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Searching for HAWC Counterparts of "Dark" Sources Reported in the 1st LHAASO Source Catalog

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The 1st LHAASO Catalog (1LHAASO)

- The **1st LHAASO Catalog** paper (https://arxiv.org/pdf/2305.17030.pdf)
  - WCDA energy range: 100 GeV - 30 TeV
  - KM2A energy range: 10 TeV - 10 PeV
  - In total, 54 sources are detected with both WCDA & KM2A
    - 43 UHE sources detected at > 4 sigma at E > 100 TeV

The 1st LHAASO Catalog (1LHAASO)

- **32 new** TeV sources (all Galactic)
  - There are **24 (/32) TeV-sources without any known TeV source association**:
    - **8 (/24) TeV-sources have GeV counterparts only,**
      - **HAWC detected 5 of these sources. Our HAWC & Fermi-LAT analysis results are presented at TeVPA 2024. See slides here!**
    - 16 (/24) TeV-sources have pulsar or PWN/SNR associations.
  - **7 (/32) TeV-sources are "dark sources"**: Gamma-ray sources that do not have any associations. These sources have conflicting extensions (with a difference of more than 0.5◦) compared to the known TeV sources within the searching region.
  - One possible extra-galactic source.

Only Fermi-LAT Associated 1LHAASO Sources

#	Target Name	R.A.$_{WCD}$ (°)	Decl.$_{WCD}$ (°)	R.A.$_{KM2}$ (°)	Decl.$_{KM2}$ (°)	TS$_{WCD}$	TS$_{KM2}$	TS$_{100}$	Ext.
1	**J1902+0648**	285.58	6.8	-	-	46.2	-	-	N
2	**J1931+1653**	-	-	292.79	16.90	-	51.8	-	N
3	**J2027+3657**	-	-	306.88	36.95	-	84.6	-	Y
4	**J1858+0330**	284.79	3.70	284.59	3.51	114.5	299.3	-	Y
5	**J1924+1609**	291.09	16.15	290.53	15.71	169.0	68.9	-	Y
6	**J0056+6346u**	13.78	63.96	14.10	63.77	106.1	380.7	94.1	Y
7	**J0500+4454**	75.01	44.92	-	-	43.6	-	-	Y
8	**J2047+4434**	-	-	311.92	44.58	-	62.4	-	Y

Primary Sources (one to one spatial correlation; one point-like source)

Secondary Sources (complex regions; more than one point-like source)

No HAWC detection

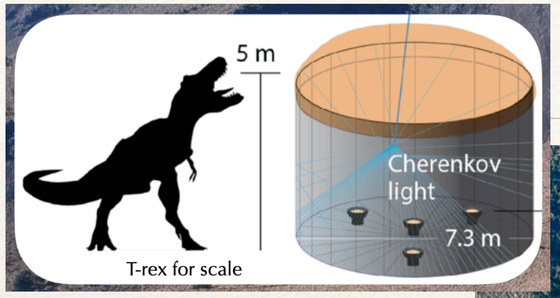
Dark 1LHAASO Sources

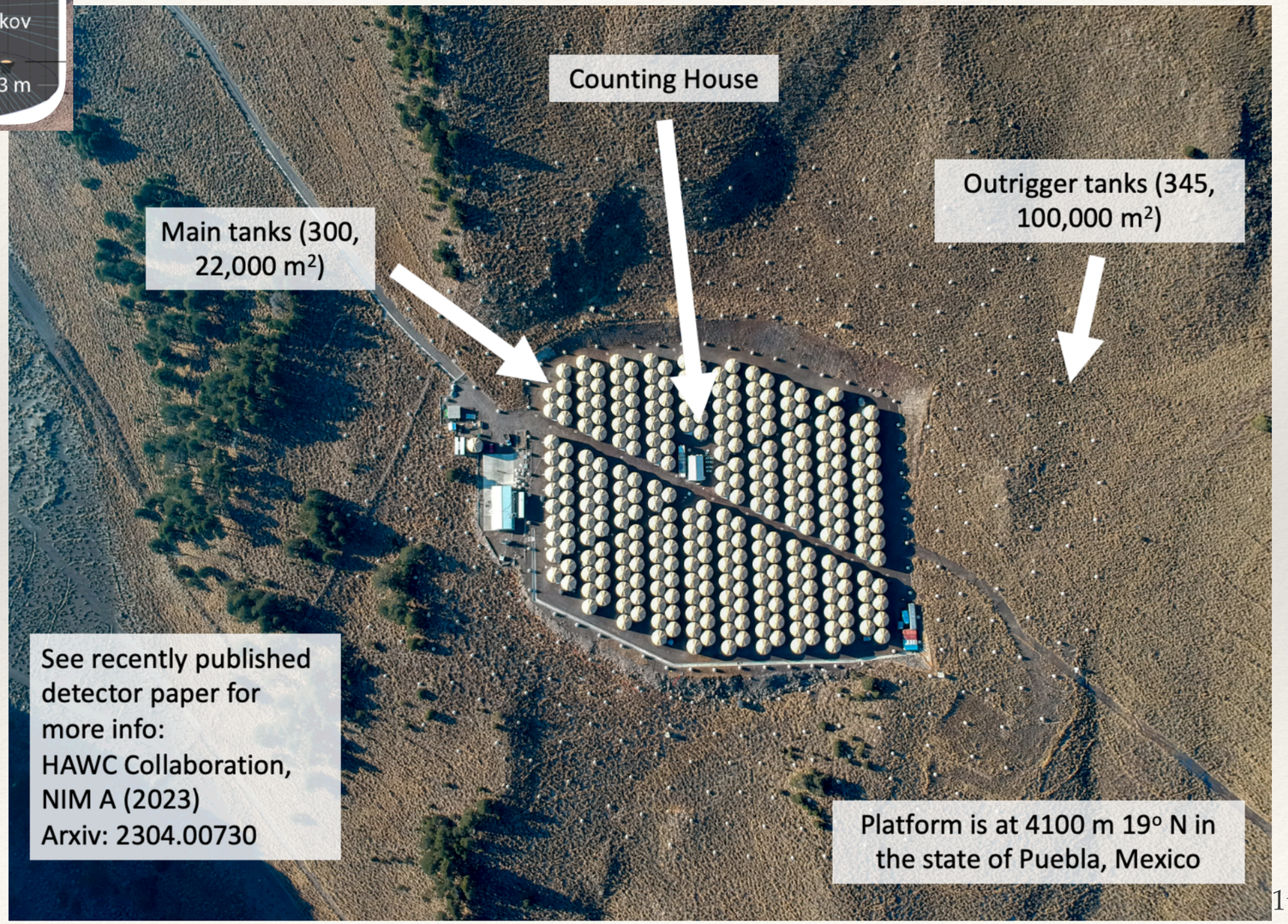
#	Target Name	R.A.$_{WCD}$ (°)	Decl.$_{WCD}$ (°)	R.A.$_{KM2}$ (°)	Decl.$_{KM2}$ (°)	TS$_{WCD}$	TS$_{KM2}$	TS$_{100}$	Ext.
1	**J1937+2128**	294.30	21.00	294.32	21.48	65.6	134.6	-	Y
2	**J2200+5643u**	330.38	56.73	330.08	56.73	75.7	368.6	38.4	Y
3	**J2229+5927u**	337.26	59.45	337.88	59.55	228.0	163.8	31.4	Y
4	**J0007+5659u**	-	-	1.86	57.0	-	86.5	43.6	N
5	**J1959+1129u**	-	-	299.82	11.49	-	94.1	60.8	N
6	**J0212+4254u**	-	-	33.01	42.91	-	38.4	30.2	N
7	**J0206+4302u**	-	-	31.70	43.05	-	96.0	82.8	N

Primary Sources (marginal detection by HAWC)

