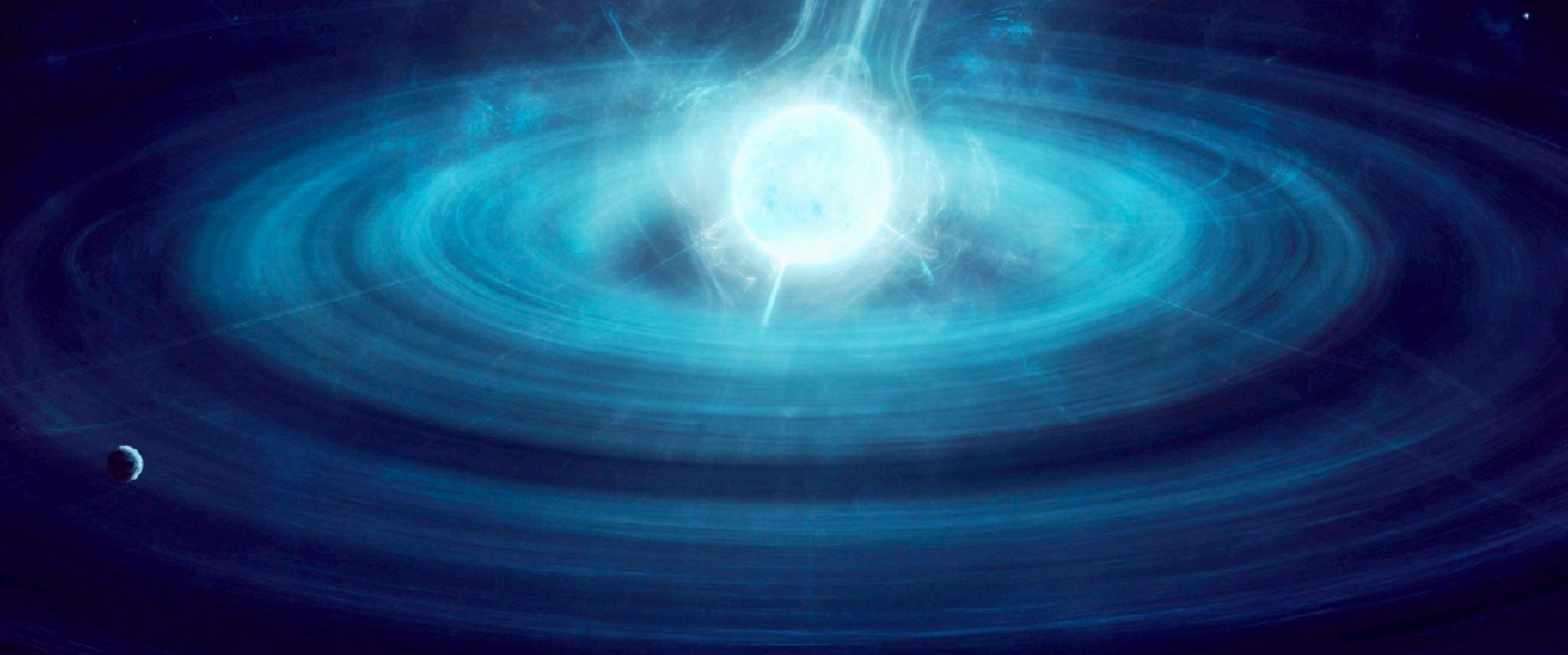


TIM LINDEN

THE RISE OF THE LEPTONS

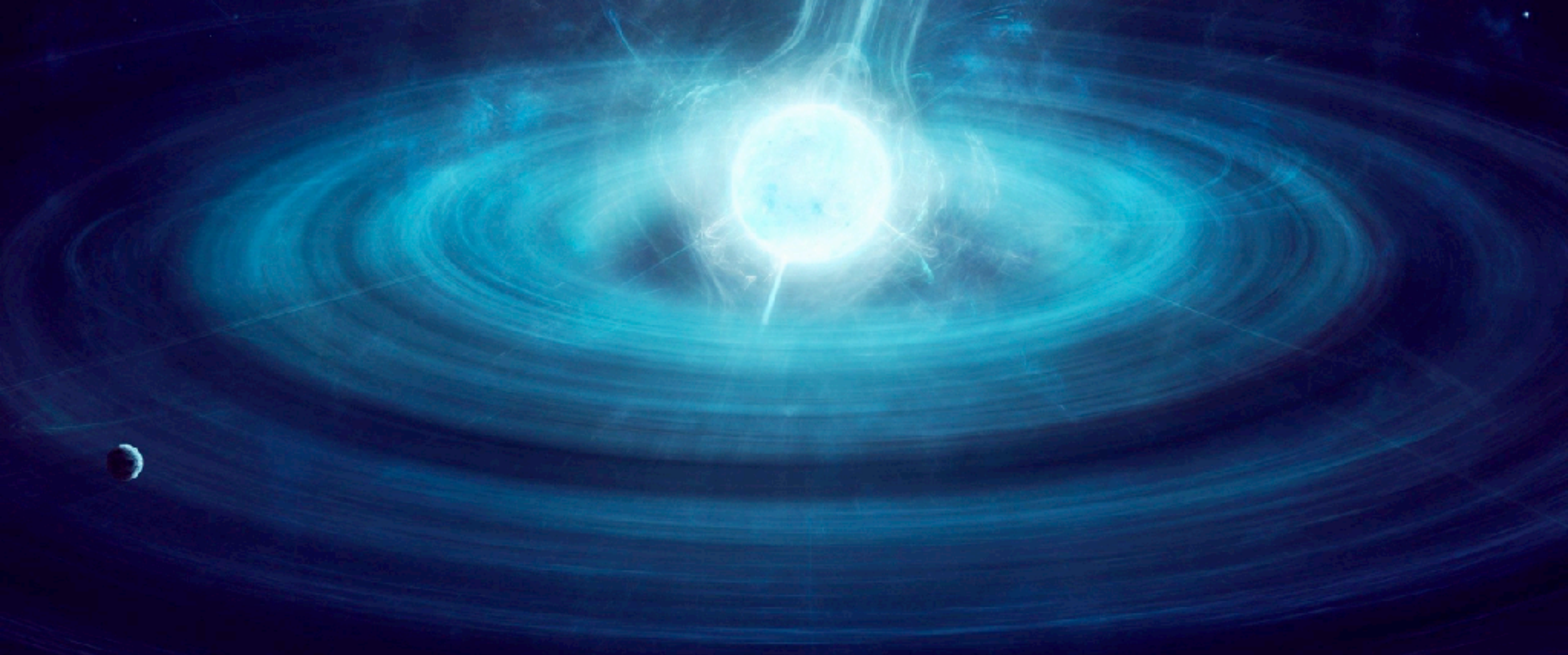
PULSAR EMISSION DOMINATES THE TEV GAMMA-RAY SKY

TeVPA 2017!

