

10 years of ultra-high-energy science with HAWC

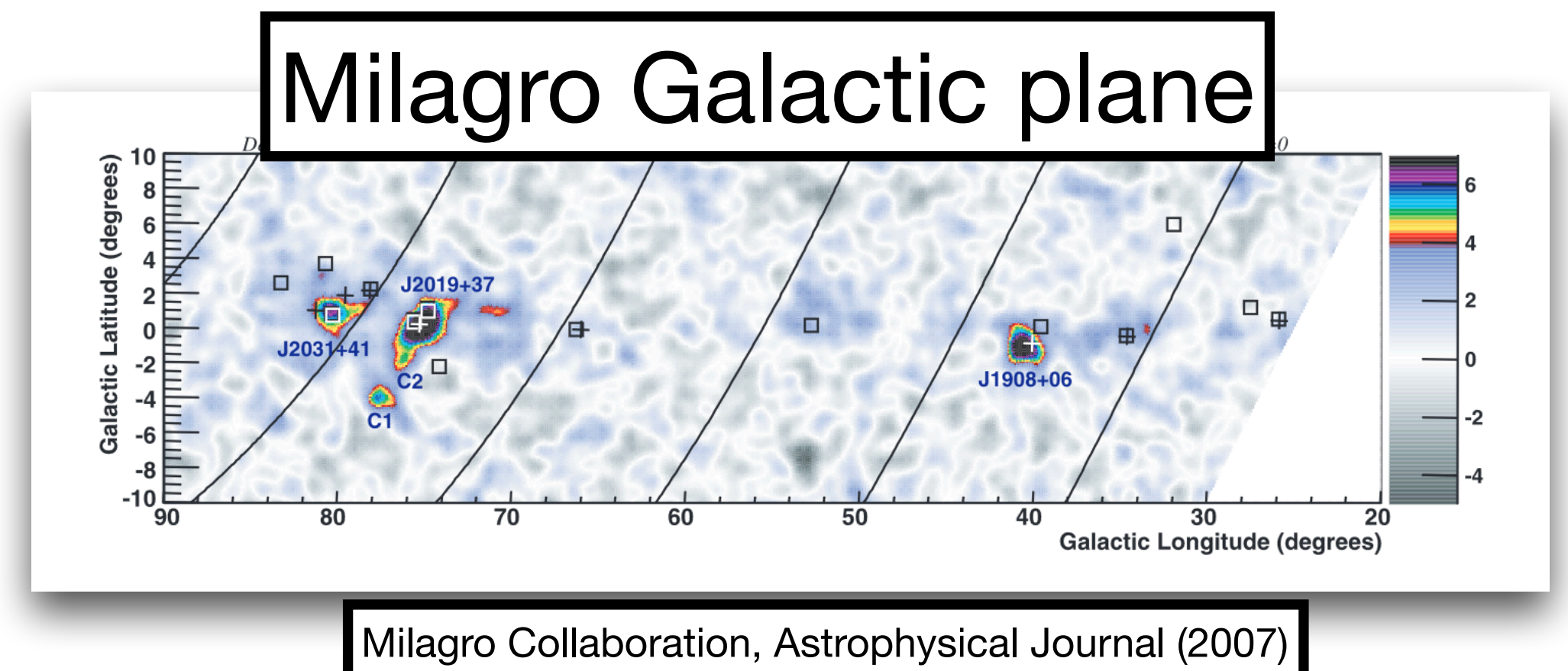
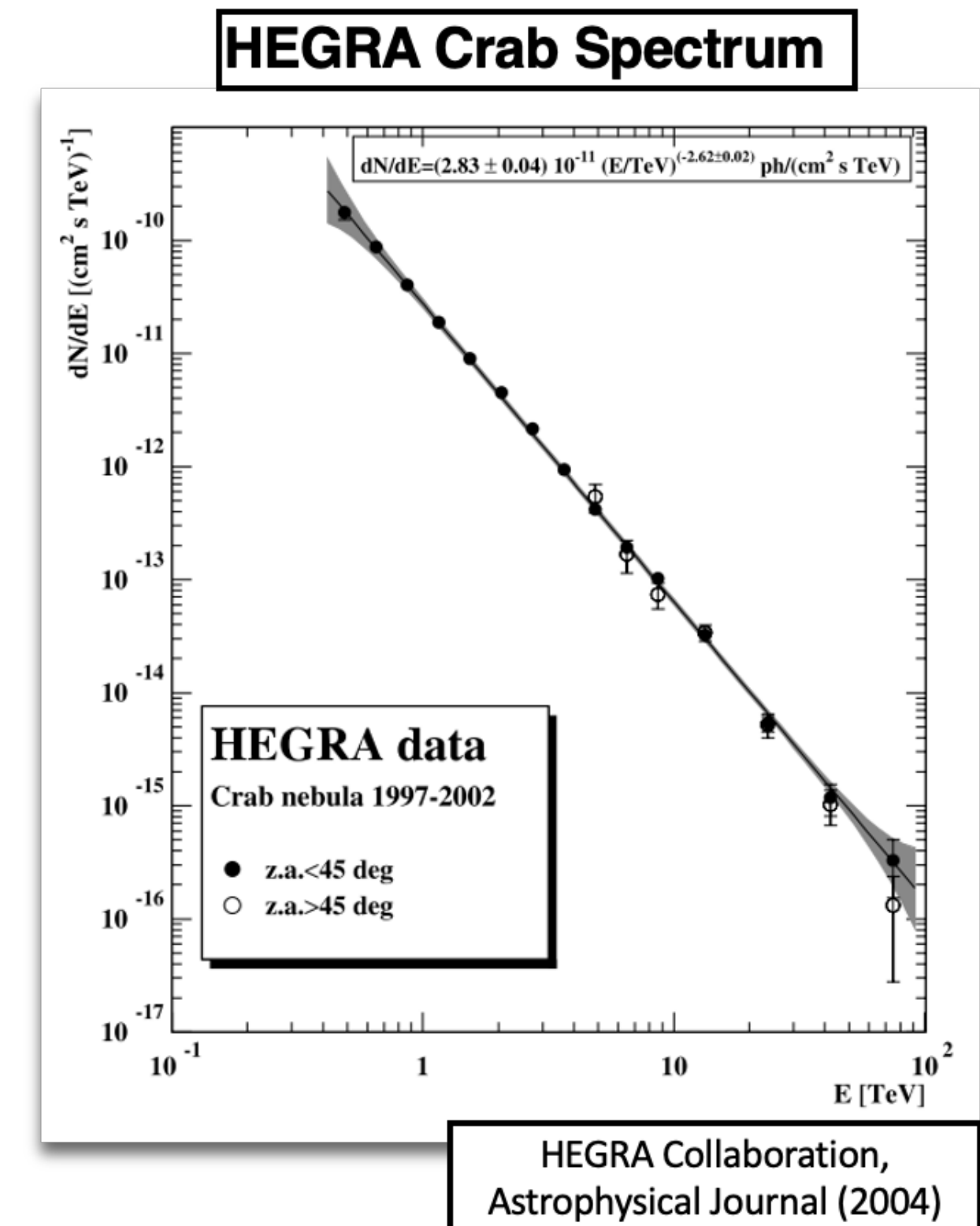
Kelly Malone, Los Alamos National Laboratory

