TIM LINDEN

THE RISE OF THE LEPTONS

PULSAR EMISSION DOMINATES THE TEV GAMMA-RAY SKY

Columbus-London -Amsterdam-Paris-Stockholm

October 13, 2017

THE OHIO STATE UNIVERSITY

CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

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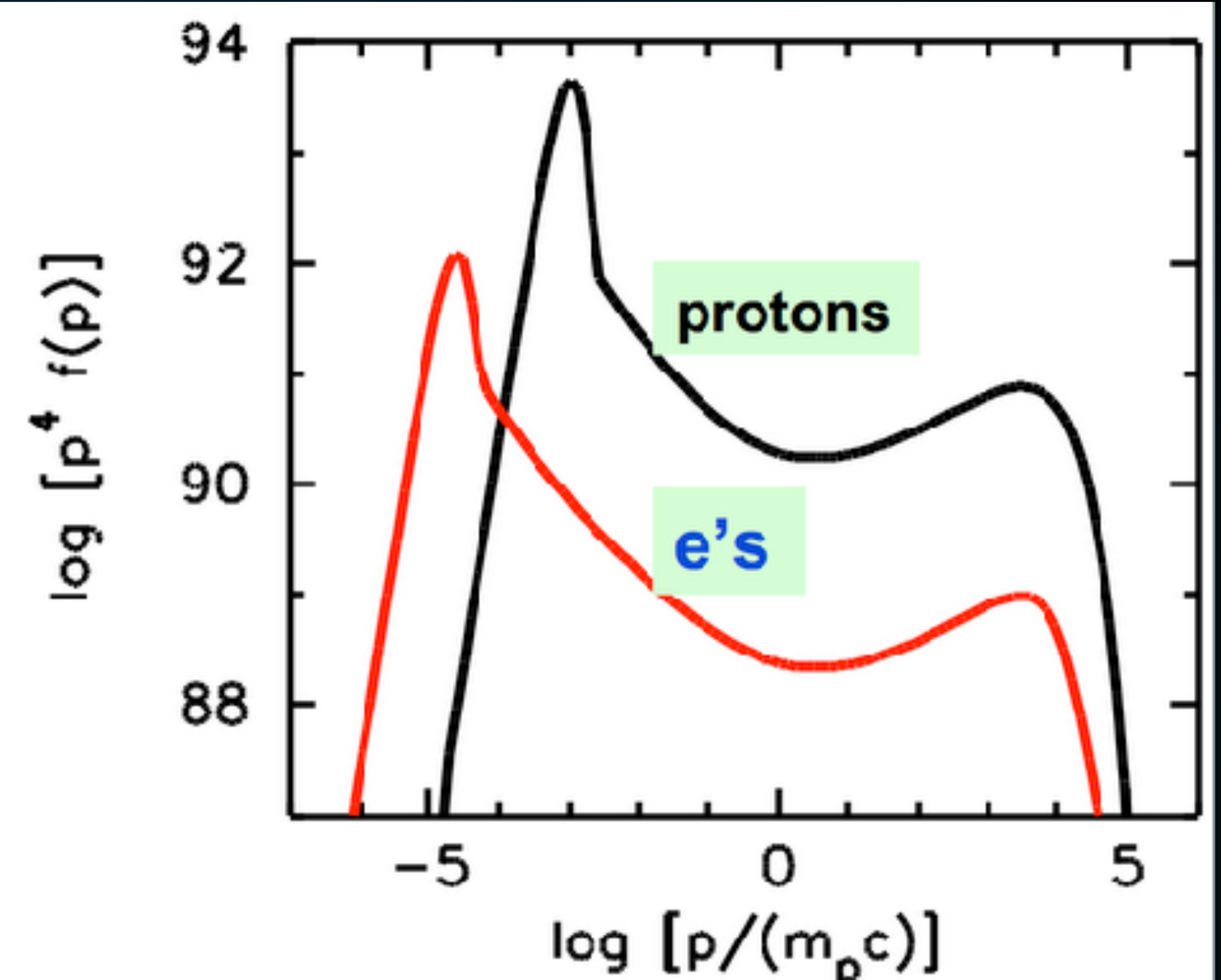
WITH: KATIE AUCHETTL, BEN BUCKMAN, JOSEPH BRAMANTE, ILIAS CHOLIS, KE FANG, DAN HOOPER, SHIRLEY LI

A UNIVERSE DOMINATED BY PROTONS

slide via Don Ellison

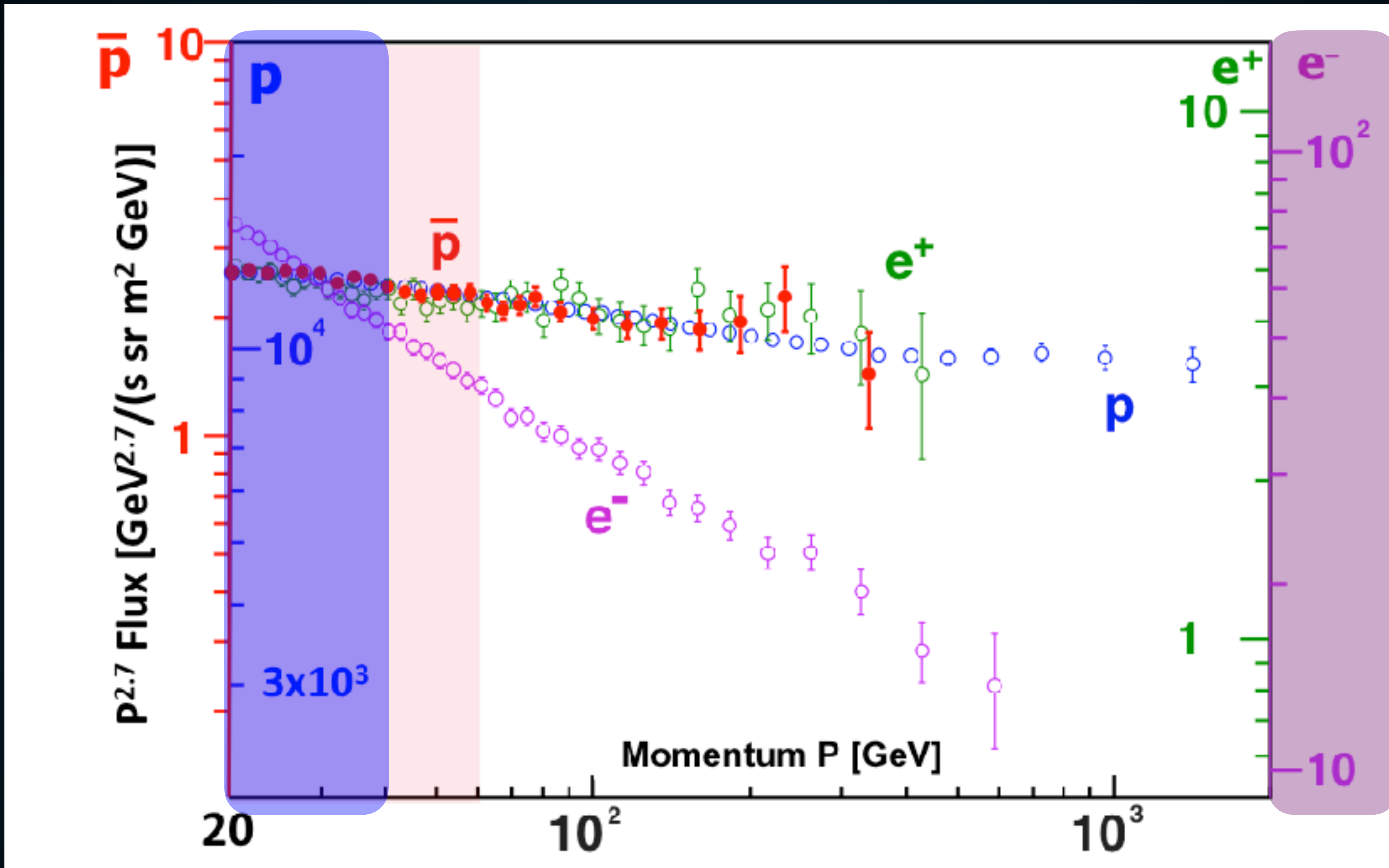
- Supernova remnants provide the only source energetic enough to explain the full energy spectrum of cosmic-ray protons up to PeV energies.
- First order Fermi acceleration naturally predicts protons dominate supernova energetics.



Spectra calculated with semi-analytic model of Blasi, Gabici & Vannoni 2005

- Observationally confirmed by X-Ray observations of SNR synchrotron and gamma-ray measurements of hadronic interactions.

LOCAL COSMIC-RAY OBSERVATIONS

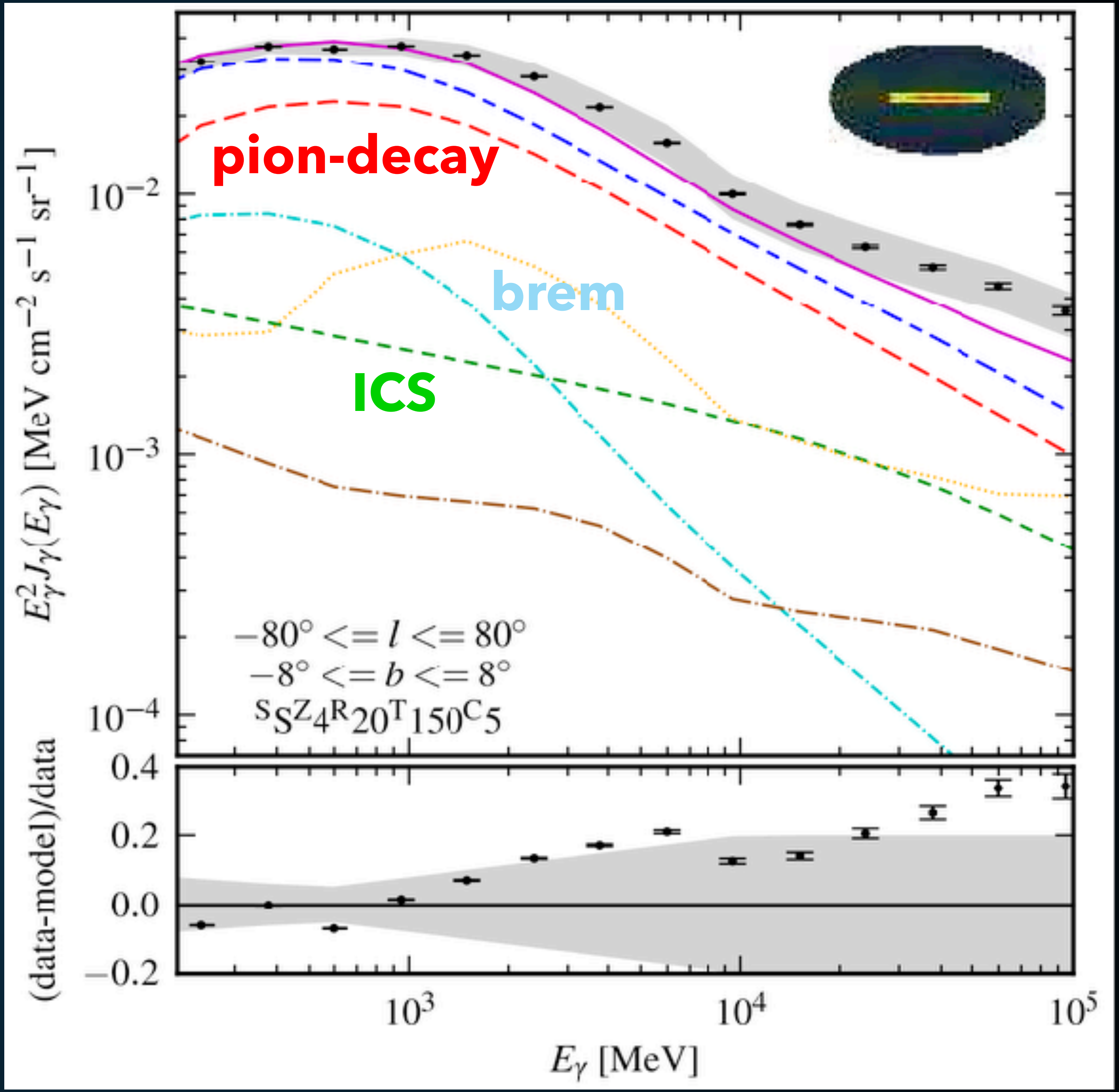


- Protons are approximately 2-3 orders of magnitude more prevalent near the solar position.

1202.4039

- Models of GeV galactic diffuse emission indicate that hadronic emission mechanisms are highlight dominant.

- Models indicate a slightly larger leptonic fraction at high energies.



A NEW PICTURE

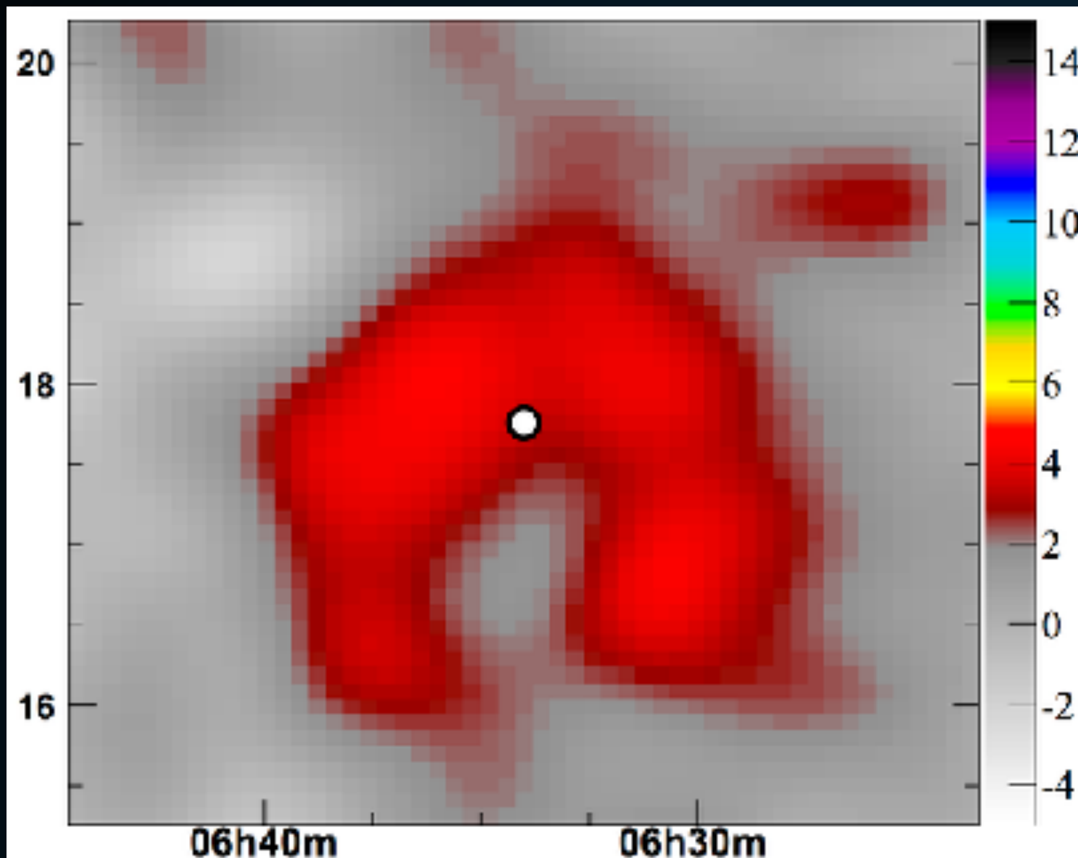
- In this talk, I will instead argue that electrons and positrons dominate the Milky Way's energetics at TeV energies:
  - 1.) Pulsars produce the majority of the bright TeV sources observed by CTA/HAWC/HESS etc.
  - 2.) Pulsars produce the majority of the TeV gamma-ray emission observed from the Milky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

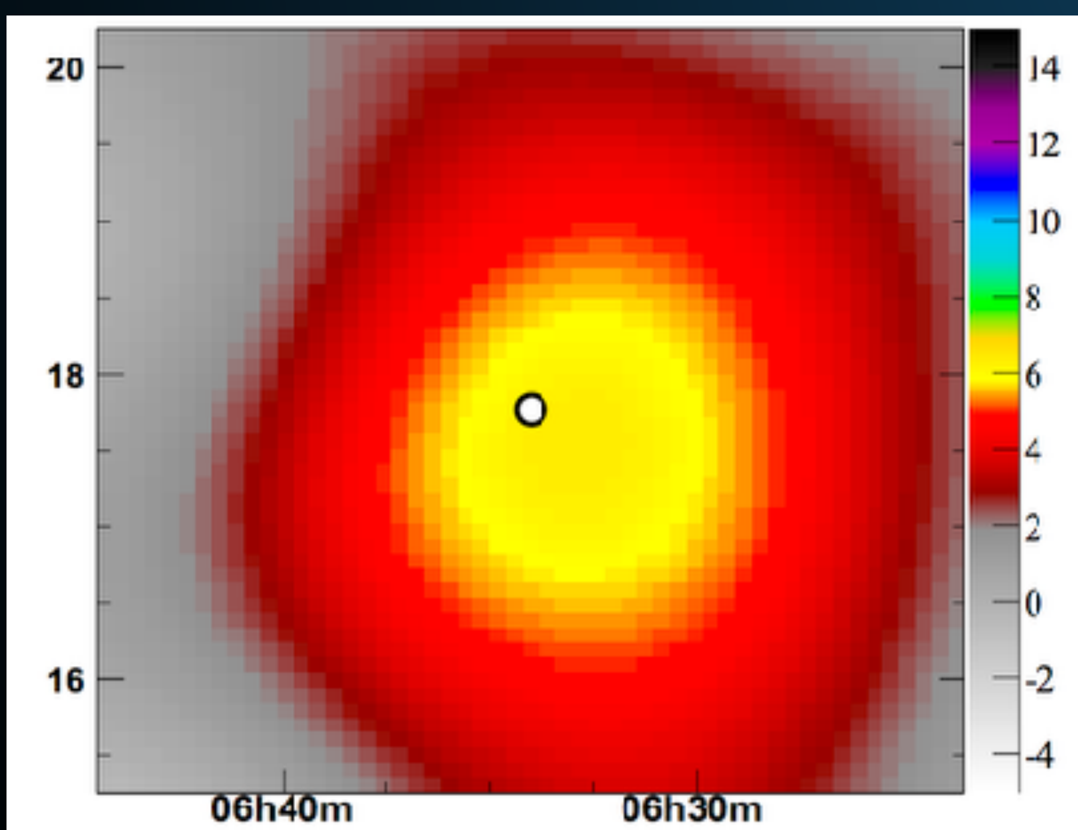
A NEW PICTURE

- Current observations necessitate these conclusions.
- Very few assumptions required in producing a theoretical model.

Let’s start without a theoretical model.

What do TeV observations tell us about pulsars?

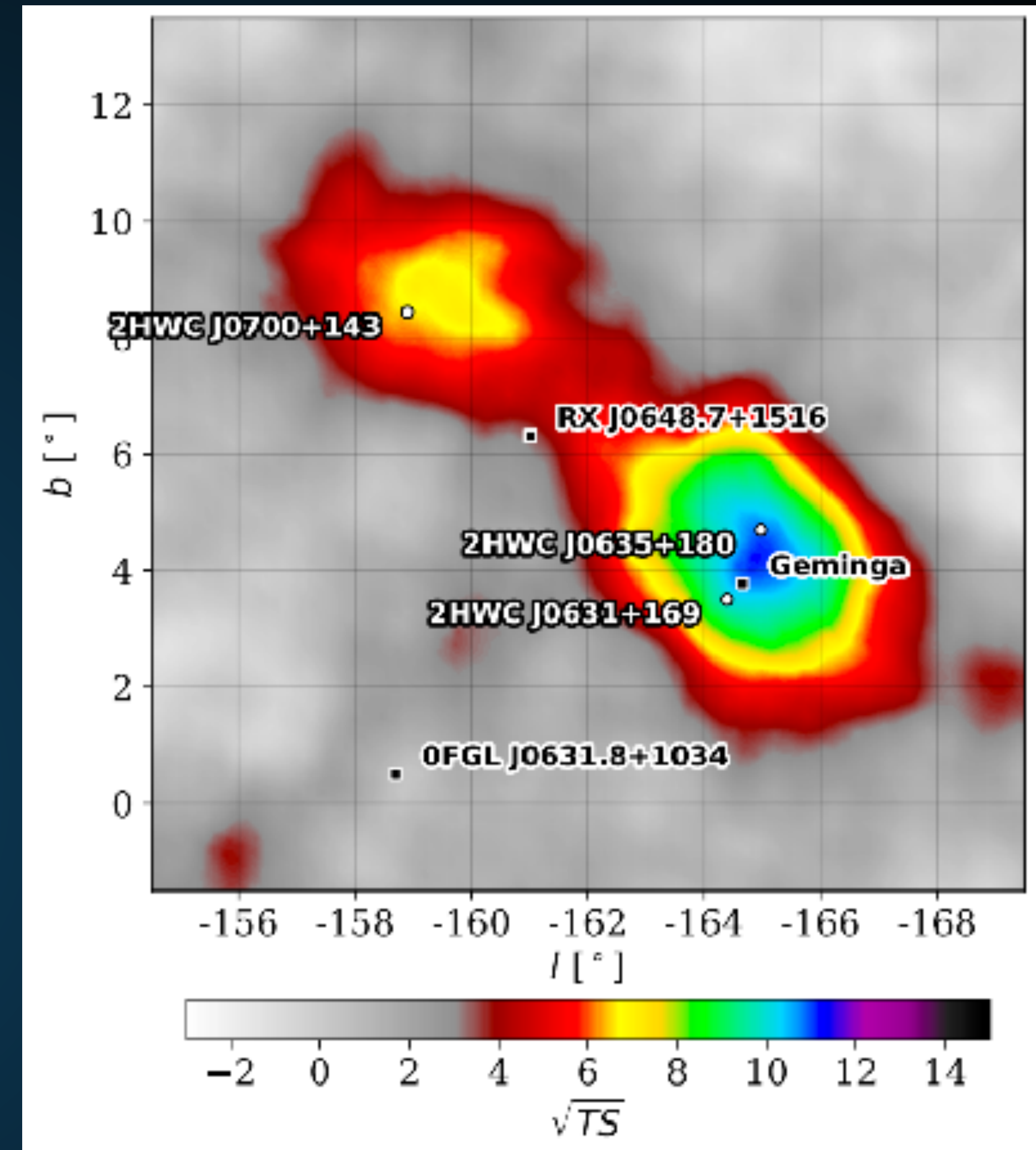




- Milagro observes extended emission from Geminga ($2.6^{+0.7}_{-0.9}$°)
- Corresponds to ~10 pc assuming Geminga distance is 250 pc.
- Note: Large distance uncertainty on Geminga:
  - 250^{+230}_{-80} pc

HAWC OBSERVATIONS OF GEMINGA AND MONOGEM

Name	Tested radius [°]	Index	$F_7 \times 10^{15}$ $[\mathrm{TeV^{-1}cm^{-2}s^{-1}}]$	TeVCat
2HWC J0534+220	-	-2.58 ± 0.01	184.7 ± 2.4	Crab
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
2HWC J0700+143	1.0	-2.17 ± 0.16	13.8 ± 4.2	-
"	2.0	-2.03 ± 0.14	23.0 ± 7.3	-



- HAWC observes Geminga
    - 4.9 x 10^{-14} TeV cm^{-2} s^{-1} at 7 TeV
- Also sees Monogem at high significance and spatial extension.
- Spatial extension for both systems is ~2°.

HESS OBSERVATIONS OF PULSAR WIND NEBULAE

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_{PWN} (pc)	$L_{1-10\,TeV}$ (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	$0.83 \pm 0.11^{*}$
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

- **HESS finds a large population of "TeV PWN"**
- **HESS systems have a higher spin down power, but are more distant.**

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 finds a large population of "TeV PWN"
- HESS systems have a higher spin down power, but are more distant.

A GLOBAL FOCUS

- **Assumption: Geminga is a typical 100-400 kyr pulsar.**

- This statement is well supported:
  - Two Nearest Systems Observed: Geminga, Monogem
  - Many similar HESS Sources
  - Geminga lies roughly at the average spin-down power for an observed young pulsar.

- We will call these sources, ``TeV halos" - for reasons which will become clear later.

THE FIRST-ORDER MODEL OF TEV HALOS

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

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

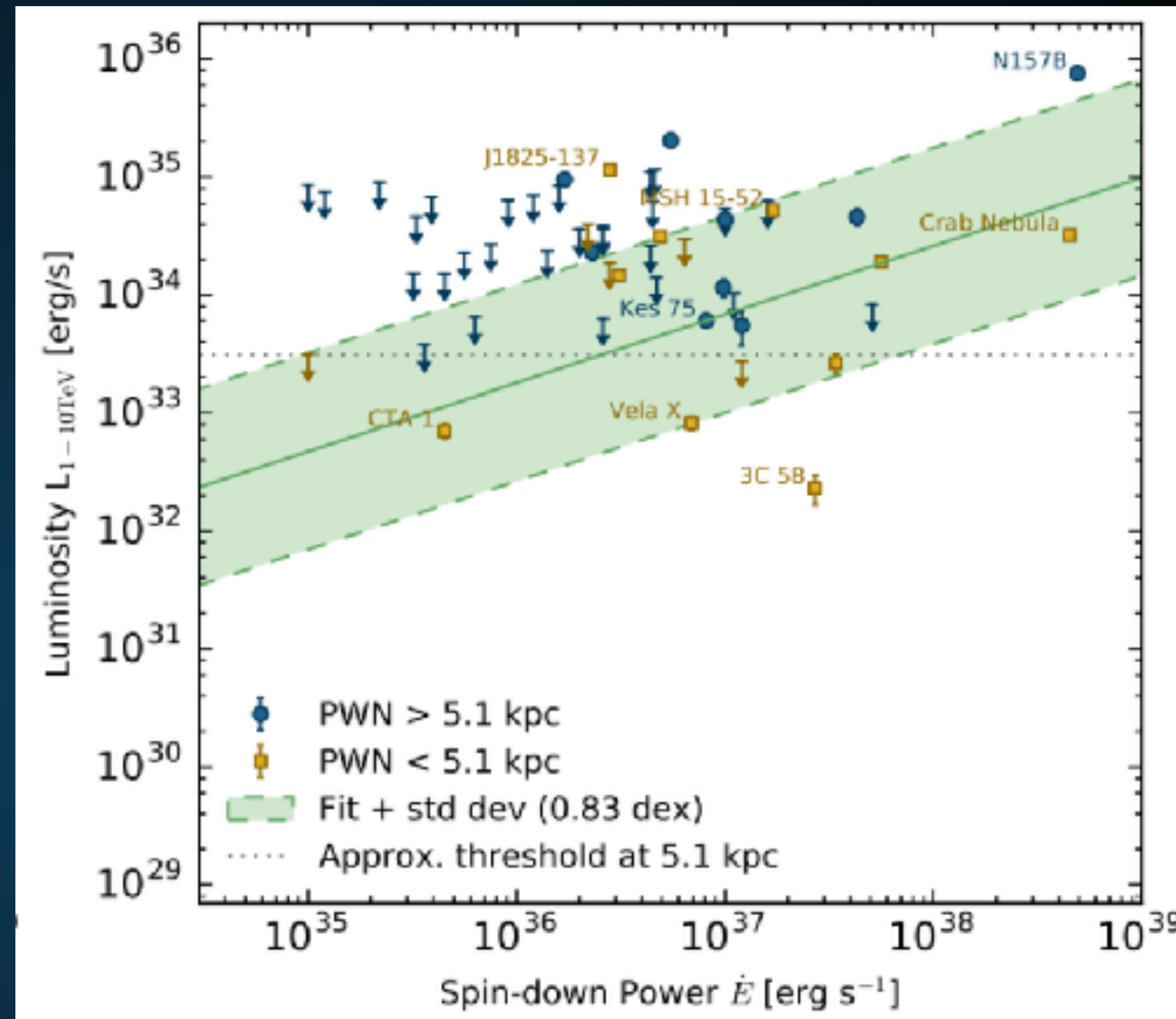
- **Assume that every pulsar converts an equivalent fraction of its spin-down power into the TeV halo flux.**
- **Can then calculate the TeV flux and extension of every TeV halo based on its spin-down power, and the observations of Geminga.**
- **Note: Using Monogem would increases fluxes by nearly a factor of 2.**

THE FIRST-ORDER MODEL OF TEV HALOS

- Alternatively can assume:

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

- This only affects the results at ~2 level.



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

Implication I:

Most TeV gamma-ray sources are TeV halos.

TEV HALOS ARE A GENERIC FEATURE OF 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

- **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
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

- **12 others with young pulsars (2.36 chance overlaps)**
- **Young pulsars may be contaminated by SNR.**

STEP I: TEV HALOS ARE A GENERIC FEATURE OF 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

- **There are 57 middle-aged pulsars in the HAWC field of view.**
- **Can produce a ranked list of the spin-down flux of these systems (spin-down luminosity divided by distance squared).**
- **If TeV halo luminosity is correlated to spin-down power, these should be among the brightest systems.**

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	—

- The five pulsars associated with TeV emission are among the seven brightest sources.
- Private communication with the HAWC collaboration reveals that the missing two sources are currently 2-3σ excesses!

