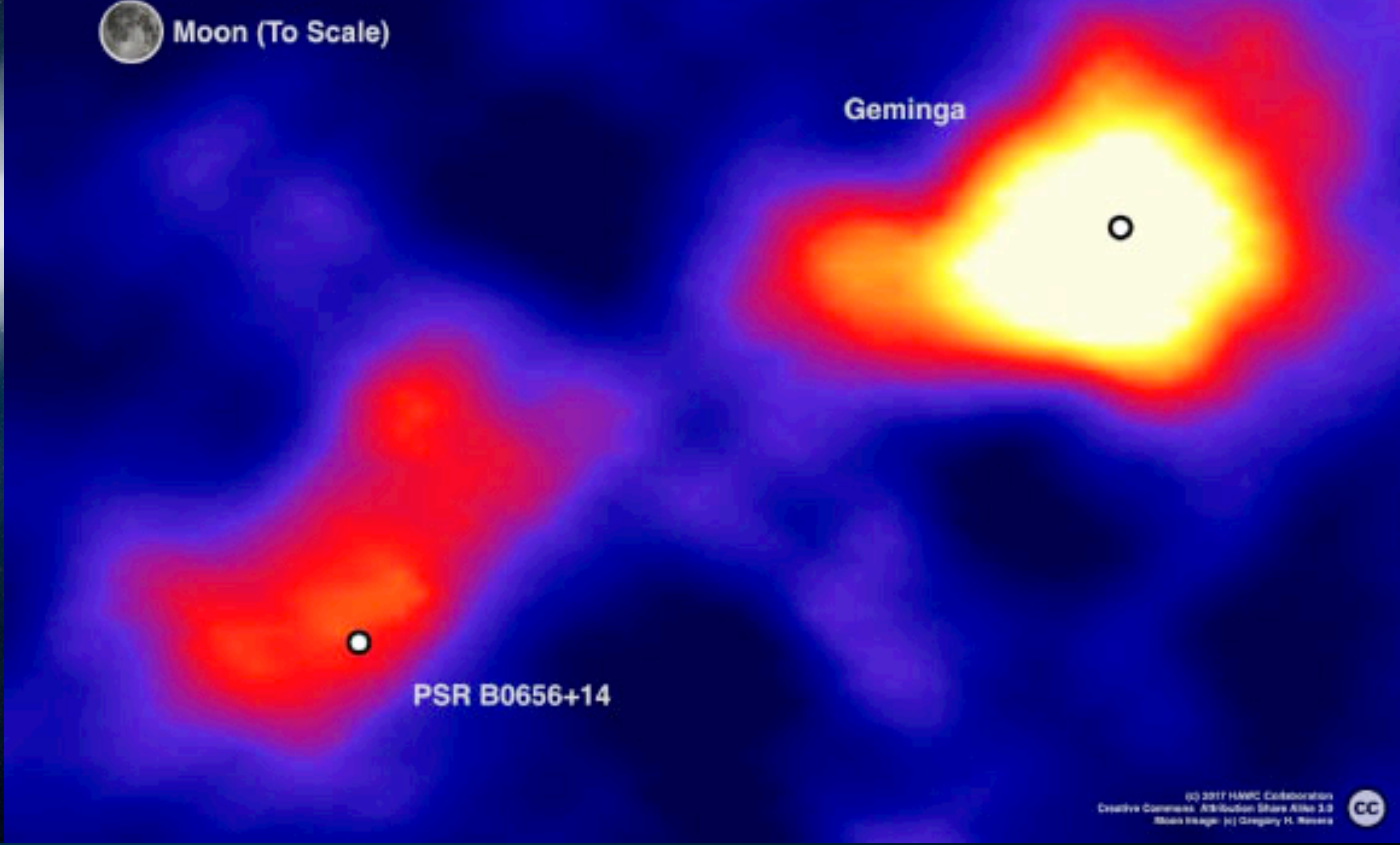
TIM LINDEN



Rise of the Leptons:

Pulsar Emission Dominates the TeV Gamma-Ray Sky

APS April Meeting

THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

TeV Flux ~ 3 x 10^{33} TeV s^{-1}

>10% of Spindown Power!

Powered by inverse Compton scattering of accelerated electrons

Extended to 5° (20 pc)!

I will call these objects TeV halos

2HWC Catalog (1702.02992)
HAWC Collaboration (1711.06223)

HESS Observations

HESS Collaboration (1702.08280)

Table 1 HGPS sources considered as firmly identified pulsar wind nebulae in this paper.

HGPS name	ATNF name	Canonical name	lg $\dot{E}$	τ_c (kyr)	d (kpc)	PSR offset (pc)	Γ	$R_{\rm PWN}$ (pc)	$L_{1-10\,\rm TeV}$ (10^{33} erg s^{-1})
J1813−178[1]	J1813−1749		37.75	5.60	4.70	< 2	2.07 ± 0.05	4.0 ± 0.3	19.0 ± 1.5
J1833−105	J1833−1034	G21.5−0.9[2]	37.53	4.85	4.10	< 2	2.42 ± 0.19	< 4	2.6 ± 0.5
J1514−591	B1509−58	MSH 15−52[3]	37.23	1.56	4.40	< 4	2.26 ± 0.03	11.1 ± 2.0	52.1 ± 1.8
J1930+188	J1930+1852	G54.1+0.3[4]	37.08	2.89	7.00	< 10	2.6 ± 0.3	< 9	5.5 ± 1.8
J1420−607	J1420−6048	Kookaburra (K2)[5]	37.00	13.0	5.61	5.1 ± 1.2	2.20 ± 0.05	7.9 ± 0.6	44 ± 3
J1849−000	J1849−0001	IGR J18490−0000[6]	36.99	42.9	7.00	< 10	1.97 ± 0.09	11.0 ± 1.9	12 ± 2
J1846−029	J1846−0258	Kes 75[2]	36.91	0.728	5.80	< 2	2.41 ± 0.09	< 3	6.0 ± 0.7
J0835−455	B0833−45	Vela X[7]	36.84	11.3	0.280	2.37 ± 0.18	1.89 ± 0.03	2.9 ± 0.3	0.83 ± 0.11*
J1837−069[8]	J1838−0655		36.74	22.7	6.60	17 ± 3	2.54 ± 0.04	41 ± 4	204 ± 8
J1418−609	J1418−6058	Kookaburra (Rabbit)[5]	36.69	10.3	5.00	7.3 ± 1.5	2.26 ± 0.05	9.4 ± 0.9	31 ± 3
J1356−645[9]	J1357−6429		36.49	7.31	2.50	5.5 ± 1.4	2.20 ± 0.08	10.1 ± 0.9	14.7 ± 1.4
J1825−137[10]	B1823−13		36.45	21.4	3.93	33 ± 6	2.38 ± 0.03	32 ± 2	116 ± 4
J1119−614	J1119−6127	G292.2−0.5[11]	36.36	1.61	8.40	< 11	2.64 ± 0.12	14 ± 2	23 ± 4
J1303−631[12]	J1301−6305		36.23	11.0	6.65	20.5 ± 1.8	2.33 ± 0.02	20.6 ± 1.7	96 ± 5

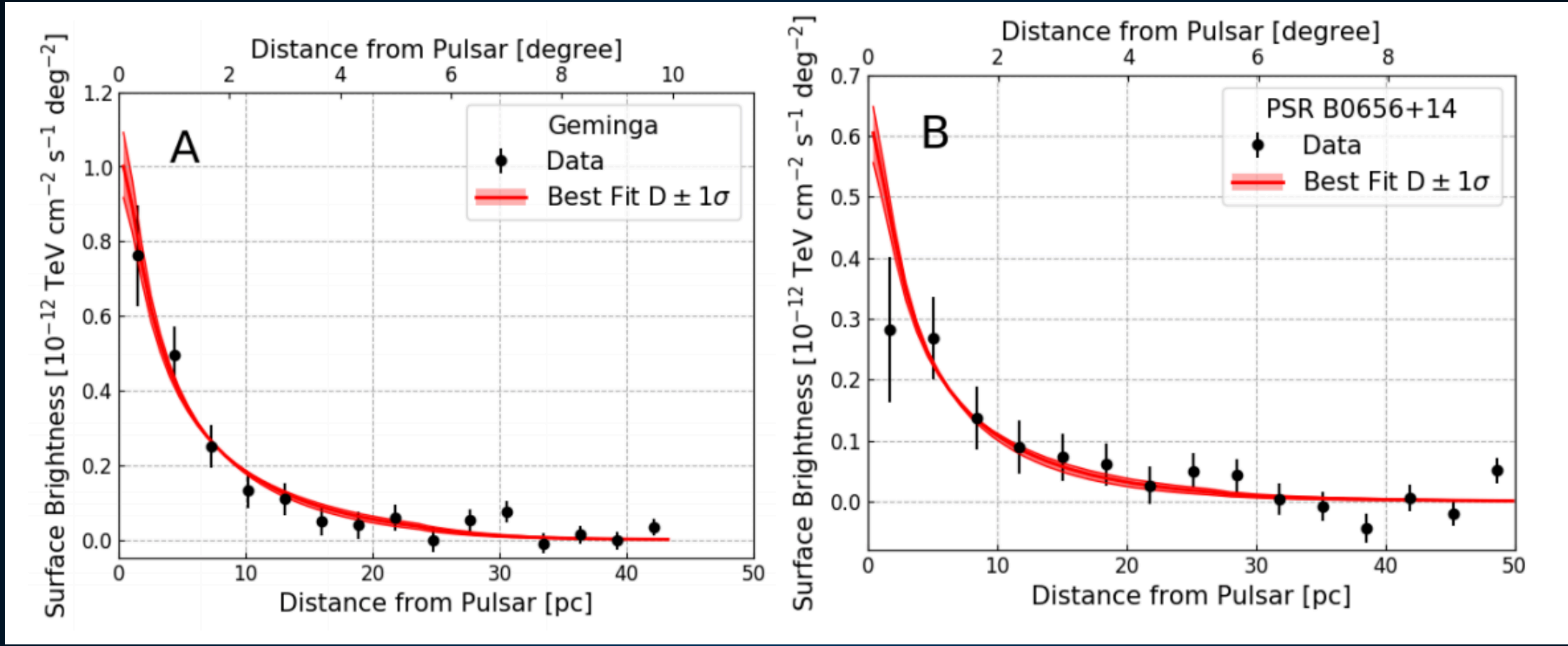
Table 4 Candidate pulsar wind nebulae from the pre-selection.

