV HALOS

- **TeV halos are a new feature**
  - **3 orders of magnitude larger than PWN in volume**
  - **Opposite energy dependence**

- **PWN are morphologically connected to the physics of the termination shock**

- **TeV halos need a similar morphological description.**



Equation for the turbulence evolution

[Jones 1993, ApJ 413, 619]

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \frac{\partial}{\partial z}\left(v_A W\right) + \Gamma_{CR} W + Q_k$$

- Diffusion in k-space (non-linear): $D_{kk} = c_k \, |v_A| \, k^{7/2} \, W^{1/2}$
- Advection of waves at the Alfvén speed
- Waves growth due to CR streaming: $\Gamma_{CR} \propto \partial f / \partial z$

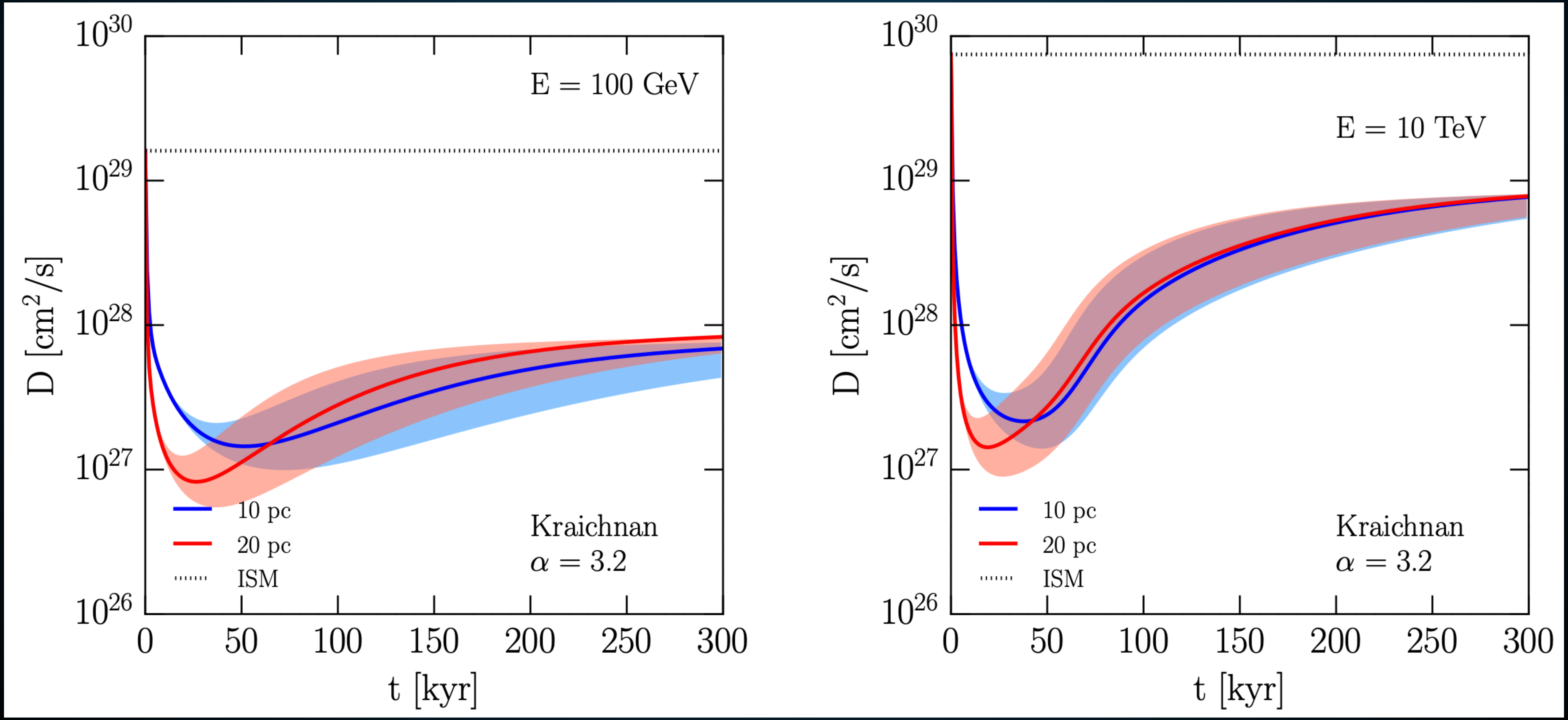
$$\Gamma_{CR} = \frac{16\pi}{3} \frac{v_A}{k\, W(k) B_0^2}\left[v\, p^4 \frac{\partial f}{\partial z}\right]$$

- External (e.g. SNe) source term in the disc: $Q \sim \delta(z)\, \delta(k - k_0)$
- In the absence of CR it returns the Kolmogorov spectrum: $W(k) \sim k^{-5/3}$

Evoli, TL, Morlino (2018; 1807.09263)

- **Low-diffusion constants can be induced in regions with significant cosmic-ray injection**

$$D_{\rm loc}(p) = \frac{\beta(p) c r_L(p)}{3} \left[\frac{2\pi}{3c_k} \frac{c f_0 p_0^4}{dU_0} \beta(p) r_L(p) \left(\frac{p}{p_0}\right)^{4-\alpha} \exp\left(-\frac{p}{p_c}\right) \right]^{-2/3}$$



CONFIRMING TEV HALOS

- **Several Methods to confirm TeV halo detections:**
  - **X-Ray PWN**
  - **X-Ray Halos**
  - **Thermal Pulsar Emission (see yesterday's talk)**

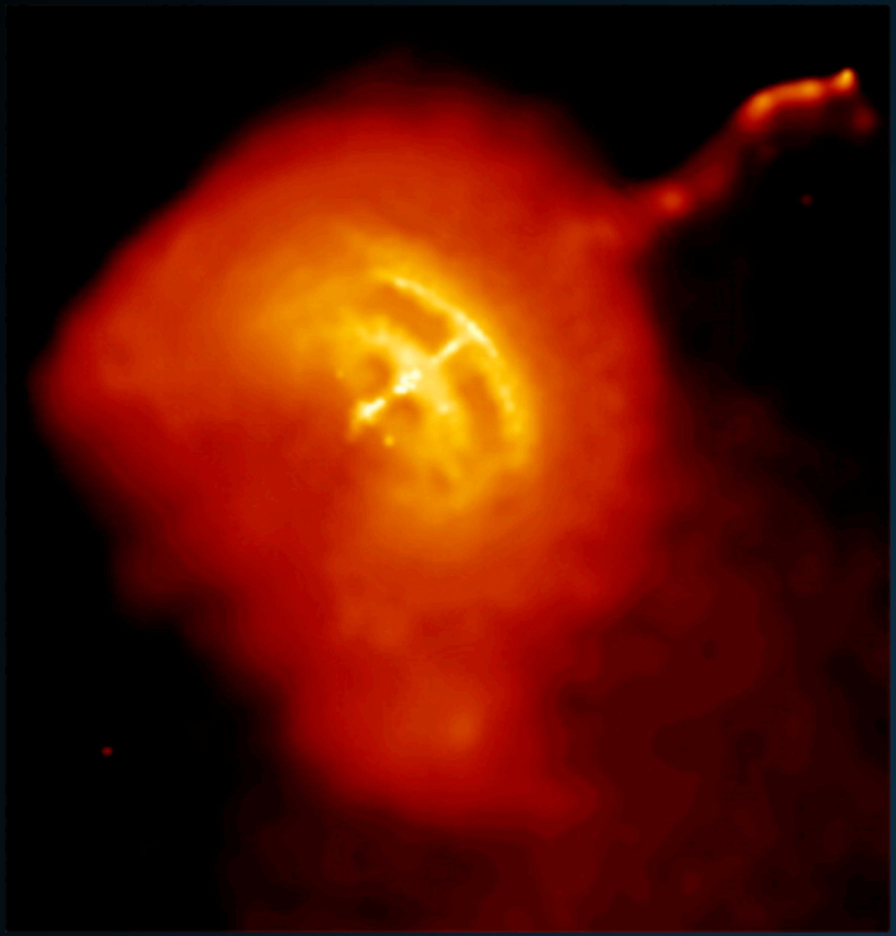
X-RAY HALOS

- **An X-Ray halo with an identical morphology as the TeV halo <u>must</u> exist.**

$$E_{\mathrm{sync,critical}} = 22\ \mathrm{eV} \left(\frac{B}{5\ \mu G}\right) \left(\frac{E_e}{10\ \mathrm{TeV}}\right)^2$$

- **However, the signal has a low surface brightness and peaks at a low energy.**

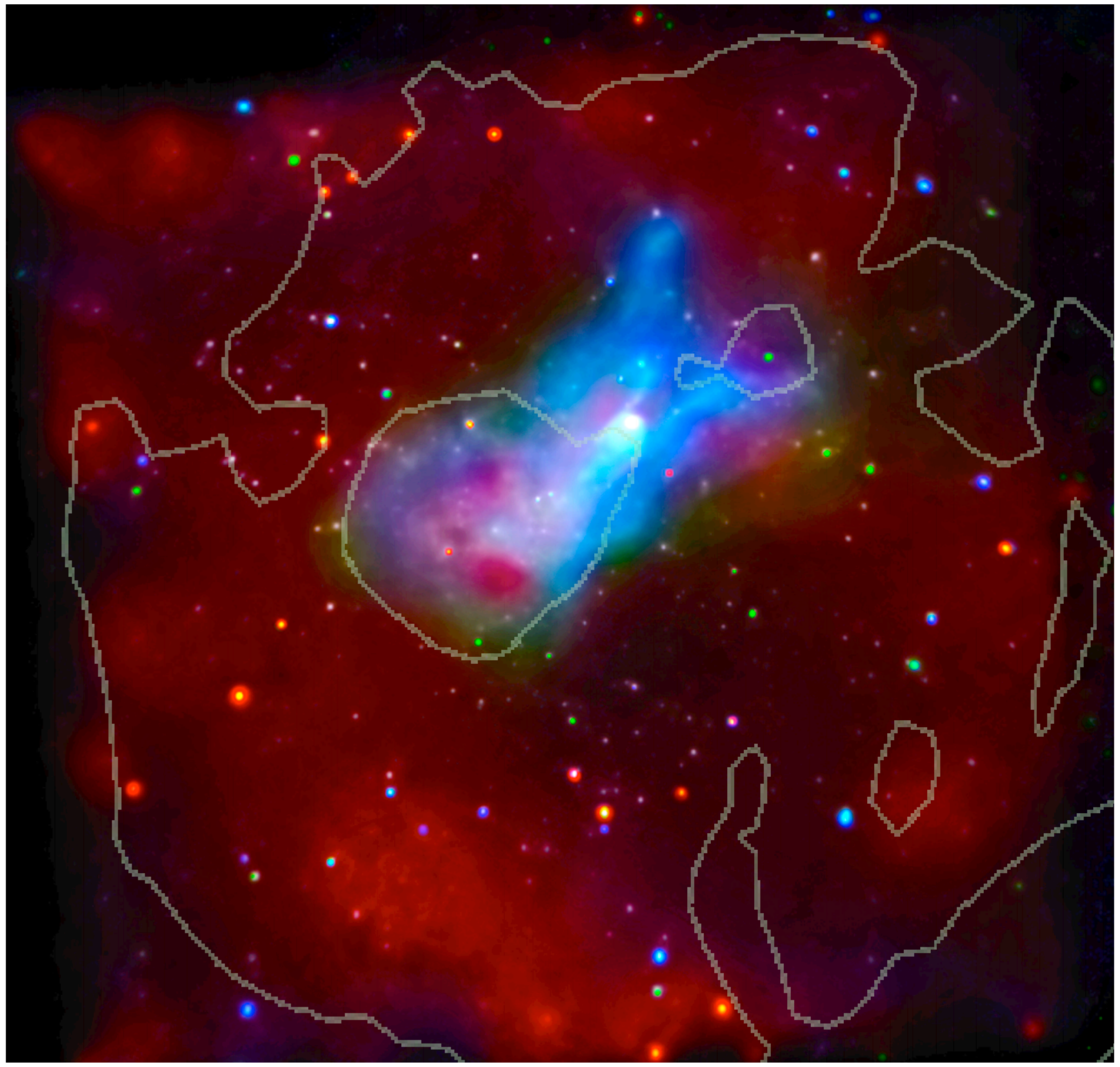
X-RAY PULSAR WIND NEBULAE



- Larger magnetic fields make compact PWN easier to observe
  - Synchrotron dominated
  - Higher energy peak
- More distant sources easier to see.
- Significant observation times require careful HAWC analysis.

A POSSIBLE DETECTION

1506.03069



- **Possible Detection! (G327-1.1)**
- **Young Pulsar (17.4 kyr)**
- **Two PWN**
  - **Diffuse PWN has significantly softer spectrum**

	Region	Area (arcsec^2)	Cts (1000)	N_H (10^{22} cm^{-2})	Photon Index	Amplitude (10^{-4})	kT (keV)	τ (10^{12} s cm^{-3})	Norm. (10^{-3})	F_1 (10^{-12})	F_2 (10^{-12})	Red. χ^2
1	Compact Source	84.657	6.34	$1.93^{+0.08}_{-0.08}$	$1.61^{+0.08}_{-0.07}$	$1.05^{+0.11}_{-0.10}$	...	...	...	0.45	...	0.80
2	Cometary PWN	971.22	7.75	1.93	$1.62^{+0.08}_{-0.07}$	$1.47^{+0.16}_{-0.14}$	...	...	...	1.09	...	...
3	Trail East	537.42	2.13	1.93	$1.84^{+0.12}_{-0.12}$	$0.44^{+0.07}_{-0.06}$	...	...	...	0.27	...	...
4	Trail West	766.56	3.12	1.93	$1.80^{+0.11}_{-0.11}$	$0.61^{+0.09}_{-0.08}$	...	...	...	0.39	...	...
5	Trail 1	424.45	1.98	1.93	$1.76^{+0.12}_{-0.12}$	$0.39^{+0.05}_{-0.05}$	...	...	...	0.26	...	...
6	Trail 2	588.19	2.13	1.93	$1.95^{+0.11}_{-0.11}$	$0.49^{+0.07}_{-0.06}$	...	...	...	0.28	...	...
7	Trail 3	994.92	2.99	1.93	$2.09^{+0.10}_{-0.10}$	$0.78^{+0.09}_{-0.08}$	...	...	...	0.42	...	...
8	Trail 4	839.48	2.38	1.93	$2.28^{+0.12}_{-0.12}$	$0.74^{+0.09}_{-0.09}$	...	...	...	0.37	...	...
9	Prong East	828.58	1.66	1.93	$1.72^{+0.14}_{-0.14}$	$0.30^{+0.06}_{-0.05}$	...	...	...	0.27	...	...
10	Prong West	971.22	2.06	1.93	$1.85^{+0.14}_{-0.14}$	$0.44^{+0.08}_{-0.07}$	...	...	...	1.09	...	...
11	Diffuse PWN*	20007	27.7	1.93	$2.11^{+0.04}_{-0.05}$	$6.91^{+0.37}_{-0.74}$	$0.23^{+0.14}_{-0.05}$	$0.21^{+0.88}_{-0.16}$	$6.0^{+16}_{-4.0}$	3.68	17.7	0.82
12	Relic PWN*	26787	17.2	1.93	$2.58^{+0.07}_{-0.10}$	$6.51^{+0.53}_{-0.71}$	0.23	0.21	$6.9^{+18}_{-5.5}$	3.14	20.3	...

CONCLUSIONS (1/2)

- TeV observations open up a new window into understanding Milky Way pulsars.