HAWC SENSITIVITY AFTER 10 YEARS

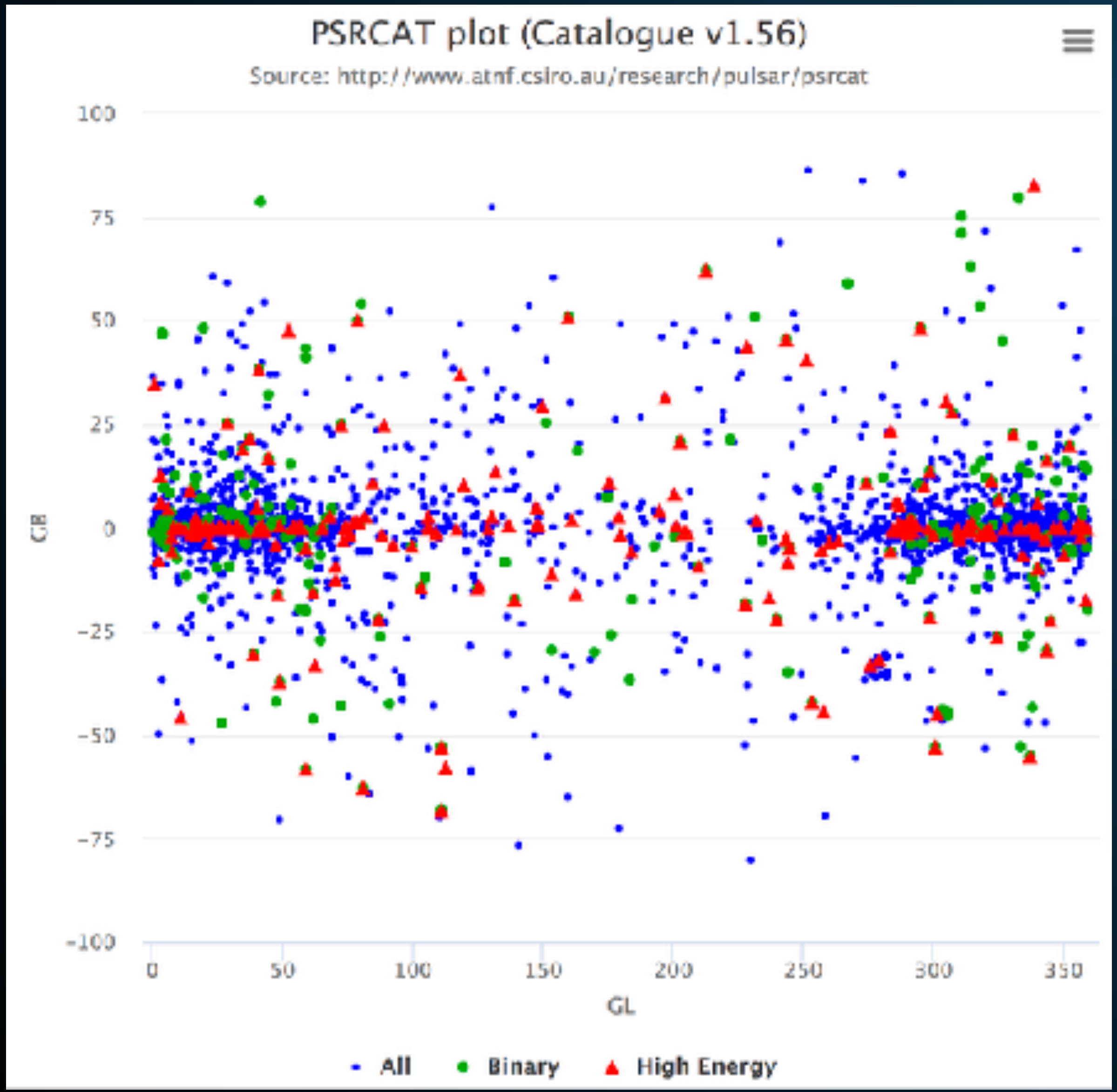
ATNF Name	Dec. (°)	Distance (kpc)	Age (kyr)	Spindown Lum. (erg s^{-1})	Spindown Flux (erg s^{-1} kpc^{-2})	2HWC
J0633+1746	17.77	0.25	342	3.2e34	4.1e34	2HWC J0631+169
B0656+14	14.23	0.29	111	3.8e34	3.6e34	2HWC J0700+143
B1951+32	32.87	3.00	107	3.7e36	3.3e34	—
J1740+1000	10.00	1.23	114	2.3e35	1.2e34	—
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	—

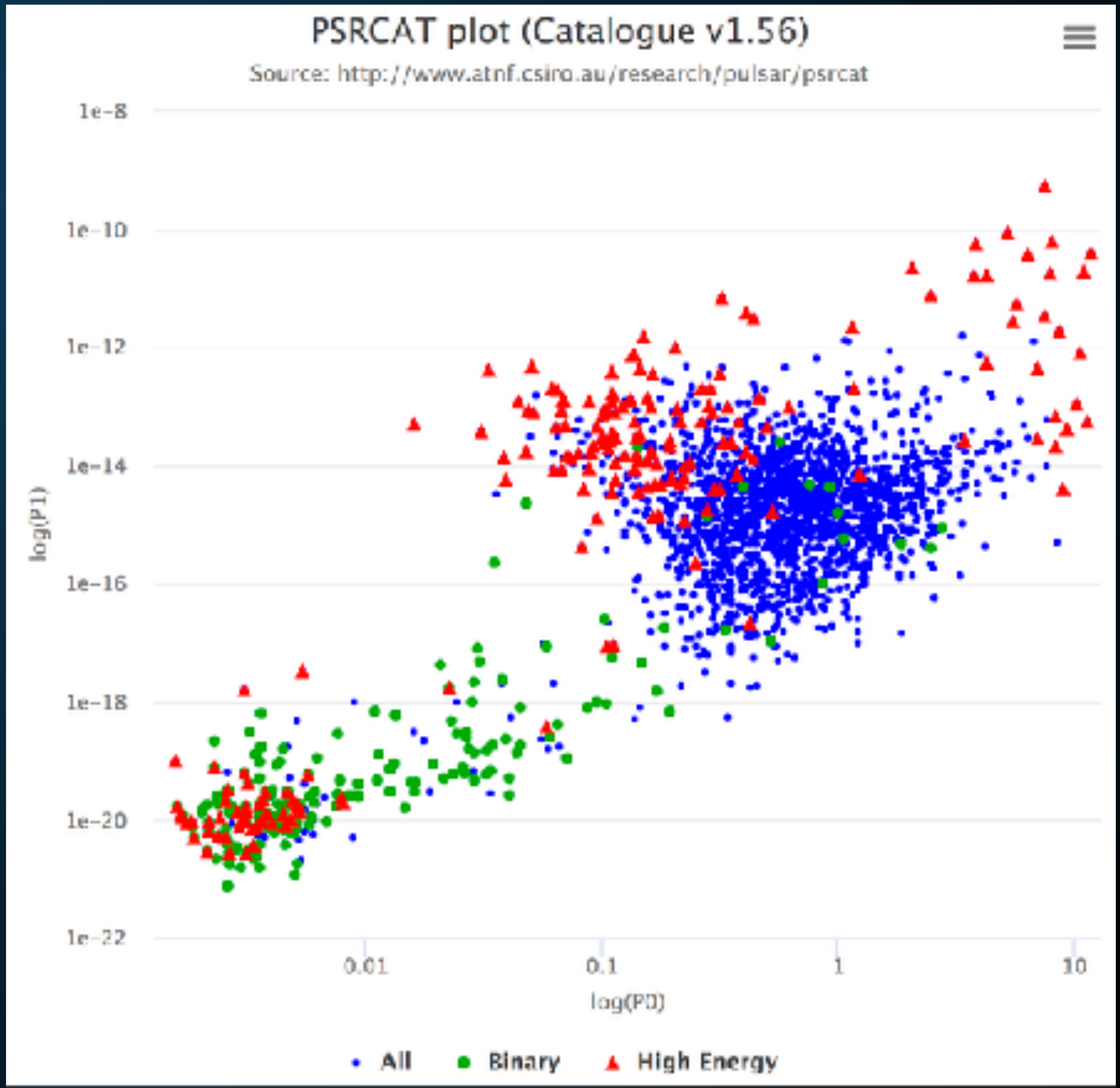
- HAWC will eventually reach a flux sensitivity of 0.02 Geminga
- Will observe
  - TeV halos from a dozen middle-aged ATNF pulsars.
  - TeV halos from ~40 additional young pulsars.

A PLETHORA OF (RADIO) PULSARS

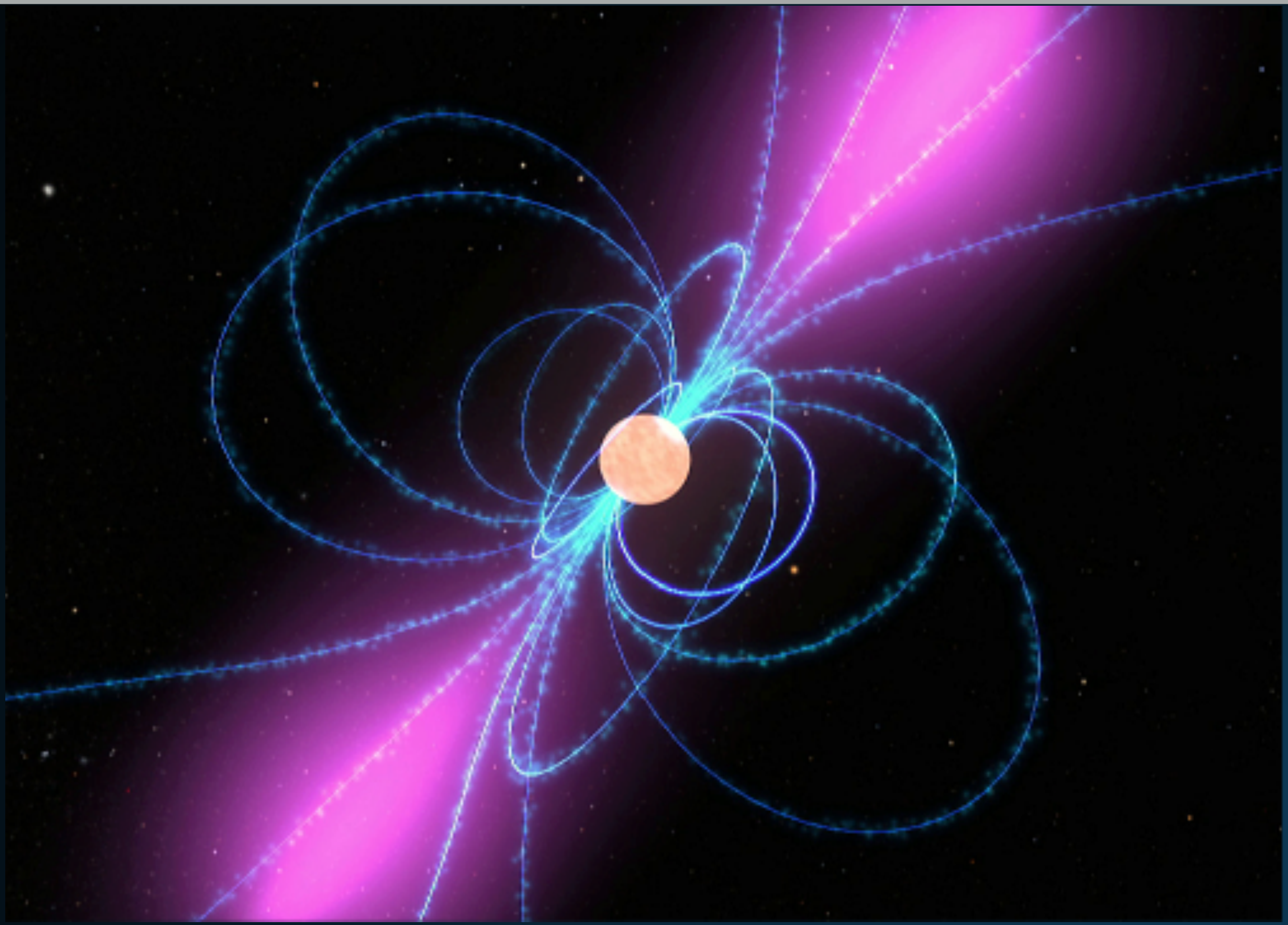
- **Pulsations detected from 2613 systems.**

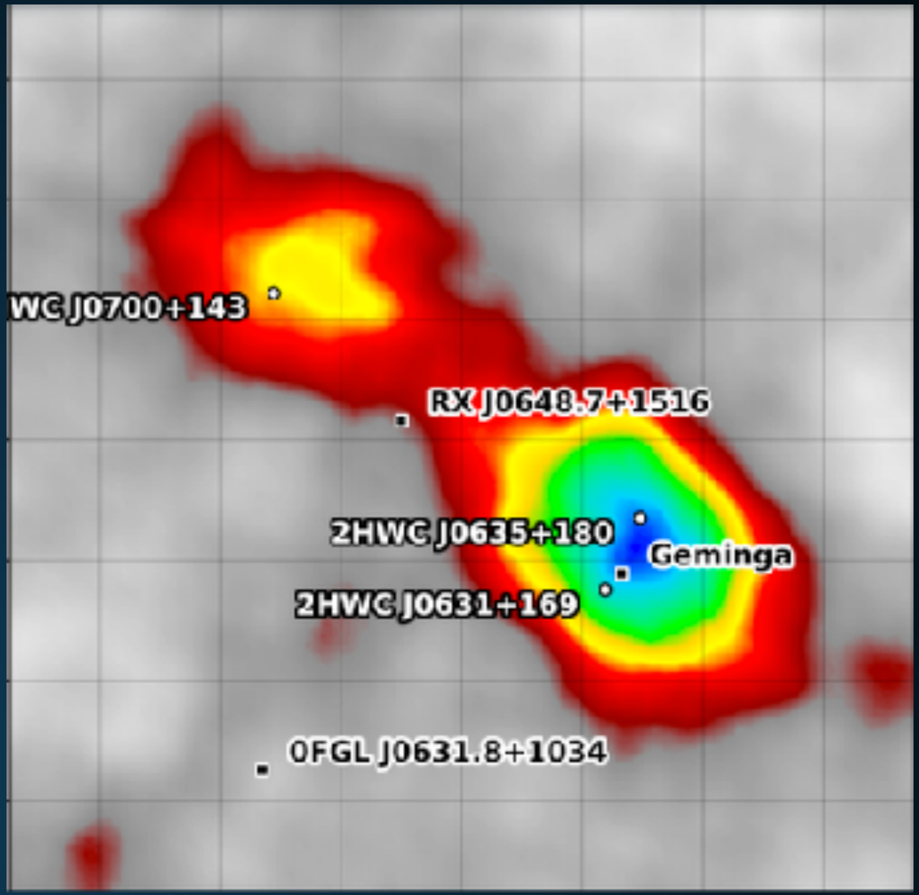
- **Vast majority in radio.**





USING TEV HALOS TO DISCOVER PULSARS





- Multi-wavelength emission from pulsar is beamed.
- 30 kyr propagation time of TeV halo implies the emission is isotropic.
- Can find off-beam pulsars by detecting the TeV halo.

- 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

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
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

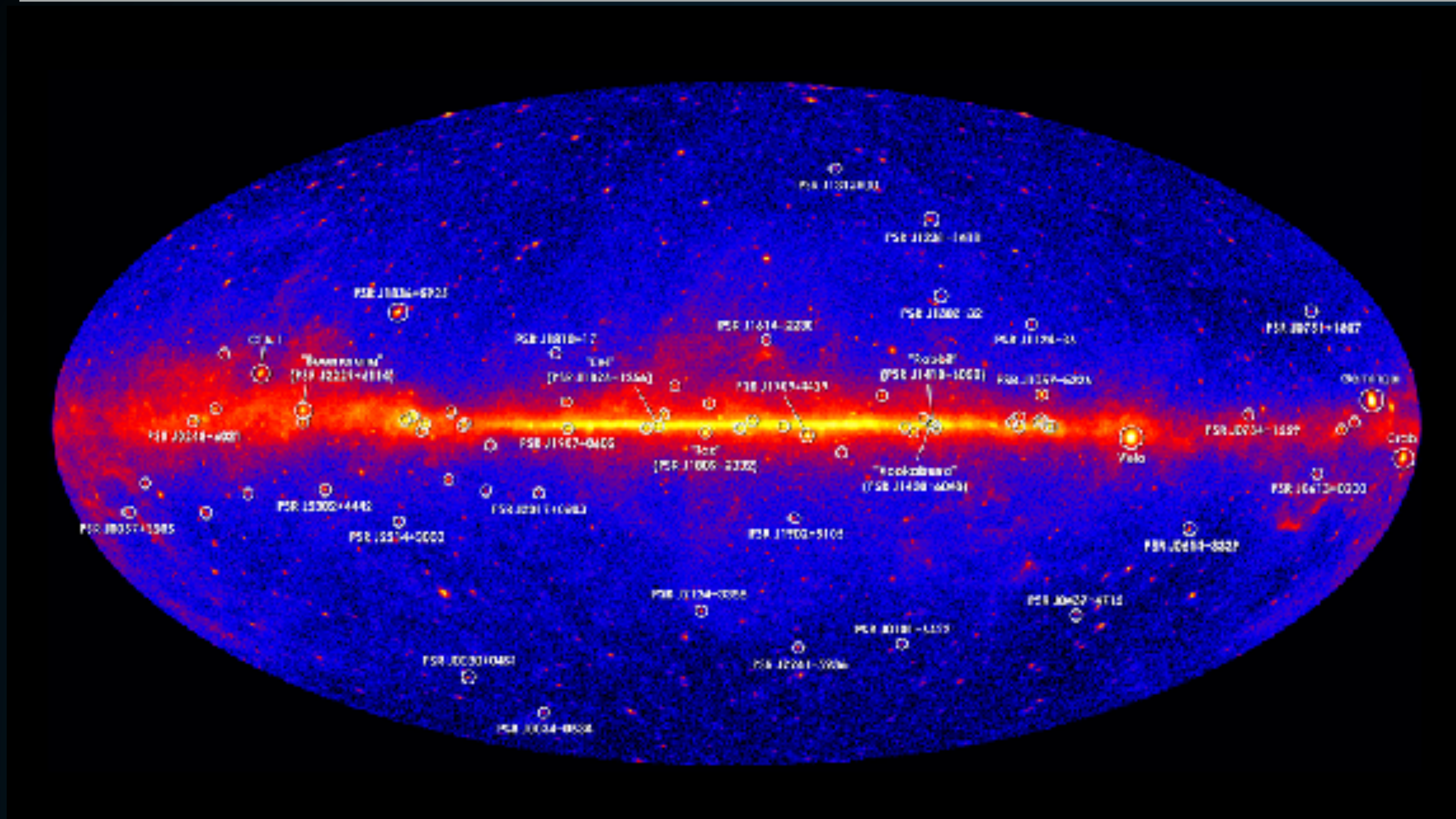
- **The beaming fractions predicts that 56^{+15}_{-11} TeV halos are currently observed by HAWC.**
- **However, only 39 total HAWC sources**
- **Chance overlaps, SNR contamination must be taken into account.**

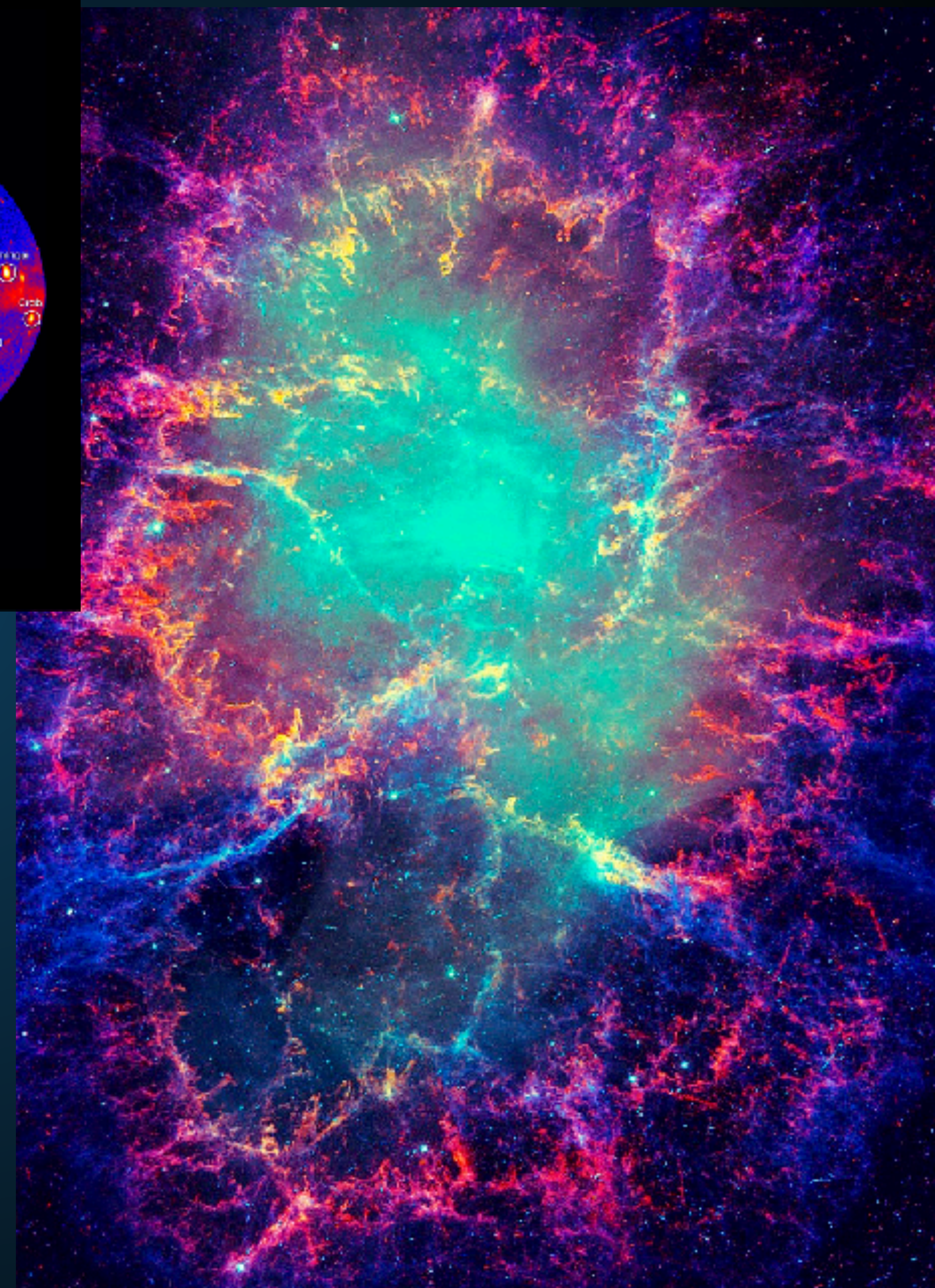
EVENTUAL TEV HALO DETECTIONS

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	—

- **10 year HAWC observations should detect 37^{+17}_{-13} TeV halos surrounding middle-aged pulsars.**
- **These numbers correspond to most of the TeV sources detectable by HAWC.**

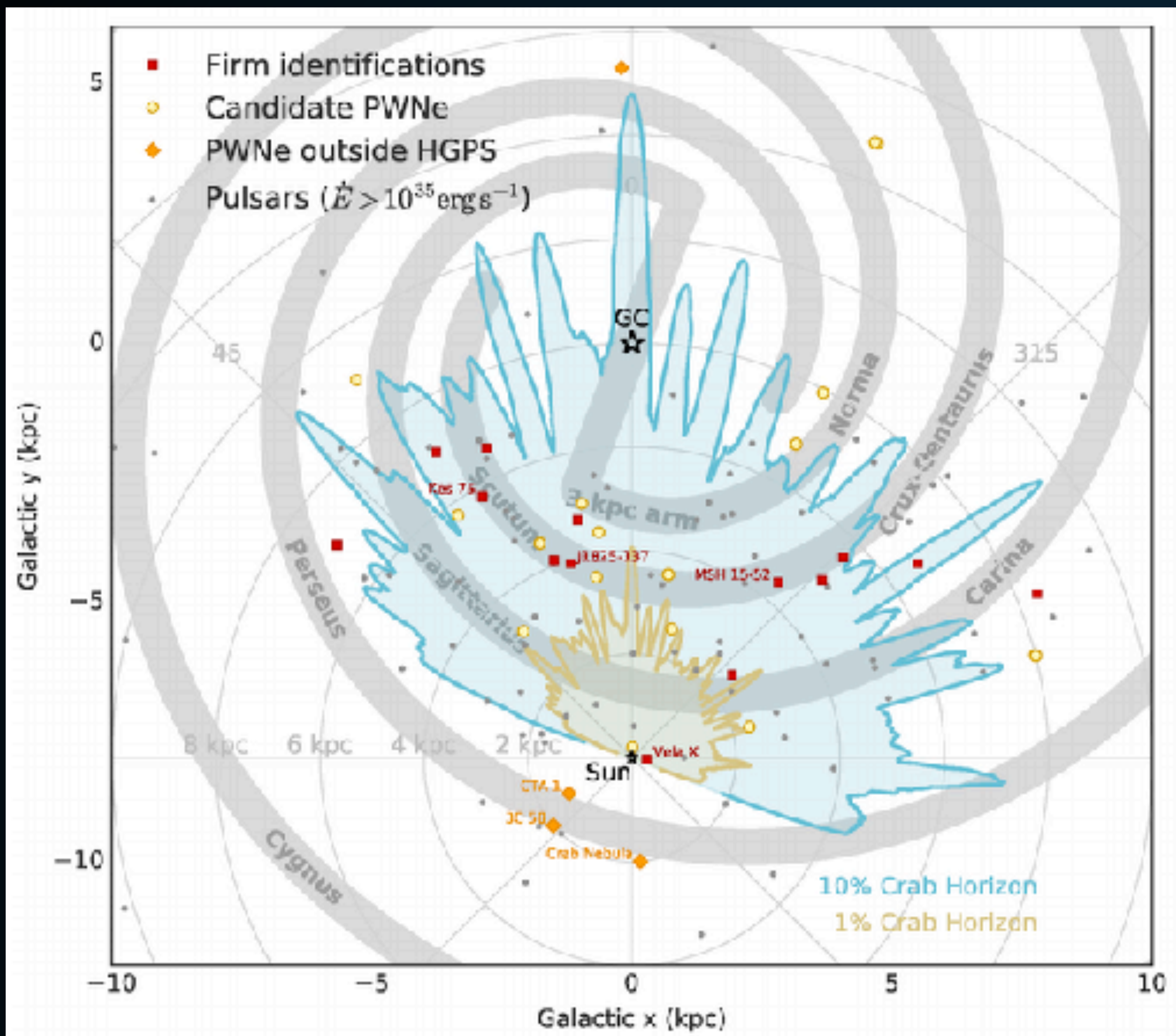
HOW MANY OF THESE SOURCES ARE NEW?

