HAWC results on other TeV Halos

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1st Workshop on Gamma-Ray Halos Around Pulsars
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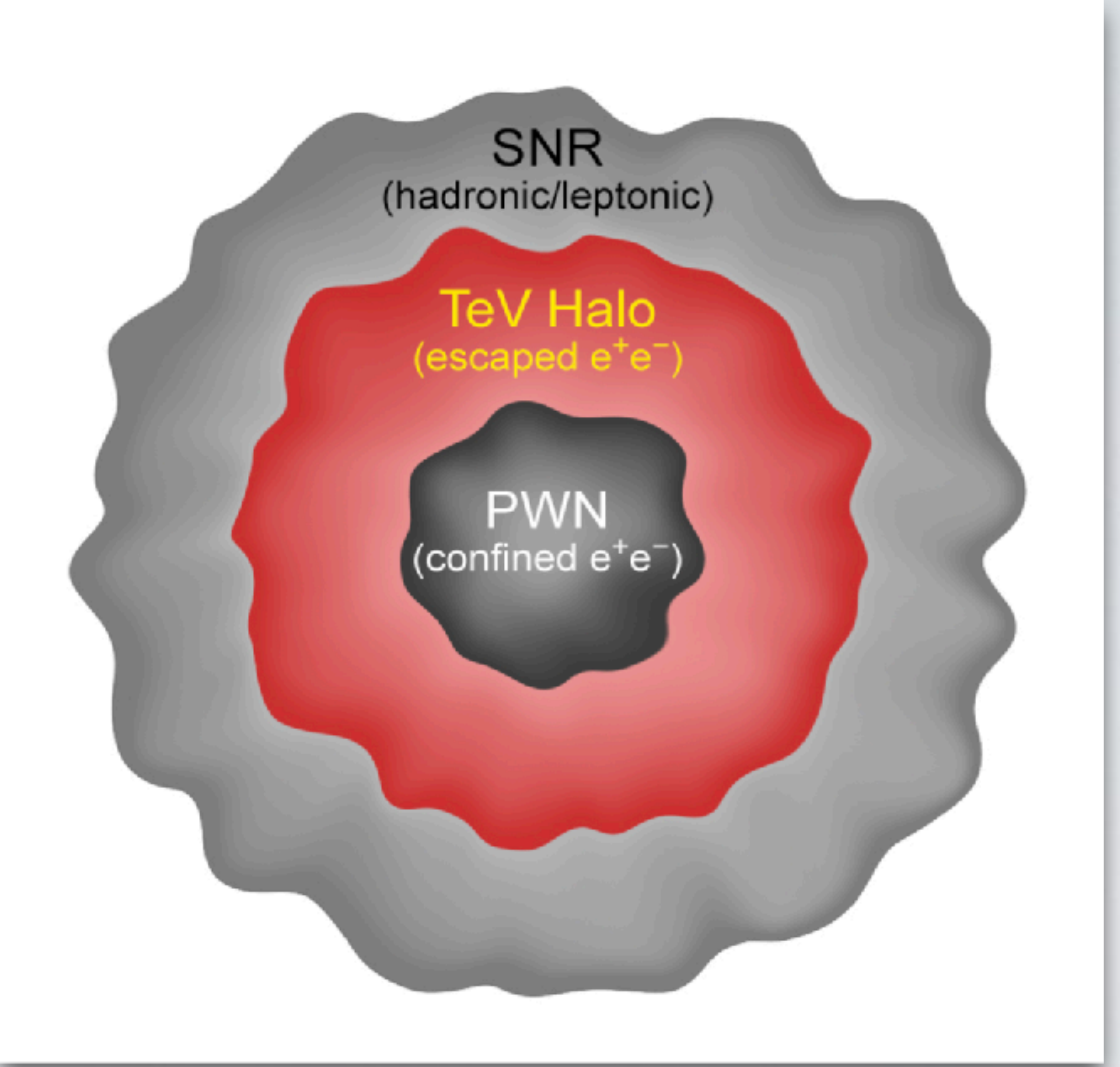
HAWC Collaboration

Note: Terminology to be used in this talk

- “TeV halo” and “gamma-ray halo” used somewhat interchangeably
- I will remain agnostic as to exactly what a gamma-ray halo is, as there are slight differences between theories (see next slides)

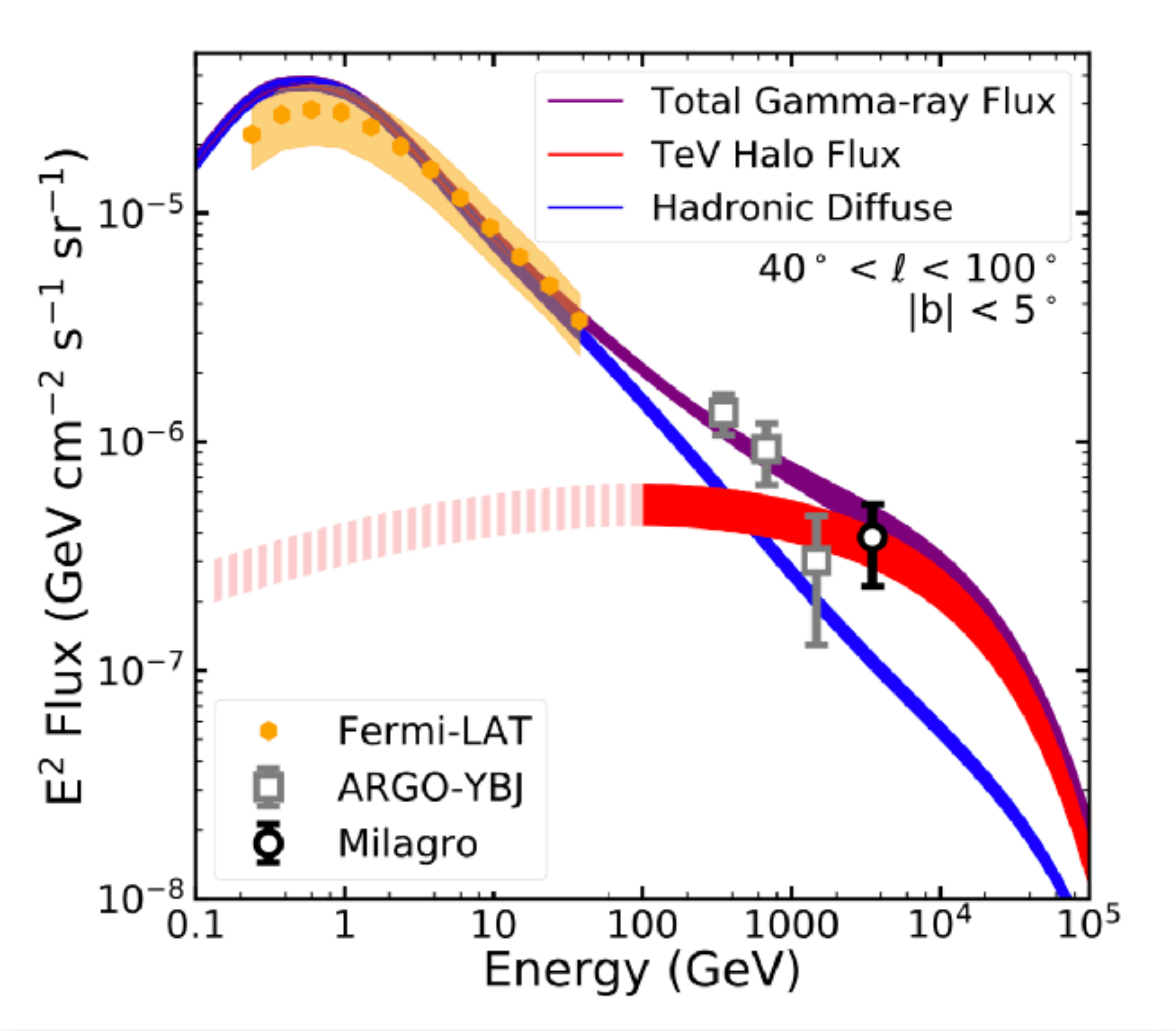
Model #1

- Halos are a new morphological source class (originally proposed by Linden et al in 2017) that are ubiquitous in our Galaxy
- High-energy electrons and positrons have escaped from the PWN; TeV gamma rays come from inverse Compton scattering
- Emission is isotropic, not beamed
- More extended than the x-ray PWN, but smaller than SNR
- Pulsar activity dominates CR diffusion. The electrons and positrons are confined in a region where diffusion is suppressed. Diffusion discussed in Manconi et al (PRD 2020) and Evoli et al (PRD 2018).



Sudoh et al, PRD 2019

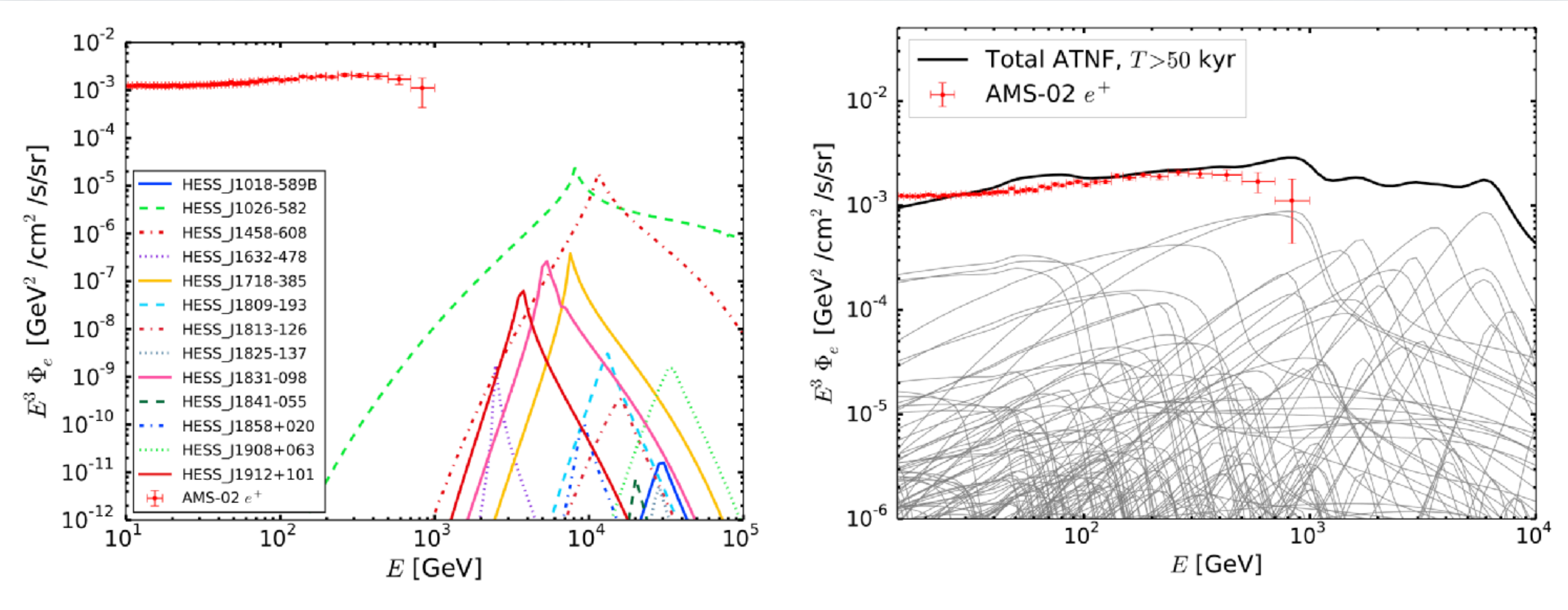
TeV halos and the Milagro excess



Linden and Buckman, PRL (2018)

