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Analysis Results of HAWC Data Corresponding to LHAASO Catalog Sources Exclusively Linked to Fermi-LAT Sources

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Contents

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,**
    - 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.
    - **Our analysis results of Fermi-LAT & HAWC data on these sources will be presented at the 11th Fermi Symposium, College Park MD, in September 2024.**
  - One possible extra-galactic source.

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

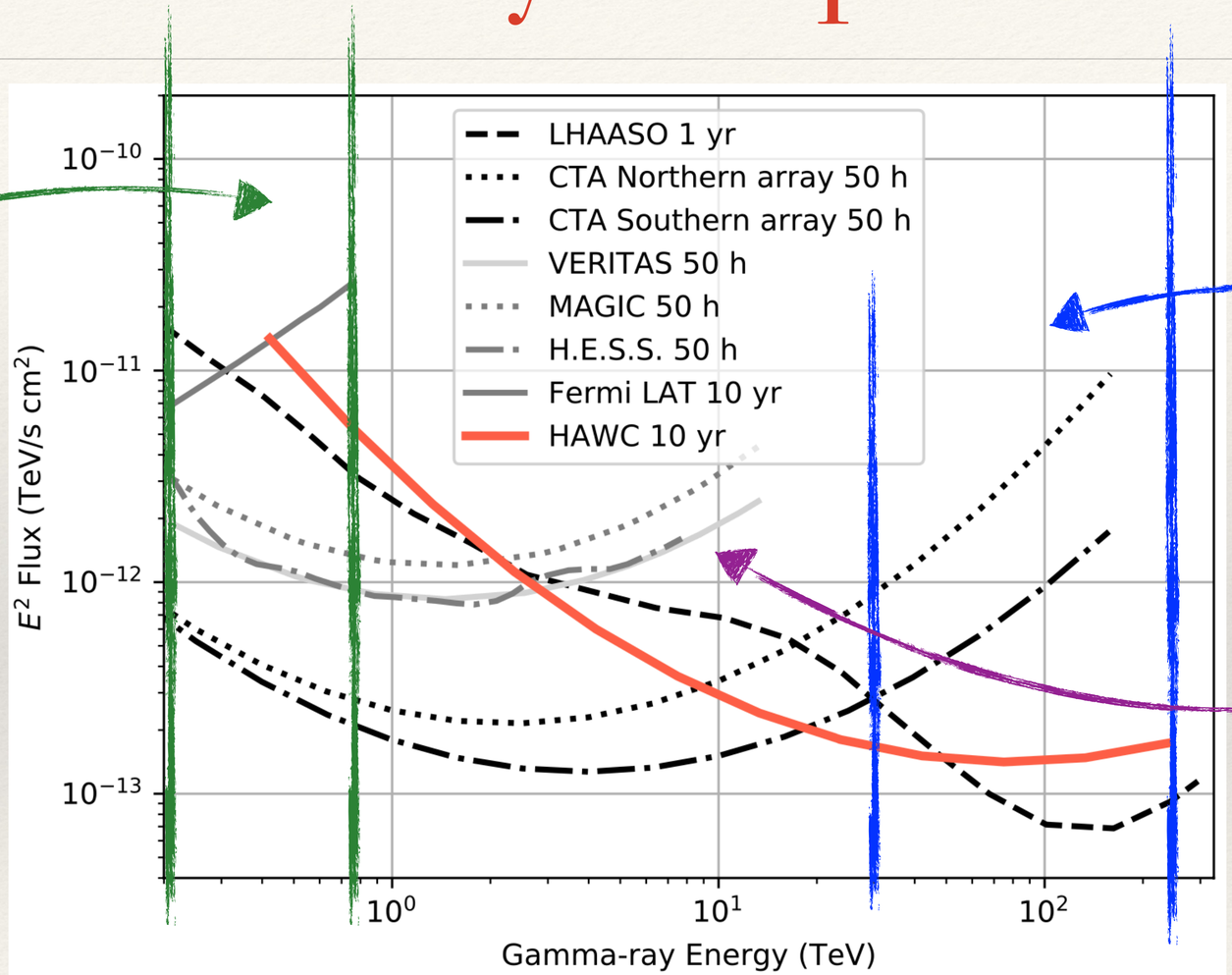
Primary Sources (one to one spatial correlation; one point-like source)

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

No HAWC detection

Sensitivity Comparison

HAWC overlaps with Fermi-LAT & LHAASO-WCD



HAWC overlaps with LHAASO-KM2

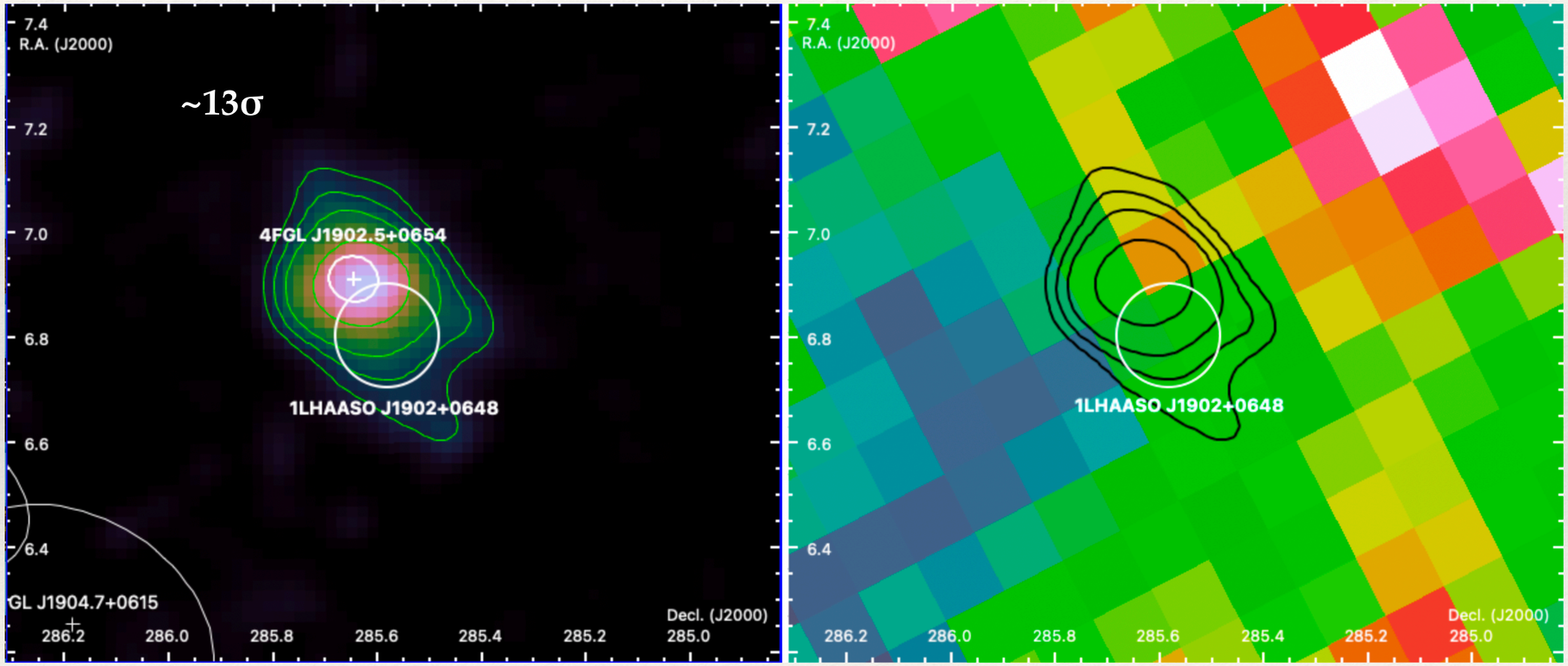
HAWC overlaps with LHAASO-WCD & LHAASO-KM2

Albert et al.(HAWC Collaboration) http://arxiv.org/abs/2405.06050

1LHAASO J1902+0648 (GeV/CO)

- **Left Panel:** Fermi-LAT TS Map with green TS contours of 16, 25, 49, 64. The white cross and the ellipse around it represent the position and its error ellipse for the Fermi-LAT 4FGL catalog source. The white circle shows the positional error circle for the LHAASO-WCD source.
- **Right Panel:** CO intensity map produced in the velocity range of [25, 45] km/s coincides with the Fermi-LAT source's TS contours shown in black. The color scale of the CO has a range of [0, 42] K km/s.

