Stacking Searches for TeV Halos around Middle-aged and Millisecond Pulsars with HAWC

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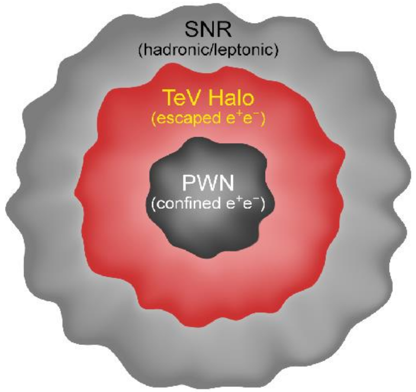
Chicago 2024

2024/8/28

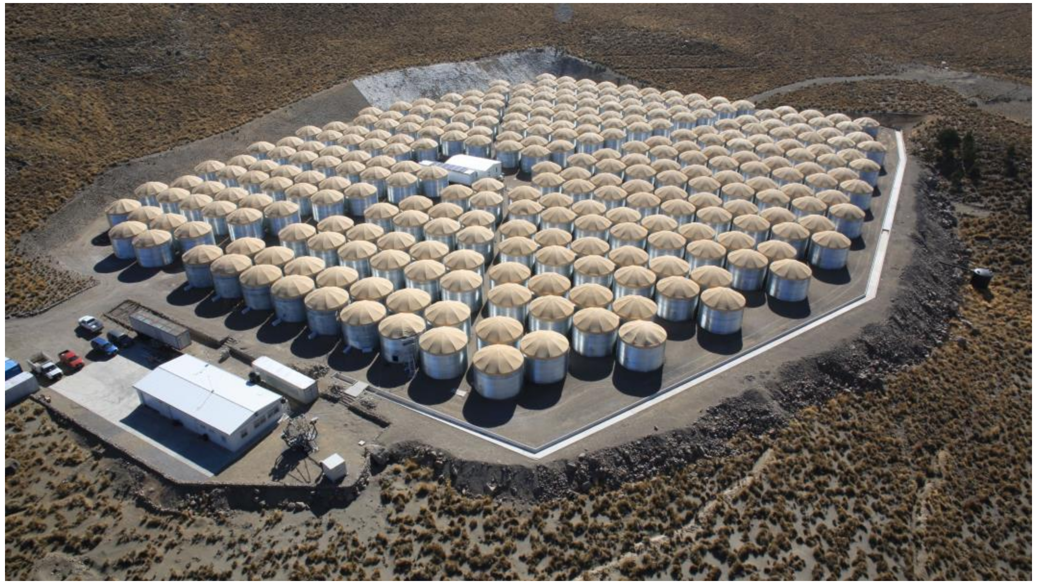
INTRODUCTION

- TeV halos: characterized as extended TeV emission around middle-aged pulsars
  - Formation mechanism unknown
  - Found around Geminga, Monogem, and several other middled-aged pulsars [A. U. Abeysekara *et al.*, Science **358**, 911 (2017), F. Aharonian *et al.*, Phys. Rev. Lett. **126**, 241103 (2021),
  - Existence around millisecond pulsars (MSPs) and links to Galactic center excess proposed [D. Hooper and T. Linden, Physical Review D 105,103013 (2022)]
- We carried out stacking analyses using data from the High Altitude Water Cherenkov (HAWC) gamma-ray observatory on samples of middle-aged pulsars and MSPs.



DATA

- HAWC is an extensive air shower observatory located in Puebla, Mexico. Sensitive to gamma rays with energies between 300 GeV ~ hundreds of TeV.
- For this work, data sets comprised by 2321 and 2565 days of observations is used.
- The data is divided in 5 quarter-decade bins, covering an energy range of 0.3-100 TeV.



METHODOLOGY

- A maximum likelihood technique is used to perform all the analysis.
- Spatial model: Each source is assumed to have a Gaussian morphology with fixed extension, scaling Geminga halo's physical extension by the source's distance.
- Spectral model: Each source is individually fitted to obtain individual likelihood profiles with a power-law:
  - $\frac{dN}{dE} = A_i N \left(\frac{E}{E_{piv}}\right)^{-p}$

where A_i is model-dependent flux factor, N is the normalization flux, E_{piv} is the pivot energy (center of each energy bin) and $p = 2.7$ is the spectral index.

