

Gran Sasso Science Institute - February 25, 2020

*The High Altitude
Water Cherenkov
Observatory*



PennState
Eberly College of Science



Miguel Alejandro Mostafá
Professor of Physics, Astronomy and Astrophysics

Outline

Introduction & Motivation 1

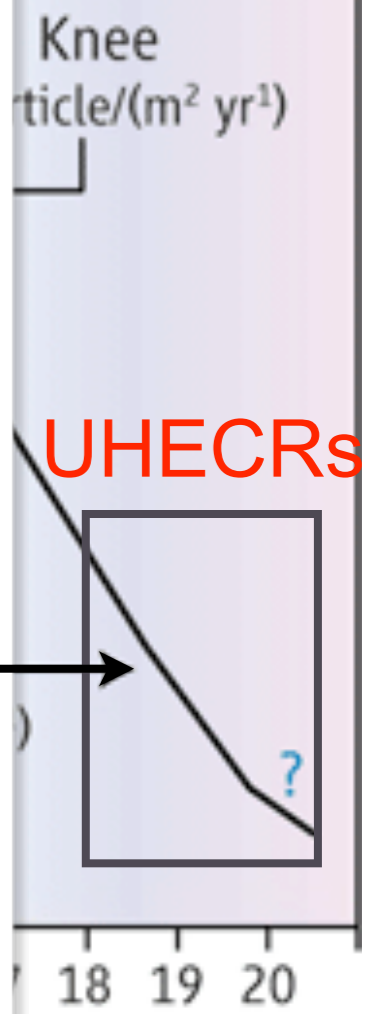
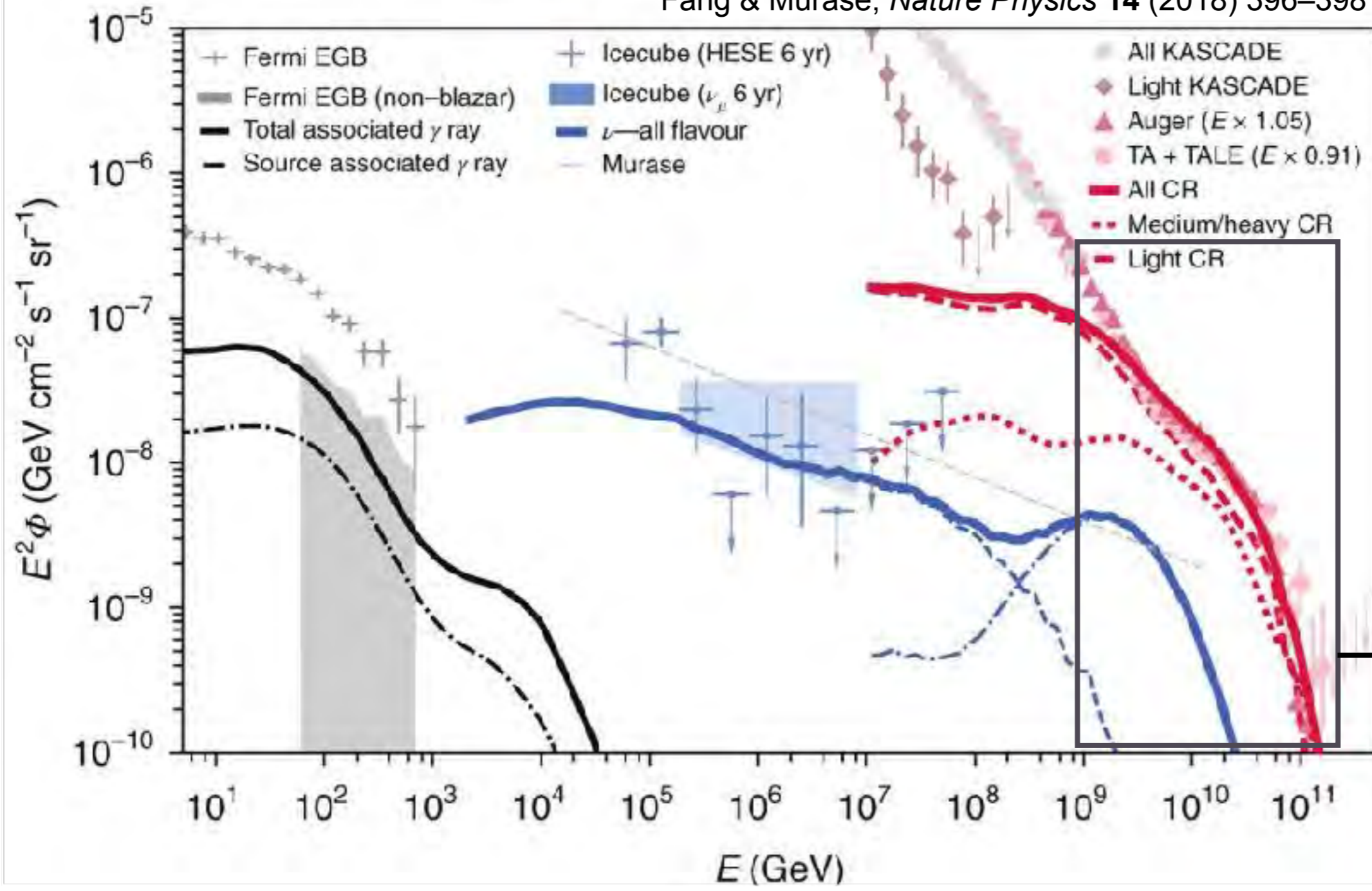
The HAWC Observatory 2

Recent results 3

Outlook 4



Fang & Murase, *Nature Physics* 14 (2018) 396–398



1 EeV $\stackrel{\text{def}}{=} 10^{18}$ eV

(log energy) (eV)

18/11/2008

1659

1639

1629

Loma Amarilla

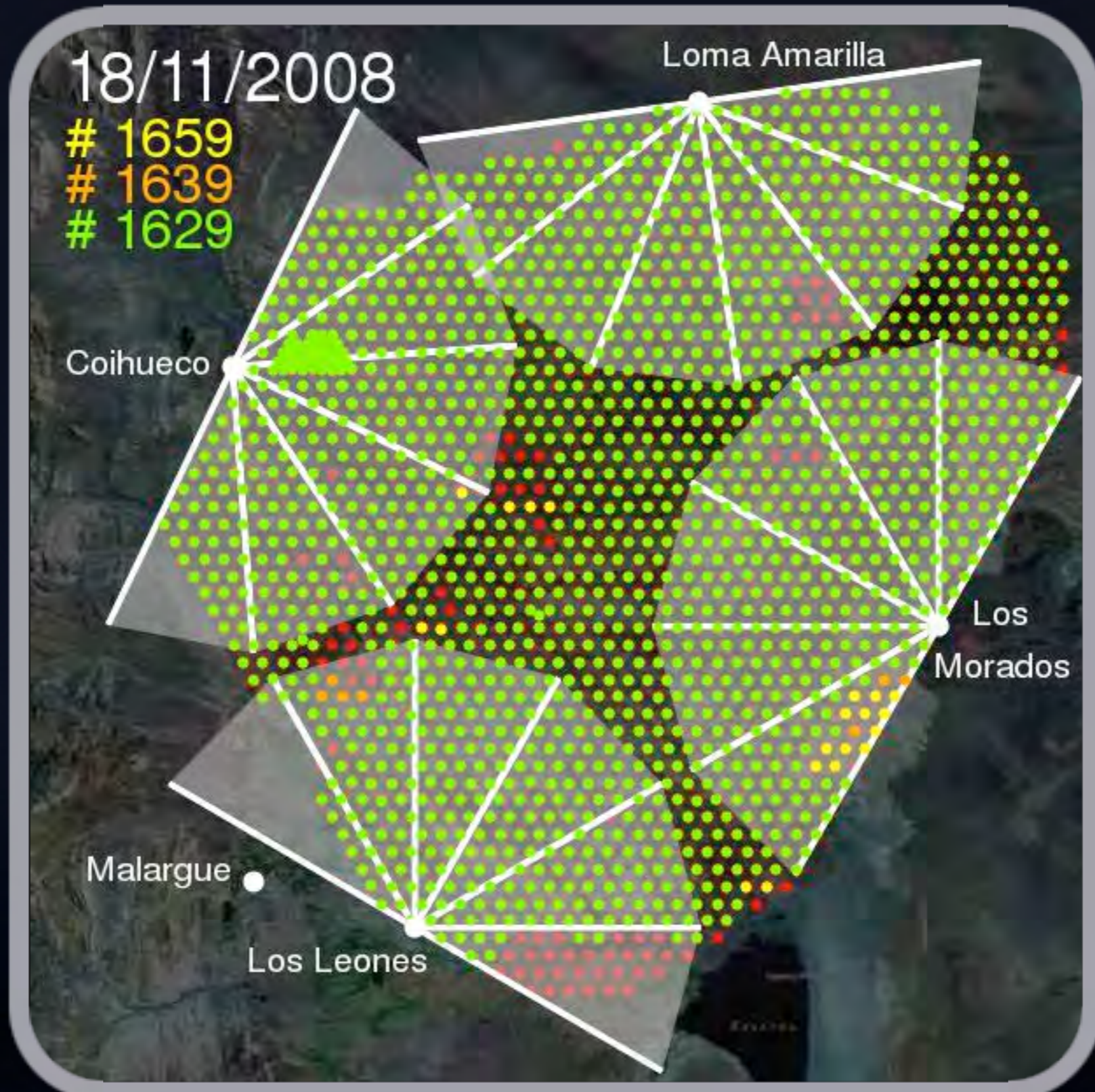
Coihueco

Los
Morados

Malargue

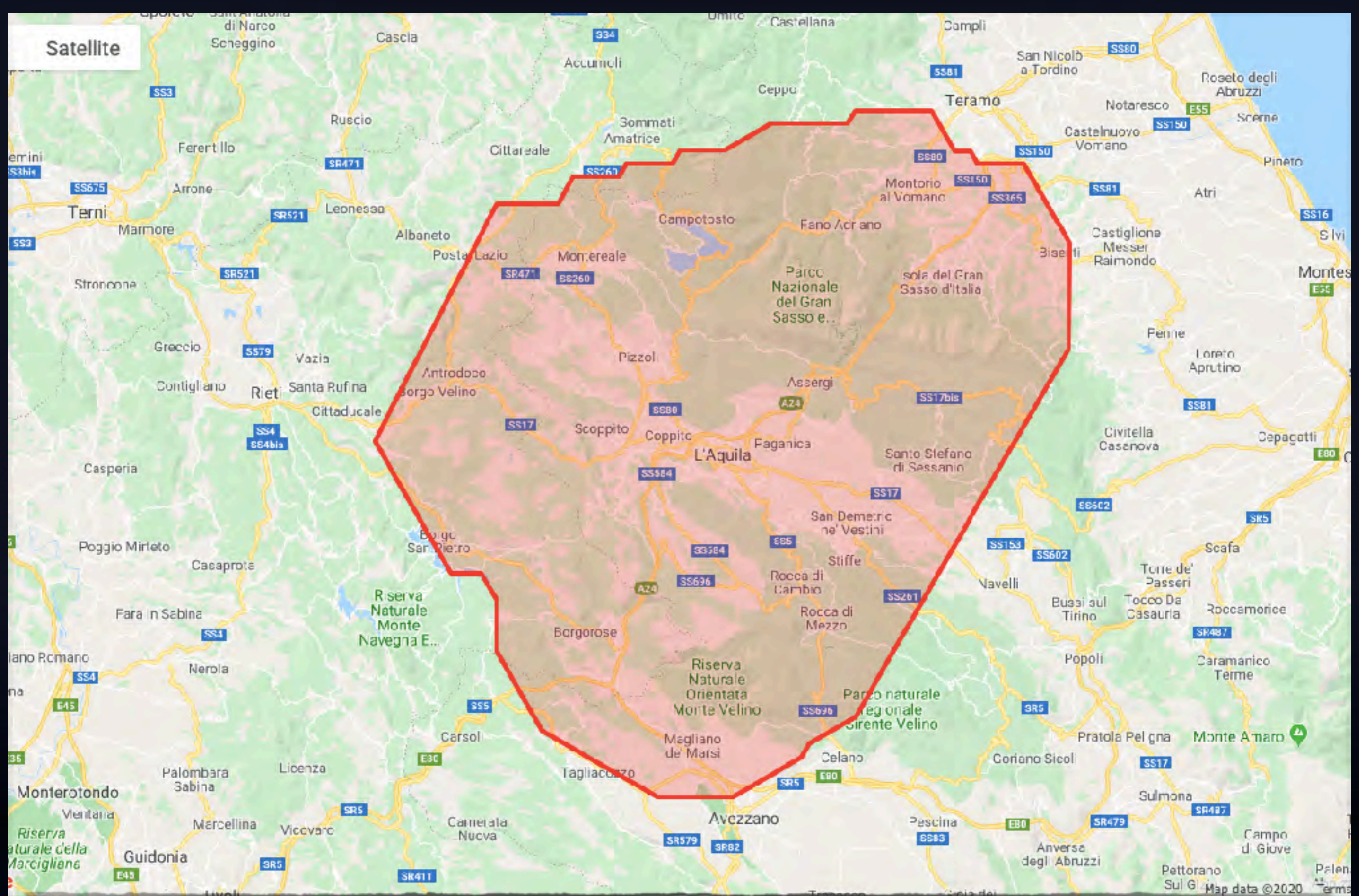
Los Leones

UHECR detection



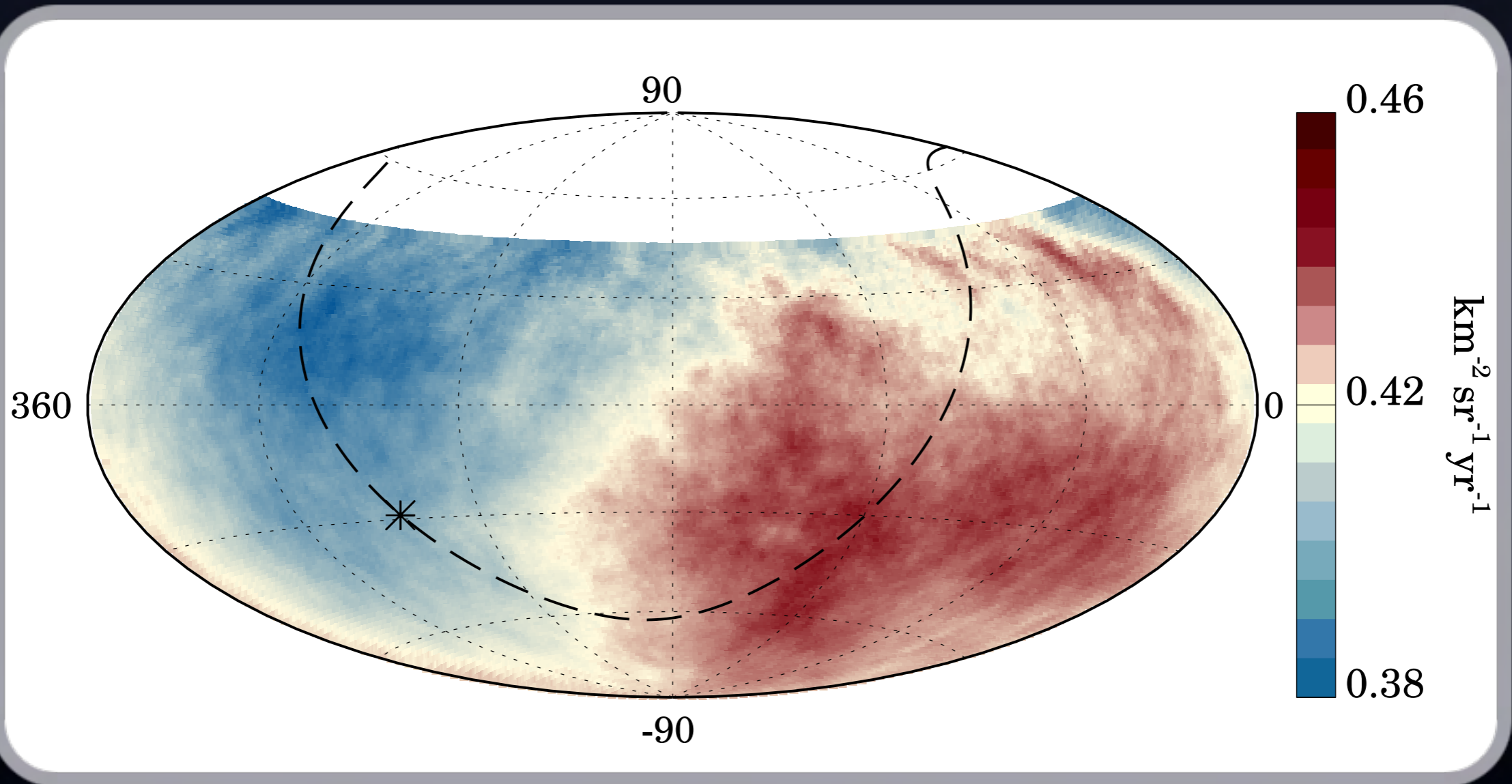


UHECR detection



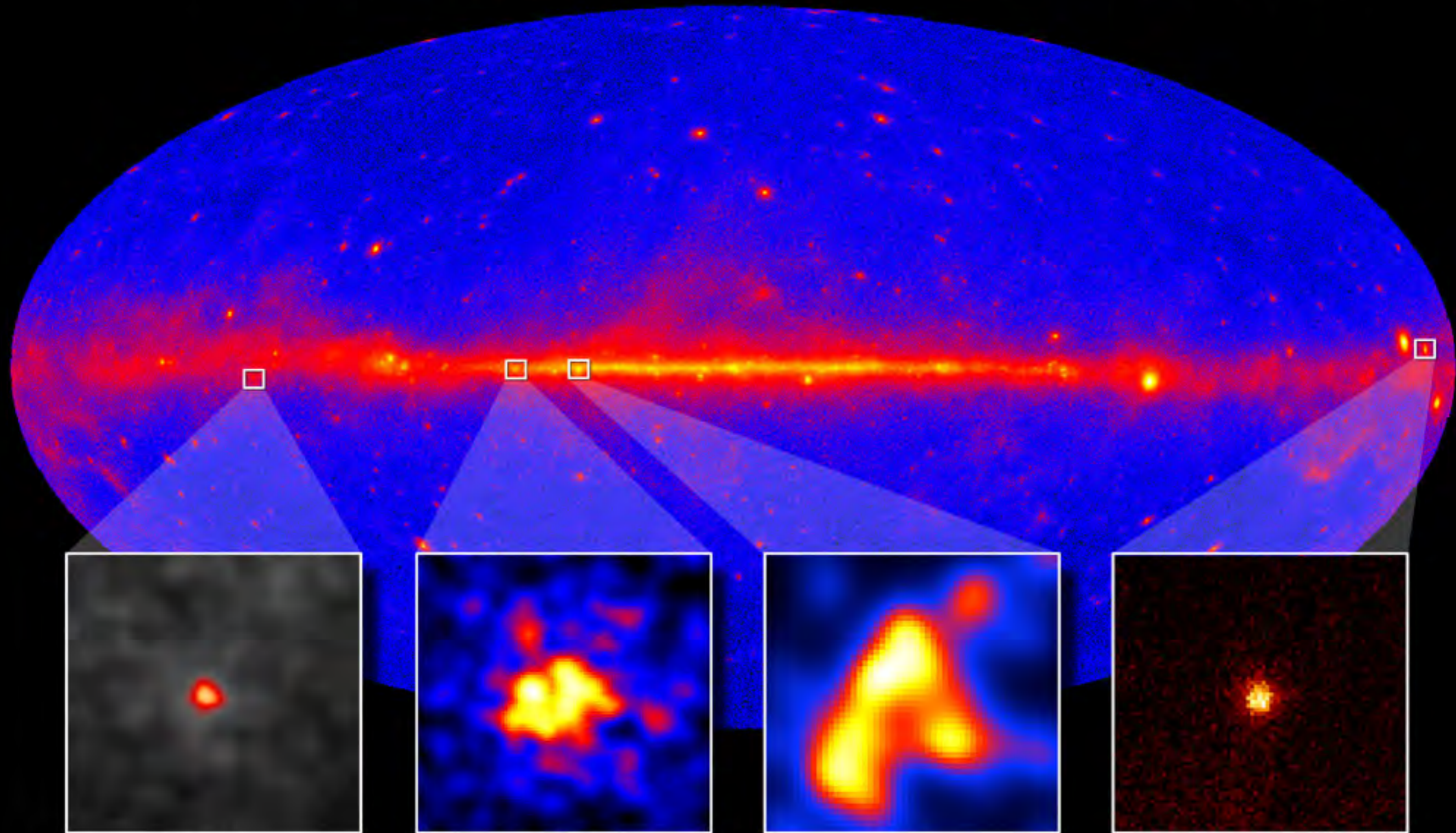
UHECR detection

$E > 8 \text{ EeV}; 45^\circ$ smoothing



UHECR sky map

NASA's Fermi telescope resolves supernova remnants at GeV energies



Cas A

W51C

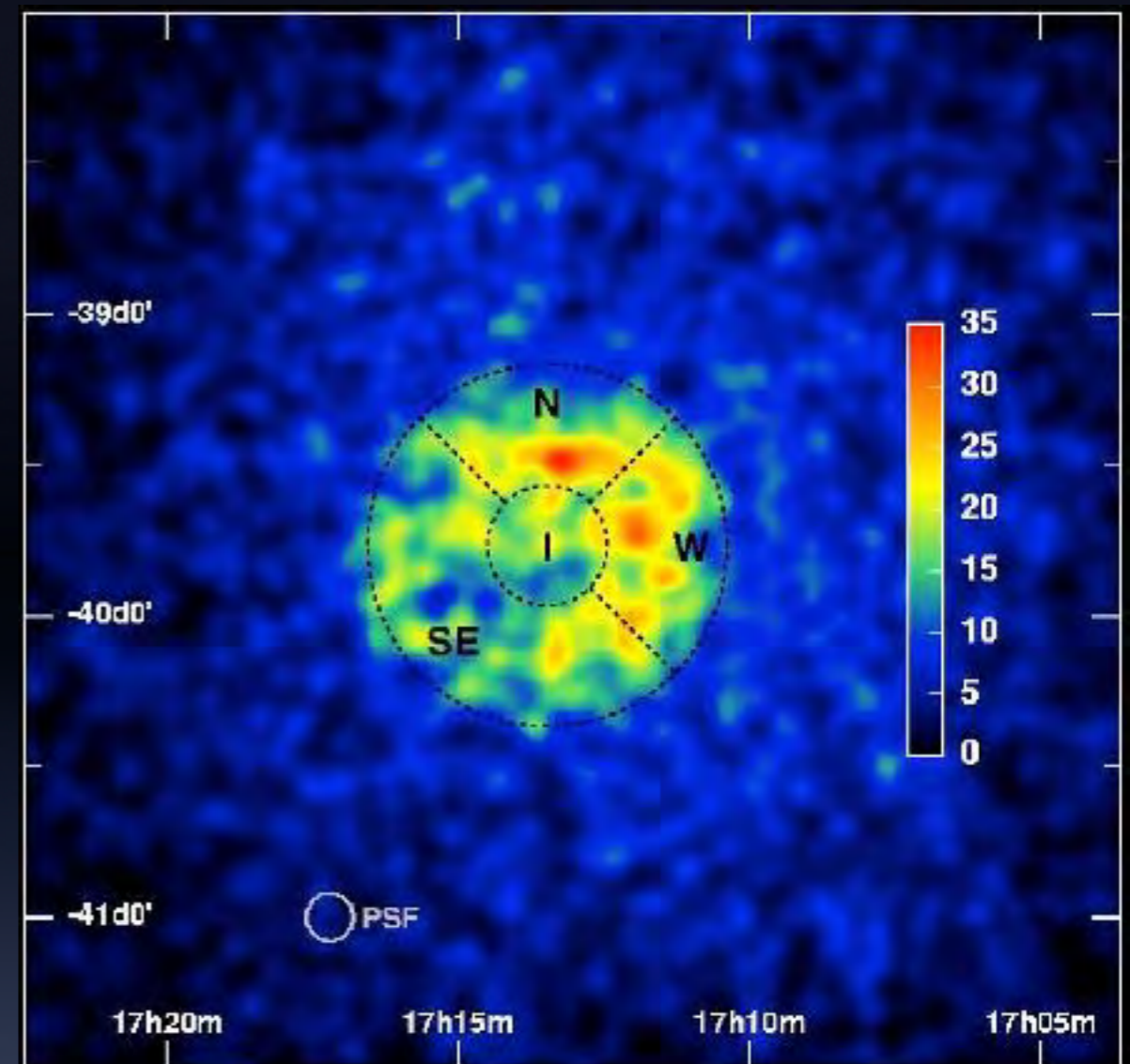
W44

IC 443

Supernova Remnants

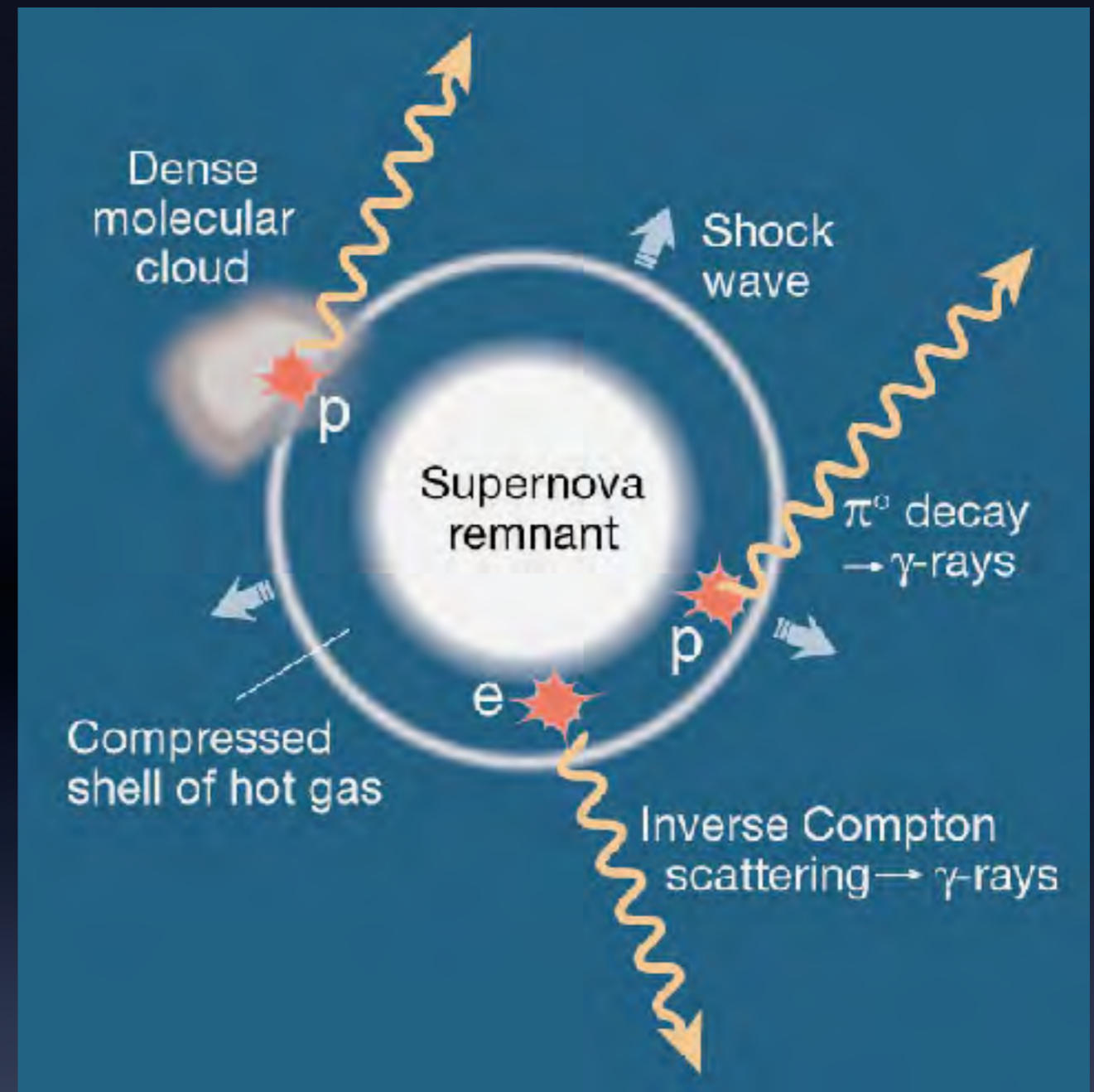
H.E.S.S. Collaboration, Nature **432** (2004) 75

- First resolved **TeV γ -ray** image of a Shell type SNR (Resolution ~ 10 arcmin)
- Acceleration source of cosmic rays, but is it evidence of protons?



Supernova Remnants

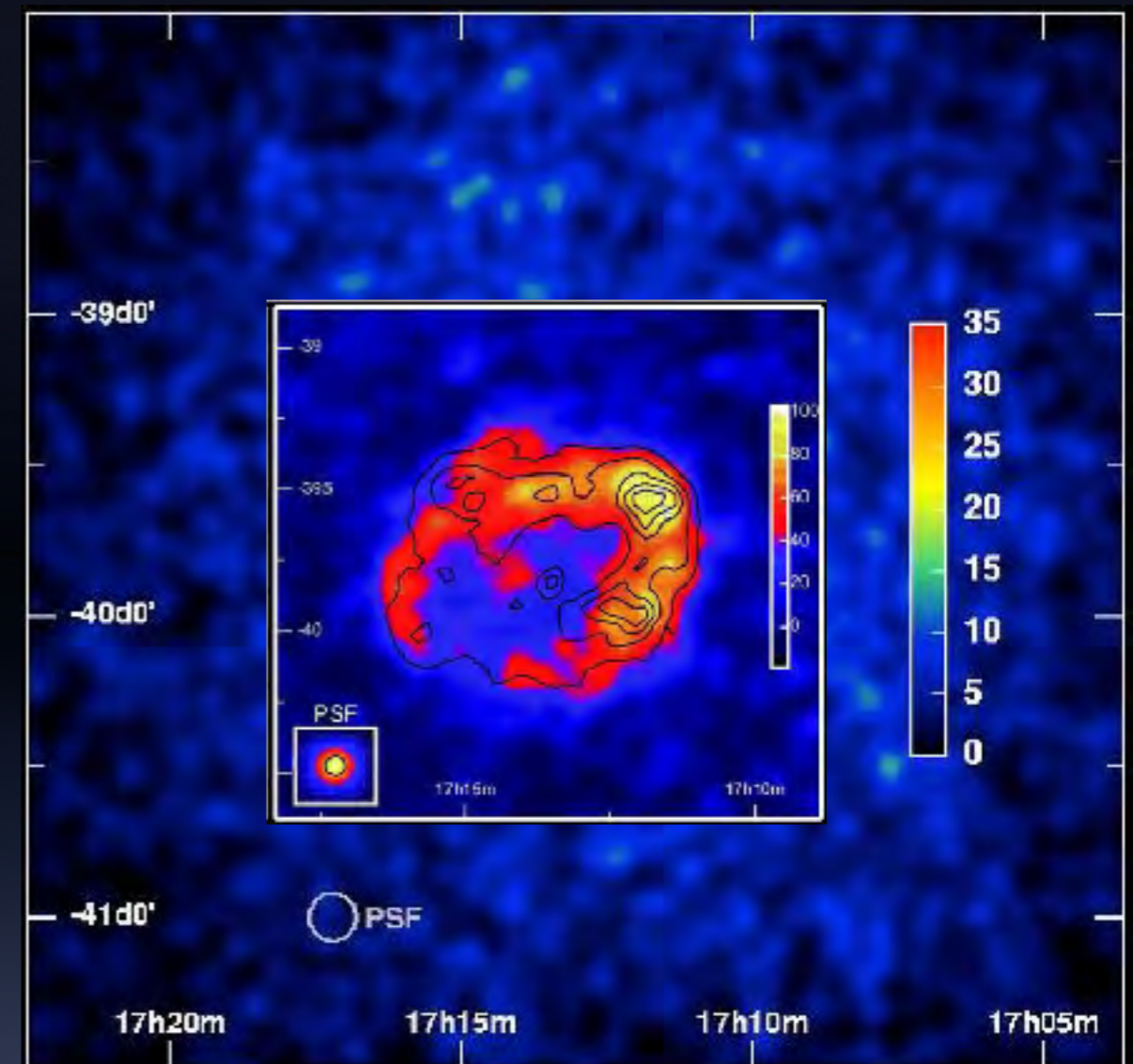
- First resolved **TeV γ -ray** image of a Shell type SNR (Resolution ~ 10 arcmin)
- Acceleration source of cosmic rays, but is it evidence of protons?