- Assuming that gamma-ray halos are generic features of pulsars, they could be responsible for a significant fraction of the Milagro excess (Linden and Buckman, PRL 2018)
- Exceeds hadronic flux above ~500 GeV

Implications for the positron excess

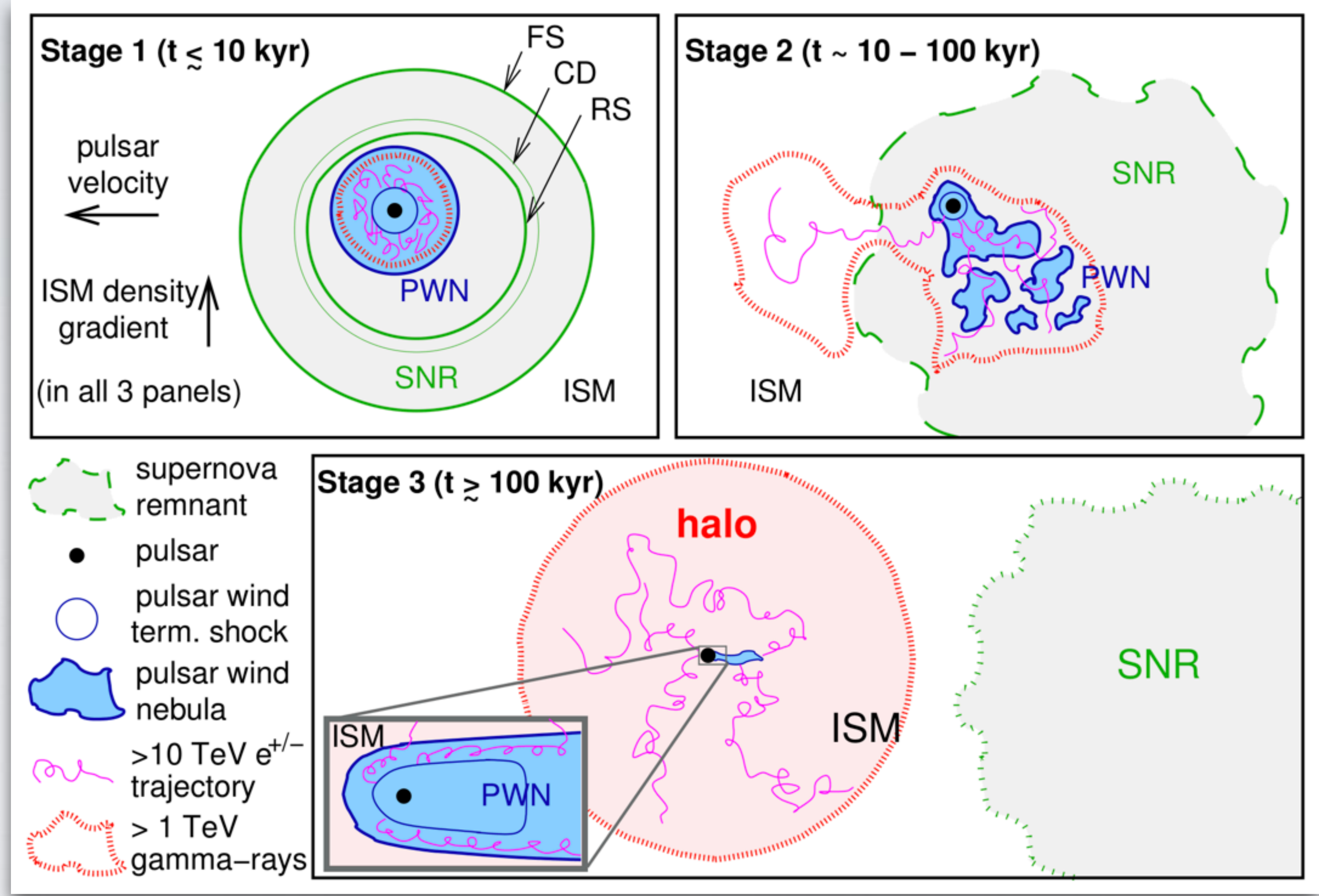


Manconi et al (PRD 2020)

Model #2

- Overdensity of relativistic electrons around a source, but source itself is not dominating the dynamics of the ISM (Giacinti et al, A&A 2020)
- Halos only form when the pulsar is very old (> 100 kyr)
- Energy density in electrons/positrons significantly less than ISM energy density
- Halos do not significantly contribute to TeV gamma-ray flux; Geminga and Monogem are the only known halos. Some other systems may be starting to transition to halos

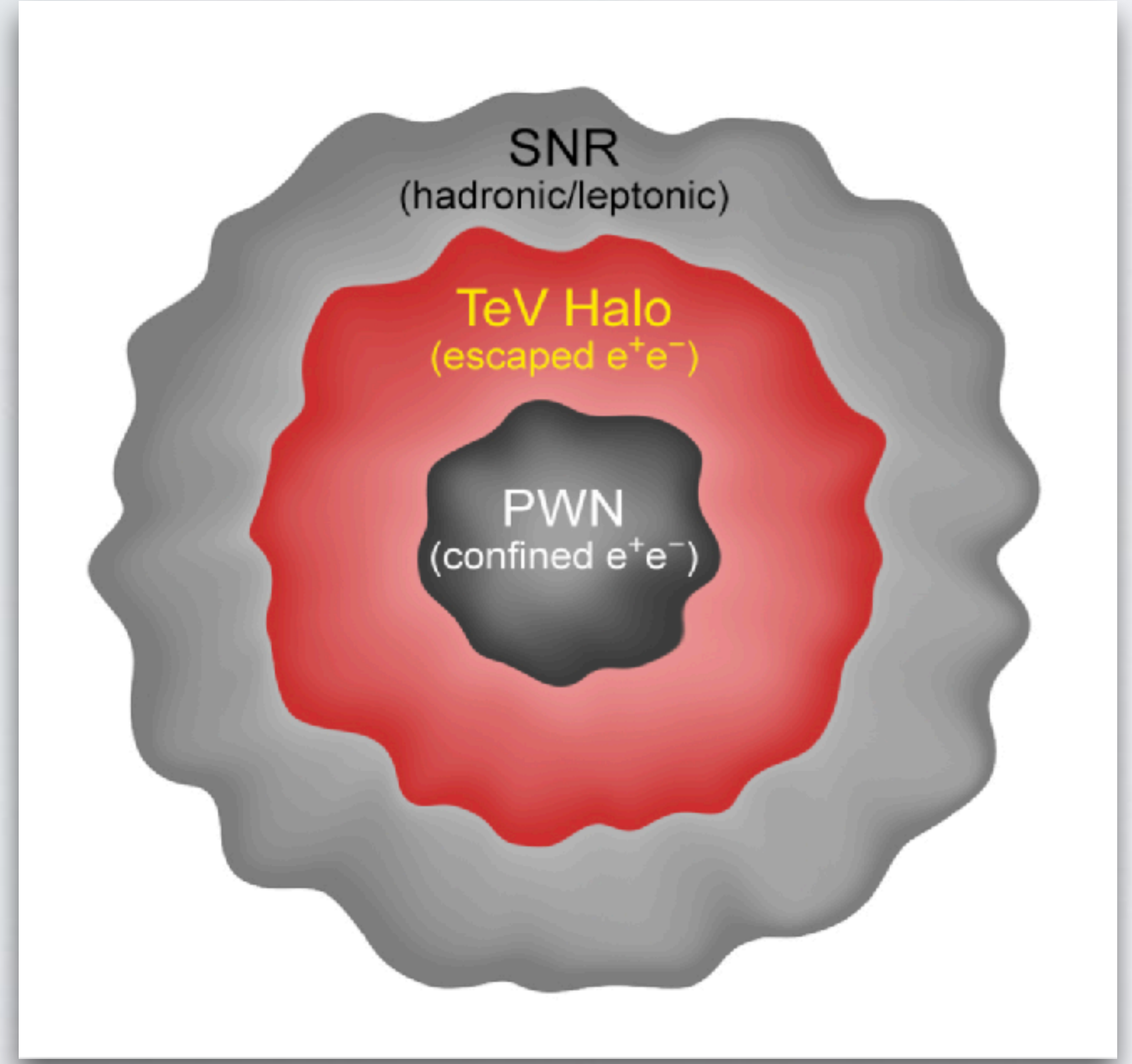
Model #2



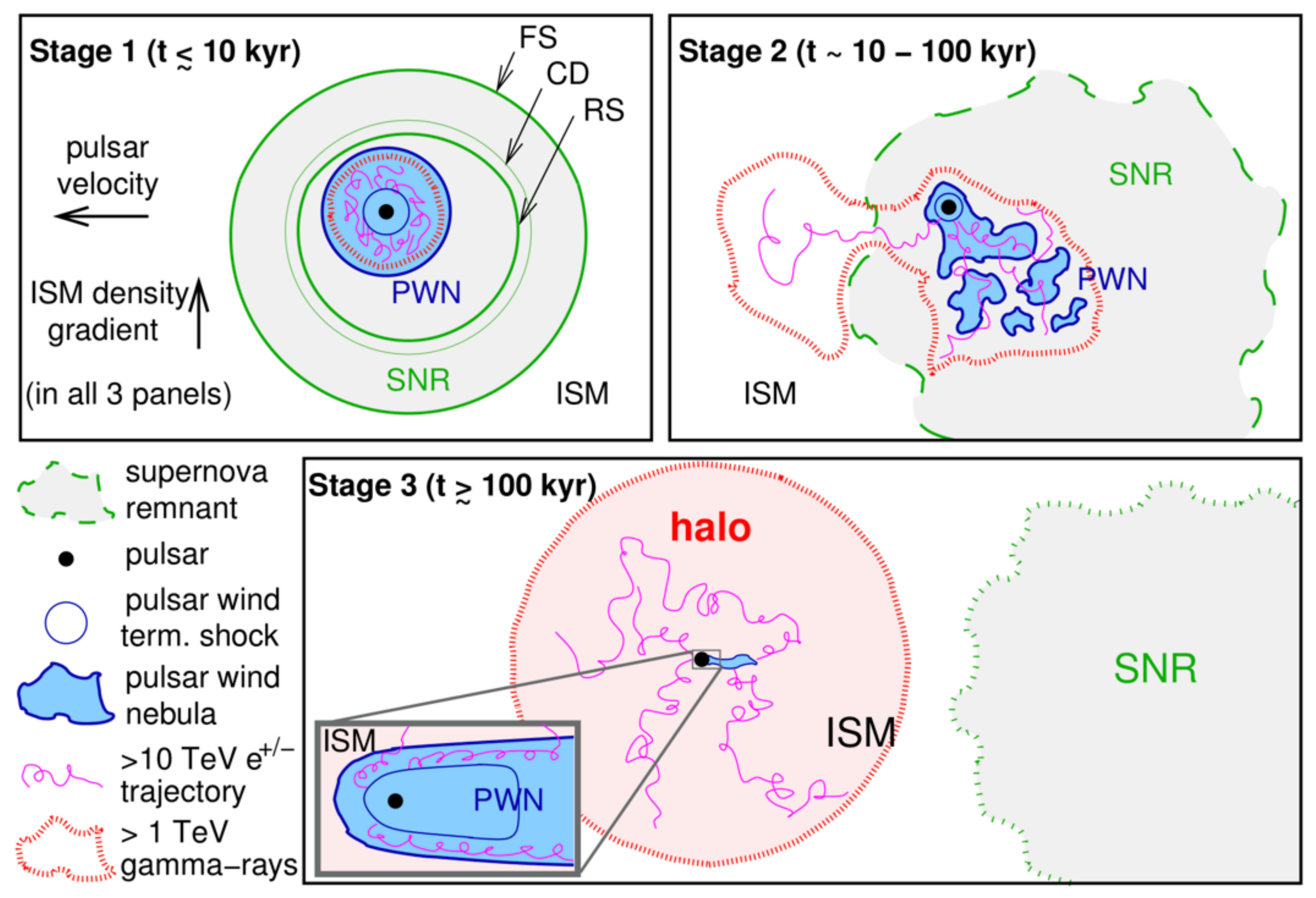
Giacinti et al, A&A (2020)