- Then we add the log-likelihood profiles and find the value $\hat{N}$ that optimized the joint likelihoods.
- We define a test statistic (TS) to be $TS \equiv 2 \ln \left[\frac{\mathcal{L}(\hat{N})}{\mathcal{L}(N=0)}\right]$.

MODELS

- Two scenarios are proposed to describe the TeV gamma-ray emission around pulsars:
- $\dot{E}/d^2$ model:

Closer and more energetic pulsars emit more gamma-rays, $A_i \propto \dot{E}/d^2$

- $F_{>100MeV}$ (or G_{100}) model:

Integrated flux between 100 MeV and 100 GeV is correlated to the very-high energy gamma-ray emission $A_i \propto F_{>100MeV}$.

Middle-aged Pulsar Sample

- From: The Third Fermi-LAT pulsar catalog (3PC) and the the Australia Telescope National Facility (ATNF) catalog
- Criteria:

1. Middle age: $P/(2\dot{P}) > 20\ kyr$
2. Not in a binary system
3. Has an associated distance
4. Within HAWC's FoV ($-26^\circ < \delta < 64^\circ$)
5. Detectable: above sensitivity level of HAWC
6. Away from any TeVCat source (except known TeV halos) within a 2° radius

- A total of 86 sources met the criteria
  - 49 gamma-ray
  - 72 radio-loud pulsars, 14 radio-quiet

MSP Sample

- From: 3PC, ATNF Catalog, the West Virginia University catalog (WVU) and the LOFAR Tied-Array All-Sky Survey (LOTAAS)
- Criteria:

1. Millisecond pulsar ($P < 0.03$s)
2. Away from the Galactic plane ($|b| > 3^\circ$)
3. Has an associated distance
4. Within HAWC's FoV ($-26^\circ < \delta < 64^\circ$)
5. Detectable: above sensitivity level of HAWC
6. Away from any TeVCat source (except known TeV halos) within a 2° radius

- A total of 57 sources met the criteria
  - 39 gamma-ray bright
  - 45 radio-loud, 12 radio-quiet

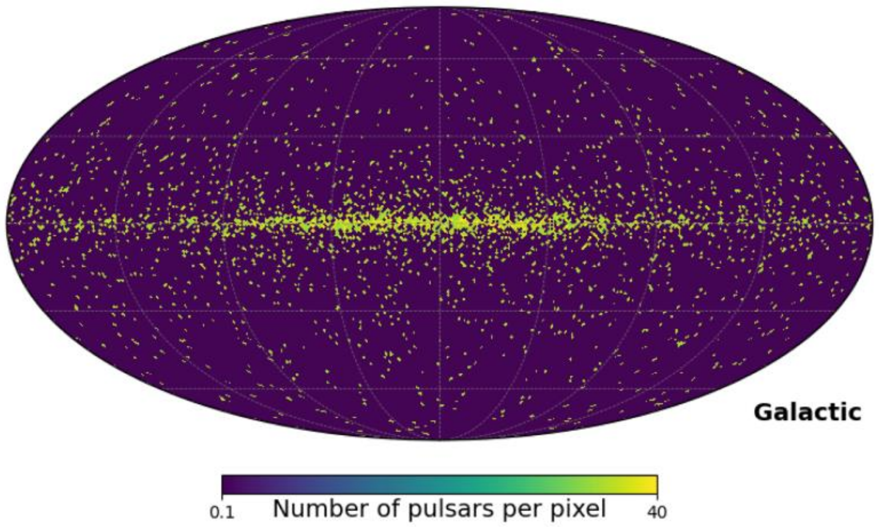
BACKGROUND TS DISTRIBUTION

- To study the background, we perform the analysis at random positions of the sky.
- 10 random locations, treated as fake sources, are stacked in each trial.
- Random points within 2° of TeVCat sources were removed.