August 8, 2017

THE OHIO STATE UNIVERSITY

CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS



TIM LINDEN

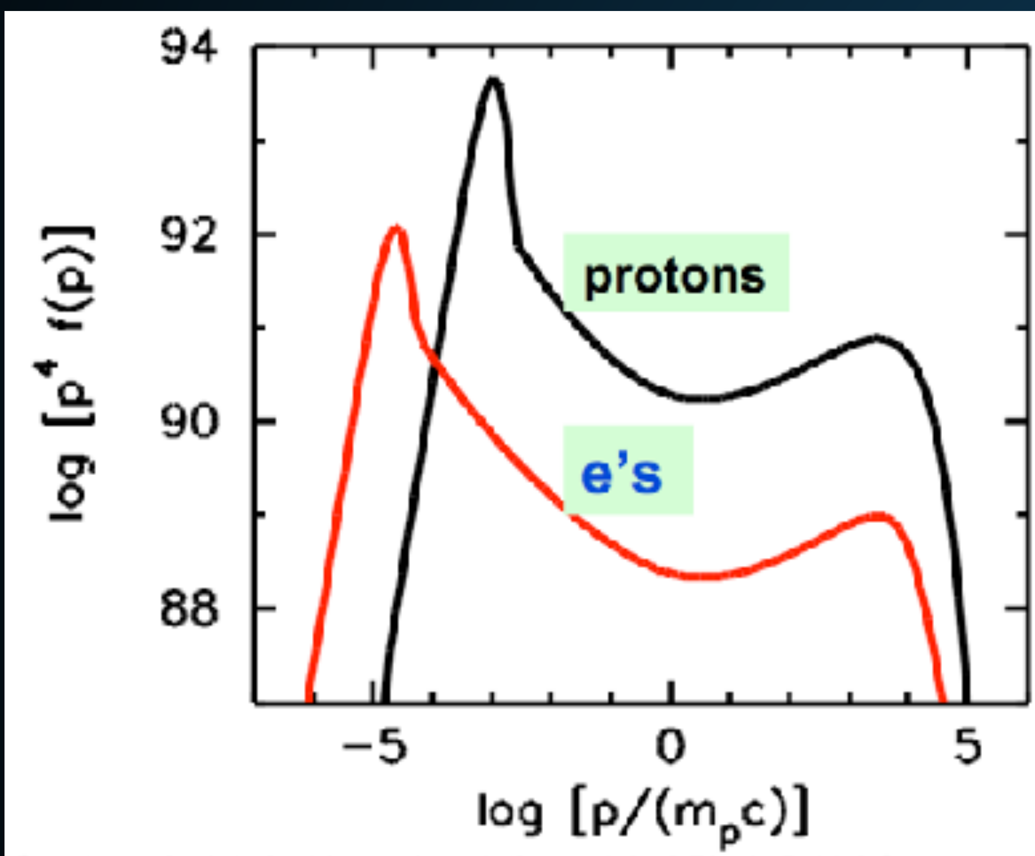
THE RISE OF THE LEPTONS

PULSAR EMISSION DOMINATES THE TEV GAMMA-RAY SKY

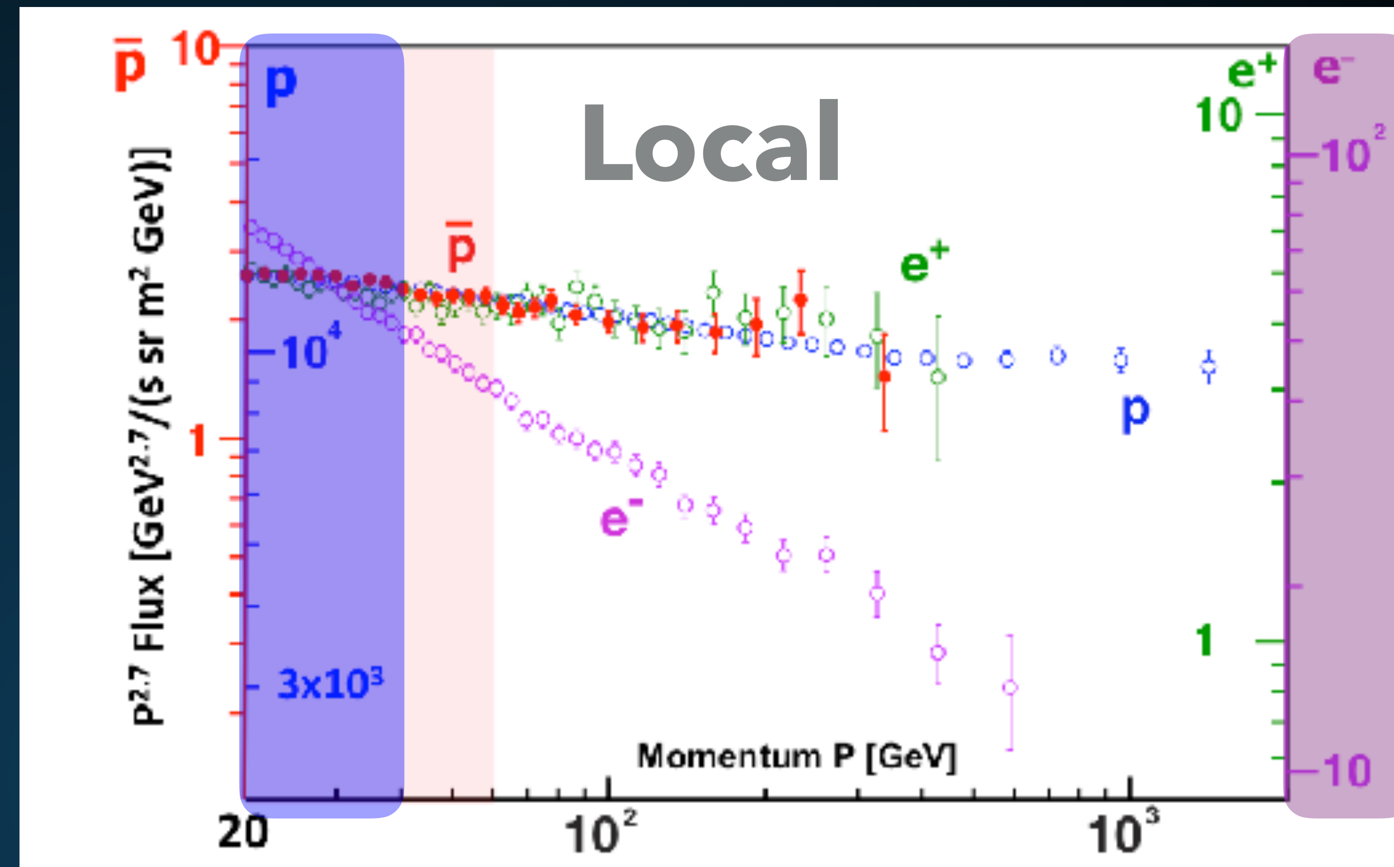
WITH: KATIE AUCHETTL, BEN BUCKMAN,
JOSEPH BRAMANTE, ILIAS CHOLIS, KE FANG,
DAN HOOPER, SHIRLEY LI