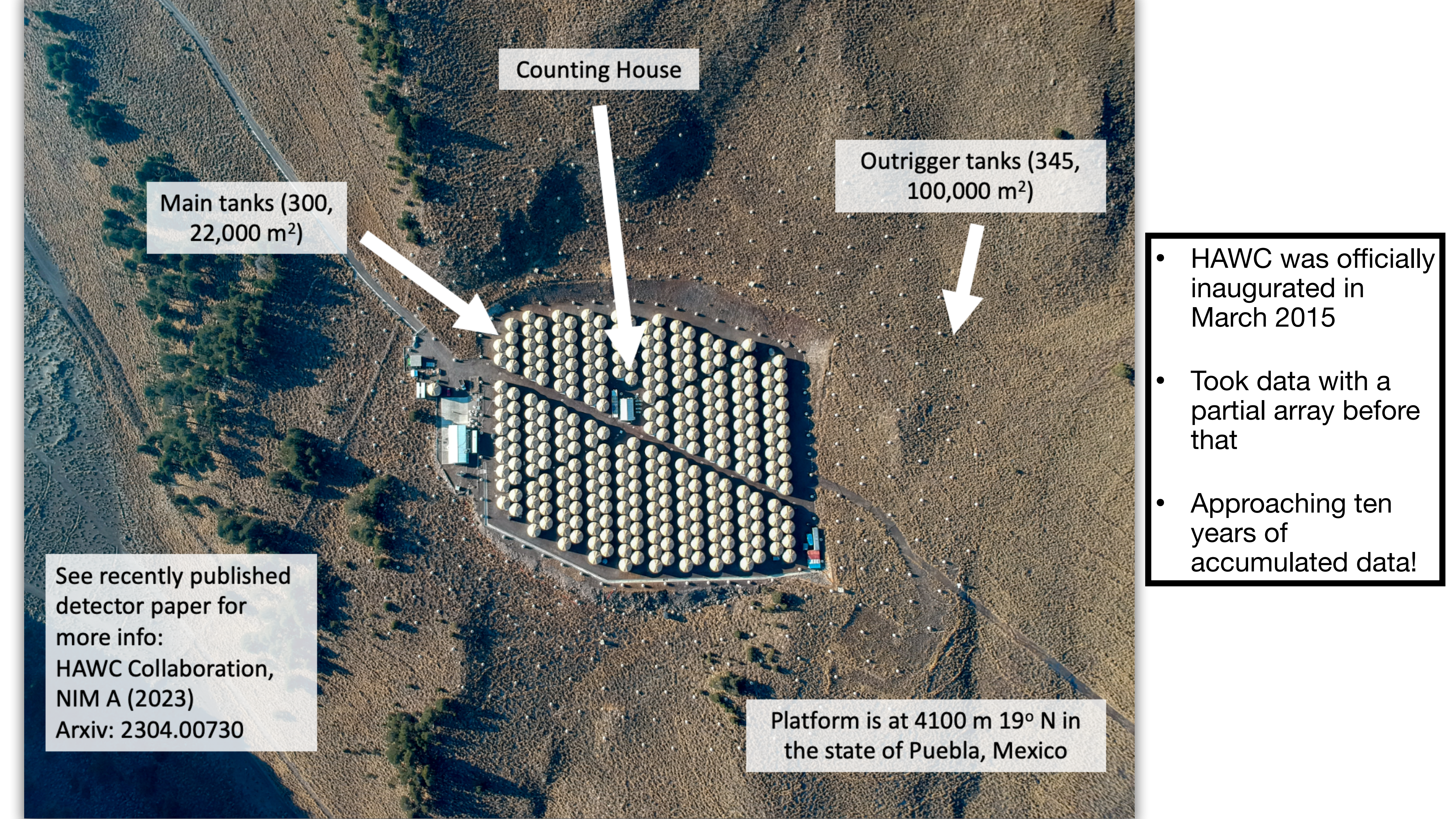
TeV Particle Astrophysics, Chicago, August 2024

UHE science before HAWC

The view of the sky in ~2013

- Many sources detected up to a few tens of TeV
 - Observations sparse above that
- HEGRA Crab PWN spectrum up to 80 TeV
 - Last bin, centered at 74 TeV, had a significance of 2.7σ
- Milagro surveyed the Galactic plane, but no dedicated energy estimator and fairly low significance





Main tanks (300,
22,000 m²)

Counting House

Outrigger tanks (345,
100,000 m²)

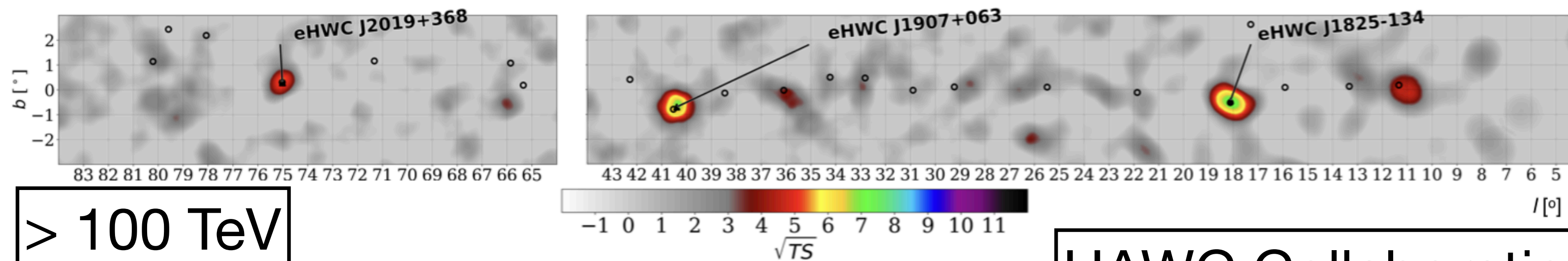
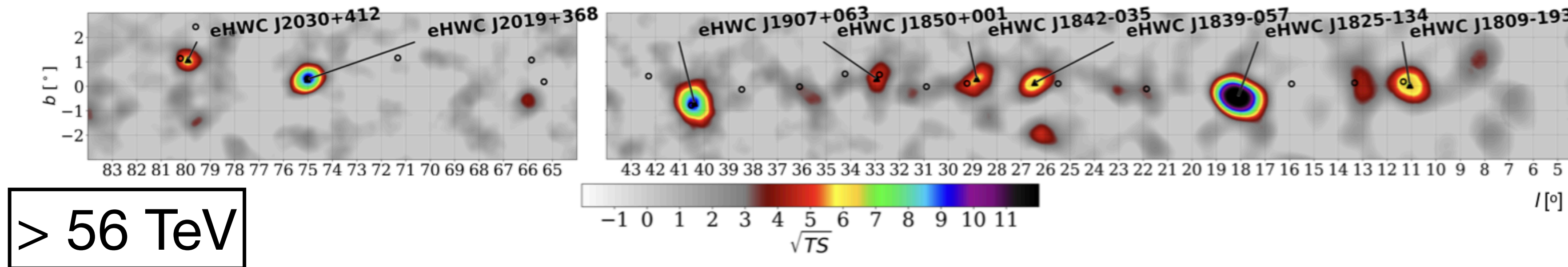
See recently published
detector paper for
more info:
HAWC Collaboration,
NIM A (2023)
Arxiv: 2304.00730

