Studies of the LHAASO Peanut region with VERITAS

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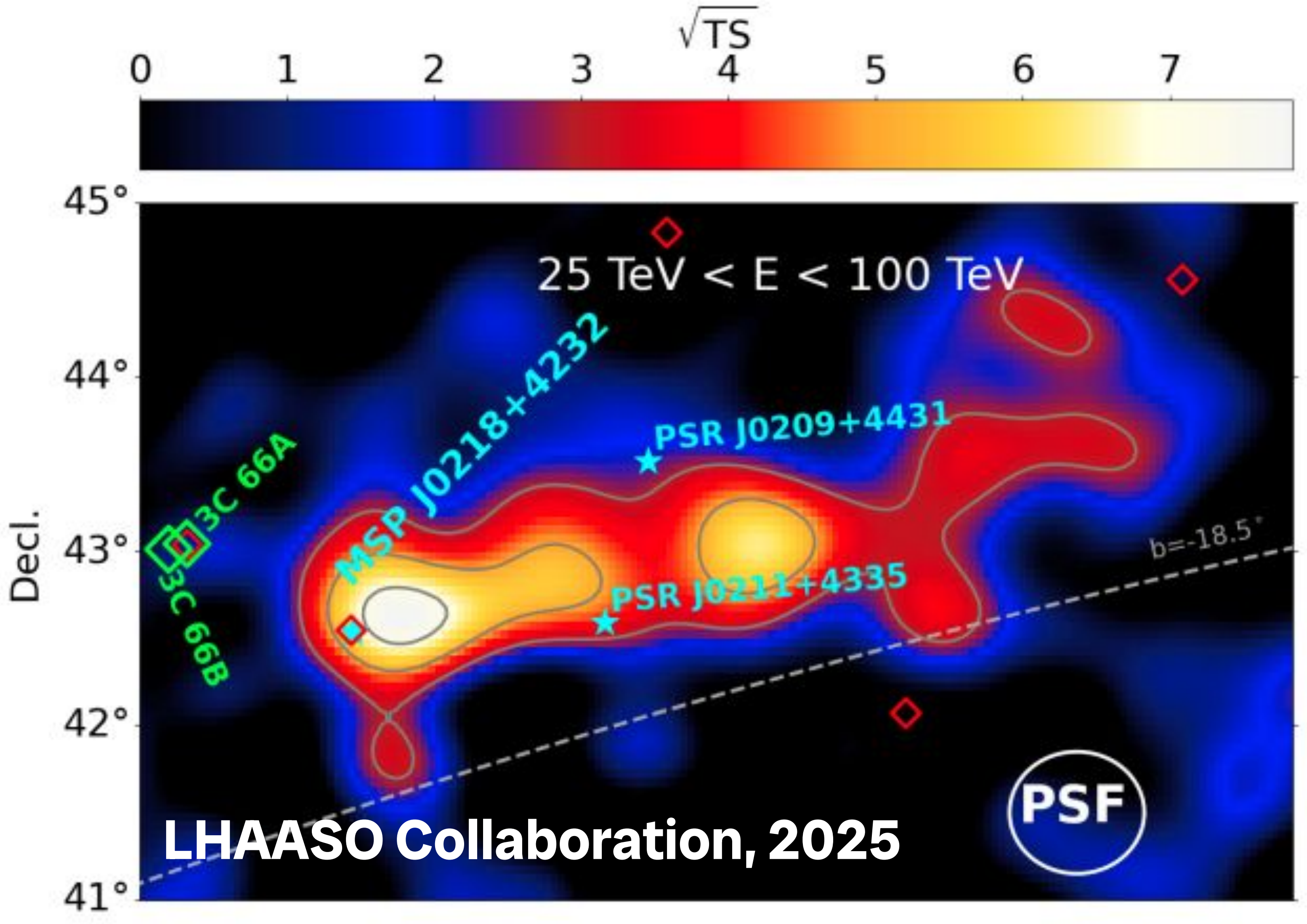
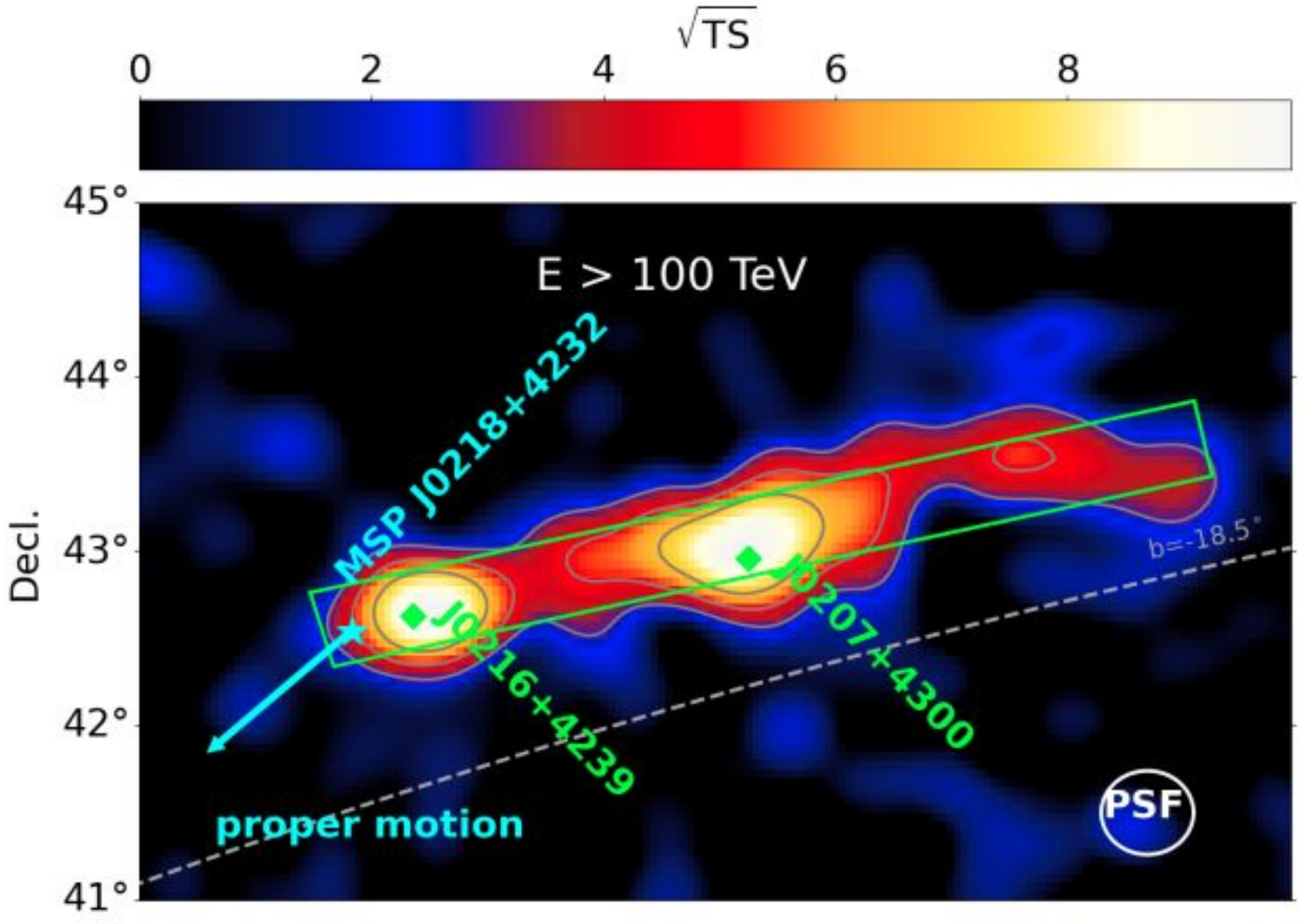
The LHAASO Peanut

The Peanut is one of the most unique sources in the 1LHAASO catalogue and requires multi-wavelength follow-up for full characterization.

- **UHE source** (+PeVatron candidate) with a cutoff at 250 TeV and highest energy photon at 760 TeV
- **Only detected > 25 TeV** and with **no MWL counterpart**
- Tentative (~3σ) association with MSP J0218+4232





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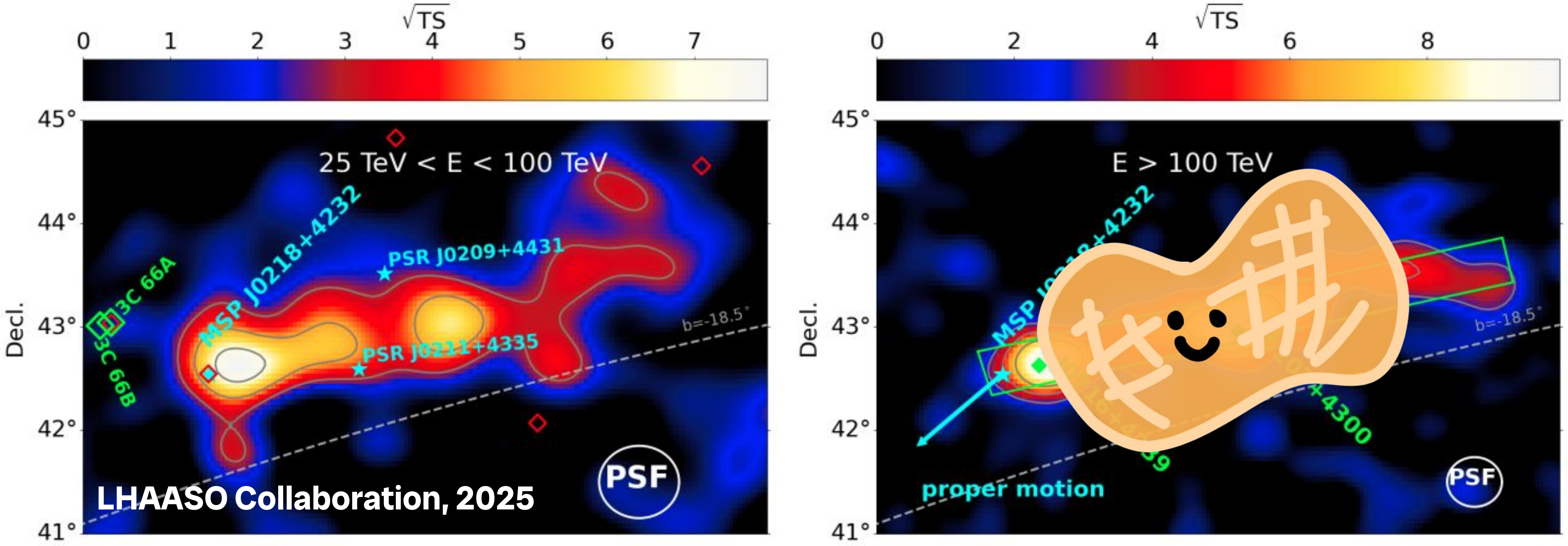