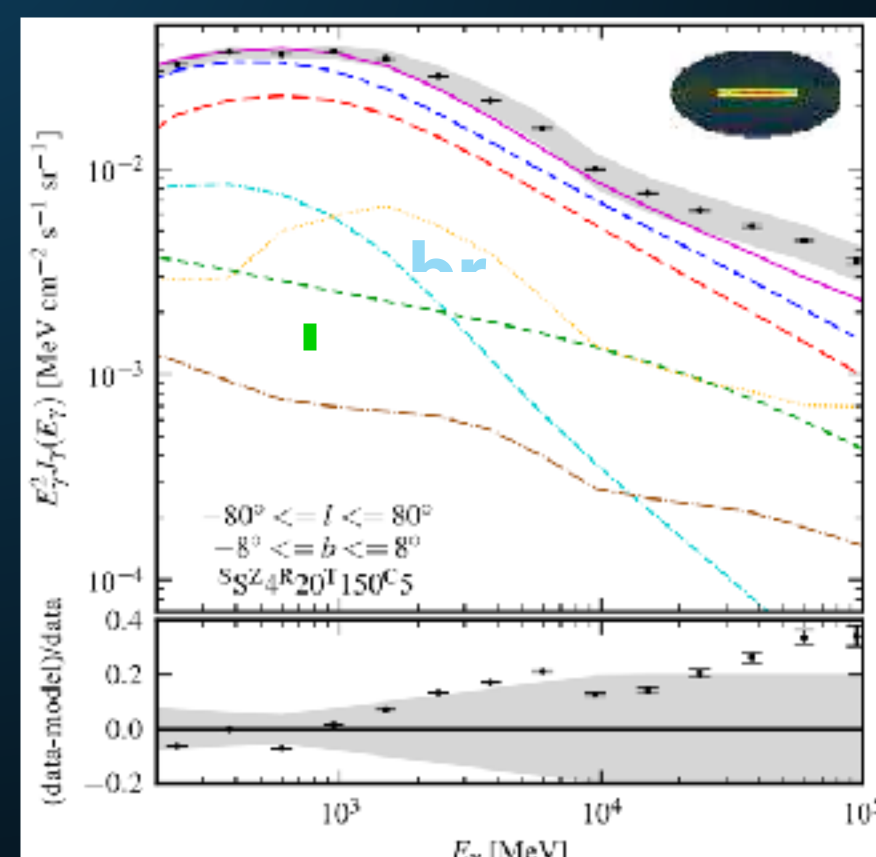
A GALAXY DOMINATED BY PROTONS

Sources



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





Gamma-Rays

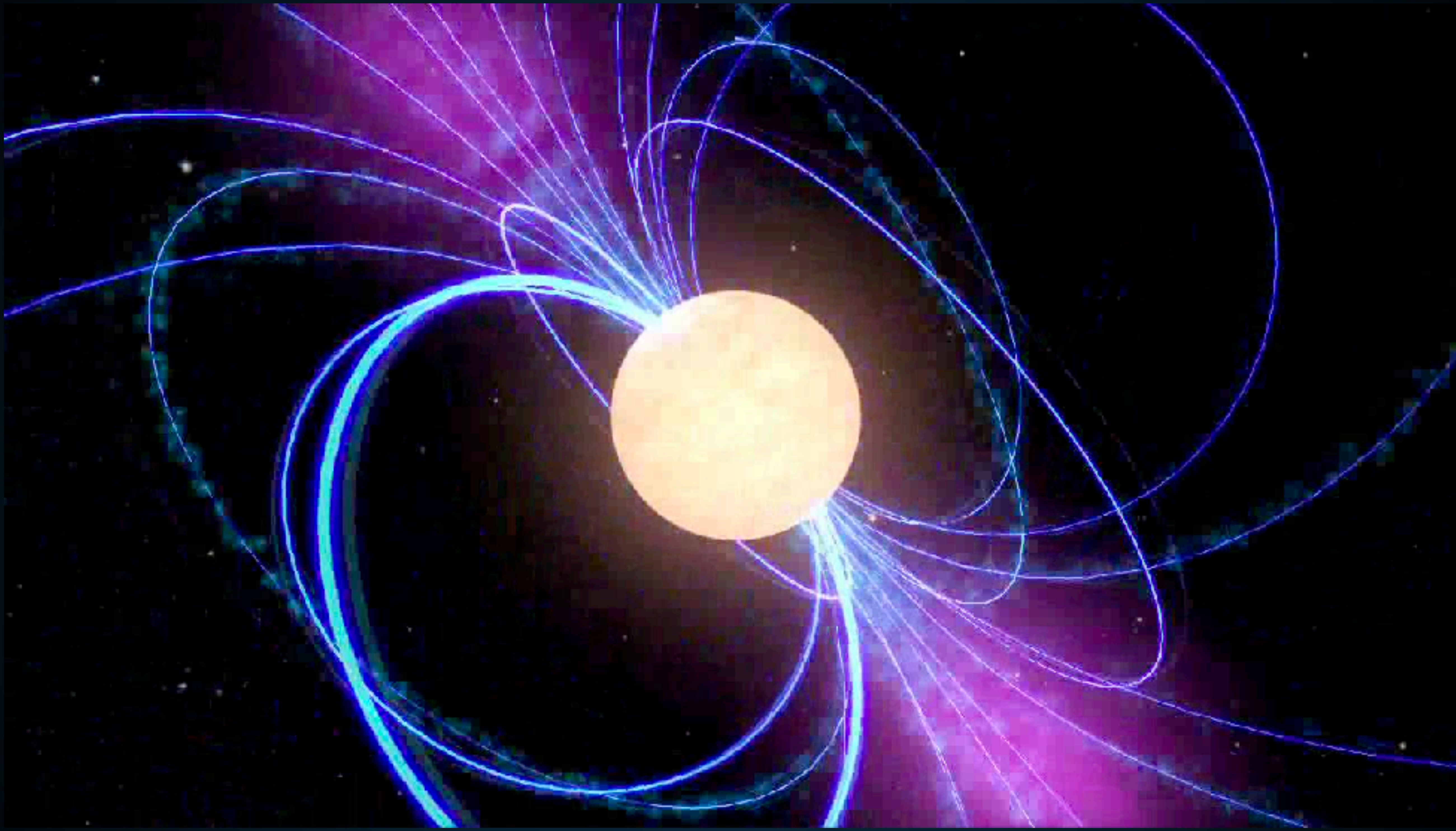
A NEW PICTURE

- In this talk, I will instead argue that electrons and positrons produced by pulsars dominate the Milky Way's energetics at TeV energies:
  - 1.) Pulsars are responsible for the rising positron fraction observed by PAMELA/AMS-02 (Hooper et al (1702.08436); see talk by Dan Hooper Wednesday, Macedonian Room, 3PM).
  - 2.) Pulsars produce the majority of the bright TeV sources observed by CTA/HAWC/HESS etc. (Linden et al. (1703.09704); this talk).
  - 3.) Pulsars produce the majority of the TeV gamma-ray emission observed from the Milky Way (Hooper et al. (1705.09293), Linden & Buckman (1707.01905); alluded to here).

A VERY SIMPLE MODEL OF PULSAR EMISSION

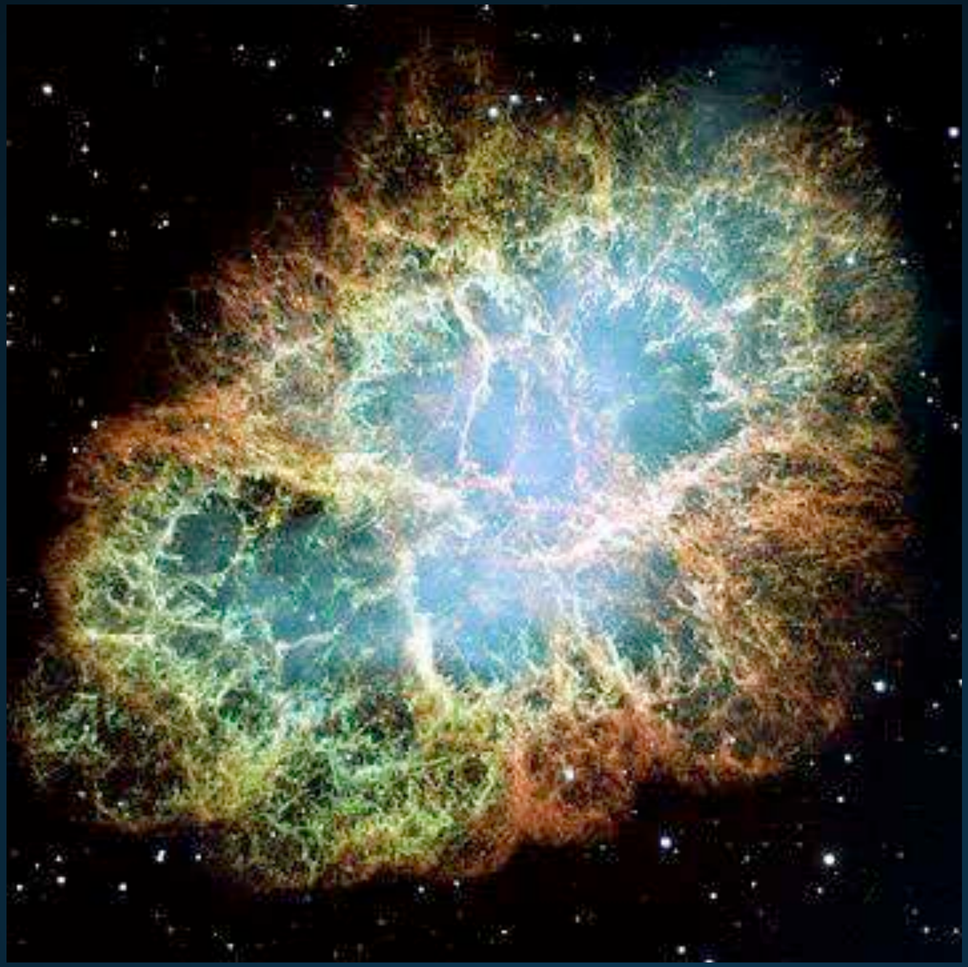
Pulsars as high-energy particle accelerators

PULSARS AS ASTROPHYSICAL ACCELERATORS



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

PHYSICS HAPPENS



- Outside the immediate pulsar magnetosphere, a number of forces are at work:
  - Synchrotron/ICS cooling
  - Reacceleration
  - Termination Shocks

