



TIM LINDEN

THE RISE OF THE LEPTONS

PULSAR EMISSION DOMINATES THE TEV GAMMA-RAY SKY

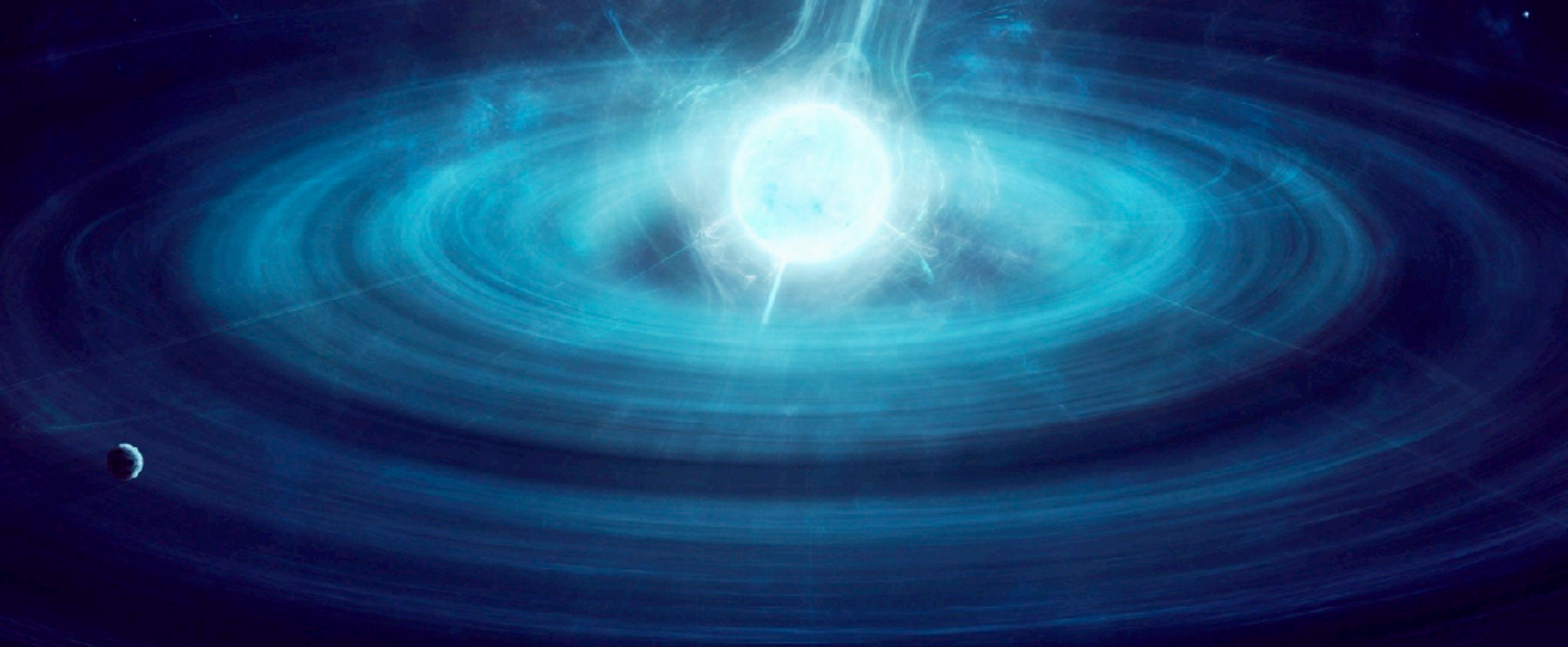
Imperial College London Brown-Bag Talk

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THE OHIO STATE UNIVERSITY

CENTER FOR COSMOLOGY AND
ASTROPARTICLE PHYSICS



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THE RISE OF THE LEPTONS

PULSAR EMISSION DOMINATES THE TEV GAMMA-RAY SKY

**WITH: KATIE AUCHETTL, BEN BUCKMAN,
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DAN HOOPER, SHIRLEY LI**

COSMIC-RAY ACCELERATION AND PROPAGATION



Start with a source of relativistic cosmic-rays

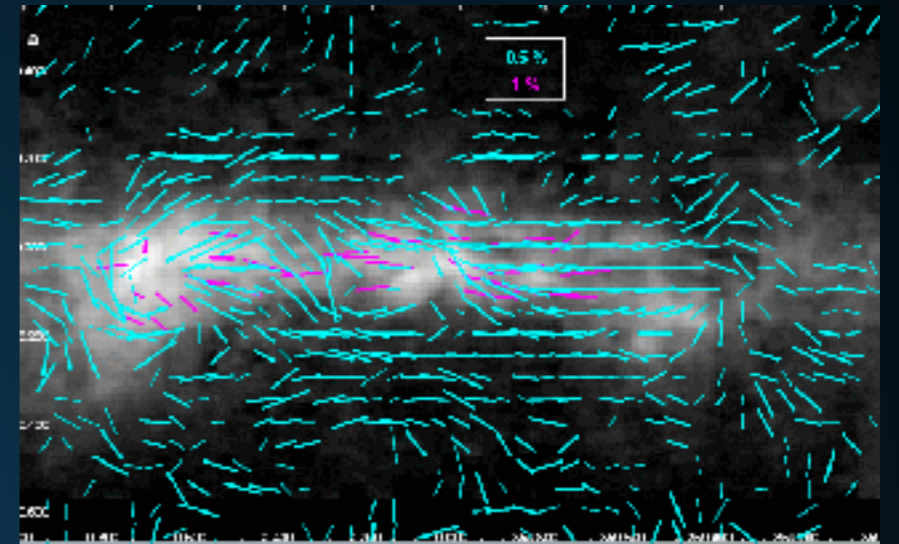
- ▶ **Supernova Explosions**
- ▶ **Supernova Remnants**
- ▶ **Pulsars**
- ▶ **Shocks/Mergers**

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

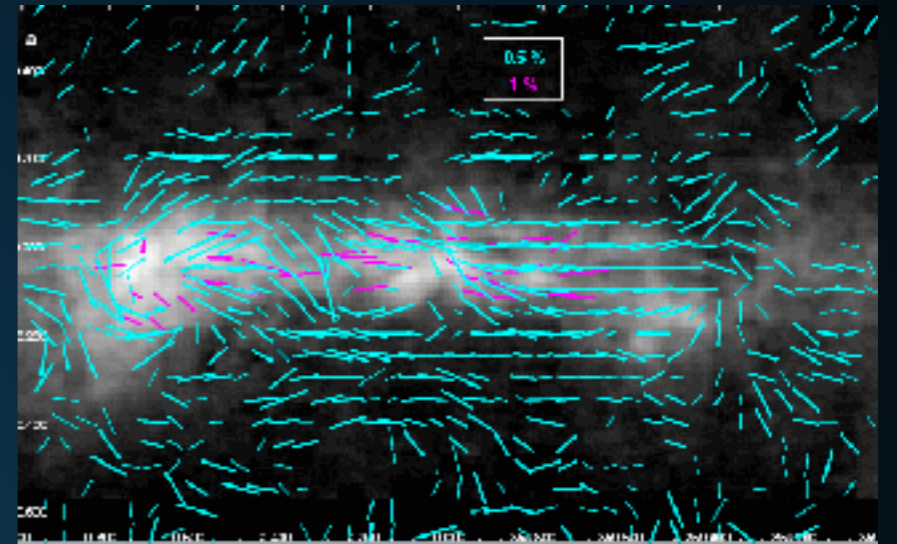
- ▶ If they propagate to Earth, can be detected:
 - ▶ AMS-02/PAMELA
 - ▶ CREAM/HEAT/CAPRICE

COSMIC-RAY ACCELERATION AND PROPAGATION

Start with a source of relativistic cosmic-rays



cosmic rays propagate

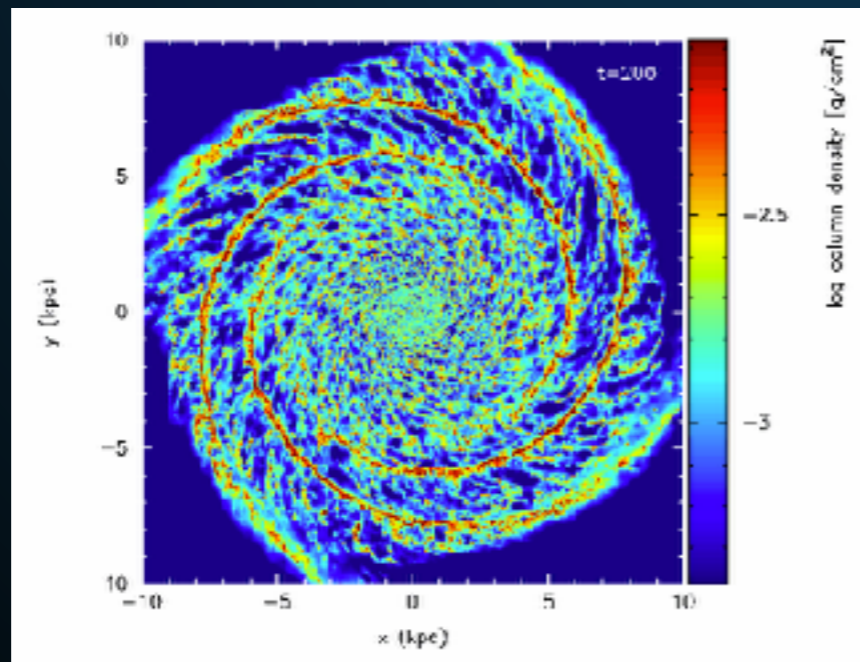


$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[p \dot{\psi} - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right]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

Solved Numerically:
e.g. Galprop

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

Gas/ISRF

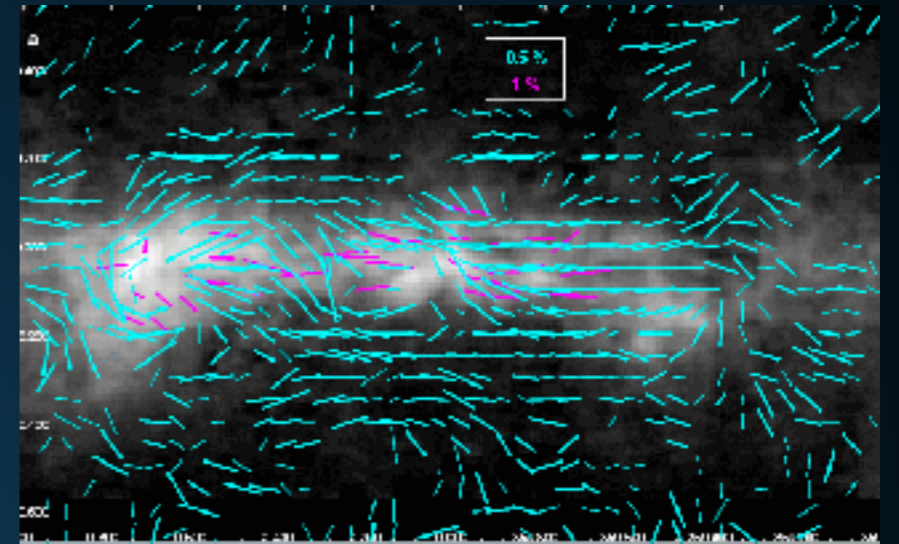


COSMIC-RAY ACCELERATION AND PROPAGATION



Start with a source of relativistic cosmic-rays

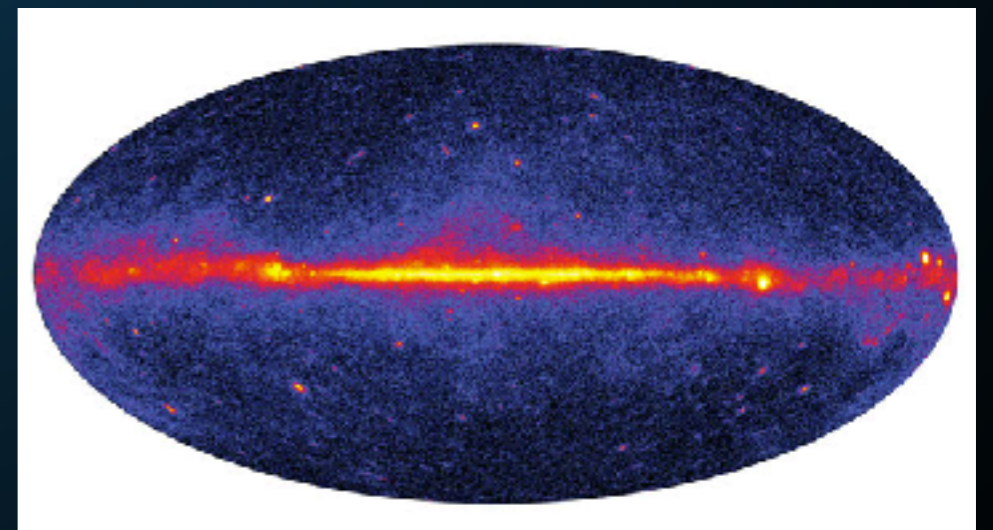
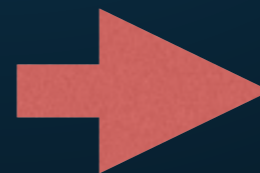
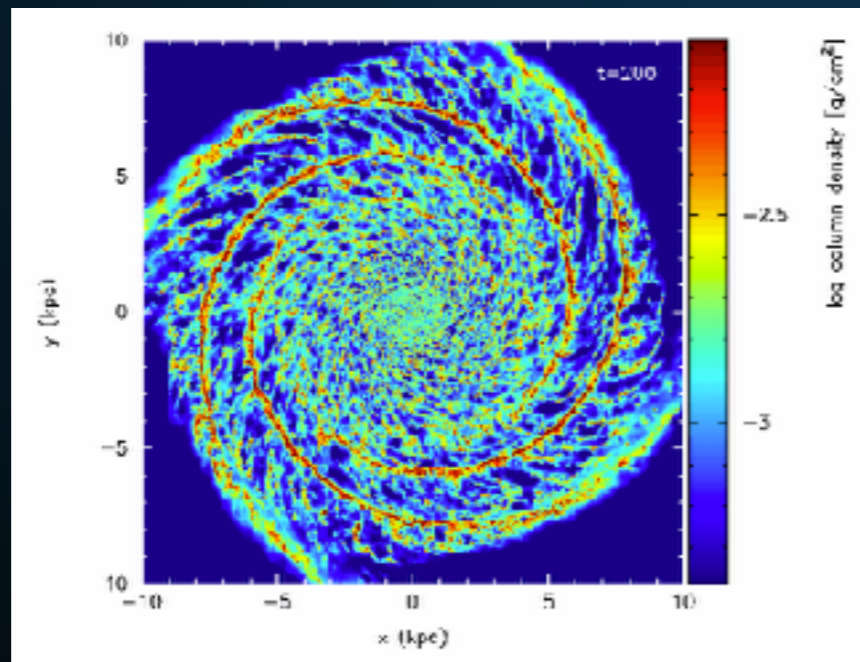
cosmic rays propagate



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

Solved Numerically:
e.g. Galprop

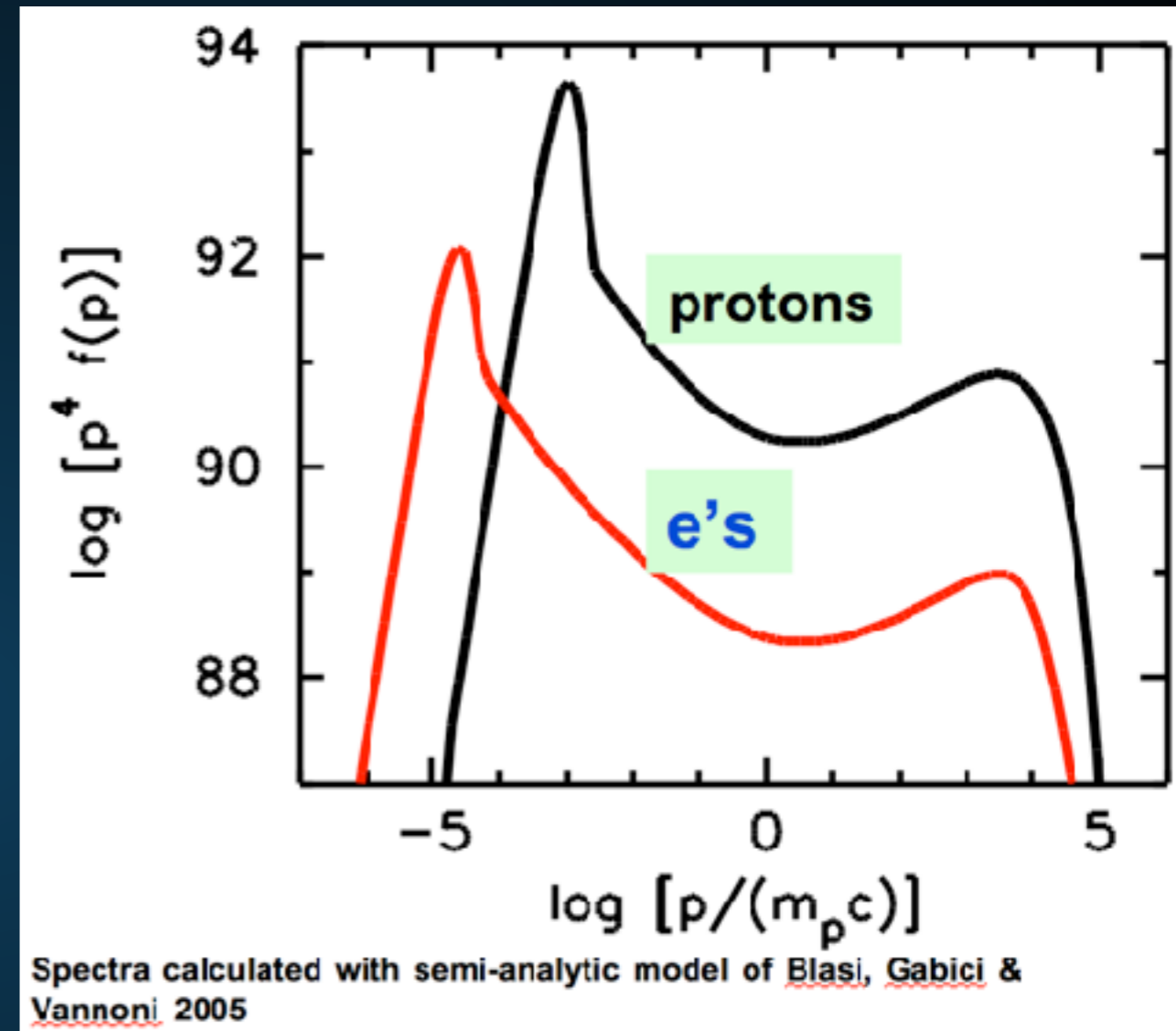
Gas/ISRF



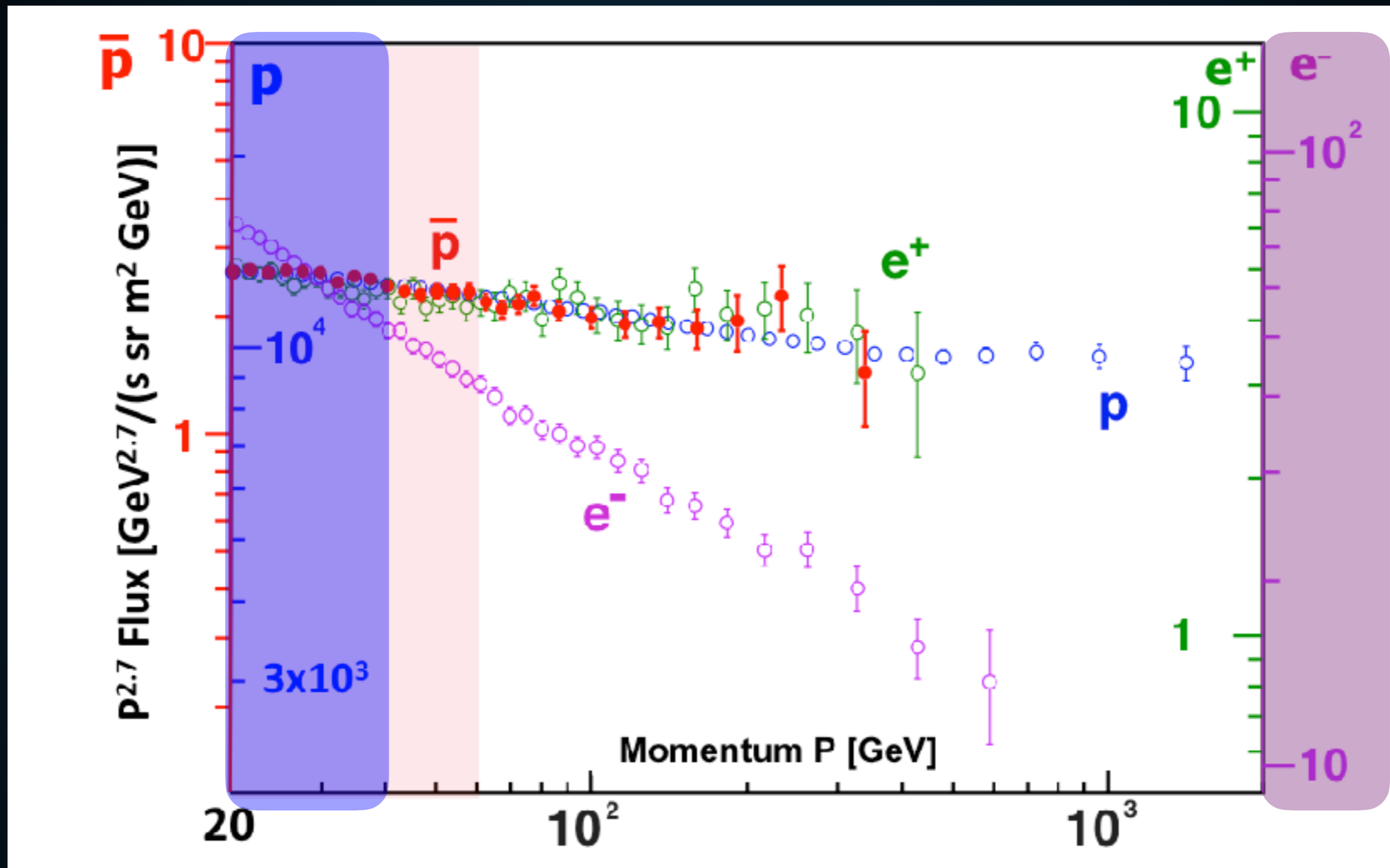
TWO DIFFERENT SOURCES OF INFORMATION

- ▶ **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**

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

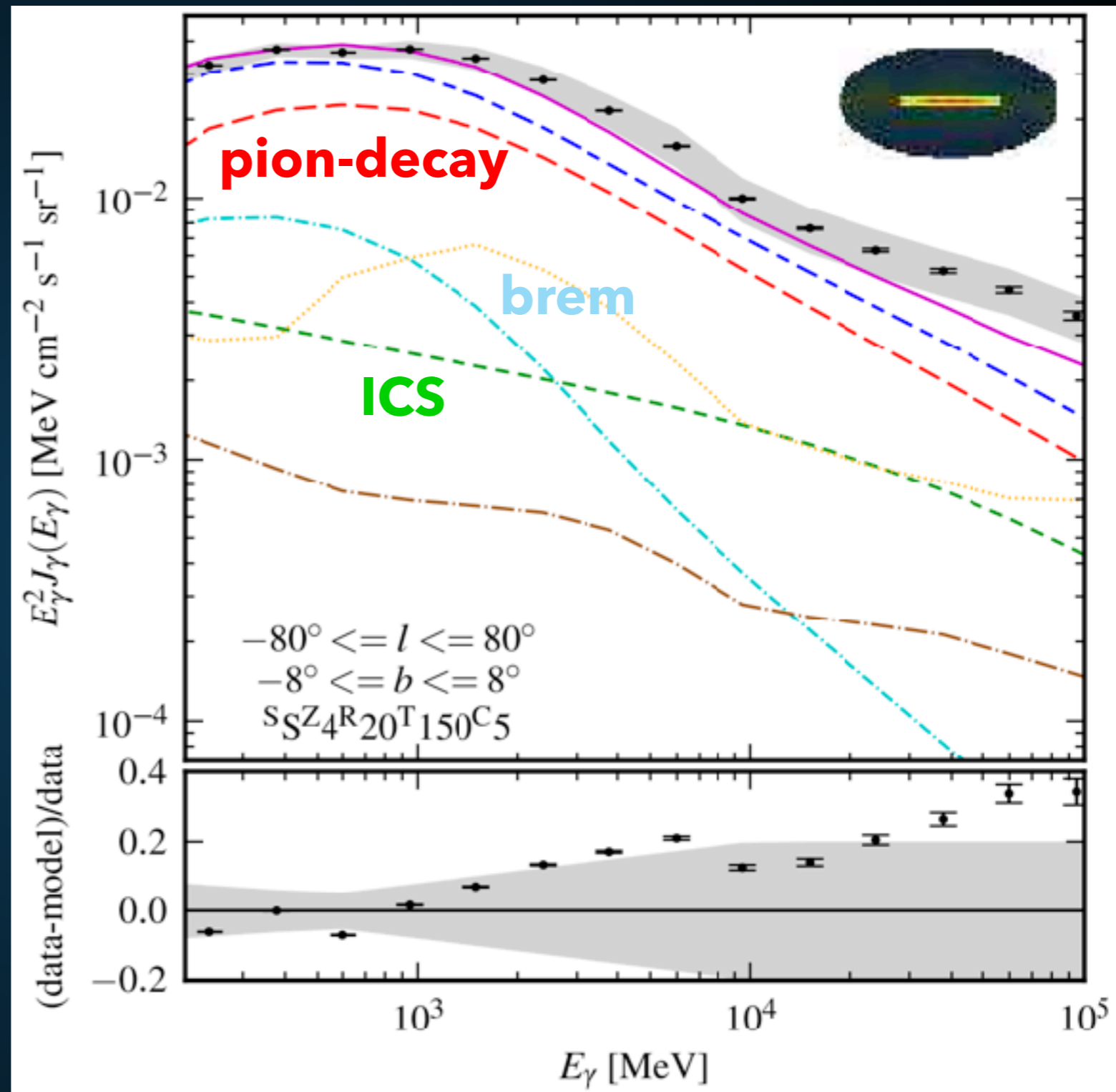


LOCAL COSMIC-RAY OBSERVATIONS



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

- ▶ Models of GeV galactic diffuse emission indicate that hadronic emission mechanisms are highlight dominant.
- ▶ Models indicate a slightly larger leptonic fraction at high energies.