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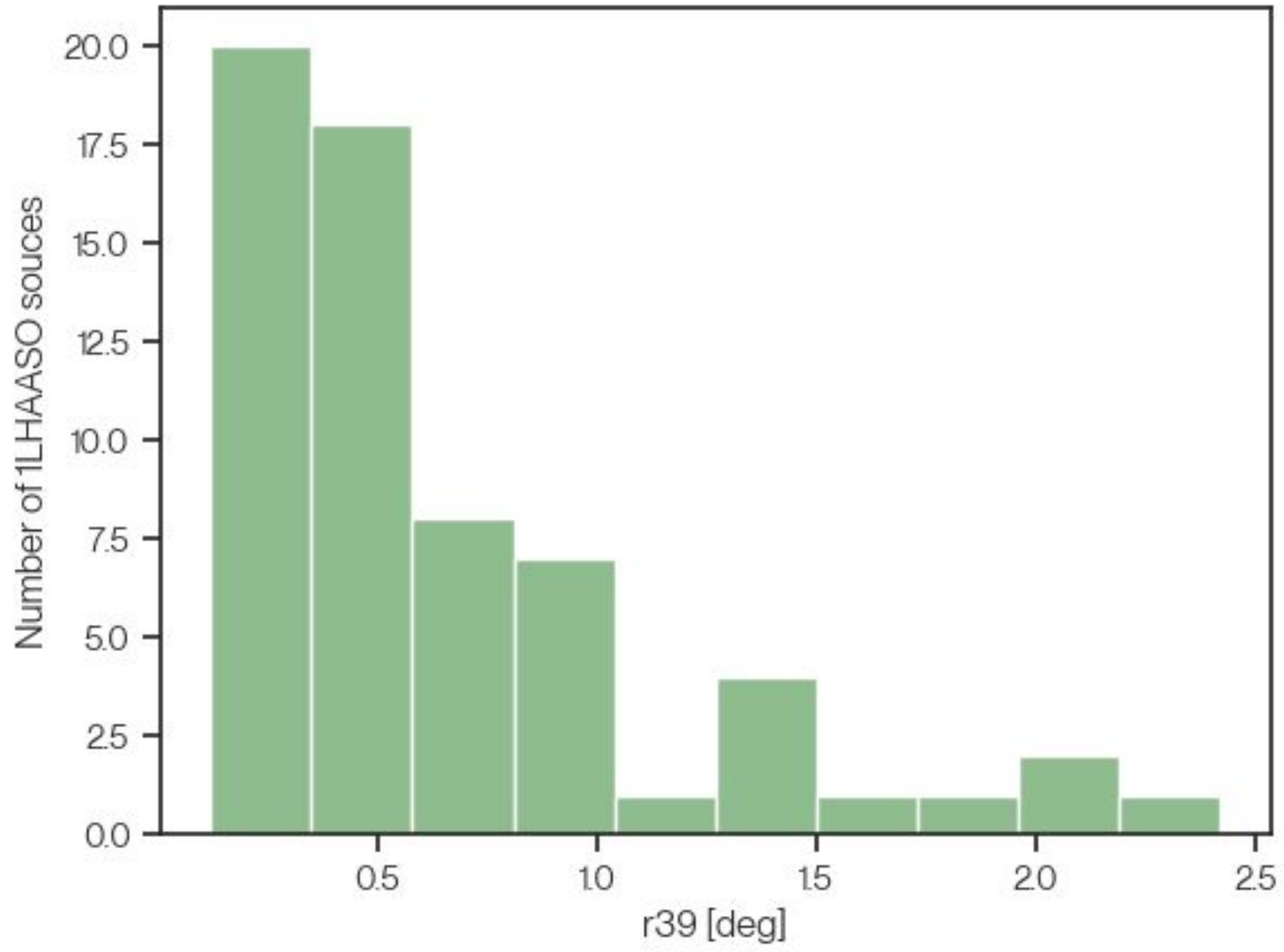
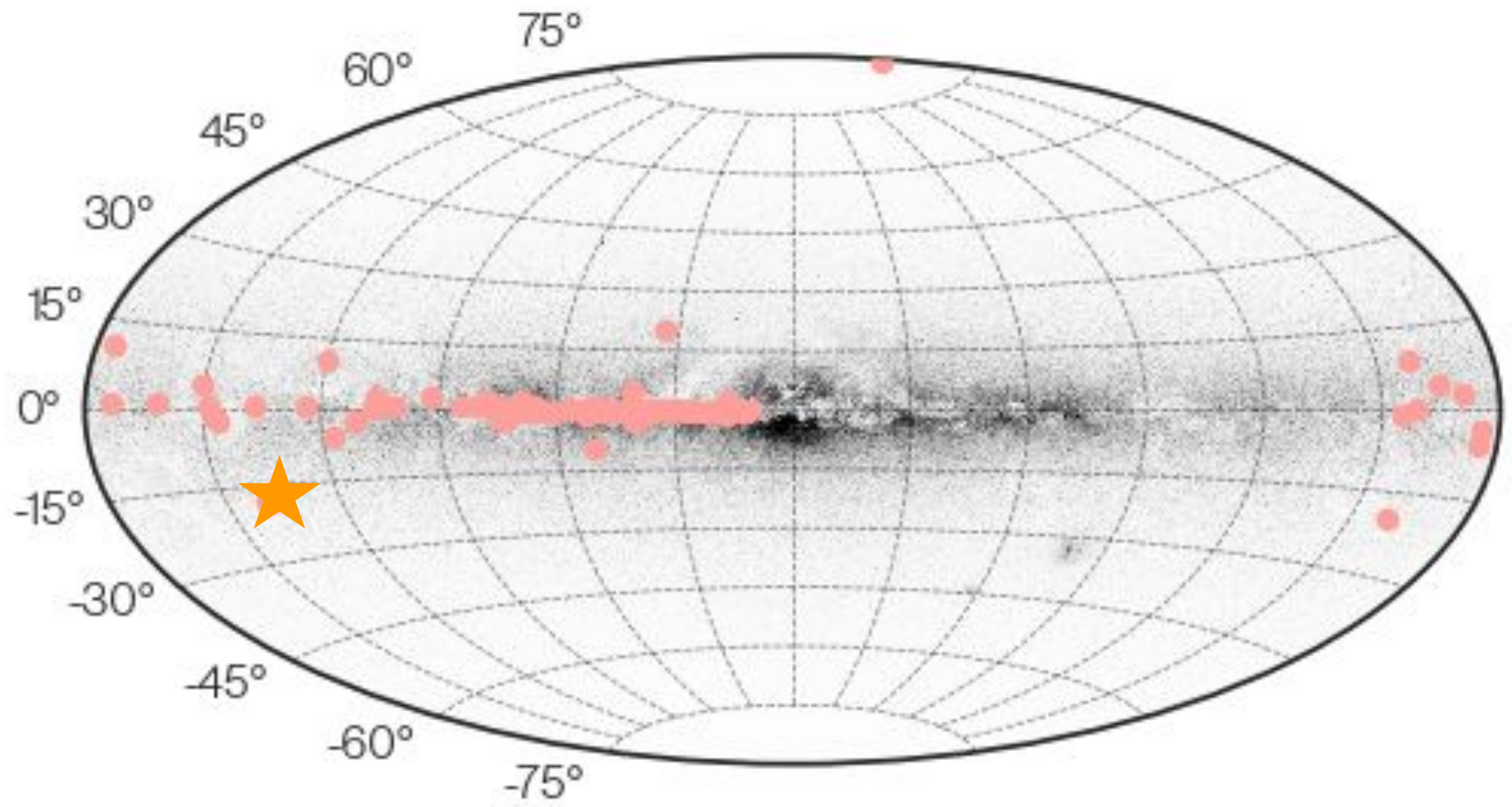
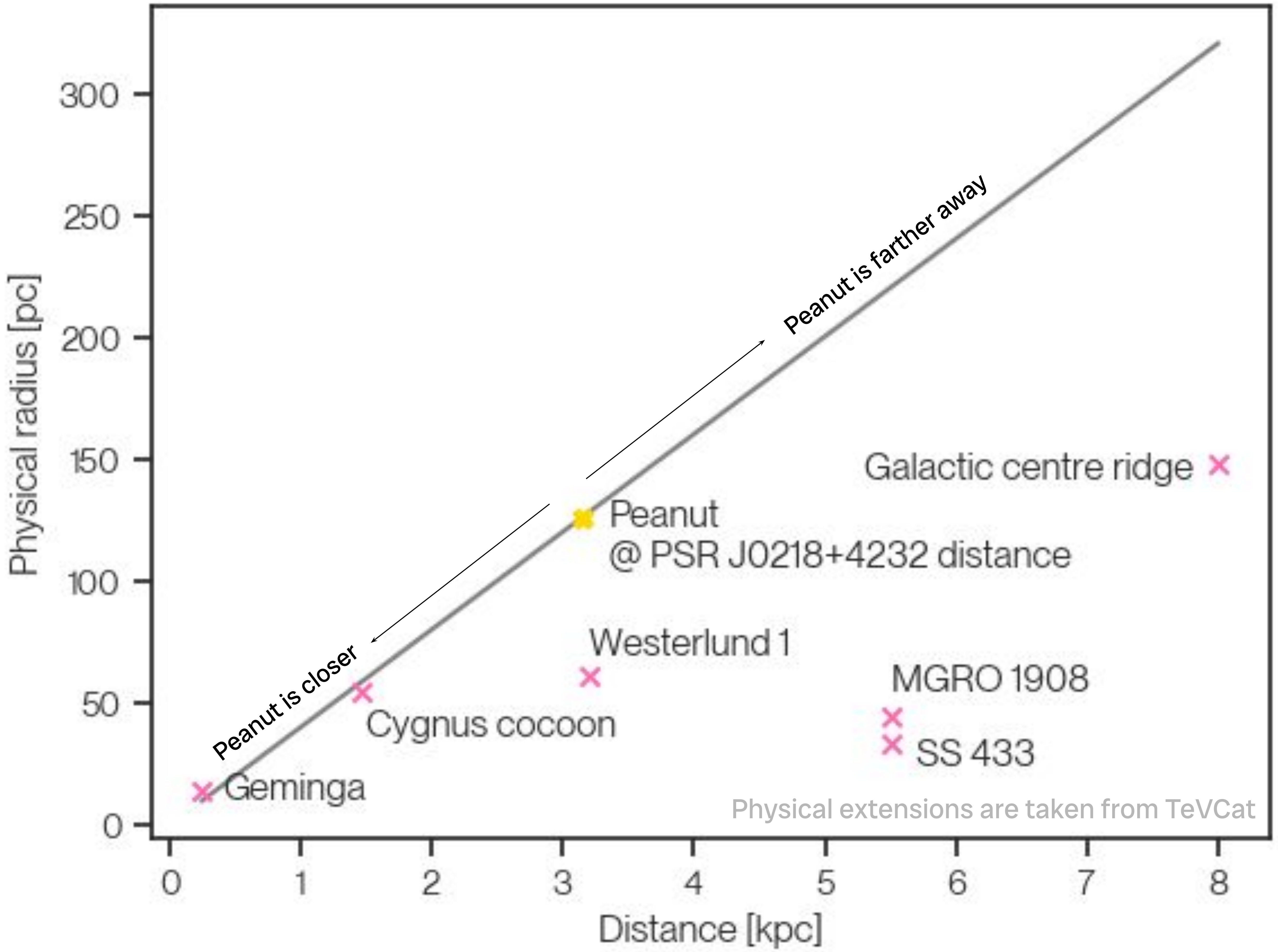
- The combination of all three components into a single source gives the **largest extension** and the largest linear diameter (assuming the MSP distance of 3.15 kpc) in 1LHAASO
- The Peanut has the **highest Galactic latitude** of all Galactic 1LHAASO sources





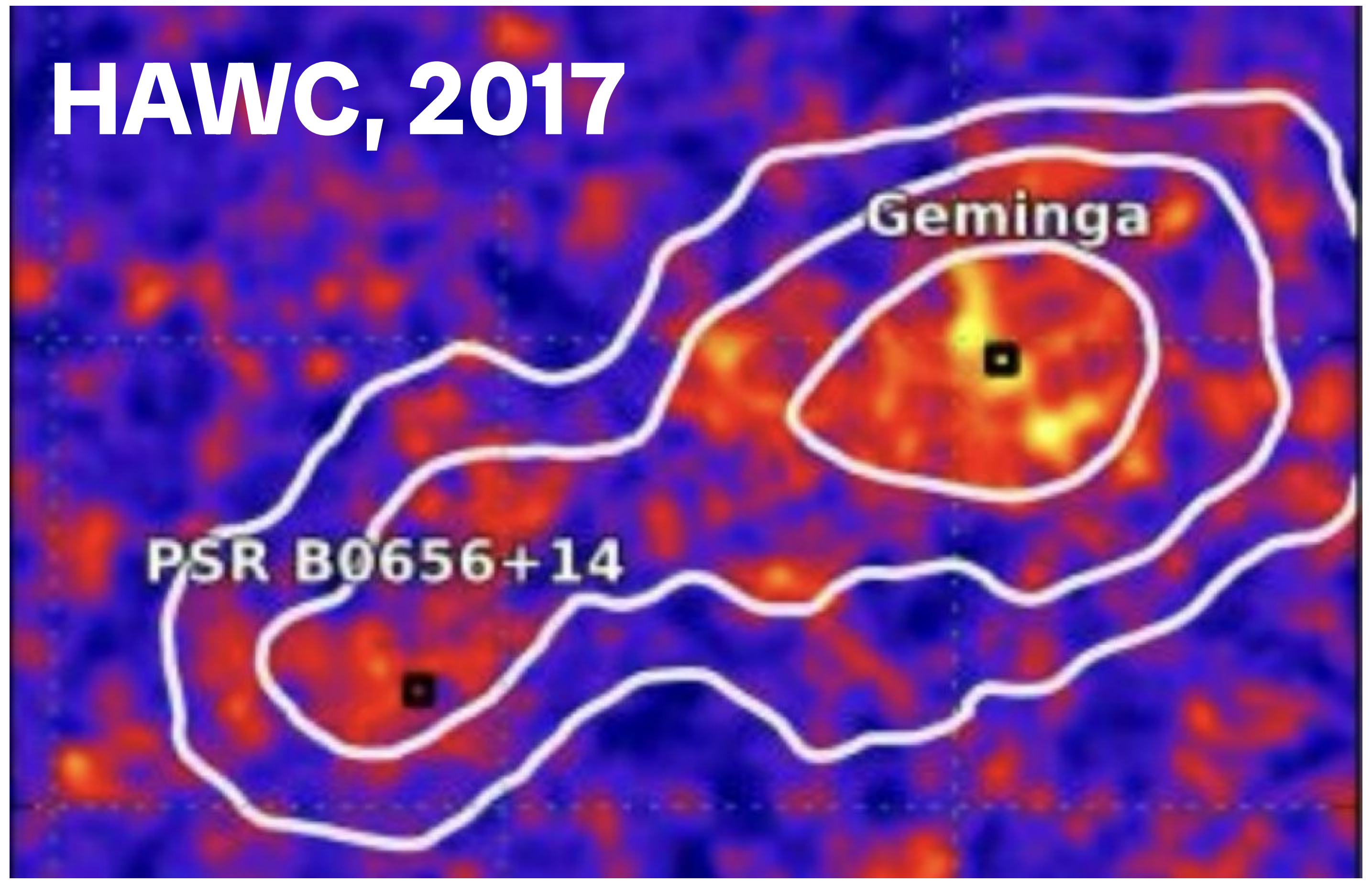
Rethinking distance & association

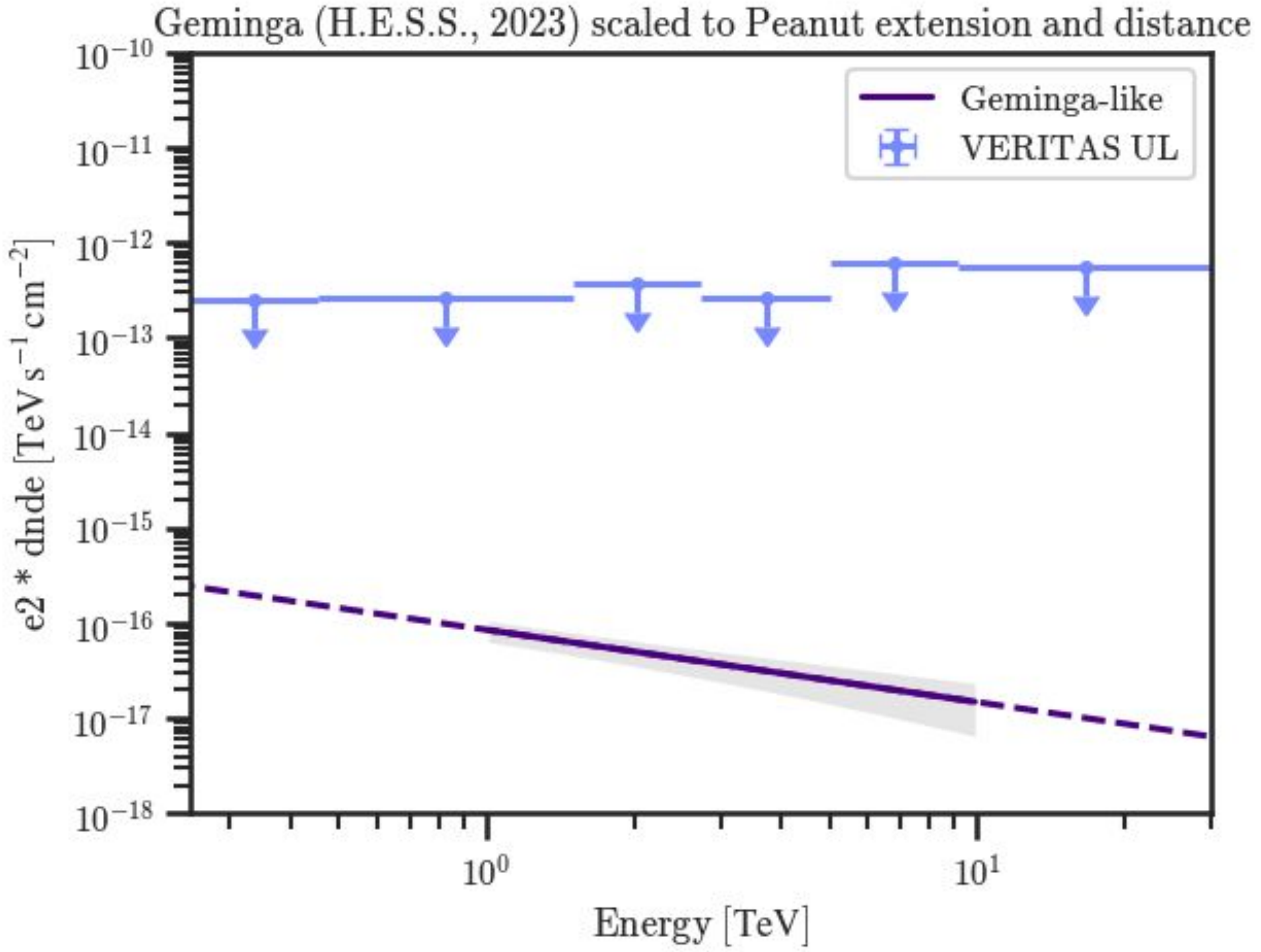
At the pulsar distance of 3.15 kpc, the Peanut is the second largest VHE source, after the Galactic centre ridge.



