Towards a Self-Consistent Model of the UHE Gamma-Ray Emission of PWNe: Insights from LHAASO and ATNF Catalogs

Samy Kaci

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Outline

- Motivation
- Identifying mis-associations
- Results
- Summary & Conclusion

The LHAASO catalog

Tsung-Dao Lee Institute

Z. Cao et al. (2024)

Table 4
1LHAASO Sources Associated Pulsars

Source Name	PSR Name	Sep. (deg)	d (kpc)	τ_c (kyr)	$\dot{E}$ (erg s^{-1})	P_c	Identified Type in TeVCat
1LHAASO J0007+7303u	PSR J0007+7303	0.05	1.40	14	4.5e+35	7.3e-05	PWN
1LHAASO J0216+4237u	PSR J0218+4232	0.33	3.15	476000	2.4e+35	3.6e-03	
1LHAASO J0249+6022	PSR J0248+6021	0.16	2.00	62	2.1e+35	1.5e-03	
1LHAASO J0359+5406	PSR J0359+5414	0.15	···	75	1.3e+36	7.2e-04	
1LHAASO J0534+2200u	PSR J0534+2200	0.01	2.00	1	4.5e+38	3.2e-06	PWN
1LHAASO J0542+2311u	PSR J0543+2329	0.30	1.56	253	4.1e+34	8.3e-03	
1LHAASO J0622+3754	PSR J0622+3749	0.09	···	208	2.7e+34	2.5e-04	PWN/TeV Halo
1LHAASO J0631+1040	PSR J0631+1037	0.11	2.10	44	1.7e+35	3.5e-04	PWN
1LHAASO J0634+1741u	PSR J0633+1746	0.12	0.19	342	3.3e+34	1.3e-03	PWN/TeV Halo
1LHAASO J0635+0619	PSR J0633+0632	0.39	1.35	59	1.2e+35	9.4e-03	
1LHAASO J1740+0948u	PSR J1740+1000	0.21	1.23	114	2.3e+35	1.4e-03	
1LHAASO J1809-1918u	PSR J1809-1917	0.05	3.27	51	1.8e+36	6.2e-04	
1LHAASO J1813-1245	PSR J1813-1245	0.01	2.63	43	6.2e+36	6.3e-06	
1LHAASO J1825-1256u	PSR J1826-1256	0.09	1.55	14	3.6e+36	1.6e-03	
1LHAASO J1825-1337u	PSR J1826-1334	0.11	3.61	21	2.8e+36	2.8e-03	PWN/TeV Halo
1LHAASO J1837-0654u	PSR J1838-0655	0.12	6.60	23	5.6e+36	2.2e-03	PWN
1LHAASO J1839-0548u	PSR J1838-0537	0.20	···	5	6.0e+36	6.1e-03	
1LHAASO J1848-0001u	PSR J1849-0001	0.06	···	43	9.8e+36	1.2e-04	PWN
1LHAASO J1857+0245	PSR J1856+0245	0.16	6.32	21	4.6e+36	3.1e-03	PWN
1LHAASO J1906+0712	PSR J1906+0722	0.19	···	49	1.0e+36	5.9e-03	
1LHAASO J1908+0615u	PSR J1907+0602	0.23	2.37	20	2.8e+36	6.8e-03	
1LHAASO J1912+1014u	PSR J1913+1011	0.13	4.61	169	2.9e+36	1.5e-03	
1LHAASO J1914+1150u	PSR J1915+1150	0.09	14.01	116	5.4e+35	1.8e-03	
1LHAASO J1928+1746u	PSR J1928+1746	0.04	4.34	83	1.6e+36	1.6e-04	
1LHAASO J1929+1846u	PSR J1930+1852	0.29	7.00	3	1.2e+37	2.6e-03	PWN
1LHAASO J1954+2836u	PSR J1954+2836	0.01	1.96	69	1.1e+36	1.6e-05	PWN
1LHAASO J1954+3253	PSR J1952+3252	0.33	3.00	107	3.7e+36	6.7e-03	
1LHAASO J1959+2846u	PSR J1958+2845	0.10	1.95	22	3.4e+35	2.8e-03	PWN
1LHAASO J2005+3415	PSR J2004+3429	0.25	10.78	18	5.8e+35	9.9e-03	
1LHAASO J2005+3050	PSR J2006+3102	0.20	6.04	104	2.2e+35	9.2e-03	
1LHAASO J2020+3649u	PSR J2021+3651	0.05	1.80	17	3.4e+36	1.5e-04	PWN
1LHAASO J2028+3352	PSR J2028+3332	0.36	···	576	3.5e+34	8.0e-03	
1LHAASO J2031+4127u	PSR J2032+4127	0.08	1.33	201	1.5e+35	1.0e-03	PWN
1LHAASO J2228+6100u	PSR J2229+6114	0.27	3.00	10	2.2e+37	2.2e-03	PWN
1LHAASO J2238+5900	PSR J2238+5903	0.07	2.83	27	8.9e+35	3.0e-04	

