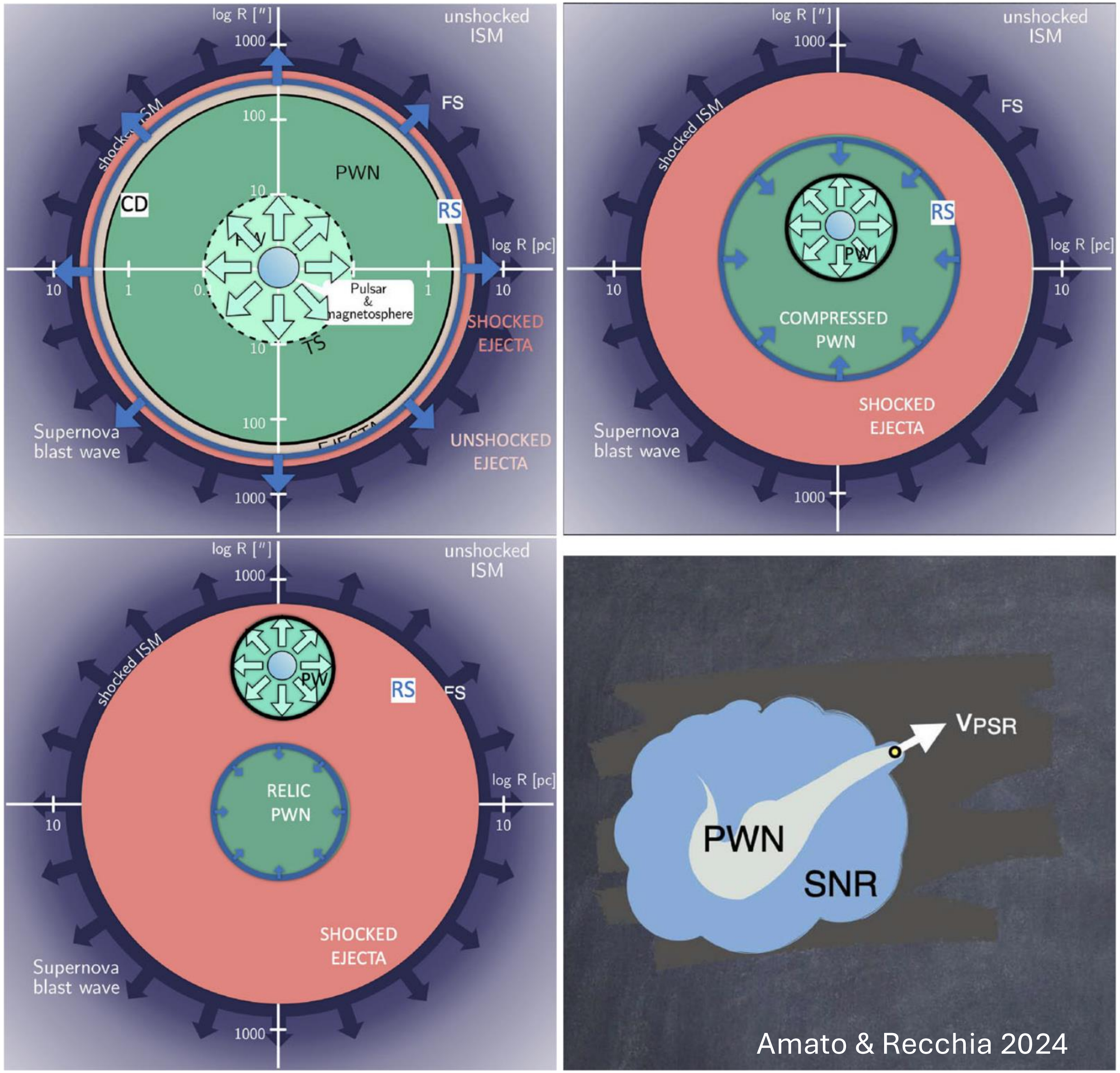
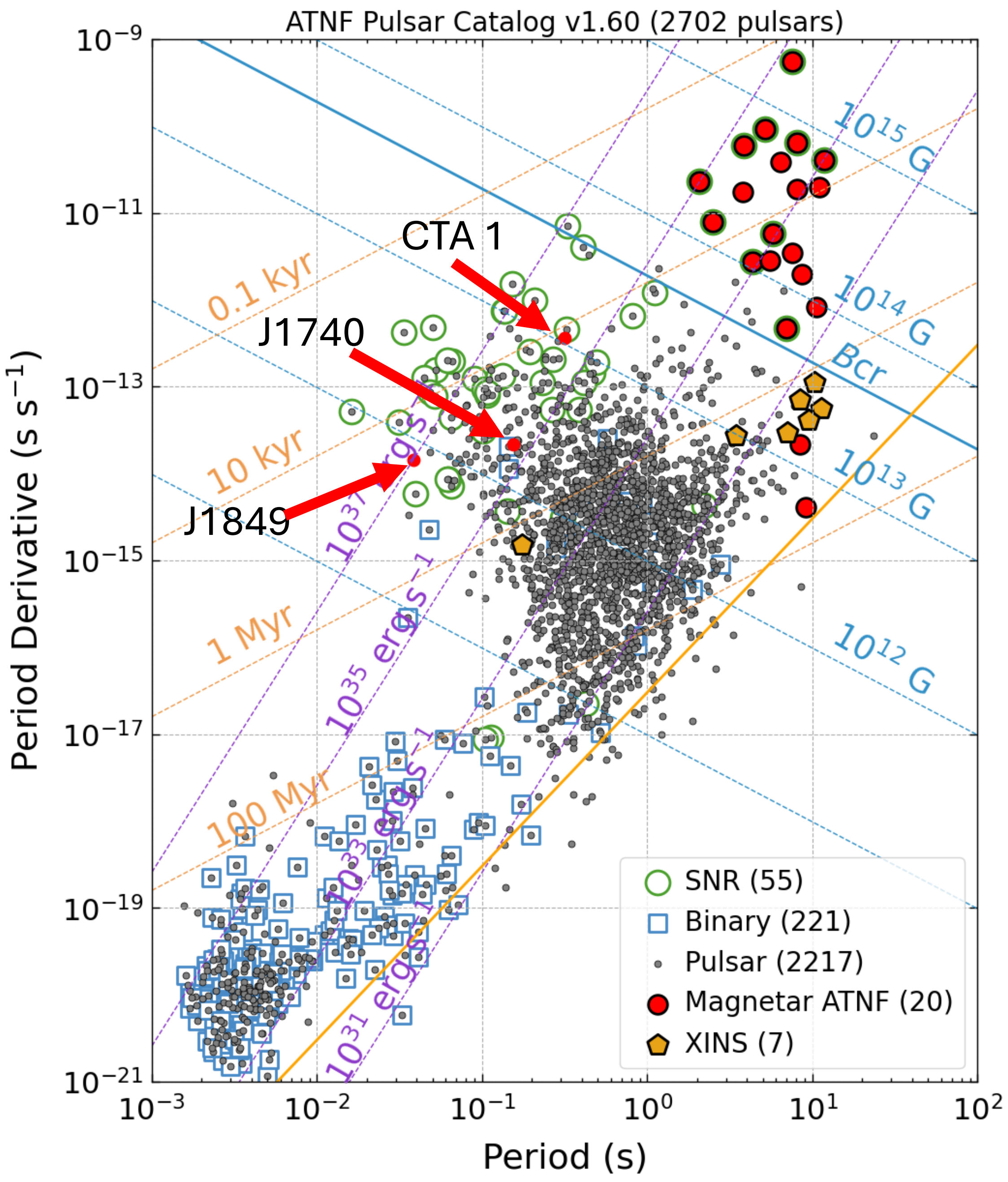
Pulsar Wind Nebulae as Galactic PeVatrons: A Comparative Study of CTA 1, PSR J1849–0001, and PSR J1740+1000