Proposed source classes: TeV halo

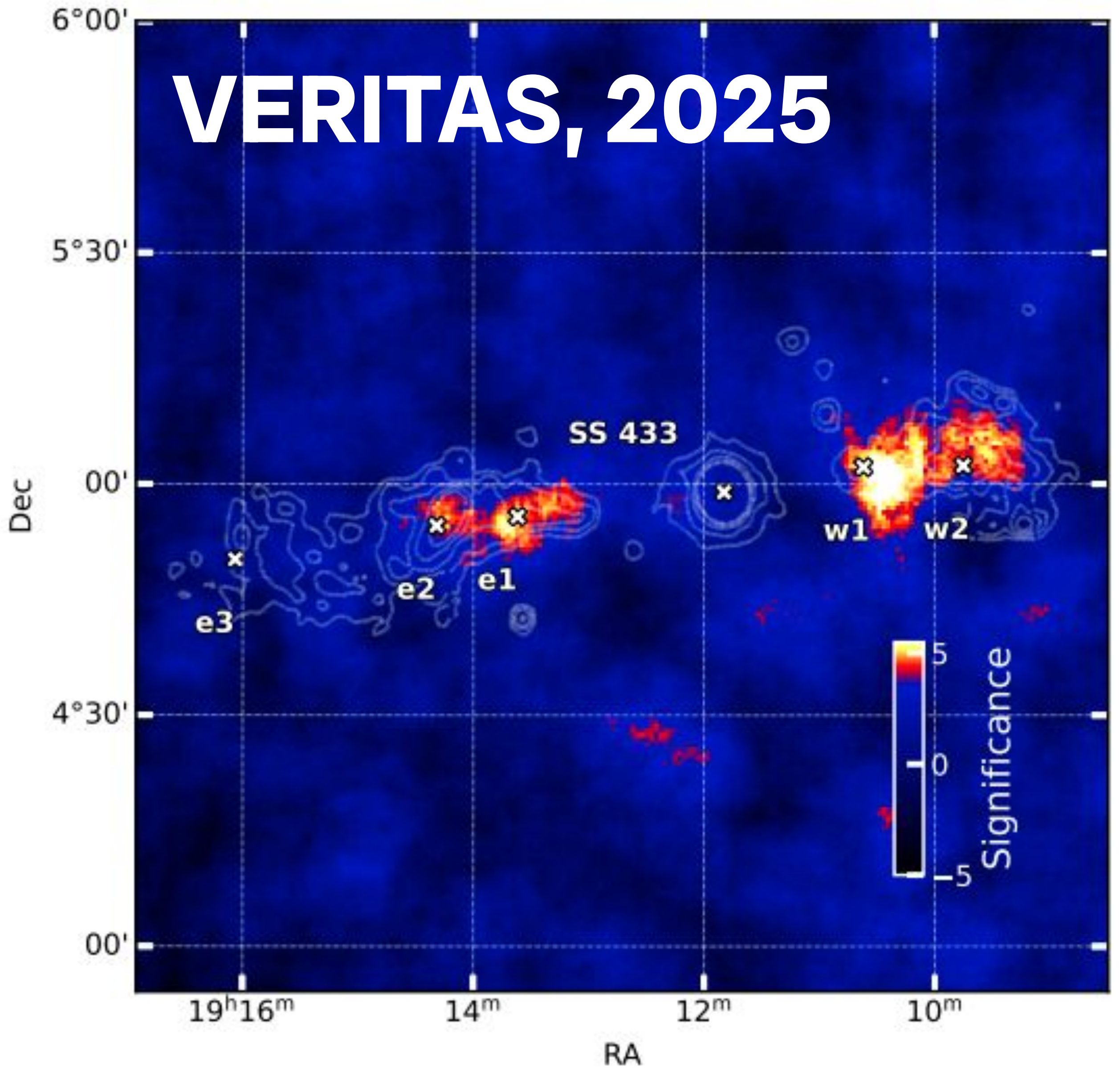
- Millisecond pulsar (MSP) **PSR J0218+4232** is the only nearby source with sufficient energetics to power the peanut
- **No MWL emission has been seen from TeV haloes** ⇒ consistent with the Peanut, though no TeV emission has been found coincident with a MSP
- Peanut diffusion $D_{\parallel} \sim 3.9 \times 10^{29}$ cm2 s-1 @ 100 TeV is ~100x that of Geminga, **$D_{\perp} \sim D_{\parallel}/400$ is roughly compatible with Geminga** (LHAASO, 2025), though it is **difficult to explain the angular size of the Peanut (∅ 250 pc) from a stationary pulsar** ($t_c \sim 16$ kyr)
- Cutoff energies from known TeV haloes are ~10x lower than the Peanut

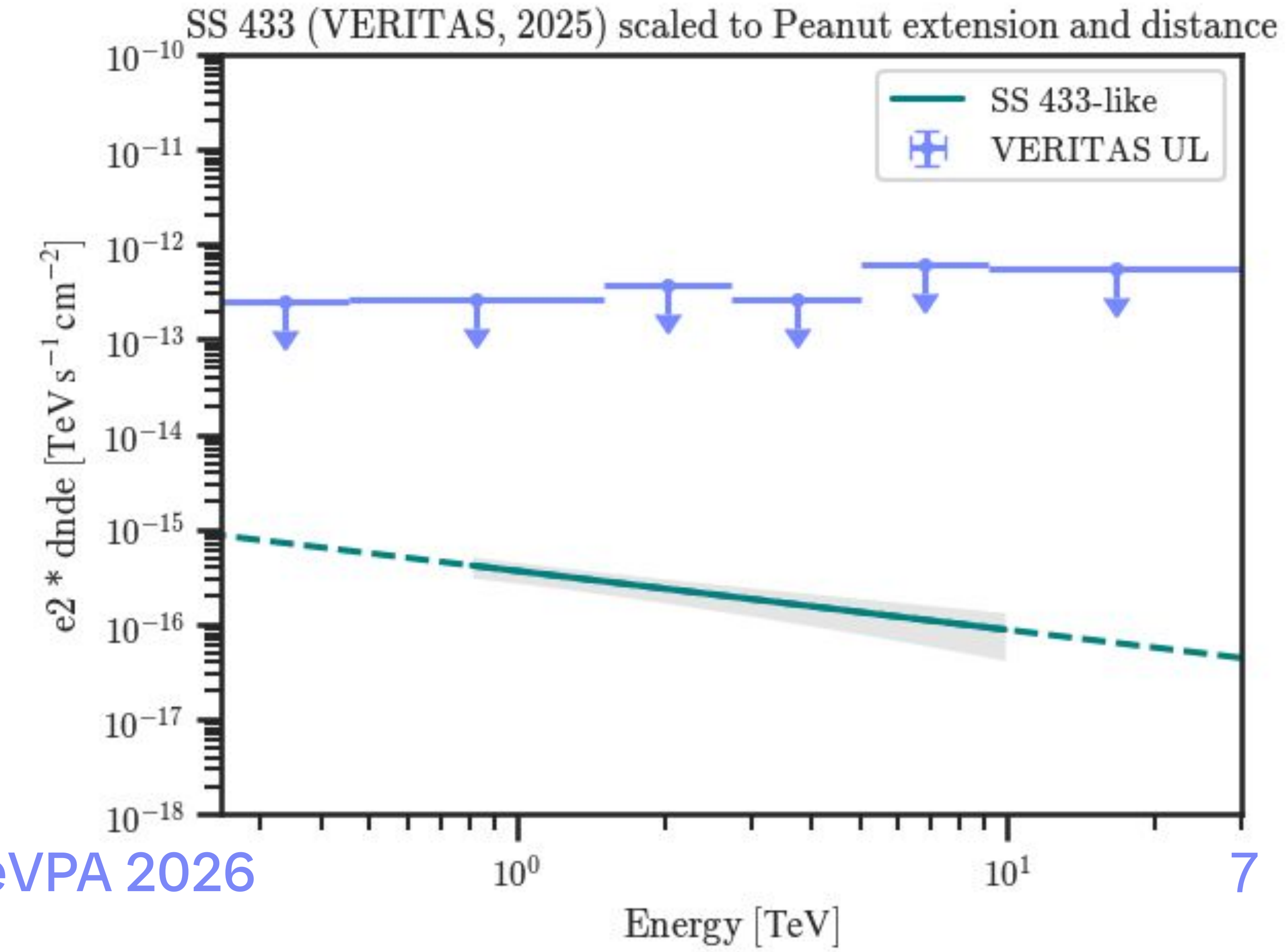




Proposed source classes: Microquasar

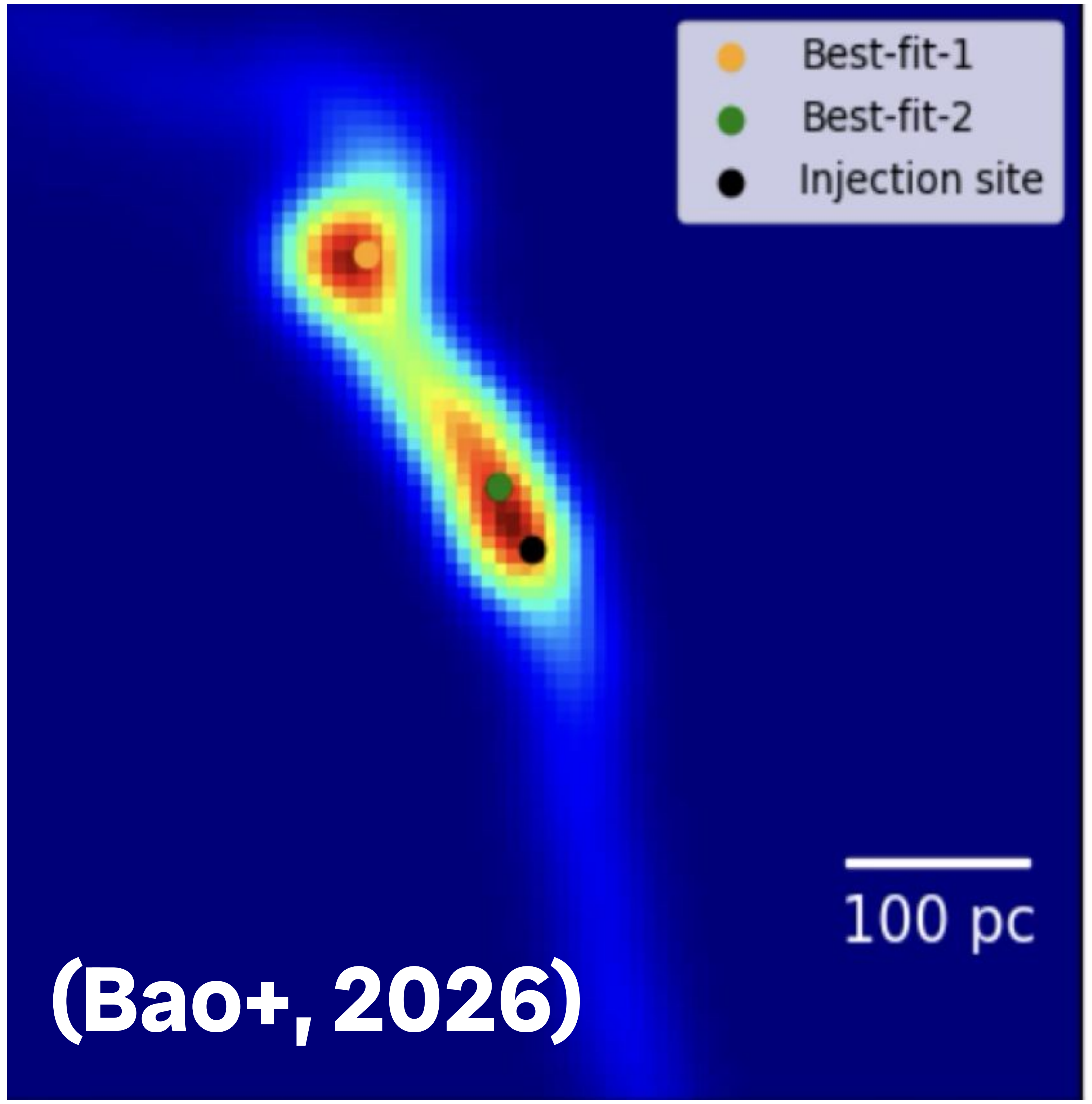
- Jets can create a double-lobed structure without a central source (e.g., SS 433)
- Microquasars are capable of **>PeV emission**
  - **Four UHE microquasars detected > 100 TeV** by LHAASO (LHAASO, 2025)
- MWL emission is seen from all known TeV microquasars
- Molecular cloud density (from HI maps; LHAASO, 2025) is estimated to be very low in the region, limiting the possibility of hadronic interactions between jets and clouds





Proposed source classes: Alternatives

- **Mirage PWN** (Bao+, 2026) model can explain the angular size and separation distance from the pulsar, using long magnetic coherence lengths, consistent with an off-plane location
  - Remains a theoretical model, derived with the Peanut in mind



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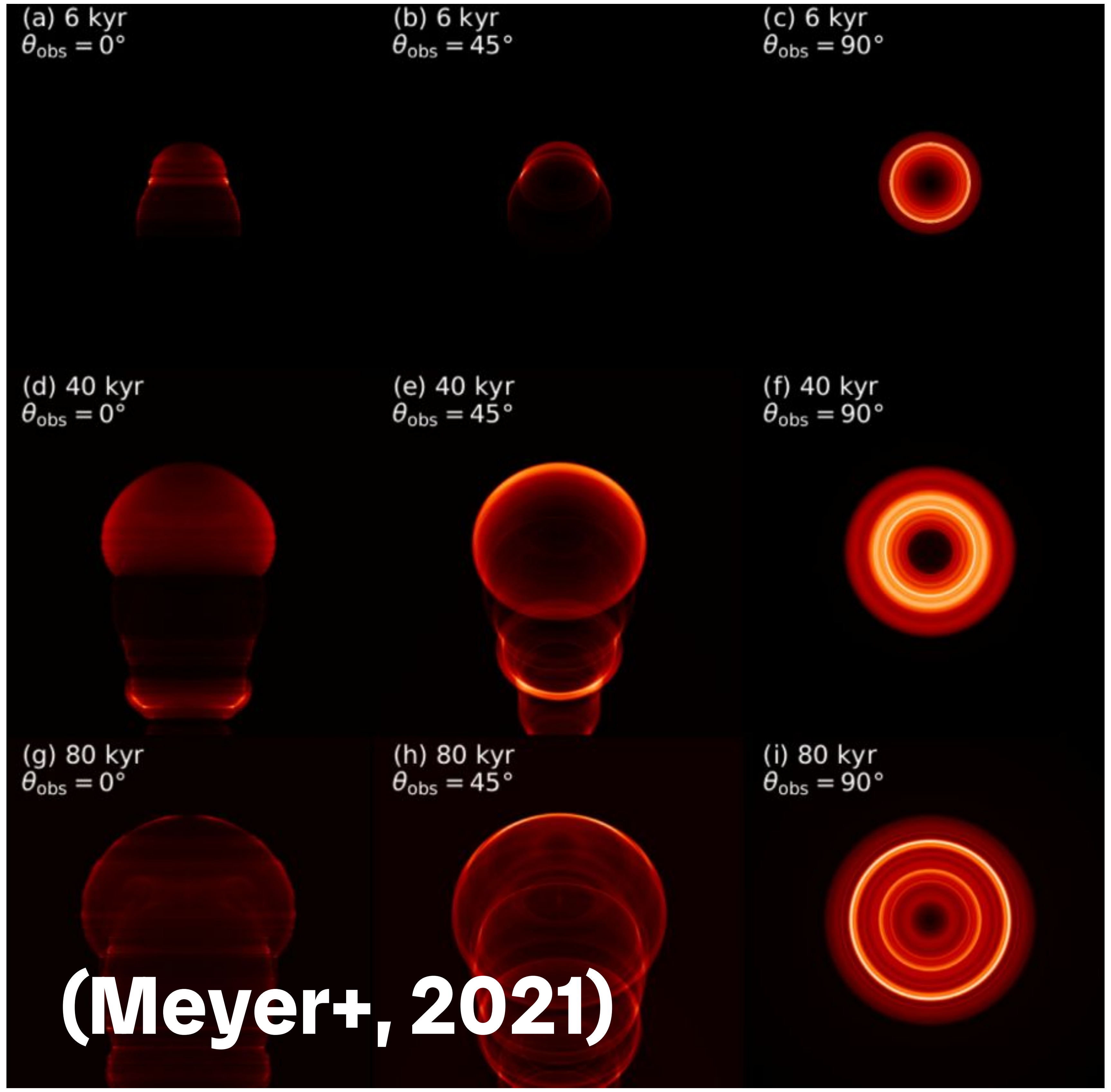
- **Runway Wolf-Rayet SNRs** (e.g., Meyer+ 2021) could produce ~100 pc off-plane structures with lobe-like emission