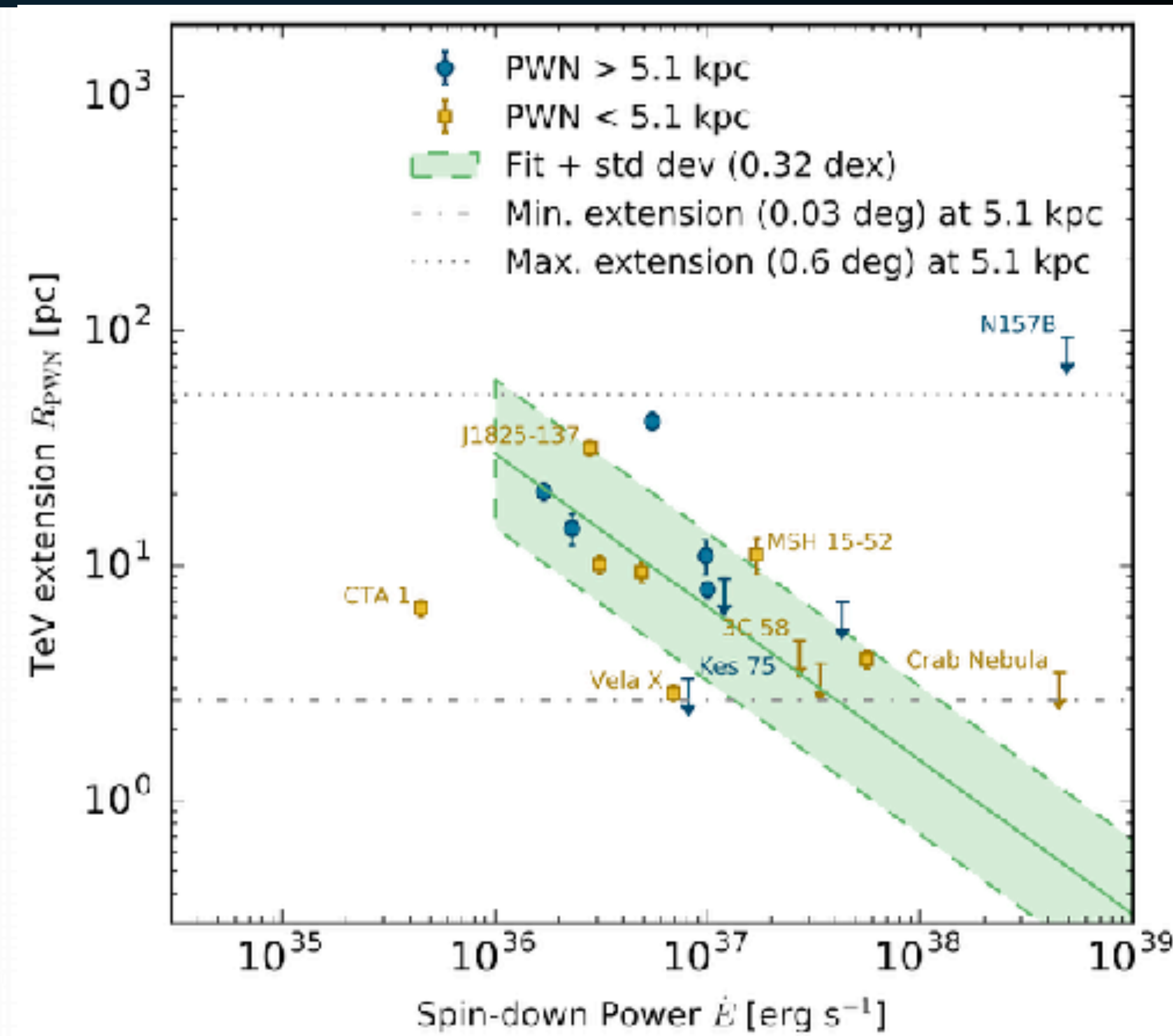




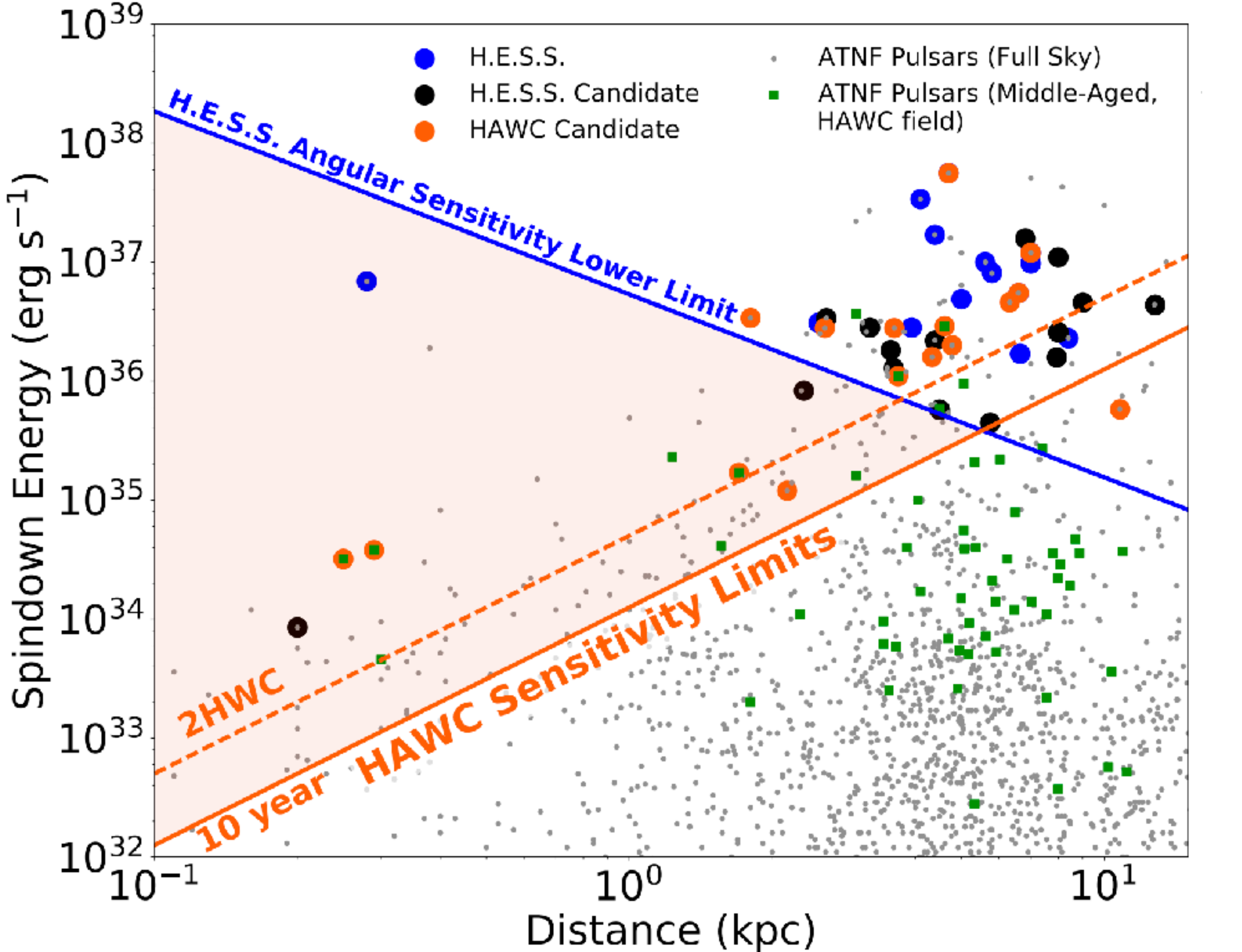
- Very few of these systems have been discovered as:
  - gamma-ray pulsars
  - X-Ray PWN
  - TeV halos by current ACTs

HESS/VERITAS DETECTIONS





- **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.**



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}

Implication II:

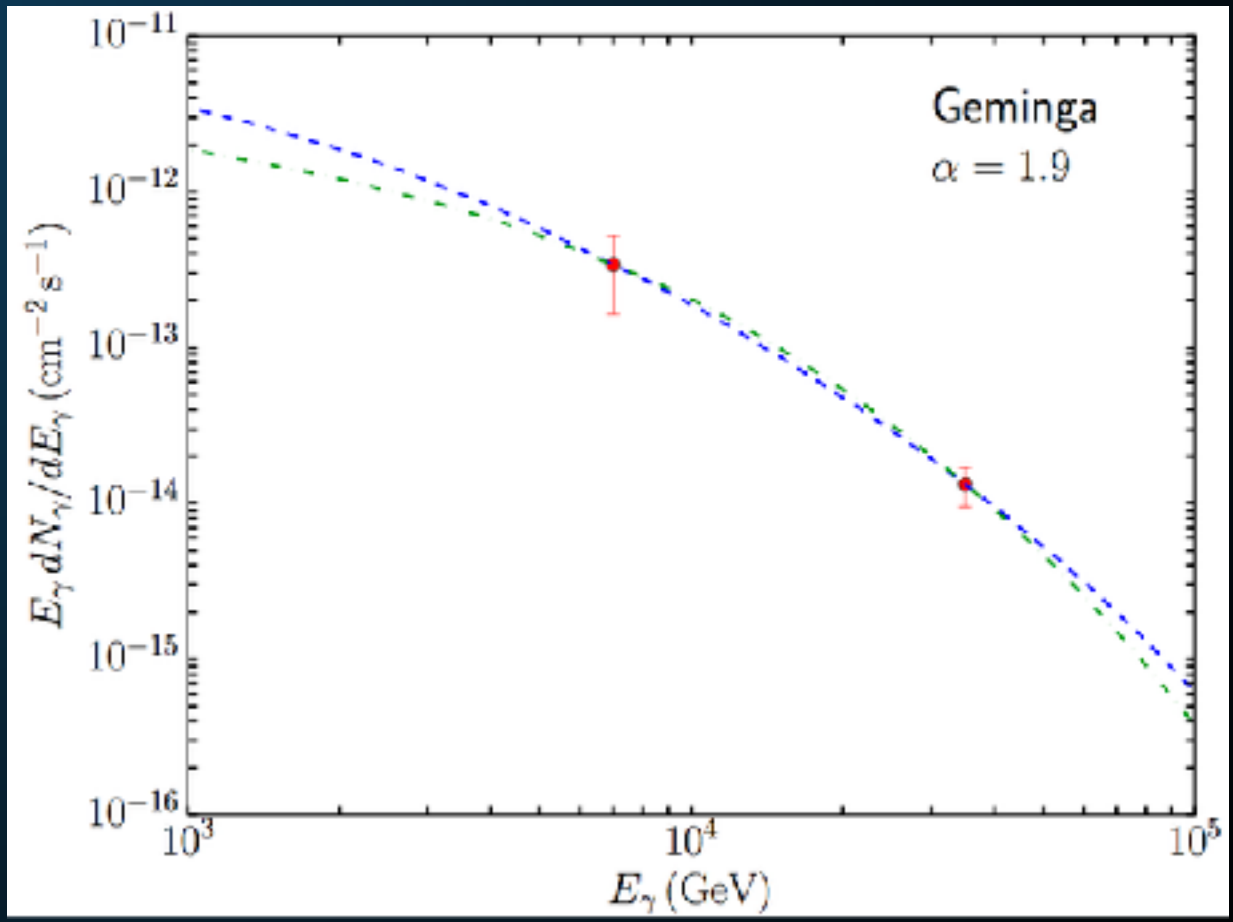
Most TeV gamma-rays are leptonic

THE SPECTRUM OF TEV HALOS

- **Geminga has a hard 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

- **This is somewhat challenging.**
  - **$dN/dE_\gamma = -\alpha/2 - 1$**
- **Klein-Nishina suppression further softens the spectrum (unavoidable).**
- **Exponential Cutoff - indicated by Milagro data.**



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"	2.0	-2.23 ± 0.08	48.7 ± 6.9	Geminga
2HWC J0635+180	-	-2.56 ± 0.16	6.5 ± 1.5	Geminga

- **Based on a joint fit to the HAWC and Milagro data, we assume:**
  - **$-1.9 < \alpha < -1.5$**
  - **$E_{cut} \cong 50$ TeV**

TOTAL HIGH-ENERGY EMISSION FROM SNR AND PULSAR

Hadronic Emission

$$E_{p,SN} = 10^{50}\ \text{erg}$$

$$\frac{dN_{p,SN}}{dE} = 4\times10^{51}\, E^{-2}\, e^{-E/1\,\text{PeV}}\ \text{GeV}^{-1}$$

$$\phi_{\gamma,\pi_0} \propto E^{-2.7} \rightarrow 4\times10^{51}\, E^{-2.7}\, e^{-E/1\,\text{PeV}}$$

Leptonic Emission

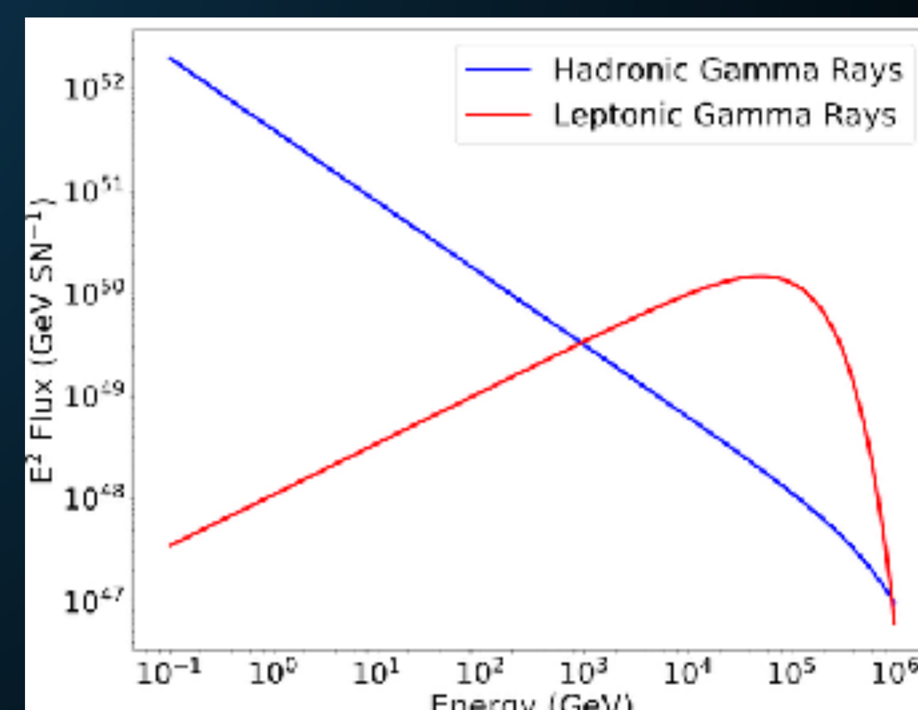
$$KE_{pulsar} = 10^{49}\ \text{erg}$$

$$e^+e^-_{pulsar} \simeq 10^{48}\ \text{erg}$$

$$\frac{dN_{e^+e^-,p}}{dE} = 1.1\times10^{48}\, E^{-1.5}\, e^{-E/100\,\text{TeV}}$$

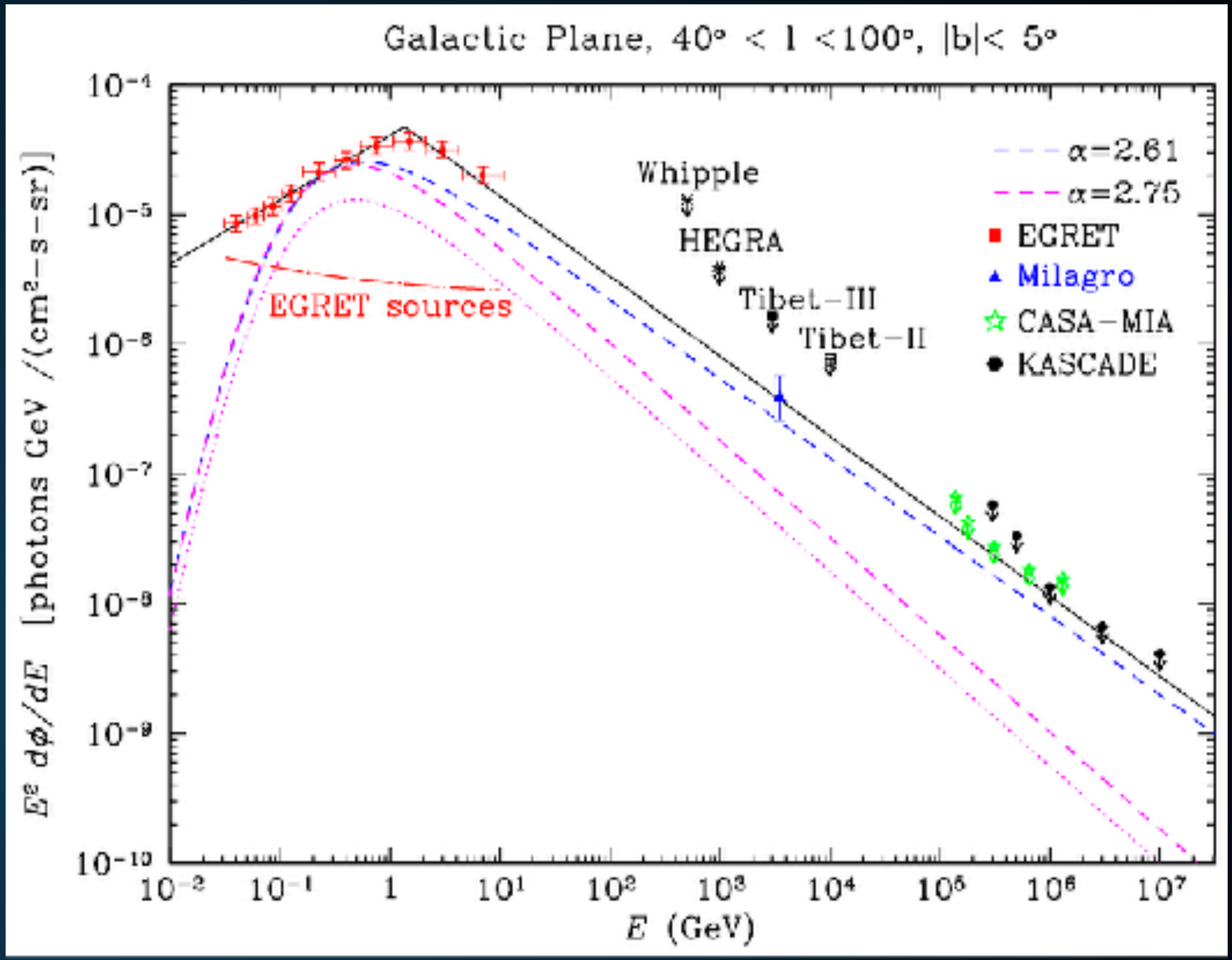
$$\phi_{\gamma,ICS} = 1.1\times10^{48}\, E^{-1.5}\, e^{-E/100\,\text{TeV}}$$

- Traditionally believe that hadronic cosmic-rays are dominant.
- Two effects at high energies:
  - Hard primary electron injection spectra
  - Milky Way is calorimetric to TeV leptons



astro-ph/0603618

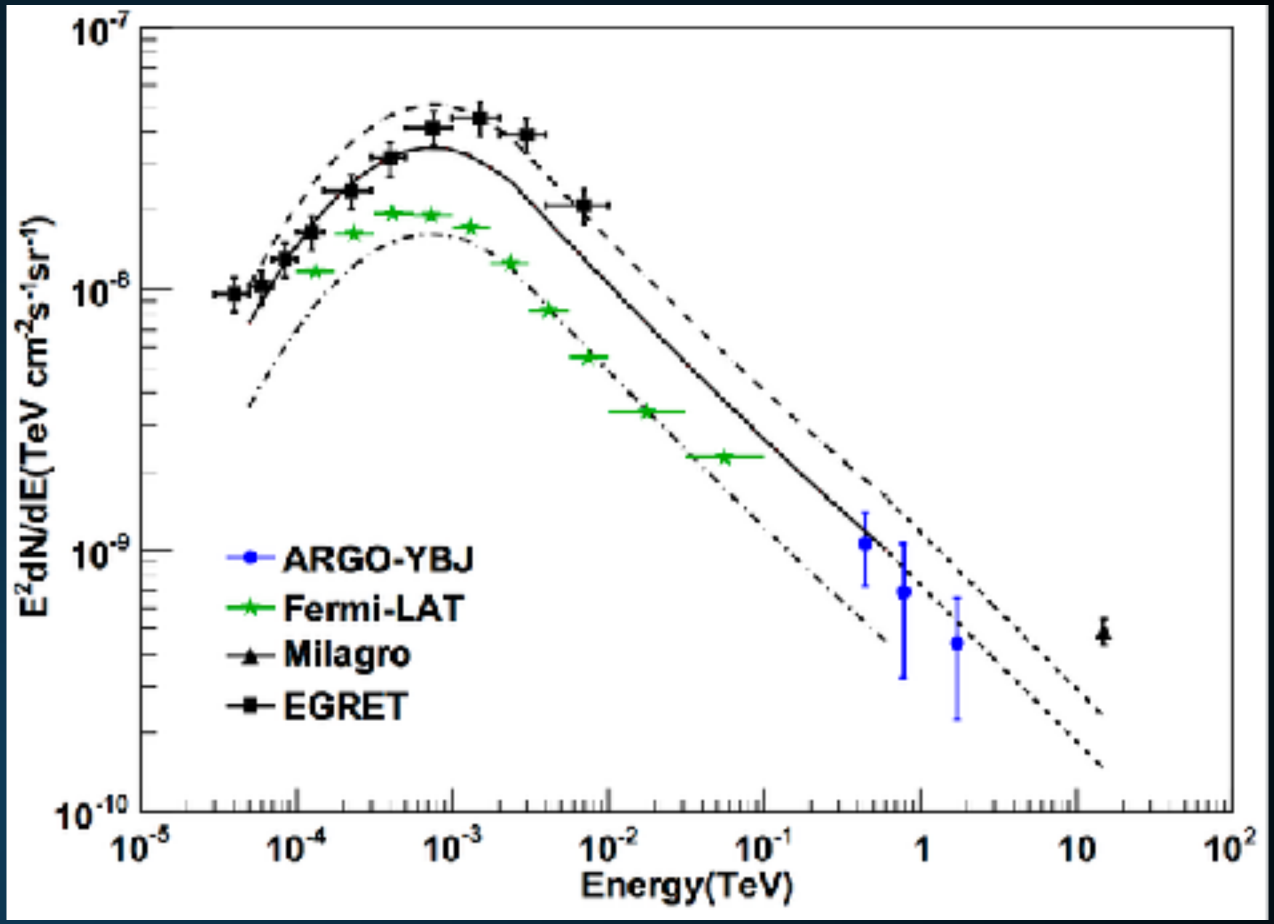
- Milagro detects bright diffuse TeV emission along the Galactic plane.



- 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).

- Recent ARGO-YBJ observations are in tension with Milagro result.



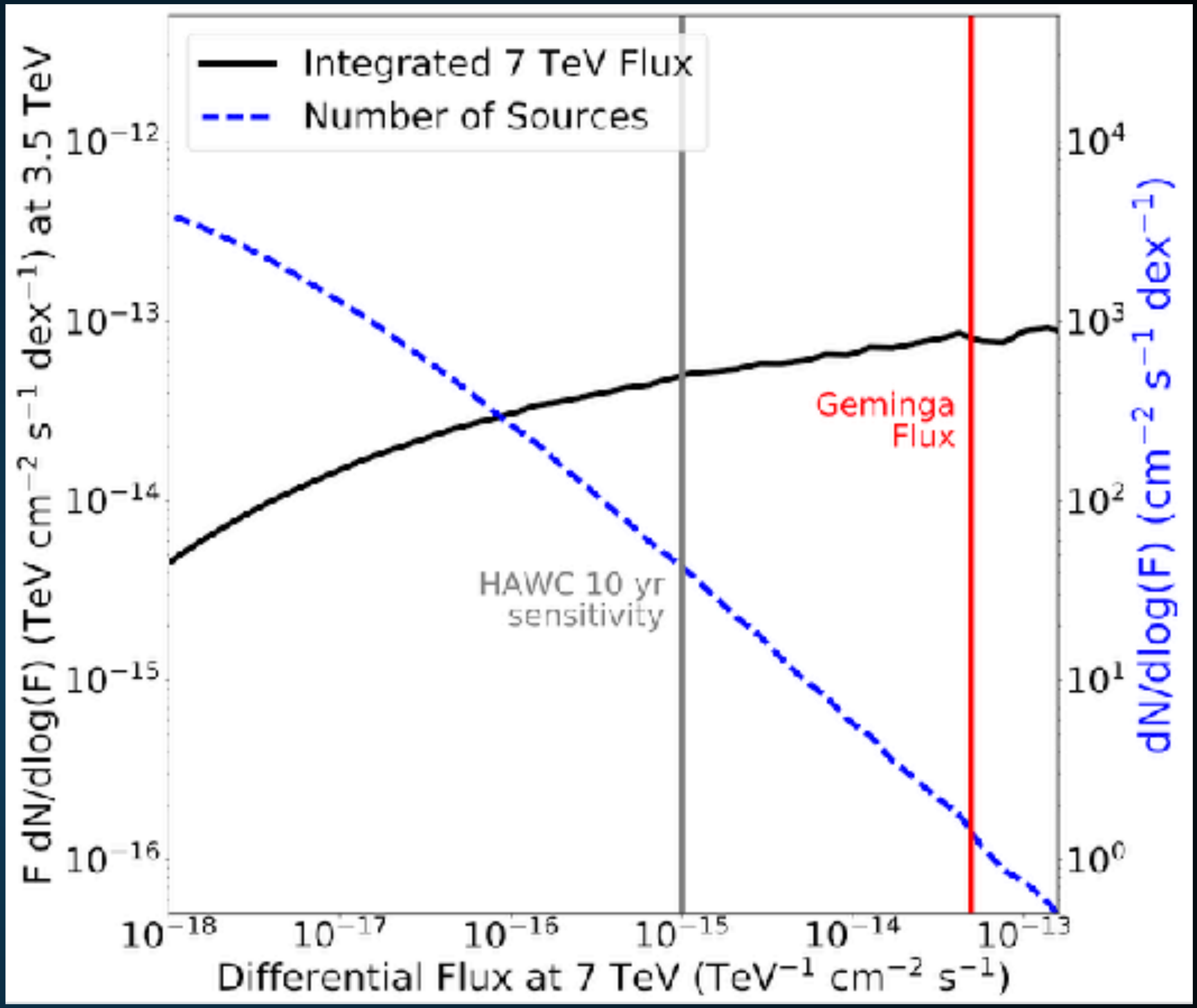
- Tension can be alleviated if the gamma-ray spectrum in the region is very hard.

- TeV halos can produce this emission!

ASSUMPTION: PULSAR POPULATION MODELS

Linden & Buckman (1707.01905)

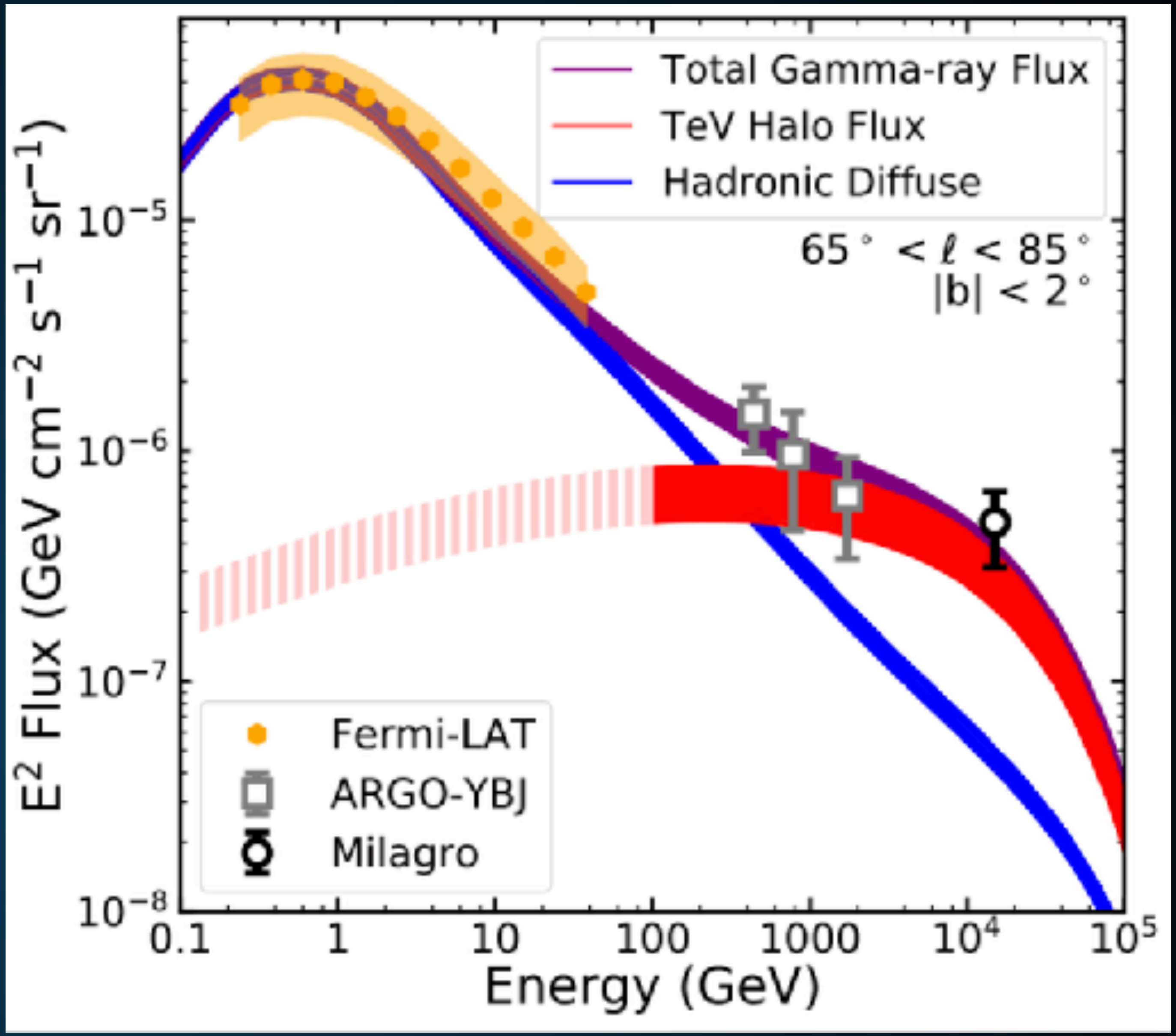
- Use a generic model for pulsar luminosities:
  - $B_0 = 10^{12.5}$ G ($10^{0.3}$ G)
  - $P_0 = 0.3$ s (0.15 s)
- Spindown Timescale of ~10^4 yr (depends on B_0)
- **Galprop model for supernova distances**



- <u>Naturally expect O(1) source as bright as Geminga</u>
- <u>HAWC eventually observes O(50) sources.</u>

Linden & Buckman (1707.01905)

- Use Geminga as a template to calculate TeV halo intensity.
- Use Geminga spectrum with complete (diffuse) cooling.
- Hadronic background from Galprop models tuned to Fermi-LAT emission.



