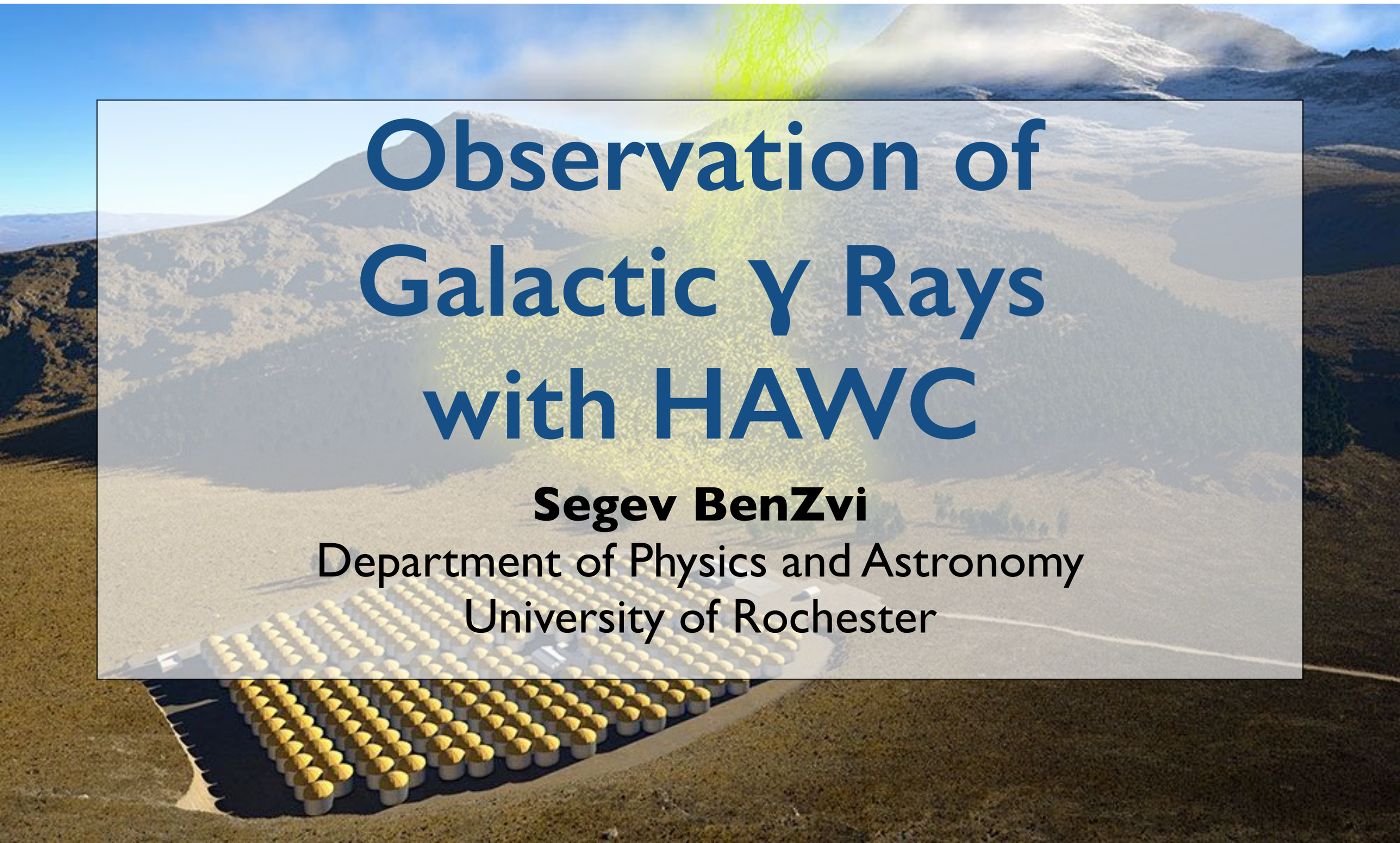
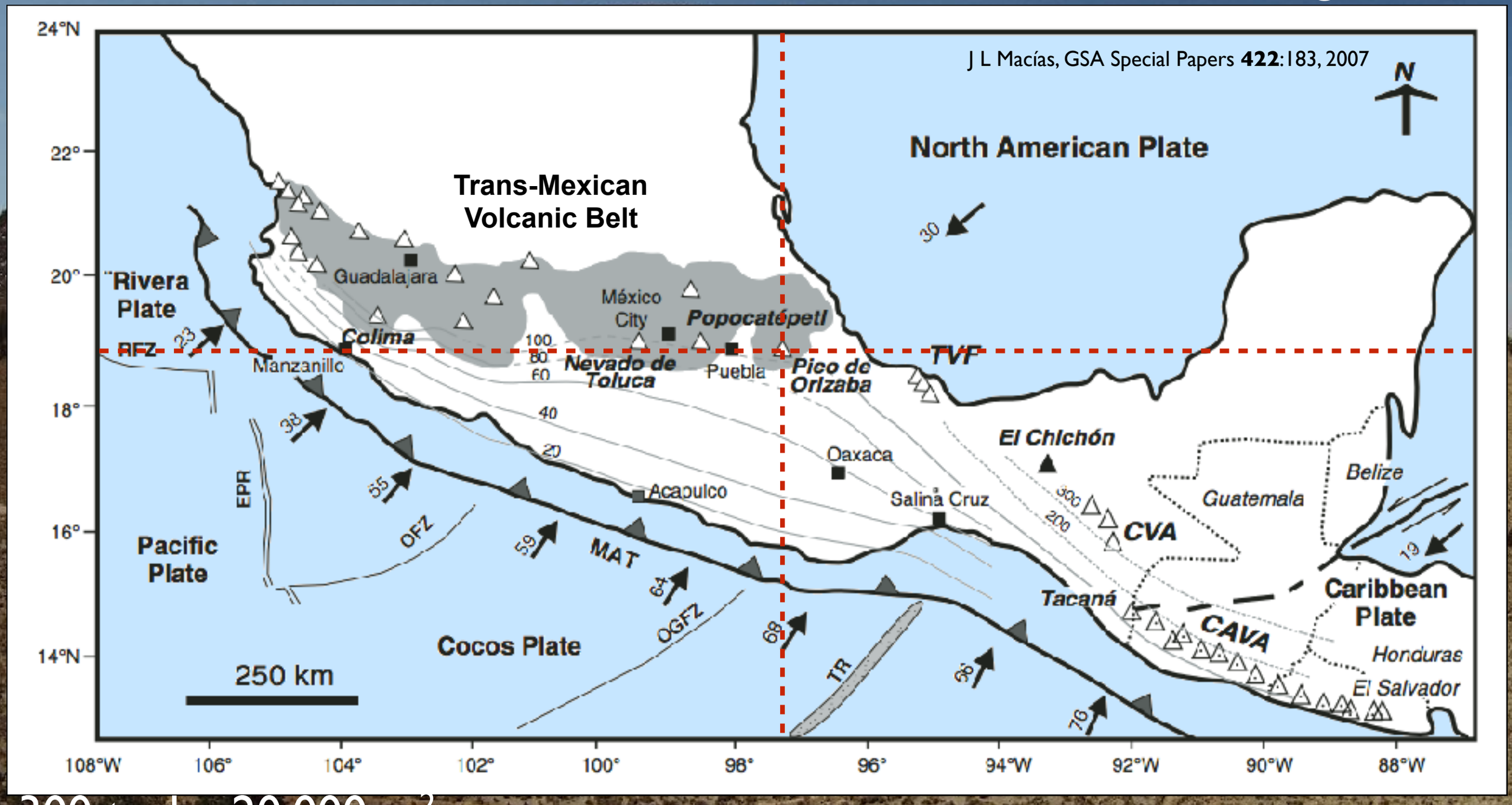


Observation of Galactic γ Rays with HAWC

Segev BenZvi
Department of Physics and Astronomy
University of Rochester

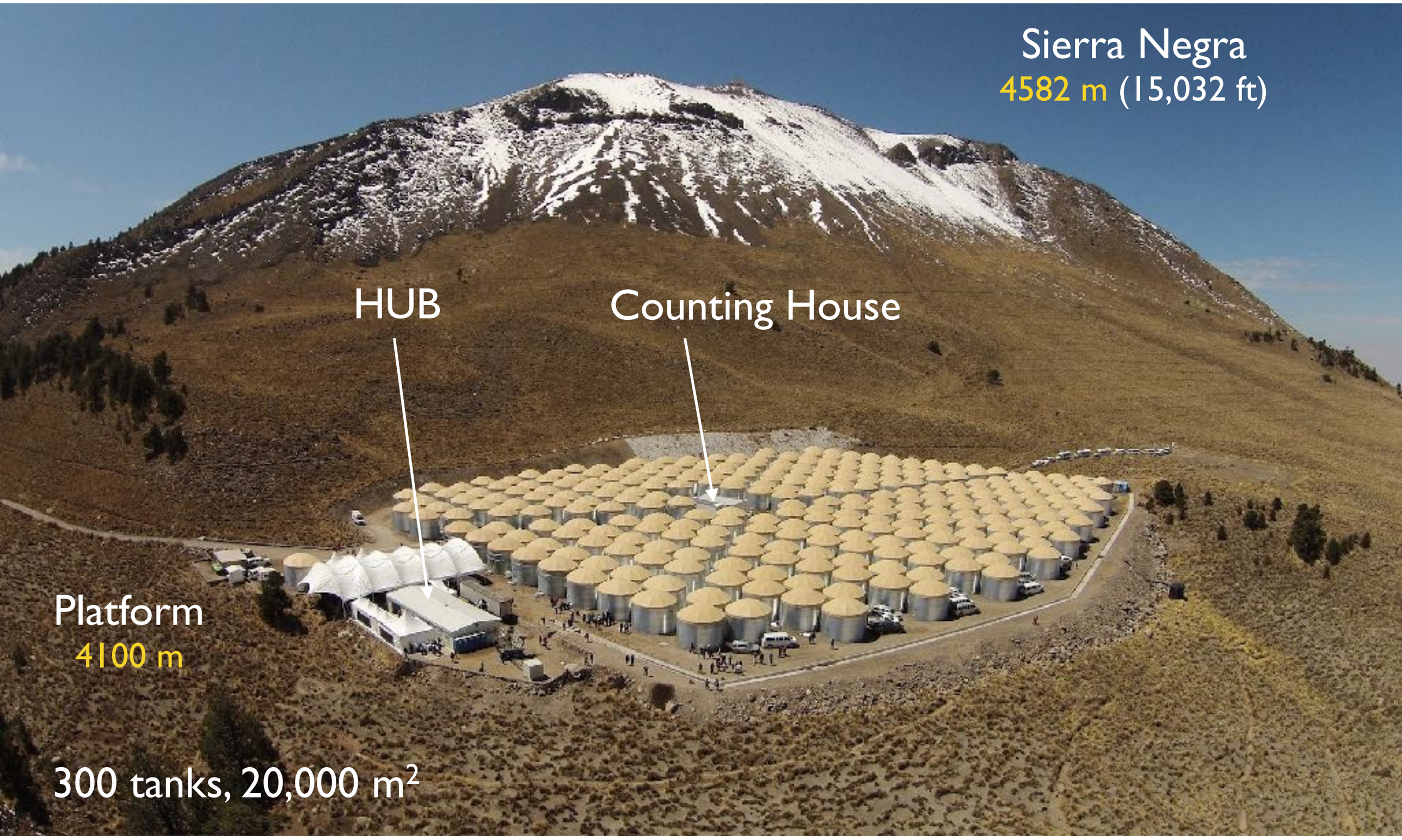
High Altitude Water Cherenkov Observatory

Sierra Negra

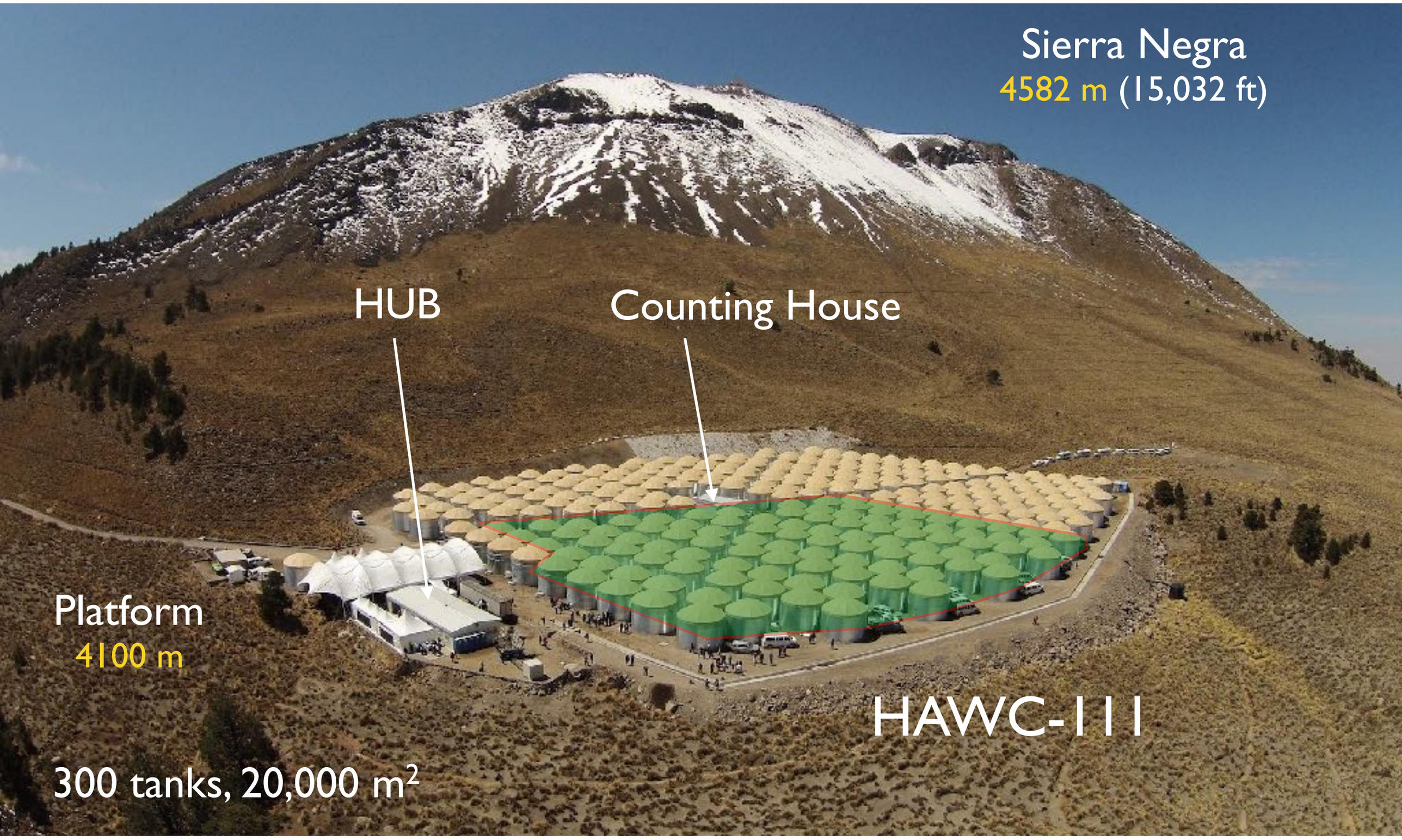


300 tanks, 20,000 m^2

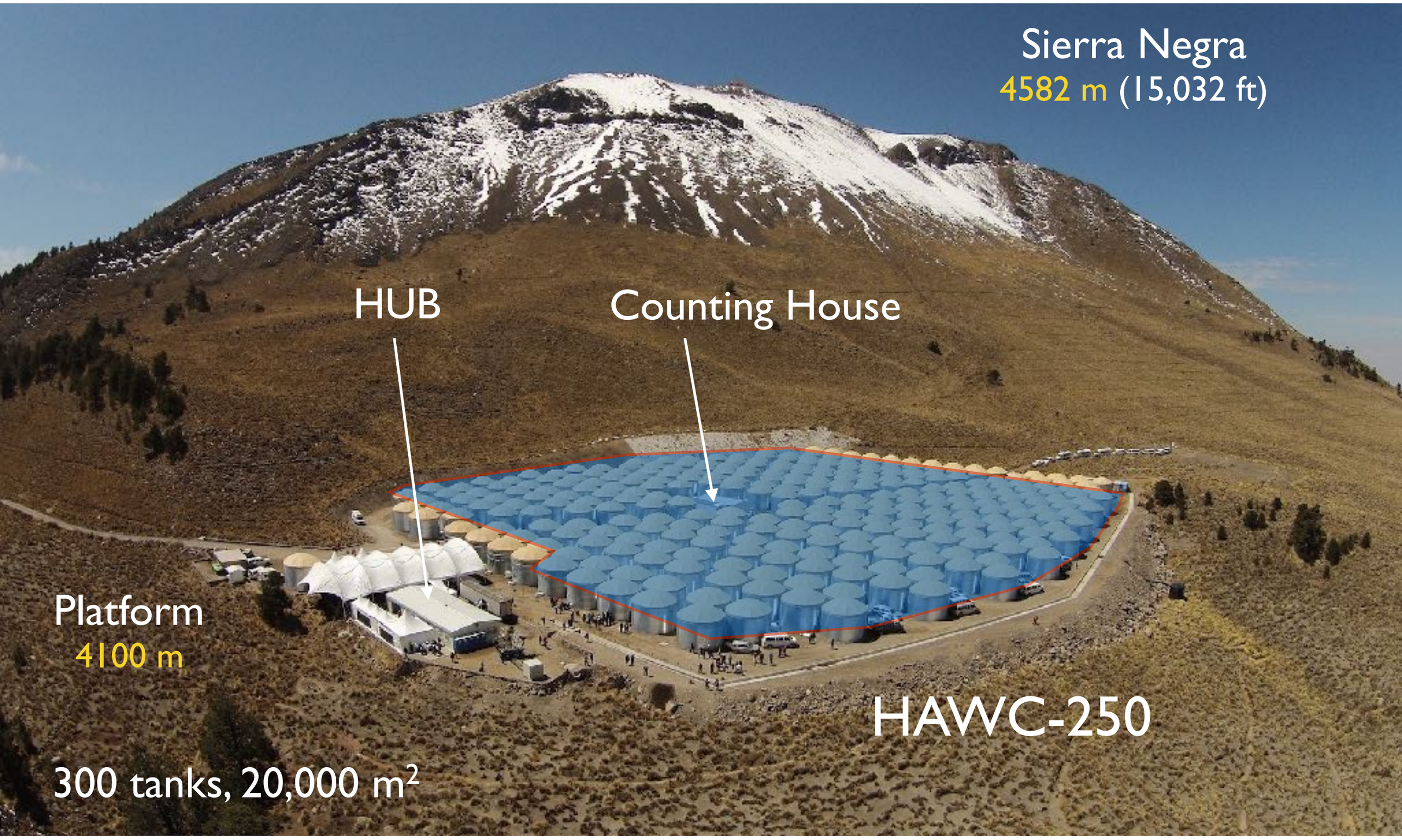
High Altitude Water Cherenkov Observatory



High Altitude Water Cherenkov Observatory



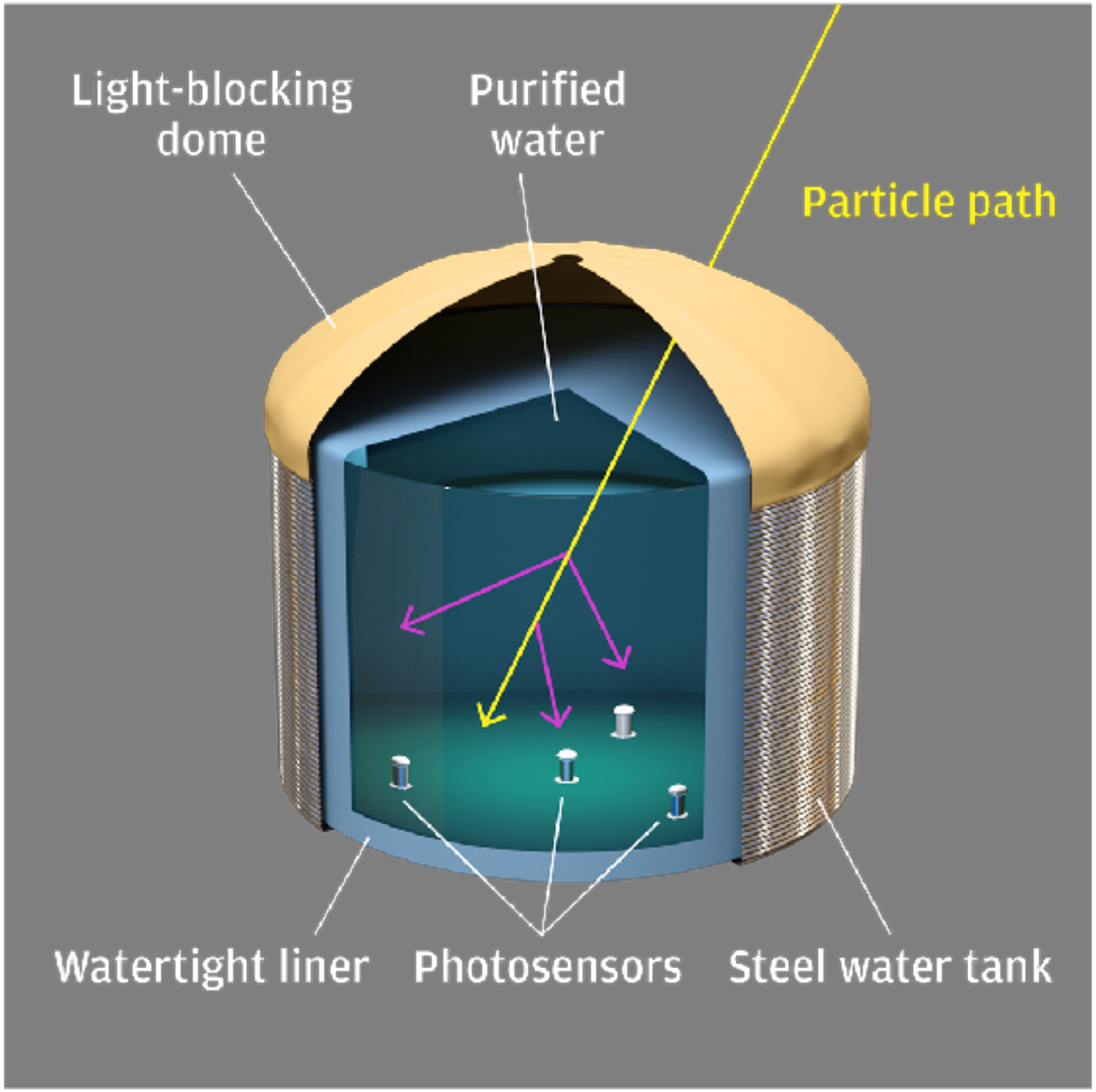
High Altitude Water Cherenkov Observatory



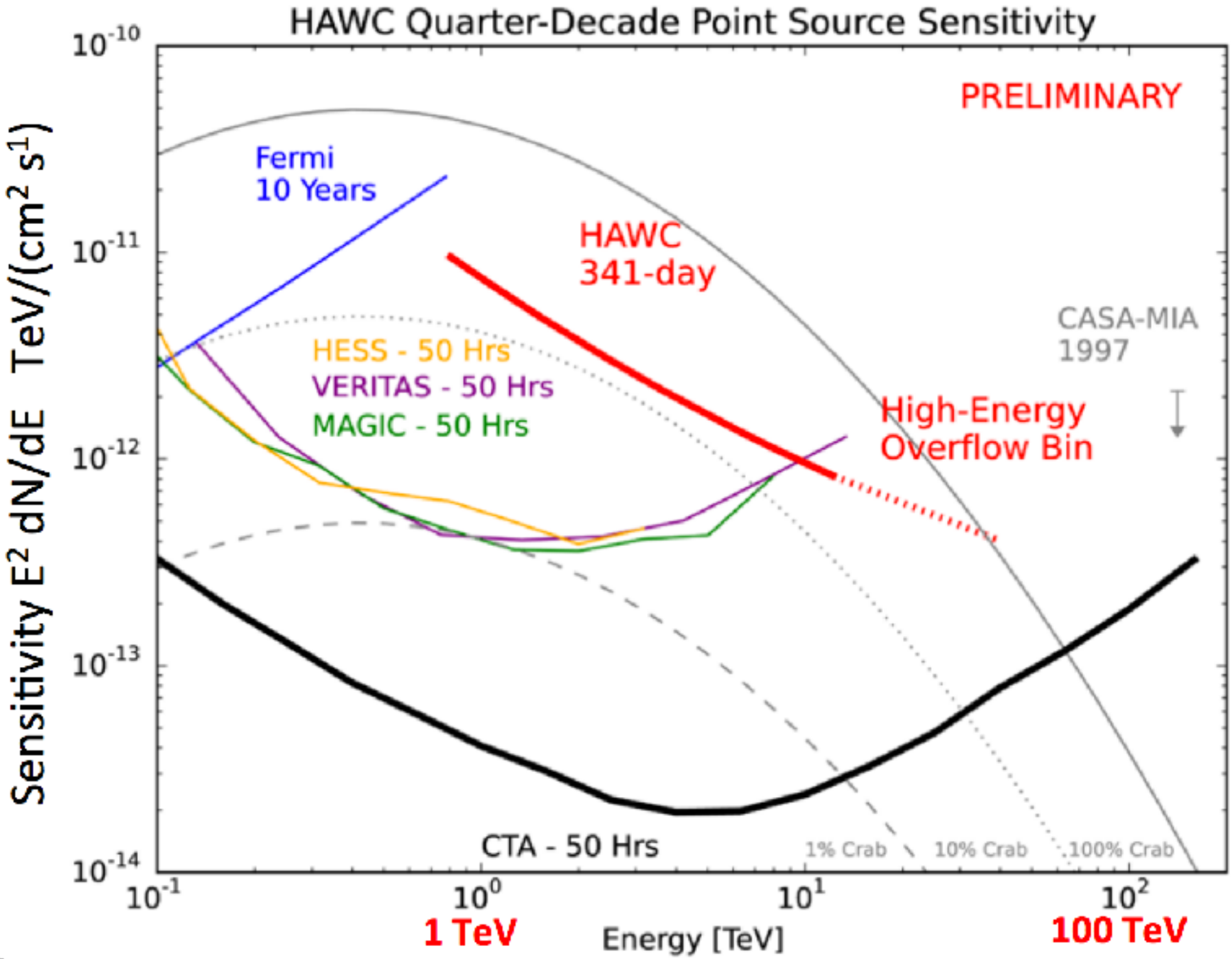
Reverse View

J. Goodman, 12 Nov 2016

Water Cherenkov Detectors



Sensitivity/Coverage Trade-off



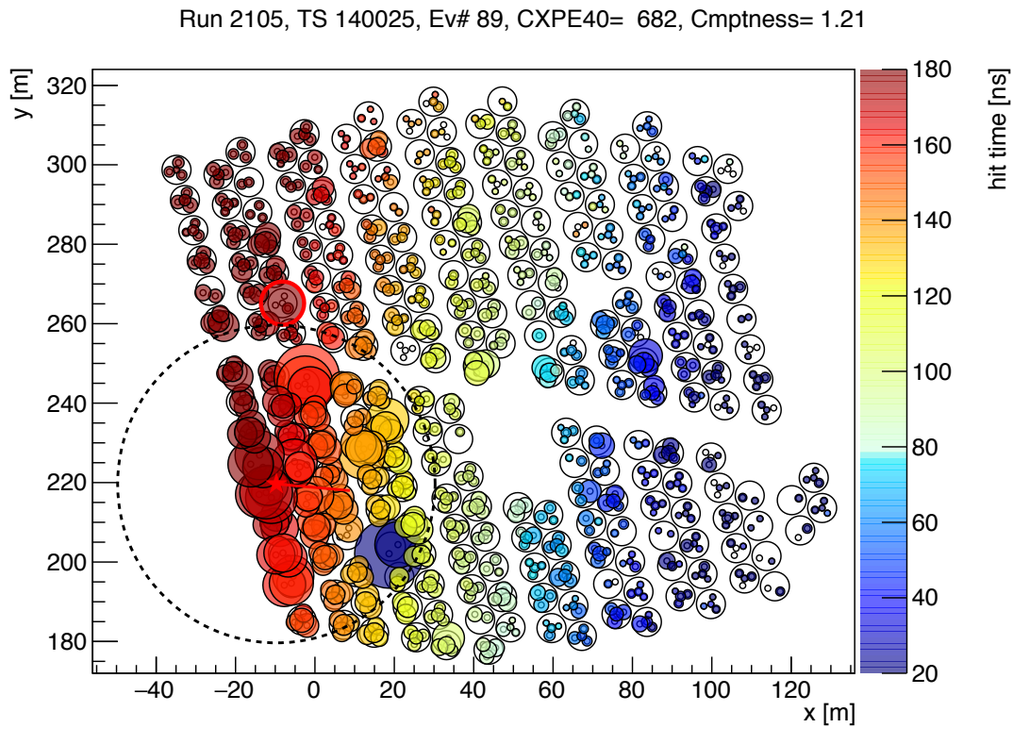
HAWC Physics

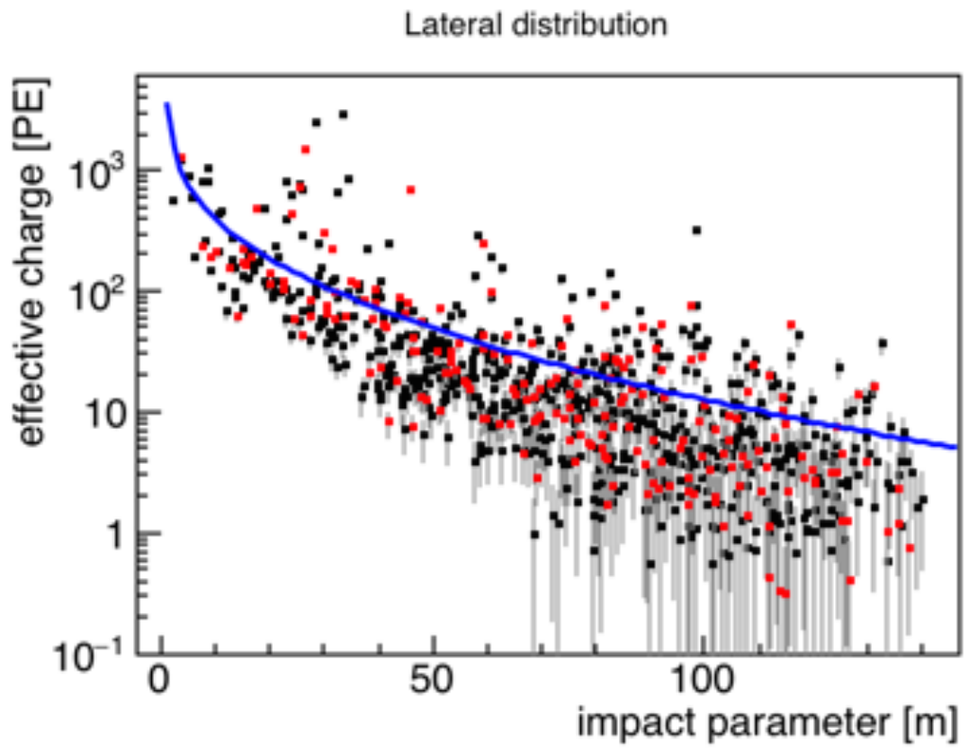
- **Primary cosmic rays**: ~100 GeV to 100 TeV
  - Cosmic-ray spectrum and anisotropy (10^{-3} level): nearby accelerators
  - Lunar shadow: calibration, antiparticles (limits)
  - Solar shadow: heliospheric/coronal magnetic field

HAWC Physics

- **Primary cosmic rays**: ~100 GeV to 100 TeV
  - Cosmic-ray spectrum and anisotropy (10^{-3} level): nearby accelerators
  - Lunar shadow: calibration, antiparticles (limits)
  - Solar shadow: heliospheric/coronal magnetic field
- **Galactic and extragalactic γ rays**: ~1 TeV to 100 TeV
  - *Unbiased wide-FOV survey* of Northern Hemisphere
  - *Continuous observations* (>90% total uptime): transient sources
  - *High energies*: distinguish IC from π^0 emission as Klein-Nishina effects become important
  - *Galactic and extragalactic diffuse emission*: CR environment, ν sources?
  - Distinguish "astrophysical" γ rays from Dark Matter