Gamma Rays (1 GeV < E < 500 GeV) **Molecular Clouds for v = [25, 45] km/s**

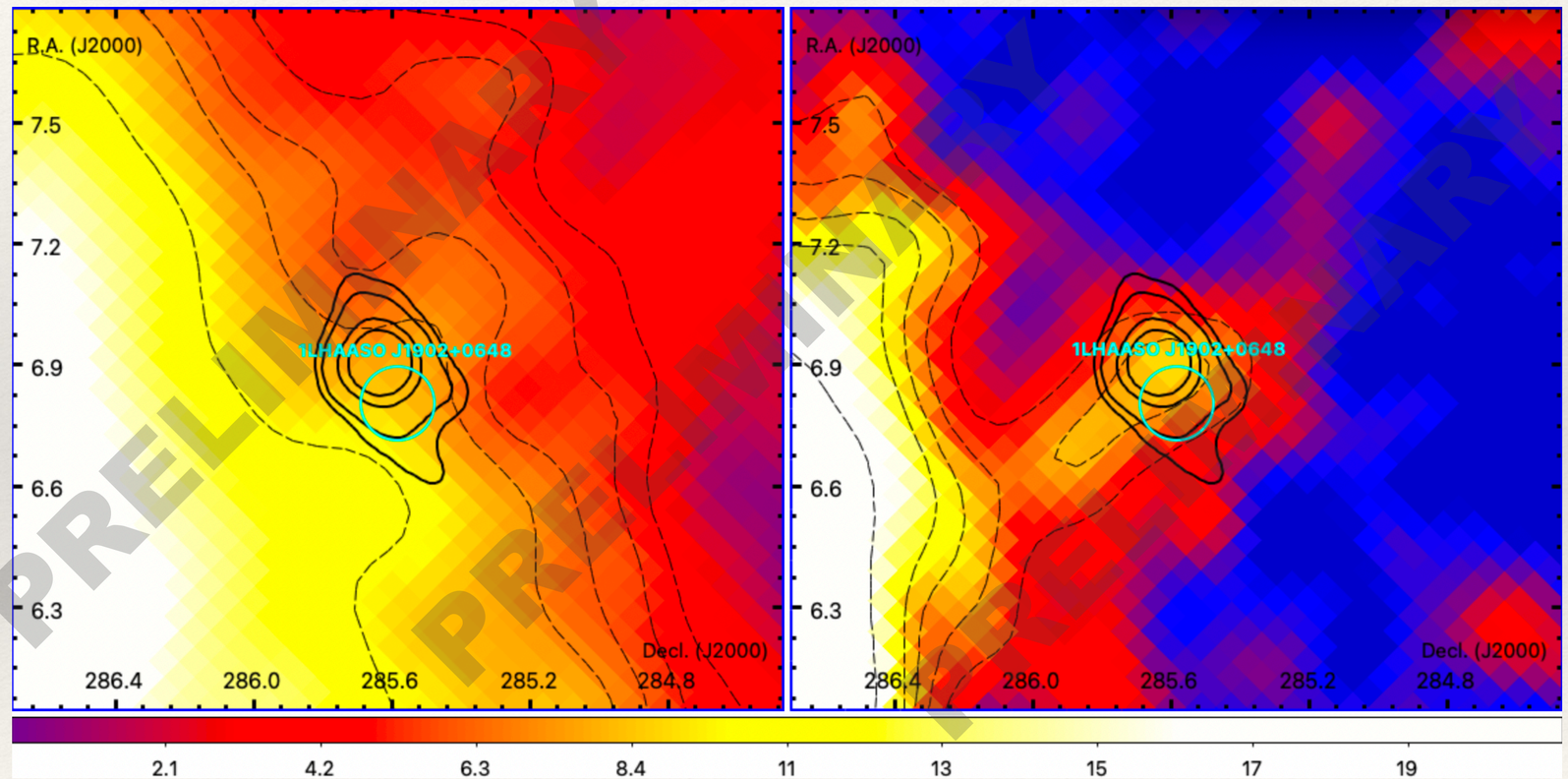


1LHAASO J1902+0648 (4FGL J1902.5+0654)

1LHAASO J1902+0648 (TeV)

- **Left Panel:** HAWC significance map produced in the energy range of 300 GeV - 10 TeV using the Ground Parameter (GP) reconstruction method.
- **Right Panel:** HAWC significance map produced in the energy range of 10 TeV - 316 TeV using the GP method.
- **Both Panels:** Dashed lines shows the HAWC significance contour levels of 4, 5, 6, 7, 10 sigma. Fermi-LAT TS contours of 16, 25, 49, 64 are shown by black solid lines. The cyan colored circle shows the positional error circle for the LHAASO-WCD source.