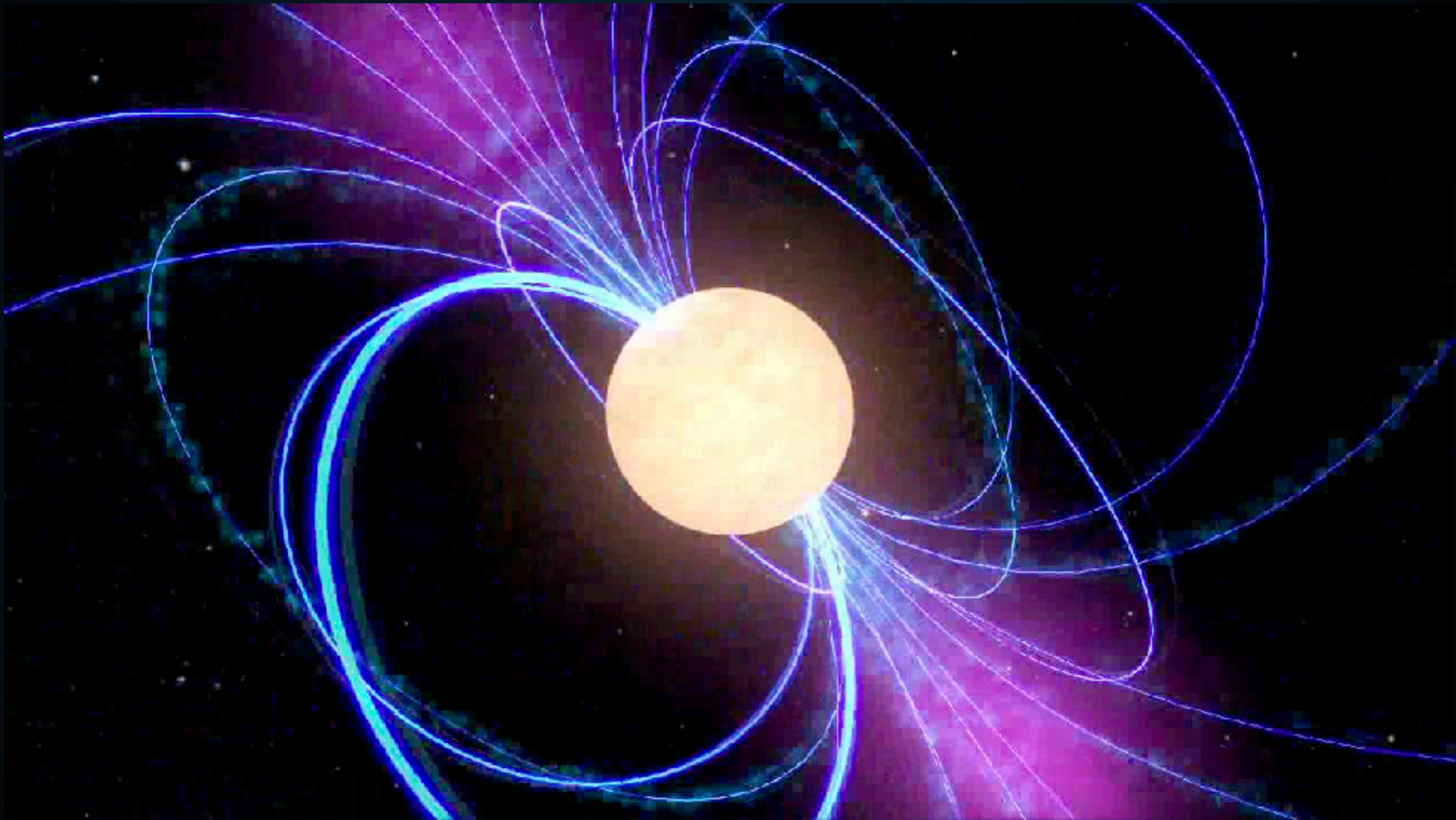
A NEW PICTURE

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

A VERY SIMPLE MODEL OF PULSAR EMISSION

Pulsars as high-energy particle accelerators

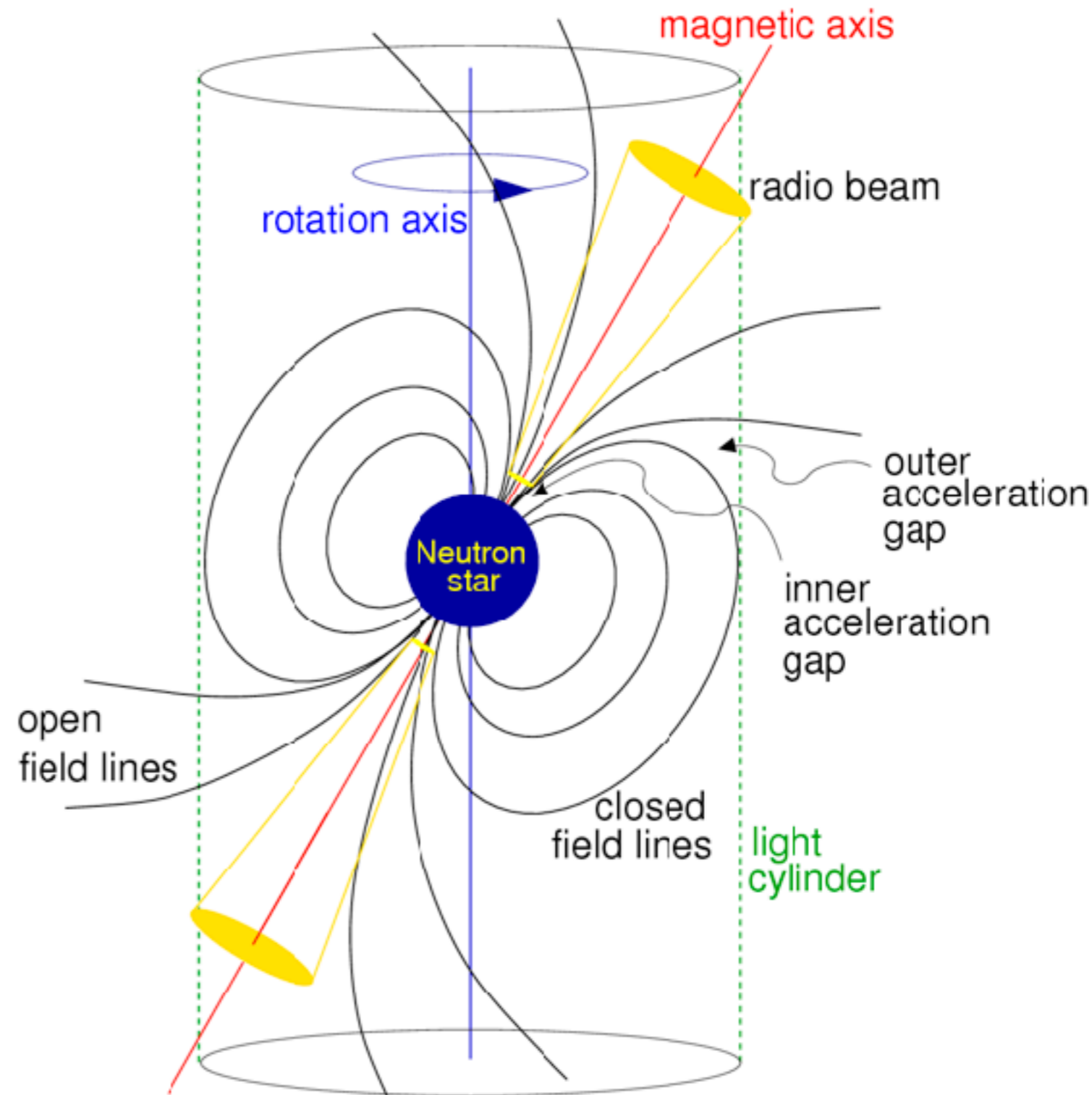
PULSARS AS ASTROPHYSICAL ACCELERATORS



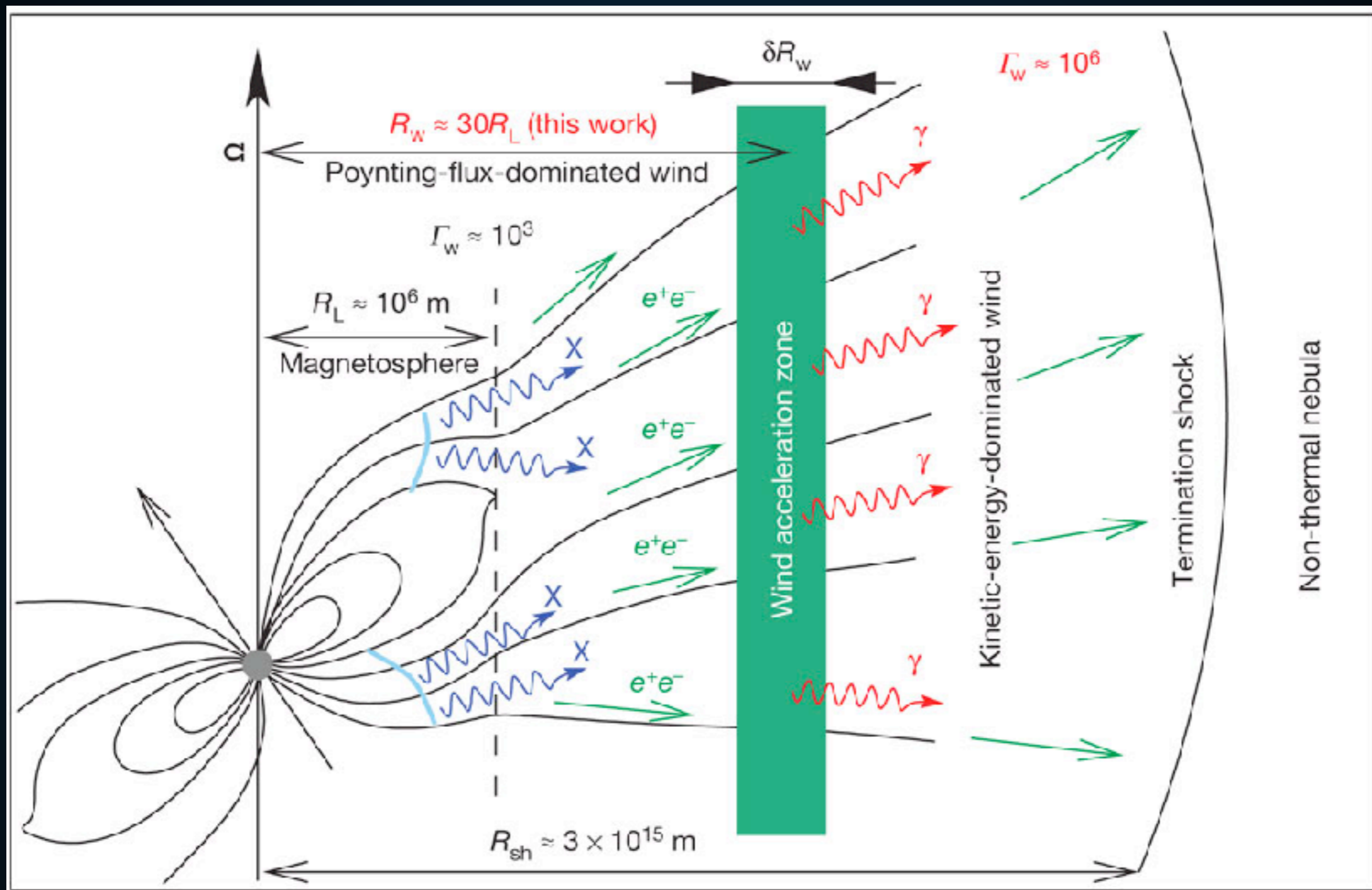
- ▶ **Rotational Kinetic Energy of the neutron star is the ultimate power source of all emission in this problem.**

PULSARS AS ASTROPHYSICAL ACCELERATORS

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

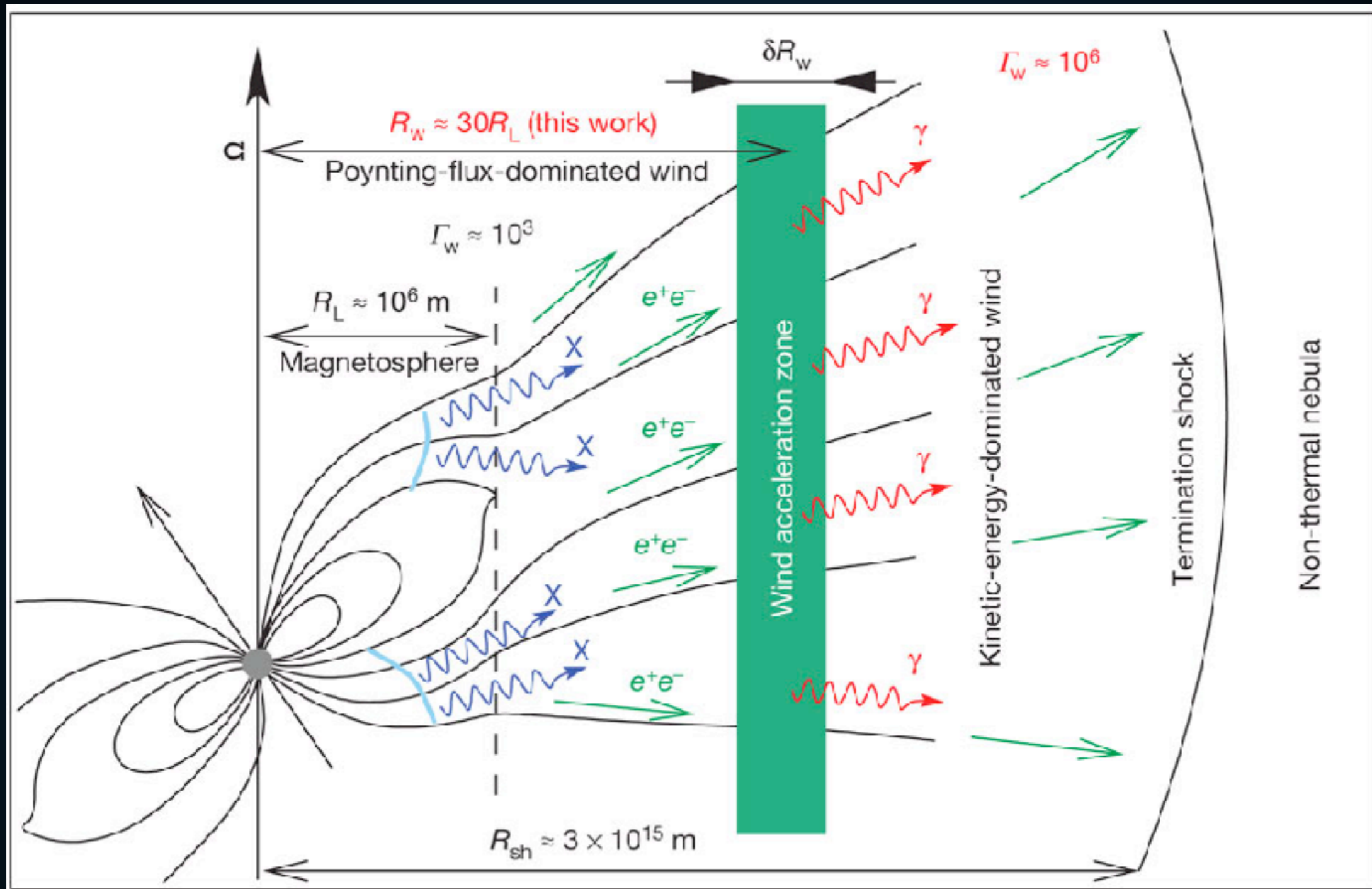


PRODUCTION OF ELECTRON AND POSITRON PAIRS



- ▶ Electrons boiled off the pulsar surface produce e^+e^- pairs
- ▶ Pair multiplicity is high, but model dependent.

PRODUCTION OF ELECTRON AND POSITRON PAIRS



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

REACCELERATION IN THE PULSAR WIND NEBULA



Blandford & Ostriker (1978)
Hoshino et al. (1992)
Coroniti (1990)
Sironi & Spitkovsky (2011)

- ▶ **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**

IN THIS TALK

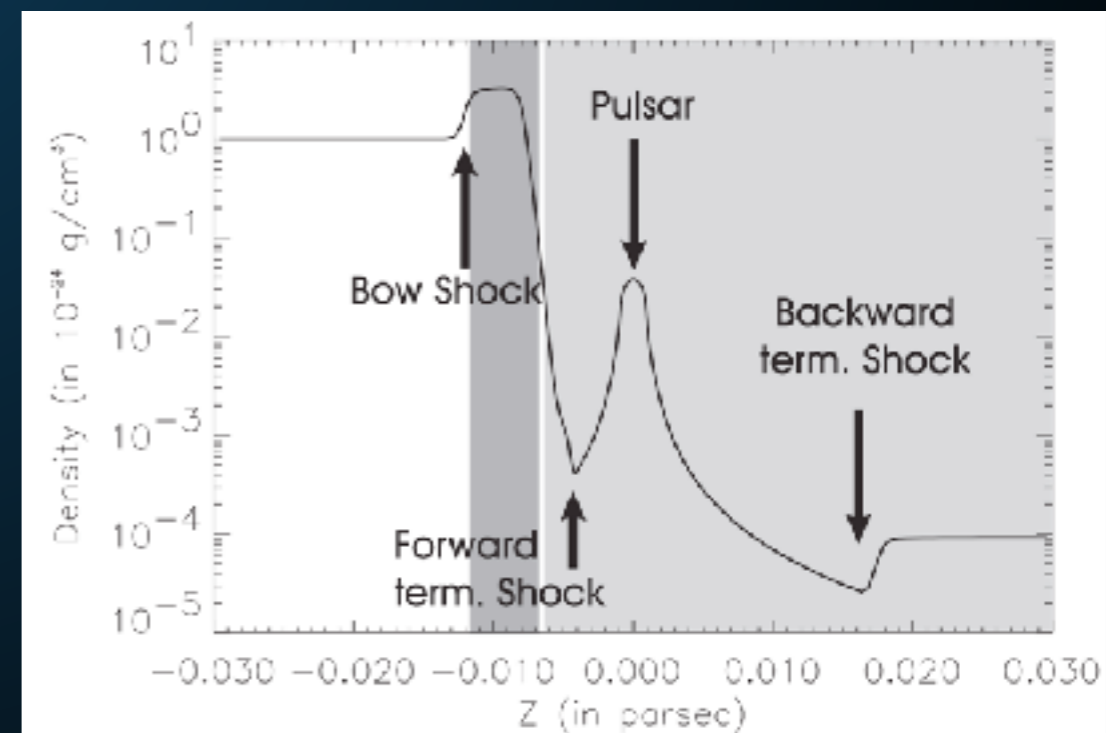
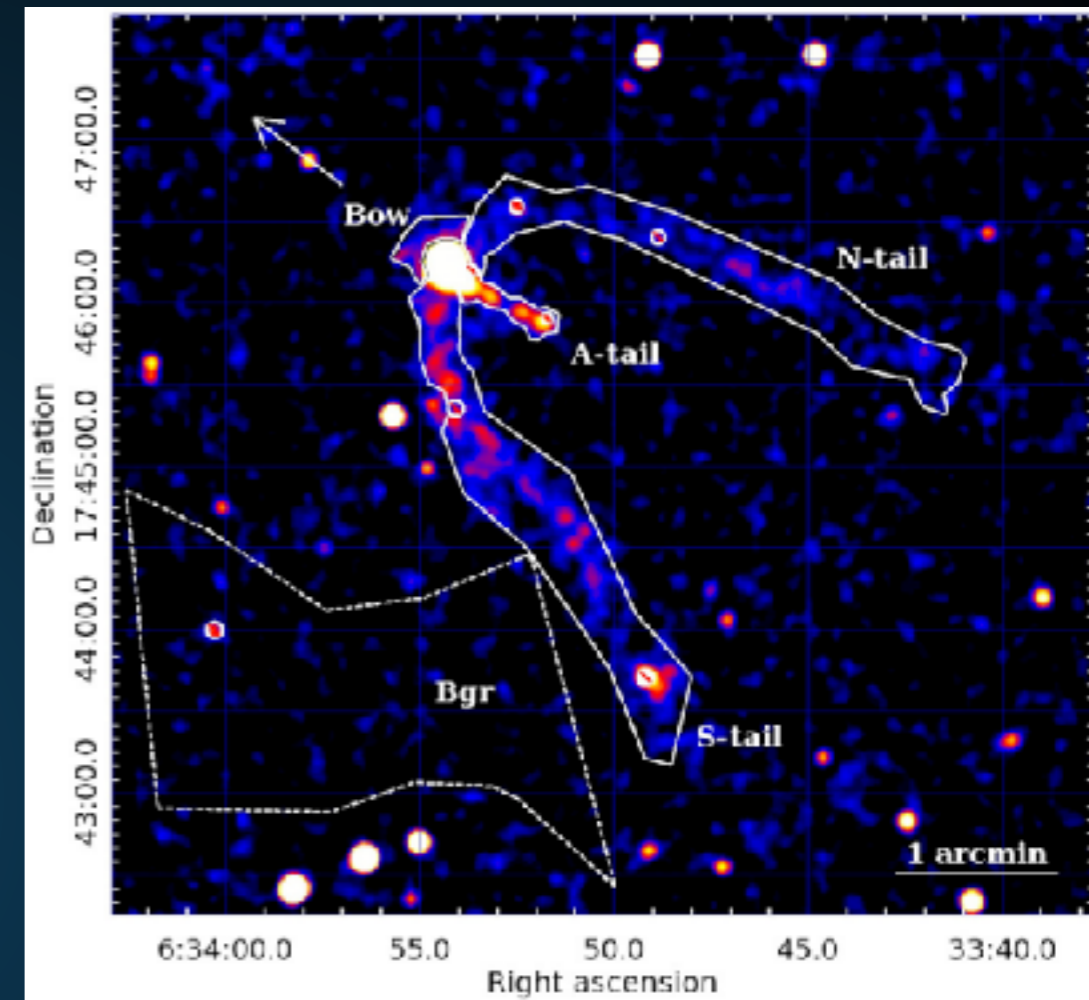
- ▶ Will remain agnostic to source of relativistic e^+e^-
- ▶ Will assume a simple power-law spectrum with an exponential cutoff:

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

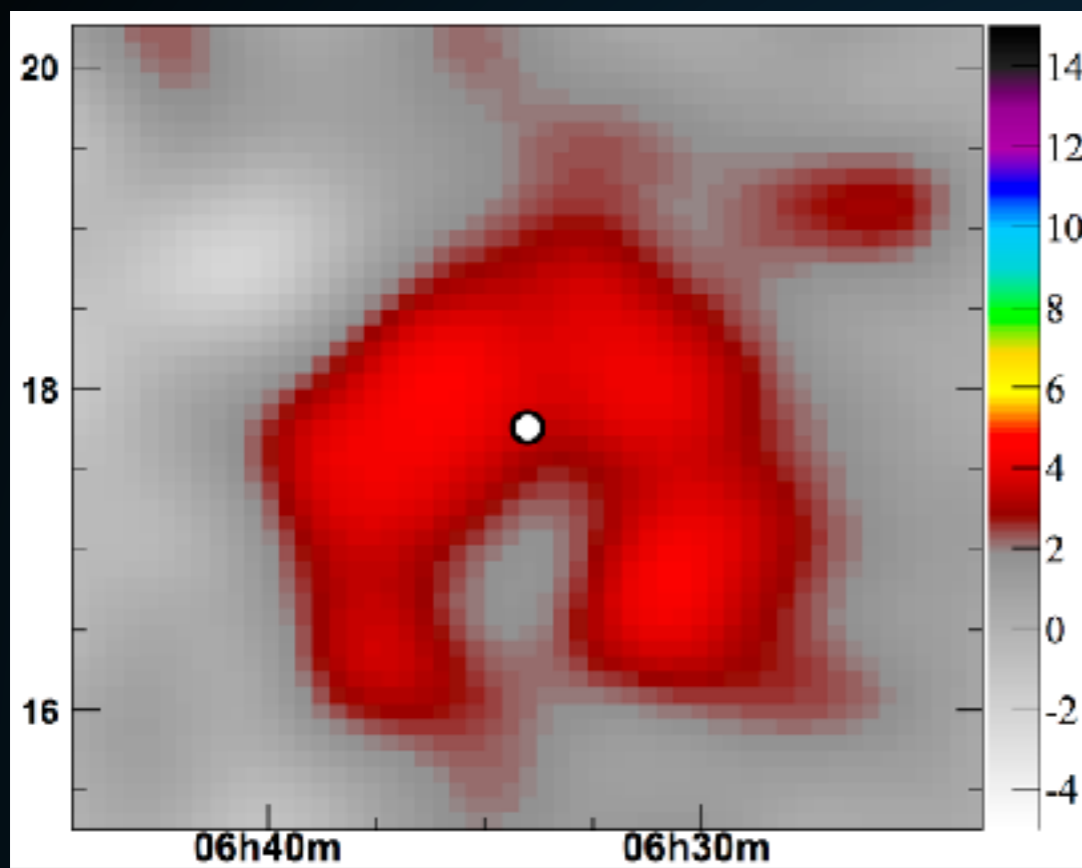
- ▶ **Extent of radio and X-Ray PWN is approximately 1 pc.**
- ▶ **Termination shock produced when ISM energy density overwhelms and stops the relativistic pulsar wind.**

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

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

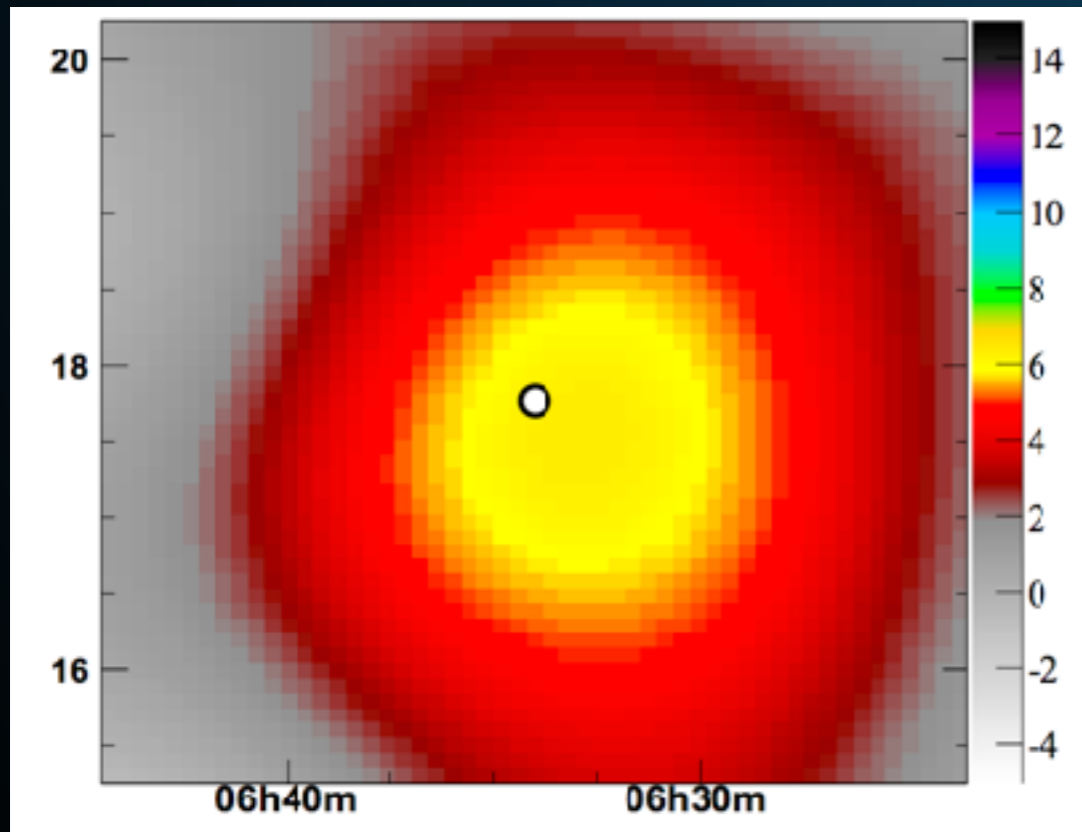


TeV observations inform pulsar models



▶ Milagro observes very extended emission from Geminga ($2.6^{+0.7}_{-0.9}^\circ$)

▶ 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 [$^{\circ}$]	Index	$F_{\gamma} \times 10^{16}$ [$\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$]	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 confirms Geminga observation.**
- ▶ **Also sees Monogem at high significance and spatial extension.**
- ▶ **Spatial extension for both systems is $\sim 2^{\circ}$.**

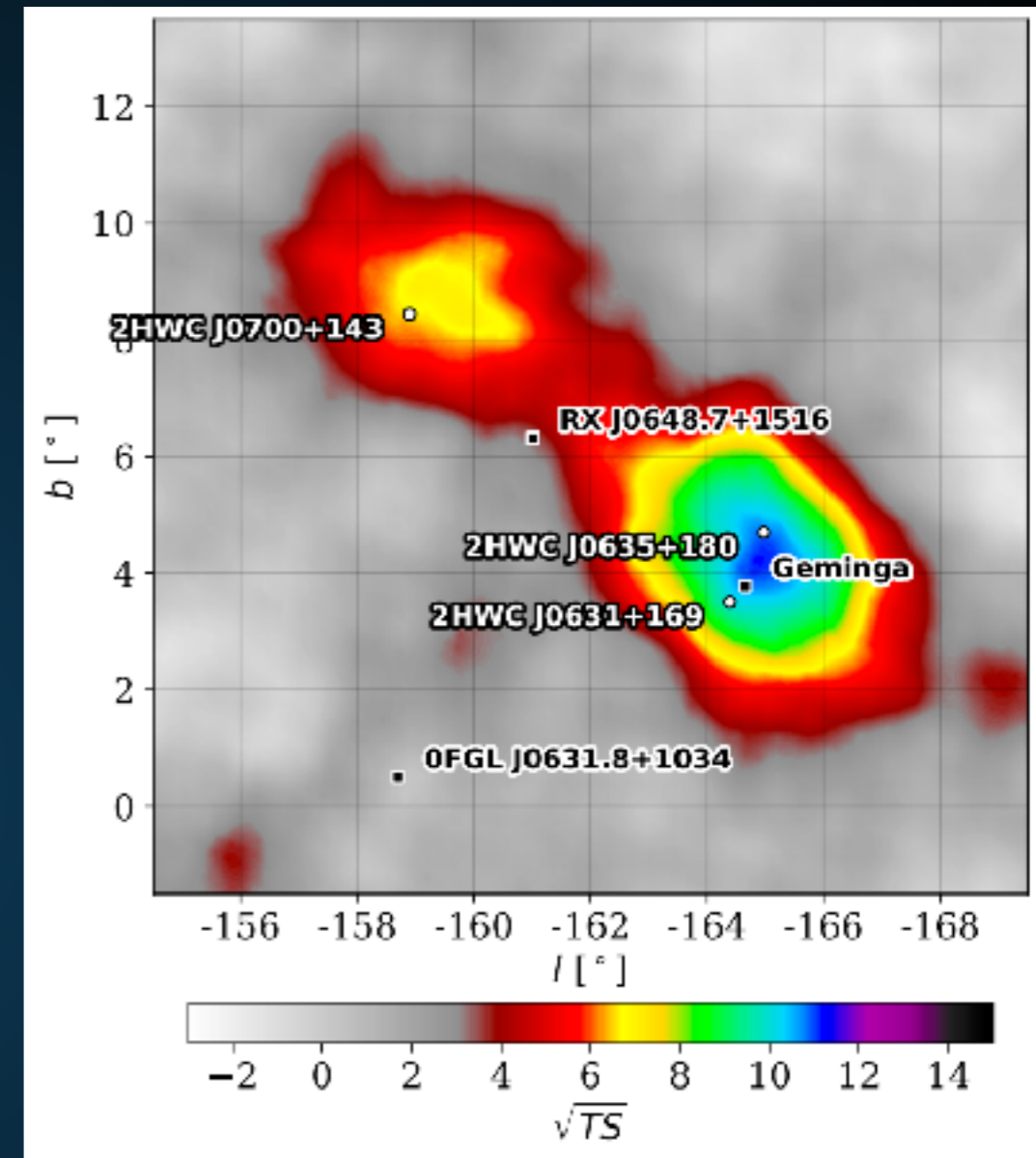


Table 1 HGPS sources considered as firmly identified pulsar wind nebulae in this paper.