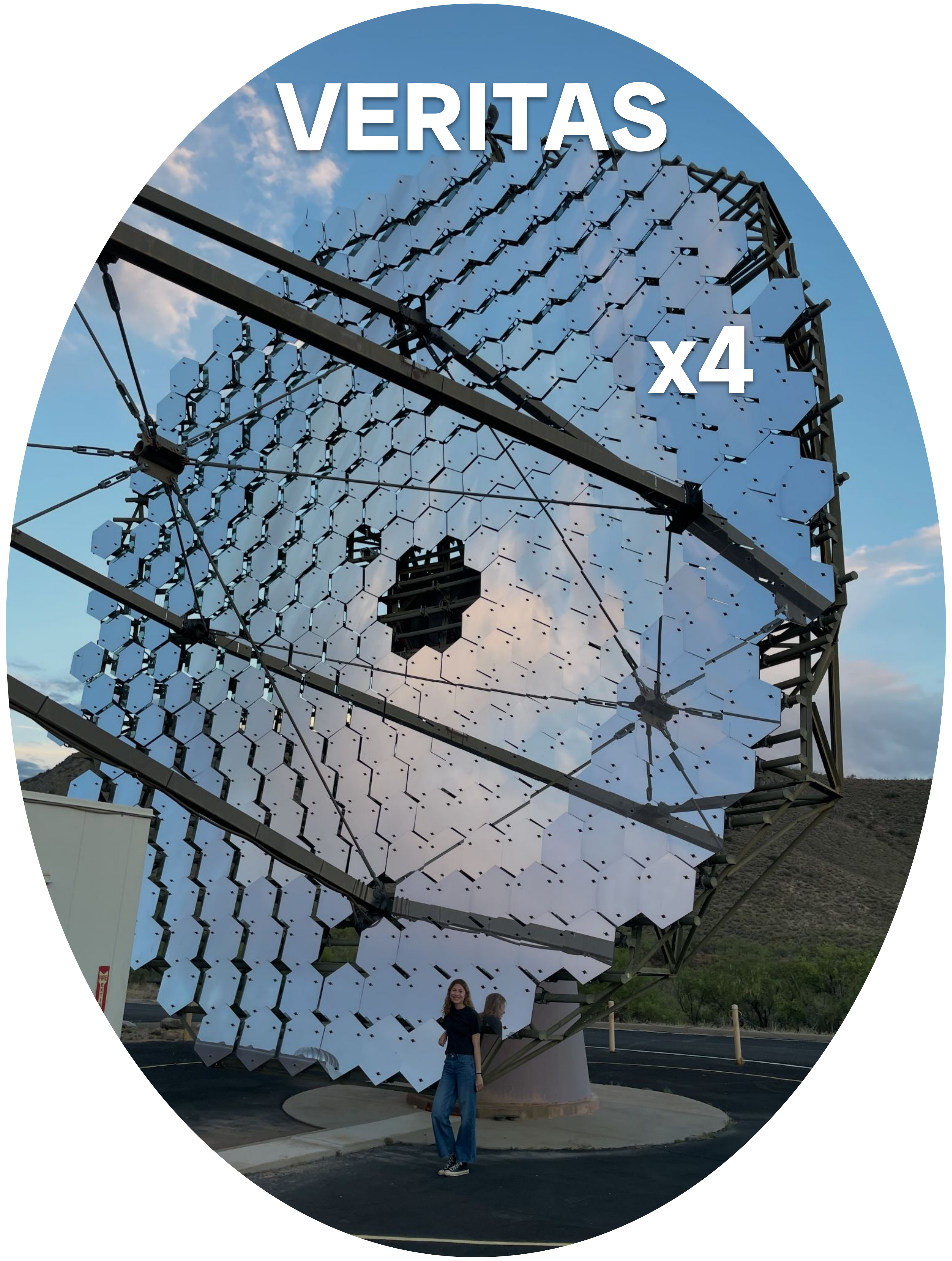


(Meyer+, 2021)

Proposed source classes: Alternatives

Your idea here!

VERITAS & LHAASO



- Pointing instrument
- 3.5 deg ∅ FoV
- 0.08 ° angular resolution @ 1 TeV
- 85 GeV- 30 TeV Energy range
- Large Effective Area (~10^5 @ 1 TeV)

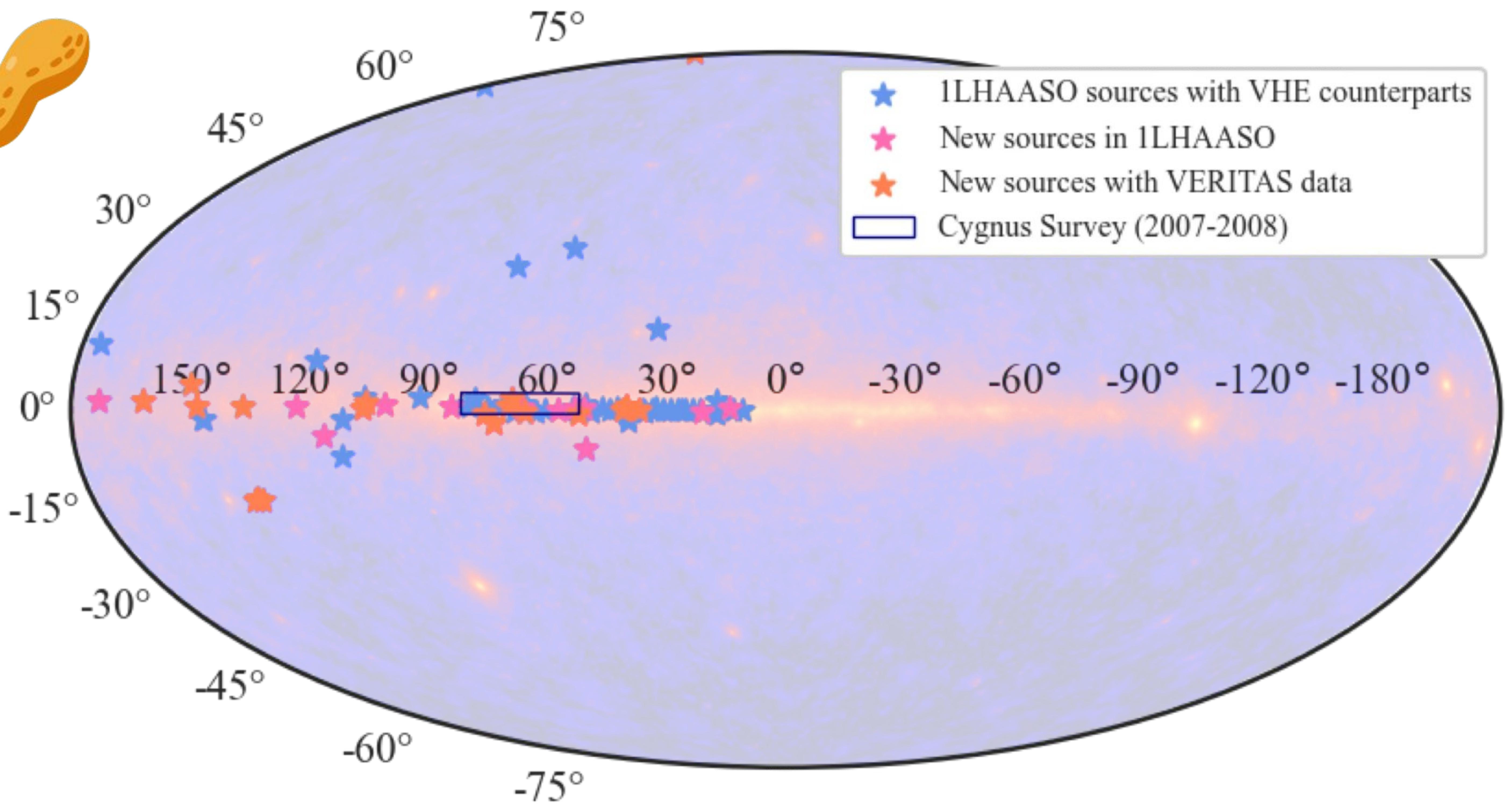
- Wide-field survey instrument
- ~2 sr FoV
- ~0.2-0.5° angular resolution
- 1-25 TeV (WCDA) and 20-2000 TeV (KM2A) energy range)
- WCDA: smaller EA (3200 @ 4.5 TeV), KM2A: large EA (~10^5 @ 100 TeV)

VERITAS & LHAASO

VERITAS has archival exposures on 17 1LHAASO sources (counting the Peanut as a single source).

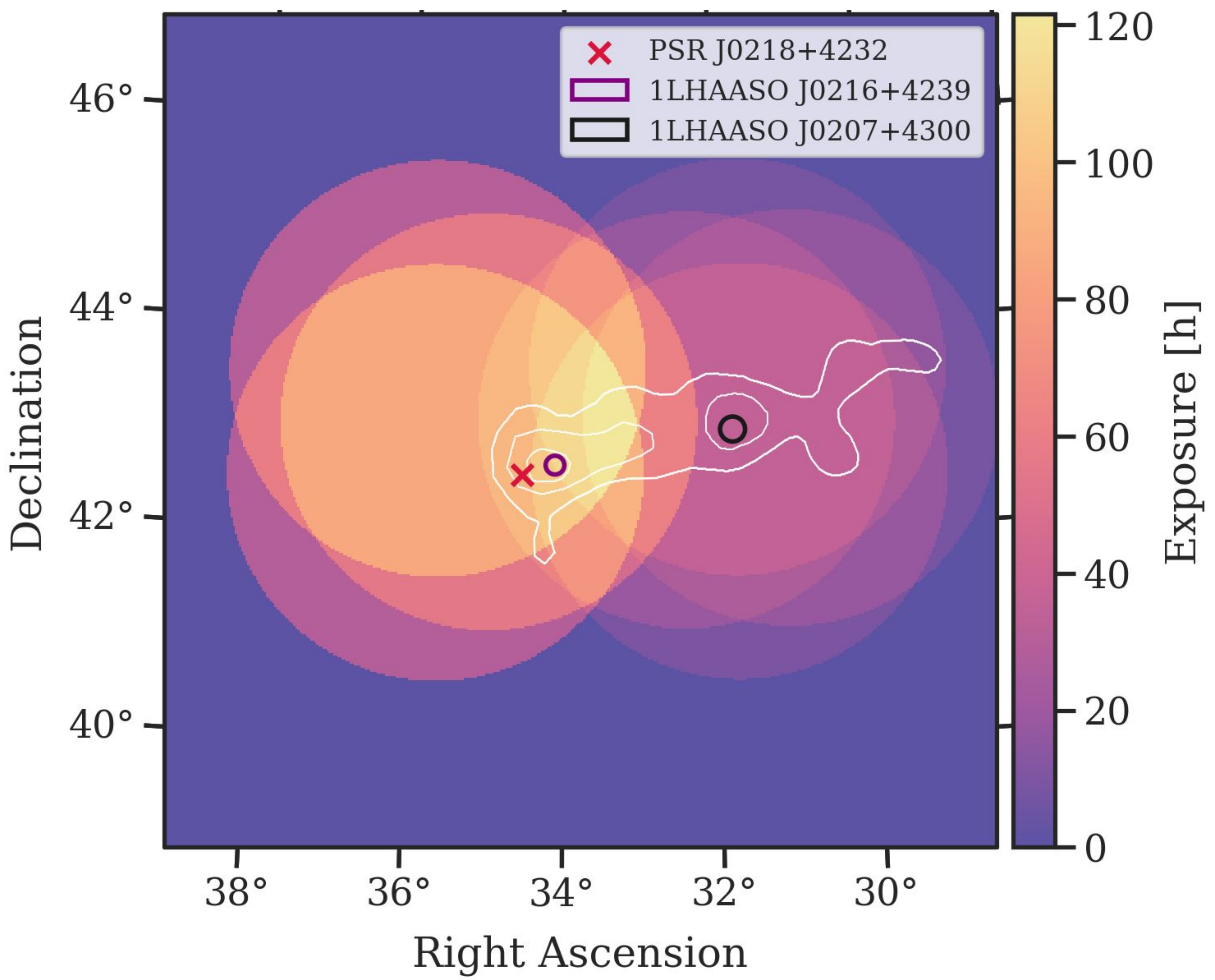
Table 1. VERITAS Archival Observations

Source ID	VERITAS Exposure [h]	Approx. VHE Extension [°]
1LHAASO J0206+4302u	0.5	Point-like
1LHAASO J0212+4254u	30.9	Point-like
1LHAASO J0216+4237u	107.4	Point-like
1LHAASO J0249+6022	153.5	0.71 (WCDA)
1LHAASO J0359+5406	29.4	0.22 (WCDA)
1LHAASO J0428+5531*	40.4	1.18 (WCDA)
1LHAASO J0500+4454	1.3	0.41 (WCDA)
1LHAASO J1219+2915	373.8	Point-like
1LHAASO J1858+0330	17.0	0.52 (WCDA)
1LHAASO J1902+0648	39.5	Point-like
1LHAASO J1906+0712	51.0	0.21 (WCDA)
1LHAASO J1931+1653	24.4	Point-like
1LHAASO J1954+3253	17.2	Point-like
1LHAASO J1959+2846u	55.1	0.29 (KM2A)
1LHAASO J2002+3244u	11.8	Point-like
1LHAASO J2027+3657	43.9	0.38 (WCDA)
1LHAASO J2028+3352	3.8	1.7 (KM2A)
1LHAASO J2229+5927u	124.5	1.98 (WCDA)
1LHAASO J2238+5900	88.0	0.51 (WCDA)



Follow-up observation strategy

- **VERITAS: 140h** of archival data (target: 3C 66A) + **40h** of new data (2025-2026) targeted on LHAASO J0207+4300
- **VERITAS pulsar:** Temporal analysis of all 180h VERITAS data using Fermi-LAT ephemerides
- **Fermi-LAT:** "off pulse" analysis of all 2008-2026 Fermi-LAT data



VERITAS analysis

The first IACT follow-up campaign on the Peanut provides a lower-energy and higher-resolution view of the source.