Seth Gagnon
Oleg Kargaltsev, Yichao Lin, Alexander Lange, Noel Klingler, Jeremy Hare, Hui Yang, Jordan Eagle
The George Washington University

PWN evolution



Examples of PWNe inside and outside SNRs



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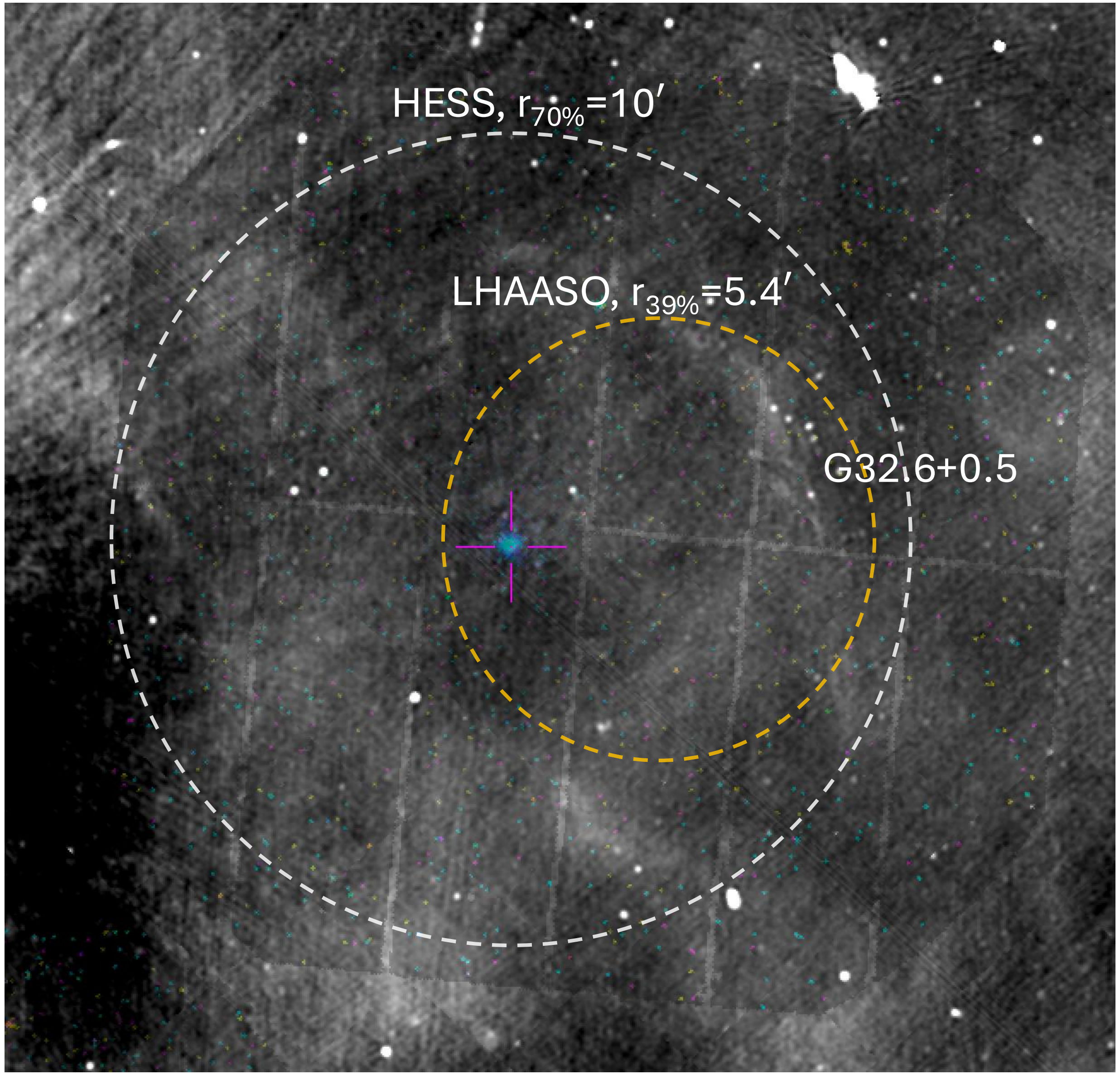
PSR J1849-0001

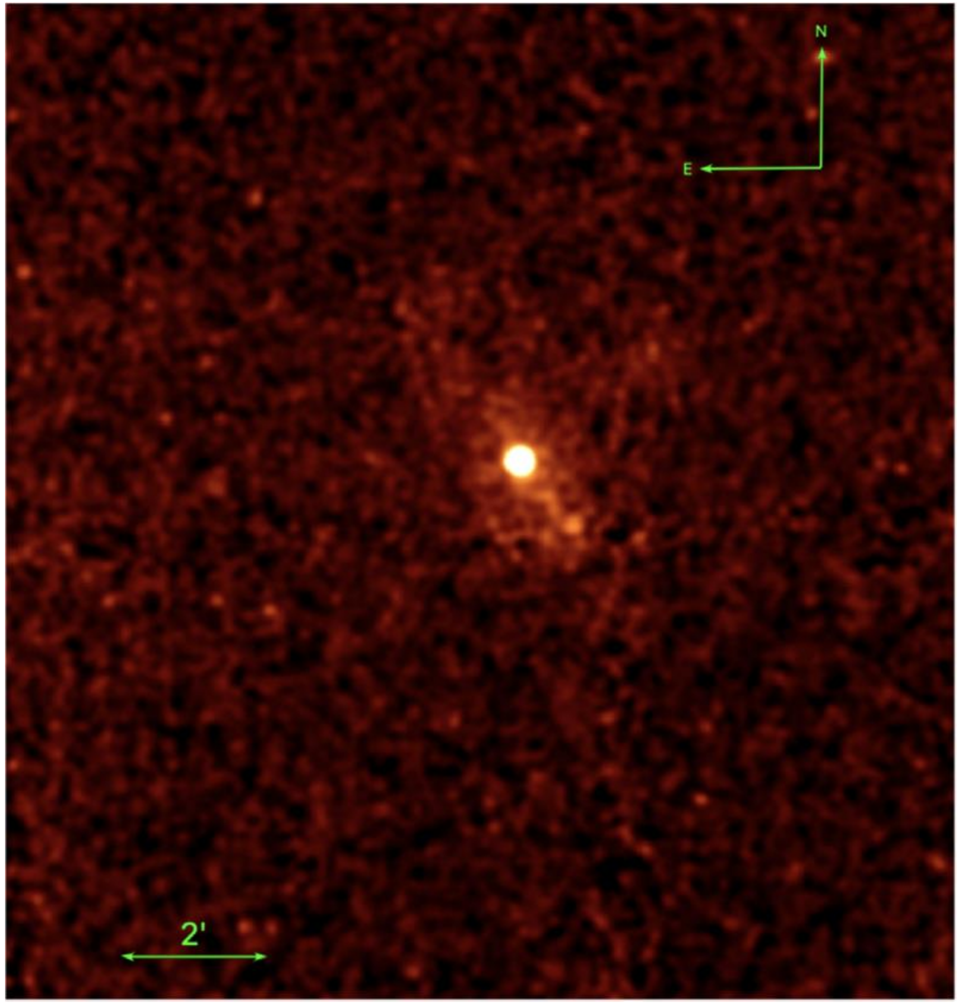
- Pulsations in X-rays (P=38 ms), gamma-ray and radio quiet
- Inside SNR
- Spin-down age, t_c = 43 kyr
- Spin-down power, $\dot{E} = 9.8\text{x}10^{36}$ erg/s
- Surface magnetic field, $B_S = 7.5\text{x}10^{11}$ G
- Detected by TAS up to 350 TeV