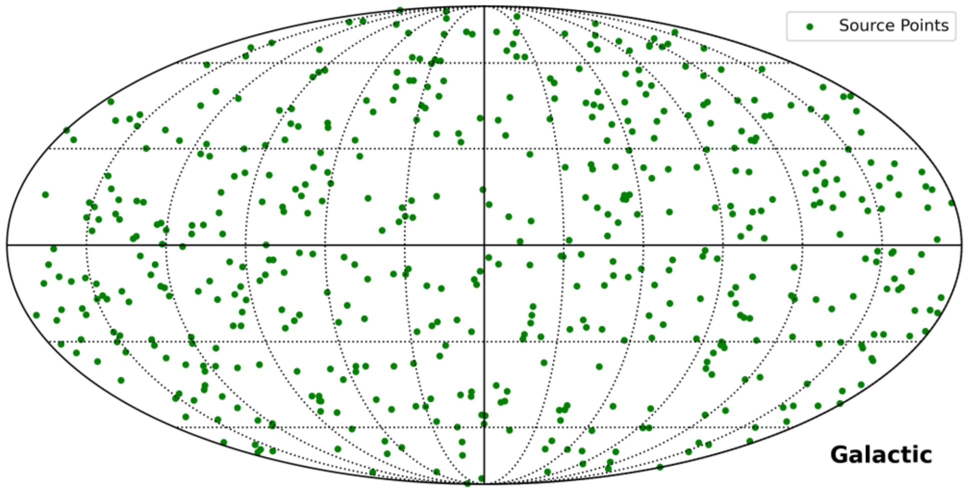
- **Middle-aged pulsars:**
- 109102 trials
- Random locations generated using a density map after normalizing the pulsar flux map
- **MSPs:**
- 11068 trials
- Random locations generated using a uniform distribution