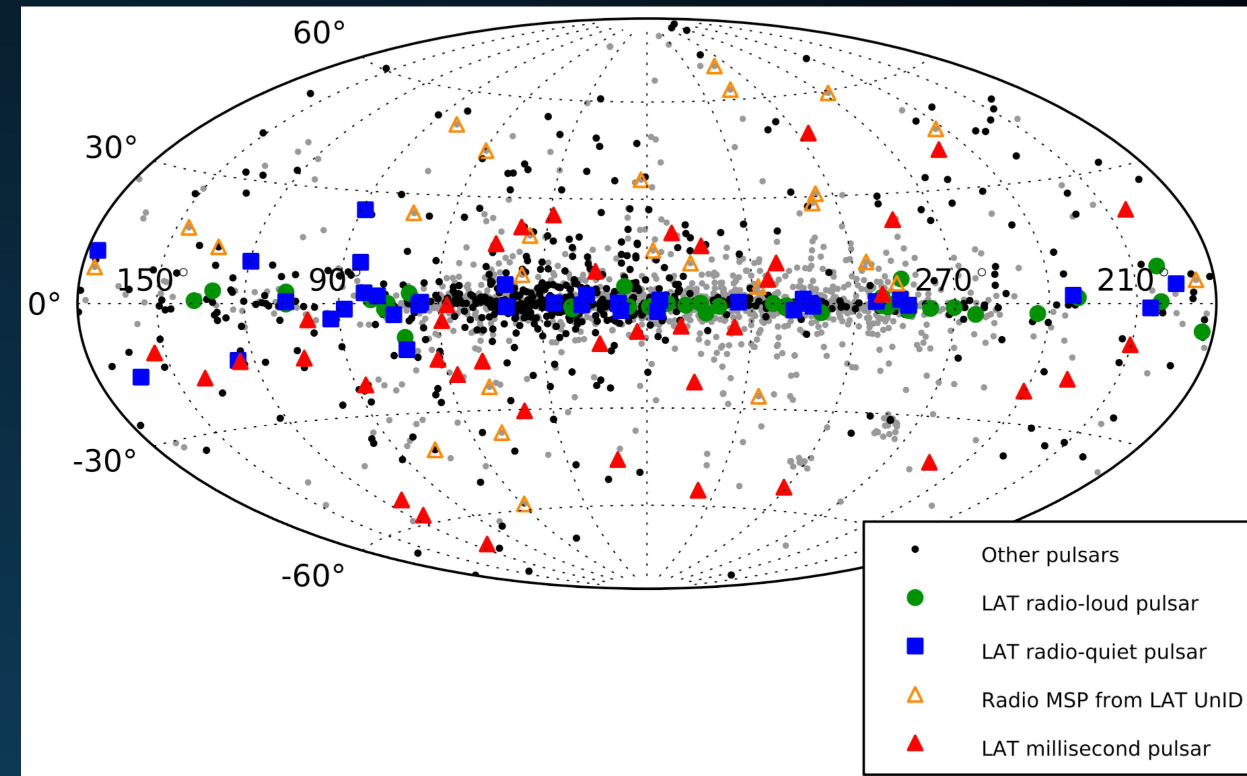
- Early indications:
  - TeV halos produce most of the TeV sources observed by ACTs and HAWC
  - TeV halos dominate the diffuse TeV emission in our galaxy.
  - Positron Excess is due to pulsar activity

- **Additional implications:**
  - **Young pulsar braking index *(upcoming: Takahiro Sudoh)***
  - **MSPs?**
  - **Galactic cosmic-ray diffusion**
  - **Source of IceCube neutrinos**
  - **TeV Dark Matter Constraints**

Extra Slides

MISSING TEV HALOS

- **Fermi-LAT has 5 middle-aged pulsars in the HAWC field.**



- **X-Ray studies have only reported 6 X-Ray PWN without pulsars in the HAWC field of view.**

PWNe With No Detected Pulsar

Gname	other name(s)	R	X	O	G	
G0.13-0.11					?	notes
G0.9+0.1					N	notes
G7.4-2.0	GeV J1809-2327, Tazzie				Y	notes
G16.7+0.1					N	notes
G18.5-0.4	GeV J1825-1310, Eel				Y	notes
G20.0-0.2					N	notes
G24.7+0.6					N	notes
G27.8+0.6					N	notes
G39.2-0.3	3C 396				Y	notes
G63.7+1.1					N	notes
G74.9+1.2	CTB 87				Y	notes
G119.5+10.2	CTA 1				Y	notes
G189.1+3.0	IC 443				?	notes
G279.8-35.8	B0453-685				N	notes
G291.0-0.1	MSH 11-62				Y	notes
G293.8+0.6					N	notes
G313.3+0.1	Rabbit				Y	notes
G318.9+0.4					N	notes
G322.5-0.1					N	notes
G326.3-1.8	MSH 15-56				N	notes
G327.1-1.1					N	notes
G328.4+0.2	MSH 15-57				N	notes
G358.6-17.2	RX J1856.5-3754	N	N		N	notes
G359.89-0.08					Y	notes

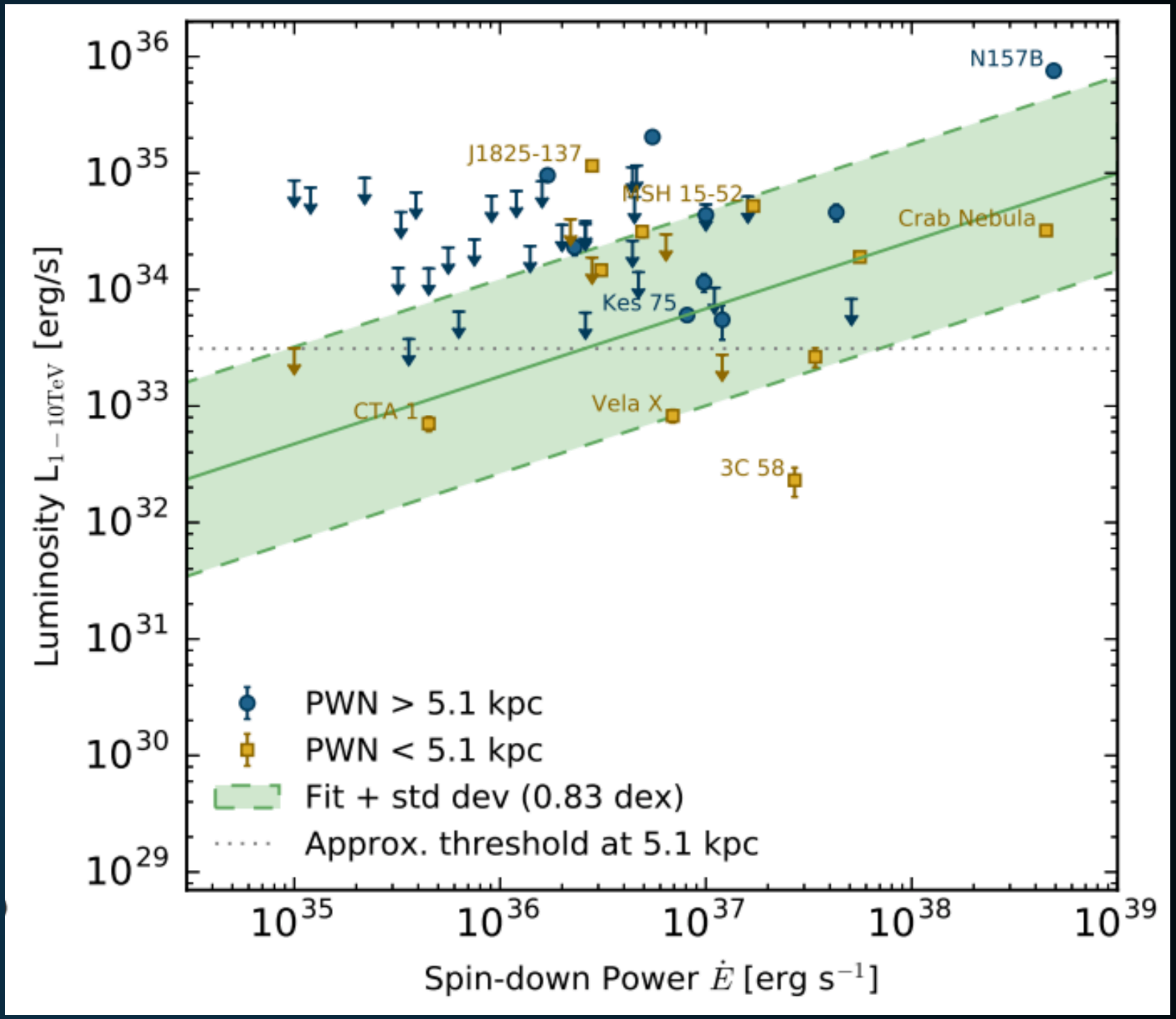
https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

What if the "Geminga"-like model is wrong?

THE FIRST-ORDER MODEL OF TEV HALOS

1702.08280

- **Alternatively can utilize HESS results which find:**

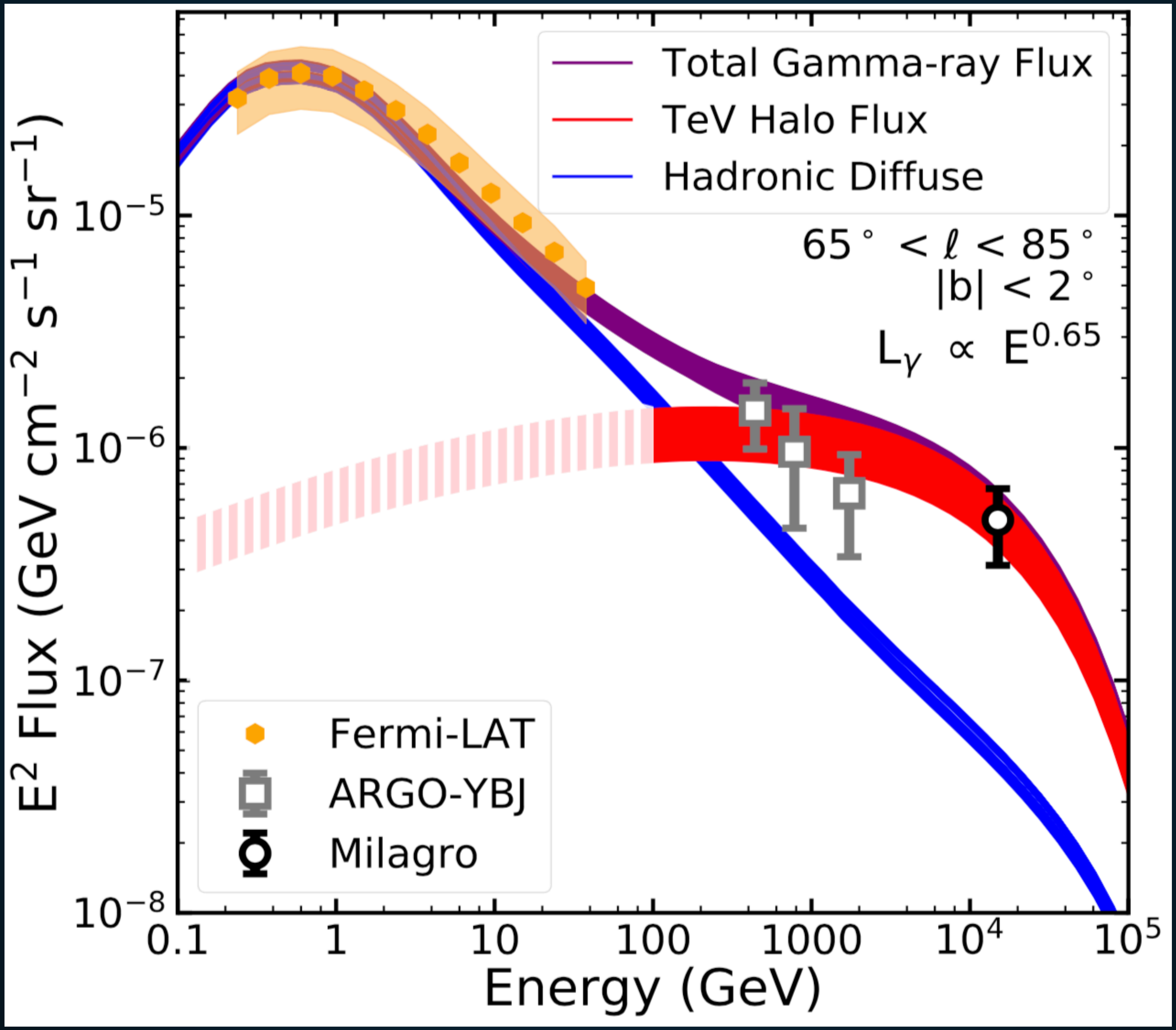


$$L = E_{dot}^{0.59}$$

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

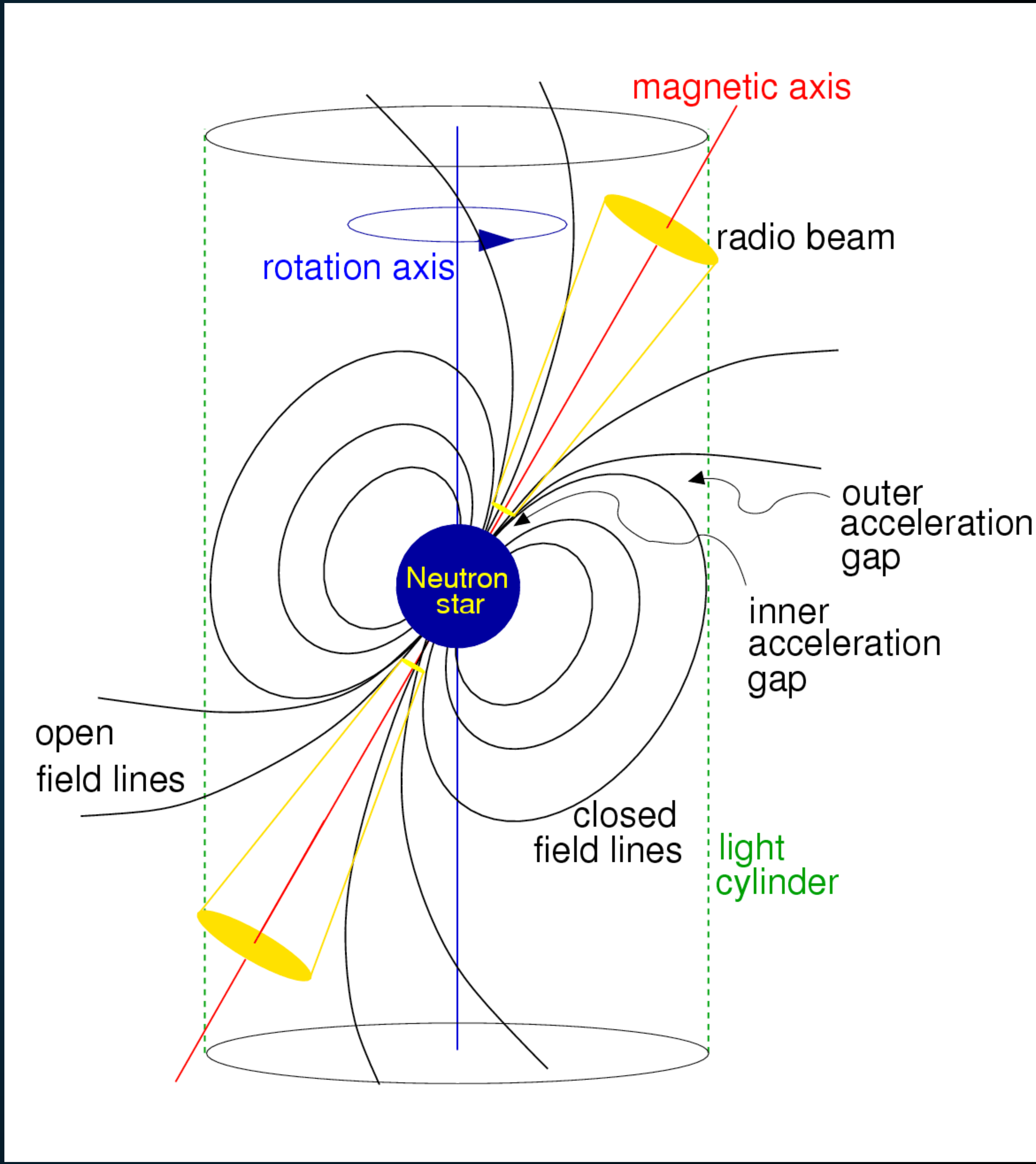
Linden & Buckman (1707.01905)