Supernova Remnants

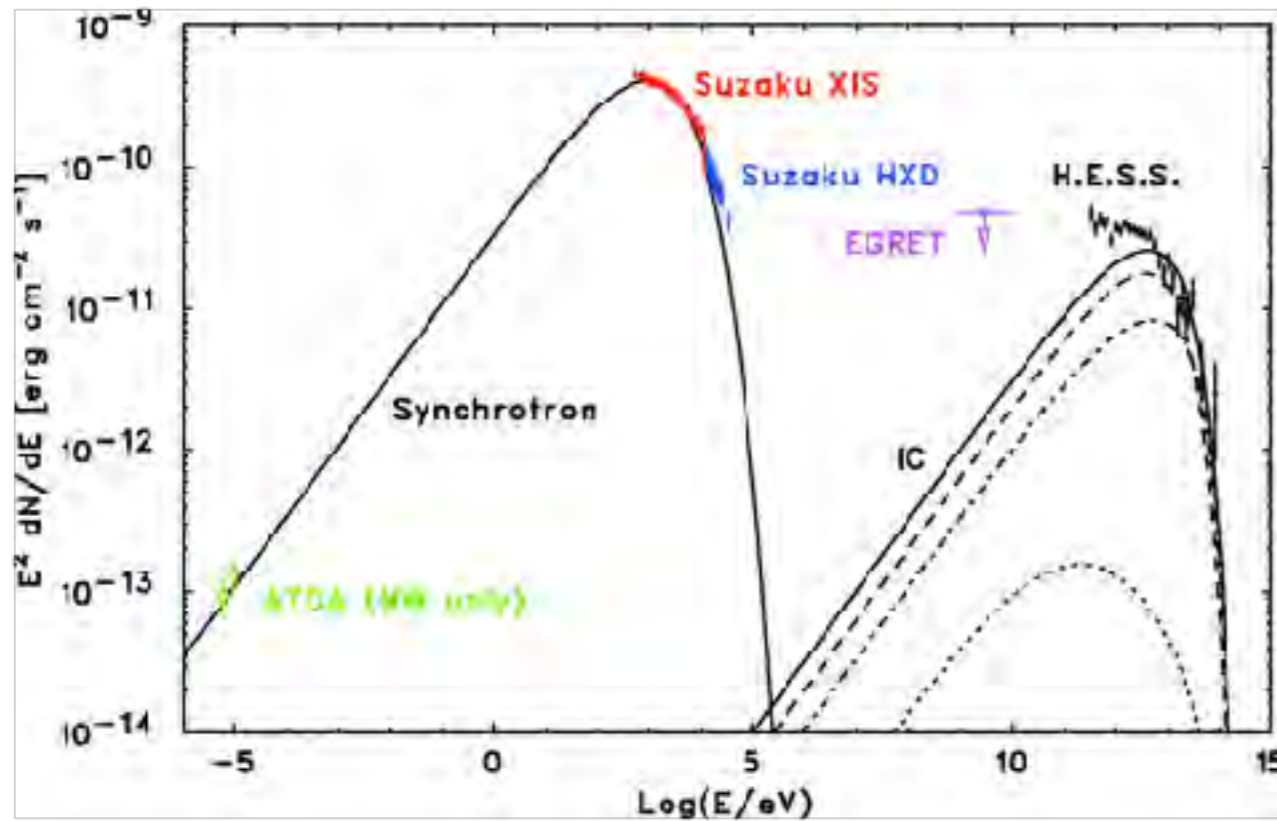
H.E.S.S. Collaboration, Nature **432** (2004) 75

- First resolved **TeV γ -ray** image of a Shell type SNR (Resolution ~ 10 arcmin)
- Acceleration source of cosmic rays, but is it evidence of protons?



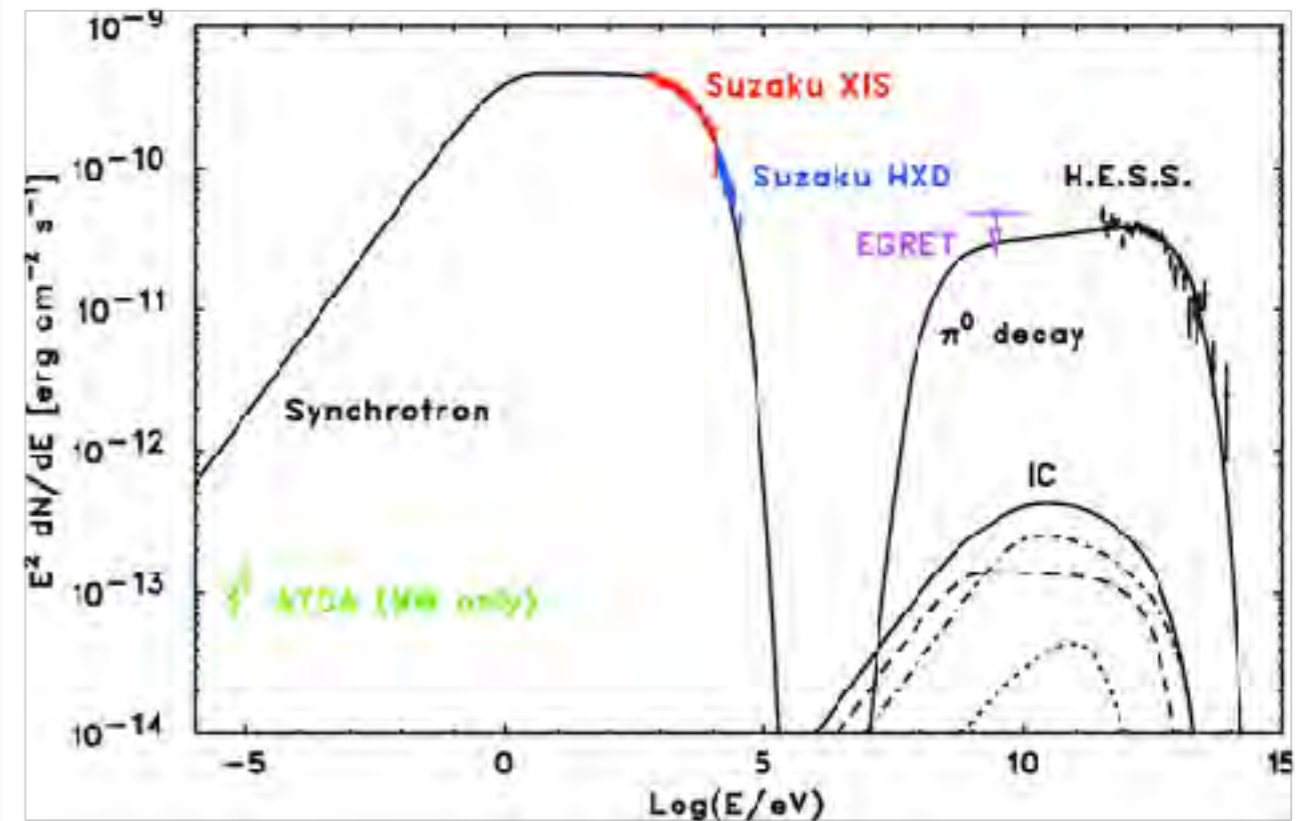
Supernova Remnants

Tanaka et al., The Astrophysical Journal 685 (2008) 988



Leptonic

vs.



Hadronic

Scientific Motivation

- Constrain the **origin of cosmic rays** by measuring gamma-ray spectra to 100 TeV.
- Probe **particle acceleration** in astrophysical jets with **wide field of view, high duty factor** observations.
- Explore **new physics** with an **unbiased survey** of the TeV sky.

Experimental Techniques

- ✓ Background free
- ✓ Large duty cycle
- ✓ Large aperture
- Small area
- **Space-based detectors**
 - Low energy threshold
 - EGRET, Fermi-LAT



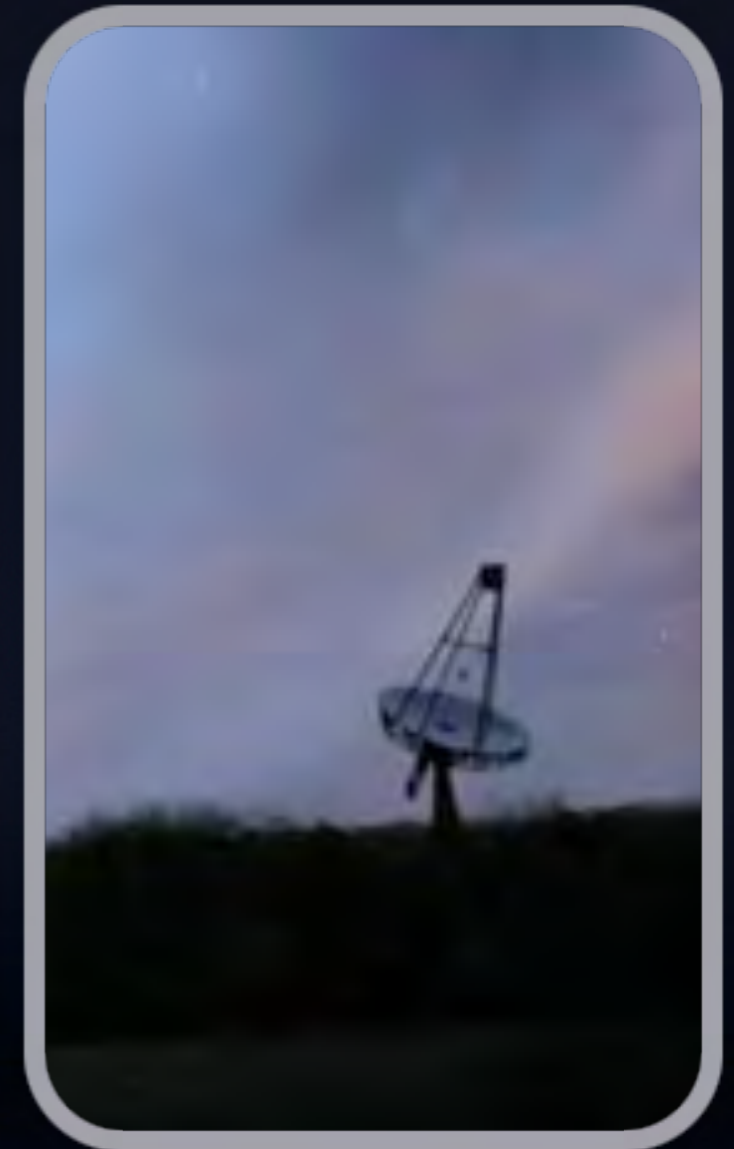
Experimental Techniques

- ✓ Large effective area
- ✓ Excellent background rejection
- Small aperture
- Low duty cycle

● Imaging Atmospheric Cherenkov Telescopes

High sensitivity

HESS, MAGIC, VERITAS



Experimental Techniques

- ✓ Large aperture
- ✓ Excellent background rejection
- ✓ Large duty cycle

- Moderate area

● Ground array of air-shower particle detectors

Large aperture + High duty cycle

Milagro, Tibet, ARGO, HAWC



HAWC

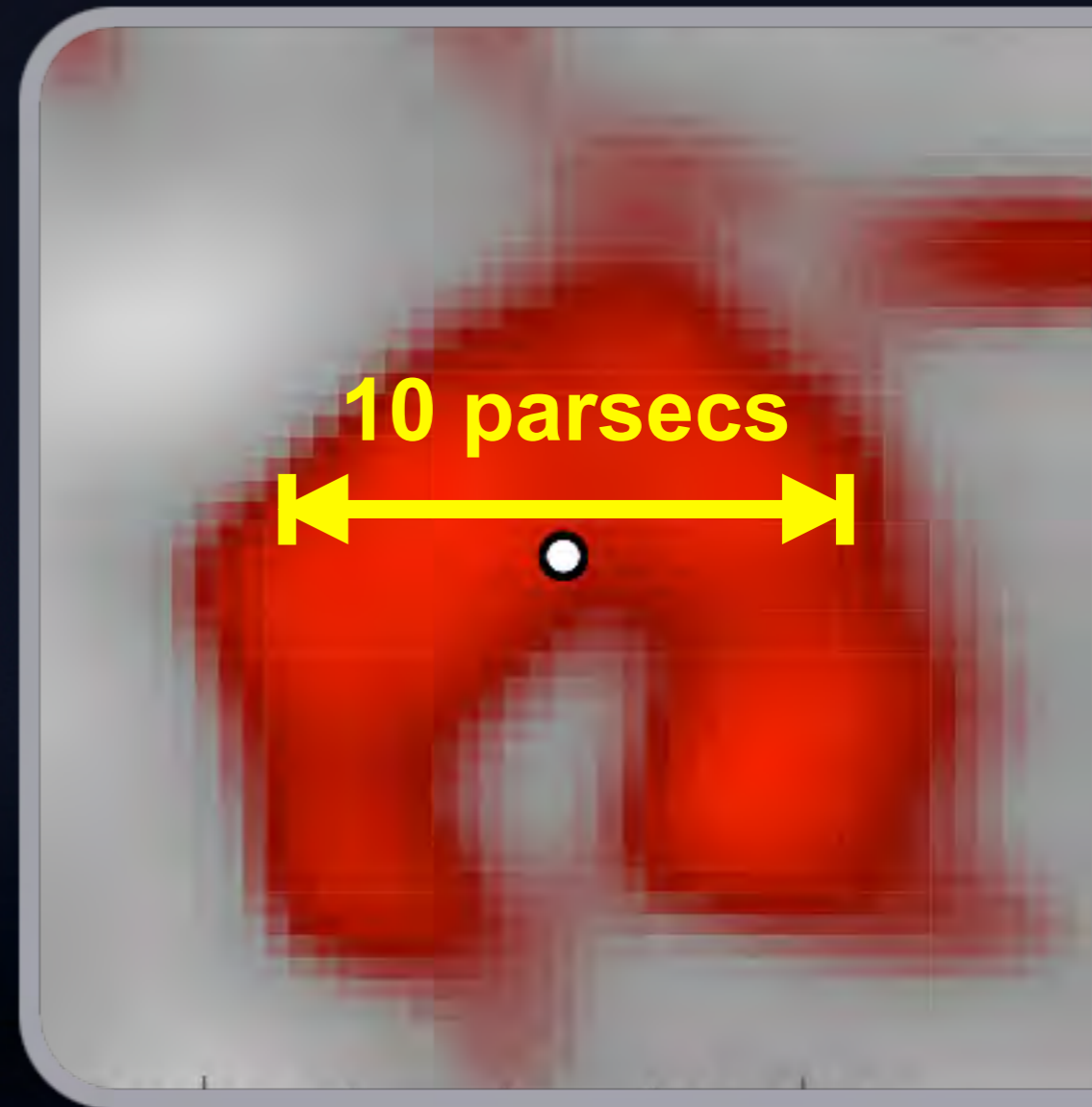


- 2nd generation water Cherenkov
- Wide instantaneous field of view (2 sr)
- High duty cycle ($> 90\%$)
- Large area (22,000 m²)

A second generation wide-field γ -ray detector

Main Features

- Most bright Galactic GeV sources **extend to TeV**
- Best instrument for **hard spectrum** and **extended sources**



The HAWC Observatory



300 - 7 m x 5 m steel Water Cherenkov Detectors
(a.k.a. tanks) with 4 PMTs at 4,100 m a.s.l. in Mexico

Water Cherenkov Detectors



300 - 7 m x 5 m steel Water Cherenkov Detectors
(a.k.a. tanks) with 4 PMTs at 4,100 m a.s.l. in Mexico

Water Cherenkov Detectors



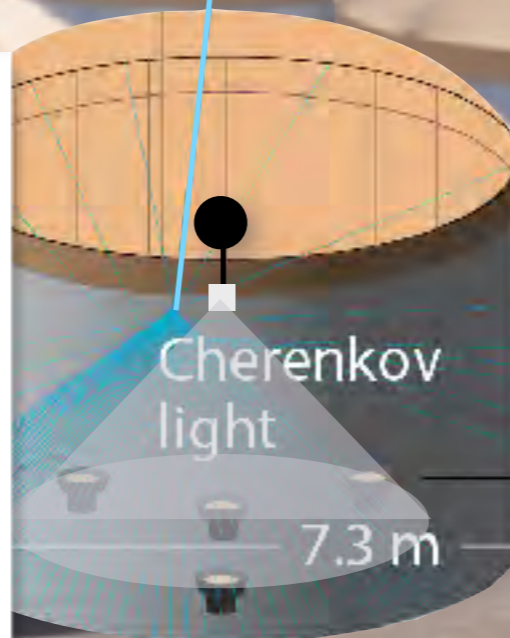
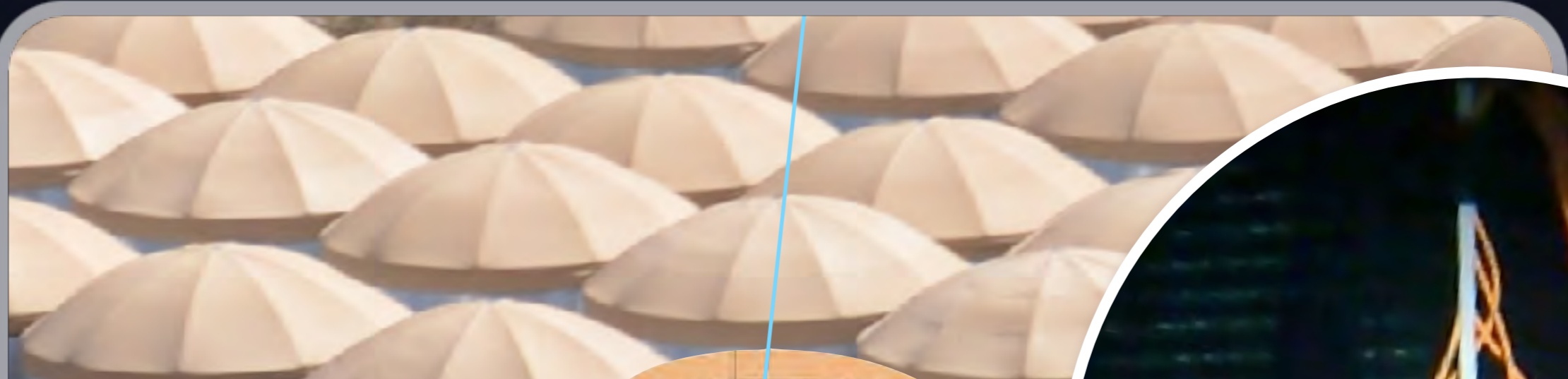
300 - 7 m x 5 m steel Water Cherenkov Detectors
(a.k.a. tanks) with 4 PMTs at 4,100 m a.s.l. in Mexico

Water Cherenkov Detectors



Water Cherenkov Detectors
PMTs at 4,100 m a.s.l. in Mexico

Water Cherenkov Detectors



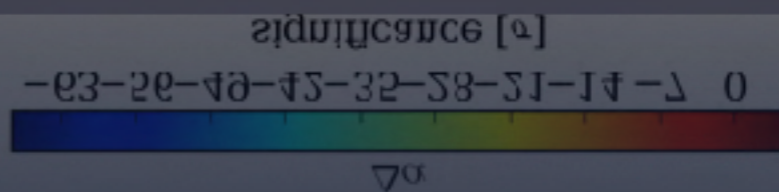
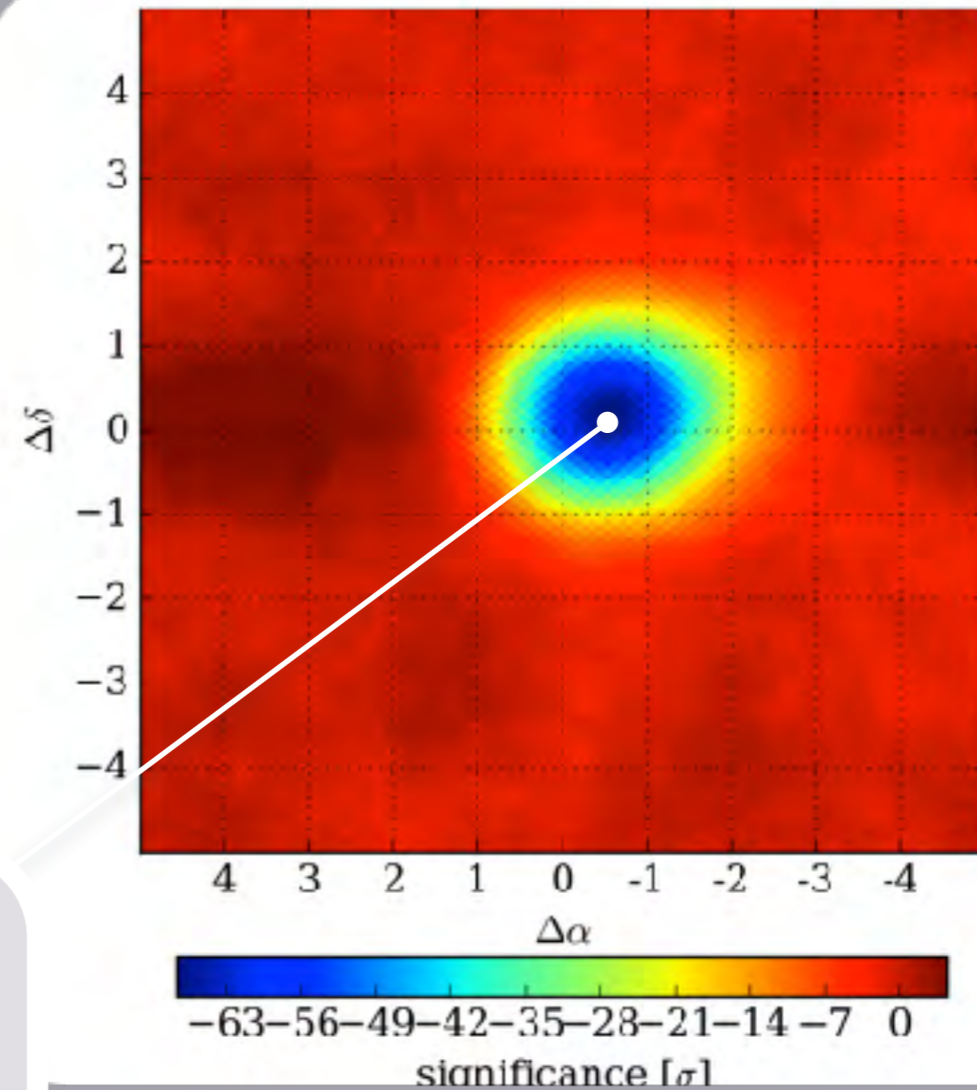
ation system

Water Cherenkov Detectors

Effect of the laser calibration on the observation of the shadow of the Moon

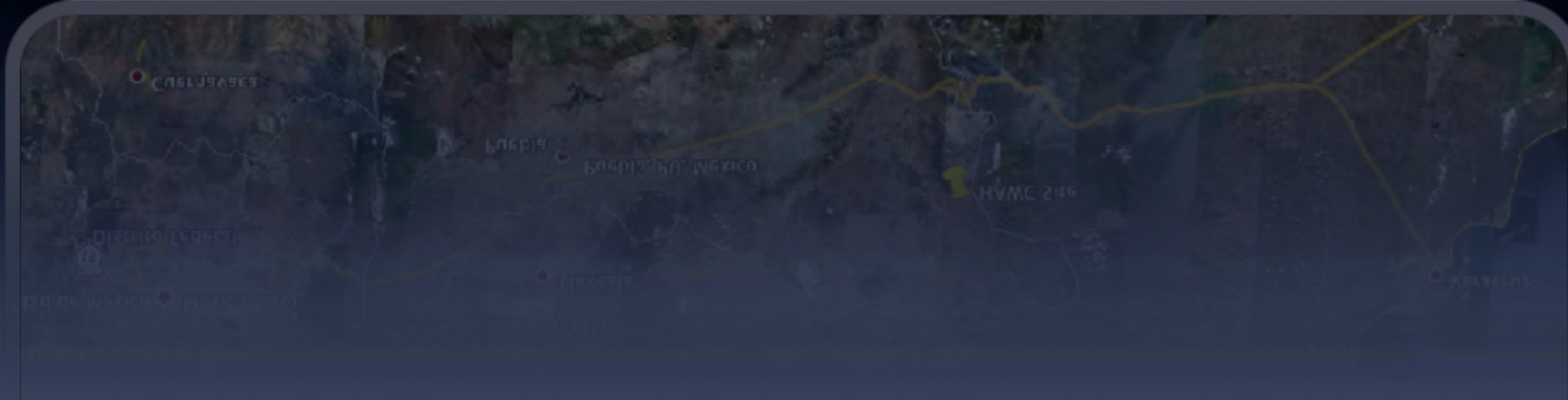
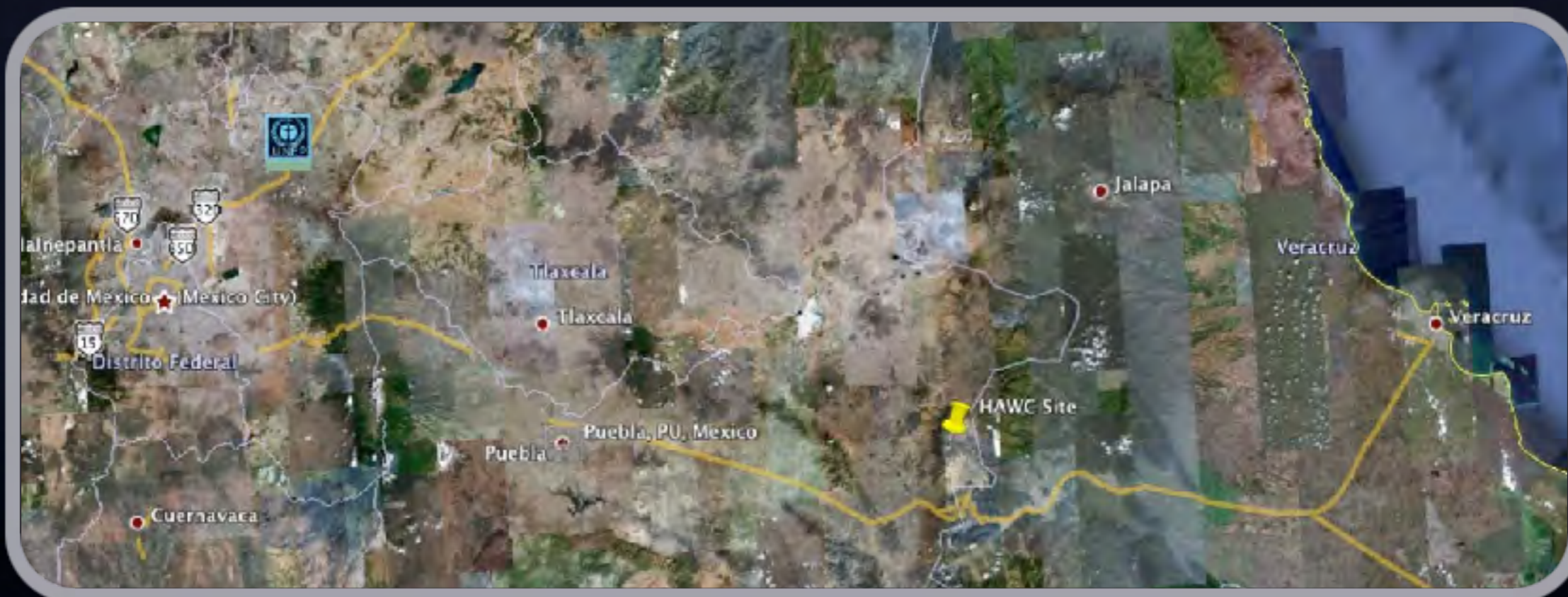
- deflection matches 2 TeV median energy
- angular resolution < shadow width of 1.2°
- position verifies pointing

Dedicated laser calibration system



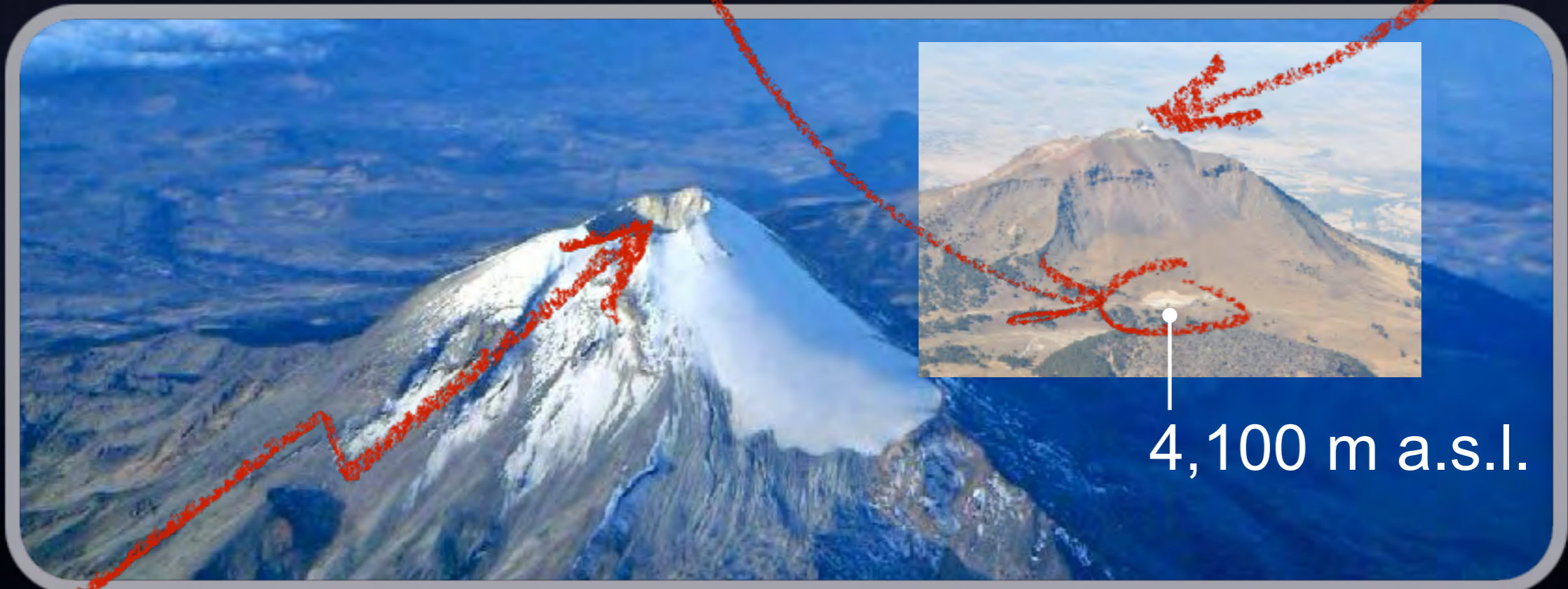
$\Delta\alpha$

HAWC site



HAWC site

LMT (4,600 m)



4,100 m a.s.l.