Platform is at 4100 m 19° N in
the state of Puebla, Mexico

- HAWC was officially inaugurated in March 2015
- Took data with a partial array before that
- Approaching ten years of accumulated data!

2019: HAWC's discovery of gamma-ray sources above 100 TeV

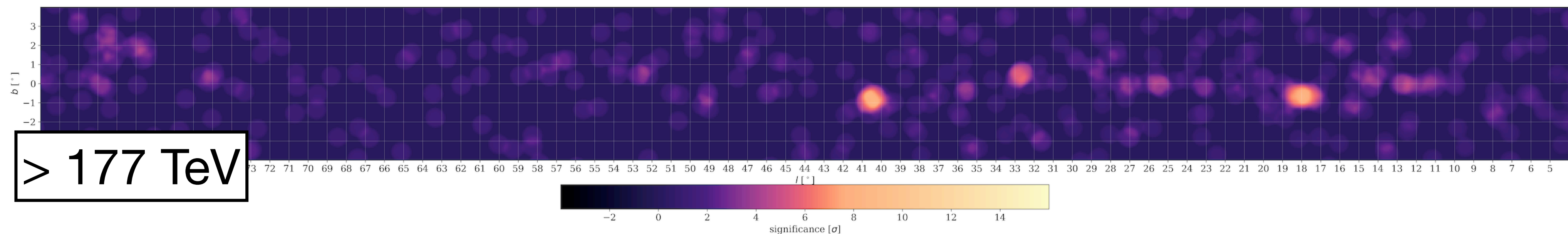
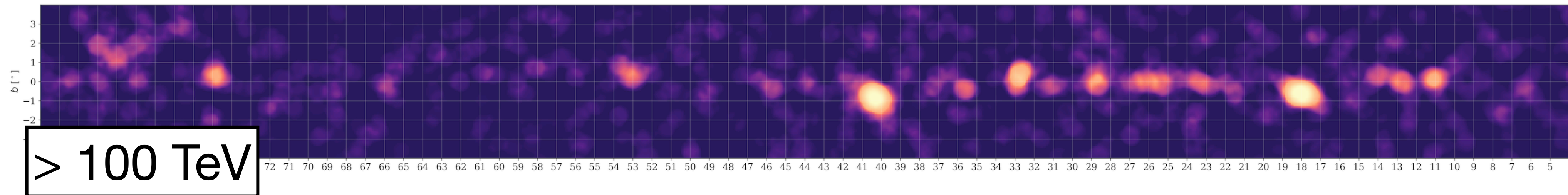
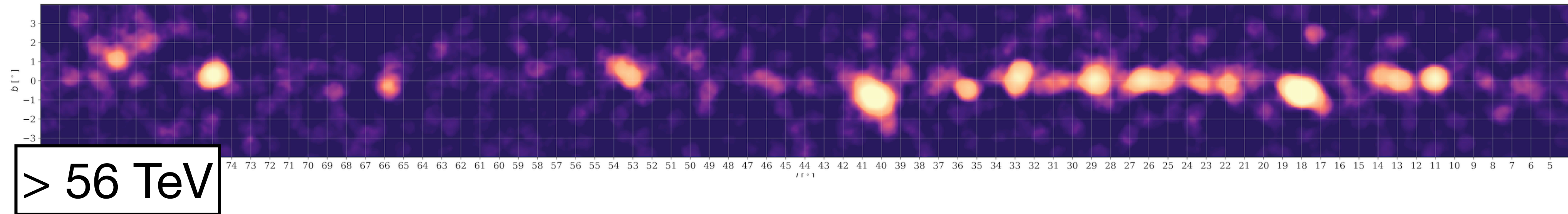
- At the time, the highest-energy astrophysical source catalog in the world
- 9 sources (8 in inner Galactic plane + Crab) emitting above 56 TeV, 3 continue past 100 TeV to > 5 sigma
- Difficulty in determining emission mechanisms, but noted that all but one source was within 0.5 degree of a pulsar with a high \dot{E} ($> 10^{36}$ erg/s)



HAWC Collaboration, PRL (2020)

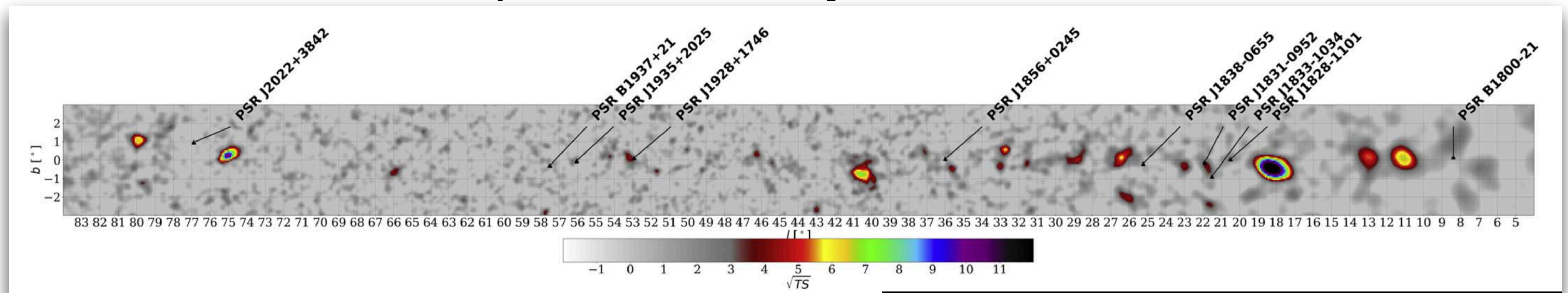
HAWC's UHE catalog today: ~2800 days of data

- With more data and updated algorithms, we now detect ~30 sources > 56 TeV, ~15 of which extend above 100 TeV and ~3 extend above 177 TeV (paper in progress, preliminary results presented at ICRC last year)
- More classes of sources than previously thought extend to high energies