- Template based on LHAASO's 2 Gaussian + rectangular strip model for direct source region comparison with LHAASO
- High level analysis using Gammapy (v2.0) FoV background estimation
  - Background models are built from source-free runs that match each data run in observing season, elevation, and azimuth
- **Stacked significance for all three template models is 0.42σ (moderate gamma/hadron cuts)/0.11σ (hard cuts)**

E_{ref} [TeV]	E_{min} [TeV]	E_{max} [TeV]	ON	OFF	UL [10^{-14} TeV^{-1} cm^{-2} s^{-1}]
0.34	0.25	0.46	49260	50002	224
0.82	0.46	1.51	43548	44112	39.3
2.04	1.51	2.75	5477	5581	9.16
3.71	2.75	5.00	2056	2141	1.92
6.75	5.00	9.10	736	759	1.37

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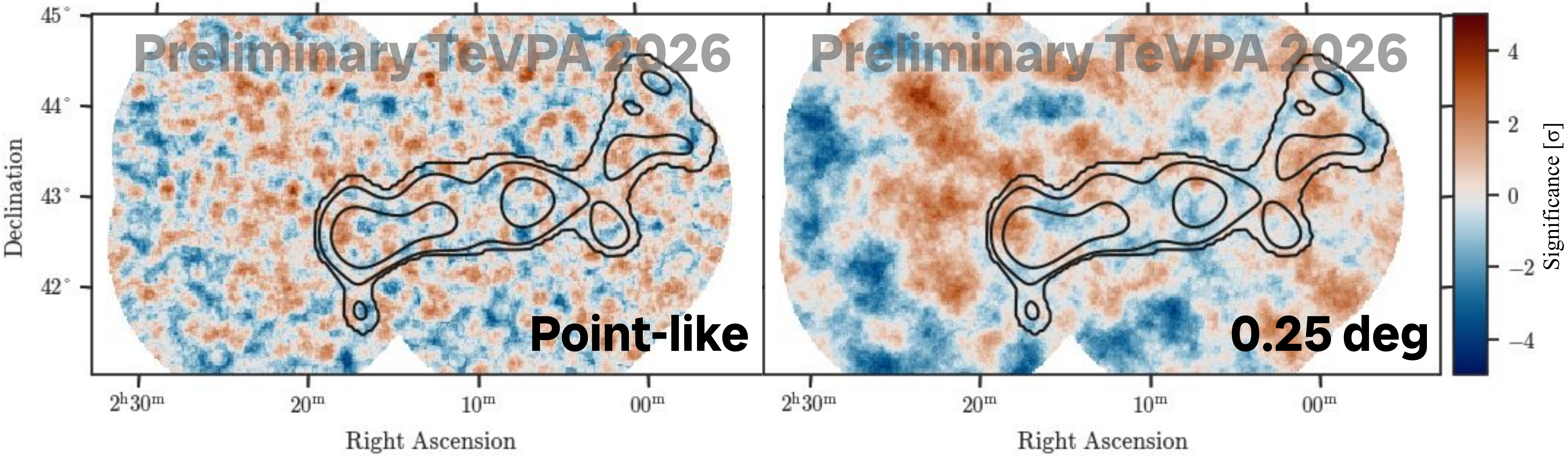

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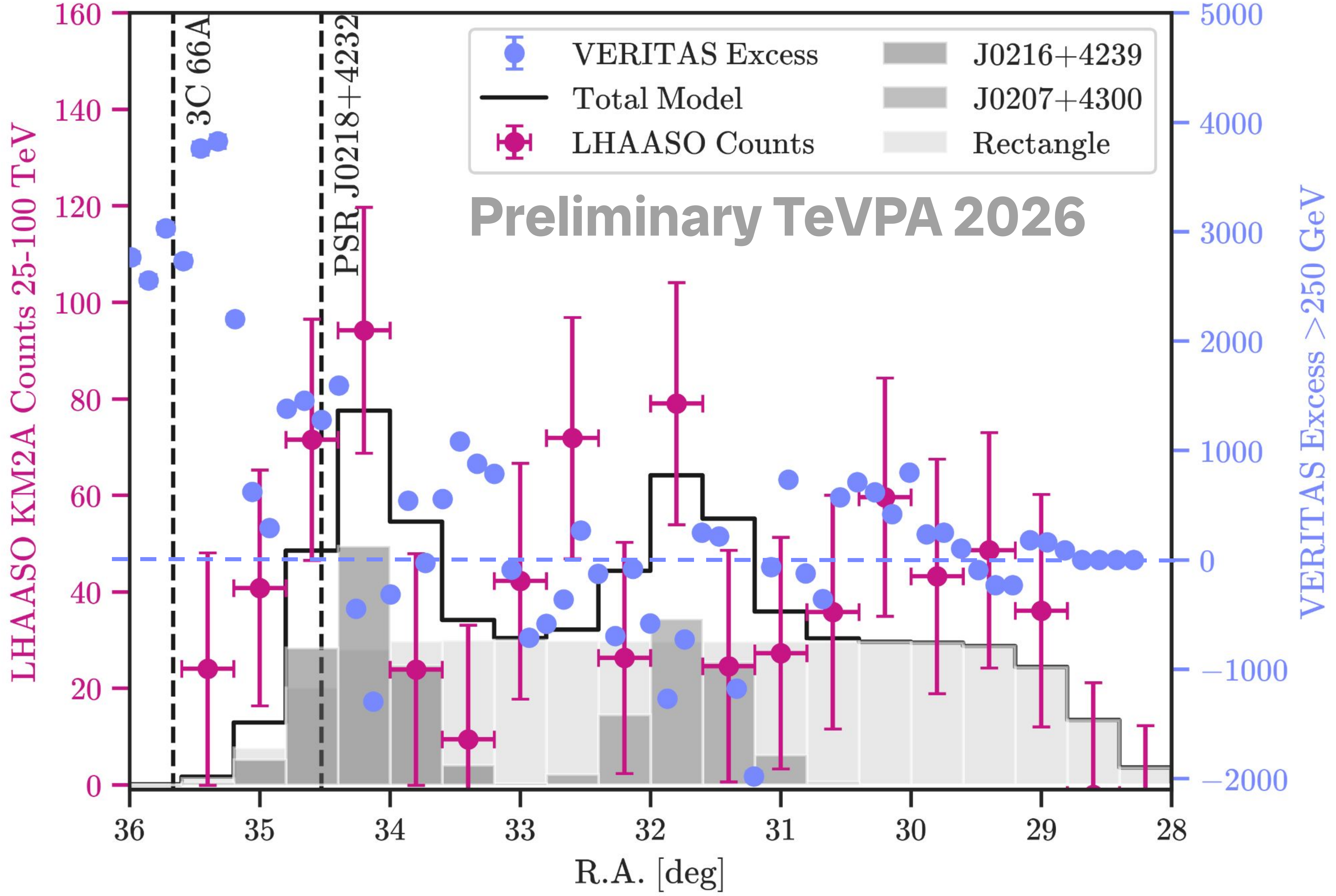

High energy analysis with VERITAS

Can we leverage non-traditional analysis methods to recover Peanut events at the edge of VERITAS' sensitivity?

Crab Nebula
(energies >10 TeV are approximate)

E_{ref} [TeV]	E_{min} [TeV]	E_{max} [TeV]	ON	OFF
11.22	10.00	12.59	290	17
14.13	12.59	15.85	217	9
17.78	15.85	19.95	160	8
22.39	19.95	25.12	113	2
28.18	25.12	31.62	66	5
35.48	31.62	39.81	48	2
44.67	39.81	50.12	20	0
56.23	50.12	63.10	21	6
70.80	63.10	79.43	12	1
89.13	**79.43**	**100**	**15**	**10**

Hadronic background decreases $\propto E^{2.7}$

New (non-hadronic?) source of background?

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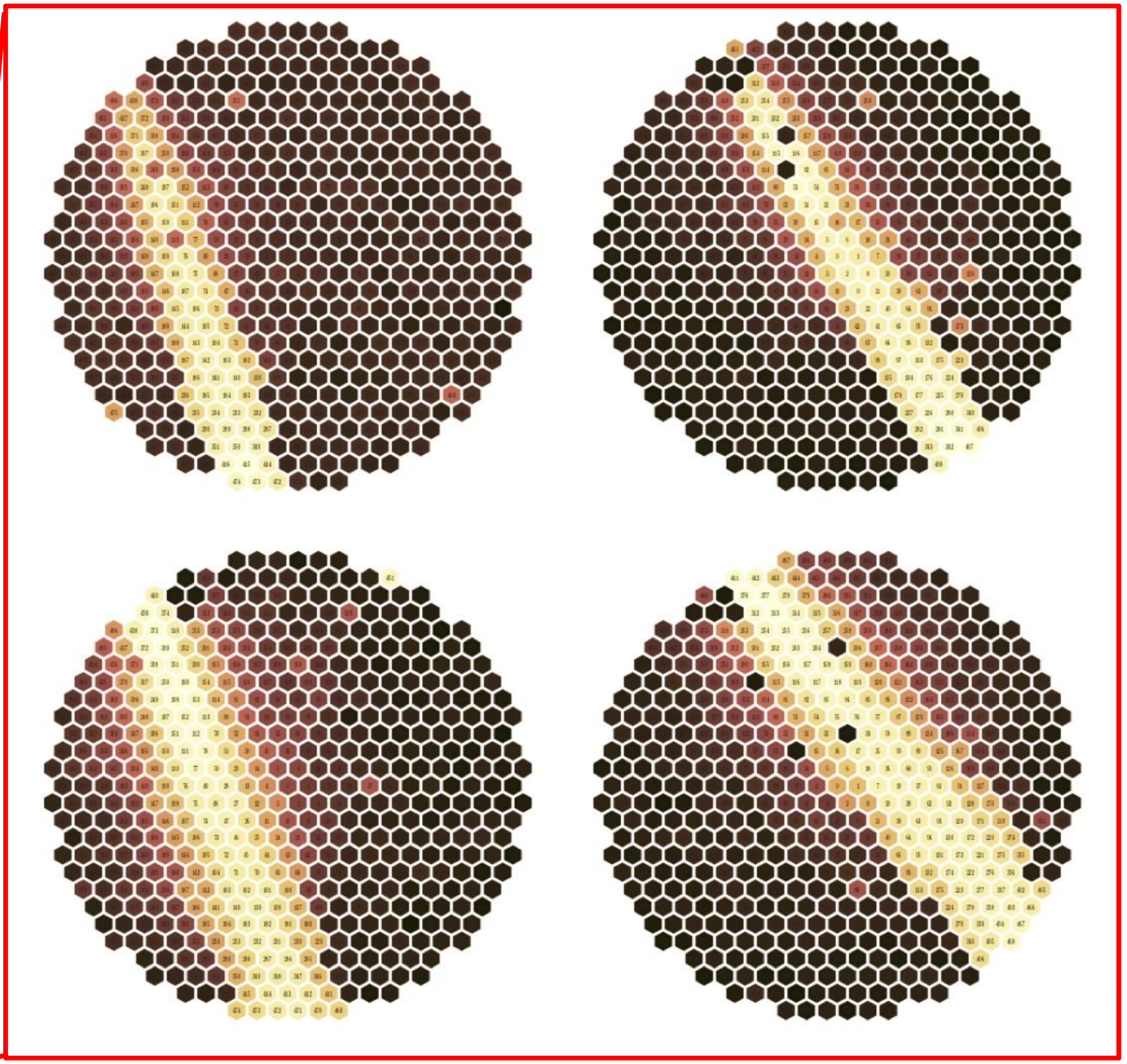

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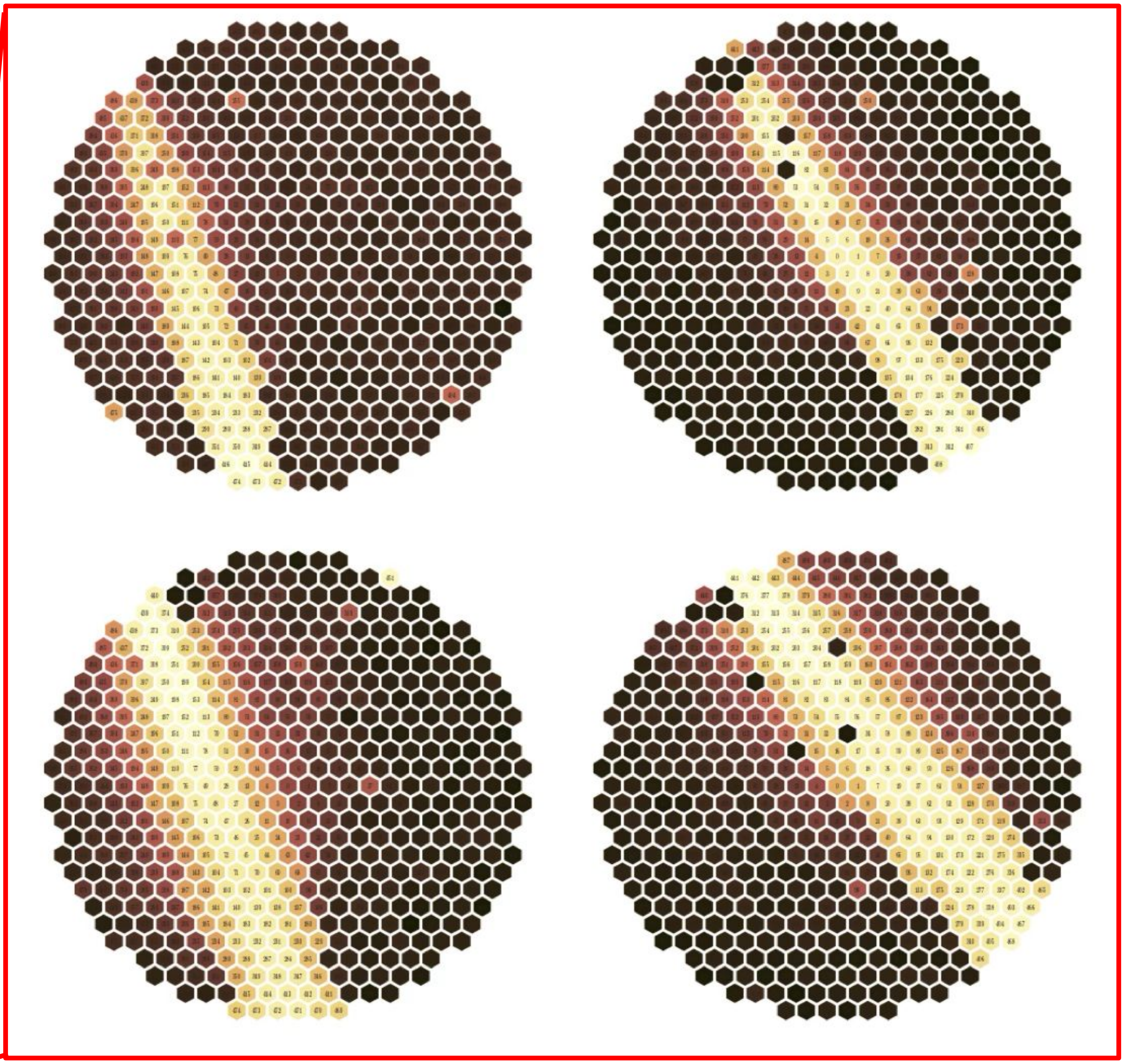
New (non-hadronic?) source of background?