- 73 sources detected by KM2A (excluding SS433).
- 31 sources associated to known pulsars (18 of them are radio-loud).

- Assume ~20% beaming fraction.
- Rough estimates give: ~2*5*18=180 Pulsar wind nebulae (PWNe) detected by LHAASO.
- Simulations of the entire Galaxy give ~160 PWNe detectable by KM2A.

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1LHAASO J1740+[illegible]	PSR J1740+1000	0.21	1.23	114	2.3e+35	1.4e-03	
1LHAASO J1809-[illegible]	[illegible]1809-1917	0.05	3.27	51	1.8e+36	6.2e-04	
1LHAASO J1813-[illegible]	[illegible]	0.01	2.63	43	6.2e+36	6.3e-06	
1LHAASO J1825[illegible]	[illegible]	[illegible]	1.55	14	3.6e+36	1.6e-03	
1LHAASO J1825-1337u	[illegible]	[illegible]	[illegible]	21	2.8e+36	2.8e-03	PWN/TeV Halo
1LHAASO J1837-0654u	PSR J18[illegible]	[illegible]	[illegible]	[illegible]	5.6e+36	2.2e-03	PWN
1LHAASO J1839-0548u	PSR J1838-0537	[illegible]	[illegible]	[illegible]	[illegible]	6.1e-03	
1LHAASO J1848-0001u	PSR J1849-0001	0.06	[illegible]	[illegible]	[illegible]	[illegible]	PWN
1LHAASO J1857+0245	PSR J1856+0245	0.16	6.32	[illegible]	[illegible]	[illegible]	PWN
1LHAASO J1906+0712	PSR J1906+0722	0.19	···	49	[illegible]	[illegible]	
1LHAASO J1908+0615u	PSR J1907+0602	0.23	2.37	20	[illegible]	[illegible]	
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1LHAASO J2031+4127u	PSR J2032+4127	0.08	1.33	201	1.5e+35	1.0e-03	PWN
1LHAASO J2228+6100u	PSR J2229+6114	0.27	3.00	10	2.2e+37	2.2e-03	PWN
1LHAASO J2238+5900	PSR J2238+5903	0.07	2.83	27	8.9e+35	3.0e-04	