MeerKat GPS, Goodhart 2024

PSR J1849-0001 in X-rays

- Hard non-thermal spectrum
- Diffuse emission extends up to ~2′
- PWN radiative efficiency, $\eta_X = L_X/\dot{E} = 8.5\text{x}10^{-2}$



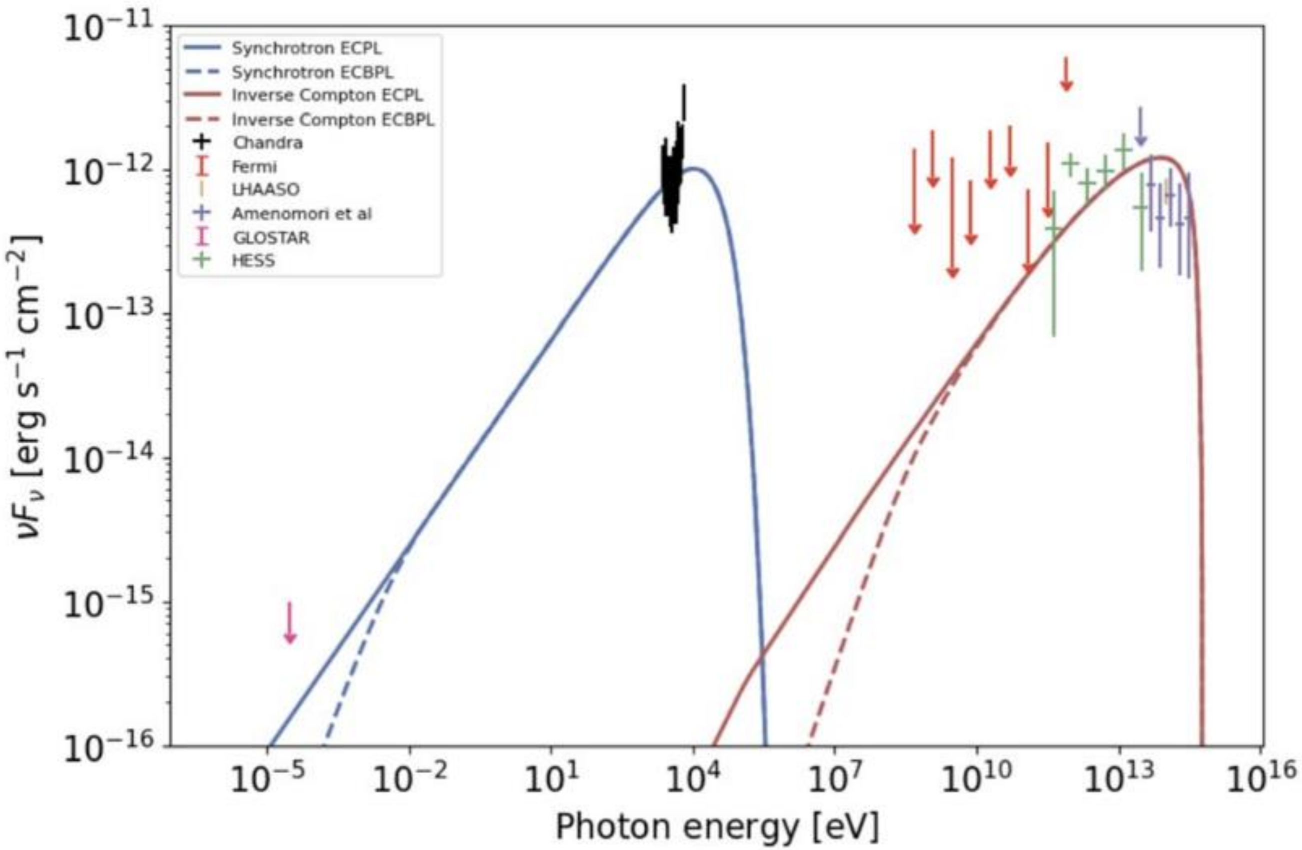
Spectral Fit Results for PWN Regions and Point Sources

Name	Area (arcsec^2)	Counts	Γ	$\mathcal{N}_{-5}$ (10^{-5} photons s^{-1} cm^{-2} keV^{-1} at 1 keV)	χ^2_ν (ν d.o.f.)	F_{-13} (10^{-13} erg cm^{-2} s^{-1})	F^{unabs}_{-13} (10^{-13} erg cm^{-2} s^{-1})
Pulsar	28	10673 ± 103	1.20 ± 0.07	46.18 ± 5.04	1.03 (311)	$19.72^{+0.24}_{-0.25}$	$38.70^{+1.33}_{-1.55}$
Inner PWN	531	422 ± 22	$\boxed{1.49 \pm 0.20}$ p=2	2.42 ± 0.66	1.05 (13)	$0.62^{+0.14}_{-0.12}$	$1.49^{+0.24}_{-0.29}$
Extended PWN	22476	3026 ± 96	1.56 ± 0.11	19.47 ± 2.93	1.0 (188)	4.78 ± 0.18	$11.46^{+0.63}_{-0.79}$
Pulsar Jet	1054	437 ± 24	1.70 ± 0.22	3.40 ± 0.99	2.01 (16)	$0.66^{+0.05}_{-0.06}$	$1.78^{+0.20}_{-0.26}$