- <u>TeV halos naturally explain the intensity and spectrum of the TeV excess.</u>

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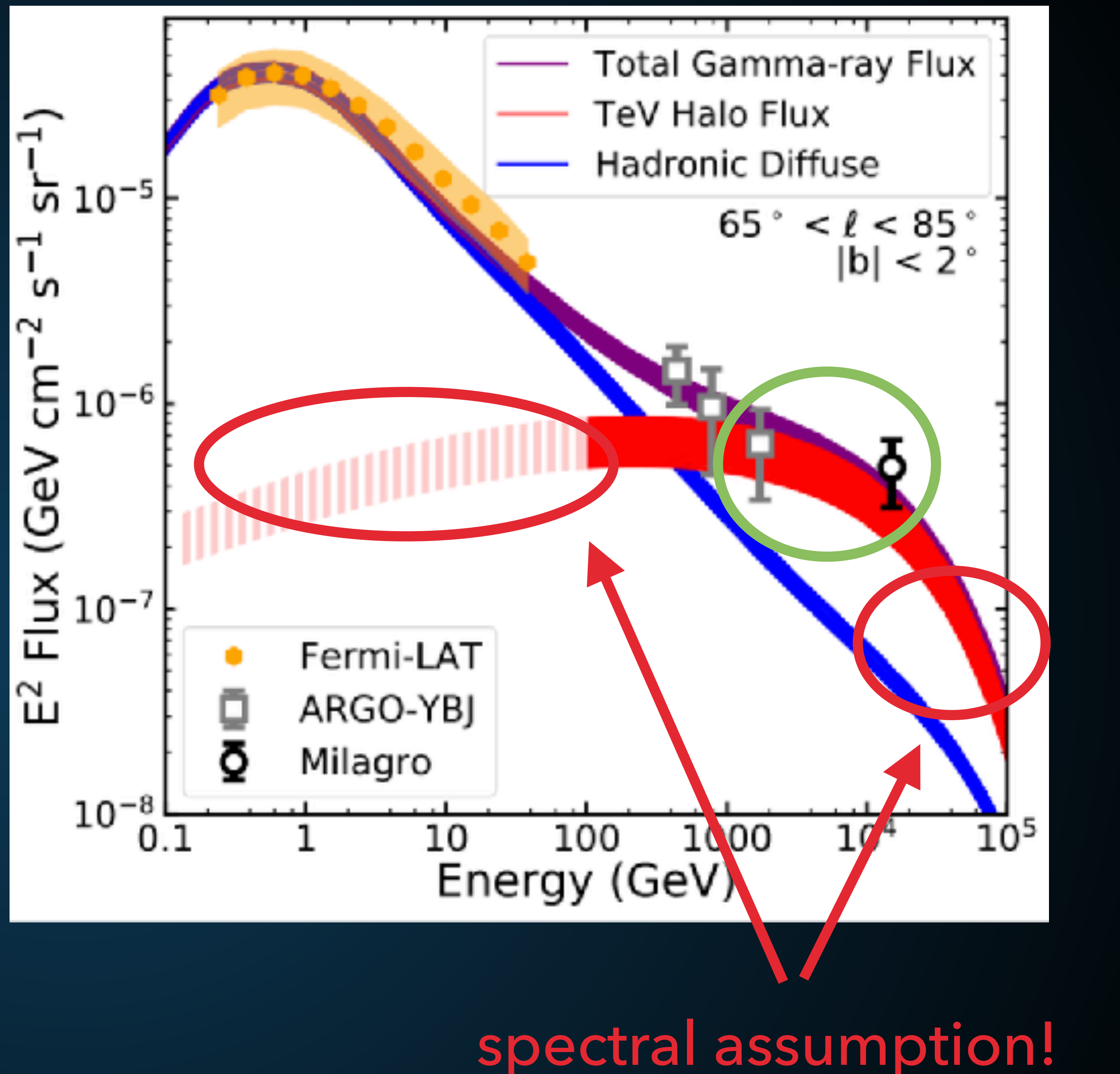
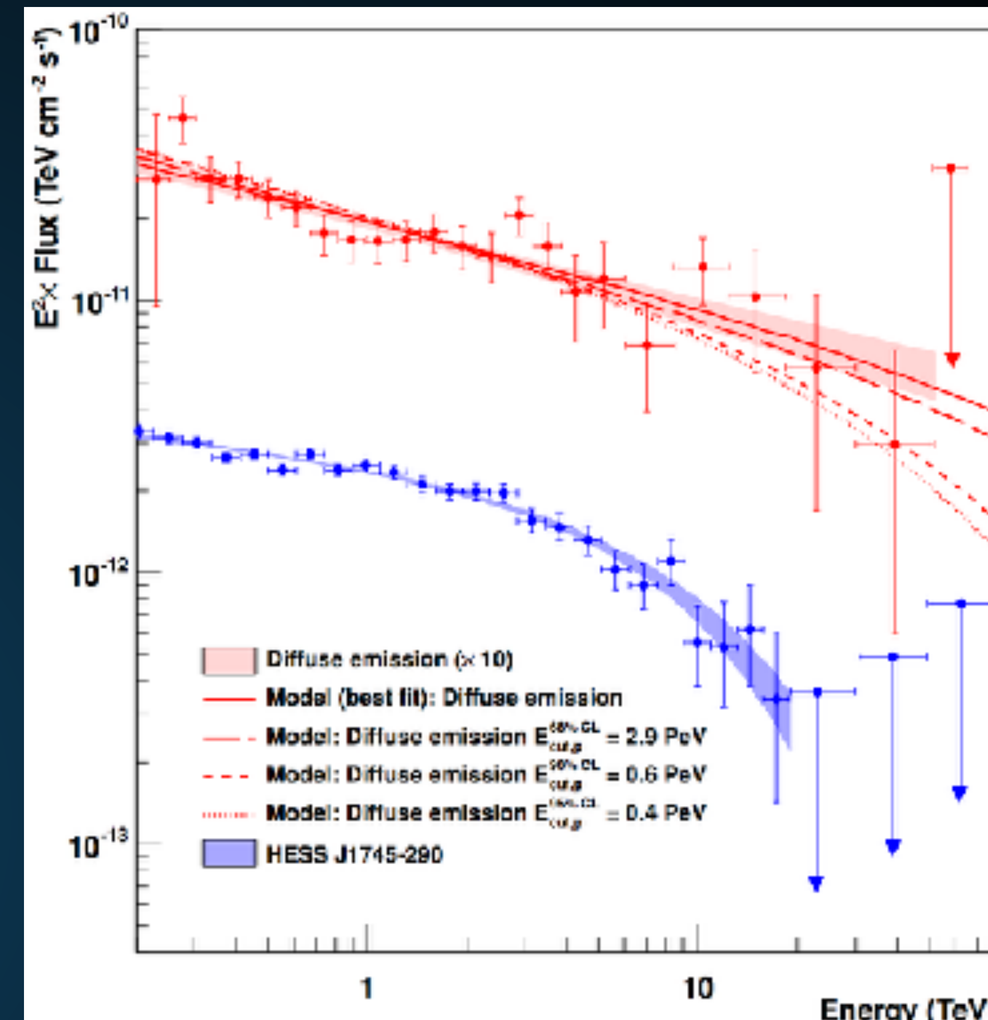


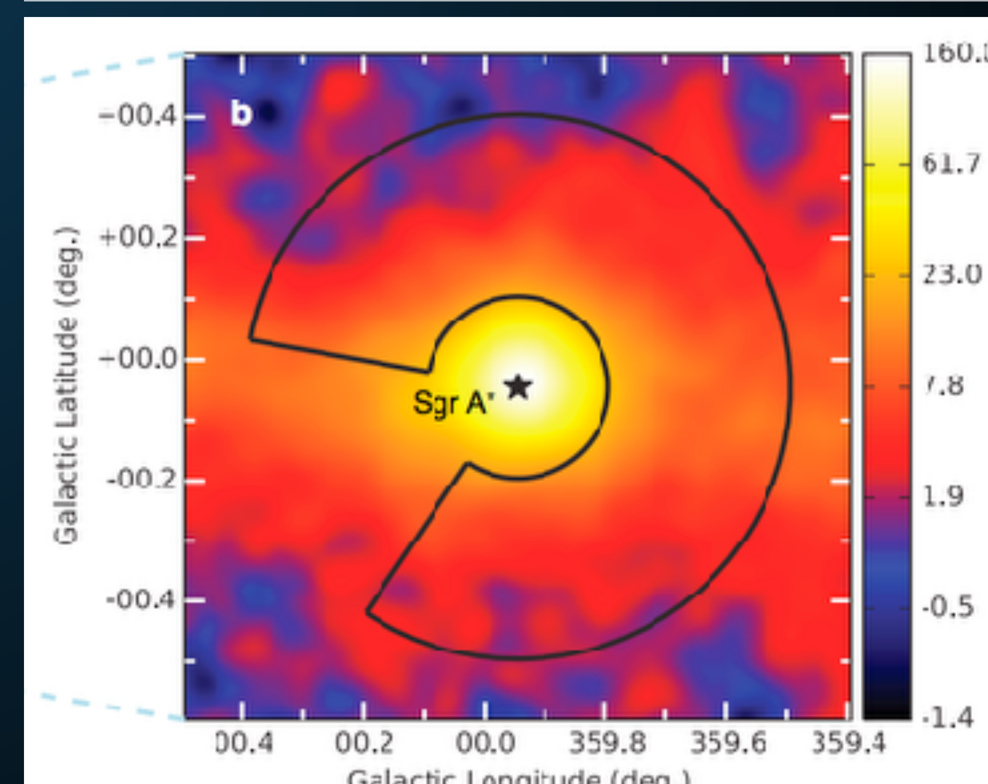
- **<u>TeV halos naturally explain the intensity and spectrum of the TeV excess.</u>**

IMPLICATION IIB: THE GALACTIC CENTER PEVATRON

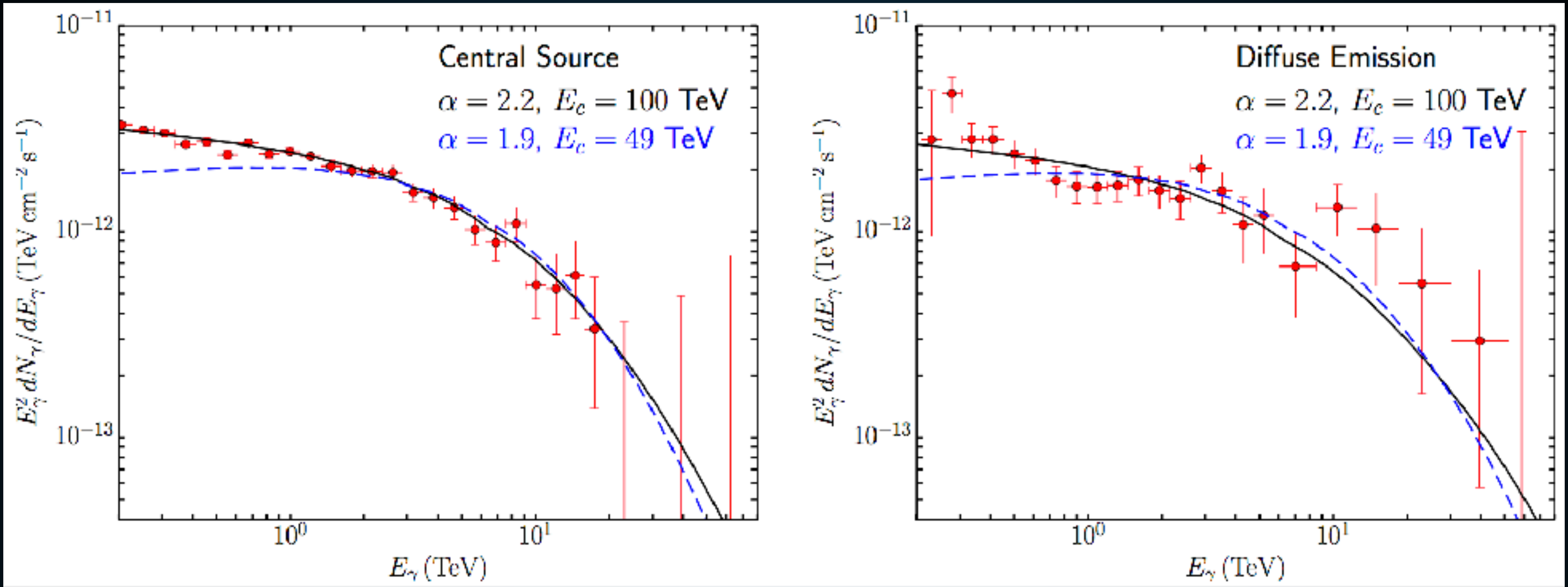
1603.07730

- HESS observations indicate 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.



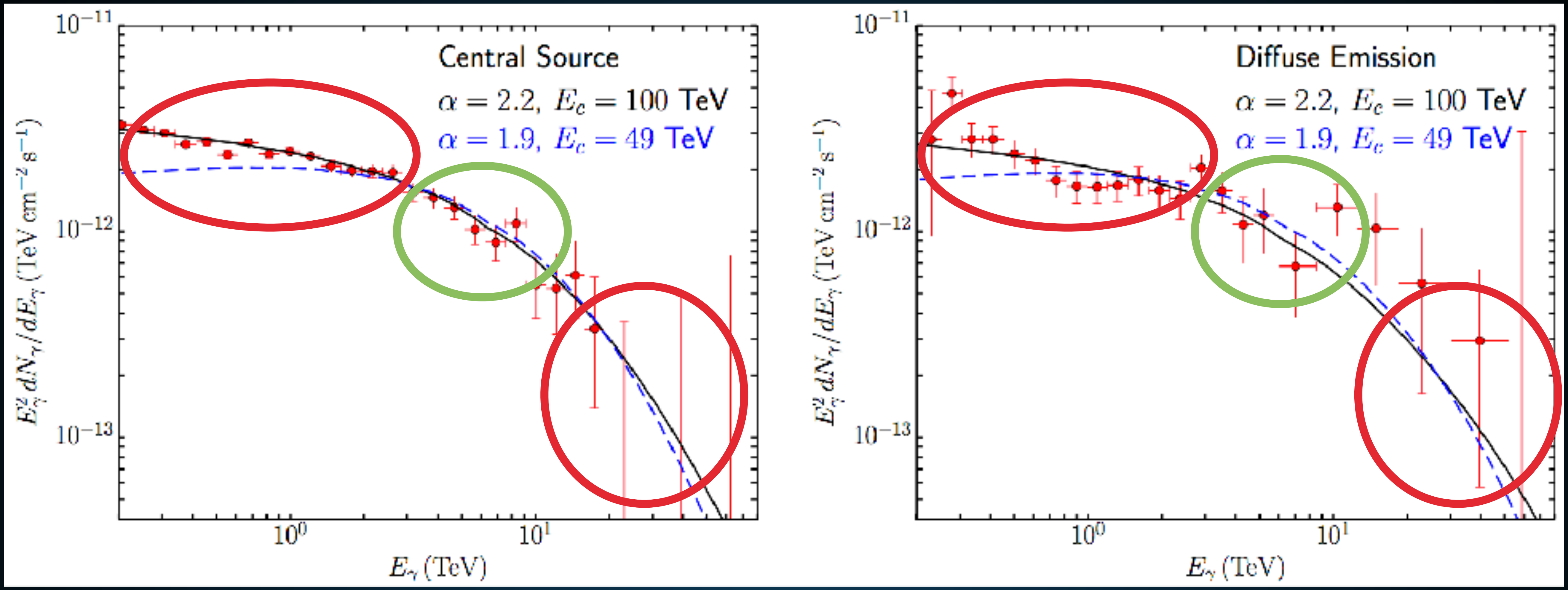


INTENSITY OF TEV HALO EMISSION IN GALACTIC CENTER



- **Assumptions: Standard values for the pulsar birthrate and kick velocity**
  - **TeV Halos survive 10 Myr (but become very dim)**
  - **Pulsar kicks ~ 400 km/s**
  - **Birth rate between 100-750 pulsars/Myr**
- **We reproduce the intensity and morphology of the HESS emission.**

INTENSITY OF TEV HALO EMISSION IN GALACTIC CENTER



- **Our model implies that TeV halos must form a substantial fraction of the HESS Pevatron emission.**
- **Implies 100-300 observable pulsars in the Galactic center, providing a handle on the missing pulsar problem (1310.7022, 1311.4846).**

Implication III:

The Positron Excess

i.e. What happens to the low-energy electrons and positrons?

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.**

$$U = \frac{1}{8\pi} B^2 = \frac{(10\,\mu G)^2}{8\pi}$$

$$= 4\times10^{-12}\ \frac{erg}{cm^3}$$

$$\int_0^{10pc} U\,dV = 5\times10^{47}\ erg$$

↳ Magnetic Flux $\simeq 5\times10^{38}\ \frac{ergs}{s}$

$$ISRF = 1\ \frac{eV}{cm^3}$$

$$\int ISRF\,dV = 8\times10^{47}\ erg$$

↳ Flux $= 8\times10^{38}\ \frac{ergs}{s}$

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

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

COSMIC-RAY DIFFUSION IN THE ISM

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

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

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

- **10 pc extent indicates D_0~ 7 x 10^{25} cm^2 s^{-1}**

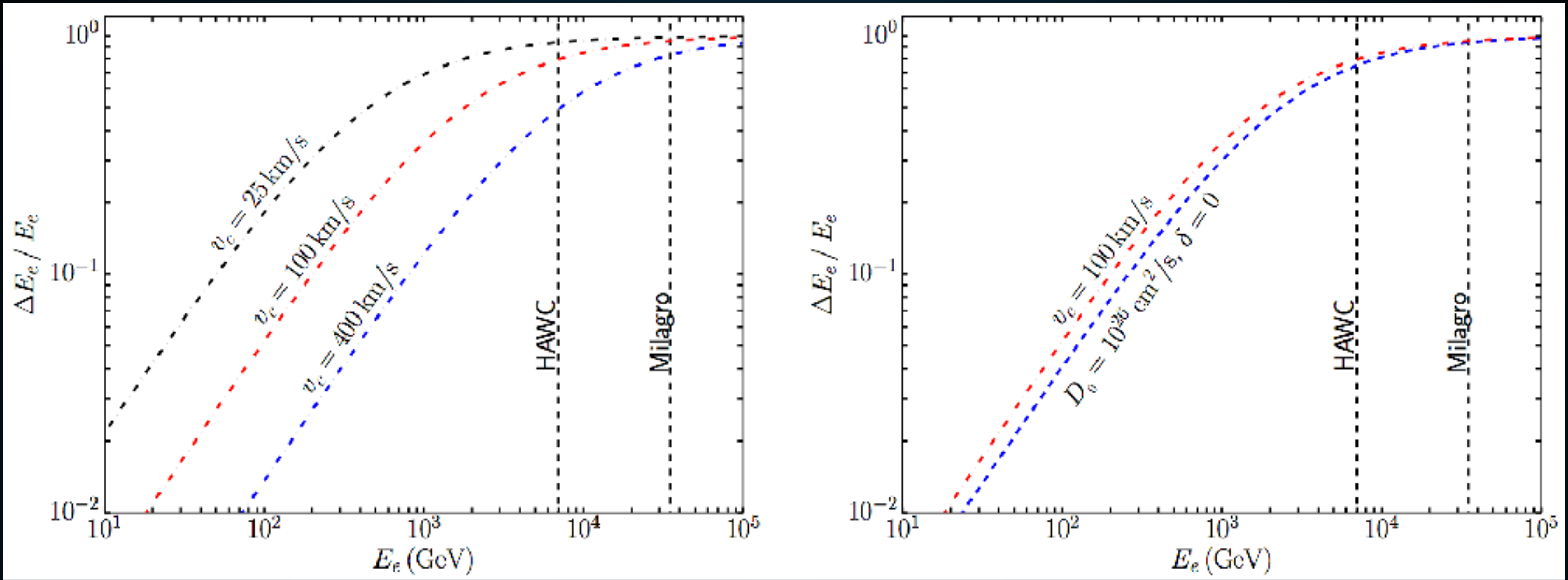
COSMIC-RAY DIFFUSION IS STANDARD

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

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

- In general, low-energy electrons travel farther before losing their energy.
- How much bigger can the region of inhibited diffusion be?
- Low-energy electrons should escape!

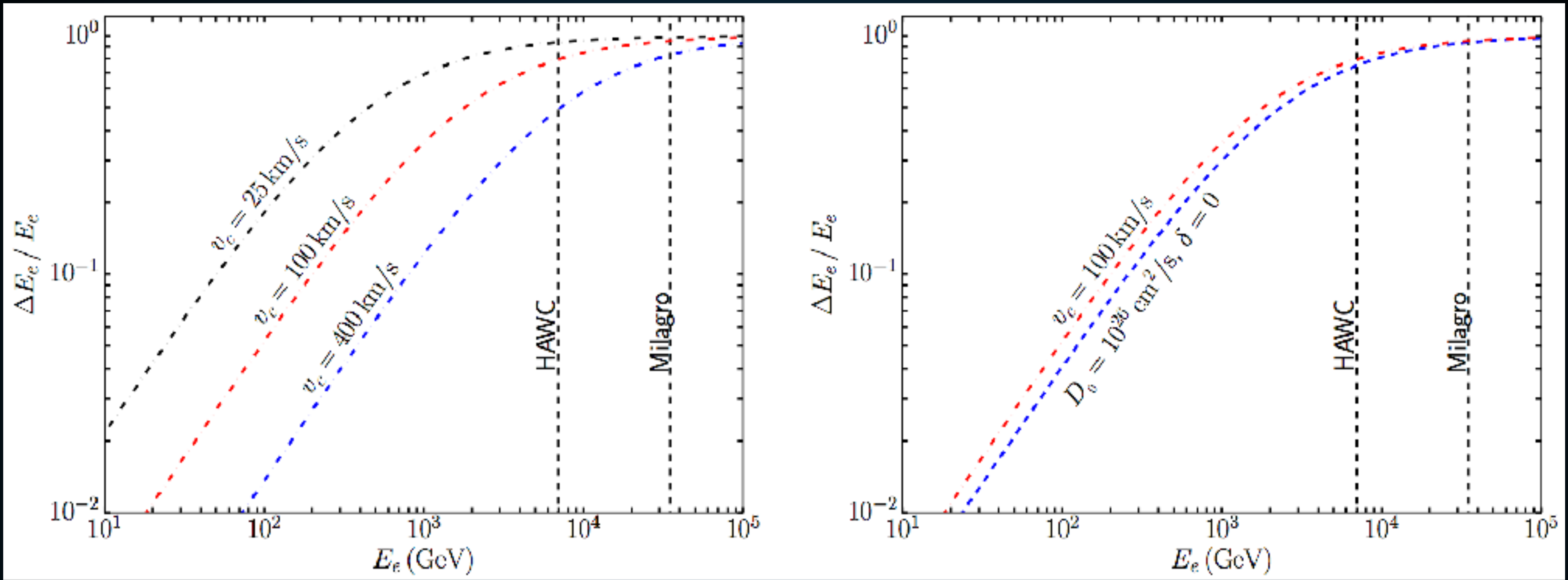
WHAT ABOUT THE LOW-ENERGY ELECTRONS?



- **Low-energy electrons lose energy slower, must escape.**

- **This is true in both convective and most diffusive (Kolmogorov, Kraichnian) scenarios.**

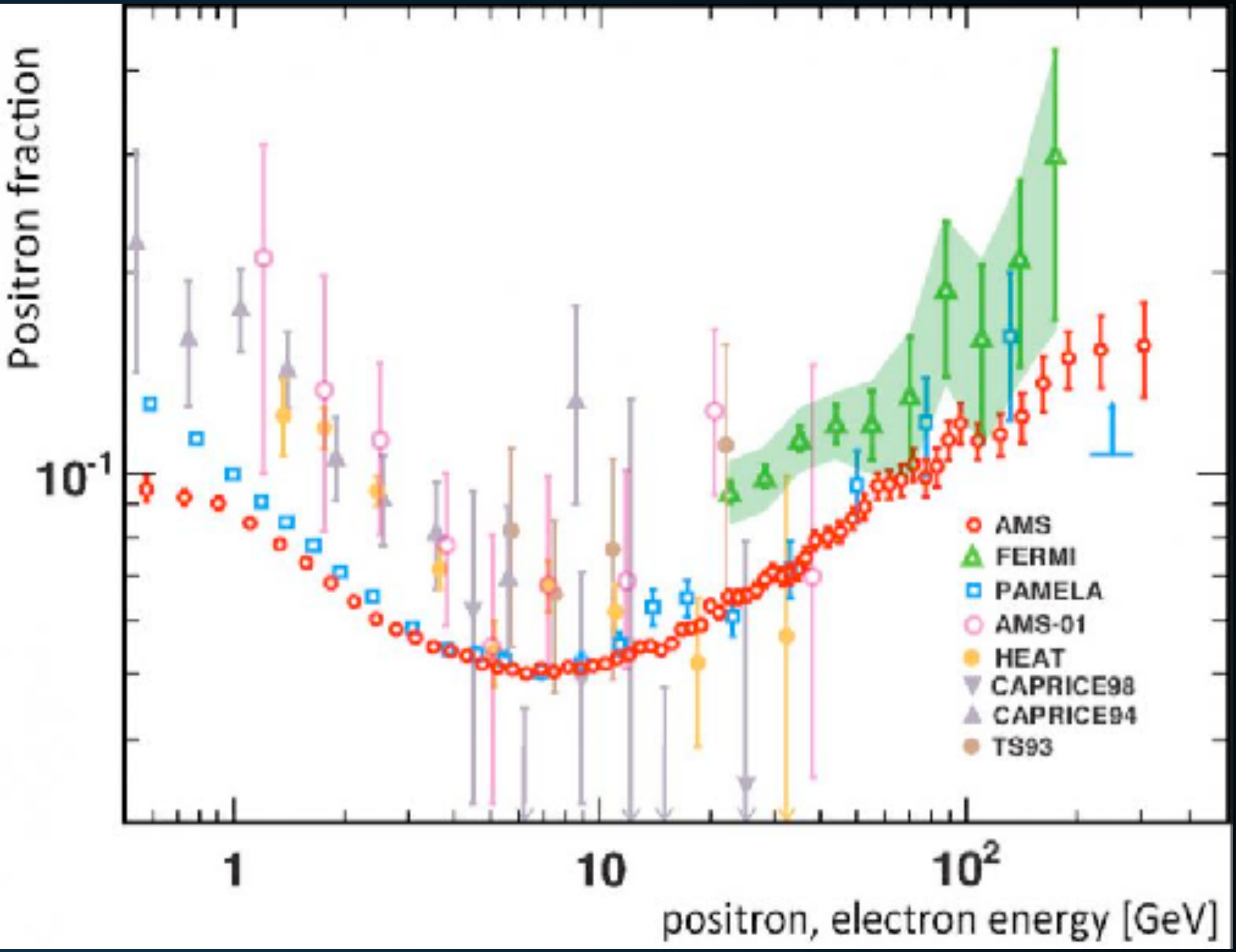
THE POSITRON EXCESS



- What do the low-energy e^+e^- do?
  - Large flux (10% of spin-down power)
  - Hard Spectrum
  - Most escape

THE POSITRON EXCESS

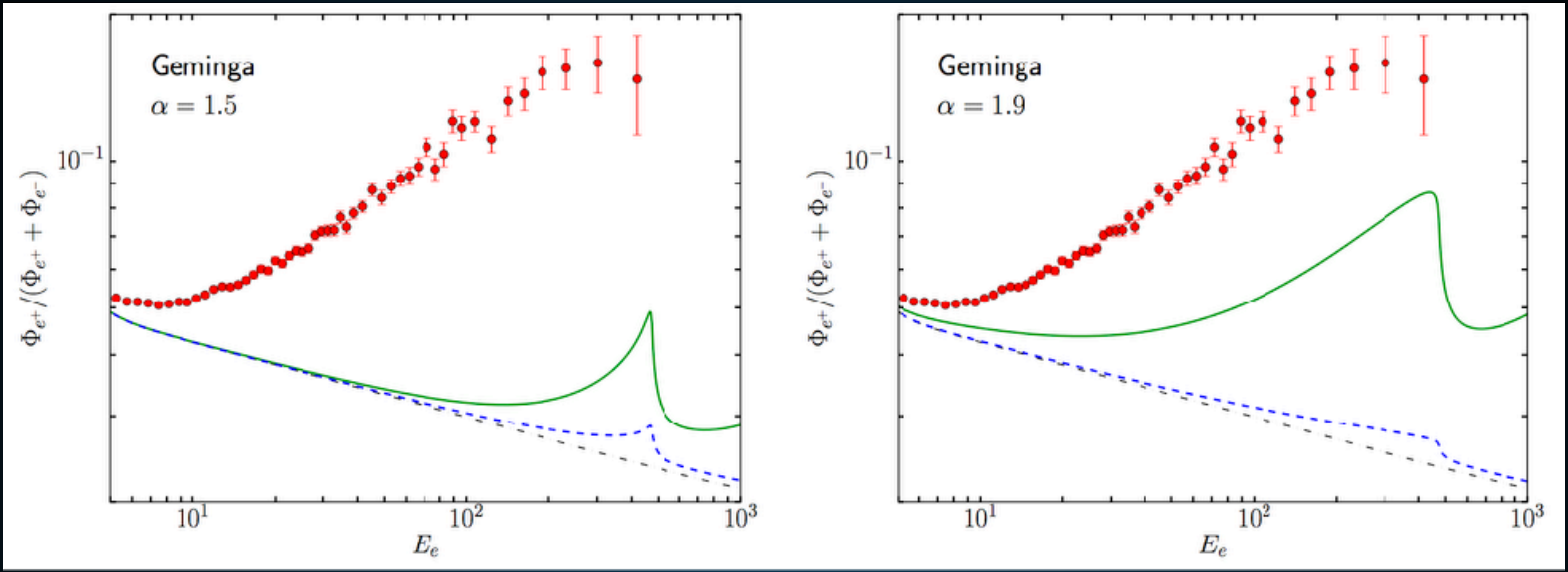
- Rising fraction of cosmic-ray positrons at energies above 10 GeV



- Standard Cosmic-Ray Secondary Production predicts the positron fraction falls as $\sim E^{-0.4}$.

- Indicates a new primary source of high energy e^+e^- pairs.