HGPS name	ATNF name	lg $\dot{E}$	τ_c (kyr)	d (kpc)	PSR offset (pc)	Γ	$R_{\rm PWN}$ (pc)	$L_{1-10\,\rm TeV}$ (10^{33} erg s^{-1})	Rating 1	2	3	4
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	⋆	↯	★	↯

- “TeV PWN” observed by HESS have similar fluxes and extensions.

TeV Halos

HAWC Collaboration (Science; 1711.06223)

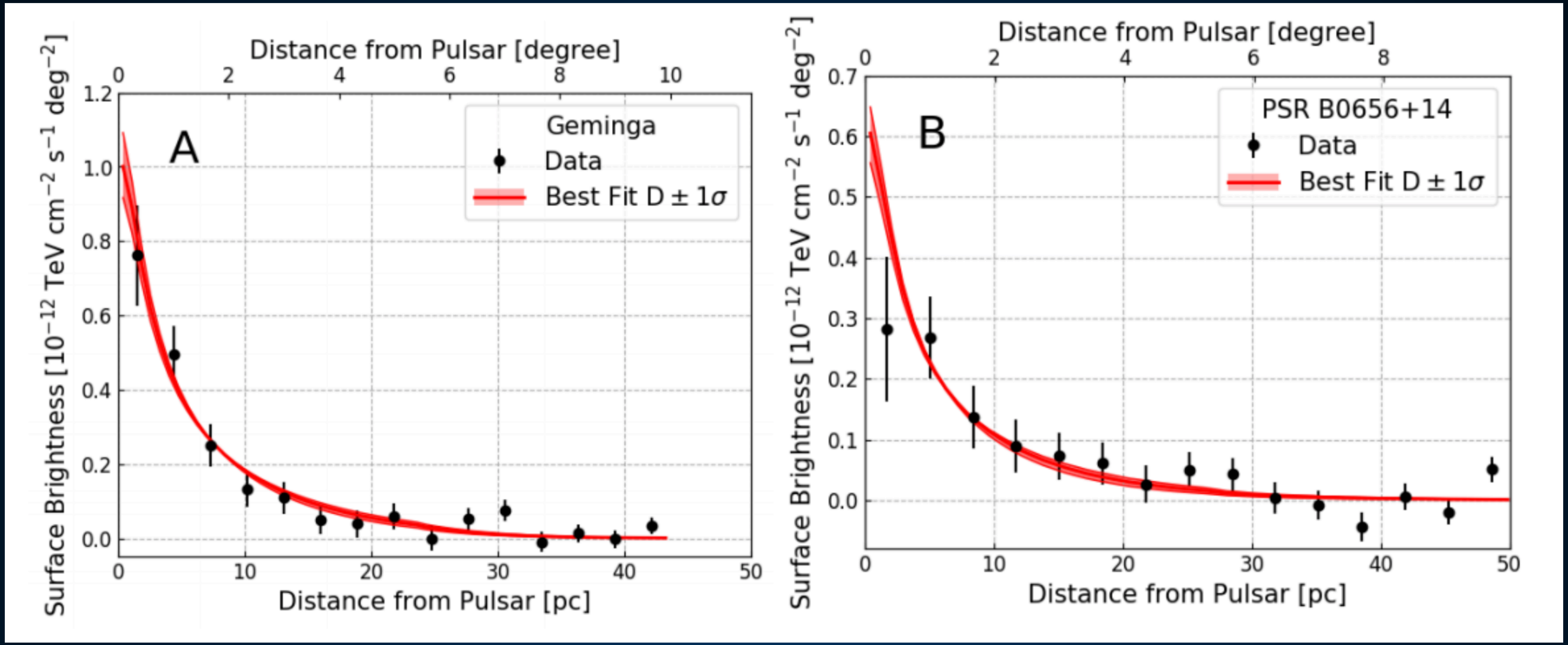


- **Why TeV Halos?**
  - **These sources are <u>much larger</u> than X-Ray PWN**

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

TeV Halos

HAWC Collaboration (Science; 1711.06223)



- **Why TeV Halos?**
  - **These sources are much smaller than diffusion through the ISM**

$\tau_{loss} \approx 30$ Kyr $\quad D_0 \approx 5 \times 10^{28}$ cm^2 s^{-1}

$$\boxed{L = \sqrt{Dt} \approx 2000 \text{ pc}}$$

TeV Halos

HAWC Collaboration (Science; 1711.06223)

a new morphology requires a new physical mechanism

The Global Population of TeV Halos

- **Make One Key Assumption:**

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

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

- **Note: Using Monogem would increases fluxes by nearly a factor of 2. The power law of this correlation doesn't greatly affect the results.**

HAWC Observations of TeV Halo Luminosities

Linden et al. (PRD; 1703.09704)

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.**
- **5 of the brightest 7 have been detected.**
- **No dimmer systems have been detected.**

HAWC Observations of TeV Halo Luminosities

Linden et al. (PRD; 1703.09704)

ATNF Name	Dec. (°)	2HWC
J0633+1746	17.77	2HWC J0631+169
B0656+14	14.23	2HWC J0700+143
B1951+32	32.87	—
J1740+1000	10.00	—
J1913+1011	10.18	2HWC J1912+099
J1831-0952	-9.86	2HWC J1831-098
J2032+4127	41.45	2HWC J2031+415
B1822-09	-9.58	—
B1830-08	-8.45	—
J1913+0904	9.07	—
B0540+23	23.48	**2HWC J0543+233**

HAWC detection of TeV emission near PSR B0540+23

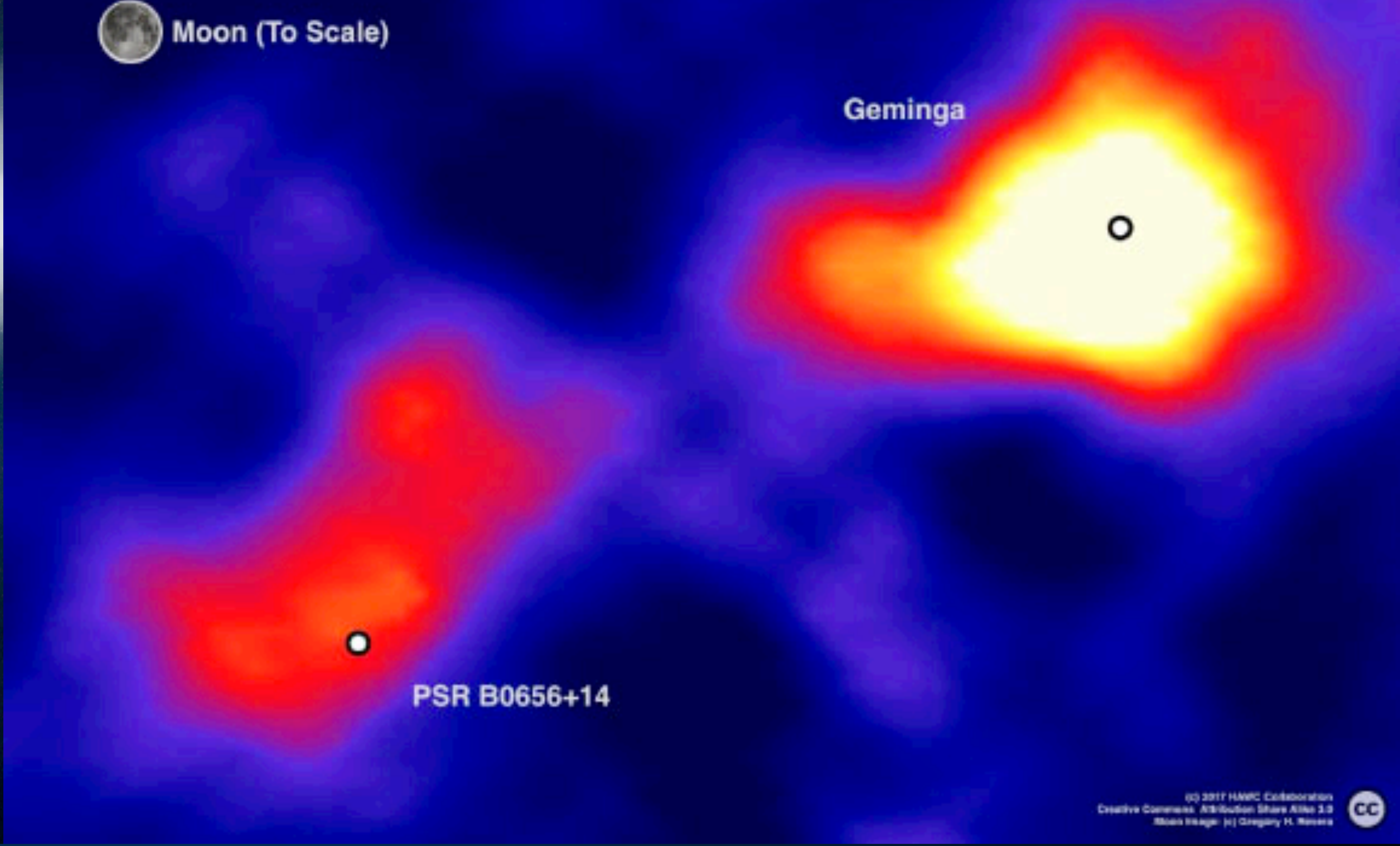
ATel #10941; *Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration*
on 9 Nov 2017; 23:11 UT
Credential Certification: Colas Riviere (riviere@umd.edu)

Subjects: Gamma Ray, TeV, VHE, Pulsar

Tweet Recommend 5

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.