HGPS name	ATNF name	Canonical name	$\lg \dot{E}$	τ_c (kyr)	d (kpc)	PSR offset (pc)	Γ	$R_{\text{PW N}}$ (pc)	$L_{1-10 \text{ TeV}}$ ($10^{33} \text{ erg s}^{-1}$)
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

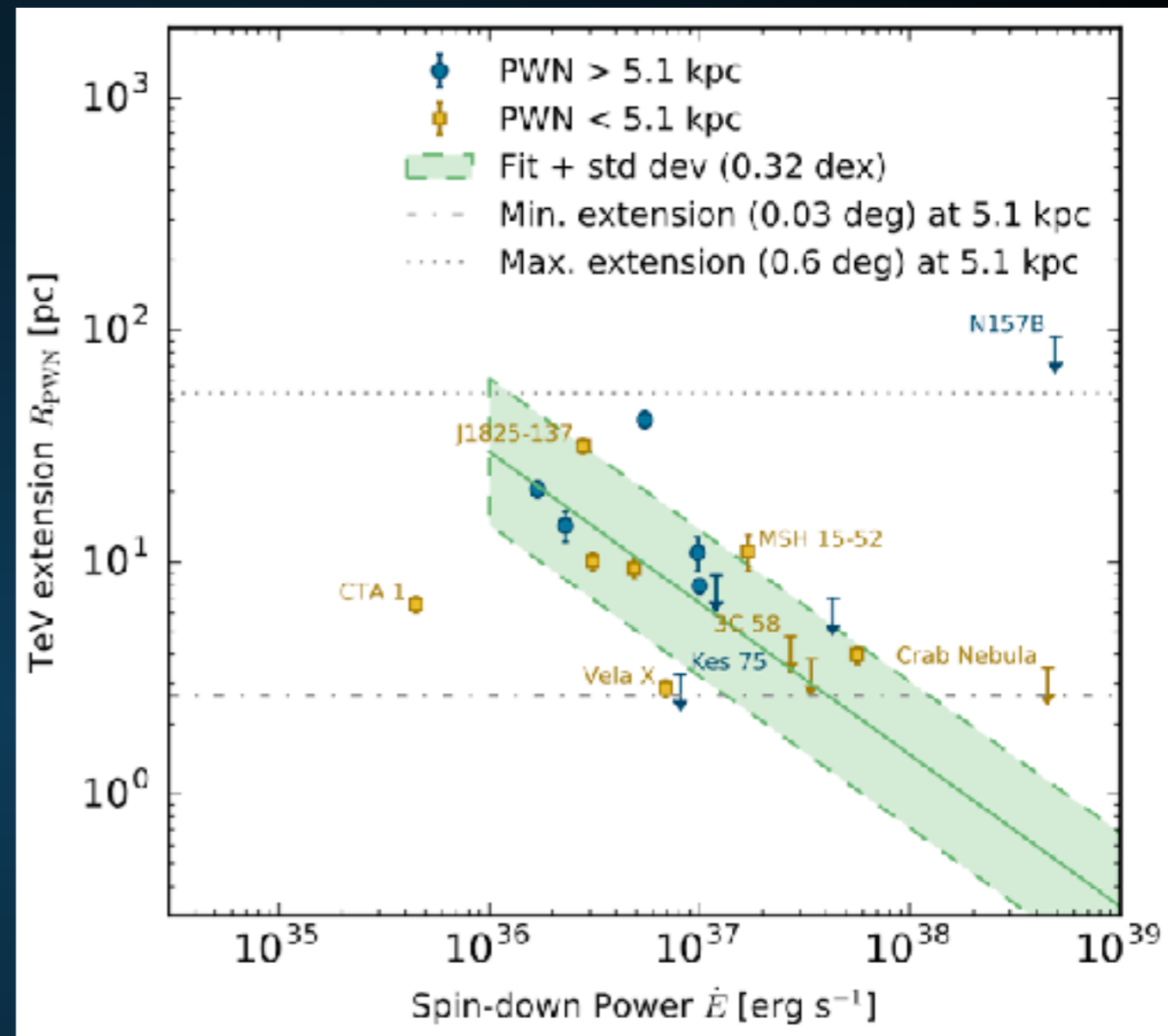
- ▶ HESS finds a large population of “TeV PWN”
- ▶ HESS systems have a higher spin down power, but are more distant.

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)	$L_{1-10 \text{ TeV}}$ ($10^{33} \text{ erg s}^{-1}$)
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.

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



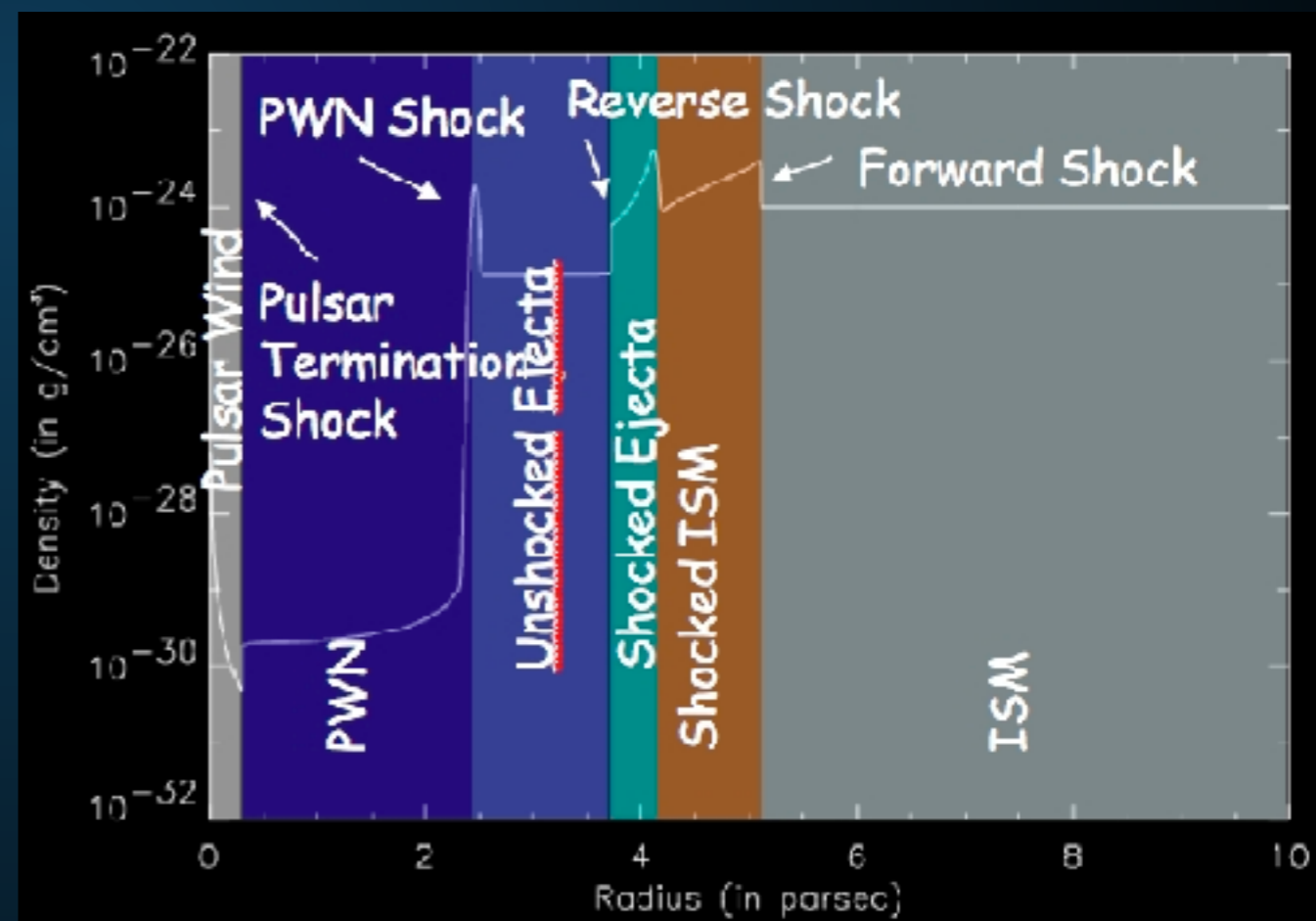
NOTE: This has the opposite energy dependence as the X-Ray PWN.

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

TeV HALOS

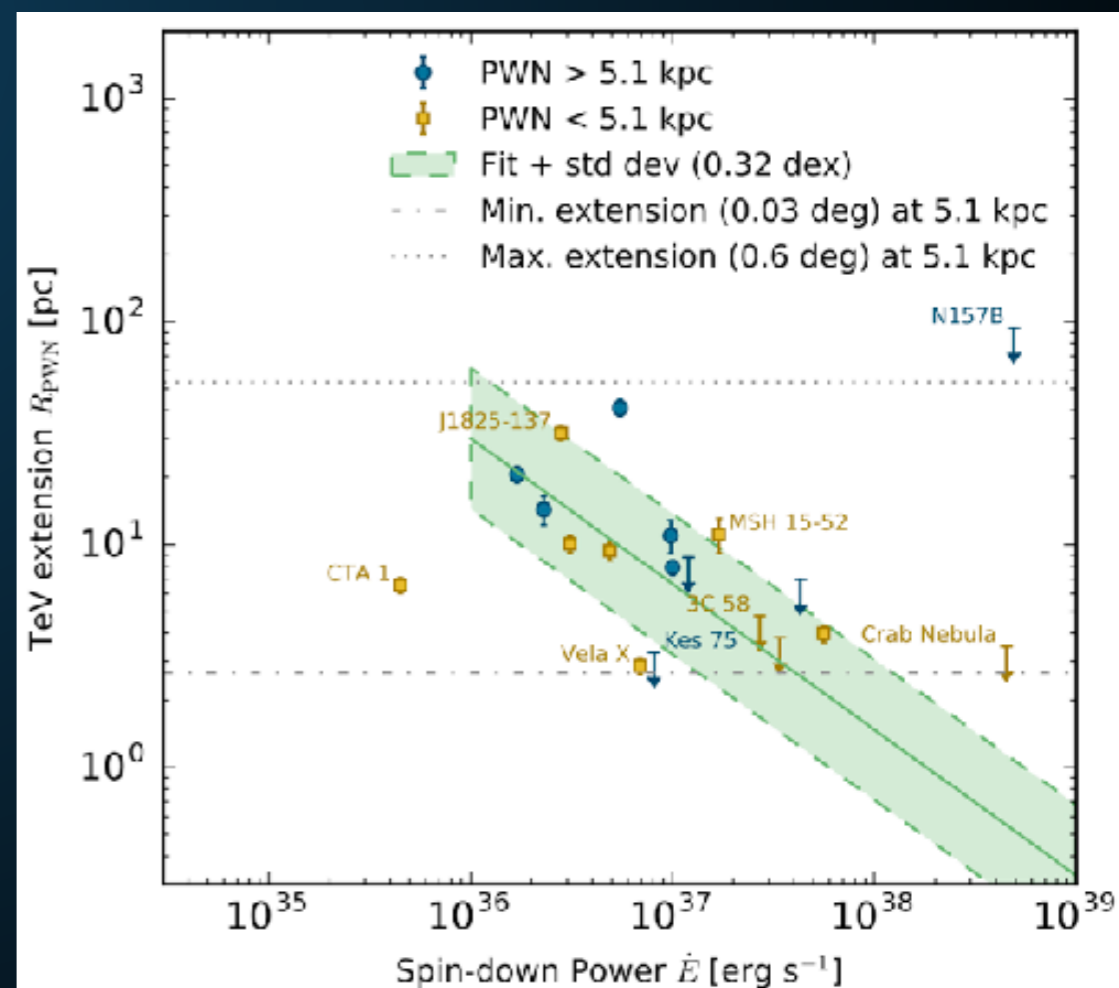
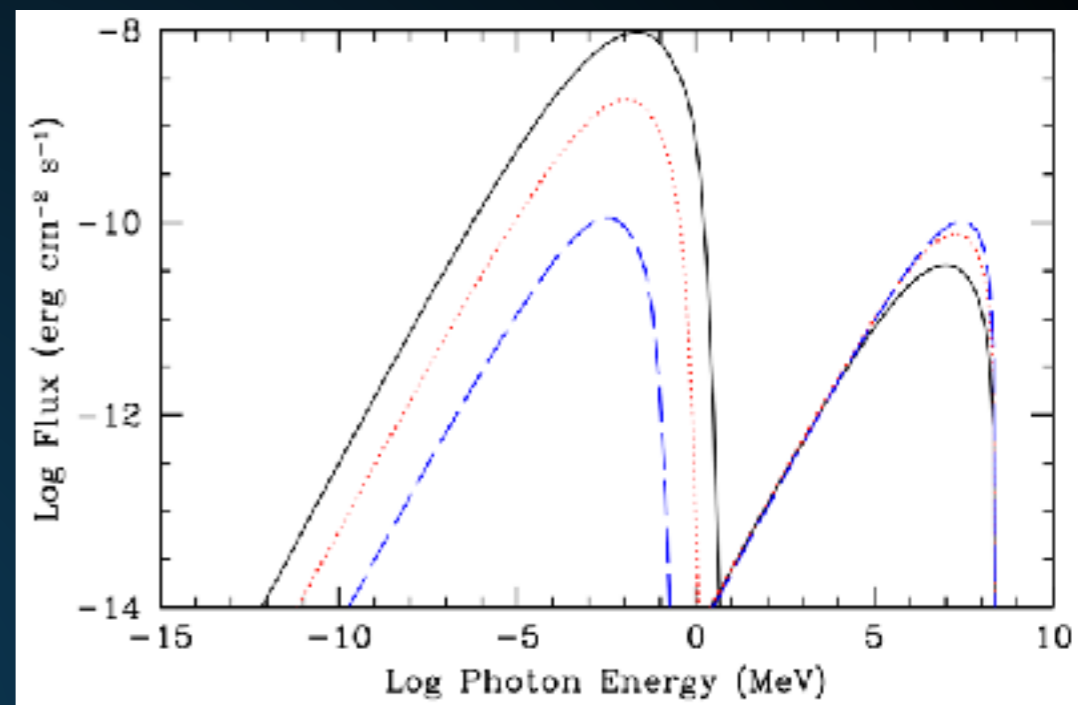
- ▶ **TeV halos are a new feature**
 - ▶ **3 orders of magnitude larger than PWN in volume**
 - ▶ **Opposite energy dependence**

- ▶ **PWN are morphologically connected to the physics of the termination shock**
- ▶ **TeV halos need a similar morphological description.**



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.**

INVERSE COMPTON SCATTERING WITH THE ISM

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

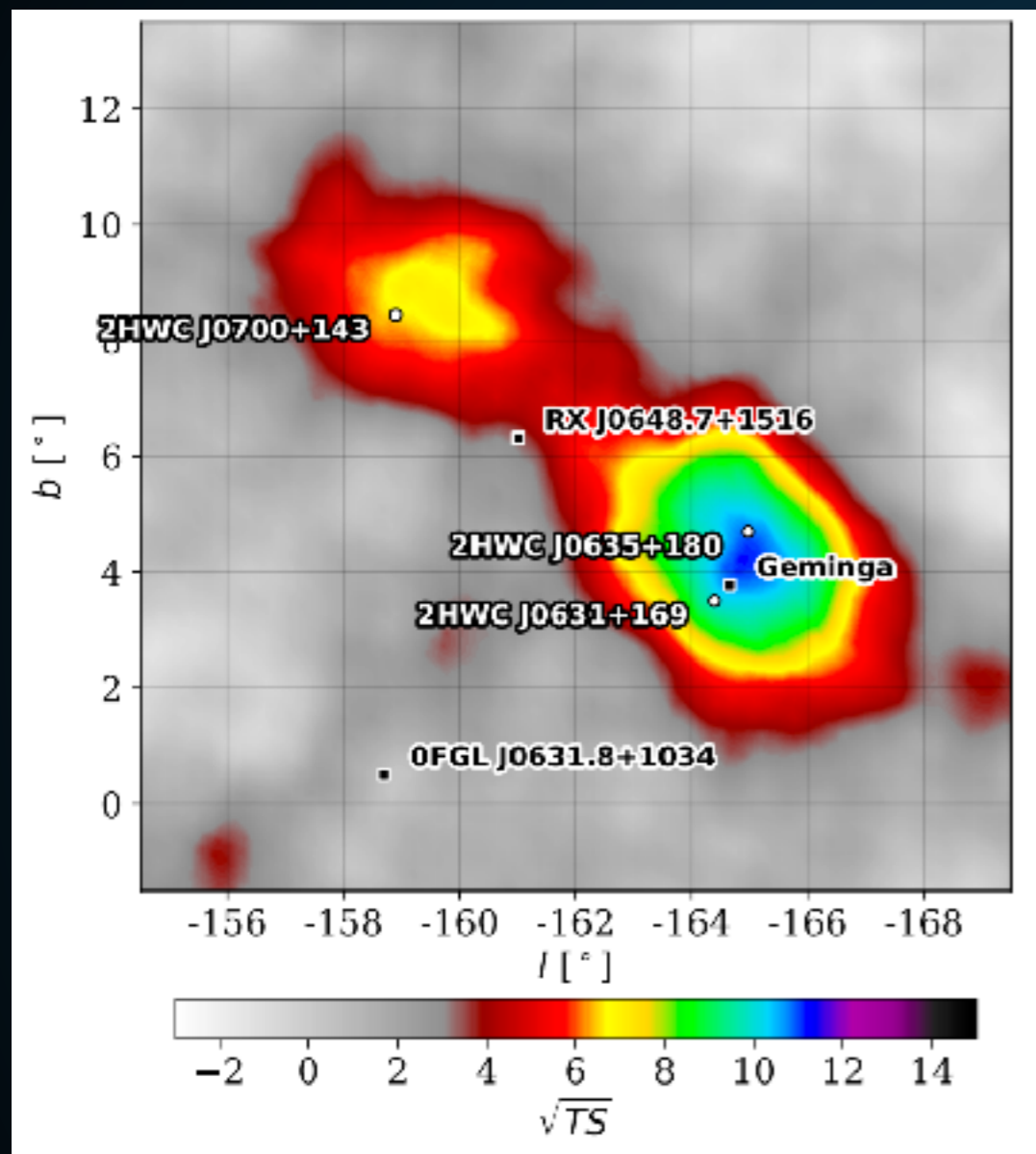
$$U = \frac{1}{8\pi} B^2 = \frac{(10 \mu\text{G})^2}{8\pi}$$
$$= 4 \times 10^{-12} \frac{\text{erg}}{\text{cm}^3}$$
$$\int_0^{10 \text{ pc}} U dV = 5 \times 10^{47} \text{ erg}$$
$$\hookrightarrow \text{Magnetic Flux} \approx 5 \times 10^{38} \frac{\text{erg}}{\text{s}}$$

$$\text{ISRF} = 1 \frac{\text{eV}}{\text{cm}^3}$$
$$\int \text{ISRF} dV = 8 \times 10^{47} \text{ erg}$$
$$\hookrightarrow \text{Flux} = 8 \times 10^{38} \frac{\text{erg}}{\text{s}}$$

- ▶ We can use typical ISM values ($5 \mu\text{G}$; 1 eV cm^{-3}) to characterize interactions.
- ▶ Nearly equal energy to synchrotron and ICS.

TWO CONTRASTING OBSERVABLES

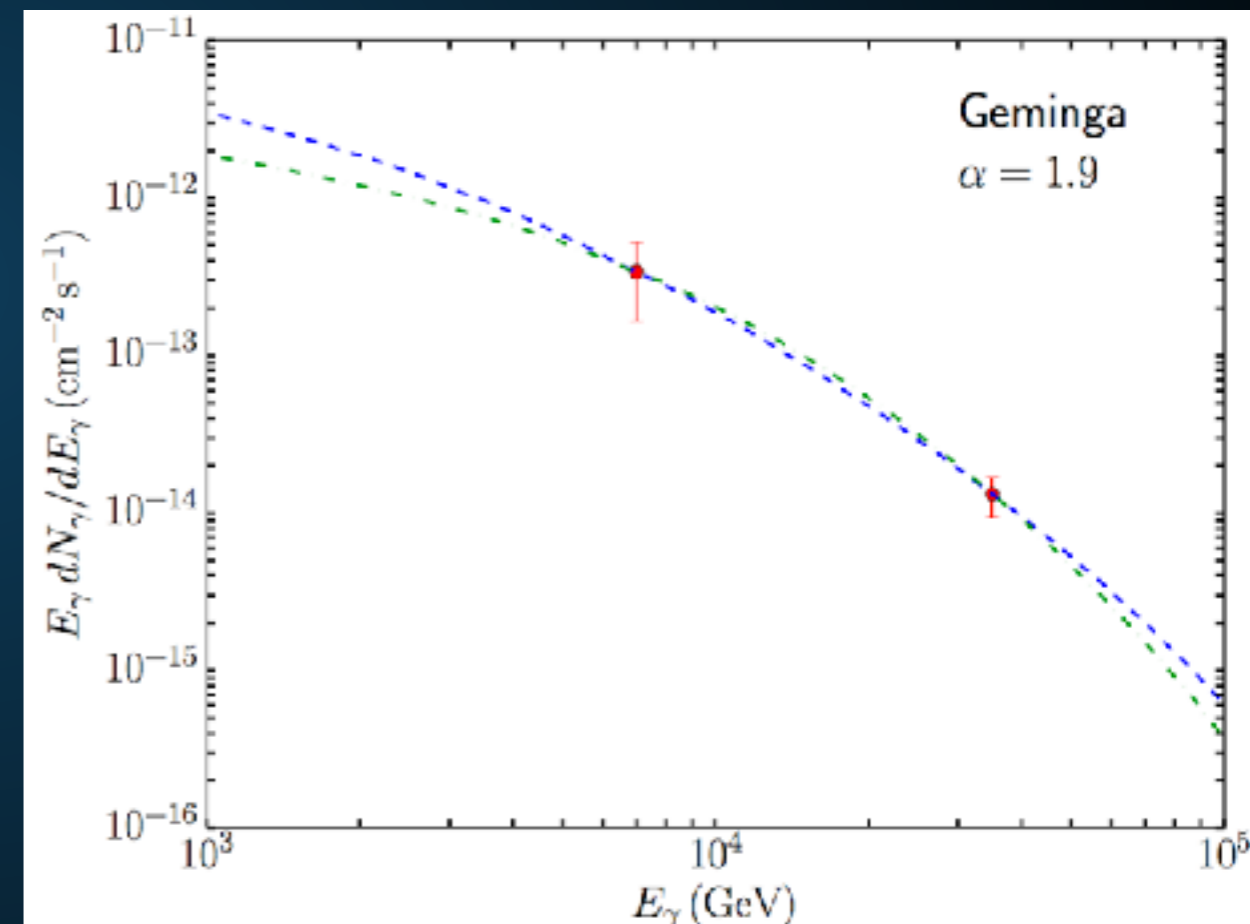
Geminga is Bright



Indicative of significant
electron cooling

Geminga has a hard-spectrum

Name	Tested radius [°]	Index	$F_\gamma \times 10^{15}$ [$\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$]	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:**

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

- ▶ **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

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

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

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

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

$$D = 1.6 \times 10^{26} \frac{\text{cm}^2}{\text{s}}$$

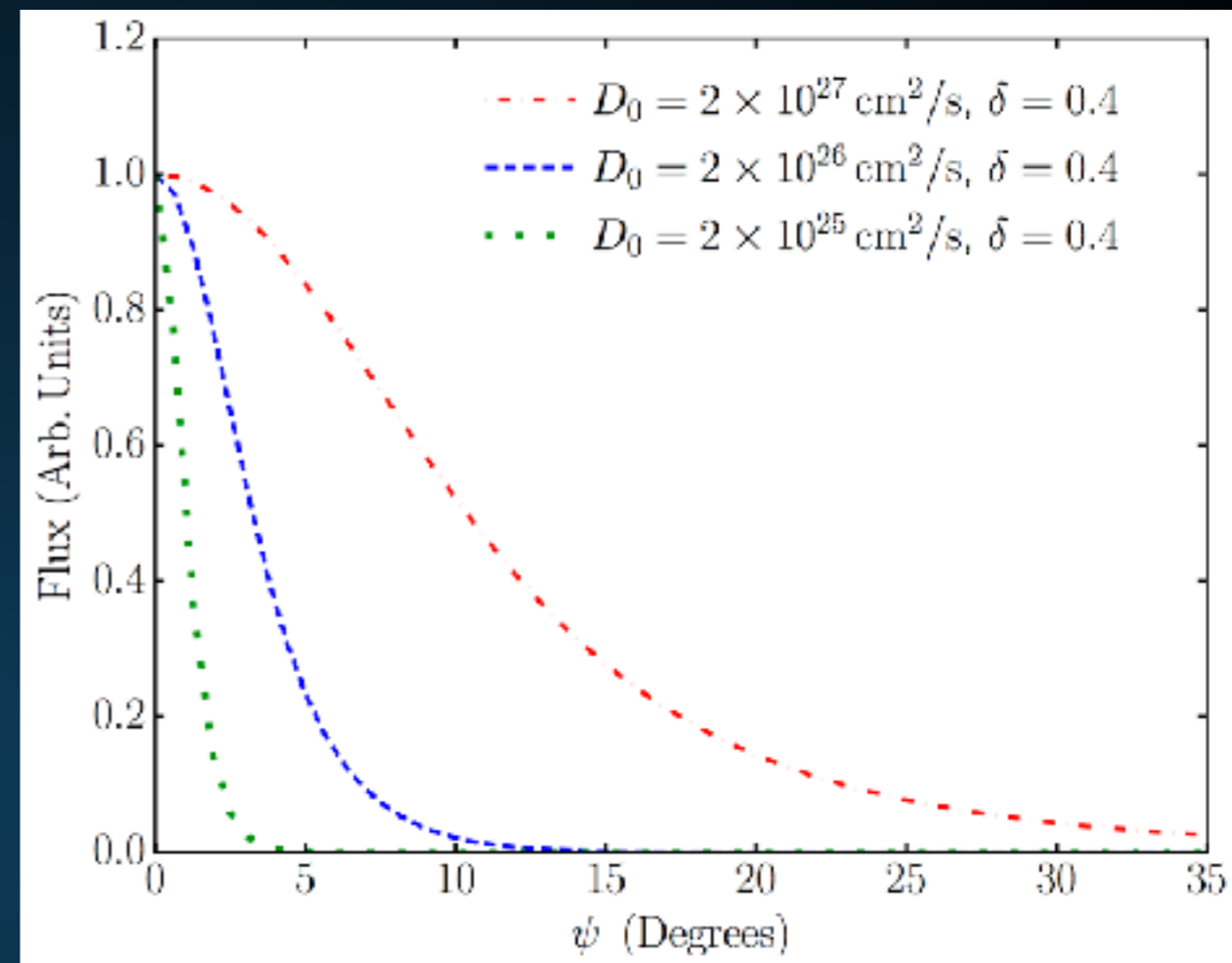
- ▶ Provides strong evidence for new morphological feature.