- **TeV halos naturally explain the TeV excess!**

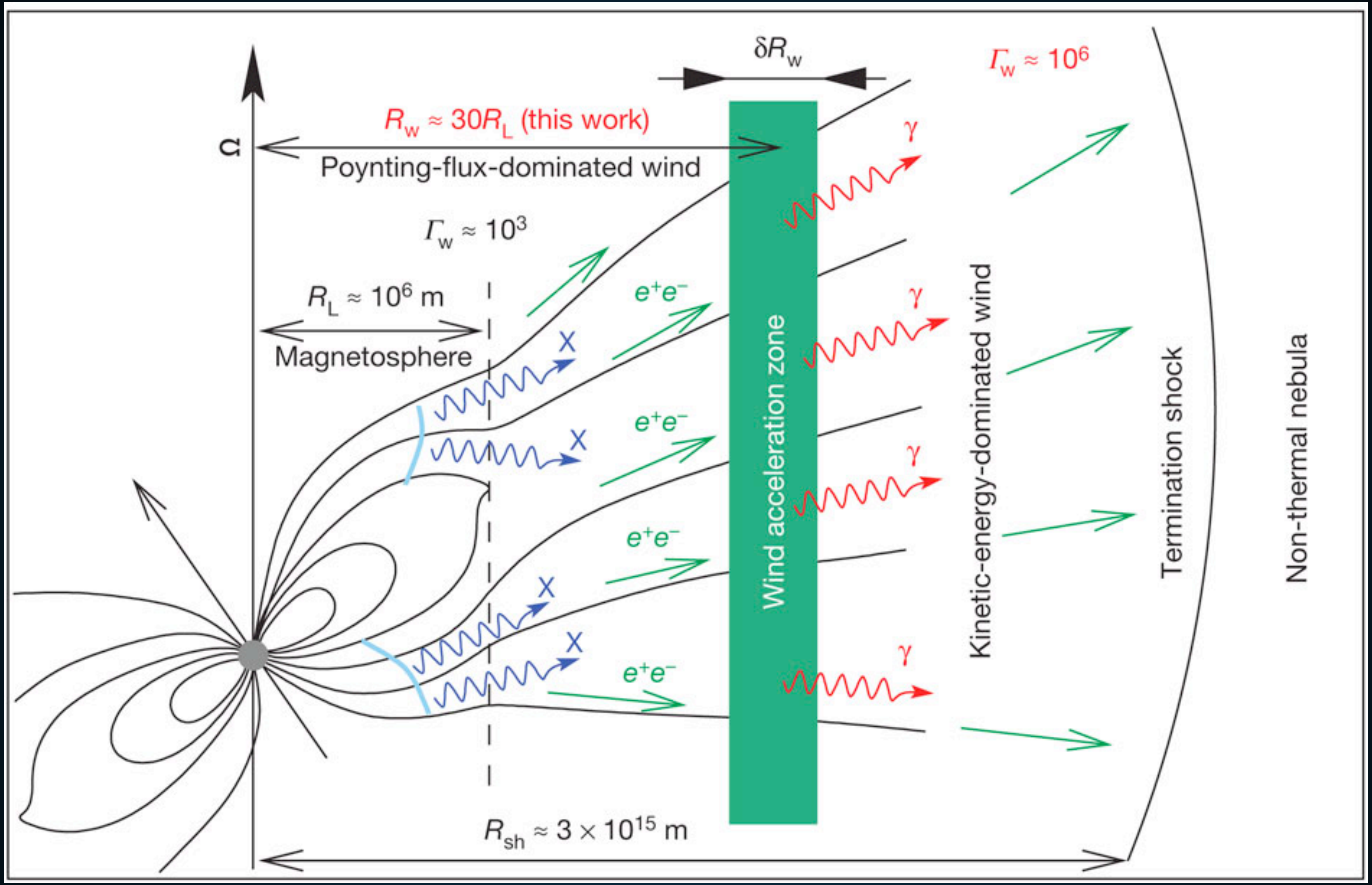


PULSARS AS ASTROPHYSICAL ACCELERATORS

- radio beam
- gamma-ray beam
- e^+e^- acceleration in pulsar magnetosphere
- e^+e^- acceleration at termination shock



PRODUCTION OF ELECTRON AND POSITRON PAIRS



- **Final e^+e^- spectrum is model dependent.**
- **Understanding this is important for MSPs.**

ENERGY LOSSES ARE DOMINATED BY THE ISM

- **It is not energetically possible for Geminga to produce the magnetic field or ISRF that these electrons interact with.**

$$U = \frac{1}{8\pi} B^2 = \frac{(10\,\mu G)^2}{8\pi}$$
$$= 4\times10^{-12}\ \frac{erg}{cm^3}$$
$$\int_0^{10pc} U\, dV = 5\times10^{47}\ erg$$
$$\hookrightarrow \text{Magnetic Flux} \approx 5\times10^{38}\ \frac{ergs}{s}$$

$$ISRF = 1\ \frac{eV}{cm^3}$$
$$\int ISRF\, dV = 8\times10^{47}\ erg$$
$$\hookrightarrow \text{Flux} = 8\times10^{38}\ \frac{ers}{s}$$

- **We can use typical ISM values (5 μG; 1 eV cm^{-3}) to characterize interactions.**

- **Nearly equal energy to synchrotron and ICS.**

X-RAY PWN DETECTIONS

PWNe With No Detected Pulsar

Gname	other name(s)	R	X	O	G	
G0.13-0.11					?	notes
G0.9+0.1					N	notes
G7.4-2.0	GeV J1809-2327, Tazzie				Y	notes
G16.7+0.1					N	notes
G18.5-0.4	GeV J1825-1310, Eel				Y	notes
G20.0-0.2					N	notes
G24.7+0.6					N	notes
G27.8+0.6					N	notes
G39.2-0.3	3C 396				Y	notes
G63.7+1.1					N	notes
G74.9+1.2	CTB 87				Y	notes
G119.5+10.2	CTA 1				Y	notes
G189.1+3.0	IC 443				?	notes
G279.8-35.8	B0453-685				N	notes
G291.0-0.1	MSH 11-62				Y	notes
G293.8+0.6					N	notes
G313.3+0.1	Rabbit				Y	notes
G318.9+0.4					N	notes
G322.5-0.1					N	notes
G326.3-1.8	MSH 15-56				N	notes
G327.1-1.1					N	notes
G328.4+0.2	MSH 15-57				N	notes
G358.6-17.2	RX J1856.5-3754	N	N		N	notes
G359.89-0.08					Y	notes

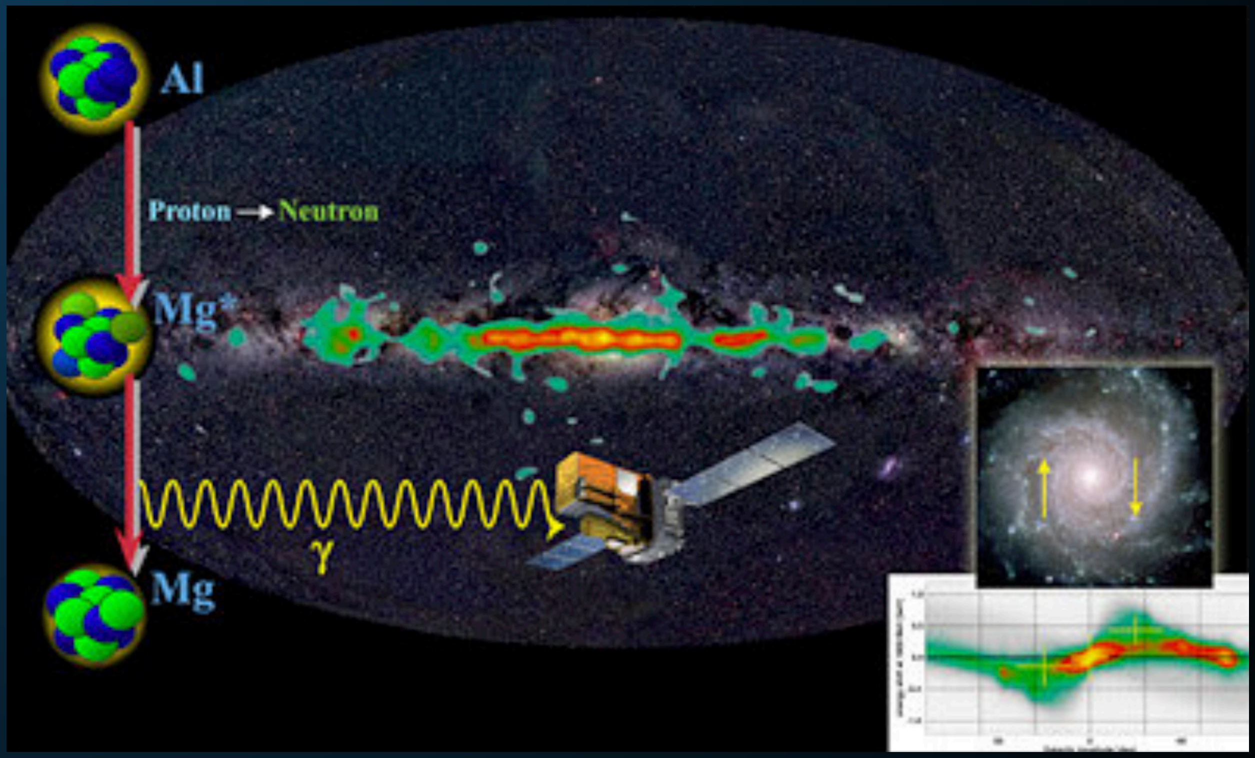
- X-Ray PWN have detected only ~6 of these 37 systems.

GEMINGA ISN'T SPECIAL

$$f \sim \frac{N_{\rm region} \times \frac{4\pi}{3} r_{\rm region}^3}{\pi R_{\rm MW}^2 \times 2 z_{\rm MW}}$$

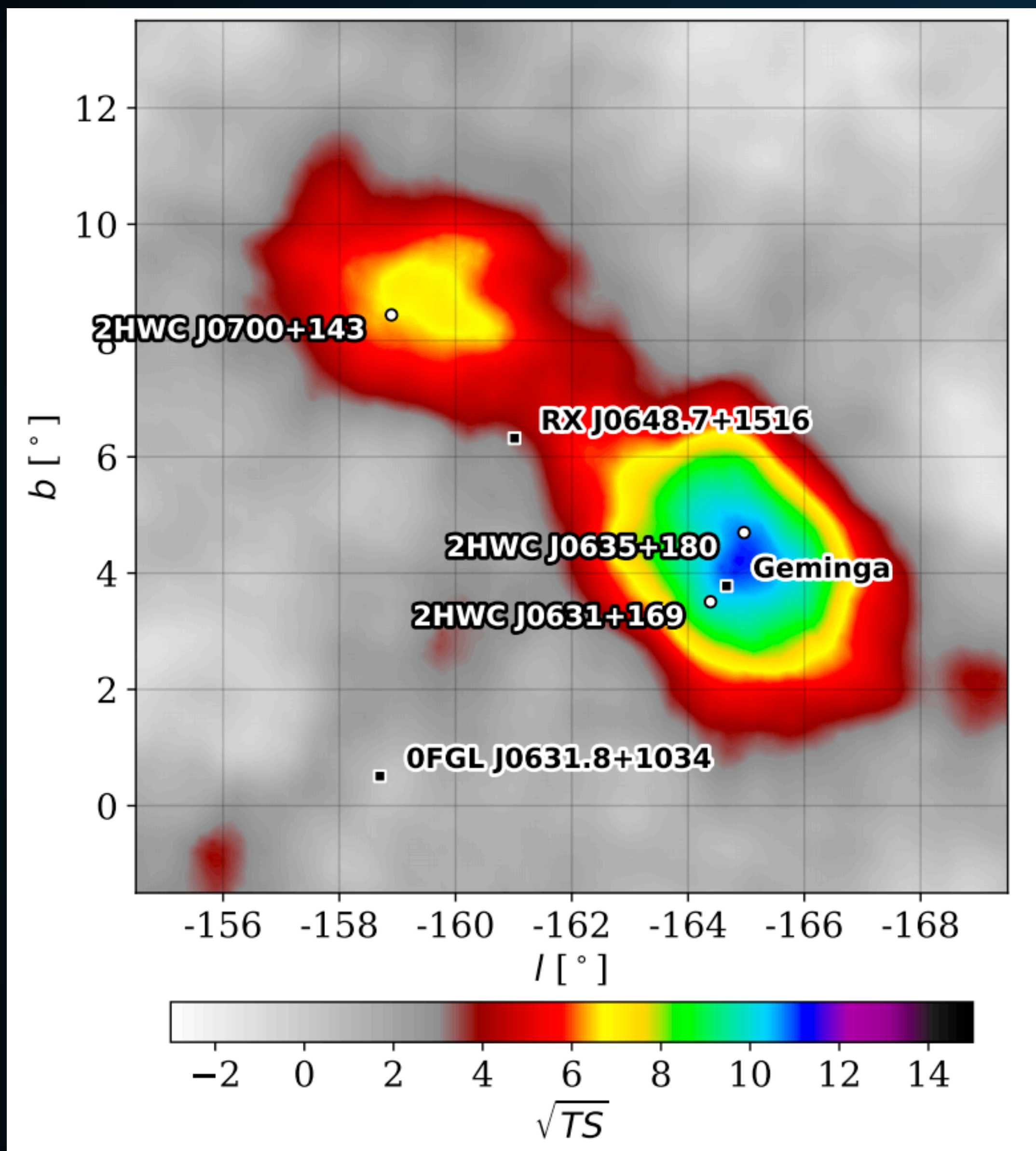
$$\sim 0.25 \times \left(\frac{r_{\rm region}}{100\,{\rm pc}}\right)^3 \left(\frac{\dot{N}_{\rm SN}}{0.03\,{\rm yr}^{-1}}\right) \left(\frac{\tau_{\rm region}}{10^6\,{\rm yr}}\right) \left(\frac{20\,{\rm kpc}}{R_{\rm MW}}\right)^2 \left(\frac{200\,{\rm pc}}{z_{\rm MW}}\right)$$

- **Galactic Supernova rate ~0.02 yr^{-1}**
- **If each supernova (and natal pulsar) produces a large diffusion region, the diffusion constant should be low everywhere.**
- **Only alternative is that a very unique event produced the local bubble.**