Sub-threshold sources: Pulsar stacking analysis

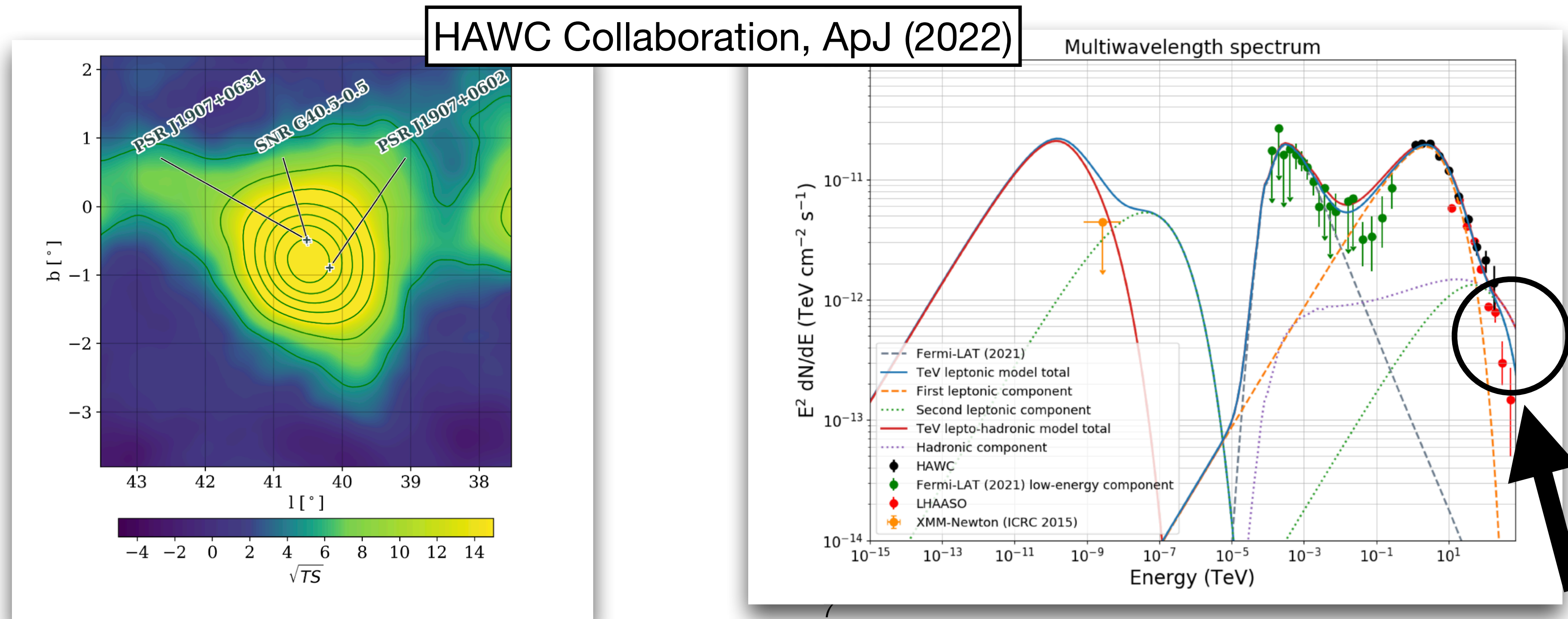
- Is > 56 TeV emission a generic feature expected near powerful pulsars?
- Performed a joint-likelihood analysis of high- \dot{E} pulsars that do not have significant UHE gamma-ray emission
- Significant detection for collection of sub-threshold sources, indicating that UHE emission is characteristic
- Result held for a variety of different weights: $1/d^2$, flux at 7 TeV, etc.



HAWC Collaboration, ApJL (2021)

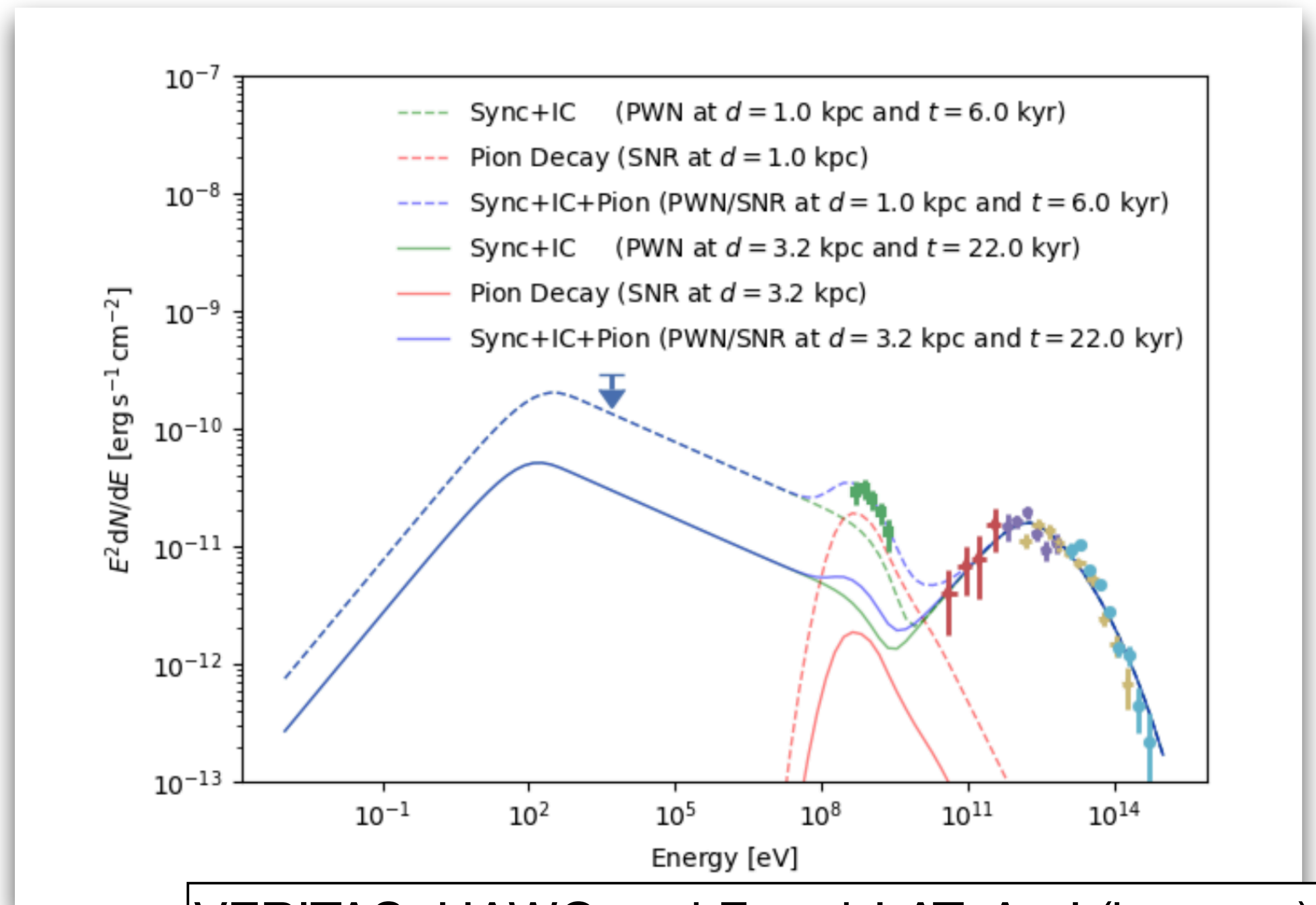
HAWC's highest-energy sources: MGRO J1908+06