No HAWC detection
No Fermi-LAT detection

HAWC Observatory



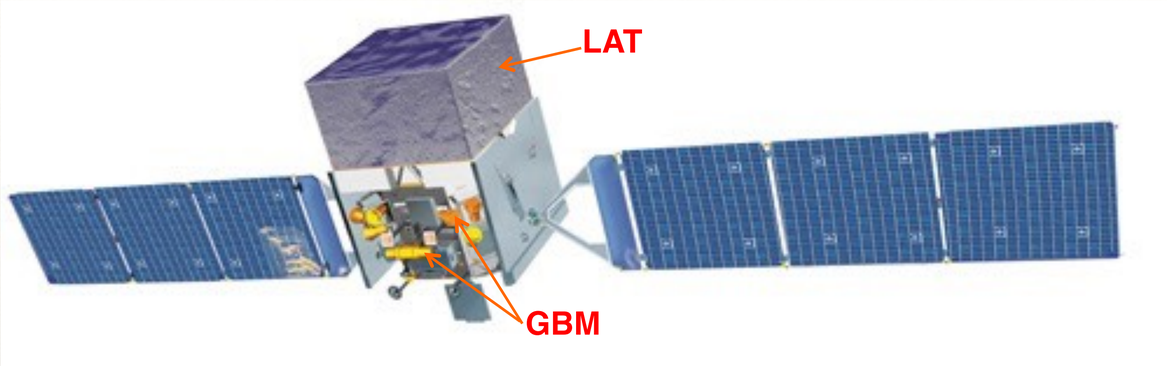


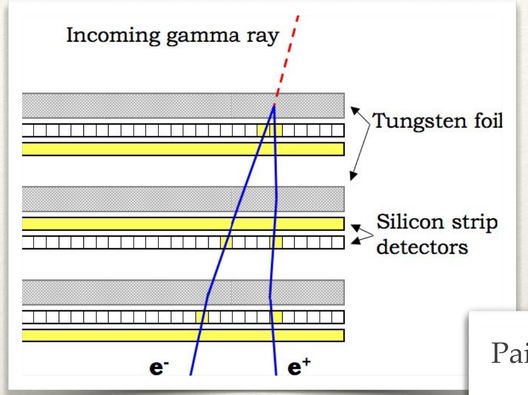
Energy Range (Pass5): from 300 GeV to about several hundred TeV

Main array completed in March 2015

Out-triggers completed in 2018

Fermi Gamma-ray Space Telescope

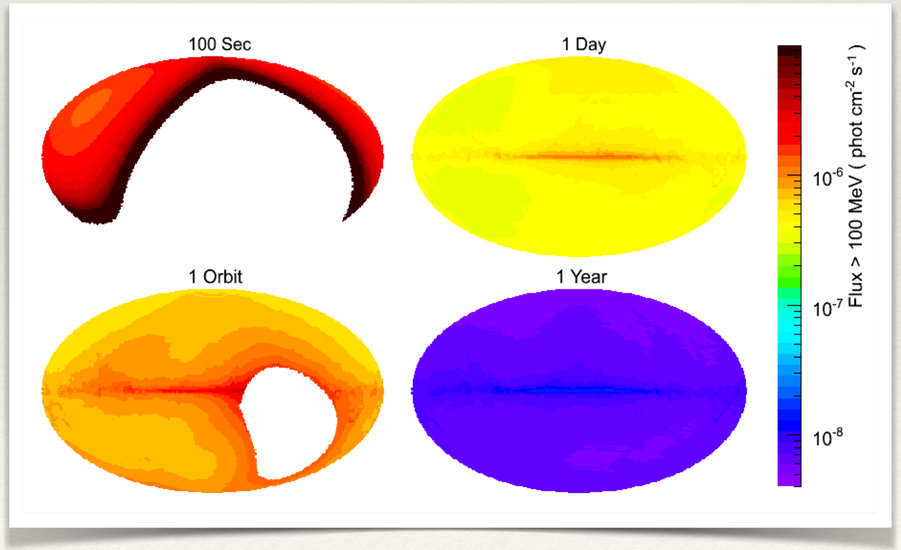




Pair-creation type Detector

- Launched in June 2008
- Two instruments:
  - **Large Area Telescope (LAT)**
    - 20 MeV – 1 TeV
  - **Gamma-ray Burst Monitor (GBM)**
    - 10 keV – 25 MeV

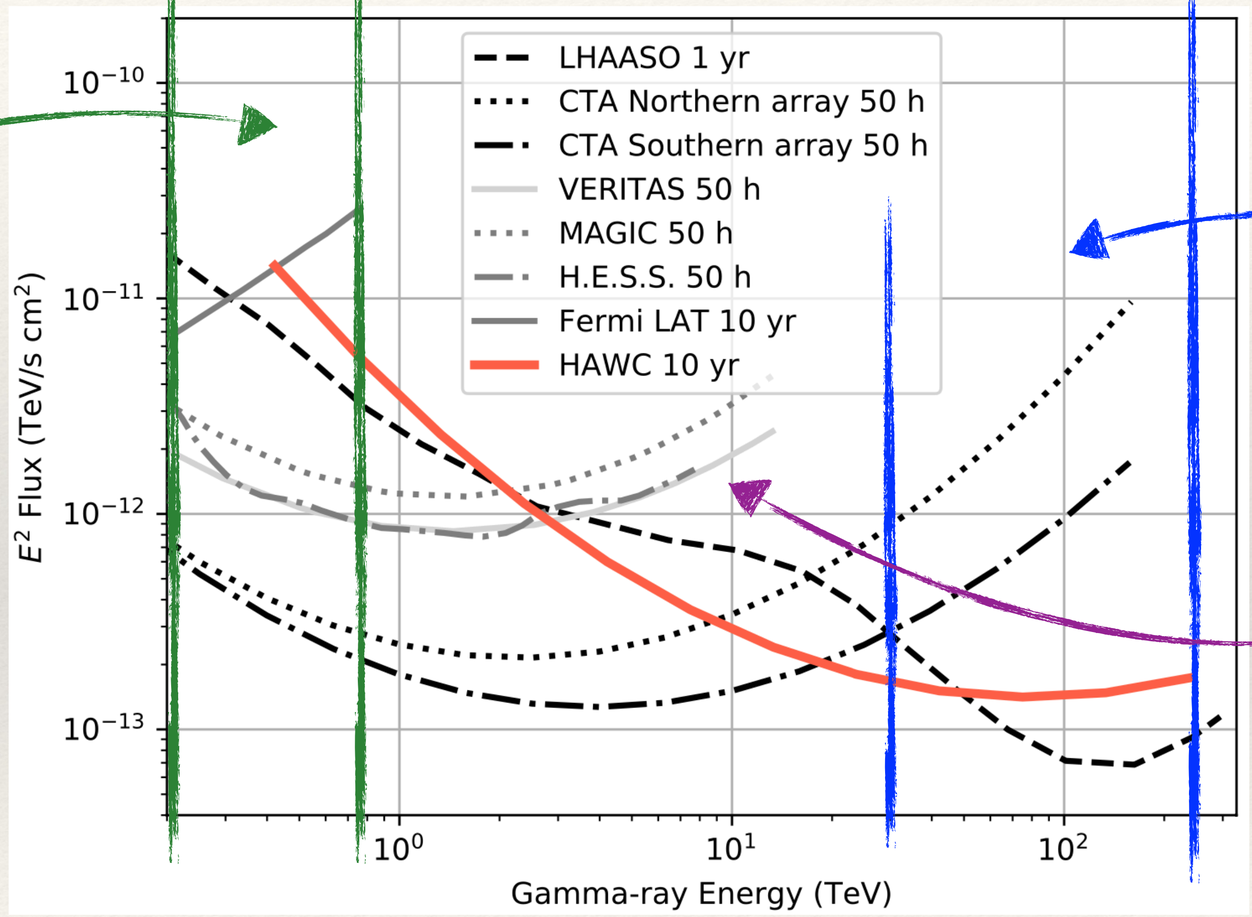
References: Atwood et al. (arXiv:0902.1089)
https://fermi.gsfc.nasa.gov/