BACKGROUND TS DISTRIBUTION

Middle-aged Pulsar background test distribution

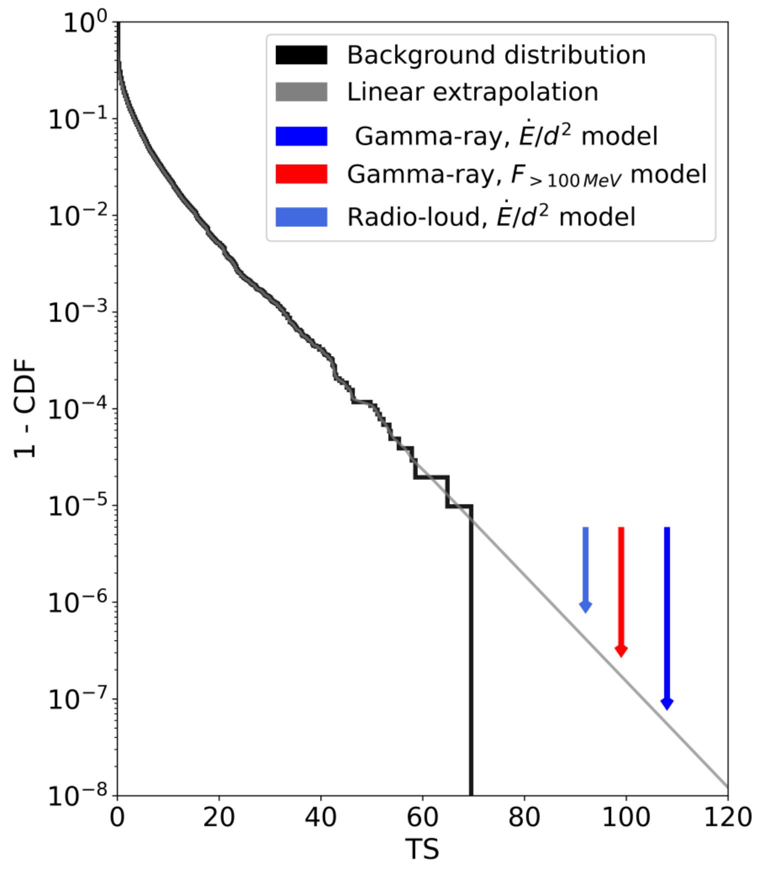


MSP background test distribution



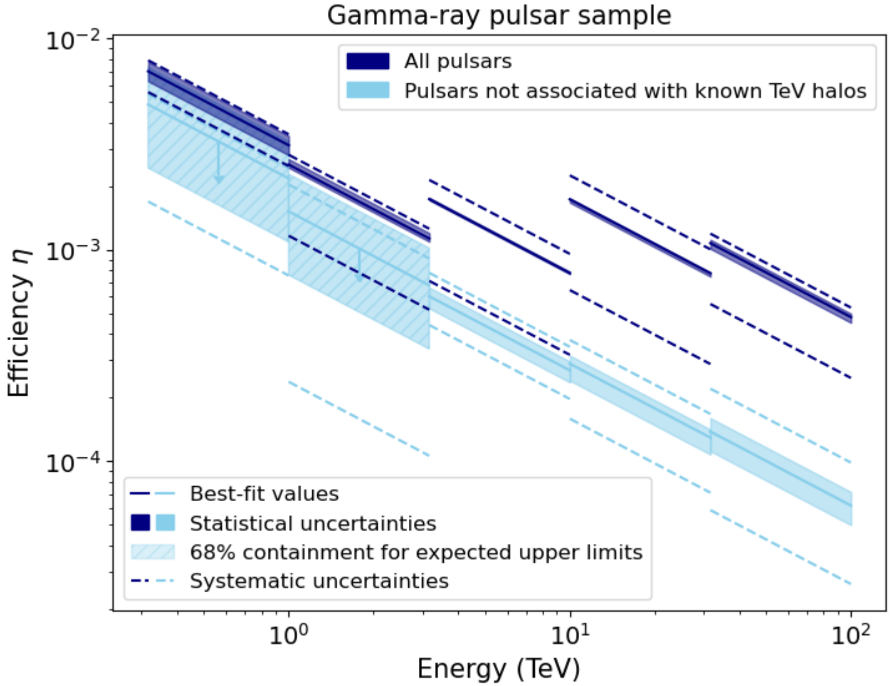
RESULTS: MIDDLE-AGED PULSARS

- When stacking the pulsars not associated with known TeV halos, the highest TS was found for gamma-ray pulsars in the spin-down scenario with TS = 108 corresponding to a post-trial significance of 5.10σ.
- This rejects a null hypothesis, where the excess emission around the middled-aged pulsars is consistent with background fluctuations.



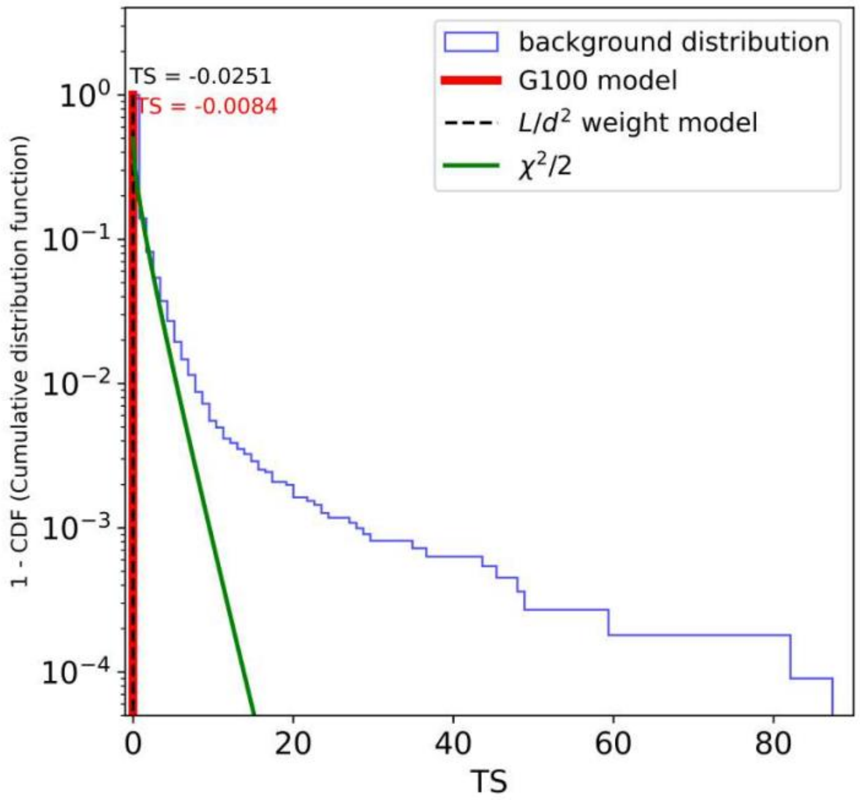
RESULTS: MIDDLE-AGED PULSARS

- On average, the differential energy flux in TeV halos is at the level of $(0.01-1)\%$ of the spin-down power.
- For gamma-ray pulsars, the energy deposited in TeV halos ranges from $(0.1-10)\%$ of that in the GeV emission of the pulsars.