TWO CONTRASTING OBSERVABLES

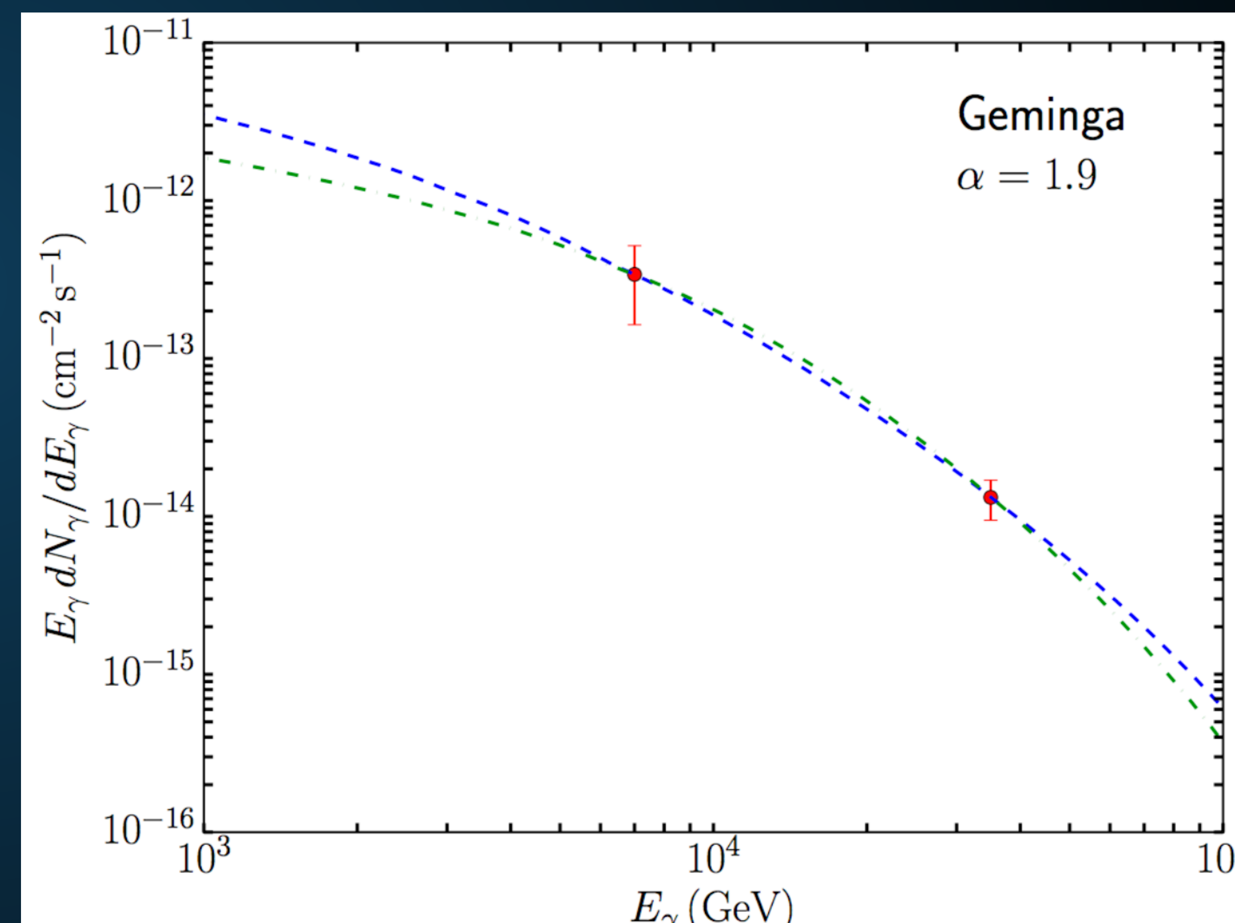
Geminga is Bright



Indicative of significant electron cooling

Geminga has a hard-spectrum

Name	Tested radius [°]	Index	$F_7 \times 10^{15}$ [$\mathrm{TeV^{-1}cm^{-2}s^{-1}}$]	TeVCat
2HWC J0631+169	-	-2.57 ± 0.15	6.7 ± 1.5	Geminga
"	2.0	-2.23 ± 0.08	48.7 ± 6.9	Geminga
2HWC J0635+180	-	-2.56 ± 0.16	6.5 ± 1.5	Geminga



Indicative of minimal electron cooling

TOTAL POWER OF TEV HALOS

- **Measured Geminga flux translates to an intensity:**

$$2.86 \times 10^{31} \text{ erg s}^{-1} \text{ at } 7 \text{ TeV}$$

- **For the best-fit spectrum, this requires an e^+e^- injection:**

$$3.8 \times 10^{33} \text{ erg s}^{-1}$$

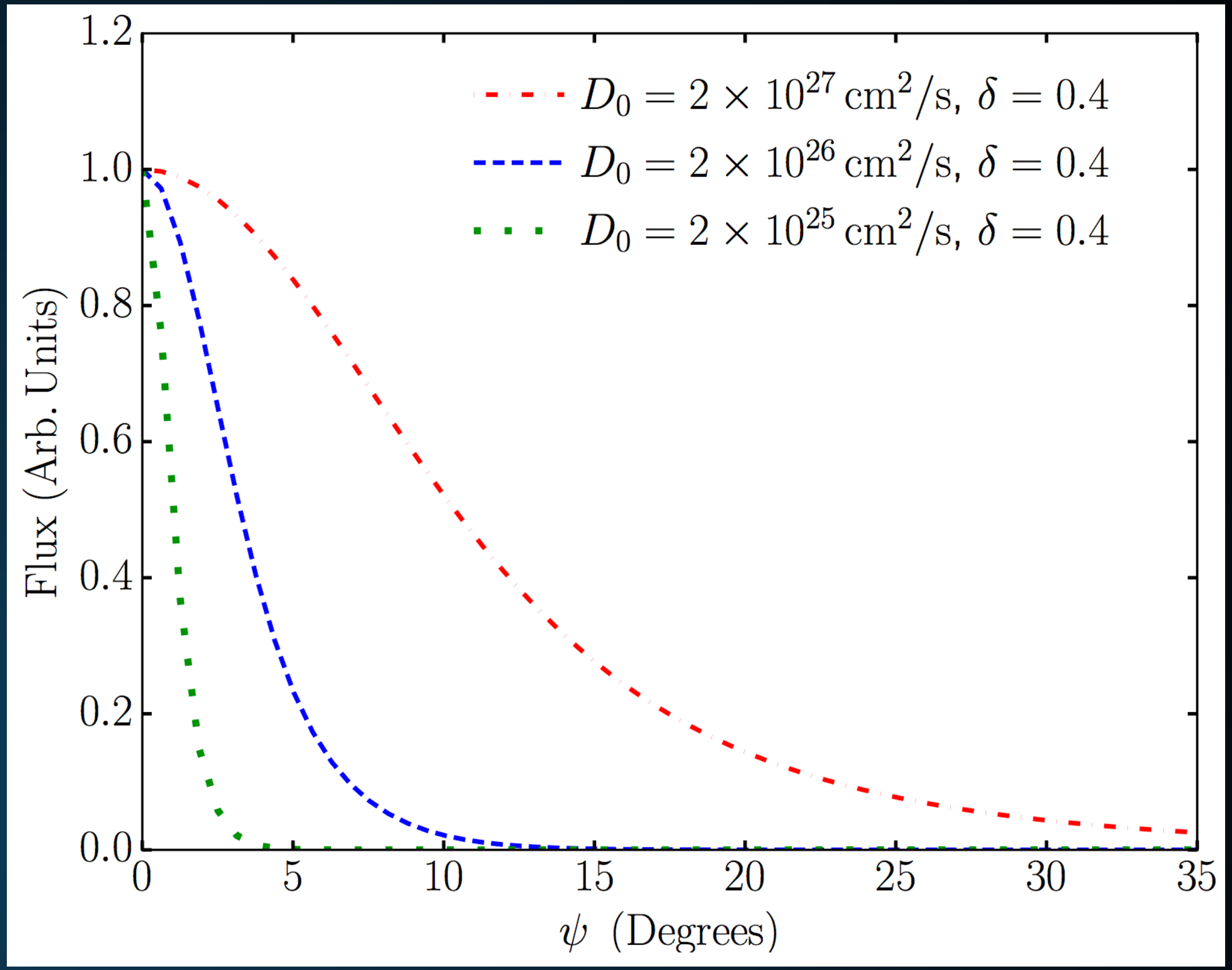
- **Total Spindown Power of Geminga is:**

$$3.4 \times 10^{34} \text{ erg s}^{-1}$$

- **Roughly 10% conversion efficiency to e^+e^- !**

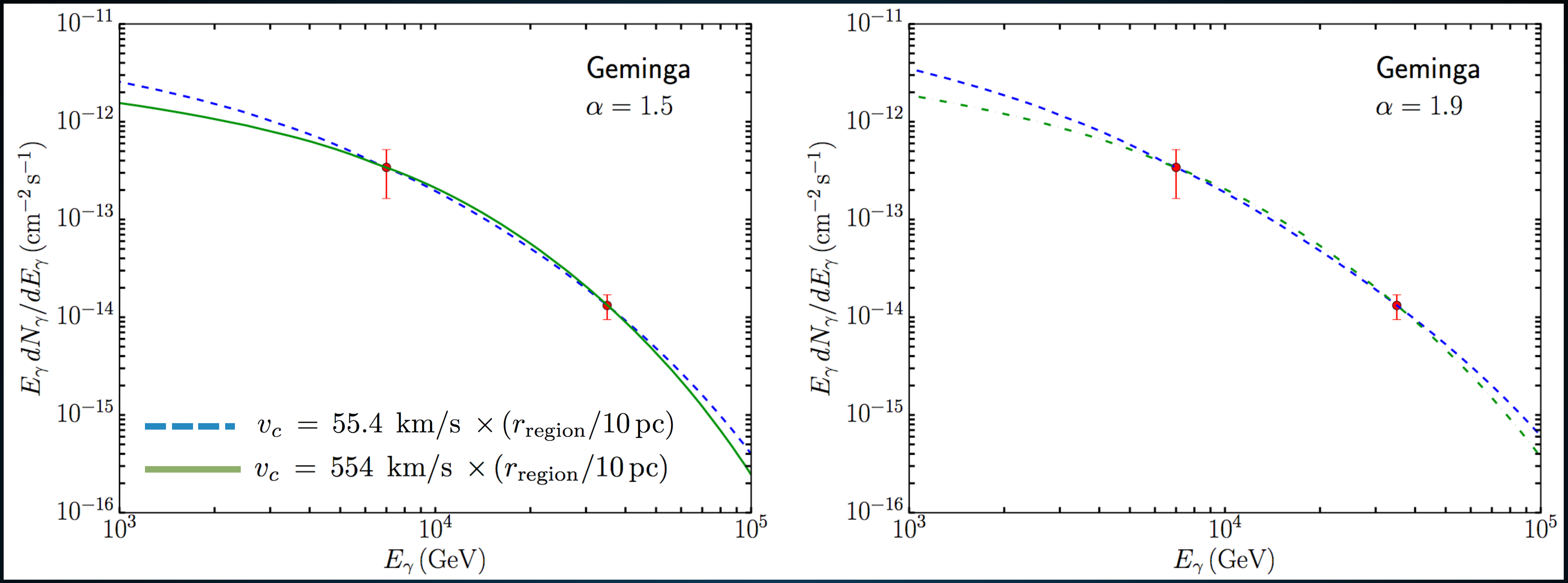
COSMIC-RAY DIFFUSION IN A TEV HALO

- Actual source of particle propagation is unknown:
  - Diffusion
  - Advection



- Particle propagation near pulsars must be orders of magnitude less efficient than typical for the ISM.
- Continues far outside the termination shock of a pulsar with no SNR.

GEMINGA SPECTRUM INDICATIVE OF CONVECTION

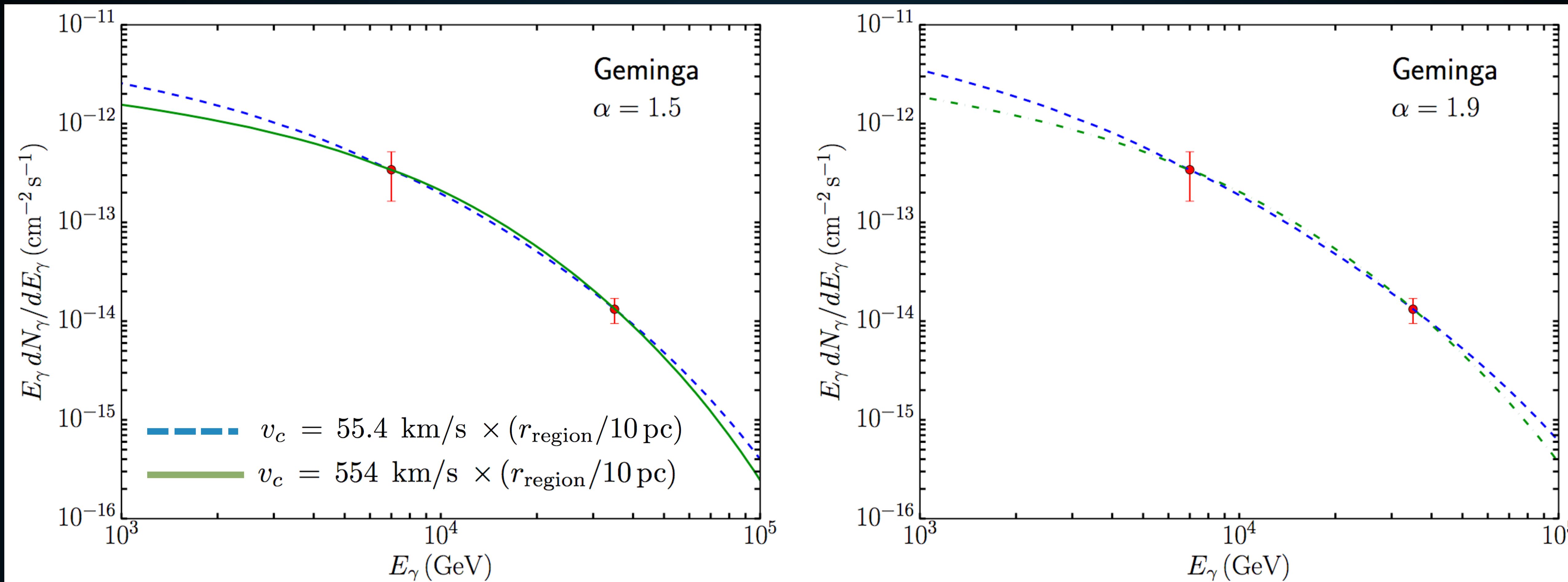


- **However, Bohmian diffusion is incompatible with the gamma-ray spectrum.**
- **If low-energy electrons are cooled, the spectrum at 7 TeV should be significantly softer.**

AN UPPER LIMIT ON THE TEV HALO SIZE

- These arguments only set a lower limit on the TeV halo size.
- What if TeV halos are much larger, but the TeV electrons die at ~10 pc?
- Will need to answer this question on the population level.