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

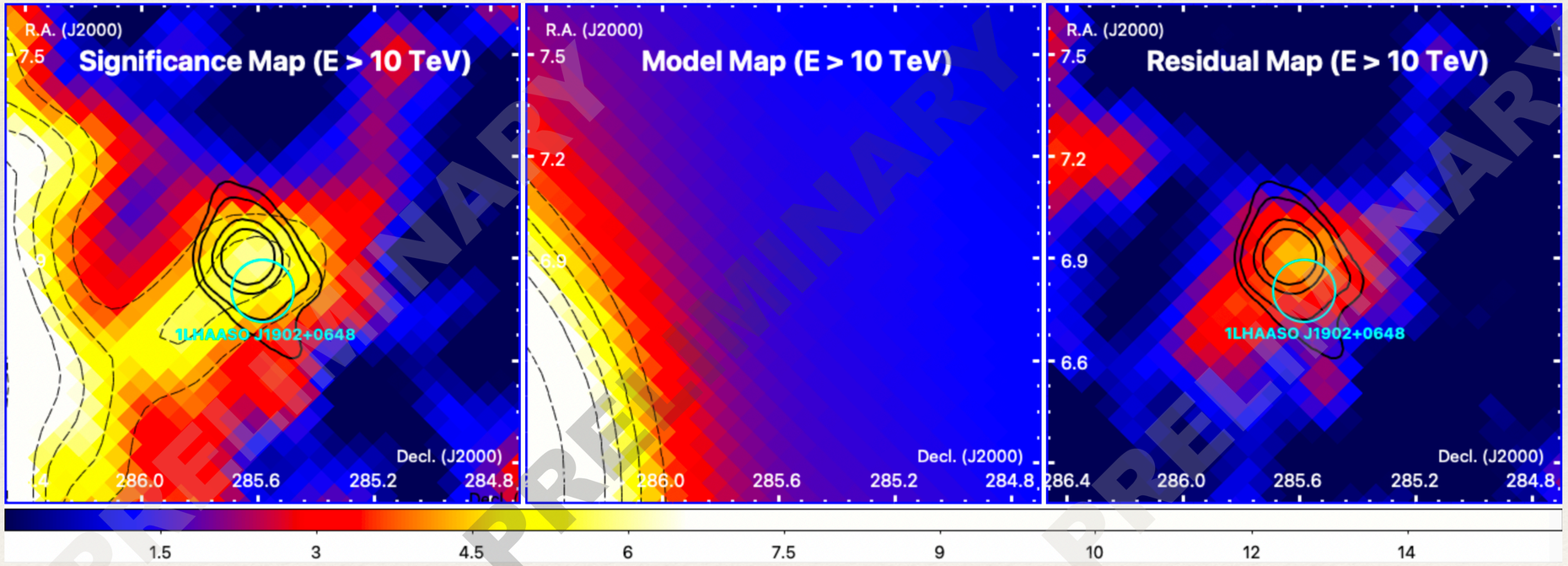


1LHAASO J1902+0648 **(4FGL J1902.5+0654)**

1LHAASO J1902+0648 (TeV)

- **Left Panel:** HAWC significance map (E>10 TeV). Dashed lines show HAWC significance contour levels of 4, 5, 6, 7, 10 sigma. Fermi-LAT TS contours (16, 25, 49, 64) are shown by black solid lines. The cyan colored circle shows the positional error circle for the LHAASO-WCD source.
- **Middle Panel:** The model map that is removed from initial data map to get the residual map shown on the right panel. Dashed lines shows the HAWC significance contour levels of 4, 5, 6, 7, 10 sigma.
- **Right Panel:** Residual significance map for energies above 10 TeV coincides with both Fermi-LAT & 1LAASO source.

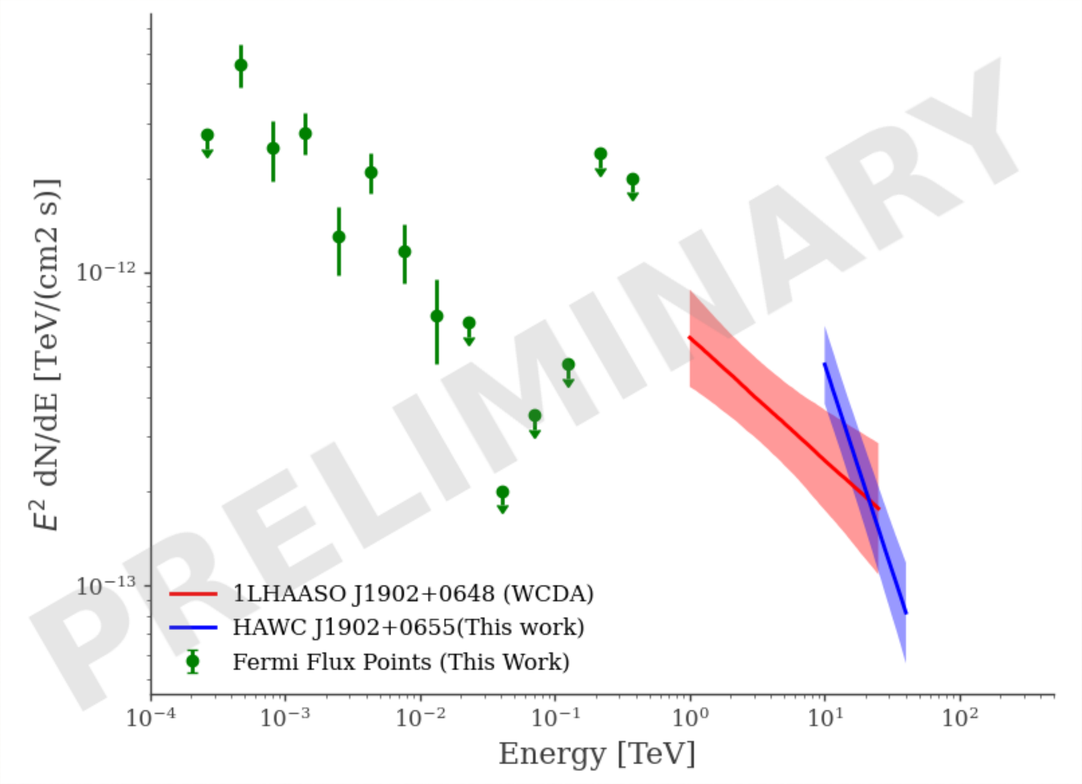
After modeling the background source, a point source detected within the energy range of 5 TeV and 39 TeV at a significance of **~5 sigma**.
The significance in the full energy range is **~10 sigma**.



1LHAASO J1902+0648 **(4FGL J1902.5+0654)**

1LHAASO J1902+0648

Fermi-LAT SED (16 years; 200 MeV < E < 500 GeV) & HAWC SED for E > 10 TeV
Preliminary power-law spectral index: 3.40 ± 0.05

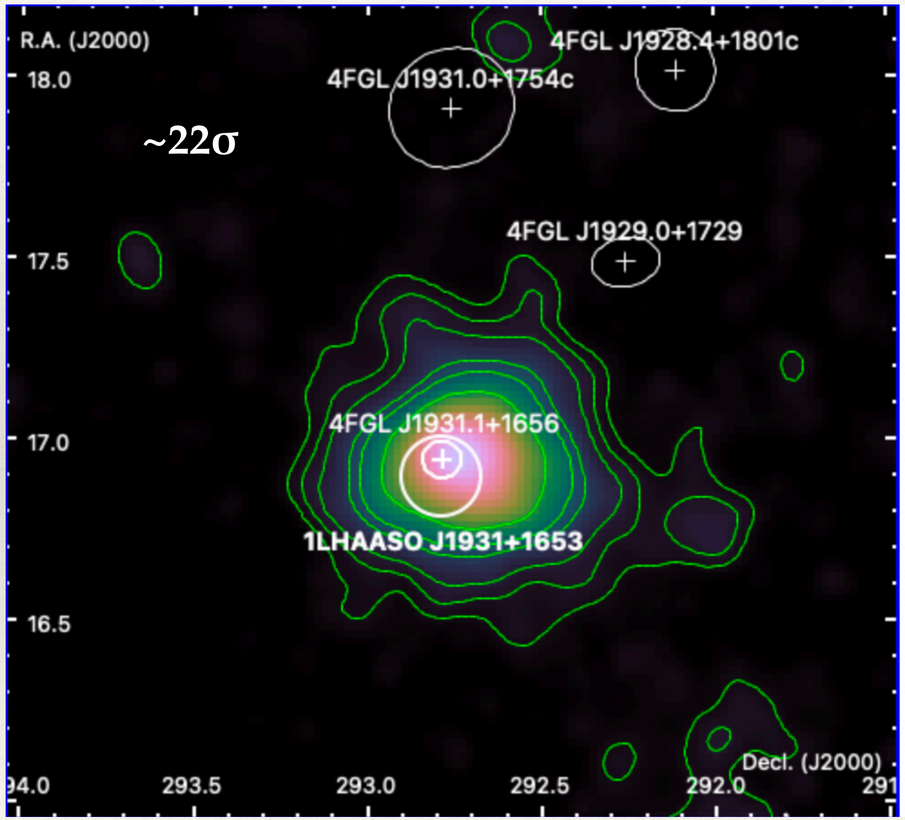


1LHAASO J1902+0648 (4FGL J1902.5+0654)