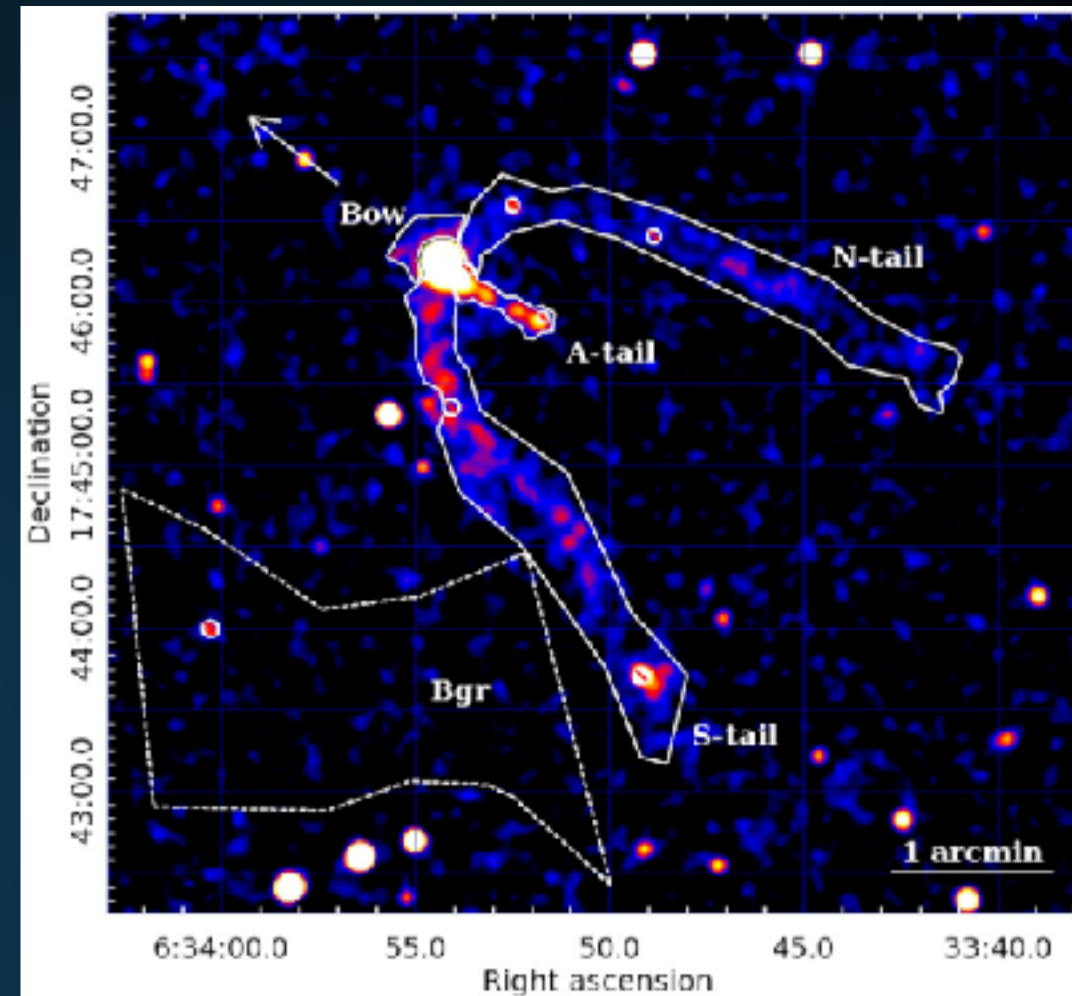
LOW-ENERGY OBSERVATIONS OF PULSAR WIND NEBULAE

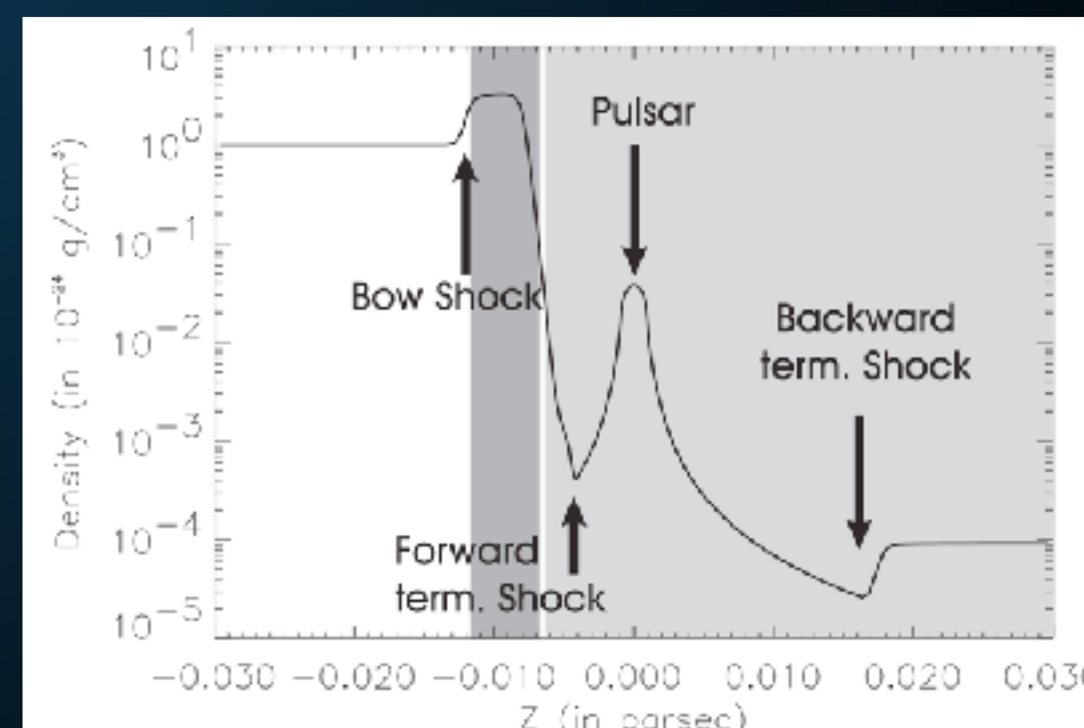
1611.03496
astro-ph/0202232

- **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.**

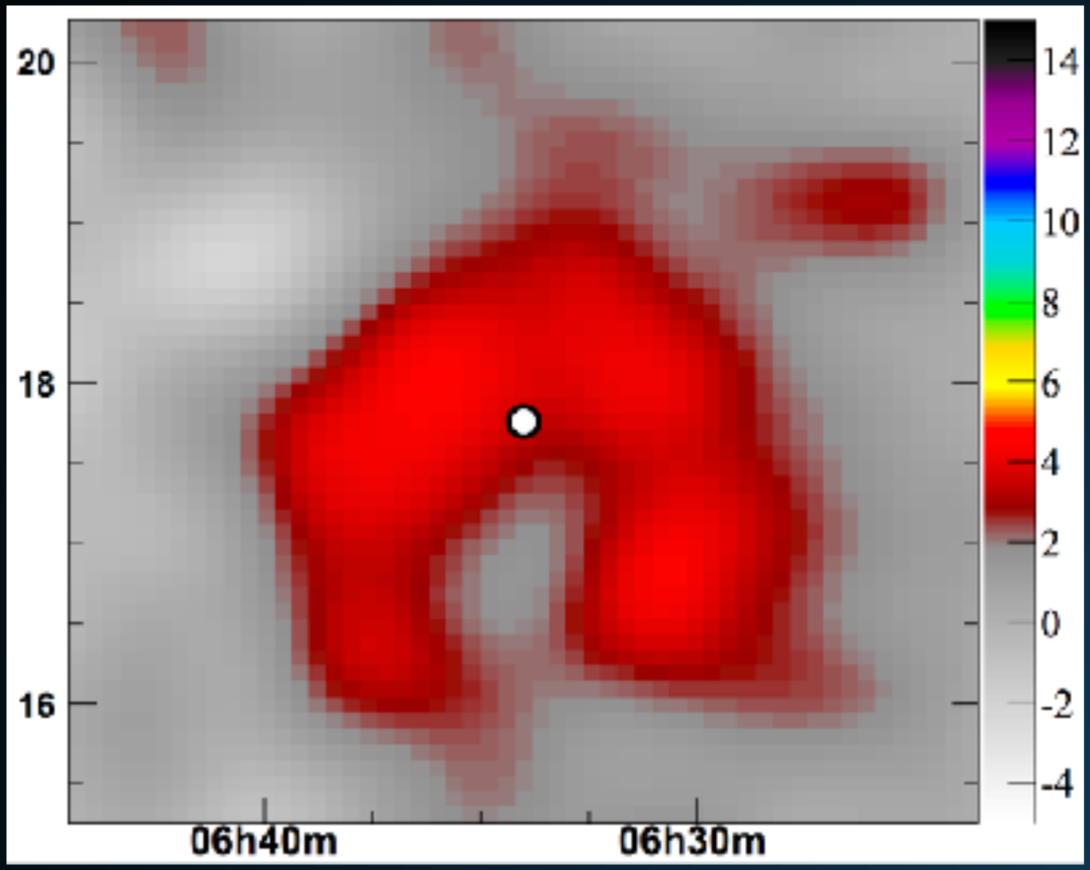
$$R_{\rm PWN} \simeq 1.5 \left(\frac{\dot{E}}{10^{35}\,{\rm erg/s}}\right)^{1/2} \times \left(\frac{n_{\rm gas}}{1\,{\rm cm}^{-3}}\right)^{-1/2} \left(\frac{v}{100\,{\rm km/s}}\right)^{-3/2} {\rm pc}$$

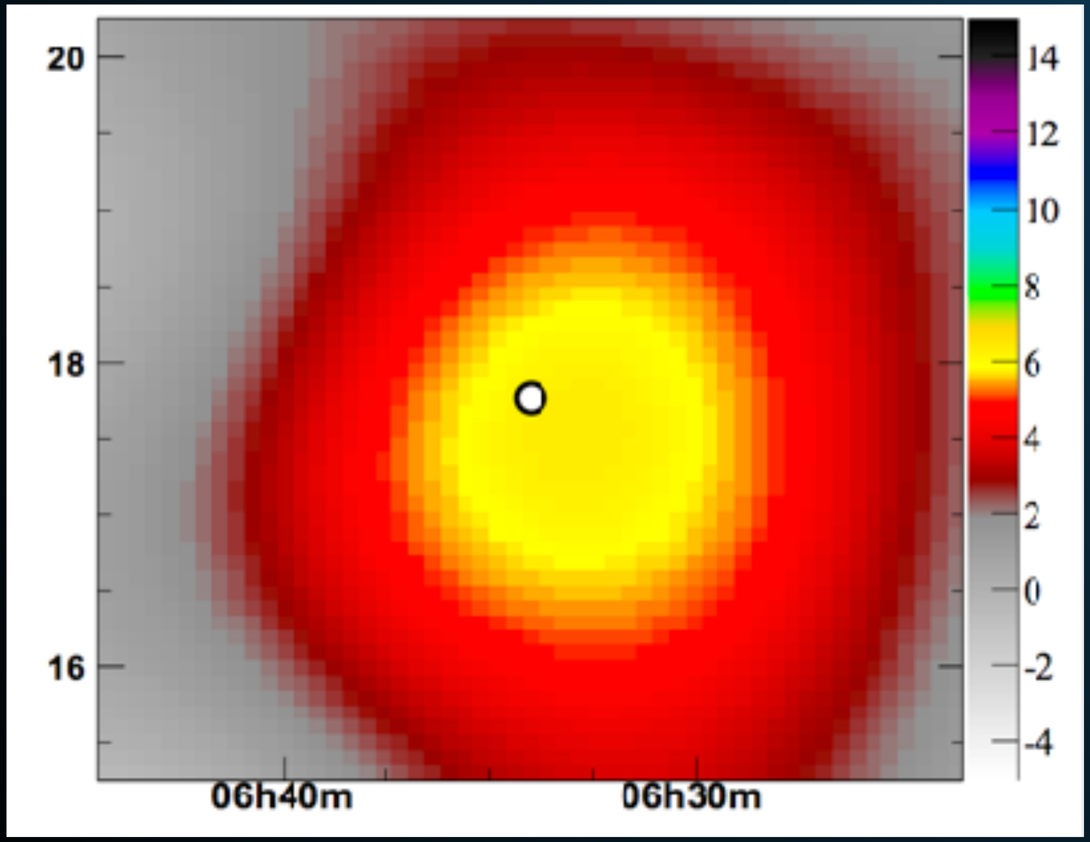
- **NOTE: The radial extent of PWN is explained by a known physical mechanism.**





TEV OBSERVATIONS OF PULSARS





- Milagro and HAWC observe very extended emission from Geminga and Monogem (~2°)
- Corresponds to ~10 pc - three orders of magnitude larger in volume than the PWN.
- Opposite energy dependence - older pulsars have larger TeV emission features.

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 ± 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 extended "TeV PWN"**
- **NOTE: The radial extent of this TeV emission is NOT explained by a known physical mechanism.**

TEV HALOS

- Extended TeV emission appears to be a generic feature of pulsars.
- We rename these objects TeV halos.

Implication I:

Most TeV gamma-ray sources are TeV halos.

HESS SOURCES COINCIDENT WITH KNOWN 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.**

TEV HALOS: THE FIRST ORDER MODEL

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

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

- **Assume that Geminga is a model for TeV halos, and every similar system is equivalently efficient at converting spin-down power to TeV gamma-ray emission.**
- **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.**

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.

- Hints that “missing sources” are coincident with non-statistically significant TeV excesses.