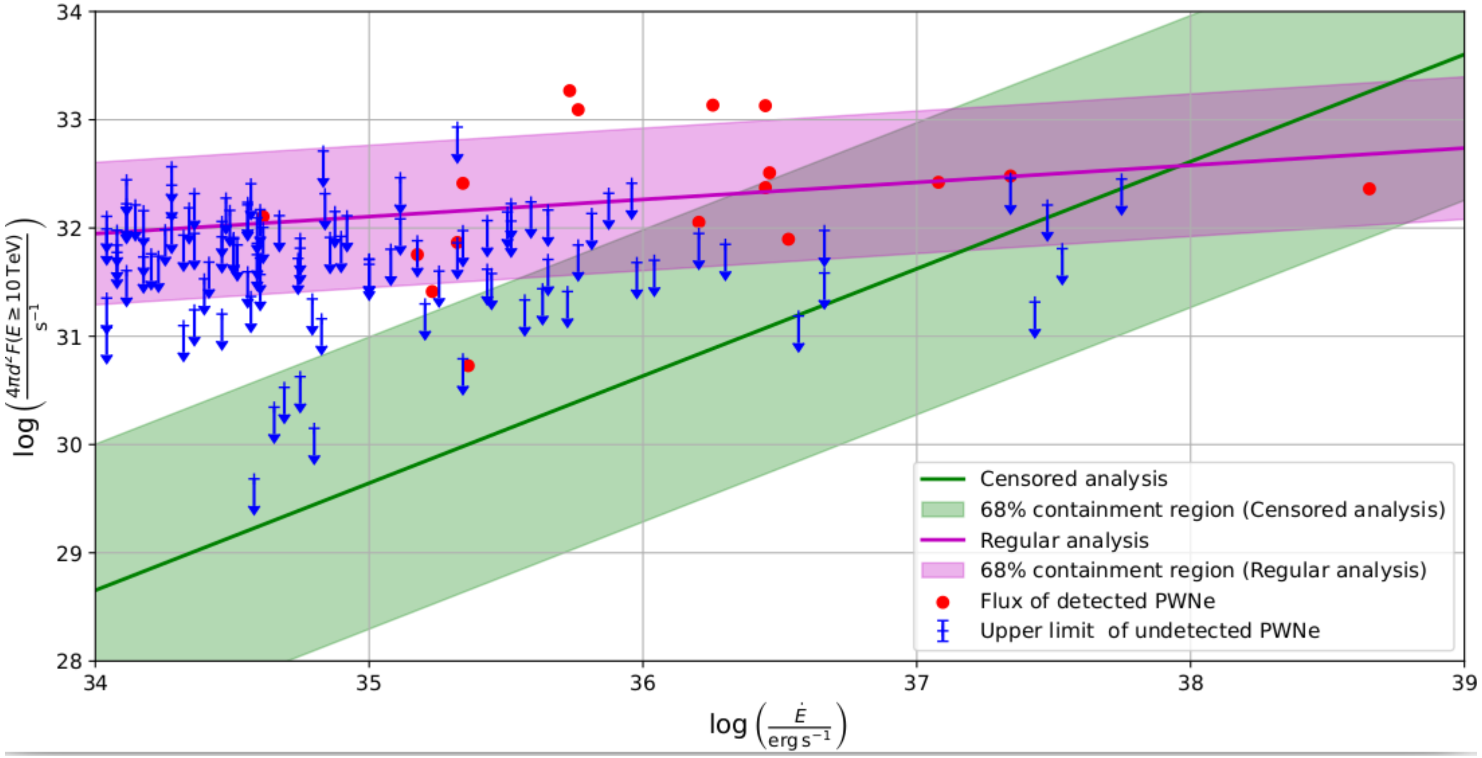
Apparent tension!

- 73 sources detected by KM2A (excluding SS433).
- 31 sources associated to known pulsars (18 of them are radio-loud).

- Assume ~20% beaming fraction.
- Rough estimates give: ~2*5*18=180 Pulsar wind nebulae (PWNe) detected by LHAASO.
- Simulations of the entire Galaxy give ~160 PWNe detectable by KM2A.

Why this tension?

S. Kaci, G. Giacinti & D. Semikoz (2025)



- Standard linear regression overpredicts of many PWNe.
- The beaming fractions of pulsars in radio may be too pessimistic.
- There are some sources that have been mis-associated to a pulsar.