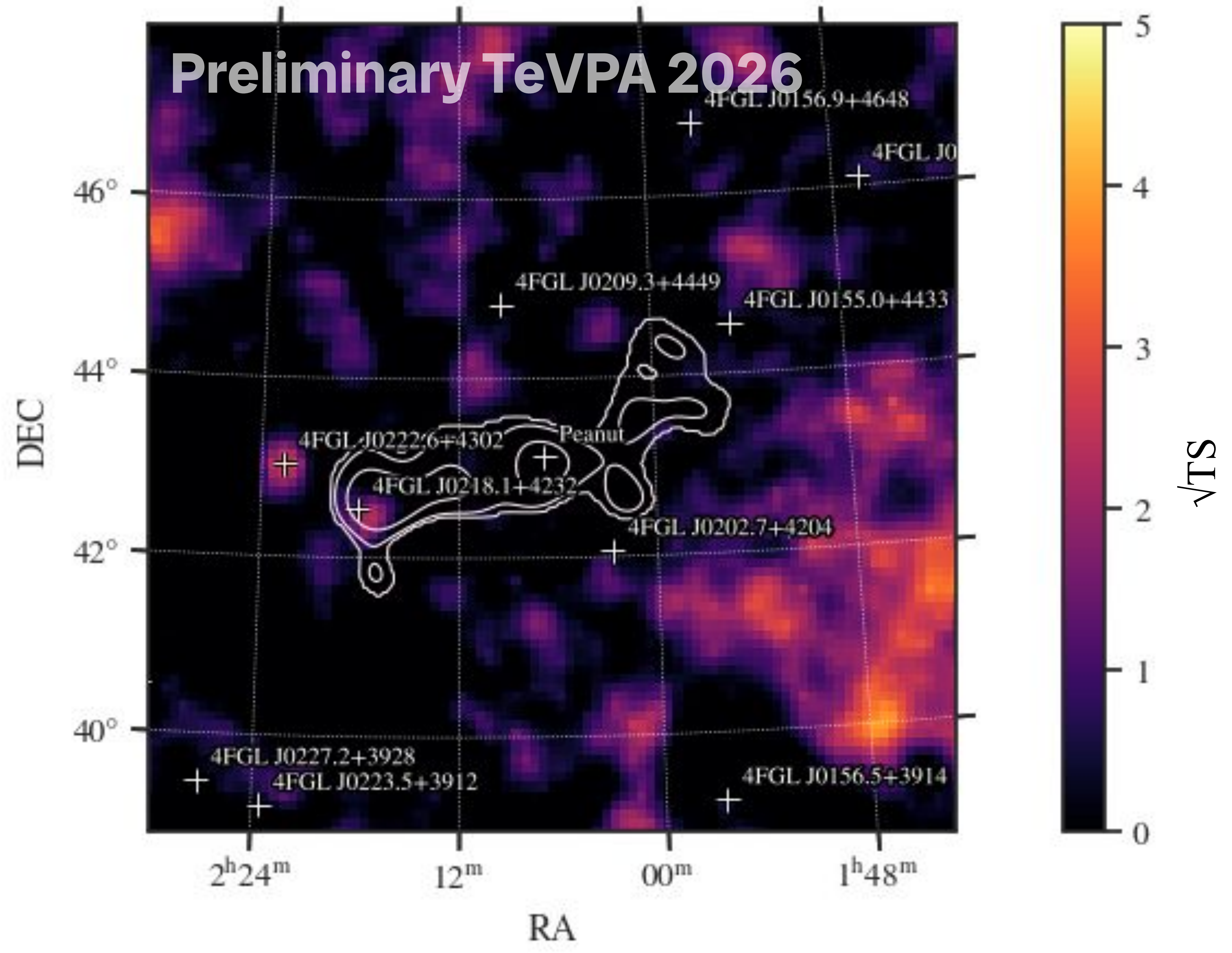
≳80 TeV events are **long** with **low parallax**
⇒ gamma-ray-like events at large core distances

Many are thrown out by core distance/Hillas parameter cuts
⇒ Adjustments to cuts and reconstruction parameters might be needed to better determine the Peanut significance at the highest energies seen by VERITAS



Fermi-LAT analysis

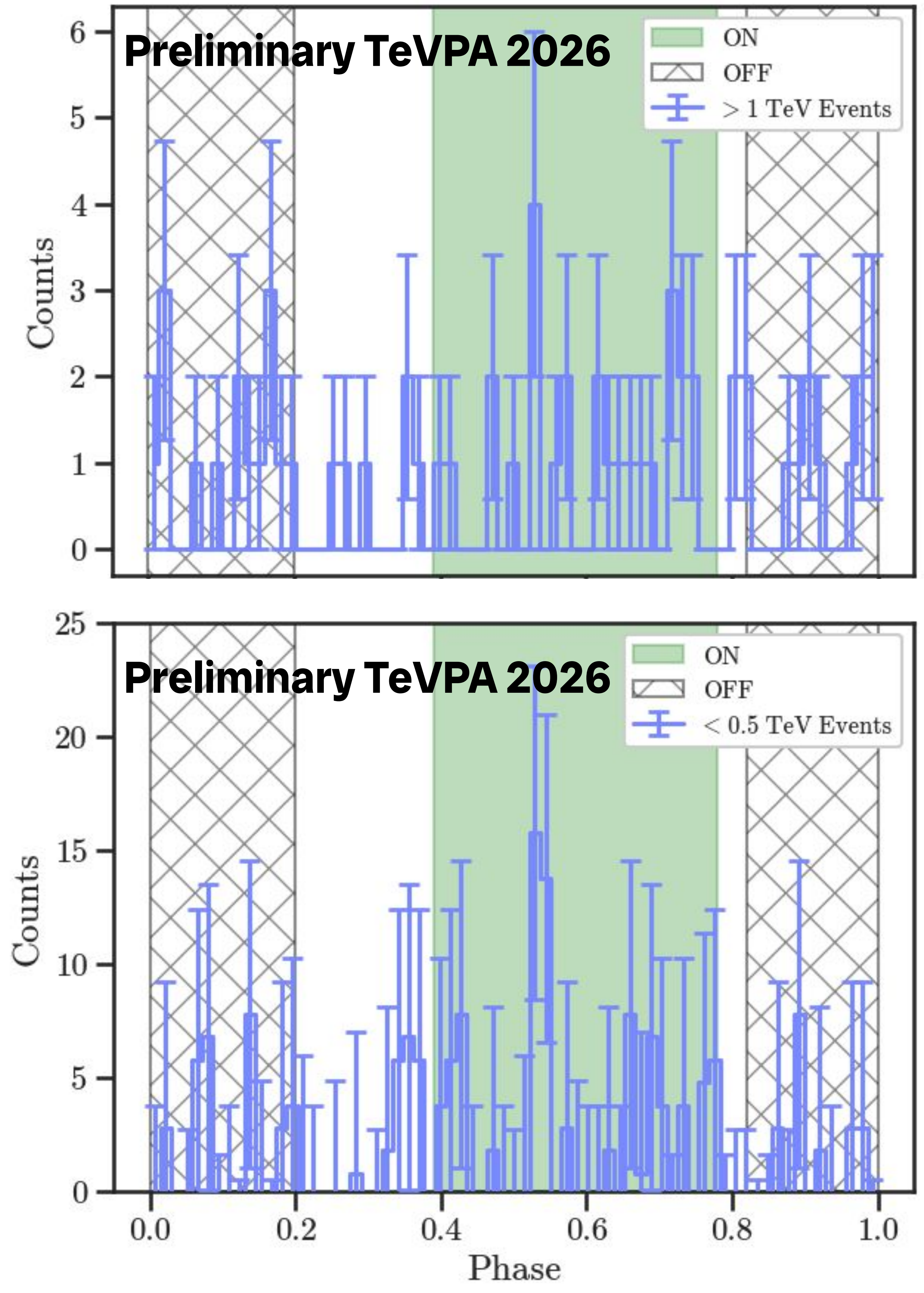
- Analyzed 18 years of Fermi-LAT data from 100 MeV - 1 TeV
- We only use events in the pulsar “off” phase, to reduce contamination from PSR J0218+4232
- Template based on LHAASO’s 2 Gaussian + rectangular strip model for direct source region comparison with LHAASO and VERITAS
- Non-detection: TS = 3.13



Pulsar analysis

A non-detection of pulsed TeV emission constrains the pulsar's leptonic power, which informs the feasibility of the pulsar as the Peanut central engine.

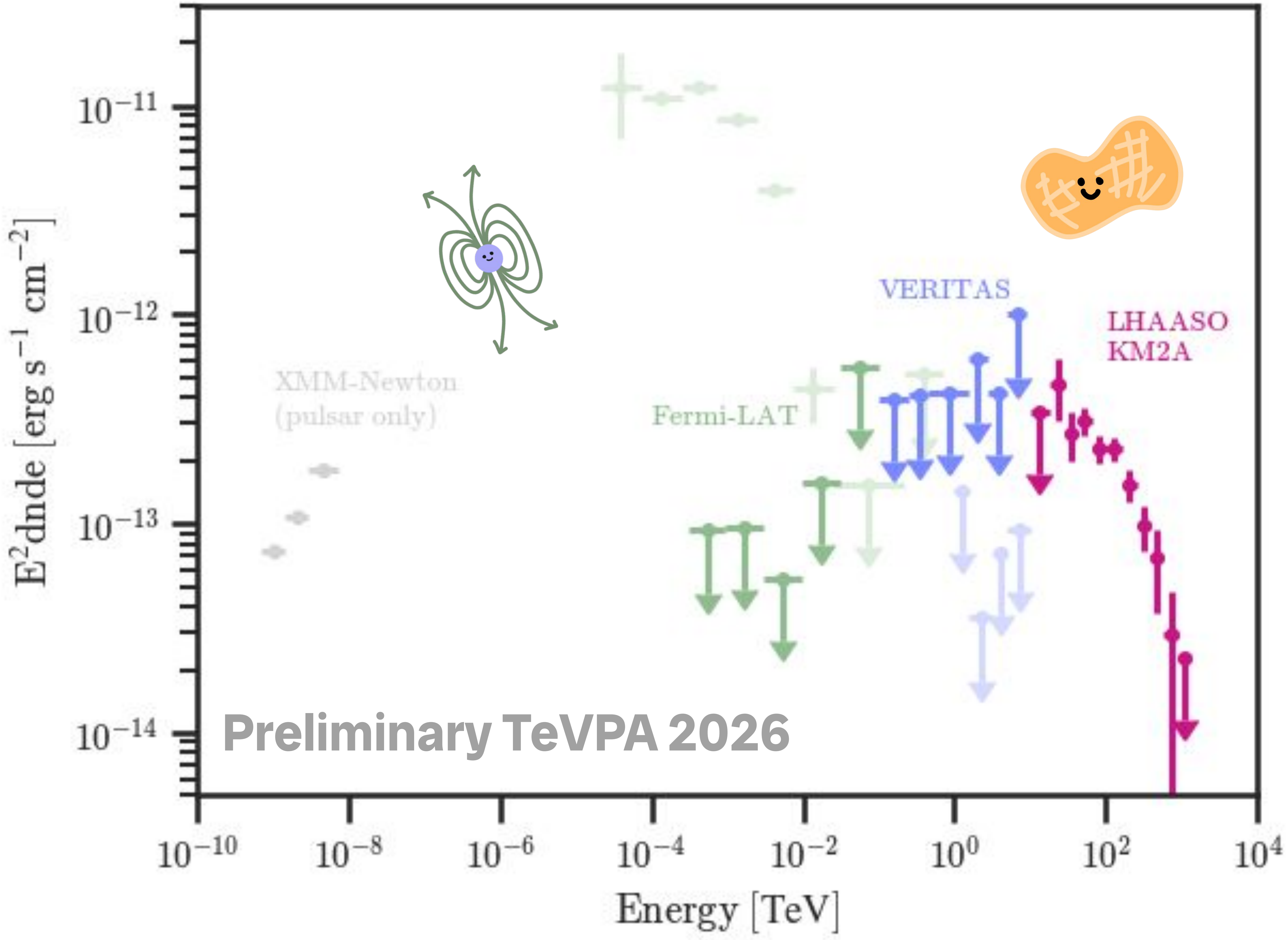
- Searched for both **soft, Crab-like** (~100 GeV extension to Fermi-LAT spectrum) and **hard, Vela-like** (distinct multi-TeV component) emission
- Ephemerides provided by the Fermi-LAT pulsar timing group
- **Non-detection of pulsed emission** in both analyses (unbinned Li & Ma)
  - Soft: 1σ, $F_{0.25\text{-}0.5\ \mathrm{TeV}} < 5.48 \times 10^{-7}\ \mathrm{cm^{-2}\ s^{-1}}$
  - Hard: -0.2σ, $F_{1\text{-}30\ \mathrm{TeV}} < 1.34 \times 10^{-17}\ \mathrm{cm^{-2}\ s^{-1}}$



A multiwavelength view of the Peanut

Desaturated points = PSR J0218+4232

Full colour points = Peanut



Modelling

VERITAS data confirm the necessity of a very hard proton spectrum in a hadronic scenario and do not favour either a hadronic or a leptonic model.