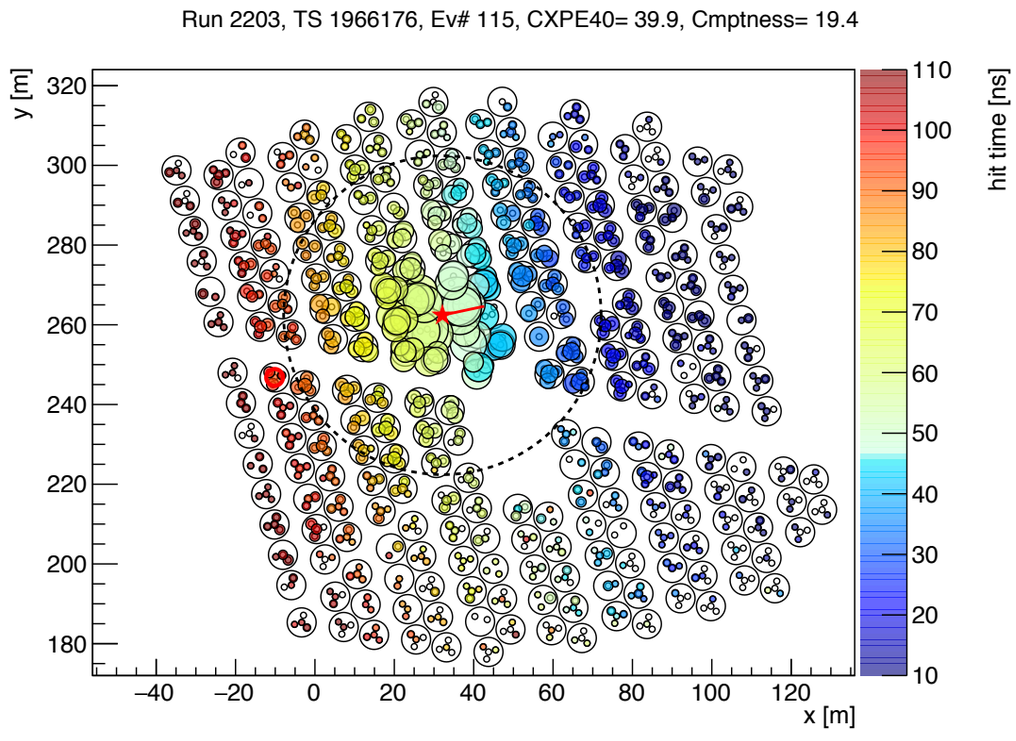
Background Suppression

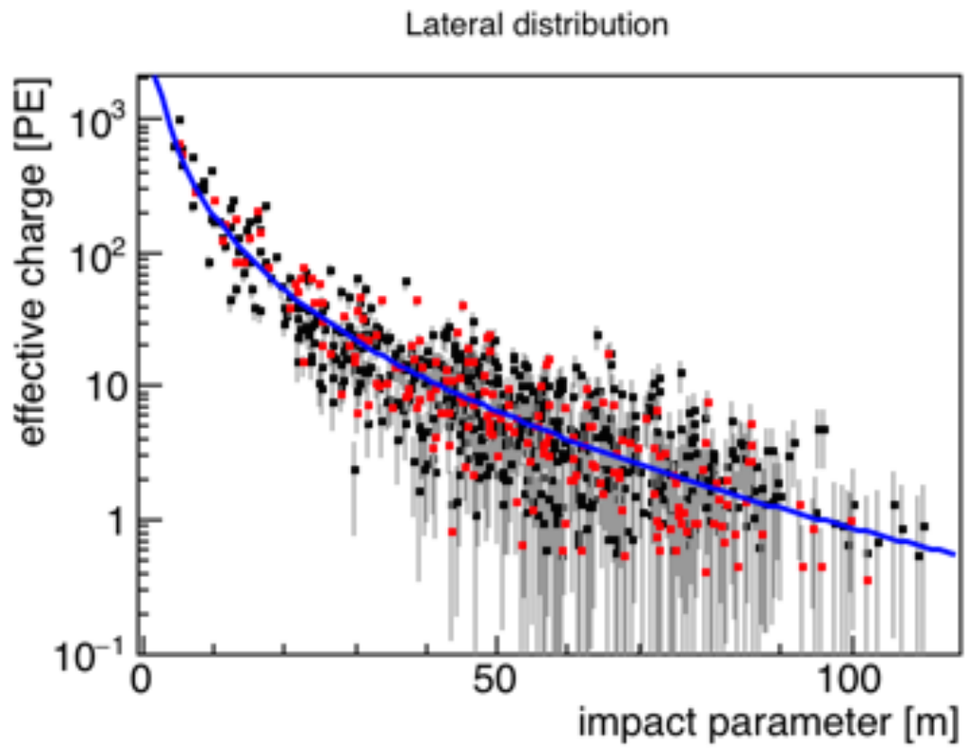




- Cosmic ray background: 25 kHz at trigger level
- Cosmic ray showers produce "clumpy" deposits of charge at large distances from the shower core
- Showers characterized by large variance in charge as a function of distance from shower core

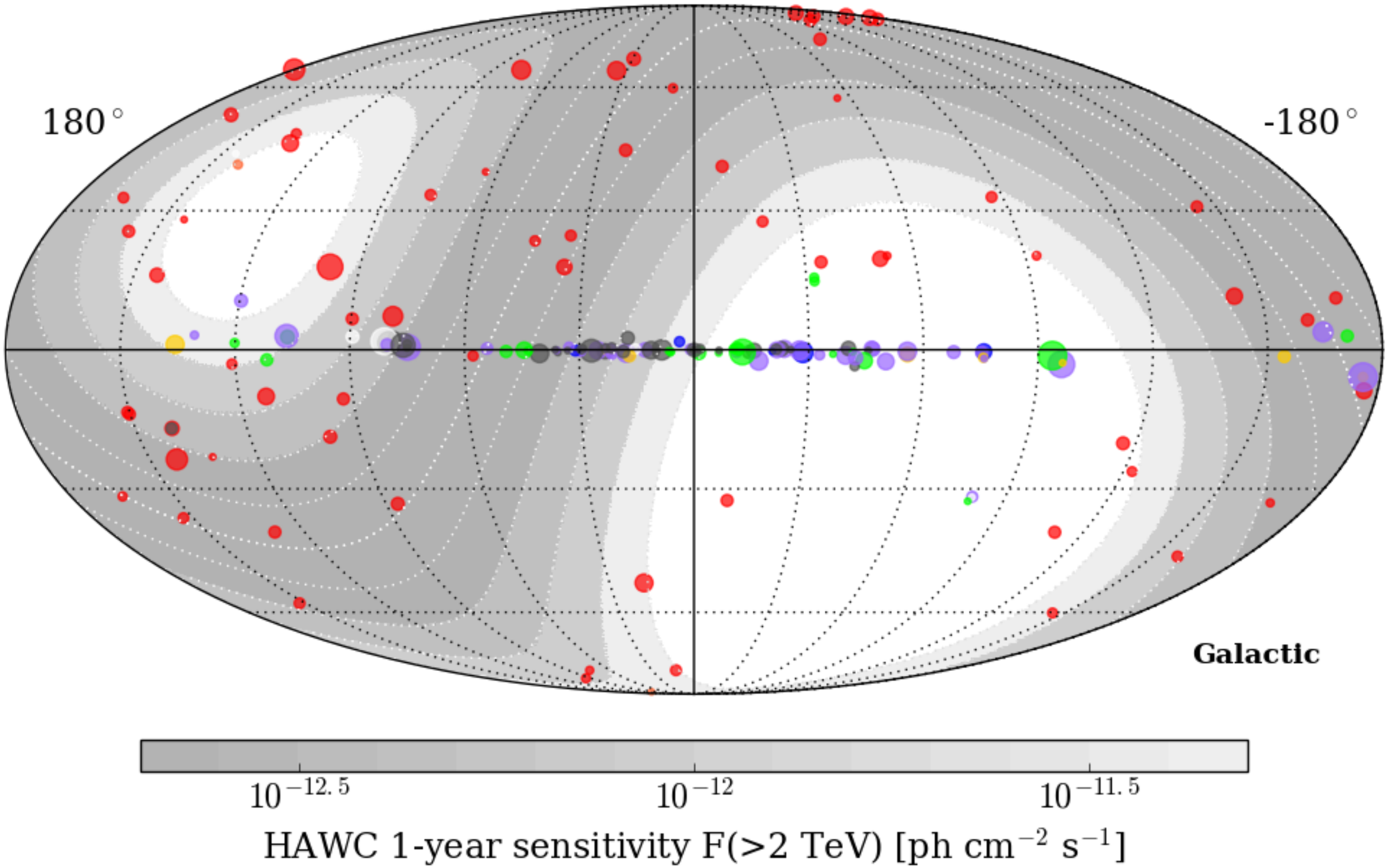
Background Suppression

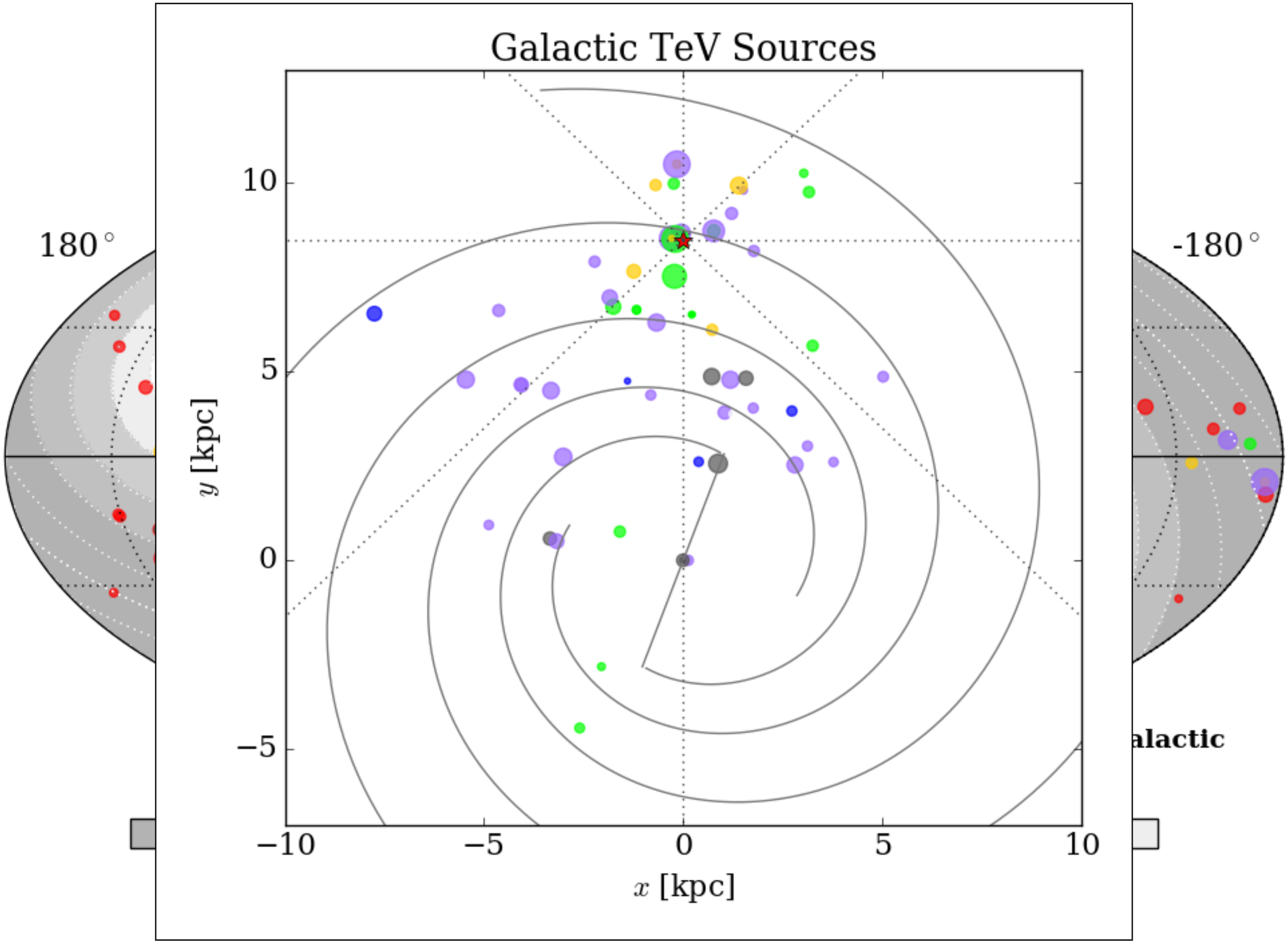


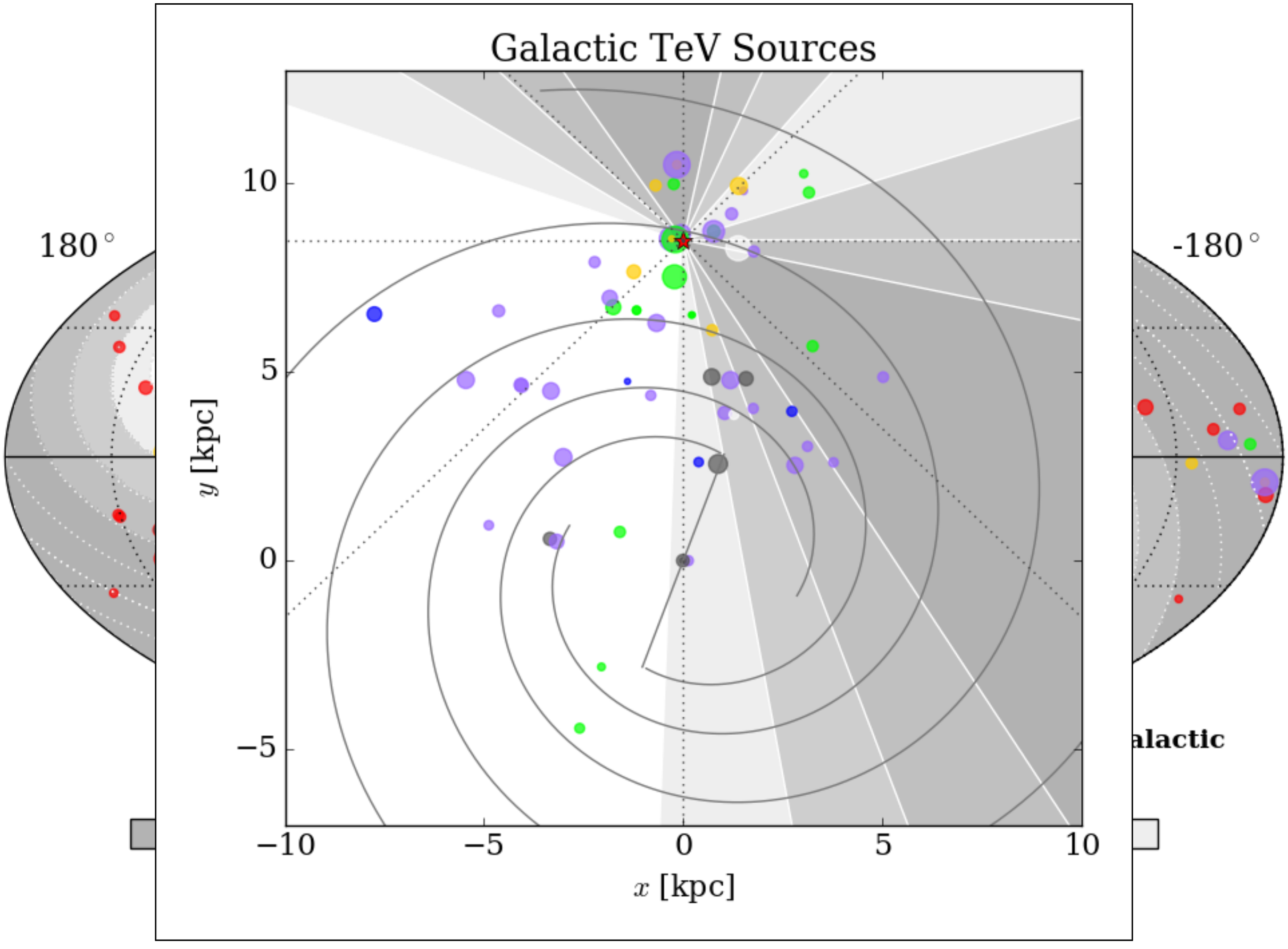


- Gamma ray signal: ~5 mHz from Crab Nebula
- Showers characterized by small variance in deposited charge vs distance from shower core
- 99.9% background suppression at 10 TeV

Sky Coverage




Galactic TeV Sources
180°
-180°
10
5
0
−5
−10
−5
0
5
10
y [kpc]
x [kpc]
alactic


Galactic TeV Sources
180°
-180°
10
5
0
−5
−10
−5
0
5
10
y [kpc]
x [kpc]
alactic

Spatial/Spectral Analysis

- Binned analysis: *fine* spatial bins, *coarse* shower size bins ("shower size" = fraction of PMTs triggered)
- Background rejection and PSF optimized in each shower size bin
- Spectral+spatial models forward-folded using Monte Carlo response function and fitted to data in shower size bins

$$\ln \mathcal{L}(\vec{n} \mid \vec{\theta}) = \sum_{i=1}^{N_{\text{bin}}} \sum_{j=1}^{N_{\text{pix}}} n_{ij} \ln \lambda_{ij}(\vec{\theta}) - \lambda_{ij}(\vec{\theta}) - \ln n_{ij}!$$

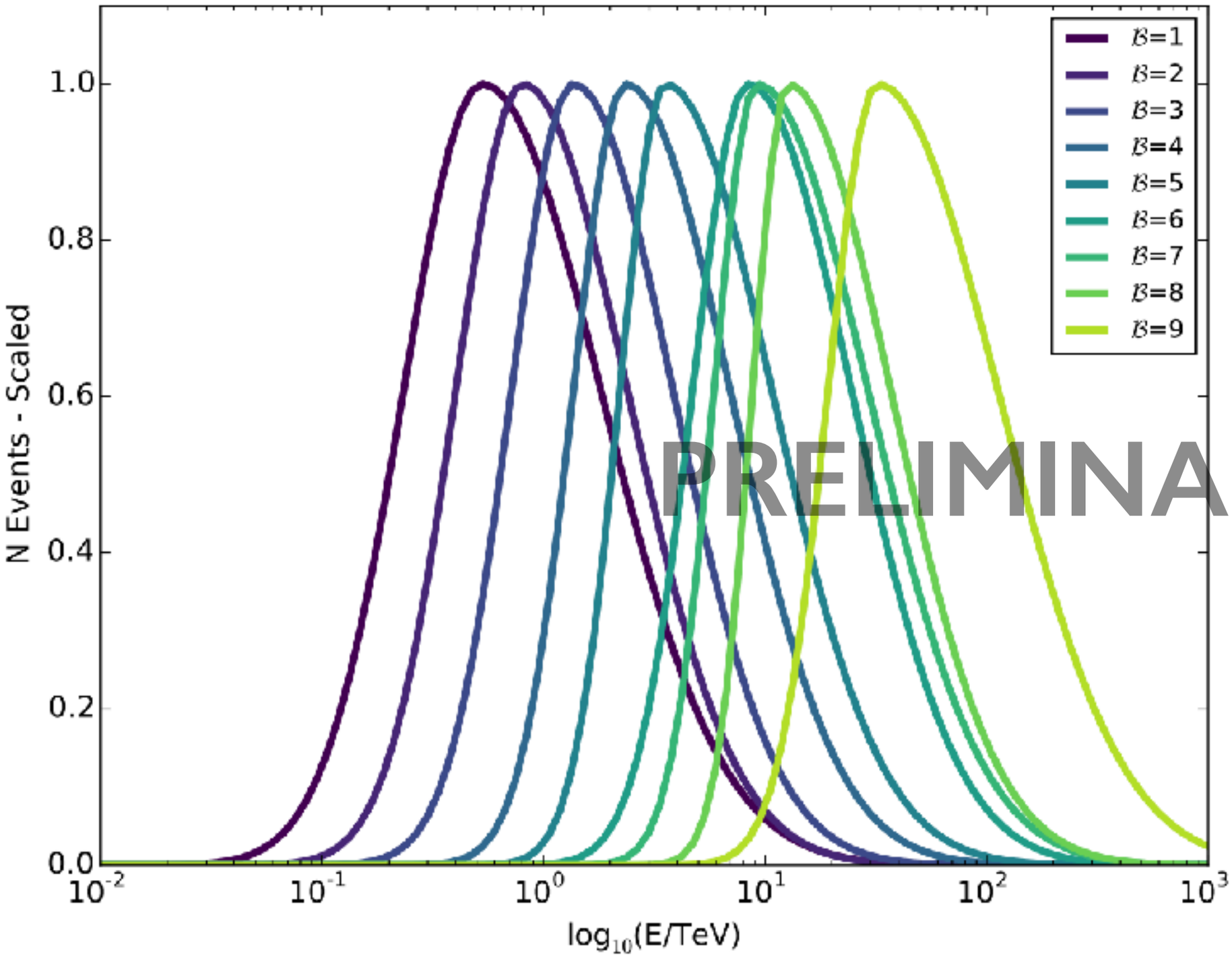
$$\text{TS} = 2\Delta \ln \mathcal{L}$$

$$\text{significance} = \sqrt{\text{TS}}$$

- Model counts: background + signal $\lambda_k = B_k + \Sigma_l f_{kl}(\theta)$

Size Bin Energy Resolution

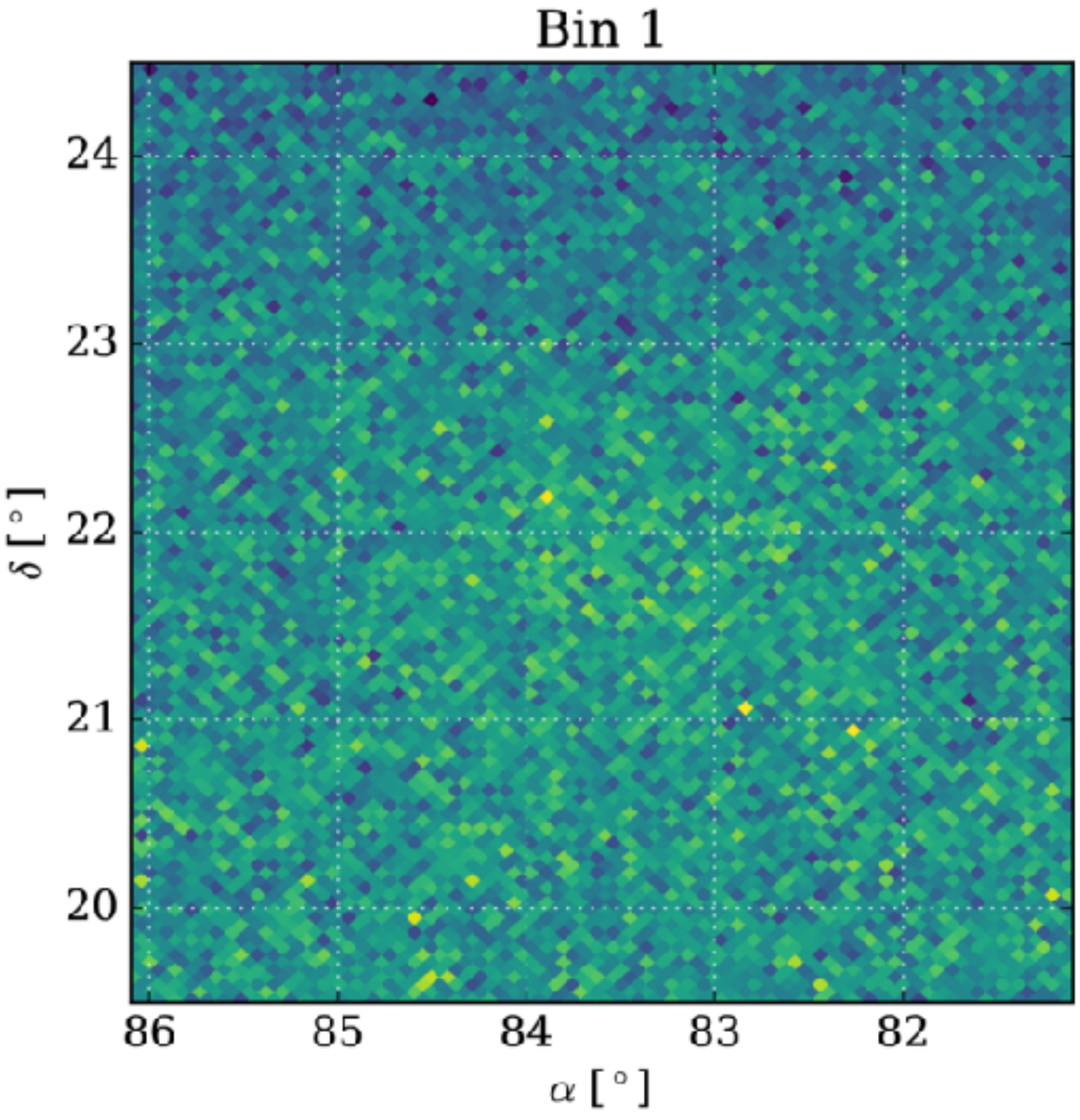
J. Pretz (PSU)



PRELIMINARY

Instrument Performance

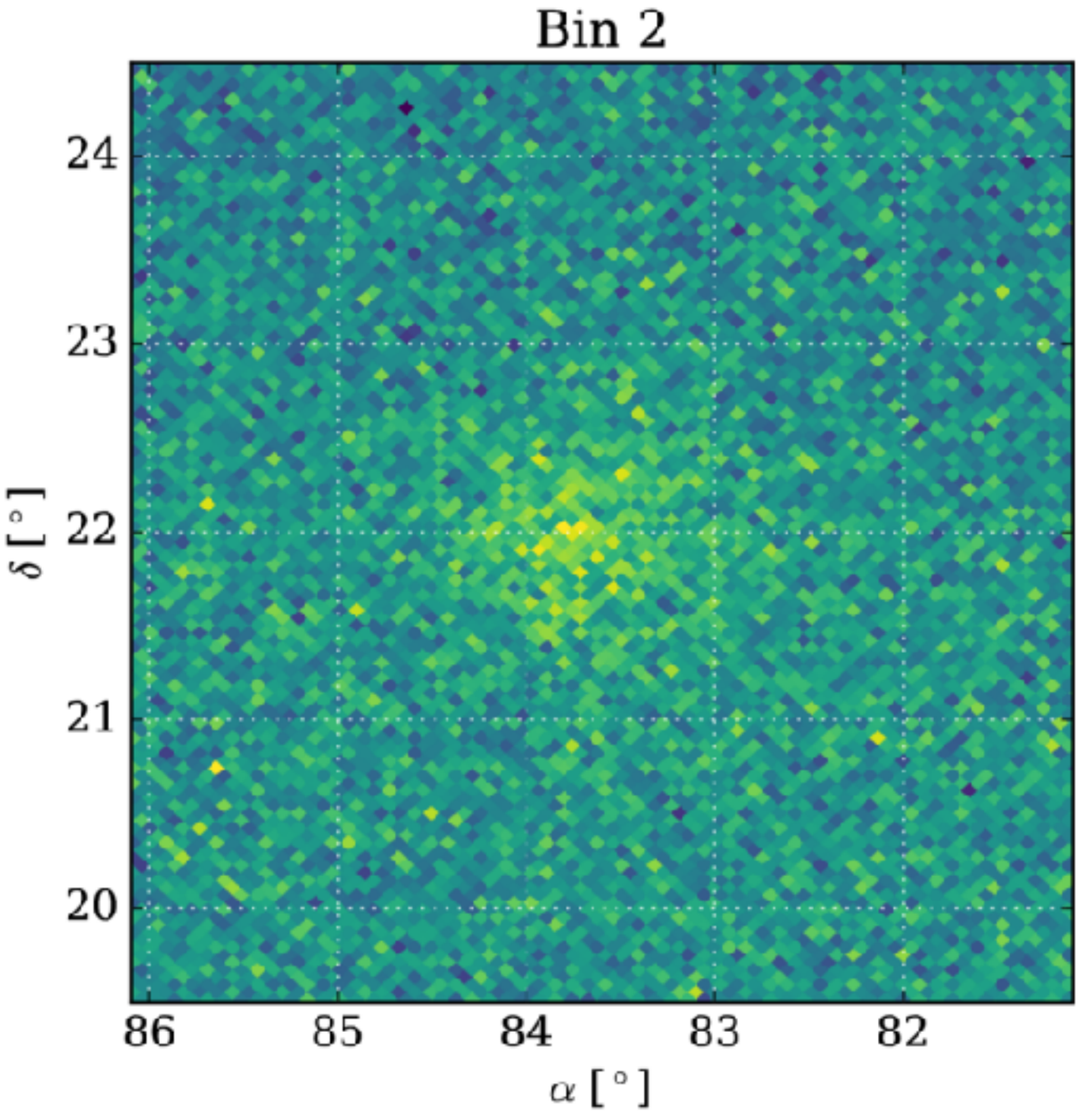
J. Pretz (PSU)



- PSF: 68% containment region ranges from ~1° to ~0.1°
- *Unprecedented* angular resolution for a surface array
- Proton efficiency: about 10^{-1} to 10^{-3}
- Gamma efficiency: ~0.7

Instrument Performance

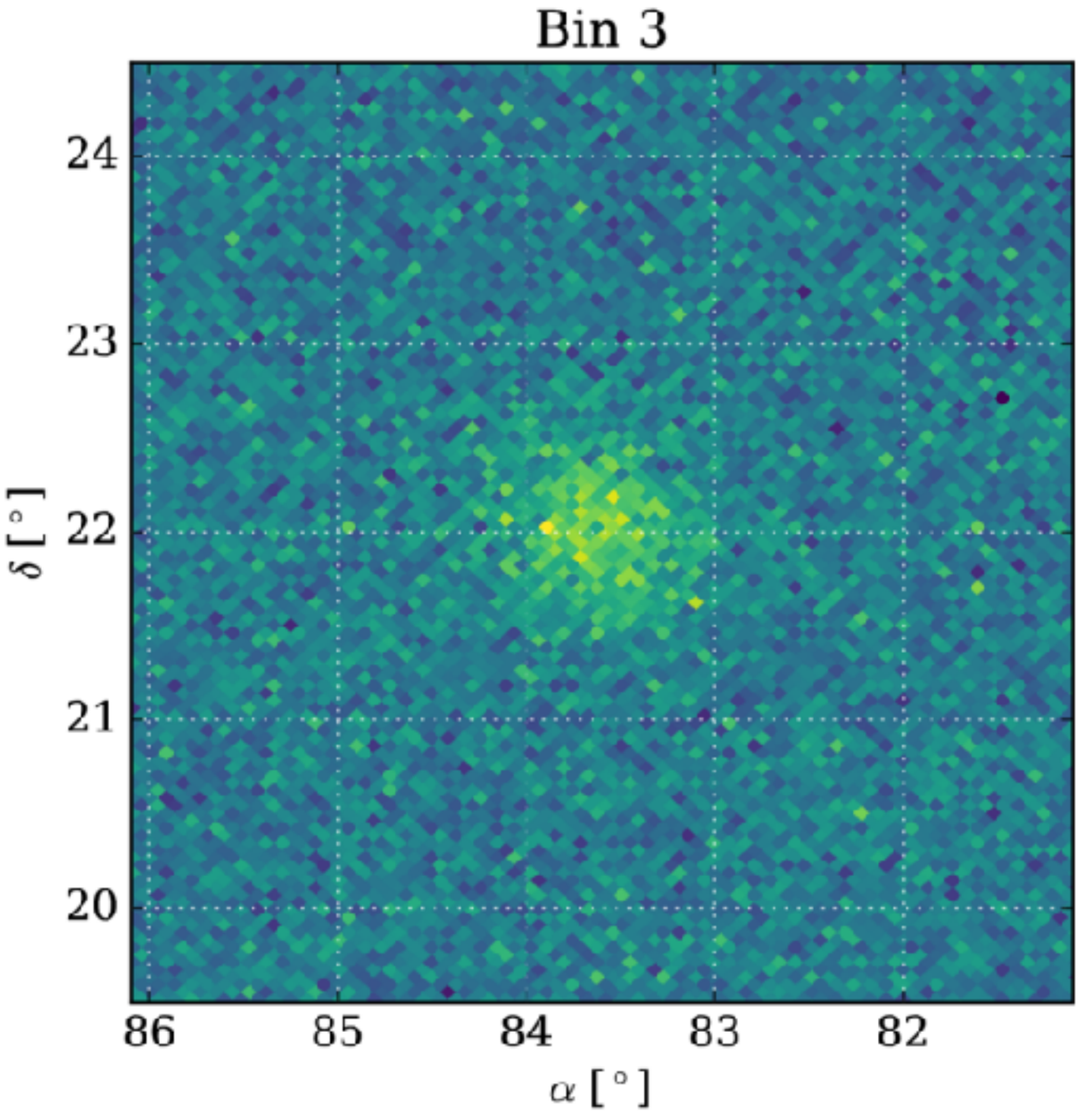
J. Pretz (PSU)



- PSF: 68% containment region ranges from ~1° to ~0.1°
- *Unprecedented* angular resolution for a surface array
- Proton efficiency: about 10^{-1} to 10^{-3}
- Gamma efficiency: ~0.7