TIM LINDEN



Rise of the Leptons:

Pulsar Emission Dominates the TeV Gamma-Ray Sky

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CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

TeV Halos are a Generic Feature of Pulsars

Linden et al. (PRD; 1703.09704)

- **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 ($\times10^{-15}$)	Actual Flux ($\times10^{-15}$)	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

TeV Halos are a Generic Feature of Pulsars

Linden et al. (PRD; 1703.09704)

- **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

Missing TeV Halos

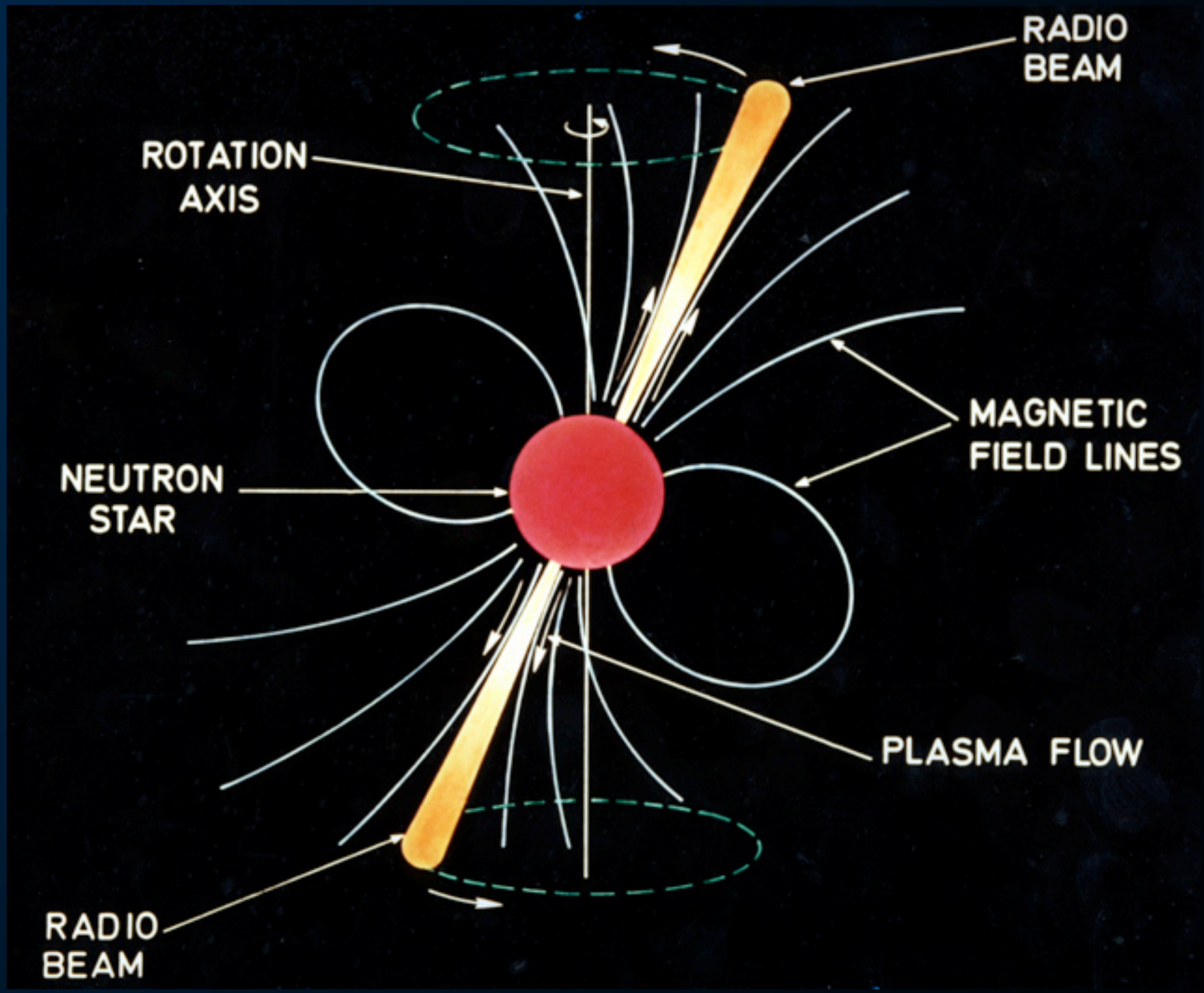
Linden et al. (PRD; 1703.09704)

- 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%.

- 1/f pulsars are unseen in radio surveys.



Missing TeV Halos

Linden et al. (PRD; 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
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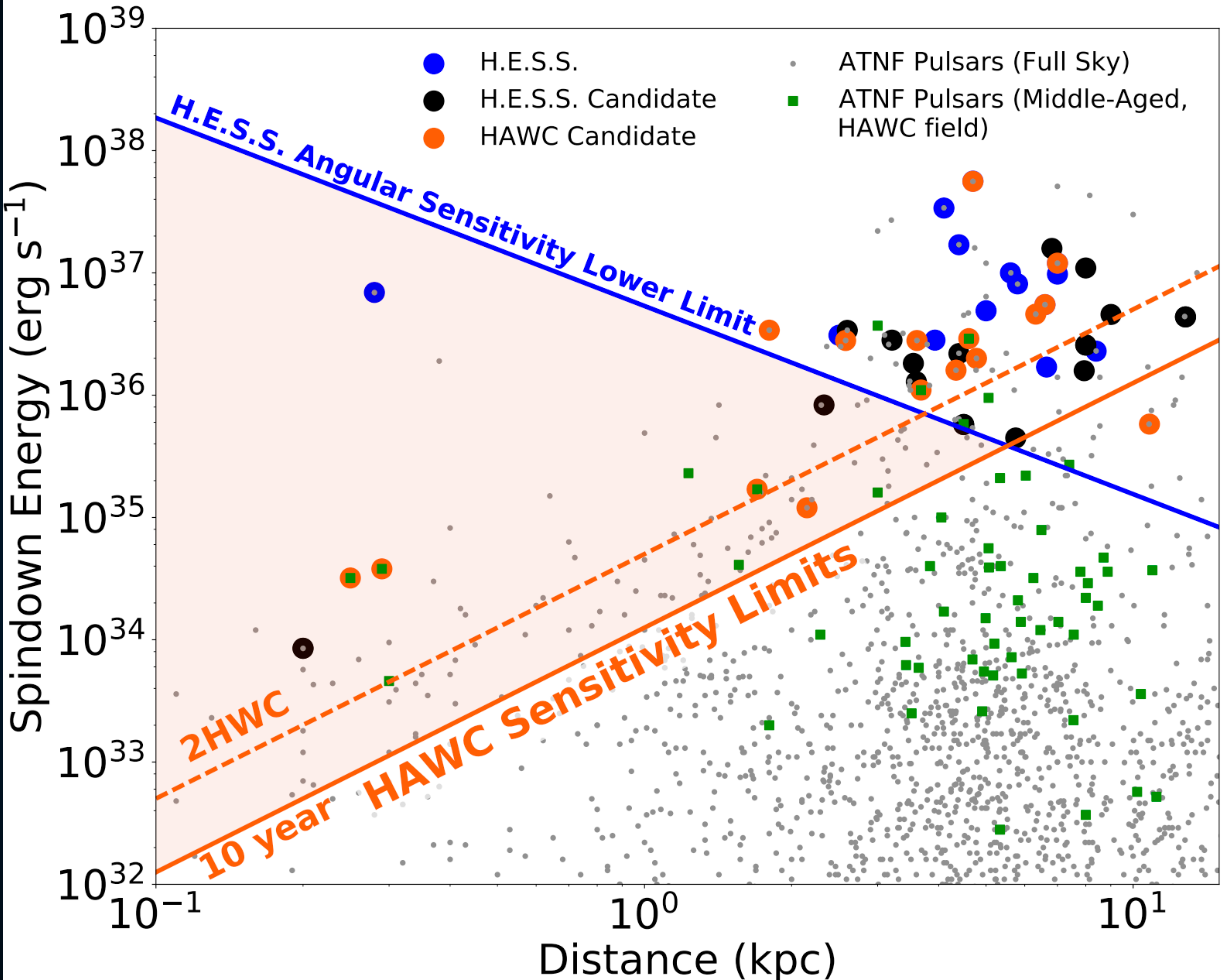
J1814-173	J1813-1749	4.7	0.54°	44.30 pc	243	152	1.60	0.11°	1.0°	5.6	0.61
J2019+367	J2021+3651	1.8	0.27°	8.48 pc	99.8	58.2	1.71	0.28°	0.7°	17.2	0.04
J1928+177	J1928+1746	4.34	0.03°	2.27 pc	8.08	10.0	0.81	0.11°	0.0°	82.6	0.002
J1908+063	J1907+0602	2.58	0.36°	16.21 pc	40.0	85.0	0.47	0.2°	0.8°	19.5	0.26
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

- **Correcting for the beaming fraction implies 56^{+15}_{-11} TeV halos are currently observed by HAWC.**
- **However, only 39 HAWC sources total.**
- **Chance overlaps, SNR contamination must be taken into account.**