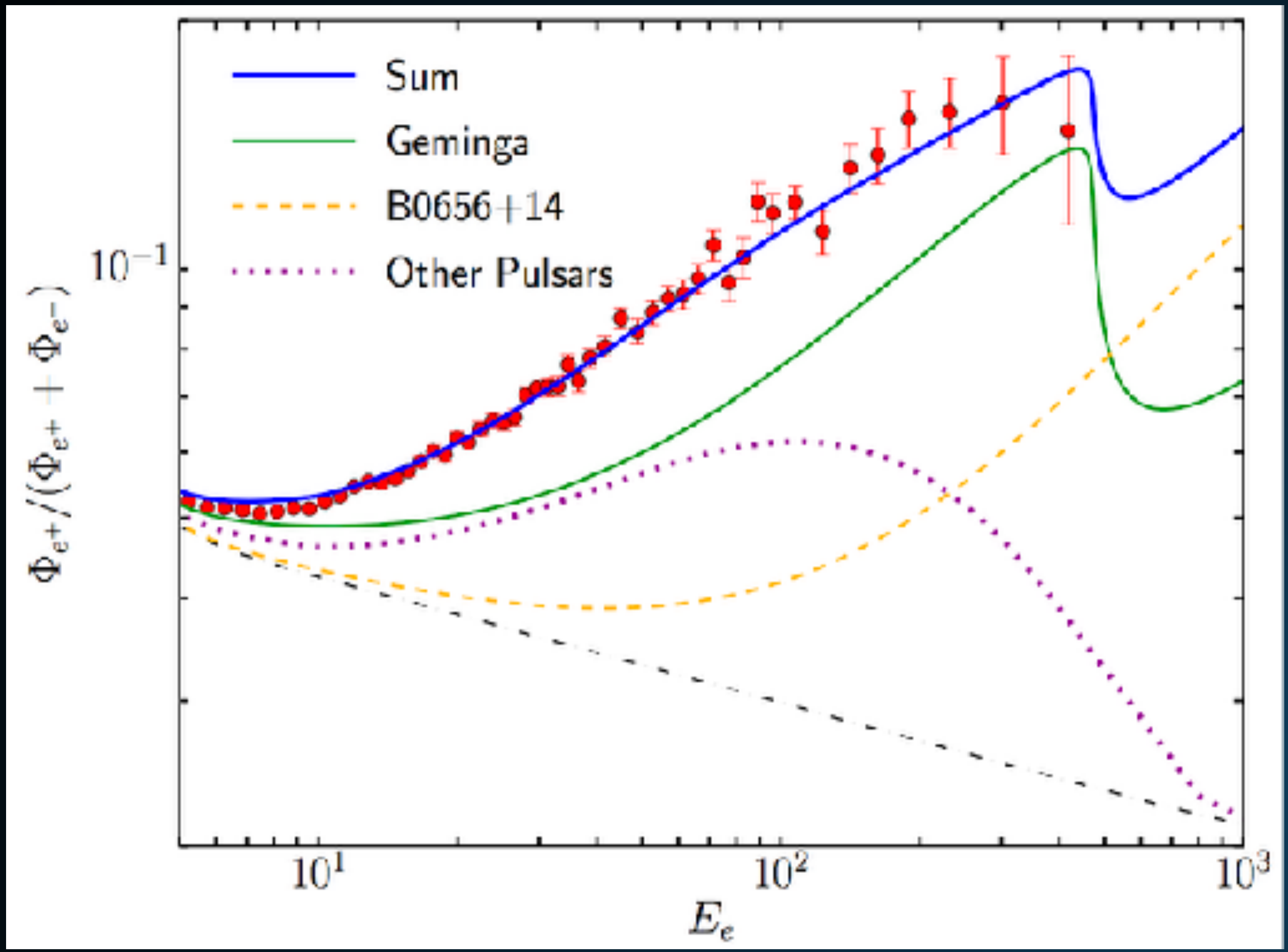
THE POSITRON FRACTION FROM TEV HALOS



- **Geminga can individually produce nearly half of the positron excess.**

- **Models not fit to the data - this contribution must exist.**

THE POSITRON FRACTION FROM TEV HALOS



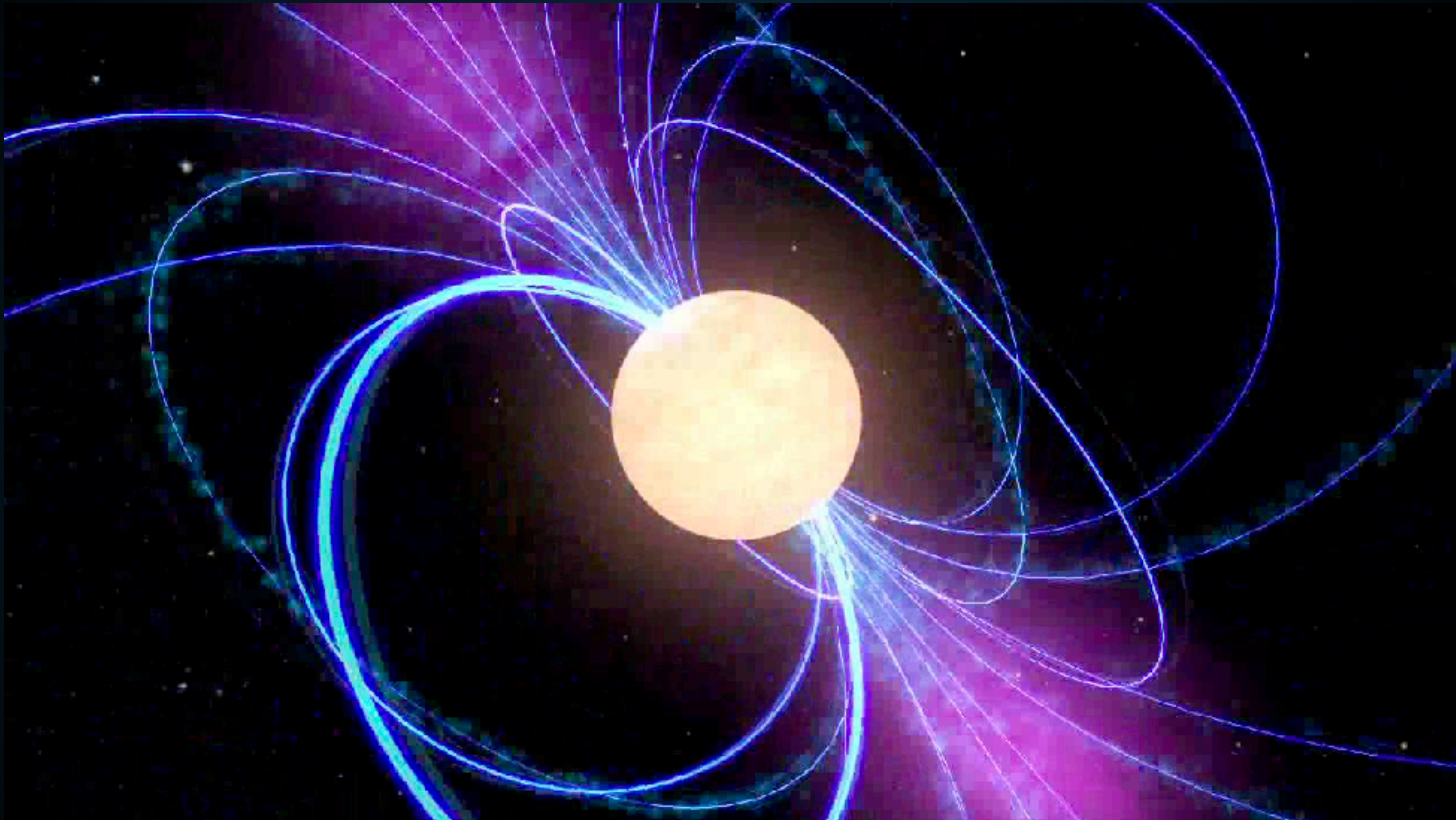
- Total Contribution from:
  - Geminga
  - Monogem
  - Average of other young pulsars

*Braking index slightly changed to fit model to data.

- Reasonable models can be exactly fit to the excess.

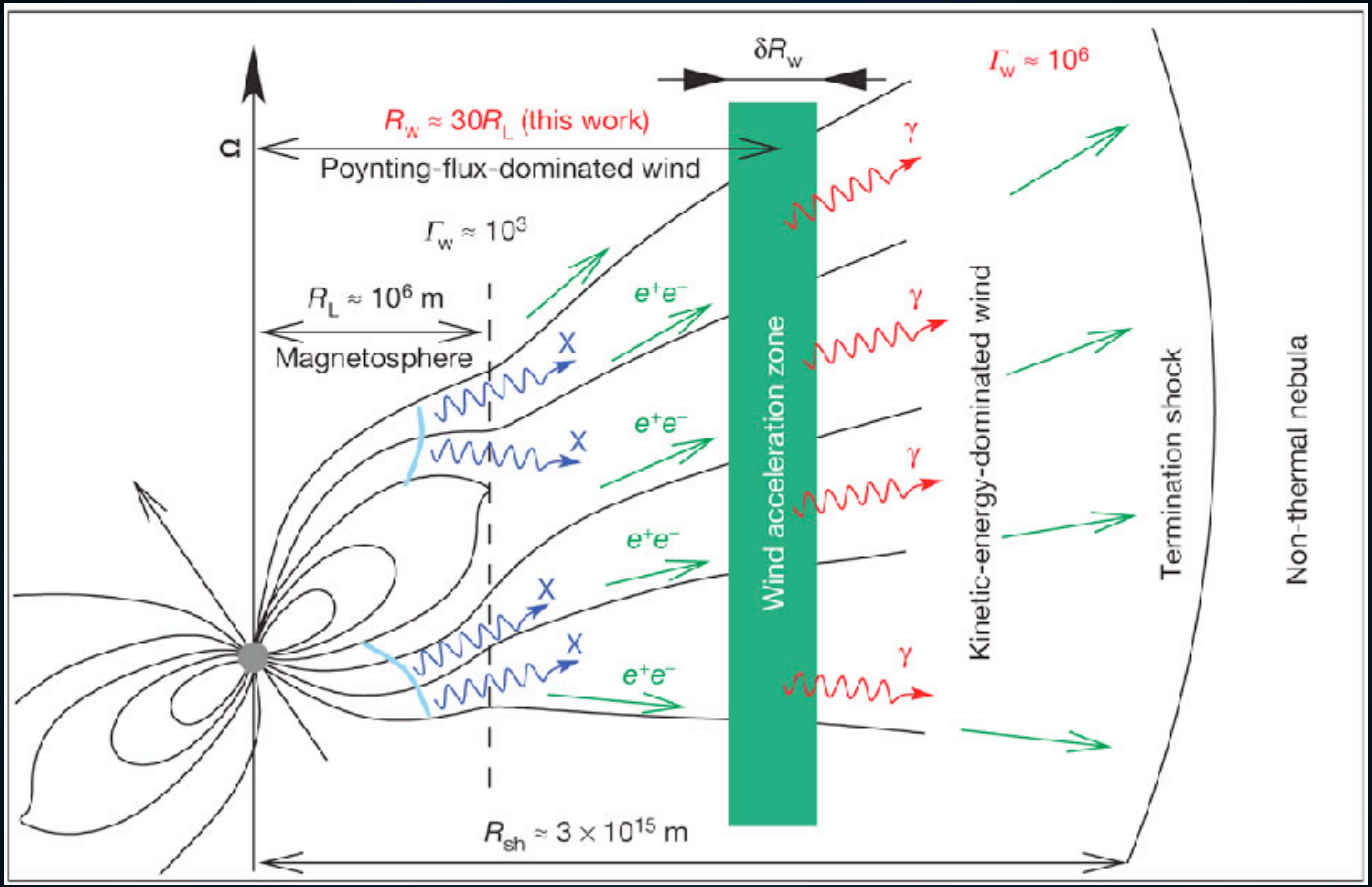
A simple model of TeV halos

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
- Pair multiplicity is high, but 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

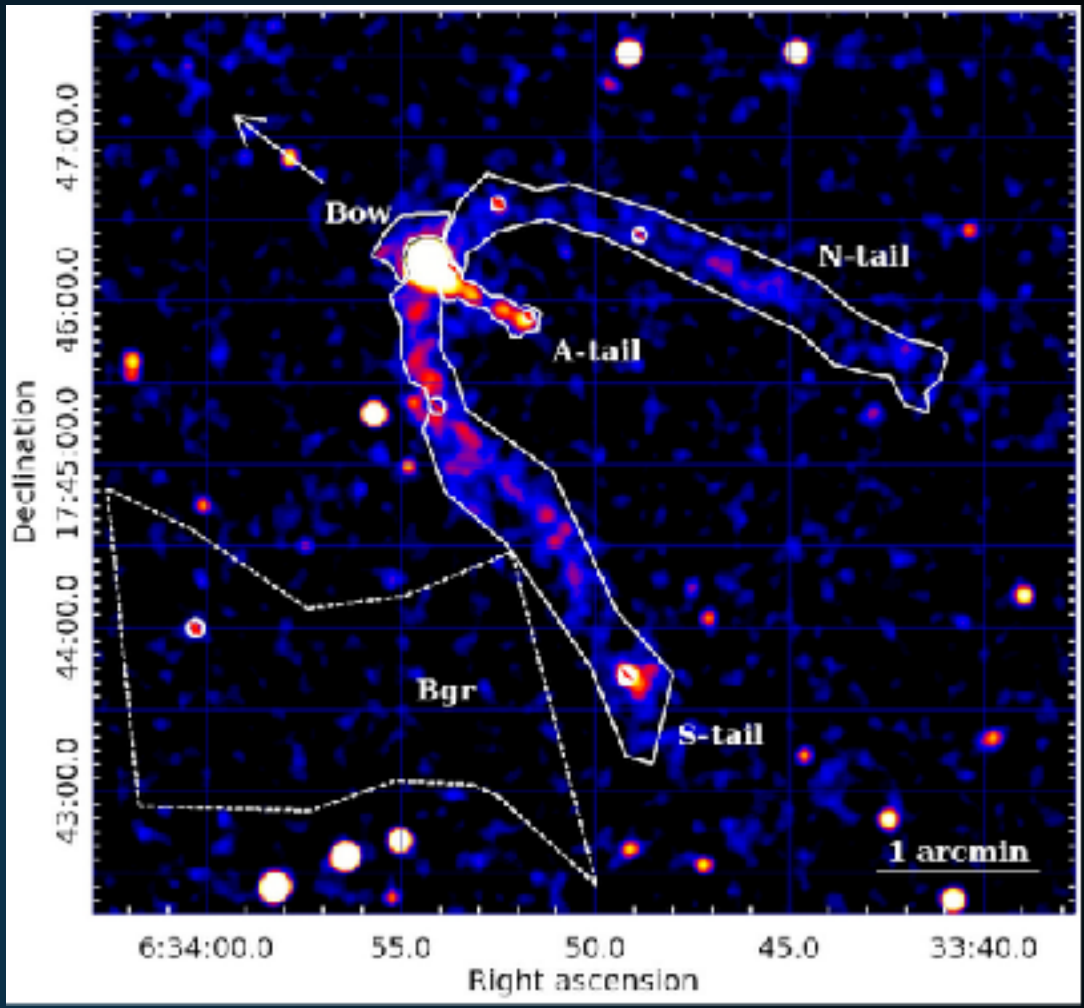
LOW-ENERGY OBSERVATIONS OF PULSAR WIND NEBULAE

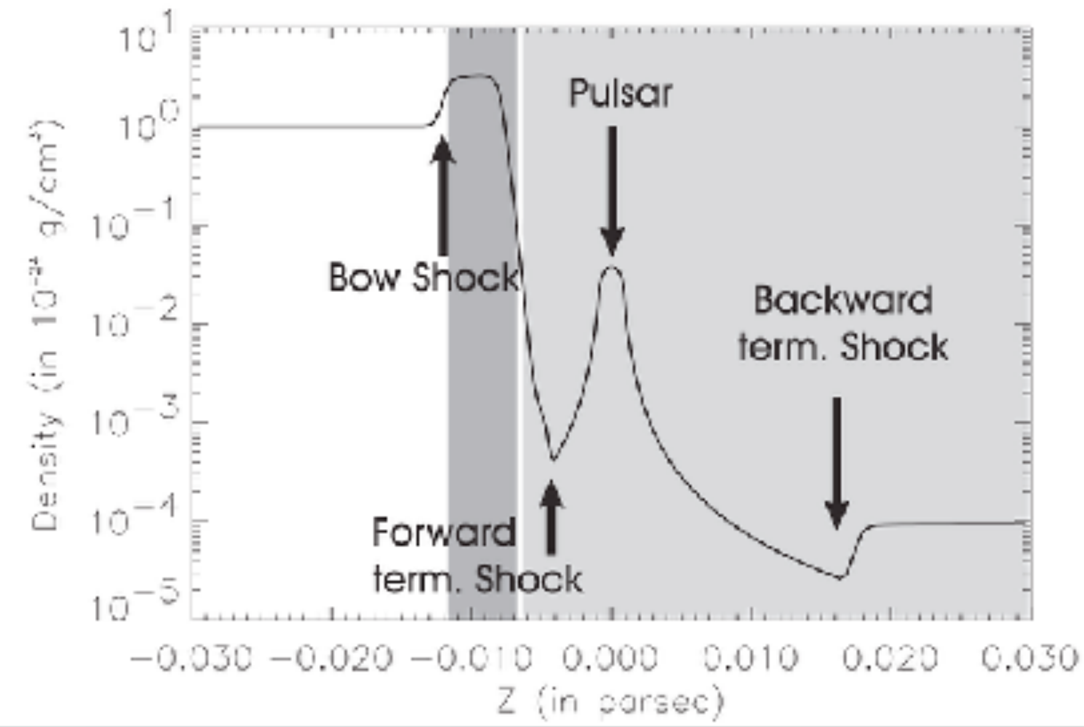
1611.03496
astro-ph/0202232

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

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

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

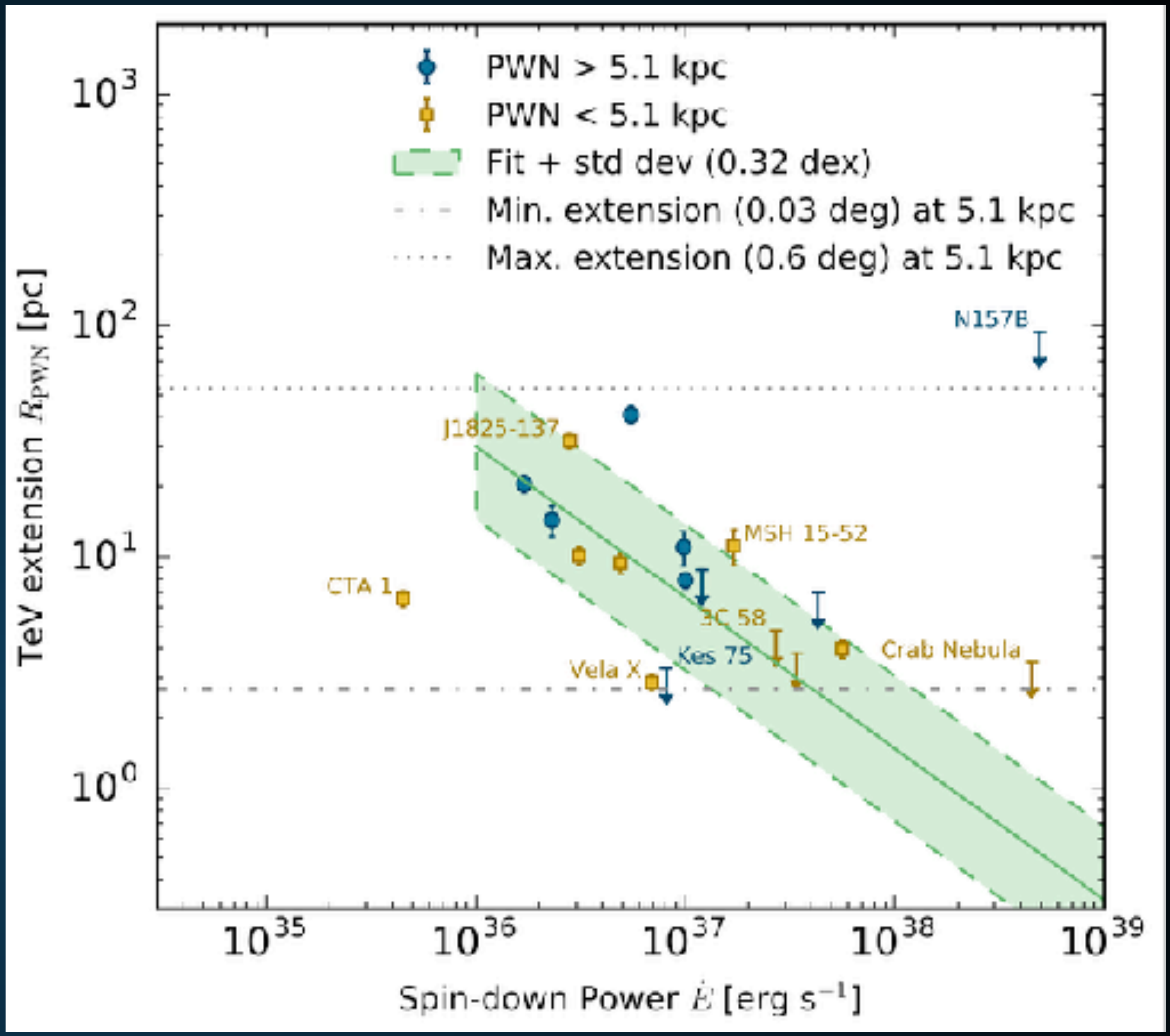




SPATIAL EXTENSION OF "TEV PWN"

1702.08280

- TeV PWN are much larger.
- Particularly true in low-energy systems.



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

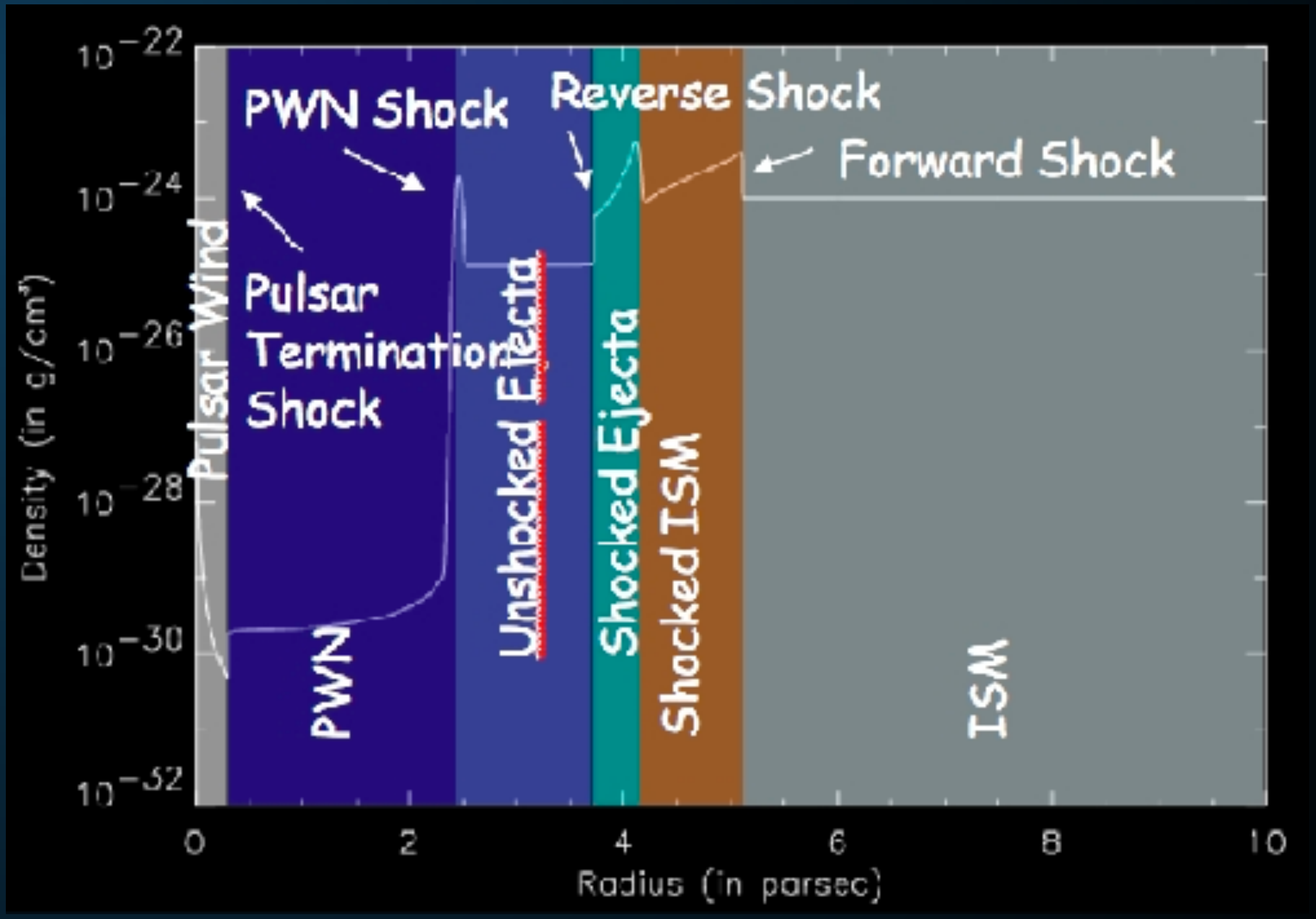
$$R_{\rm PWN} \simeq 1.5 \left(\frac{\dot{E}}{10^{35}\,{\rm erg/s}}\right)^{1/2} \times \left(\frac{n_{\rm gas}}{1\,{\rm cm}^{-3}}\right)^{-1/2} \left(\frac{v}{100\,{\rm km/s}}\right)^{-3/2} {\rm pc}$$

TEV HALOS

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

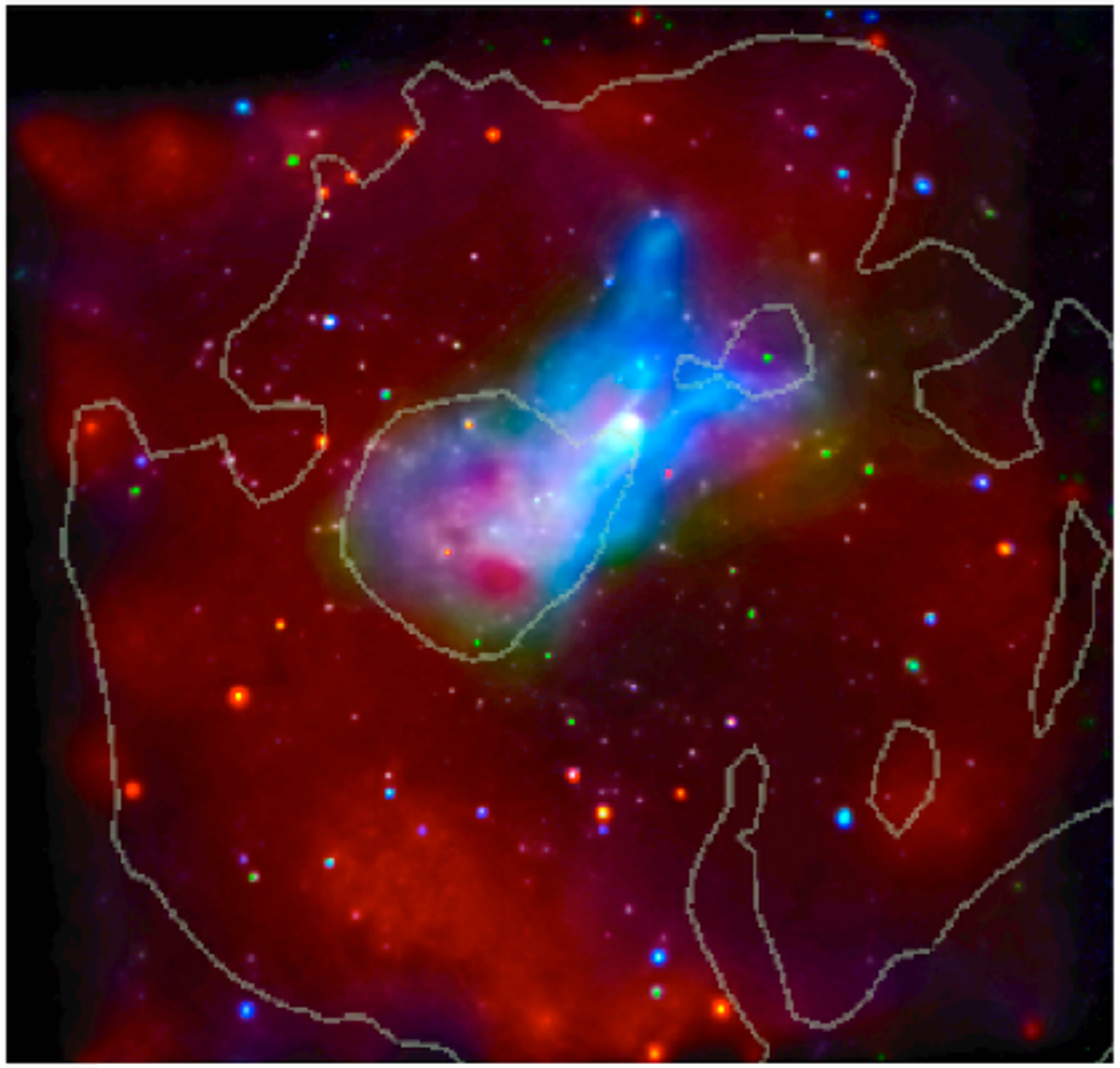
- PWN are morphologically connected to the physics of the termination shock

- TeV halos need a similar morphological description.