Pico de Orizaba (18,500 ft)

Deployment status



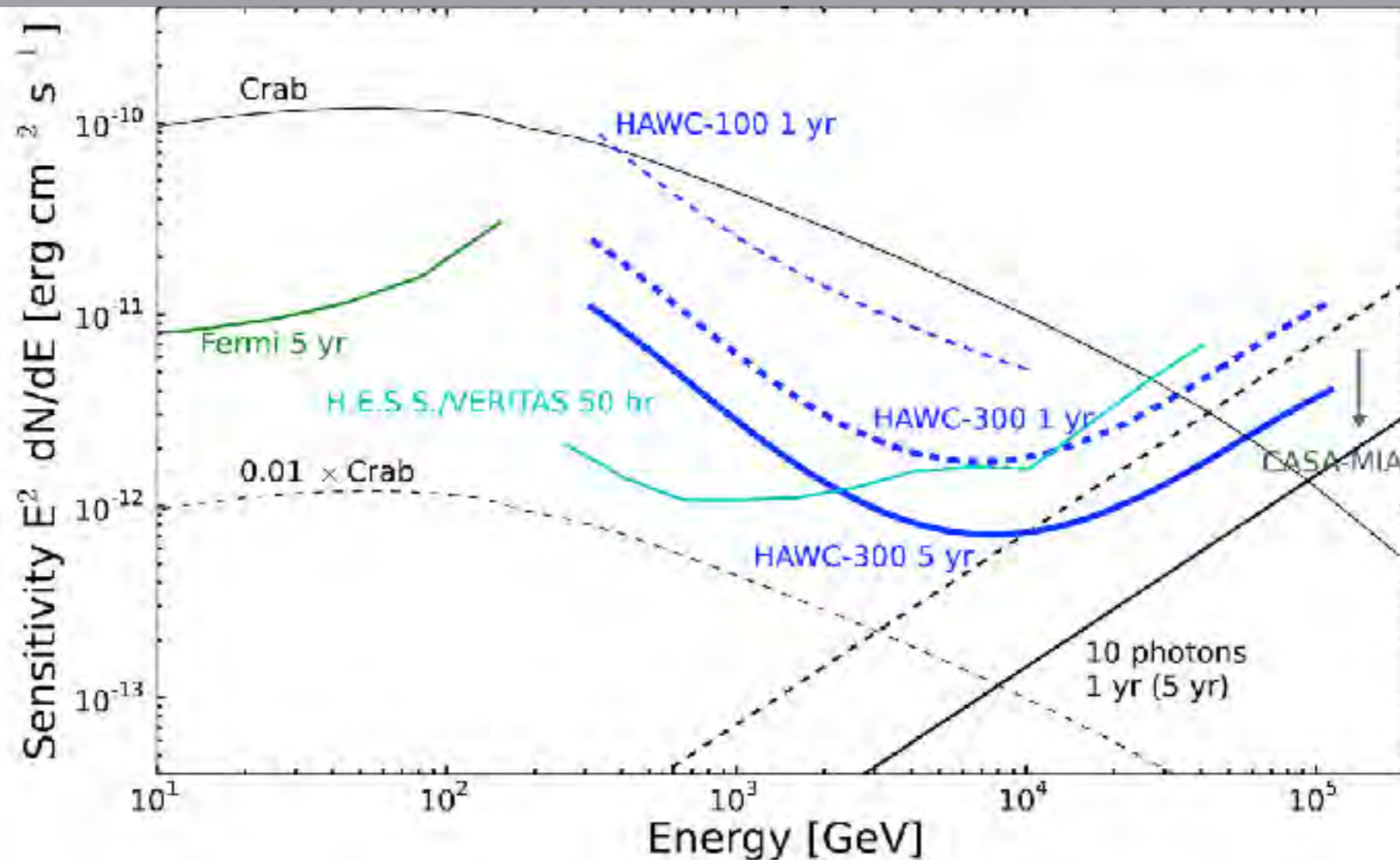
From 2011 to 2015

Deployment status



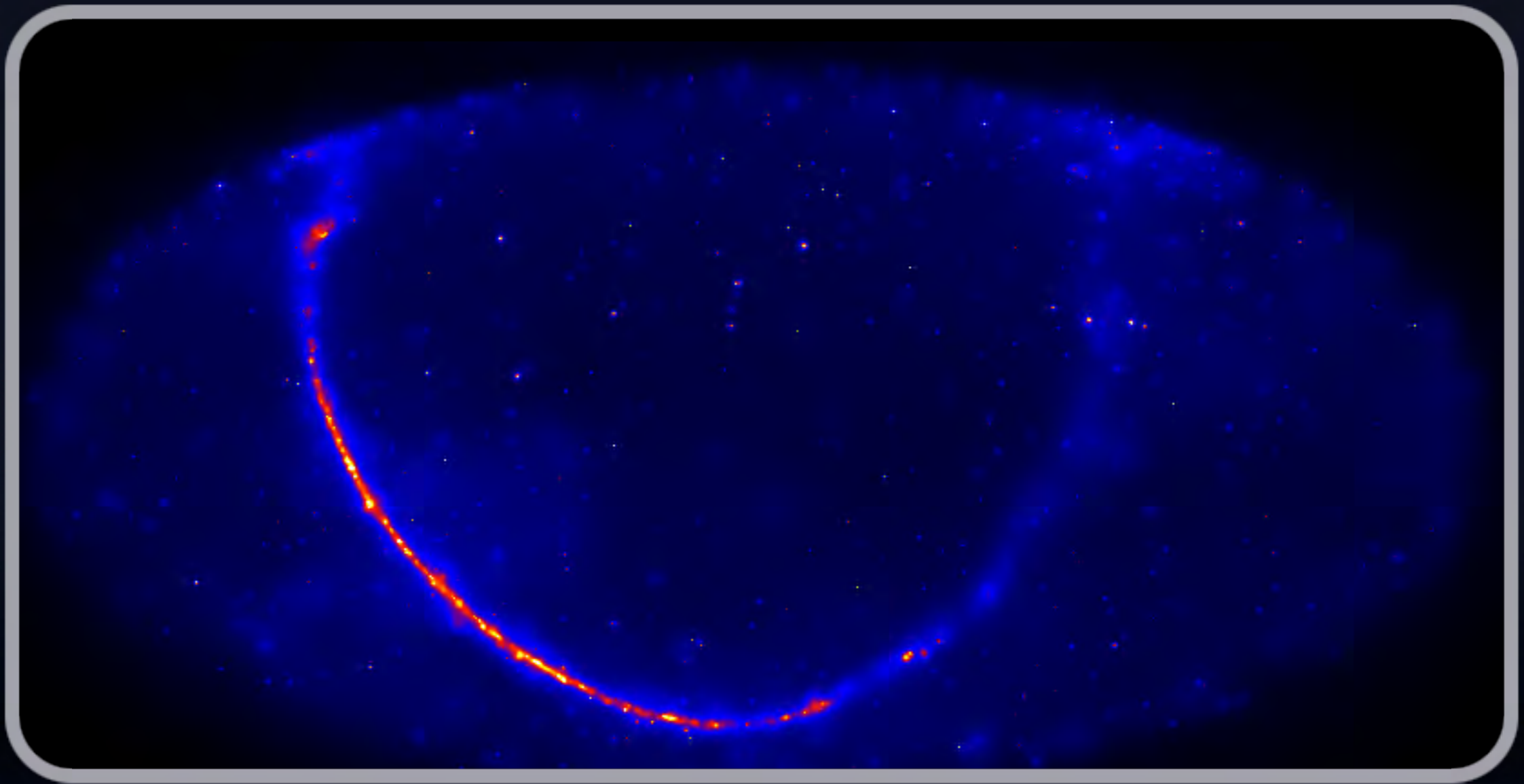
From 2011 to 2015

Design improvements



x15 more sensitive than Milagro

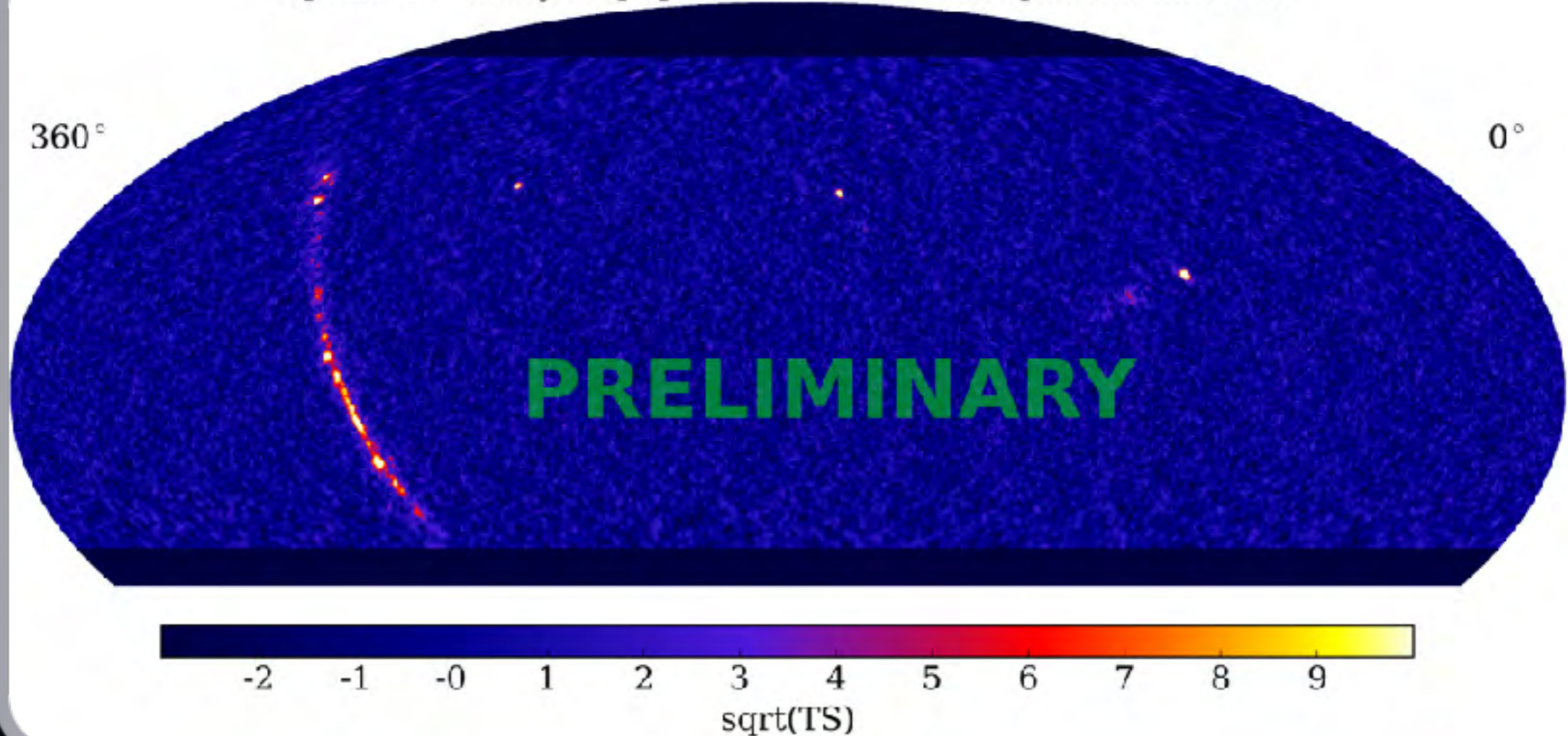
Design improvements



Fermi-LAT sky smoothed map
 $E > 50$ GeV (Pass 8 - 6 years of data)
(courtesy of M. Ajello)

Design improvements

Equatorial all sky map, point source search, spectral index -2.7



Fermi-LAT sky smoothed map
 $E > 50$ GeV (Pass 8 - 6 years of data)
(courtesy of M. Ajello)

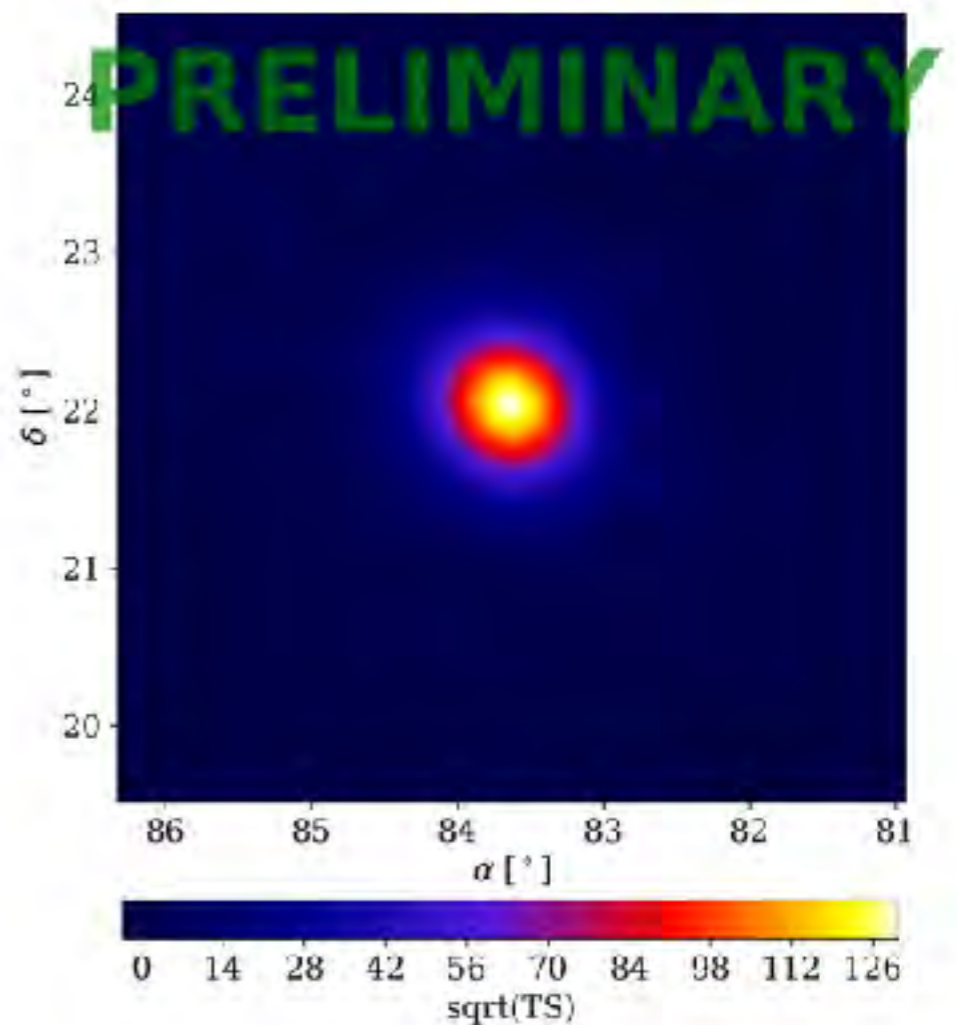
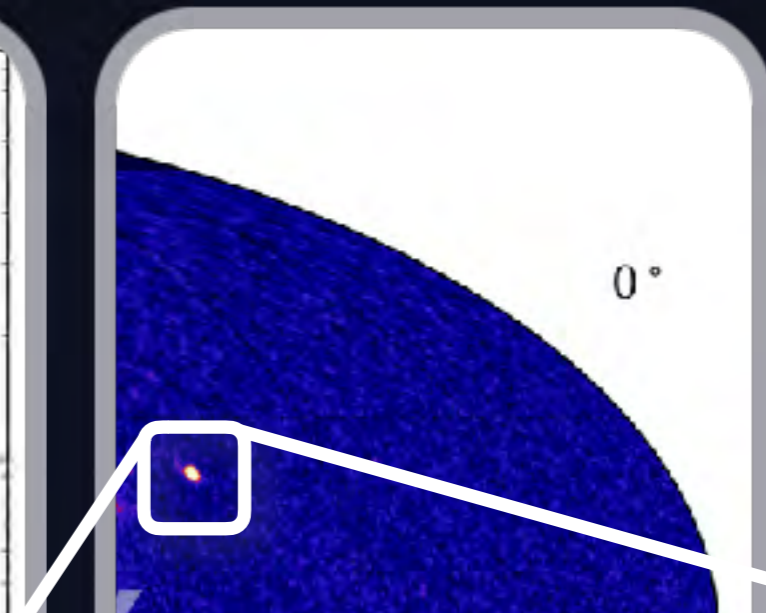
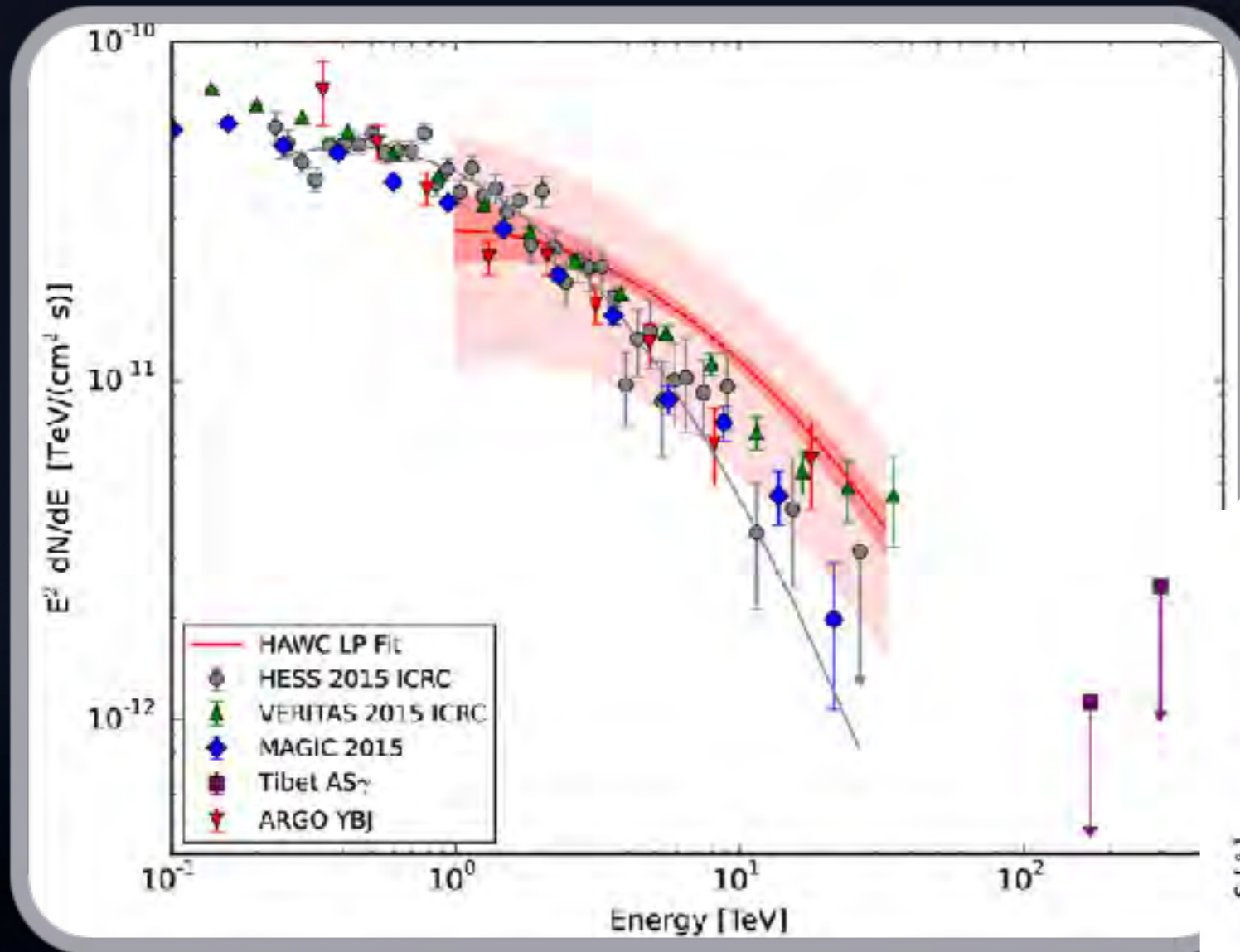
Preliminary HAWC smoothed map
 $E > 500$ GeV (~ 1 year of data)
Full array

A photograph of three people dressed in traditional Mexican attire, including large sombrero hats and colorful ponchos, riding a carousel horse. The scene is set outdoors with trees in the background. The image is overlaid with a dark, semi-transparent background.

Science Results

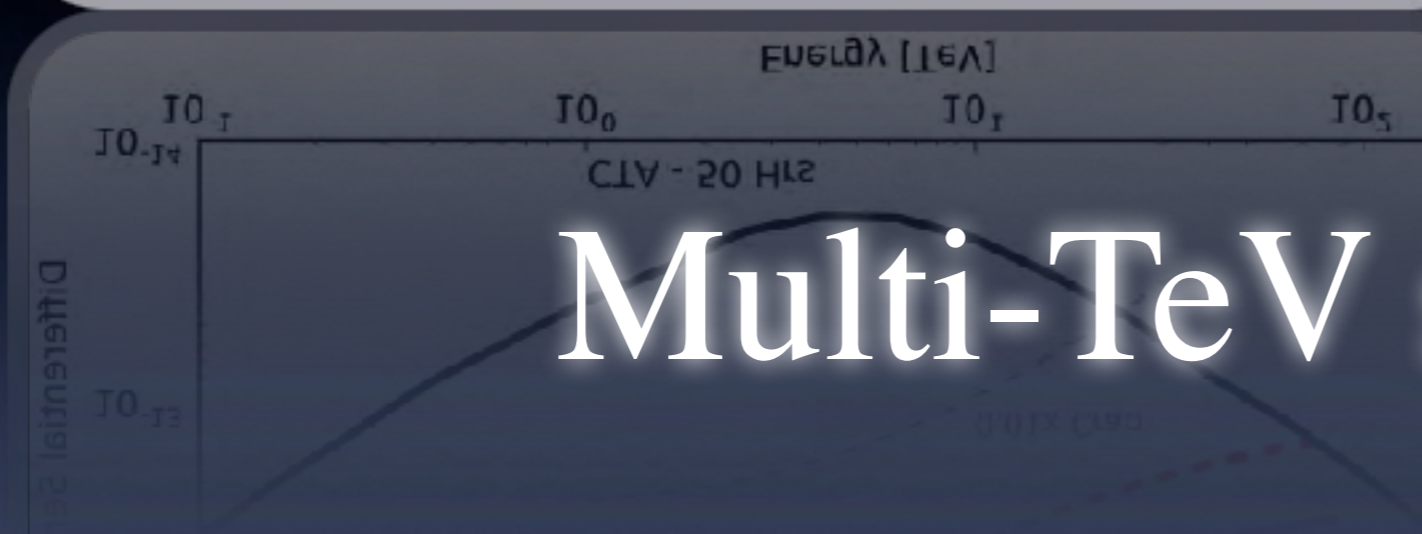
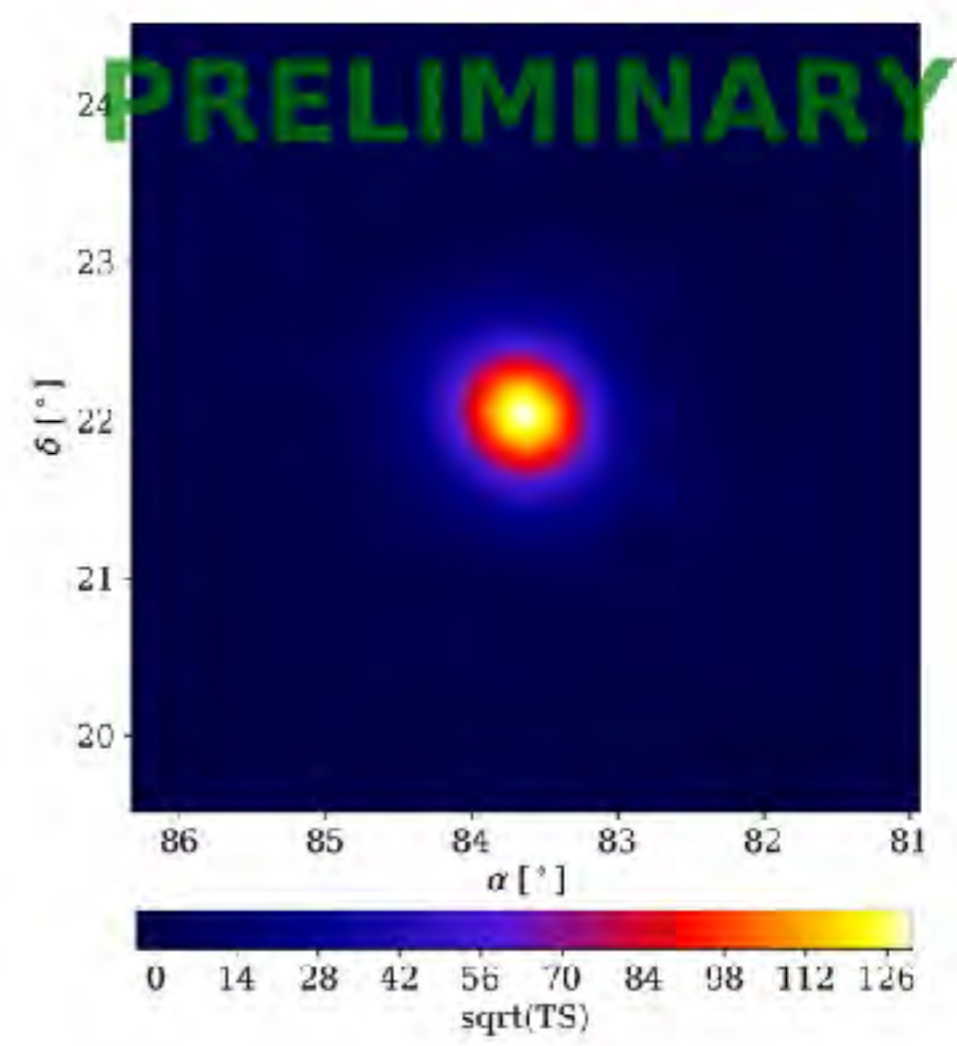
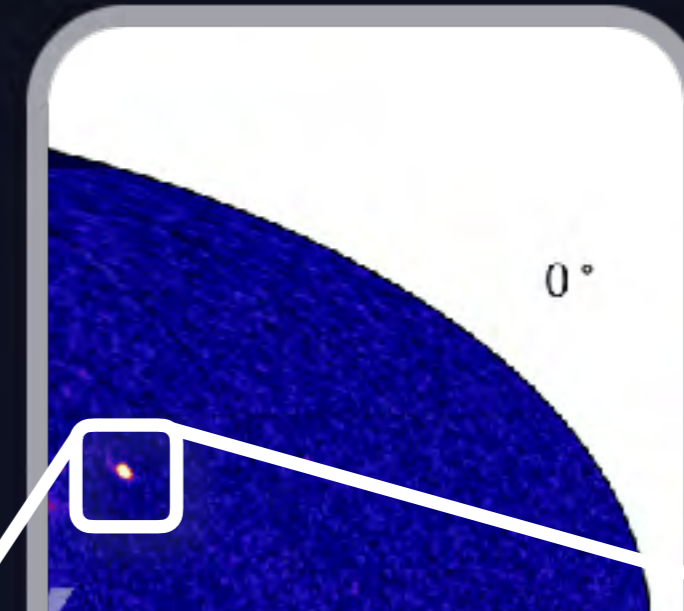
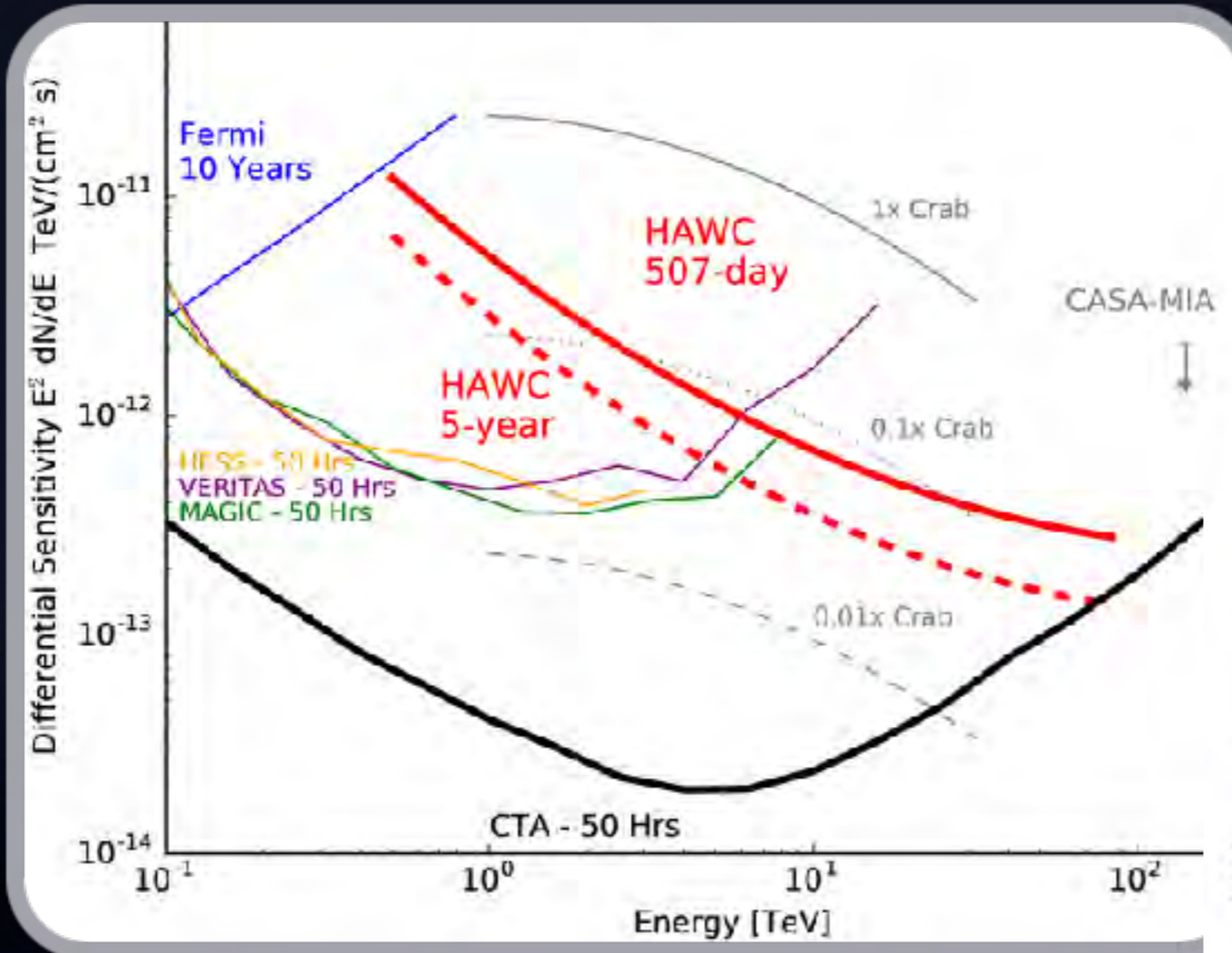
Penn State HAWCers in Mexico (2017)