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.

SPECTRUM OF TEV HALOS

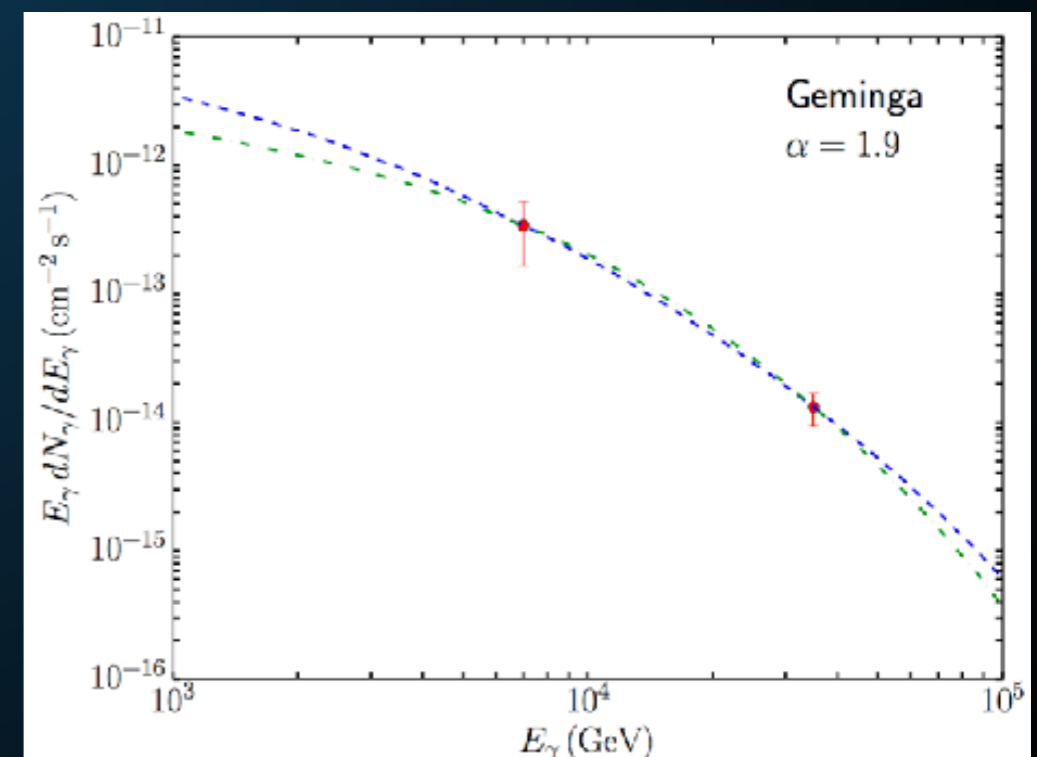
- ▶ **Geminga has a hard gamma-ray spectrum**

Name	Tested radius [°]	Index	$F_{\gamma} \times 10^{15}$ [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

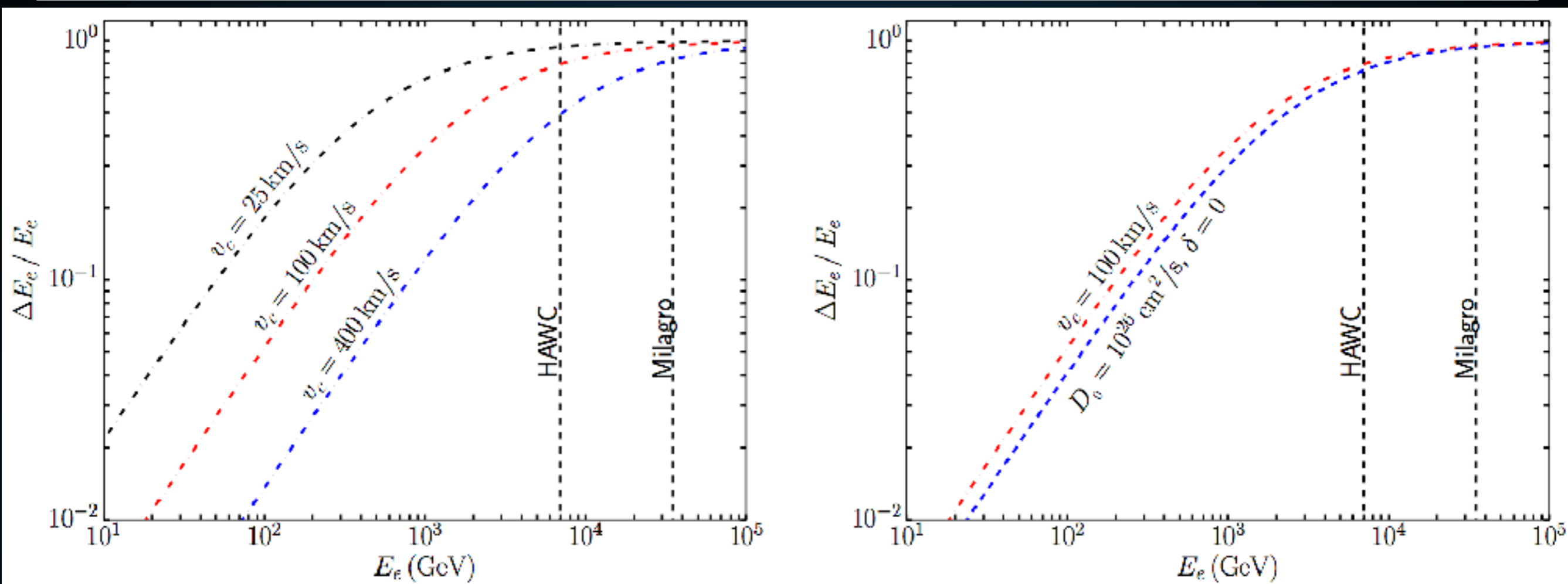
- ▶ **Electrons cannot be completely cooled, or else gamma-ray spectrum would be too soft (Klein-Nishina effects)**
- ▶ **Combined with Milagro observation at 30 TeV, this requires:**

- ▶ $-1.9 < \alpha < -1.5$

- ▶ $E_{\text{cut}} \approx 50 \text{ TeV}$



WHAT ABOUT THE LOW-ENERGY ELECTRONS?



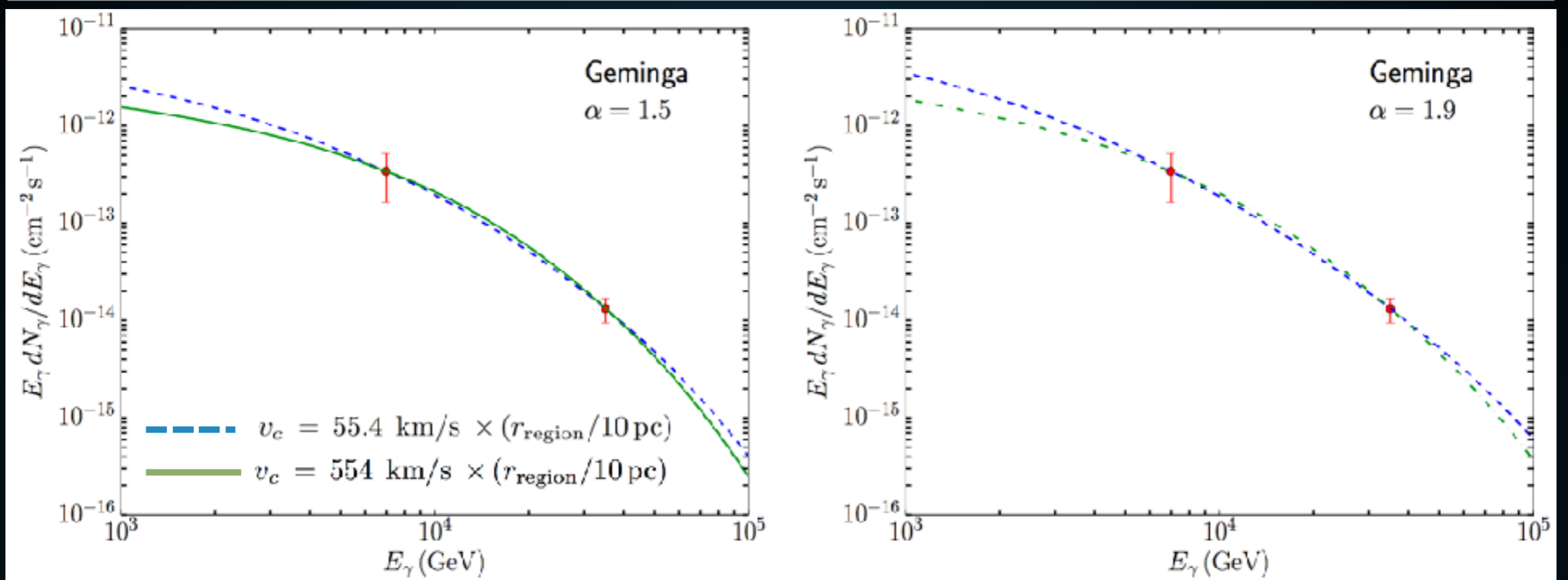
- ▶ **Low-energy electrons lose energy slower, must escape.**
- ▶ **This is true in both convective and most diffusive (Kolmogorov, Kraichnian) scenarios.**

BOHMIAN DIFFUSION

$$\tau_{\text{Diff}} \propto \frac{L^2}{D_0 E^\delta} \quad \tau_{\text{loss}} \propto E^{-1}$$
$$\left(\frac{\Delta E}{E} \right) \sim \frac{\tau_{\text{Diff}}}{\tau_{\text{loss}}} \propto E^{1-\delta}$$

- ▶ More generically, low-energy electrons can only be confined if the diffusion is Bohmian (diffusion coefficient scales as E^1 .)

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.

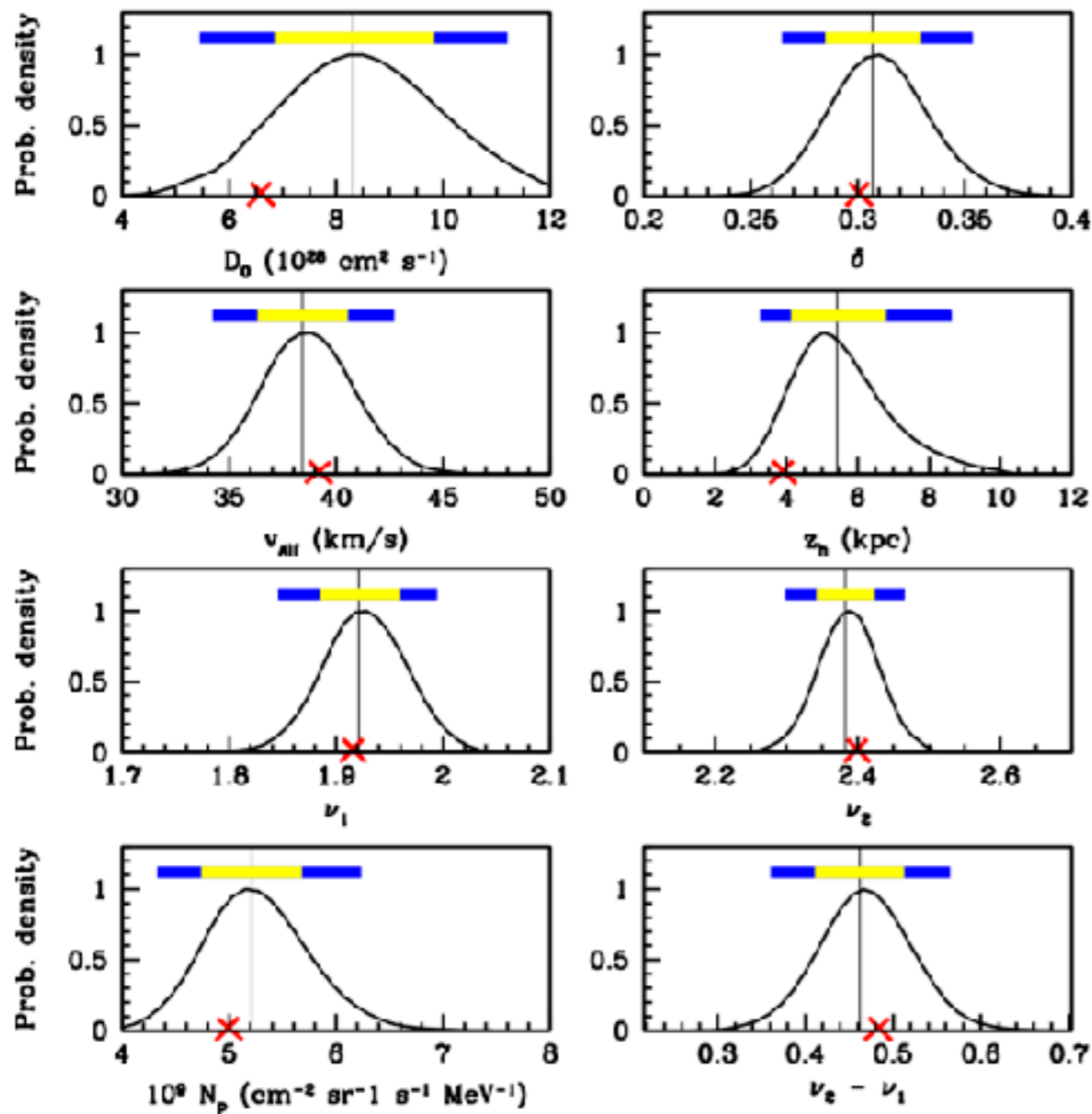
AN UPPER LIMIT ON THE TEV HALO SIZE

- ▶ **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.**

A GLOBAL FOCUS

- ▶ **New Assumption: Geminga is typical of a 100-400 kyr pulsar.**
- ▶ **Two Nearest Systems Observed: Geminga, Monogem**
- ▶ **Indications of many similar HESS sources.**

EFFECT OF TEV HALOS ON ISM PROPAGATION



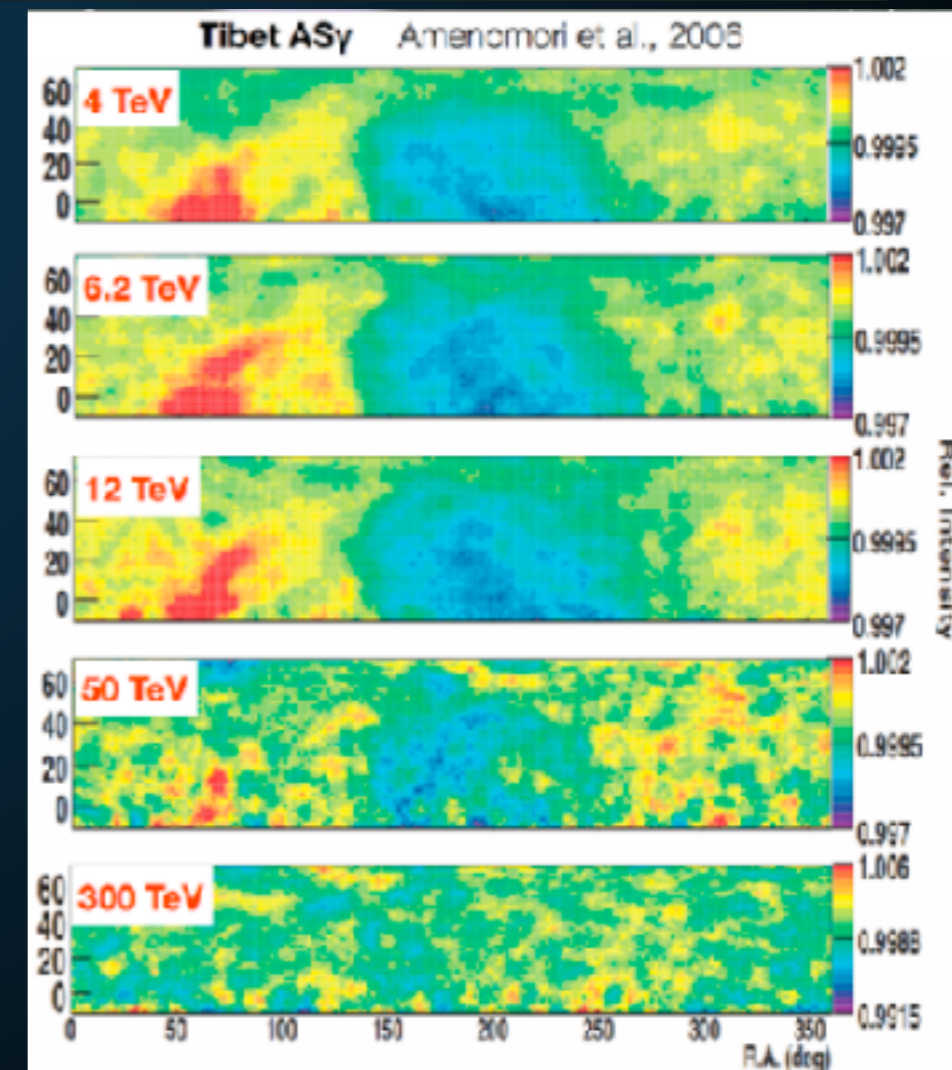
- ▶ Multiple cosmic-ray observations indicate that the average diffusion constant is $\sim 5 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$
- ▶ Inhibited cosmic-ray propagation in TeV halos must not substantially affect this number.

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

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

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.



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 ($\times 10^{-15}$)	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

- ▶ **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
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 2-3 σ excesses!**

TeV HALOS: THE FIRST ORDER MODEL

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

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

- ▶ 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 increase fluxes by nearly a factor of 2.

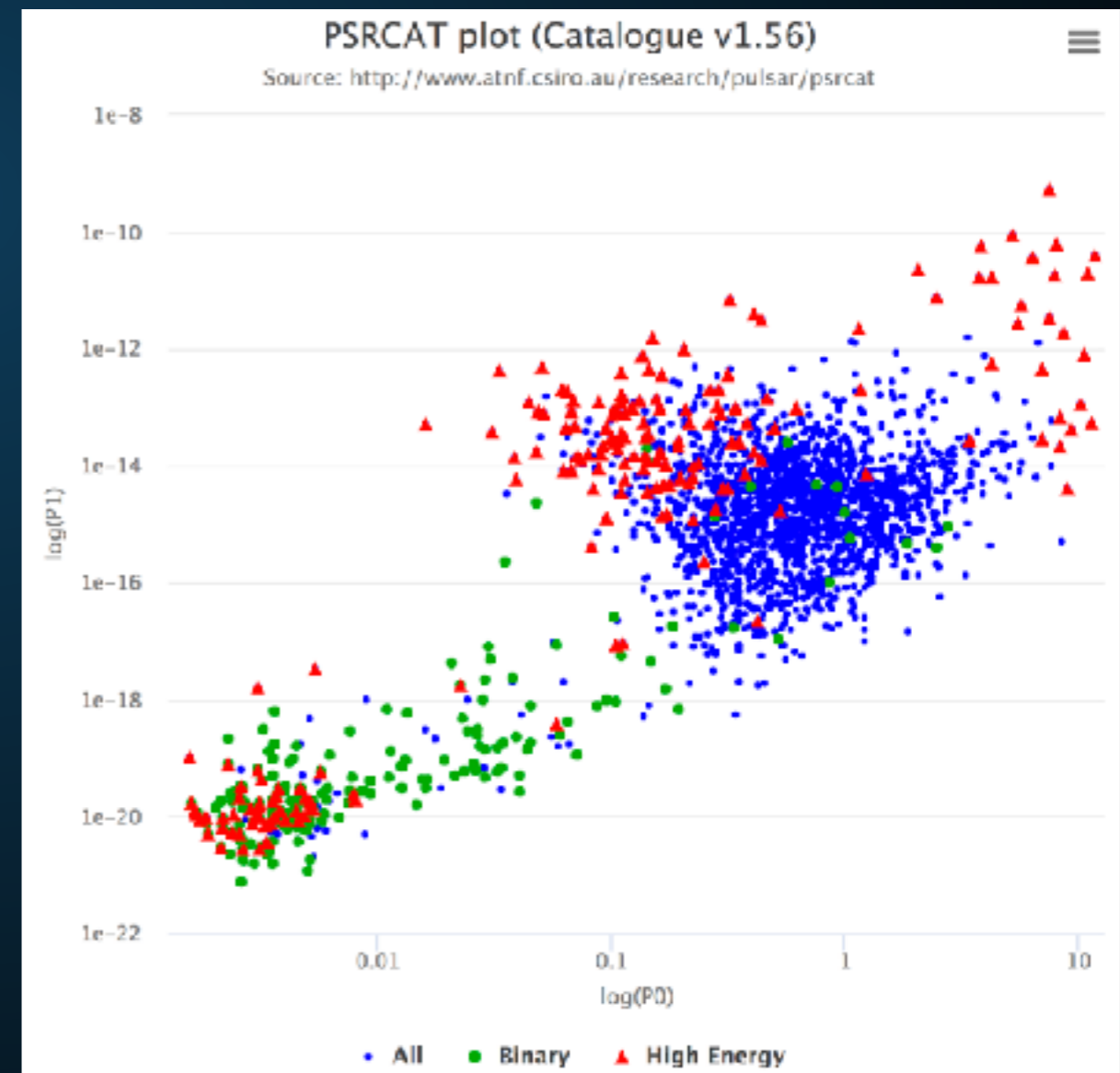
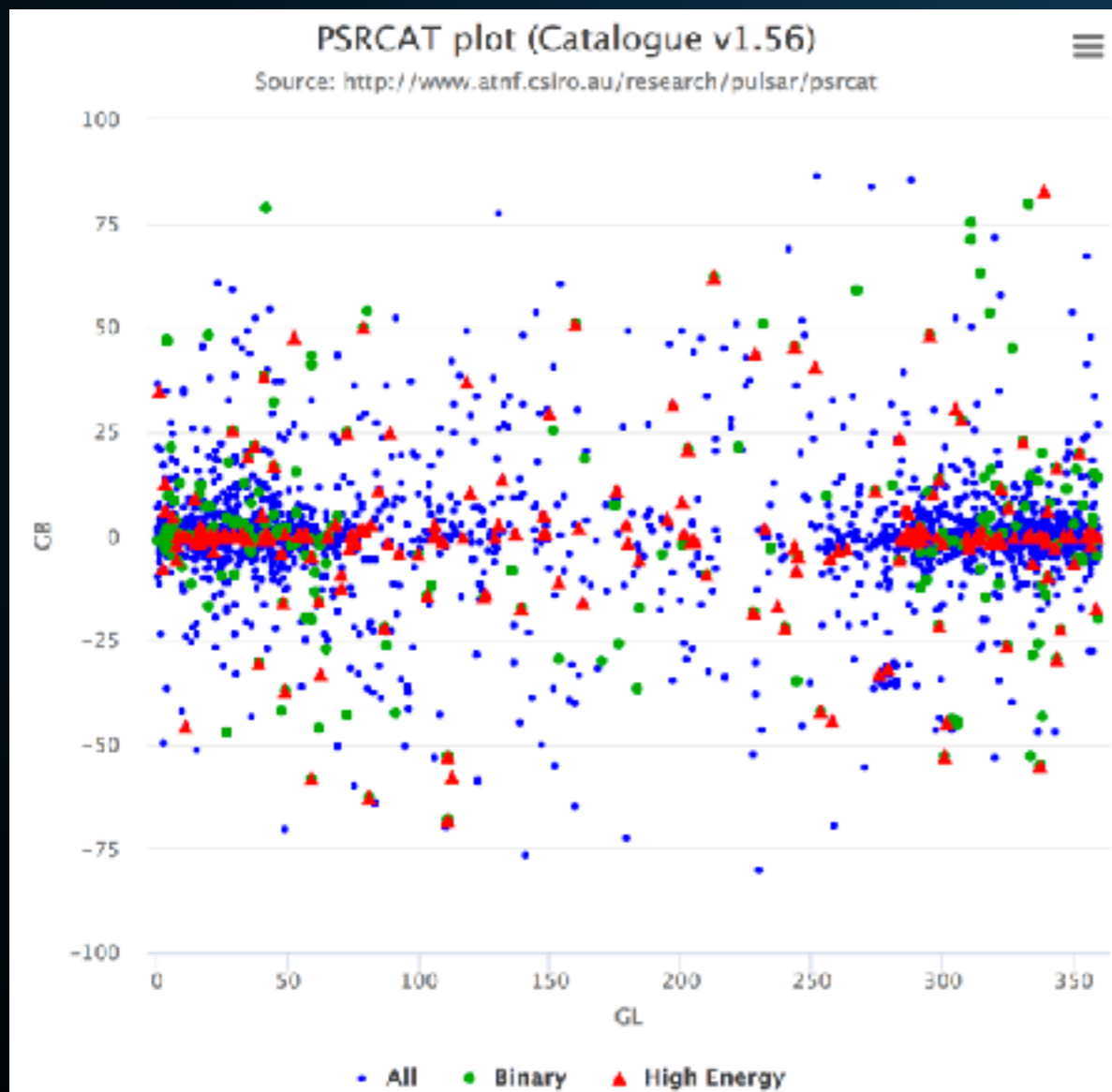
HAWC SENSITIVITY AFTER 10 YEARS