Instrument Performance

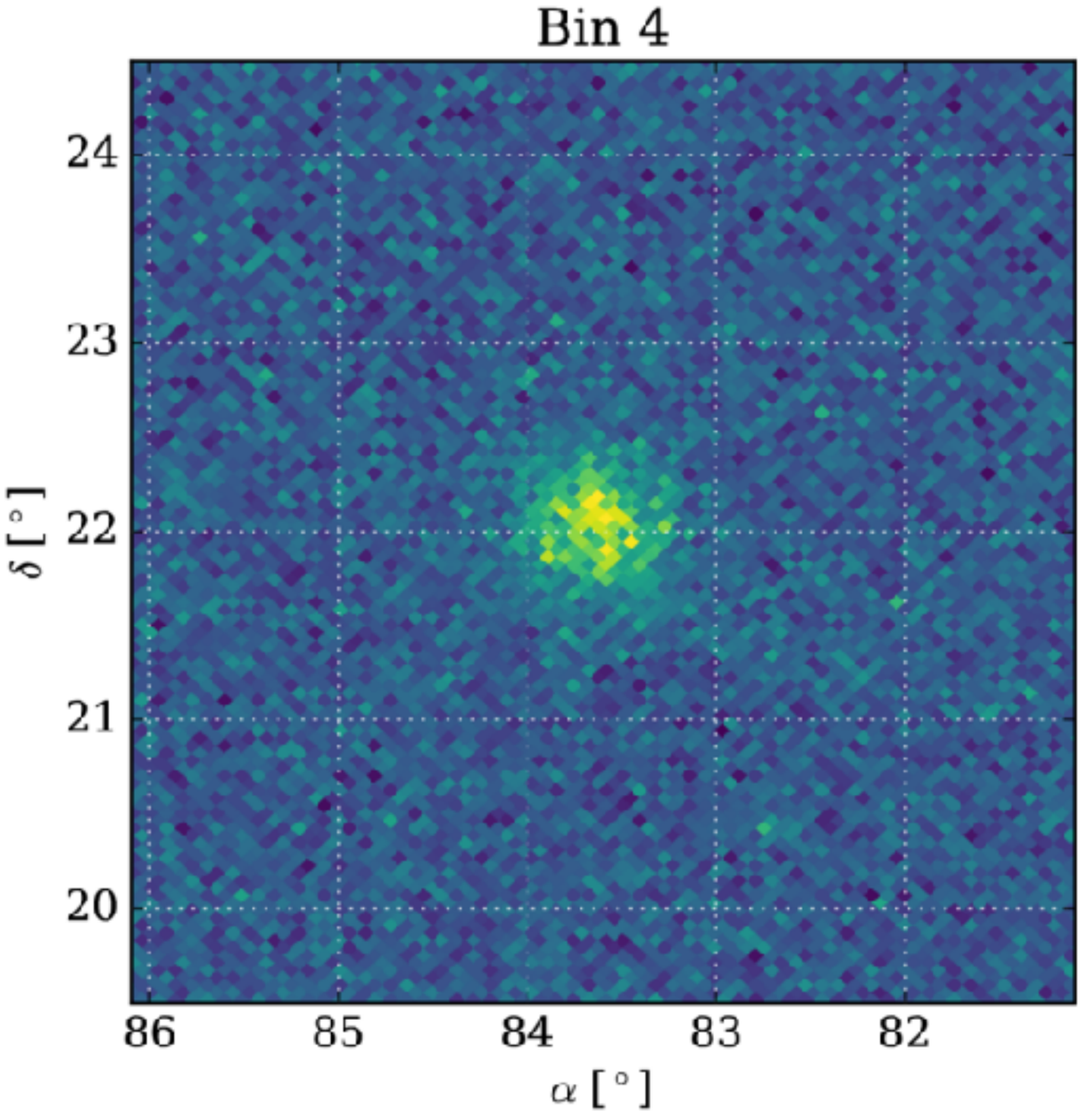
J. Pretz (PSU)



- PSF: 68% containment region ranges from ~1° to ~0.1°
- *Unprecedented* angular resolution for a surface array
- Proton efficiency: about 10^{-1} to 10^{-3}
- Gamma efficiency: ~0.7

Instrument Performance

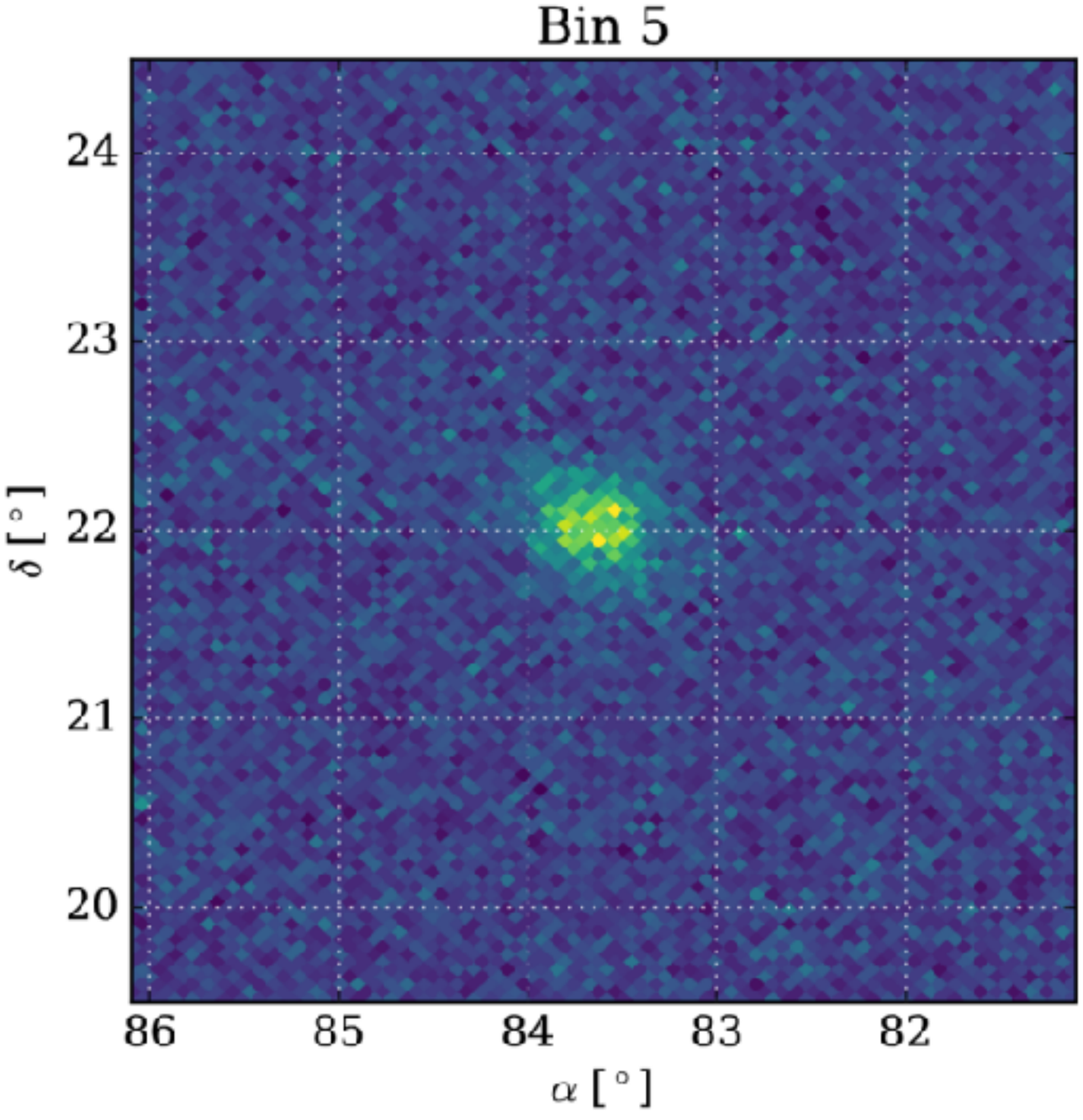
J. Pretz (PSU)



- PSF: 68% containment region ranges from ~1° to ~0.1°
- *Unprecedented* angular resolution for a surface array
- Proton efficiency: about 10^{-1} to 10^{-3}
- Gamma efficiency: ~0.7

Instrument Performance

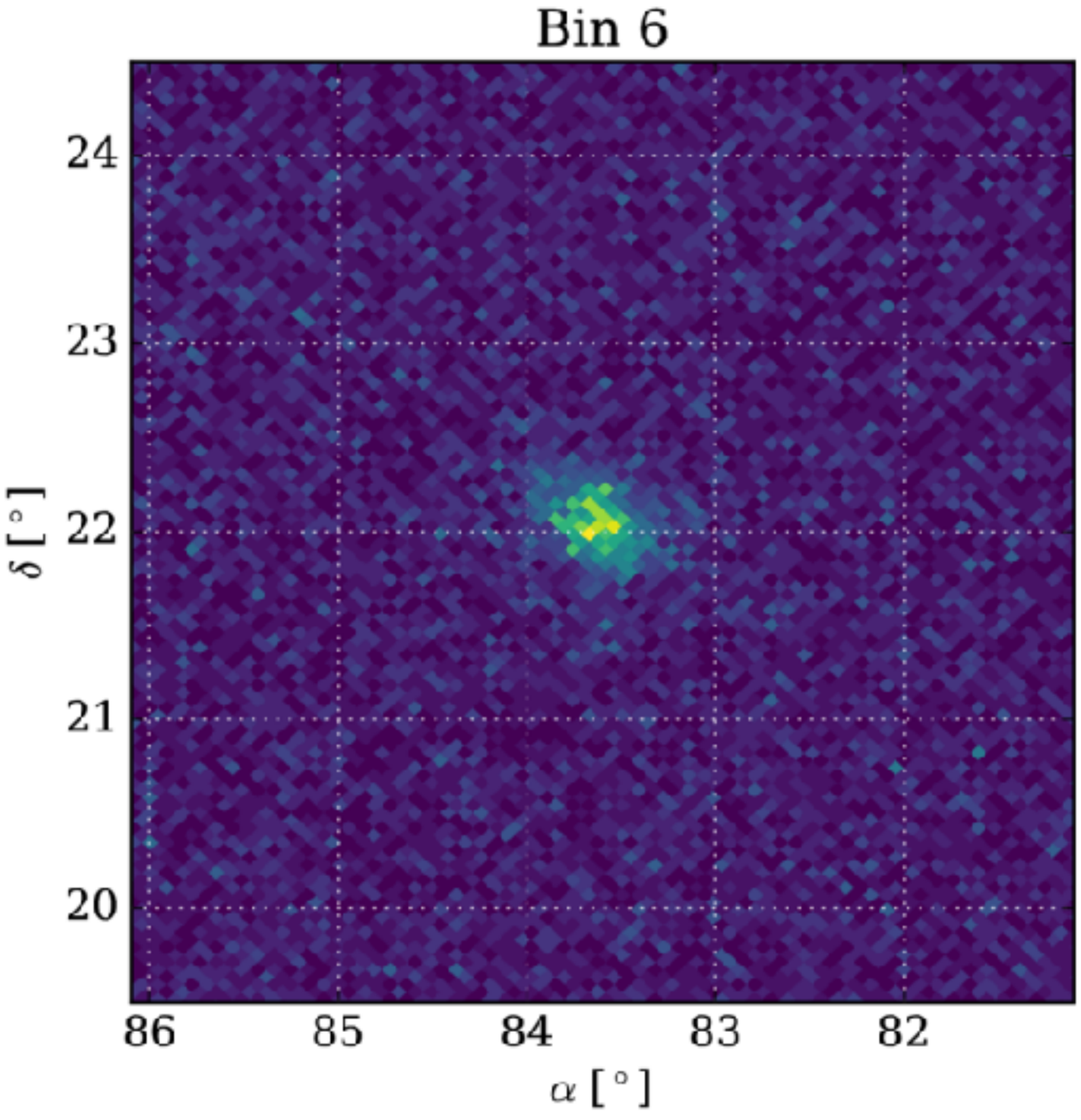
J. Pretz (PSU)



- PSF: 68% containment region ranges from ~1° to ~0.1°
- *Unprecedented* angular resolution for a surface array
- Proton efficiency: about 10^{-1} to 10^{-3}
- Gamma efficiency: ~0.7

Instrument Performance

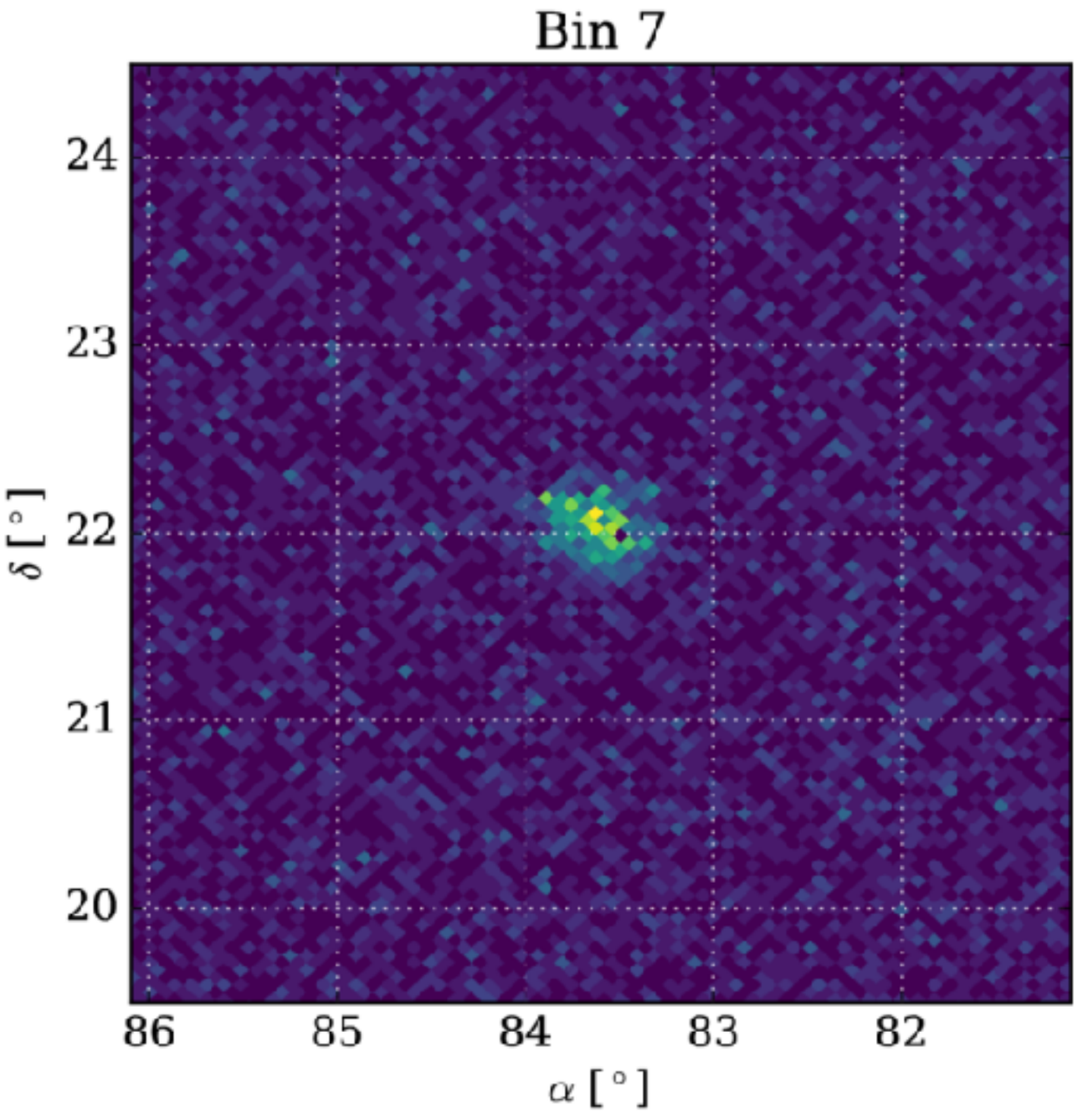
J. Pretz (PSU)



- PSF: 68% containment region ranges from ~1° to ~0.1°
- *Unprecedented* angular resolution for a surface array
- Proton efficiency: about 10^{-1} to 10^{-3}
- Gamma efficiency: ~0.7

Instrument Performance

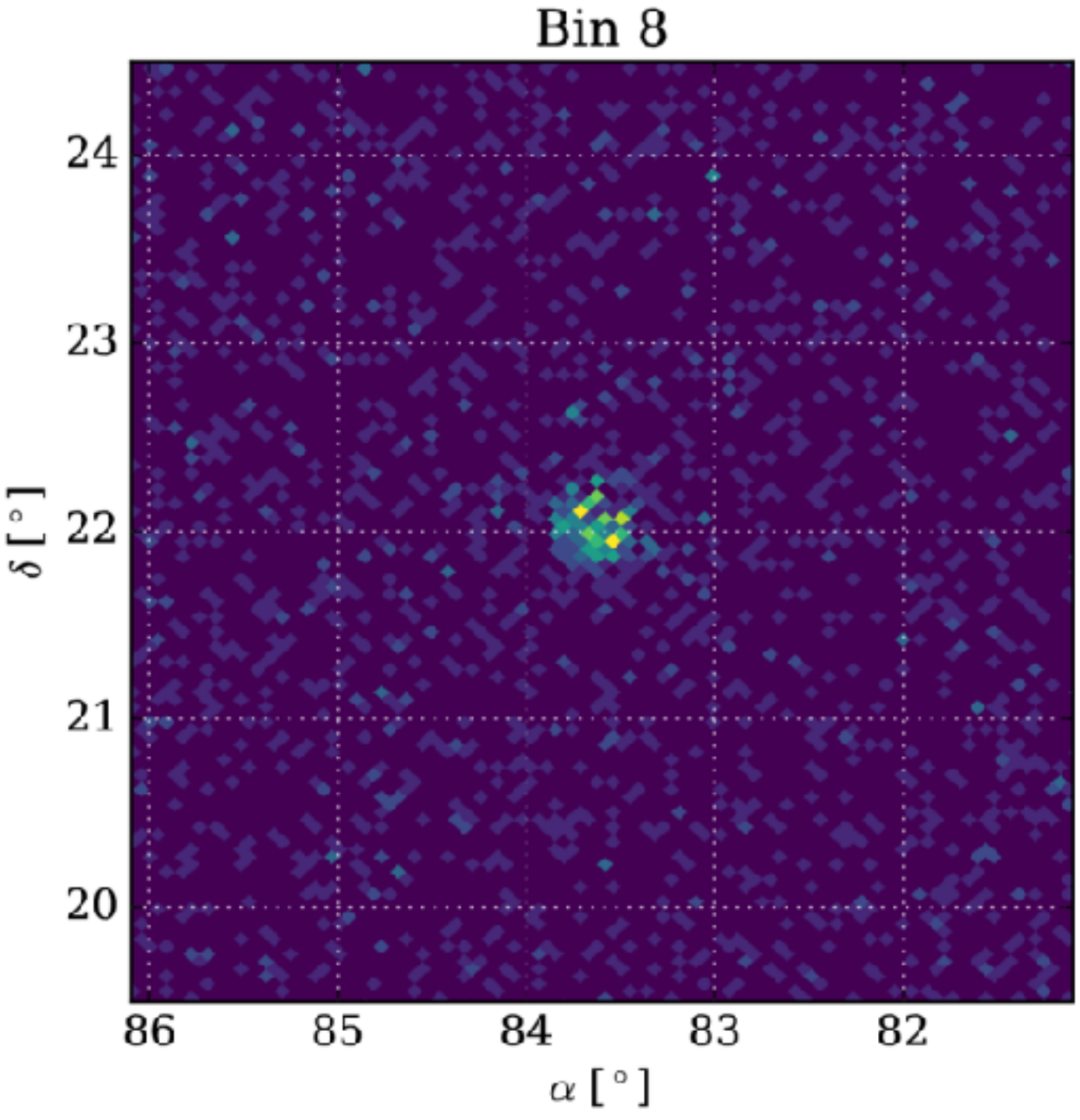
J. Pretz (PSU)



- PSF: 68% containment region ranges from ~1° to ~0.1°
- *Unprecedented* angular resolution for a surface array
- Proton efficiency: about 10^{-1} to 10^{-3}
- Gamma efficiency: ~0.7

Instrument Performance

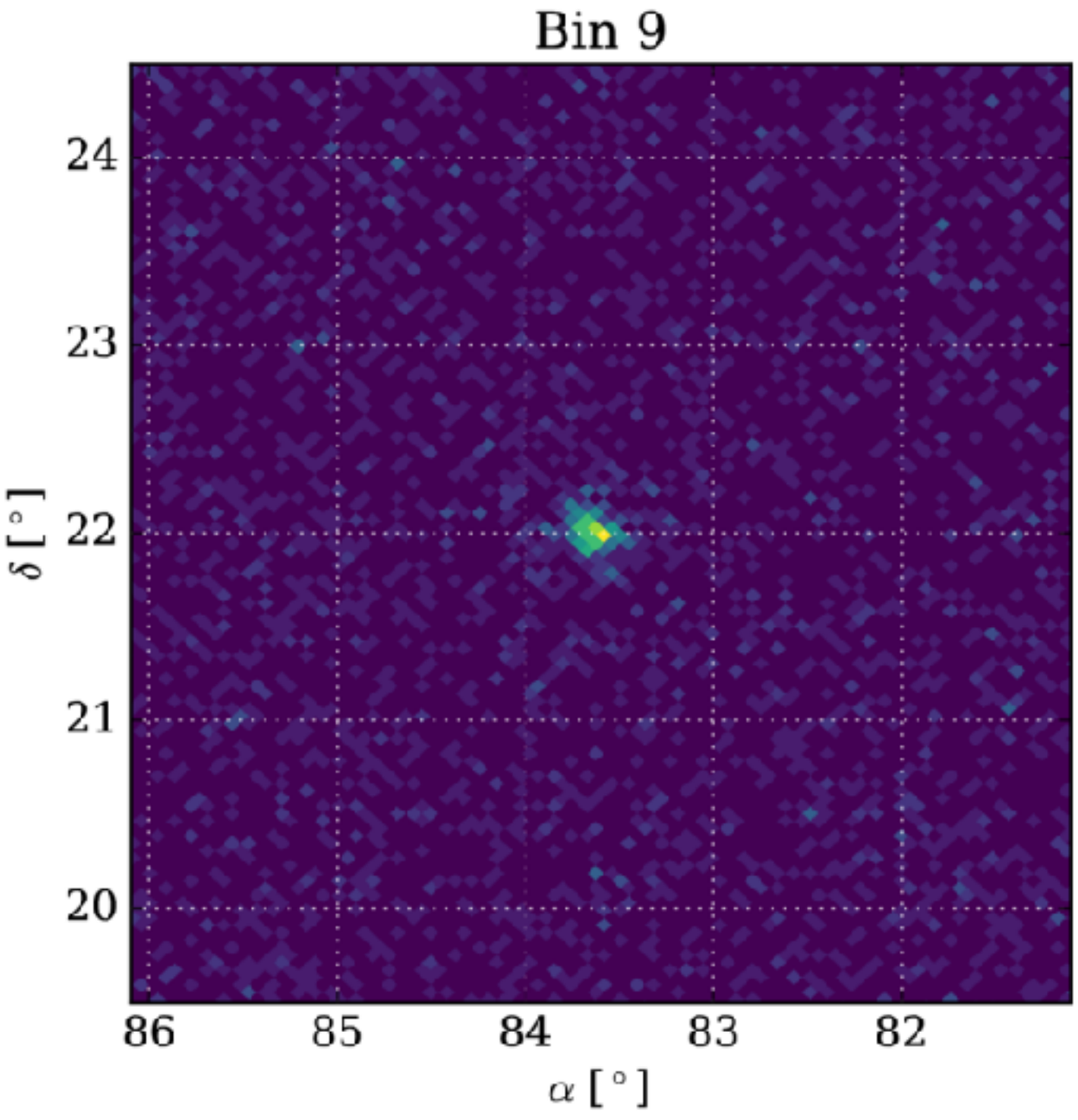
J. Pretz (PSU)



- PSF: 68% containment region ranges from ~1° to ~0.1°
- *Unprecedented* angular resolution for a surface array
- Proton efficiency: about 10^{-1} to 10^{-3}
- Gamma efficiency: ~0.7

Instrument Performance

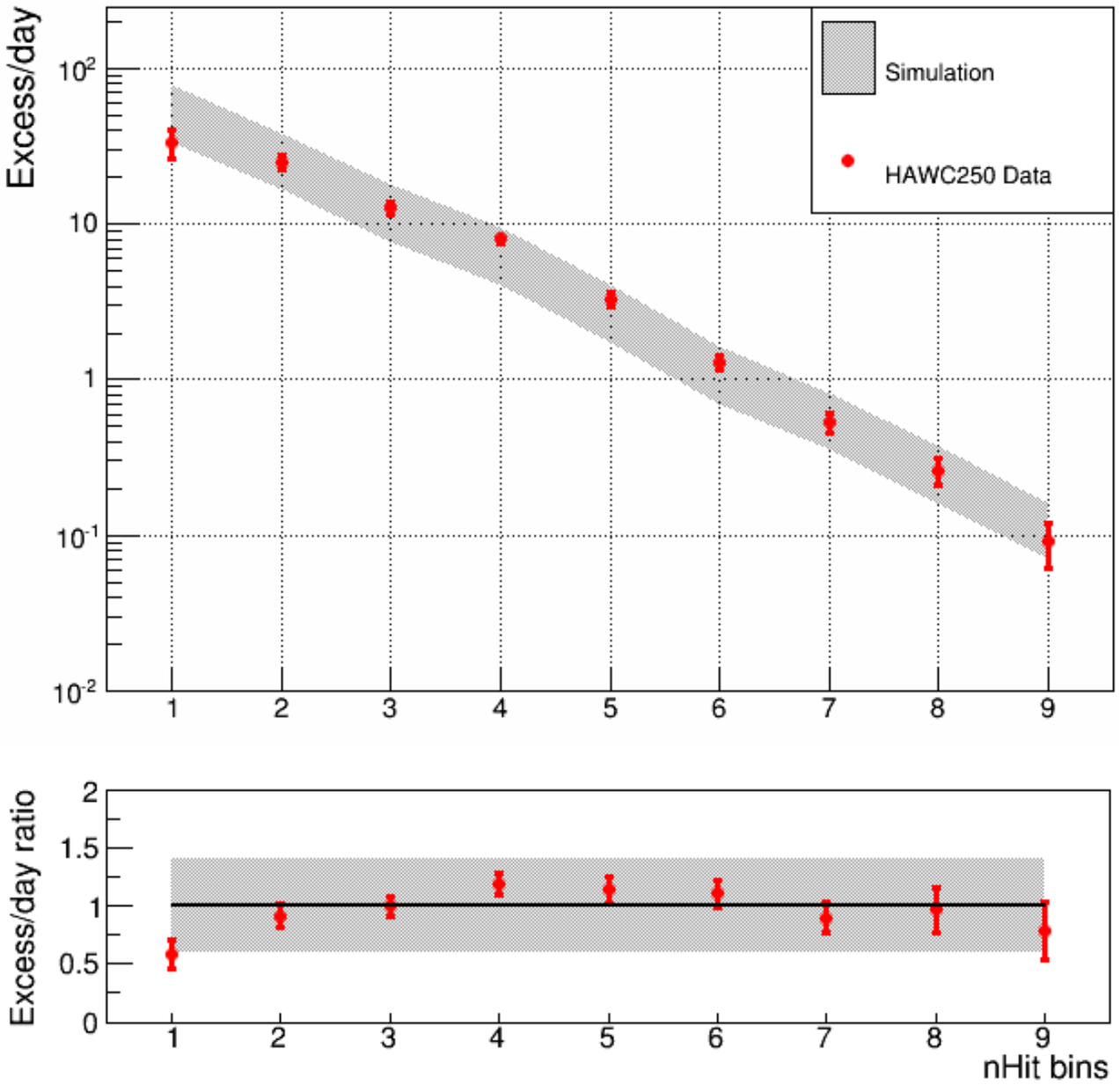
J. Pretz (PSU)



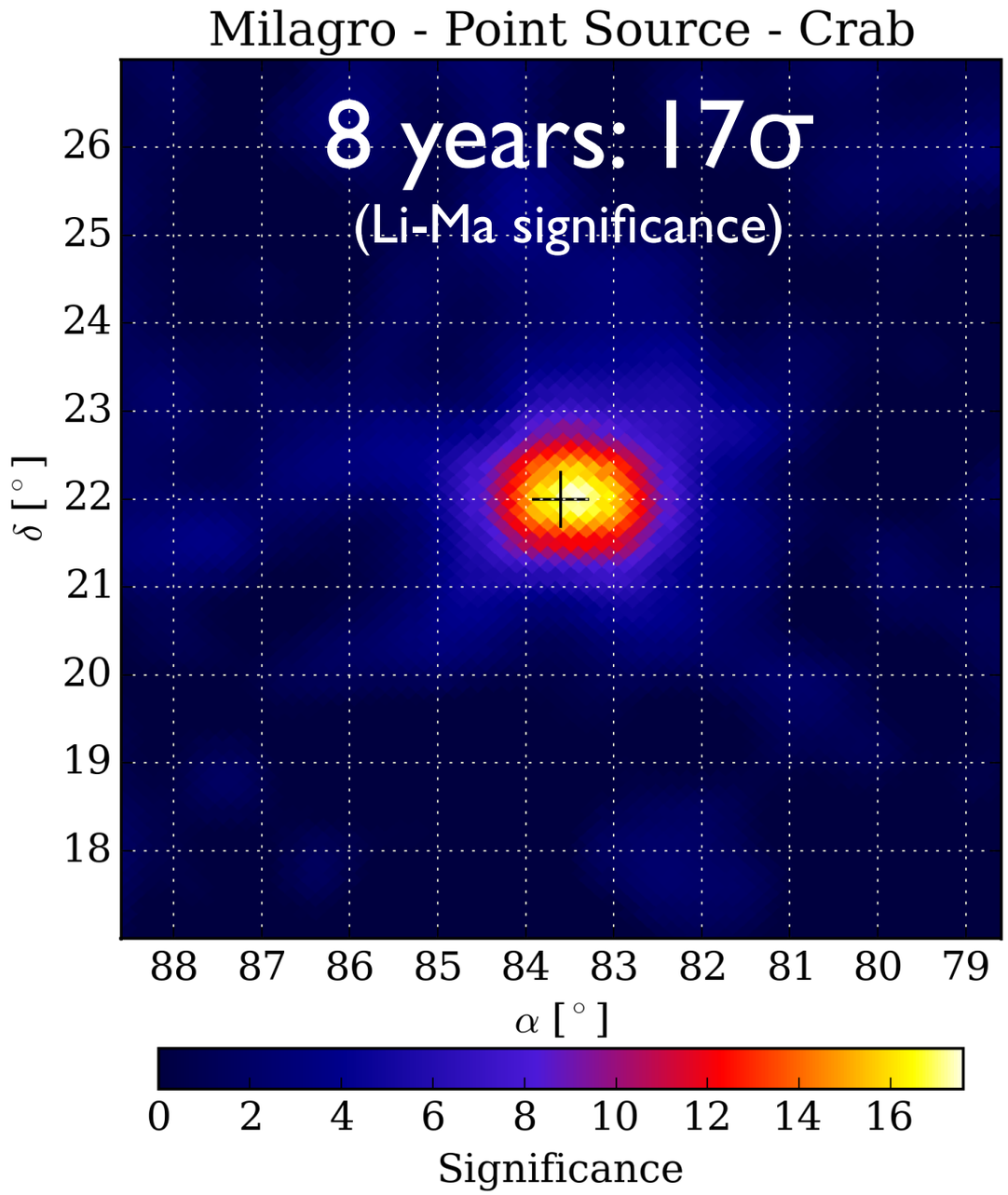
- PSF: 68% containment region ranges from ~1° to ~0.1°
- *Unprecedented* angular resolution for a surface array
- Proton efficiency: about 10^{-1} to 10^{-3}
- Gamma efficiency: ~0.7