The Crab



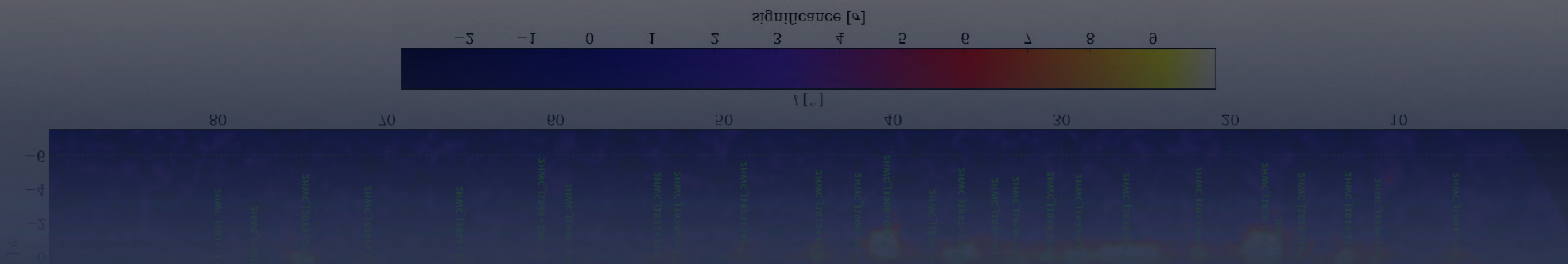
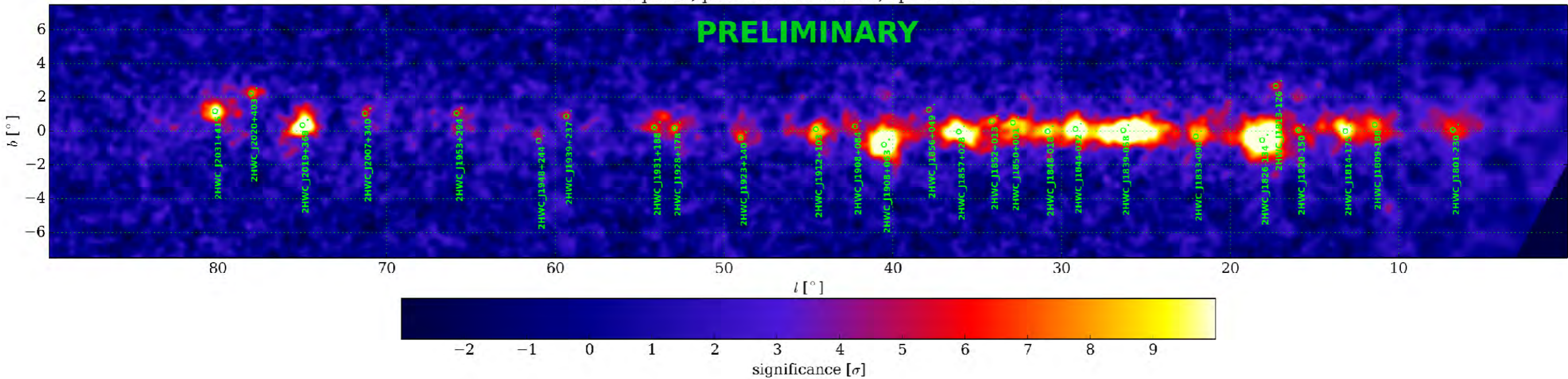
Multi-TeV γ

The Crab



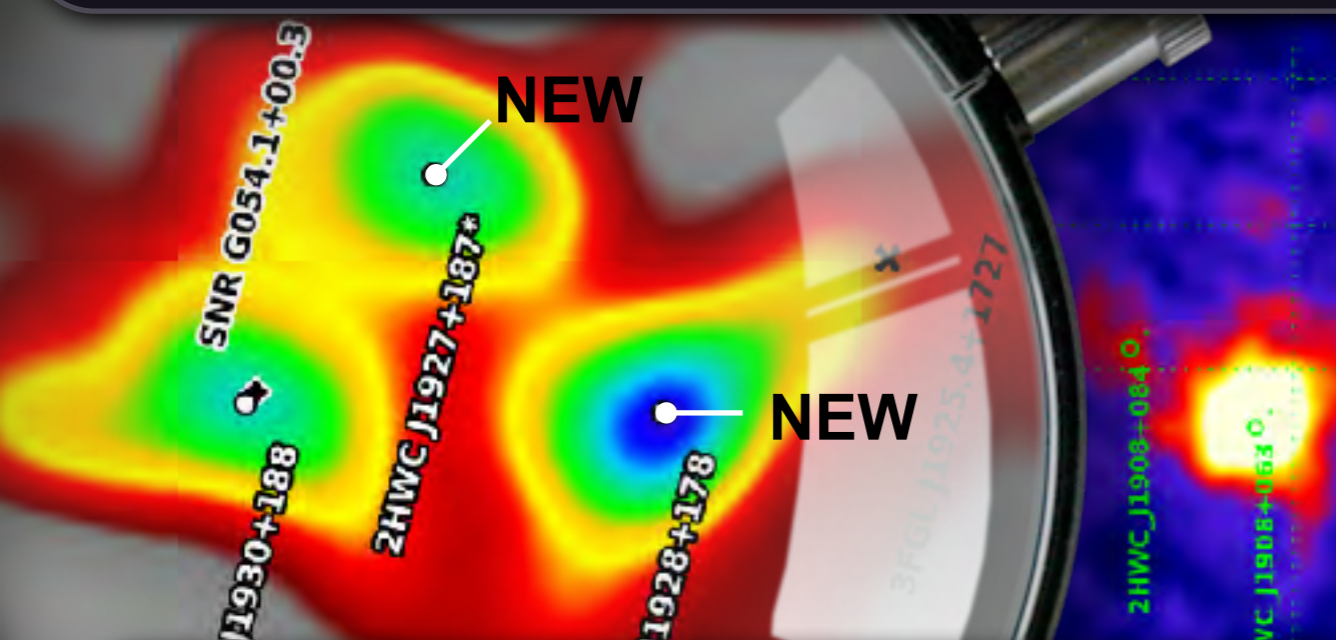
first HAWC catalog

Galactic plane, point source search, spectral index -2.7



2HWC J1930+188

- coincident with VER J1930+188
- SNR G54.1+00.3 — PSR J1930+1852
- TeV emission was reported to be point-like and likely from PWN
- nearby molecular CO cloud

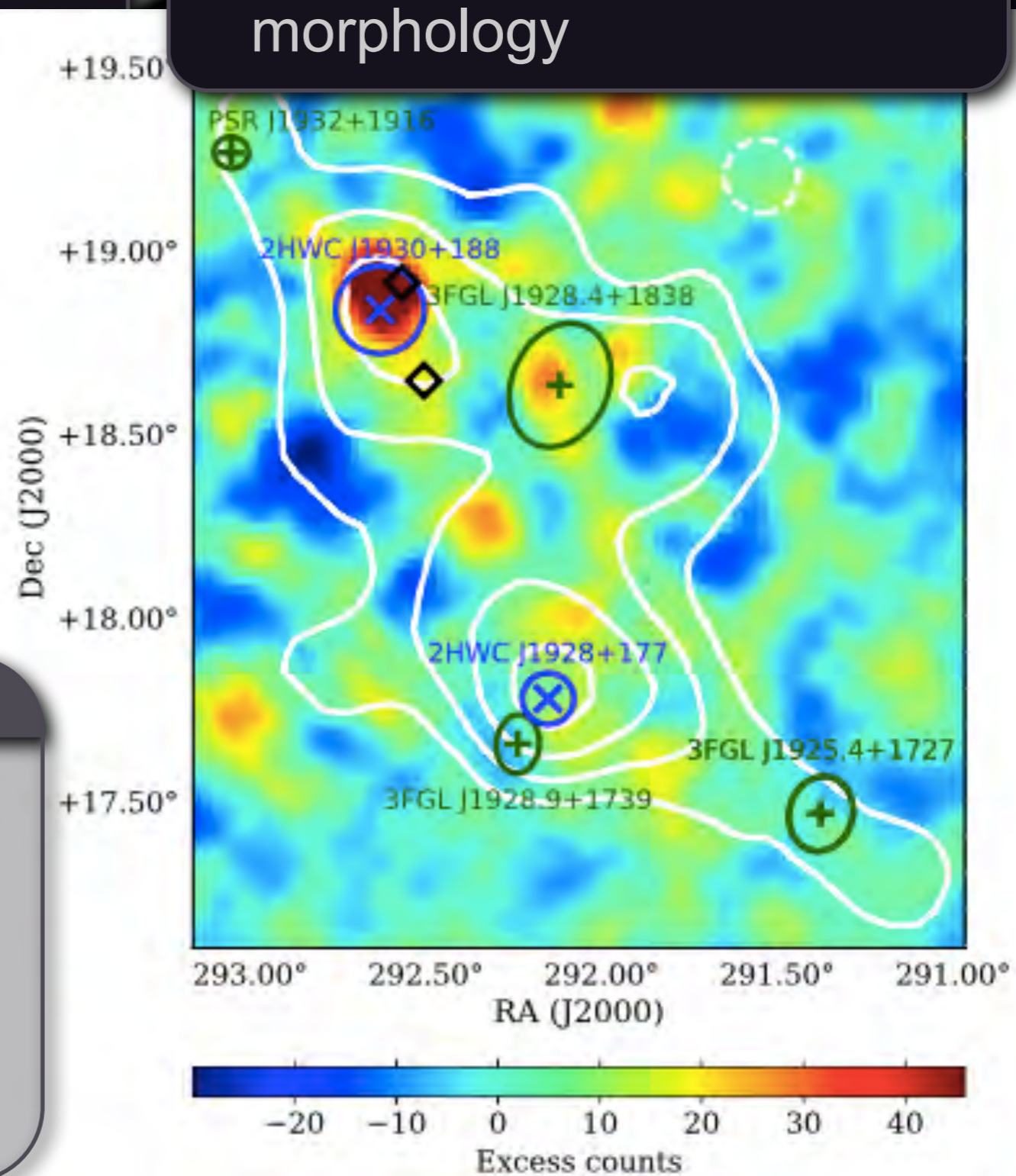


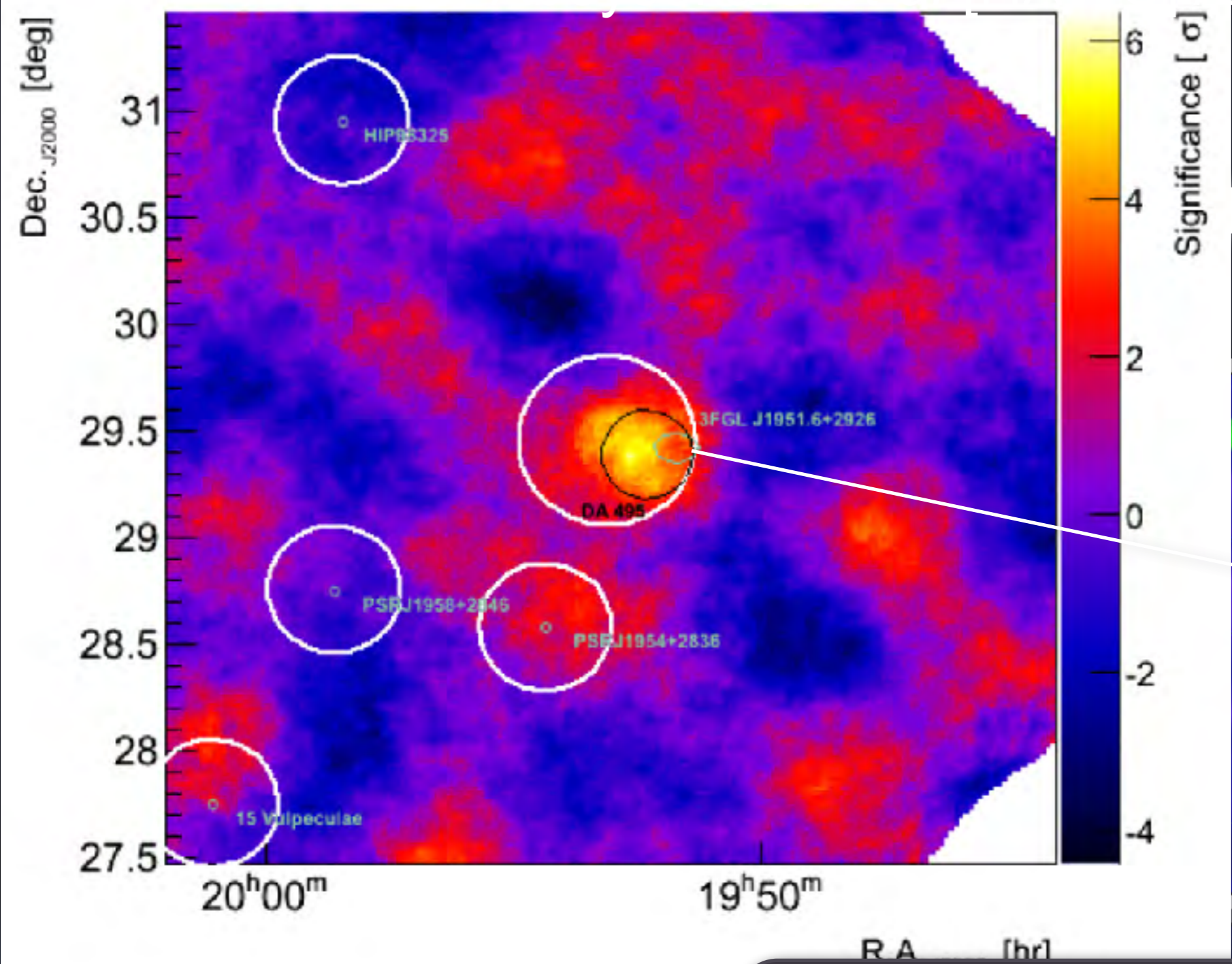
2HWC J1928+178

- coincident with PSR J1928+1746
- tail towards unidentified source
- 3FGL J1925.4+1727
- VERITAS pt-src upper limit ~1.4% of Crab

2HWC J1927+187*

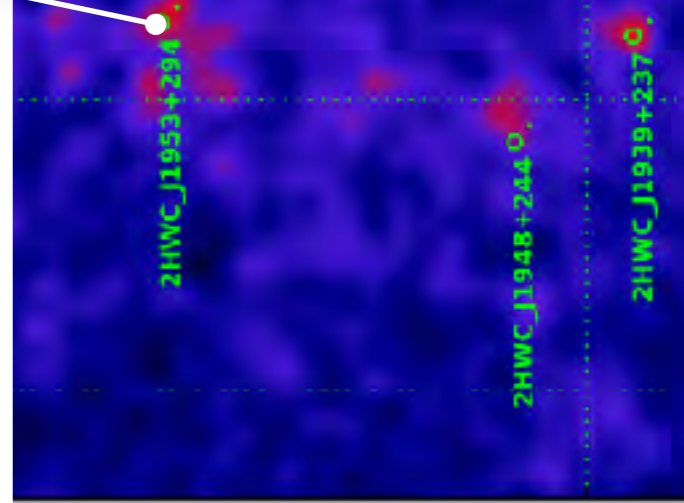
- associated with 2HWC J1930+188?
- ongoing analysis on spatial morphology





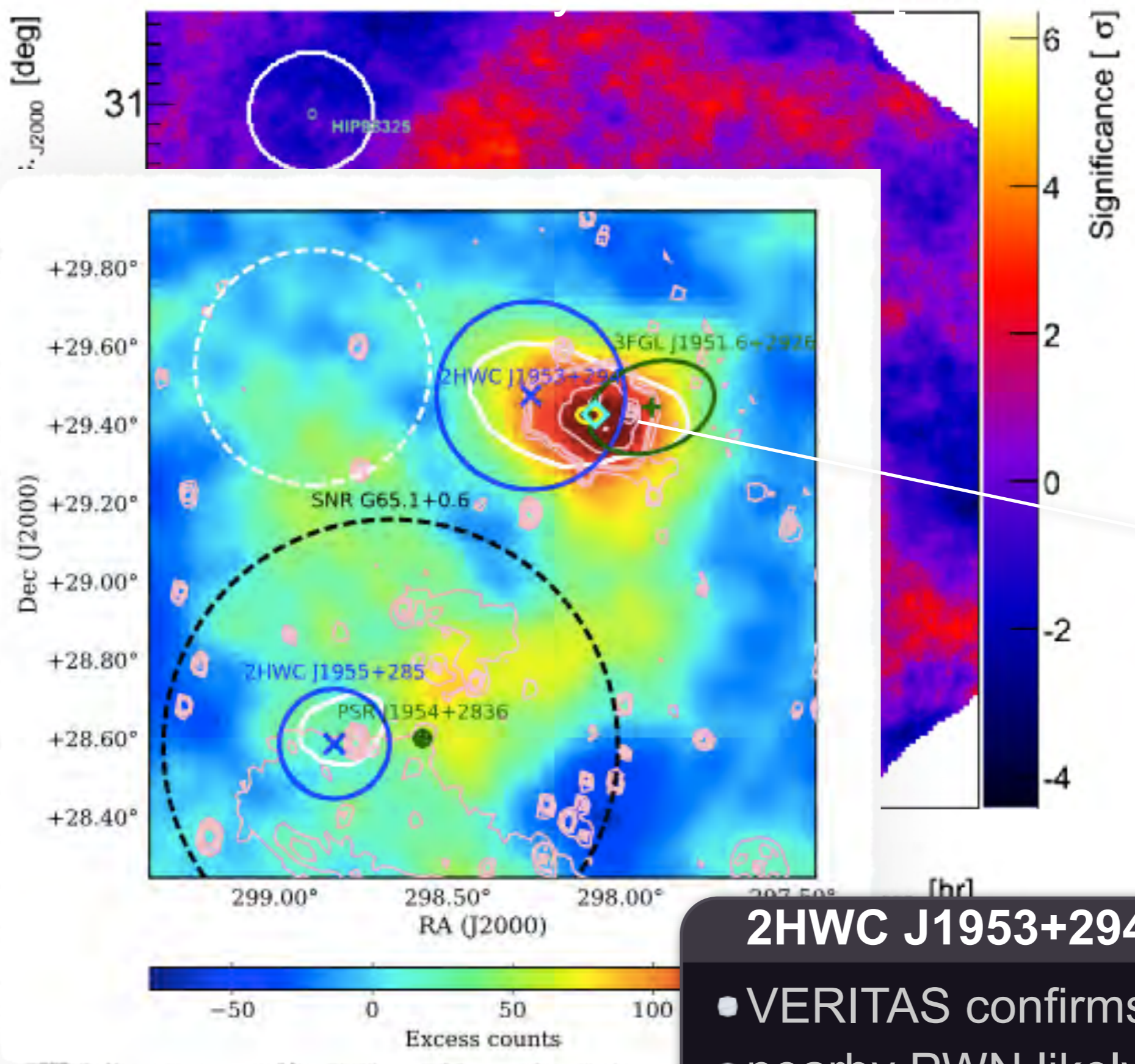
g

ARY



- **2HWC J1953+294**
- VERITAS confirms **HAWC detection**
- nearby PWN likely counterpart

2HWC J1953+294

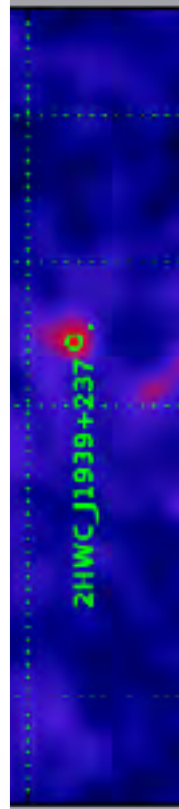
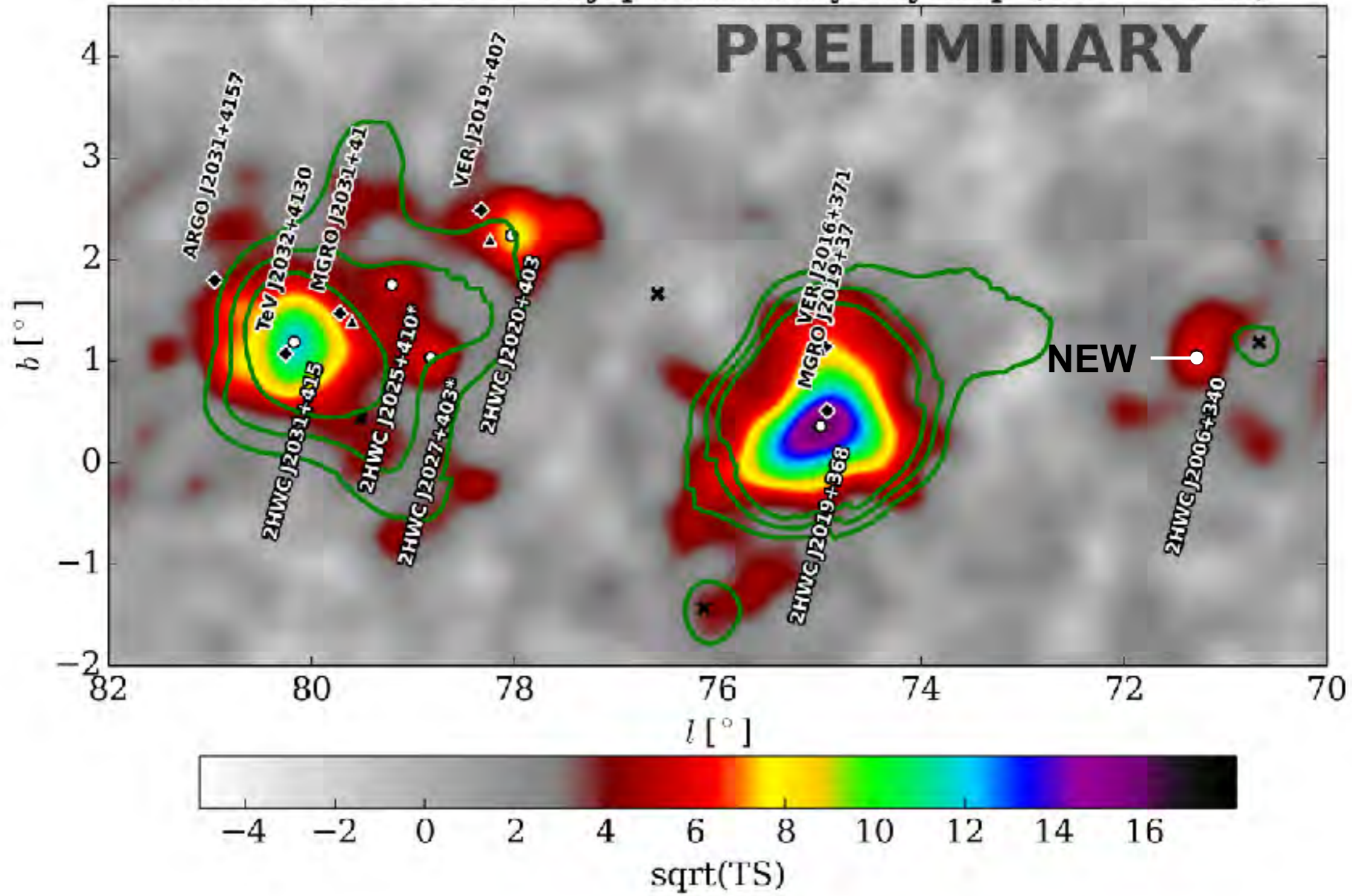


g

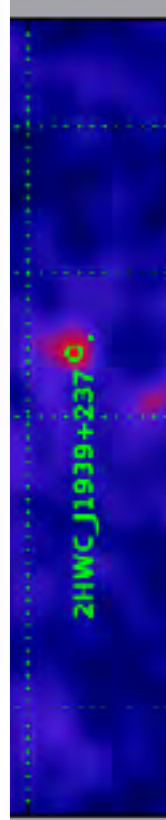
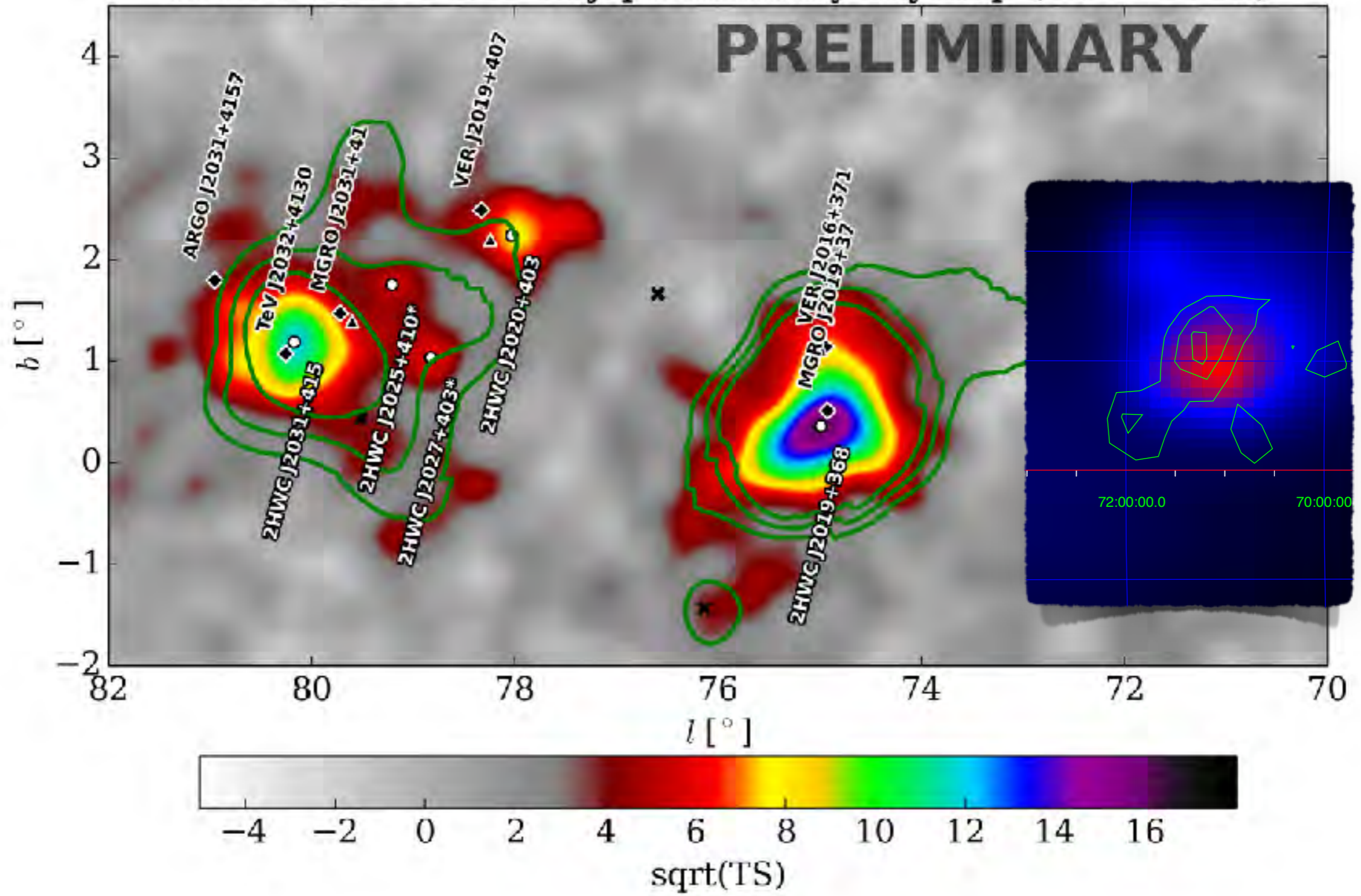
ARY

- 2HWC J1953+294
- VERITAS confirms HAWC detection
- nearby PWN likely counterpart