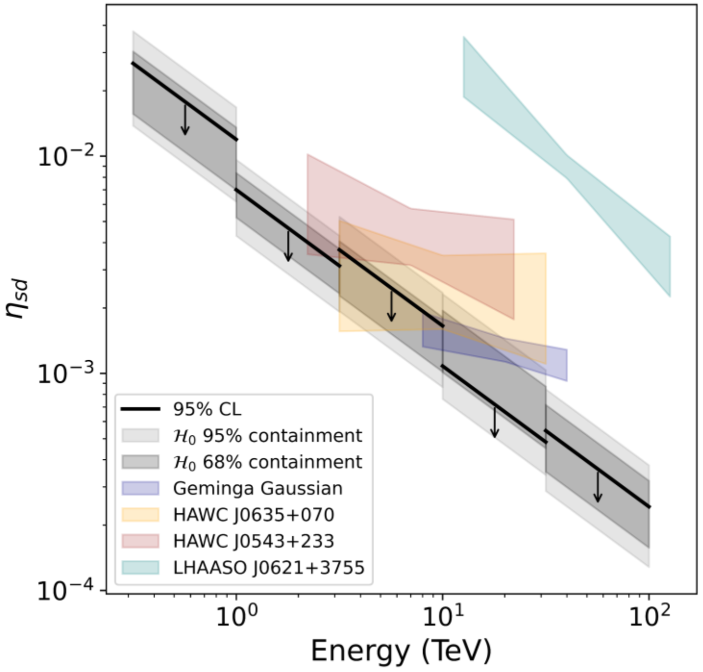
RESULTS: MSPS

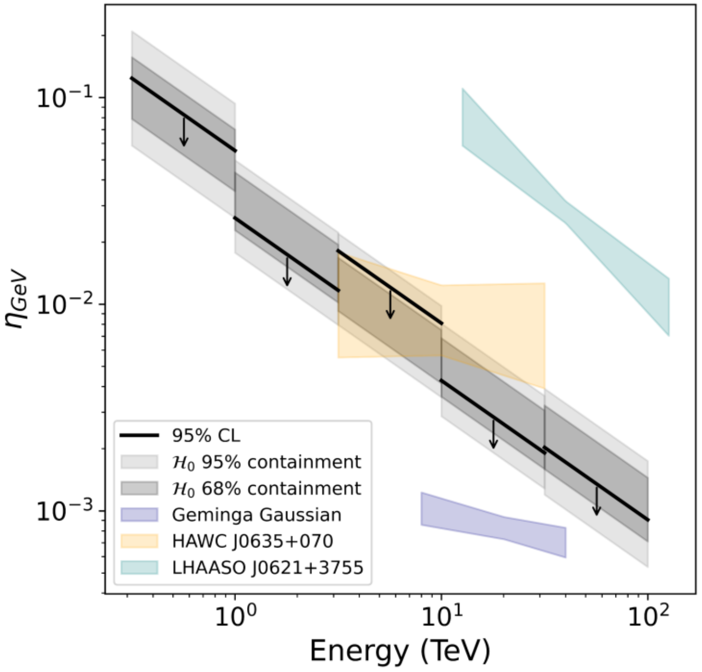
- In all weighting schemes and energy ranges, we find that the stacked TS is consistent with which is expected from background fluctuations.



RESULTS: MSPS

- Our limits suggest that the TeV halo emission efficiency of MSPs is lower than the observed TeV halos, especially for above 10 TeV.