PLEC = Exponential cutoff power law with β = 1

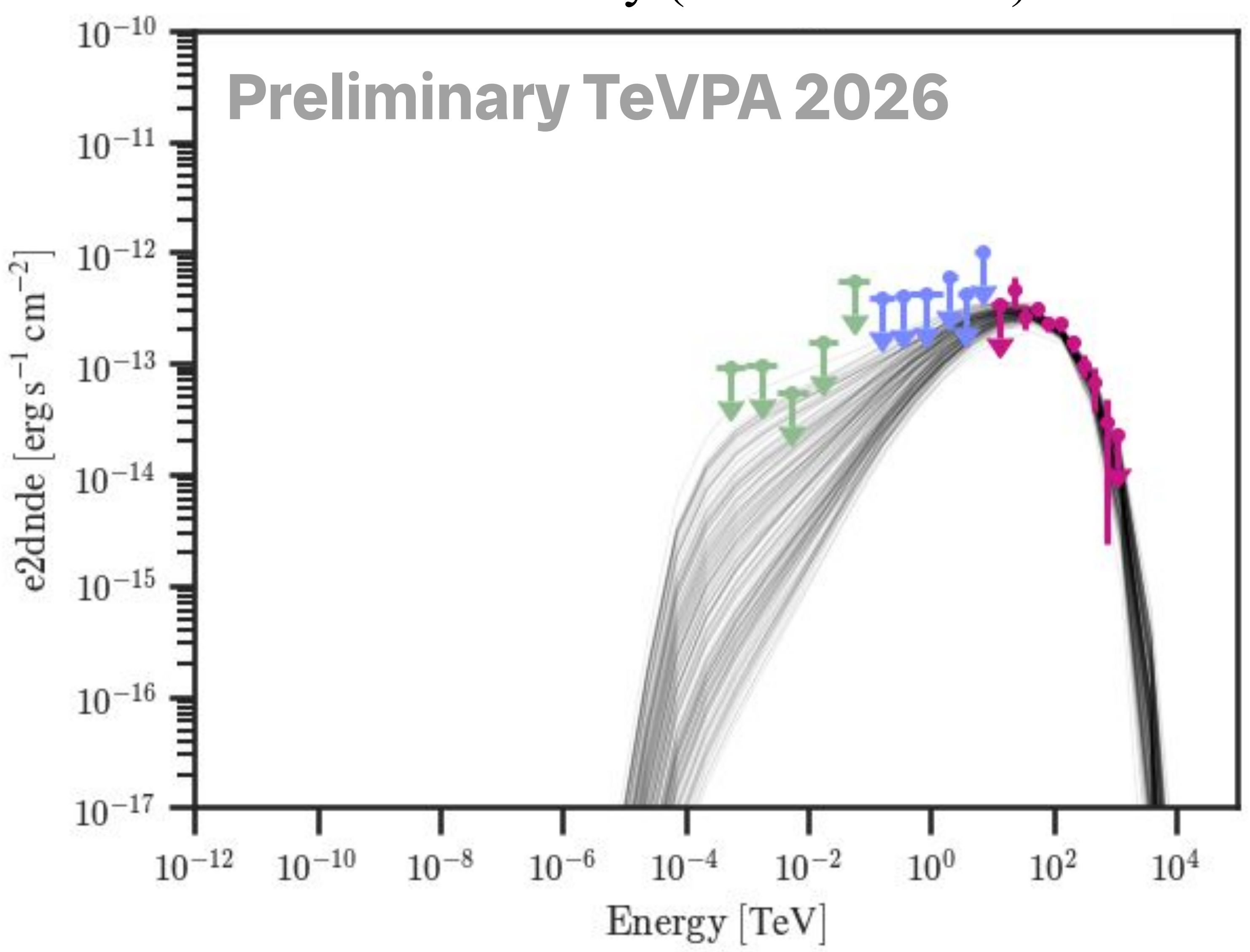
PLEC2 = Exponential cutoff power law with β = 2

Naima IC (Khangulyan+ 2014) and pion decay (Kelner+ 2006) models were used for this work.

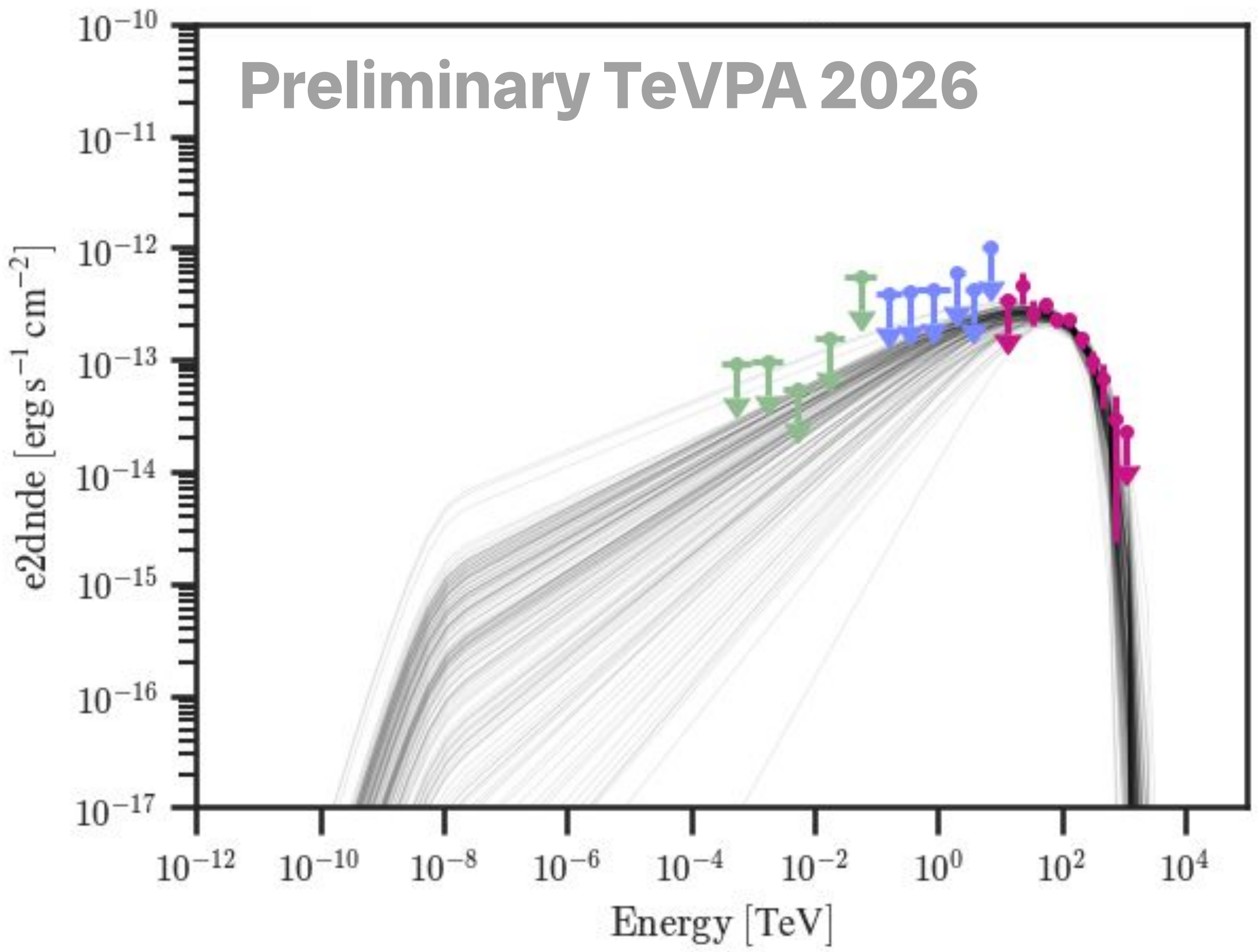
[*] hadronic modelling assumes nH = 1 cm-3, though observations of CO in the region imply a much lower molecular cloud density

Model	$W_{e/p,>50/>100\ \mathrm{TeV}}$ [erg]	Index	E_c [TeV]	AIC
IC-CMB (this work)	$1.1 \pm 0.1 \times 10^{45}$	$2.28^{+0.13}_{-0.25}$	610^{+170}_{-120}	8.3
LHAASO-only IC-CMB (PLEC2)	$1.2 \pm 0.3 \times 10^{45}$	2.48 ± 0.27	770 ± 240	-
Pion Decay (this work)	$4.3 \pm 0.5 \times 10^{48}$	$1.27^{+0.37}_{-0.48}$	870^{+480}_{-290}	8.2
LHAASO-only Pion Decay (PLEC)	$3.5 \pm 0.2 \times 10^{48}$	1.45 ± 0.55	860 ± 480	-

Pion Decay (Kellner+ 2006)

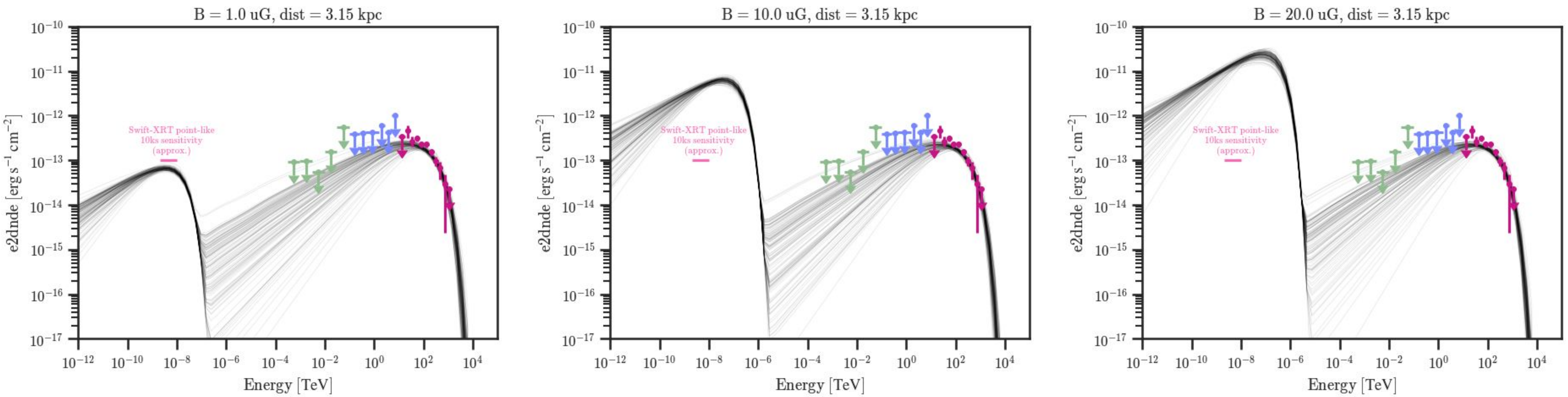


IC-CMB



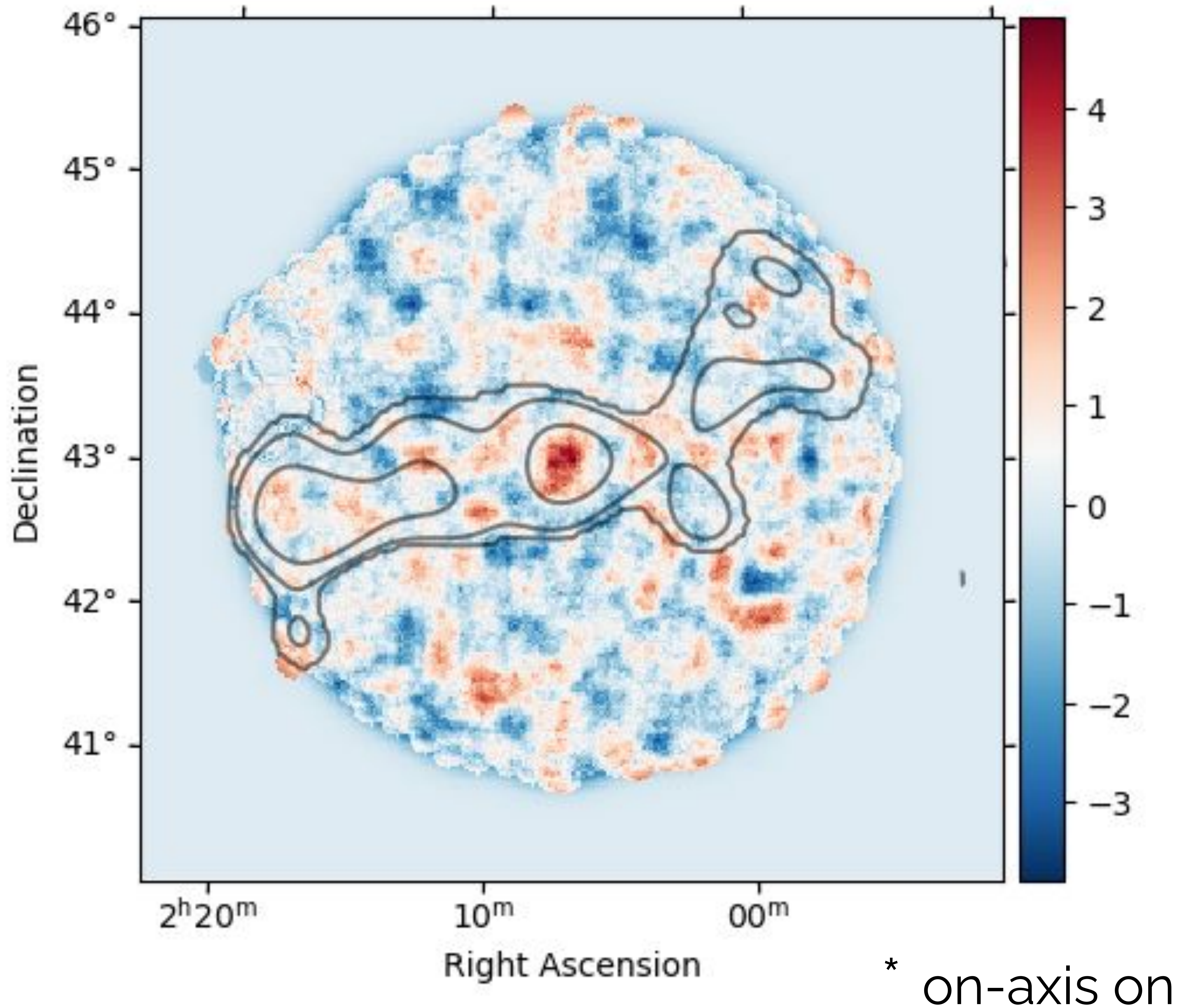
Modelling: synchrotron predictions

Assuming the LHAASO emission arises from SSC processes, we can estimate X-ray flux from synchrotron emission at fixed B-values.