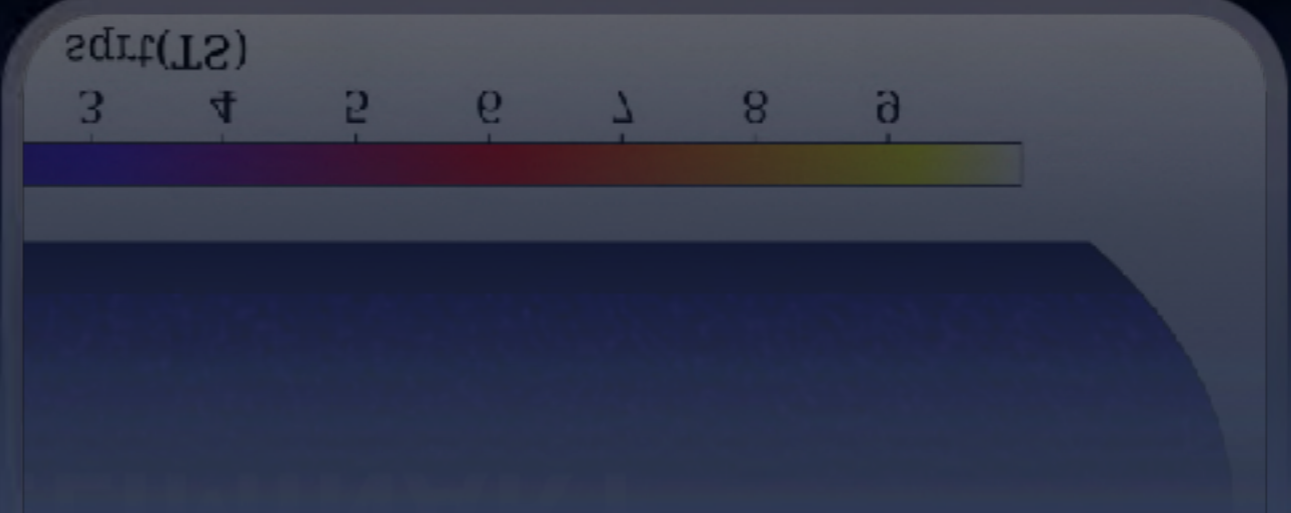
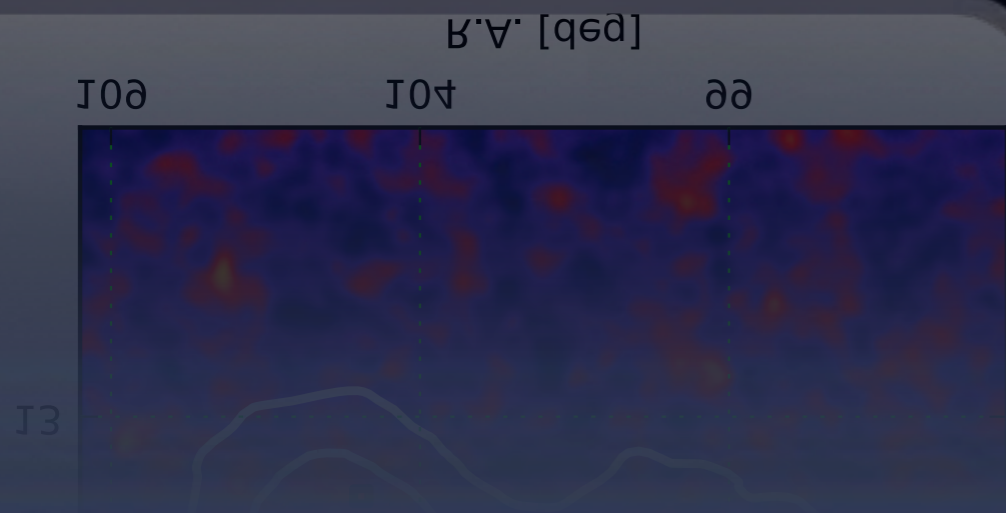
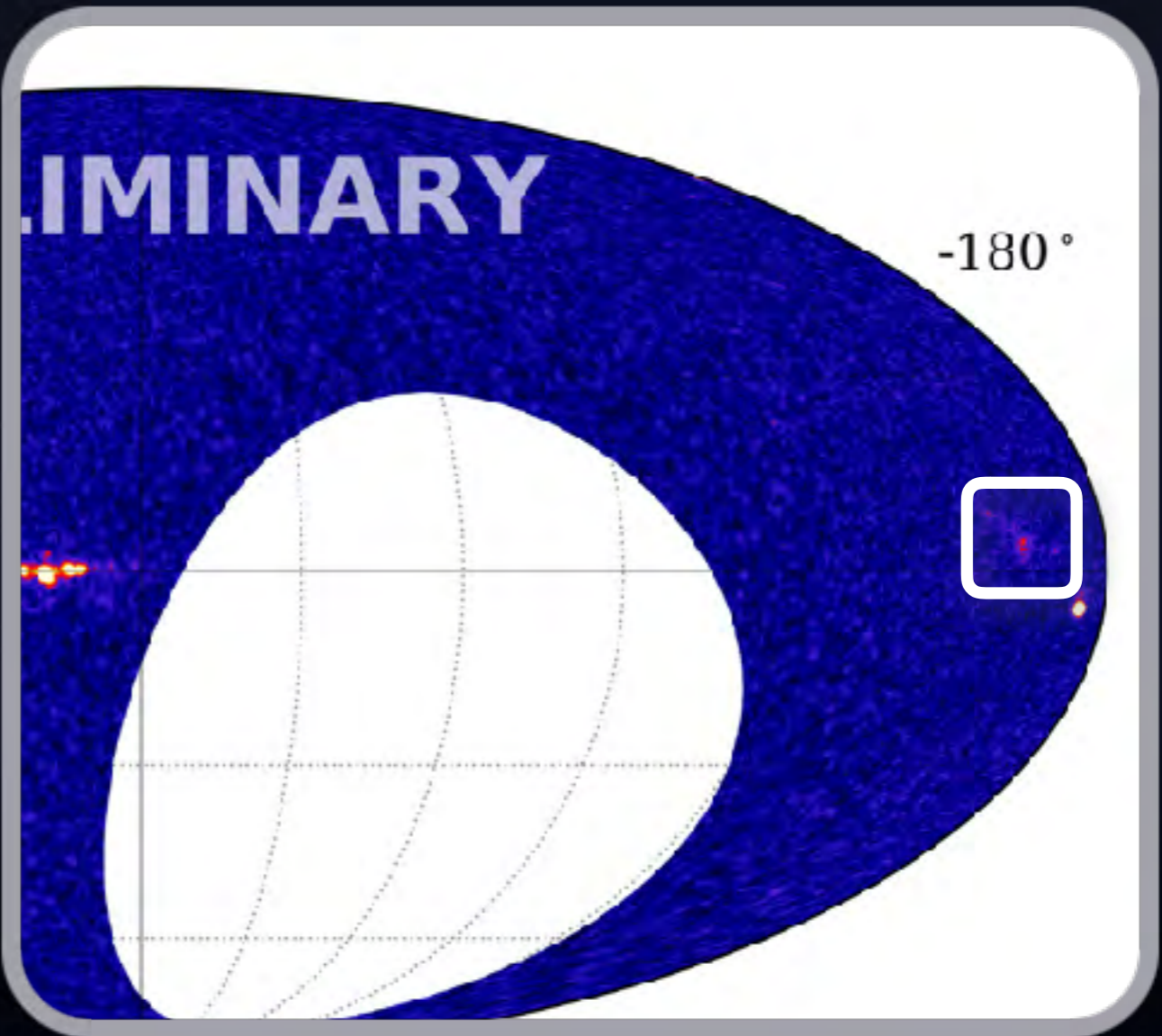
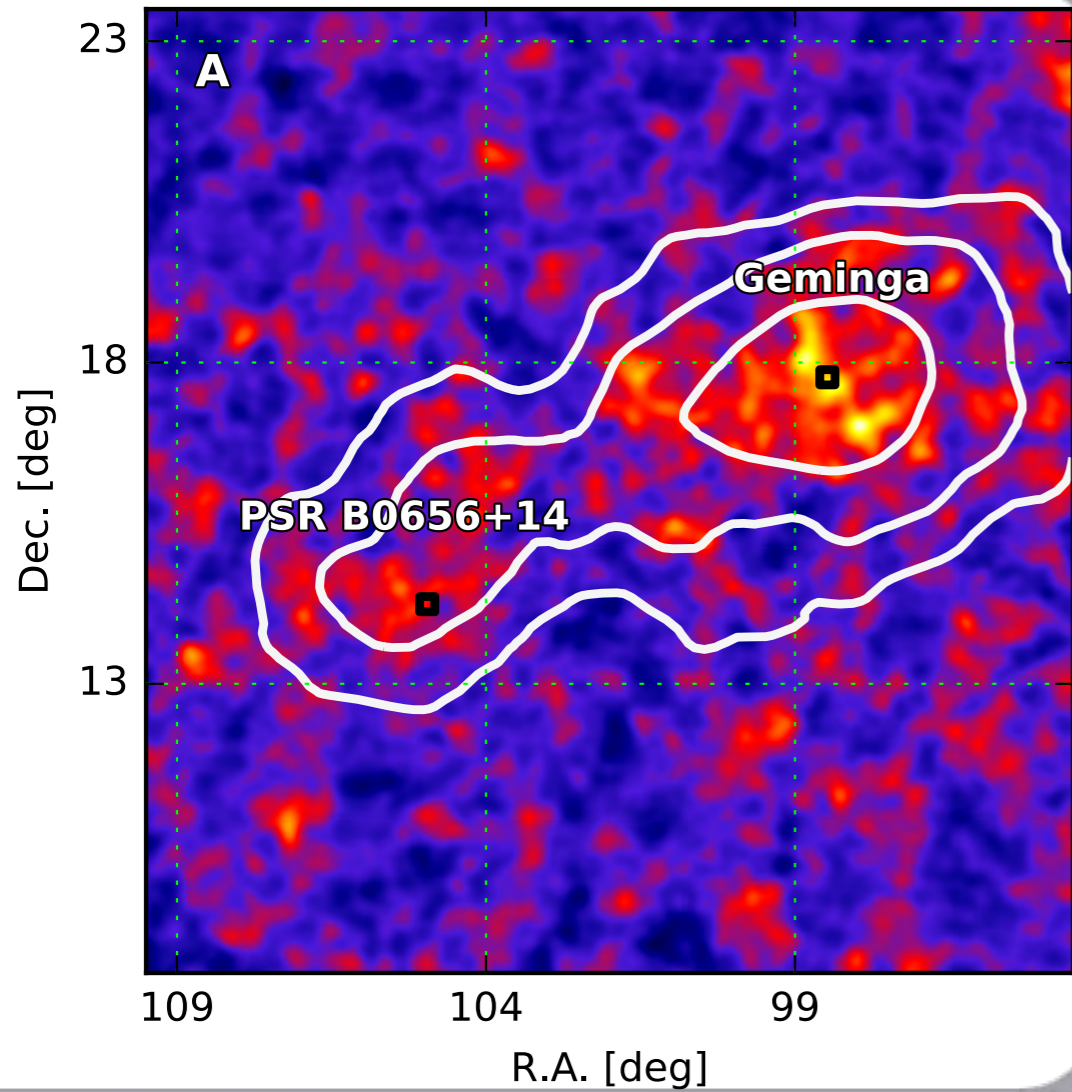
HAWC Pass 4 341-day preliminary skymap (2014-2015)



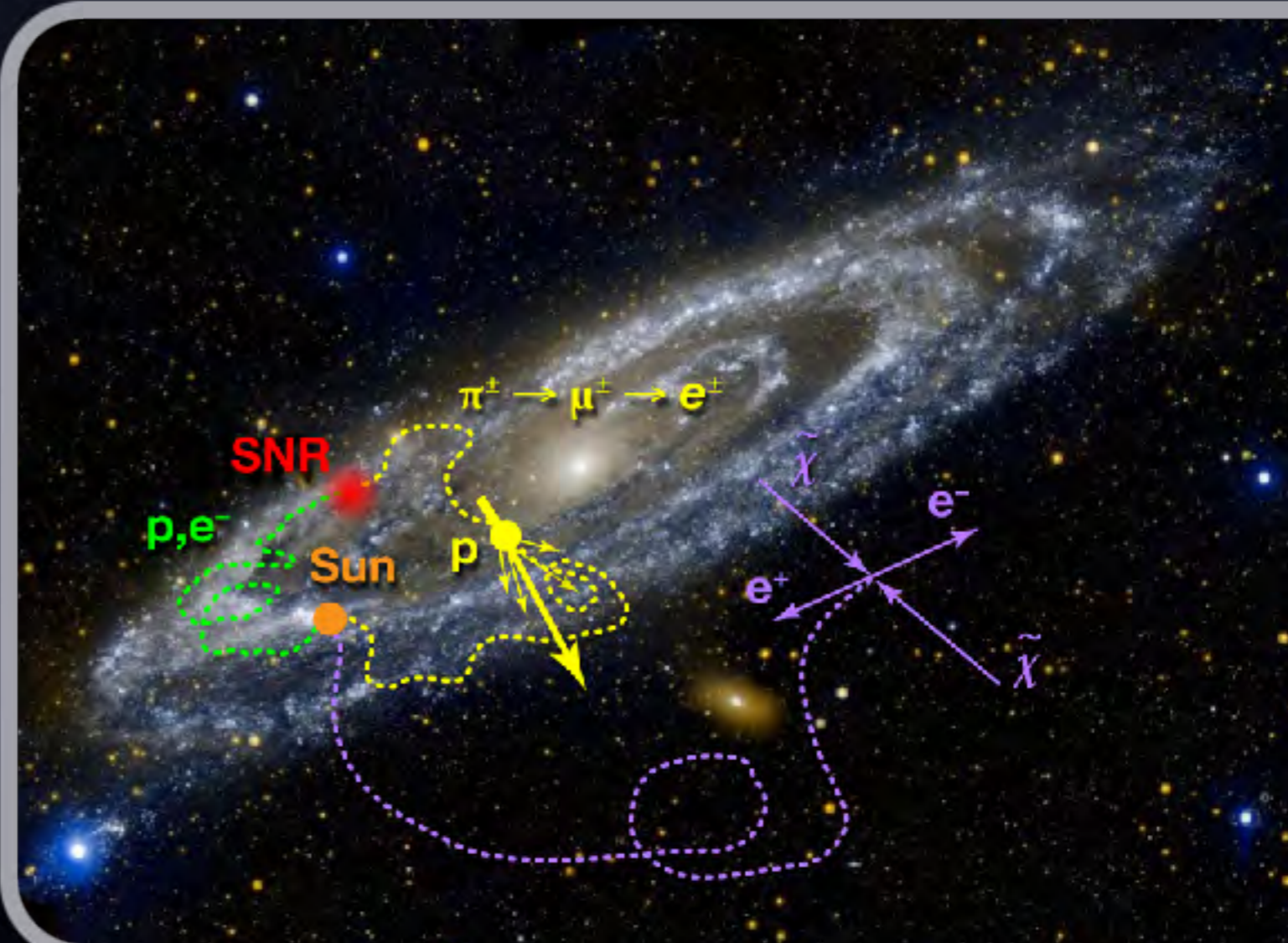
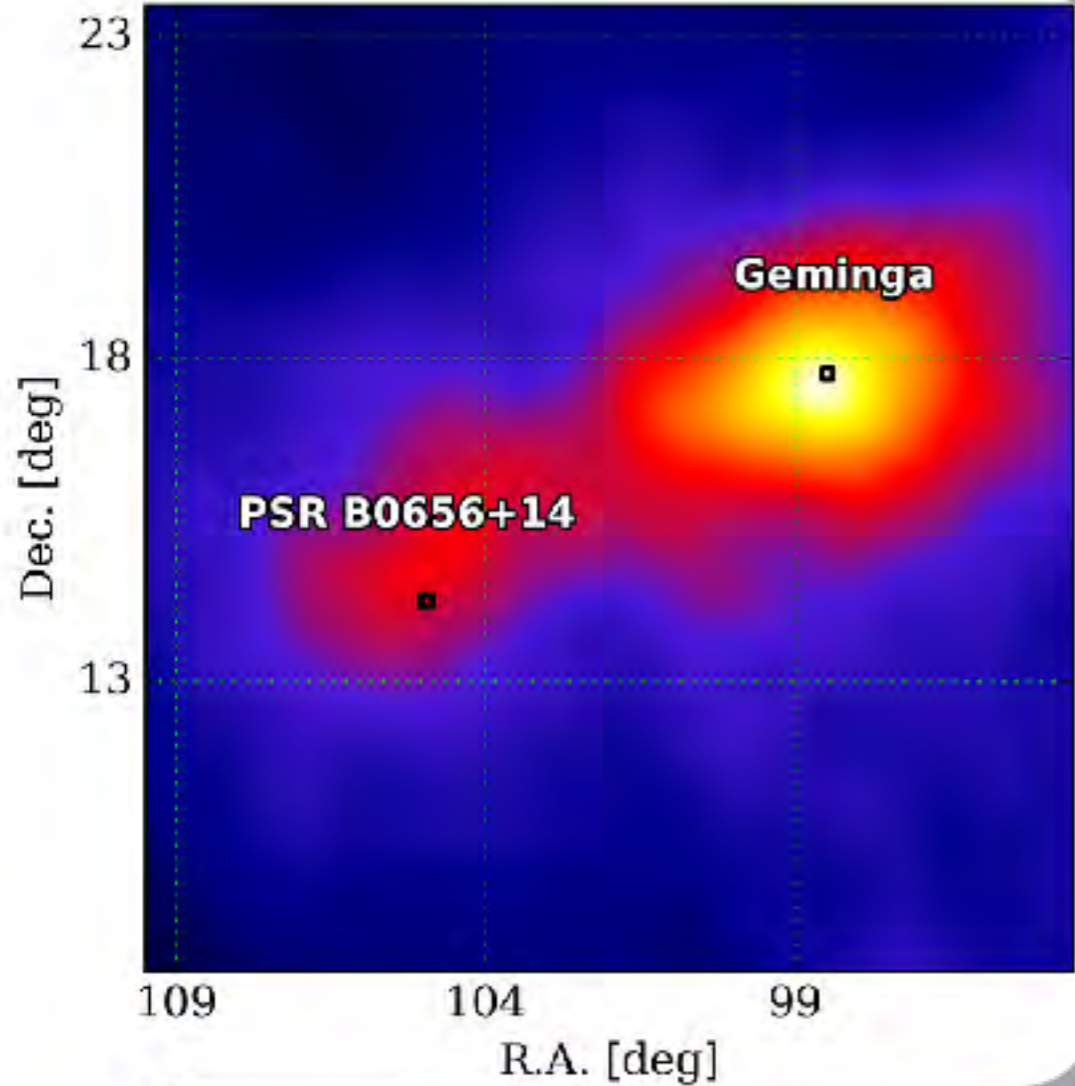
HAWC Pass 4 341-day preliminary skymap (2014-2015)



Geminga

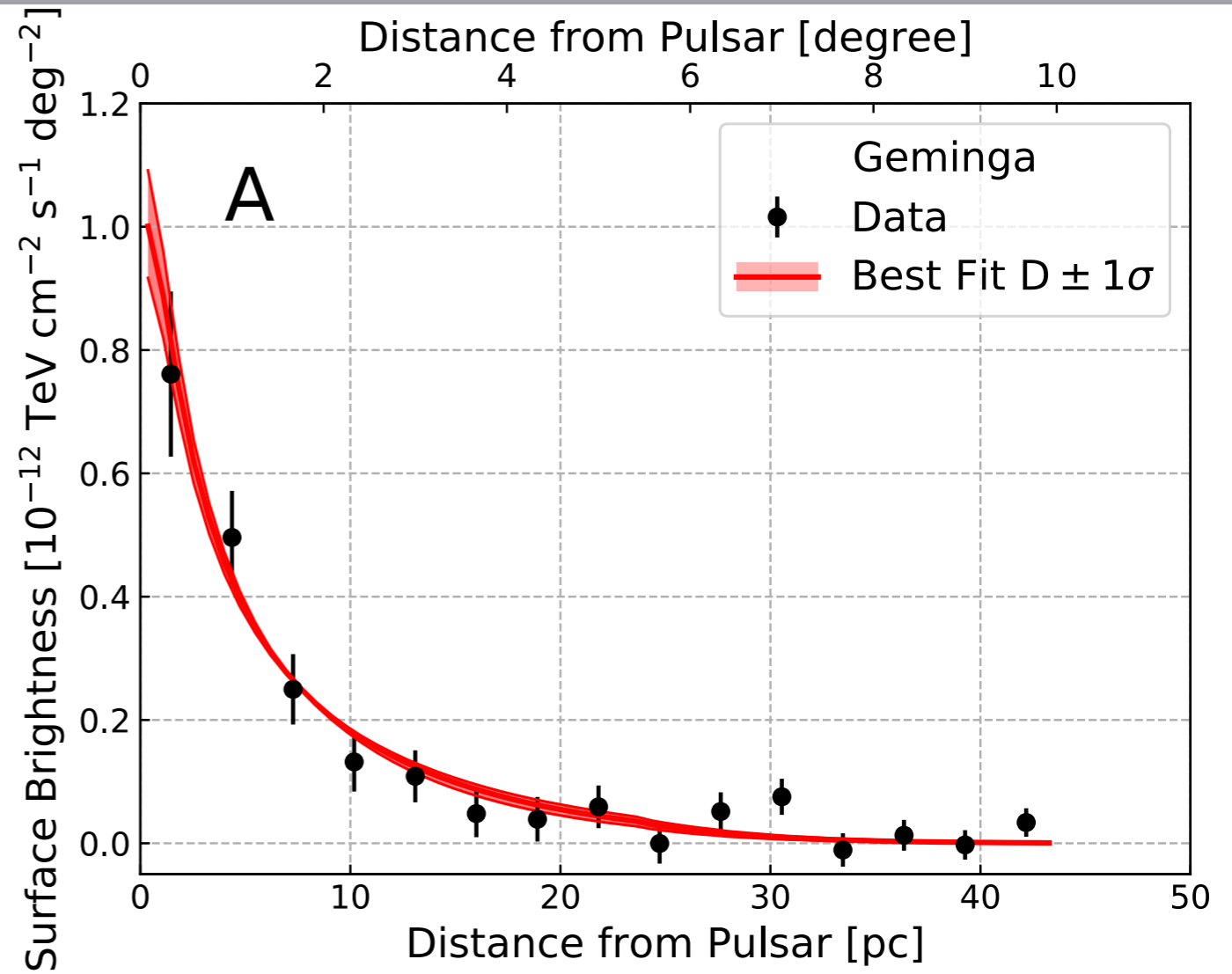
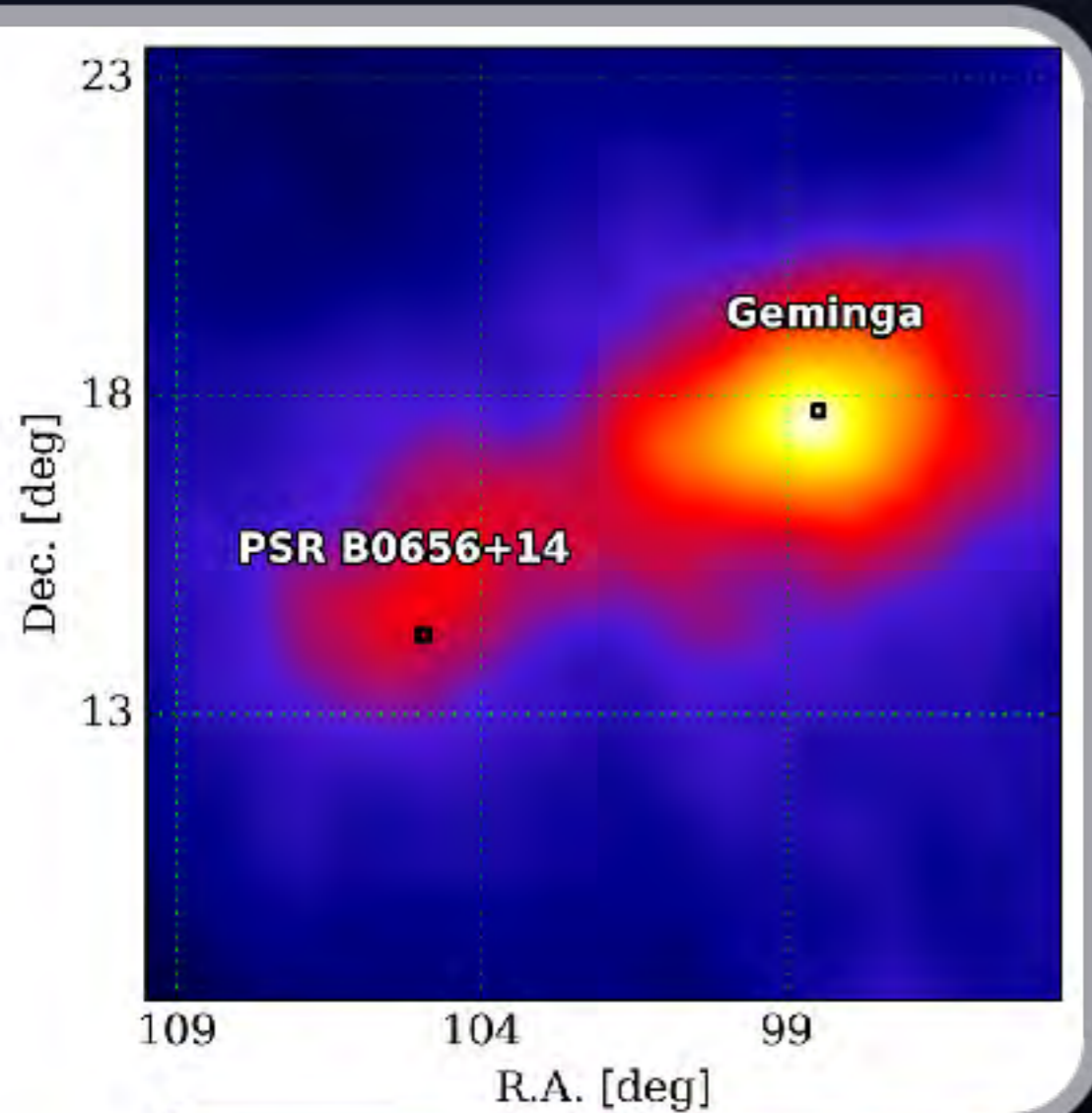


Positron excess from nearby pulsars?



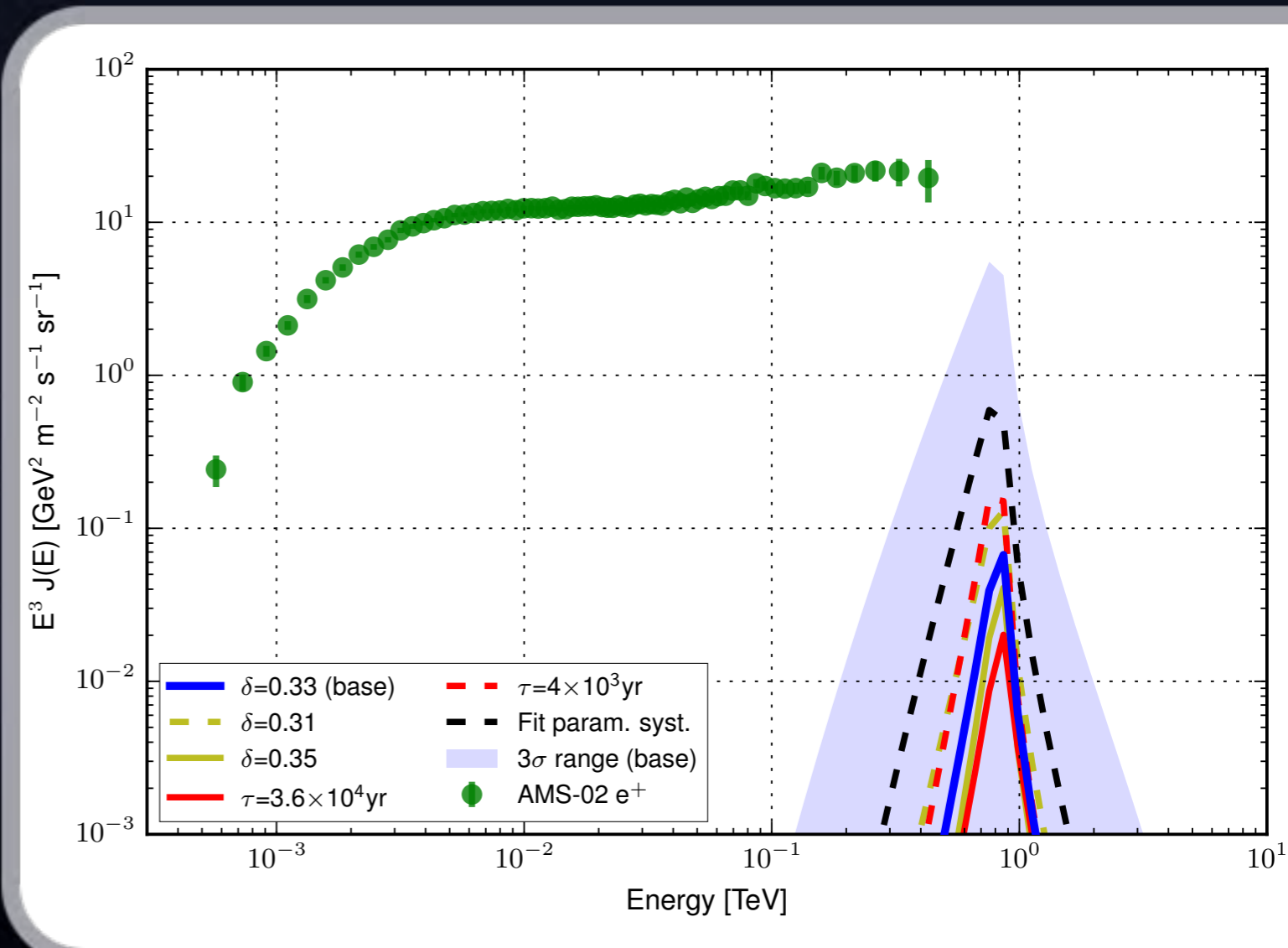
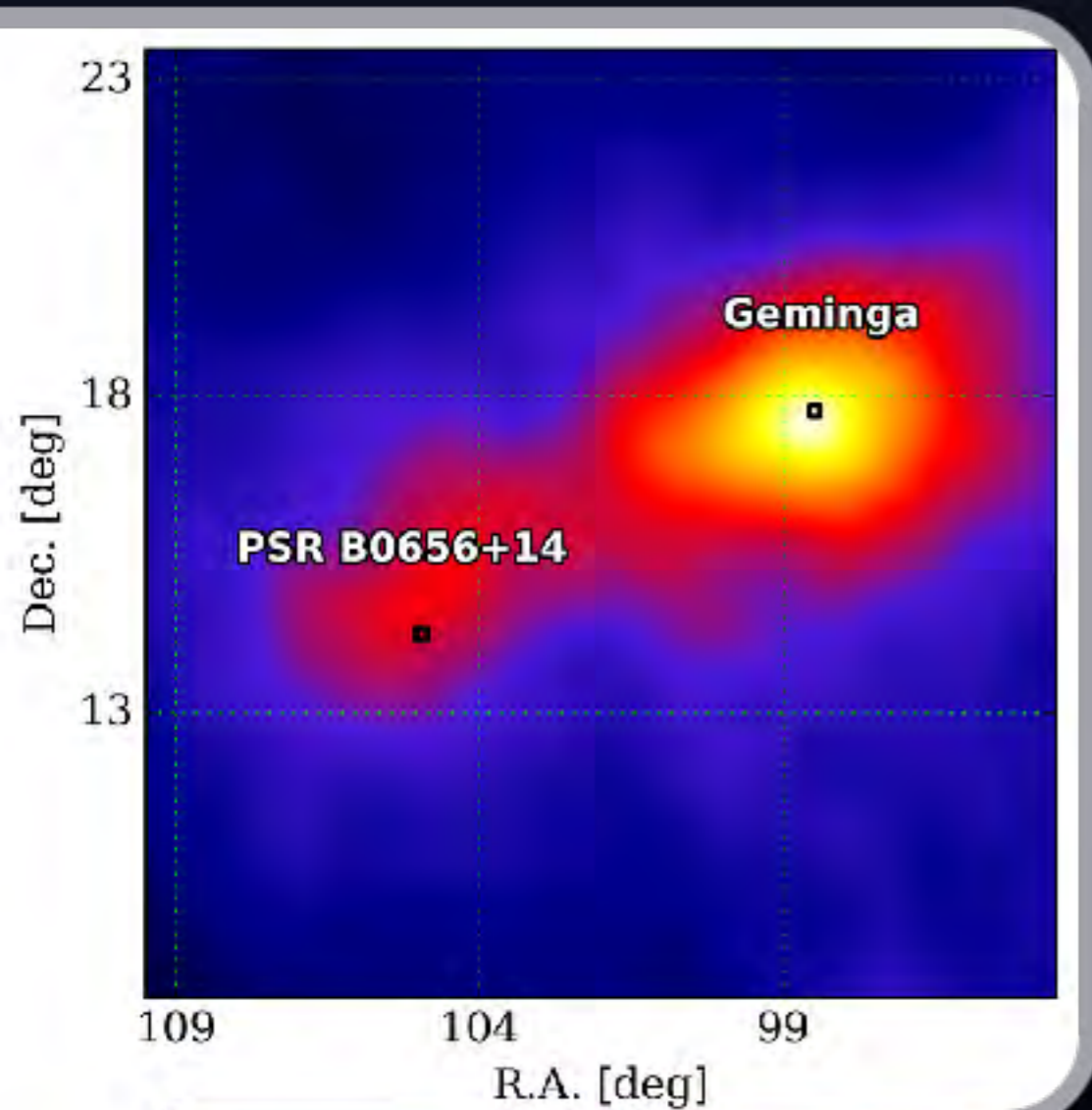
Extended emission

surface brightness



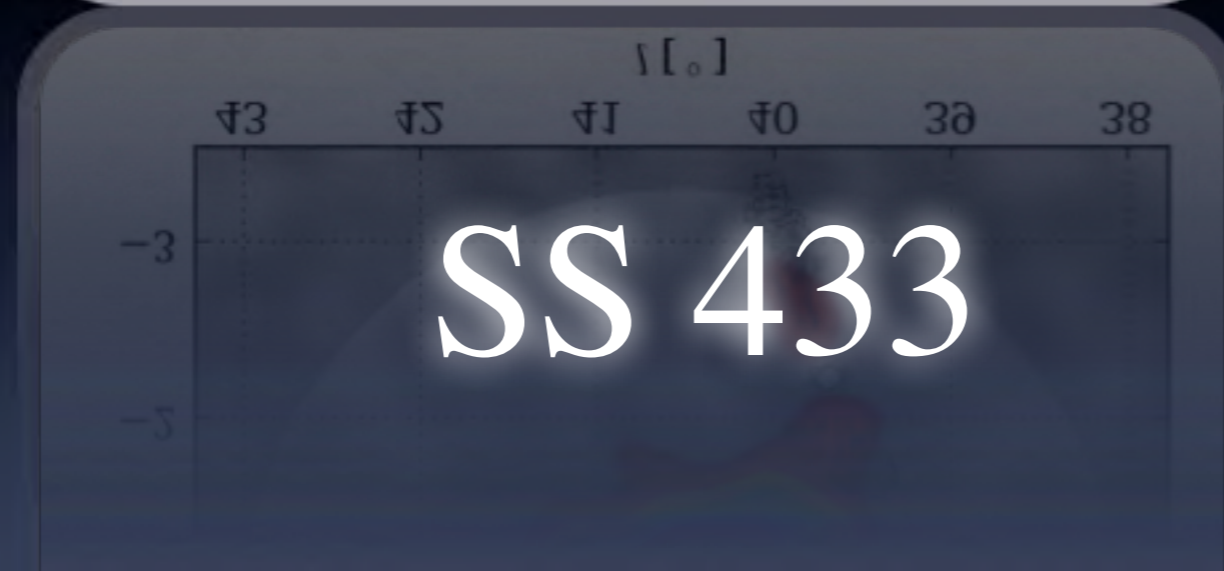
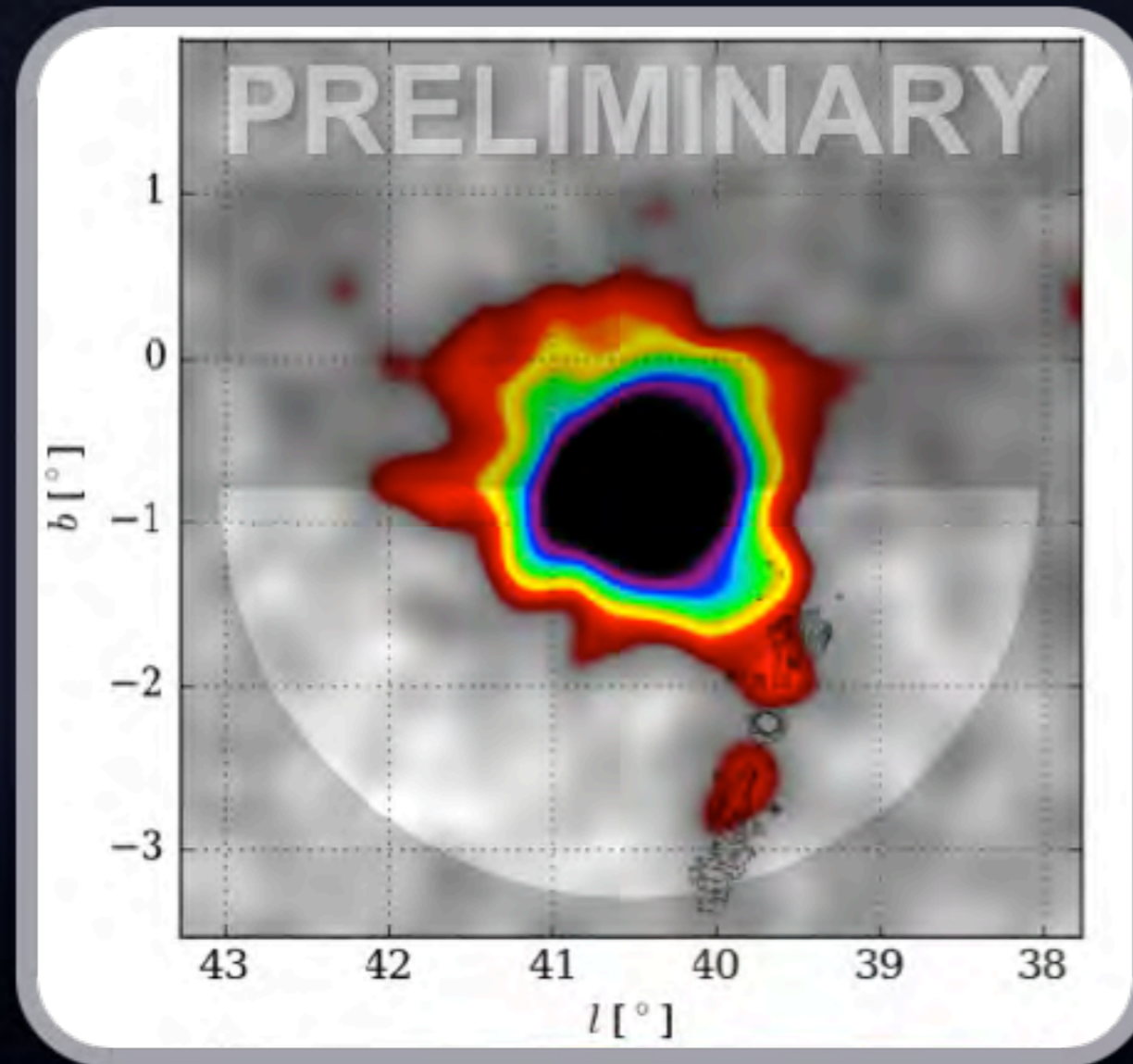
Extended emission