- Crowded region, with multiple pulsars and an SNR in the region
- HAWC sees this source > 40 sigma with an extended source morphology
- > 200 TeV emission makes it a PeVatron candidate
- HAWC published a paper with multi-wavelength modeling, but was unable to conclusively determine emission mechanisms. Models start to diverge right where HAWC runs out of statistics



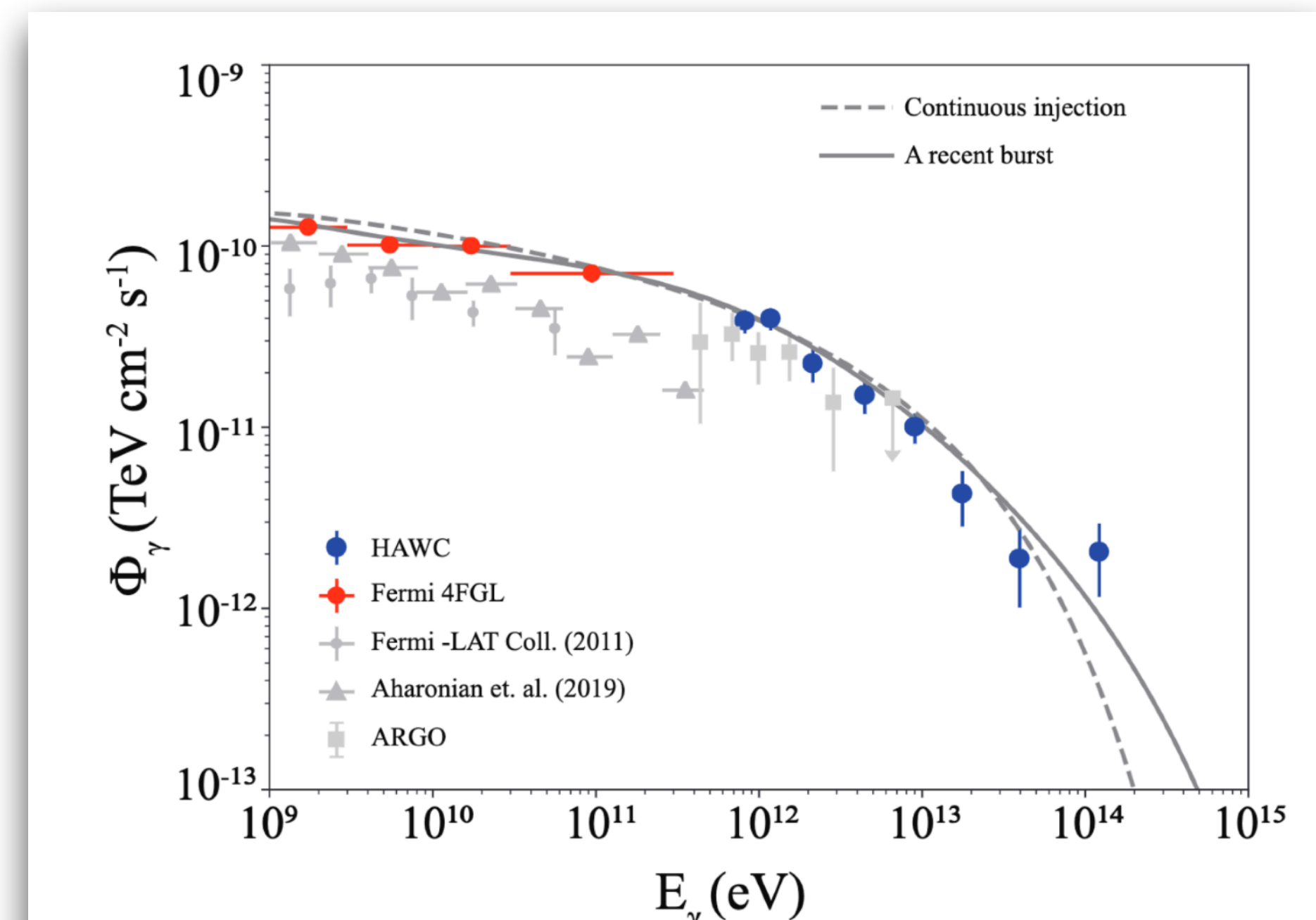
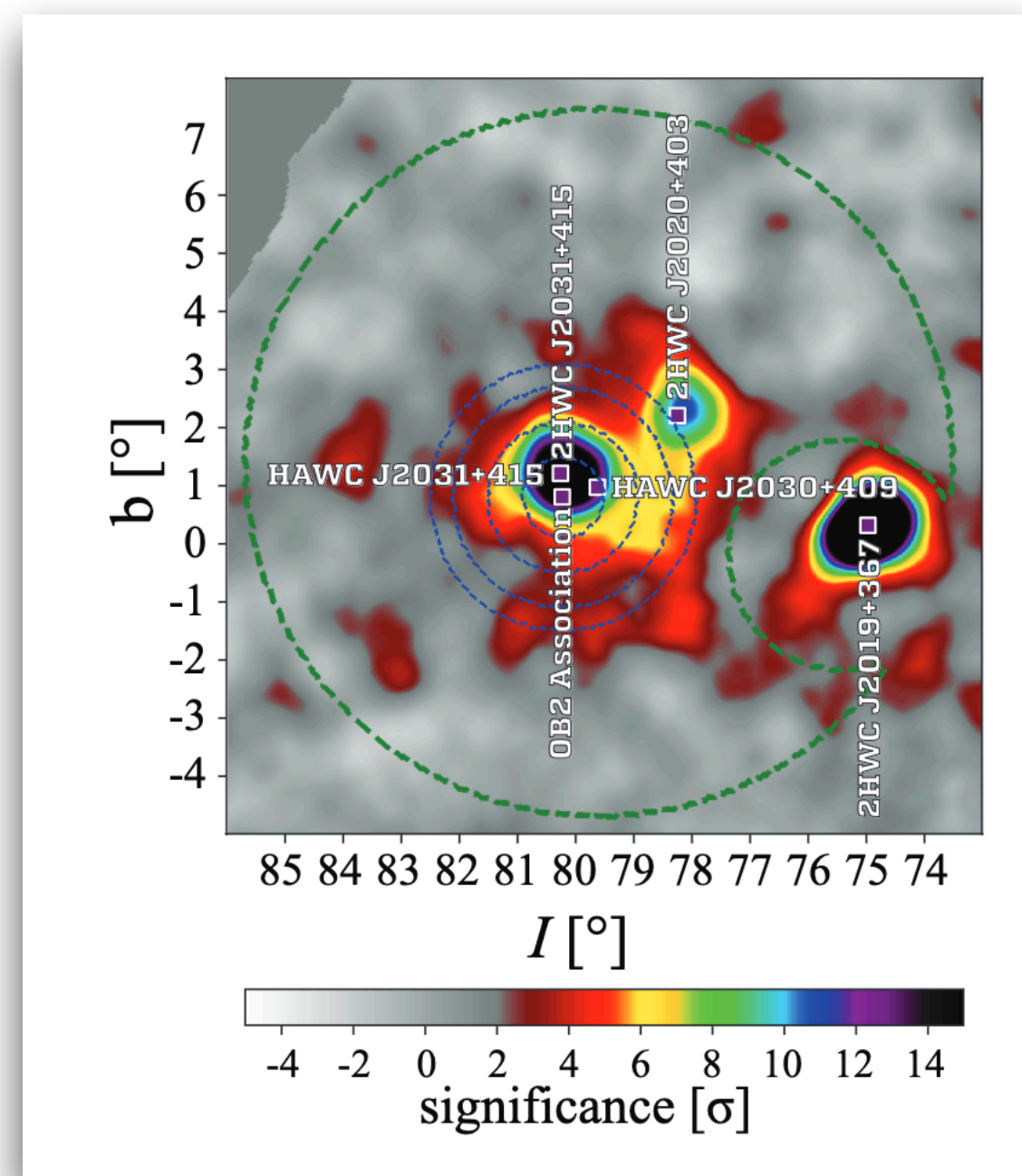
HAWC's highest-energy sources: MGRO J1908+06