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**
  - **Galactic cosmic-ray diffusion**
  - **Source of IceCube neutrinos**
  - **TeV Dark Matter Constraints**

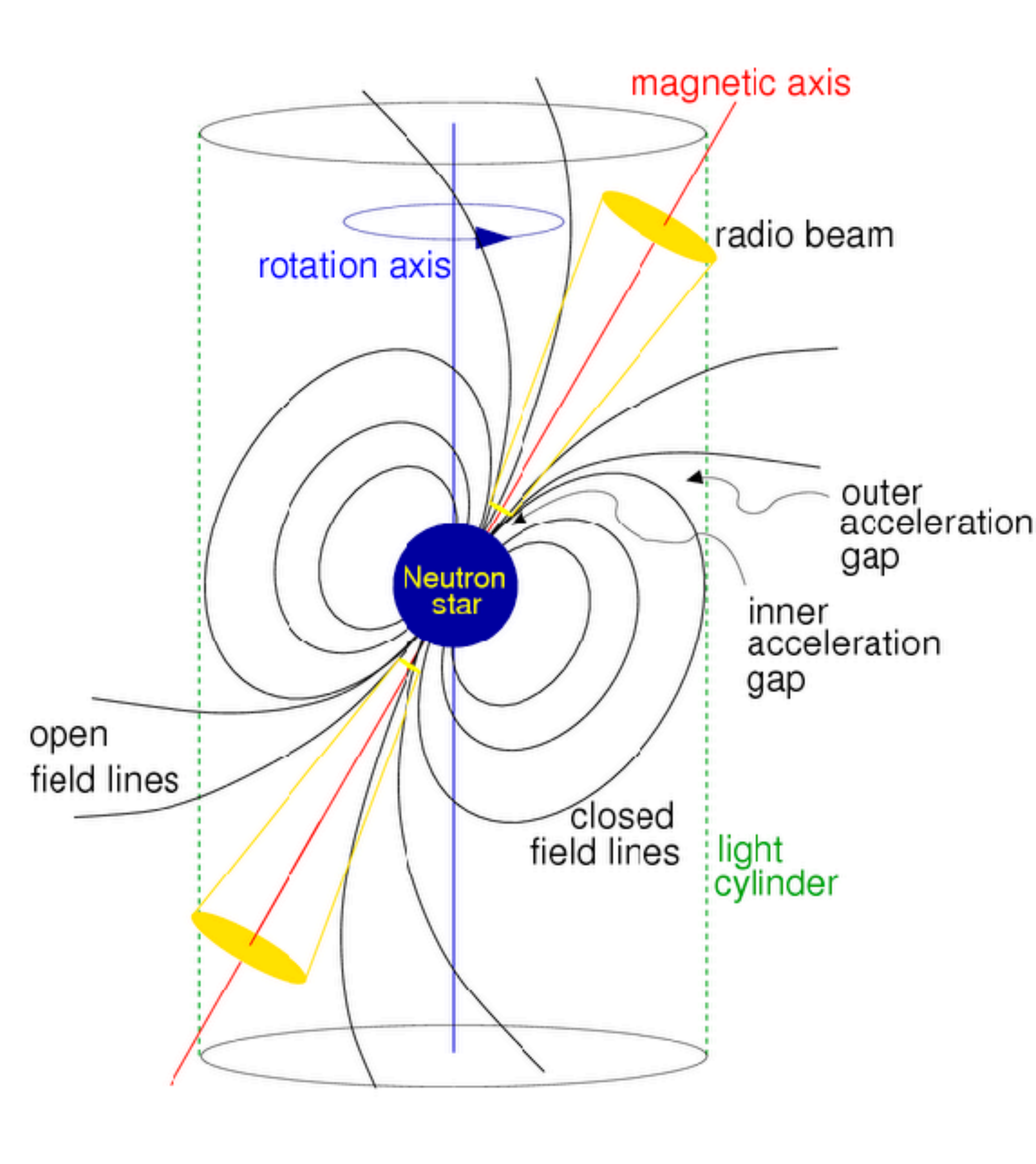
Extra Slides

CONFIRMING TEV HALOS

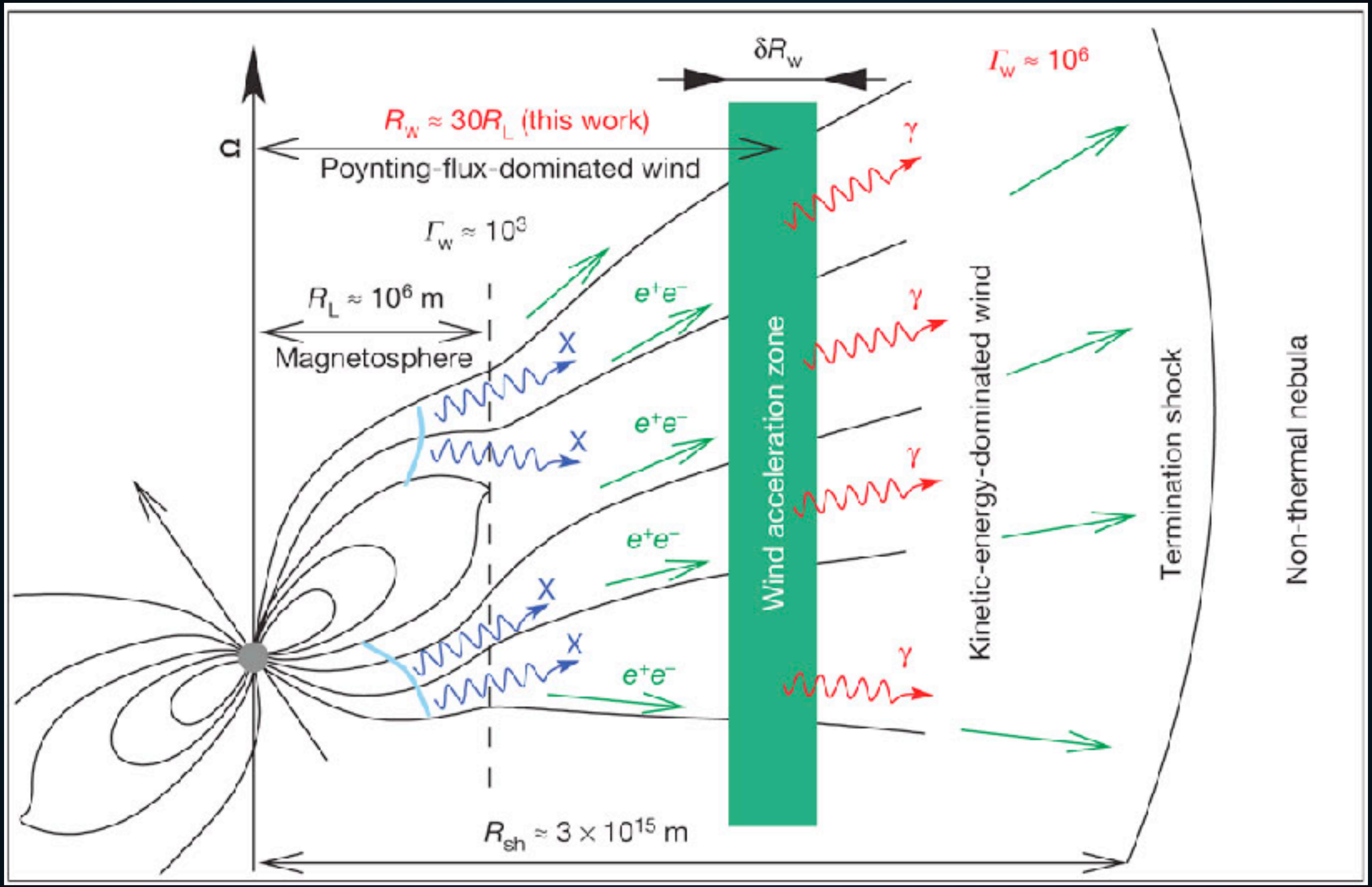
- **Several Methods to confirm TeV halo detections:**
  - **X-Ray halos**
  - **X-Ray PWN**

PULSARS AS ASTROPHYSICAL ACCELERATORS

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



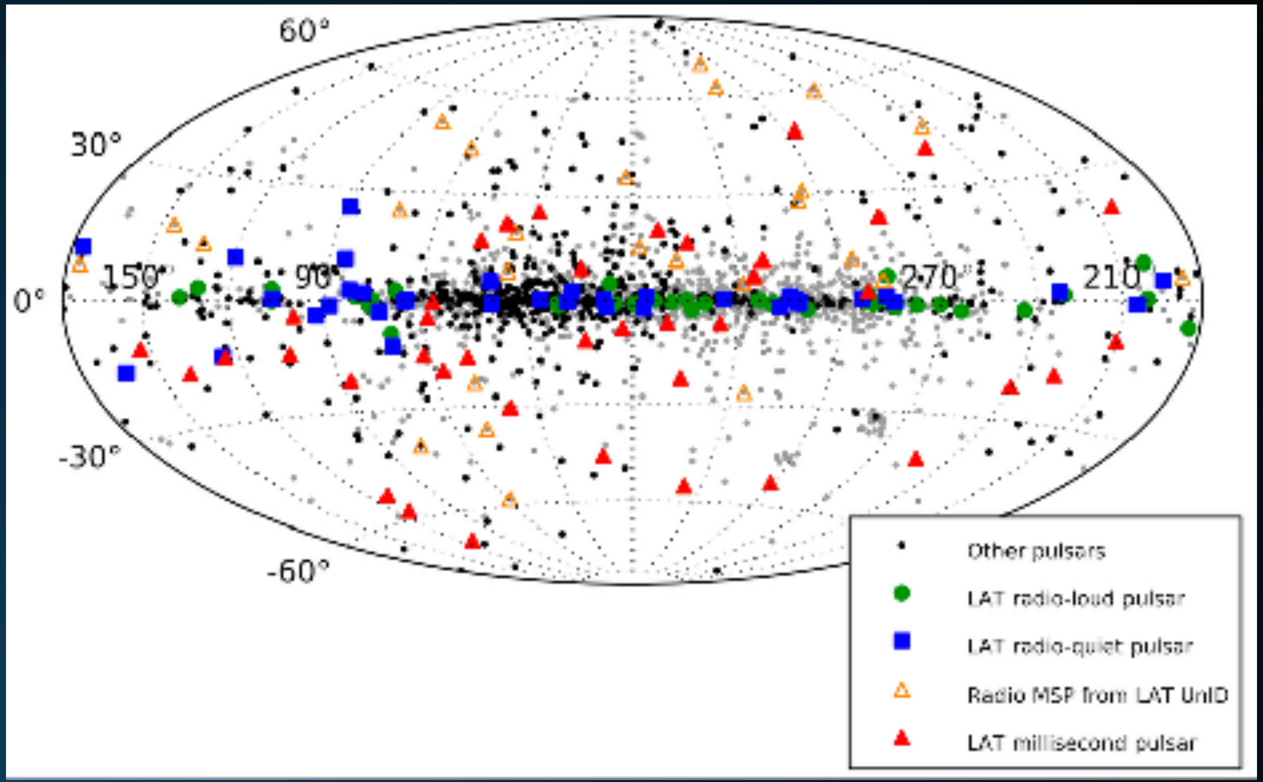
PRODUCTION OF ELECTRON AND POSITRON PAIRS



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

FERMI-LAT DETECTIONS

- **Fermi-LAT has detected 54 new pulsars**
  - **35 younger than 100 kyr**
  - **Only 5/35 in HAWC field of view**



- **Fermi-LAT has detected only ~5 of these 37 systems.**

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

X-RAY PWN DETECTIONS

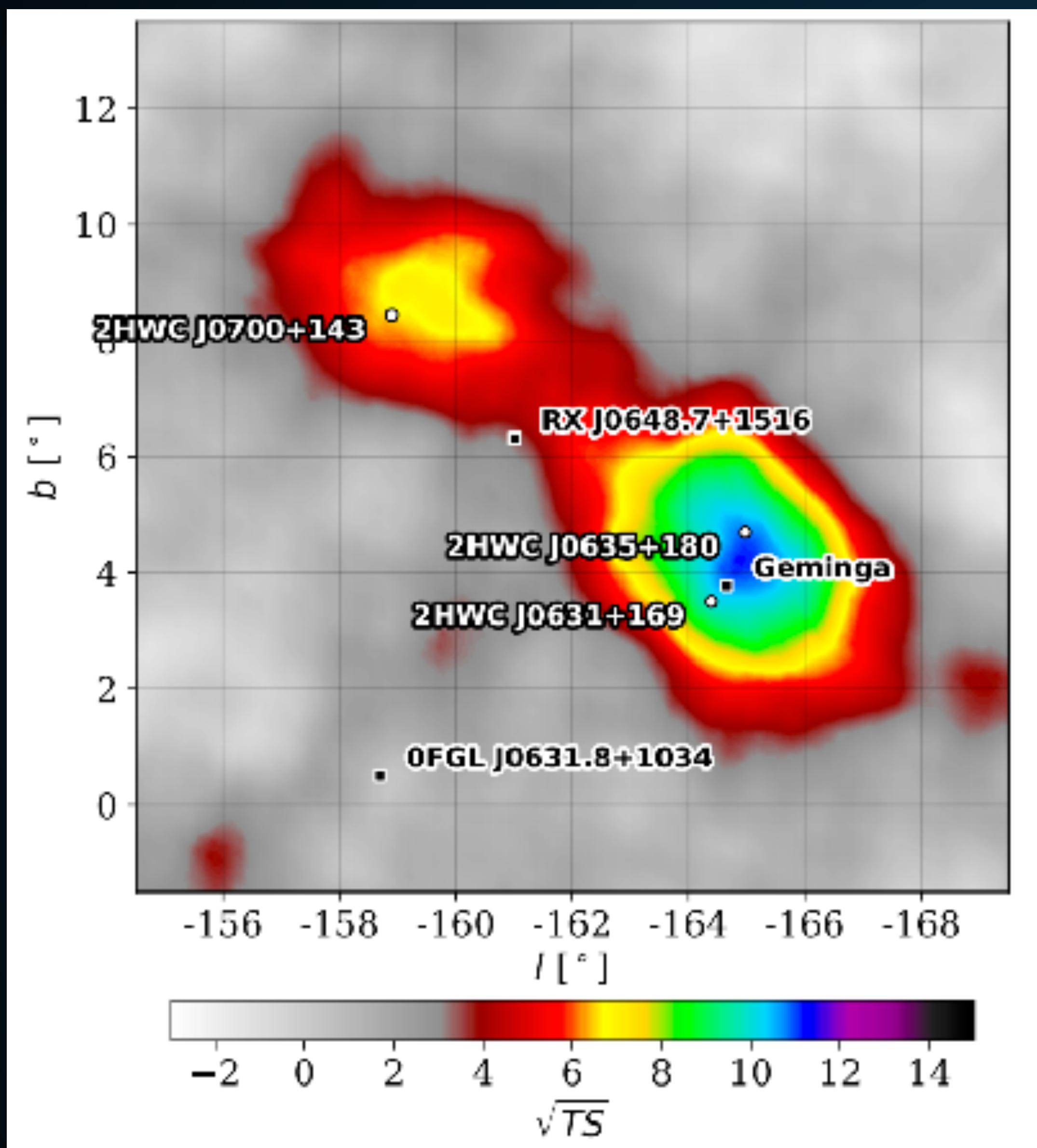
PWNe With No Detected Pulsar

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.**

TWO CONTRASTING OBSERVABLES

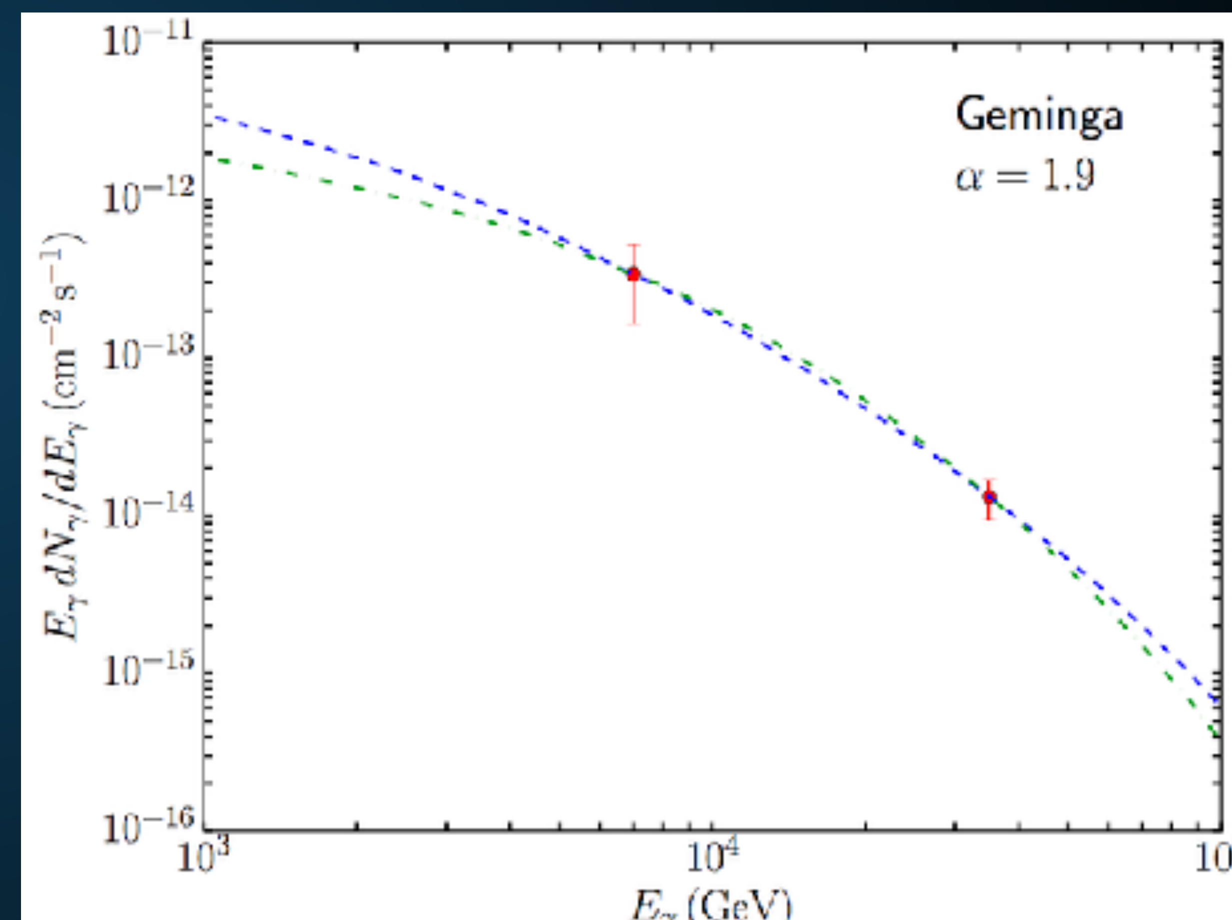
Geminga is Bright



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

COSMIC-RAY DIFFUSION IN A TEV HALO

- **Energy constraints demand that ~30 TeV electrons lose the majority of their energy before exiting TeV halo.**

$$\tau = 3.1 \times 10^{4}\,\mathrm{yr}\left(\frac{E_e}{10\,\mathrm{TeV}}\right)^{-1}$$

- **This strongly constrains the efficiency of particle propagation near the halo.**

$$D = \frac{L^2}{6\tau} = \frac{(10\,\mathrm{pc})^2}{6(3.1\times10^{4}\,\mathrm{yr})} = \frac{(3.08\times10^{19}\,\mathrm{cm})^2}{5.86\times10^{12}\,\mathrm{s}}$$

$$\boxed{D = 1.6\times10^{26}\,\frac{\mathrm{cm}^2}{\mathrm{s}}}$$

- **Provides strong evidence for new morphological feature.**

TOTAL POWER OF TEV HALOS

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

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

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

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

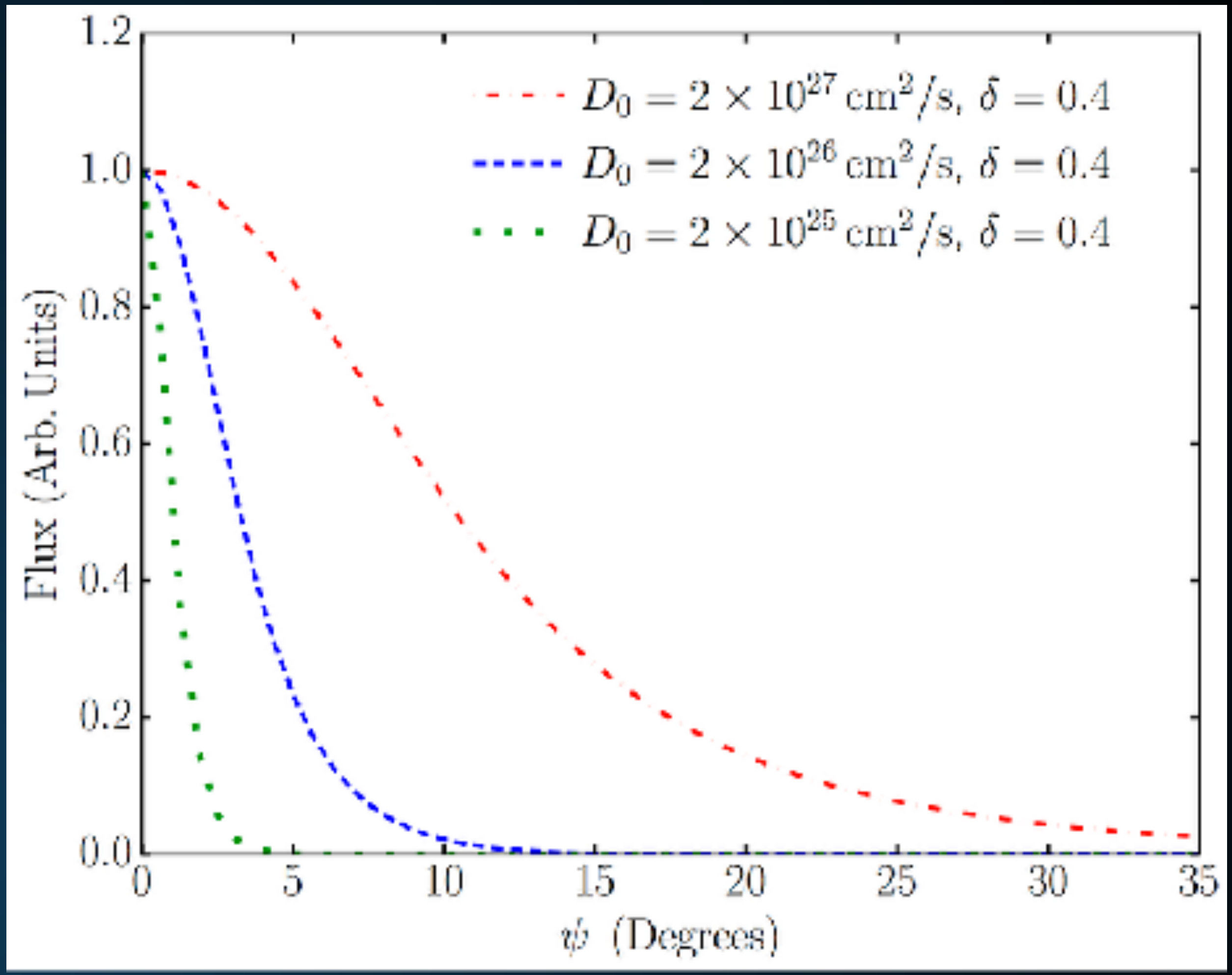
- **Total Spindown Power of Geminga is:**

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

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

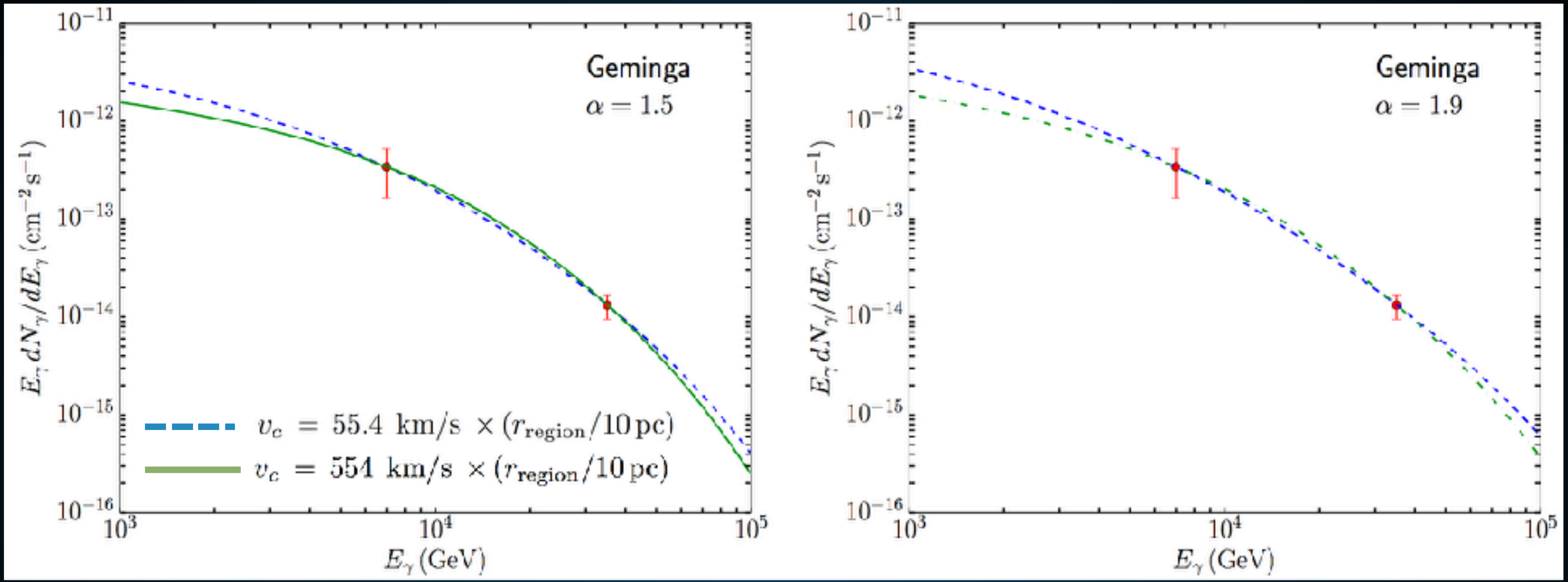
COSMIC-RAY DIFFUSION IN A TEV HALO

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



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

GEMINGA SPECTRUM INDICATIVE OF CONVECTION

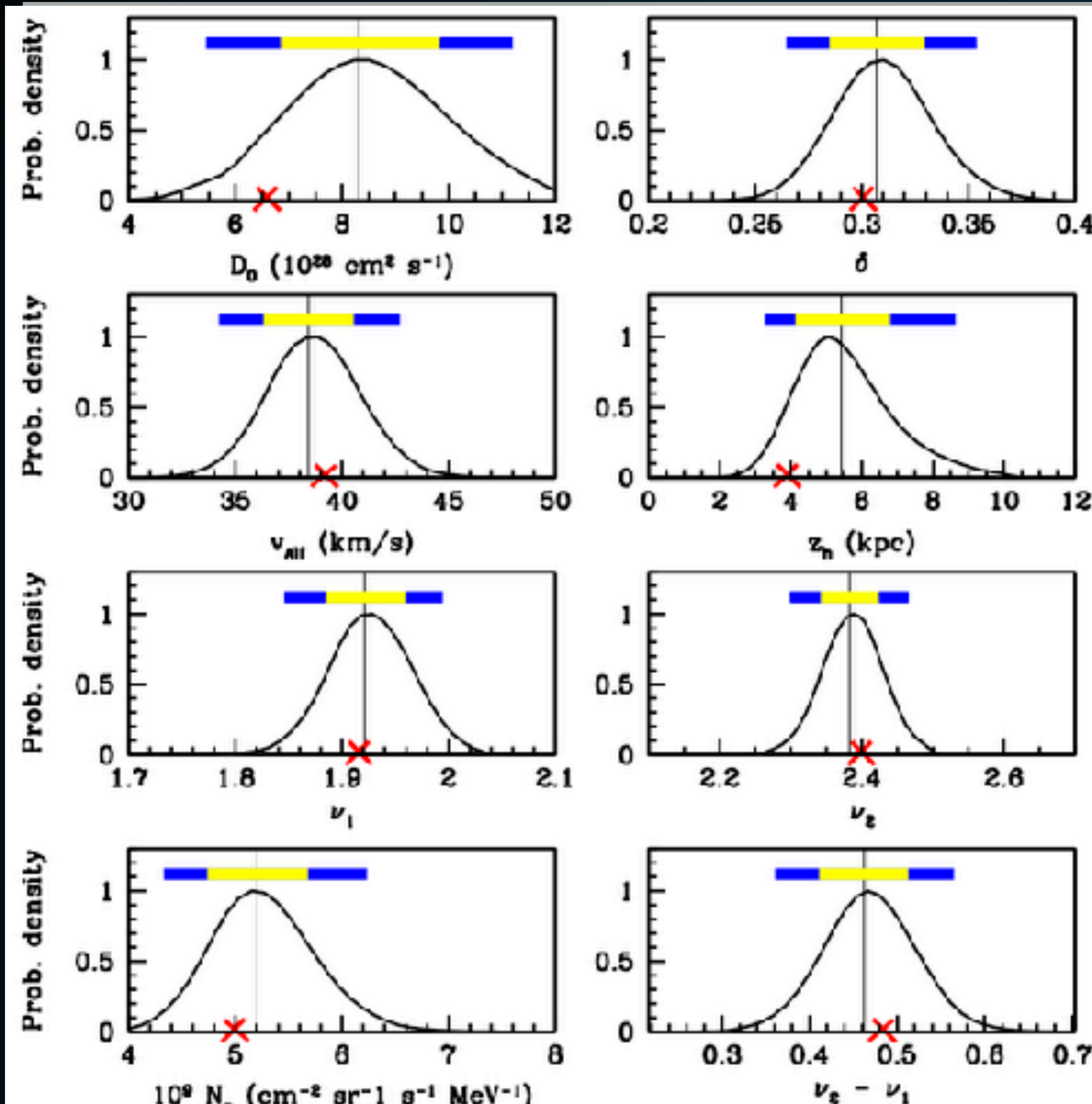


- **However, Bohmian diffusion is incompatible with the gamma-ray spectrum.**
- **If low-energy electrons are cooled, the spectrum at 7 TeV should be significantly softer.**

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.