Estimated positron energy flux at Earth

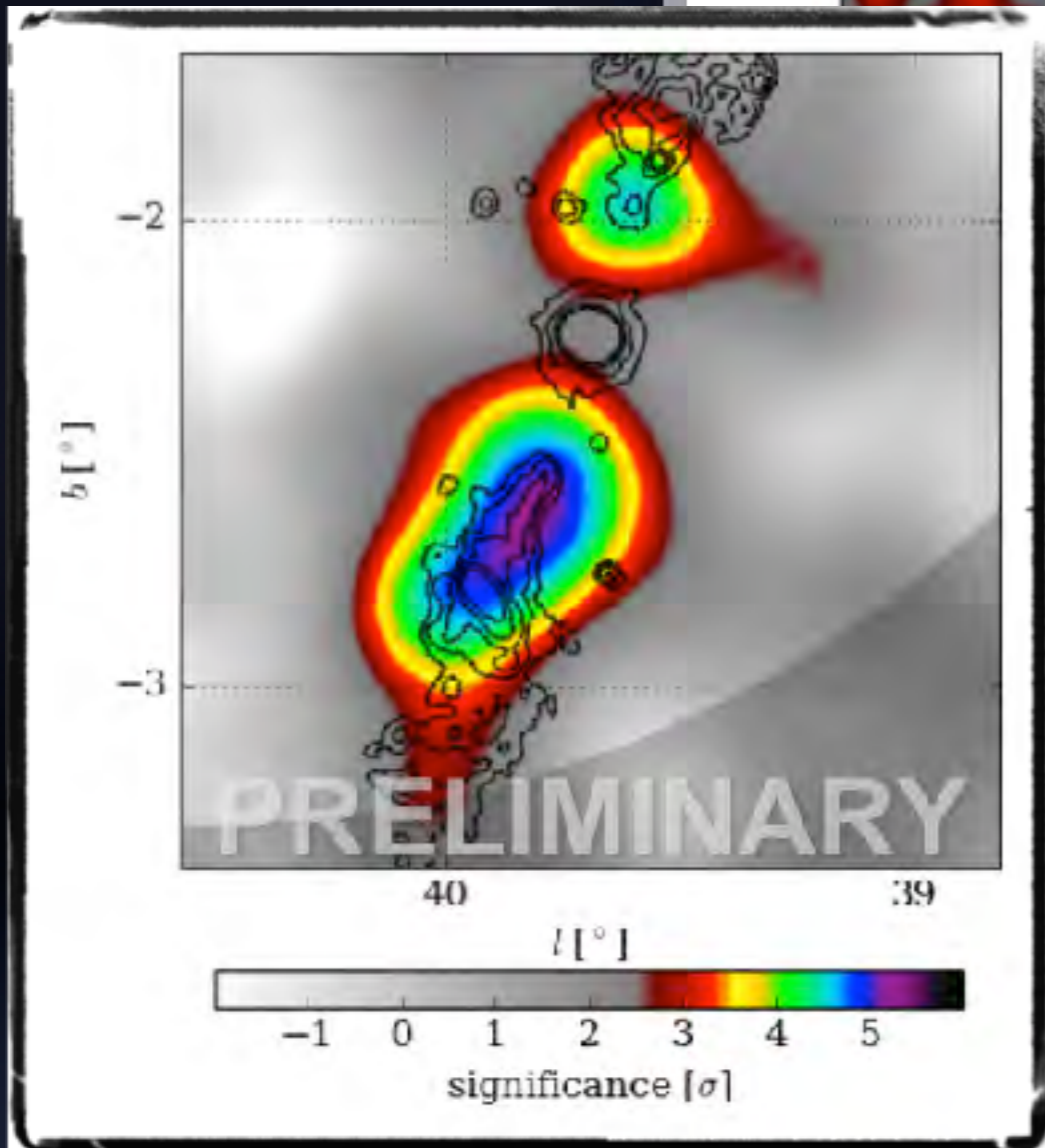
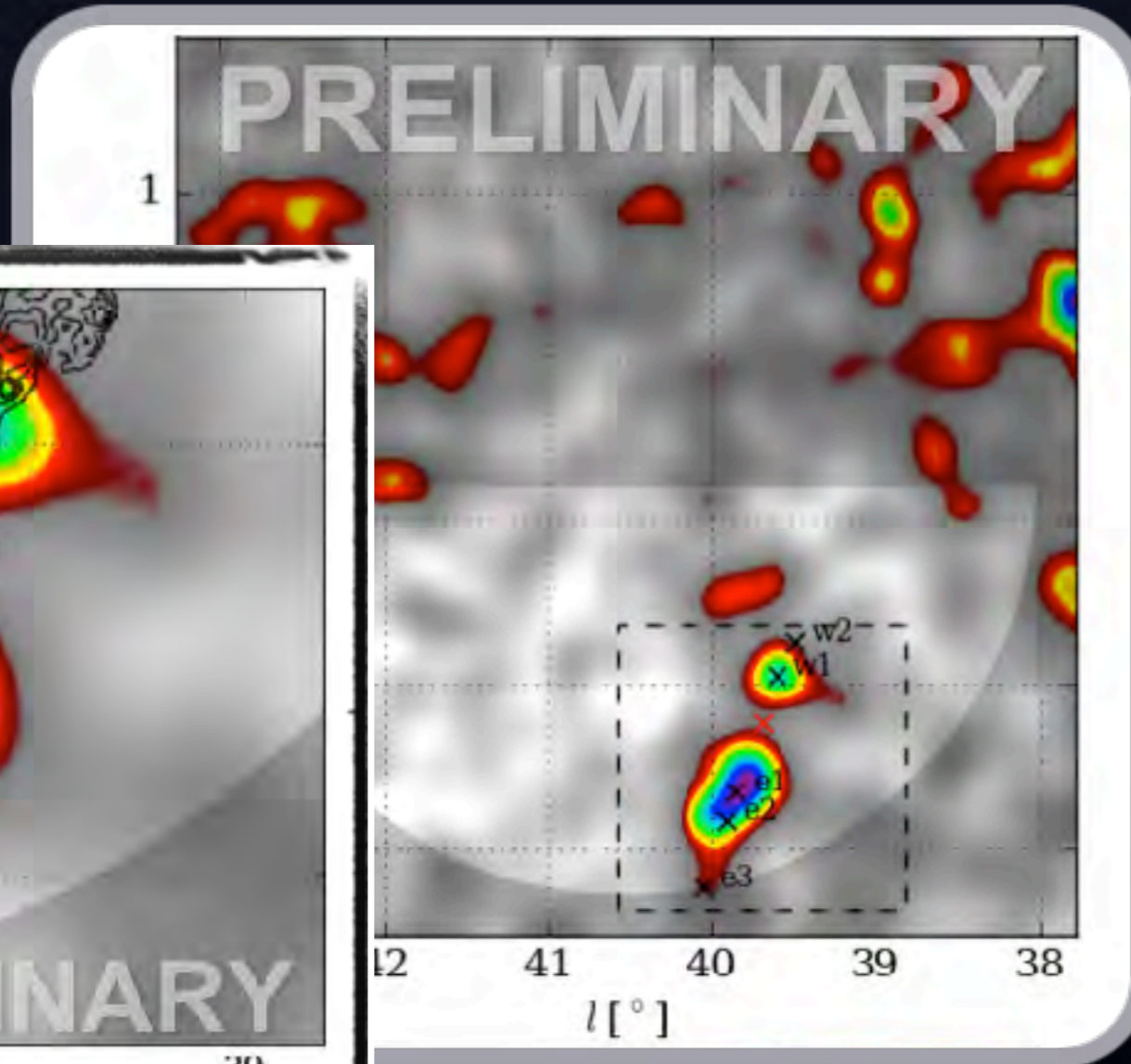


Extended emission

VHE emission from the jets of a microquasar



VHE emission from the jets of a microquasar

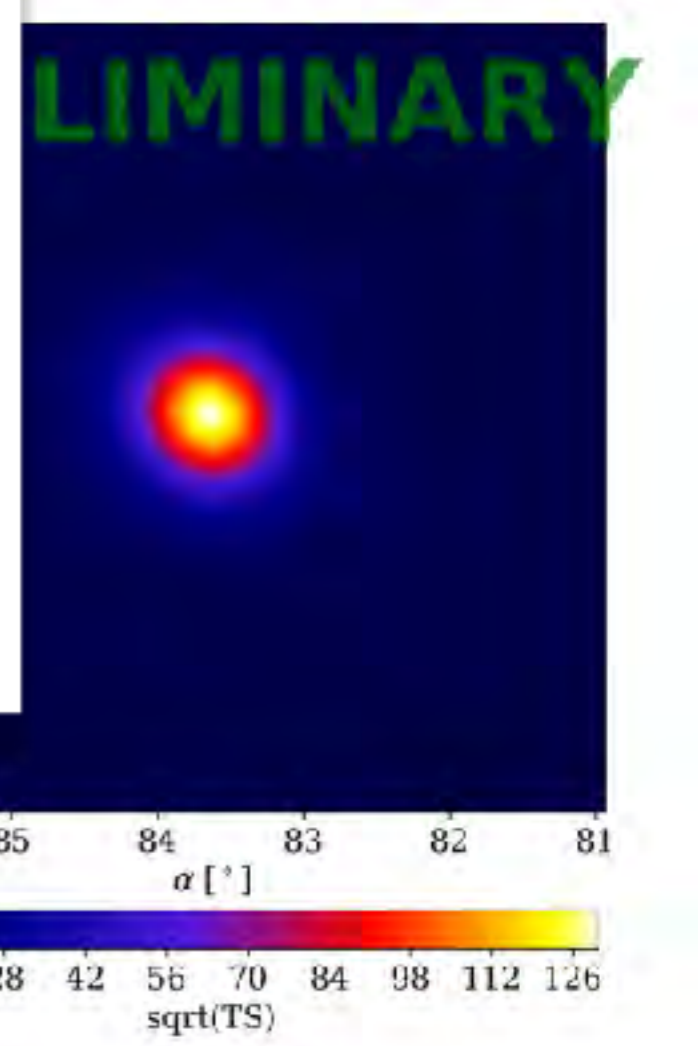
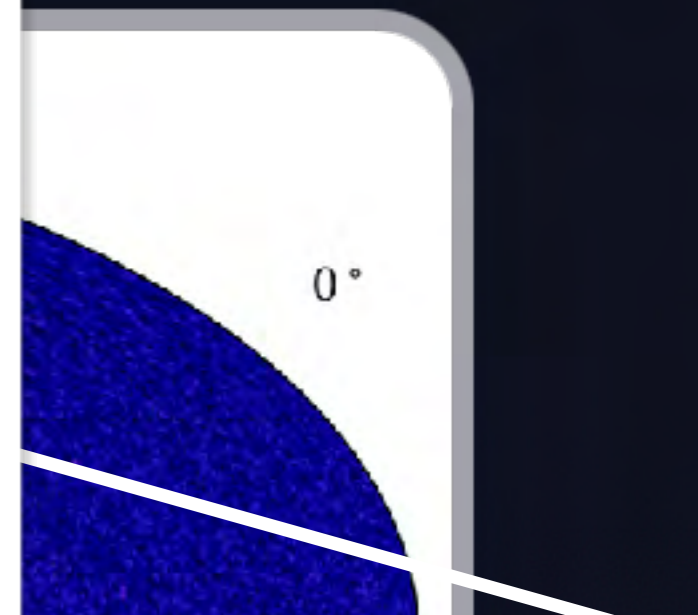
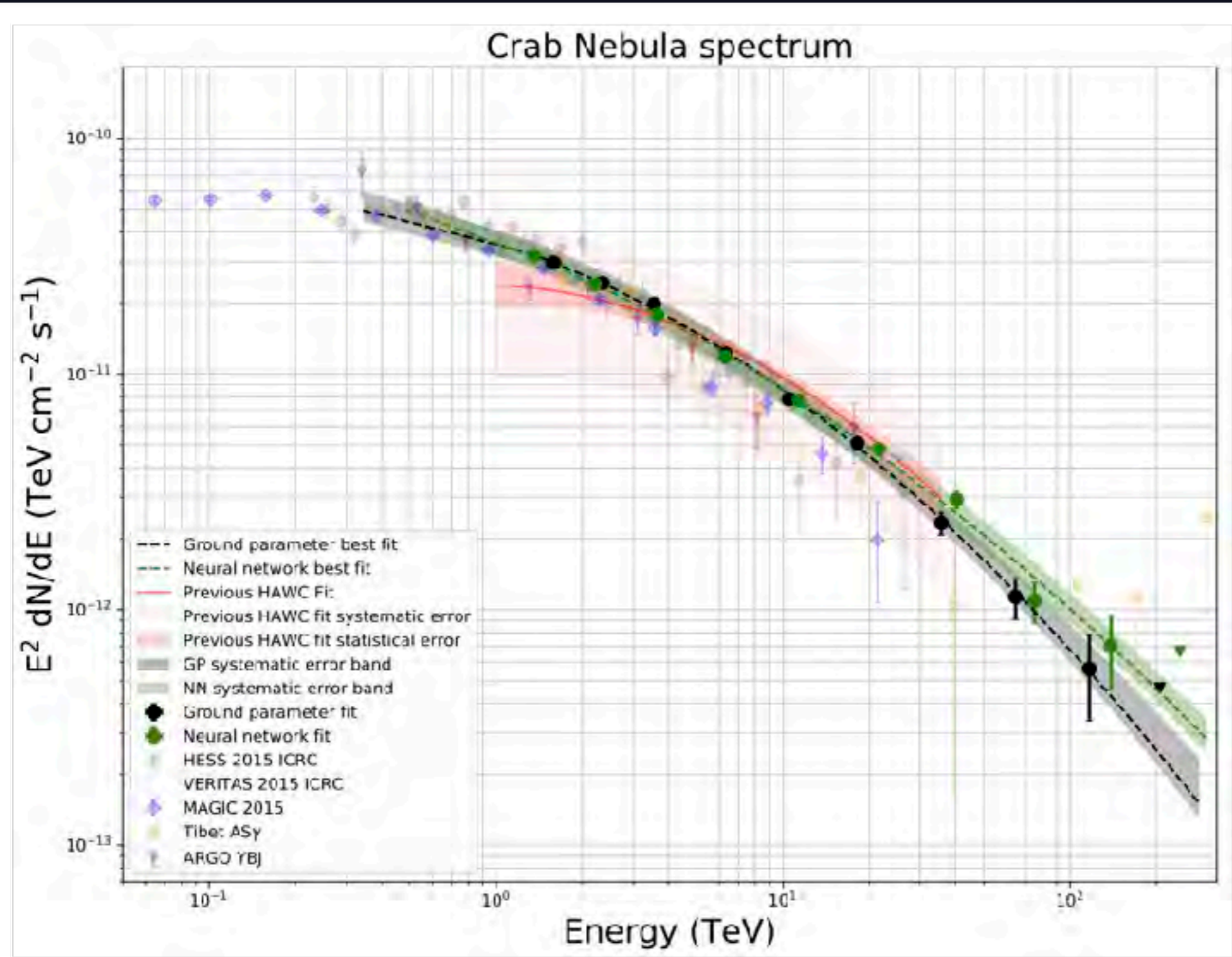


SS 433

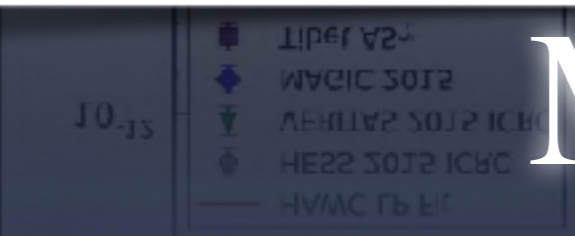


Recent Developments


Penn State HAWC group at home (2018)



Multi-TeV s



PHYSICAL REVIEW LETTERS

[Highlights](#) [Recent](#) [Accepted](#) [Collections](#) [Authors](#) [Referees](#) [Search](#) [Press](#) [About](#) 

Featured in Physics

Editors' Suggestion

Multiple Galactic Sources with Emission Above 56 TeV Detected by HAWC, a.k.a. Kelly's thesis

A. U. Abeysekara *et al.* (HAWC Collaboration)
Phys. Rev. Lett. **124**, 021102 – Published 15 January 2020

Physics See Synopses/ Catalog of High Energy Gamma Ray Sources



Article

References

No Citing Articles

Supplemental Material

PDF

HTML

Export Citation



ABSTRACT

We present the first catalog of gamma-ray sources emitting above 56 and 100 TeV with data from the High Altitude Water Cherenkov Observatory, a wide field-of-view observatory capable of detecting gamma rays up to a few hundred TeV. Nine sources are observed above 56 TeV, all of which are likely galactic in origin. Three sources continue emitting past 100 TeV, making this the highest-energy gamma-ray source catalog to date. We report the integral flux of each of these objects. We also report spectra for three highest-energy sources and discuss the possibility that they are PeVatrons.




Revised 21 November 2019 Received 18 September 2019

DOI: <https://doi.org/10.1103/PhysRevLett.124.021102>

Issue

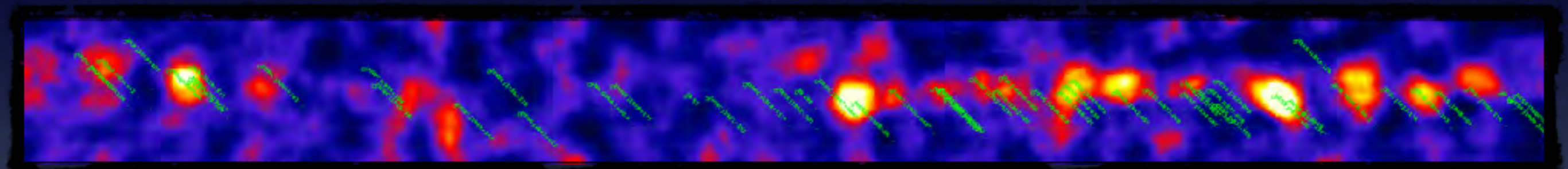
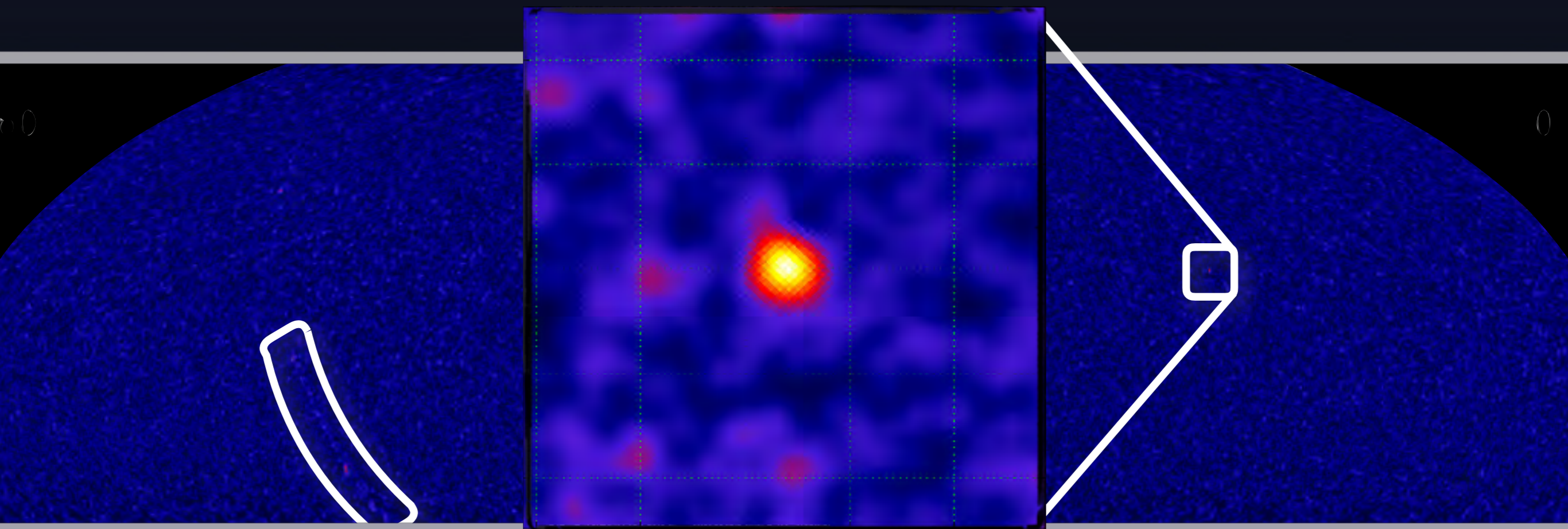
Vol. 124, Iss. 2 – 17 January
2020

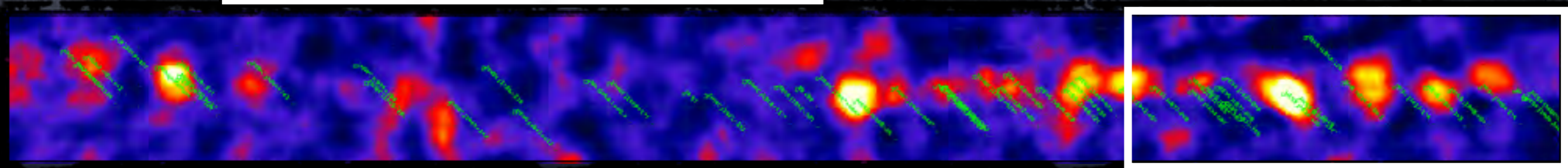
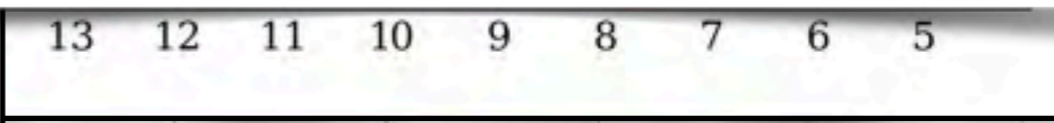
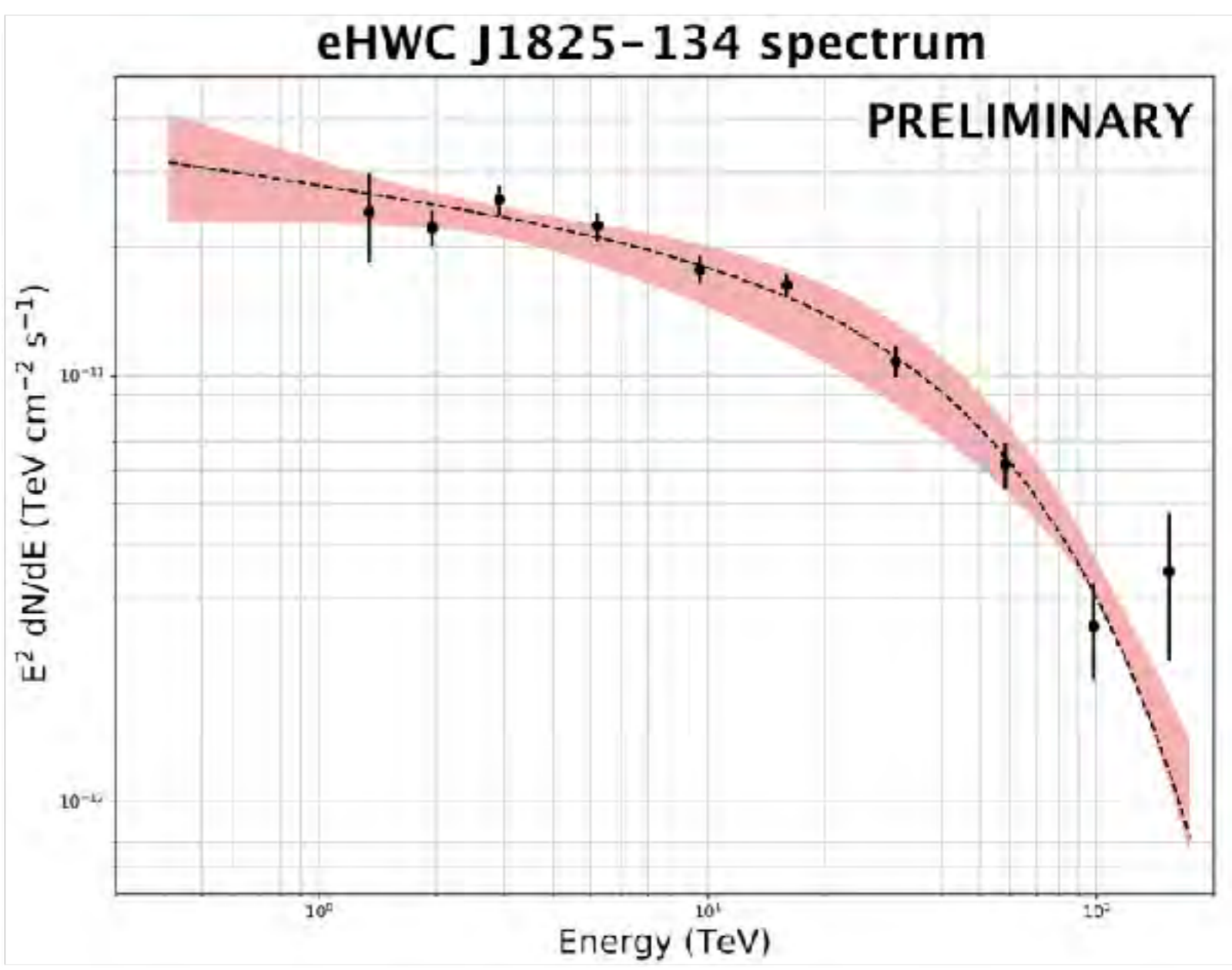
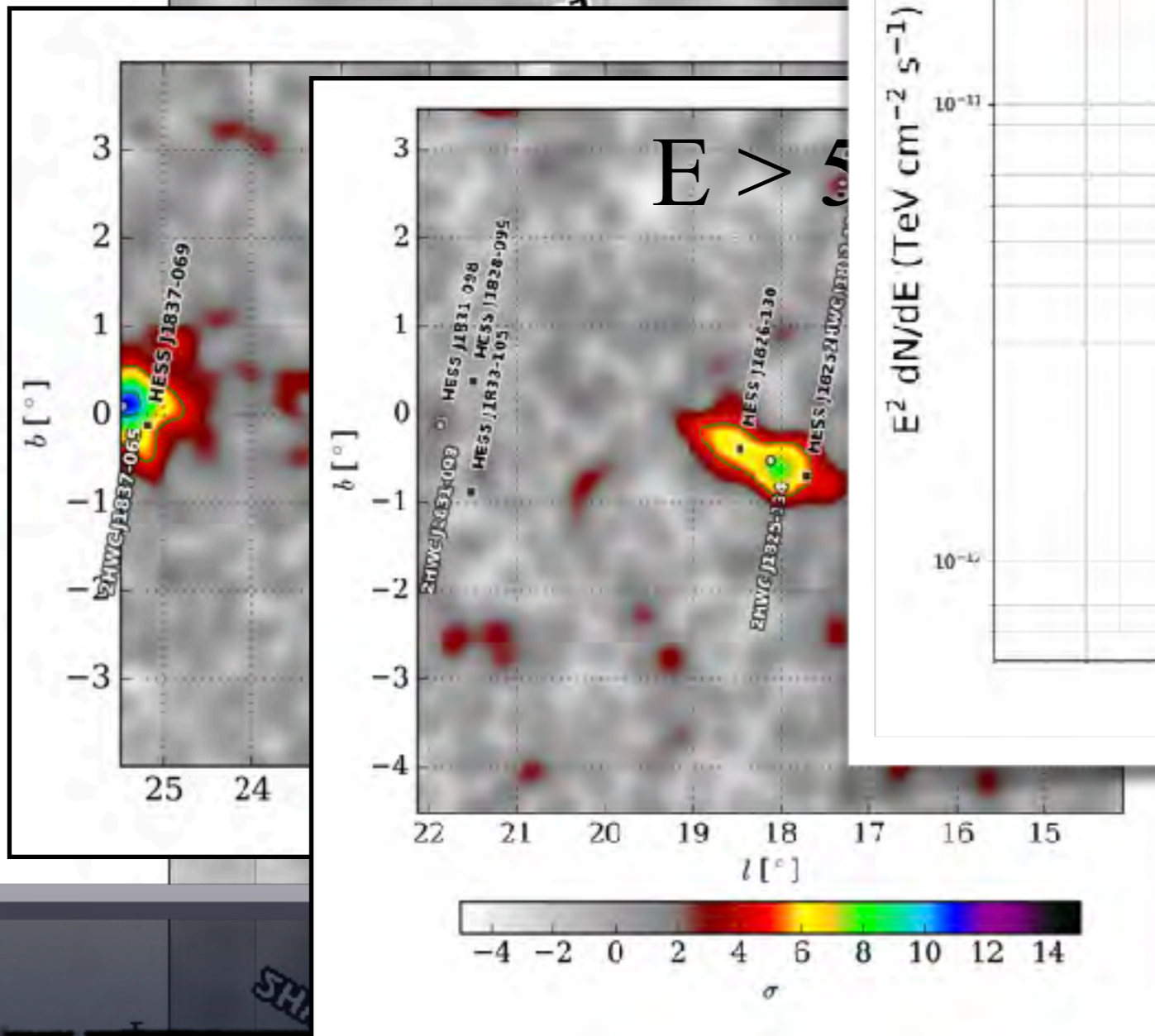
 Check for updates