Sensitivity to Point Sources

Sensitivity Comparison

HAWC overlaps with Fermi-LAT & LHAASO-WCD



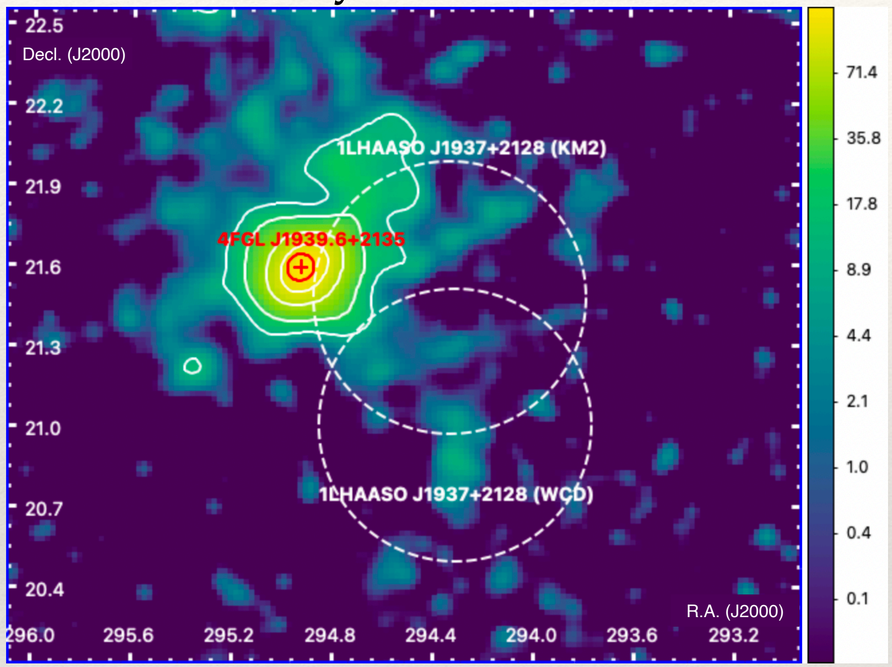
HAWC overlaps with LHAASO-KM2

HAWC overlaps with LHAASO-WCD & LHAASO-KM2

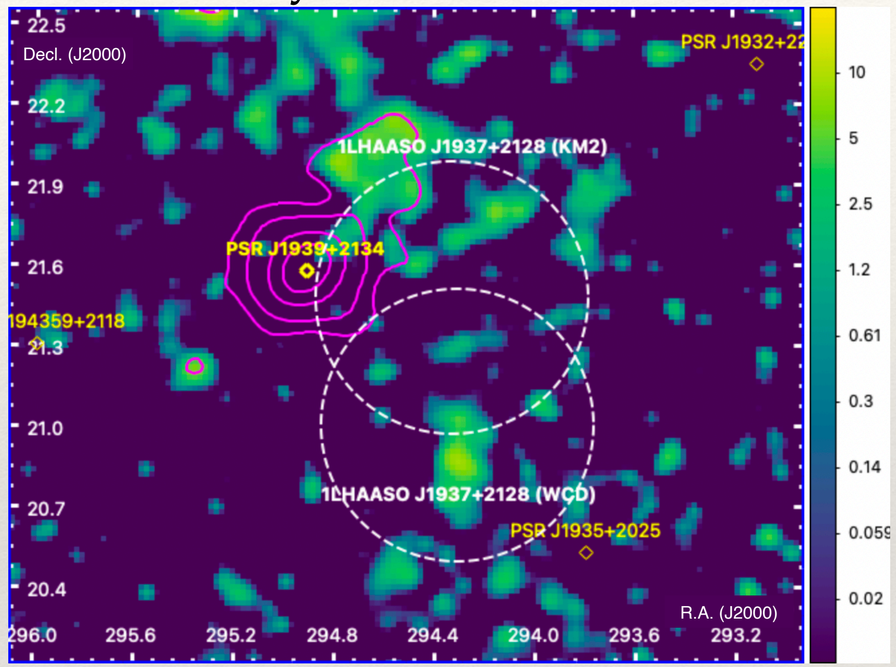
HAWC Performance Paper: A. Albert et al 2024 ApJ 972 144

1LHAASO J1937+2128 (GeV)

Gamma Rays (1 GeV < E < 500 GeV)



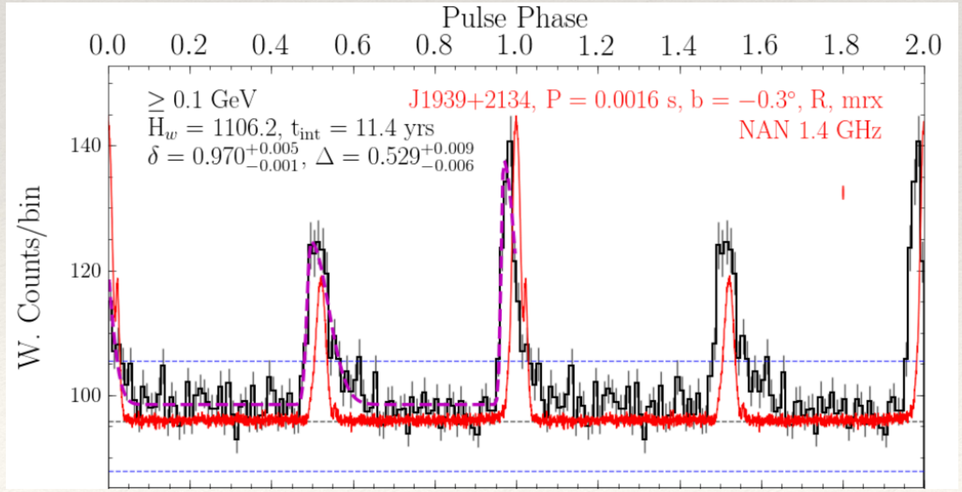
Gamma Rays (1 GeV < E < 500 GeV)