HAWC SENSITIVITY AFTER 10 YEARS

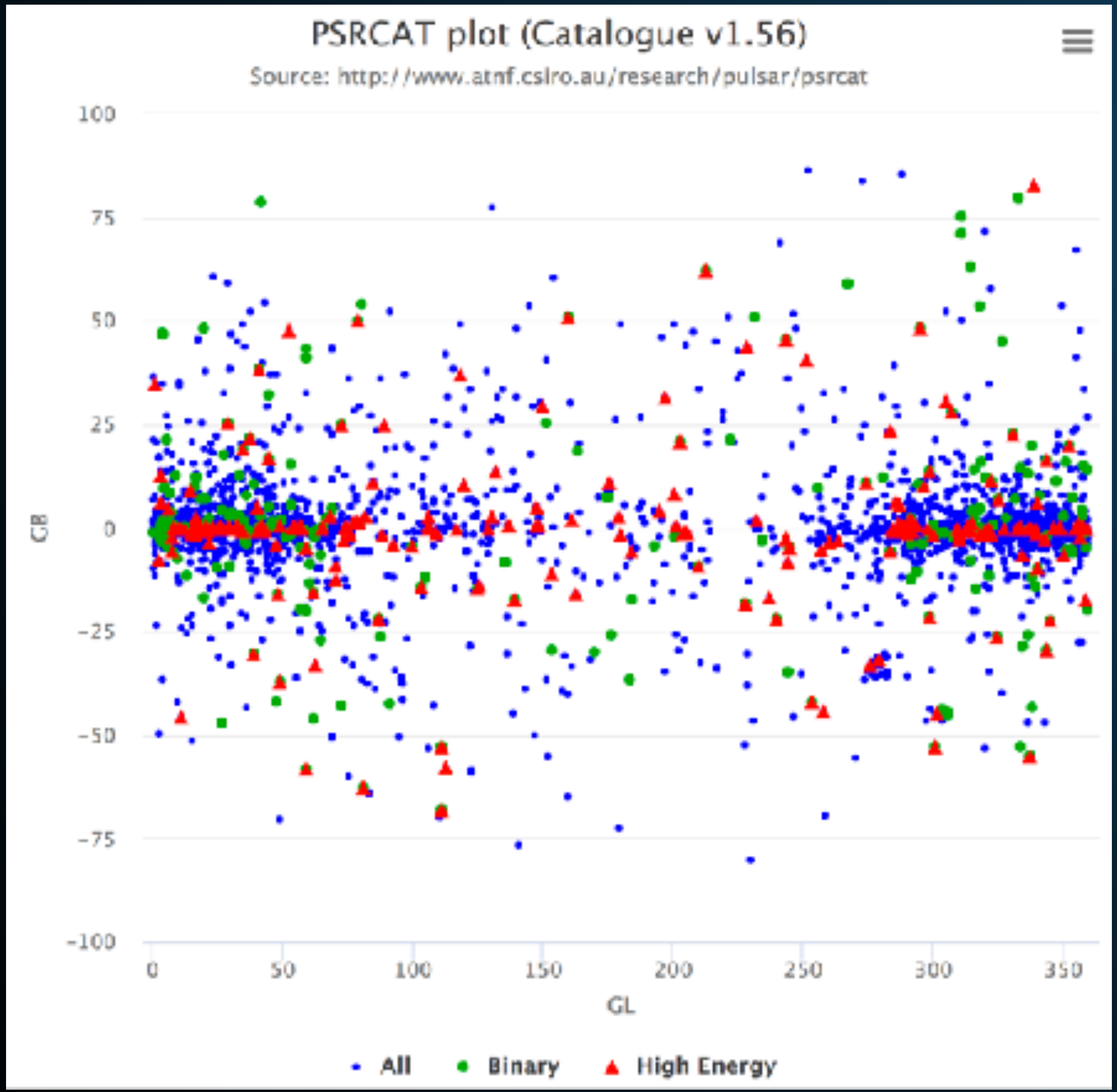
ATNF Name	Dec. (°)	Distance (kpc)	Age (kyr)	Spindown Lum. (erg s^{-1})	Spindown Flux (erg s^{-1} kpc^{-2})	2HWC
J0633+1746	17.77	0.25	342	3.2e34	4.1e34	2HWC J0631+169
B0656+14	14.23	0.29	111	3.8e34	3.6e34	2HWC J0700+143
B1951+32	32.87	3.00	107	3.7e36	3.3e34	—
J1740+1000	10.00	1.23	114	2.3e35	1.2e34	—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

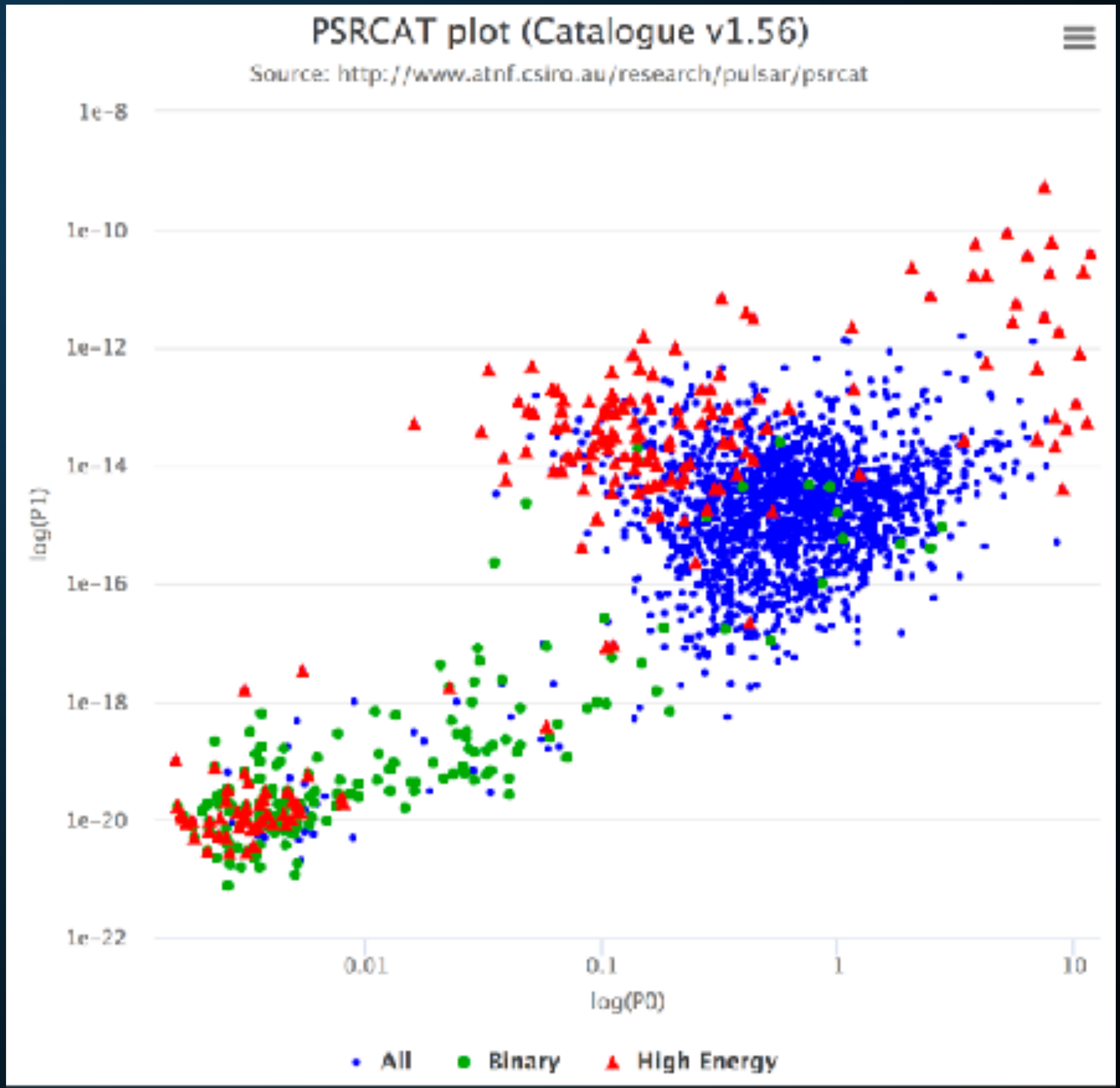
- **HAWC will eventually reach a flux sensitivity of 0.02 Geminga**
- **Will observe**
  - **TeV halos from a dozen middle-aged ATNF pulsars.**
  - **TeV halos from ~40 additional young pulsars.**

WHY DO WE CARE?

- Maybe HAWC is seeing ~20 TeV halos.