- New joint paper with VERITAS and Fermi-LAT on the ArXiv this month
- Constraints on magnetic field, source age, and distance → inverse Compton most likely emission mechanism



HAWC's highest energy sources: The Cygnus Cocoon

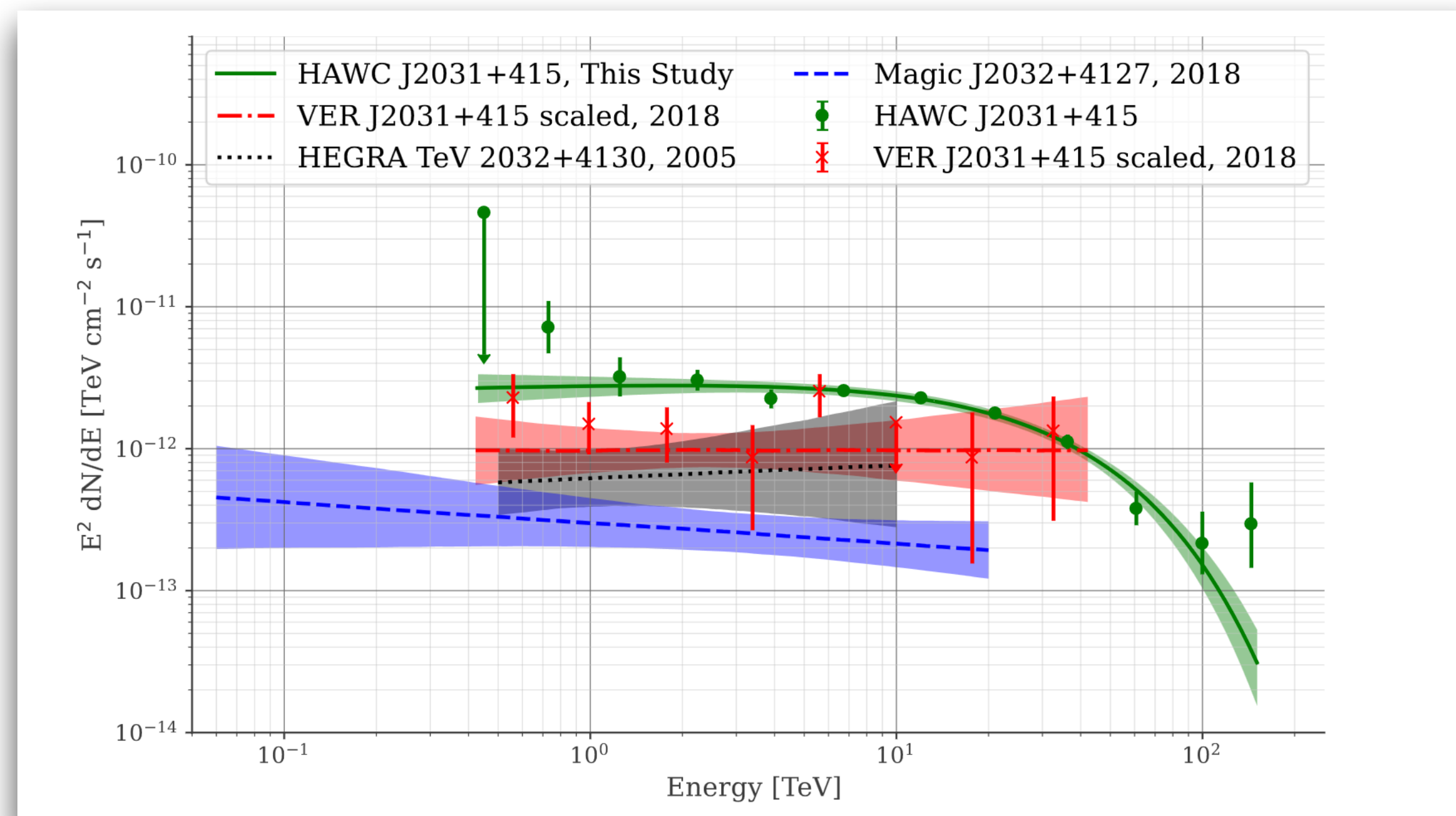
- Cygnus Cocoon: Superbubble surrounding a region of massive star formation
- 100 TeV gamma rays are hadronic in origin, implying CR acceleration up to \sim PeV



HAWC Collaboration, Nature Astronomy (2021)