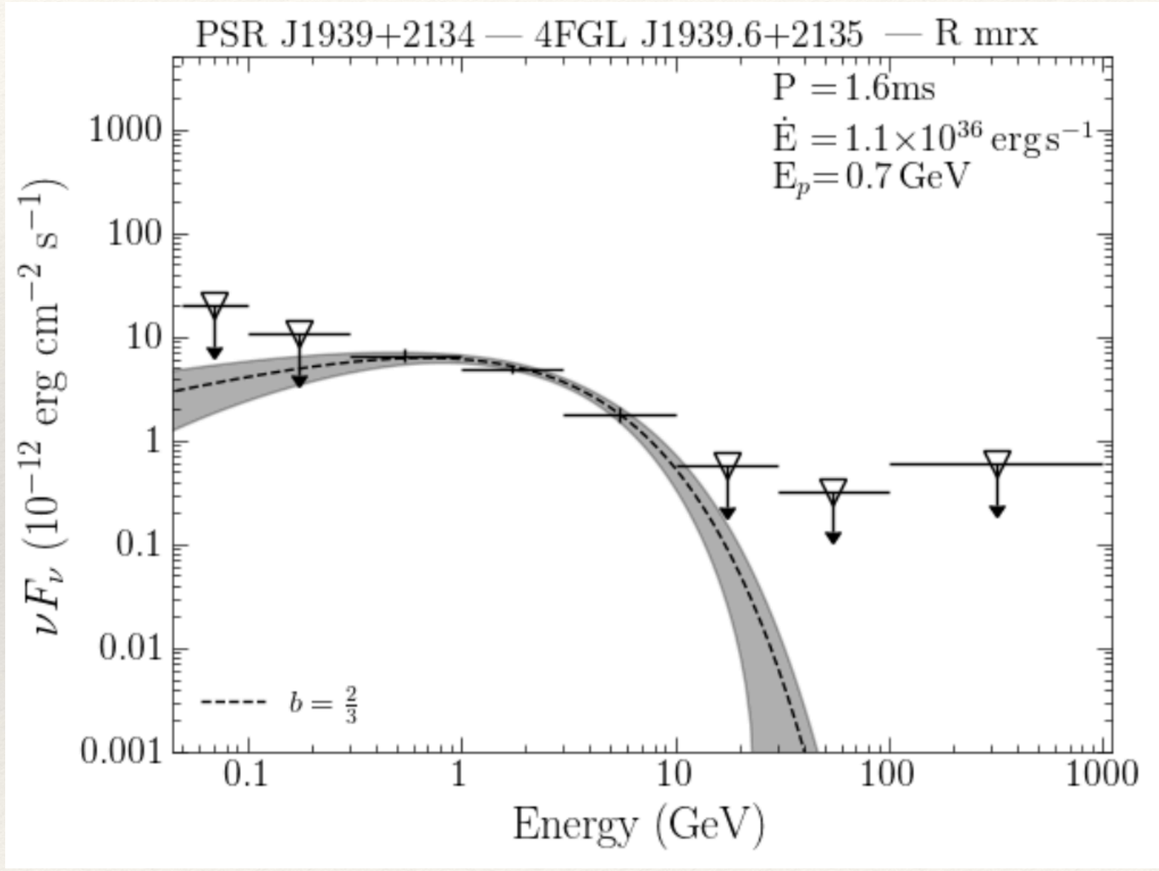


- **Left Panel:** Fermi-LAT TS map (color-bar in log-scale) with white TS contours overlaid (9, 25, 49, 100). The red cross and the ellipse around it represent the position and its error ellipse for 4FGL J1939.6+2135, where this source was excluded from the gamma-ray background emission model to create the map. The white dashed circles show the positional error of KM2 and WCD detection locations for 1LHAASO J1937+2128.
- **Right Panel:** Fermi-LAT TS map (color-bar in log-scale) with magenta TS contours from the map on the left plot overlaid. The yellow diamond and the ellipse around it represent the position and its error ellipse for 4FGL J1939.6+2135, where this source was included into the gamma-ray background emission model to create the map. The yellow diamond shows the millisecond pulsar location that is associated with 4FGL J1939.6+2135.

Gamma-ray from PSR J1939+2134 (B1937+21)

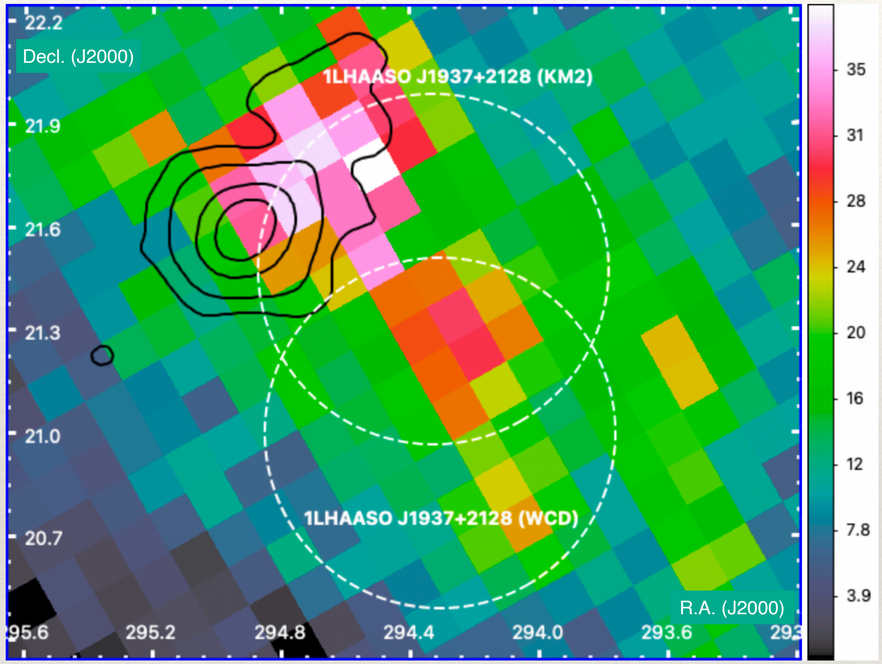
- One of the fastest millisecond pulsars ever discovered
- The Galactic free electron density (NE2001) model places this MSP at **d = 2.5 ± 1.0 kpc** & d > 2 kpc from the spectral analyses of the binary companion at optical wavelengths (van Kerkwijk et al. 2011).
- Detection of pulsed gamma-ray emission: Guillemot, L. et al., ApJ, vol. 744, iss. 1, article id. 33 (2012).
- Phase-aligned in radio and GeV gamma-ray bands



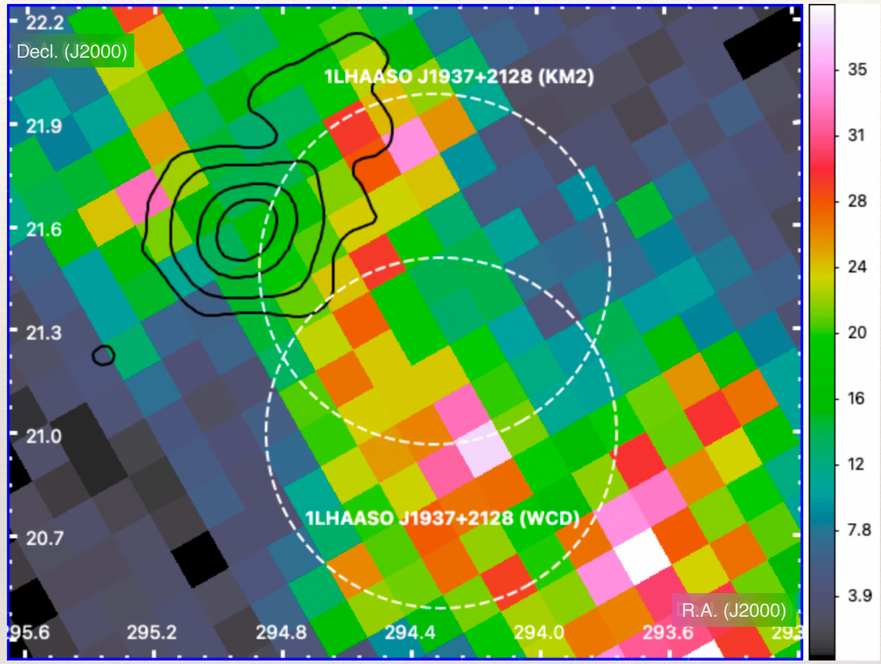


1LHAASO J1937+2128 (CO)