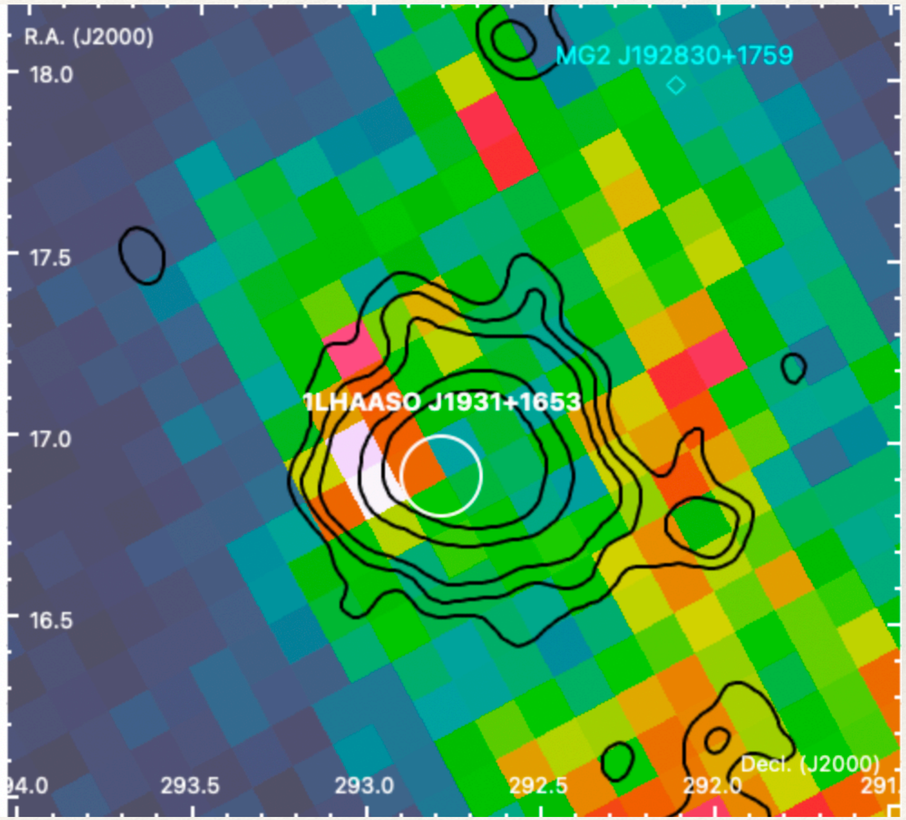
1LHAASO J1931+1653 (GeV/CO)

- **Left Panel:** Fermi-LAT TS Map with green TS contours of 9, 16, 25, 49, 64, 100, 229. The white cross and small circle around it represent the position and its error circle for 4FGL J1931.1+1656. The white circle shows the positional error circle for 1LHAASO J1931+1653.
- **Right Panel:** CO intensity map produced in the velocity range of [45, 70] km/s coincides with the Fermi-LAT source's TS contours shown in black. The color scale of the CO has a range of [0, 60] K km/s. Associated source is shown in cyan color.

Gamma Rays (1 GeV < E < 500 GeV)



Molecular Clouds for v = [45,70] km/s

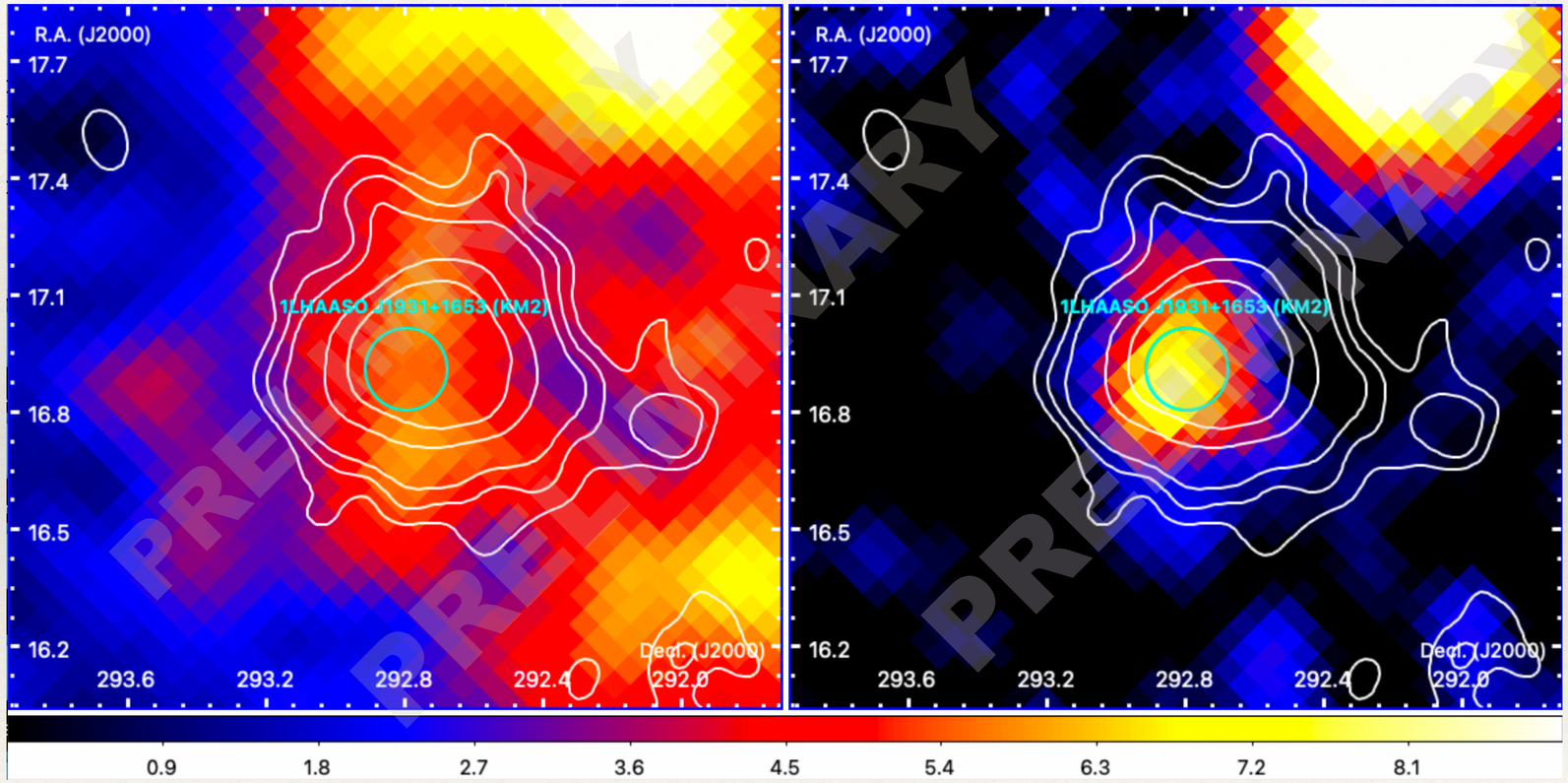


1LHAASO J1931+1653 (4FGL J1931.1+1656)

1LHAASO J1931+1653 (TeV)

- **Left Panel:** HAWC significance map produced in the energy range of 300 GeV - 10 TeV using the GP method.
- **Right Panel:** HAWC significance map produced in the energy range of 10 TeV - 316 TeV using the GP method. After modeling the background source, a point source is detected at a significance of ~8 sigma.
- **Both Panels:** Fermi-LAT TS contours of 9, 16, 25, 49, 64, 100, 229 are shown in white. The cyan colored circle shows the positional error circle for the LHAASO-KM2 source.