CONCLUSION

- **Middle-aged pulsars:**
- The resulted TS rejects the null hypothesis at the level of 5.10σ.
- Our analysis implies that TeV halos may commonly exist around isolated middle-aged pulsars.
- **MSPs:**
- We find no significant emission at the positions of MSPs.
- The TeV halos of MSPs should not significantly contribute to the Galactic diffuse emission at TeV or higher energies.
- As their TeV halos are not constrained by TeV or radio observations, MSPs remain one of the plausible explanations to the Galactic Center gamma-ray excess.

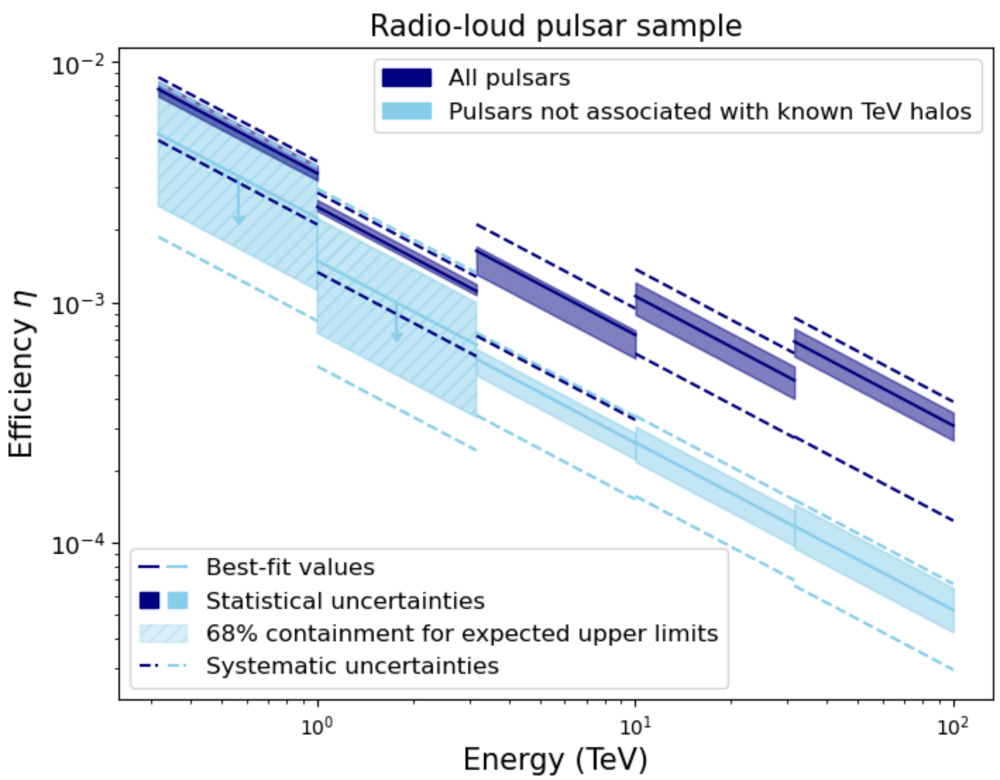
THANK YOU

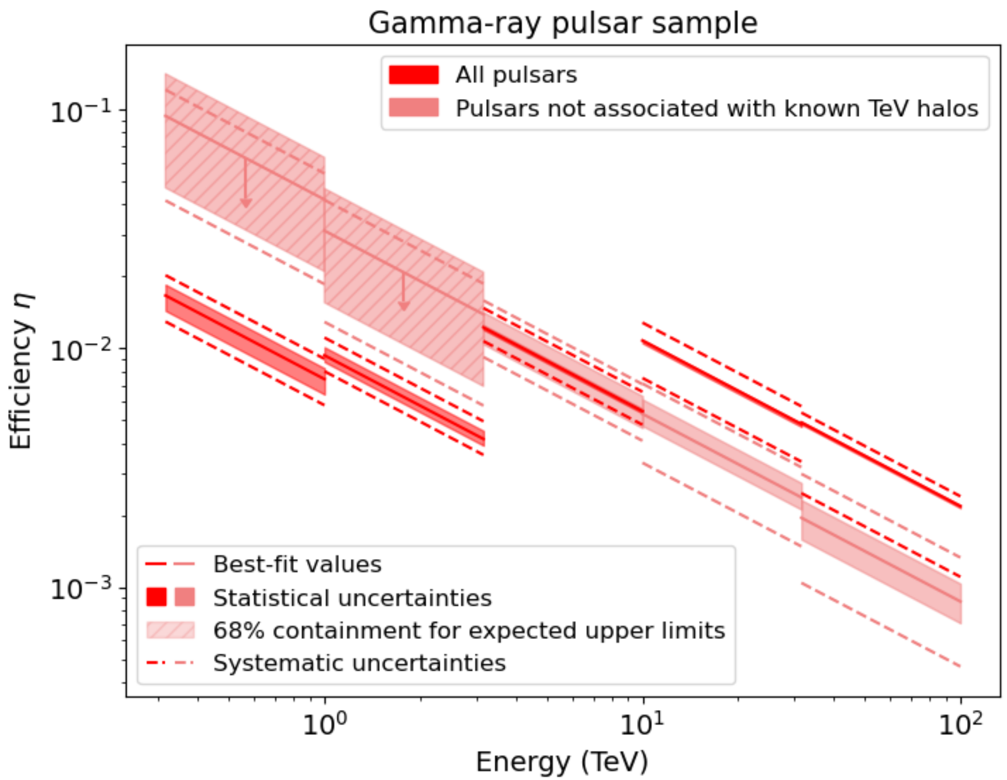
BACK-UP SLIDES

- Total normalization flux is defined as $\mathcal{N} = \sum_{i=1}^{n} \widehat{N} A_i$.
- And the total differential flux of the stacked sample is $\frac{dN}{dE} = \mathcal{N}\left(\frac{E}{E_{piv}}\right)^{-p}$.

- Weighting scheme difference:
- Middle-aged pulsars: $A_i = \dot{E}_i / d_i^2$ and $A_i = F_{>100MeV,i}$
- MSPs: $A_i = \frac{\dot{E}_i/d_i^2}{\sum \dot{E}/d^2}$ and $A_i = \frac{F_{>100MeV,i}}{\sum F_{>100MeV}}$, normalized such that $\sum_{i=1}^{n} A_i = 1$

RESULTS: MIDDLE-AGED PULSARS





The measured efficiency of conversion of spin-down power to gamma-ray power output for the radio-loud sample (left) and GeV power for the gamma-ray sample (right).