Molecular Clouds for v = [-20, 15] km/s



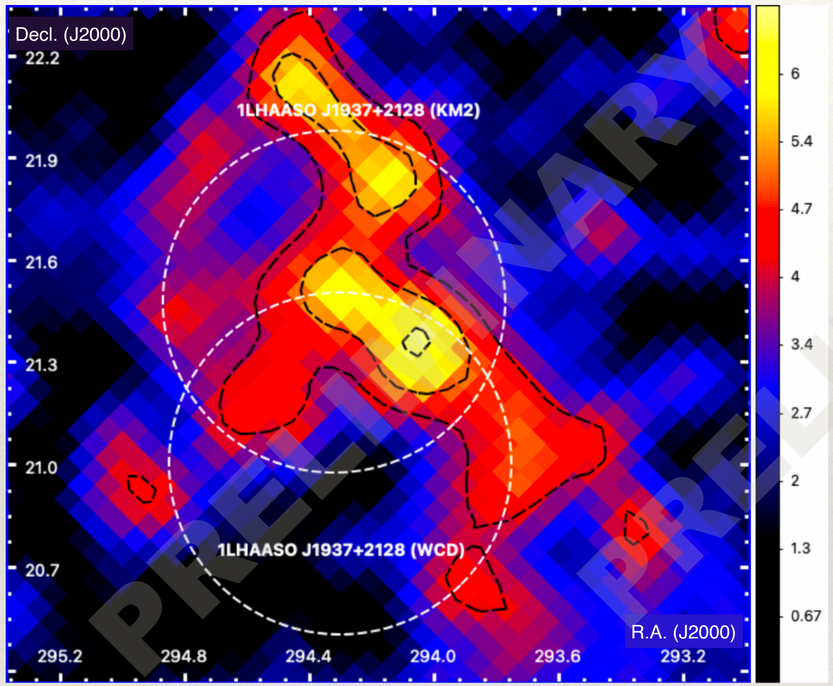
Molecular Clouds for v = [25, 50] km/s



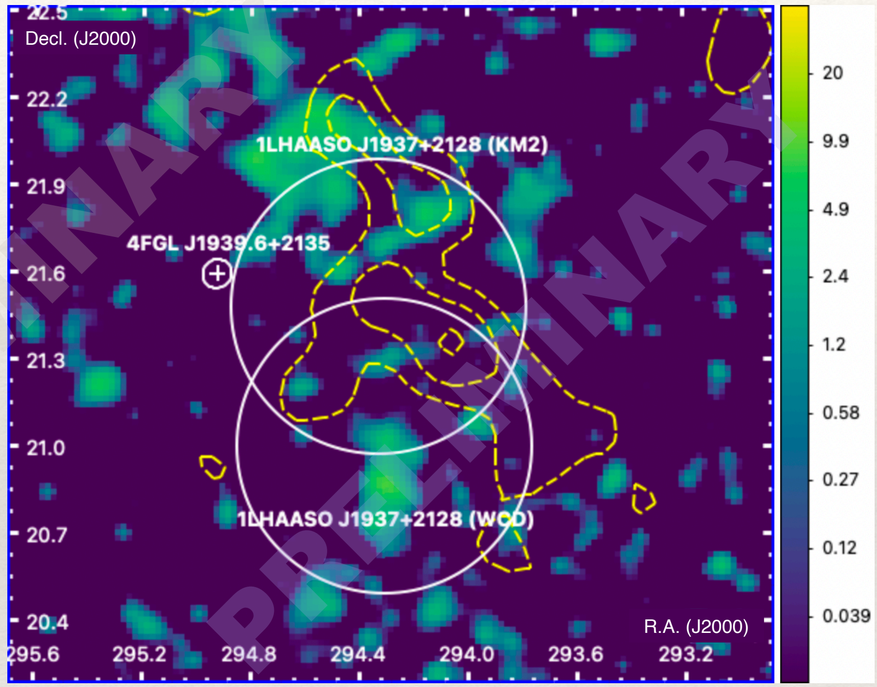
- **Right Panel:** CO intensity map produced in the velocity range of [-20, 15] km/s. The black contours are corresponding to the GeV emission from 4FGL J1939.6+2135 (TS = 9, 25, 49, 100). The positional error ellipses for 1LHAASO J1937+2128 are given in white dashed circles (for the KM2 and WCD detections).
- **Left Panel:** CO intensity map produced in the velocity range of [25, 50] km/s. The black contours are corresponding to the GeV emission from 4FGL J1939.6+2135 (TS = 9, 25, 49, 100). The positional error ellipses for 1LHAASO J1937+2128 are given in white dashed circles (for the KM2 and WCD detections).

1LHAASO J1937+2128 (TeV/GeV)

Gamma Rays (300 GeV < E < 316 TeV)



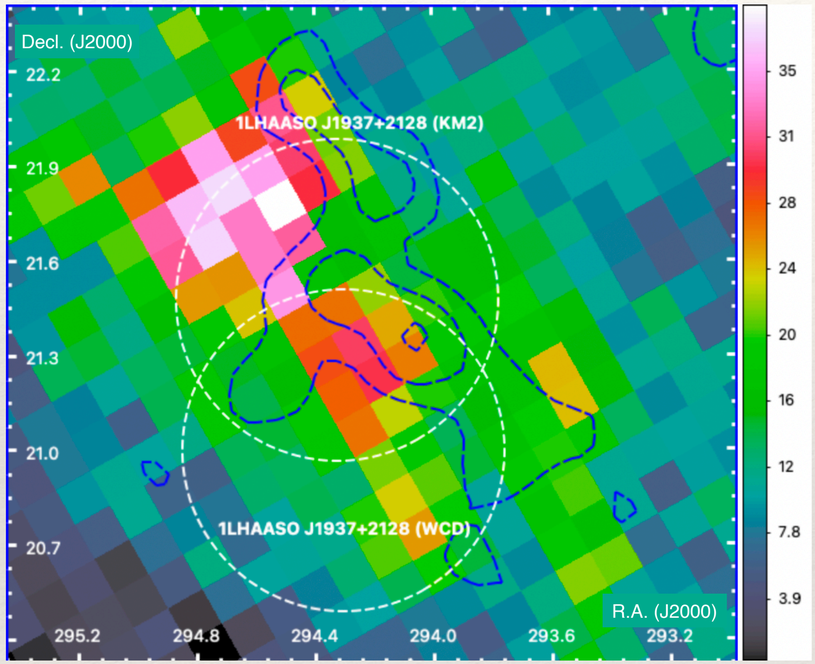
Gamma Rays (1 GeV < E < 500 GeV)



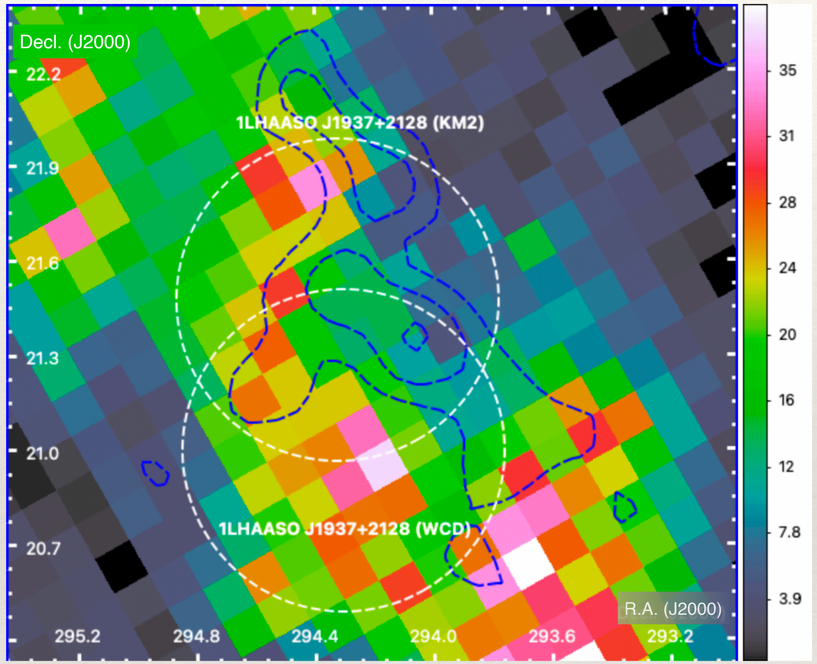
- **Left Panel:** HAWC pre-trial significance map. The color scale shows significance values in the range of [0, 6.49] sigma. The white dashed circles show the positional error of KM2 and WCD detection locations for 1LHAASO J1937+2128.
- **Right Panel:** Fermi-LAT TS map with white dashed HAWC significance contours overlaid (4, 5, 6.1 sigma). The white cross and the ellipse around it represent the position and its error ellipse for 4FGL J1939.6+2135, where this source was included in the gamma-ray background emission model. The white circles show the positional error of KM2 and WCD detection locations for 1LHAASO J1937+2128.