HAWC's highest energy sources: HAWC J2031+415

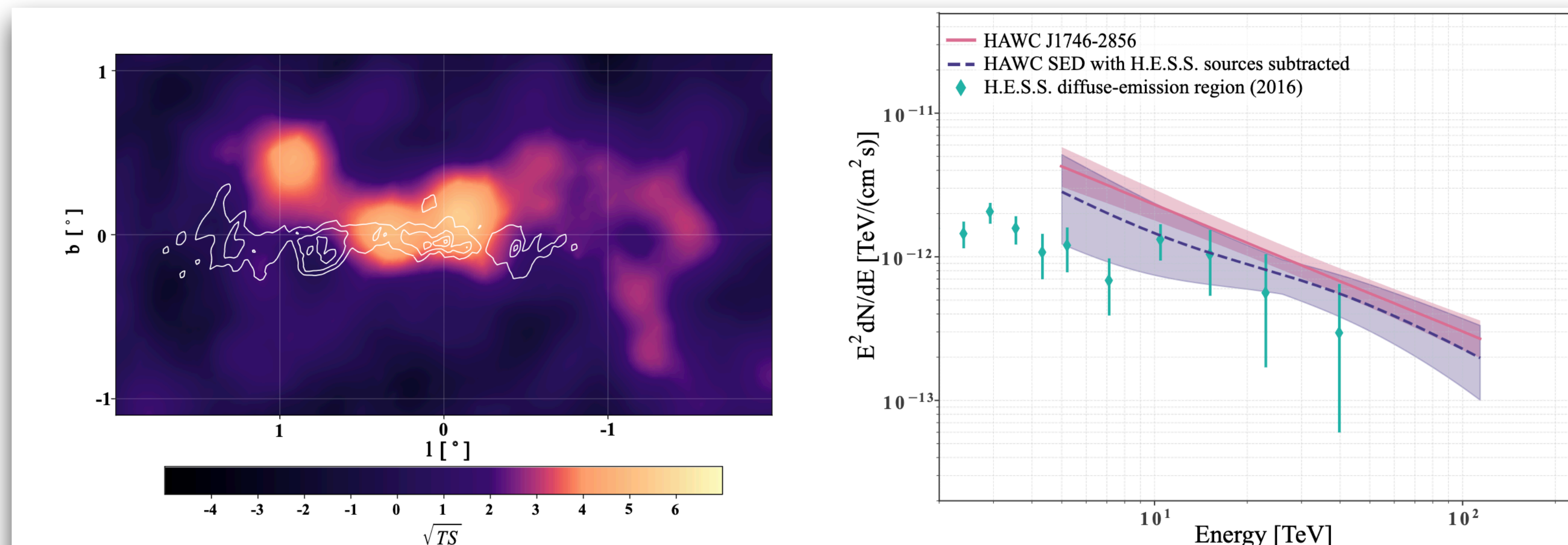
- TeV J2032+4130: First TeV gamma-ray source with no lower-energy counterparts. Since resolved into multiple sources (including the Cocoon)
- New HAWC paper associates HAWC J2031+415 with the binary system containing PSR J2032+4127 and MT91 213.
- HAWC emission likely from PWN and is ultra-high-energy



ArXiv 2407.02879, submitted to journal

HAWC's highest energy sources: The Galactic Center

- HAWC detects a point-like source with a power-law spectrum
- Energy range: 6 to 114 TeV, no evidence of cutoff up to 100 TeV
- Both Sgr A* and the Arc (HESS J1746-285) spatially coincident with HAWC source. Result remains significant when contamination from these point sources are subtracted out
- UHE gamma rays can originate via hadronic interactions of PeV CR protons with the dense ambient gas
- **Confirms PeVatron at the Galactic center**



HAWC Collaboration: ArXiv 2407.03682 (submitted to journal)

Other ultra-high-energy sources with talks at this conference

Source	Speaker	Time
Microquasar V4641 Sgr	X. Wang	Tues. Aug 27, 4:30pm (401 ERC)
SS433 Jet Lobes	C. Rho	TODAY, 2:45pm (161 ERC)
J1825 region	D. Huang	TODAY, 3:15 pm (161 ERC)
LHAASO J2018+5157 / LHAASO J0341+5258	P. Bangale (joint HAWC/VERITAS contribution)	TODAY, 4:15pm (161 ERC)
1LHAASO sources linked to Fermi-LAT sources	T. Ergin	TODAY, 4:45pm (161 ERC)