Commonalities between the models

- Both models predict large extended emission
- Generic feature of pulsars; question is at what age do these halos form



Sudoh et al, PRD 2019

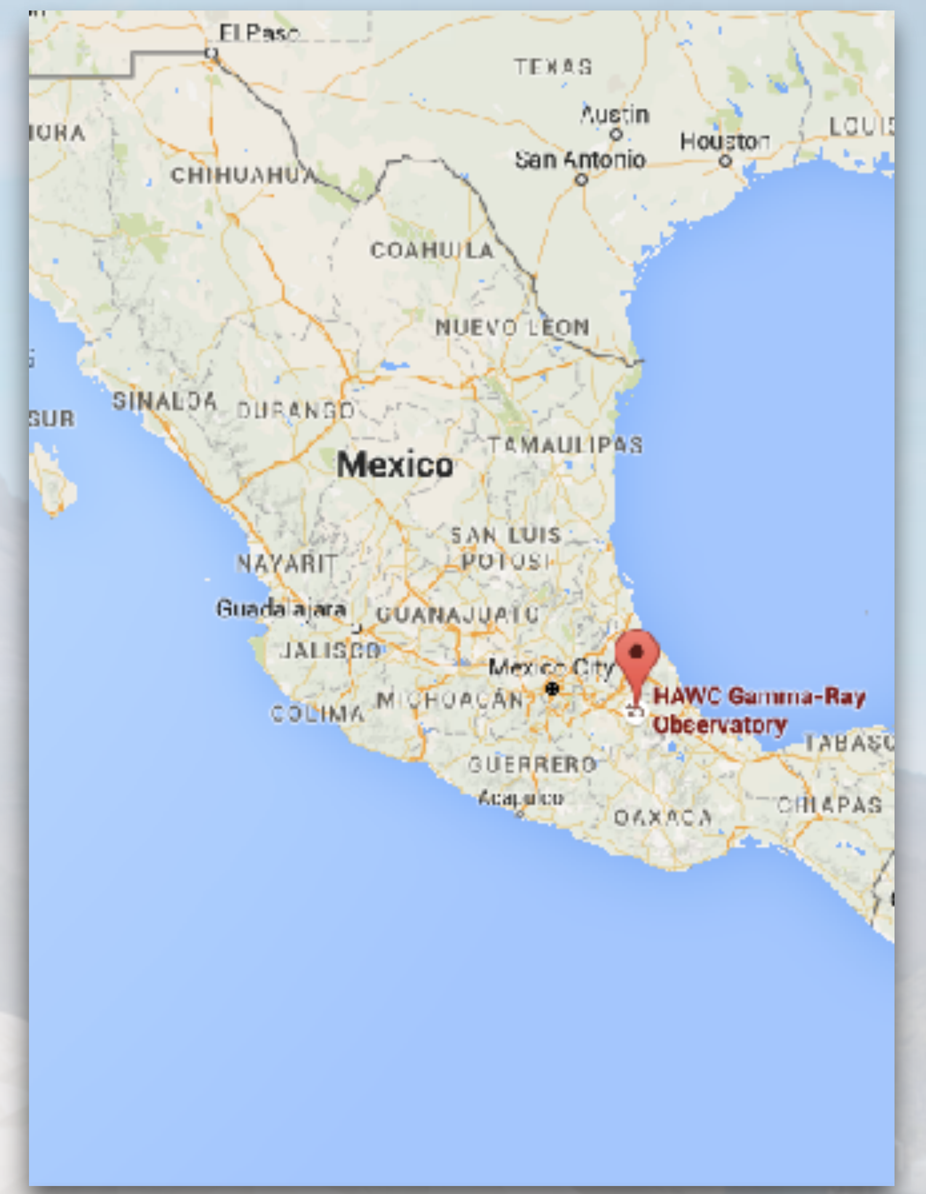


Giacinti et al, A&A (2020)

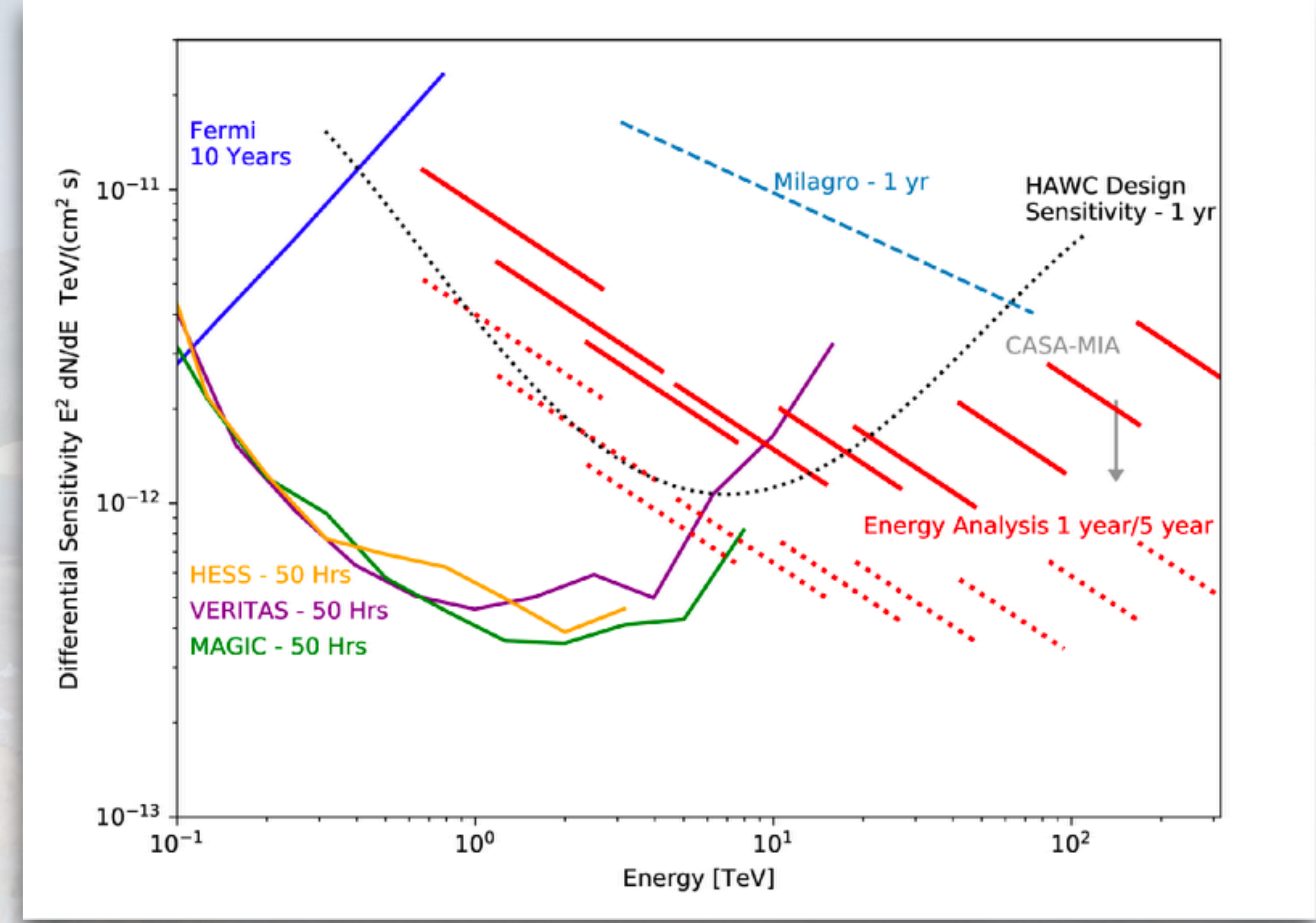
Introduction to HAWC

HAWC with Pico de Orizaba in the background

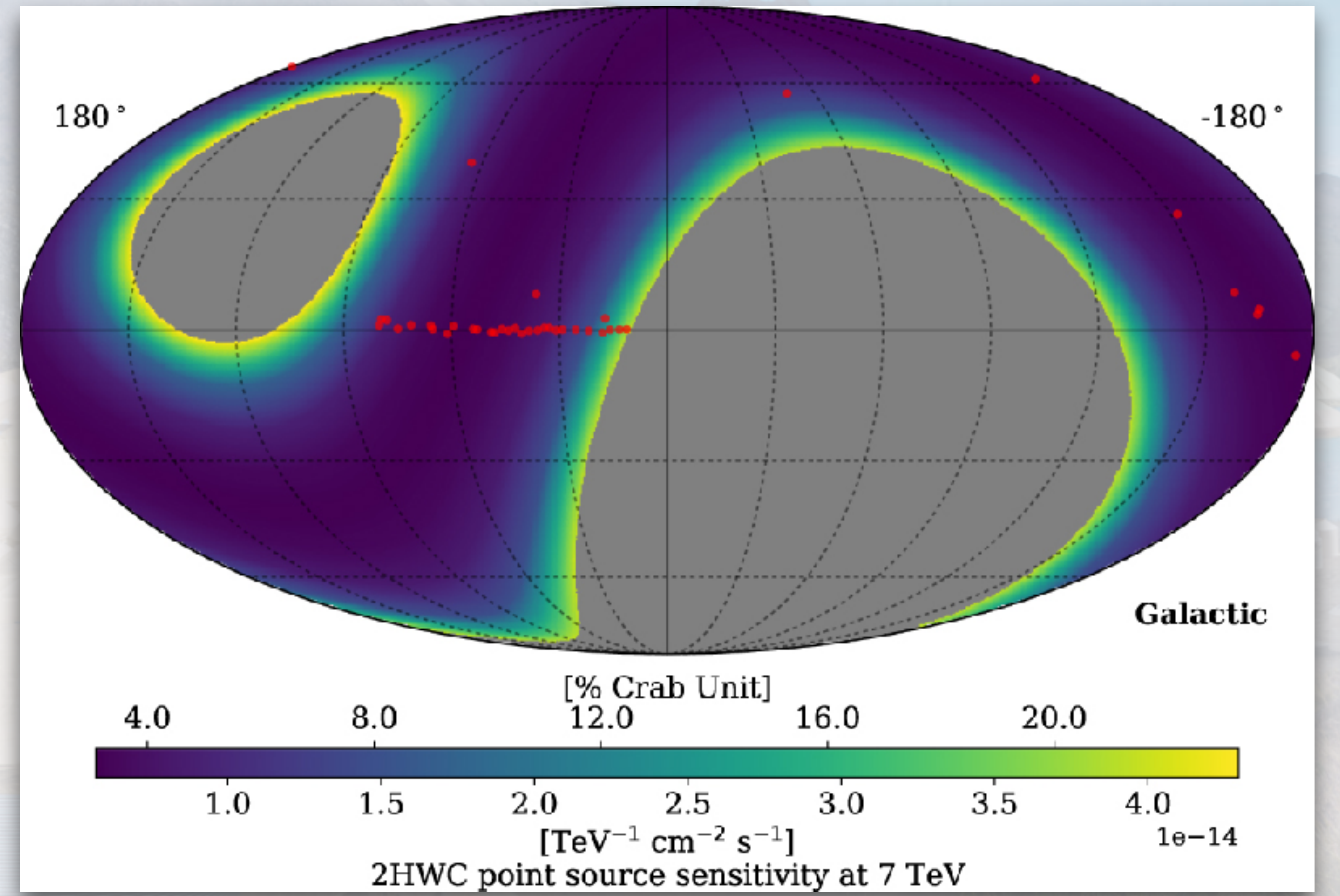
Number of tanks	300 (4 PMTs/200,000 L of water in each)
Area	22,000 m^2
Location	Puebla, Mexico (19^o North)
Altitude	4100 m
Duty Cycle	> 95%
Coverage	2/3 of sky per day
Sensitivity	300 GeV to > 100 TeV
Angular resolution	> 0.1 degrees



Above 10 TeV, HAWC is the most sensitive currently-operating experiment in the world. Wide field-of-view makes it an optimal experiment for detecting large extended sources



HAWC differential sensitivity



HAWC point source sensitivity
From HAWC Collaboration, ApJ (2017)

Using HAWC to discover invisible pulsars

- Paper by Linden et al (PRD 2017) predicts that halos will be a significant fraction of all HAWC sources; could be used to find misaligned pulsars. Tables below are potential TeV halos.