1LHAASO J1937+2128 (CO)

Molecular Clouds for v = [-20, 15] km/s



Molecular Clouds for v = [25, 50] km/s

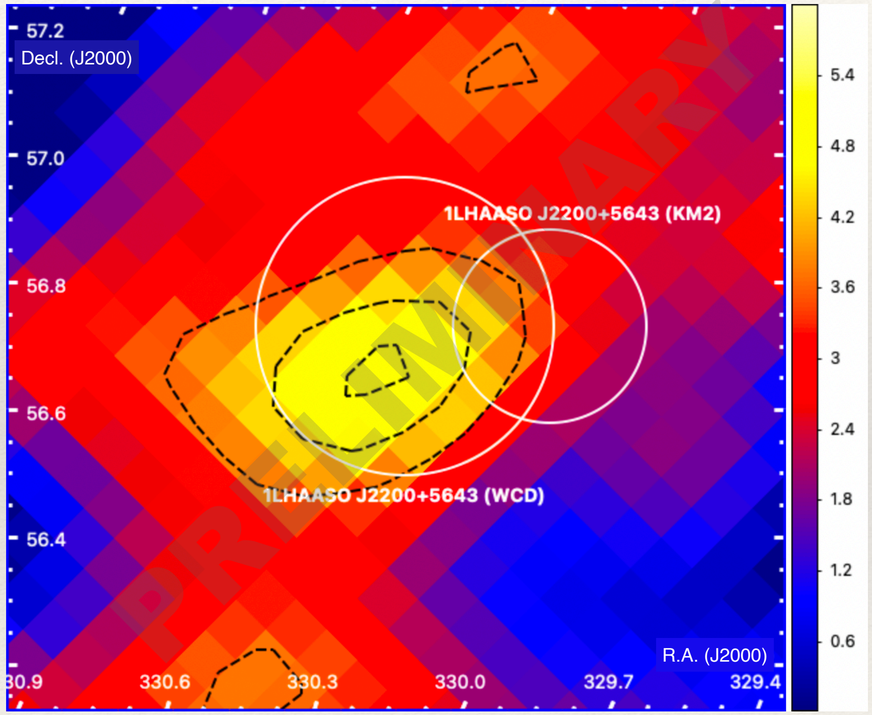


- **Right Panel:** CO intensity map produced in the velocity range of [-20, 15] km/s. The white diamond is the pulsar location that is overlapping with 4FGL J1939.6+2135. The positional error ellipses for 1LHAASO J1937+2128 are given in white and blue colors (for the KM2 and WCD detections, respectively). HAWC significance contours shown in black dashed line are overlaid (4, 5, 6.1 sigma).
- **Left Panel:** Fermi-LAT TS map with white dashed HAWC significance contours overlaid (4, 5, 6.1 sigma). The white cross and the ellipse around it represent the position and its error ellipse for 4FGL J1939.6+2135, where this source was included in the gamma-ray background emission model. The white and cyan circles show the positional error of KM2 and WCD detection locations for 1LHAASO J1937+2128.

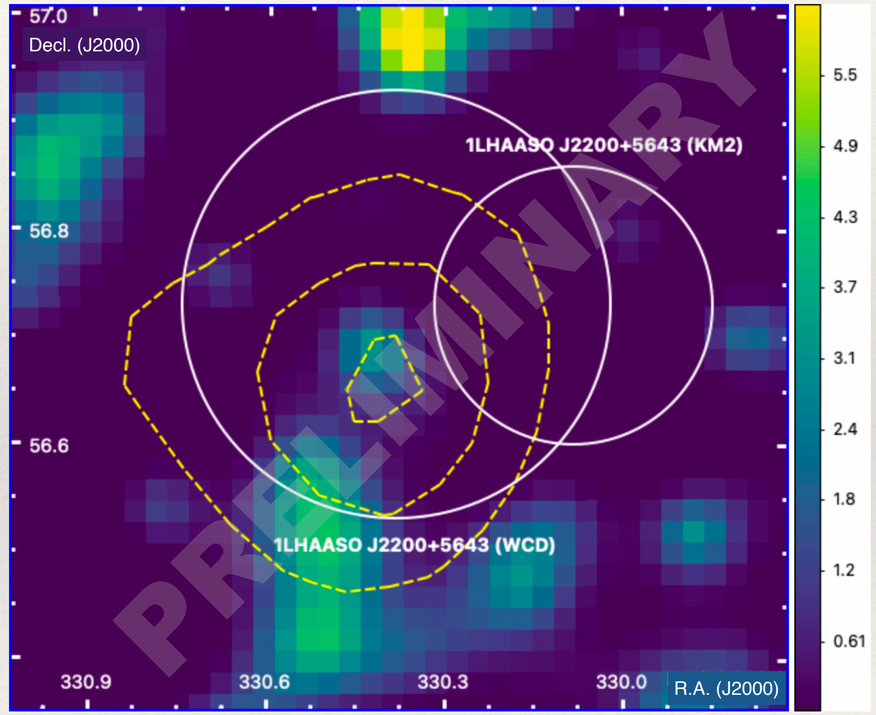
1LHAASO J2200+5643u (TeV/GeV)

- LHAASO KM2 and WDC positional error ellipses of 1LHAASO J2200+5643u are shown by white circles on both plots.
- **Left Panel:** HAWC significance map. Black dashed lines show the HAWC significance contour levels of 3.6, 4.5, 5.1 sigma.
- **Right Panel:** Fermi-LAT TS map (color-bar in log-scale). The HAWC significance contours are overlaid as yellow dashed lines.

Gamma Rays (300 GeV < E < 316 TeV)



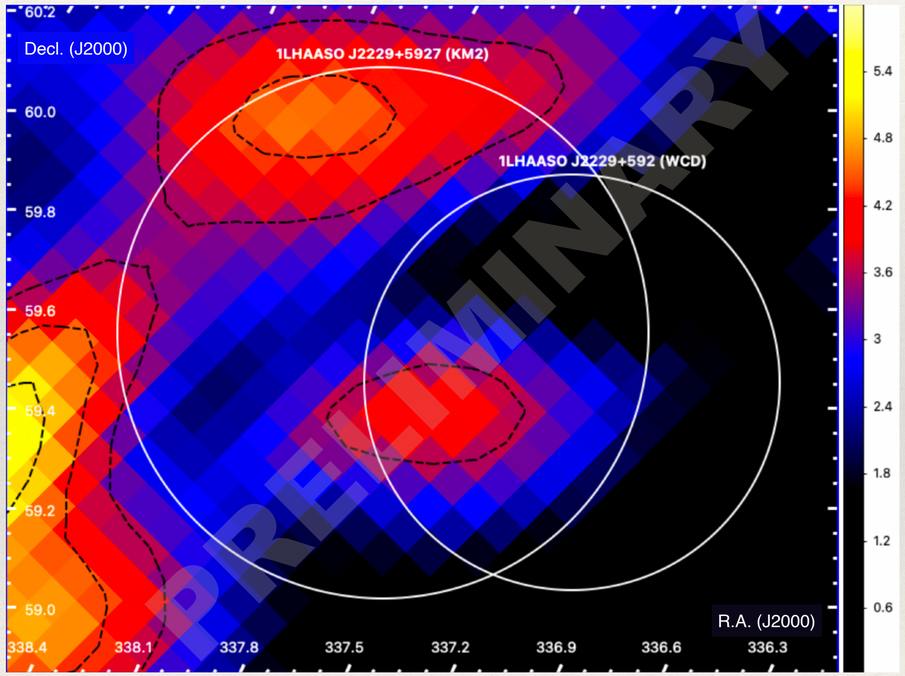
Gamma Rays (1 GeV < E < 300 GeV)