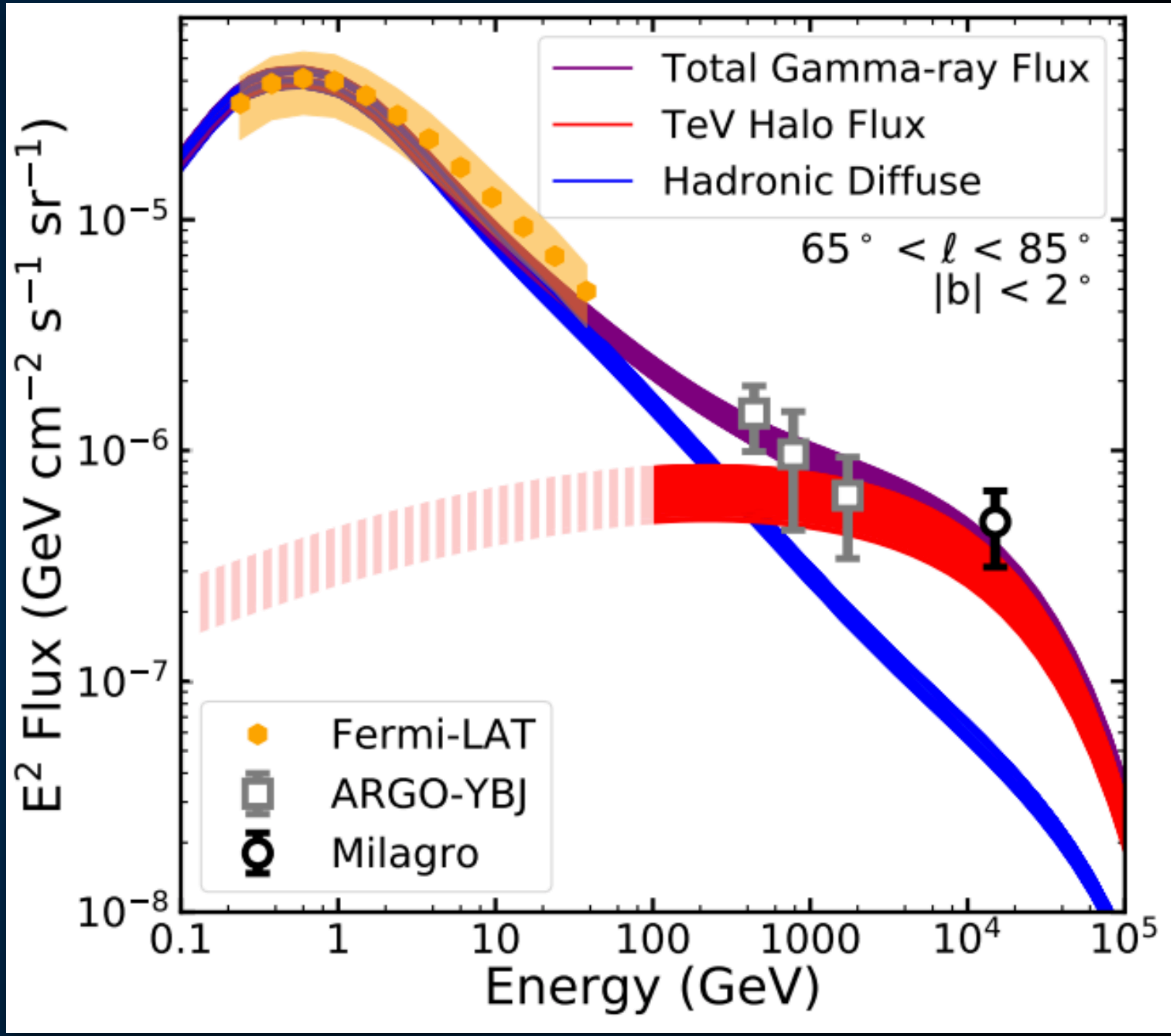
H.E.S.S.
H.E.S.S. Candidate
HAWC Candidate
ATNF Pulsars (Full Sky)
ATNF Pulsars (Middle-Aged, HAWC field)
H.E.S.S. Angular Sensitivity Lower Limit
2HWC
10 year
HAWC Sensitivity Limits
Spindown Energy (erg s^{-1})
Distance (kpc)
10^{32}
10^{33}
10^{34}
10^{35}
10^{36}
10^{37}
10^{38}
10^{39}
10^{-1}
10^{0}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

IMPLICATIONS

Implication I: The TeV Excess

Linden & Buckman (PRL; 1707.01905)

- Milagro detects bright diffuse TeV emission along the Galactic plane.



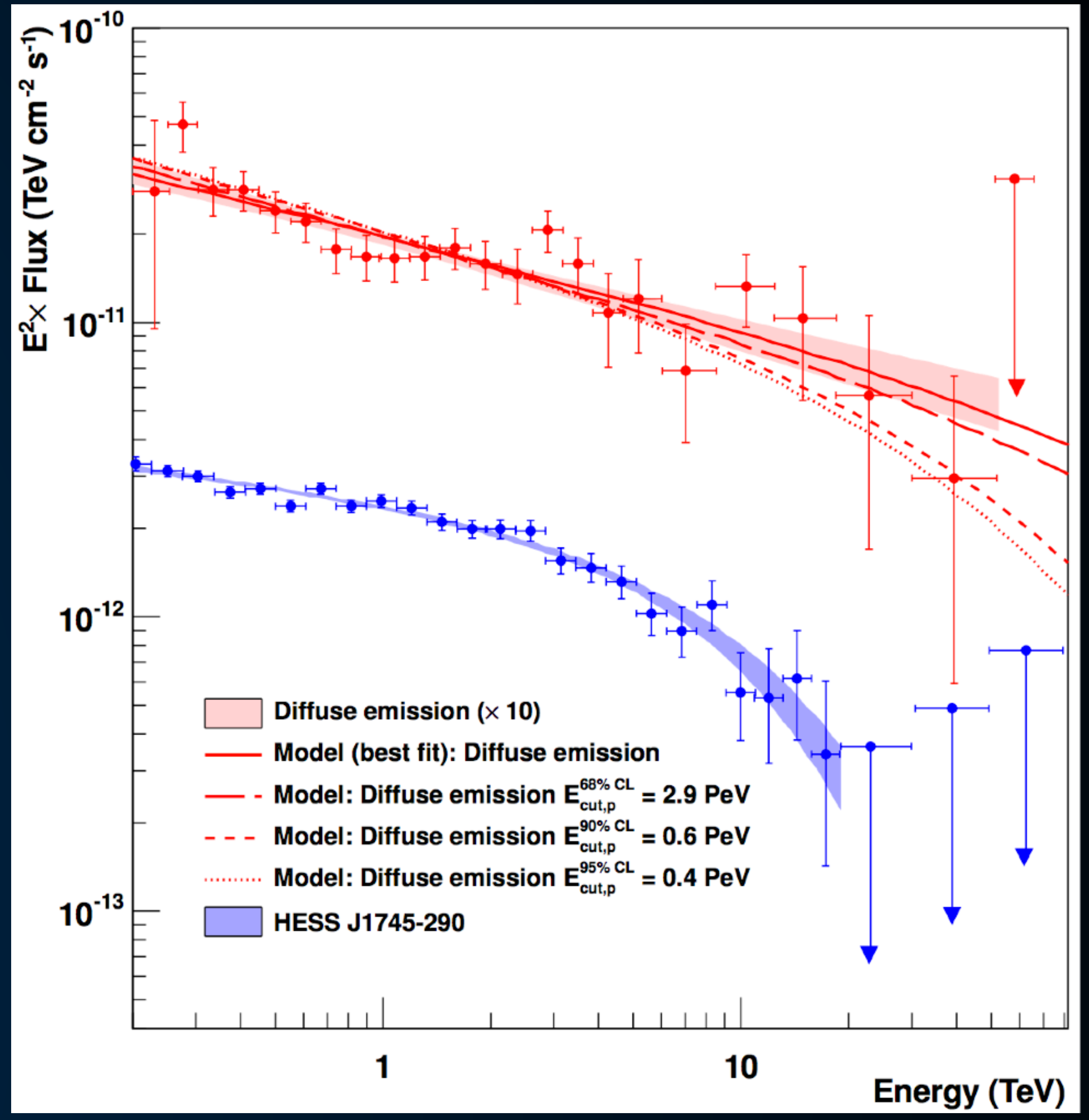
- Difficult to explain with pion decay, due to steeply falling local hadronic CR spectrum.

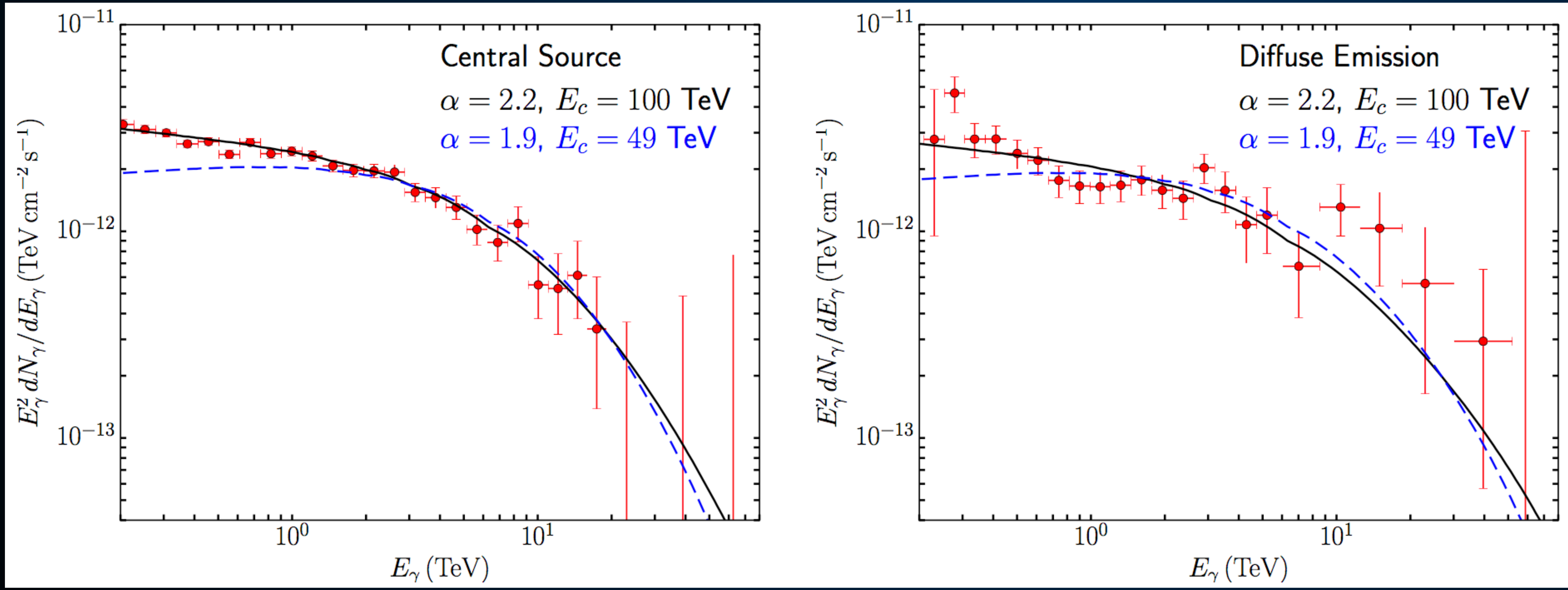
- The Geminga and Monogem TeV halo spectra naturally explain both the spectrum and intensity of this emission.

Implication II: The Galactic Center Pevatron

- HESS observes 50 TeV diffuse emission from the Galactic center.
- If hadronic, it is evidence for PeV proton acceleration.
- TeV halos explain the spectrum and intensity of this emission.