Gagnon et al 2024

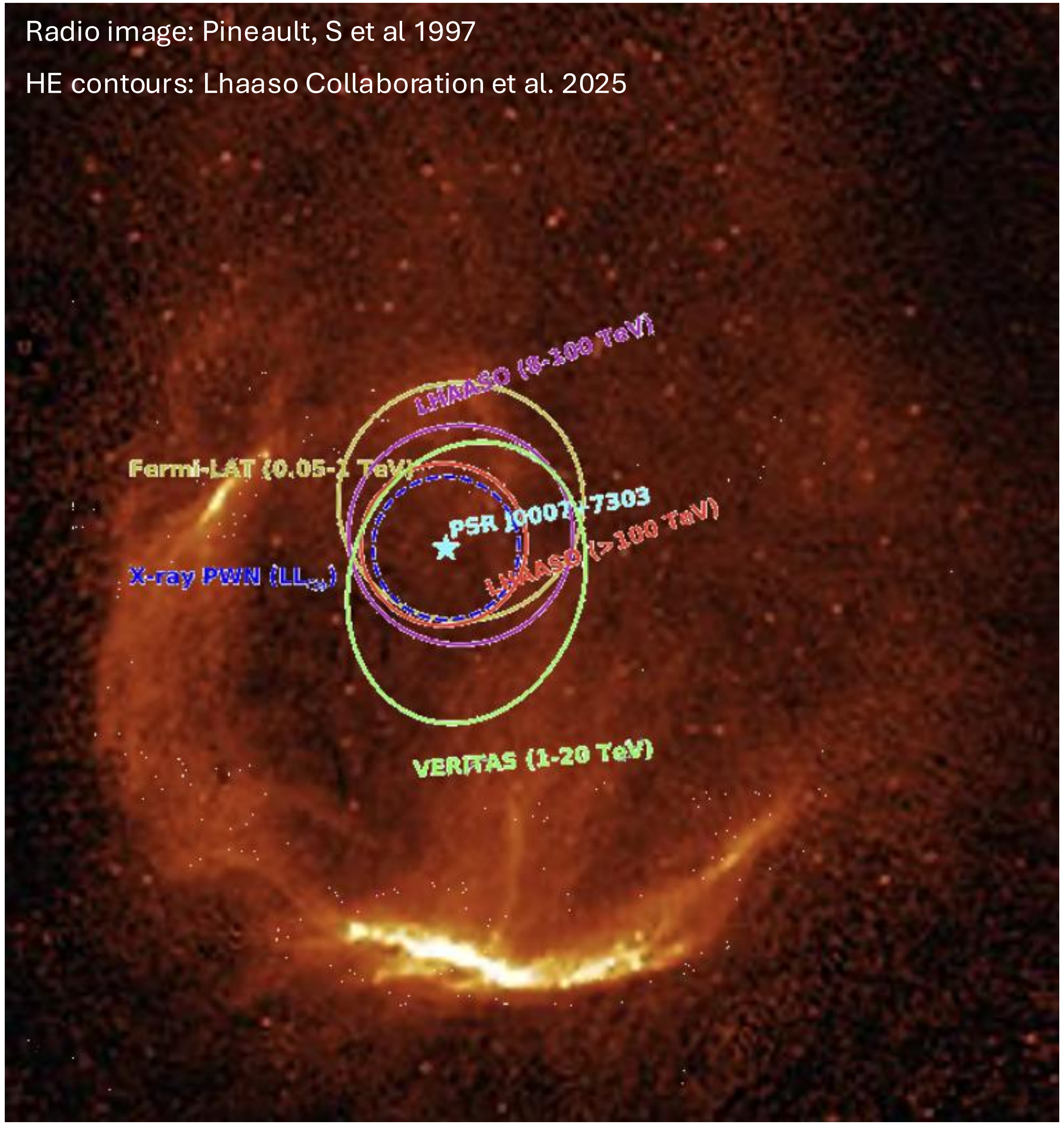
PSR J1849-0001 – SED modeling

- B = 2.0 uG
- Cutoff energy $E_{e,c}$ = 600 TeV
- Energy electron gains across full polar cap potential drop, E_{PC}= 5.7 PeV
- If current $\dot{E}$ is taken then
  $$\frac{E_{e,c}}{E_{PC}} = 10\%$$
- However, $\dot{E}$ could have been much larger when 600 TeV electrons were produced by the pulsar especially if its true age is significantly smaller than 43 kyrs.
- So, this case cannot be used to prove that pulsars can accelerate particles to a good fraction of potential drop.



CTA 1

- Pulsations discovered in X-ray and Gamma-rays (P=316 ms), radio quiet
- Inside SNR
- Spin-down age, t_c =14 kyrs
- Spin-down power, $\dot{E} = 4.5\text{x}10^{35}$ erg/s
- Large surface magnetic field, B_S =1.1x10^{13} G
- Detected by LHAASO up to 300 TeV (~12′)



Radio image: Pineault, S et al 1997

HE contours: Lhaaso Collaboration et al. 2025

CTA 1 in X-rays

- Hard non-thermal spectrum
- Diffuse emission extends ~10′
- PWN η_X =2.4x10^{-5}
- Angular extent expected for Bohm diffusion

$$\delta_B \approx 60'(E_e/125\,\mathrm{TeV})^{0.5}(t_c/8\,\mathrm{kyr})^{0.5}(d/1.4\,\mathrm{kpc})^{-1}(B/1.5\,\mu\mathrm{G})^{-0.5}$$