Geminga and Monogem

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

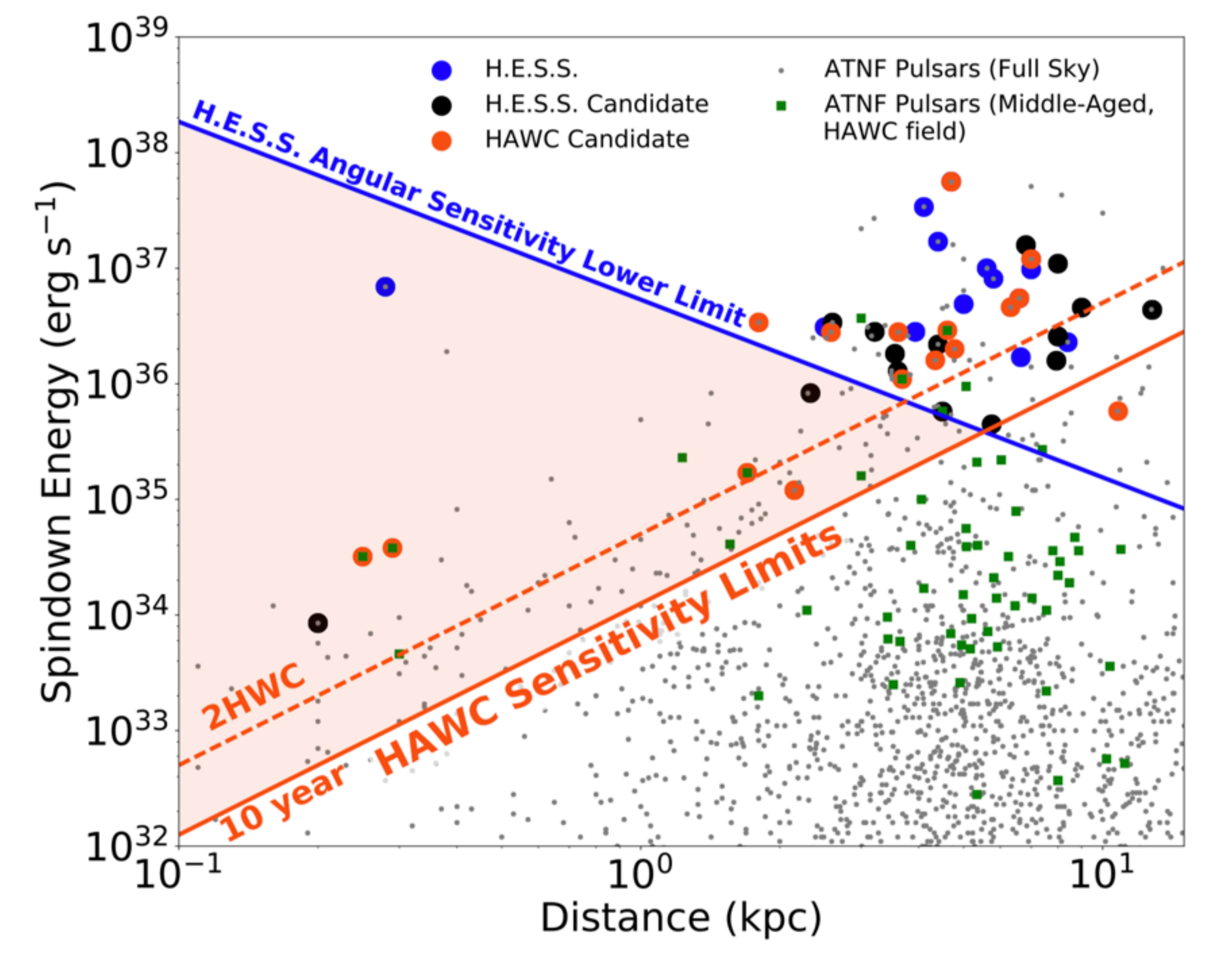
Linden et al, PRD (2017)

Using HAWC to discover invisible 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	—

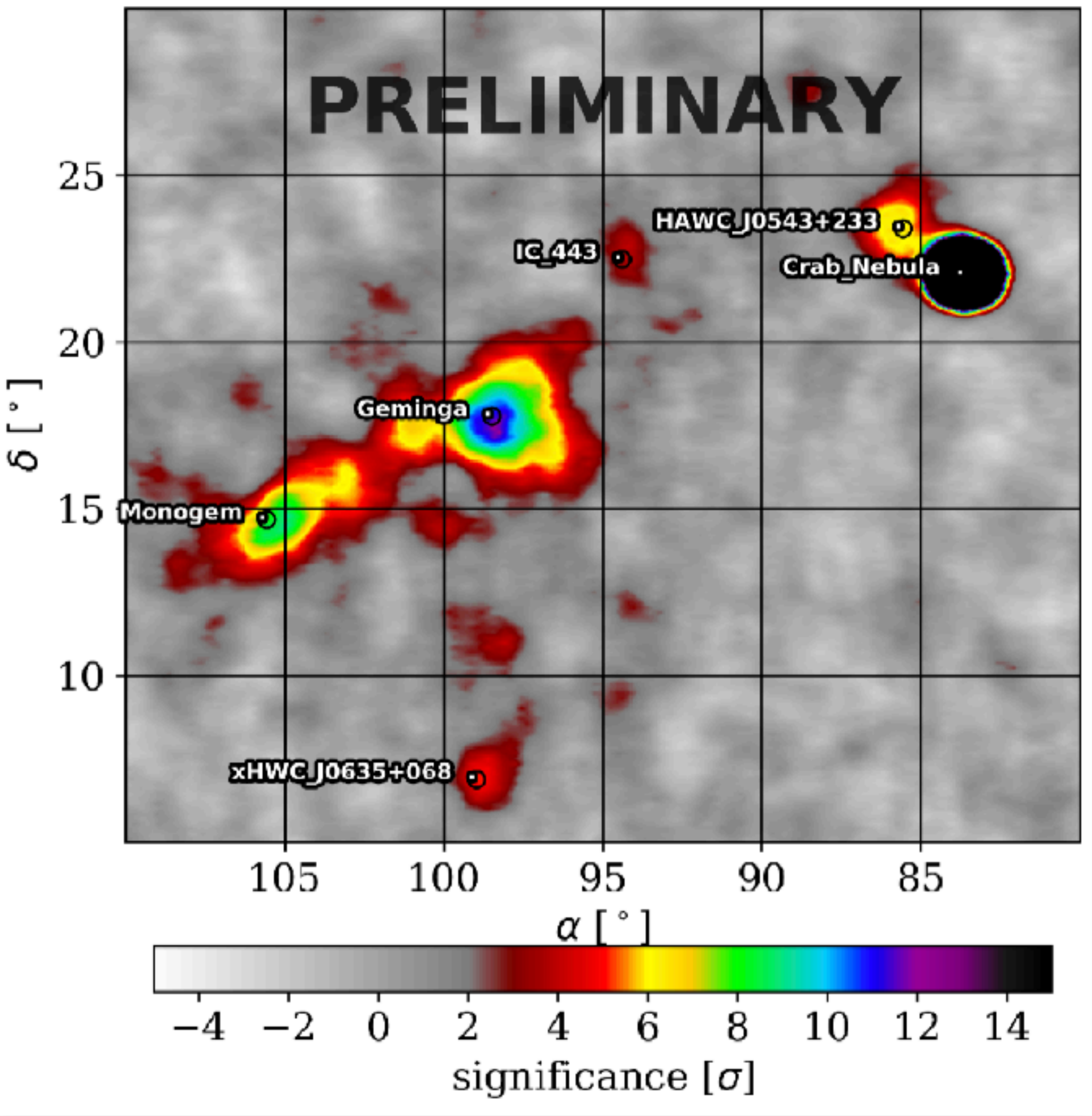
Linden et al, PRD (2017)

HAWC provides a new discovery space for halo observations



Linden et al, PRD (2017)

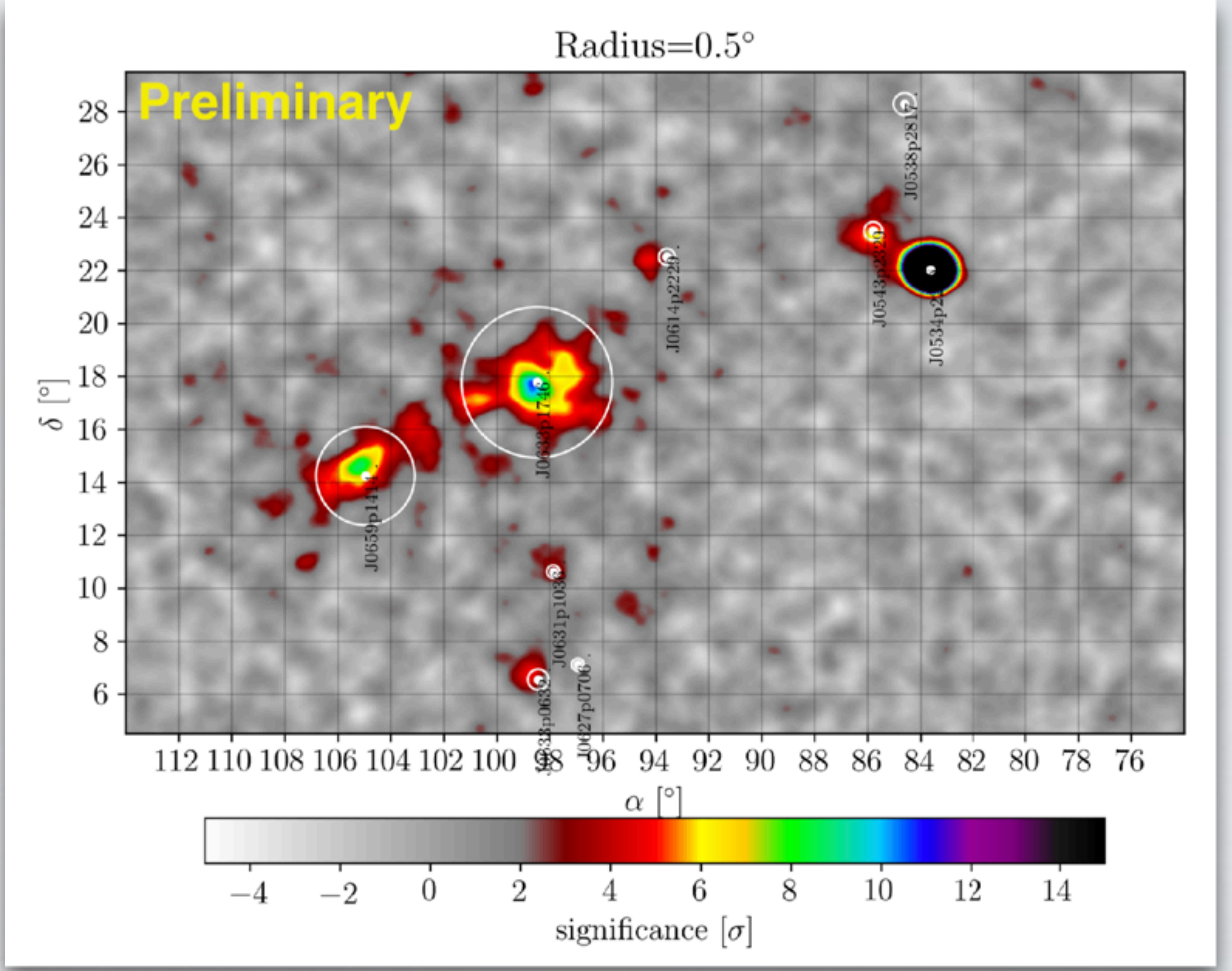
TeV halo results since HAWC's Geminga paper