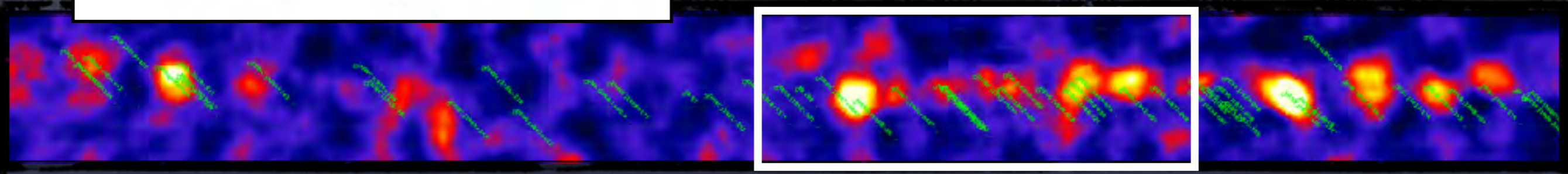
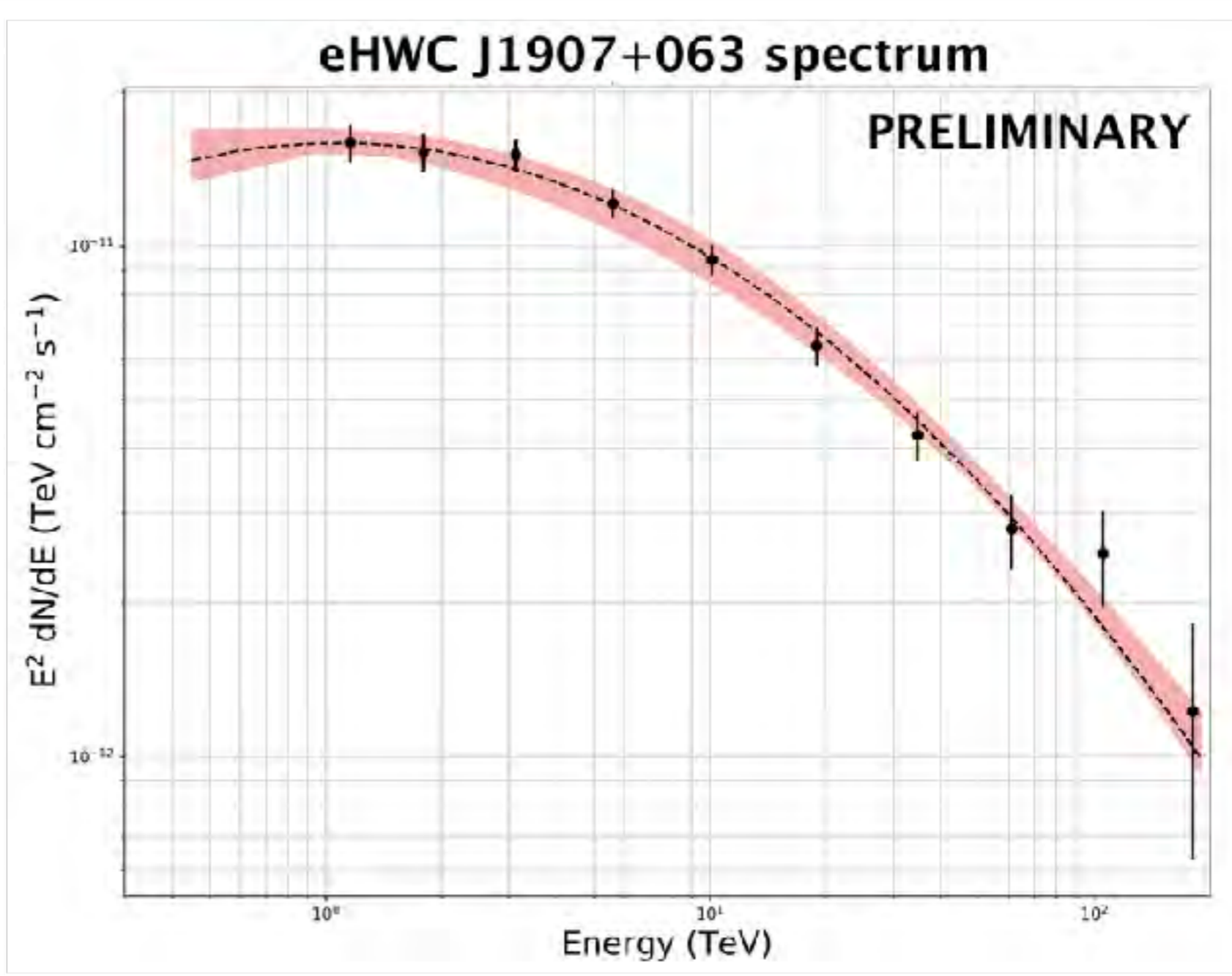
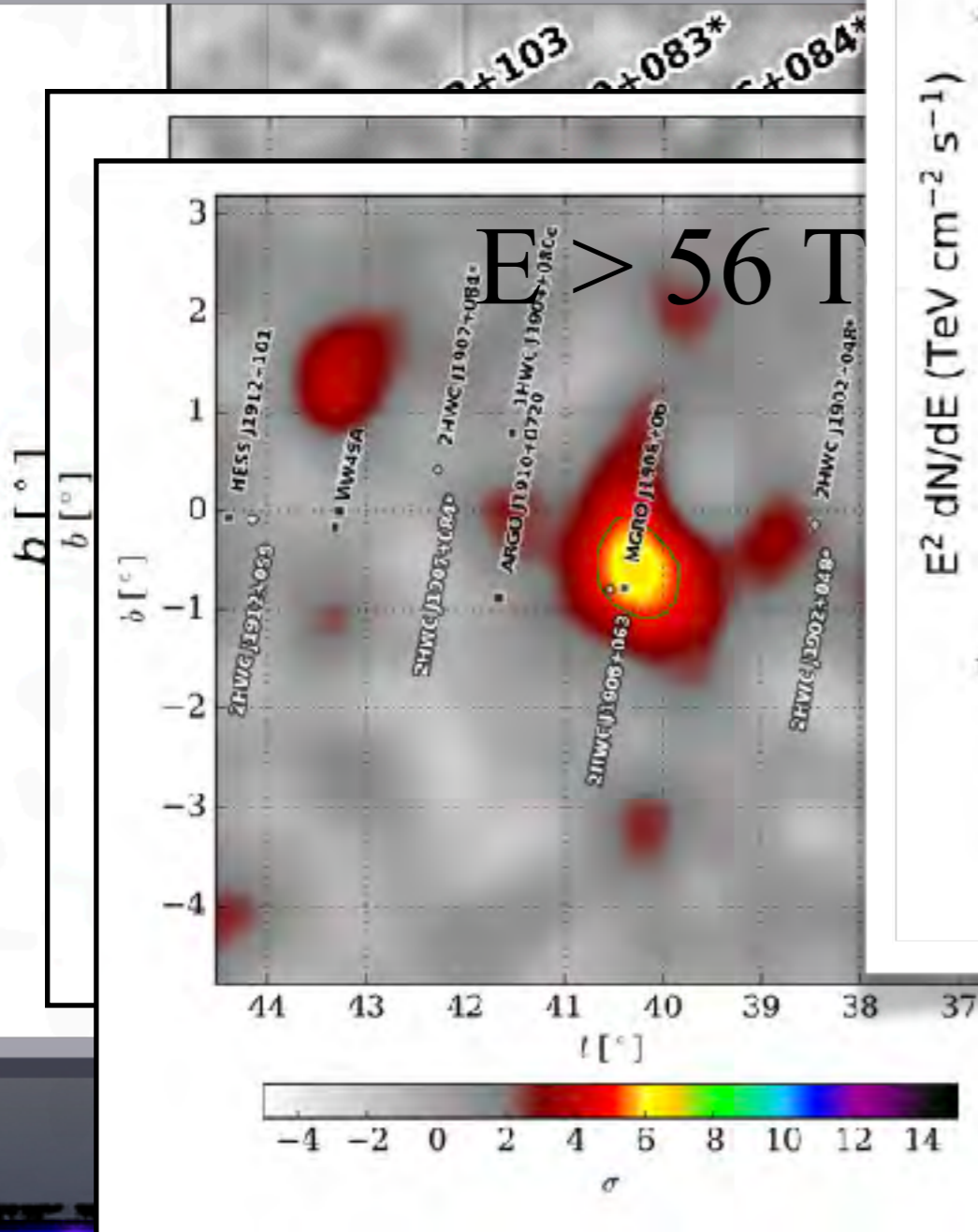
Reuse & Permissions

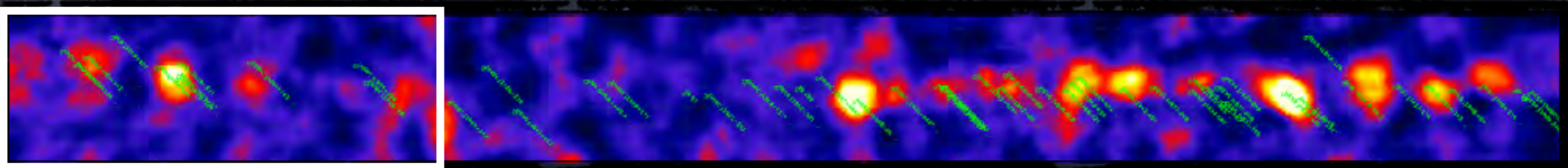
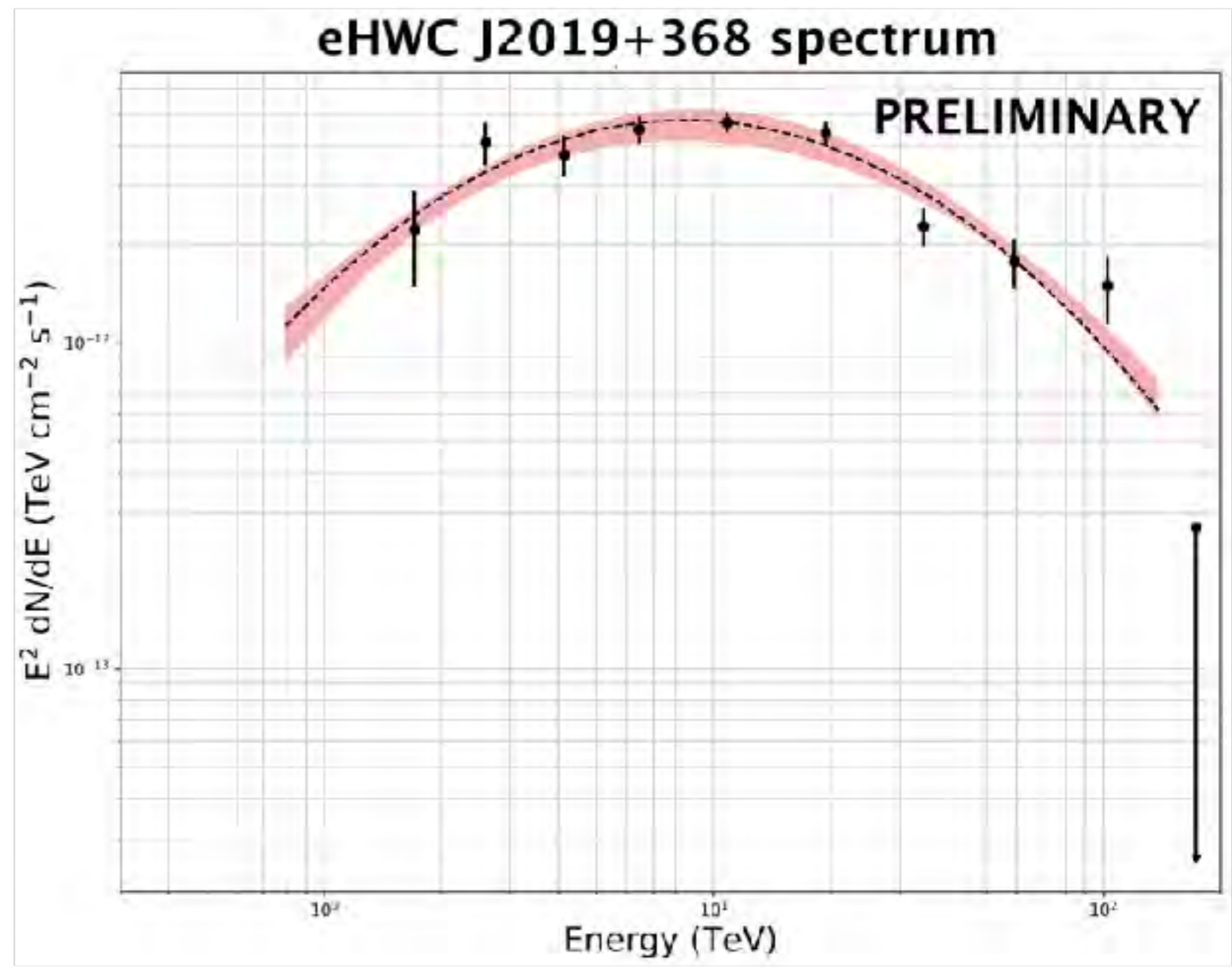
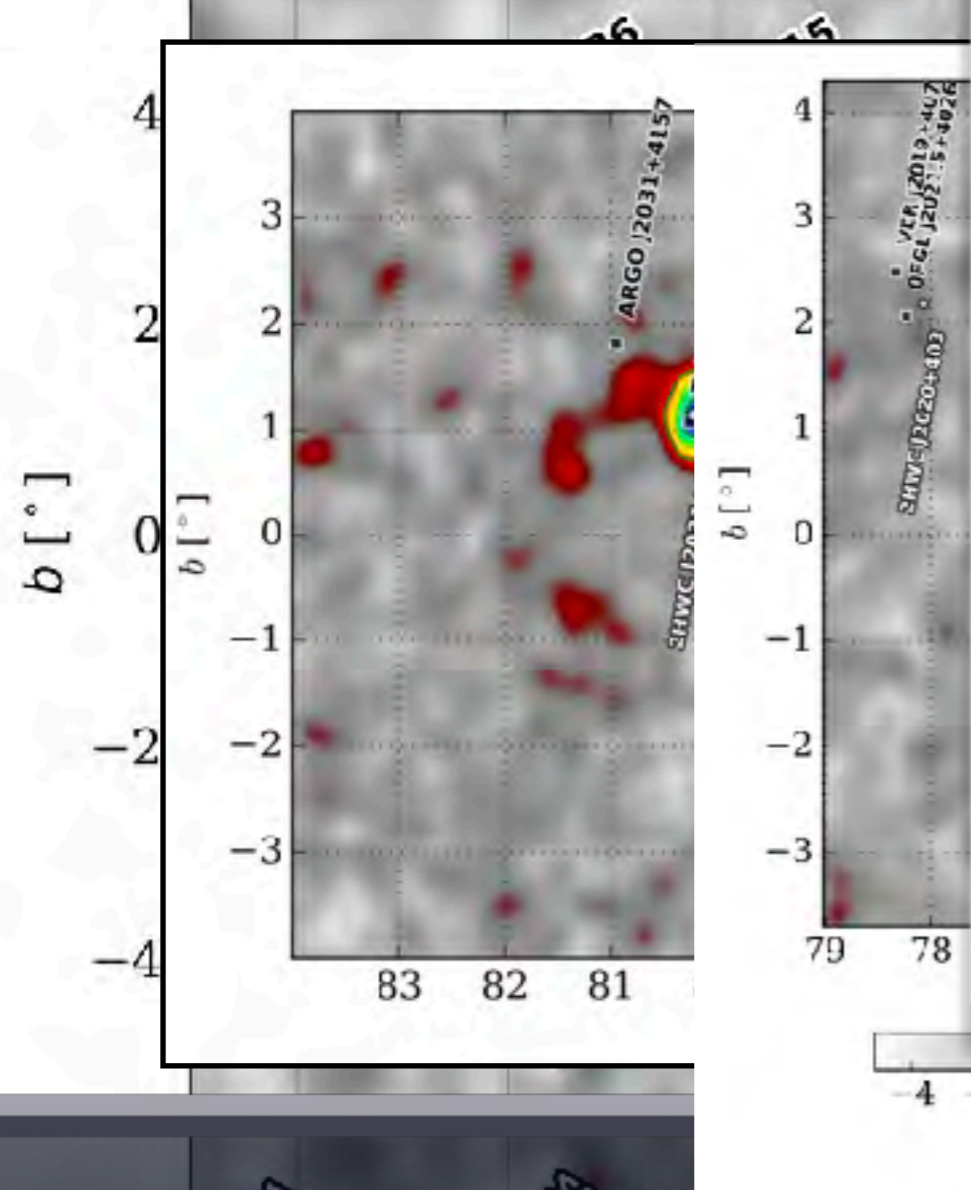
PHYSICAL
REVIEW

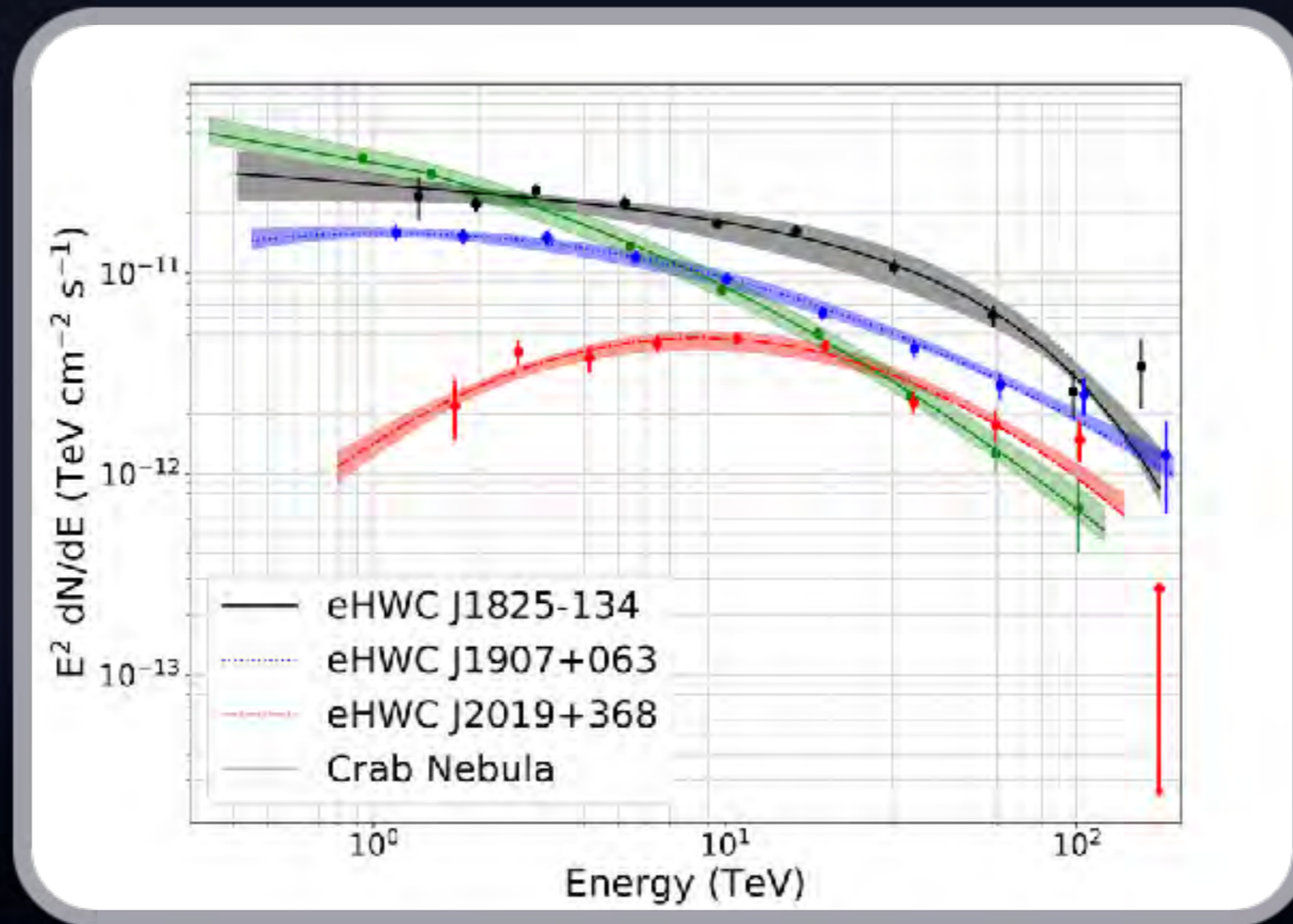
γ -ray sky above 56 TeV





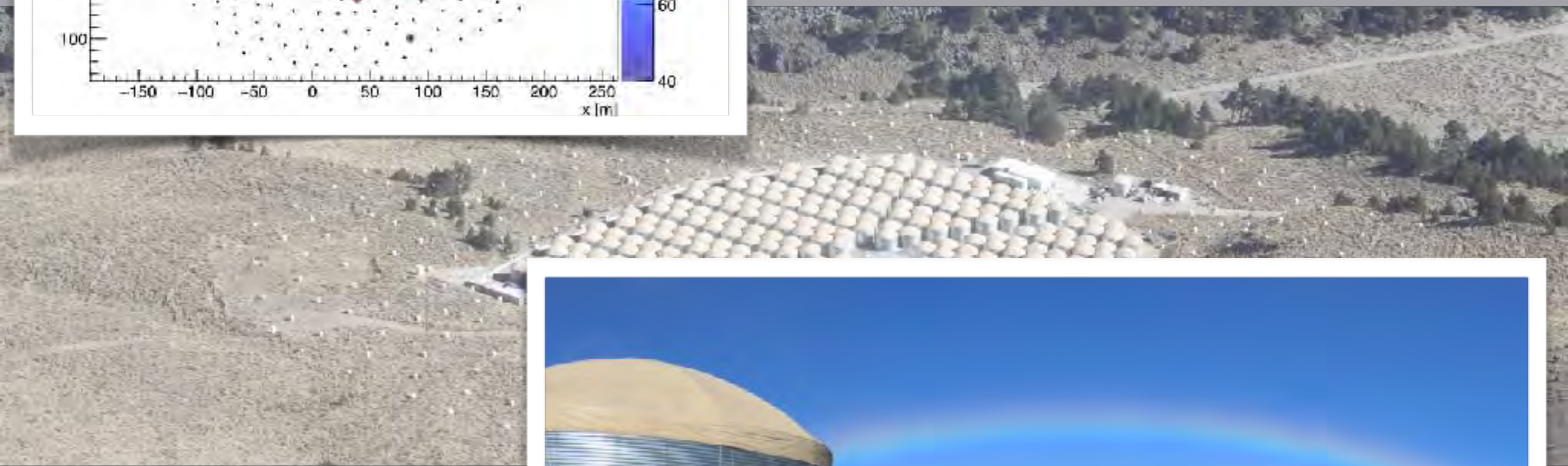
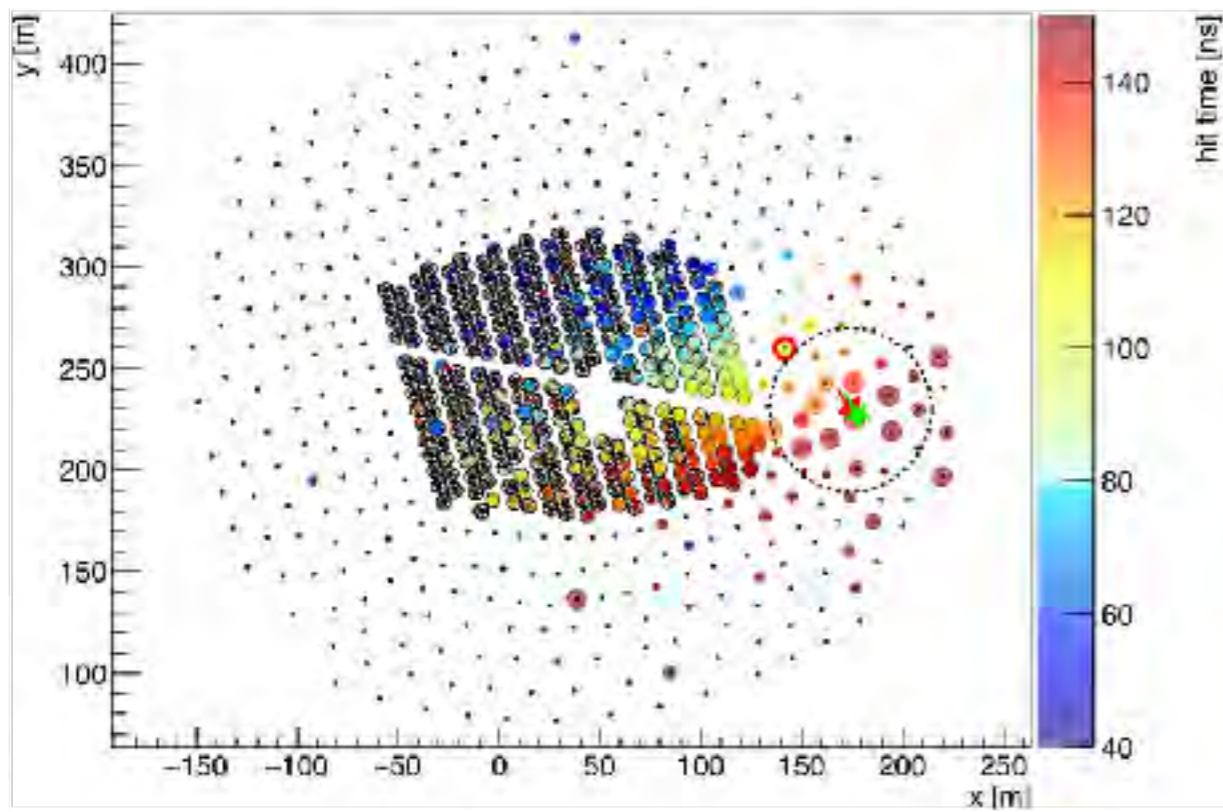




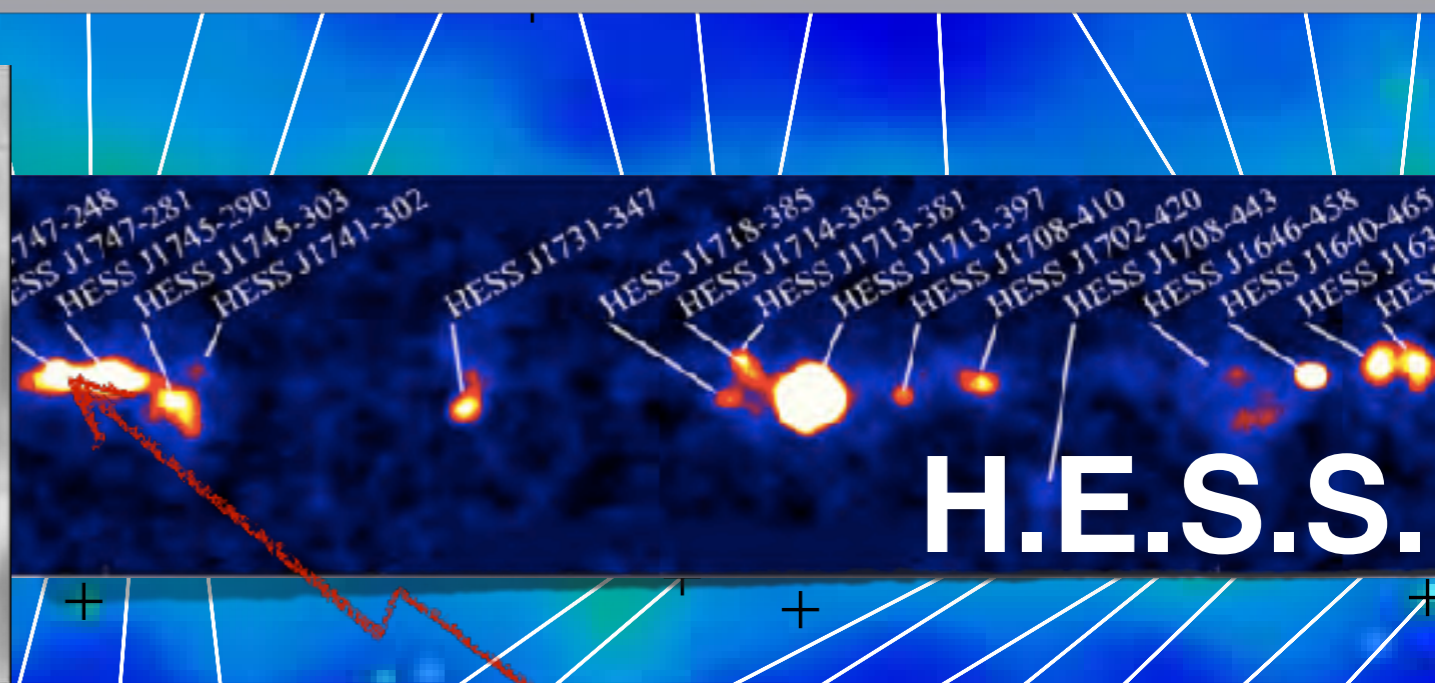
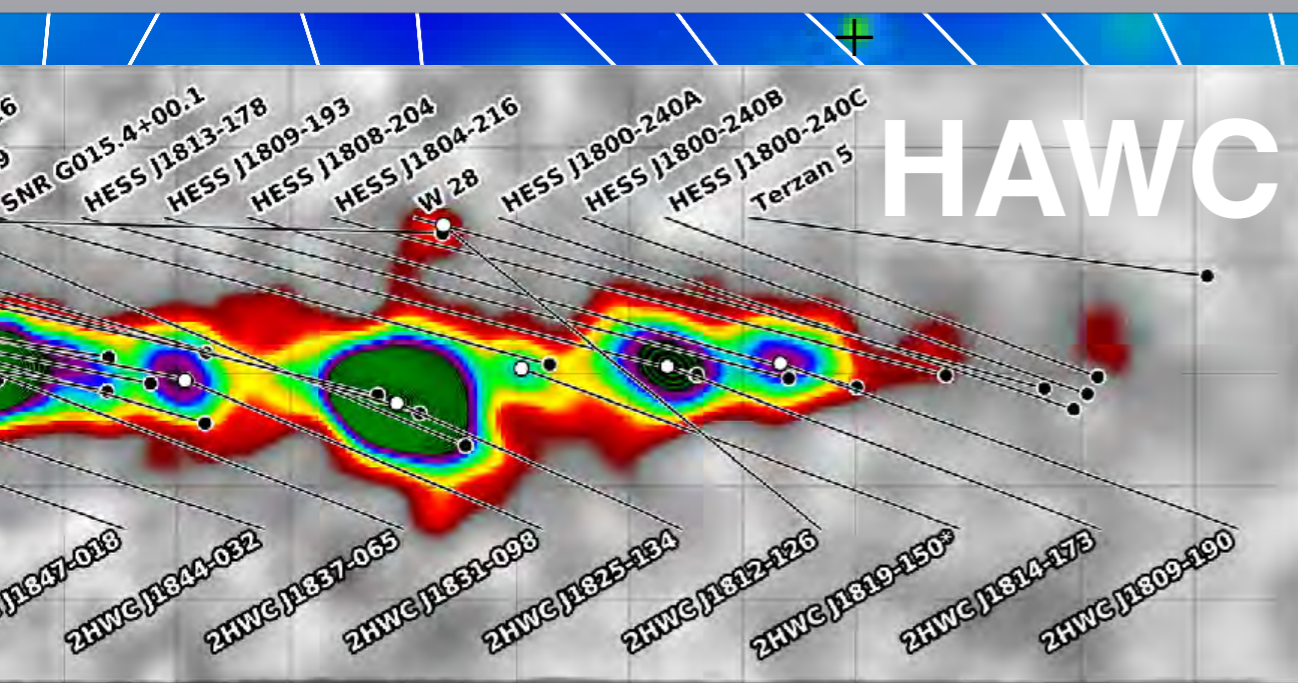