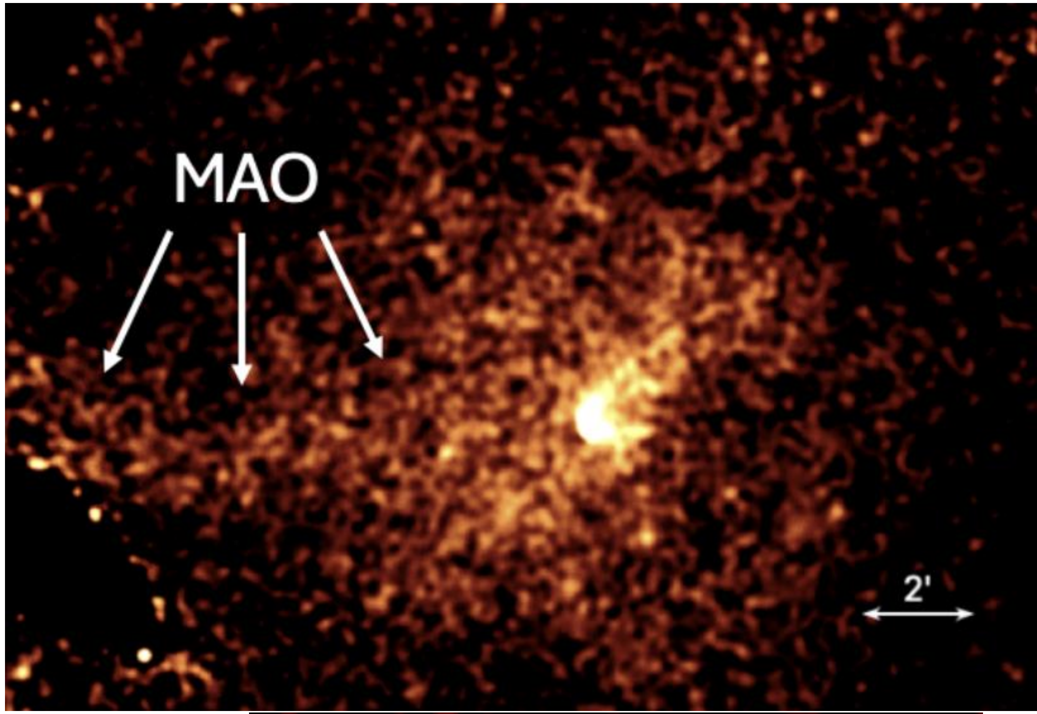
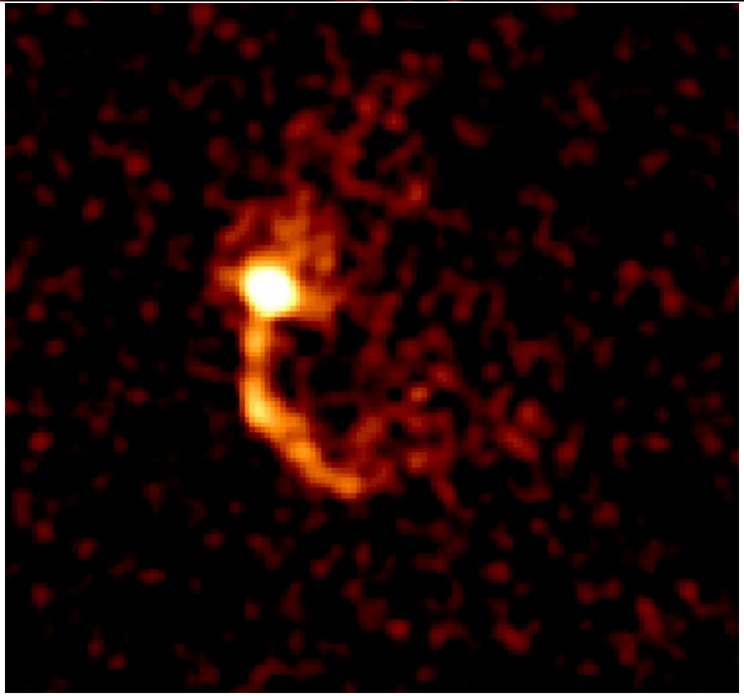


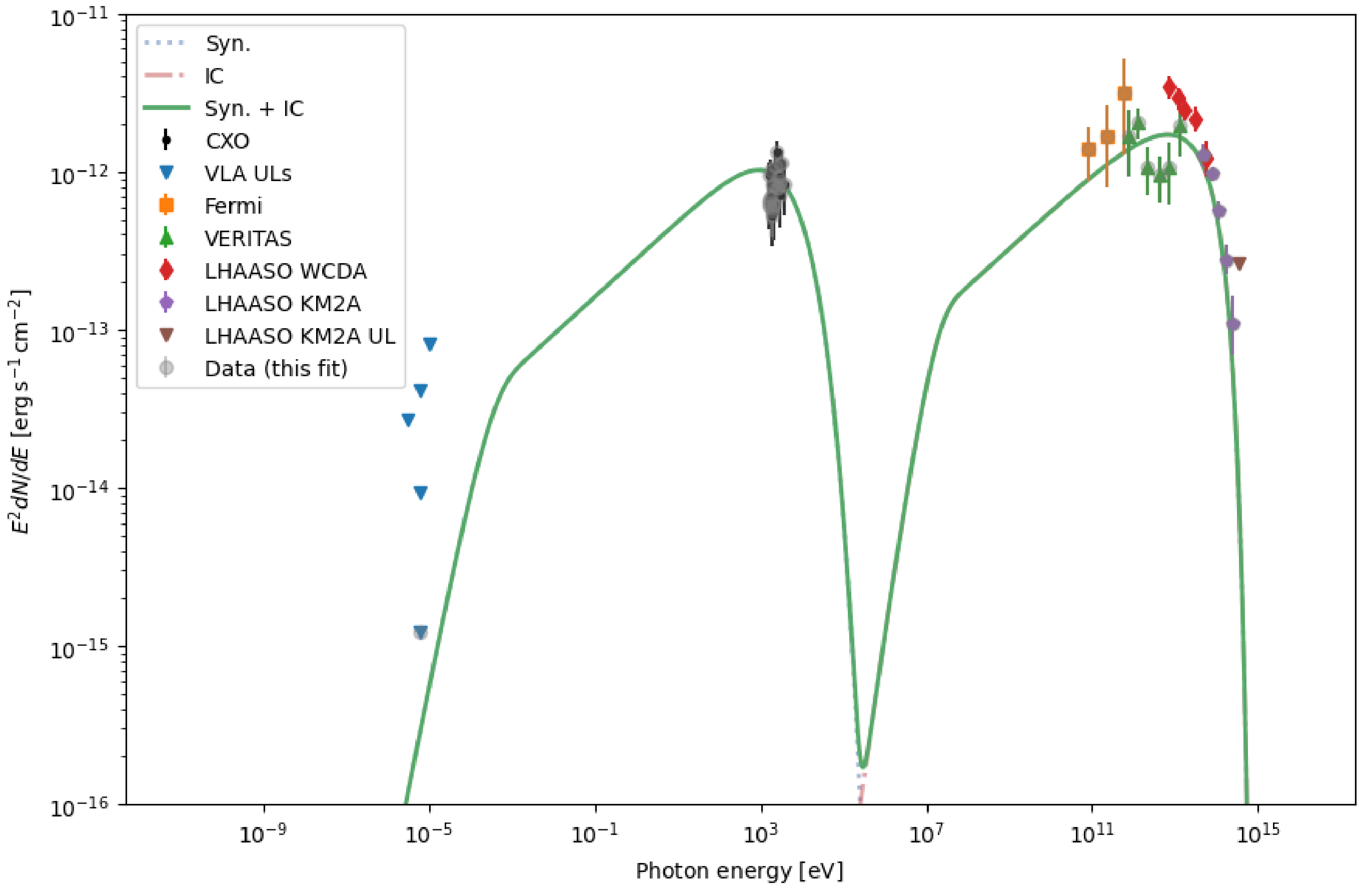
Table 2. Spectral Fit Results for PWN Regions and Point Sources

Region	Area	Counts	Γ p=1.68	$\mathcal{N}_{-6}$	Fit Statistic (d.o.f)	F_{-14}^{unabs}
Pulsar	0.97	252	2.42 ± 0.18	8.05 ± 0.83	38.21 (25)	2.76 ± 0.33
Torus	21.30	459	1.34 ± 0.11	4.81 ± 0.49	40.52 (39)	$3.45^{+0.46}_{-0.39}$
Jet	64.15	338	1.25 ± 0.20	3.29 ± 0.79	23.41 (28)	$2.60^{+0.43}_{-0.37}$
Counter Jet†	22.03	87	1.70 ± 0.34	1.69 ± 0.58	402.31 (2674)	$0.90^{+0.28}_{-0.23}$
Extended Nebula	163,066.48	95,175	1.85 ± 0.11	300.26 ± 29.22	87.01 (74)	$140.38^{+16.25}_{-14.46}$