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	—

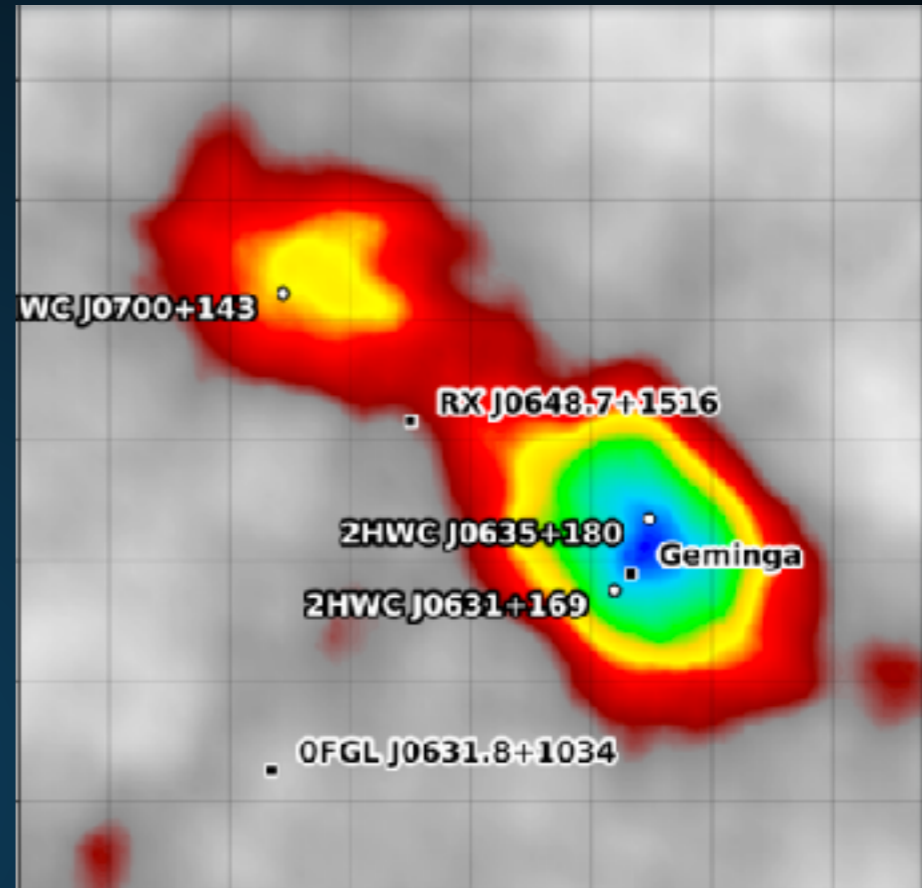
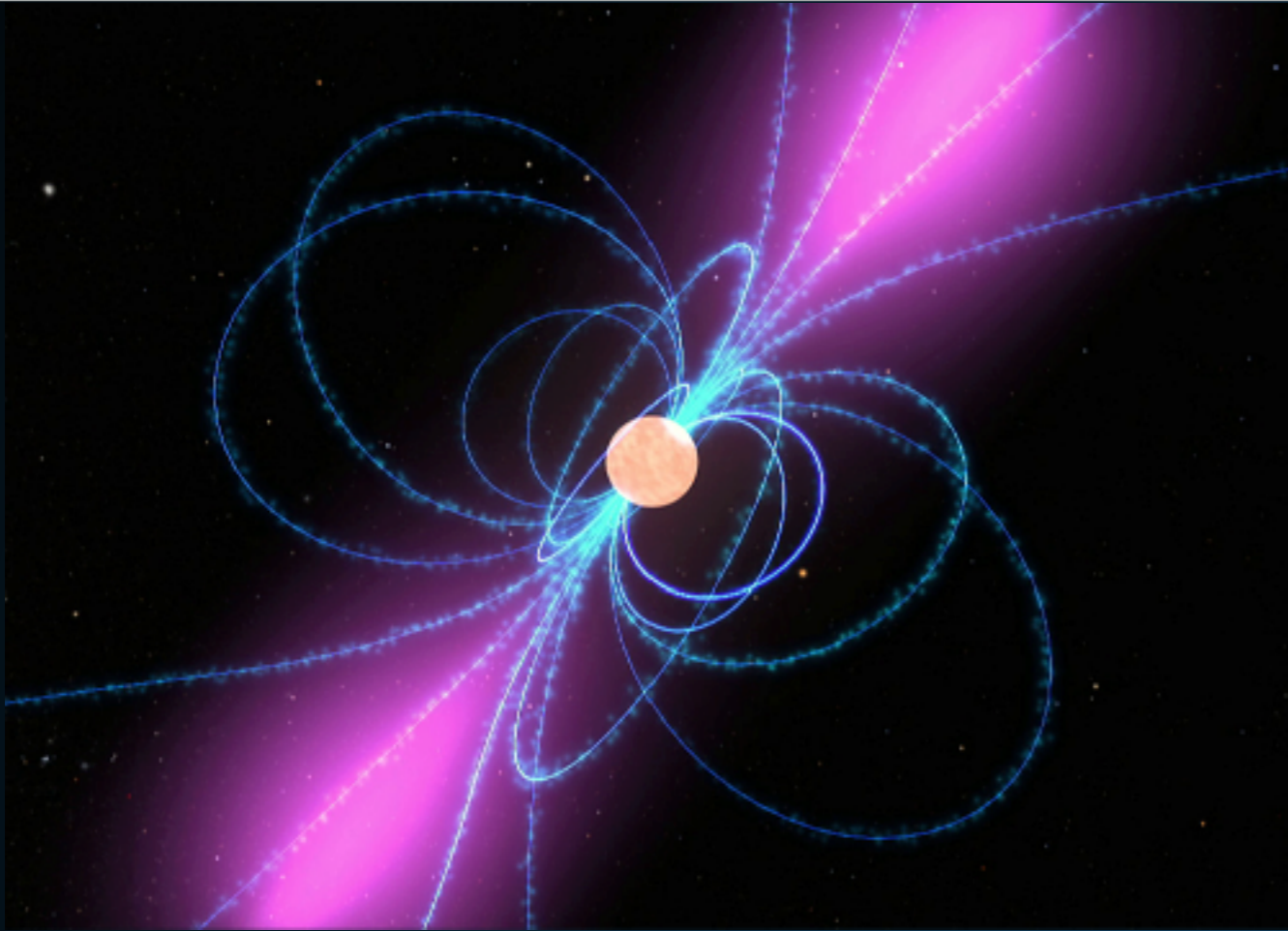
- ▶ **HAWC will eventually reach a flux sensitivity of 0.02 Geminga**
- ▶ **Will observe**
 - ▶ **TeV halos from a dozen middle-aged ATNF pulsars.**
 - ▶ **TeV halos from ~40 additional young pulsars.**

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.**

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

- ▶ **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 $^\circ$	0.91 pc	43.0	23.0	1.87	2.0 $^\circ$	1.73 $^\circ$	111	0.0
J0631+169	J0633+1746	0.25	0.89 $^\circ$	3.88 pc	48.7	48.7	1.0	2.0 $^\circ$	2.0 $^\circ$	342	0.0
J1912+099	J1913+1011	4.61	0.34 $^\circ$	27.36 pc	13.0	36.6	0.36	0.11 $^\circ$	0.7 $^\circ$	169	0.30
J2031+415	J2032+4127	1.70	0.11 $^\circ$	3.26 pc	5.59	61.6	0.091	0.29 $^\circ$	0.7 $^\circ$	181	0.002
J1831-098	J1831-0952	3.68	0.04 $^\circ$	2.57 pc	7.70	95.8	0.080	0.14 $^\circ$	0.9 $^\circ$	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 $^\circ$	3.67 pc	23.2	9.8	2.37	0.07 $^\circ$	0.0 $^\circ$	2.89	0.002
J1814-173	J1813-1749	4.7	0.54 $^\circ$	44.30 pc	243	152	1.60	0.11 $^\circ$	1.0 $^\circ$	5.6	0.61
J2019+367	J2021+3651	1.8	0.27 $^\circ$	8.48 pc	99.8	58.2	1.71	0.28 $^\circ$	0.7 $^\circ$	17.2	0.04
J1928+177	J1928+1746	4.34	0.03 $^\circ$	2.27 pc	8.08	10.0	0.81	0.11 $^\circ$	0.0 $^\circ$	82.6	0.002
J1908+063	J1907+0602	2.58	0.36 $^\circ$	16.21 pc	40.0	85.0	0.47	0.2 $^\circ$	0.8 $^\circ$	19.5	0.26
J2020+403	J2021+4026	2.15	0.18 $^\circ$	6.75 pc	2.48	18.5	0.134	0.23 $^\circ$	0.0 $^\circ$	77	0.01
J1857+027	J1856+0245	6.32	0.12 $^\circ$	13.24 pc	11.0	97.0	0.11	0.08 $^\circ$	0.9 $^\circ$	20.6	0.06
J1825-134	J1826-1334	3.61	0.20 $^\circ$	12.66 pc	20.5	249	0.082	0.14 $^\circ$	0.9 $^\circ$	21.4	0.14
J1837-065	J1838-0655	6.60	0.38 $^\circ$	43.77 pc	12.0	341	0.035	0.08 $^\circ$	2.0 $^\circ$	22.7	0.48
J1837-065	J1837-0604	4.78	0.50 $^\circ$	41.71 pc	8.3	341	0.024	0.10 $^\circ$	2.0 $^\circ$	33.8	0.68
J2006+341	J2004+3429	10.8	0.42 $^\circ$	80.07 pc	0.48	24.5	0.019	0.04 $^\circ$	0.9 $^\circ$	18.5	0.08

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

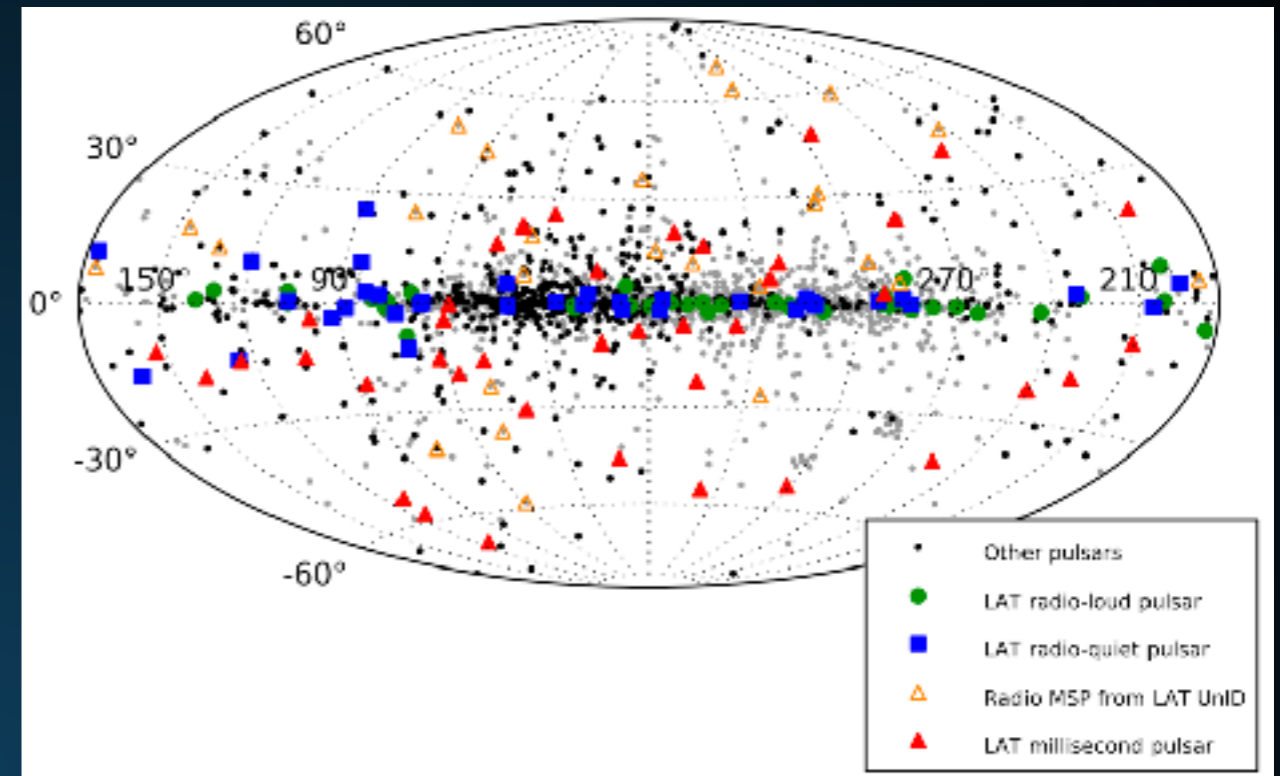
EVENTUAL TEV HALO DETECTIONS

ATNF Name	Dec. (°)	Distance (kpc)	Age (kyr)	Spindown Lum. (erg s^{-1})	Spindown Flux ($\text{erg s}^{-1} \text{kpc}^{-2}$)	2HWC
J0633+1746	17.77	0.25	342	$3.2\text{e}34$	$4.1\text{e}34$	2HWC J0631+169
B0656+14	14.23	0.29	111	$3.8\text{e}34$	$3.6\text{e}34$	2HWC J0700+143
B1951+32	32.87	3.00	107	$3.7\text{e}36$	$3.3\text{e}34$	—
J1740+1000	10.00	1.23	114	$2.3\text{e}35$	$1.2\text{e}34$	—
J1913+1011	10.18	4.61	169	$2.9\text{e}36$	$1.1\text{e}34$	2HWC J1912+099
J1831-0952	-9.86	3.68	128	$1.1\text{e}36$	$6.4\text{e}33$	2HWC J1831-098
J2032+4127	41.45	1.70	181	$1.7\text{e}35$	$4.7\text{e}33$	2HWC J2031+415
B1822-09	-9.58	0.30	232	$4.6\text{e}33$	$4.1\text{e}33$	—
B1830-08	-8.45	4.50	147	$5.8\text{e}35$	$2.3\text{e}33$	—
J1913+0904	9.07	3.00	147	$1.6\text{e}35$	$1.4\text{e}33$	—
B0540+23	23.48	1.56	253	$4.1\text{e}34$	$1.4\text{e}33$	—

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

FERMI-LAT DETECTIONS

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



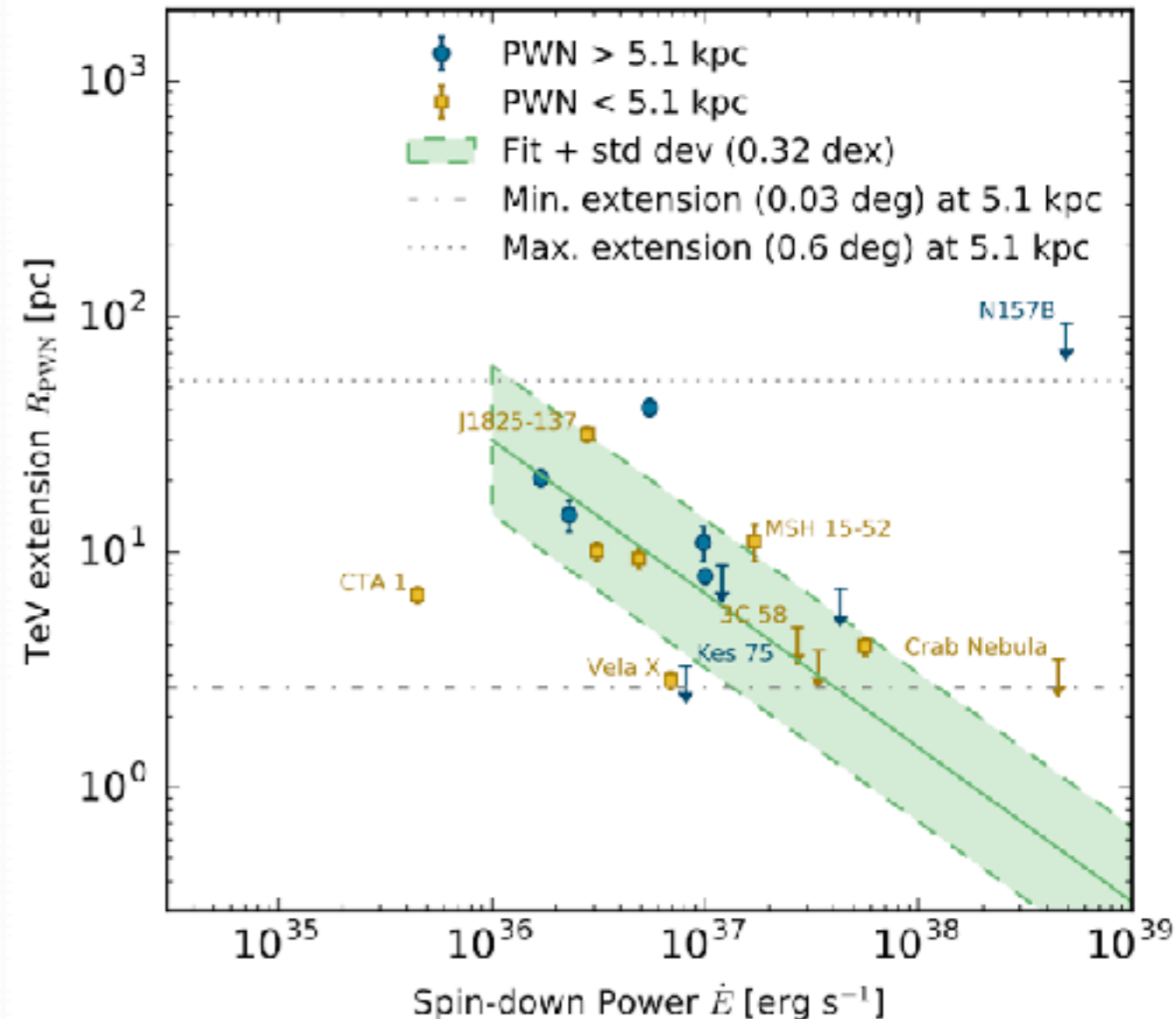
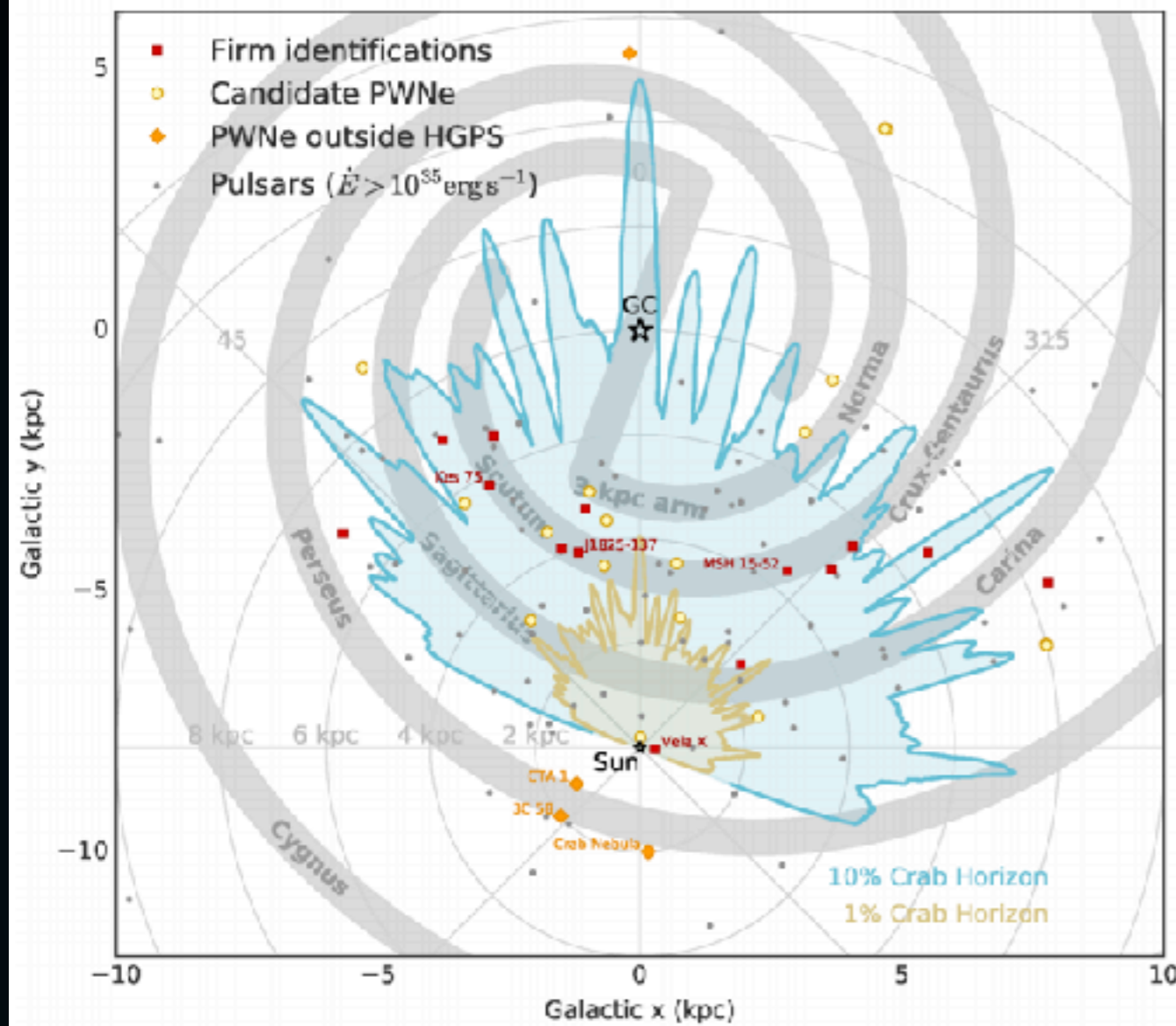
- ▶ **Fermi-LAT has detected only ~5 of these 37 systems.**

X-RAY PWN DETECTIONS

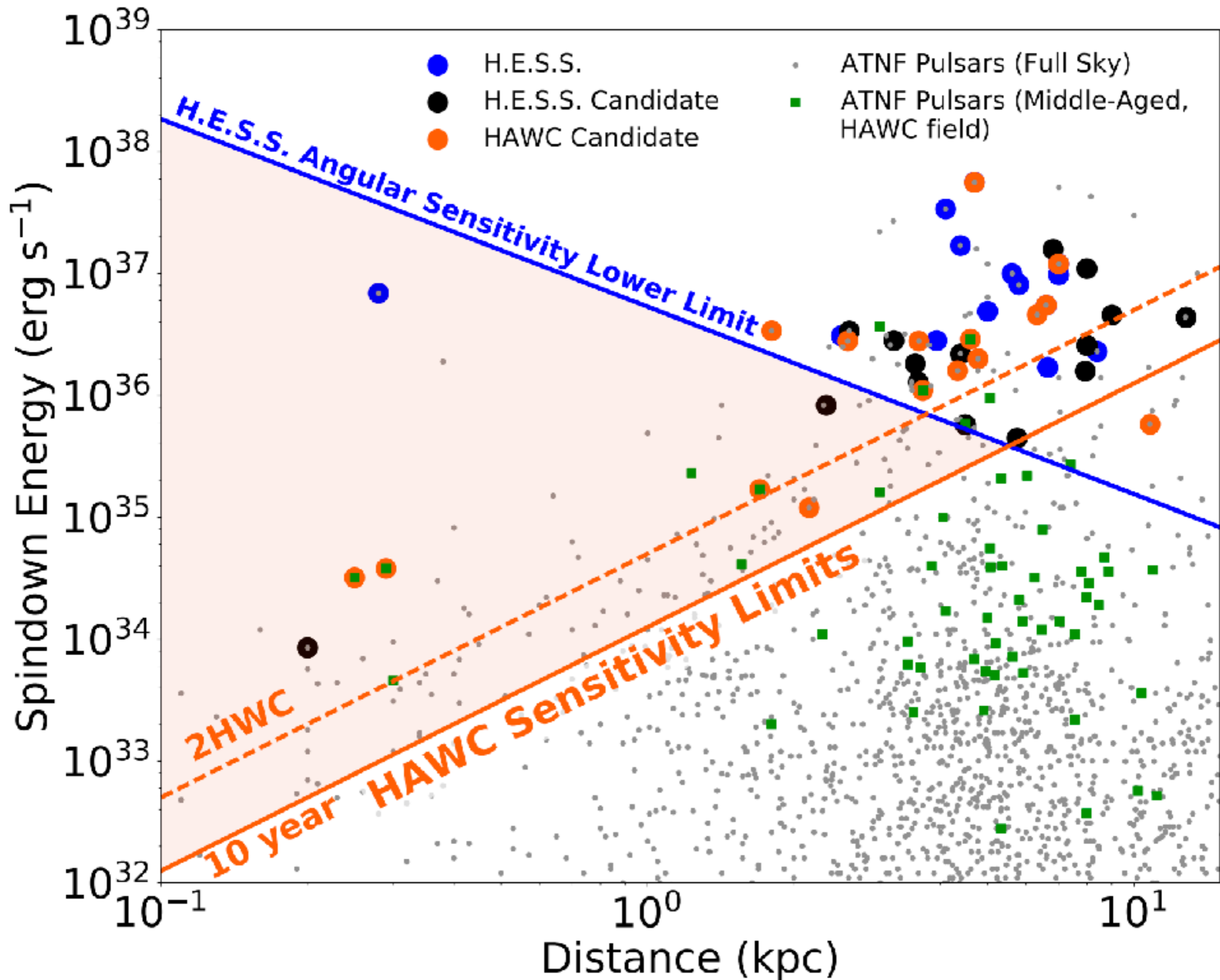
PWNe With No Detected Pulsar						
Gname	other name(s)	R	X	O	G	
G0.13-0.11					?	notes
G0.9+0.1					N	notes
G7.4-2.0	GeV J1809-2327, Tazzie				Y	notes
G16.7+0.1					N	notes
G18.5-0.4	GeV J1825-1310, Ecl				Y	notes
G20.0-0.2					N	notes
G24.7+0.6					N	notes
G27.8+0.6					N	notes
G39.2-0.3	3C 396				Y	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.

HESS/VERITAS DETECTIONS

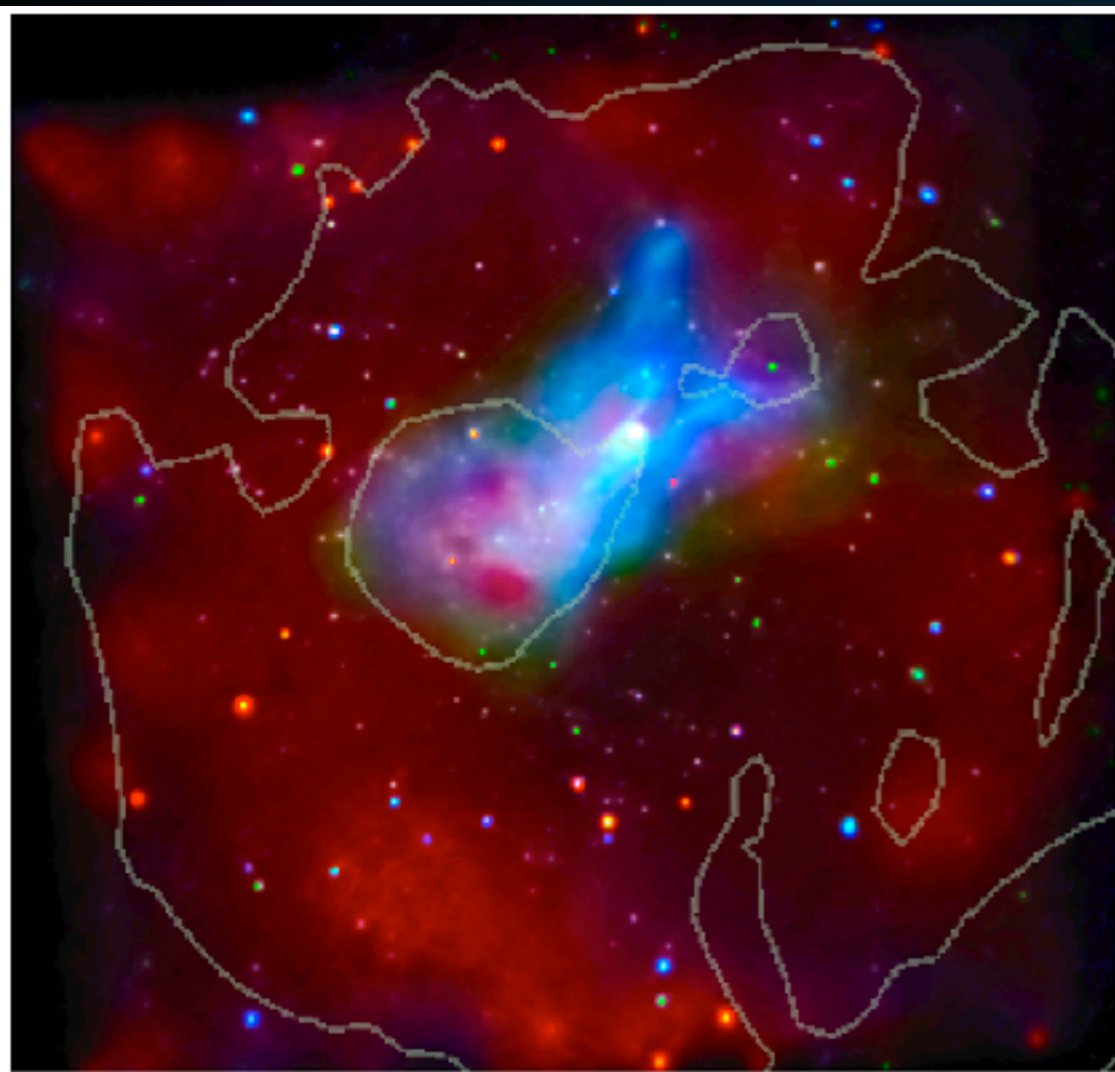


- ▶ Targeted ACTs are sensitive to the flux from TeV halos.
- ▶ ACTs are not sensitive to sources extended $>0.5^\circ$.
- ▶ Large parameter space available only to HAWC.