- Two more halos found in the outer galaxy; announced via ATels (#10941 and #12013)
- Both are ~1-2 kpc away from us and are middle-aged (59 and 253 kyr old)
- Both have fairly hard TeV spectra

HAWC systematic search for sub threshold TeV halos

- Predicted flux and extent assume a Geminga-like system
- 13 pulsar halo candidates reported, including some not previously known to be TeV emitters



A. Smith, ICRC 2019

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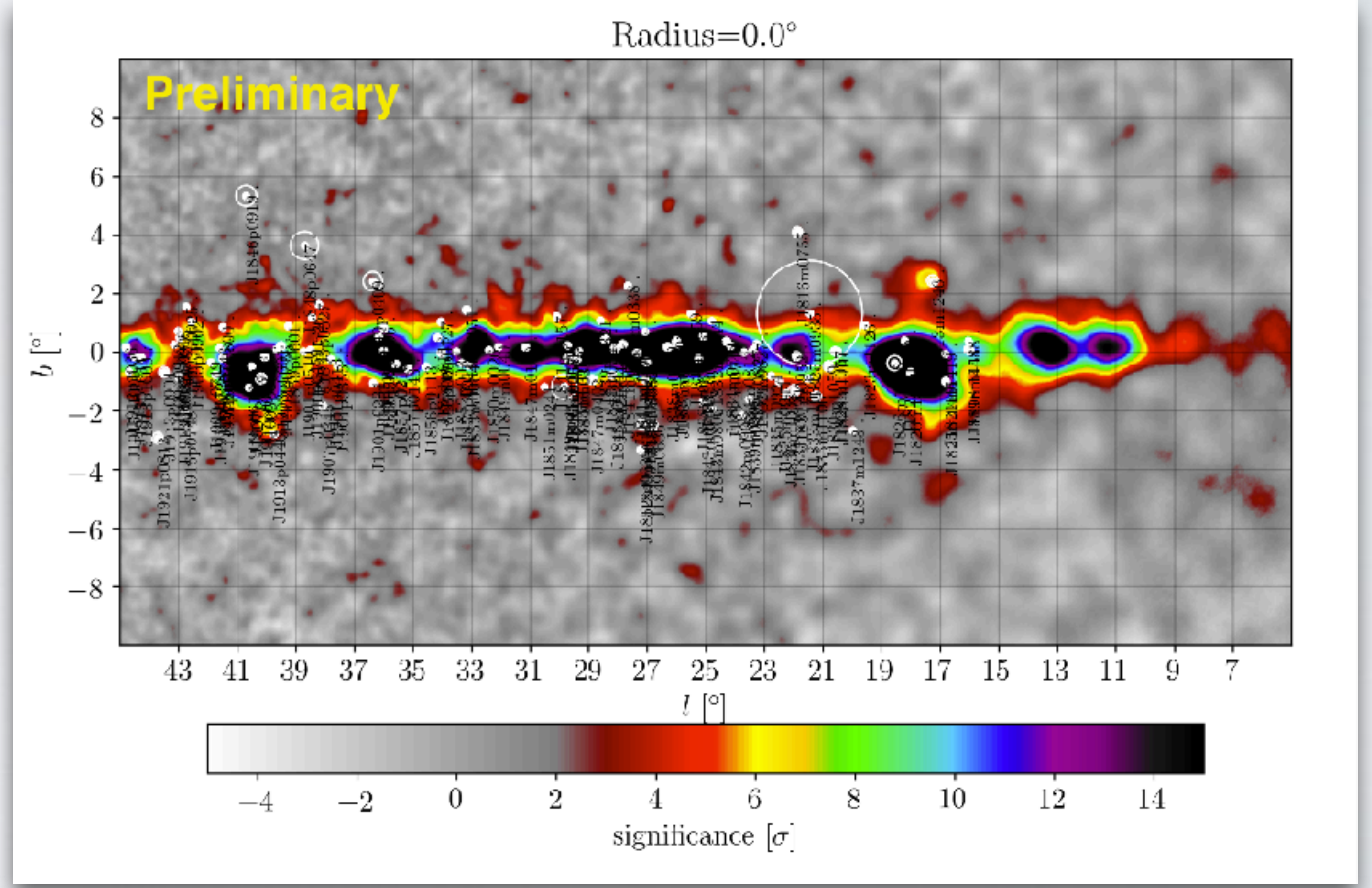

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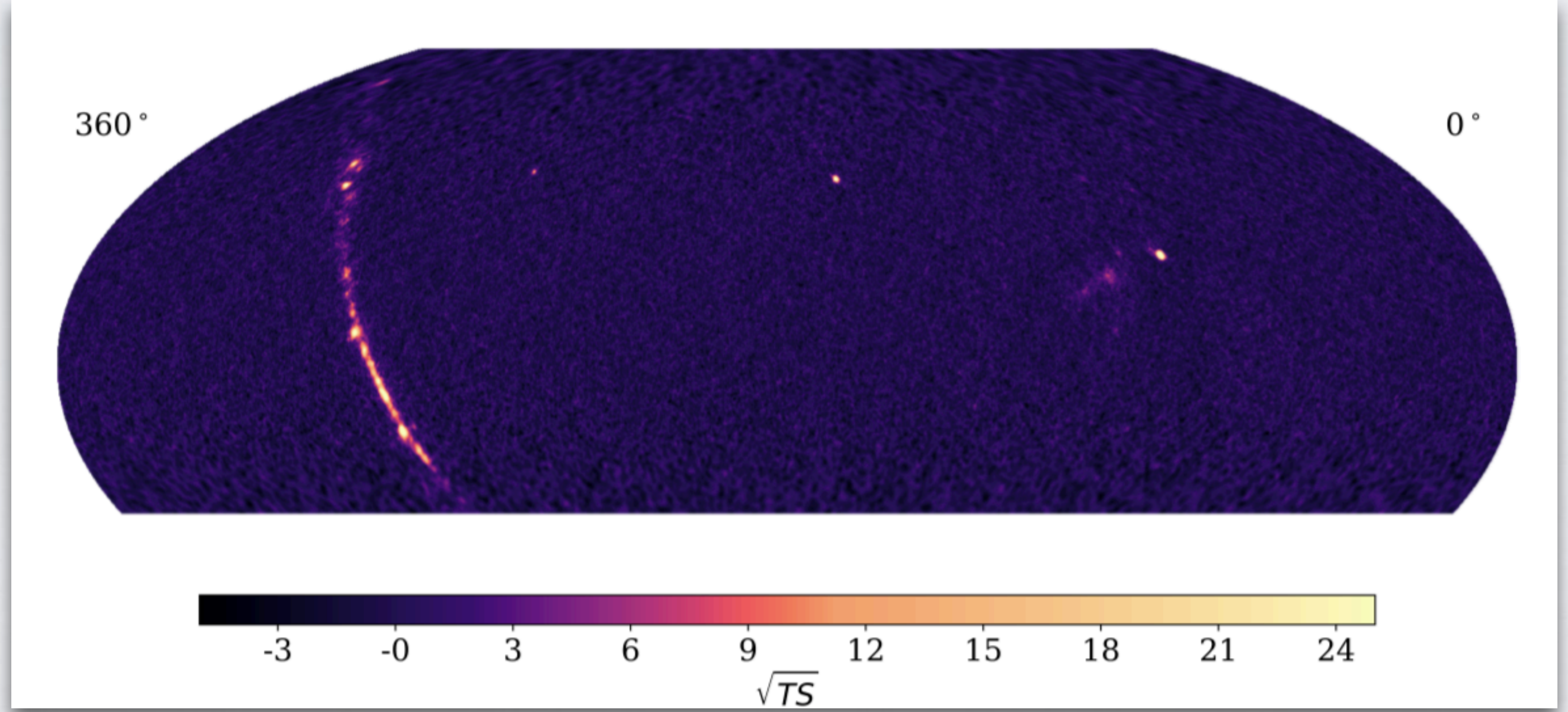
Common Name	JName	Dist(kpc)	Age(ky)	Size(°)	$\sqrt{TS}$	$\frac{Flux_{meas}}{Flux_{pred}}$	in TeVCat
Crab	J0534+2200	2.00	1	0.04	161.68	0.22	x
Geminga	J0633+1746	0.19	342	1.79	17.66	1.00	x
Monogem	J0659+1414	0.29	111	1.17	9.89	0.76	x
	J1740+1000	1.23	114	0.28	2.99	0.24	
	J0633+0632	1.35	59	0.24	3.47	0.68	x
	J0729-1448	2.68	35	0.12	1.74	1.36	
	J0631+1036	2.10	44	0.15	3.30	0.87	
	J0538+2817	1.30	618	0.26	0.96	0.39	
	J0614+2229	1.74	89	0.19	2.02	0.94	
	J0543+2329	1.56	253	0.22	6.29	3.70	x
	J1846+0919	1.53	360	0.22	1.83	1.41	
	J0357+3205	0.83	540	0.41	0.13	0.26	
	J0922+0638	1.10	497	0.31	0.00	0.02	

Table 1: Properties of the 13 pulsar halo candidates.