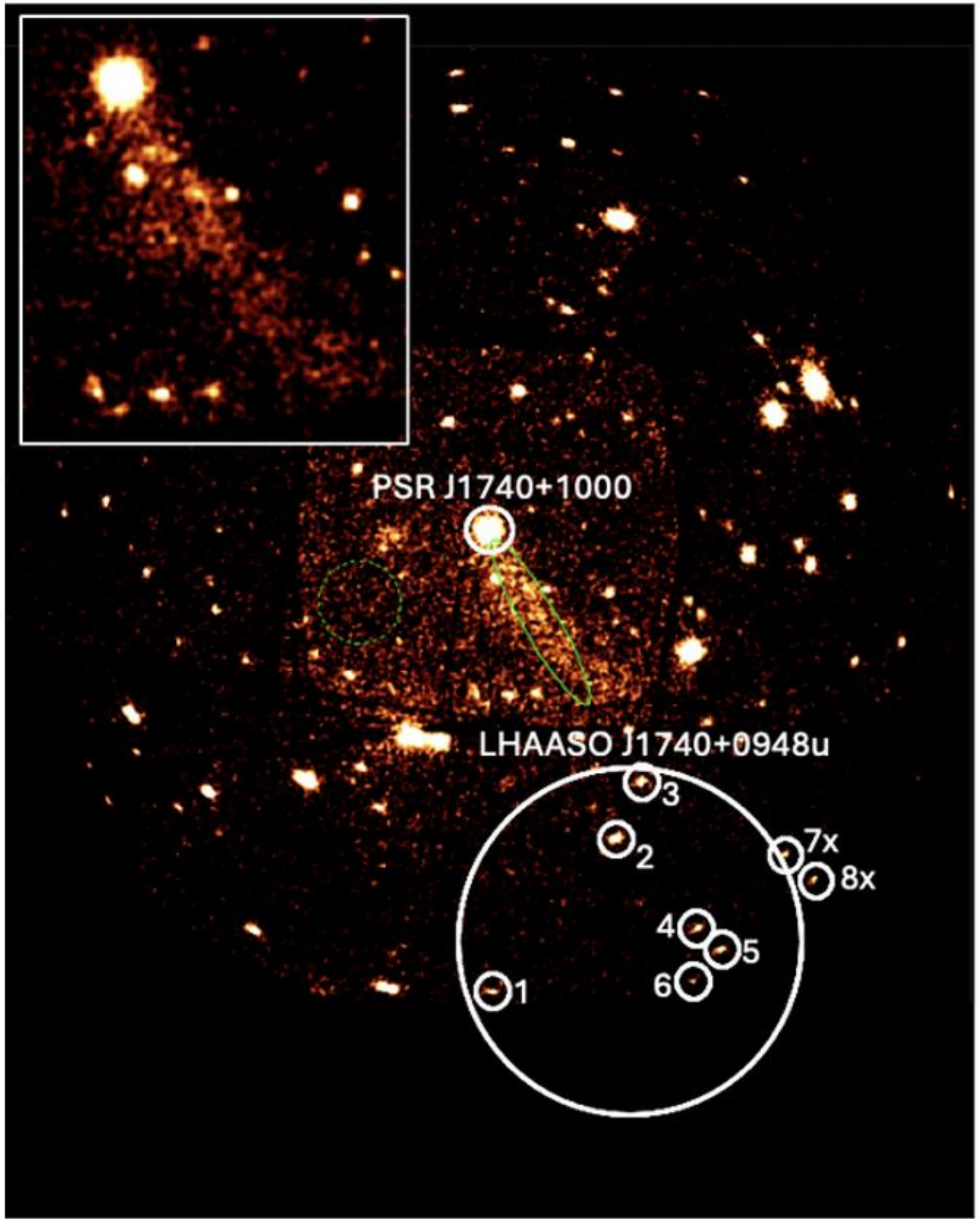
CTA 1 – SED Modeling

- B = 1.75 uG
- Cutoff energy $E_{e,c}$ = 250 TeV
- Polar cap potential drop, E_{PC}= 1.4 PeV
- $\frac{E_{e,c}}{E_{PC}} = 20\%$