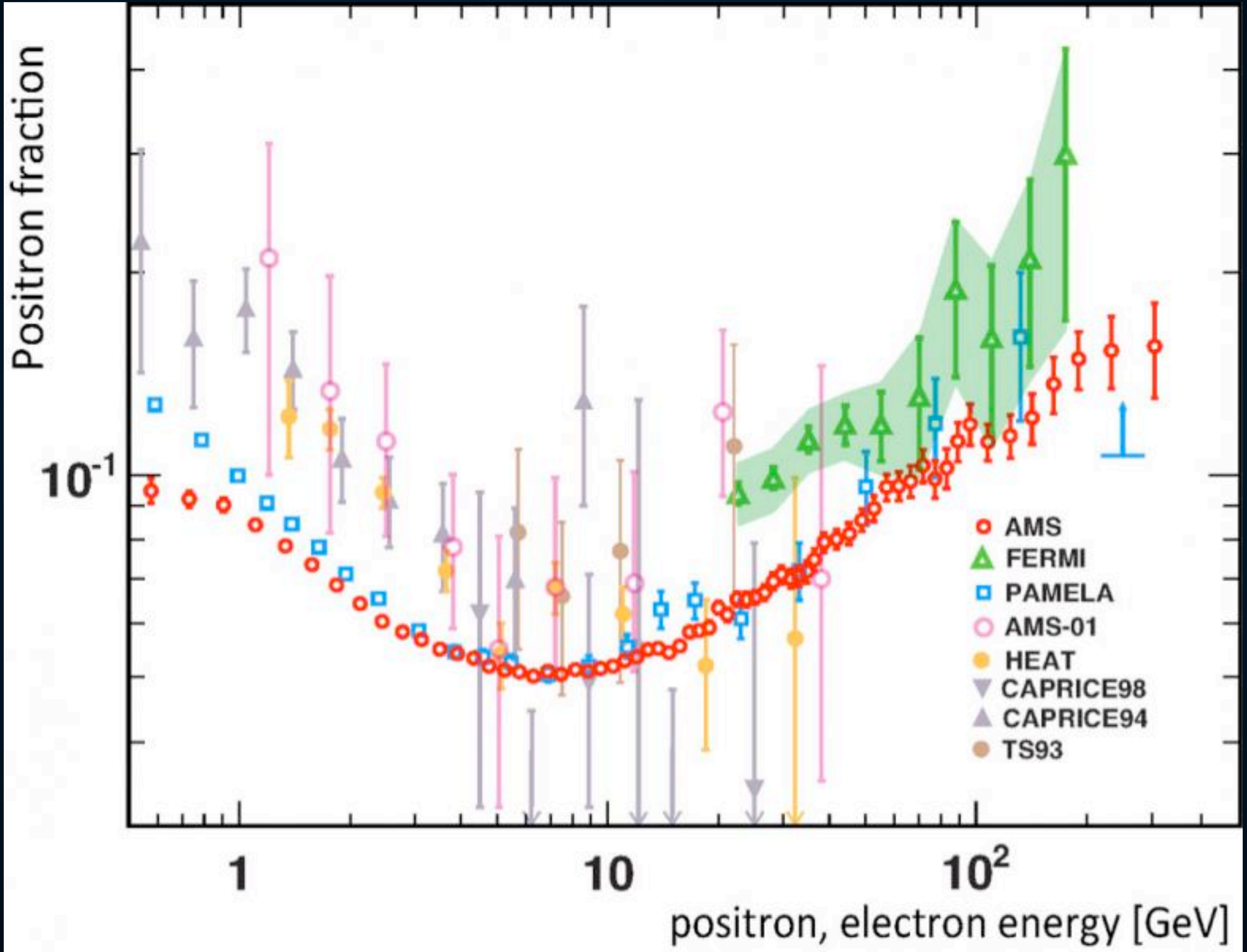
HESS Collaboration (1603.07730)





Hooper, Cholis & Linden (1705.09293)

Implication III: The Positron Excess

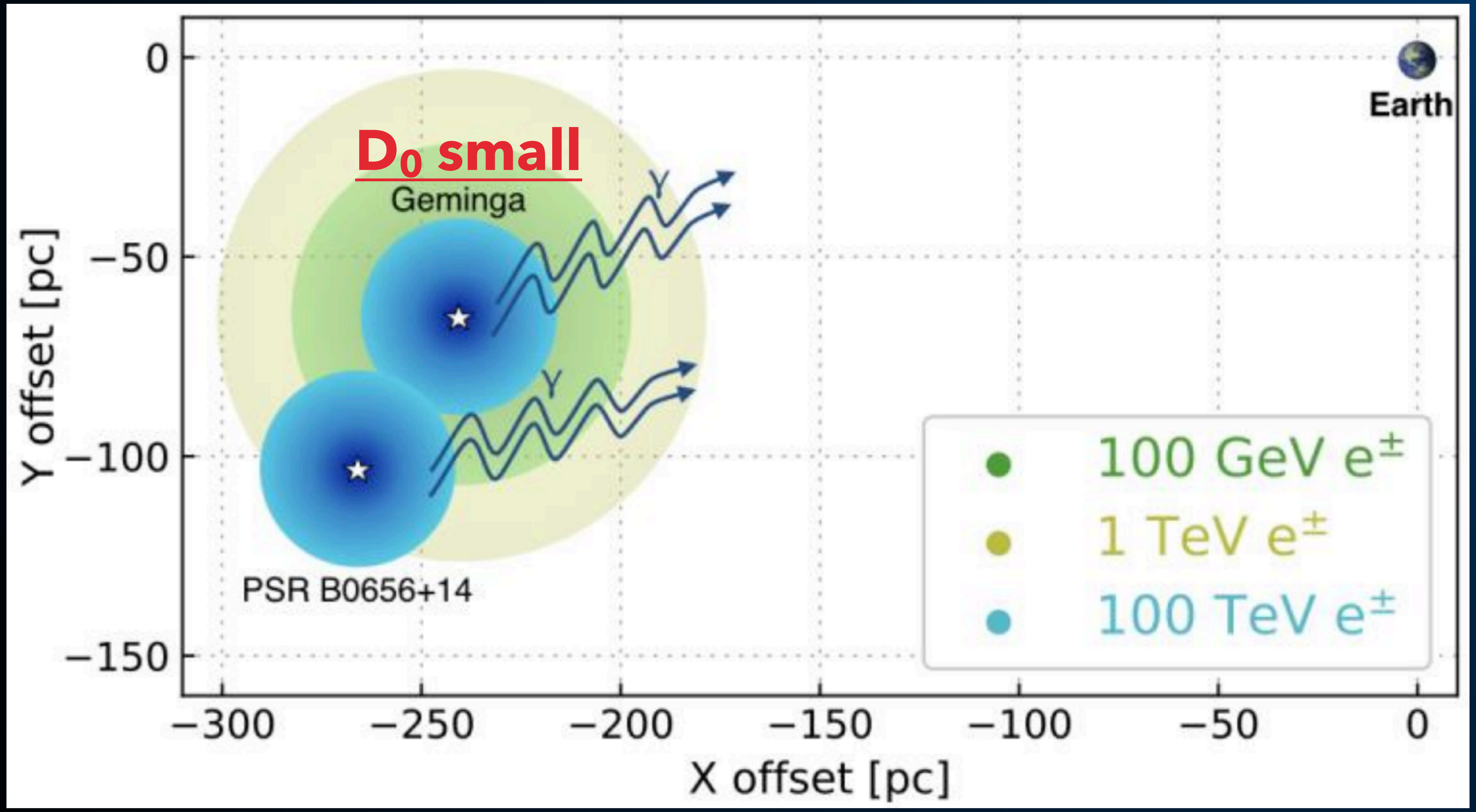


Implication III: The Positron Excess

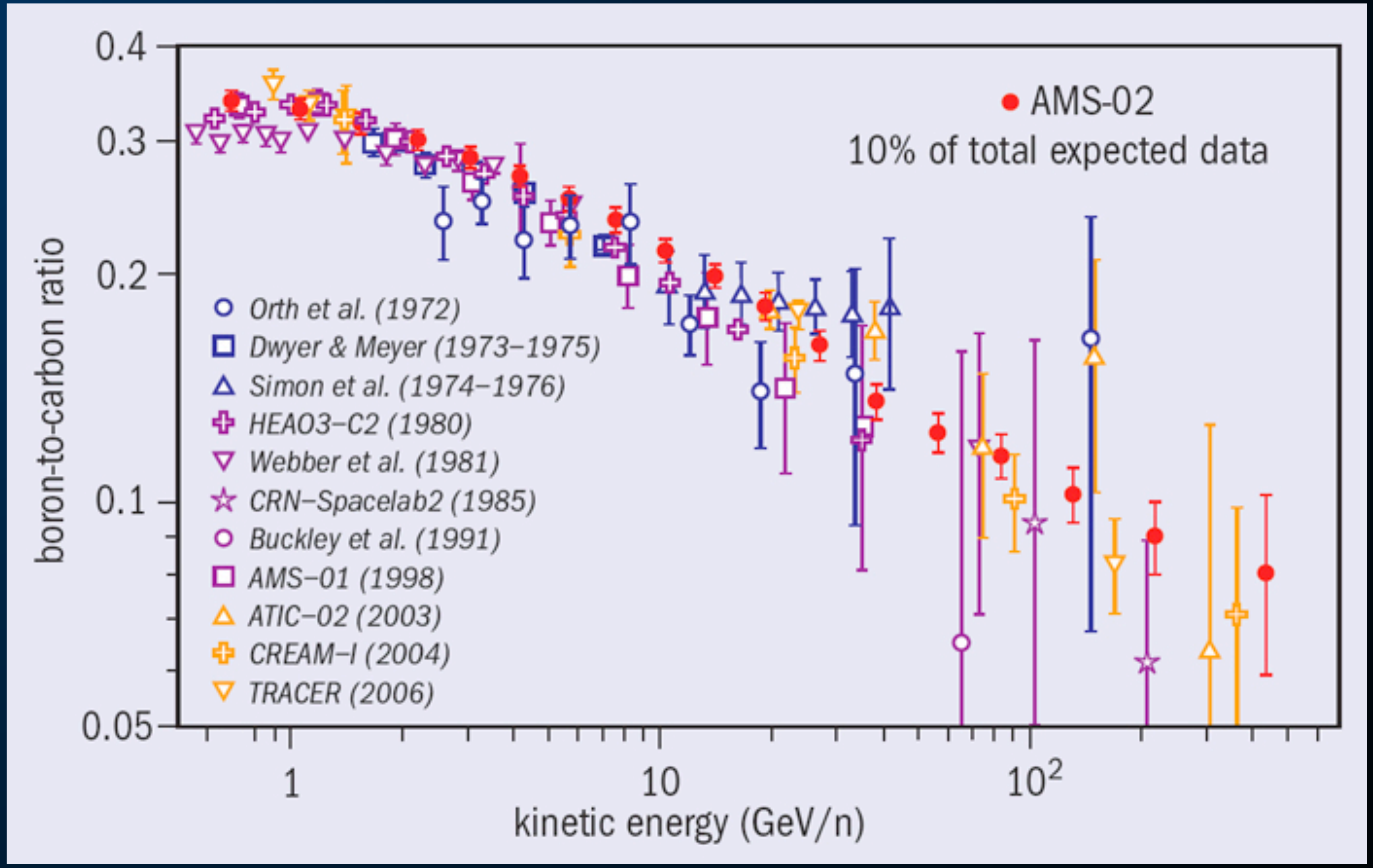
- What we want to know is the average diffusion constant between Geminga and Earth.