EFFECT OF TEV HALOS ON ISM PROPAGATION



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

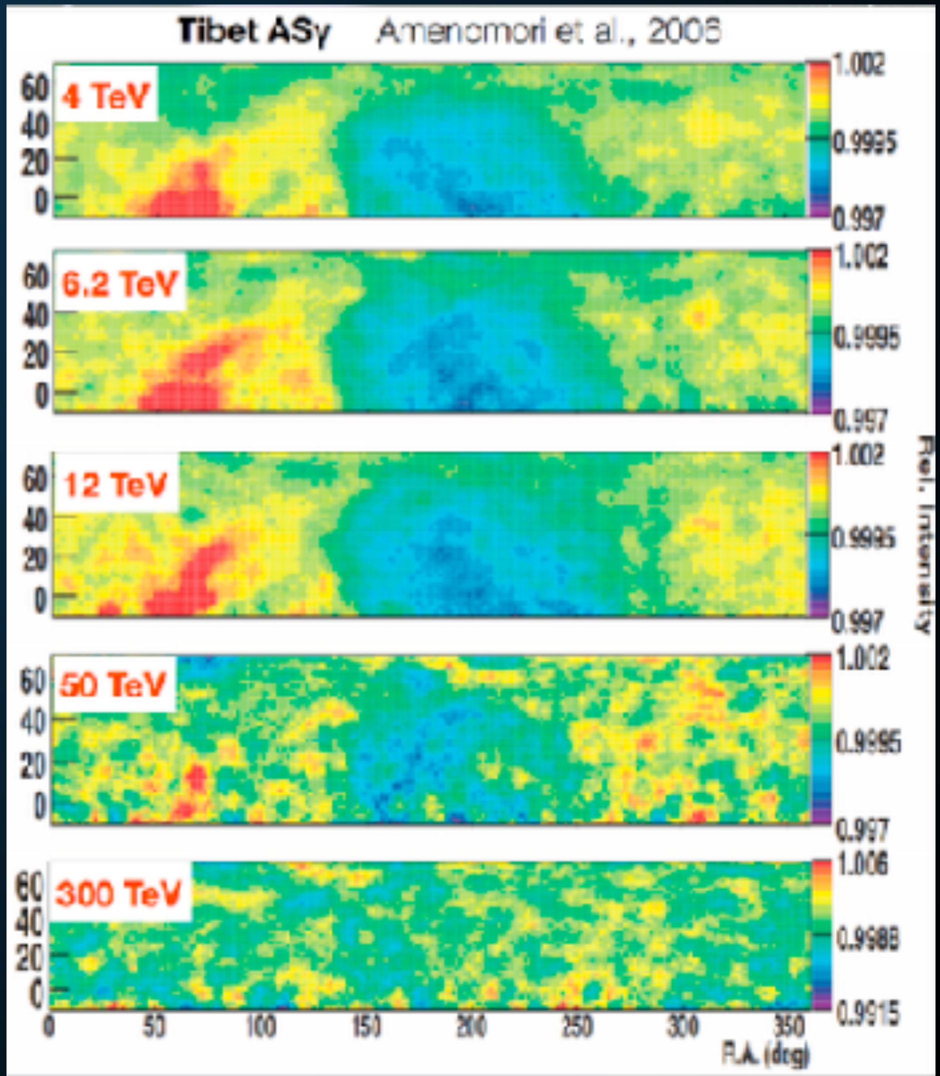
- **Inhibited cosmic-ray propagation in TeV halos must not substantially affect this number.**

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

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

CAN WE BE INSIDE A TEV HALO?

- We probably cannot be inside a TeV halo without affecting cosmic-ray anisotropies.
- If we are at the center of a TeV halo, it must be huge.
- Would make understanding the e^+e^- flux even more difficult.



AN ALTERNATIVE EXPLANATION

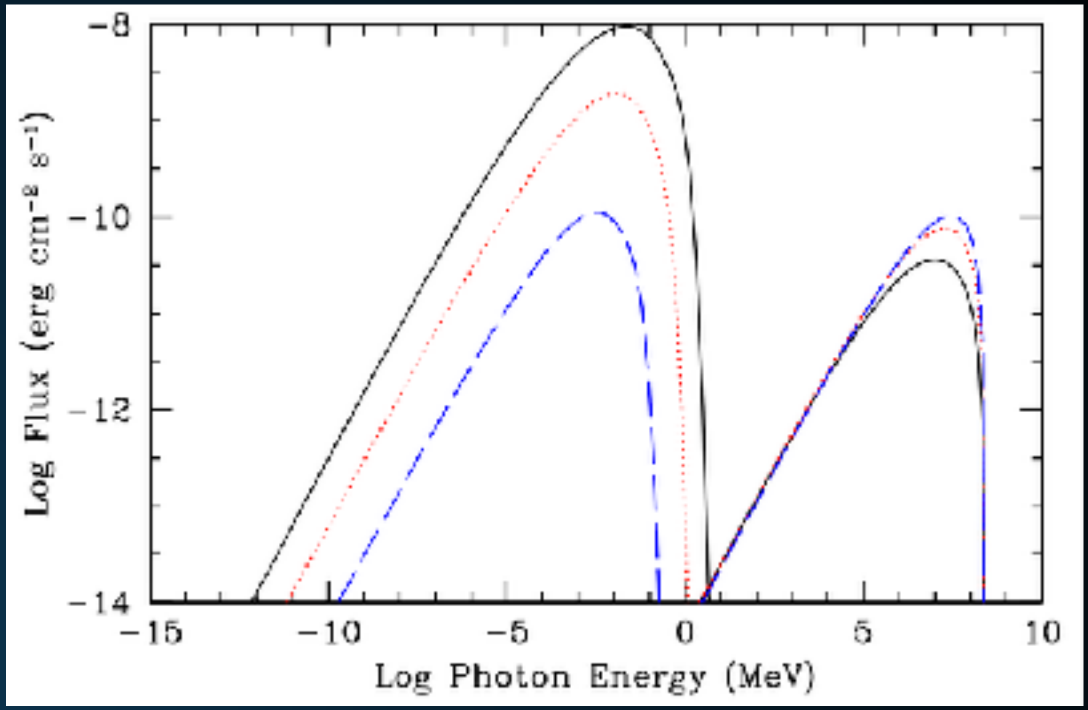
- Maybe TeV electrons propagate farther?

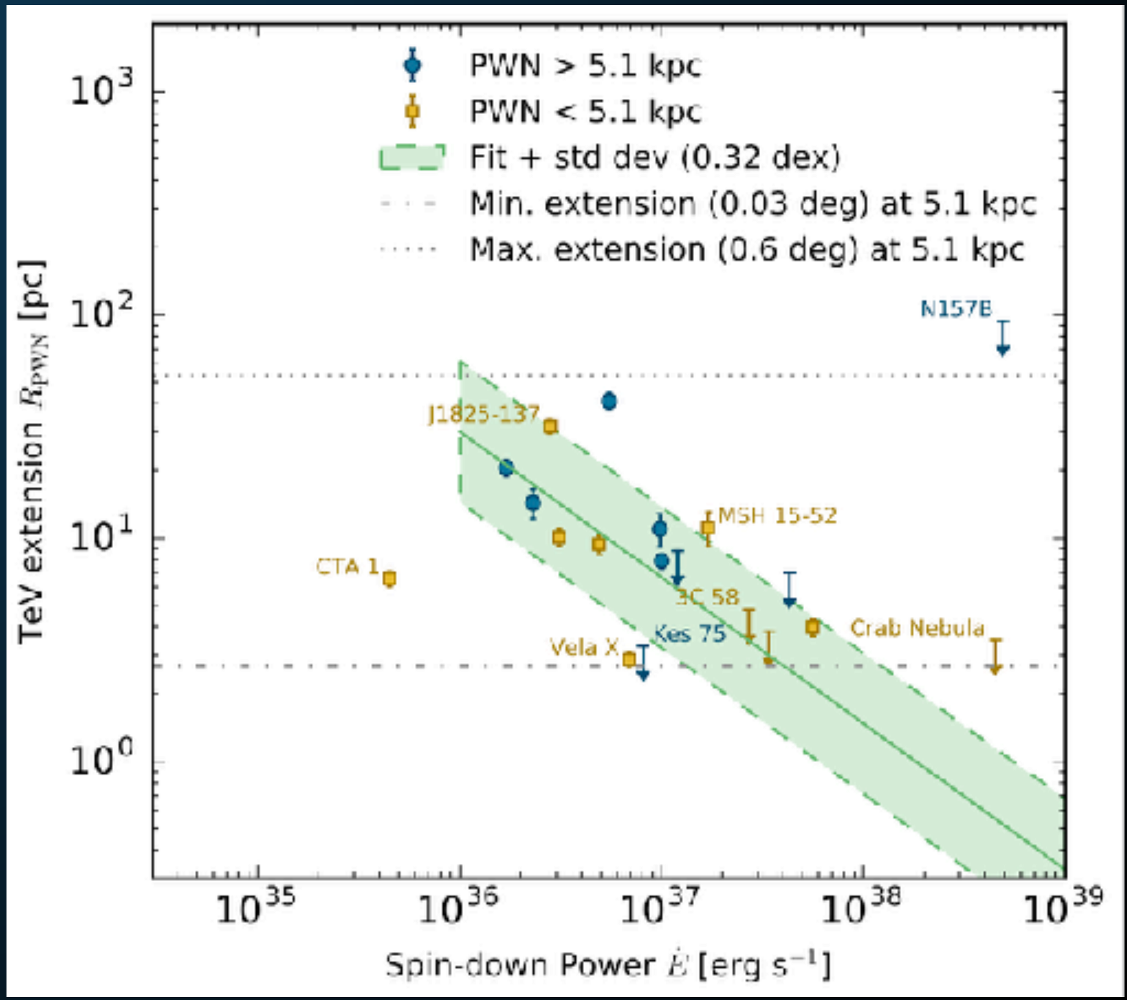
- Energy loss time-scale: E^{-1}.

- Propagation Distance in t: $E^{0.16}$.

- Size of Halo: $E^{-0.33}$.

- Moving from PeV to ~50 TeV electrons leads to 10x larger radius.





GEMINGA - A TEMPLATE FOR TEV HALOS

- **Will now use Geminga as a standard template for TeV halos.**
  - **Bright (nearby)**
  - **High latitude (low background)**
  - **Middle-Aged (no associated SNR)**
- **Would get same (actually slightly better) results if we used Monogem.**

IN THIS TALK

- **Will remain agnostic to source of relativistic e+e-**
- **Will assume a simple power-law spectrum with an exponential cutoff:**

$$\frac{dN}{dE} = E^{-\alpha} \exp(-E/E_{\mathrm{cut}})$$

X-RAY HALOS

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

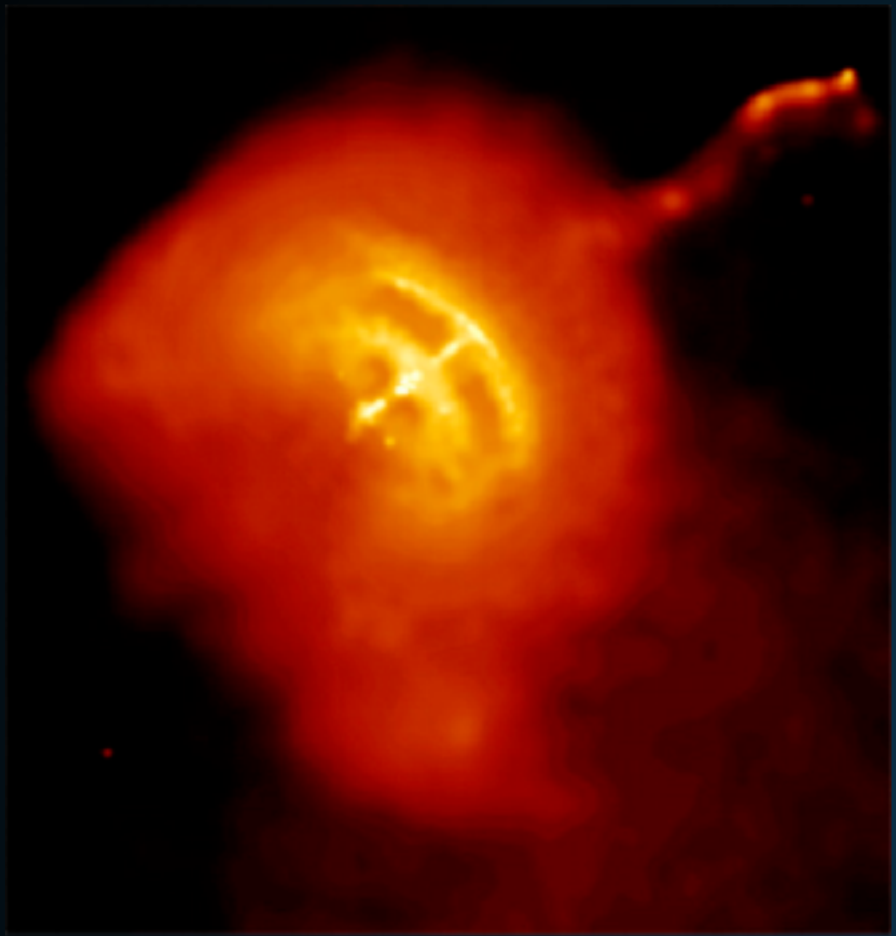
$$U = \frac{1}{8\pi} B^2 = \frac{(10\mu G)^2}{8\pi}$$
$$= 4\times10^{-12} \frac{erg}{cm^3}$$
$$\int_0^{10pc} U\,dV = 5\times10^{47} erg$$
$$\hookrightarrow \text{Magnetic Flux} \simeq 5\times10^{38} \frac{ers}{s}$$

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

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

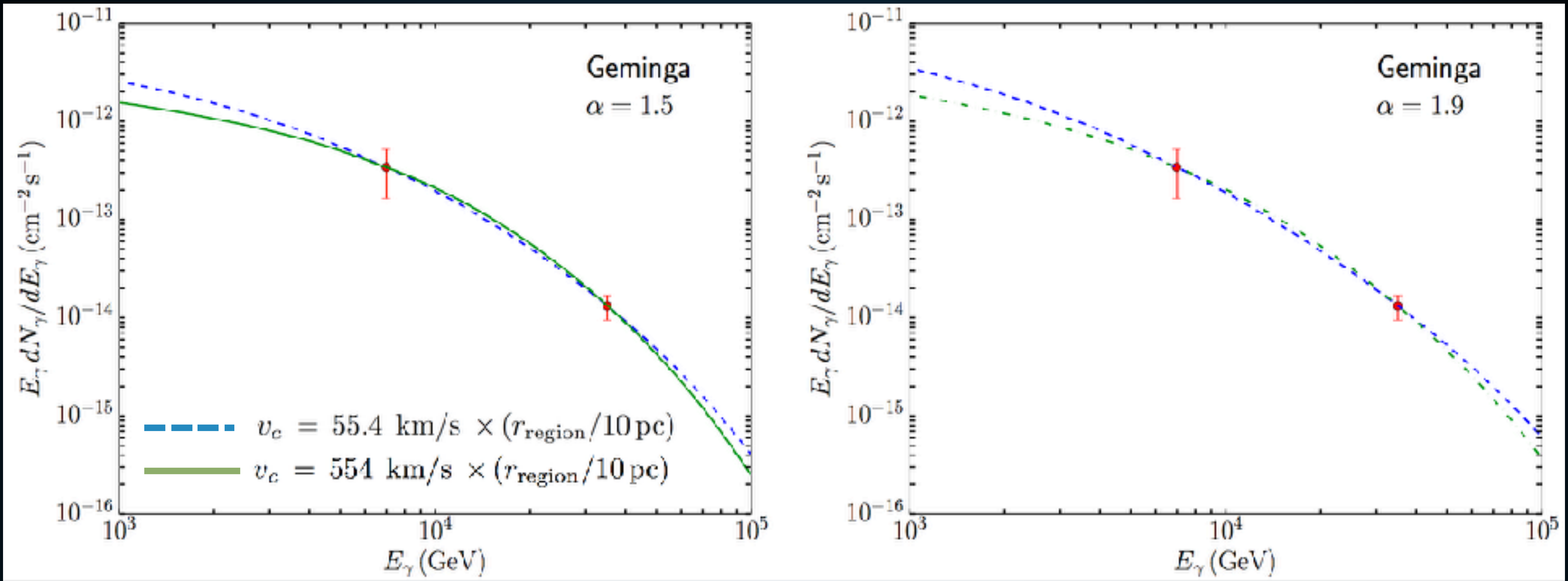
- However, the signal has a low surface brightness and peaks at a low energy.

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.

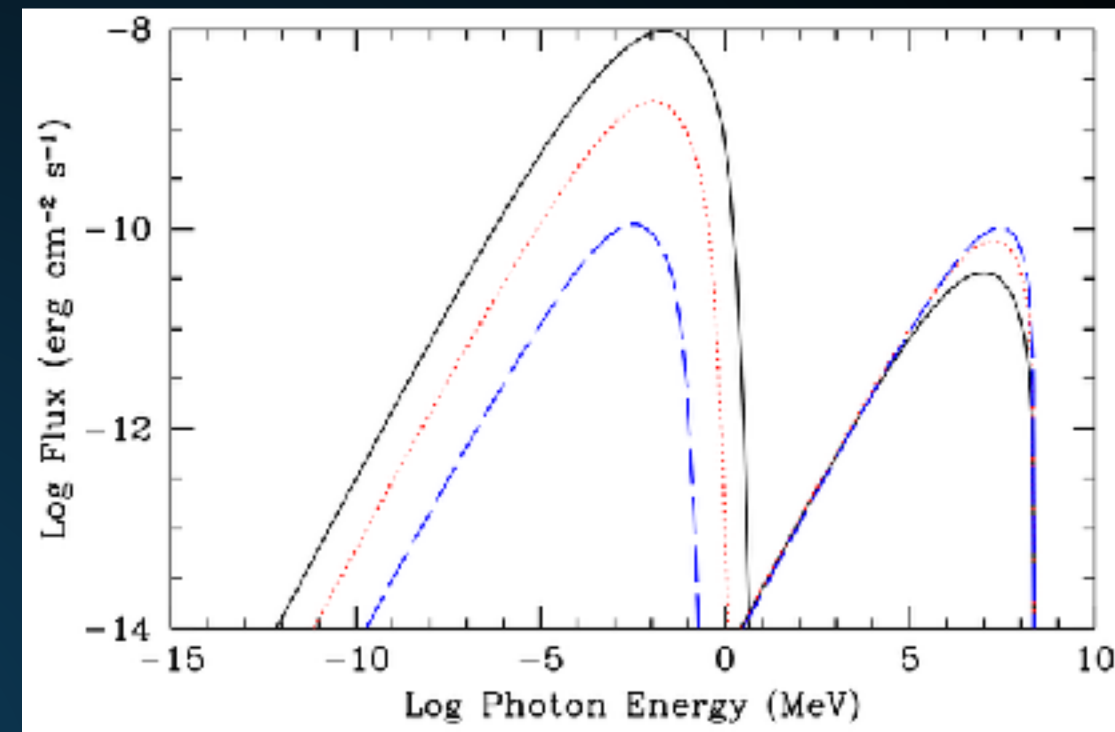
GEMINGA SPECTRUM INDICATIVE OF CONVECTION

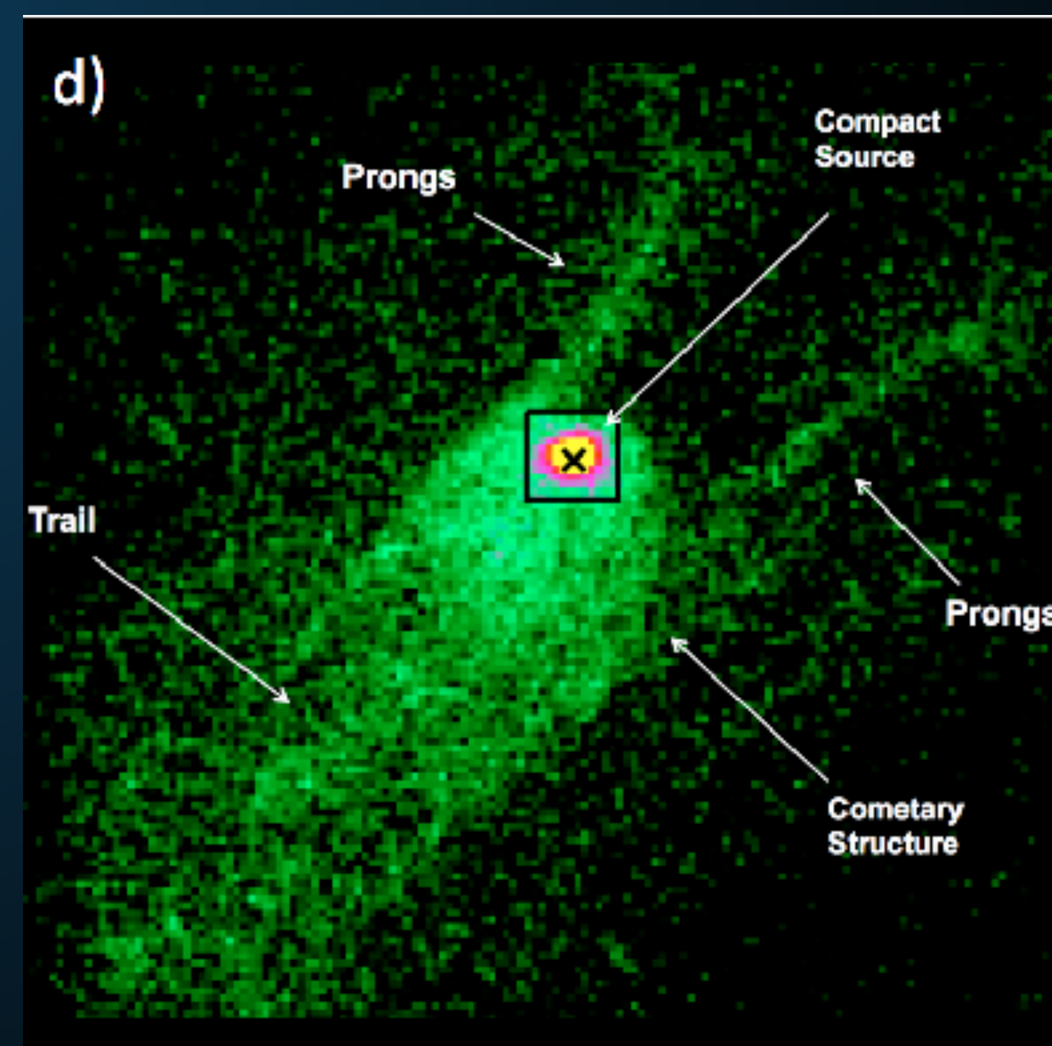


- **Geminga spectrum is fit better with convective models.**
- **Energy-independent diffusion provides identical results**
- **Best-fit spectral-index (-2.23 +/- 0.08) prefers high convection**

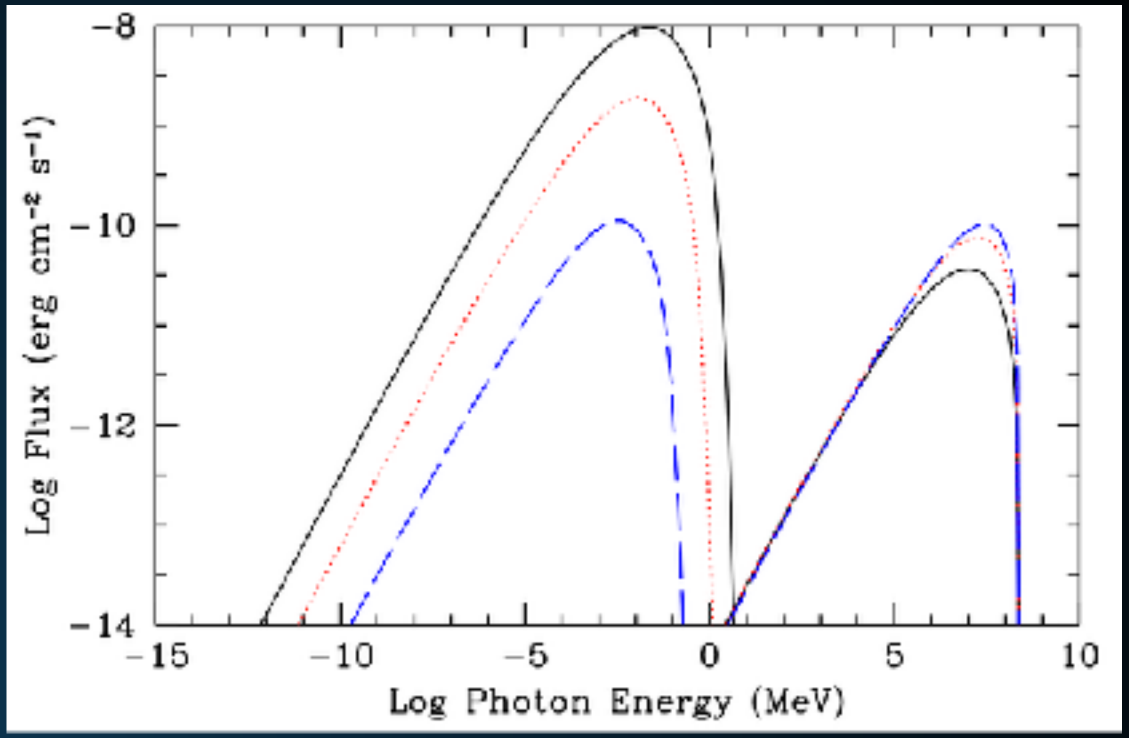
WHY ARE HIGH-ENERGY ELECTRONS TRAPPED?

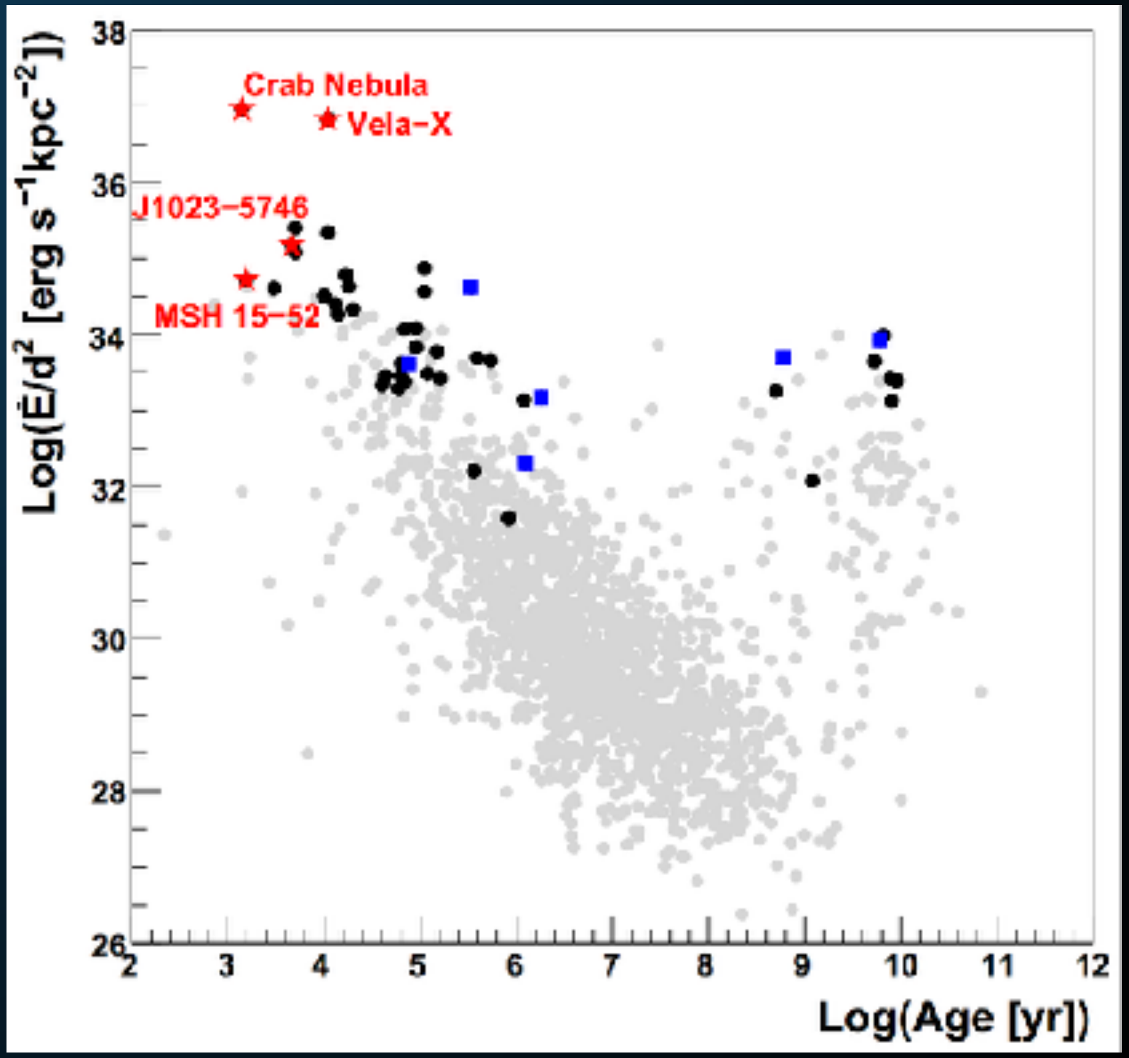
- Cooling dominated by 20 μG magnetic field.
- Energy loss time: ~40 years
- Distance Traveled: ~6 pc for standard diffusion constant. Real diffusion must be slower.
- The spectrum changes as a function of distance and time.