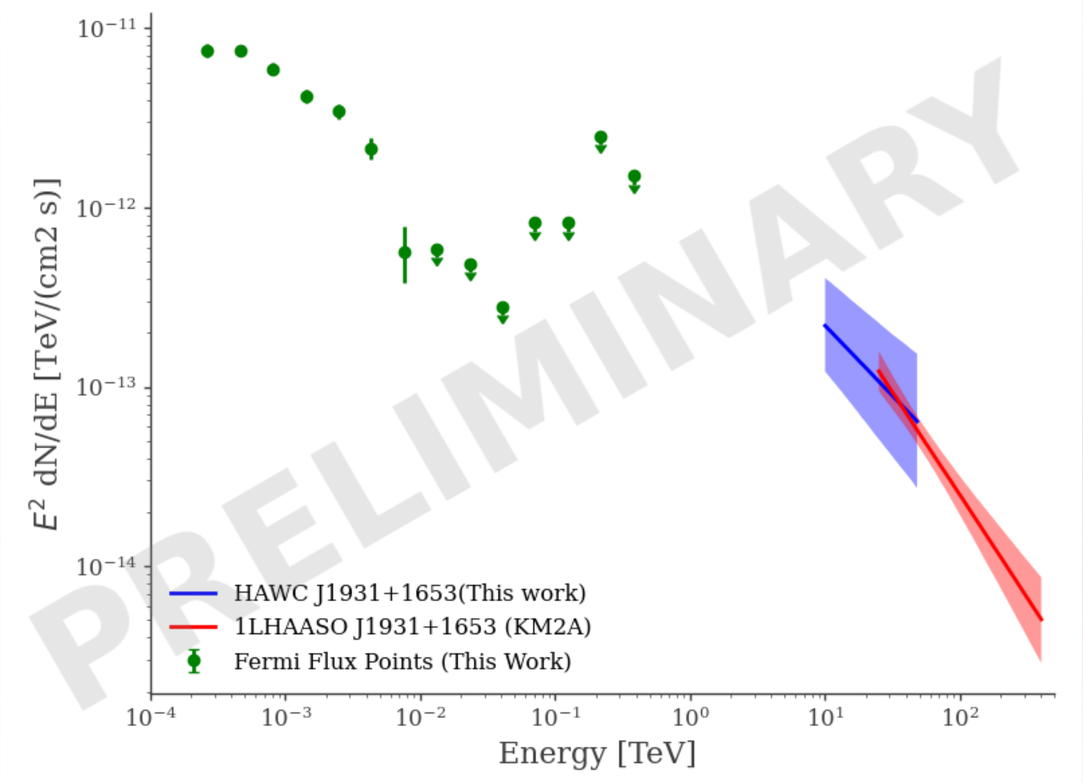
TeV Gamma Rays (E < 10 TeV) **TeV Gamma Rays (E > 10 TeV)**



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

1LHAASO J1931+1653

Fermi-LAT SED (16 years; 200 MeV < E < 500 GeV) & HAWC SED for E > 10 TeV
Preliminary power-law spectral index: 2.79 ± 0.23

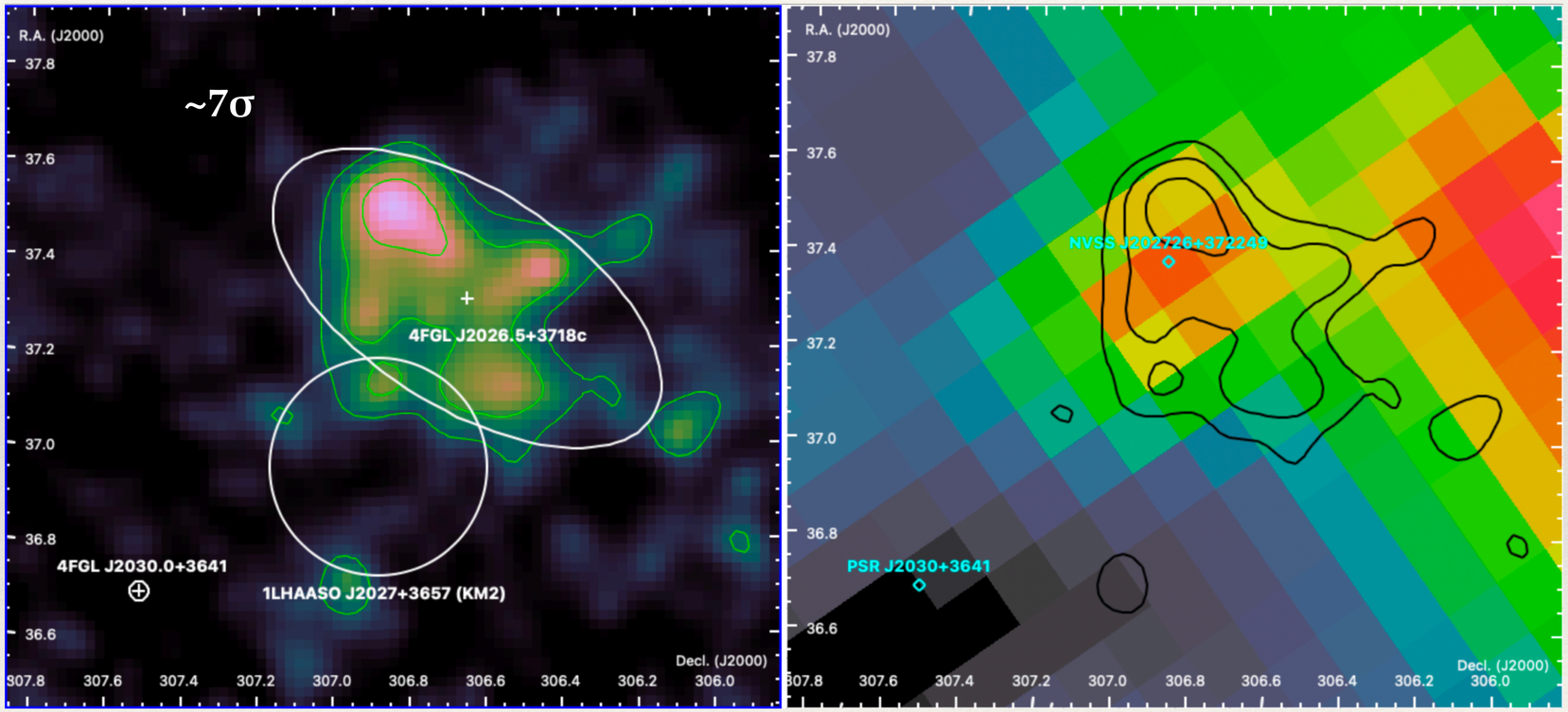


1LHAASO J1931+1653 (4FGL J1931.1+1656)

1LHAASO J2027+3657 (GeV/CO)

- **Left Panel:** Fermi-LAT TS Map with green TS contours of 9, 16, 25. The white cross and the ellipse around it represent the position and its error ellipse for the Fermi-LAT 4FGL catalog source. The white circle shows the positional error circle for the LHAASO-KM2 source. At the left-bottom side of the map is another Fermi-LAT catalog source shown in white color.
- **Right Panel:** CO intensity map produced in the velocity range of [-10, 5] km/s coincides with the Fermi-LAT source's TS contours shown in black. The color scale of the CO has a range of [0, 29] K.km/s. The cyan diamond markers are sources from radio catalogs associated with the two given Fermi-LAT catalog sources.