CONFIRMING TEV HALOS

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



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

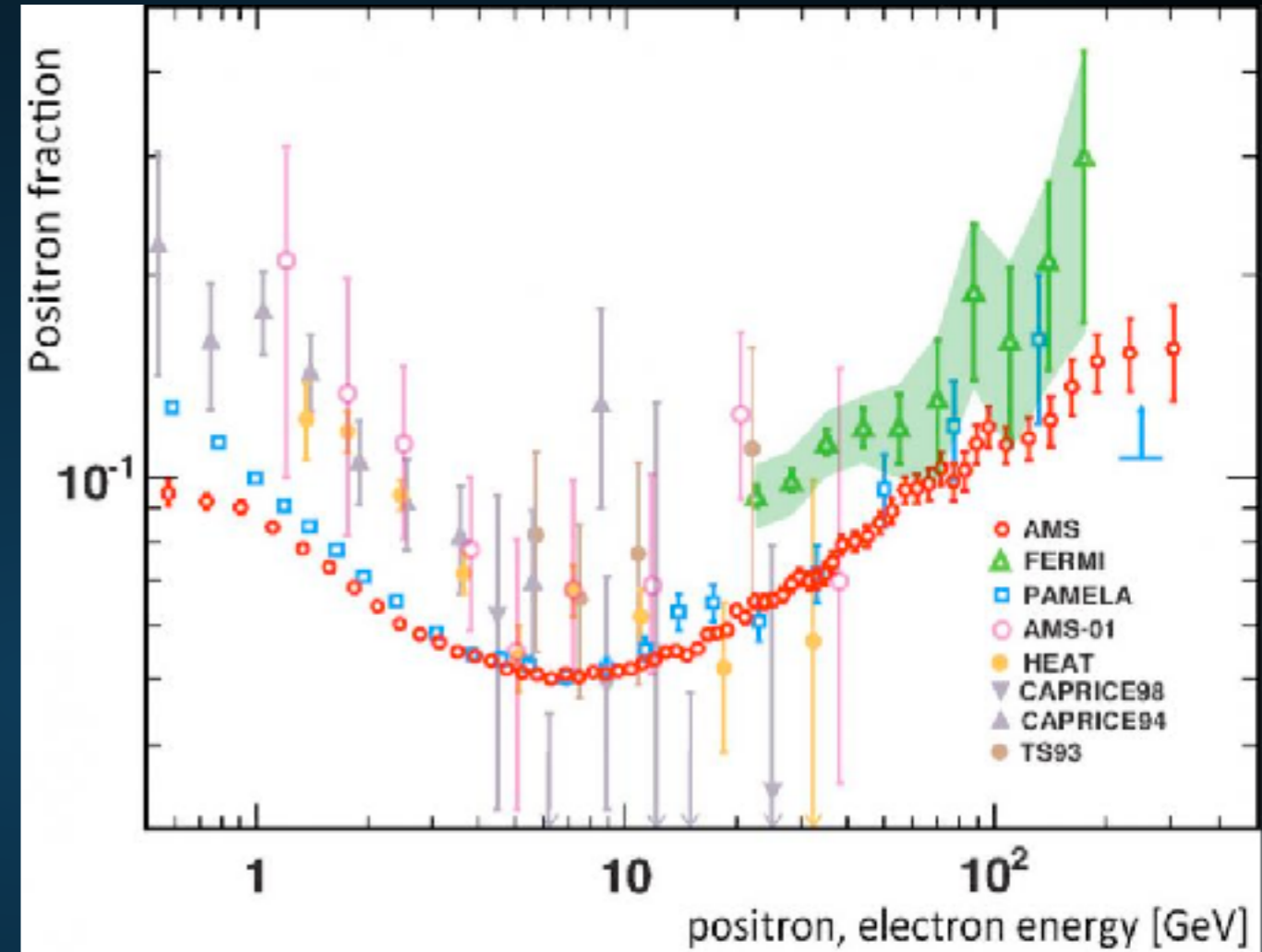
Region	Area (arcsec ²)	Cts (1000)	N _H (10 ²² cm ⁻²)	Photon Index	Amplitude (10 ⁻⁴)	kT (keV)	τ (10 ¹² s cm ⁻³)	Norm. (10 ⁻³)	F ₁ (10 ⁻¹²)	F ₂	Red. χ ²
1 Compact Source	84.657	6.34	1.93 ^{+0.08} _{-0.08}	1.61 ^{+0.08} _{-0.07}	1.05 ^{+0.11} _{-0.10}	...	...	...	0.45	...	0.80
2 Cometary PWN	971.22	7.75	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	...

Implication II: The Positron Excess

THE POSITRON EXCESS

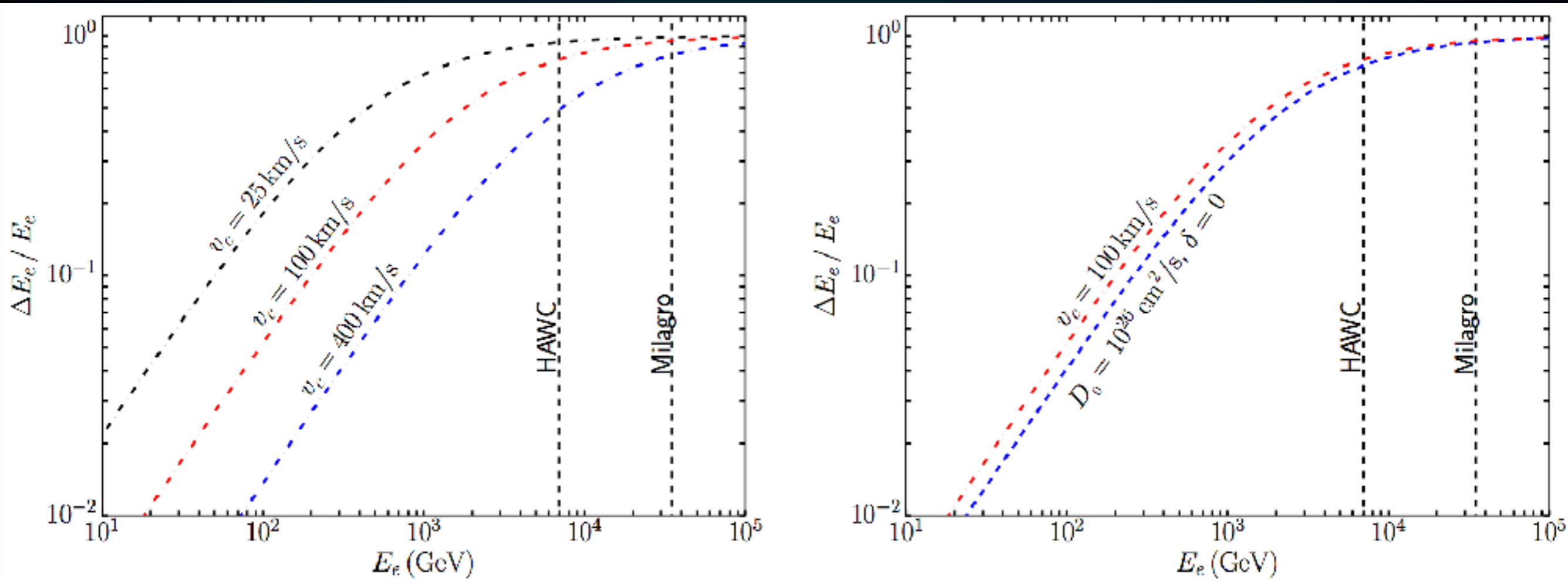
▶ Rising fraction of cosmic-ray positrons at energies above 10 GeV

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



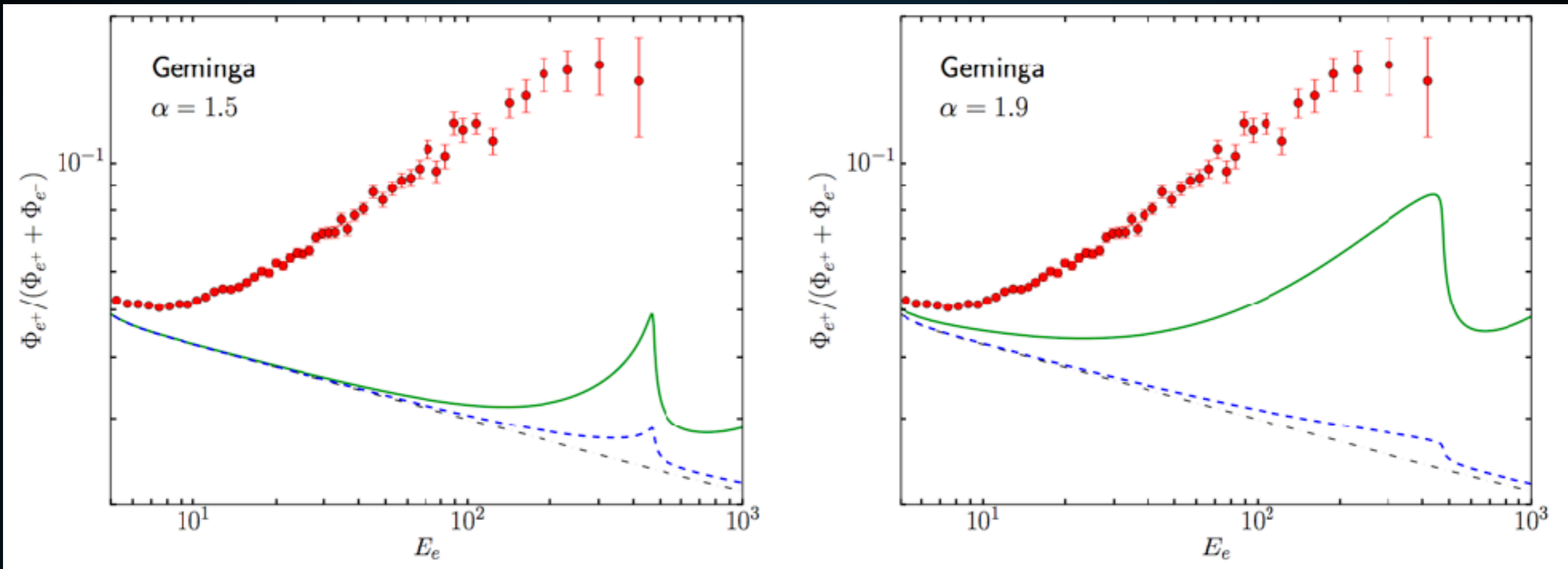
▶ Indicates a new primary source of high energy e^+e^- pairs.

IMPLICATION I: THE POSITRON EXCESS



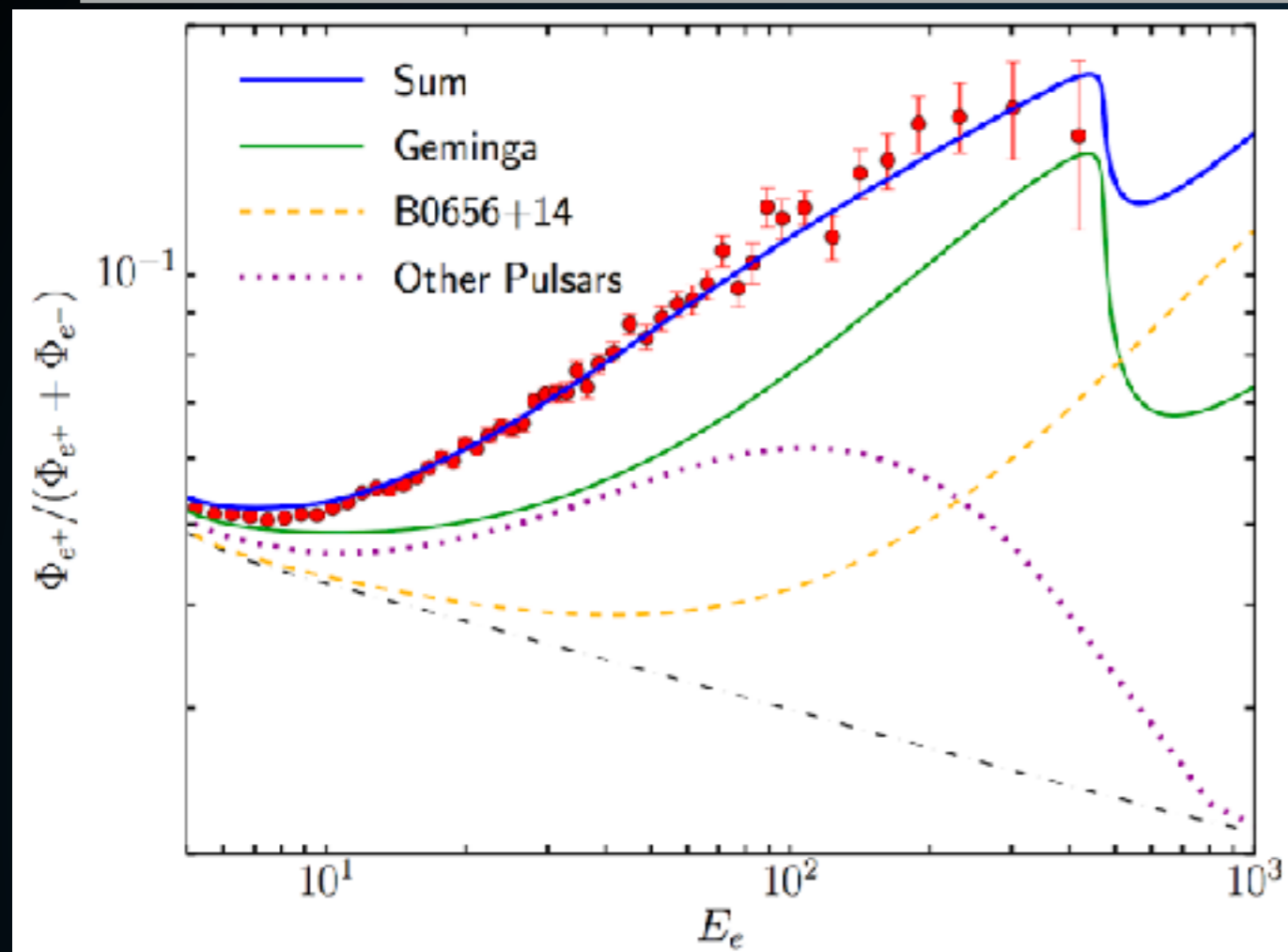
- ▶ **What do the low-energy e^+e^- do?**
 - ▶ **Large flux (10% of spin-down power)**
 - ▶ **Hard Spectrum**
 - ▶ **Most escape**

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



*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.**

Implication III:

Most TeV gamma-rays are leptonic

TOTAL HIGH-ENERGY EMISSION FROM SNR AND PULSAR

Hadronic Emission

$$E_{p,SN} = 10^{50} \text{ erg}$$
$$\frac{dN_{p,SN}}{dE} = 4 \times 10^{51} E^{-2} e^{-E/1 \text{ PeV}} \text{ GeV}^{-1}$$
$$\phi_{\gamma, \pi_0} \propto E^{-2.7} \rightarrow 4 \times 10^{51} E^{-2.7} e^{-E/1 \text{ PeV}}$$

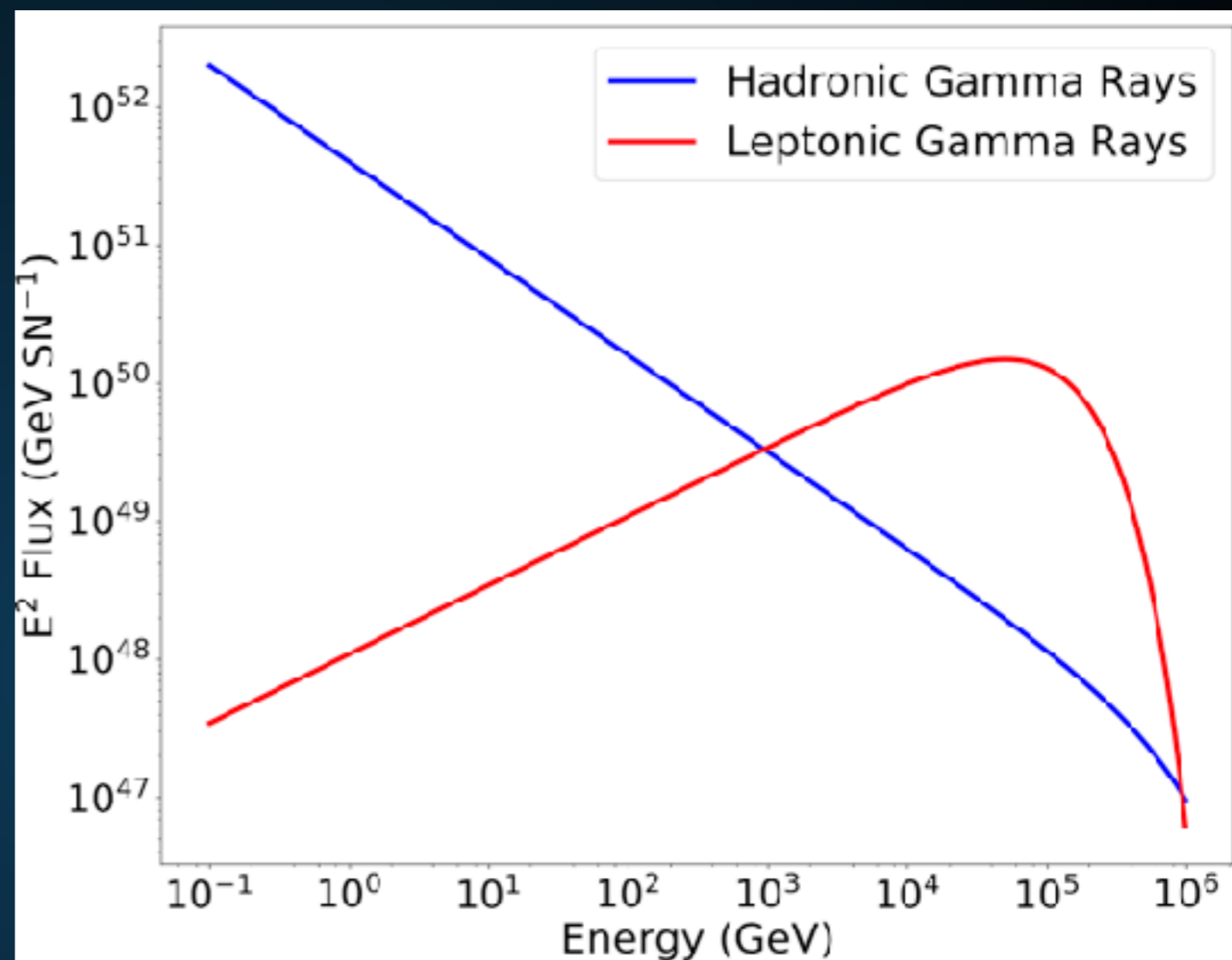
Leptonic Emission

$$KE_{pulsar} = 10^{49} \text{ erg}$$
$$e^+e^-_{pulsar} \approx 10^{48} \text{ erg}$$
$$\frac{dN_{e^+e^-,p}}{dE} = 1.1 \times 10^{48} E^{-1.5} e^{-E/100 \text{ TeV}}$$
$$\phi_{\gamma, \text{Ics}} = 1.1 \times 10^{48} E^{-1.5} e^{-E/100 \text{ TeV}}$$

- ▶ 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

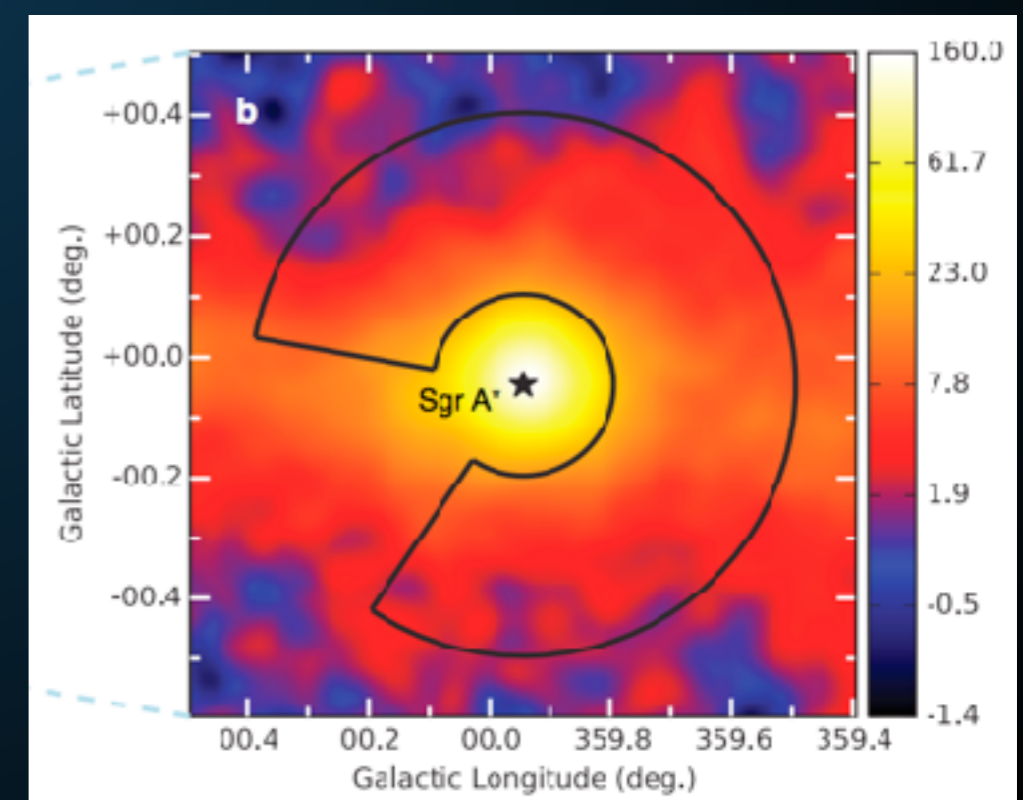
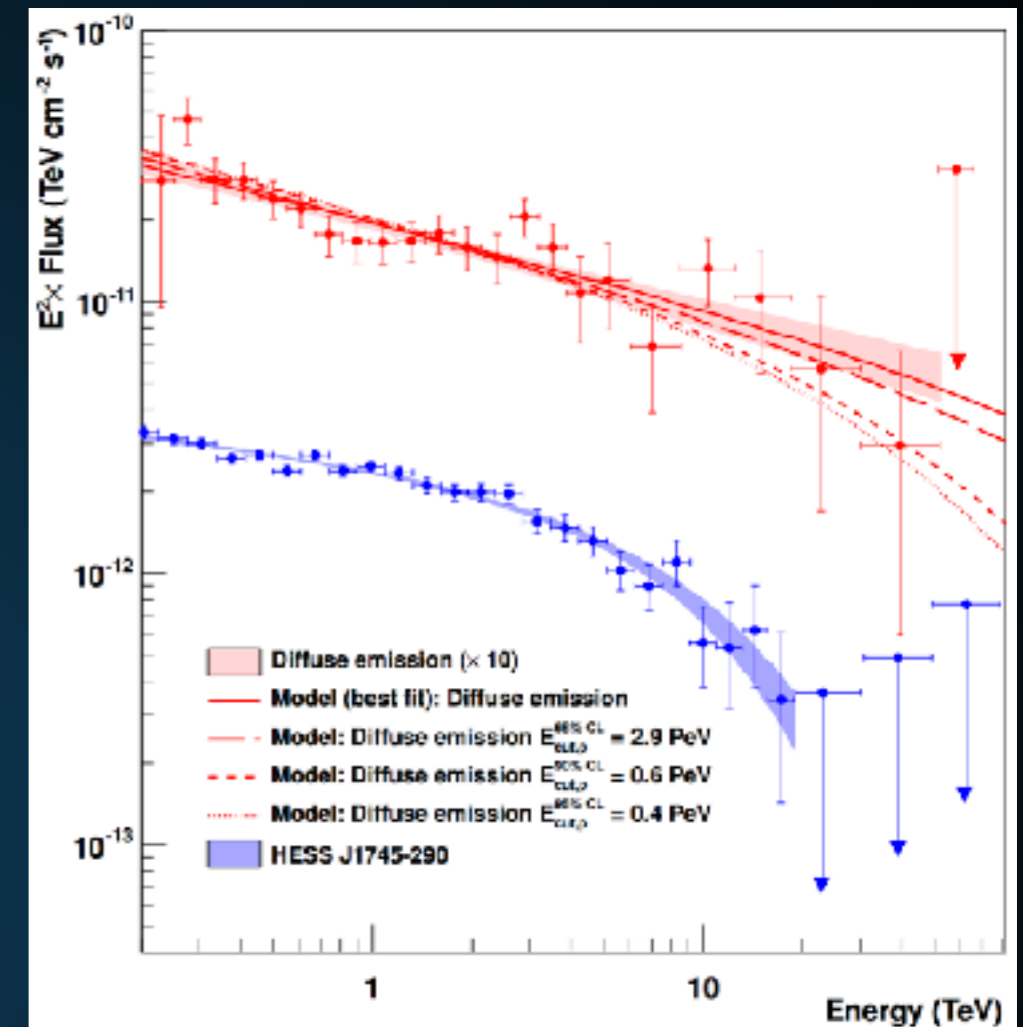
TOTAL HIGH-ENERGY EMISSION FROM SNR AND PULSAR

- ▶ **At high energies, leptonic gamma-rays become dominant.**
- ▶ **There are many TeV halos in the Milky Way**

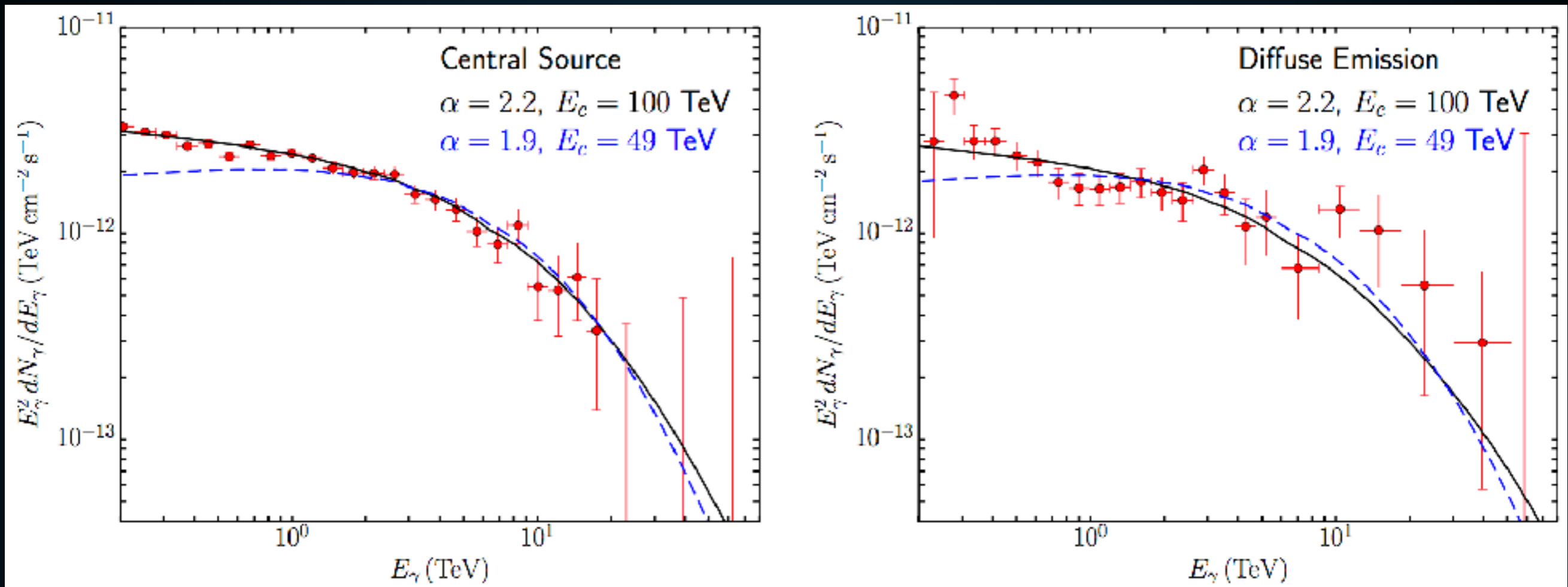


- ▶ **Dim TeV halos will be observed as a new diffuse gamma-ray emission component.**

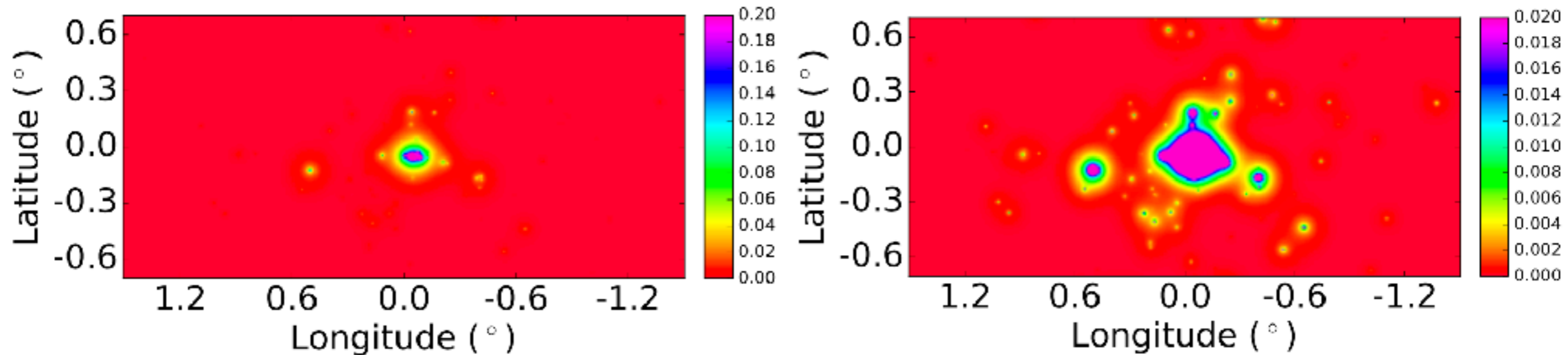
- ▶ HESS observations indicate diffuse ~ 50 TeV emission from the Galactic center
- ▶ If this emission is hadronic, it indicates PeV particle acceleration in the GC
- ▶ Spherical symmetry hints at Galactic Center source.