Outline

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Adaptation of Mattox's procedure

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- Probability of correct identification given by:

$$p\left(\mathrm{id}|\mathrm{r}\right) = \frac{\left[\eta/\left(1-\eta\right)\right]\mathrm{LR}}{\left[\eta/\left(1-\eta\right)\right]\mathrm{LR}+1}$$

- LR is the likelihood ratio given by:

$$\mathrm{LR} \equiv 3\frac{\mathrm{r}_0^2}{\Psi^2}\exp\left(-\mathrm{r}^2\left(3\Psi^{-2}-\mathrm{r}_0^{-2}\right)\right)$$

with:

$$r_0 \equiv \left[\pi\rho\left(\dot{E}/d^2\right)\right]^{-1/2}$$

- Eta is the probability of correct identification p(id) given by:

$$p\left(\mathrm{id}\right) \equiv \int_{\tilde{F}}^{+\infty}\mathcal{N}\left(x|\mu_0,\sigma_0^2\right)dx = 0.5\times\mathrm{erfc}\left(\frac{\tilde{F}-\mu_0}{\sigma_0\sqrt{2}}\right)$$

Construction of the probability Eta

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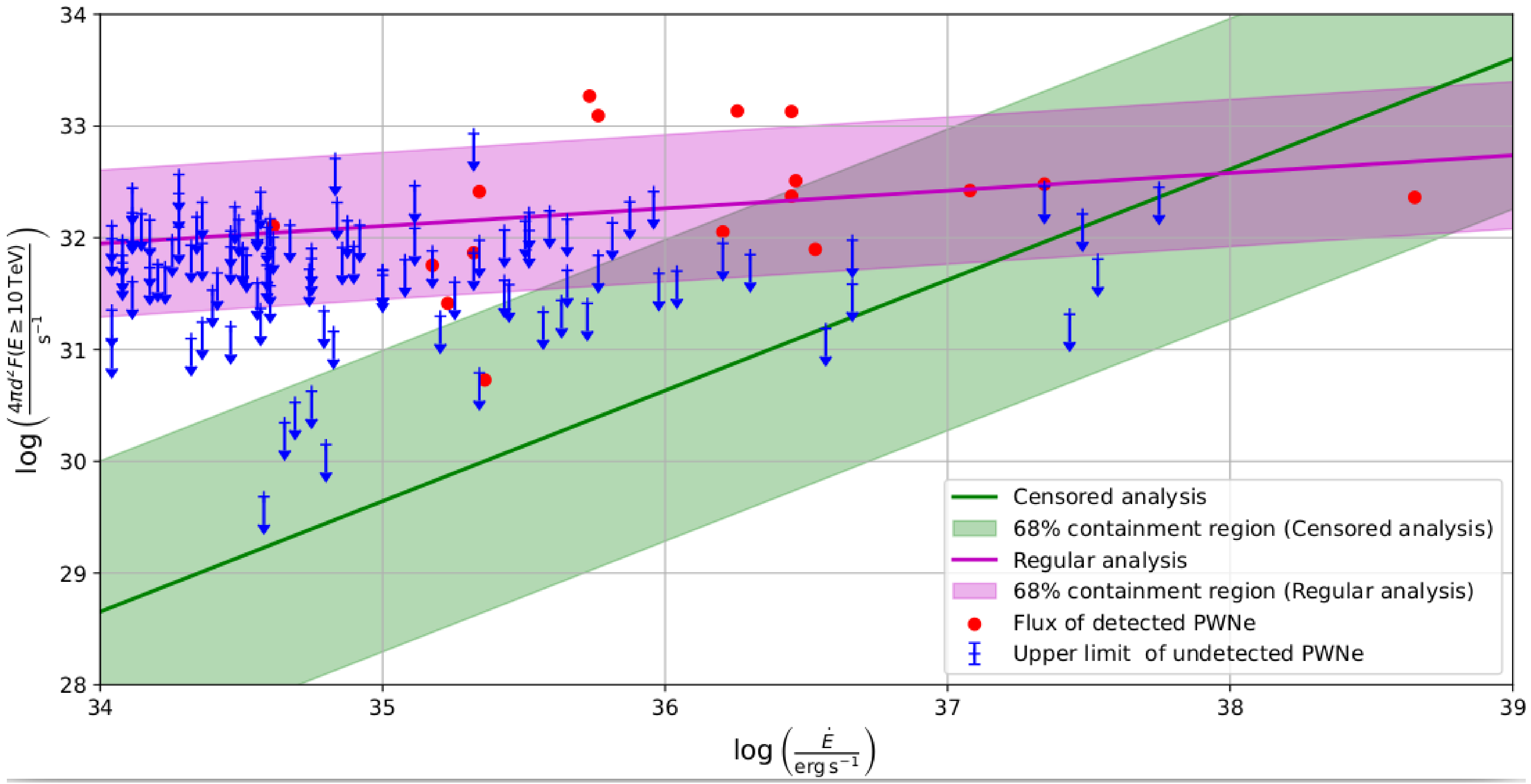
S. Kaci, G. Giacinti & D. Semikoz (2025)