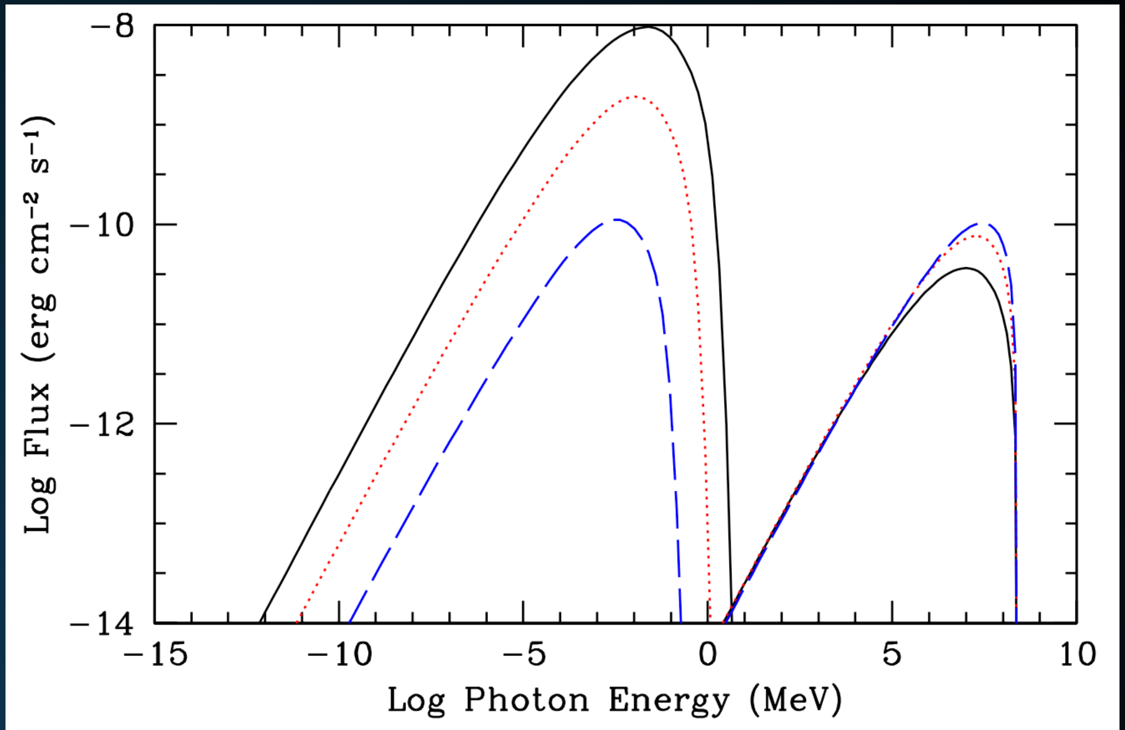
GEMINGA SPECTRUM INDICATIVE OF CONVECTION

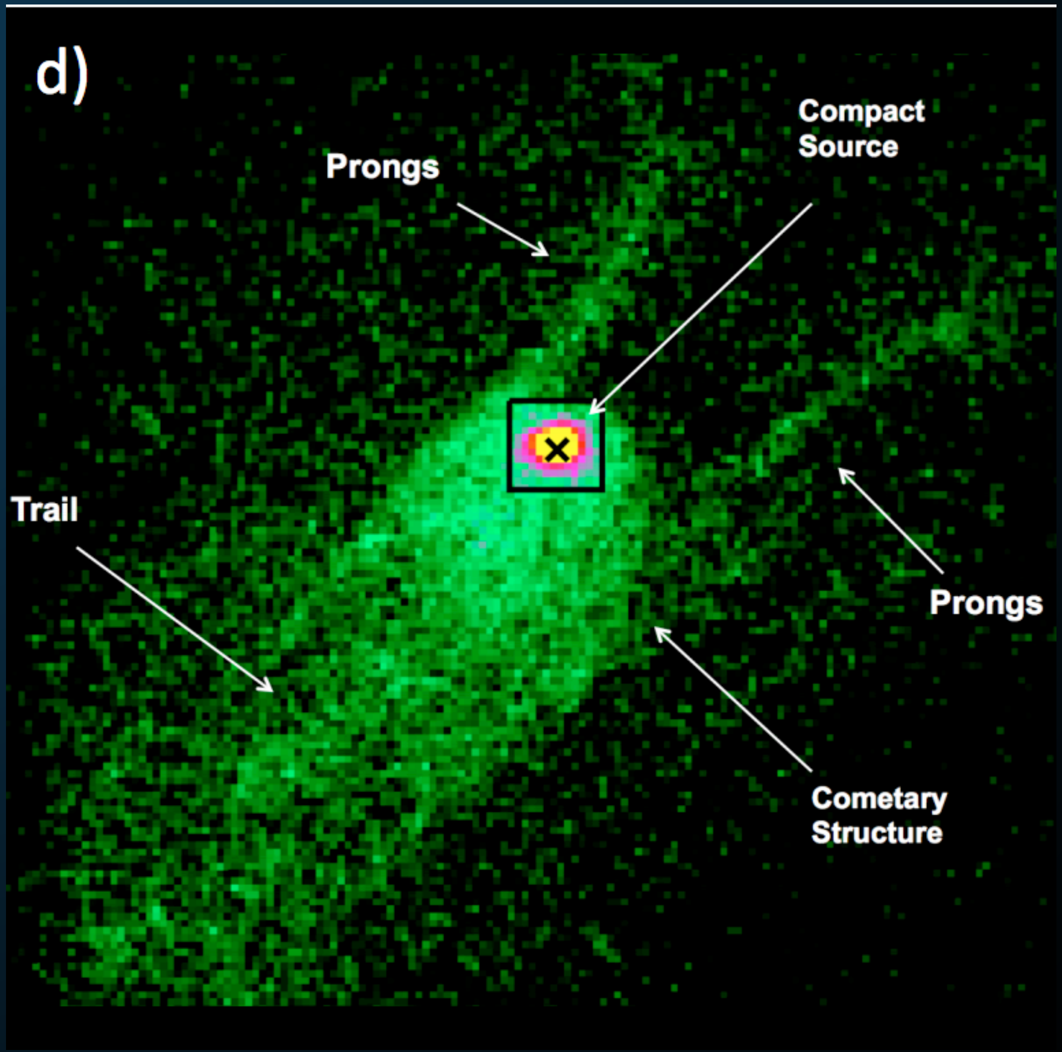


- **Geminga spectrum is fit better with convective models.**
- **Energy-independent diffusion provides identical results**
- **Best-fit spectral-index (-2.23 +/- 0.08) prefers high convection**

WHY ARE HIGH-ENERGY ELECTRONS TRAPPED?

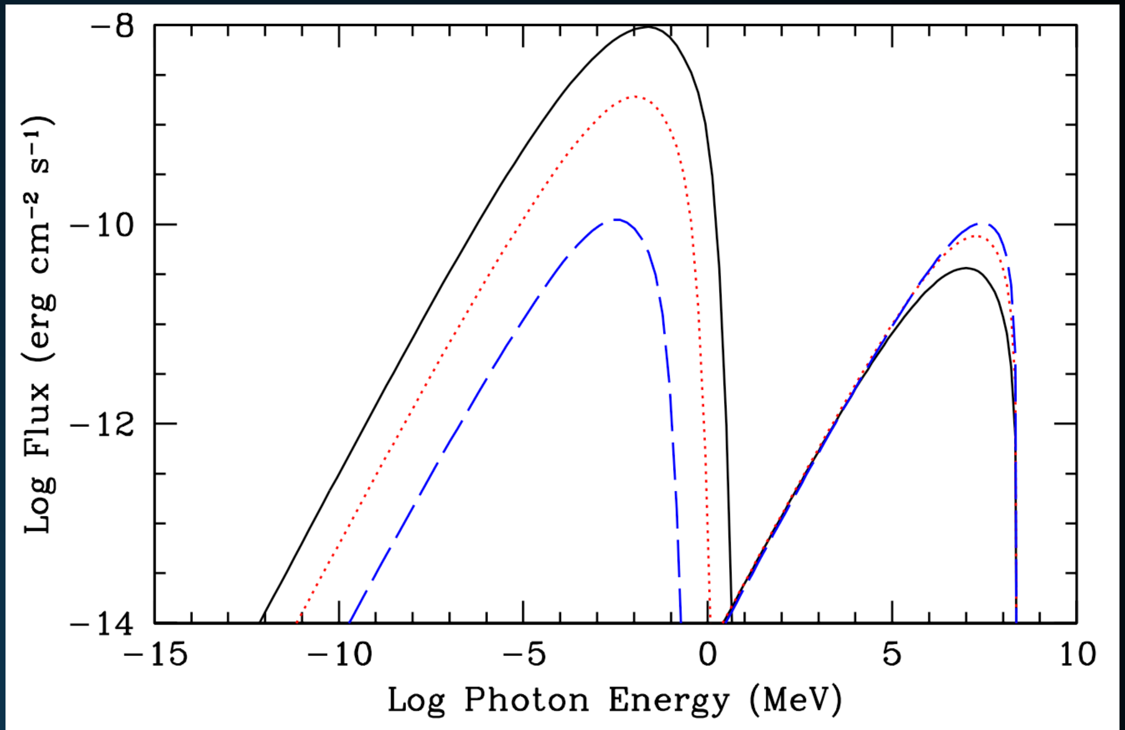
- Cooling dominated by 20 μG magnetic field.
- Energy loss time: ~40 years
- Distance Traveled: ~6 pc for standard diffusion constant. Real diffusion must be slower.
- The spectrum changes as a function of distance and time.

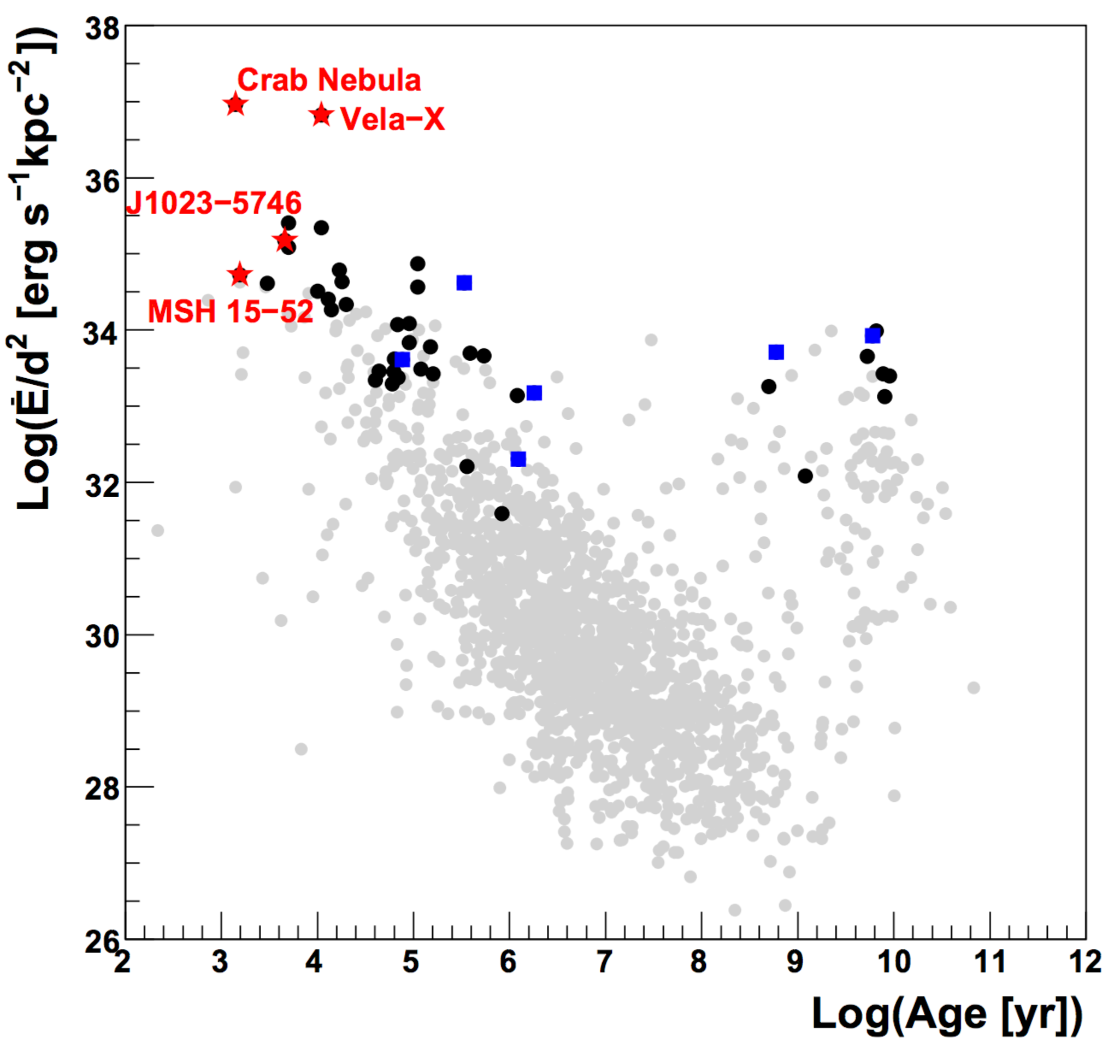




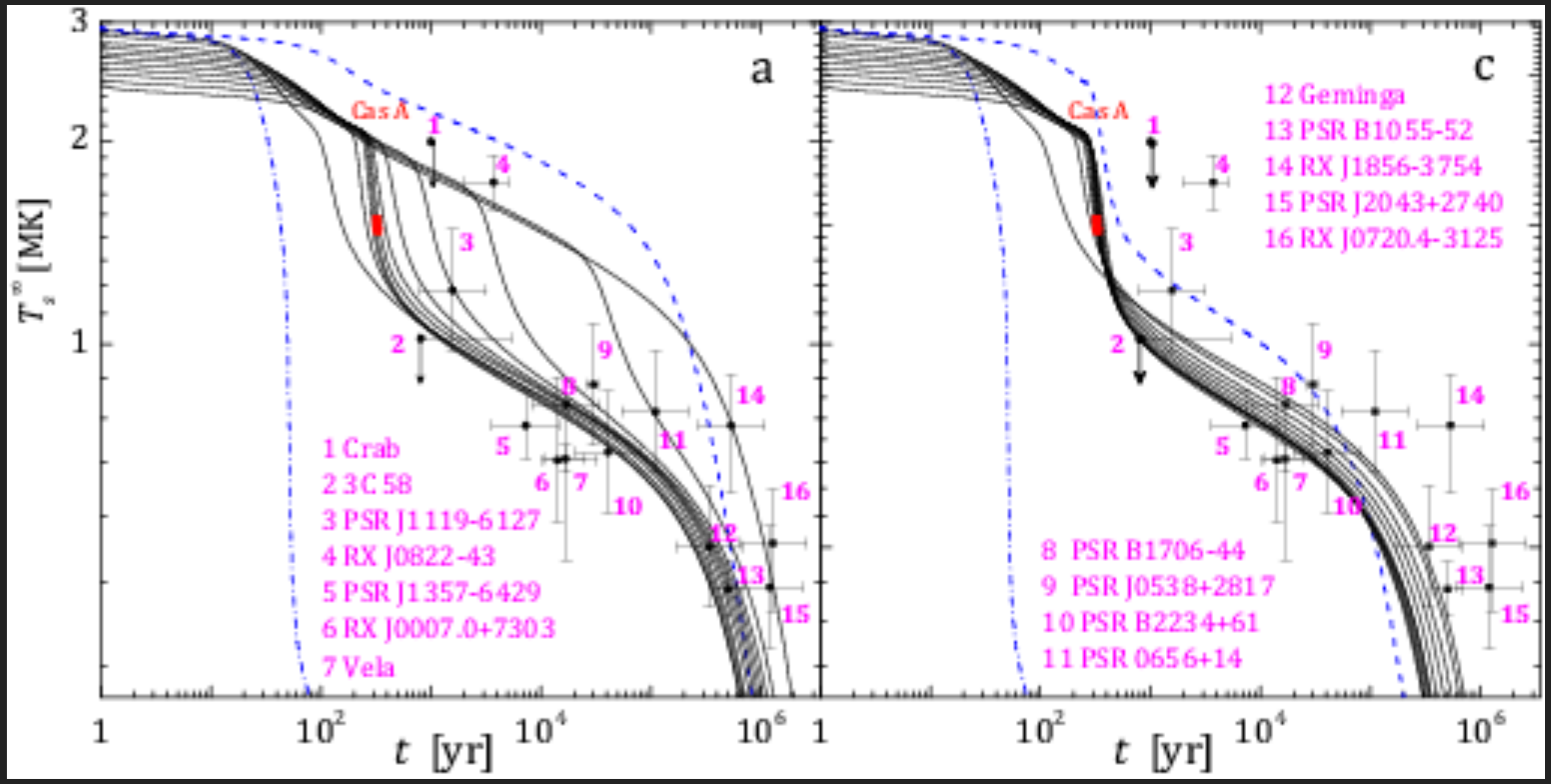
FERMI-LAT OBSERVATIONS OF PWN

- Gamma-Ray produced through ICS should accompany synchrotron emission.
- Synchrotron observations imply very hard GeV gamma-ray spectrum.
- Conclusively prove leptonic nature of emission.