Feasibility of an IACT detection

VERITAS 300h: point-like detection

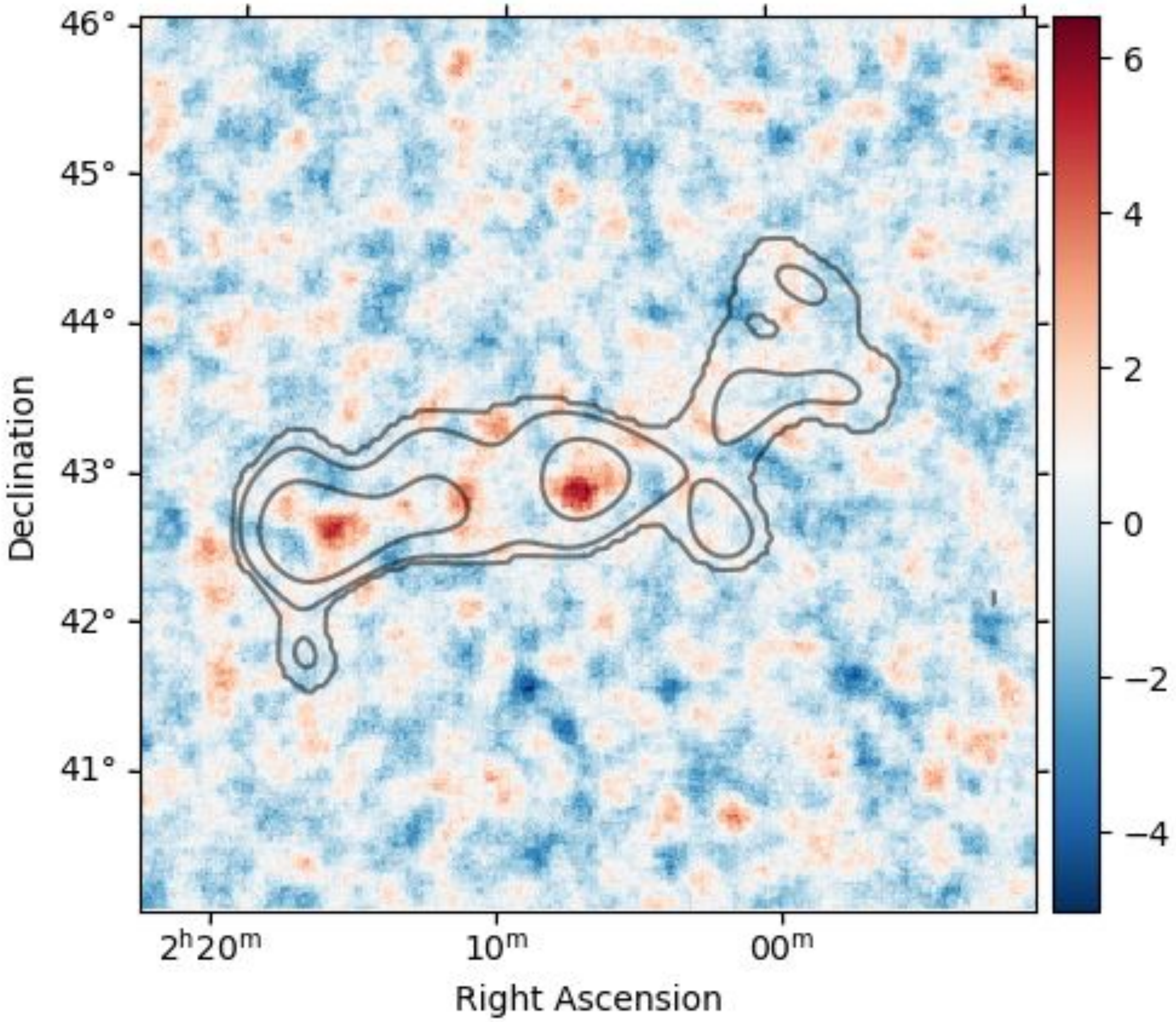


Gammapy **simulated** datasets with FoV background method

* on-axis only
* Post-2012 high elevation IRFs

Feasibility of an IACT detection

CTAO-North 30h: point-like detection

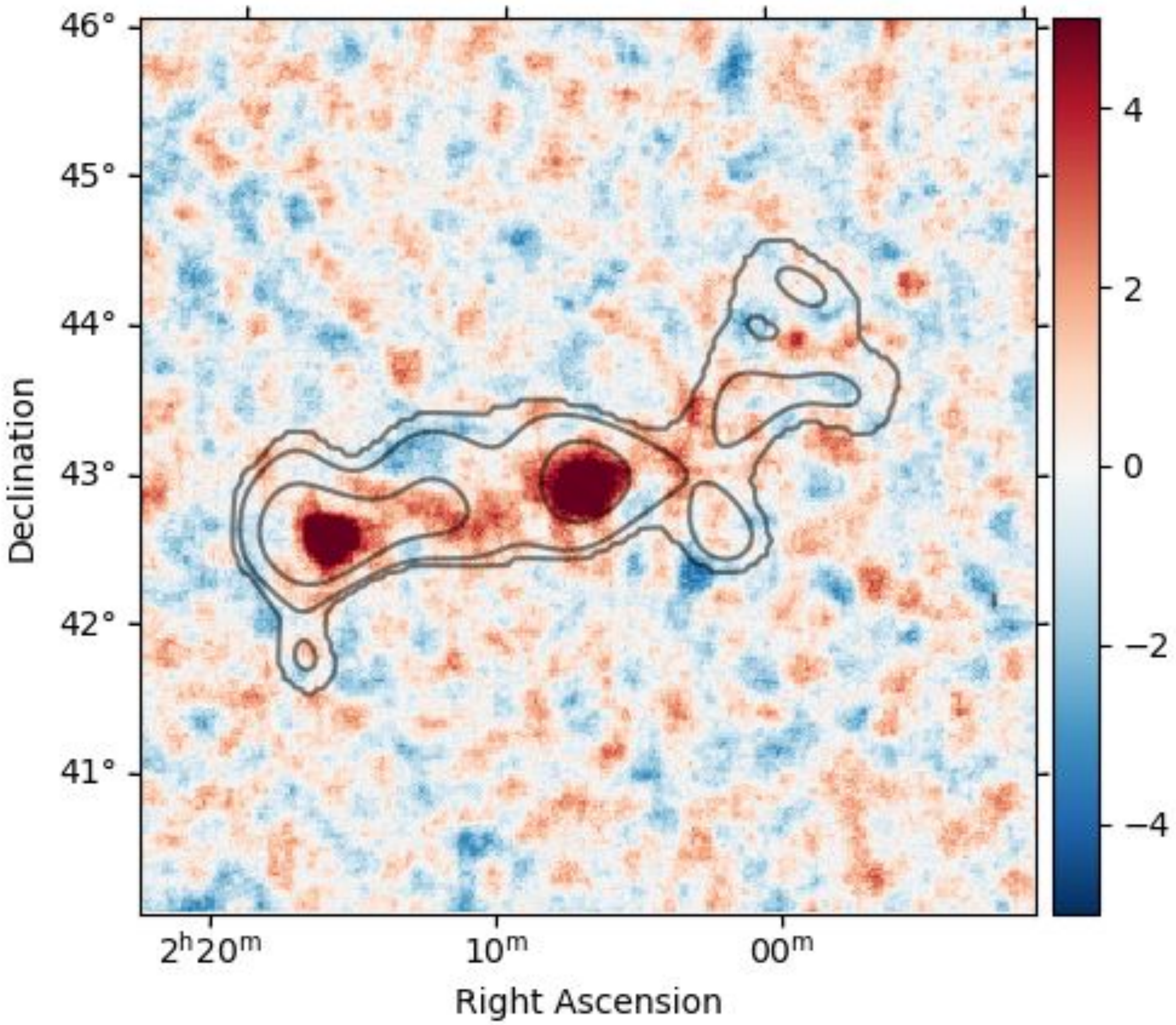


Gammapy **simulated** datasets with FoV background method

* Prod5 20deg ZA IRFs in Gammapy v2.0

Feasibility of an IACT detection

CTAO-North 300h: beginning of bridge detection



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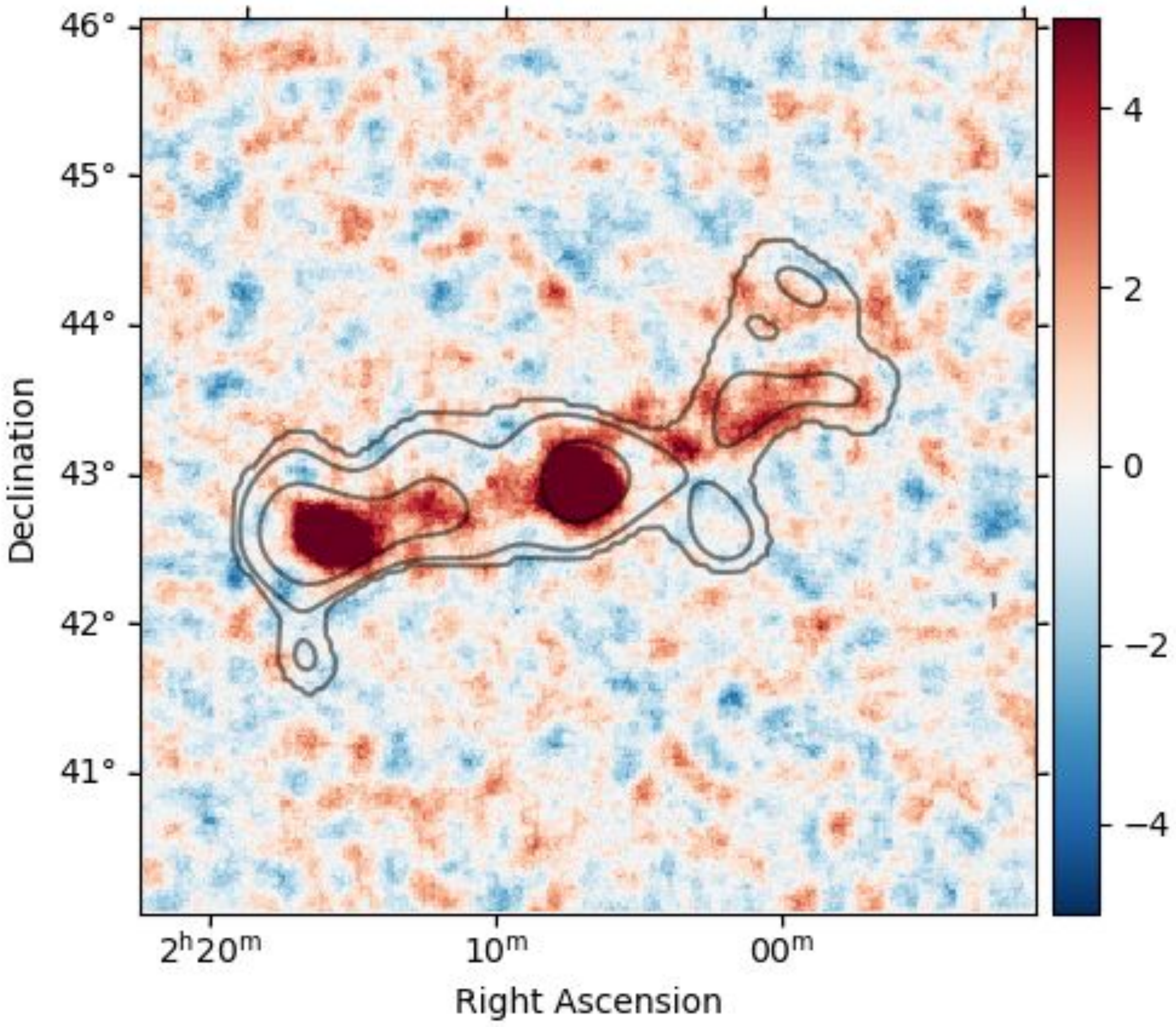
Feasibility of an IACT detection

CTAO-North 1000h: full strip detection



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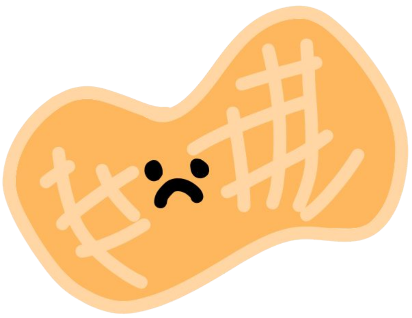
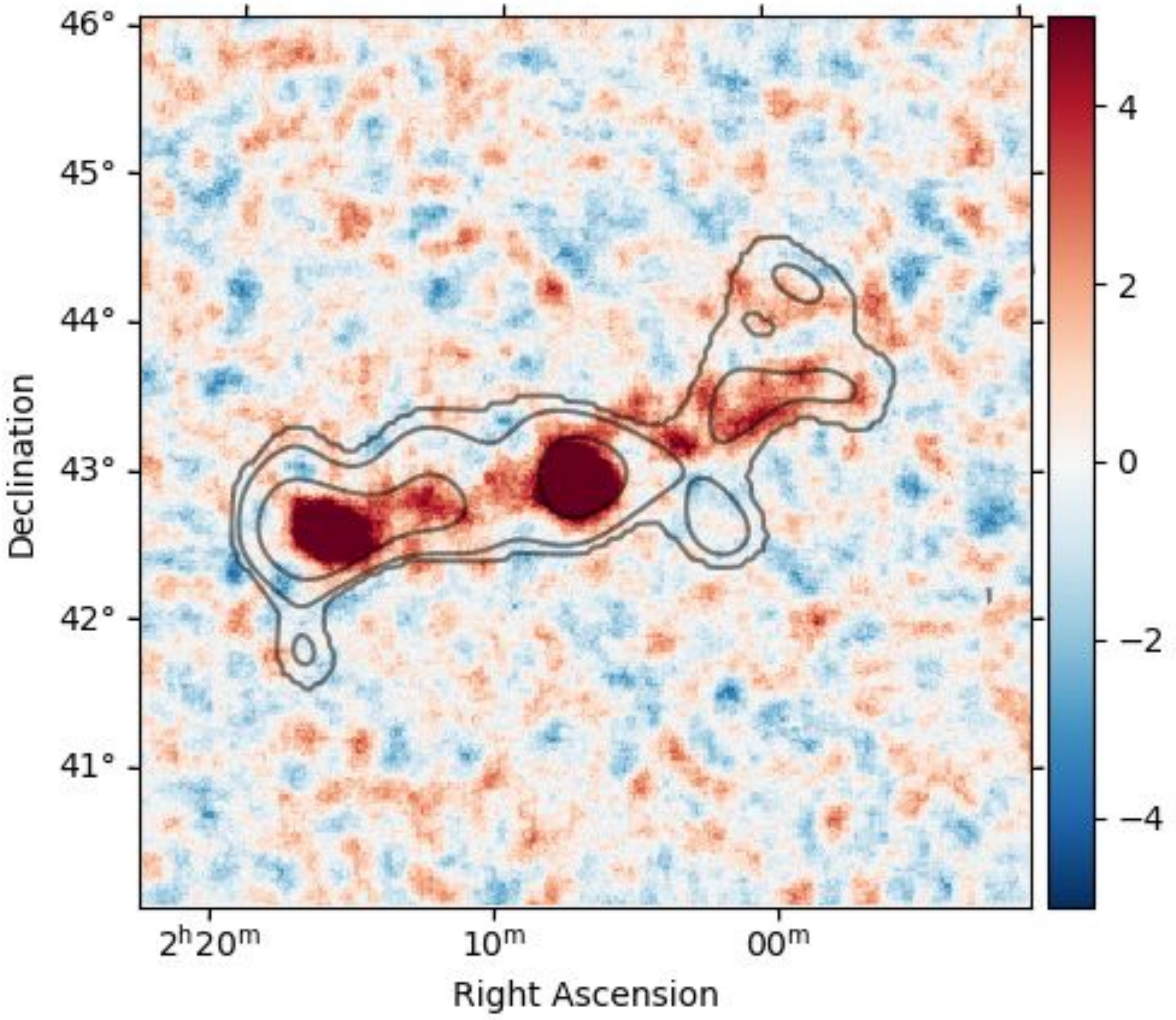


An IACT detection of the Peanut's morphology will be difficult with current and next-generation IACTs



Gammapy **simulated** datasets with FoV background method

* Prod5 20deg ZA IRFs in Gammapy v2.0

Summary

Due to its angular size, off-plane nature, and ultra-high-energy photons, the Peanut is one of the most intriguing 1LHAASO sources, but multi-wavelength follow up has proven challenging.

The Peanut remains undetected down to 100 MeV with complete VERITAS observations of the region and a detailed, extended Fermi-LAT analysis.

These non-detections challenge the association of the Peanut with any known TeV source classes and with millisecond pulsar PSR J0218+4232.

⇒ **The Peanut remains a source of unknown origin and association.**