Censored regression

- Performed by finding the maximum of the likelihood function:

$$\mathcal{L}(\theta) \equiv \mathcal{L}_{\text{detected}}(\theta)\,\mathcal{L}_{\text{undetected}}(\theta)$$

- Standard likelihood function for detected sources:

$$\mathcal{L}_{\text{detected}}(\theta) = \prod_{i=0}^{N} P(y_i|x_i, \theta)$$

- Cumulative probability for the likelihood function of undetected sources:

$$\mathcal{L}_{\text{undetected}}(\theta) = \prod_{j=0}^{M} P(y_j \le y_{\text{lim}}|x_j, \theta)$$

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Alleviating the tension

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Name	IACT	$\dot{E}$	d	$p\,(\mathrm{id})$	Fraction of misaligned pulsars 0%	50%	67%	80%	Aligned?
					$p\,(\mathrm{id}\vert\mathrm{r})$				
		(10^{36} erg s^{-1})	(kpc)	(%)	(%)	(%)	(%)	(%)	(Y/N)
1LHAASO J0249+6022	—	0.21	2.0	7.91	93.74	91.19	86.61	77.05	Y
1LHAASO J0359+5406‡	—	1.3	3.45	12.30	97.84	97.51	96.59	93.59	Y
1LHAASO J0534+2200u	Crab Nebula	450	2.0	74.73	99.99*	99.99*	99.99*	99.99*	Y
1LHAASO J0542+2311u	—	0.041	1.56	1.75	25.55	24.49	22.81	19.81	Y
1LHAASO J0631+1040	—	0.17	2.1	12.67	98.28*	98.28*	98.28*	98.28*	Y
1LHAASO J1740+0948u	—	0.23	1.23	29.52	91.91	91.89	91.74	91.71	Y
1LHAASO J1809-1918u	—	1.8	3.27	4.78	87.66	87.06	85.04	81.44	Y
1LHAASO J1825-1337u	HESS J1825-137	2.8	3.61	6.40	92.15*	91.84*	90.31*	87.63*	Y
1LHAASO J1908+0615u	—	2.8	2.37	16.83	96.74*	96.49*	95.32*	93.11	Y
1LHAASO J1912+1014u	—	2.9	4.61	14.65	83.70	82.63	78.78	72.91	Y

Alleviating the tension

S. Kaci, G. Giacinti & D. Semikoz (2025)

Table 1. Summary of the properties of the pulsars associated to the LHAASO sources reported by KM2A, together with the probabilities of correct association for different percentages of misaligned pulsars in the simulation.