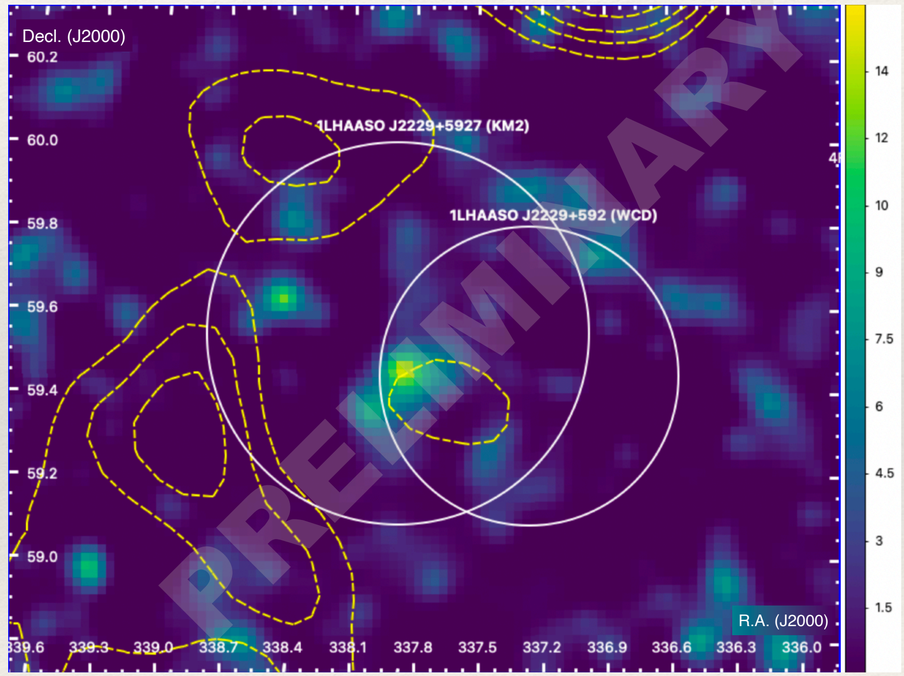
1LHAASO J2229+5927u (TeV/GeV)

- LHAASO KM2 and WCD positional error ellipses of 1LHAASO J2229+5927u are shown by white circles on both plots.
- **Left Panel:** HAWC significance map. Black dashed lines show the HAWC significance contour levels of 3.5, 4.3, 5 sigma.
- **Right Panel:** Fermi-LAT TS map (color-bar in log-scale). The HAWC significance contours are overlaid as yellow dashed lines.

Gamma Rays (300 GeV < E < 316 TeV)



Gamma Rays (1 GeV < E < 300 GeV)



Conclusion

- In the 1st LHAASO source catalog (1LHAASO), seven TeV sources were reported to be without having any known counterparts in other wavebands, i.e. are “dark” sources.
- **Preliminary HAWC analysis reveals detection (pre-trail significances ~ 5-6 sigma) of three out of seven 1LHAASO dark sources (1LHAASO J1937+2128, 1LHAASO J2200+5643u, 1LHAASO J2229+5927u)**.
- We also analyzed data taken by Fermi-LAT over the last 16 years including 1LHAASO positional error ellipses of KM2 and WDC detections. We compared resulting GeV morphologies with HAWC significance distributions.
  - We found **no significant GeV gamma-ray emission overlapping with the three 1LHAASO sources detected by HAWC, except 1LHAASO J1937+2128.**
    - **However, Fermi-LAT detected source location, associated with a millisecond pulsar, doesn’t overlap with HAWC significance contours.**
- The analysis of the HAWC sources and the search for multi-wavelength associated sources are ongoing!

Backup Slides

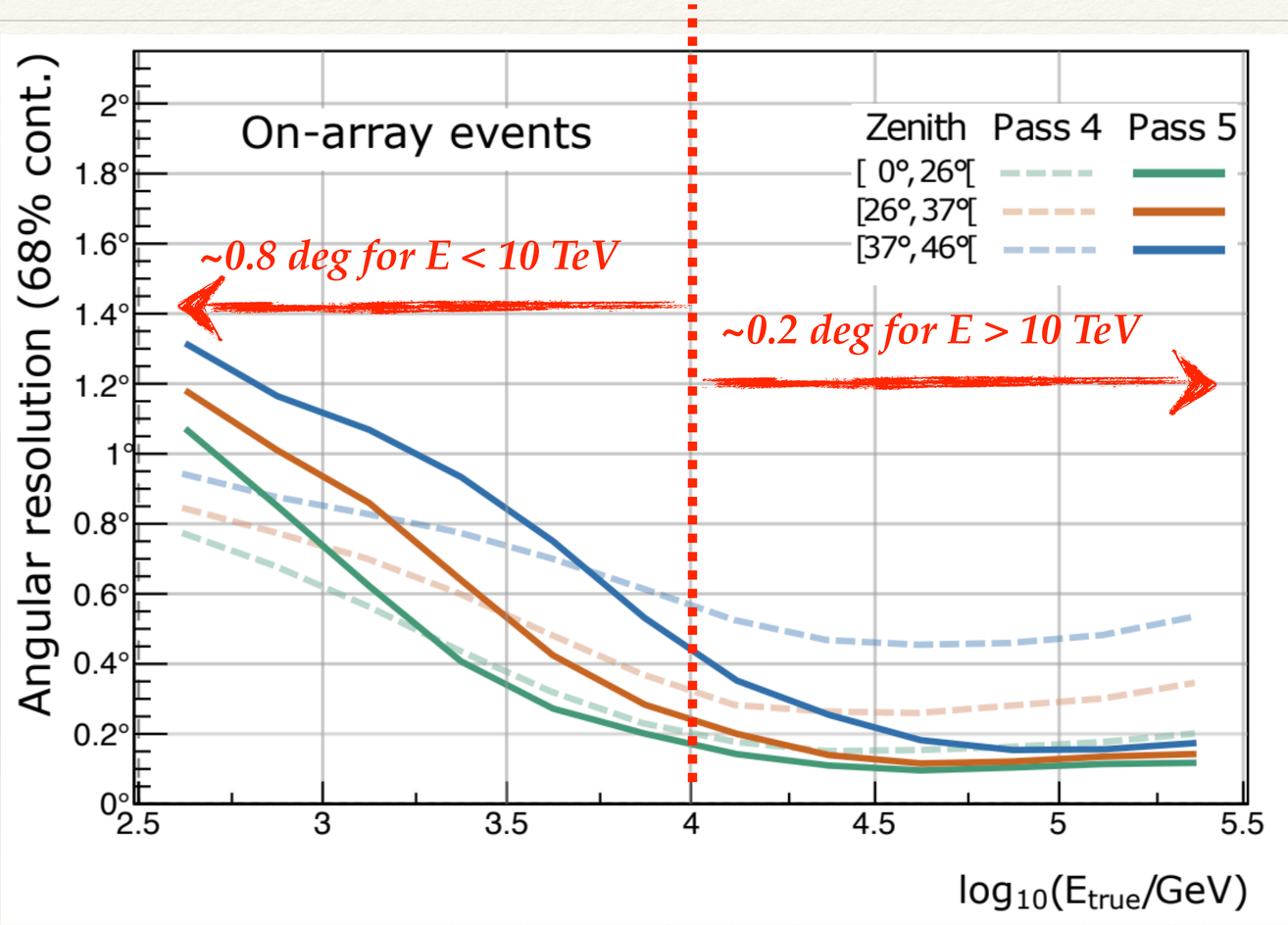
Fermi Analysis Details

- Data Set: 2008 - 2024 (16 years)
- Event class: 128, event type: 3
- Energy range: 1- 500 GeV
- Max zenith angle: 90 deg
- ROI width: 10 deg
- IRFs: P8R3_SOURCE_V3
- Background sources:
  - Fermi 14-year source (4FGL-DR4) catalog point-like & extended sources
  - Galactic diffuse emission template: gll_iem_v07.fits
  - Isotropic emission template iso_P8R3_SOURCE_V3_v1.txt

HAWC Analysis Details

- Data Set: 2015 - 2023 (9 years)
- Maps are produced using the fHit method.