Verification: Crab Nebula

F. Salesa Greus, ICRC 2015

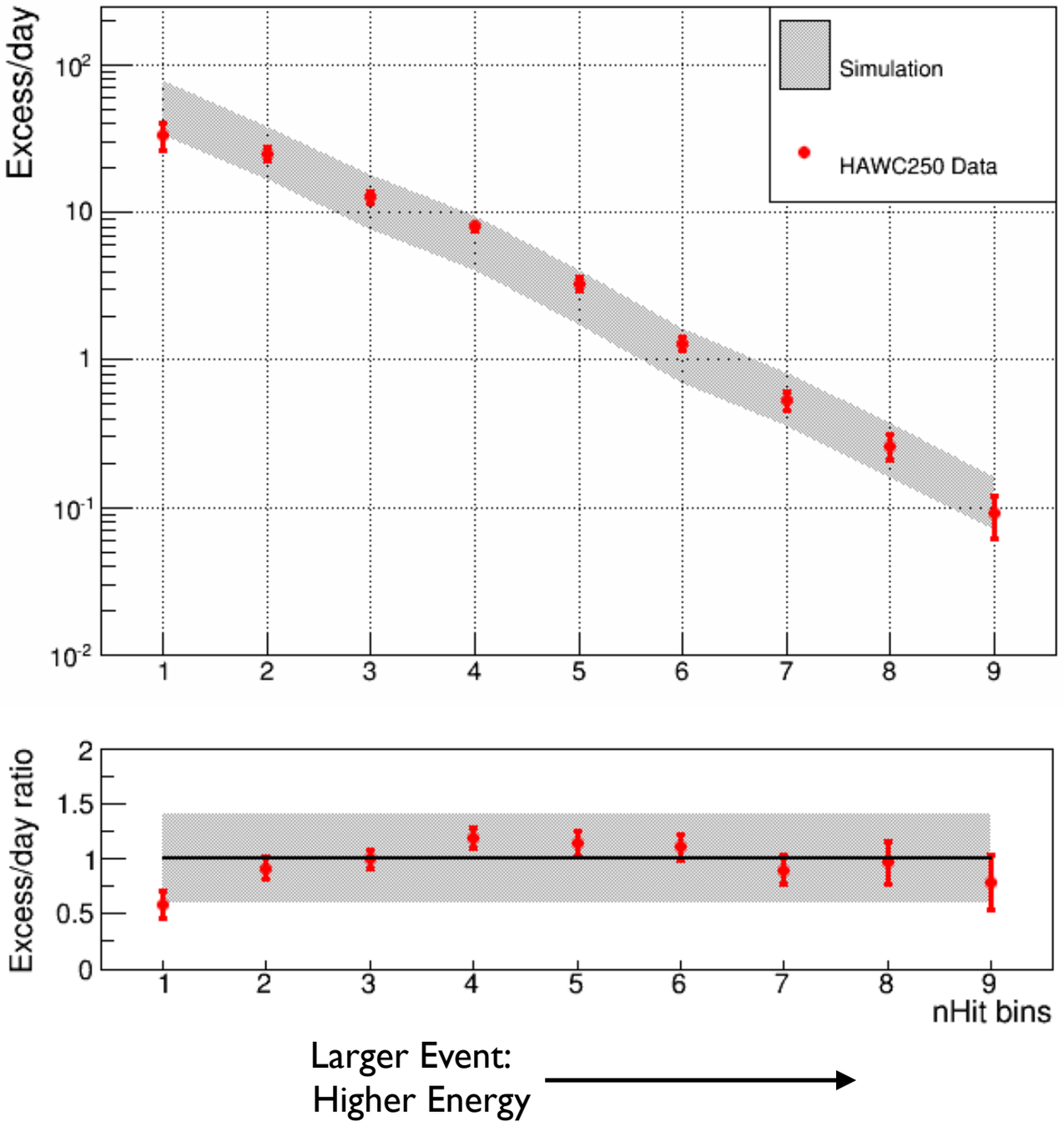


Larger Event:
Higher Energy →

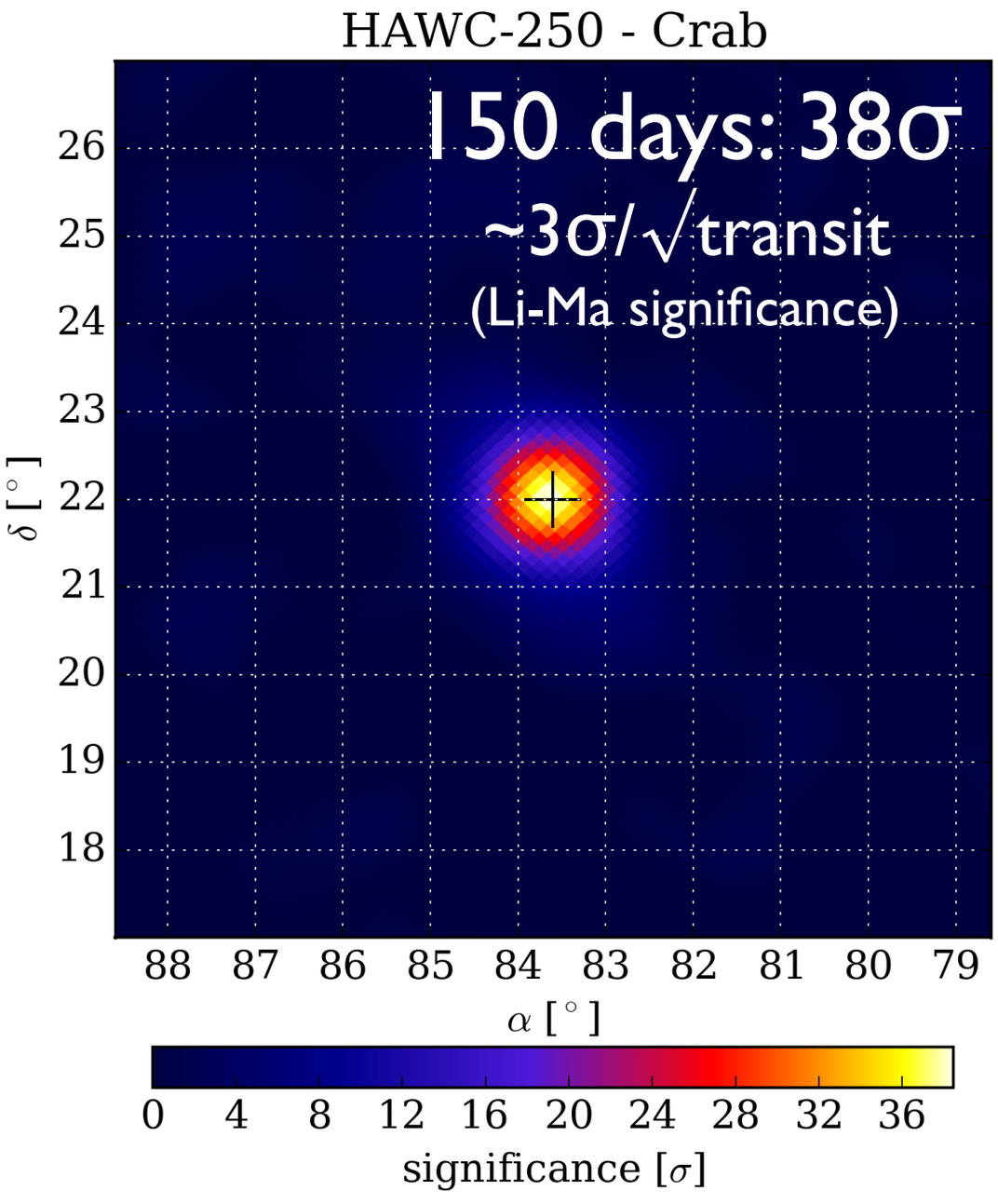


Verification: Crab Nebula

F. Salesa Greus, ICRC 2015

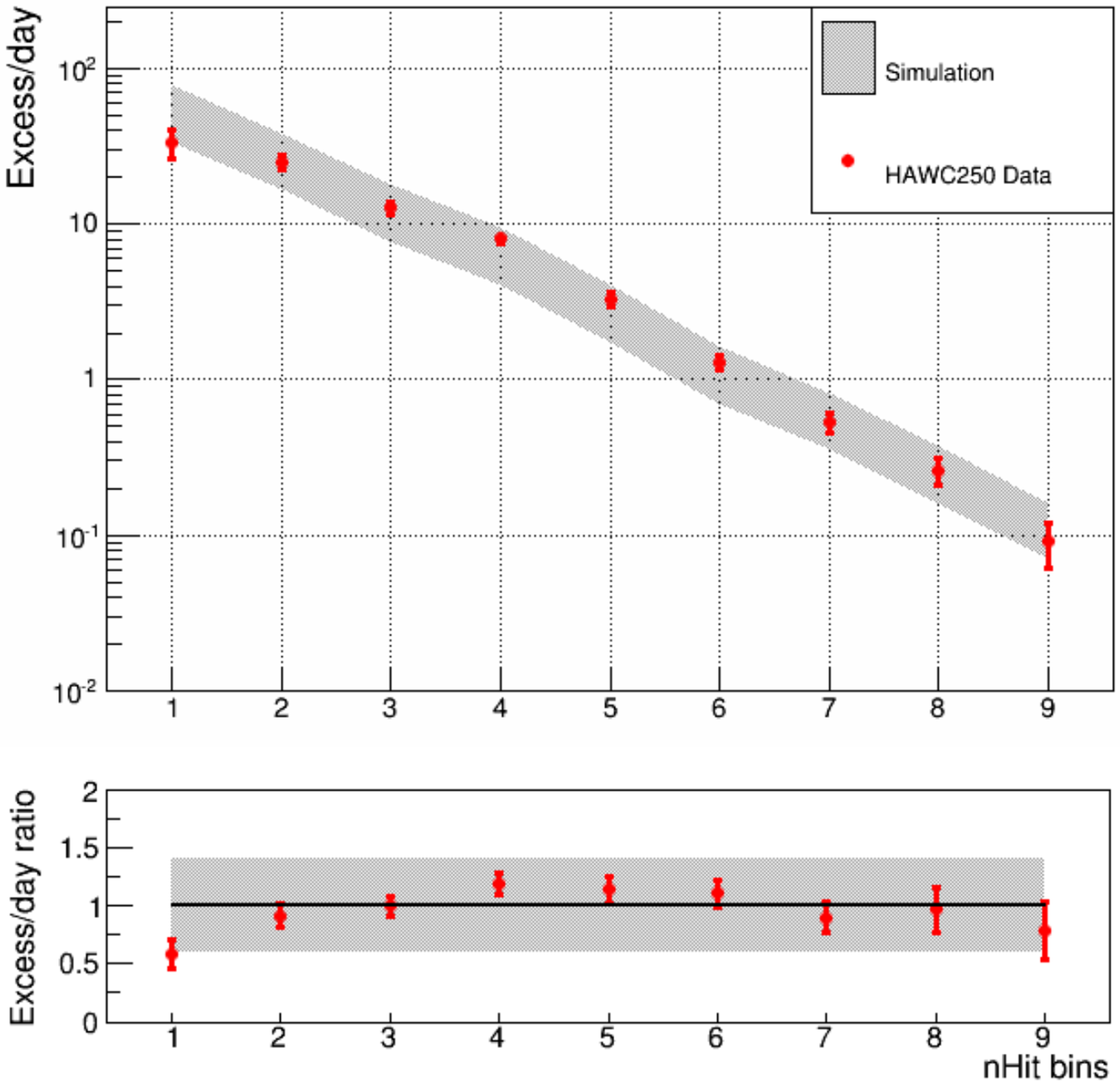


Larger Event:
Higher Energy →

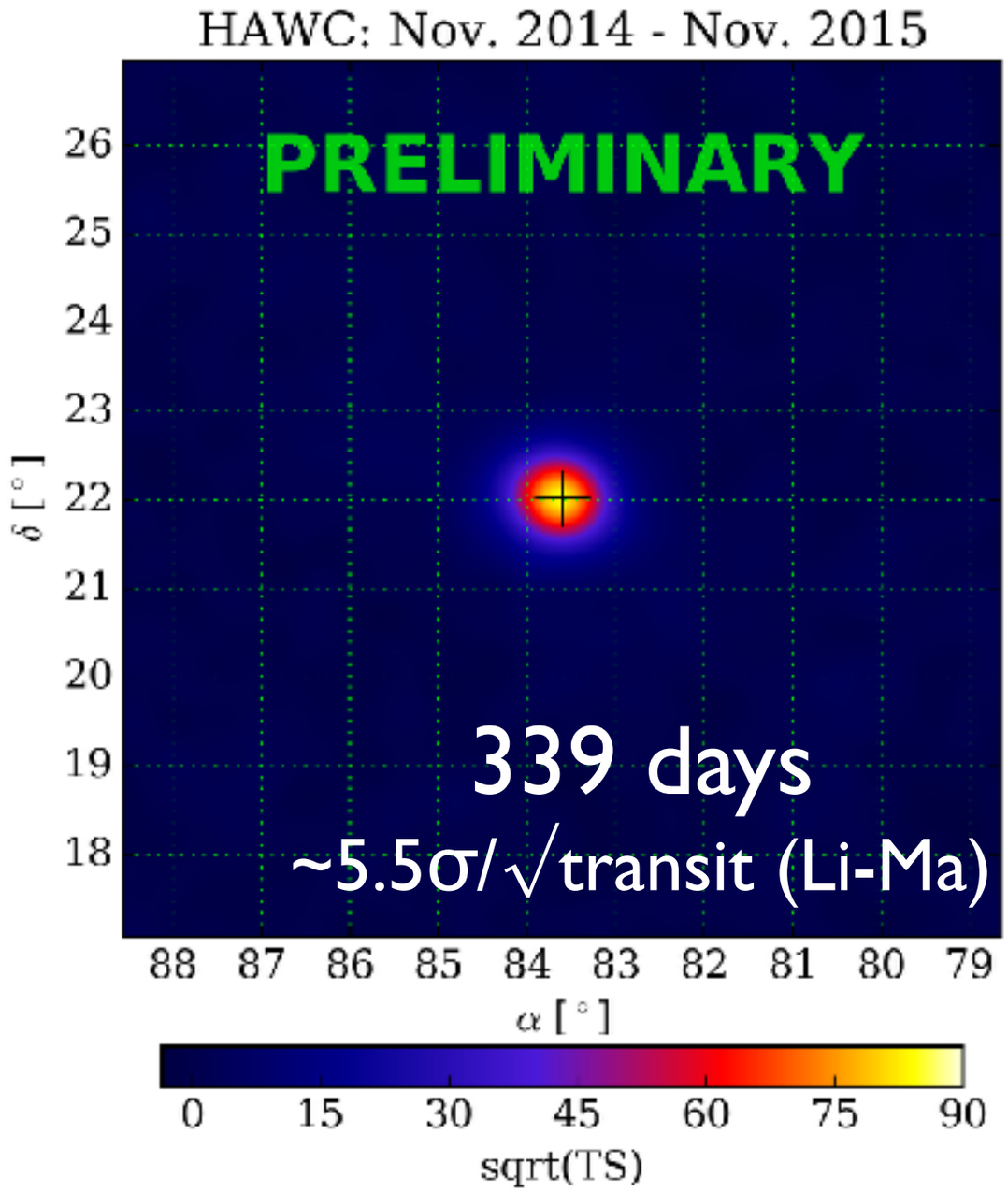


Verification: Crab Nebula

F. Salesa Greus, ICRC 2015



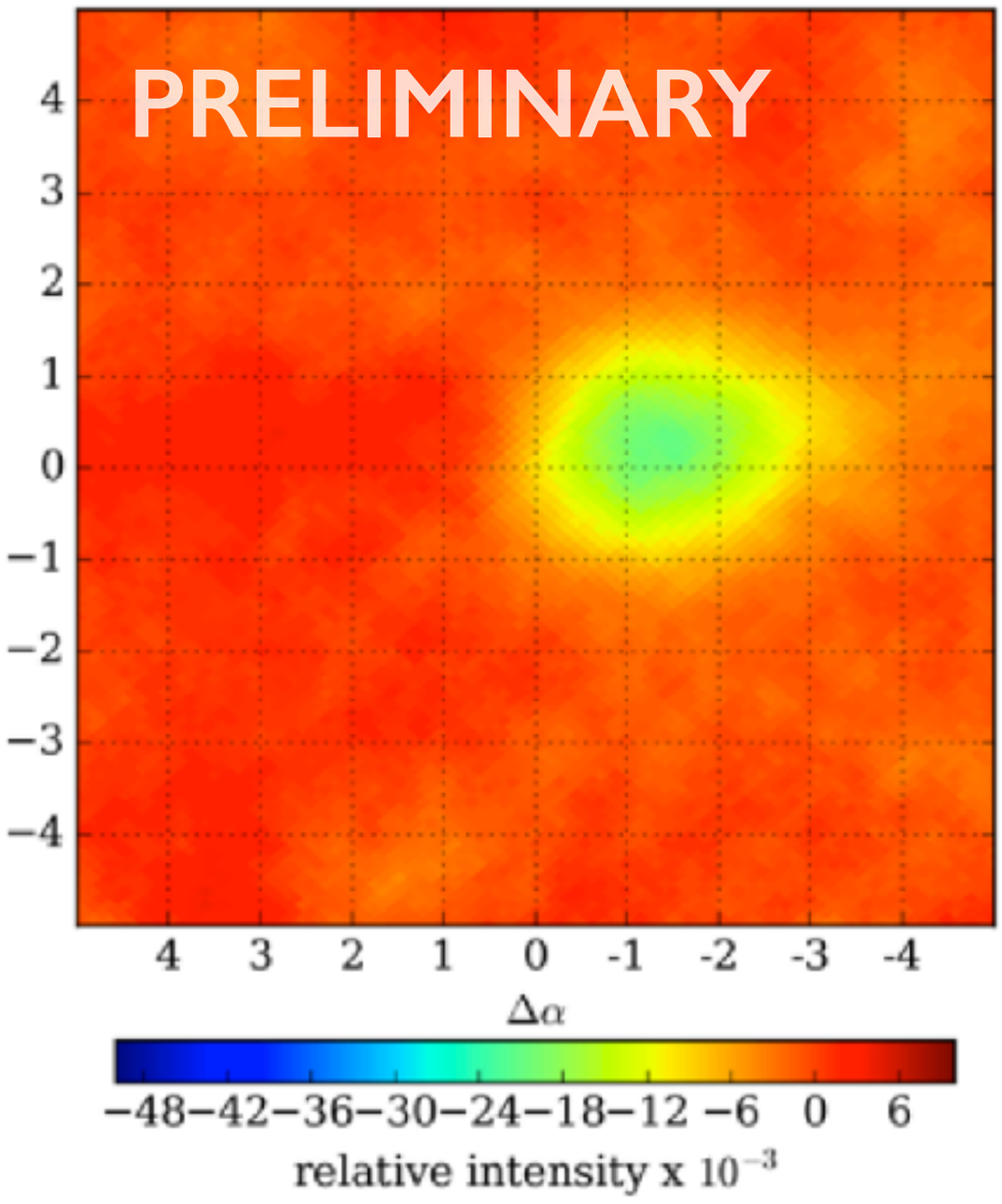
Larger Event:
Higher Energy →

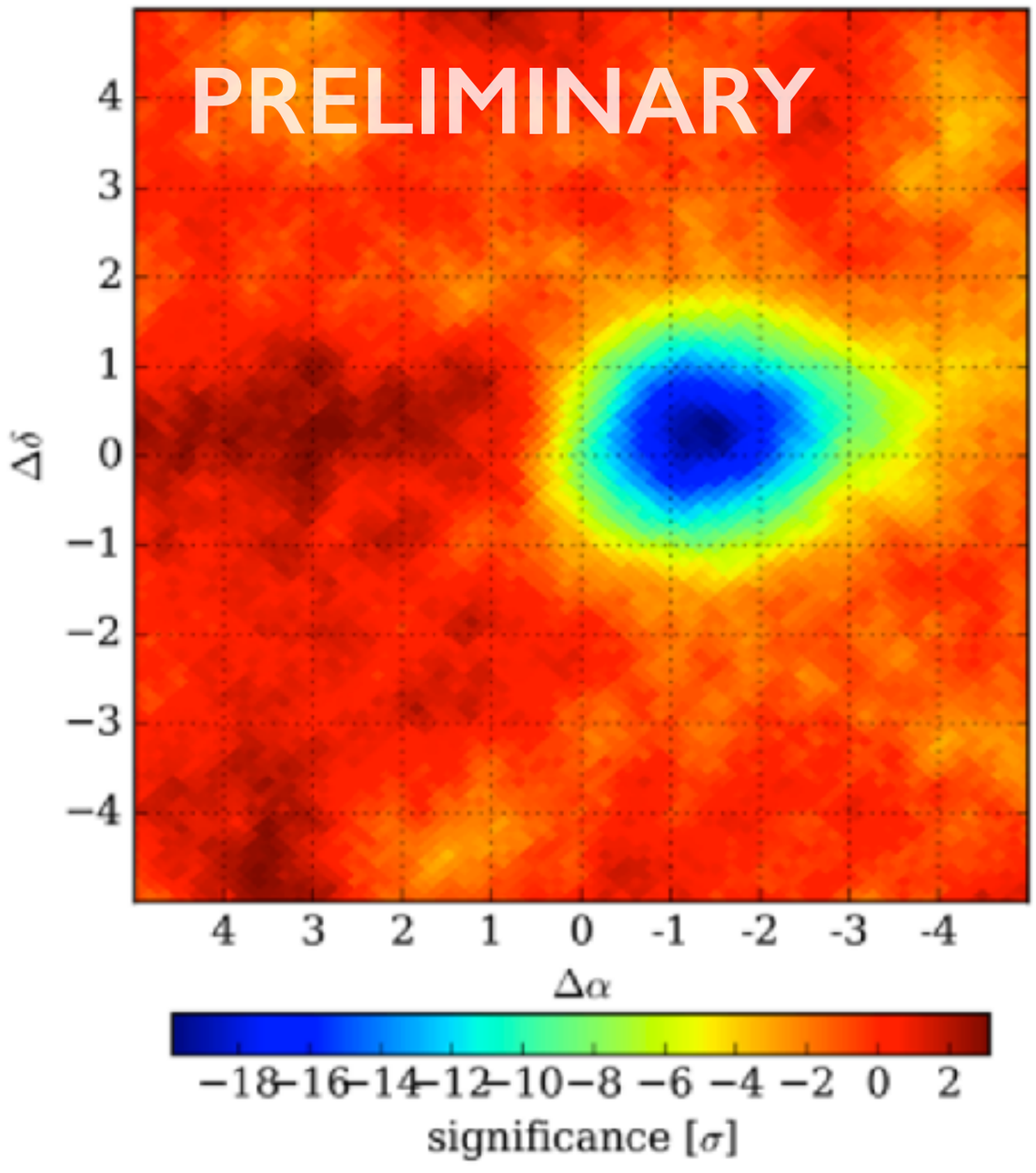


Lunar Shadow

Median Energy: 0.6 TeV

Z. Hampel-Arias
UW-Madison

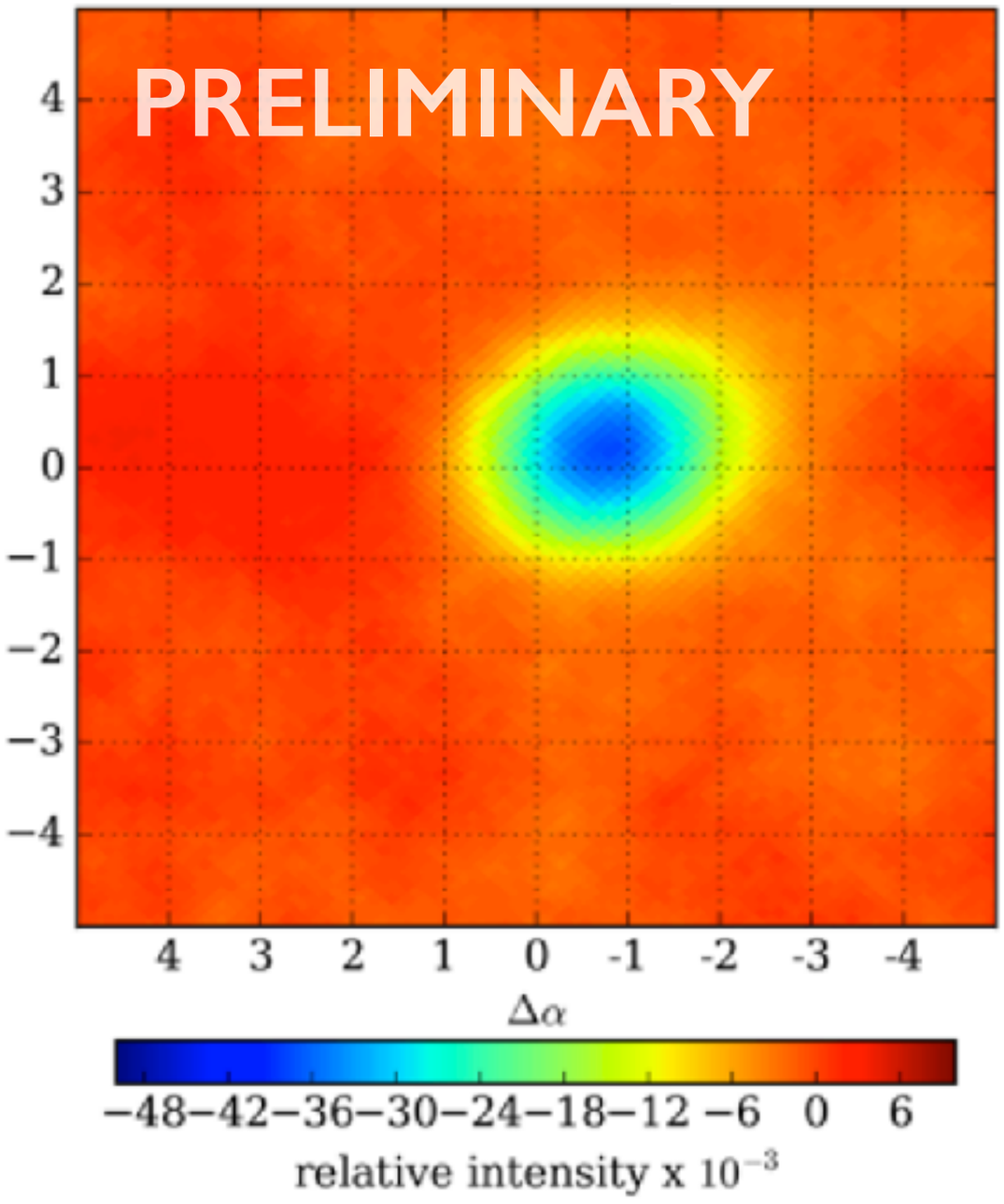


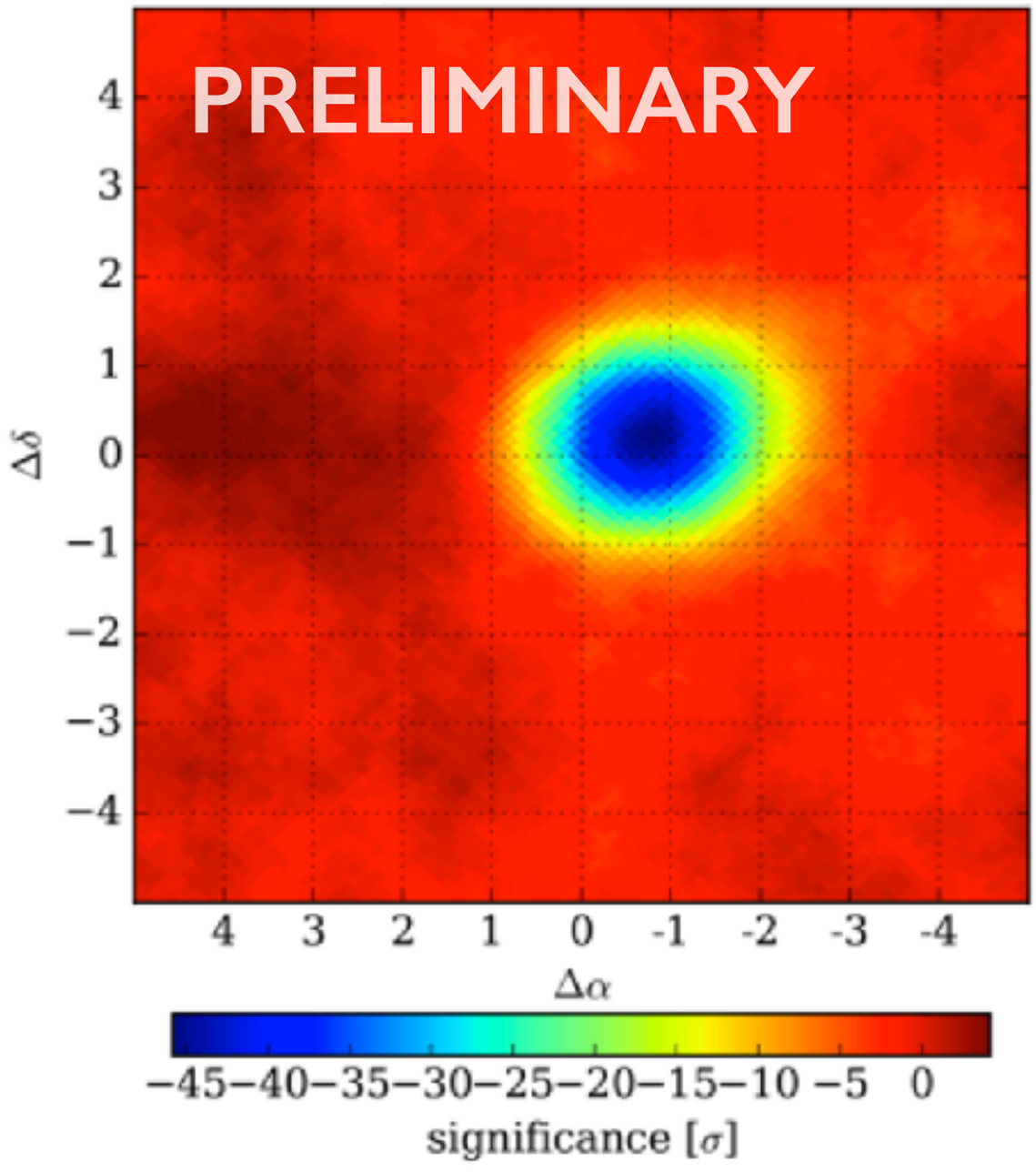


Lunar Shadow

Median Energy: 1.3 TeV