A. Smith, ICRC 2019

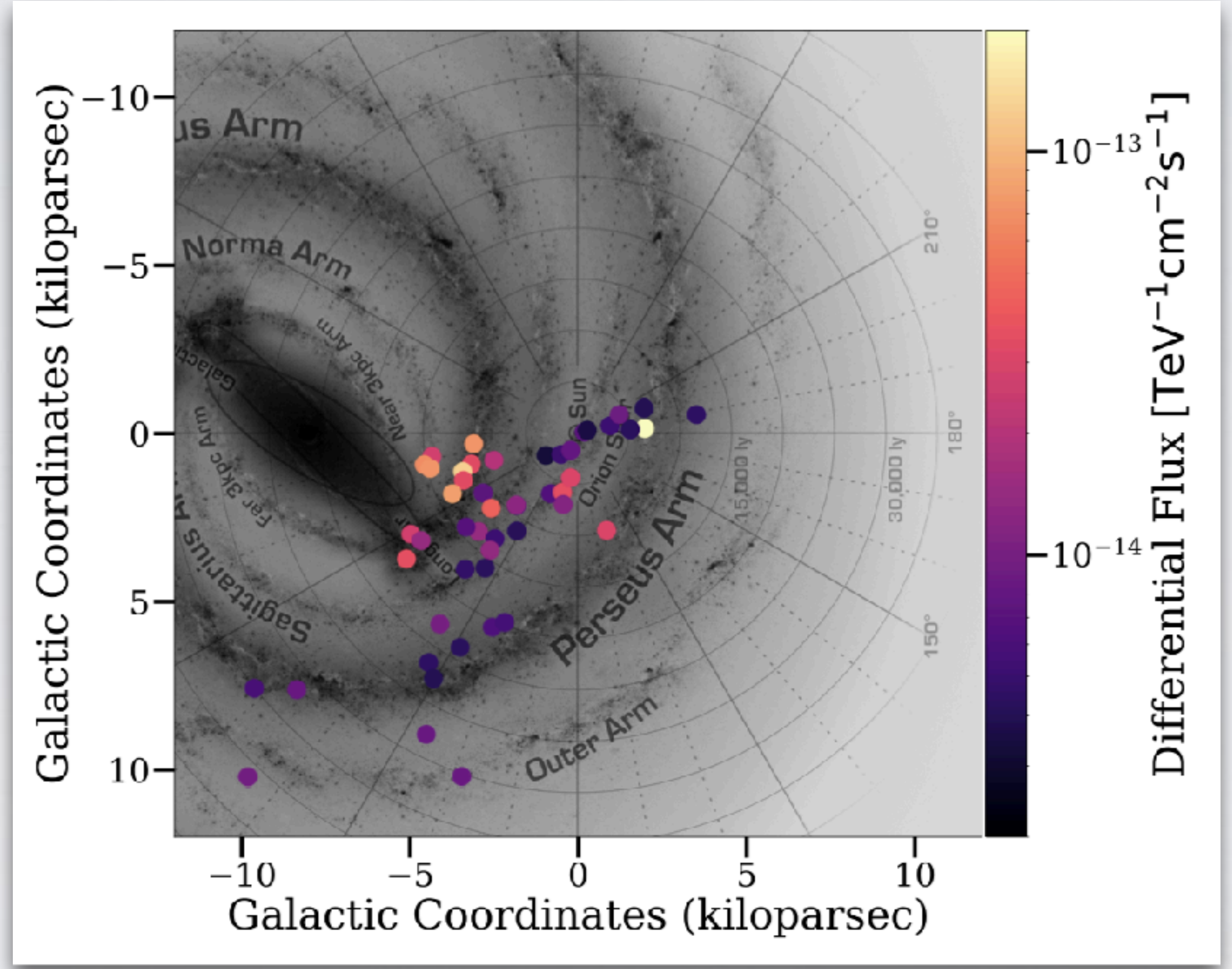
3HWC catalog

- 3rd catalog of sources, recently accepted by ApJ Supplement Series (available on the Arxiv: 2007.08582); catalog available at https://data.hawc-observatory.org/datasets/3hwc-survey/index.php
- 65 sources (26 more than last catalog)
- Paper includes section on TeV halo candidates



HAWC Collaboration, arXiv 2007.08582

HAWC spatial coincidences with ATNF pulsars



HAWC Collaboration, arXiv 2007.08582

HAWC sources and TeV halo candidate pulsars

Table 4. HAWC Sources with the corresponding associated TeV halo candidate pulsars. The age of the pulsar in kyr and the spin-down luminosity, $\dot{E}$, in erg s^{-1} are also given. The Separation column indicates the angular distance between the HAWC source and the ATNF pulsar (Manchester et al. 2005). The TeVCat column lists the previously detected TeV counterpart of each source.

HAWC	l [°]	b [°]	Pulsar	Age [kyr]	$\dot{E}$ [erg s^{-1}]	Distance [kpc]	Separation [°]	TeVCat
3HWC J0540+228	184.58	-4.13	B0540+23	253.0	4.09e+34	1.56	0.83	HAWC J0543+233
3HWC J0543+231	184.67	-3.52	B0540+23	253.0	4.09e+34	1.56	0.36	HAWC J0543+233
3HWC J0631+169	195.63	3.45	J0633+1746	342.0	3.25e+34	0.19	0.95	Geminga
3HWC J0634+180	195.00	4.62	J0633+1746	342.0	3.25e+34	0.19	0.38	Geminga Pulsar
3HWC J0659+147	200.60	8.40	B0656+14	111.0	3.8e+34	0.29	0.51	2HWC J0700+143
3HWC J0702+147	200.91	9.01	B0656+14	111.0	3.8e+34	0.29	0.77	2HWC J0700+143
3HWC J1739+099	33.89	20.34	J1740+1000	114.0	2.32e+35	1.23	0.13	...
3HWC J1831-095	22.13	0.02	J1831−0952	128.0	1.08e+36	3.68	0.27	HESS J1831-098
3HWC J1912+103	44.50	0.15	J1913+1011	169.0	2.87e+36	4.61	0.31	HESS J1912+101
3HWC J1923+169	51.58	0.89	J1925+1720	115.0	9.54e+35	5.06	0.67	...
3HWC J1928+178	52.93	0.20	J1925+1720	115.0	9.54e+35	5.06	0.85	2HWC J1928+177
3HWC J2031+415	80.21	1.14	J2032+4127	201.0	1.52e+35	1.33	0.11	TeV J2032+4130

HAWC Collaboration, arXiv 2007.08582

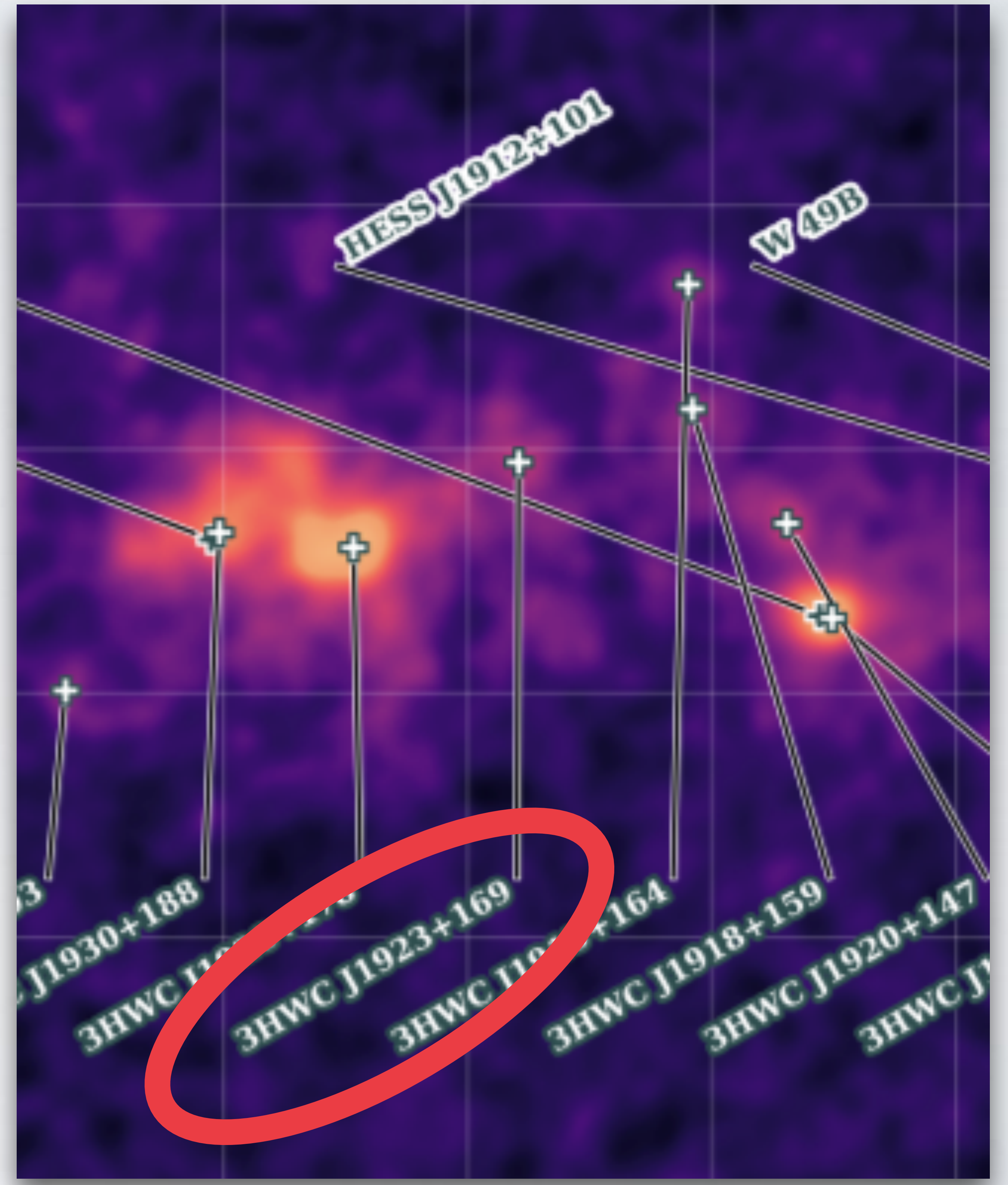
TeV halo candidates not previously detected at TeV energies

3HWC J1739+099

- Pulsar is 114 kyr old and 0.13 degrees away from HAWC source
- TS of HAWC source is 28.2

3HWC J1923+169

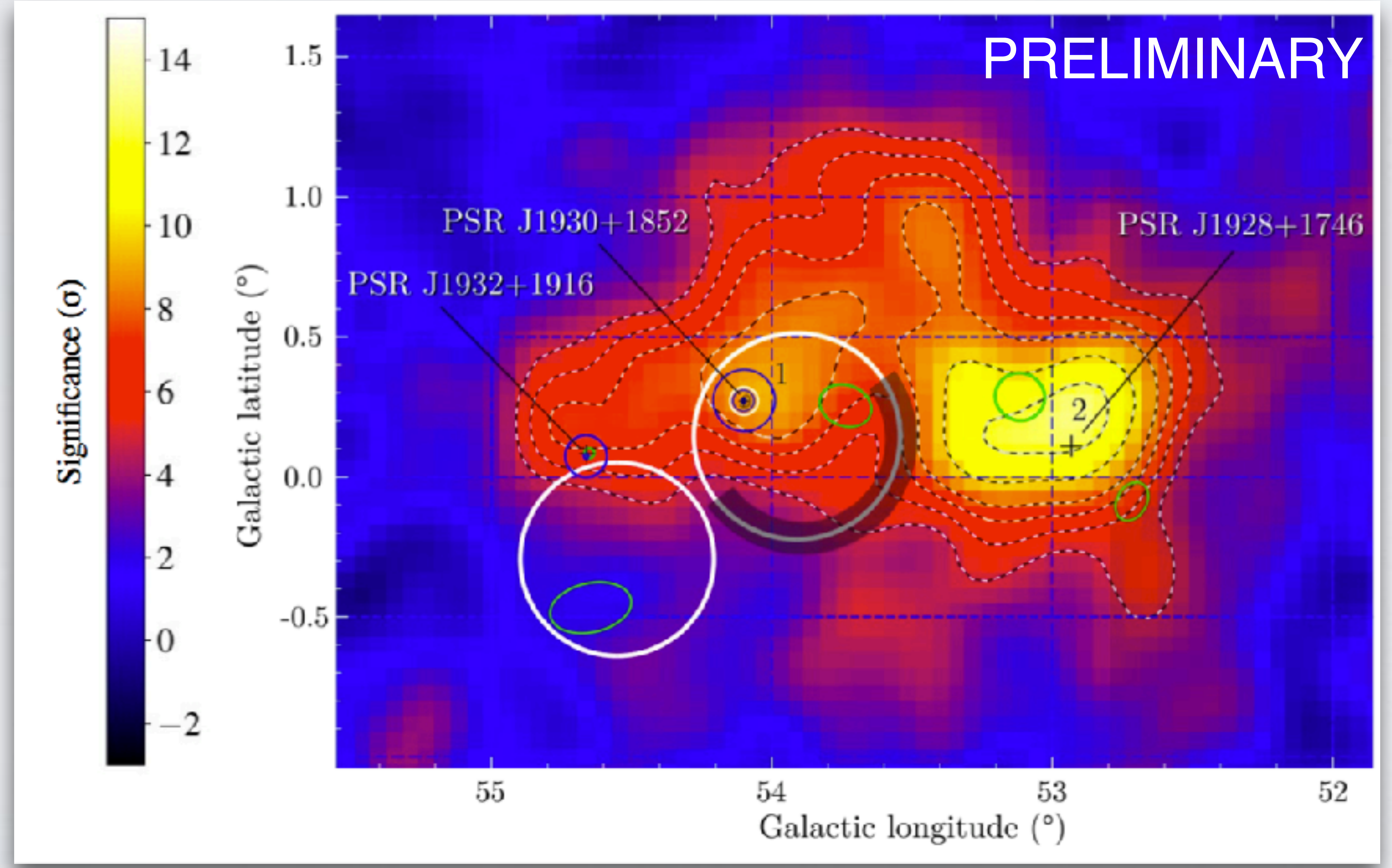
- In Galactic plane
- Pulsar is 115 kyr old and 0.67 degrees away from HAWC source
- TS of HAWC source is 46.1