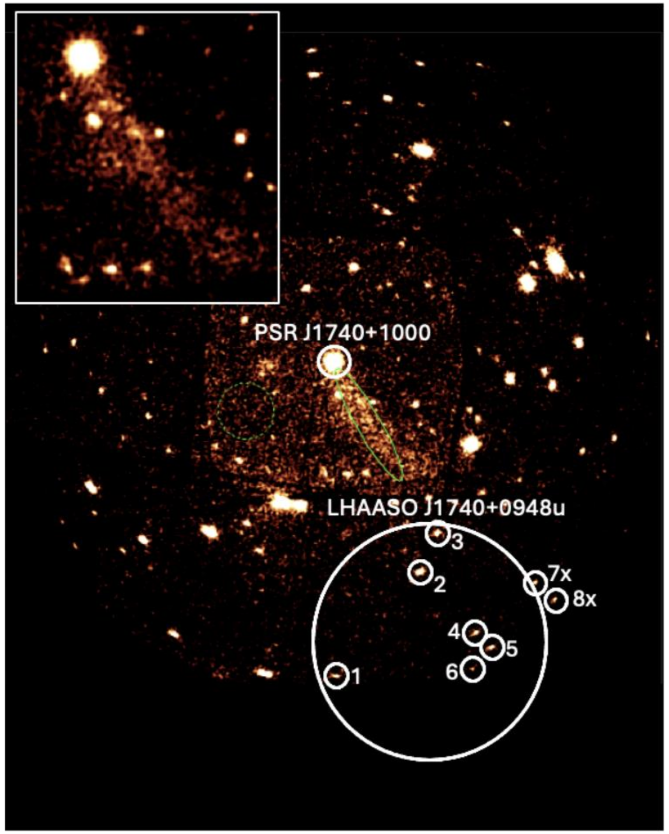
PSR J1740-1000

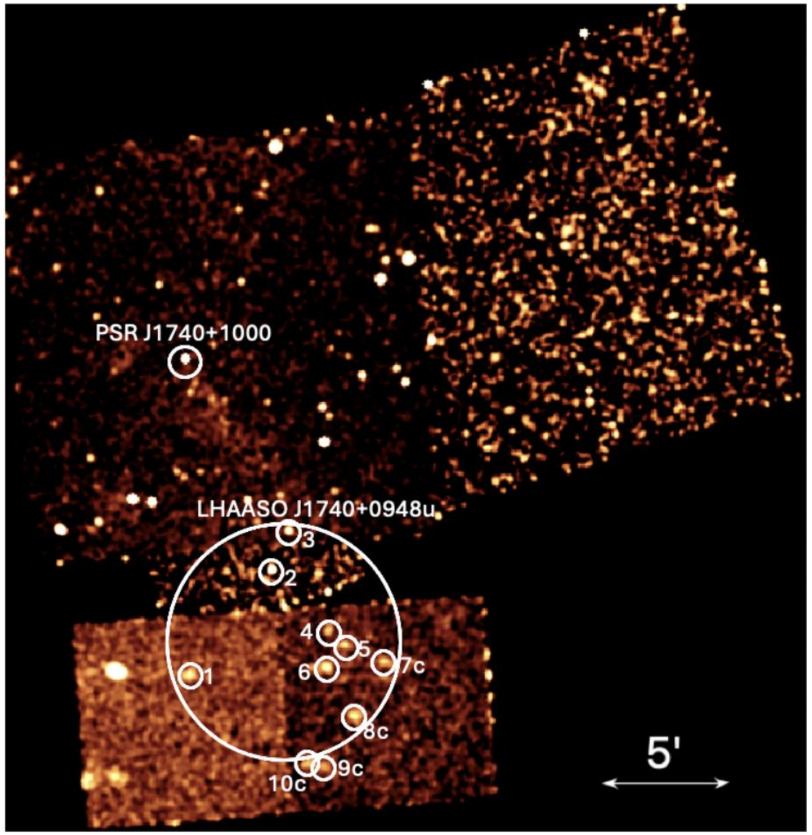
- Pulsations discovered in X-ray and Gamma-rays (P=154 ms), radio quiet
- No known SNR
- Spin-down age, t_c =114 kyrs
- Spin-down power, $\dot{E}$ =2.3x10^{35} erg/s
- Surface magnetic field, B_S =1.8x10^{12} G
- The tail (or MAO) points towards the UHE LHAASO detection (~13′away)
- Detected by LHAASO up to 300 TeV (~9')



PSR J1740-1000 in X-rays

- Hard non-thermal spectrum, Γ=1.6
- Tail extends ~5′
- PWN η_X=1x10^{-4}
- LHAASO source is most likely associated with this pulsar

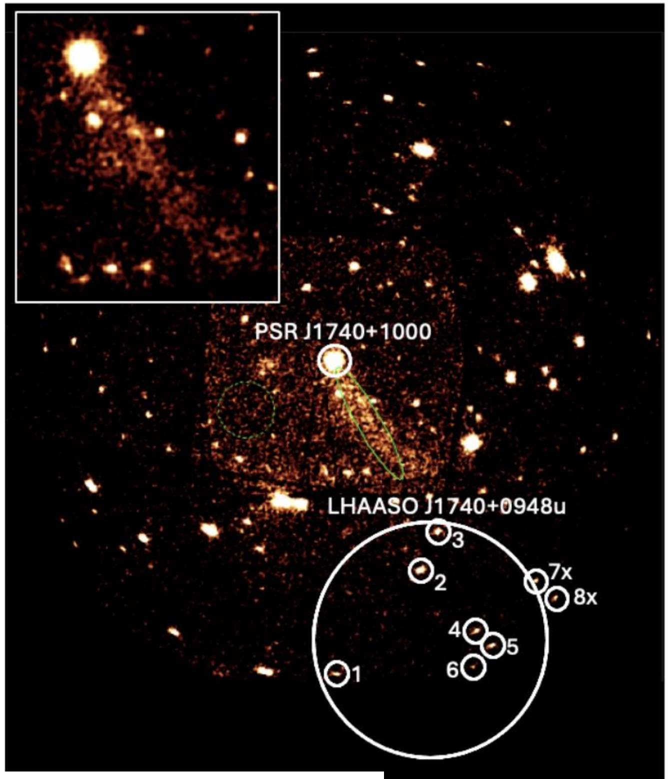


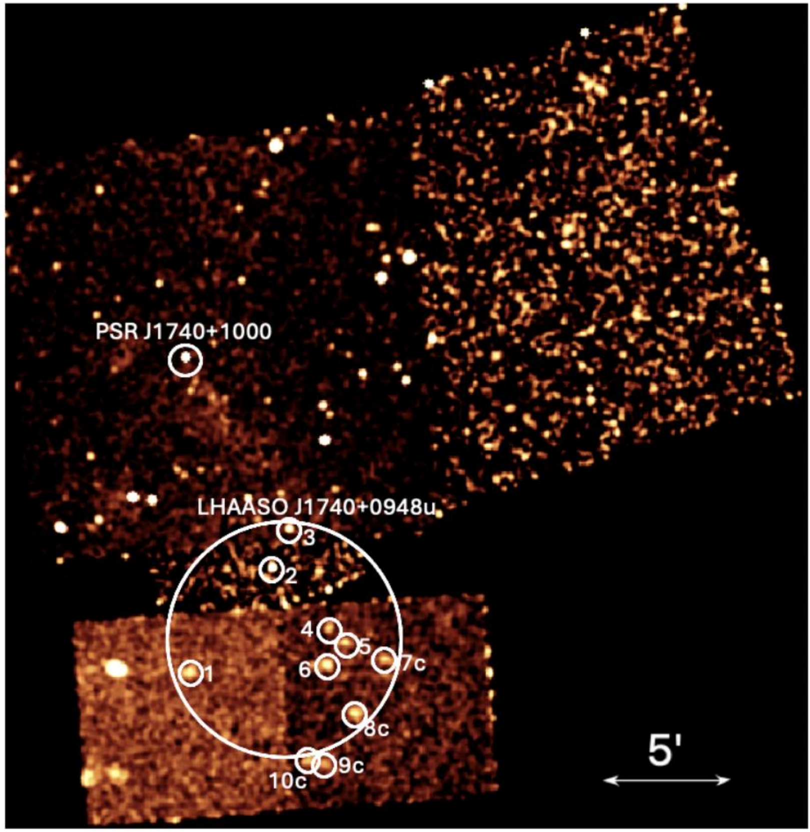


- $\delta_{\rm B} \approx 74'(B/1\ \ \mu{\rm G})^{-1/2}(E_e/100\ \ {\rm TeV})^{1/2}(t/10\ \ {\rm kyrs})^{1/2}(d/1.2\ {\rm kpc})^{-1}$

Can some other source than a pulsar produce the emission seen by LHAASO?