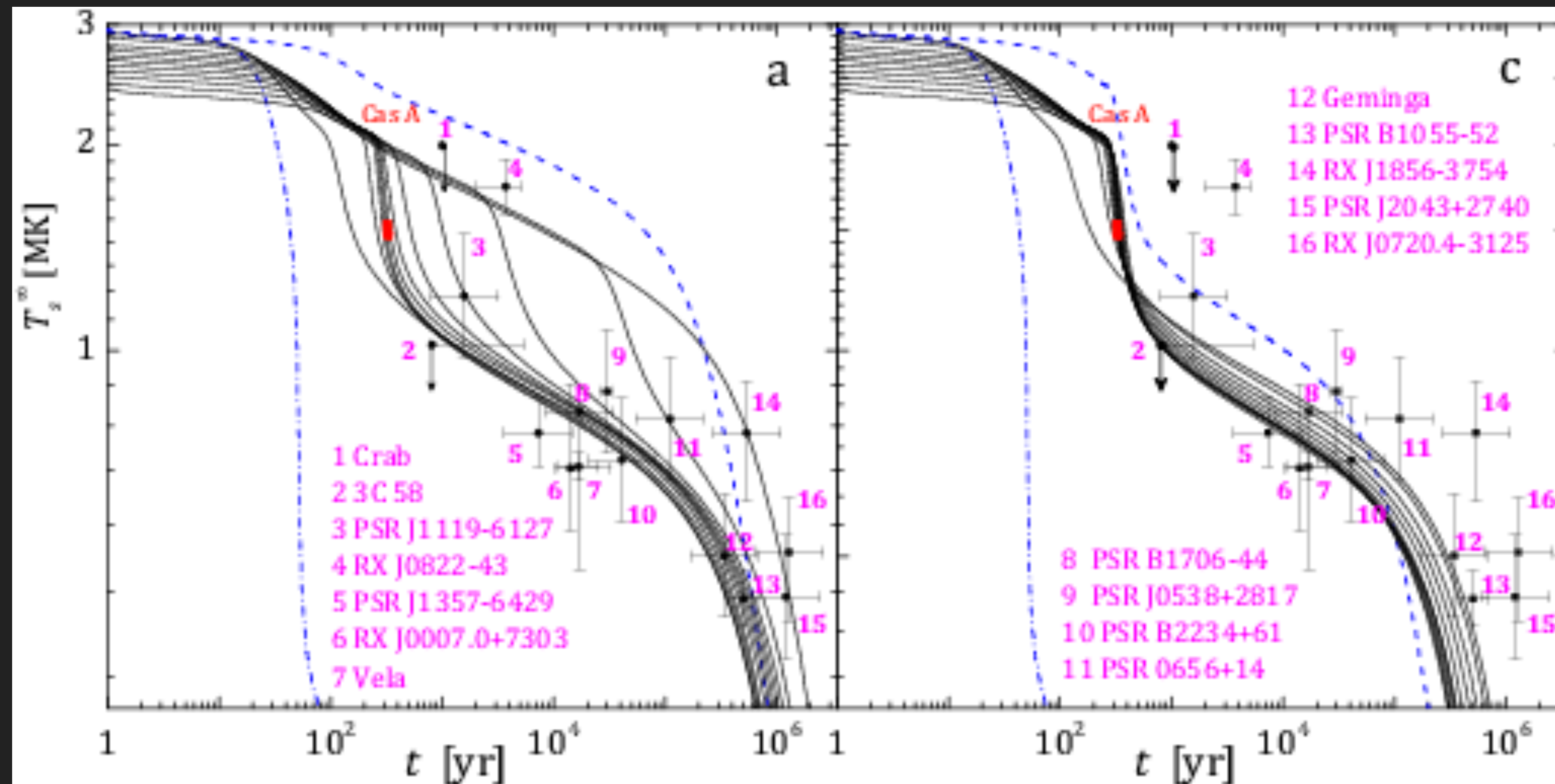


- Gamma-Ray produced through ICS should accompany synchrotron emission.
- Synchrotron observations imply very hard GeV gamma-ray spectrum.
- Conclusively prove leptonic nature of emission.





THERMAL PULSAR EMISSION



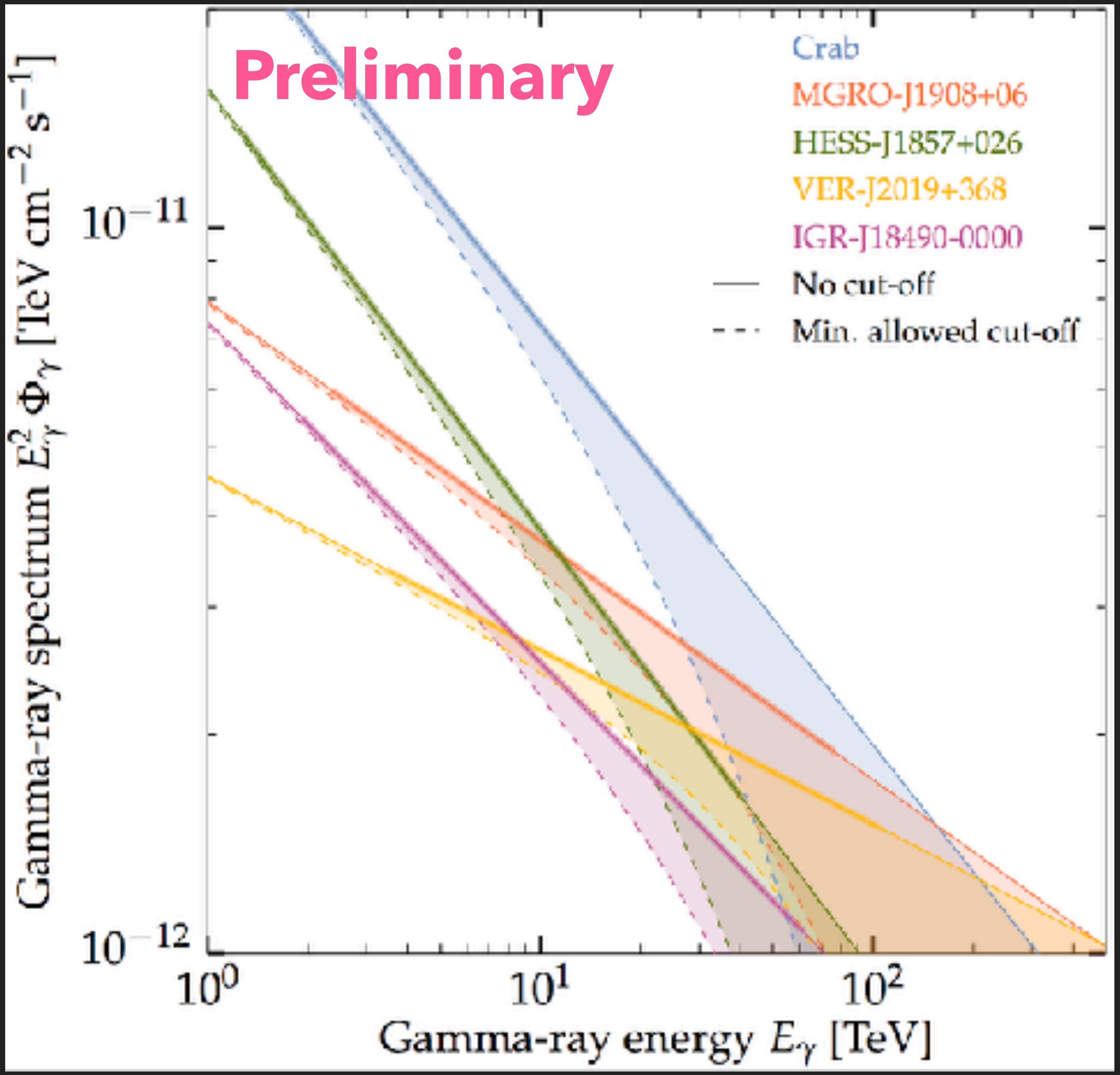
- Hot neutron stars can also be observed via their isotropic thermal emission.
- X-Ray observations can be sensitive to ~2 kpc for 10^6 K NS.
- Cooler NS extremely hard to see.
- Could potentially detect a system which has recently ceased producing TeV particles.

ICECUBE NEUTRINOS FROM 2HWC SOURCES

Bustamante, Li, TL, Beacom (TBS)

- HAWC sources are potential IceCube neutrino sources.

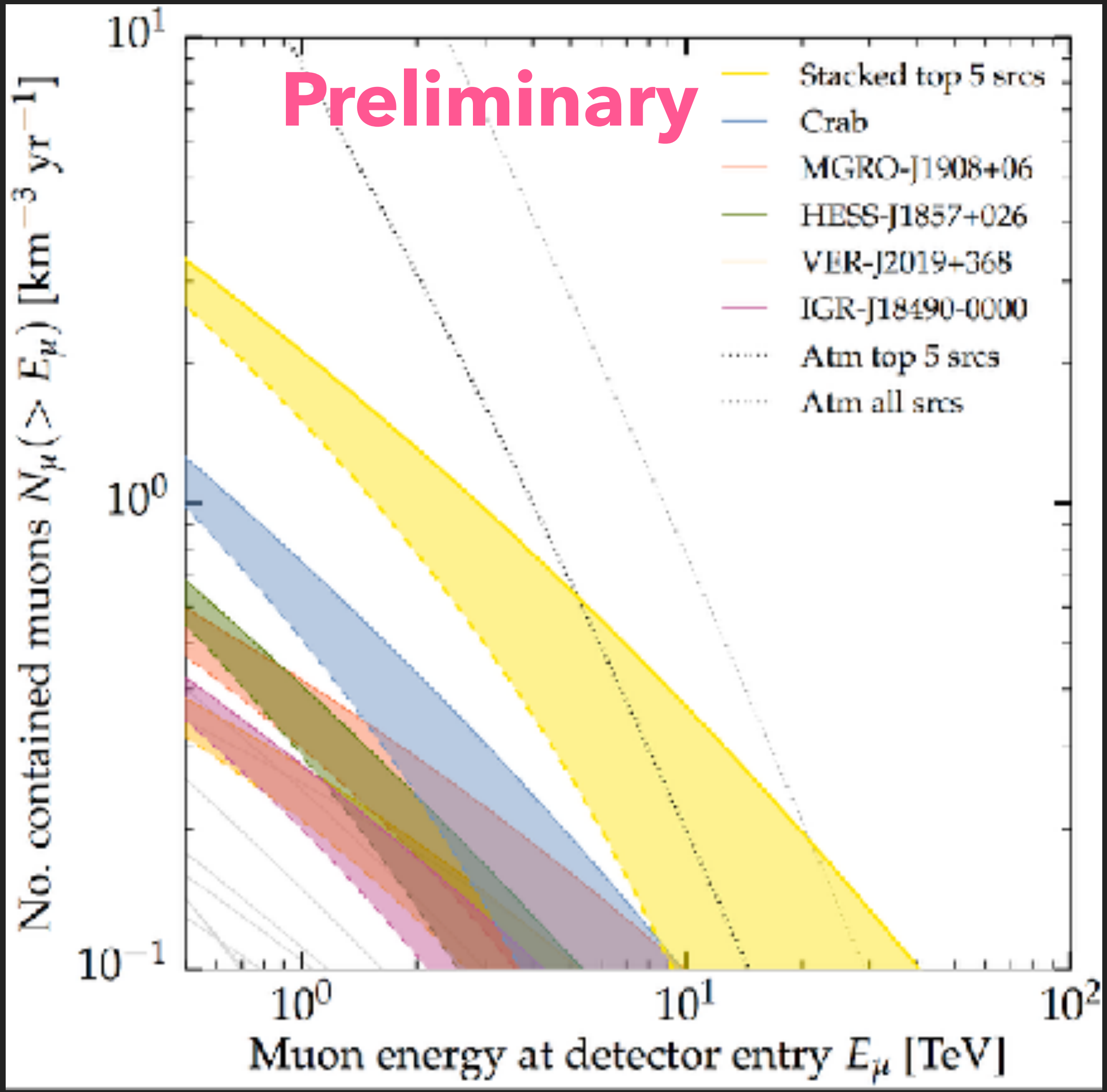
- Spectral measurements of HAWC sources are imperative to calculating the expected neutrino flux.

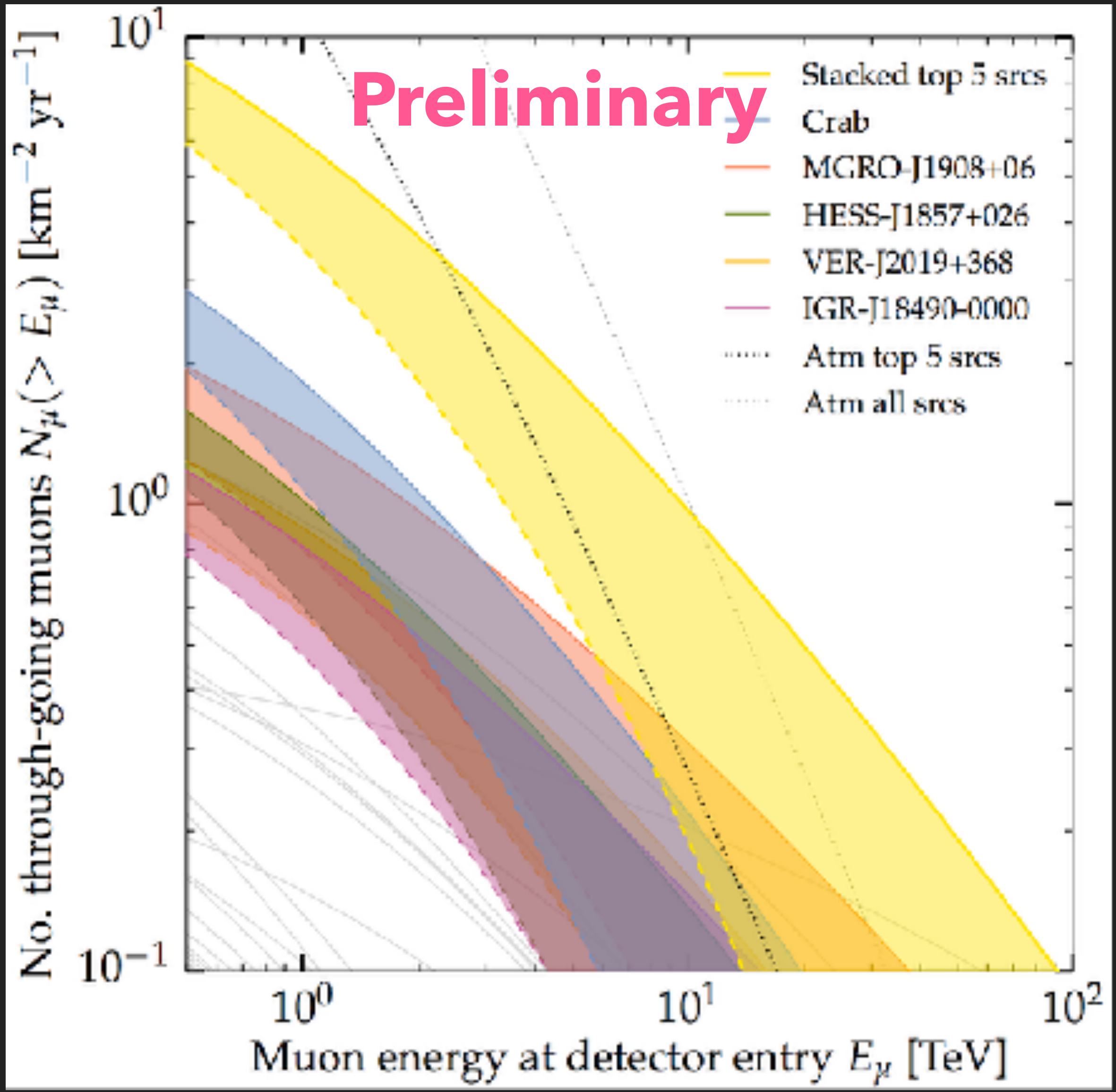


- Here we produce an analysis taking into account a 20% uncertainty in total flux, as well as spectral uncertainty due to an exponential cutoff.

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.

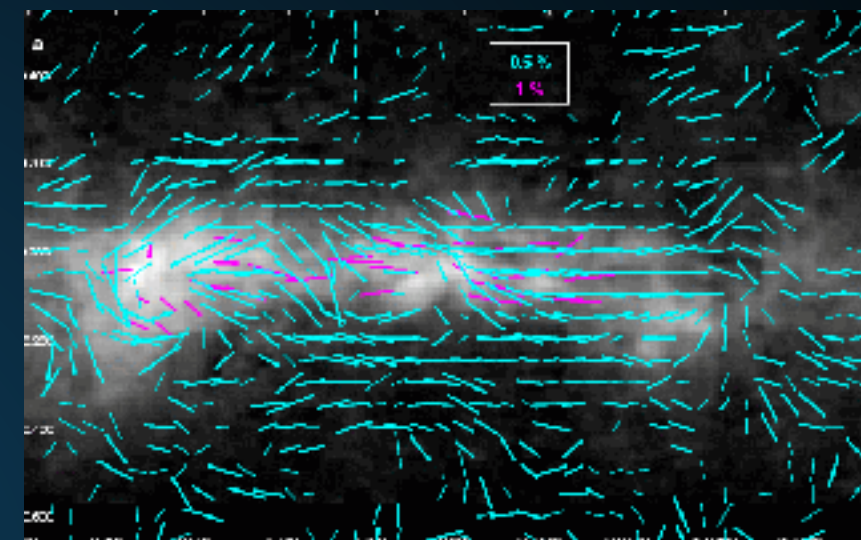
COSMIC-RAY ACCELERATION AND PROPAGATION

Start with a source of relativistic cosmic-rays

- Supernova Explosions
- Supernova Remnants
- Pulsars
- Shocks/Mergers

Start with a source of relativistic cosmic-rays

cosmic rays propagate



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

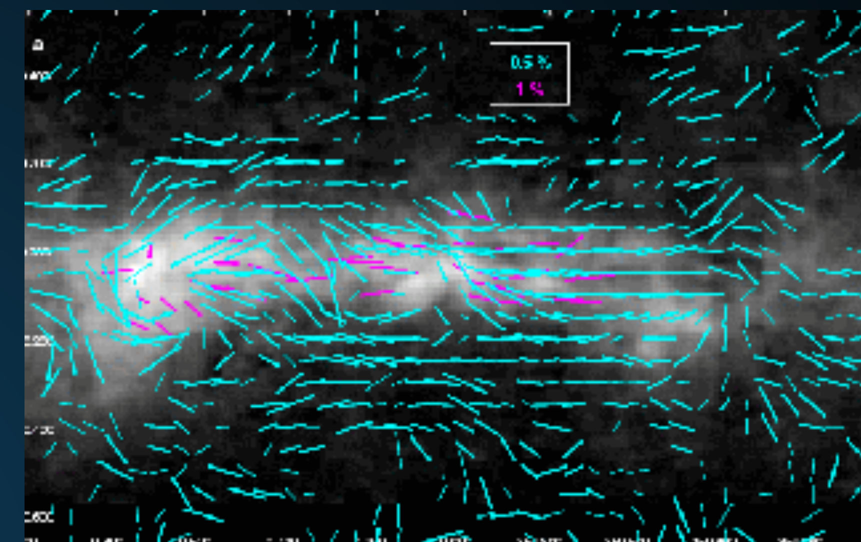
Solved Numerically:
e.g. Galprop

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

COSMIC-RAY ACCELERATION AND PROPAGATION

Start with a source of relativistic cosmic-rays

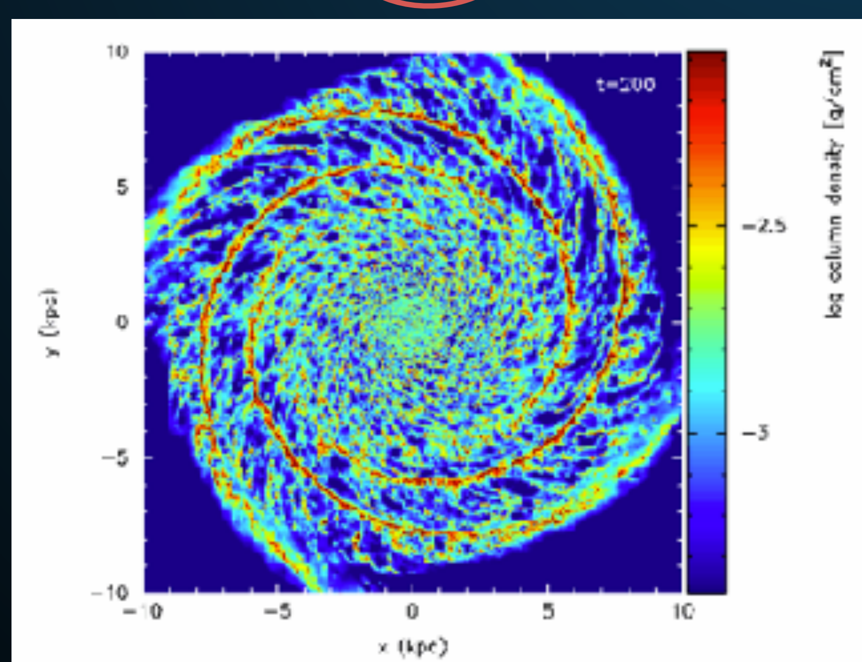
cosmic rays propagate



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

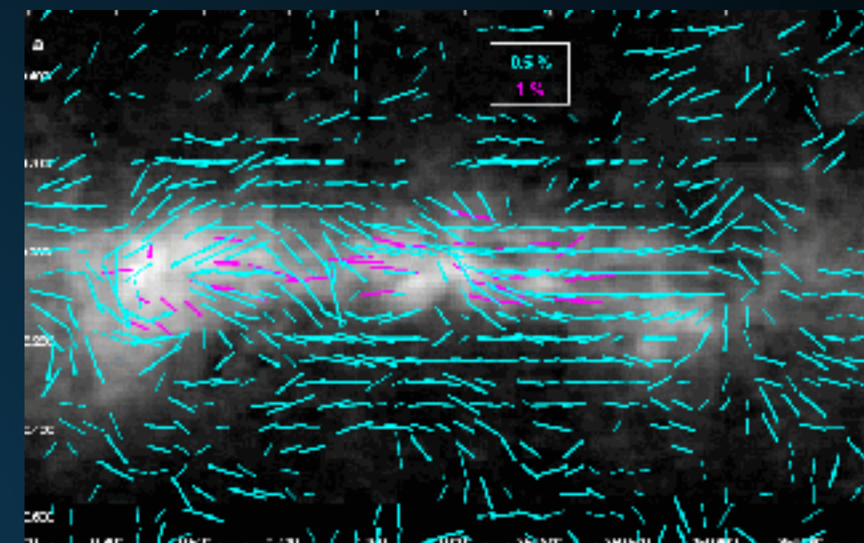
Solved Numerically:
e.g. Galprop

Gas/ISRF



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

Start with a source of relativistic cosmic-rays

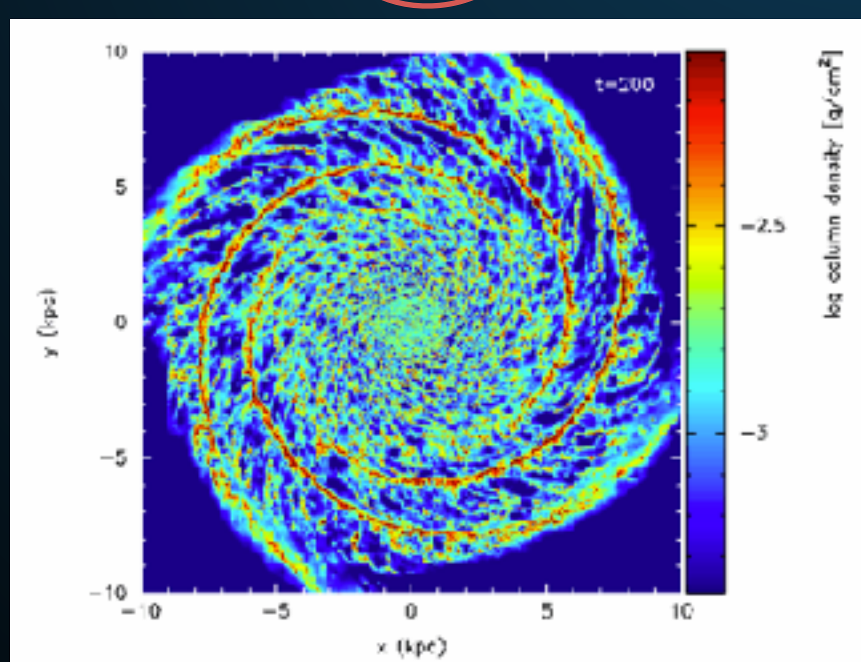


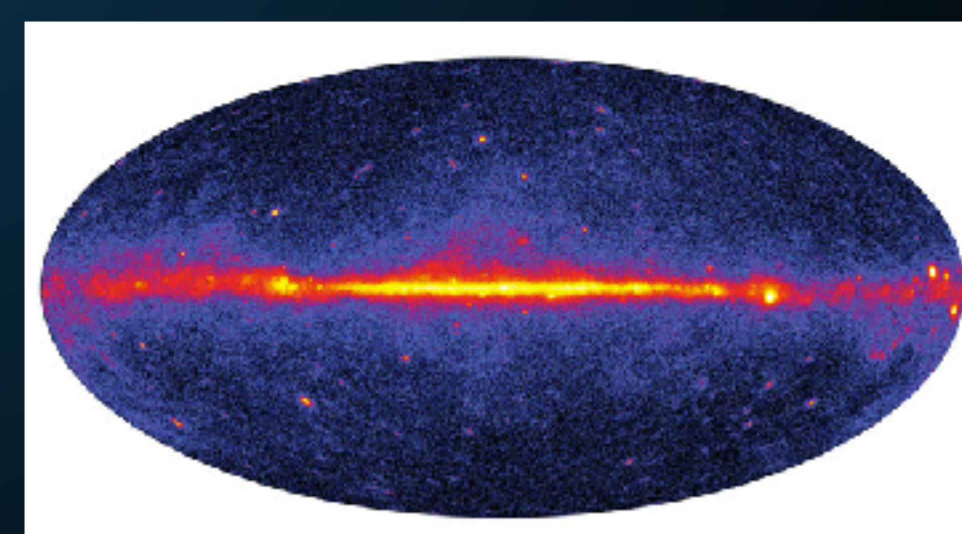
cosmic rays propagate

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

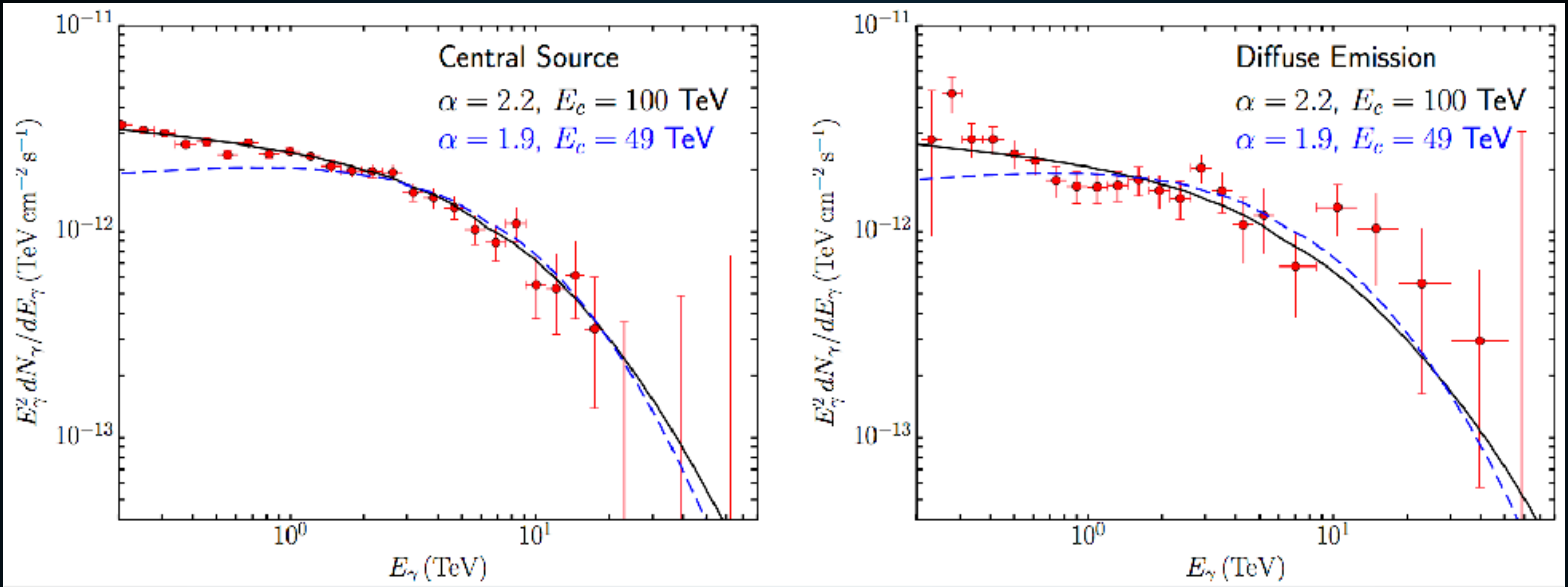
Solved Numerically:
e.g. Galprop

Gas/ISRF





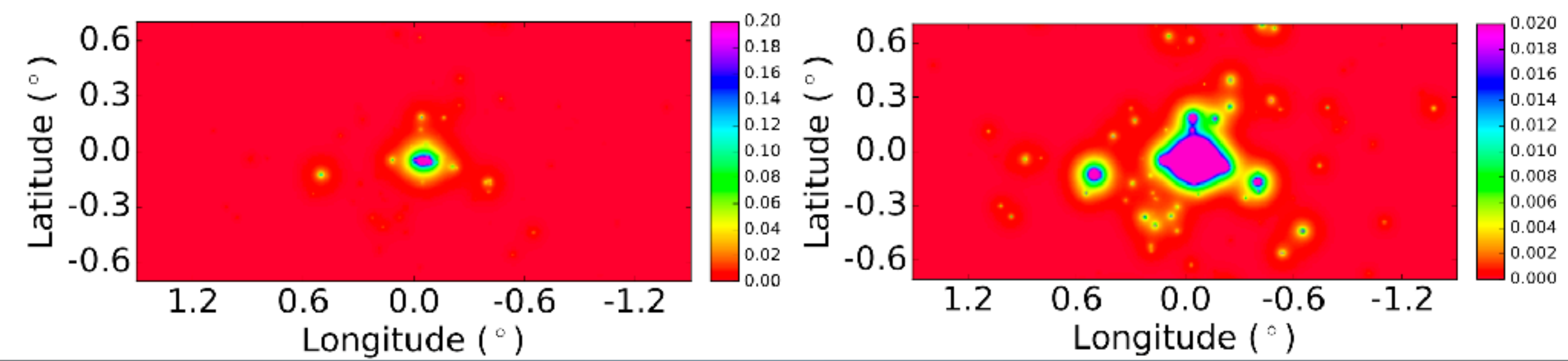
TEV HALOS PRODUCE THE PEVATRON SPECTRUM



- 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?

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.**

TWO DIFFERENT SOURCES OF INFORMATION

- This provides us two ways to learn about cosmic rays:
  - Investigating the cosmic-rays that directly hit satellites on Earth
    - Can directly detect cosmic-ray species
    - Only a local measurement
    - Solar Modulation
  - Investigating the gamma-ray signal from cosmic-ray interactions
    - Can understand propagation near sources
    - Don’t directly know the cosmic-ray species, or even if the gamma-ray is galactic
    - Line of sight