Name	IACT	$\dot{E}$	d	$p\,(\mathrm{id})$	$p\,(\mathrm{id}\vert\mathrm{r})$, fraction of misaligned pulsars 0%	50%	67%	80%	Aligned?
		(10^{36} erg s^{-1})	(kpc)	(%)	(%)	(%)	(%)	(%)	(Y/N)
1LHAASO J0249+6022	—	0.21	2.0	7.91	93.74	91.19	86.61	77.05	Y
1LHAASO J0359+5406[‡]	—	1.3	3.45	12.30	97.84	97.51	96.59	93.59	Y
1LHAASO J0534+2200u	Crab Nebula	450	2.0	74.73	99.99*	99.99*	99.99*	99.99*	Y
1LHAASO J0542+2311u	—	0.041	1.56	1.75	25.55	24.49	22.81	19.81	Y
1LHAASO J0631+1040	—	0.17	2.1	12.67	98.28*	98.28*	98.28*	98.28*	Y
1LHAASO J1740+0948u	—	0.23	1.23	29.52	91.91	91.89	91.74	91.71	Y
1LHAASO J1809-1918u	—	1.8	3.27	4.78	87.66	87.06	85.04	81.44	Y
1LHAASO J1825-1337u	HESS J1825-137	2.8	3.61	6.40	92.15*	91.84*	90.31*	87.63*	Y
1LHAASO J1908+0615u	—	2.8	2.37	16.83	96.74*	96.49*	95.32*	93.11	Y
1LHAASO J1912+1014u	—	2.9	4.61	14.65	83.70	82.63	78.78	72.91	Y
1LHAASO J1914+1150u	—	0.54	14.01	1.58	26.82	22.66	18.16	12.45	Y
1LHAASO J1928+1746u	—	1.6	4.34	18.35	98.28*	98.08*	97.49*	96.33*	Y
1LHAASO J1929+1846u	HESS J1930+188	12	7.0	29.68	92.65*	92.13*	89.23*	84.70*	Y
1LHAASO J2005+3415	—	0.58	10.78	2.29	23.55	18.81	13.89	8.86	Y
1LHAASO J2005+3050	—	0.22	6.04	3.58	45.03	37.78	29.11	19.21	Y
1LHAASO J2020+3649u	—	3.4	1.80	29.25	99.83*	99.83*	99.79*	99.70*	Y
1LHAASO J2031+4127u	VER J2032+414	0.15	1.33	7.56	93.02*	92.14*	89.75*	84.99*	Y
1LHAASO J2228+6100u	—	22	3.0	35.07	98.64*	98.59*	98.34*	97.89*	Y
1LHAASO J2238+5900	—	0.89	2.83	9.37	92.39	89.28	83.51	72.86	N
1LHAASO J0007+7303u	VER J0006+729	0.45	1.40	11.68	99.42	99.42	99.39	99.29	N
1LHAASO J0622+3754[†]	—	0.027	—	13.75	96.81	96.81	96.73	96.52	N
1LHAASO J0635+0619	—	0.12	1.35	10.03	88.26	88.26	88.26	88.26	N
1LHAASO J0634+1741u	Geminga	0.032	0.19	17.26	91.61	91.61	91.61	91.61	N
1LHAASO J1813-1245	—	6.2	2.63	28.07	99.22	99.18	99.05	98.83	N
1LHAASO J1825-1256u	—	3.6	1.55	24.34	99.45	99.43	99.33	99.15	N
1LHAASO J1837-0654u	HESS J1837-069	5.5	6.60	7.02	85.24	83.94	79.89	73.14	N
1LHAASO J1839-0548u[†]	—	5.7	—	52.44	99.69	99.69	99.69	99.69	N
1LHAASO J1848-0001u[†]	HESS J1849-000	9.8	—	51.27	99.97	99.96	99.96	99.96	N
1LHAASO J1954+2836u	—	1.0	1.96	38.12	99.80	99.79	99.73	99.61	N
1LHAASO J1959+2846u	—	0.34	1.95	19.52	95.46	95.03	93.30	89.82	N
1LHAASO J2028+3352[†]	—	0.035	—	47.79	92.63	92.58	92.49	92.03	N