In principle UHE could be produced by nearby blazar (<180 Mpc)





	name	Class	Class_prob^a	Class_prob_e^b	CT	#_CTP^c	Sep ($'$)^d	Sign.^{e}	PU ($''$)^f	F_b(ergs cm^{-2}s^{-1})^g
1	4XMM J174025.5+094703	AGN	0.97	0.02	30.48	1	4.77	52.34	0.94	3.77×10^{-14}
2	4XMM J174011.2+095122	AGN	0.39	0.22	0.09	0	2.95	166.81	0.46	3.07×10^{-14}
3	4XMM J174008.4+095258	AGN	0.96	0.02	23.10	1	4.39	58.09	0.53	2.06×10^{-14}
4	4XMM J174001.8+094849	AGN	0.97	0.03	16.36	1	1.33	90.47	0.52	2.36×10^{-14}
5	4XMM J173959.2+094814	AGN	0.97	0.02	26.43	1	1.98	94.92	0.68	2.38×10^{-14}
6	4XMM J174002.3+094721	AGN	0.99	0.02	33.16	1	1.73	74.10	0.61	3.53×10^{-14}
7x	4XMM J173951.8+095055	AGN	0.58	0.25	0.78	0	4.45	35.40	0.66	1.19×10^{-14}
8x	4XMM J173948.5+095015	AGN	0.43	0.22	0.15	0	4.89	51.35	0.61	1.58×10^{-14}
1	2CXO J174025.2+094700	NS	0.45	0.24	0.28	1	4.71	5.7	5.28	2.89×10^{-14}
2	2CXO J174011.3+095122	AGN	0.44	0.12	0.92	3	2.95	3.64	5.84	4.95×10^{-14}
3	2CXO J174008.4+095259	AGN	0.99	0.02	26.24	2	4.40	7.67	0.93	1.72×10^{-14}
4†	2CXO J174001.7+094850	-	-	-	-	-	1.37	2.41	6.84	0.55×10^{-14}
5	2CXO J173959.1+094817	AGN	0.934	0.06	8.91	3	2.01	4.28	4.27	1.03×10^{-14}
6	2CXO J174002.1+094721	AGN	0.88	0.08	7.35	2	1.75	6.45	4.63	4.26×10^{-14}
7c	2CXO J173952.1+094733	AGN	0.72	0.04	6.96	4	3.86	4.61	6.02	2.48×10^{-14}
8c	2CXO J173957.1+094521	AGN	0.85	0.10	5.35	2	4.08	5.09	6.92	3.42×10^{-14}
9c*	2CXO J174002.8+094315	-	-	-	-	-	5.44	3.56	11.53	0
10c*	2CXO J174005.4+094323	-	-	-	-	-	5.24	1.82	15.27	0

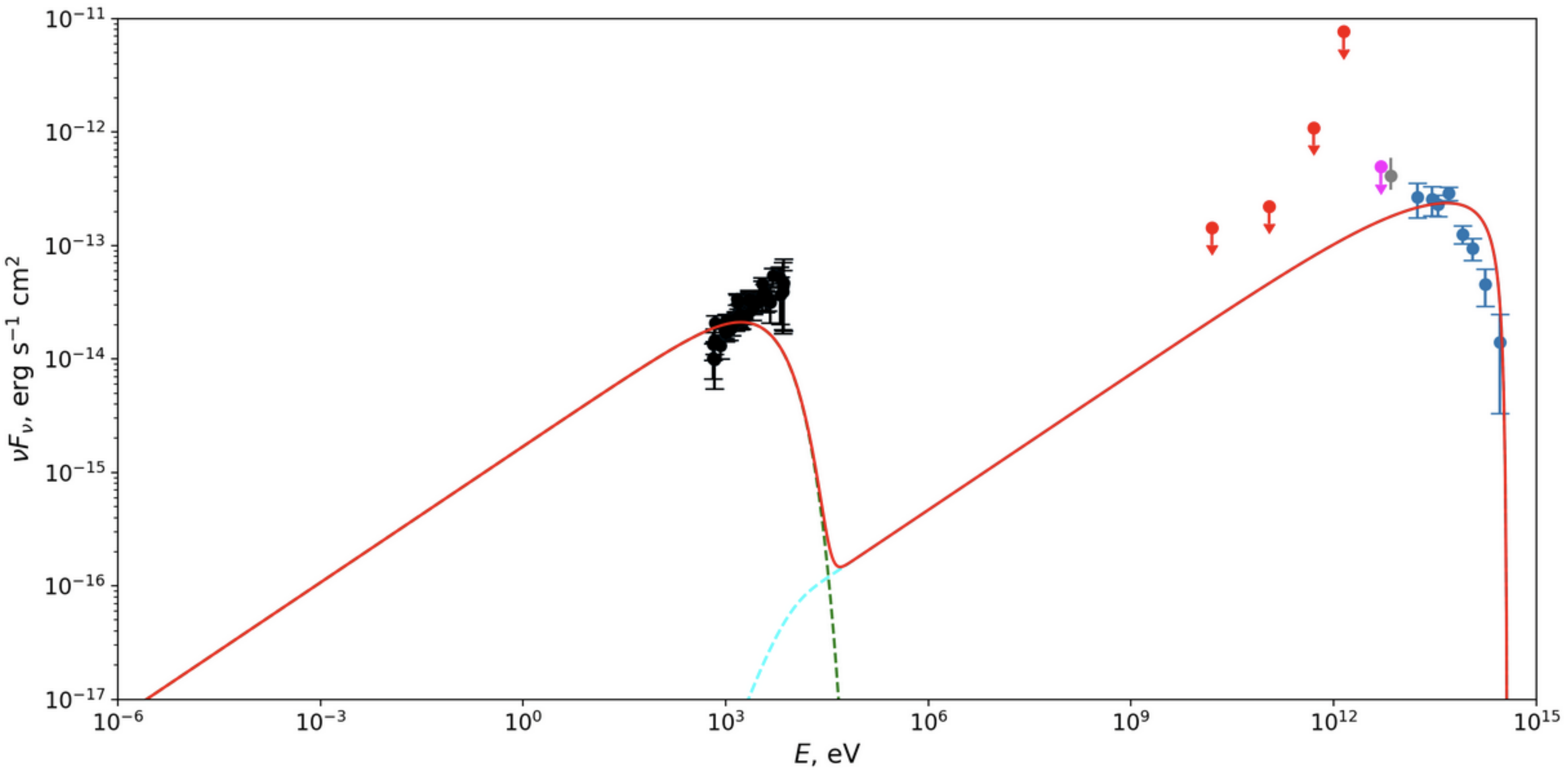
None of these looks like a nearby blazar from our multiwavelength analysis.

PSR J1740-1000 – SED modeling

- Max electron energy inferred from the LHAASO detection is 850 TeV which is ~80% of the total potential drop across the pulsar polar cap.

$$B = B(z) = B_0\left(\frac{z}{z_0}\right)^{\beta} \qquad v = v(z) = v_0\left(\frac{z}{z_0}\right)^{\alpha}$$

$$r = r(z) = r_0\left(\frac{z}{z_0}\right)^{\gamma},$$



Parameter	Value
v_0	50,000 km/s
z_0	6.2e17 cm
B	1 uG
γ	1
β	-0.3
α	-0.7
$E_{e,c}$	400 TeV

$E_{e,c}\,/E_{PC}$=40%

Model described in Benbow et al 2021

This case provides evidence that pulsar can accelerate particles to a large fraction of their potential drop.

Conclusion

- UHE sources can be associated with both young PWNe still within their remnants and older supersonic PWNe that left their remnants
- For pulsars with PWN inside SNRs it can be more difficult to say what actually produces UHE emitting particles: pulsar? SNR forward shock? SNR reverse shock interacting with PWN?
- Supersonic PWNe are cleaner cases in this sense. For J1740, after ruling out other possibilities for UHE accelerators, we find that pulsar can accelerate particles (inside the compact PWN) to 40% of polar cap potential drop.