Z. Hampel-Arias
UW-Madison

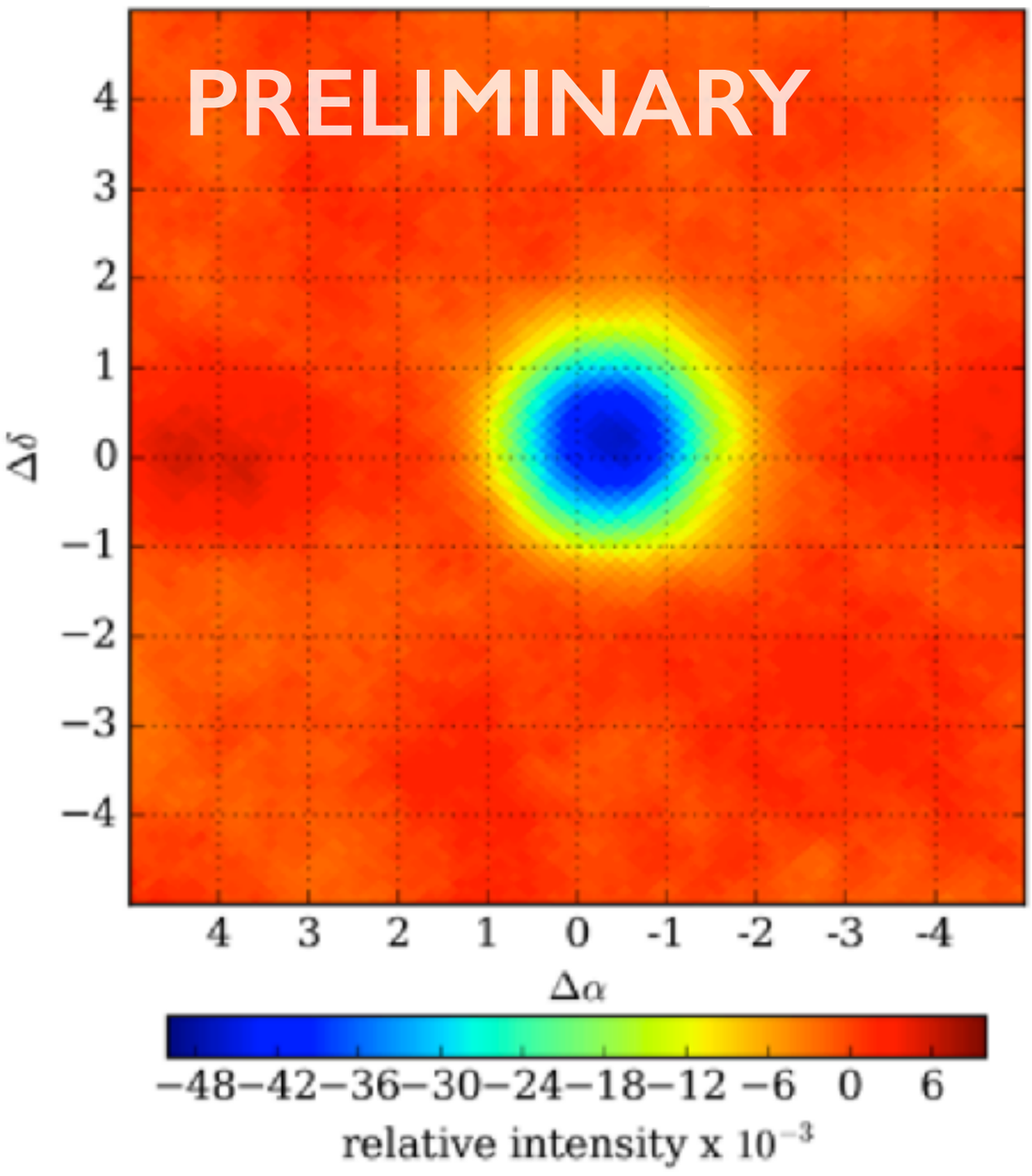


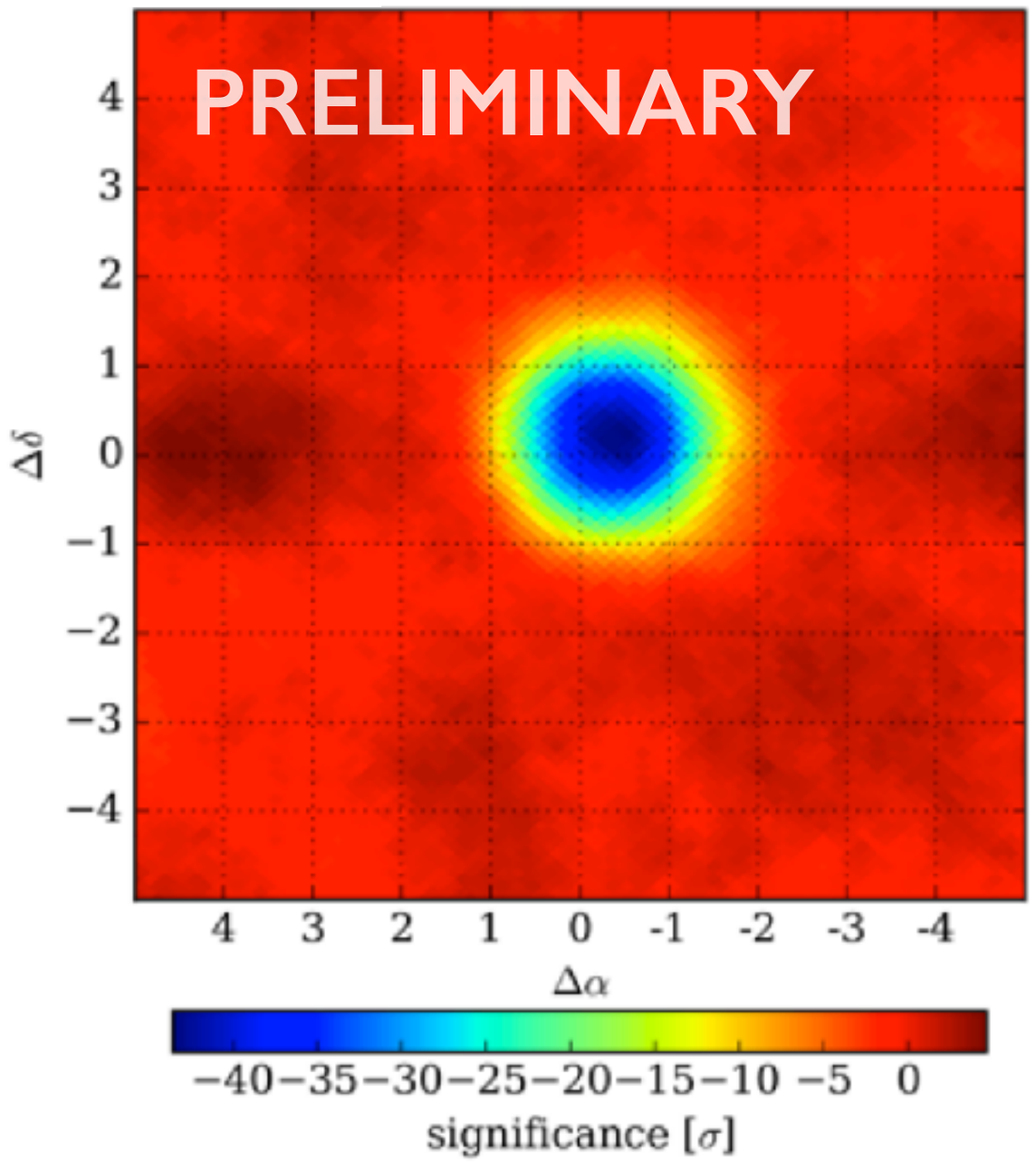


Lunar Shadow

Median Energy: 5.0 TeV

Z. Hampel-Arias
UW-Madison

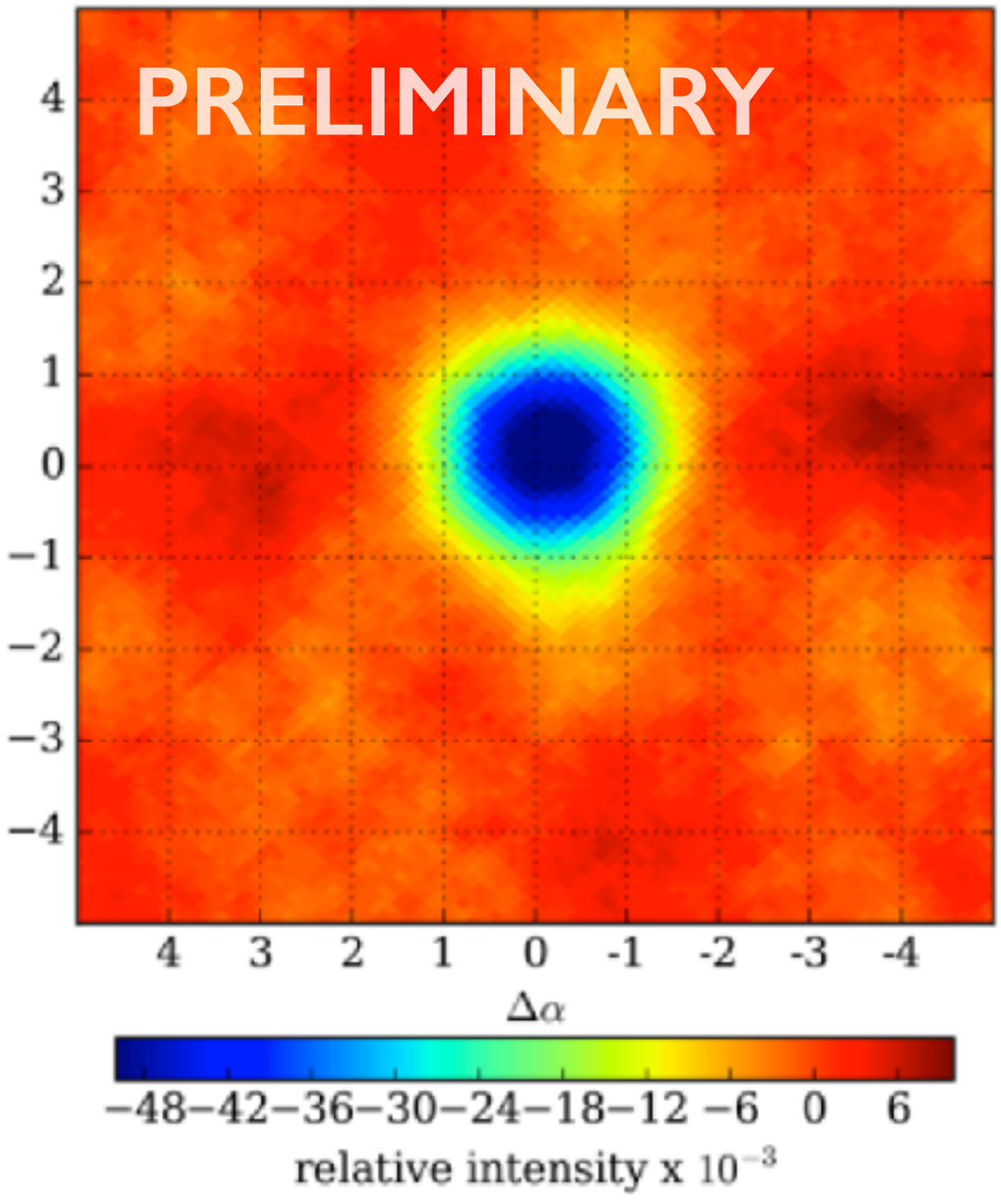


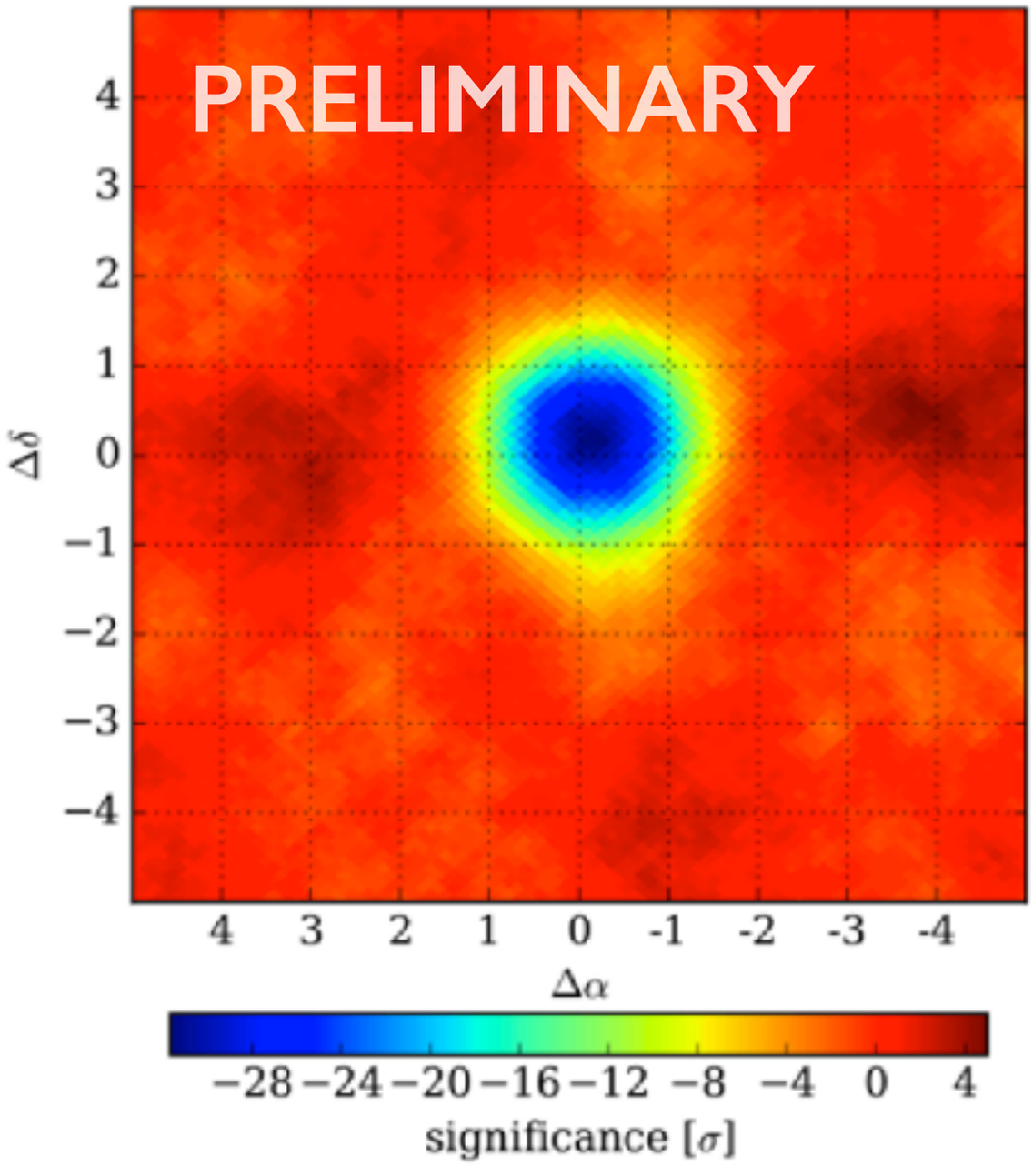


Lunar Shadow

Median Energy: 17.2 TeV

Z. Hampel-Arias
UW-Madison

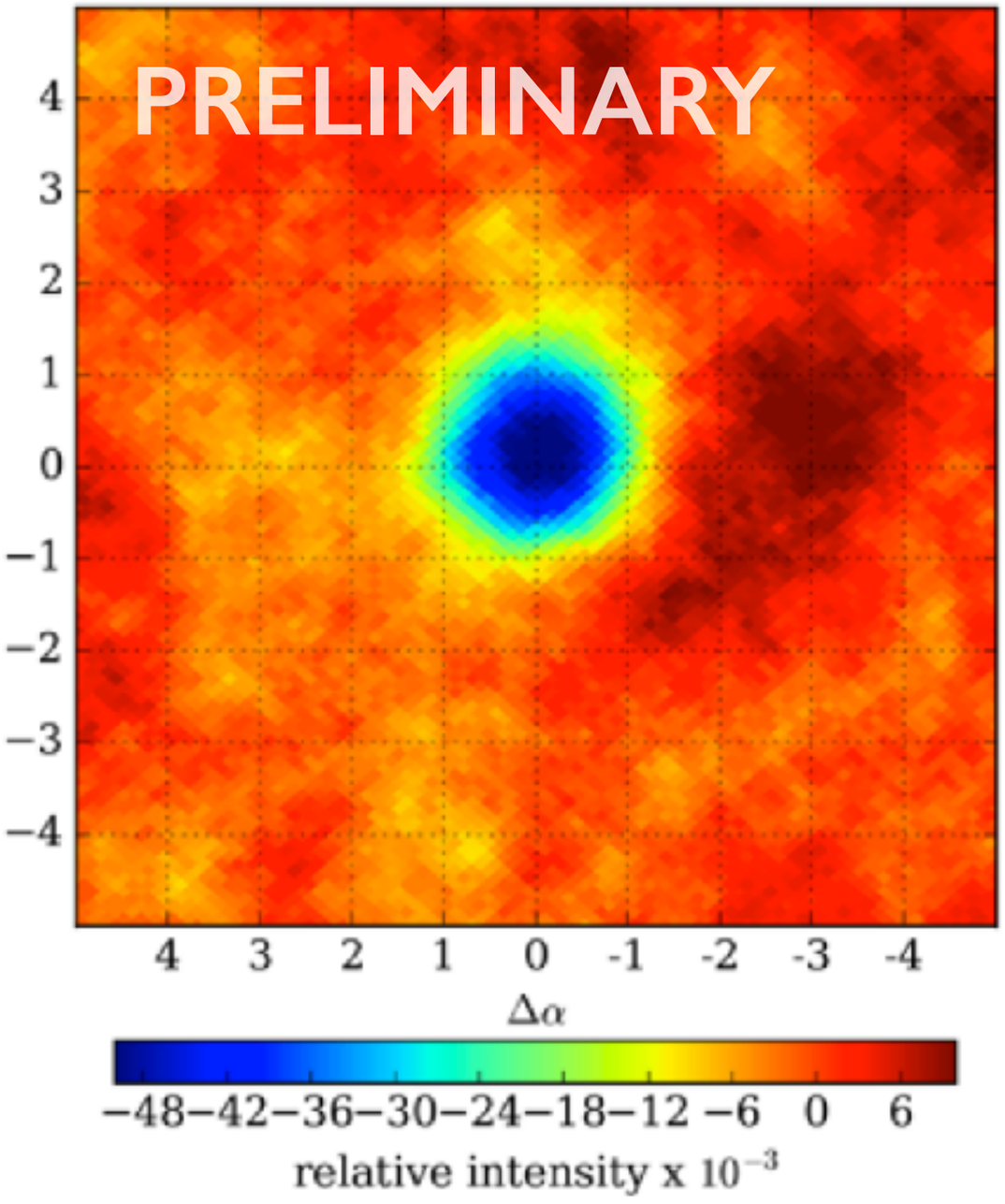


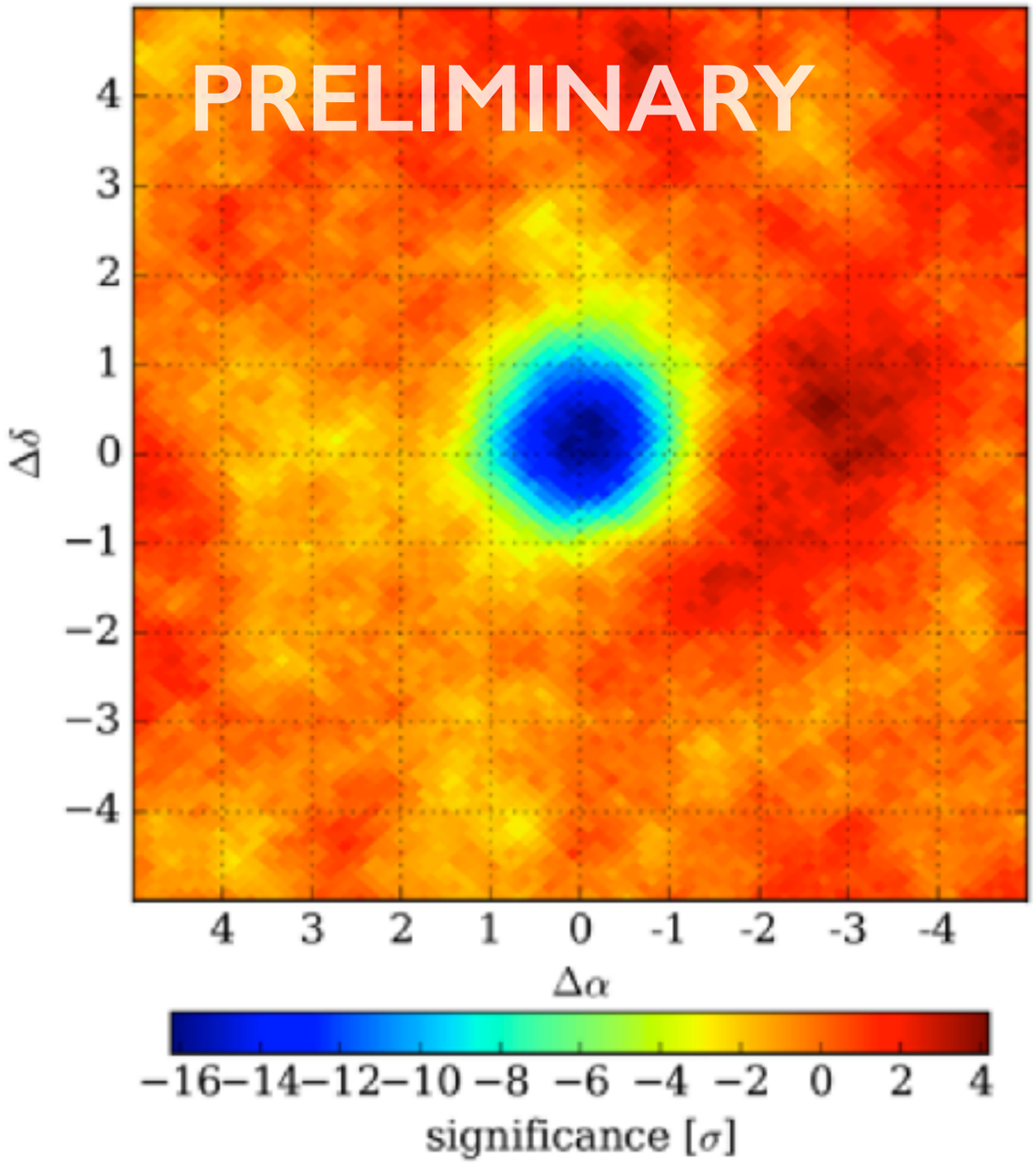


Lunar Shadow

Median Energy: 51.0 TeV

Z. Hampel-Arias
UW-Madison

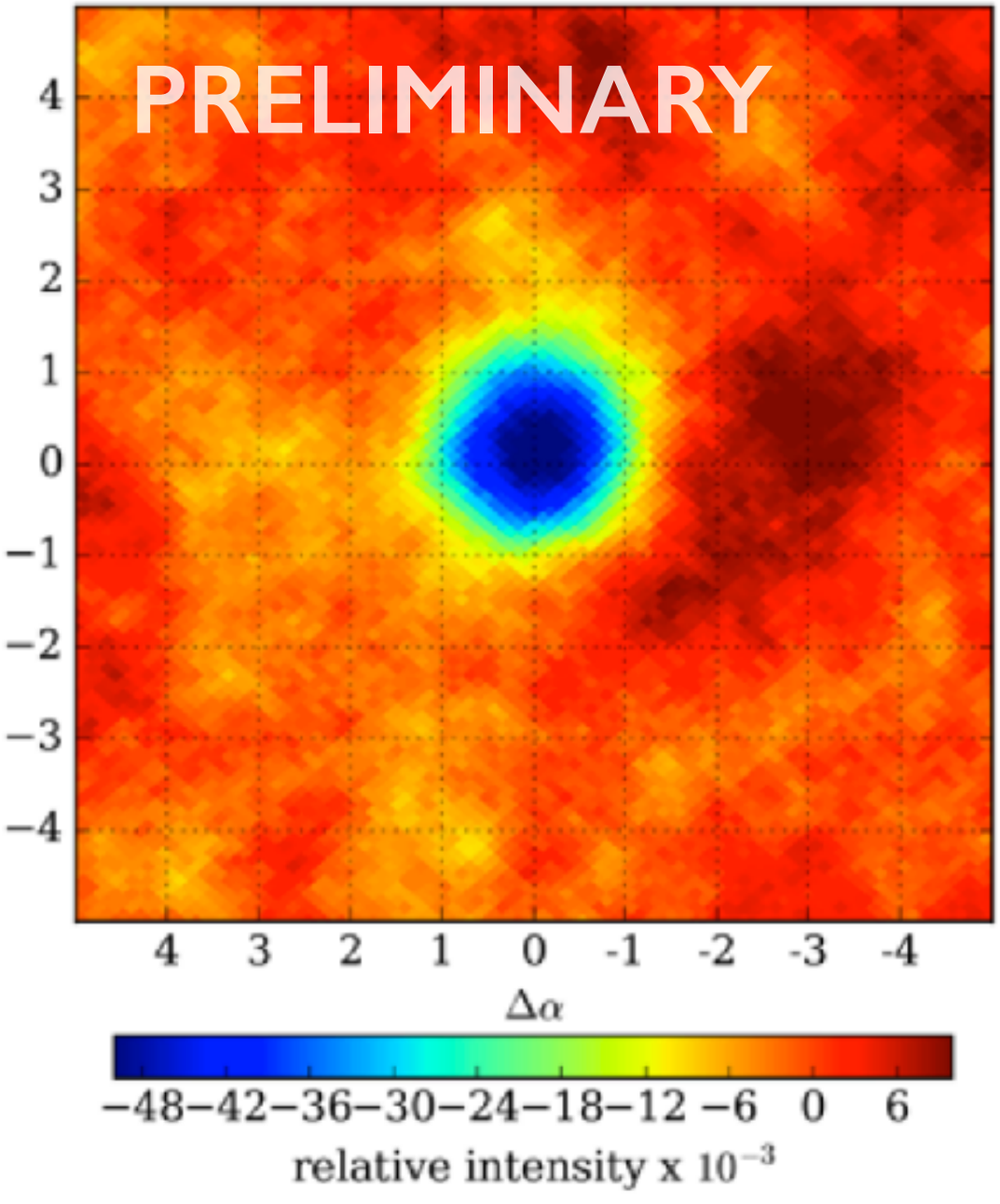


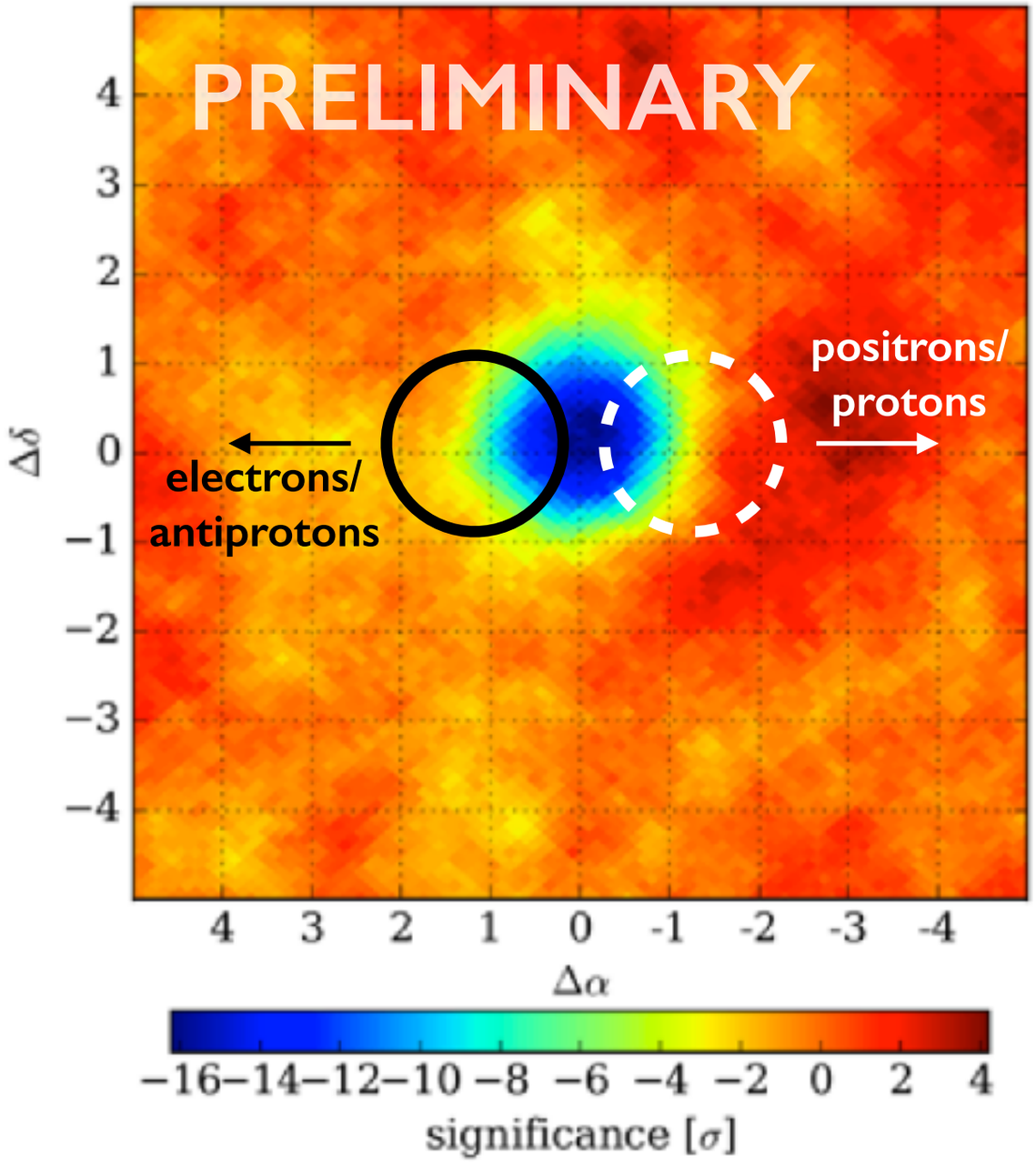


Lunar Shadow

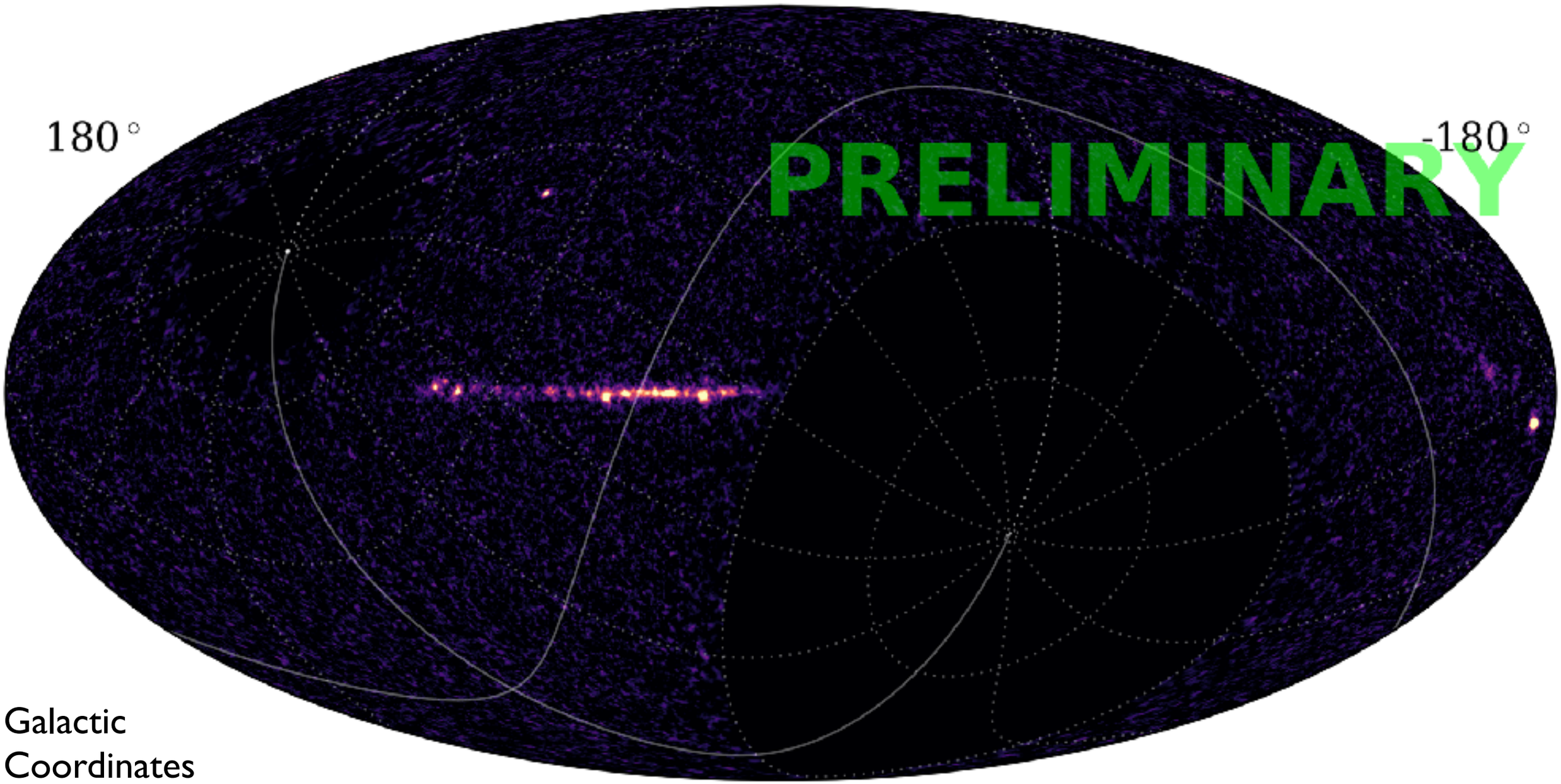
Median Energy: 51.0 TeV

Z. Hampel-Arias
UW-Madison