TeV HALOS PRODUCE THE PEVATRON SPECTRUM

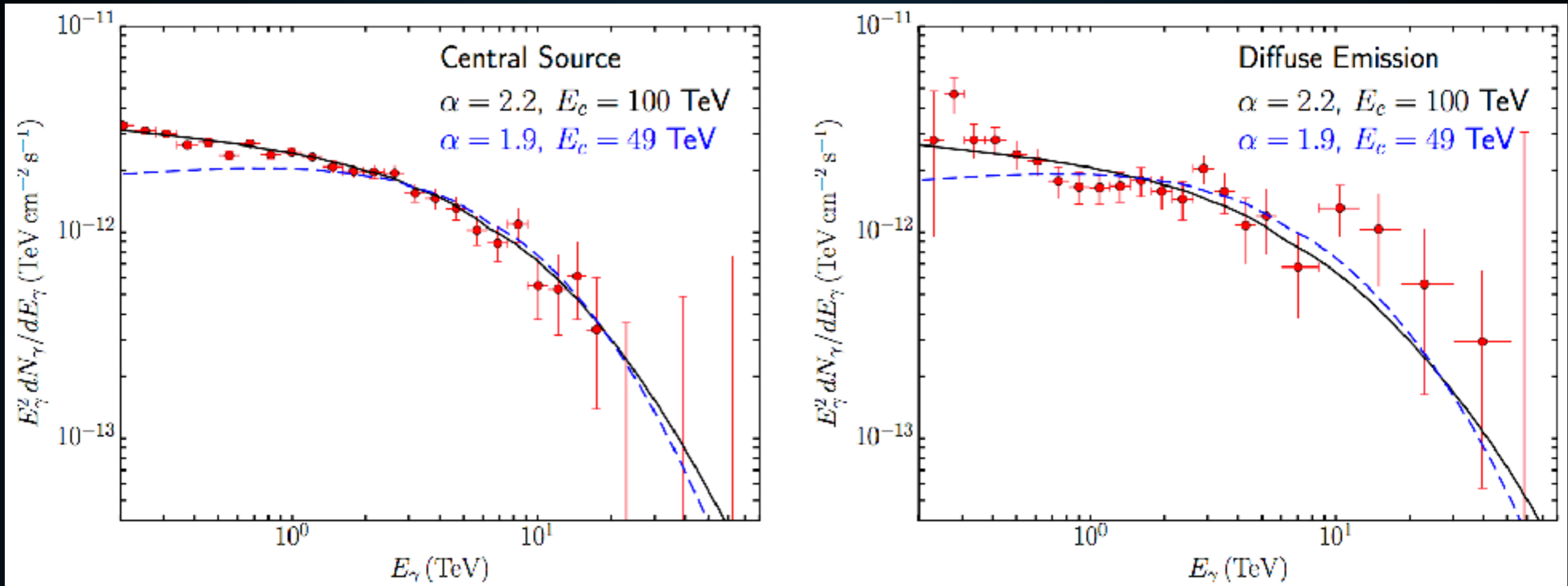


- ▶ The TeV halo spectrum from Geminga naturally reproduces the HESS observations.
- ▶ Slightly softer spectra preferred.
 - ▶ Some evidence that Geminga spectrum is particularly hard.
 - ▶ Hadronic diffuse background contamination?



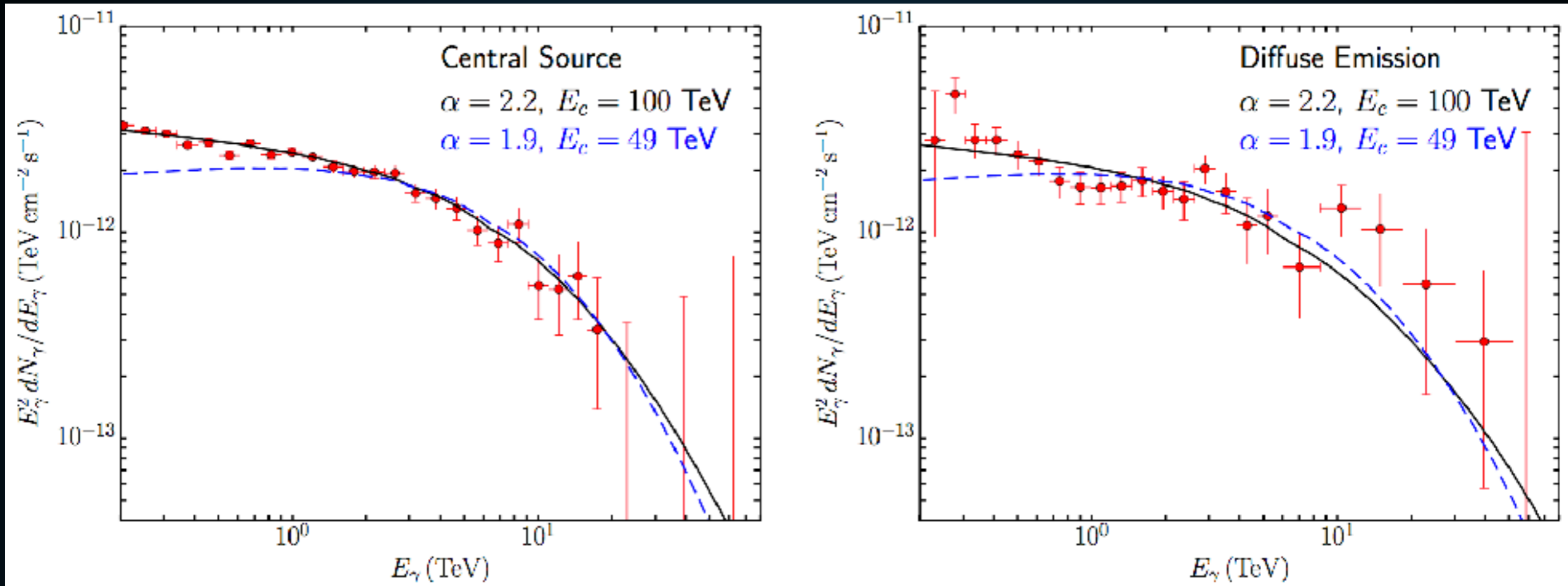
- ▶ **Significant star (pulsar) formation in the Galactic center**
- ▶ **Pulsars formed in the central parsec will be kicked into surrounding medium.**
- ▶ **Source of diffuse gamma-rays in the Galactic center.**

INTENSITY OF TEV HALO EMISSION IN GALACTIC CENTER



- ▶ Using standard values for the propagation of these sources:
 - ▶ TeV Halos survive 10 Myr (but become very dim)
 - ▶ Pulsar kicks $\sim 400 \text{ km/s}$
 - ▶ Birth rate between 100-750 pulsars/Myr
- ▶ We reproduce the intensity and morphology of the HESS emission.

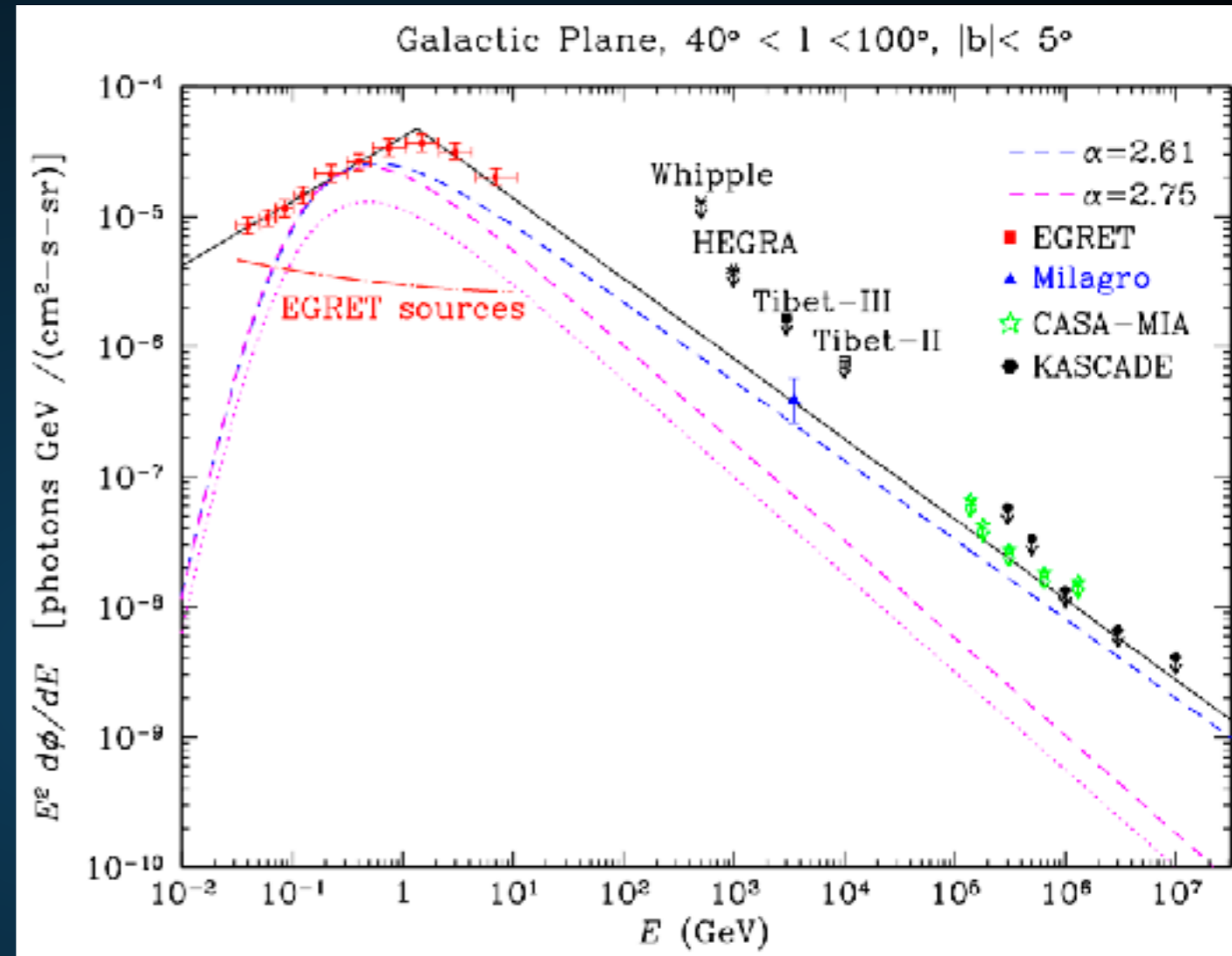
INTENSITY OF TEV HALO EMISSION IN GALACTIC CENTER



- ▶ 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).

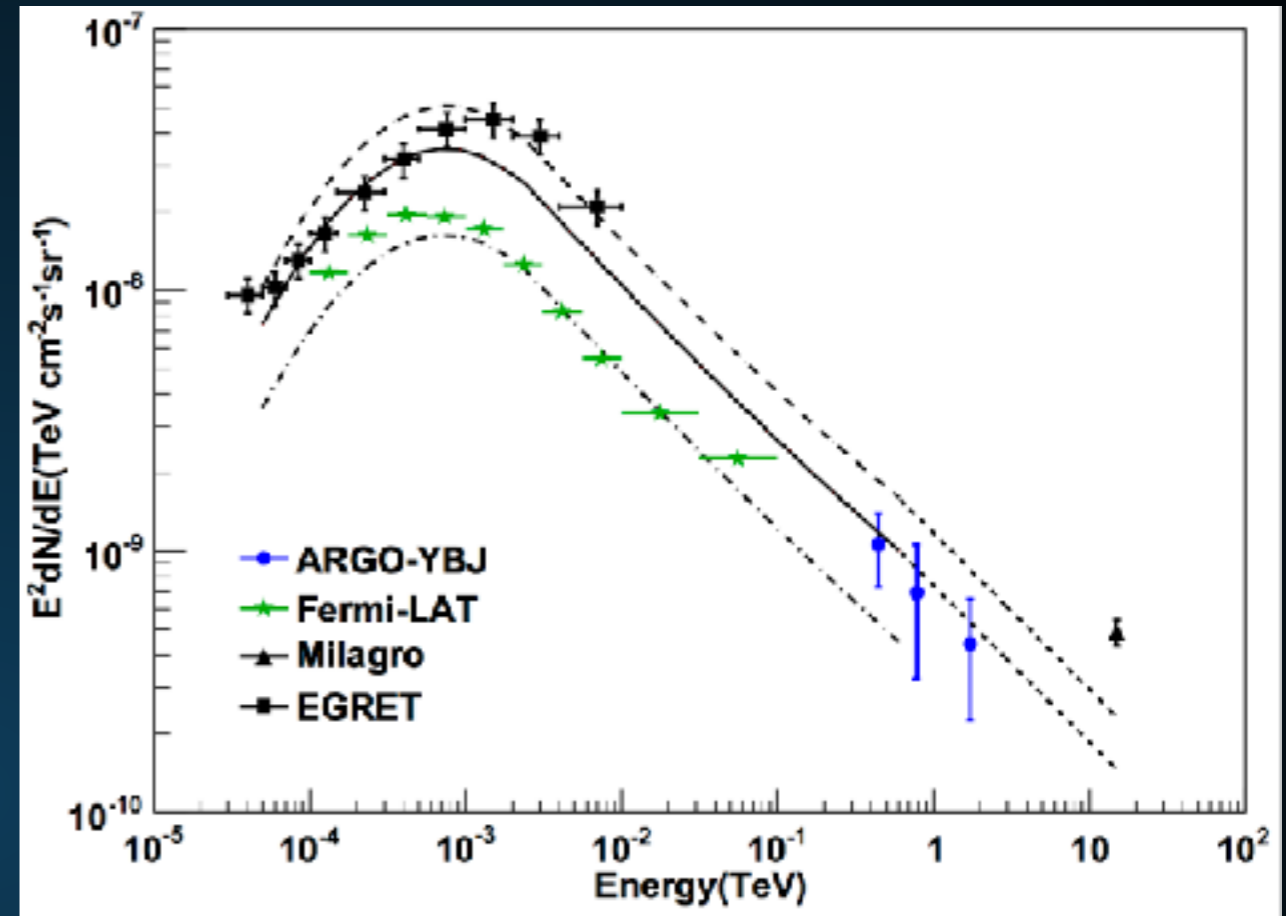
▶ **Milagro detects bright diffuse TeV emission along the Galactic plane.**

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

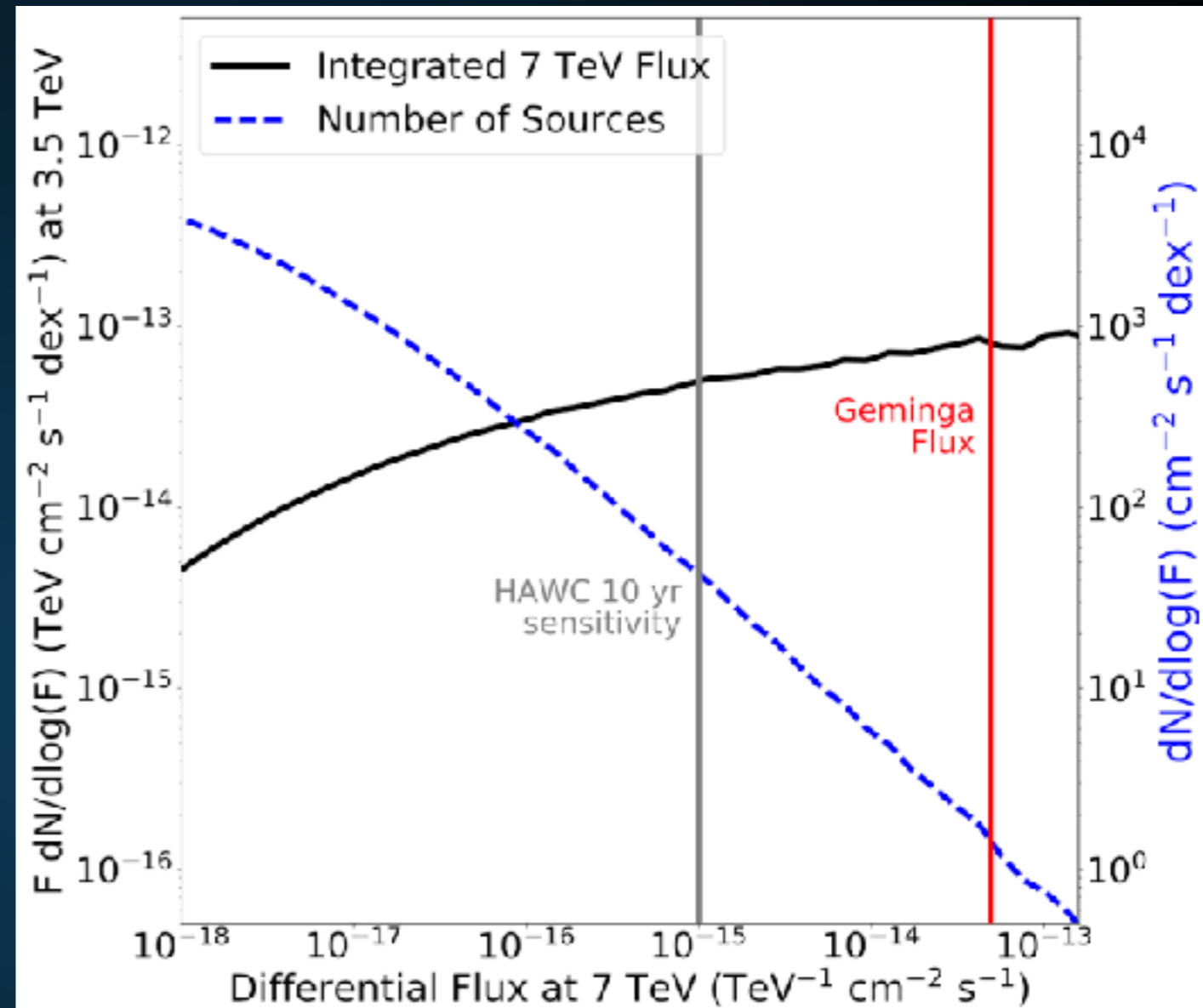


▶ **Can harden gamma-ray emission to some extent using radially dependent diffusion constants (1504.00227).**

- ▶ 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!

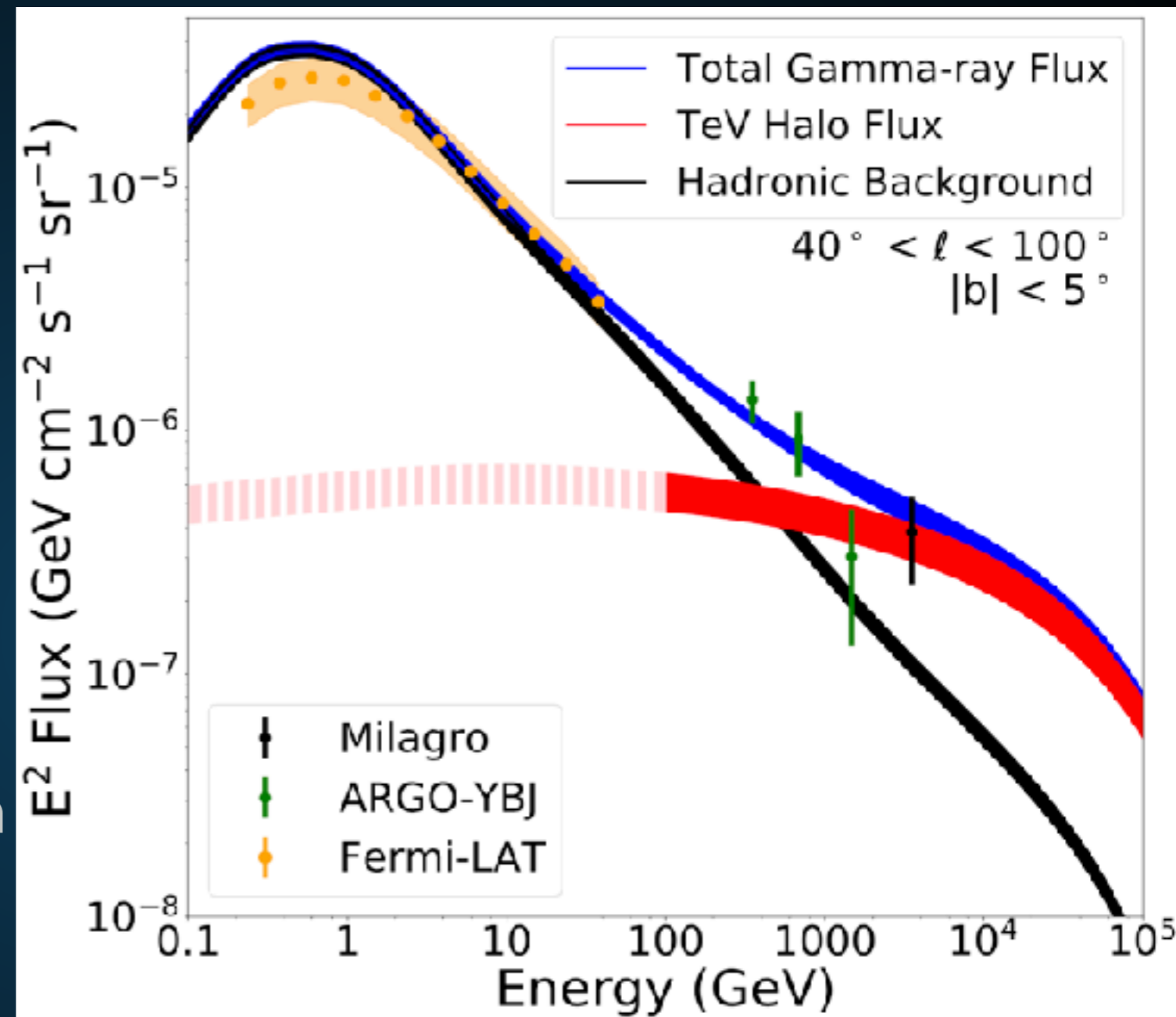


- ▶ Use a generic model for pulsar luminosities:
 - ▶ $B_0 = 10^{12.5} \text{ G}$ ($10^{0.3} \text{ G}$)
 - ▶ $P_0 = 0.3 \text{ s}$ (0.15 s)
- ▶ Spindown Timescale of $\sim 10^4 \text{ yr}$ (depends on B_0)
- ▶ Galprop model for supernova distances



- ▶ Naturally expect O(1) source as bright as Geminga
- ▶ HAWC eventually observes O(50) sources.

- ▶ 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.



- ▶ TeV halos naturally explain the intensity and spectrum of the TeV excess.

TeV PARTICLE ASTROPHYSICS

TeVPA 2017

AUGUST 7-11

COLUMBUS, OH

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Julia Becker-Tjus (Ruhr U. Bochum)	Marek Kowalski (DESY)
Veronica Bindi (U. Hawaii at Manoa)	Mariangela Lisanti (Princeton U.)
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Fiona Harrison (Caltech)	Todd Thompson (Ohio State U.) [‡]
Xiangdong Ji (Shanghai Jiao Tong U.)	Abigail Veregg (U. of Chicago)
Marc Kamionkowski (Johns Hopkins U.)	[‡] = To be confirmed

THE OHIO STATE UNIVERSITY
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TeVPA 2017

tevpa2017.osu.edu

- ▶ August 7–11, Columbus, OH
- ▶ Registration and abstract submission are open
- ▶ Pre-meeting mini-workshops on Sunday, August 6

- ▶ **TeV observations open up a new window into understanding Milky Way pulsars.**
- ▶ **Early indications:**
 - ▶ **Positron Excess is due to pulsar activity**
 - ▶ **TeV halos produce most of the TeV sources observed by ACTs and HAWC**
 - ▶ **TeV halos dominate the diffuse TeV emission in our galaxy.**

- ▶ **Additional implications:**
 - ▶ **Young pulsar braking index**
 - ▶ **Galactic cosmic-ray diffusion**
 - ▶ **Source of IceCube neutrinos**

Extra Slides

X-RAY HALOS

- ▶ An X-Ray halo with an identical morphology as the TeV halo must exist.

$$U = \frac{1}{8\pi} B^2 = \frac{(10 \mu\text{G})^2}{8\pi}$$
$$= 4 \times 10^{-12} \frac{\text{erg}}{\text{cm}^3}$$
$$\int_0^{10 \text{ pc}} U dV = 5 \times 10^{47} \text{ erg}$$

↳ Magnetic Flux $\approx 5 \times 10^{38} \frac{\text{erg}}{\text{s}}$

$$ISRF = 1 \frac{\text{eV}}{\text{cm}^3}$$
$$\int ISRF dV = 8 \times 10^{47} \text{ erg}$$

↳ Flux = $8 \times 10^{38} \frac{\text{erg}}{\text{s}}$

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

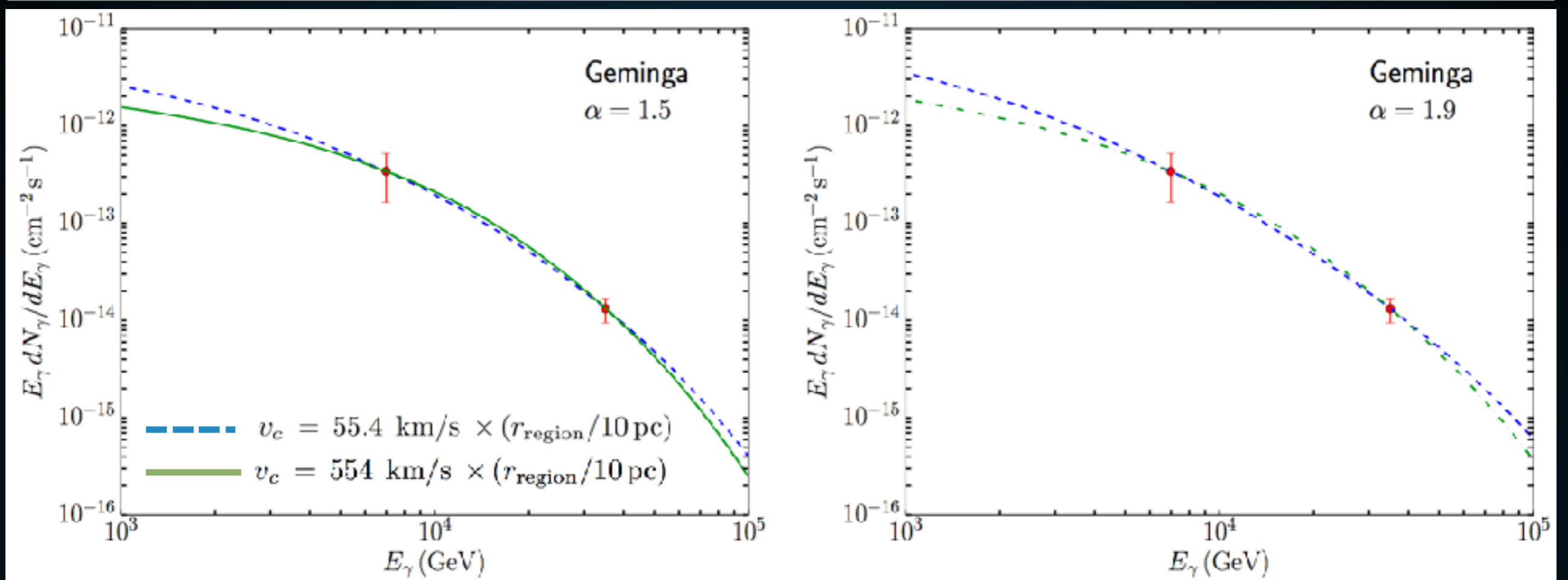
- ▶ However, the signal has a low surface brightness and peaks at a low energy.