SPATIAL DISTRIBUTION OF PULSARS IN THE GALAXY

- From Steppa, C. & Egberts, K (2020), the pulsars distribute in the Galaxy as

$$\rho(r,z) = \left(\frac{r + r_{\mathrm{off}}}{R_\odot + r_{\mathrm{off}}}\right)^{\alpha} \exp\left[-\beta\left(\frac{r - R_\odot}{R_\odot + r_{\mathrm{off}}}\right)\right] \exp\left(-\frac{|z|}{z_0}\right),$$

where r and z are the distance to the Galactic center and height over the Galactic plane, respectively. We take $R_\odot$ = 8.5 kpc, r_{off} = 0.55 kpc, α =1.64, β =4.01, and z_0 = 0.18 kpc.

- ρ does not depend on the azimuthal angle ϕ if we assume an azimuth symmetric distribution.

SPATIAL DISTRIBUTION OF PULSARS IN THE GALAXY

- The pulsar flux in direction of Galactic longitude *l* and latitude *b* with a solid angle $d\Omega = \sin(b)\, db dl$ is:

$$\frac{dF}{d\Omega} = \int_0^\infty ds\, \rho(s, l, b)$$

where *s* is the line of sight.

- To generate random sources following the pulsar distribution:
- 1. Compute a healpy map for every point *(l, b)* in the sky. This describes the probability of seeing a pulsar in a random direction.
- 2. Generate random sources using this probability map and use them for the background test.