- More than 2600 pulsars are already detected in radio





- **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
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J1814-173	J1813-1749	4.7	0.54°	44.30 pc	243	152	1.60	0.11°	1.0°	5.6	0.61
J2019+367	J2021+3651	1.8	0.27°	8.48 pc	99.8	58.2	1.71	0.28°	0.7°	17.2	0.04
J1928+177	J1928+1746	4.34	0.03°	2.27 pc	8.08	10.0	0.81	0.11°	0.0°	82.6	0.002
J1908+063	J1907+0602	2.58	0.36°	16.21 pc	40.0	85.0	0.47	0.2°	0.8°	19.5	0.26
J2020+403	J2021+4026	2.15	0.18°	6.75 pc	2.48	18.5	0.134	0.23°	0.0°	77	0.01
J1857+027	J1856+0245	6.32	0.12°	13.24 pc	11.0	97.0	0.11	0.08°	0.9°	20.6	0.06
J1825-134	J1826-1334	3.61	0.20°	12.66 pc	20.5	249	0.082	0.14°	0.9°	21.4	0.14
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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

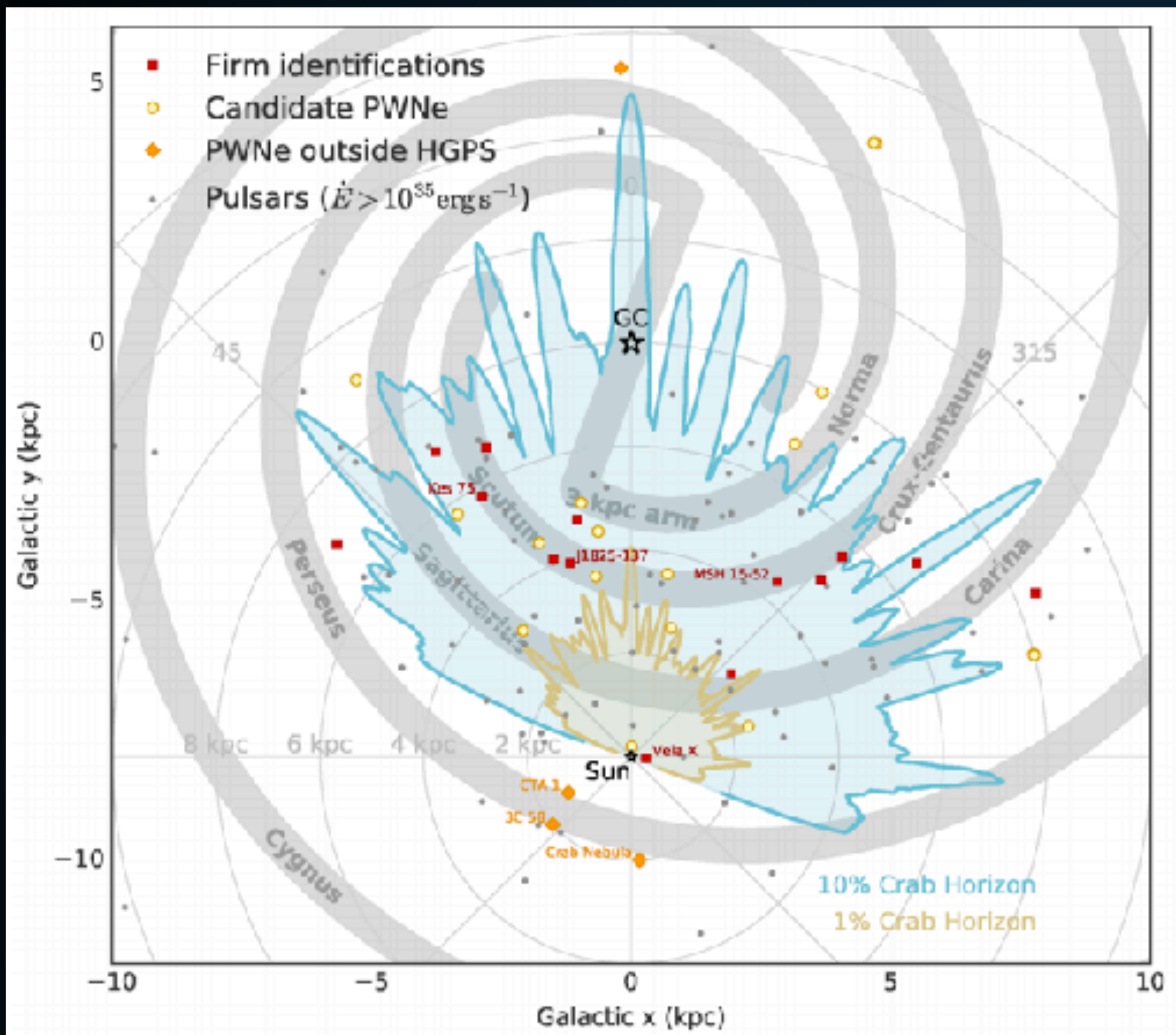
- The beaming fractions predicts that 56^{+15}_{-11} TeV halos are currently observed by HAWC.
- However, only 39 total HAWC sources
- Chance overlaps, SNR contamination must be taken into account.
- But most unassociated HAWC sources must be TeV halos.