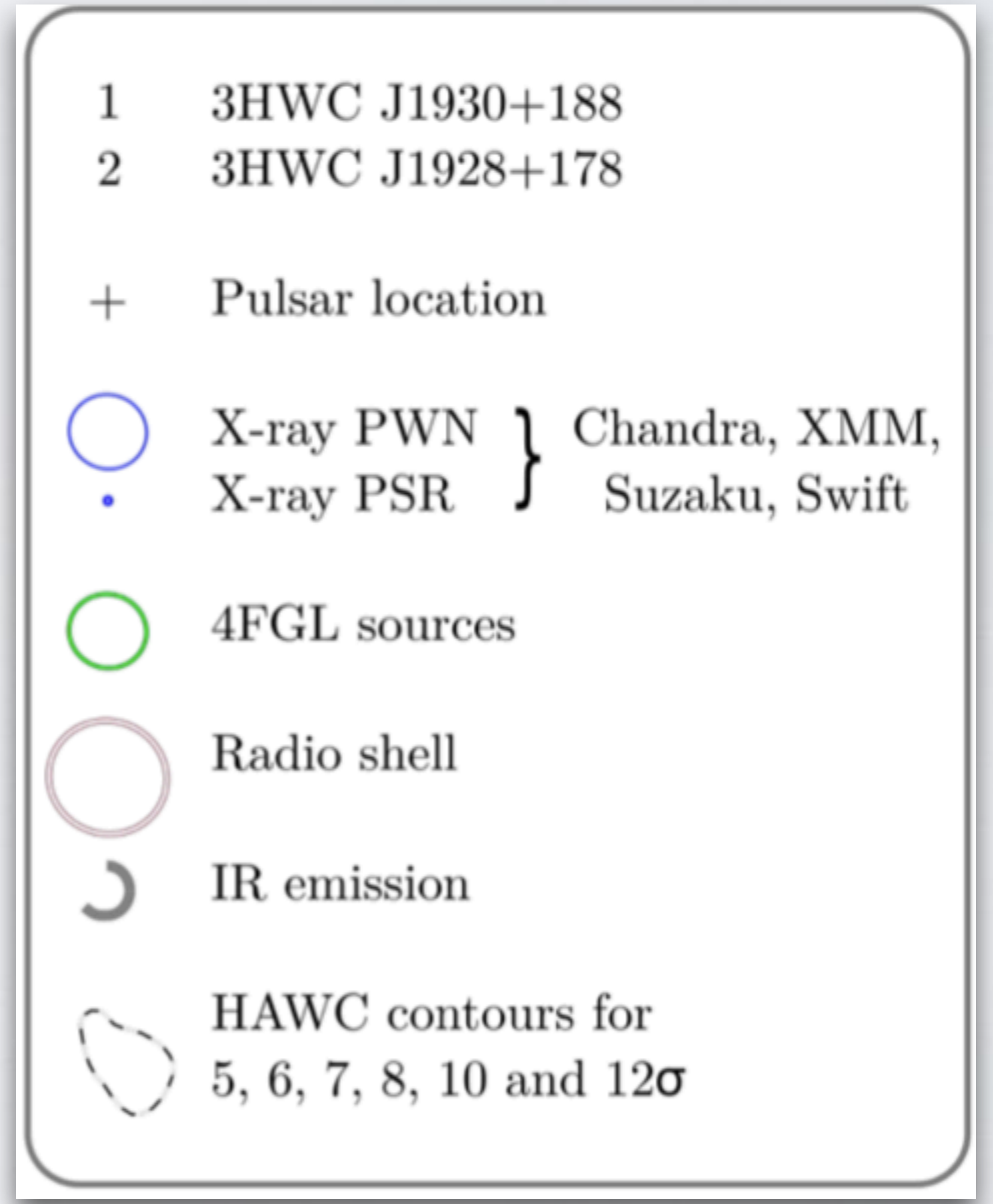


HAWC Collaboration, arXiv 2007.08582

Transitional systems

- HAWC may also be detecting systems that are transitioning to a TeV halo
- 3HWC J1928+178 may be an example of this. Powered by PSR J1927+1746 (82 kyr old)
- See poster by Armelle Jardin-Blicq



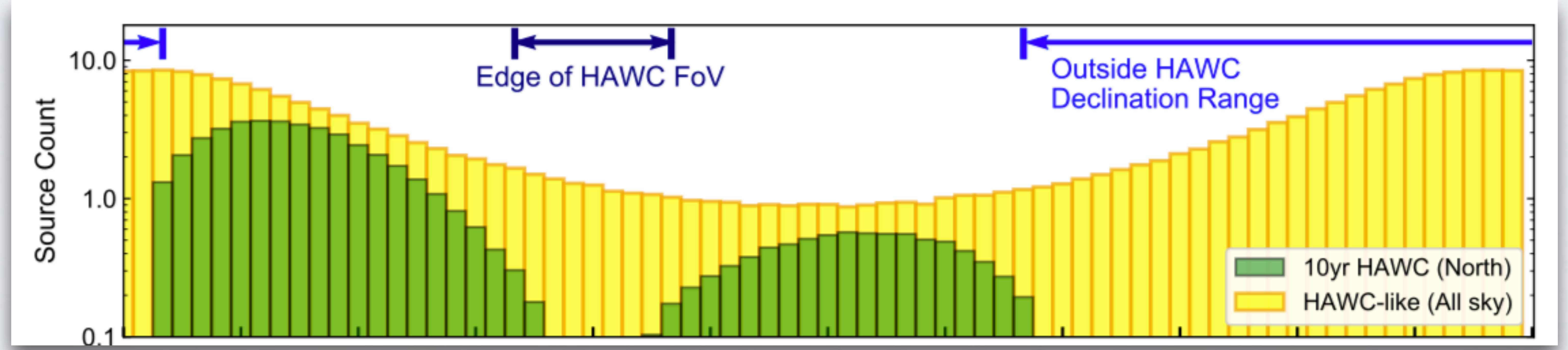


What can we learn from TeV halos?

See Astro2020 White Paper by Fleischhack et al (on Arxiv, 1903.07647)

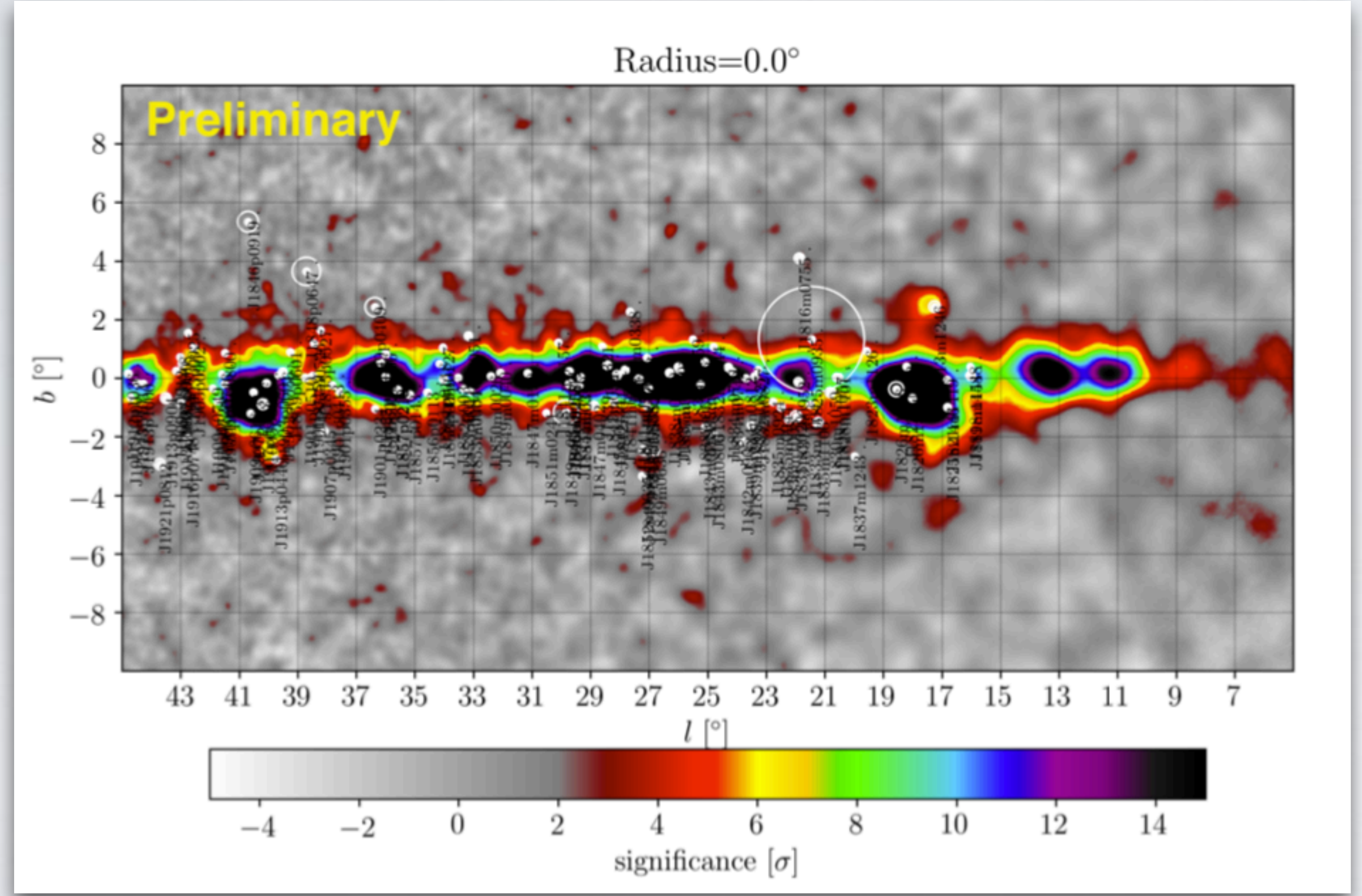
- Constrain positron excess
- Find mis-aligned pulsars
- Understand Galactic diffuse emission
- Understand Galactic pulsar populations

To do this, there is a lot we must understand about TeV halos and how they form and evolve