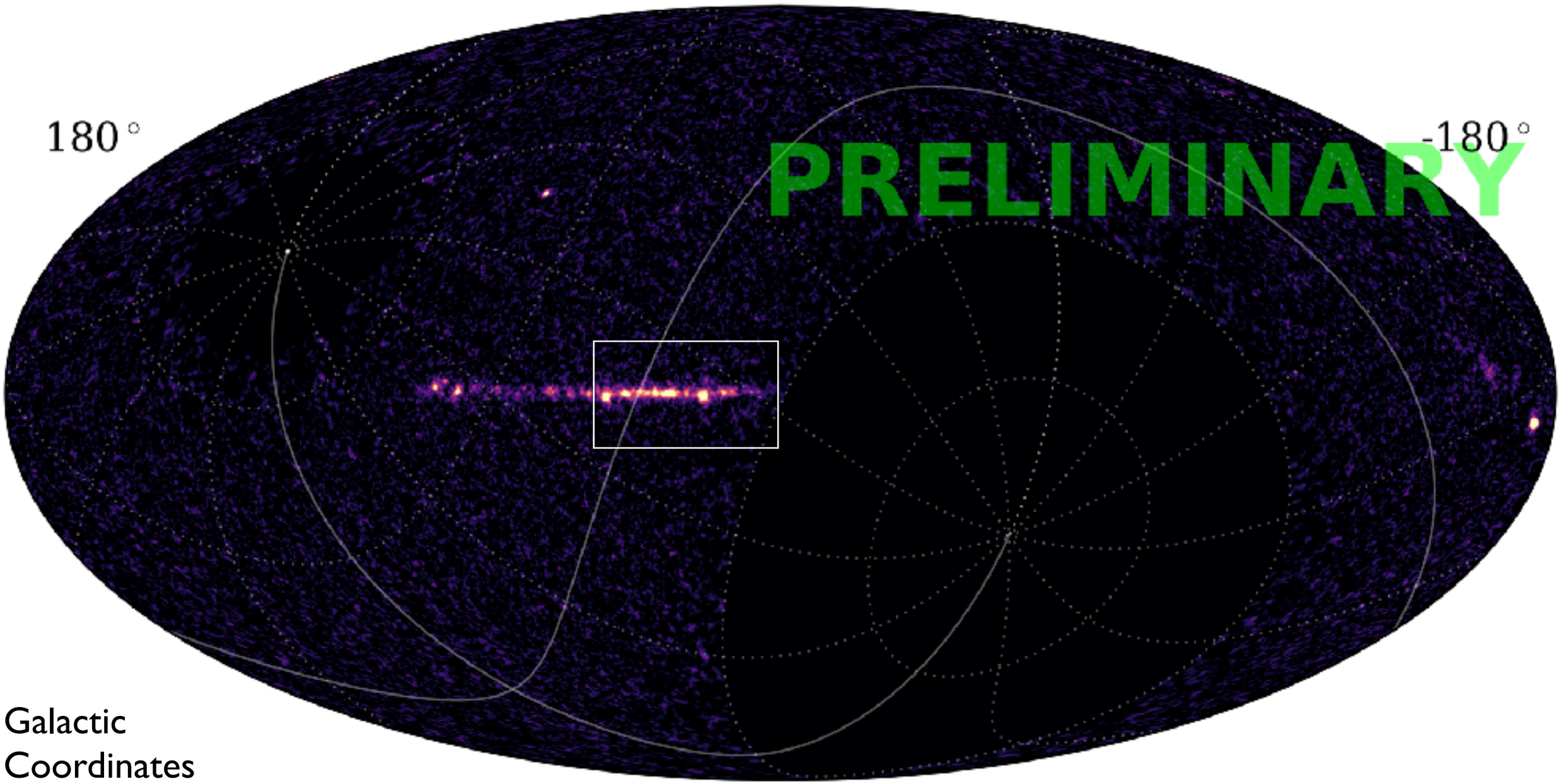




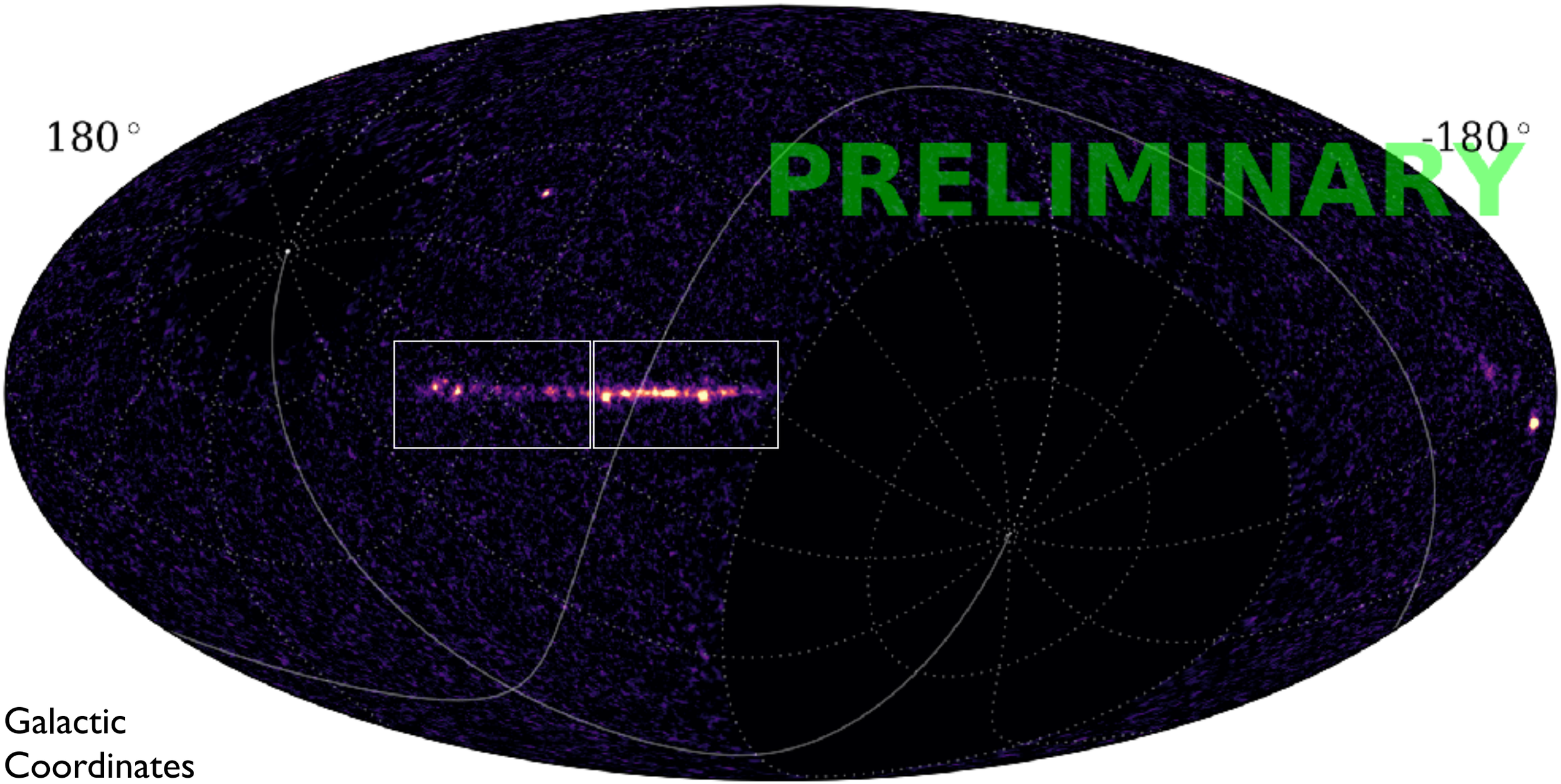
γ-Ray Observations



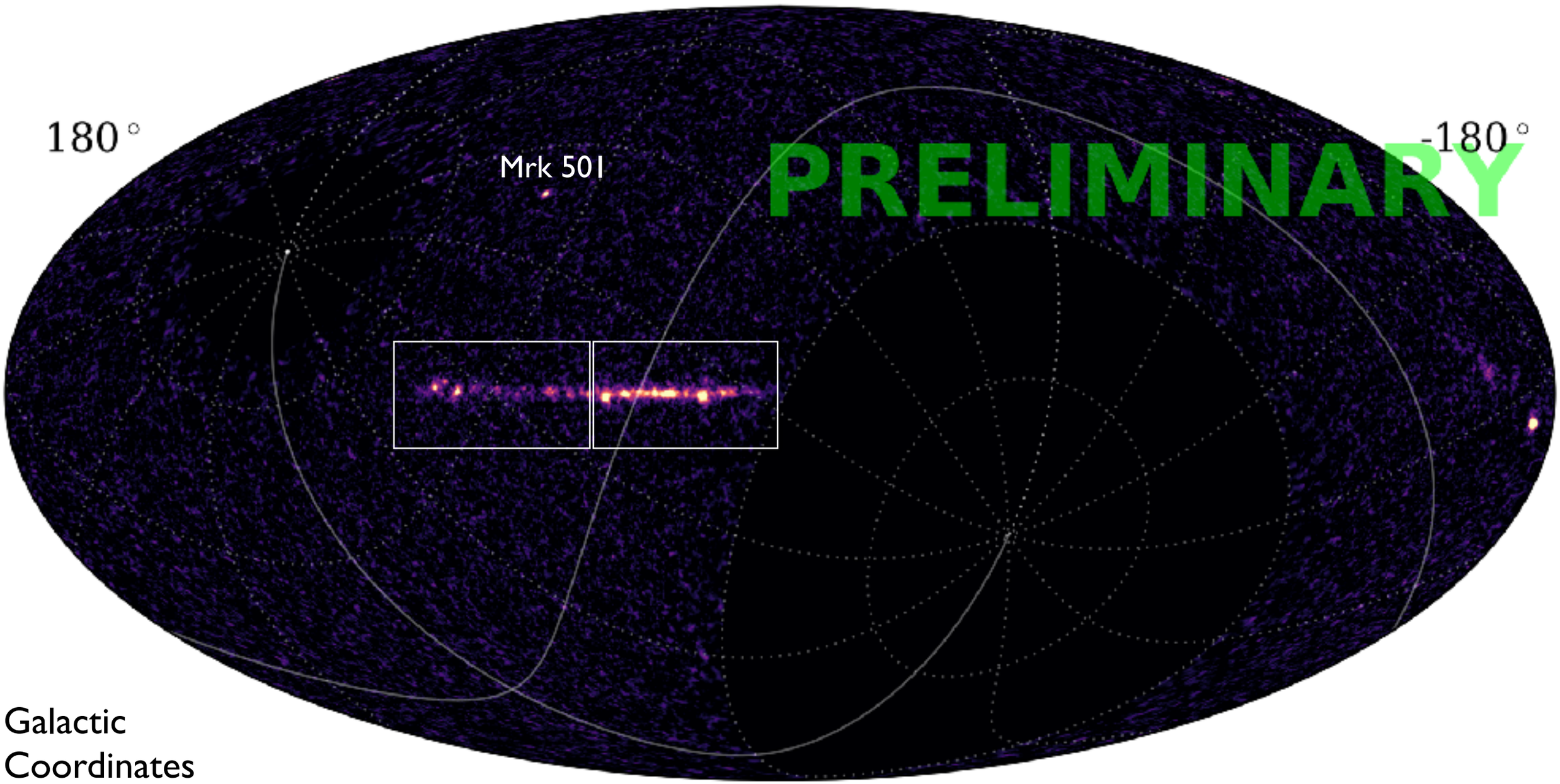
γ-Ray Observations



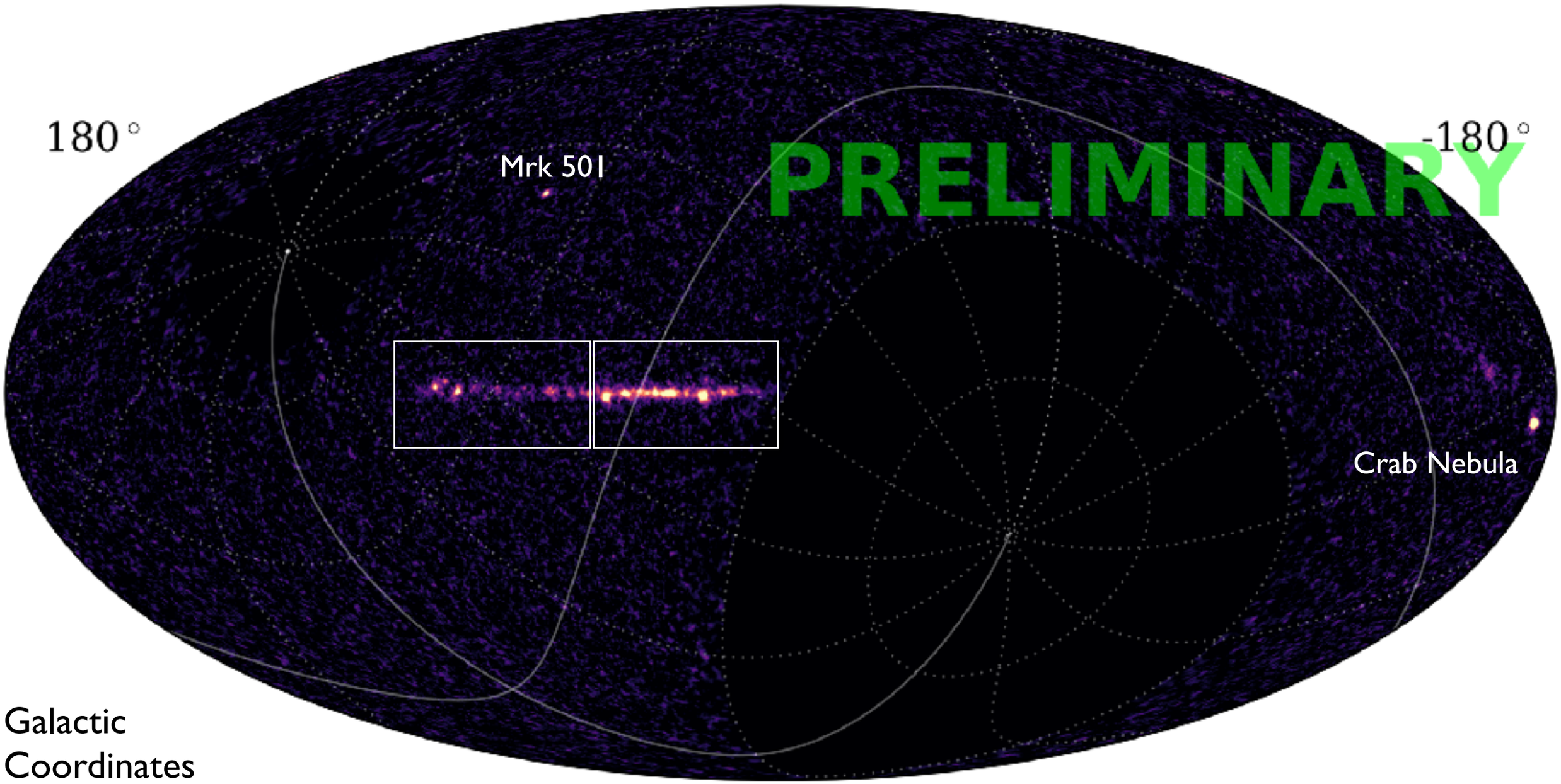
γ-Ray Observations



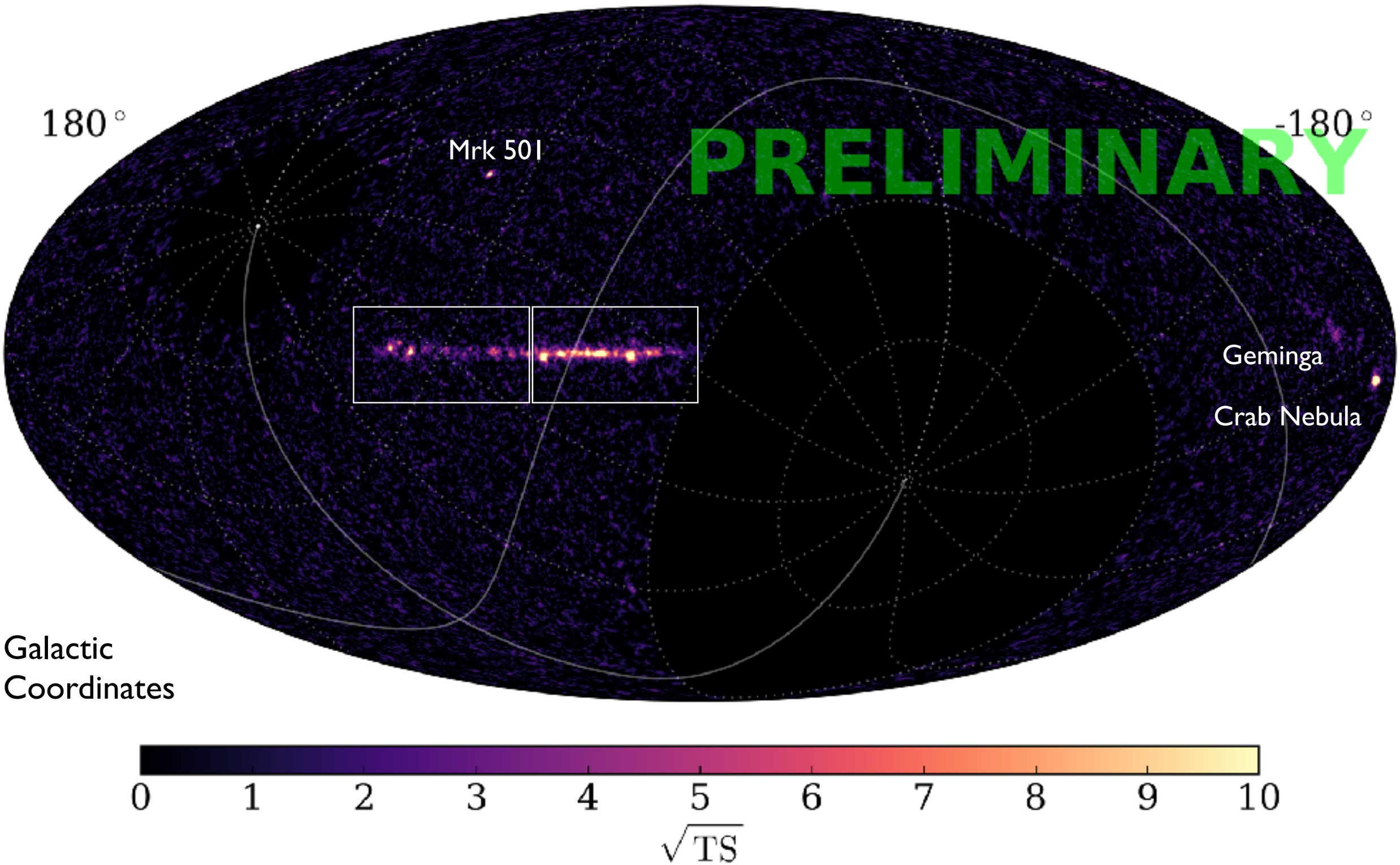
γ-Ray Observations



γ-Ray Observations



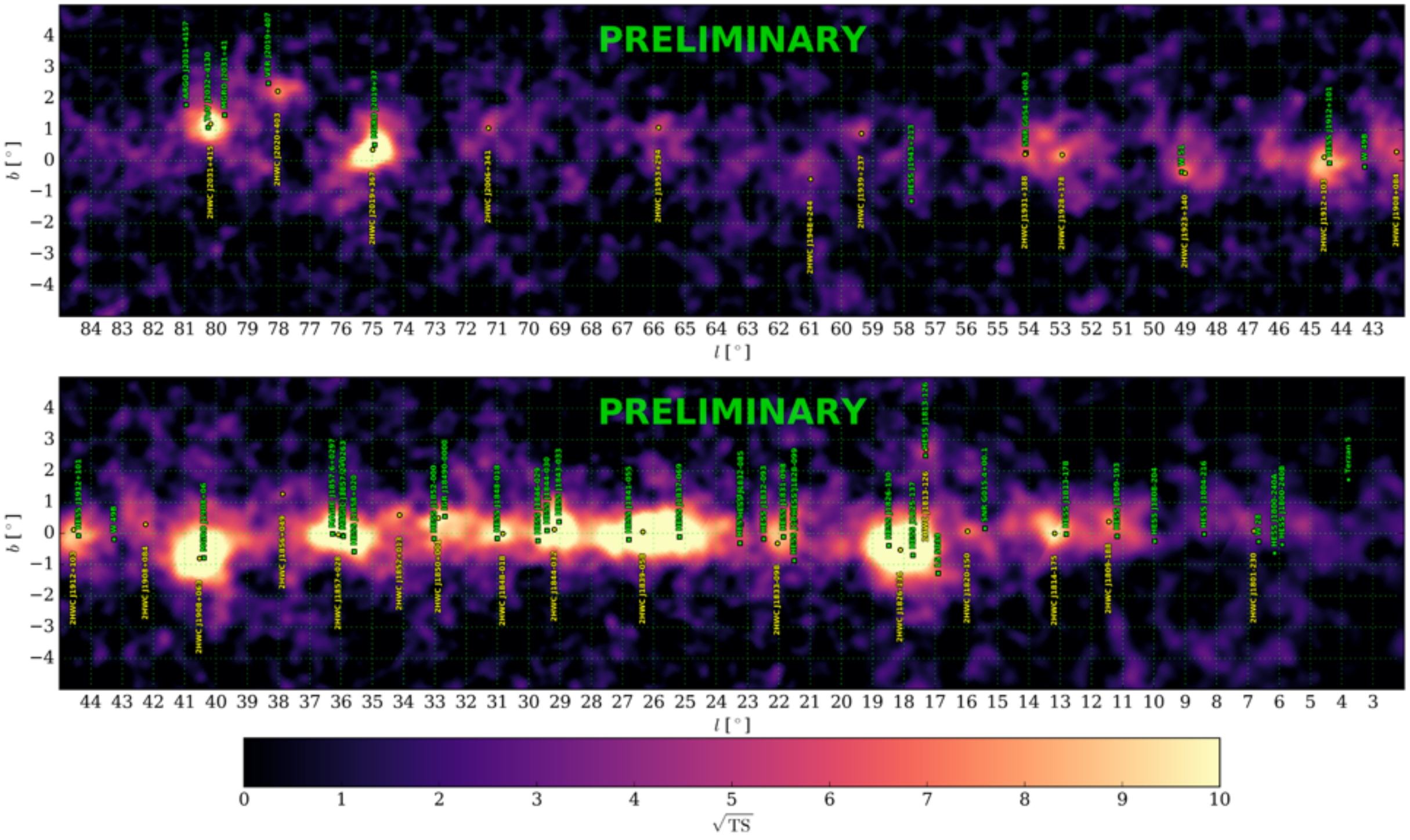
γ-Ray Observations



Galactic Plane

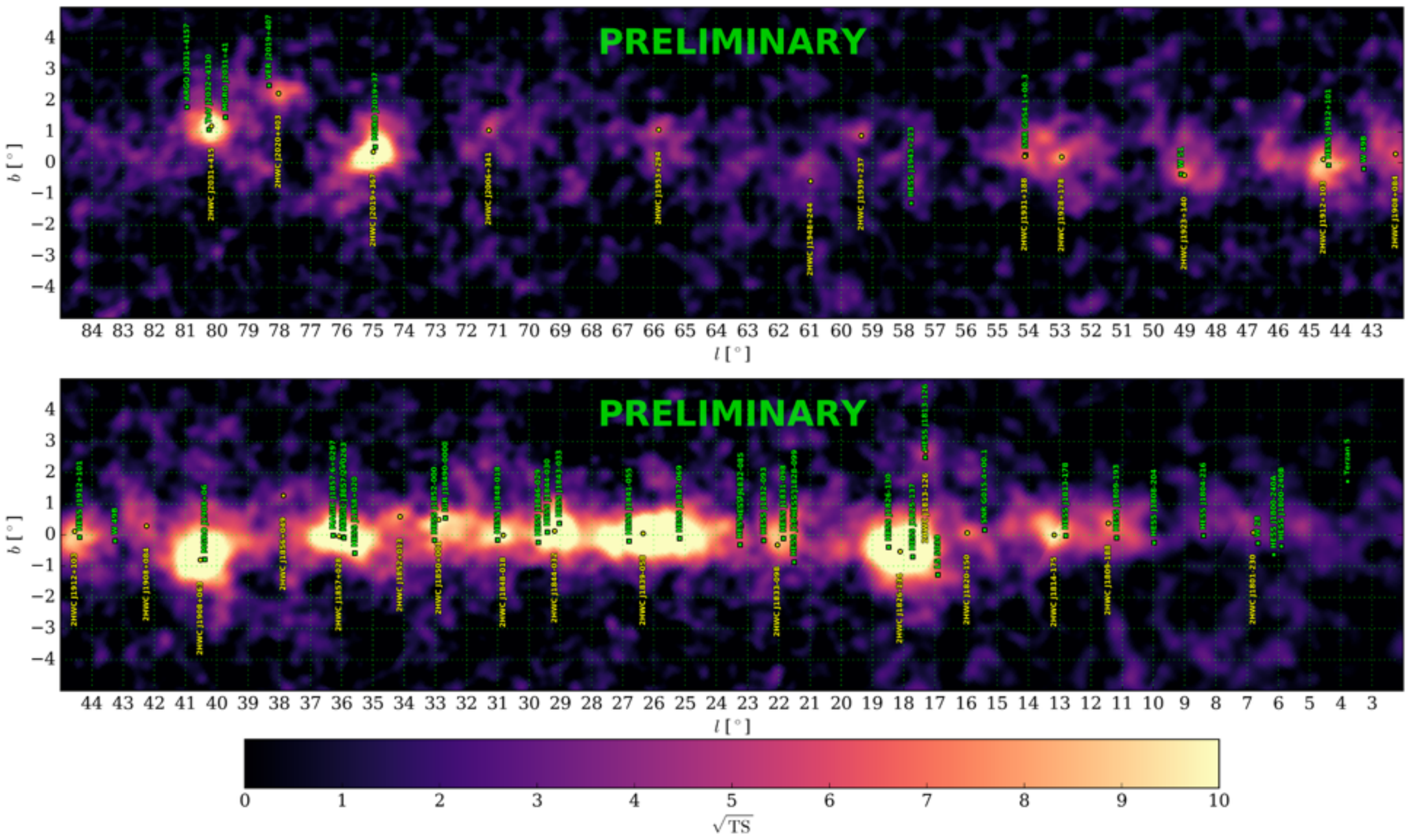
TeVCat Sources
HAWC Sources

C. Rivière, UMD



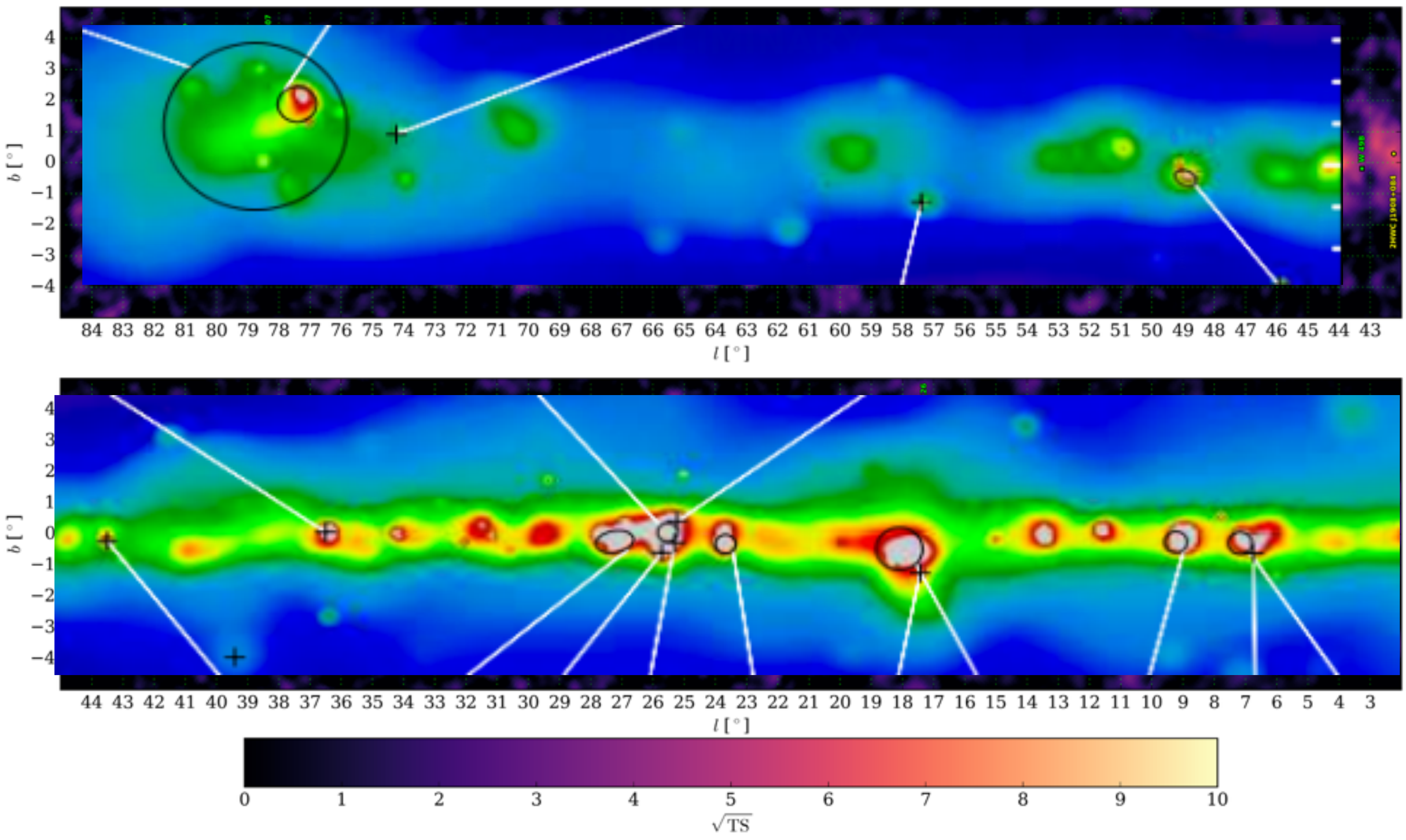
HAWC + Fermi-LAT

C. Rivière, UMD



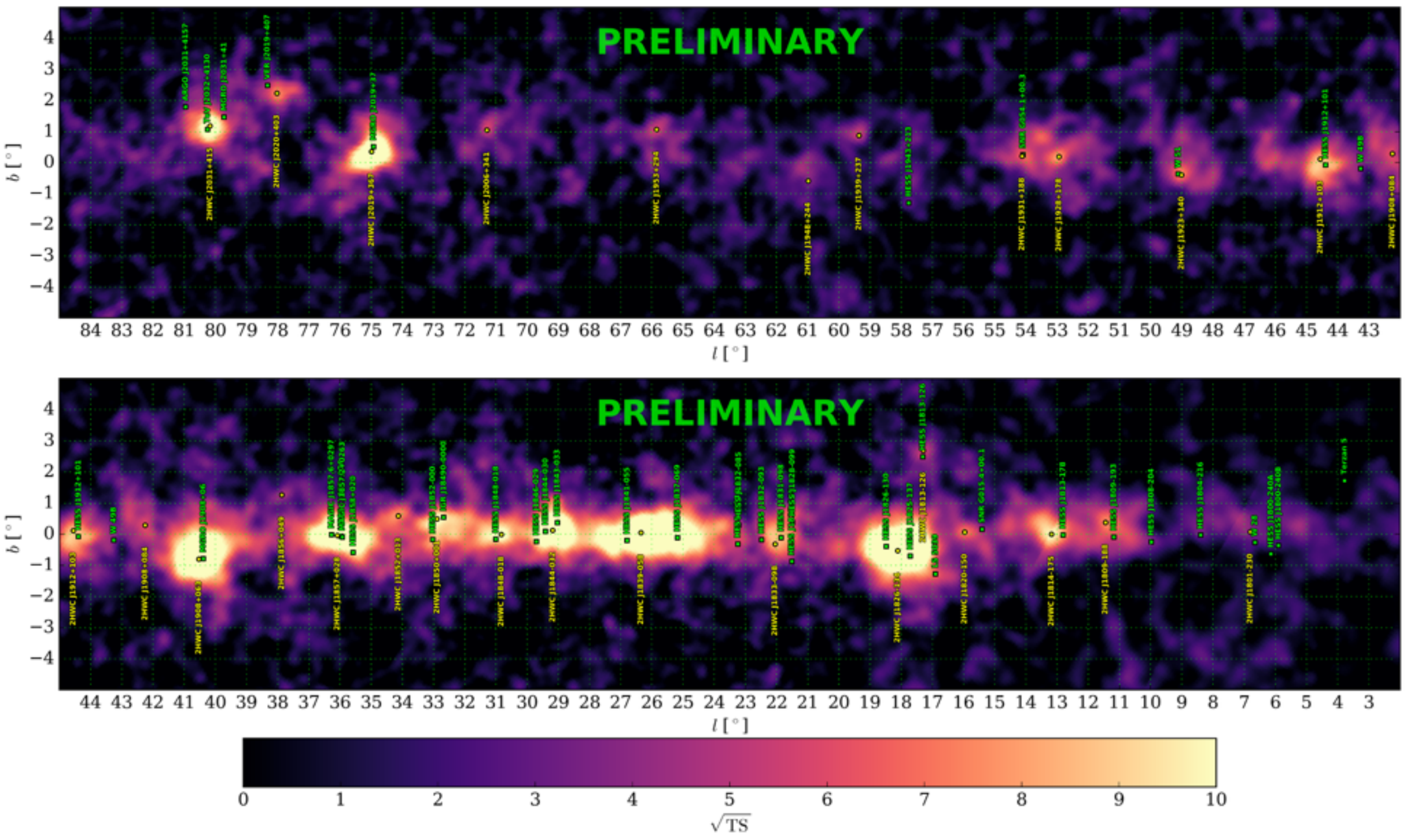
HAWC + Fermi-LAT

C. Rivière, UMD



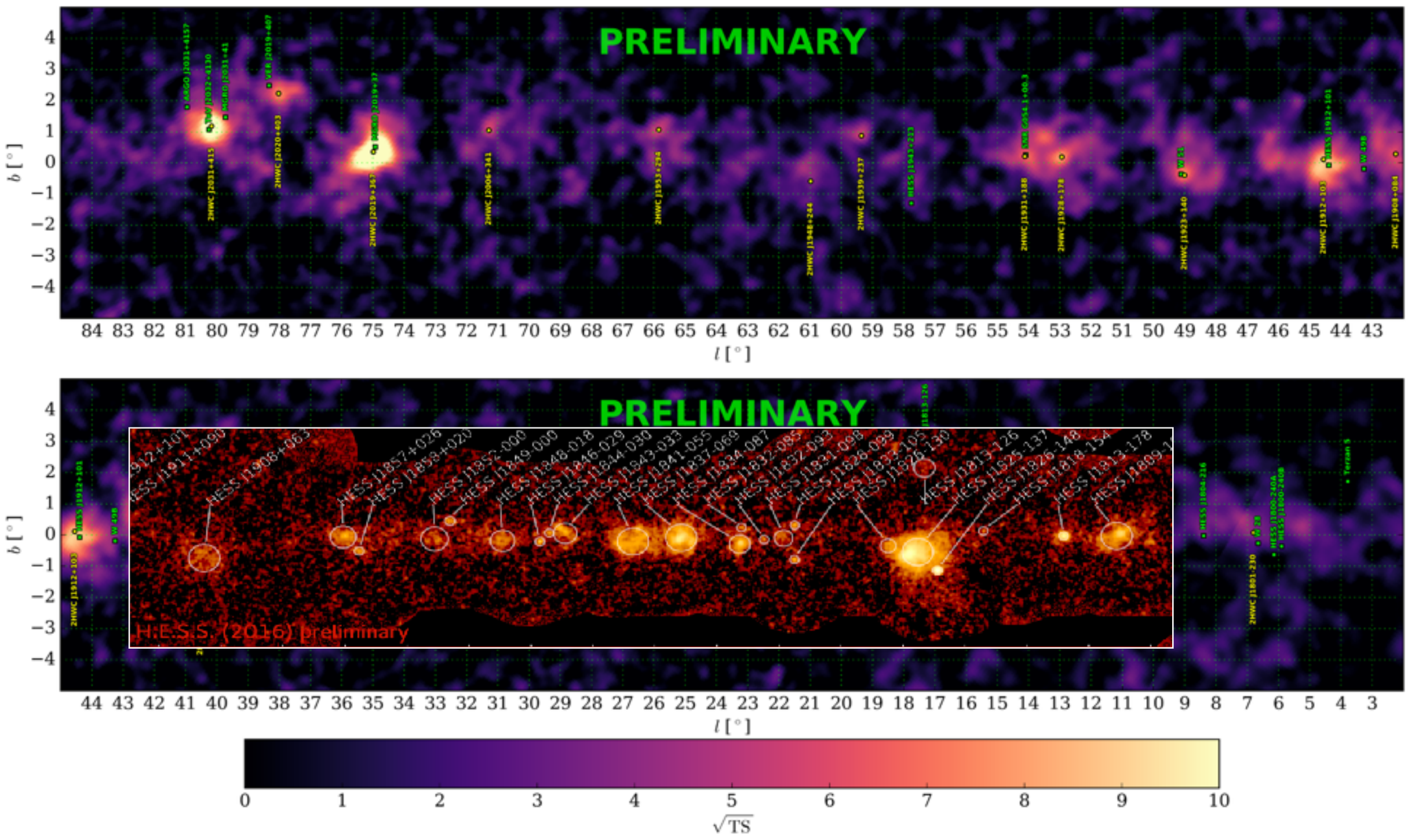
HAWC + H.E.S.S.