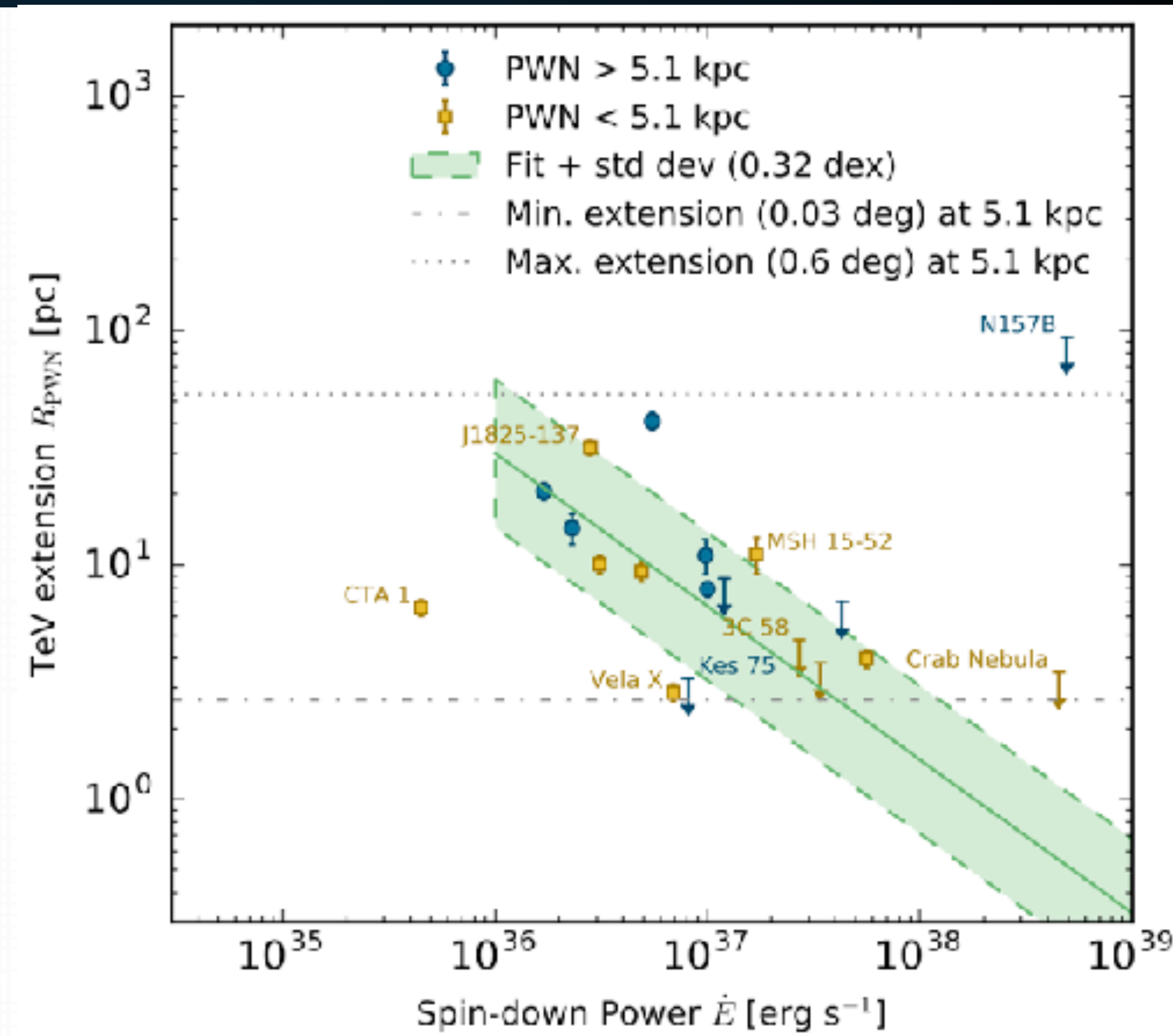
EVENTUAL TEV HALO DETECTIONS

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	—

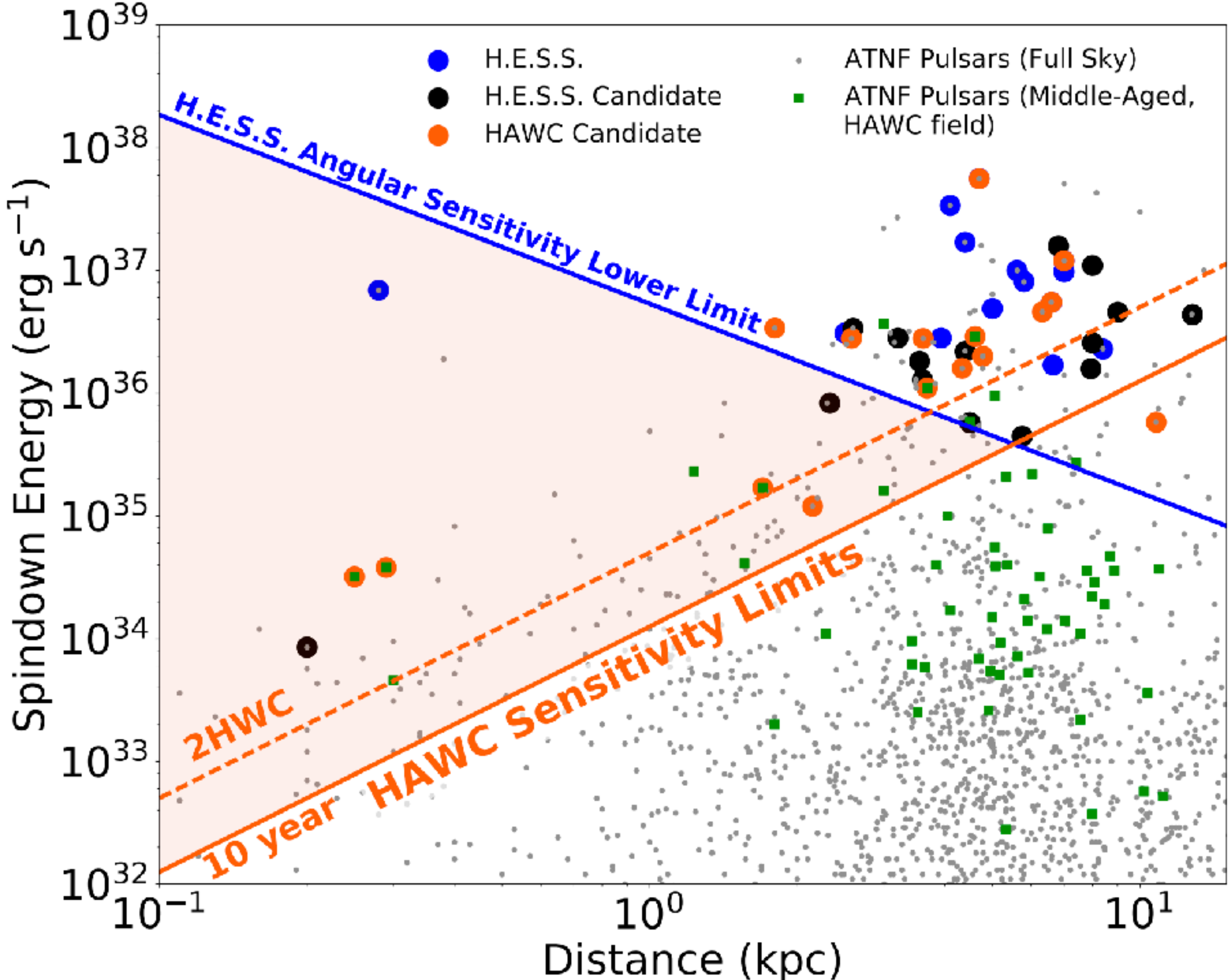
- **10 year HAWC observations should detect 37^{+17}_{-13} TeV halos surrounding middle-aged pulsars.**
- **These numbers correspond to most of the TeV sources detectable by HAWC.**
- **Most of these sources not detected at other wavelengths.**

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.



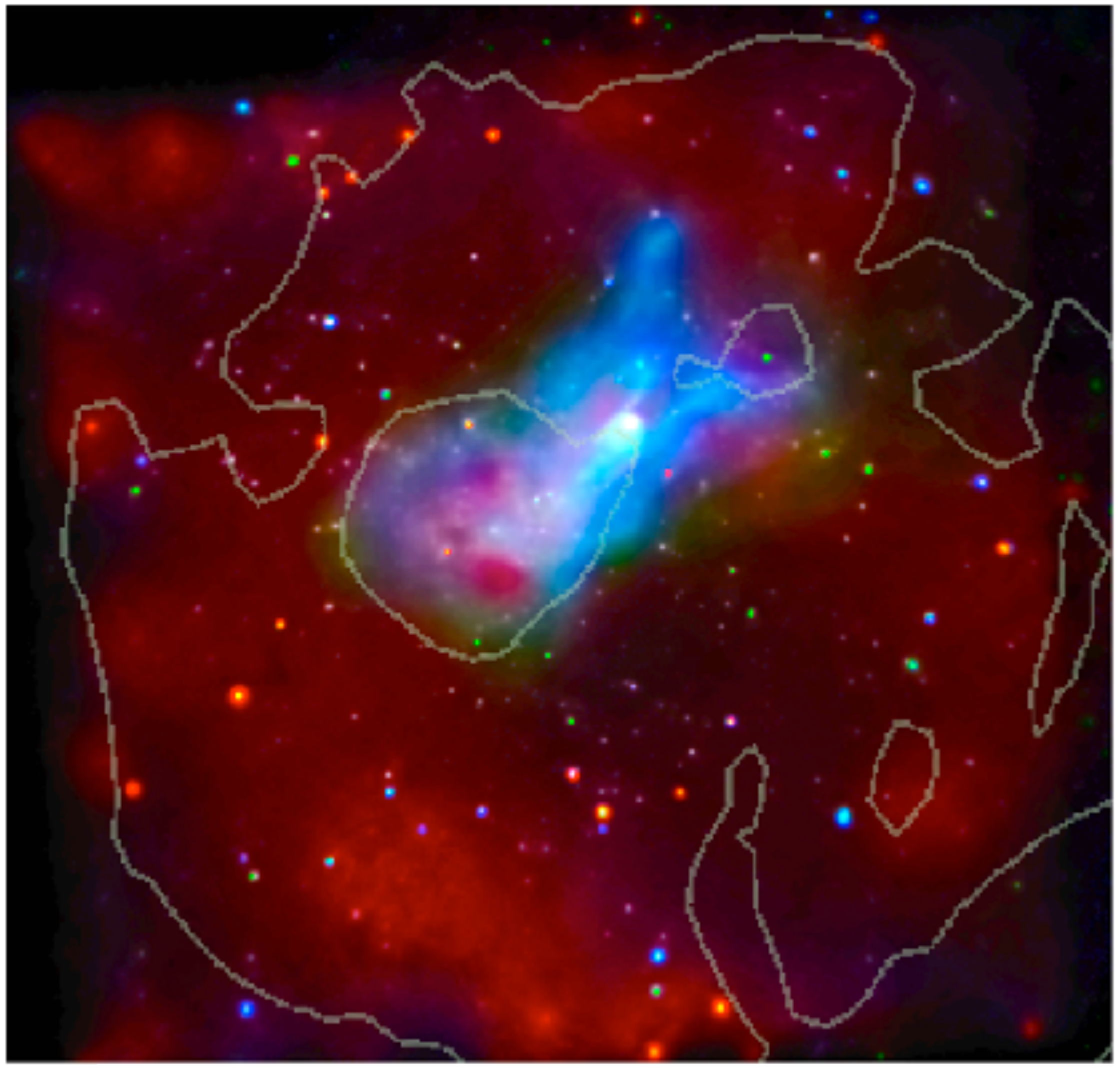
H.E.S.S.
H.E.S.S. Candidate
HAWC Candidate
ATNF Pulsars (Full Sky)
ATNF Pulsars (Middle-Aged, HAWC field)
H.E.S.S. Angular Sensitivity Lower Limit
2HWC
10 year HAWC Sensitivity Limits
Spindown Energy (erg s^{-1})
Distance (kpc)
10^{39}
10^{38}
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
10^{-1}
10^{0}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

CONFIRMING TEV HALOS

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

A POSSIBLE DETECTION

1506.03069



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

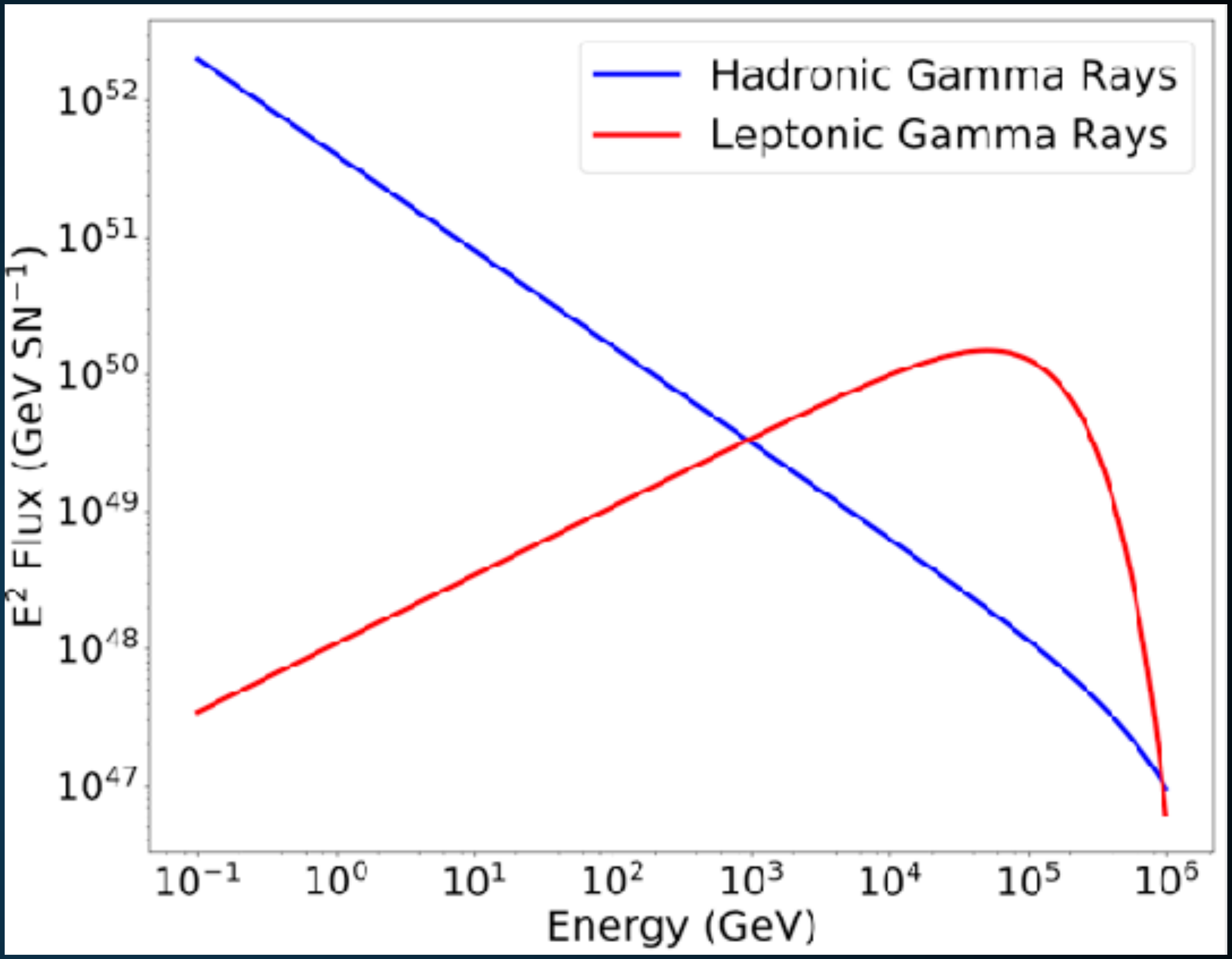
	Region	Area (arcsec^2)	Cts (1000)	N_H (10^{22} cm^{-2})	Photon Index	Amplitude (10^{-4})	kT (keV)	τ (10^{12} s cm^{-3})	Norm. (10^{-3})	F_1 (10^{-12})	F_2 (10^{-12})	Red. χ^2
1	Compact Source	84.657	6.34	$1.93^{+0.08}_{-0.08}$	$1.61^{+0.08}_{-0.07}$	$1.05^{+0.11}_{-0.10}$	...	...	...	0.45	...	0.80
2	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	...