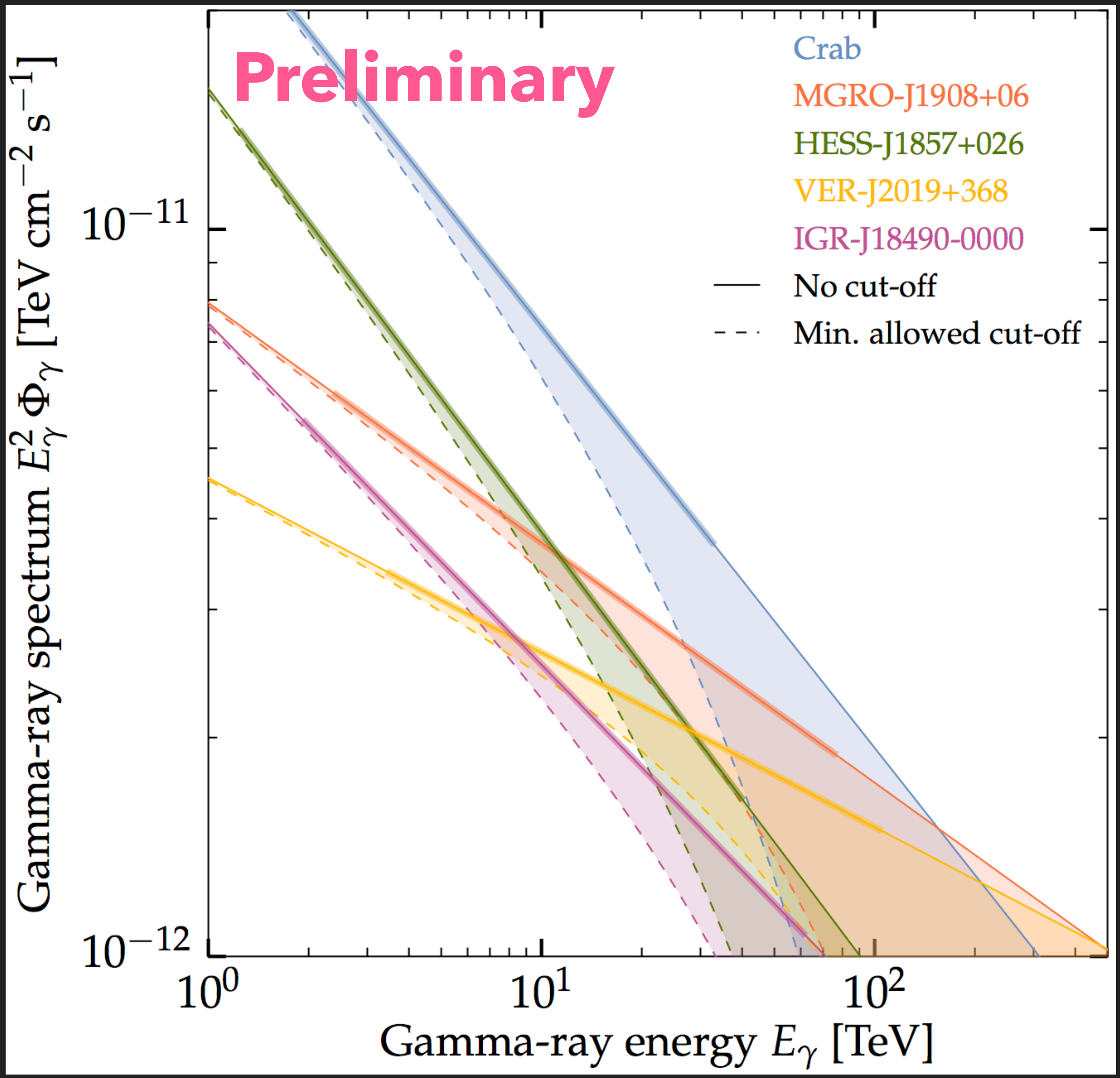
THERMAL PULSAR EMISSION



- Hot neutron stars can also be observed via their isotropic thermal emission.
- X-Ray observations can be sensitive to ~2 kpc for 10^6 K NS.
- Cooler NS extremely hard to see.
- Could potentially detect a system which has recently ceased producing TeV particles.

Bustamante, Li, TL, Beacom (TBS)

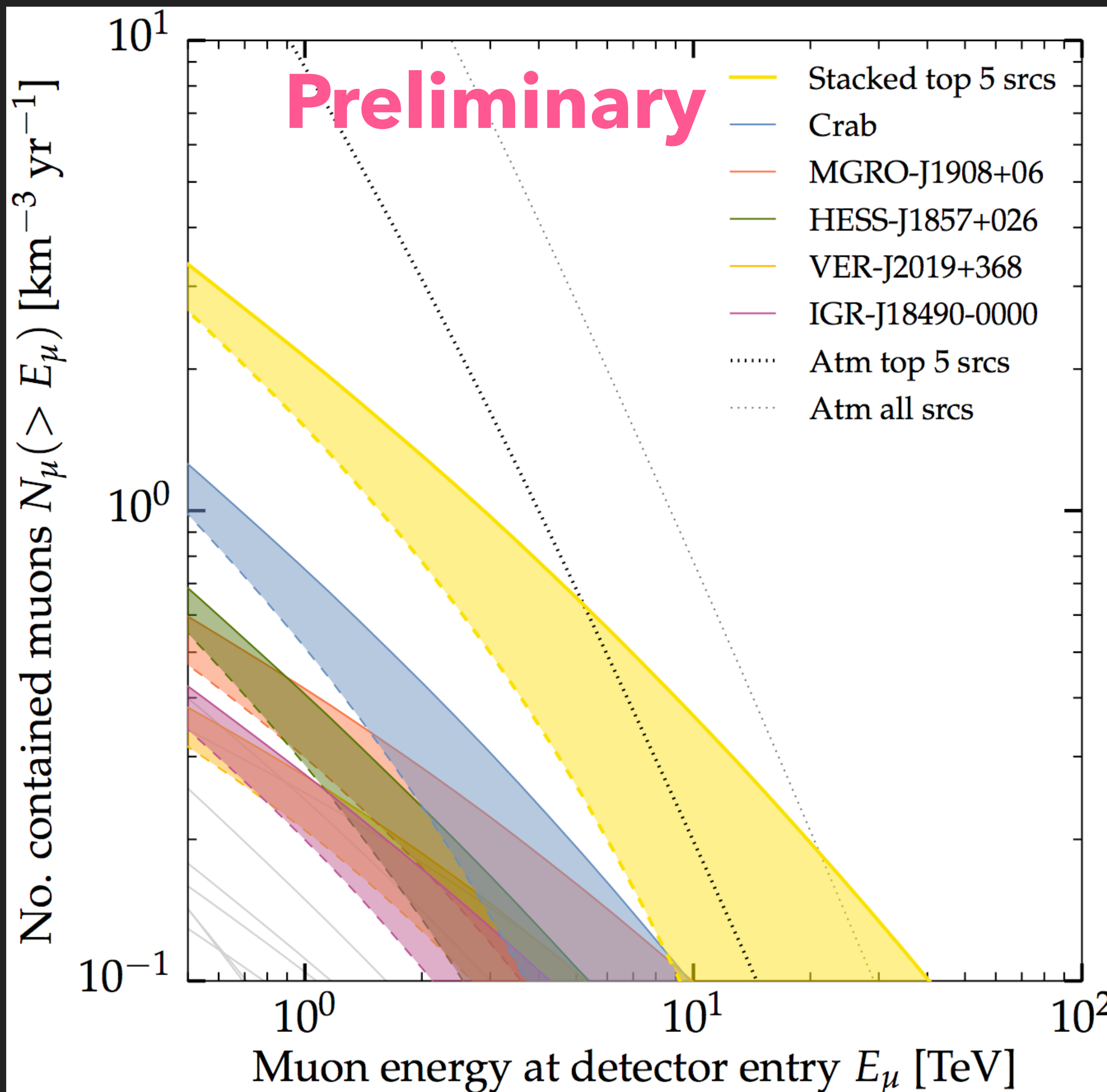
- HAWC sources are potential IceCube neutrino sources.
- Spectral measurements of HAWC sources are imperative to calculating the expected neutrino flux.

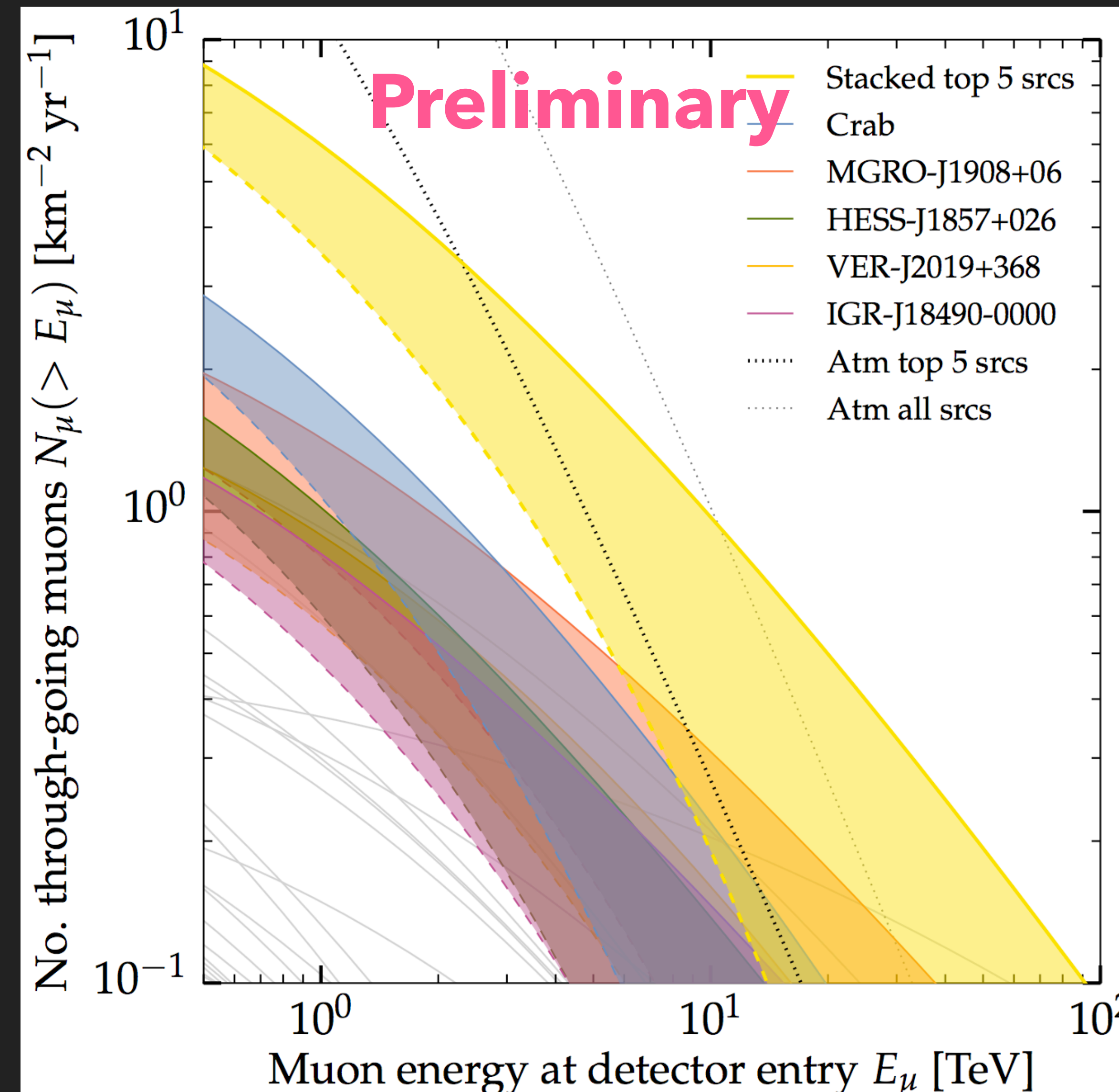


- Here we produce an analysis taking into account a 20% uncertainty in total flux, as well as spectral uncertainty due to an exponential cutoff.

ICECUBE NEUTRINOS FROM 2HWC SOURCES

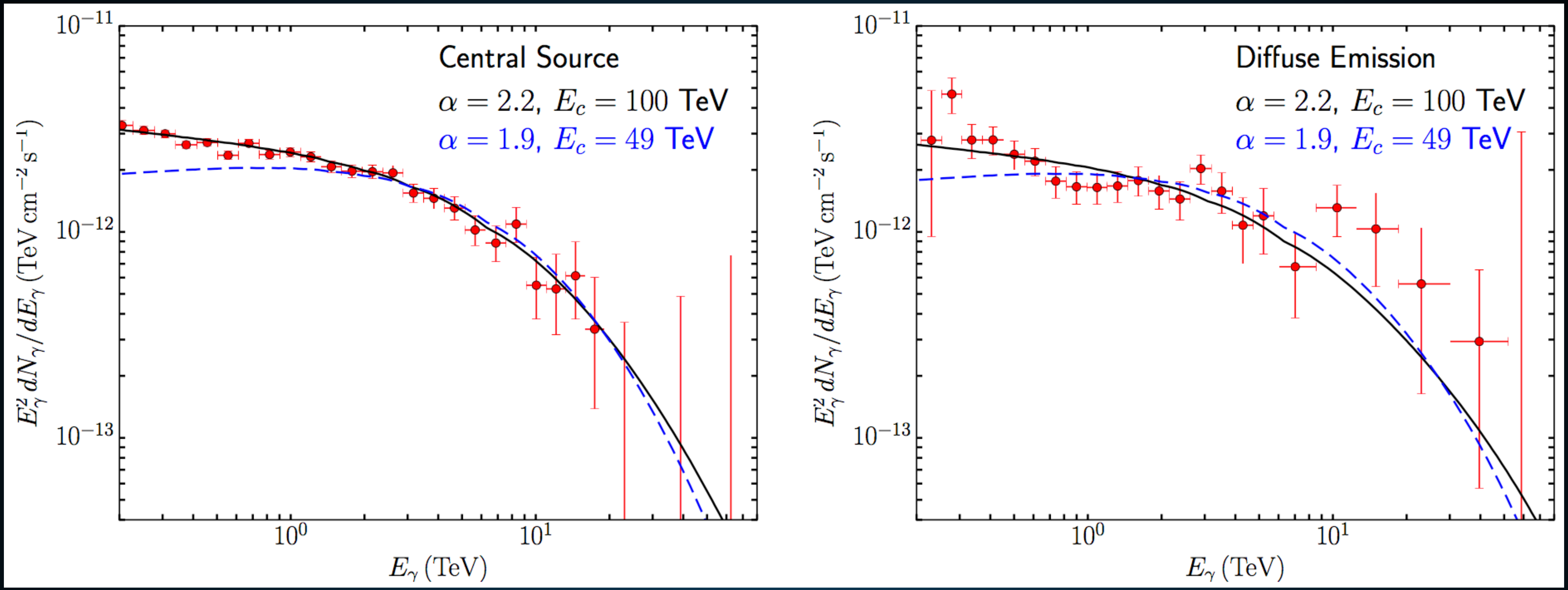
Bustamante, Li, TL, Beacom (TBS)





- **If these sources are hadronic, their stacked neutrino flux is detectable in current IceCube data.**
- **Alternatively, can place a strong constraint on the hadronic fraction of the brightest HAWC sources.**

TEV HALOS PRODUCE THE PEVATRON SPECTRUM

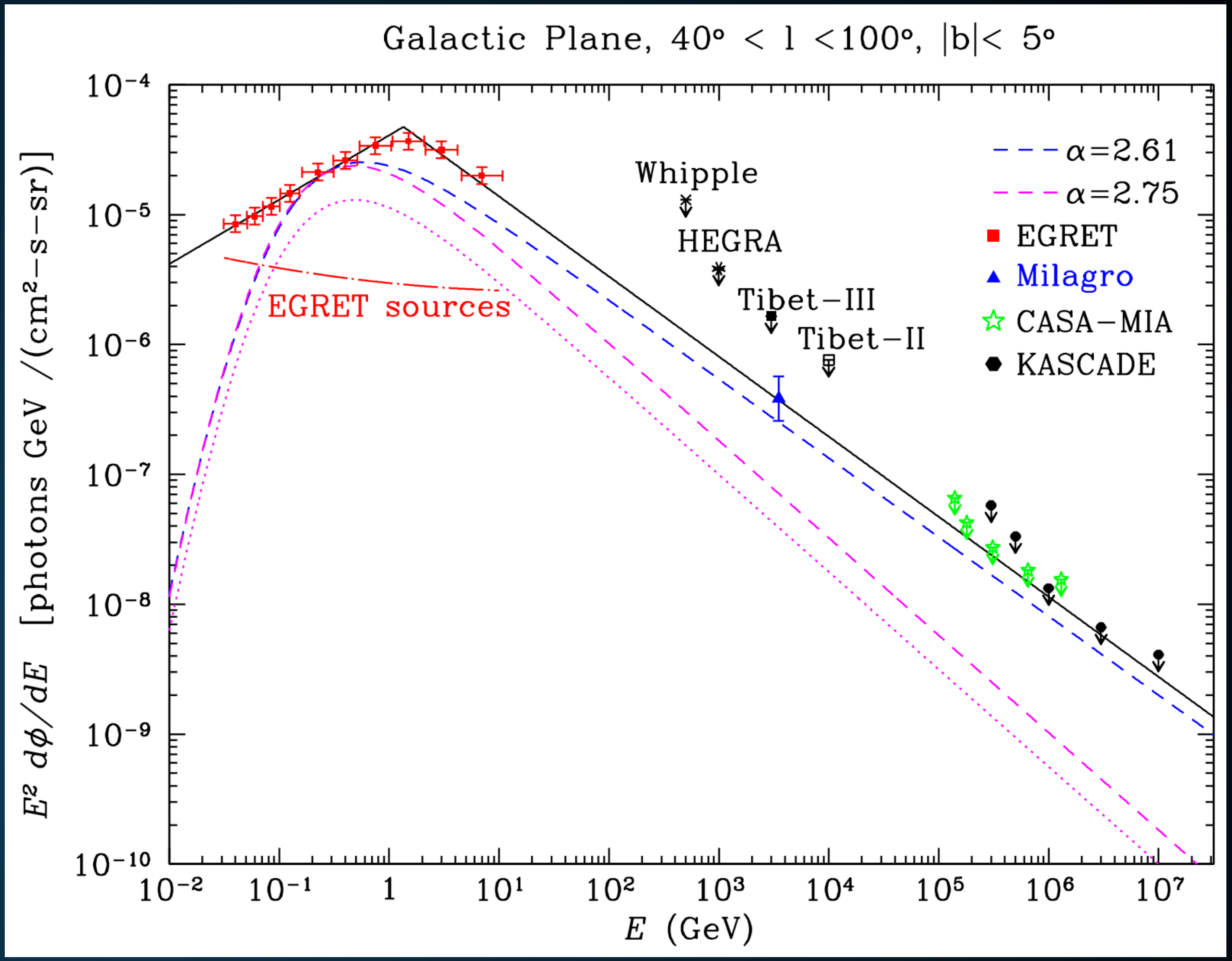


- The TeV halo spectrum from Geminga naturally reproduces the HESS observations.
- Slightly softer spectra preferred.
  - Some evidence that Geminga spectrum is particularly hard.
  - Hadronic diffuse background contamination?