- What we have is:

Diffuse Constant Near Geminga



Diffuse Constant in Milky Way

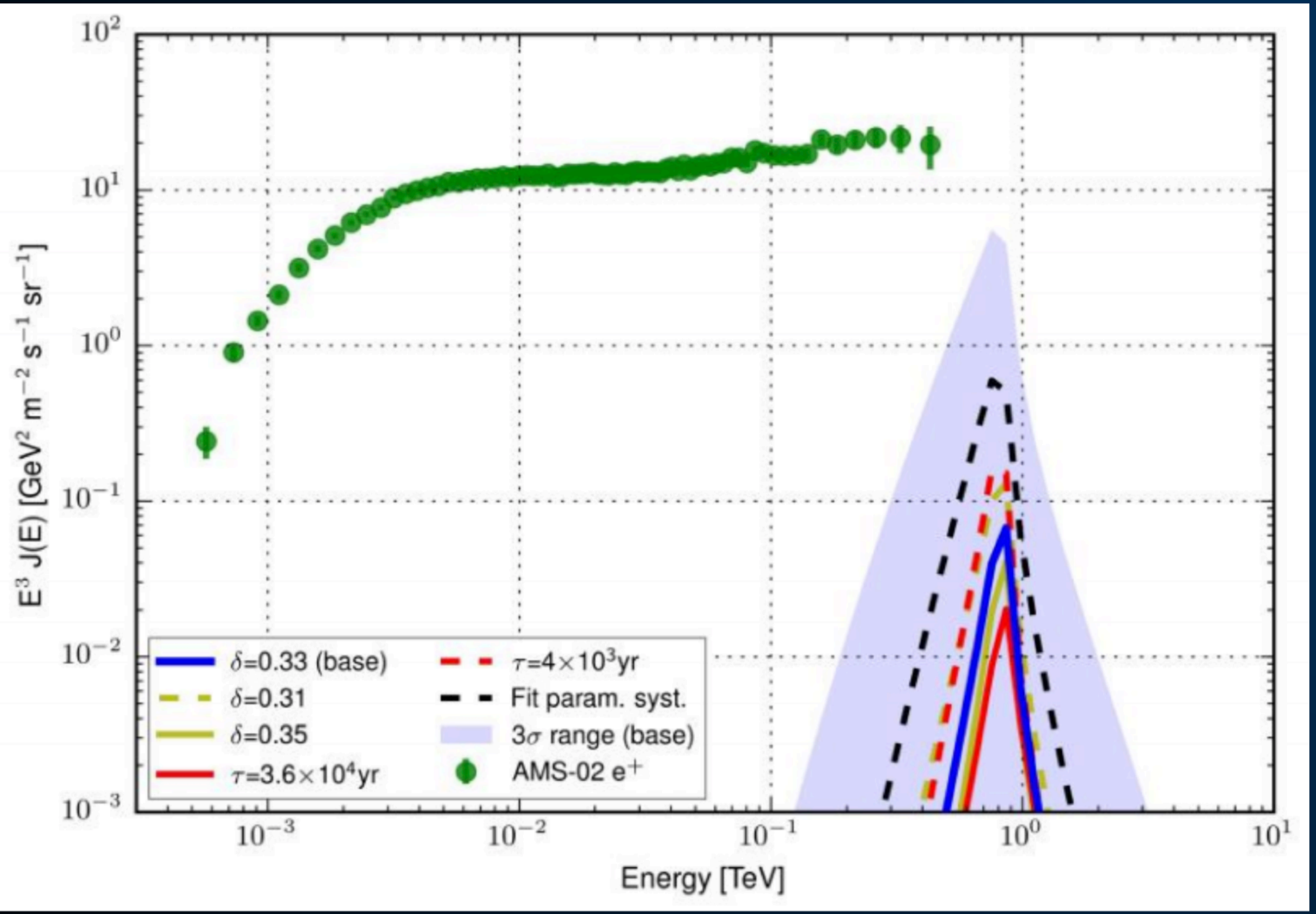


Implication III: The Positron Excess

Extrapolate Low Diffusion Constant UP to Earth

implies:

Low-Energy Positrons do not make it to Earth

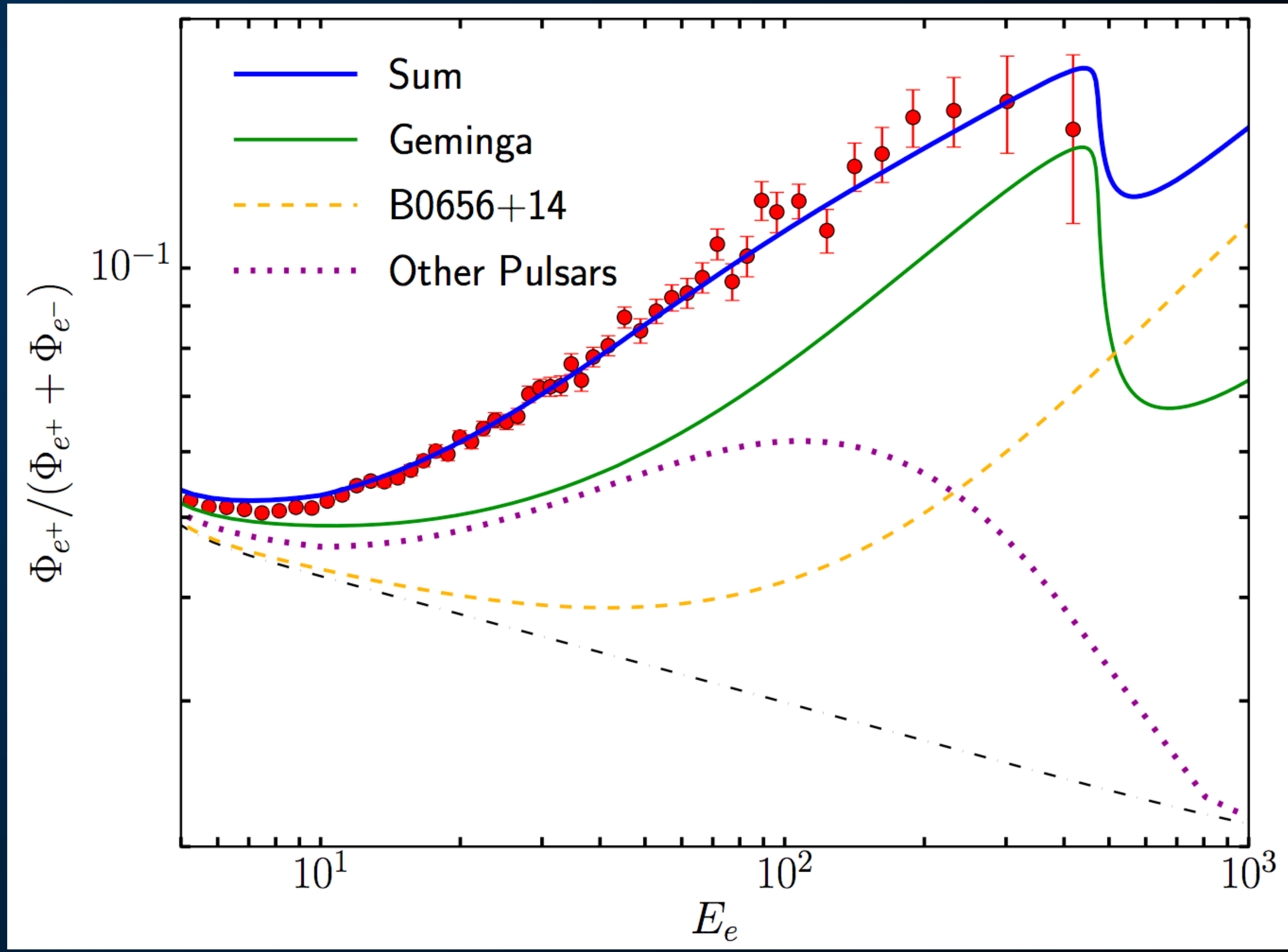


HAWC Collaboration (Science; 1711.06223)

Extrapolate High Diffusion DOWN to Earth

implies:

Low-Energy Positrons do make it to Earth



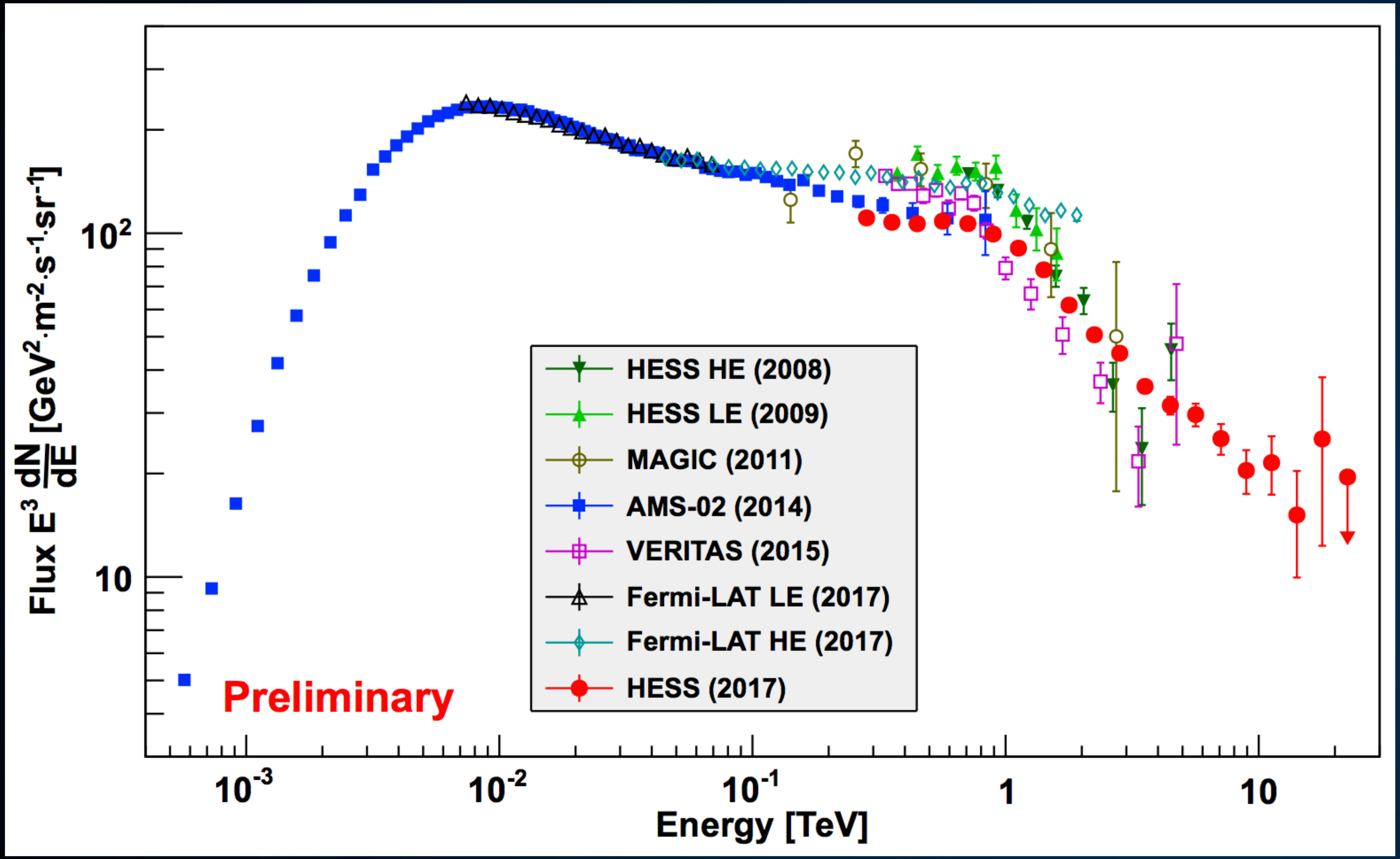
Hooper et al. (1702.08436)

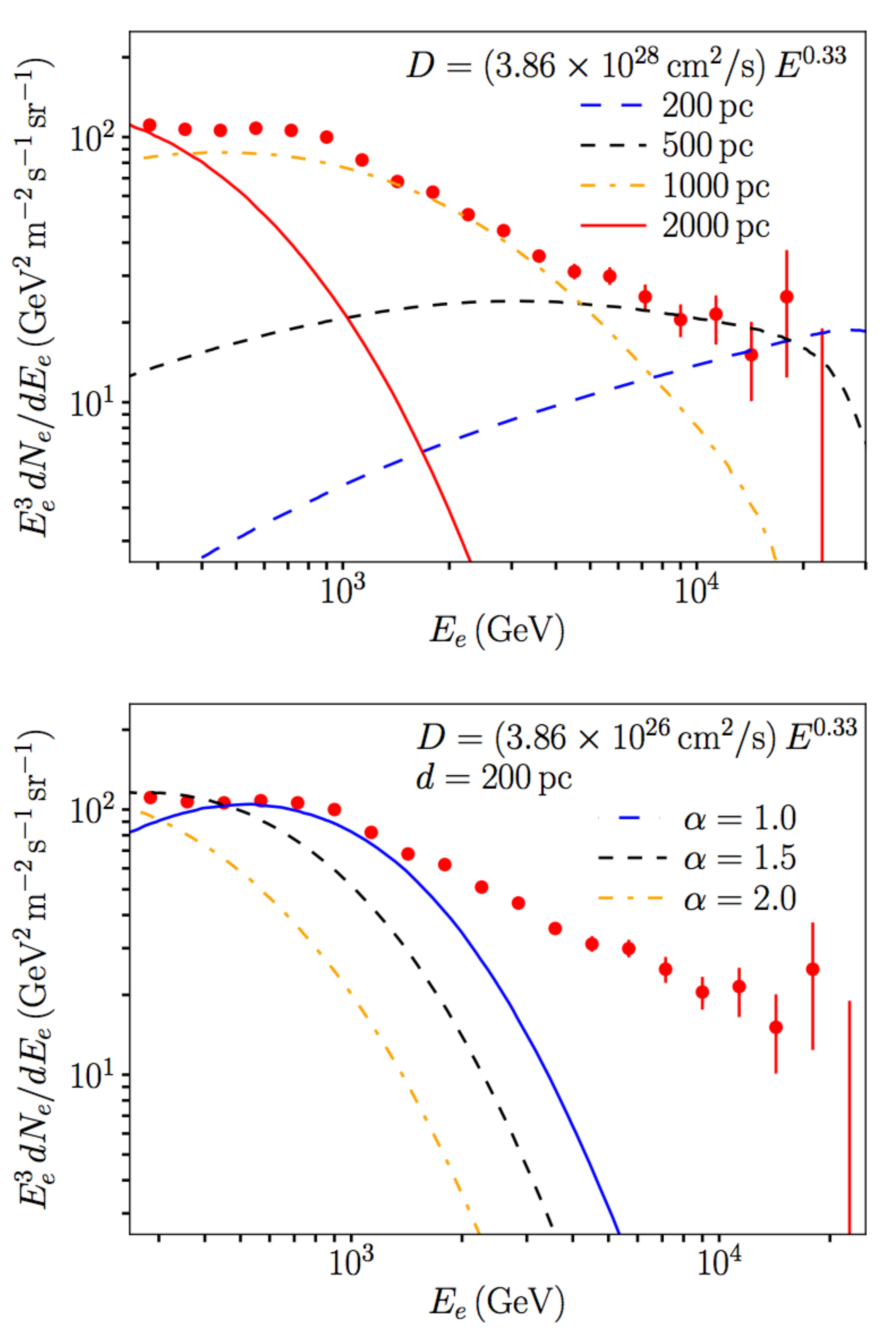
Profumo et al. (1803.09731)

Fang et al. (1803.02640)

Implication III: The Positron Excess

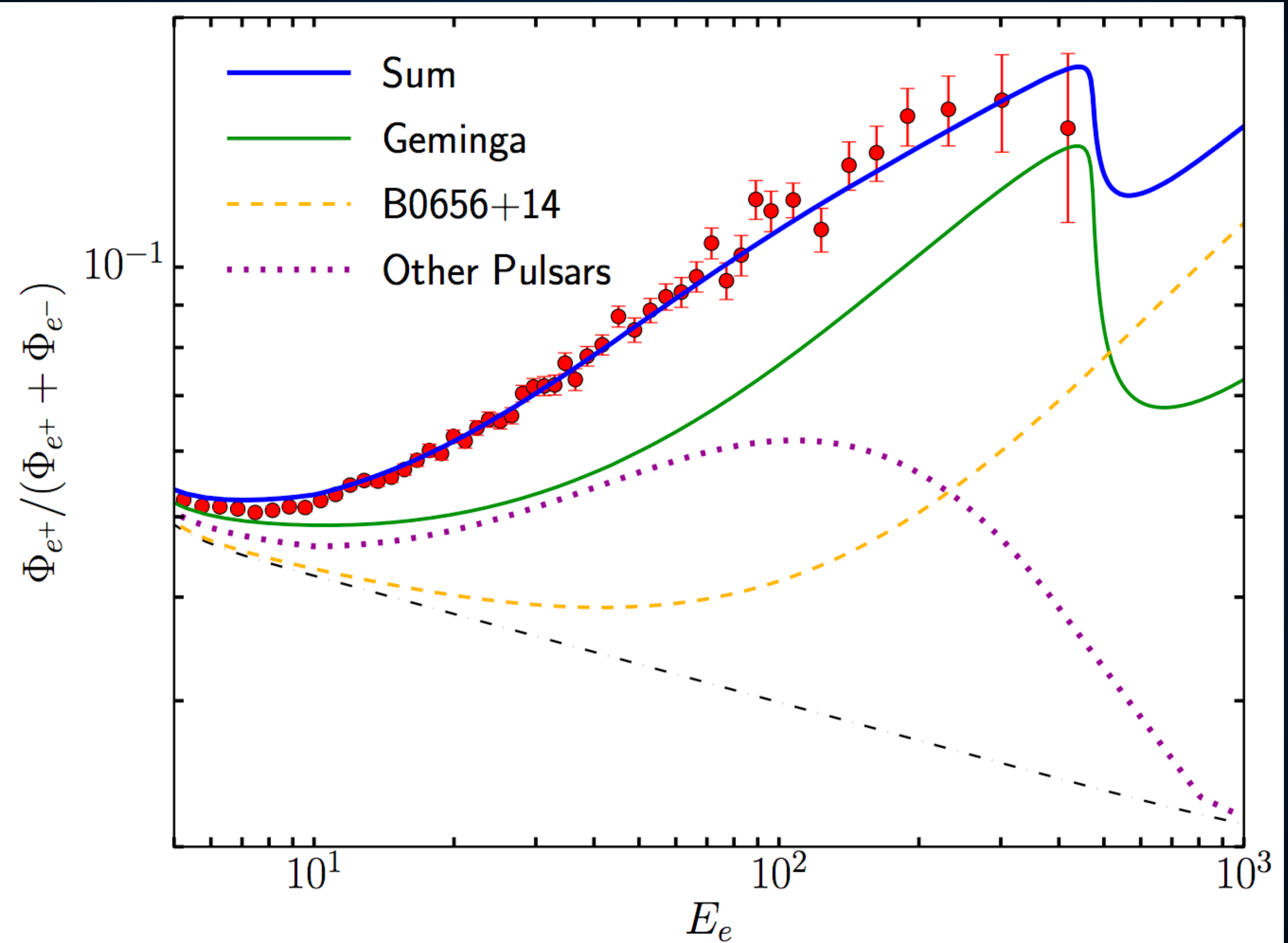
Hooper & Linden (1711.07482)