Implication II:

Most TeV gamma-rays are leptonic

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

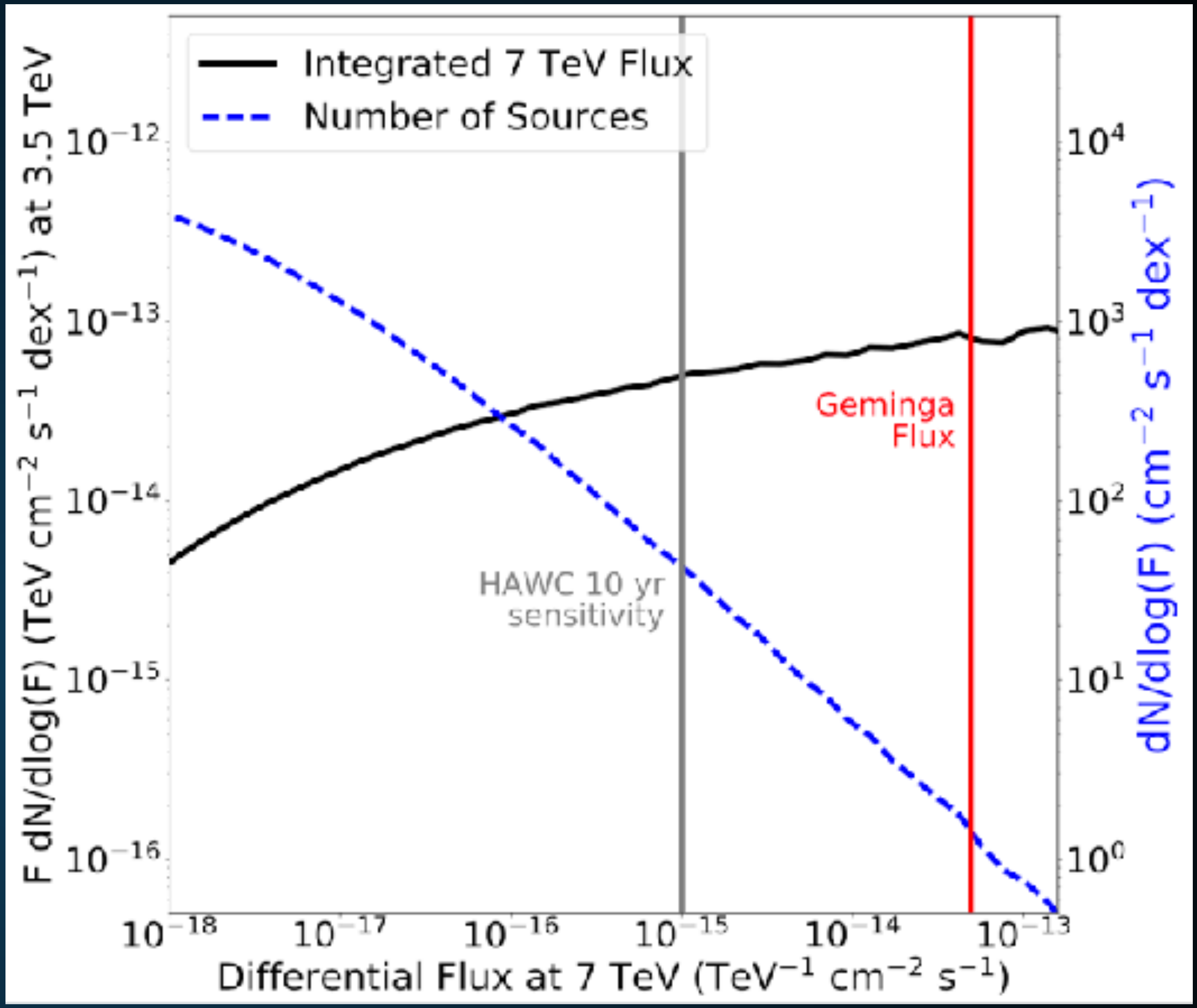
- Dim TeV halos will be observed as a new diffuse gamma-ray emission component.

TOTAL HIGH-ENERGY EMISSION FROM SNR AND PULSAR

What about dim TeV halos?

Linden et al. (TBS)

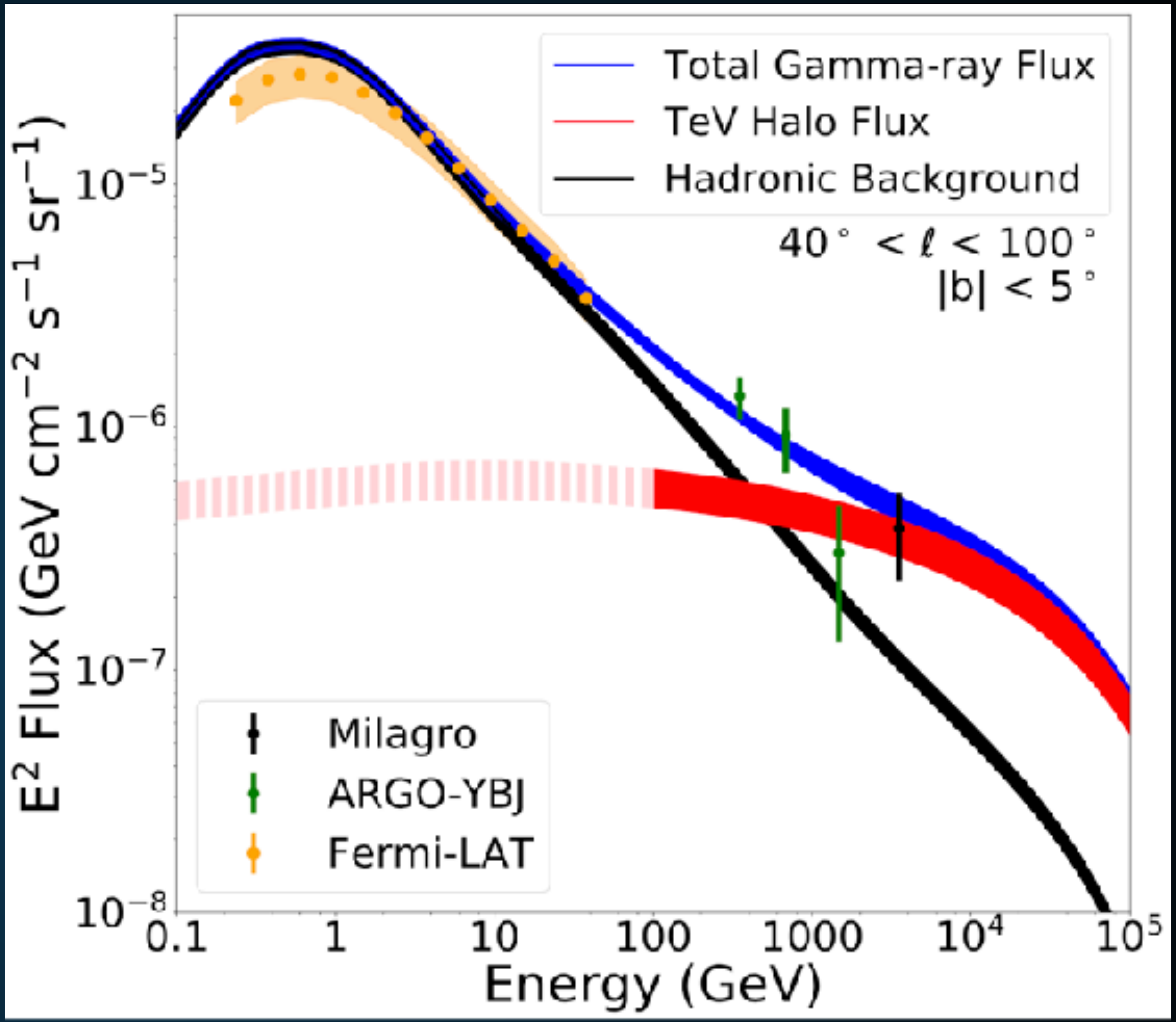
- Use a generic model for pulsar luminosities:
  - $B_0 = 10^{12.5}$ G ($10^{0.3}$ G)
  - $P_0 = 0.3$ s (0.15 s)
- Spindown Timescale of ~10^4 yr (depends on B_0)
- Galprop model for supernova distances



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

Linden et al. (TBS)

- 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 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.

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