Sudoh et al, PRD 2019

Future work: Deep observations of TeV halos

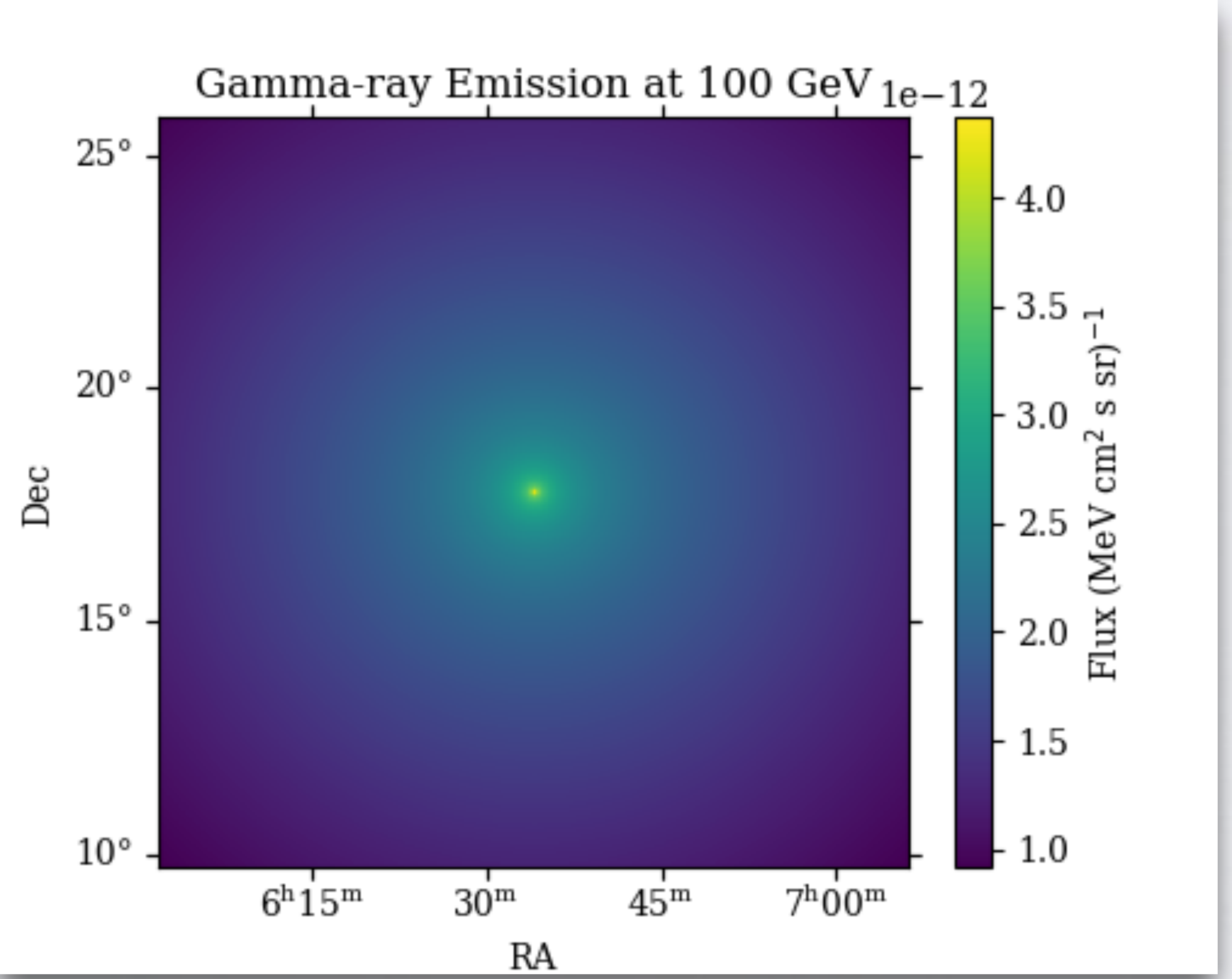


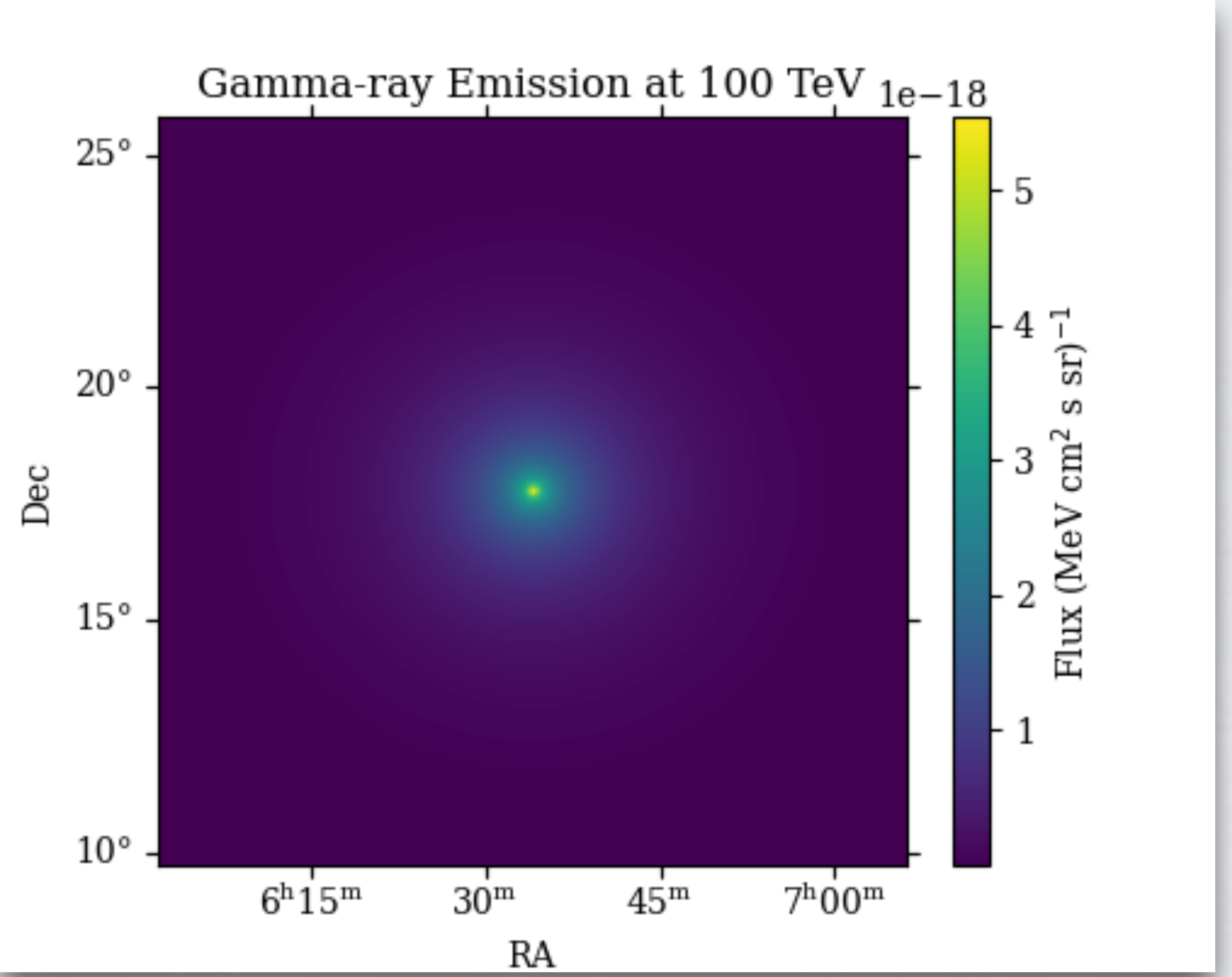
A. Smith, ICRC 2019

- Many TeV halo candidates are in confused regions in the inner Galactic plane, which requires multi-source fitting algorithms to disentangle sources
- Others are in fairly isolated regions, and analyses are in progress.
- Being able to study the inner Galaxy will allow us to look at many more TeV halo candidates; survey all known pulsars to see if they are similar to each other

Future work: Template fits

- 3D templates containing spectral and spatial information with units of flux in every pixel can be used to constrain the diffusion coefficient in TeV halos
- Method being used to study Geminga currently
- See poster by Ramiro Torres Escobedo in this workshop



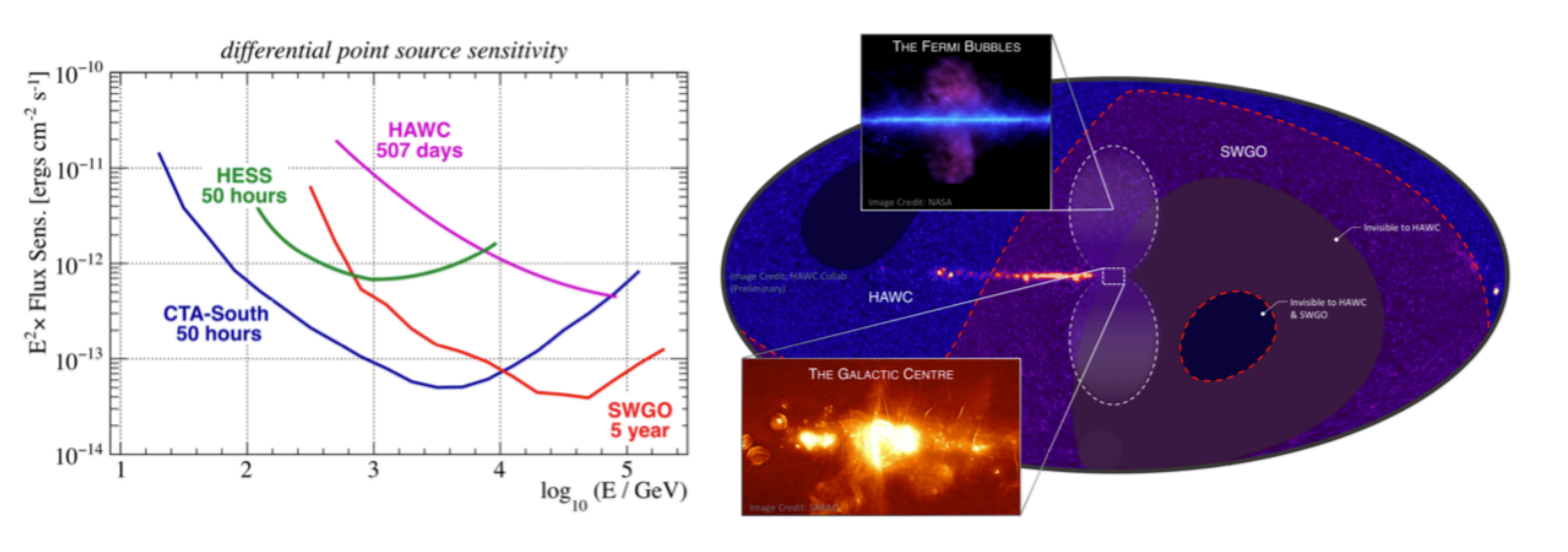


Future work: TeV halo stacking analysis

- Search for sub threshold TeV halos in HAWC data
- Can give a limit on the fraction of middle-aged pulsars that have halos

SWGO

- Proposed HAWC-like detector to be located in the Southern Hemisphere
- Larger detector leading to better sensitivity
- Latitude chosen to optimize sensitivity to Galactic sources (including the Galactic center)
- Improvements to TeV halo surveys



SWGO White paper: Arxiv 1907.07737

Conclusions

- HAWC's wide field-of-view makes it an optimal instrument to discover TeV halos
- Several TeV halo candidates identified, many in recent 3HWC catalog
- HAWC can also study transitional systems to help us learn about pulsar evolution
- TeV halos can be used to constrain the positron excess, find misaligned pulsars, learn about diffuse emission, etc.
- Many HAWC analyses in progress