X-RAY PULSAR WIND NEBULAE



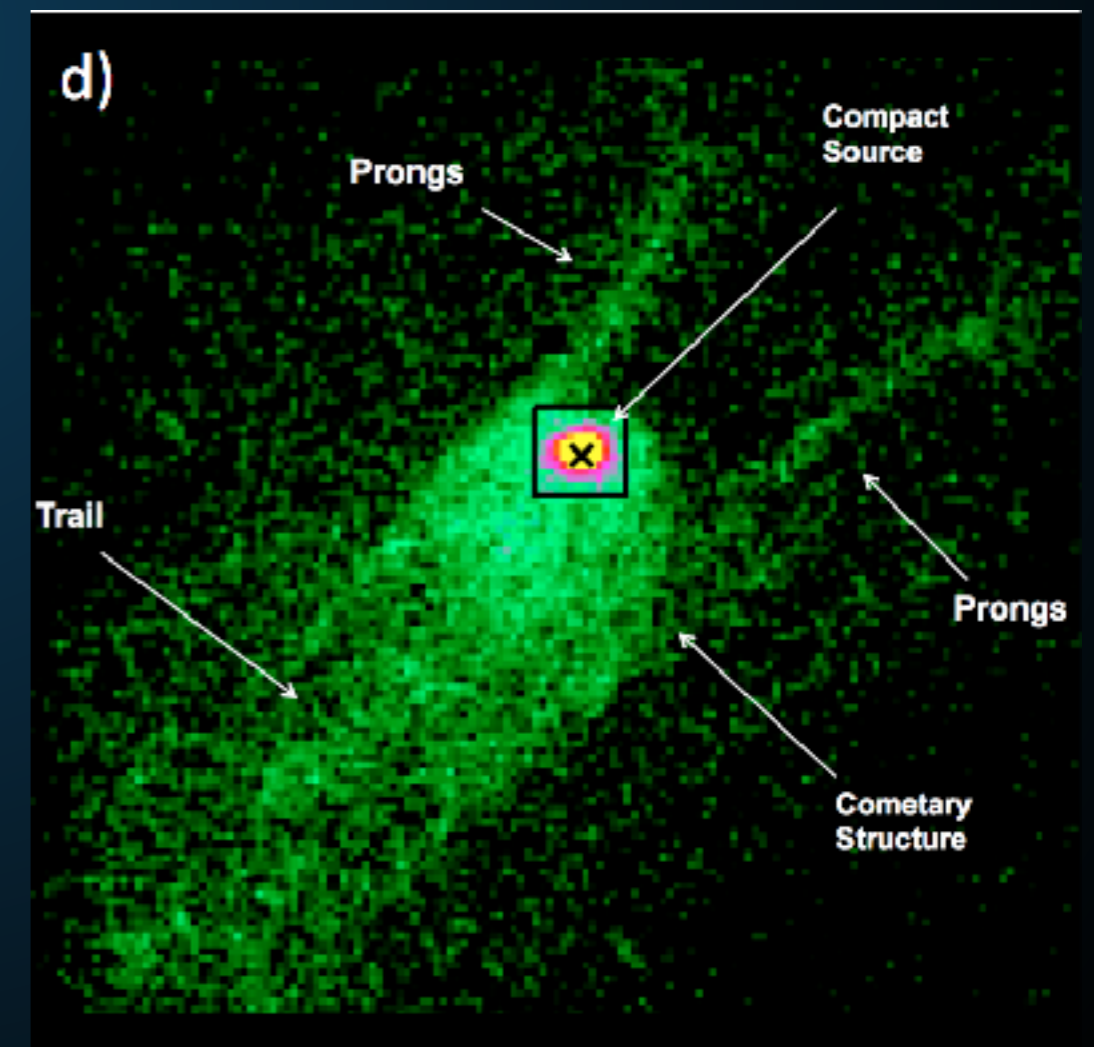
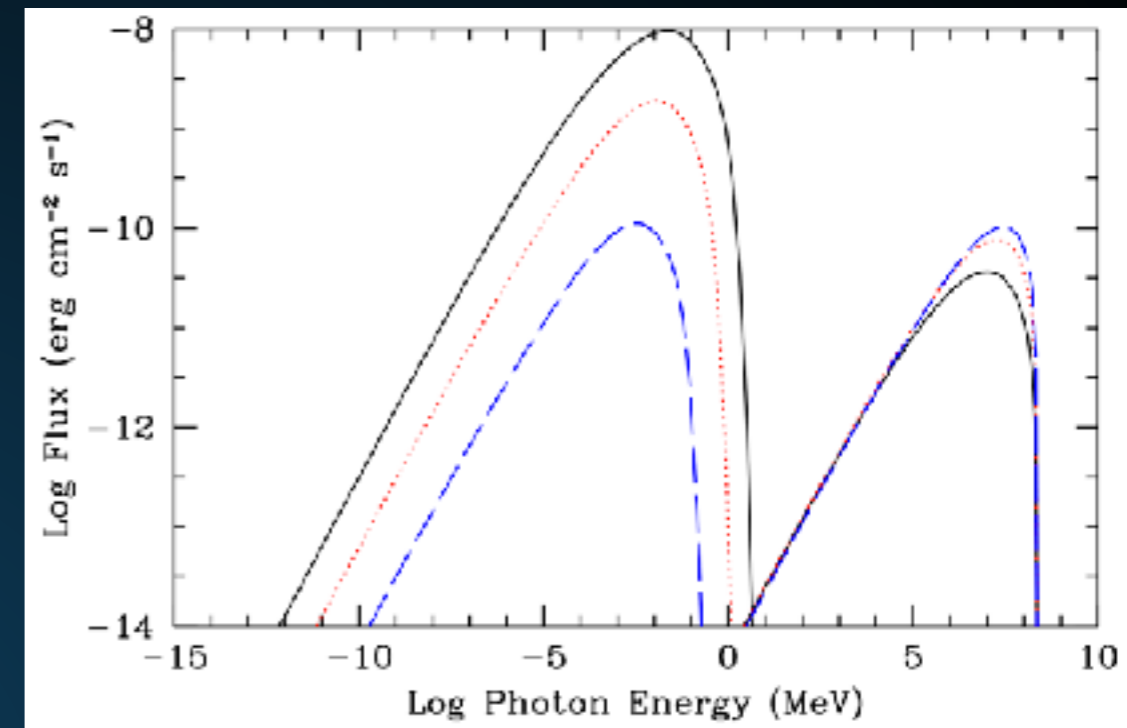
- ▶ **Larger magnetic fields make compact PWN easier to observe**
 - ▶ **Synchrotron dominated**
 - ▶ **Higher energy peak**
- ▶ **More distant sources easier to see.**
- ▶ **Significant observation times require careful HAWC analysis.**

GEMINGA SPECTRUM INDICATIVE OF CONVECTION

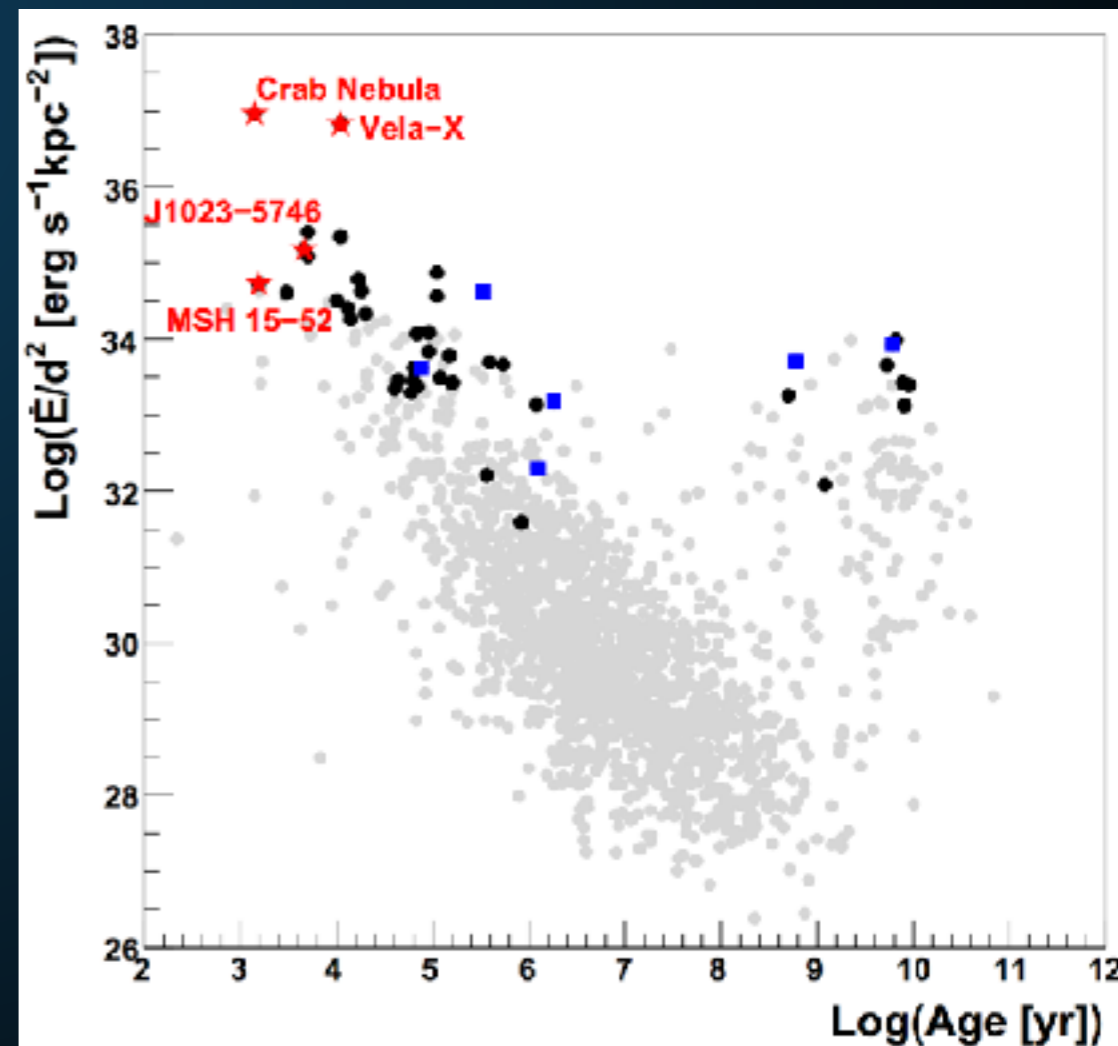
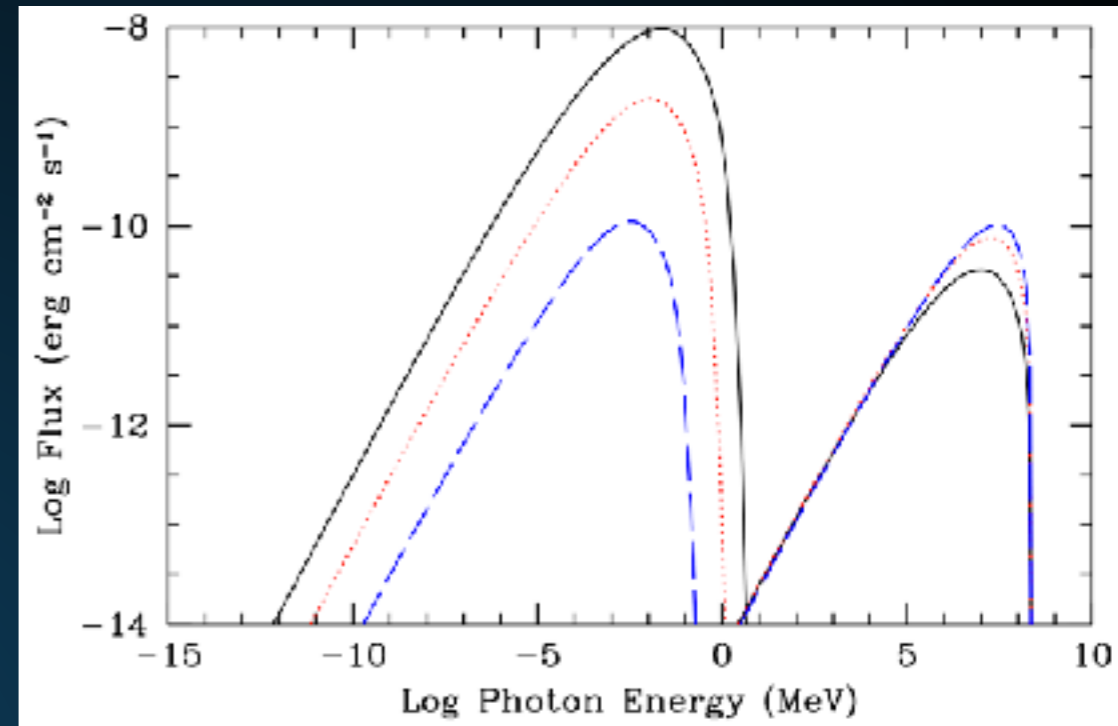


- ▶ Geminga spectrum is fit better with convective models.
- ▶ Energy-independent diffusion provides identical results
- ▶ Best-fit spectral-index (-2.23 ± 0.08) prefers high convection

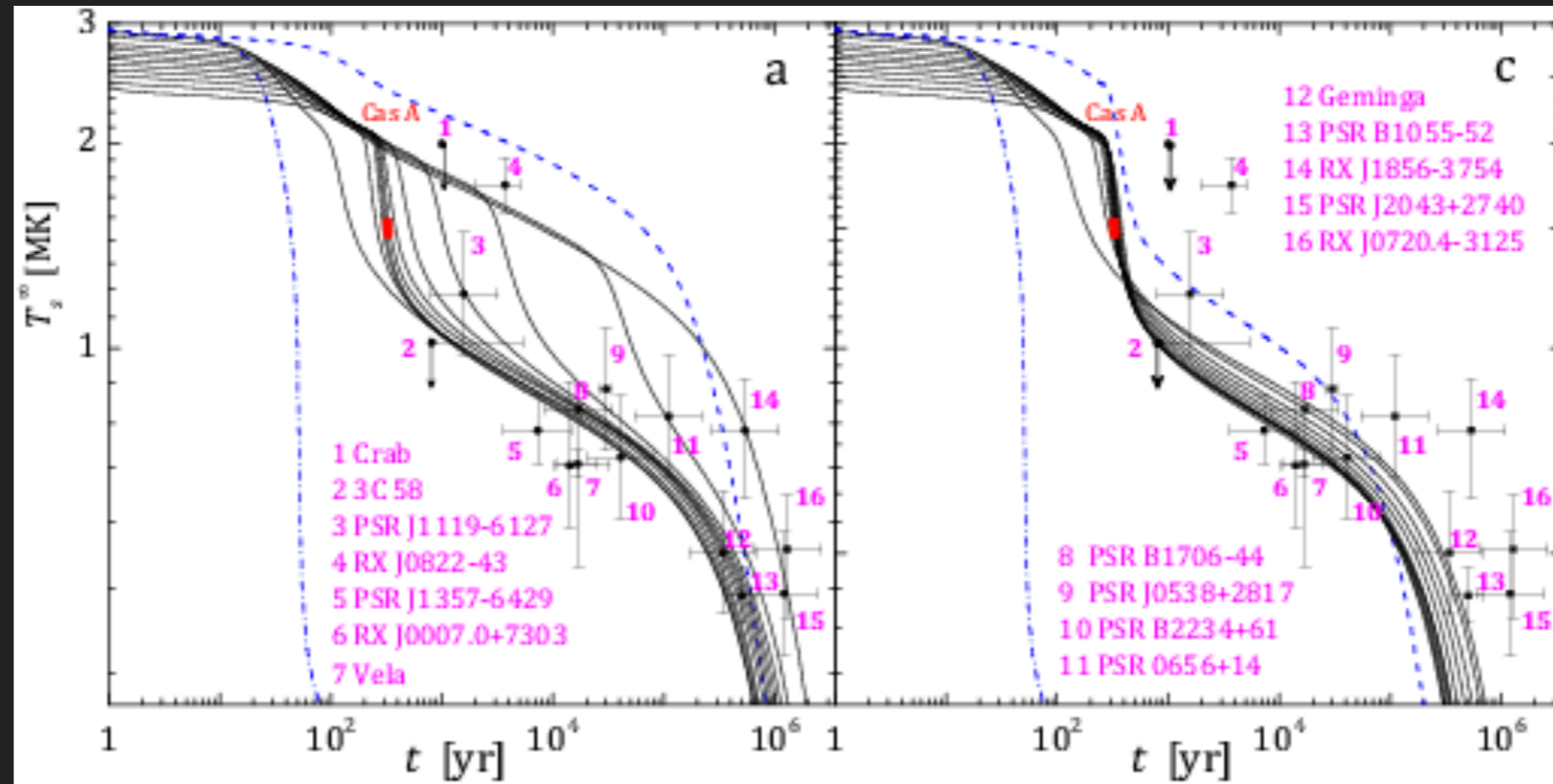
- ▶ Cooling dominated by $20 \mu\text{G}$ magnetic field.
- ▶ Energy loss time: ~ 40 years
- ▶ Distance Traveled: ~ 6 pc for standard diffusion constant. Real diffusion must be slower.
- ▶ The spectrum changes as a function of distance and time.



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

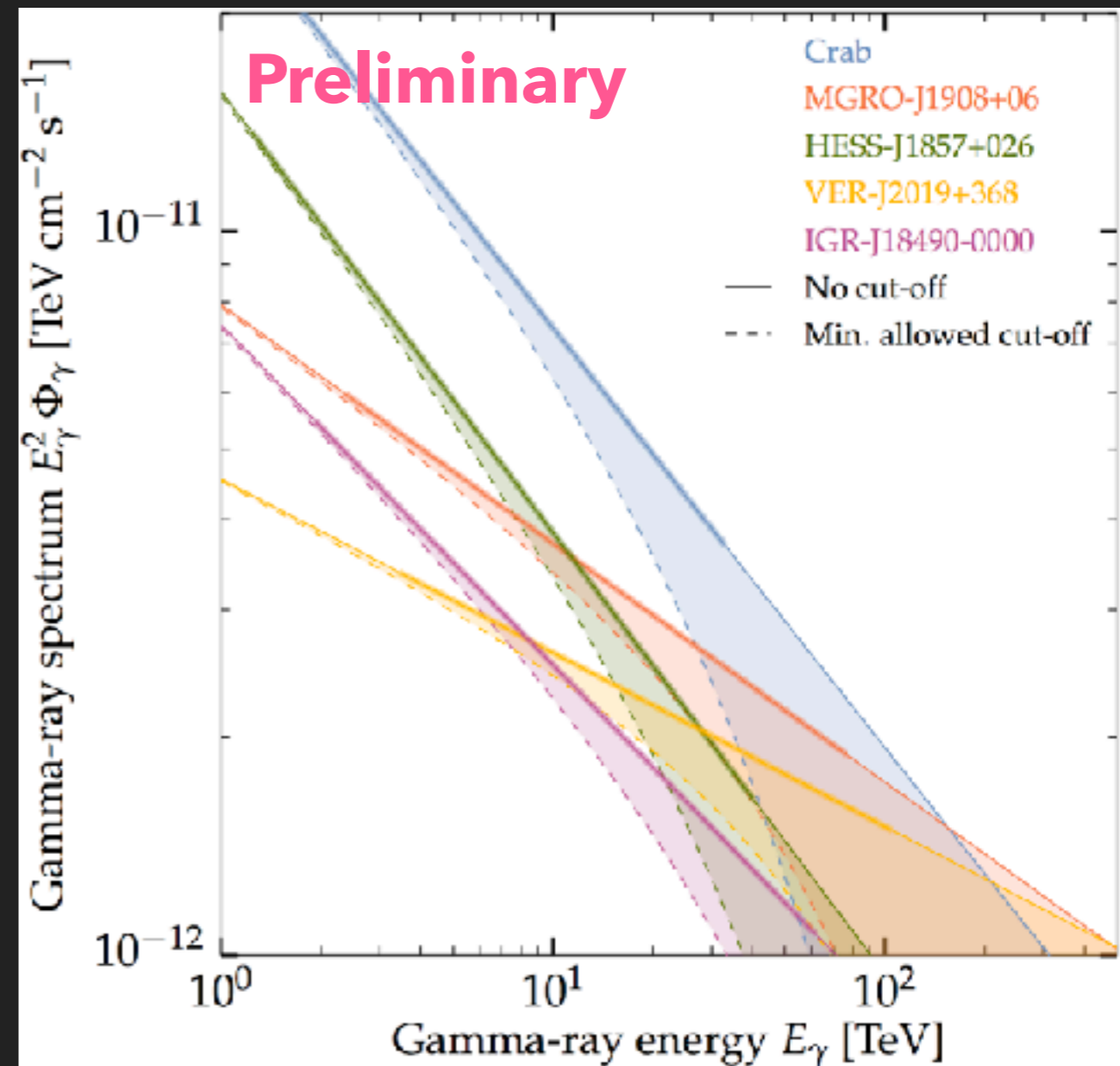


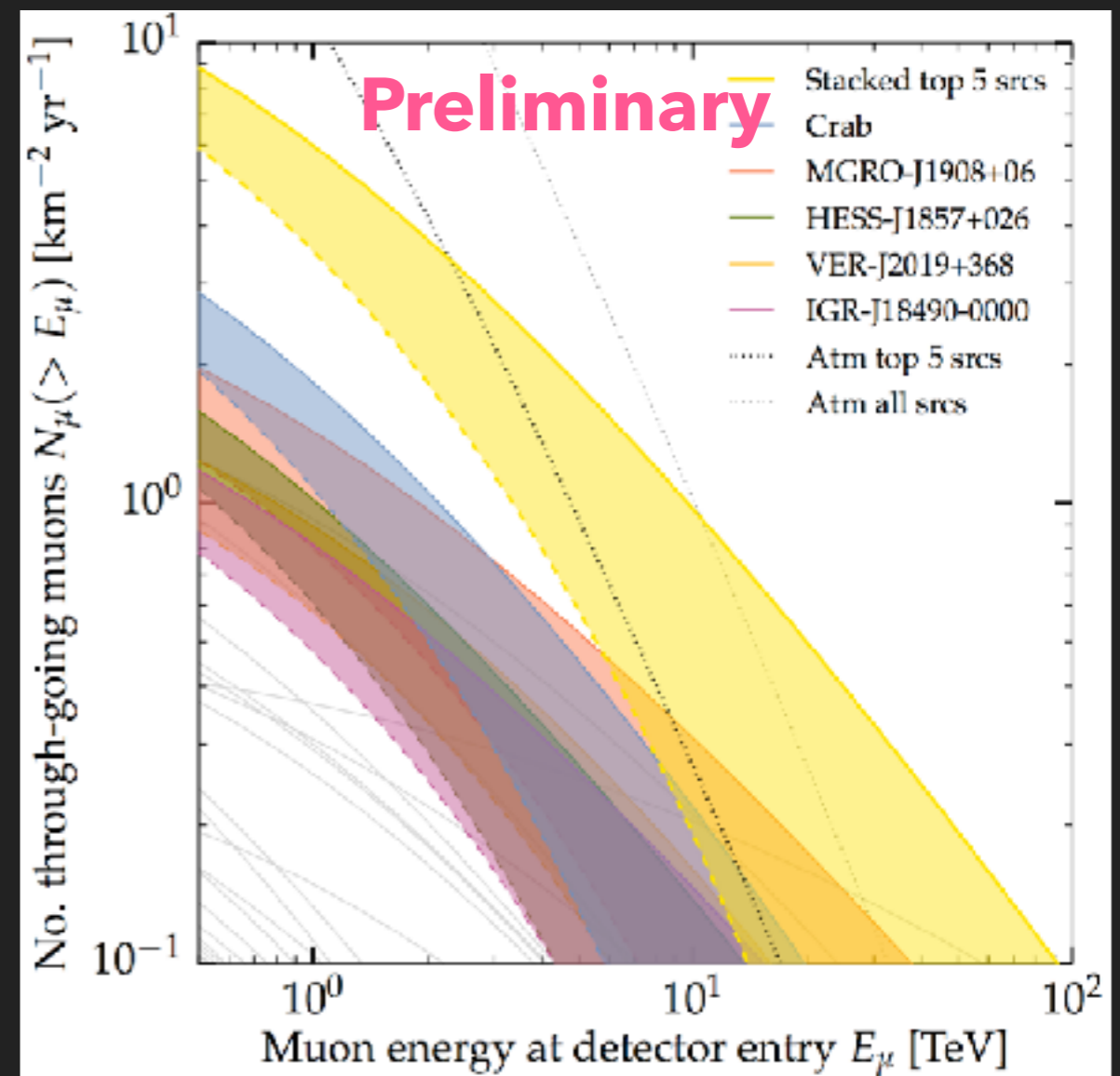
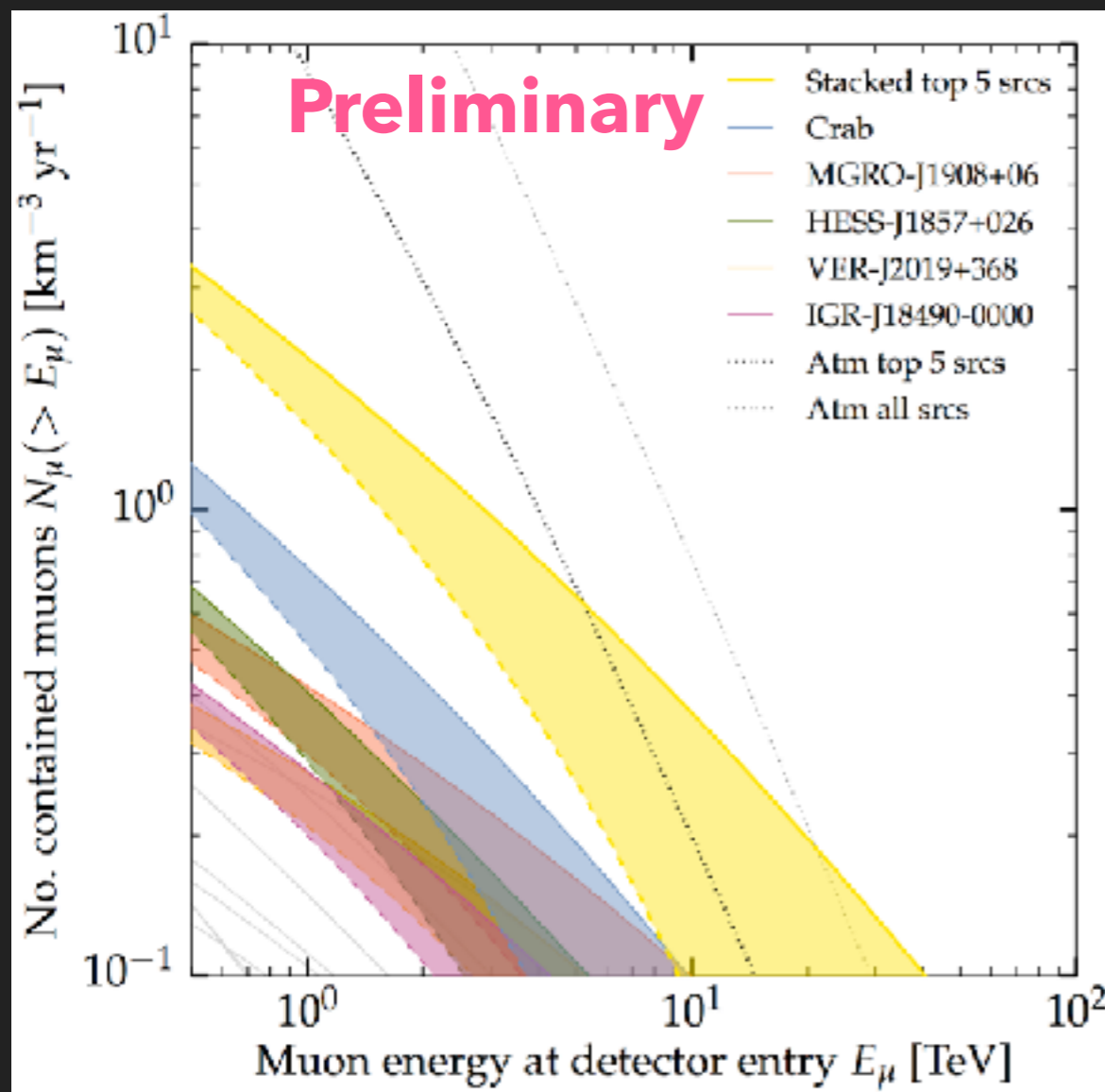
THERMAL PULSAR EMISSION



- ▶ 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.

- ▶ **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.**





- ▶ 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.