Gamma Rays (1 GeV < E < 500 GeV) **Molecular Clouds for v = [-10,5] km/s**

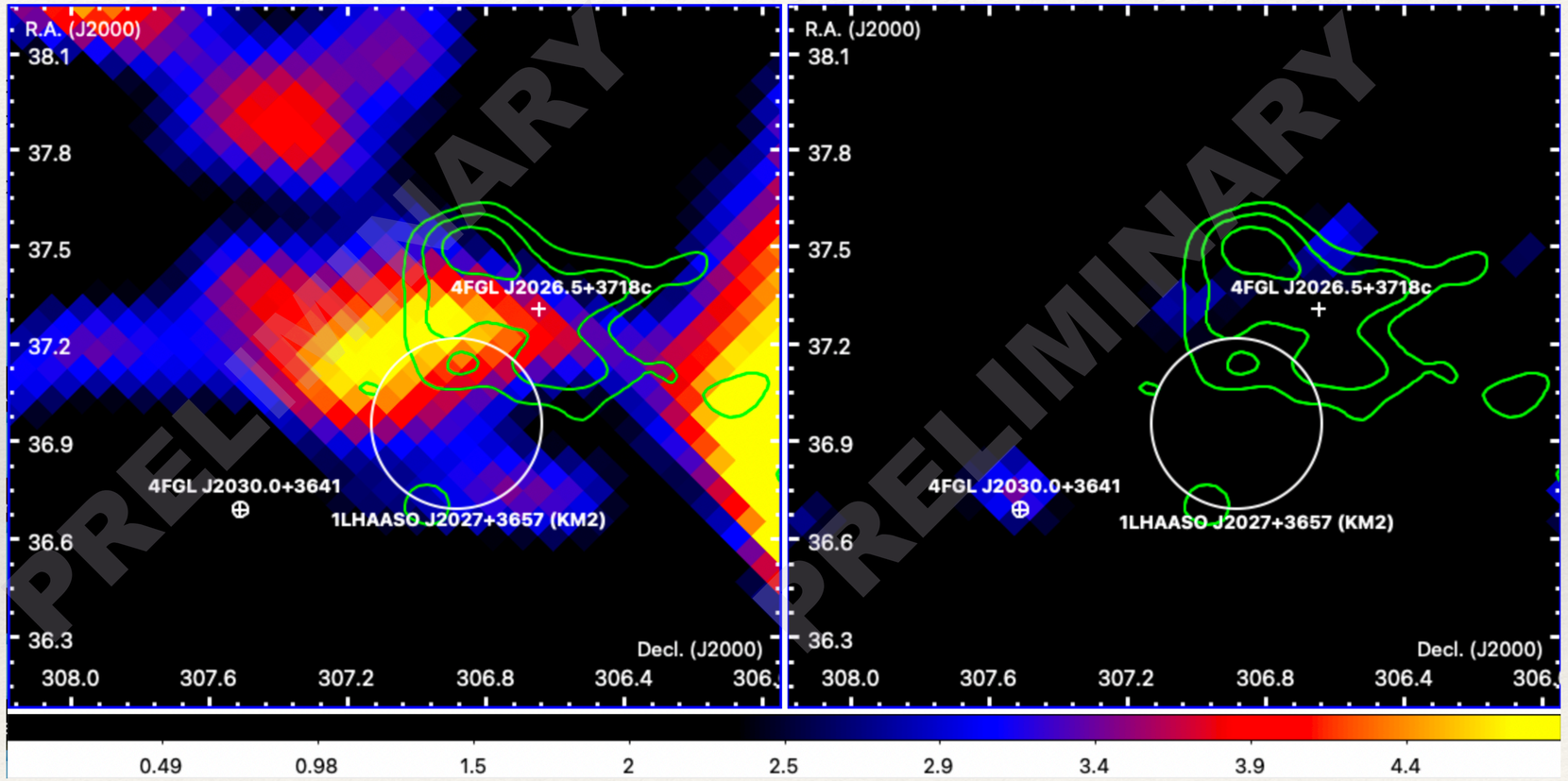


1LHAASO J2027+3657 (4FGL J2026.5+3718c)

1LHAASO J2027+3657 (TeV)

- **Left Panel:** HAWC significance map produced in the energy range of 300 GeV and 10 TeV using the GP method. The pre-trial significance at the location of the 1LHAASO source is **~7 sigma**.
- **Right Panel:** HAWC significance map produced in the energy range of 10 TeV and 316 TeV using the GP method.
- **Both Panels:** The Fermi-LAT TS contours of 9, 16, 25 are shown in green color. Another Fermi-LAT catalog source is shown in white color. The white circle shows the positional error circle for the LHAASO-KM2 source. The significance color scale range goes up to 4.9 sigma.

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

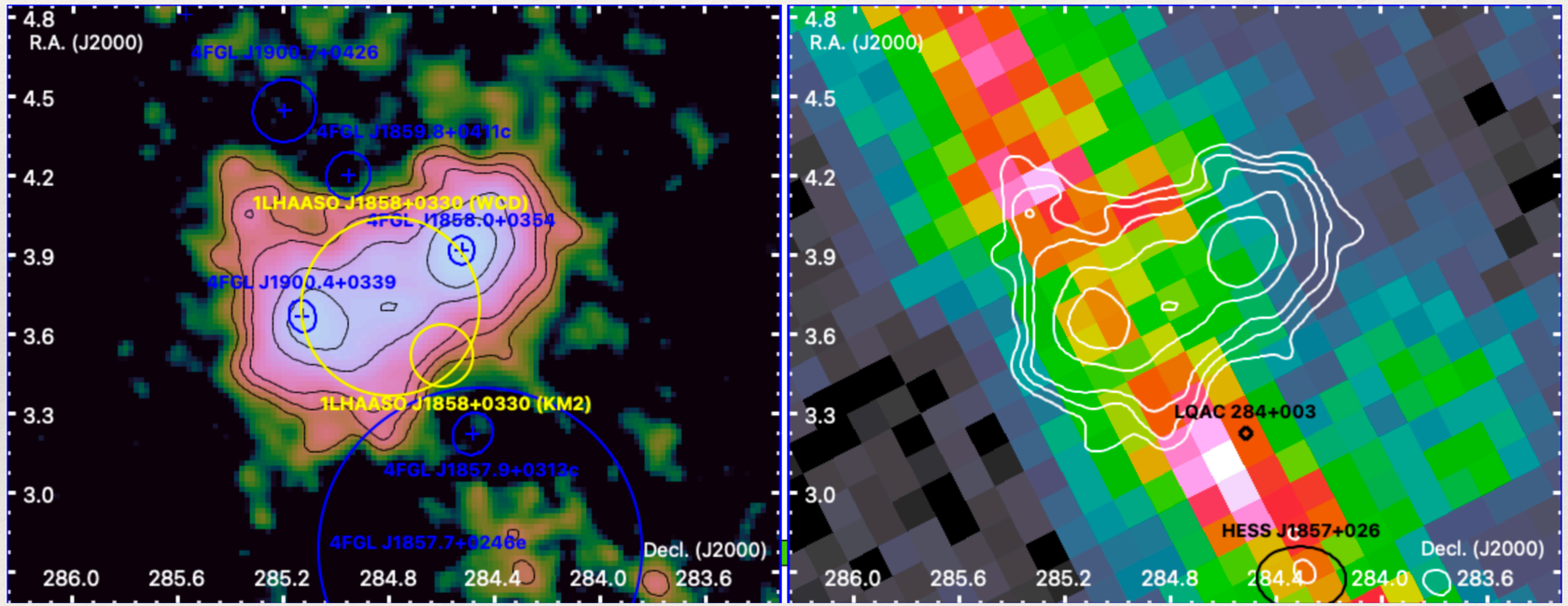


1LHAASO J2027+3657 (4FGL J2026.5+3718c)

1LHAASO J1858+0330 (GeV/CO)

- **Left Panel:** Fermi-LAT TS Map with black TS contours of 9, 16, 25, 64, 100. Map colors are distributed in log-scale. Blue crosses and ellipses around them show positions and their errors for the Fermi-LAT 4FGL catalog sources, and the single big blue circle is an extended source. The yellow circles show the positional error circle for the LHAASO-WCD & LHAASO-KM2 source.
- **Right Panel:** CO intensity map produced in the full velocity range overlapping with the Fermi-LAT sources' TS contours shown in white. The color scale of the CO has a range of [0,140] K.km/s. The black crosses and circles are the Fermi-LAT associated sources.