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

Implication III: The Positron Excess



The Limited Assumptions in TeV Halo Observations

TeV Gamma-Ray Luminosity Roughly Proportional to Spindown Power

= TeV halos explain the Milagro TeV Excess

+ High Energy electrons trapped in TeV halos

= Most HAWC Sources are TeV halos

+ Low energy electrons escape from TeV halos

= Pulsars explain the positron excess

+ GC pulsars consistent with massive stars

= TeV halos explain the HESS pevatron

+ MSPs produce TeV halos

= New Population of Blind Search TeV MSPs

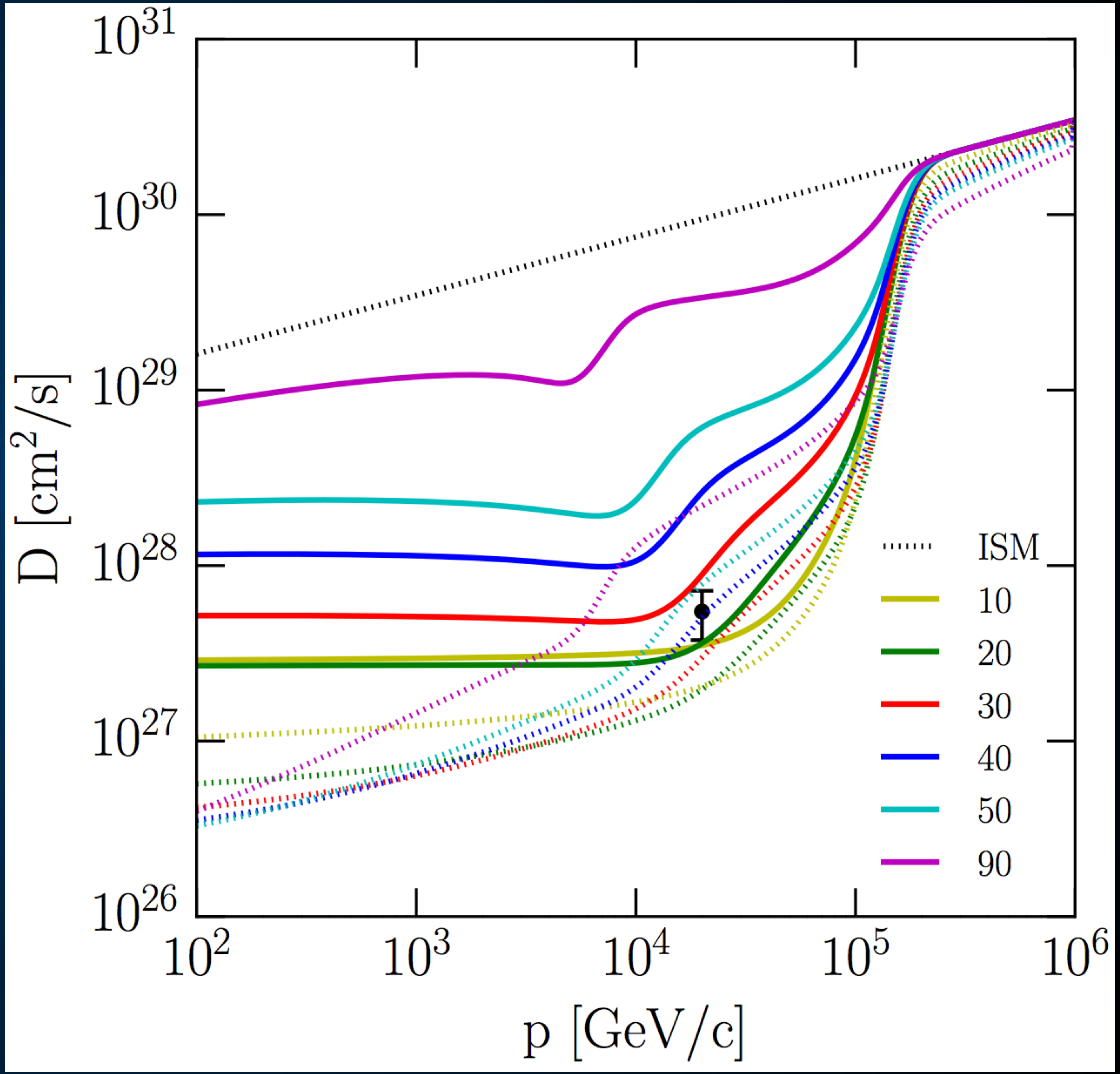
A First Model for TeV Halo Emission

- At presents, all results directly based on observations – no model for the low-diffusion constant in TeV halos.

- Cosmic-Ray Self Generated Turbulence appears capable of producing inhibited diffusion near pulsars, at least for young systems.

Stay Tuned!

Evoli et al. (TBS)



Conclusions (1/2)

- TeV halos are a new dynamical object.
- Have already observed ~20 objects; >100 inevitable
- Simple extrapolations of observed systems imply:
  - TeV halos dominate the TeV source number.
  - TeV halos dominate Milky Way diffuse emission.
  - TeV halos produce the positron excess.

Conclusions (2/2)

- TeV Halos will provide new insight into pulsar birth, death, and evolution, providing a new handle into the multi-wavelength study of neutron star dynamics.

- TeV halos provide the first evidence for significant inhomogeneities in Galactic cosmic-ray propagation — new insights into cosmic-ray observations (e.g. AMS-02).

Implication III: The Positron Excess

What about 100 GeV electrons?

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

$$L(E) \propto \sqrt{D_0 E^{\delta - 1}}$$

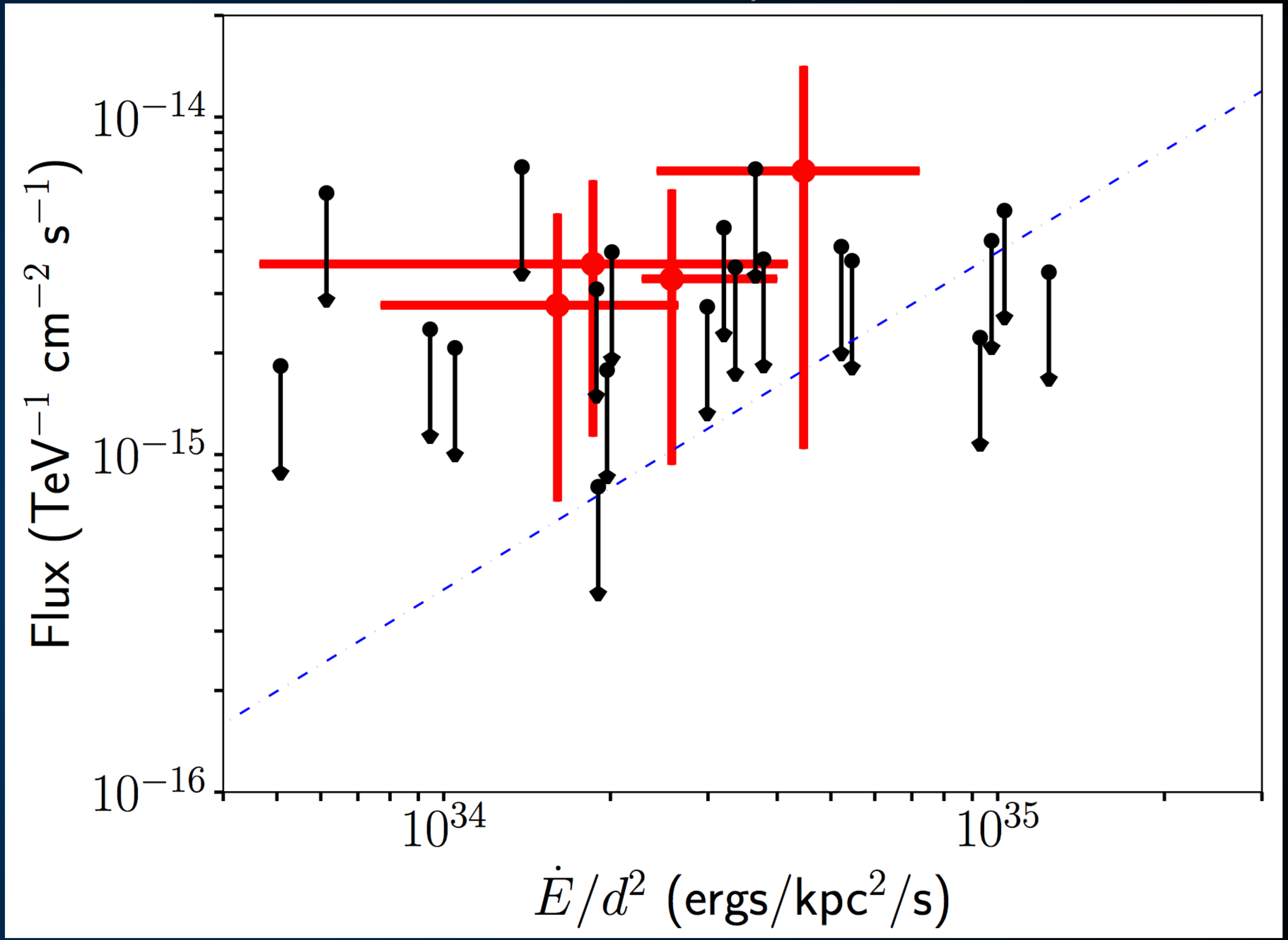
Low Energy Electrons lose energy slower – and thus travel farther through the Milky Way

Additional Implications for MSPs

Hooper & Linden (1803.08046)

- MSPs not expected to be bright enough to be individually detected.

- Stacked analysis of MSP population provides some (2-3σ) evidence for TeV halo emission from MSPs.



- Would vastly increase the total TeV halo population, especially at high latitudes.