IMPLICATION IIA: THE TEV EXCESS

astro-ph/0603618

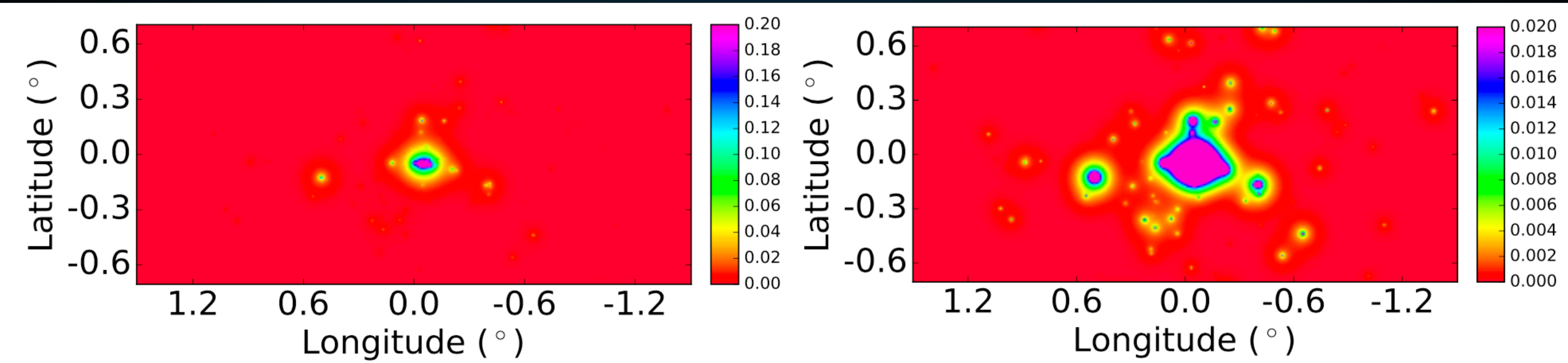
- Milagro detects bright diffuse TeV emission along the Galactic plane.
- Difficult to explain with pion decay, due to steeply falling local hadronic CR spectrum.



- Can harden gamma-ray emission to some extent using radially dependent diffusion constants (1504.00227).

DIFFUSE EMISSION FROM TEV HALOS

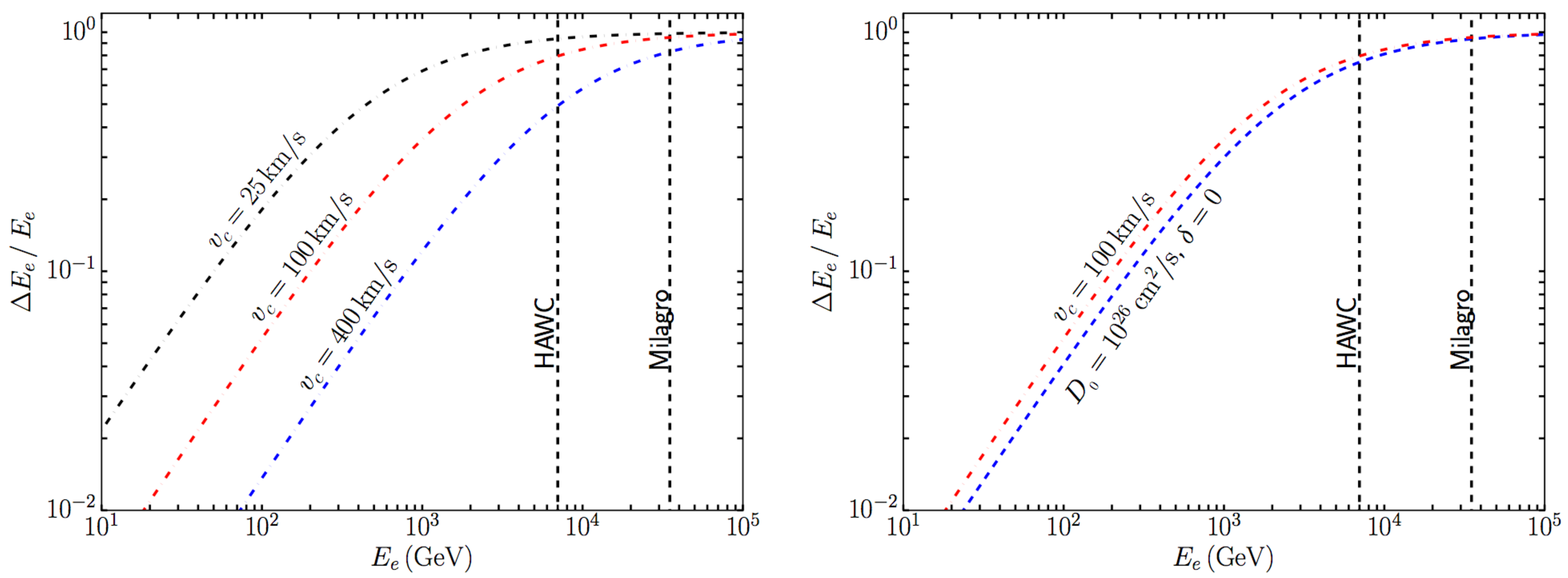
1705.09293



- **Significant star (pulsar) formation in the Galactic center**
- **Pulsars formed in the central parsec will be kicked into surrounding medium.**
- **Source of diffuse gamma-rays in the Galactic center.**

WHAT ABOUT THE LOW-ENERGY ELECTRONS?

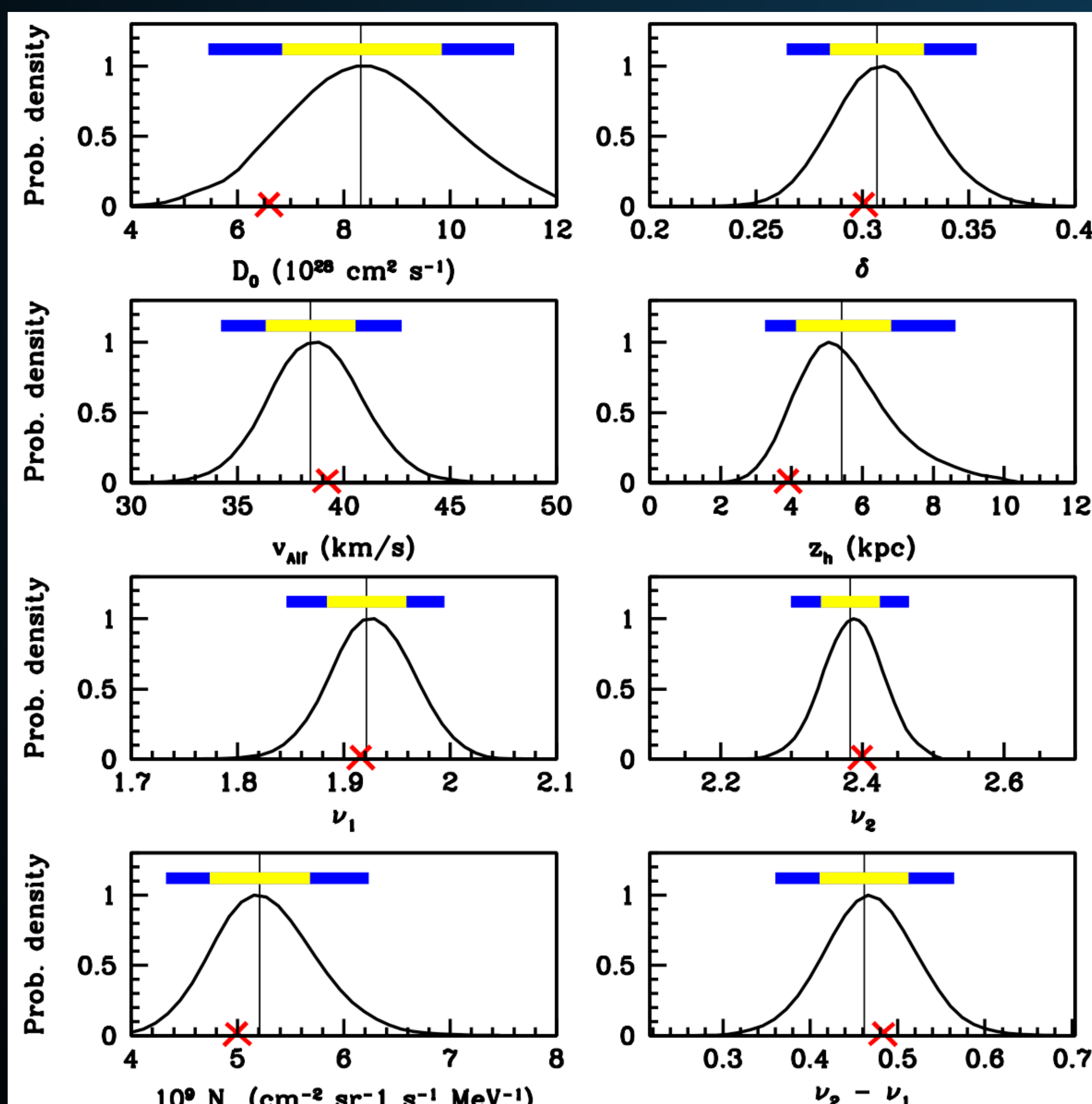
Fraction of energy lost before Electrons Travel a constant distance

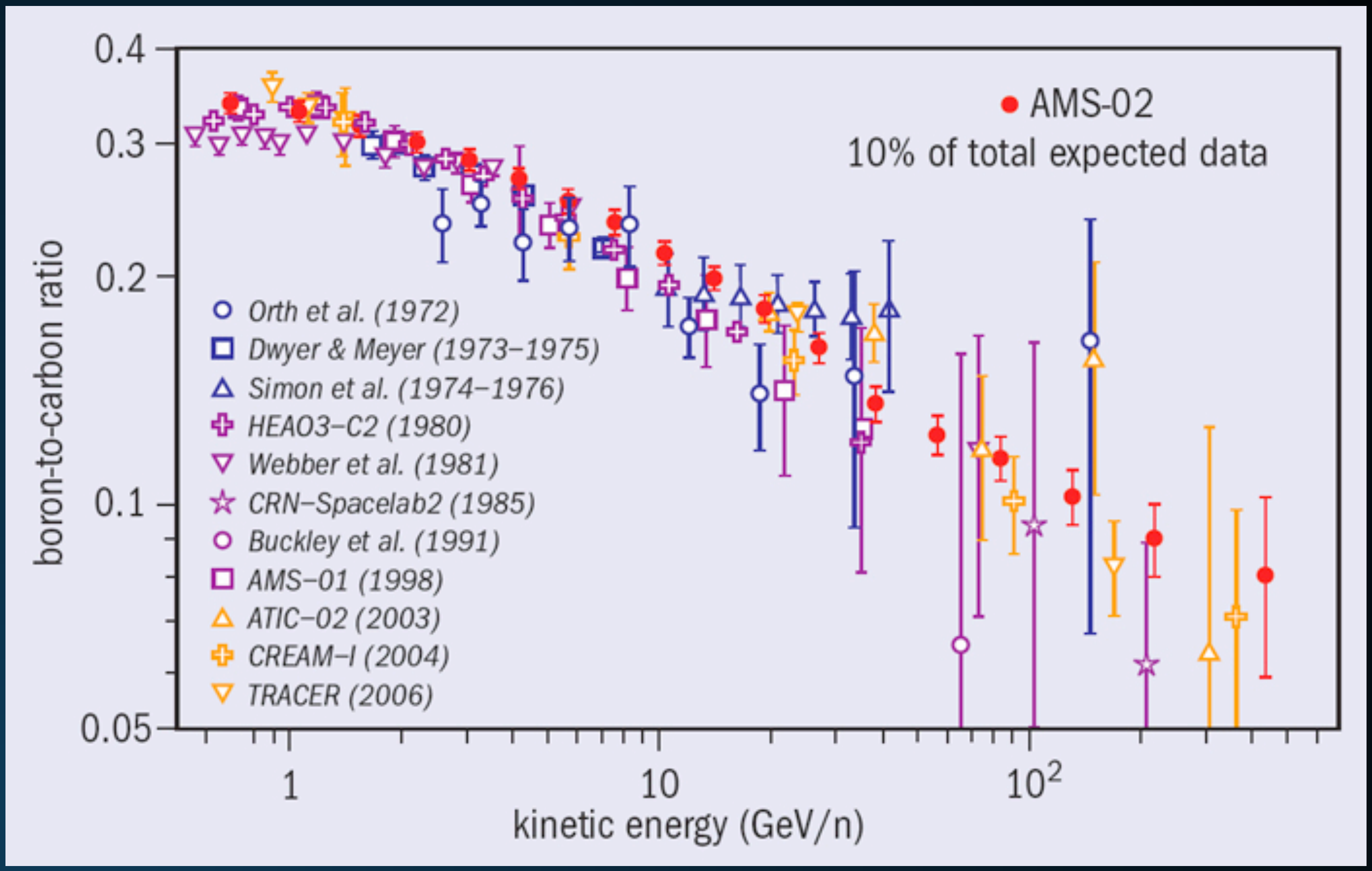


- **Low-energy electrons lose energy slower, must travel farther.**
- **This is true in both convective case (shown here) as well as most diffusive (e.g. Kolmogorov, Kraichnian) scenarios.**
- **Where do these electrons go?**