Gamma Rays (1 GeV < E < 500 GeV) **Molecular Clouds for v = [35,100] km/s**

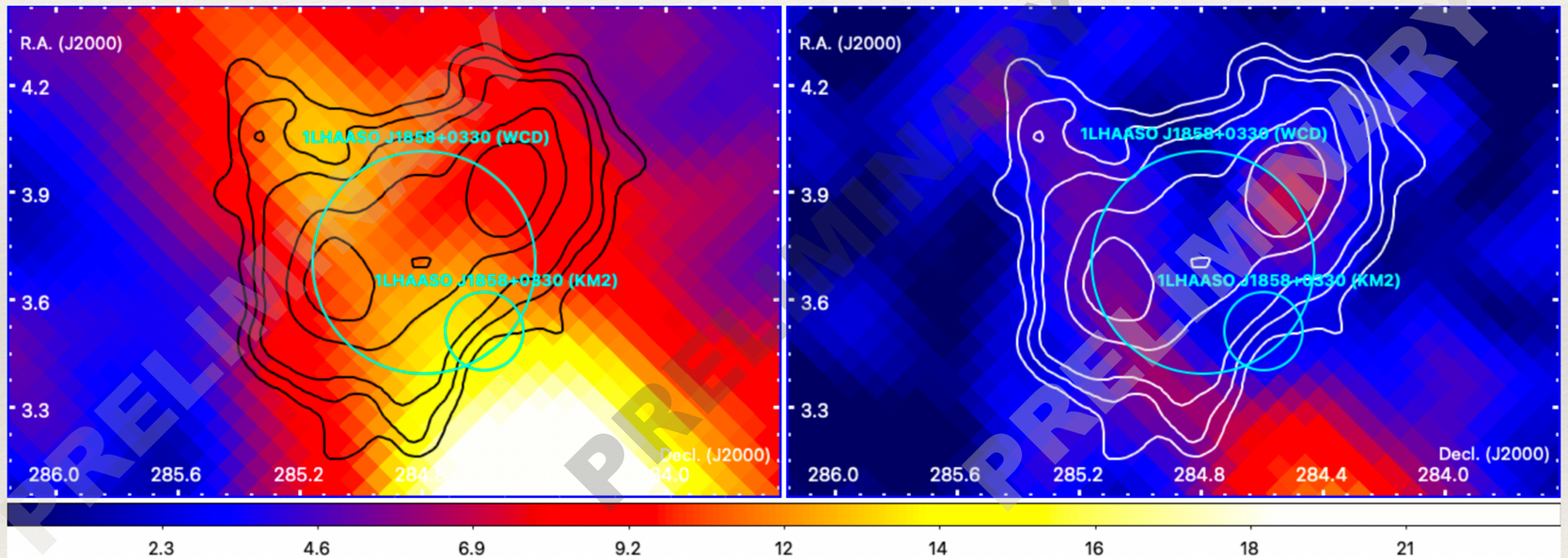


1LHAASO J1858+0330 (4FGL J1858.0+0354 & 4FGL J1900.4+0339)

1LHAASO J1858+0330 (TeV)

- **Left Panel:** HAWC significance map produced in the energy range of 300 GeV - 10 TeV using the GP reconstruction method. Fermi-LAT TS contours of 9, 16, 25, 64, 100, 500 are shown in black. The pre-trial significance at the location of the 1LHAASO source is **~18 sigma**.
- **Right Panel:** HAWC significance map produced in the energy range of 10 TeV - 316 TeV using the GP method. Fermi-LAT TS contours of 9, 16, 25, 64, 100, 500 are shown in white.
- **Both Panels:** The cyan colored circles show the positional error circle for the LHAASO-WCD & LHAASO-KM2 detection.

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

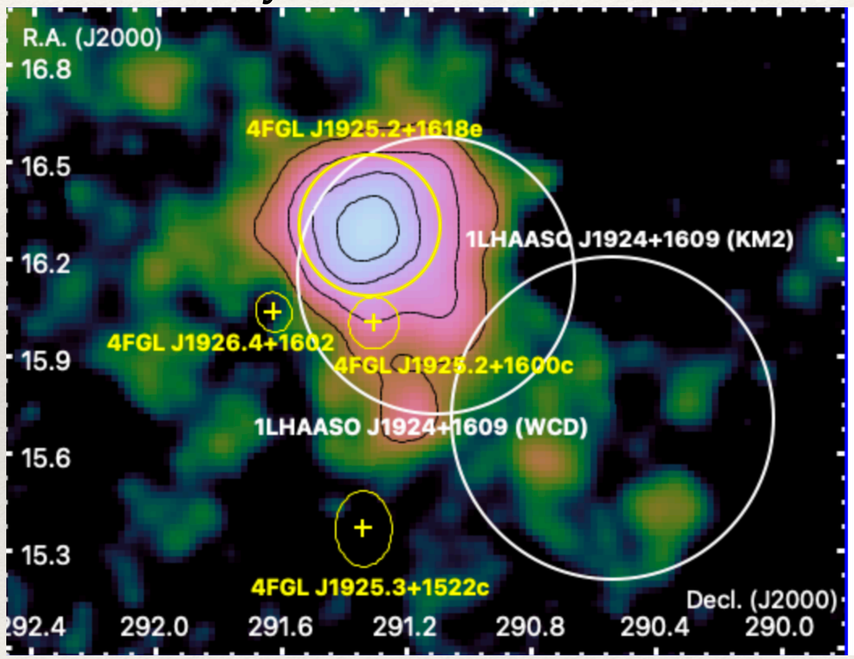


1LHAASO J1858+0330 (4FGL J1858.0+0354 & 4FGL J1900.4+0339)