Name	RA [°]	Dec [°]	$TS^{1/2}$ (this work)	$TS^{1/2}$ (HL22)
PSRJ0023+0923	5.82	9.39	1.34	1.33
PSRJ0030+0451	7.61	4.86	0.94	2.55
PSRJ0034-0534	8.59	-5.58	1.92	0.10
PSRJ0218+4232	34.53	42.54	1.52	1.56
PSRJ0337+1715	54.43	17.25	1.54	0.25
PSRJ0557+1550	89.38	15.84	-0.15	0.14
PSRJ0605+3757	91.27	37.96	-8.20×10^{-2}	-1.02
PSRJ0613-0200	93.43	-2.01	1.73	6.00×10^{-2}
PSRJ0621+2514	95.30	25.23	-0.10	1.62
PSRJ0751+1807	117.79	18.13	-1.44×10^{-2}	-2.09
PSRJ1023+0038	155.95	0.64	0.83	2.56
PSRJ1231-1411	187.80	-14.20	-4.99×10^{-2}	-2.00×10^{-2}
PSRJ1300+1240	13.00	12.68	-0.14	-0.59
PSRJ1400-1431	210.15	-14.53	0.12	-1.04
PSRJ1622-0315	245.75	-3.26	0.88	-0.51
PSRJ1630+3734	247.65	37.58	1.40	-0.59
PSRJ1643-1224	250.91	-12.42	-4.29×10^{-2}	0.66
PSRJ1710+4923	257.52	49.39	0.66	-0.62
PSRJ1719-1438	259.79	-14.63	-4.61×10^{-2}	-0.56
PSRJ1737-0811	264.45	-8.19	-9.14×10^{-2}	-0.16
PSRJ1741+1351	265.38	13.86	-7.93×10^{-2}	2.64
PSRJ1744-1134	266.12	-11.58	-6.74×10^{-2}	-0.95
PSRJ1745-0952	266.29	-9.88	1.23	-1.97
PSRJ1843-1113	280.92	-11.23	1.76	0.15
PSRJ1911-1114	287.96	-11.24	-6.82×10^{-2}	-2.00×10^{-2}
PSRJ1921+1929	290.35	19.49	3.38×10^{-3}	0.62
PSRJ1939+2134	19.66	21.58	0.83	3.34
PSRJ1959+2048	19.99	20.80	0.95	2.12
PSRJ2017+0603	304.34	6.05	0.13	-0.37
PSRJ2042+0246	310.55	2.77	0.40	-0.67
PSRJ2043+1711	310.84	17.19	-8.46×10^{-3}	-0.72
PSRJ2214+3000	333.66	30.01	1.98	0.33
PSRJ2234+0611	338.60	6.19	-0.11	-0.23
PSRJ2234+0944	338.70	9.74	1.34	0.80
PSRJ2256-1024	344.23	-10.41	1.21	0.45
PSRJ2302+4442	345.70	44.71	-9.28×10^{-2}	-1.00×10^{-2}
PSRJ2339-0533	354.91	-5.55	0.63	-0.35

TABLE I. Hooper/Linden's MSP list. $TS^{1/2}$ in this work is obtained by fitting a point-like source with a power-law spectrum $dN/dE \propto E^{-2.7}$ to the HAWC pass 5.1 data. $TS^{1/2}$ (HL22) is the square root TS obtained from Hooper and Linden [1].

DIFFERENCE WITH HOOPER & LINDEN

- [D. Hooper and T. Linden, Physical Review D 105,103013 (2022)]
  - A total of 37 MSPs selected based on $-20° < \delta < 50°$ and $\dot{E}/d^2 > 5 \times 10^{33}$ erg kpc^{-2} s^{-1}.
  - Among them, four sources are found with $(TS)^{1/2} \geq 2.55$ using the public HAWC software.
- This work:
  - Data from HAWC's fifth pass, with updated reconstructed algorithms to inspect these sources.
  - Gamma-ray emission in the regions is consistent with background fluctuations with more data and better event reconstruction.
  - All sources have $(TS)^{1/2} < 2$.
- The detection in Hooper and Linden is most likely a result of detecting stray galactic plane emission from sources near the galactic plane. In our work, this excess emission is absent due to the exclusion of the Galactic plane during source selection.

CONSISTENCY WITH THE 1LHAASO MSP DETECTION

- LHAASO’s first source catalog detects 11 pulsars older than 100k years
  - This marks the corresponding 1LHAASO sources to possibly be PWNe/TeV halos
- Among which PSR J0218+4232 is a millisecond pulsar
  - Expected to produce VHE emission but with a lack of observation evidence
  - Spatial coincidence between this MSP and 1LHAASOJ0216+4237u is at a confidence level of 2.9σ
  - Favor the existence of VHE emission around MSPs