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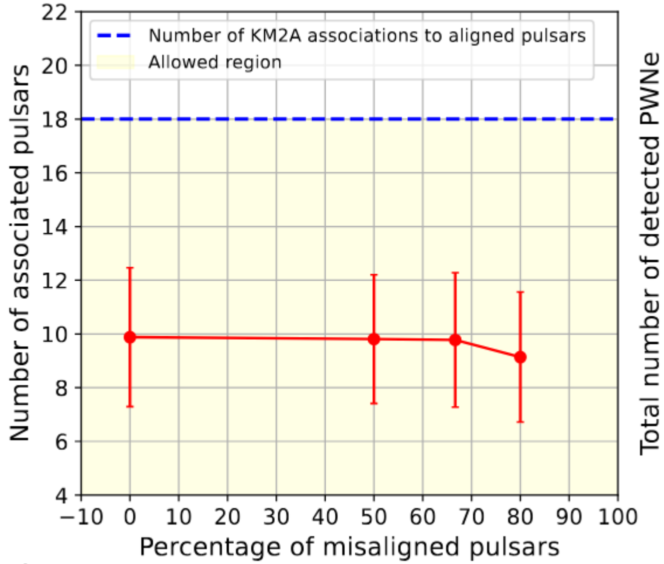

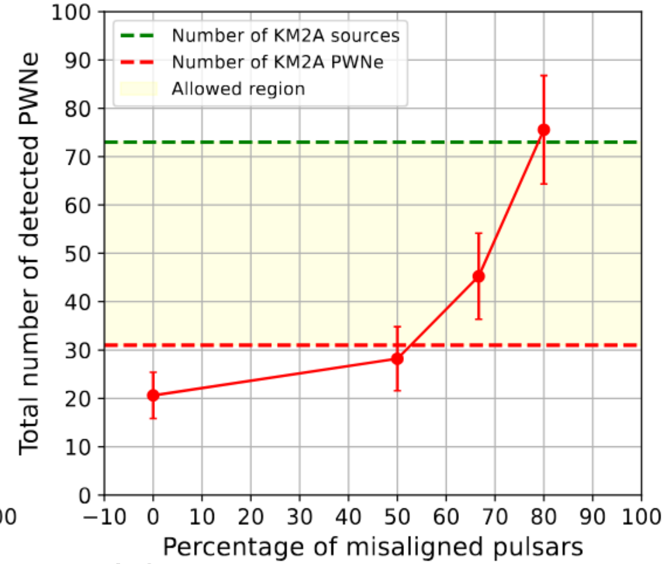

- 8 sources among the 18 related to aligned pulsars are likely to be the correct association.
- 17 among the 31 sources are probably the right association.
- Many unidentified LHAASO sources must be associated to PWNe (with a misaligned pulsar).