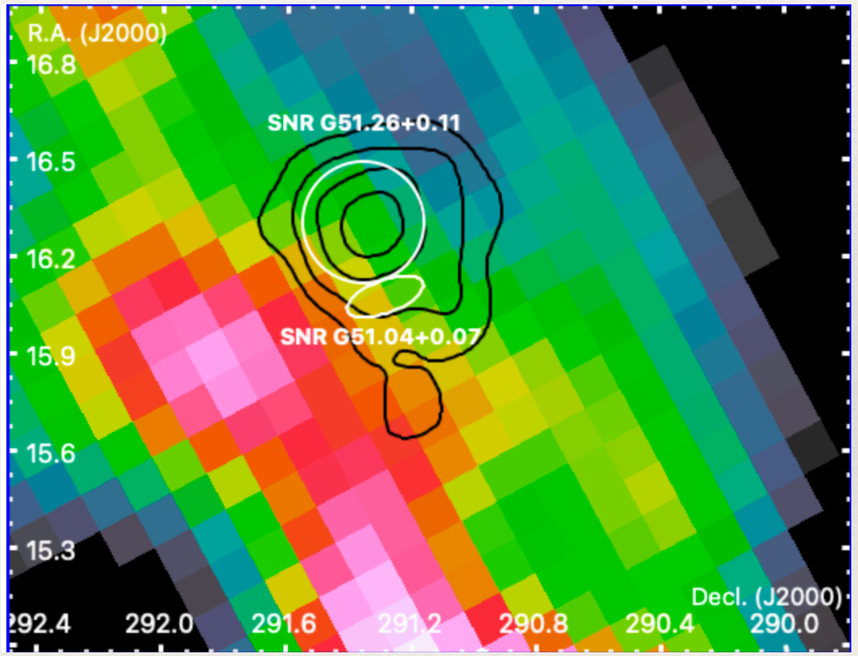
1LHAASO J1924+1609 (GeV/CO)

- **Left Panel:** Fermi-LAT TS Map with black TS contours of 25, 64, 124, 186, 248. Map colors are distributed in log-scale. Yellow crosses and ellipses around them show positions and their errors for the Fermi-LAT 4FGL catalog sources, and the single big yellow circle is an extended source. The white circles show the positional error circle for the LHAASO-WCD & LHAASO-KM2 source.
- **Right Panel:** CO intensity map produced in the full velocity range overlapping with the Fermi-LAT sources' TS contours shown in black. The color scale of the CO has a range of [0, 68] K.km/s. The white circles are representing two separate SNRs.

Gamma Rays (1 GeV < E < 500 GeV)



Molecular Clouds for v = [-300,300] km/s

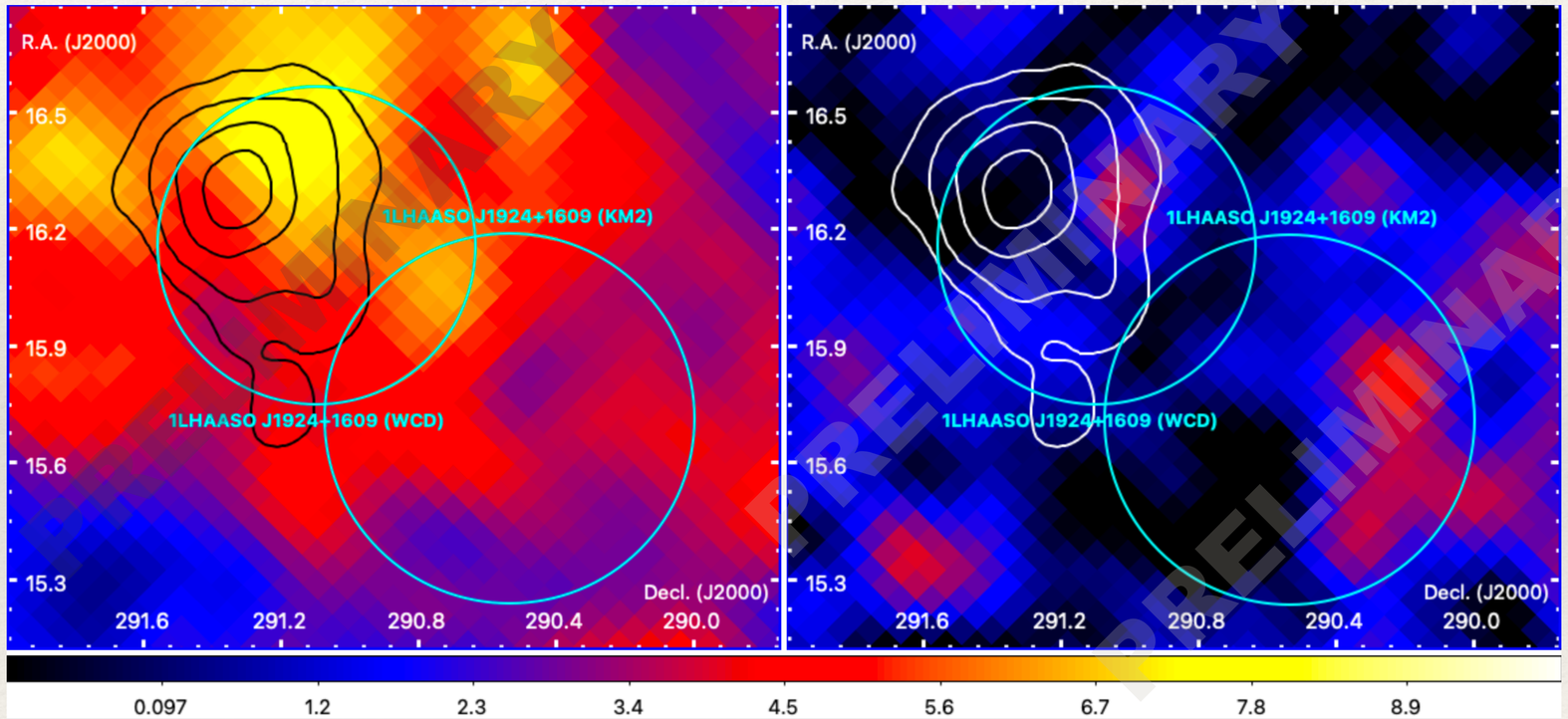


1LHAASO J1924+1609 (G51.26+0.11 & 4FGL J1925.2+1600c)

1LHAASO J1924+1609 (TeV)

- **Left Panel:** HAWC significance map produced in the energy range of 300 GeV - 10 TeV using the GP reconstruction method. Fermi-LAT TS contours of 25, 64, 124, 186, 248 are shown in black. The pre-trial significance at the location of the 1LHAASO source is **~8 sigma**.
- **Right Panel:** HAWC significance map produced in the energy range of 10 TeV - 316 TeV using the GP method. Fermi-LAT TS contours of 25, 64, 124, 186, 248 are shown in white.
- **Both Panels:** The cyan colored circles show the positional error circle for the LHAASO-WCD & LHAASO-KM2 detection.

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



1LHAASO J1924+1609 (G51.26+0.11 & 4FGL J1925.2+1600c)

Conclusion

- In the 1st LHAASO source catalog (1LHAASO), eight TeV sources were reported to be without having any known TeV counterparts, but overlapping only with Fermi-LAT gamma ray sources.
- **HAWC detected five out of eight 1LHAASO sources with pre-trail significances > 5 sigma** in the preliminary analyses.
  - Two sources were modeled as a point source with a power-law type spectrum above 10 TeV:
    - HAWC spectral index of 1LHAASO J1902+0648 was found to be harder than the reported LHAASO WCD spectral index (2.39 ± 0.18).
    - HAWC spectral index of 1LHAASO J1931+1653 was found to be softer than reported LHAASO KM2 spectral index (3.15 ± 0.25).
- **A more detailed HAWC data analysis & a multi-wavelength analysis is still ongoing!**
- We also analyzed data taken by Fermi-LAT over the last 16 years at the positions of the GeV sources overlapping with the 1LHAASO positional error ellipses. We compared resulting GeV morphologies with HAWC significance distributions.
  - We found that **all detected HAWC sources are spatially overlapping with GeV gamma-ray sources from the 14-year Fermi-LAT catalog**.

Backup Slides