EFFECT OF TEV HALOS ON ISM PROPAGATION

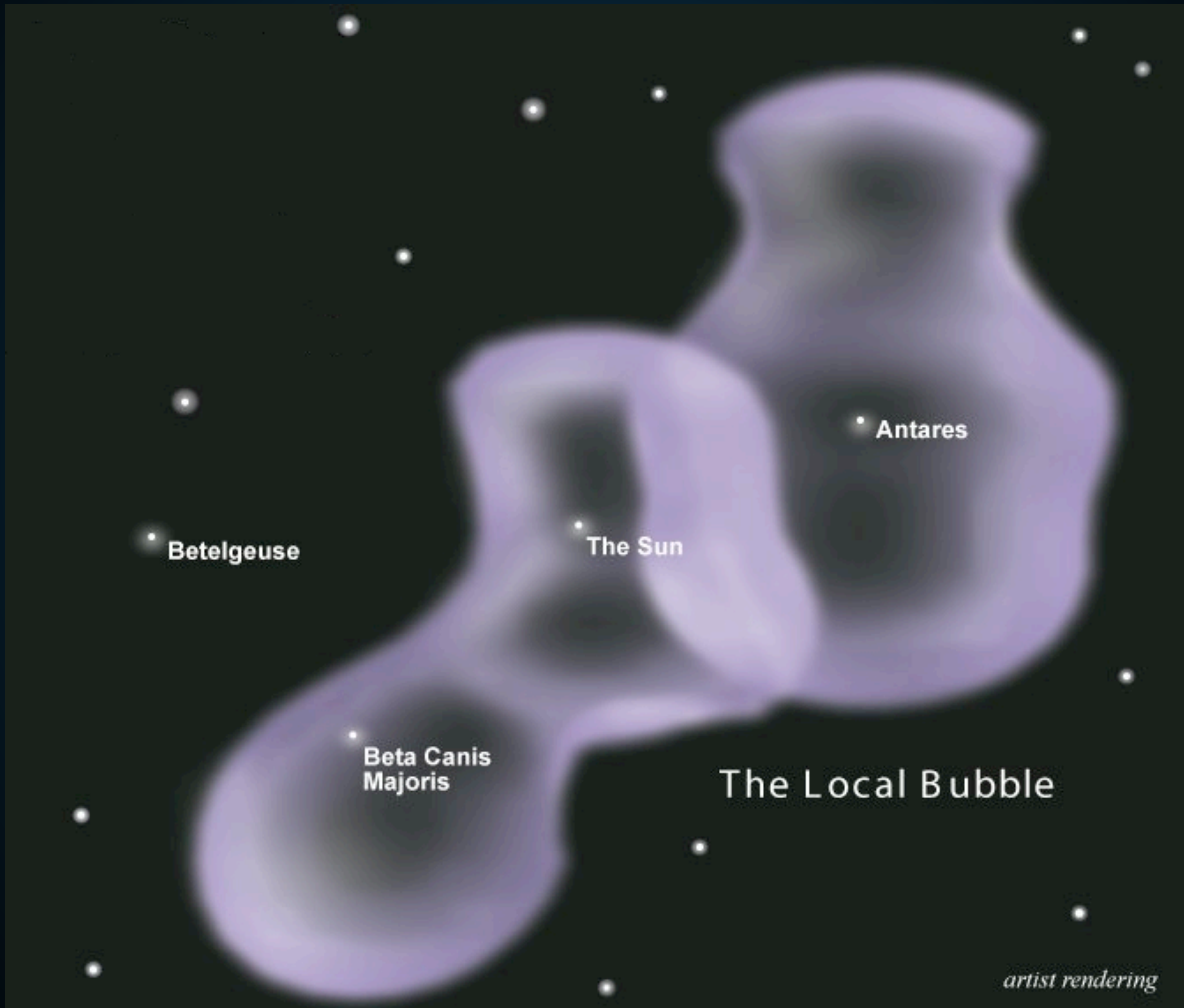
- **Multiple cosmic-ray observations indicate that the average diffusion constant is ~5x10^{28} cm^{2}s^{-1}**





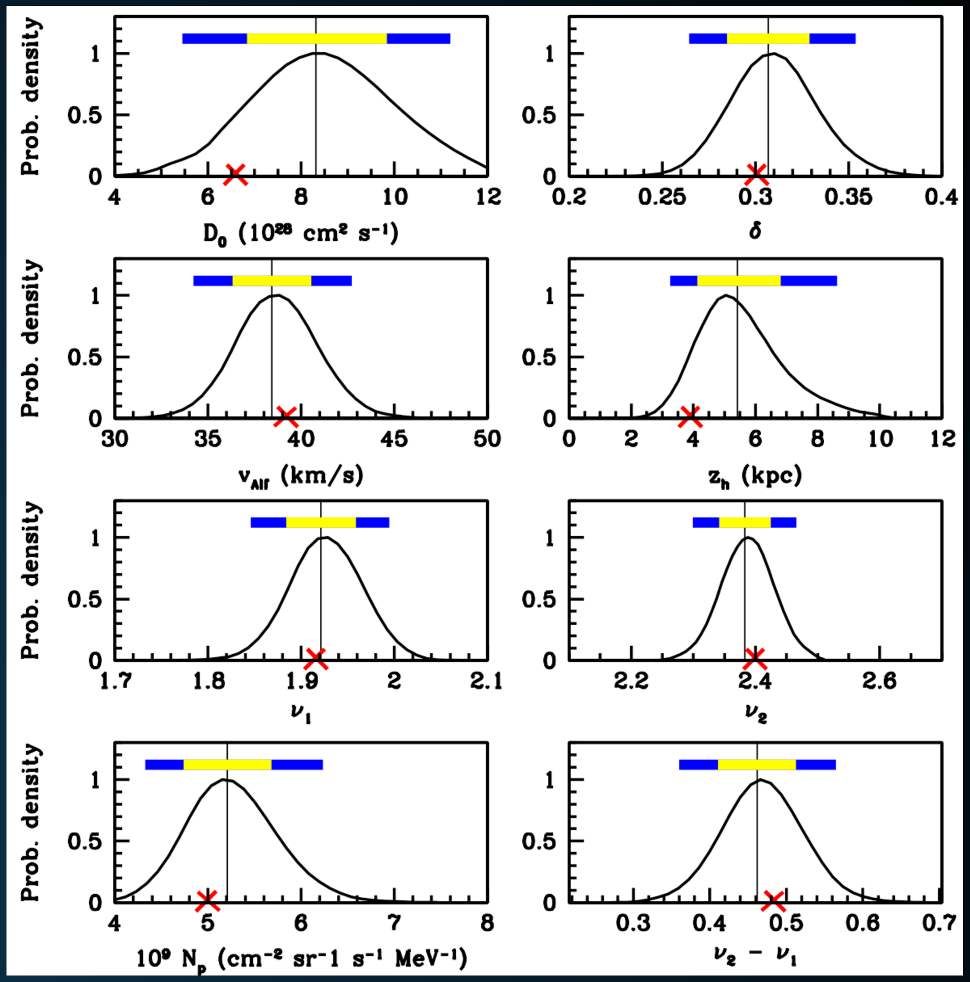
- **Assume that diffusion reverts back to the standard case outside the TeV halo.**
- **Primary difference between our results and those from HAWC.**

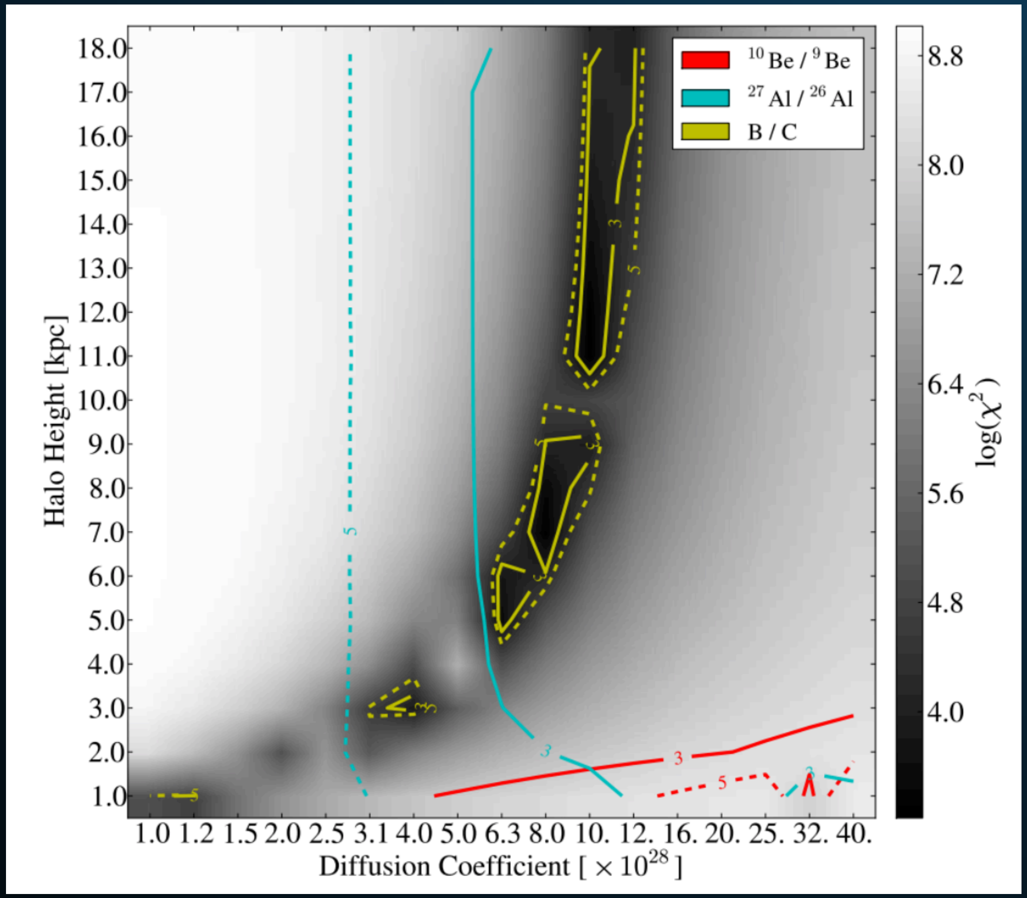
CAN THE DIFFUSION CONSTANT BETWEEN GEMINGA AND US BE LOW?

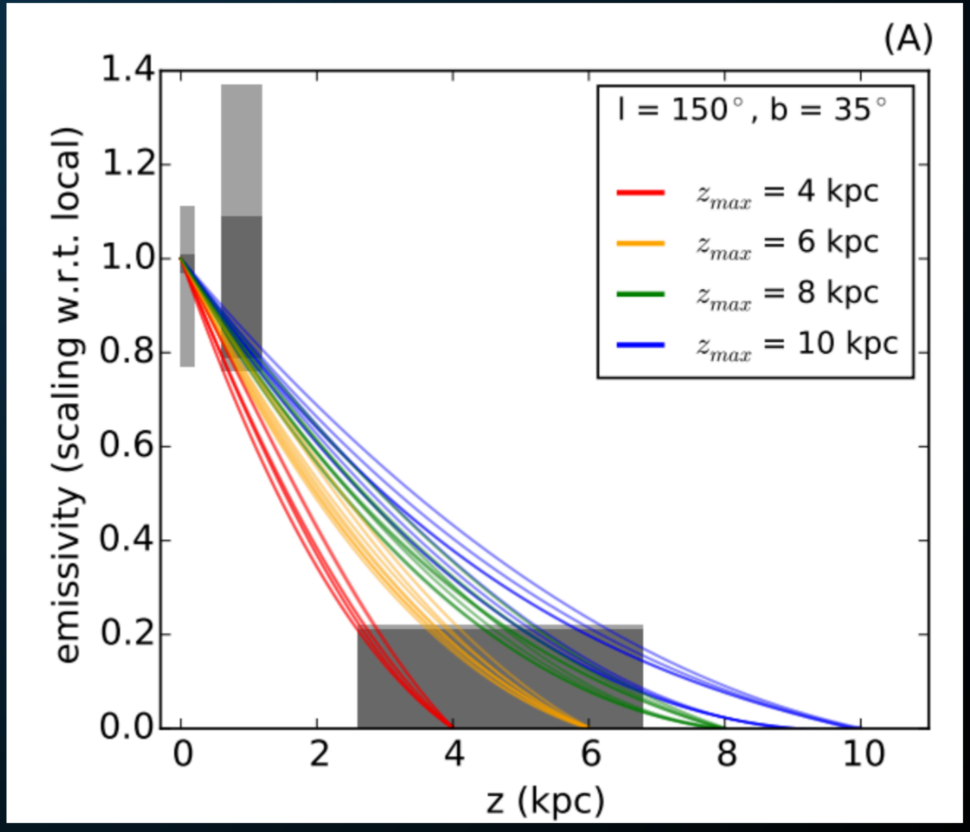


SCENARIO 1: THE MILKY WAY DIFFUSION CONSTANT IS LOW

- **Cosmic-Ray primary to secondary ratios tell us about:**
  - **The average grammage encountered by cosmic-rays before they escape the galaxy (e.g. B/C)**
  - **The average time cosmic-rays are confined in the galaxy ($^{10}Be/^{9}Be$).**







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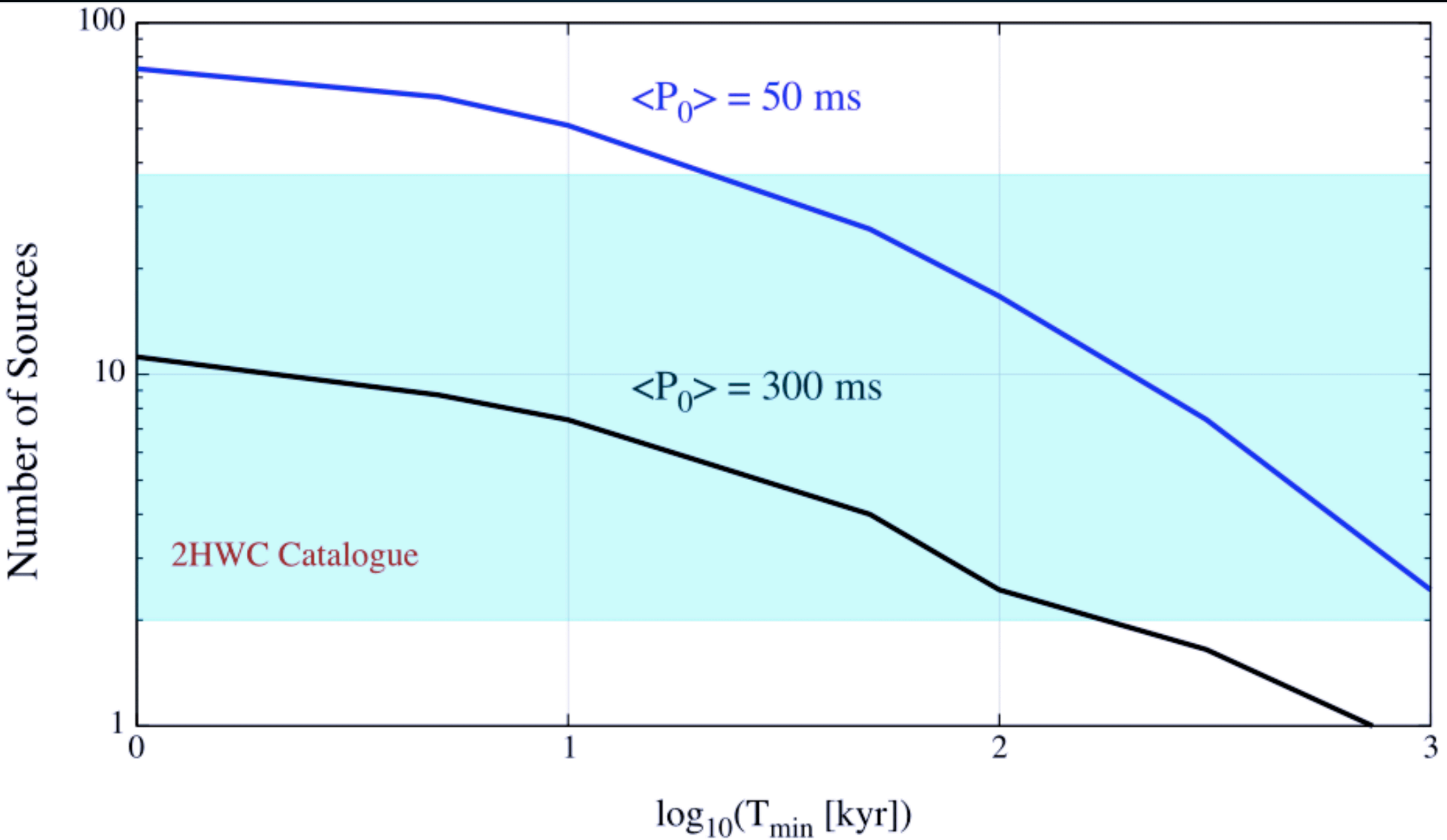

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