Contribution to the diffuse background

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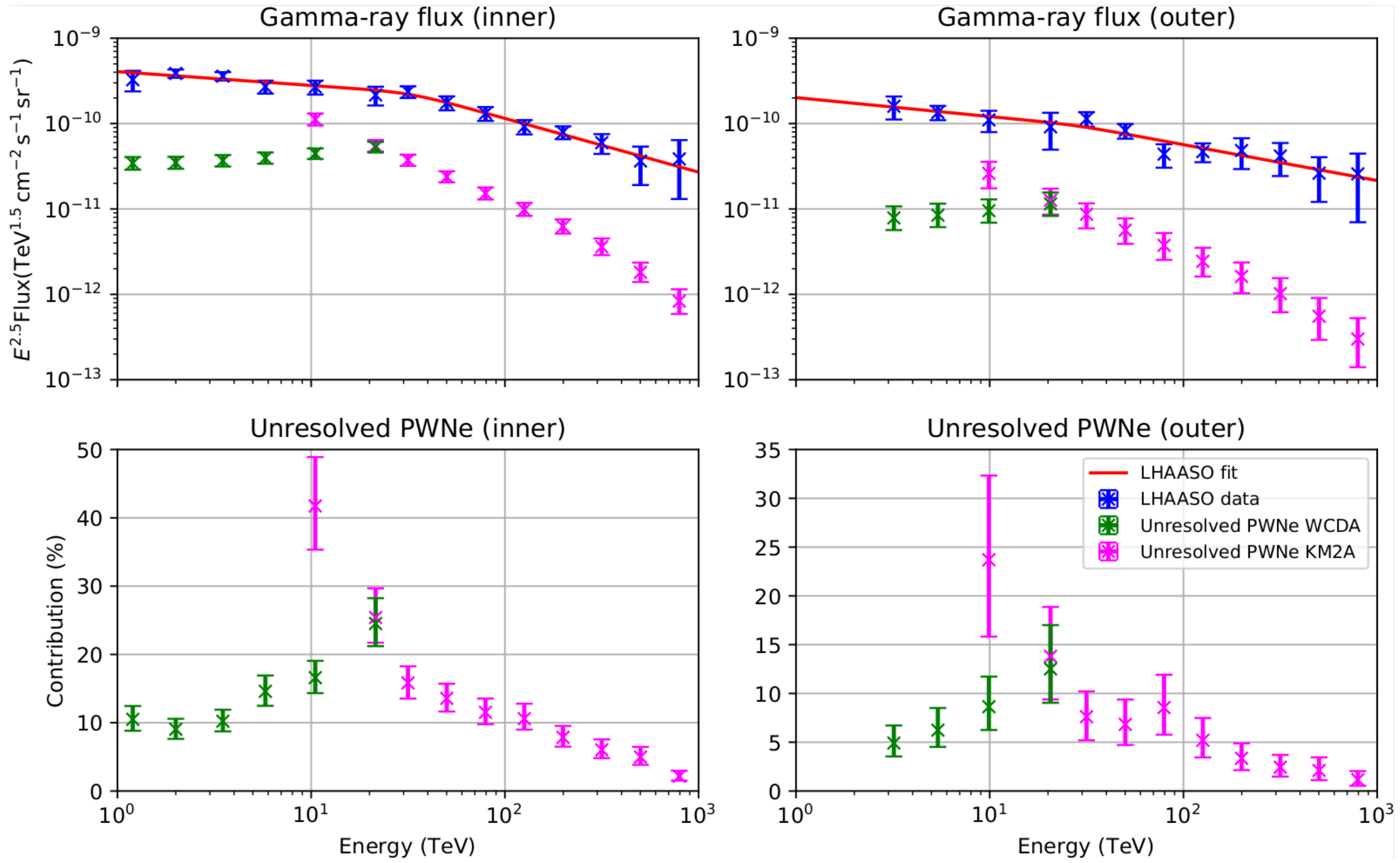

- Run simulations of the entire Galaxy using our best-fit parameters.
- Took into account gamma-ray absorption using the survival probabailities of S. Vernetto & P. Lipari (2016).
- The contribution of PWNe to the diffuse background is mostly negligible.
- It peaks at 30% at most at 25TeV in the inner Galaxy.

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Summary & Conclusion

- There is an apparent tension between the LHAASO observations and the standard 20% beaming fraction.
- This tension disappears if some sources have been mis-associated.
- Many of the unidentified LHAASO sources must be PWNe whose parent pulsar is radio-quiet.
- The contribution of unresolved PWNe to the diffuse background is negligible.
- The more radio quiet pulsars become visible in radio, the more important the tension will become.
- This work has been done completely independently from the 2nd LHAASO catalog. Applying our modeling to the 2nd LHAASO catalog will help to robustly assess its reliability.

谢谢！