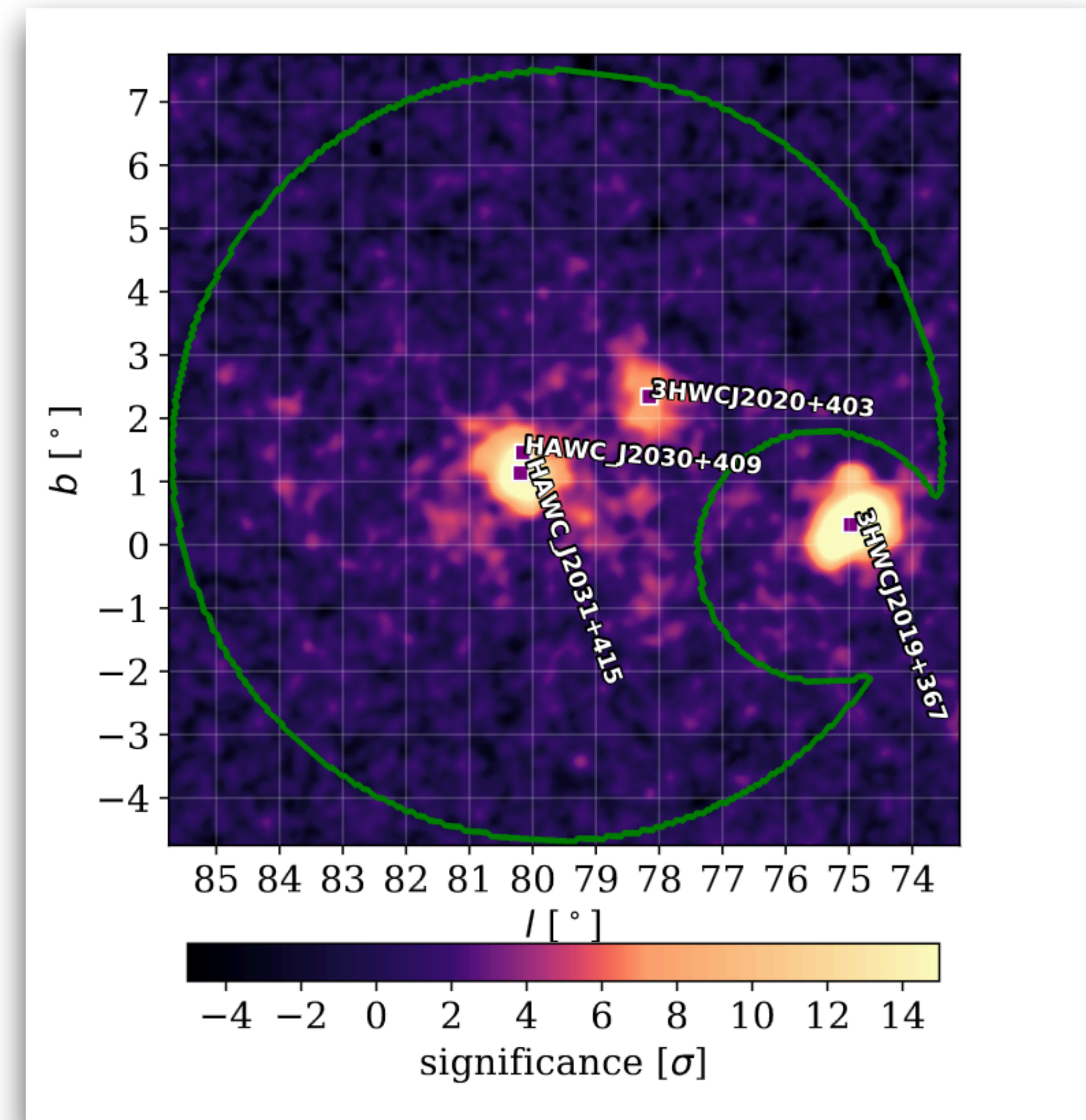
Transient alerts

- HAWC has just (this summer) started producing real-time alerts for ultra-high-energy events
 - Anticipated alert rate: ~1/month
 - Our highest-quality UHE events
- Plan to distribute alerts to AMON (in progress)
- Good synergy with IceCube astrophysical neutrino energies, etc.
- Contact me (kmalone@lanl.gov) if you would like more information
 - Alerts are XML files, contain information on the right

Parameter
Ground parameter energy estimate
Neural network energy estimate
Alert statistic (out of 50)
False positive rate
RA of event
Declination of event
Error in location (based on PSF at that energy)

Transient alerts: Archival dataset

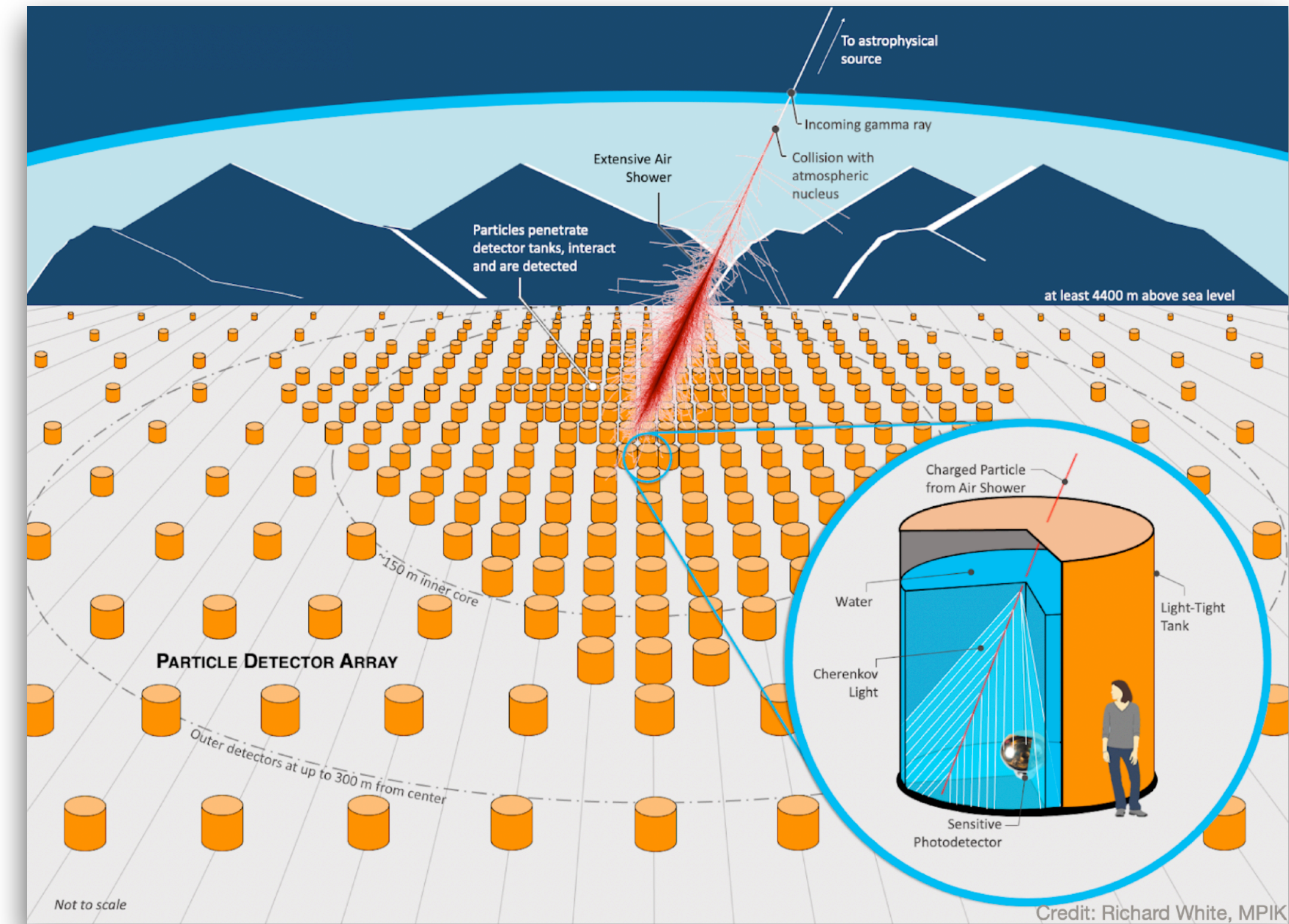
- Alert code has been run over HAWC's archival dataset (2800 days of data dating back to ~2015)
 - Coincidence analysis with IceCube archival alert data in progress
- 160 HAWC events, 2 had the maximum possible alert ranking statistic score
- Both were in the Cygnus region and had energies of > 400 TeV. One's location is in the Cocoon while the other was 0.35 degrees away from MGRO J2031+41 (the binary system)



ArXiv 2407.02879, submitted to journal

SWGGO

- Full-sky coverage of UHE events is essential to determining the nature of cosmic rays
- The Southern Wide-Field Gamma-Ray Observatory is a proposed experiment to be built in South America
- **Pampa la Bola in the Atacama Astronomical Park in Chile chosen as the site for SWGGO on July 31**



- Press release: https://www.swgo.org/SWGOWiki/doku.php?id=site_press_release
- Pampa la Bola is at an altitude of 4770 m

Conclusions

- Ultra-high-energy gamma ray sources are numerous
- Many types of source classes appear to emit above this energy threshold (PWN, star-forming regions, etc.)
- HAWC is beginning to look for transients in UHE data