HAWC Angular Resolution

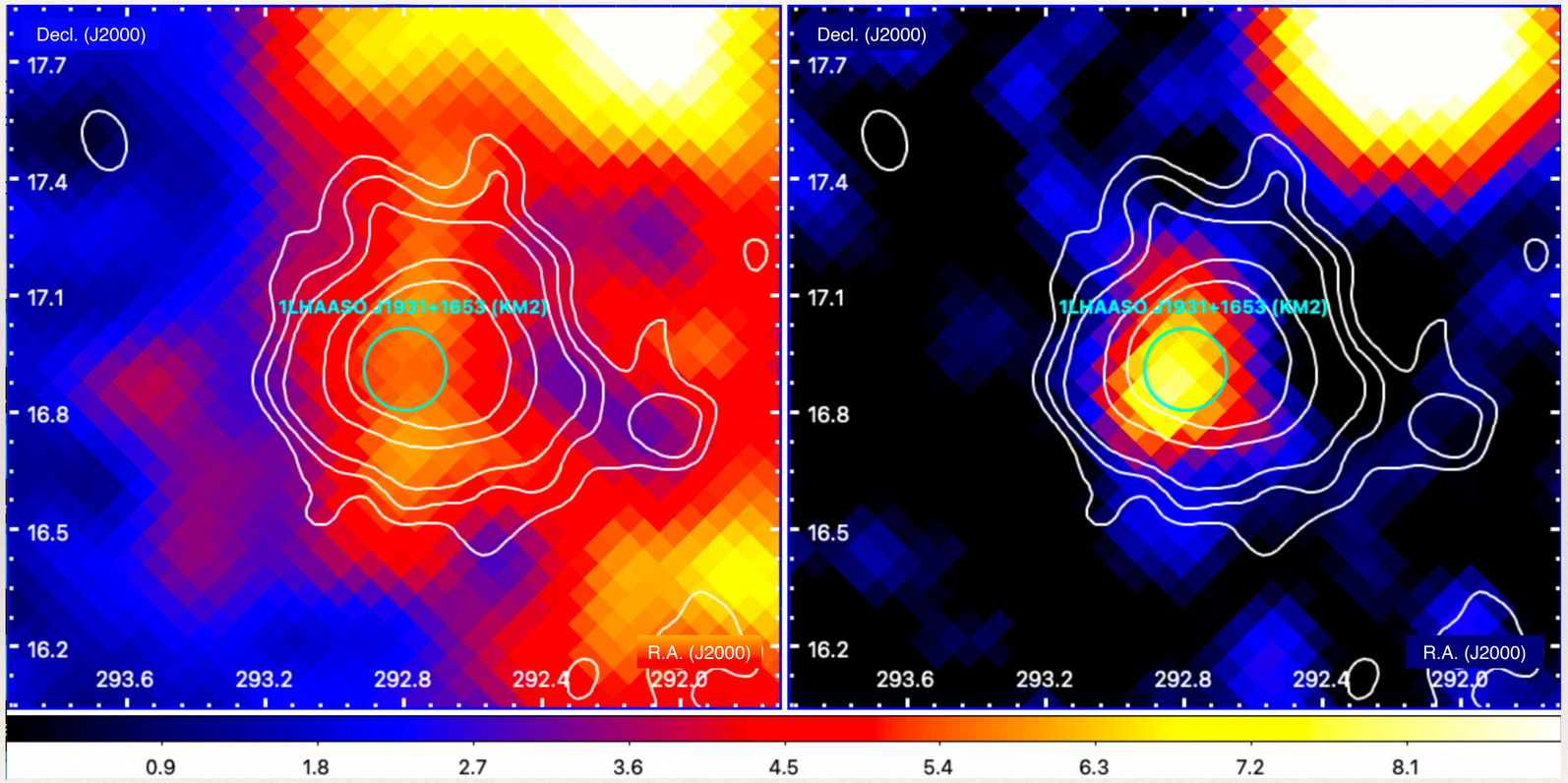


HAWC Performance Paper: A. Albert et al 2024 ApJ 972 144

HAWC Angular Resolution

TeV Gamma Rays (E < 10 TeV) **TeV Gamma Rays (E > 10 TeV)**

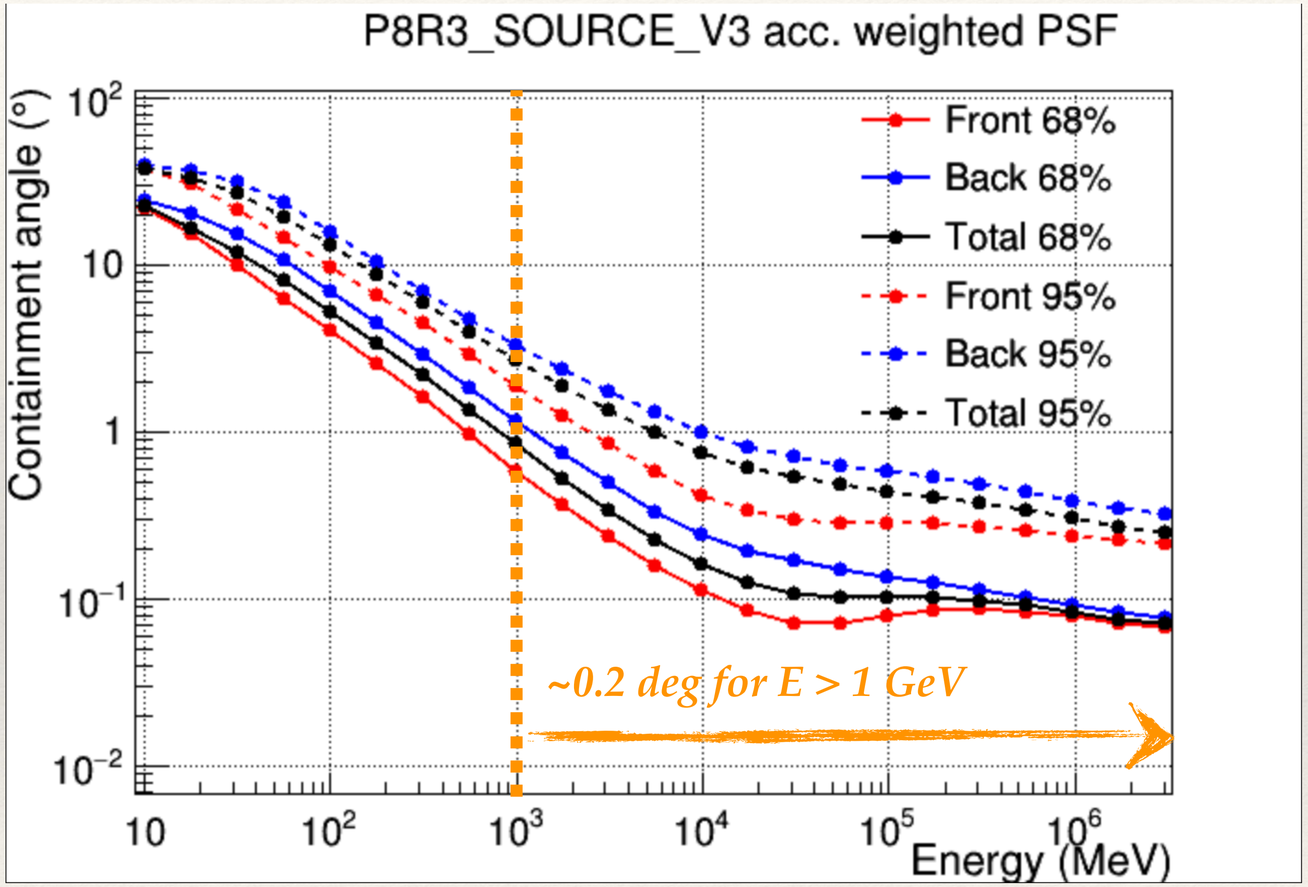
~0.8 deg for E < 10 TeV



~0.4 deg for E > 10 TeV

1LHAASO J1931+1653 (4FGL J1931.1+1656)

Fermi-LAT Angular Resolution



Fermi-LAT Angular Resolution