C. Rivière, UMD

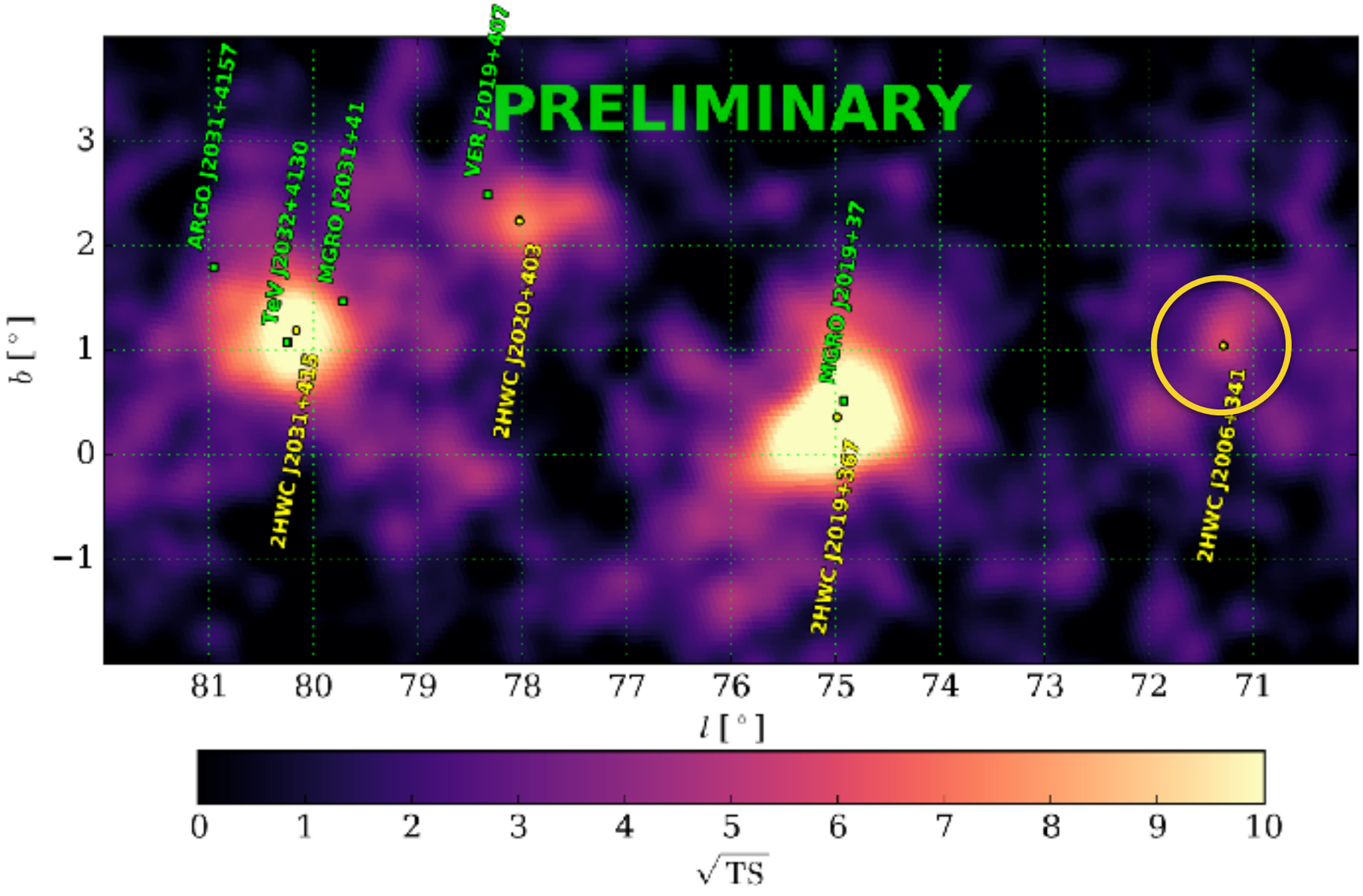


HAWC + H.E.S.S.

C. Rivière, UMD



New Sources



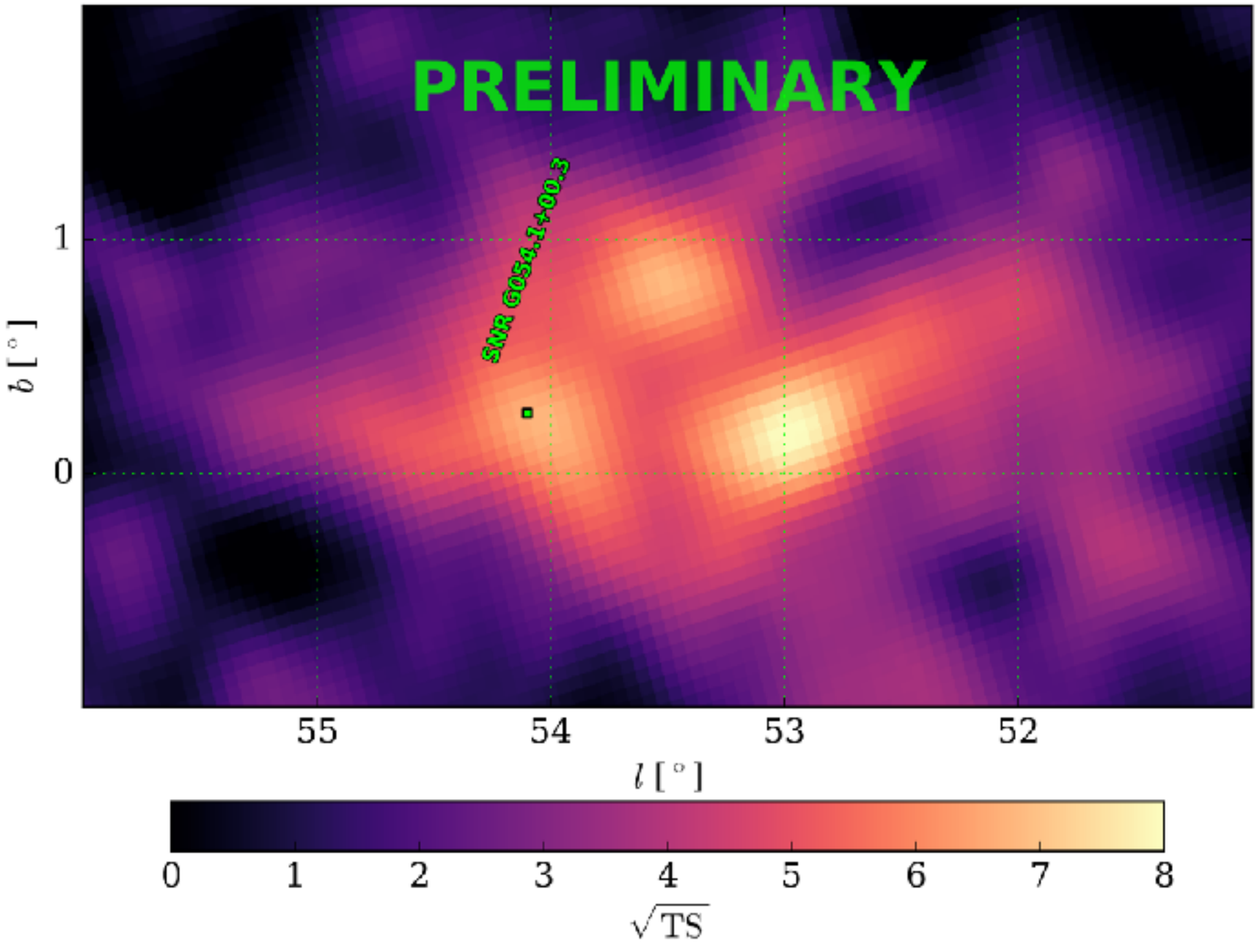
C. Rivière, UMD

Example:
2HWC J2006+341
√TS ~ 6

0.6° from UID source
3FGL J2004.4+3338

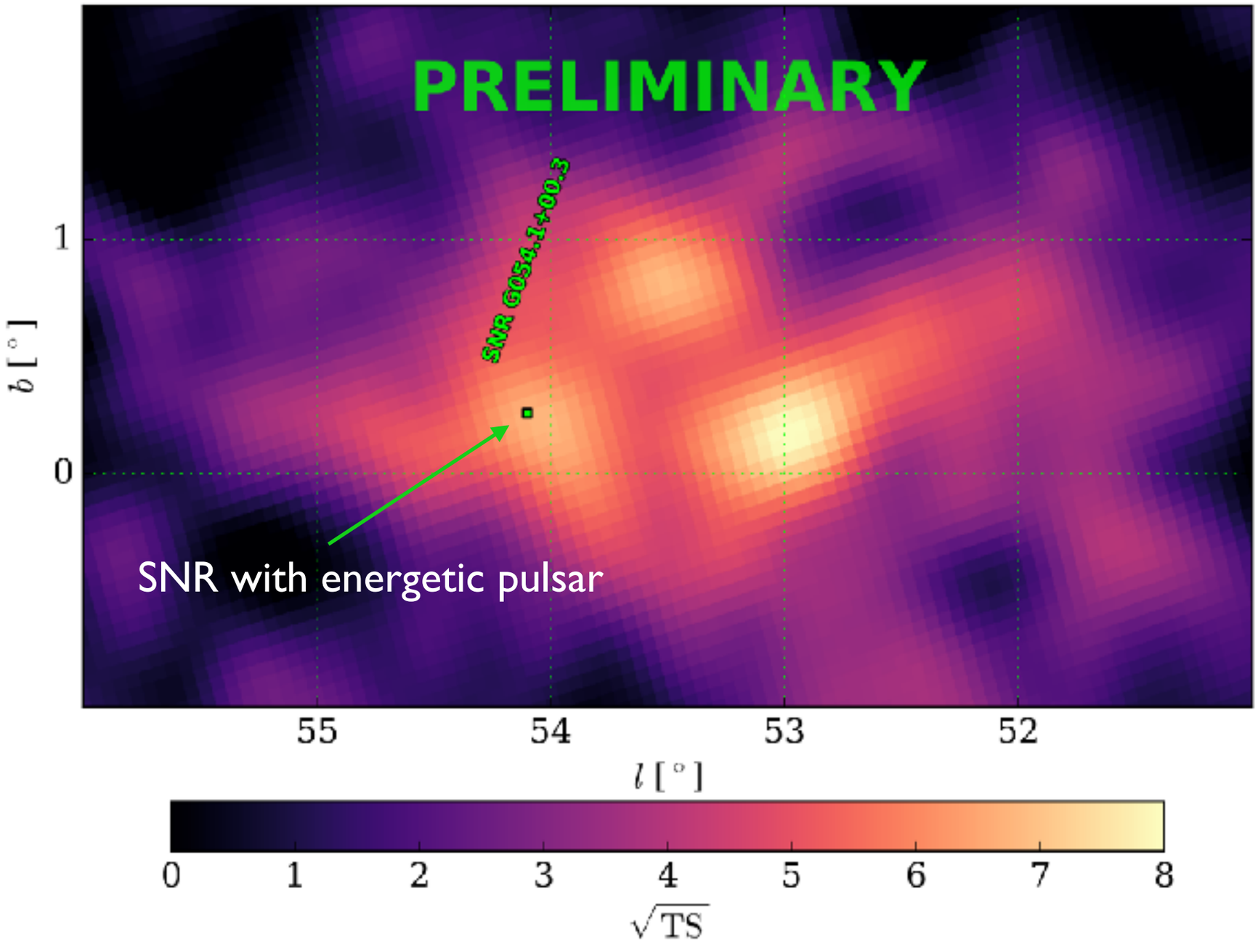
- Several new source candidates with no TeV counterpart; multiwavelength studies by IACTs in progress
- Note: 5σ post-trials corresponds to √TS ~ 7

Examples: New Sources



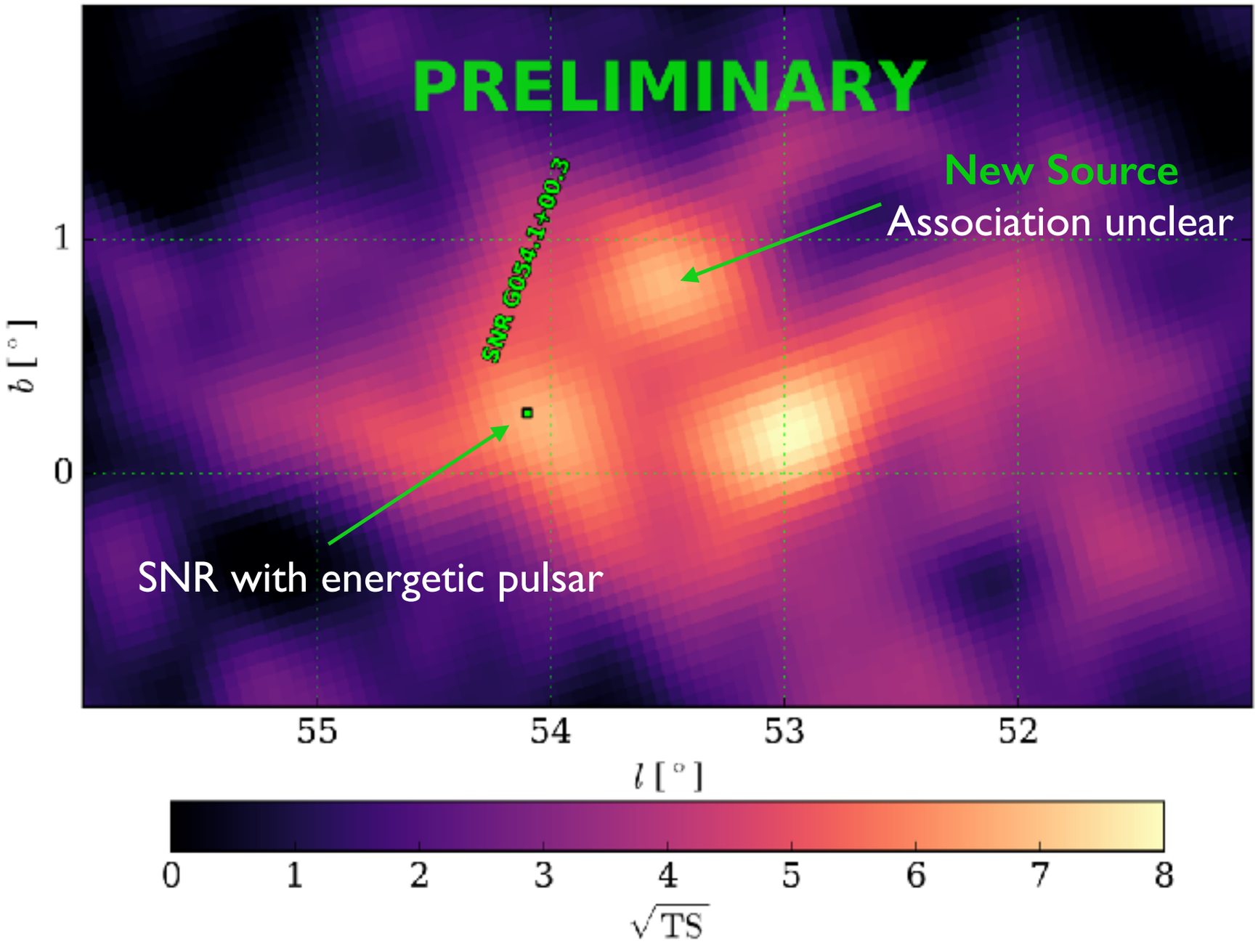
- Preliminary catalog shared with MoU partners. Paper in progress

Examples: New Sources



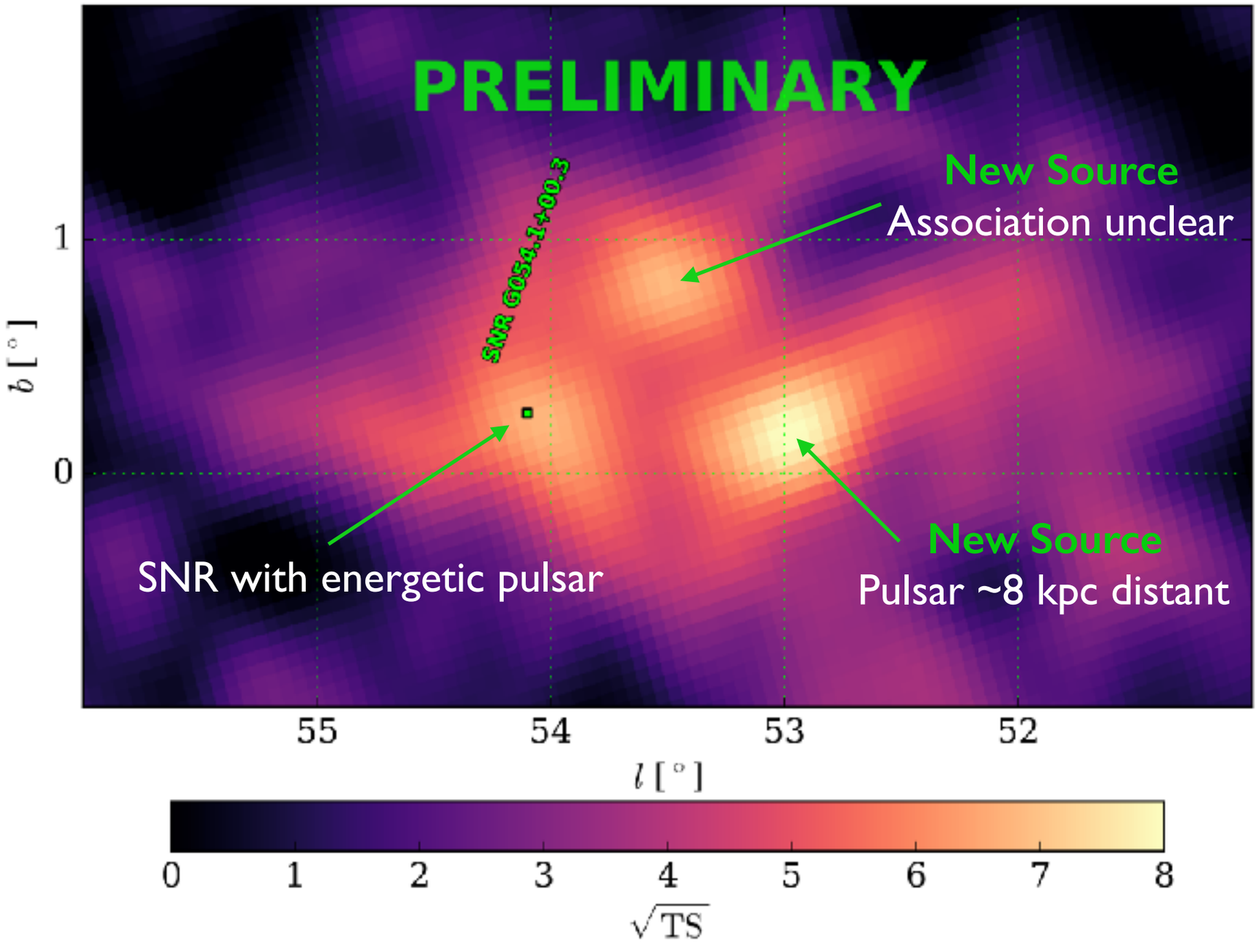
- Preliminary catalog shared with MoU partners. Paper in progress

Examples: New Sources



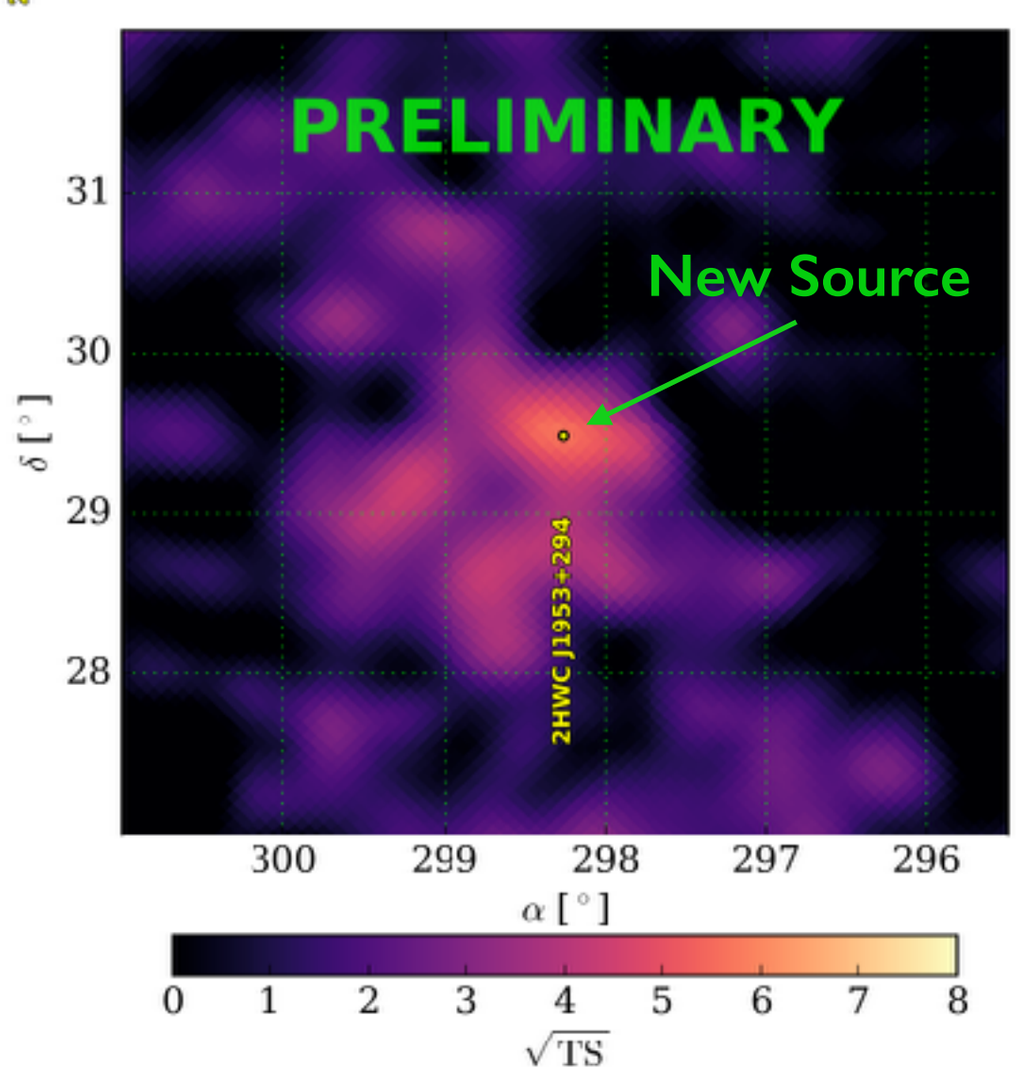
- Preliminary catalog shared with MoU partners. Paper in progress

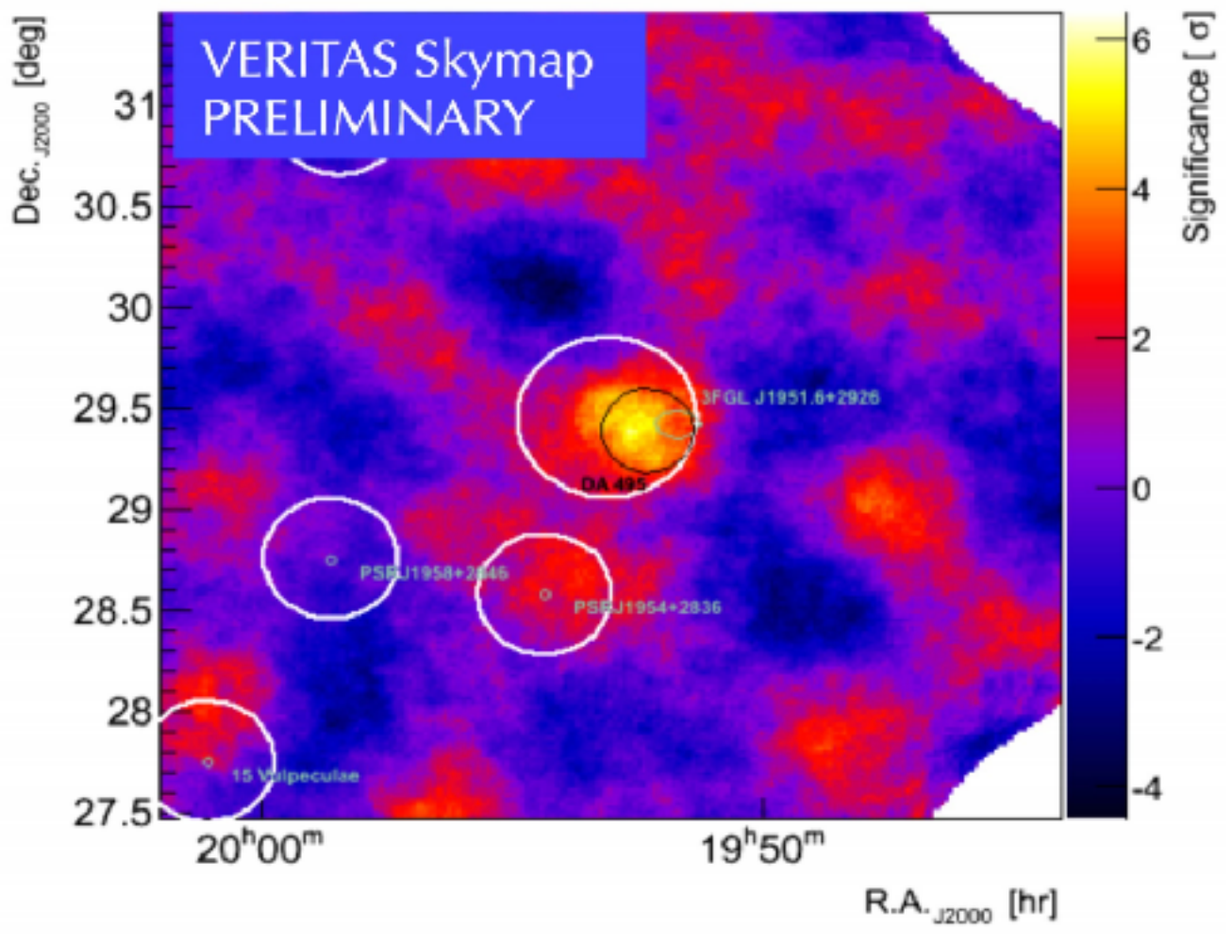
Examples: New Sources



- Preliminary catalog shared with MoU partners. Paper in progress

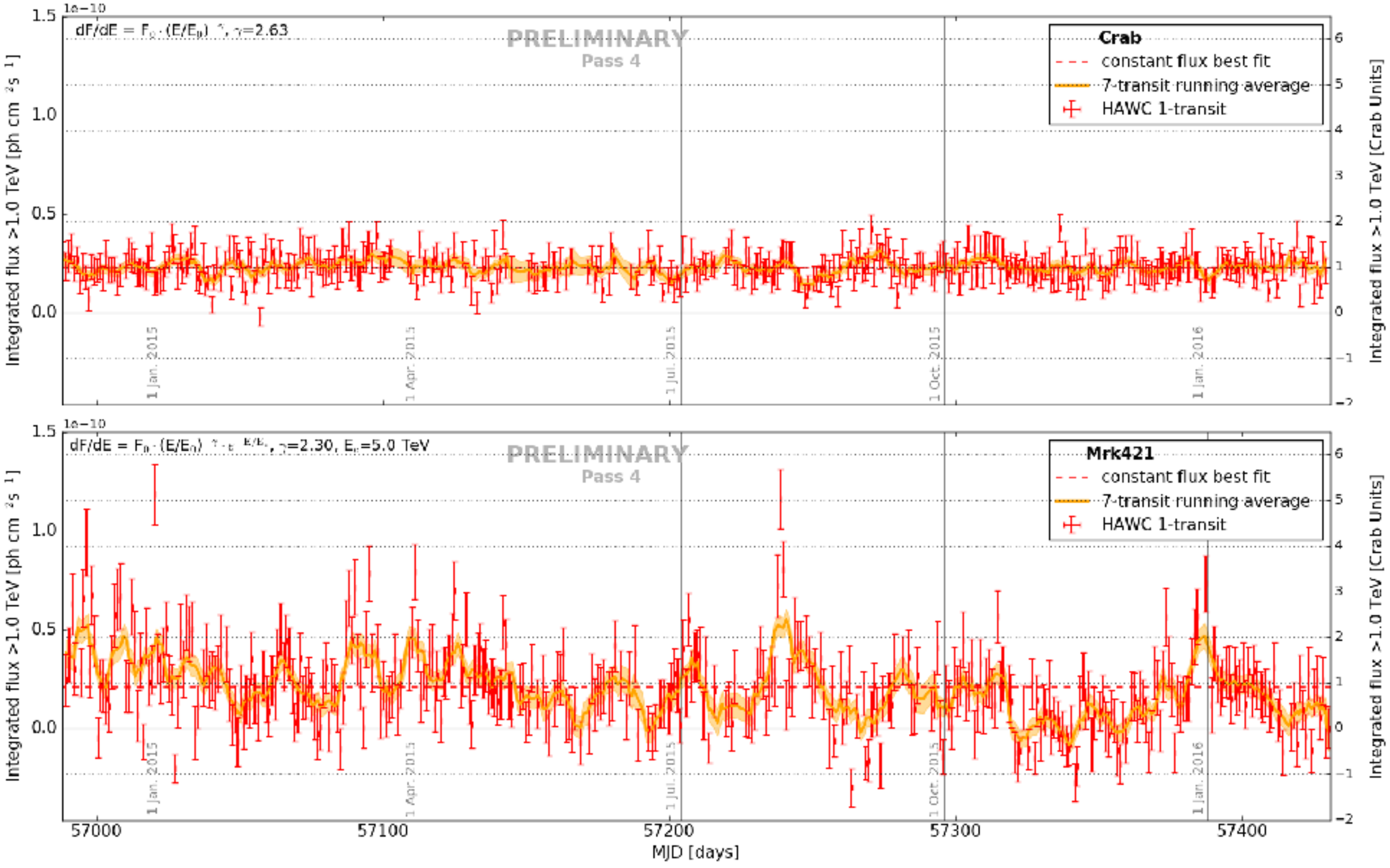
Examples: New Sources



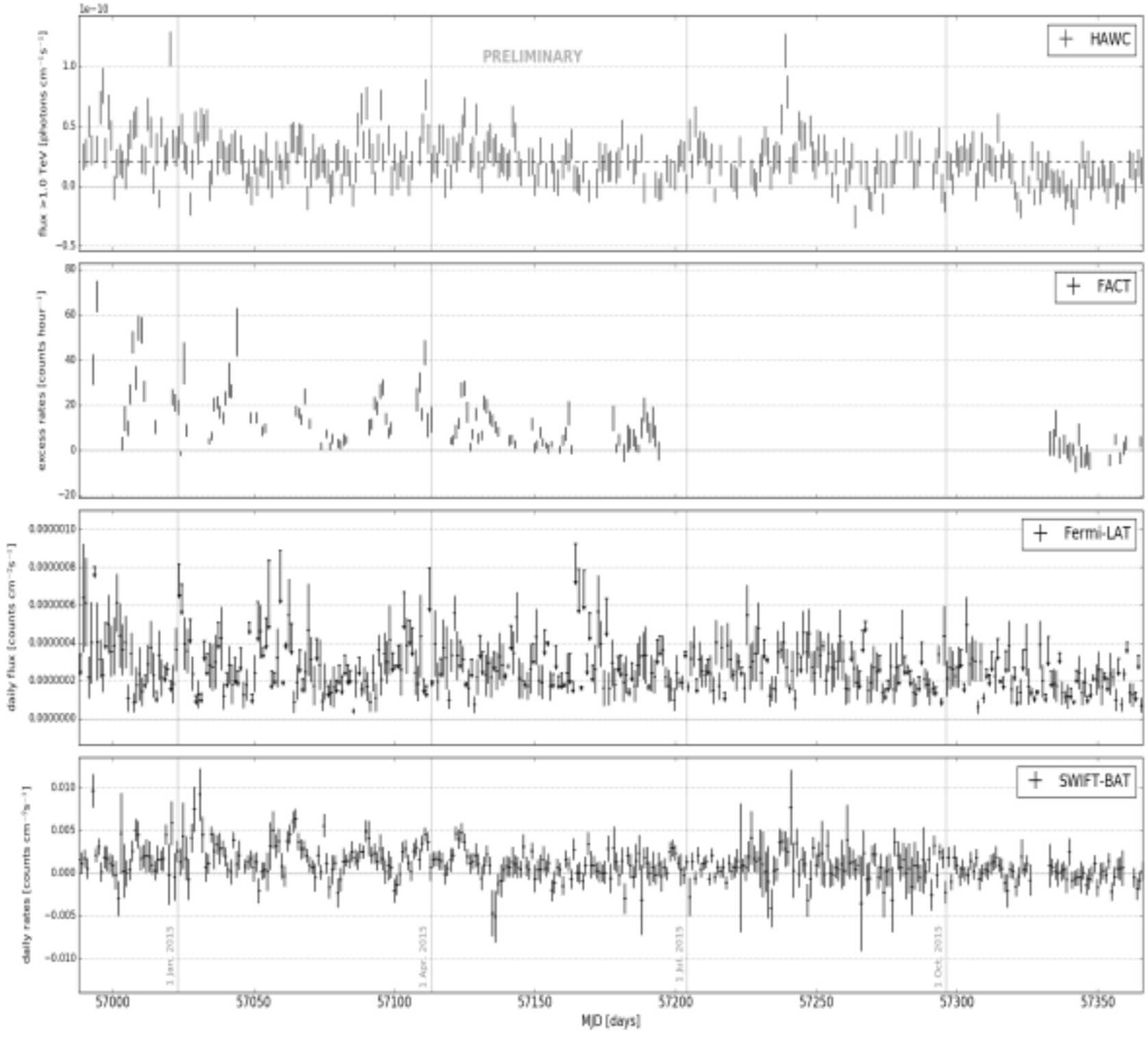


- Previously unknown source, followed up with VERITAS and confirmed with archival data + new observations
- Tentatively associated with 3FGL J1951.6+2926