The highest energy sources

Outriggers



Outlook: HAWC South



Fermi-LAT

Galactic Center

HAWC South

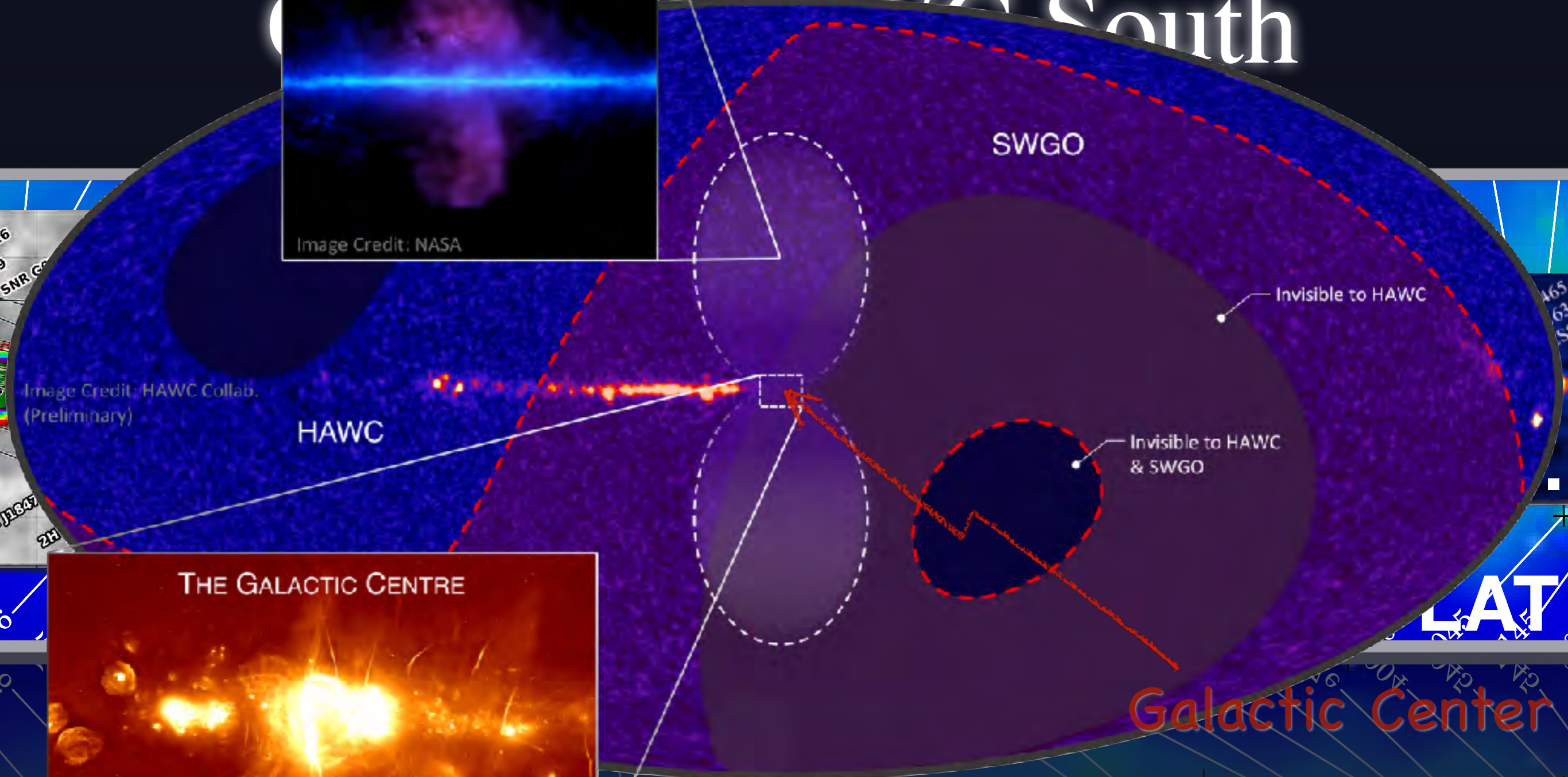
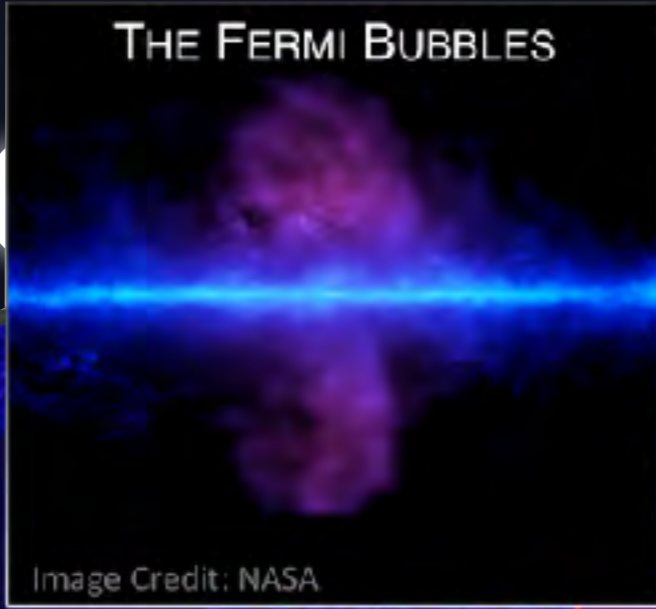


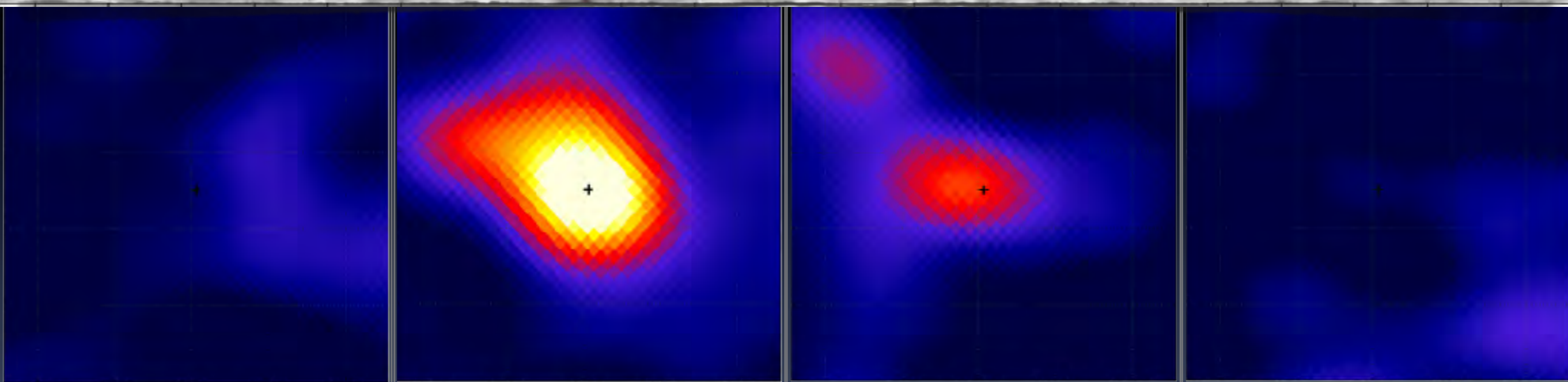
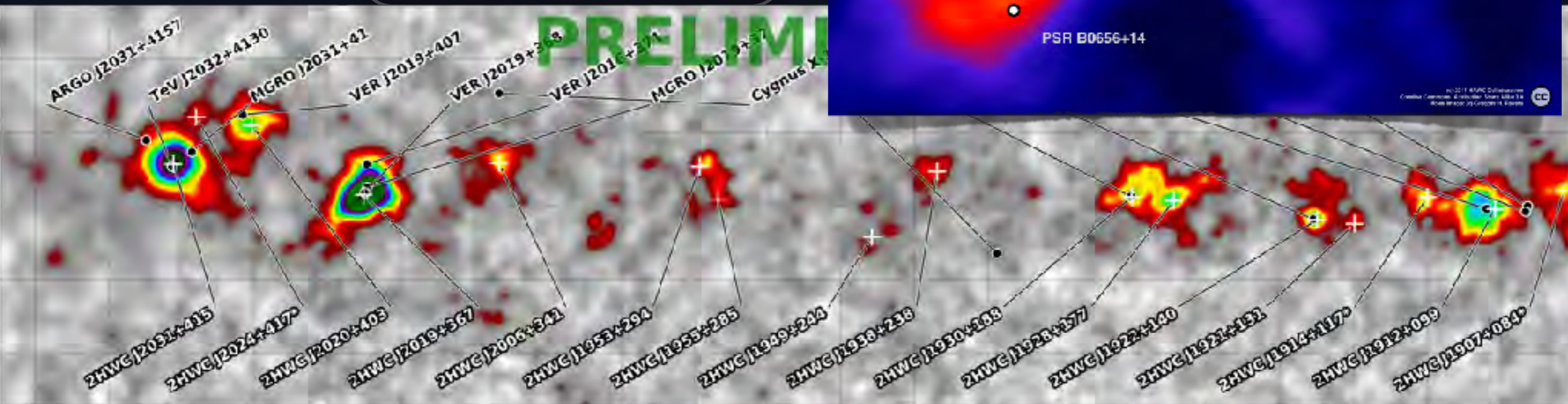
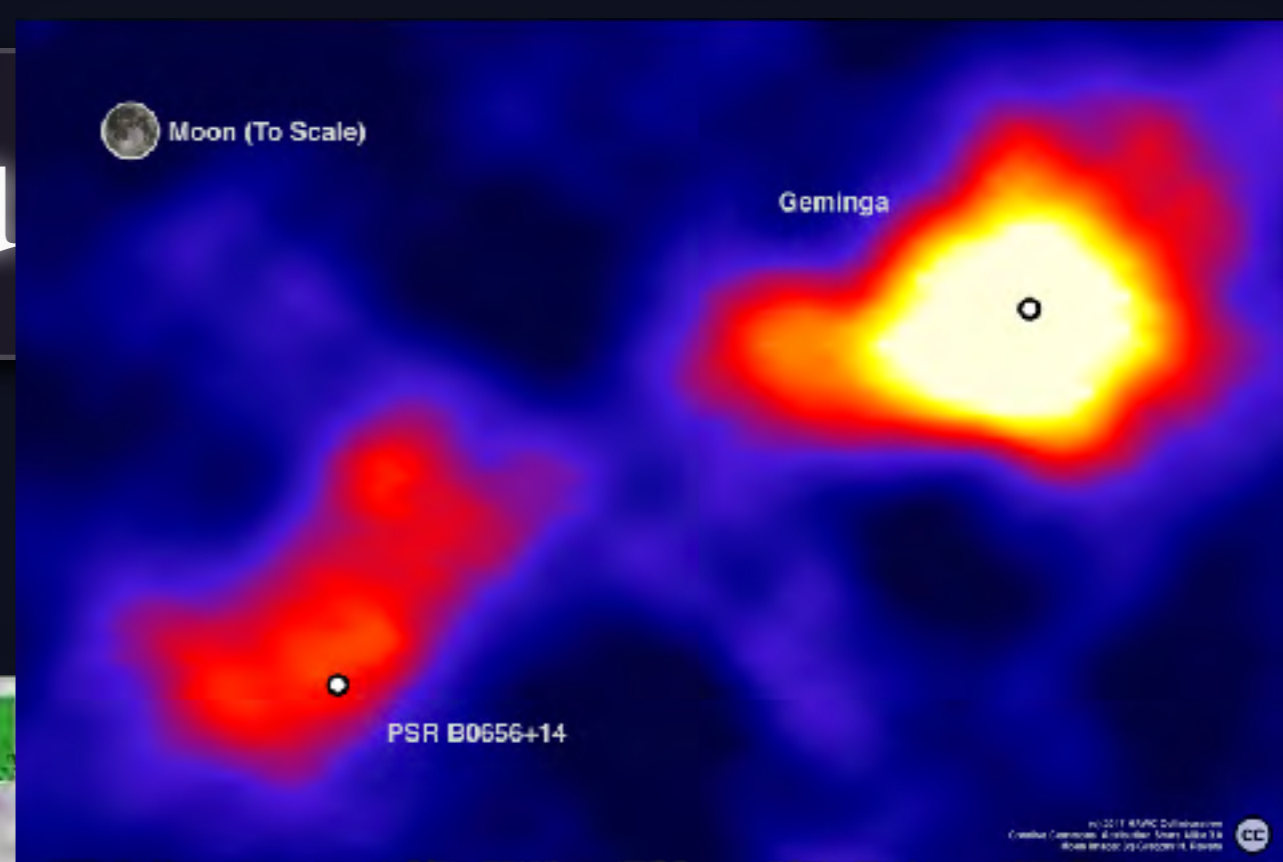
Image Credit: HAWC Collab. (Preliminary)



Conclu

Main results

- Extended regions, transient events, highest energies



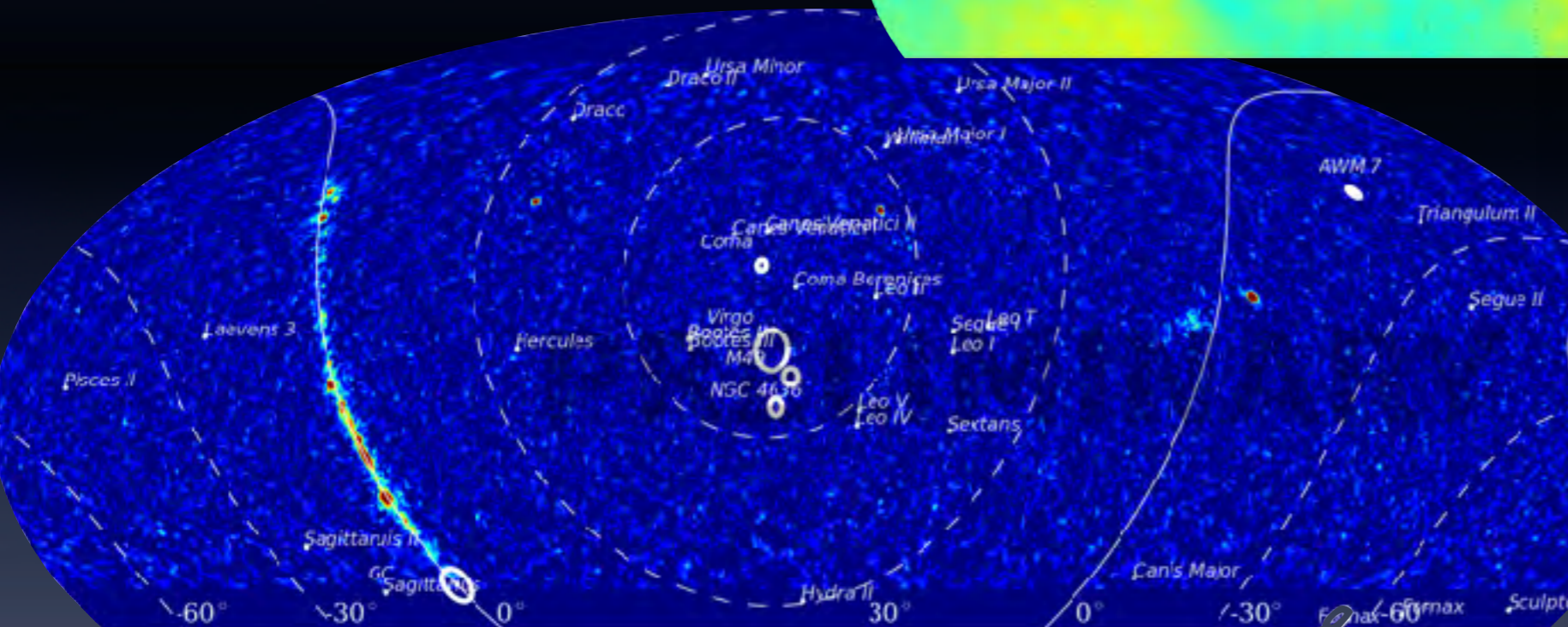
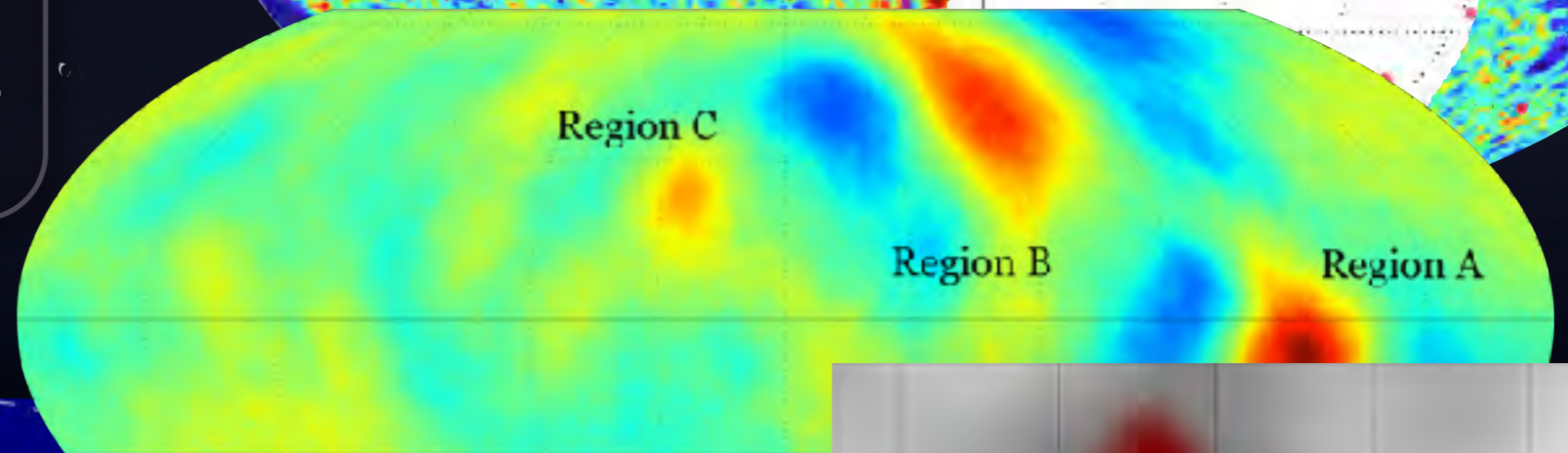
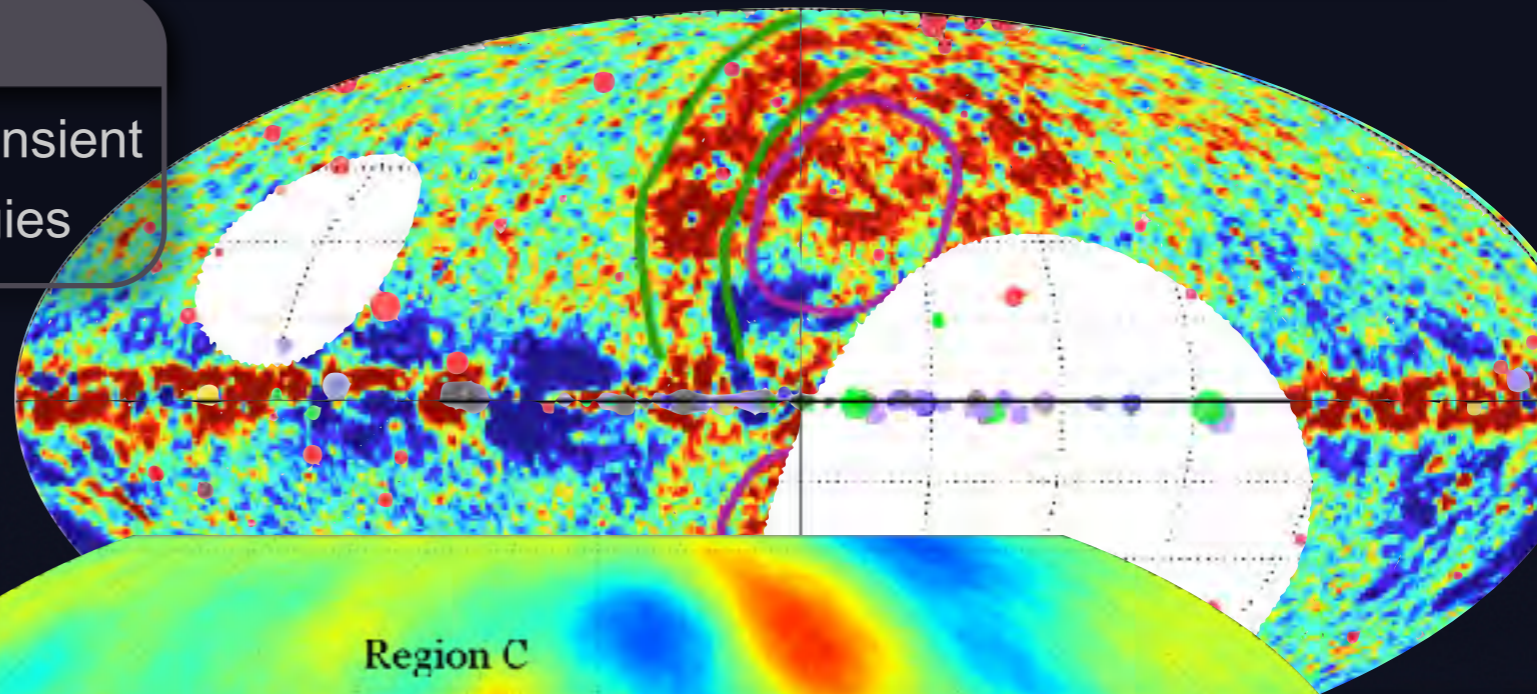
Conclusions

Main results

- Extended regions, transient events, highest energies

Other results

- Dark matter, extended regions, diffuse emission, cosmic rays, ...
- EBL, solar physics, ...



Conclusions

Main results

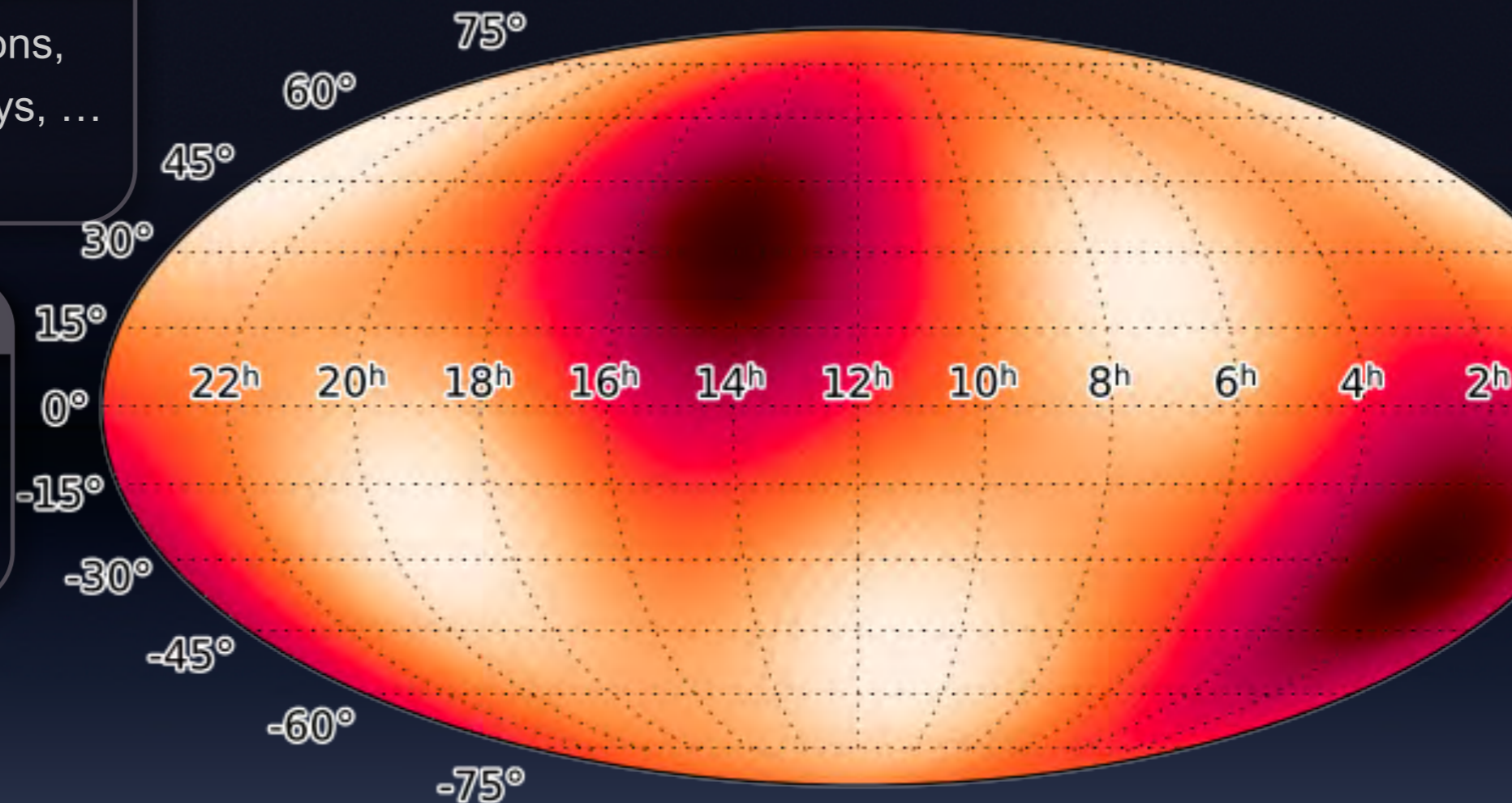
- Extended regions, transient events, highest energies

Other results

- Dark matter, extended regions, diffuse emission, cosmic rays, ...
- EBL, solar physics, ...

Multi-wavelength physics

- MoUs with IceCube, IACTs, etc
- AMON
- HAWC alerts



Conclusions

Main results

- Extended regions, transient events, highest energies

Other results

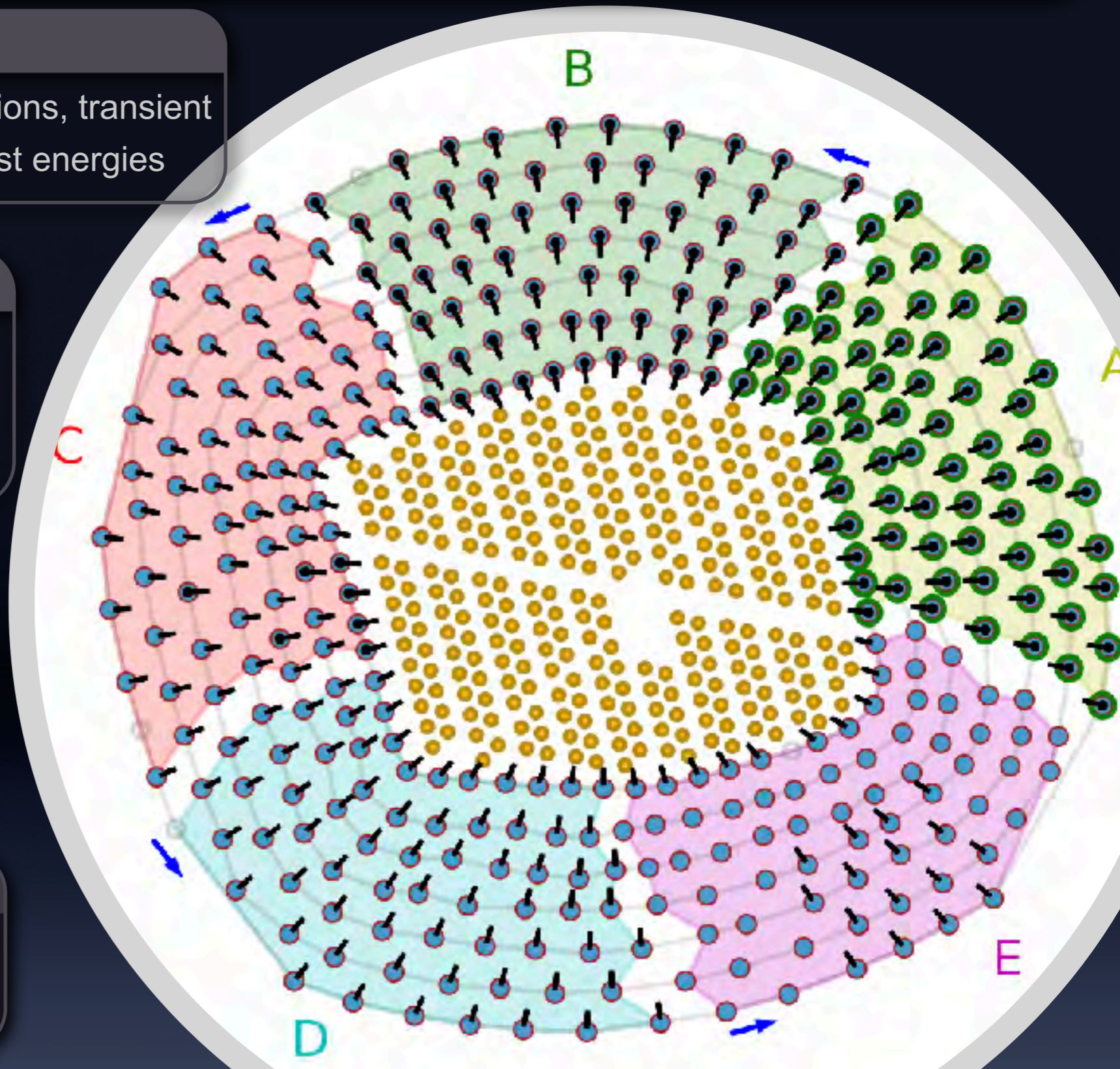
- Dark matter, extended regions, diffuse emission, cosmic rays, ...
- EBL, solar physics, ...

Multi-wavelength physics

- MoUs with IceCube, IACTs, etc
- AMON
- HAWC alerts

Outlook

- Array of Outriggers
- Southern Observatory





Thank you very much

The HAWC Collaboration

Recent HAWC publications

- “Multiple Galactic Sources with Emission Above 56 TeV Detected by HAWC,” *Physical Review Letters* 124 (2020) 021102
- “Measurement of the Crab Nebula Spectrum Past 100 TeV with HAWC,” *The Astrophysical Journal* 881 (2019) 134
- “Searching for dark matter sub-structure with HAWC,” *Journal of Cosmology and Astroparticle Physics* 07 (2019) 022
- “MAGIC and Fermi-LAT gamma-ray results on unassociated HAWC sources,” *Monthly Notices of the Royal Astronomical Society* 485, 356 (2019)
- “All-sky Measurement of the Anisotropy of Cosmic Rays at 10 TeV and Mapping of the Local Interstellar Magnetic Field,” *The Astrophysical Journal* 871, 96 (2019)
- “Very-high-energy particle acceleration powered by the jets of the microquasar SS 433,” *Nature* 562, 82-85 (2018)
- “Constraints on spin-dependent dark matter scattering with long-lived mediators from TeV observations of the Sun with HAWC,” *Physical Review D* 98, 123012 (2018)