Steady and Transient Emission



Daily Monitoring of Sources



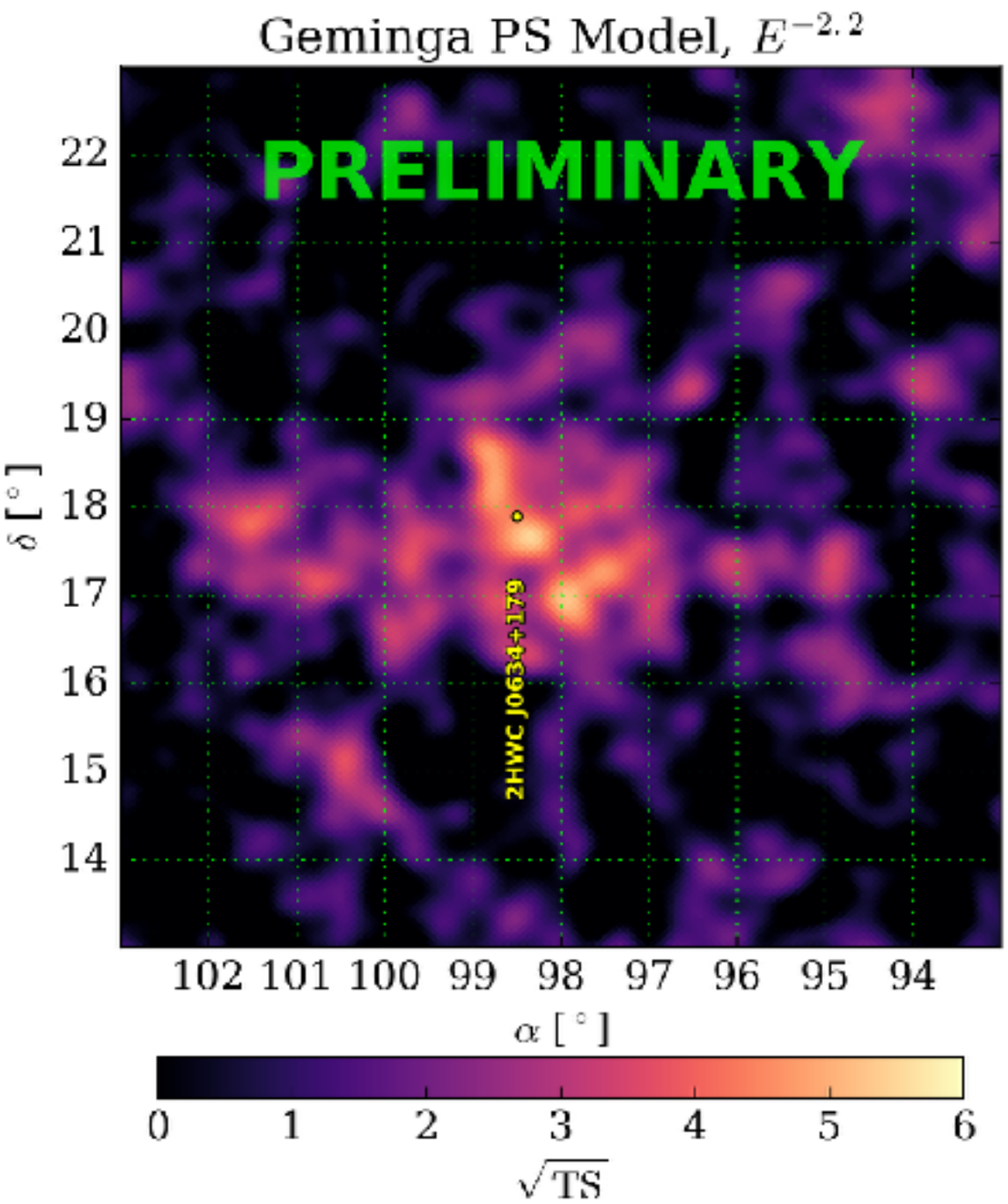
HAWC

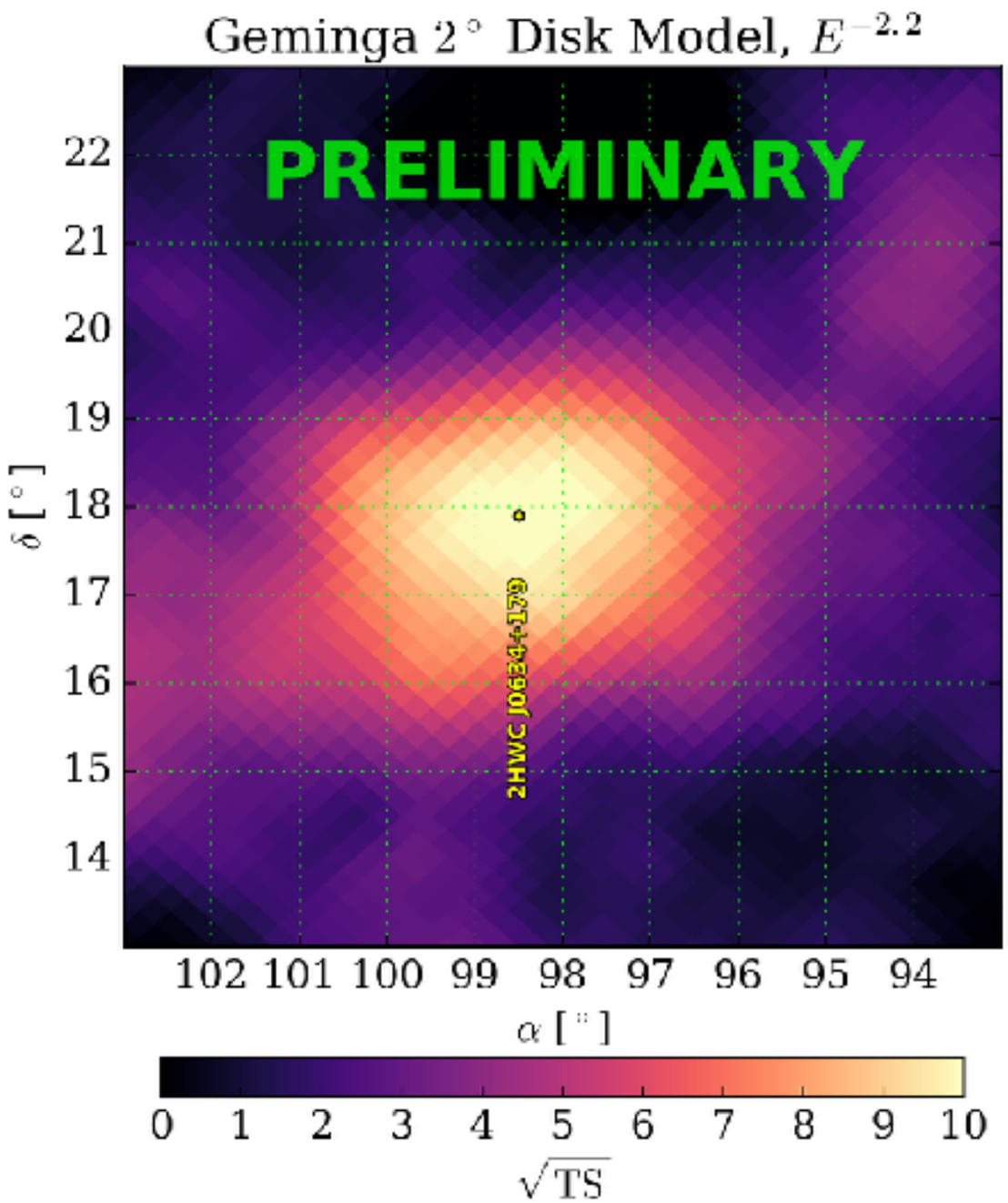
FACT

Fermi-LAT

SWIFT-BAT

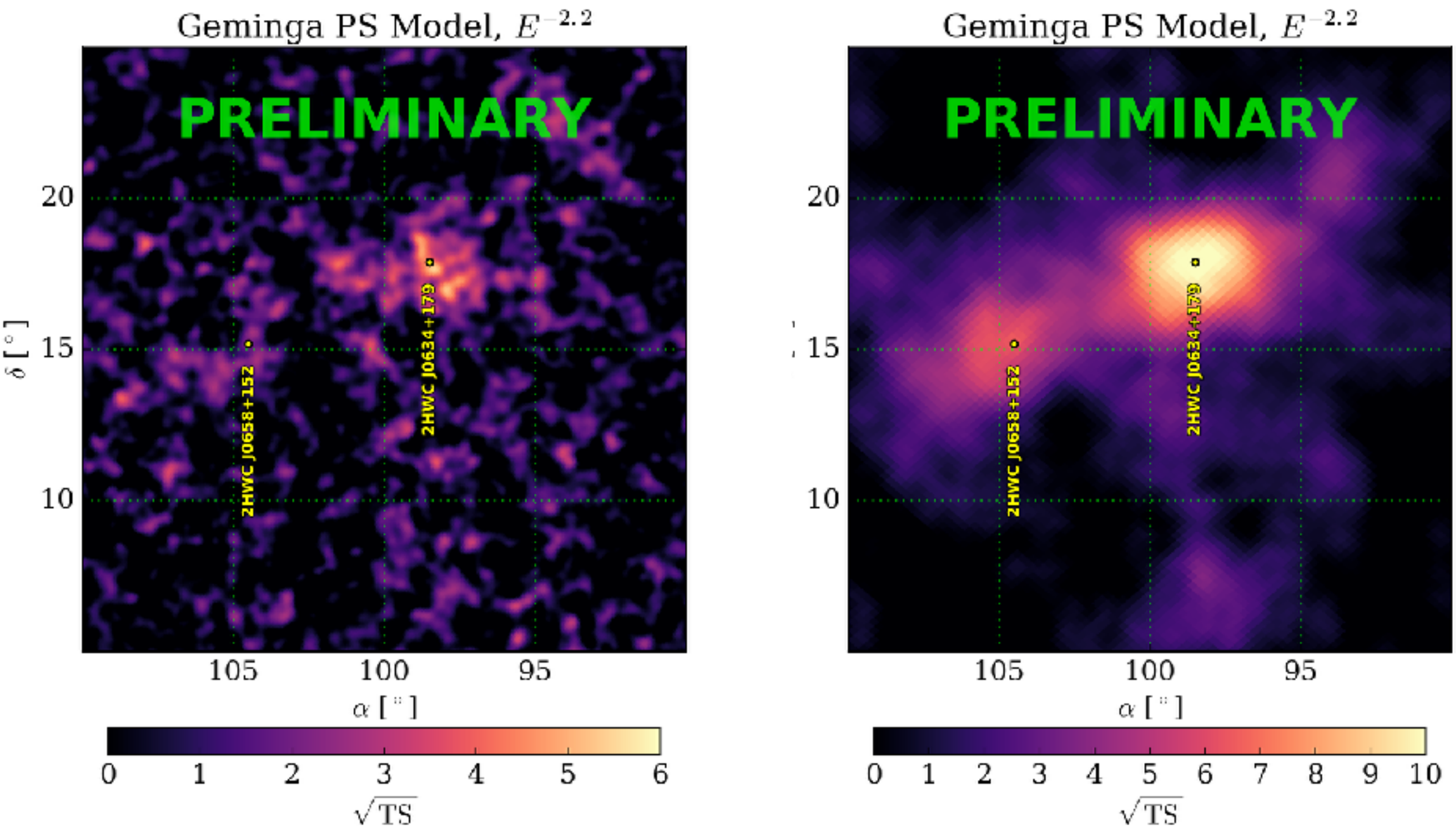
Spatially Extended Emission





P. Salesa-Greus, IFJ-PAN

Geminga and PSR J0659+14

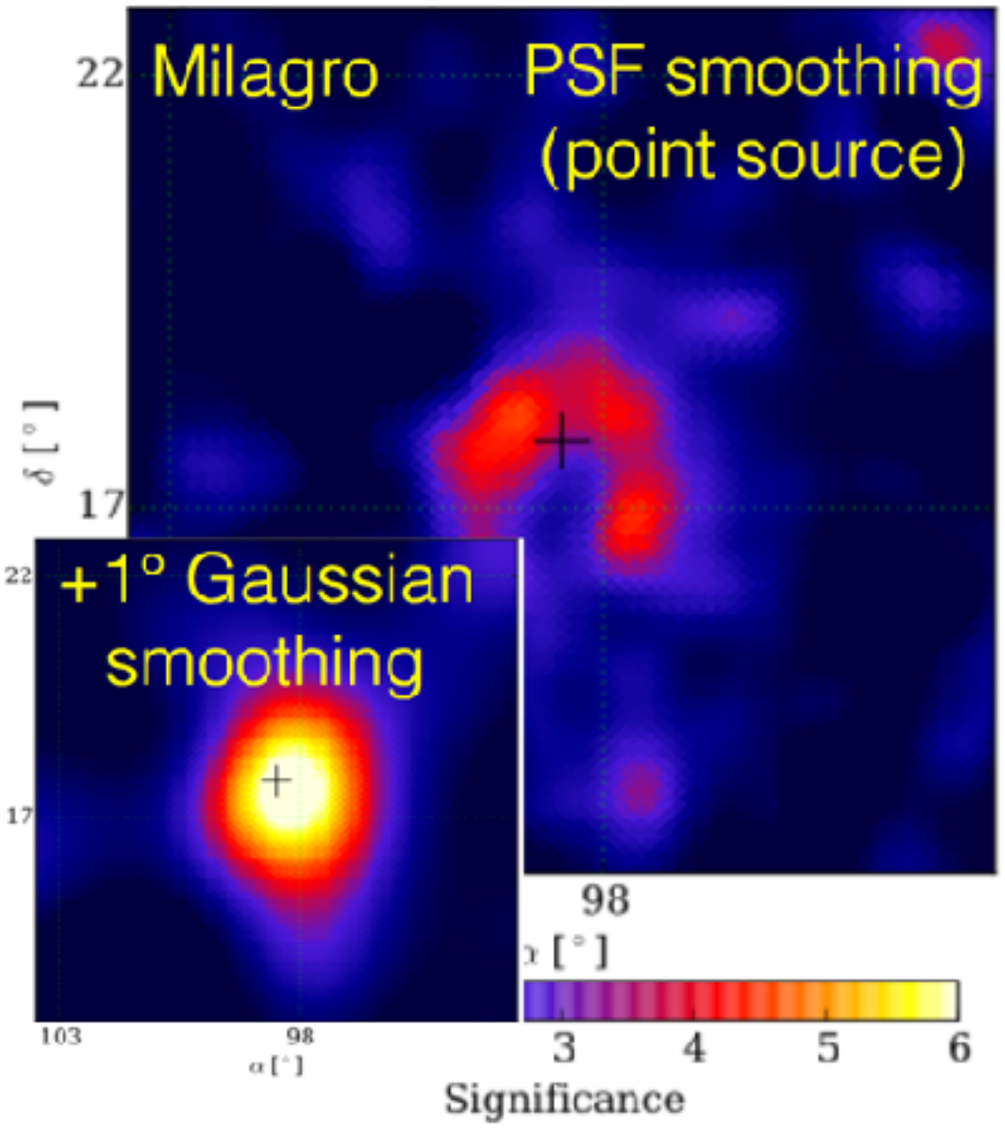


P. Salesa-Greus, IFJ-PAN

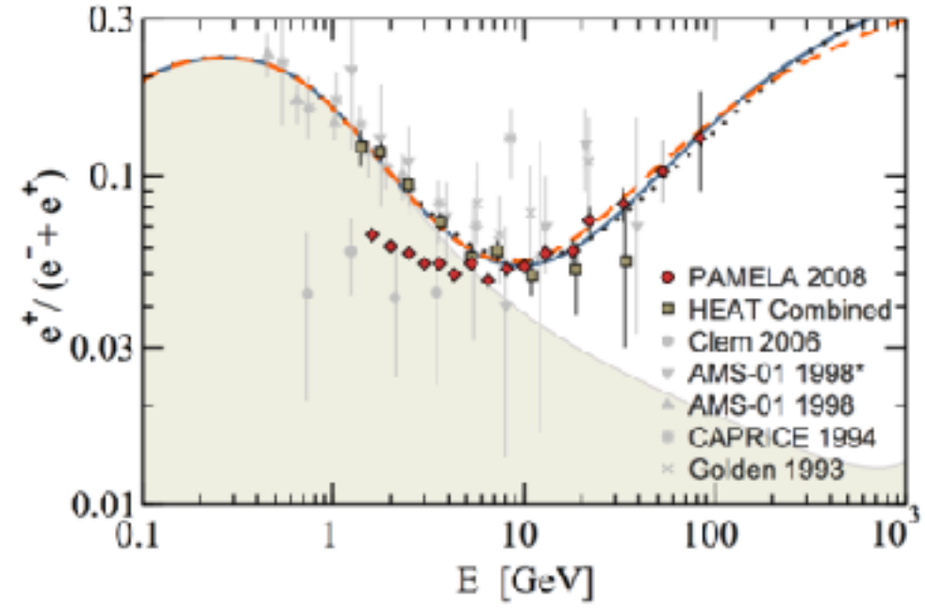
Indirect Measurement of e^+e^-?

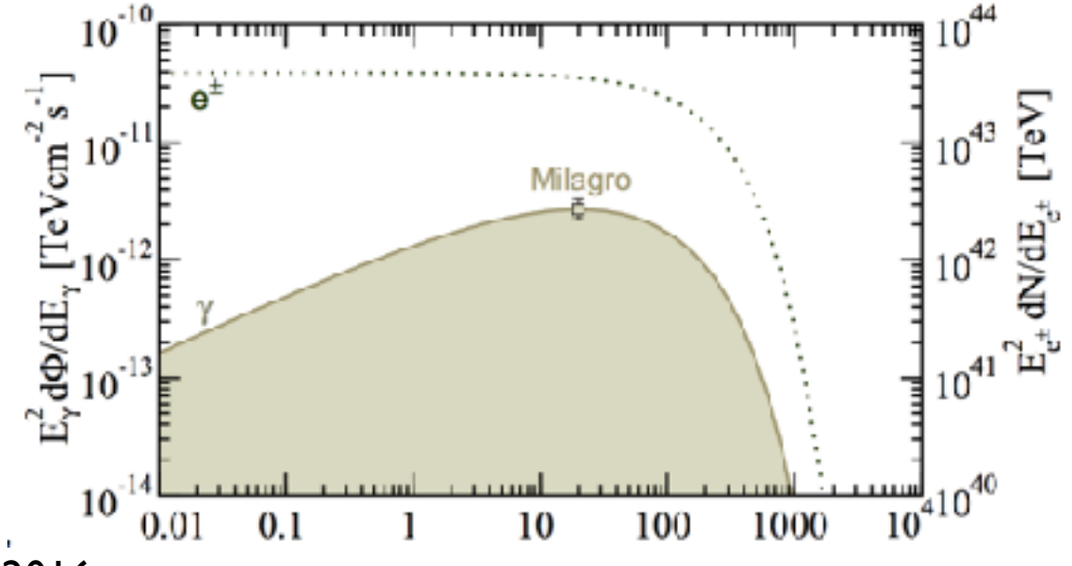
- Positron excess at Earth; created by nearby middle-aged pulsar?
- Geminga could be that pulsar. 300 kyr old, ~250 pc distant. *Paper in progress*

Milagro Collaboration: ApJ **700**:2009, L27

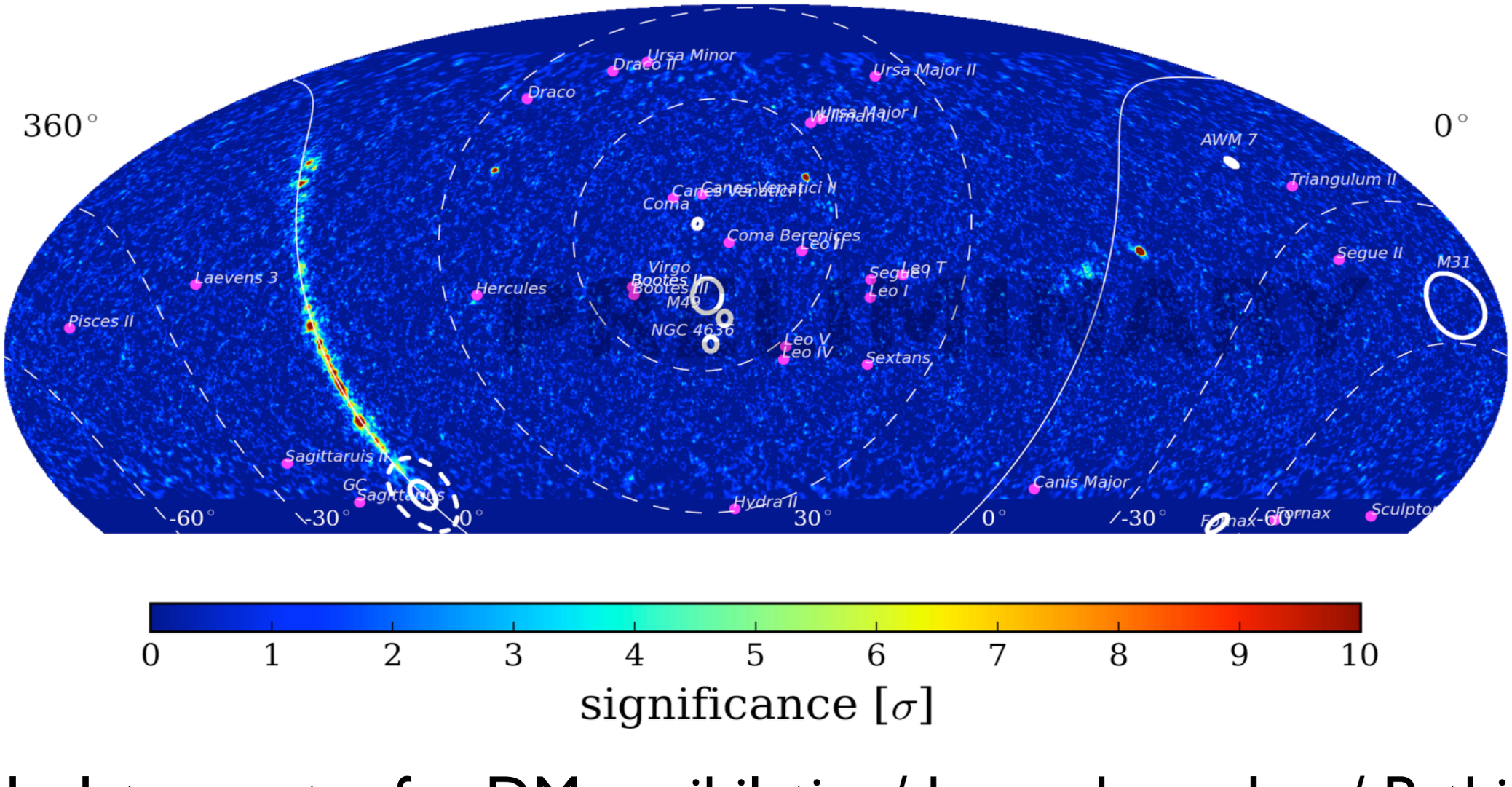


H. Yüksel et al., PRL **103**:0511101, 2009





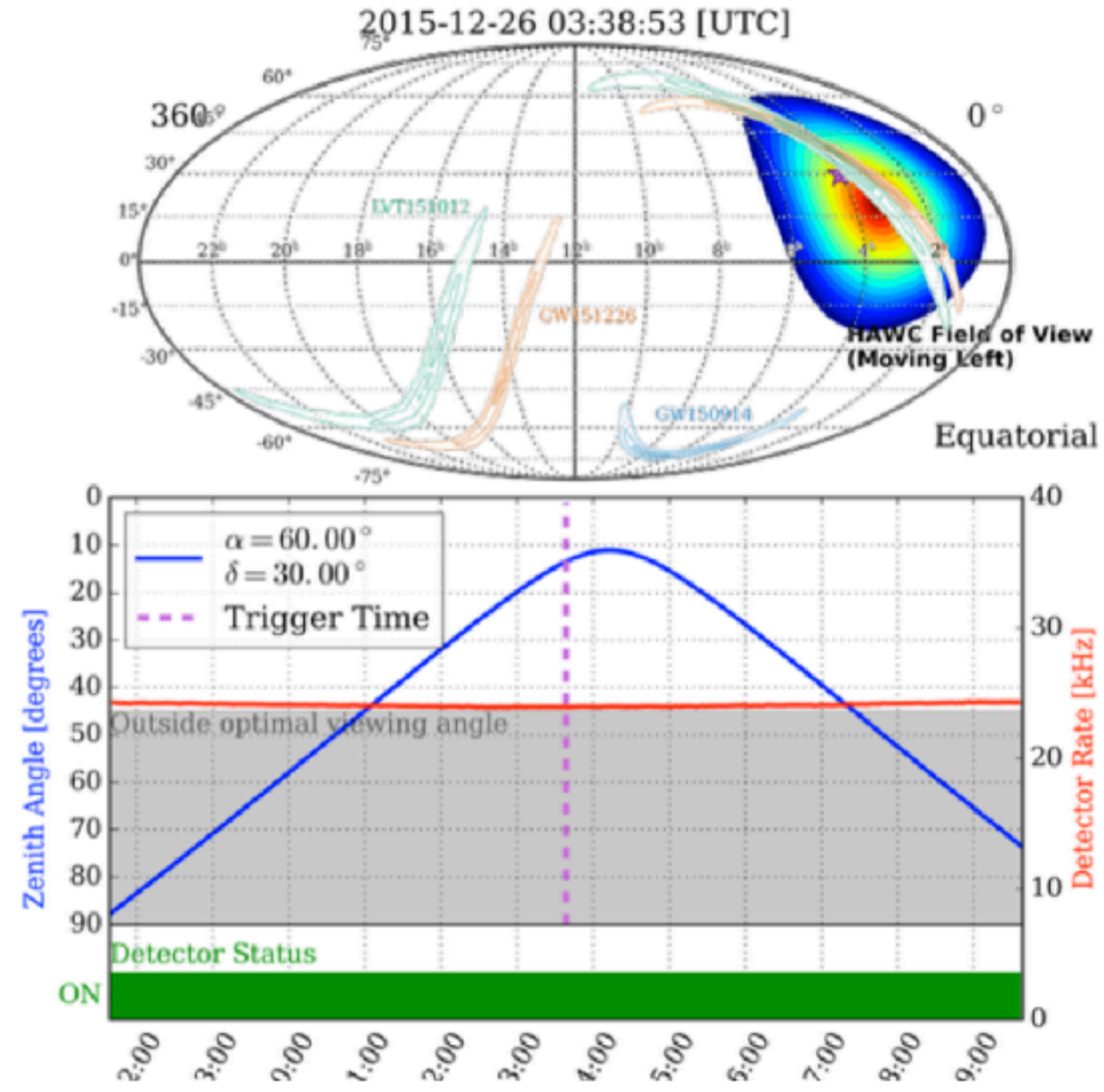
Dark Matter Targets



- Calculate spectra for DM annihilation/decay channels w/ Pythia 8
- Determine count ULs from HAWC maps, convert to $\langle \sigma v \rangle$ using CORSIKA+GEANT4

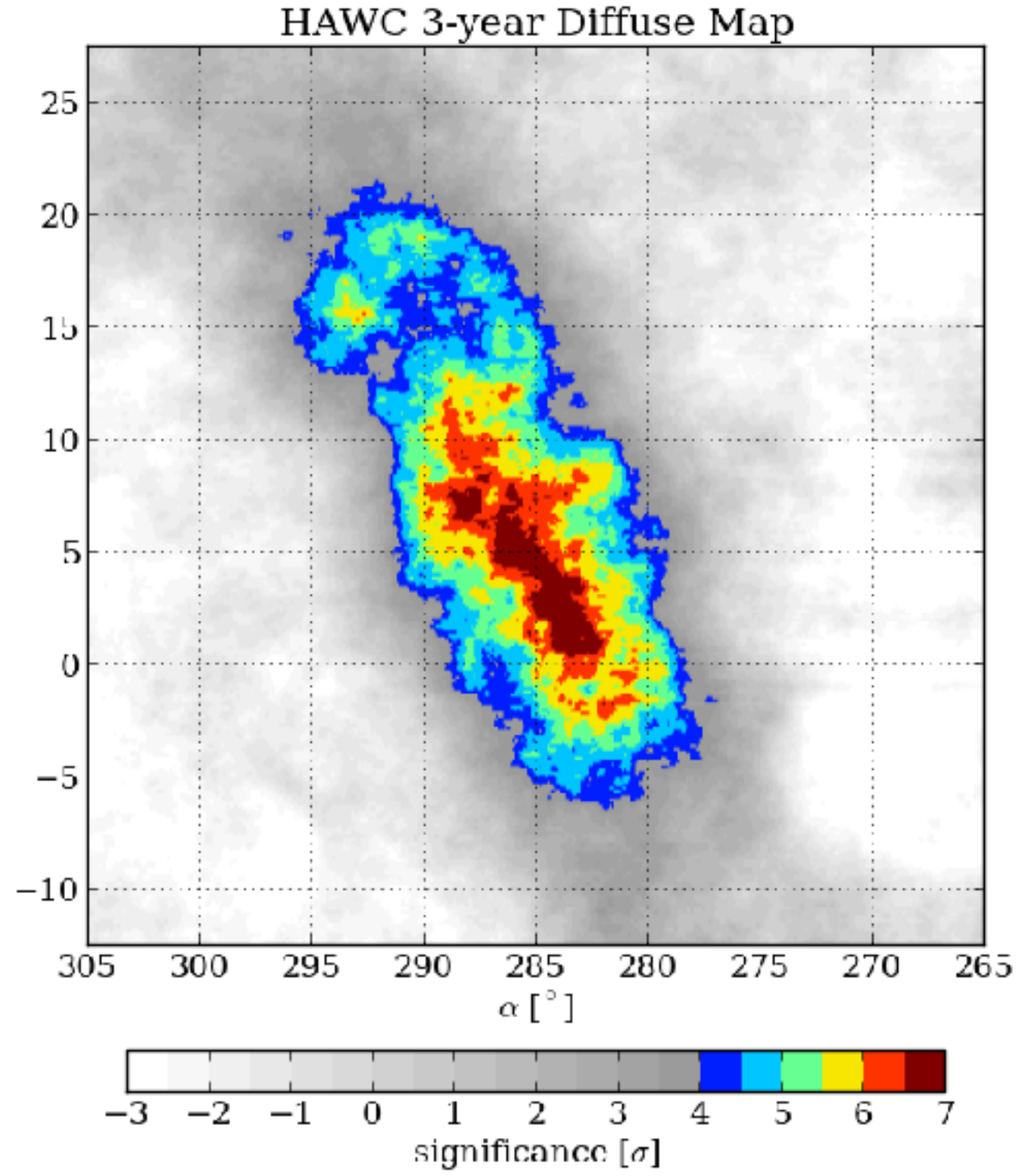
GW Wave Counterparts

- GW151226
  - $14.2M_\odot + 7.5M_\odot$
  - $z = 0.09 \pm 0.03$
- Transient found 9.93s after GW trigger
  - 5σ pre-trials
  - p=0.08 post-trials
  - Compatible with background



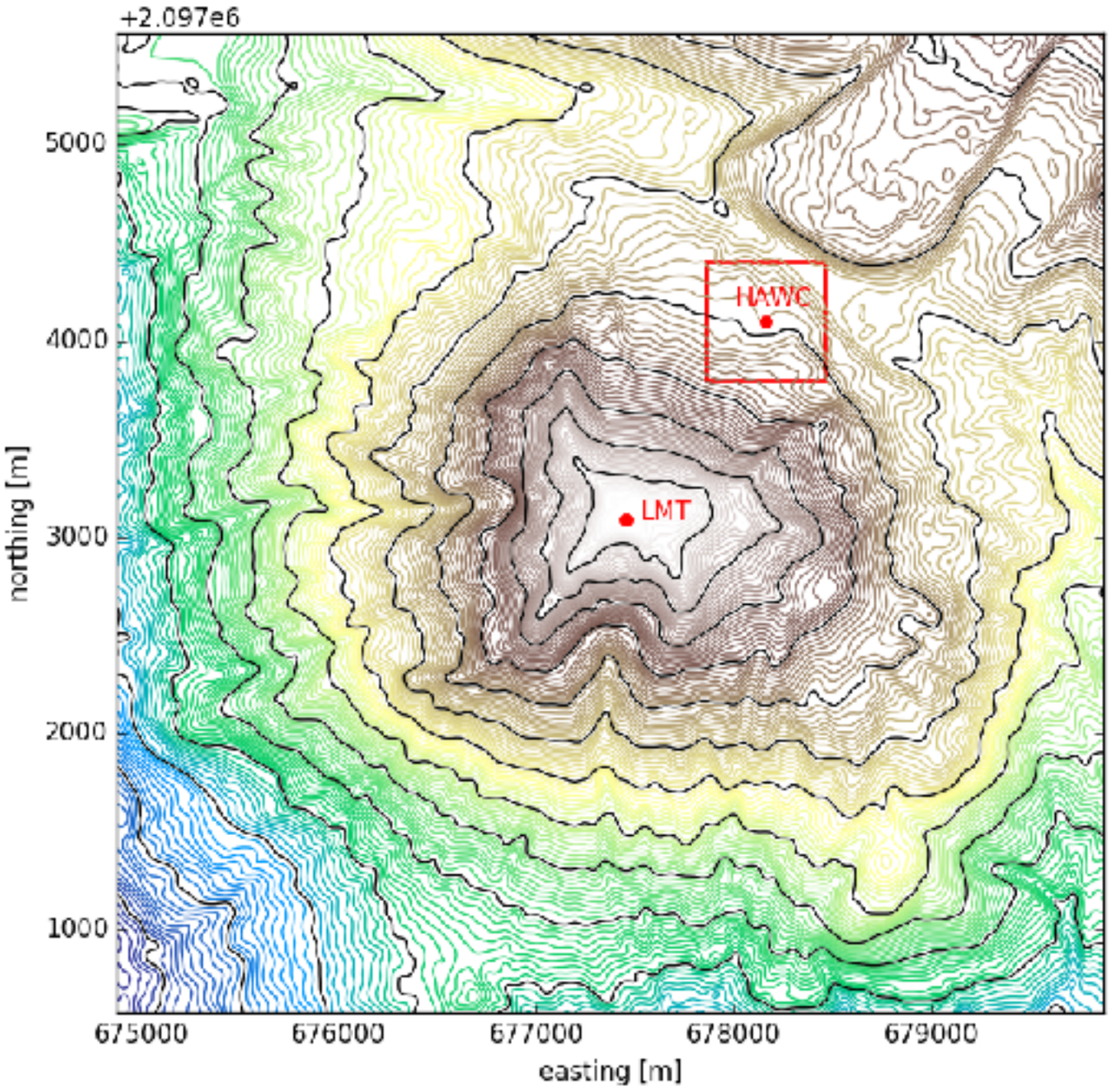
Diffuse Sensitivity

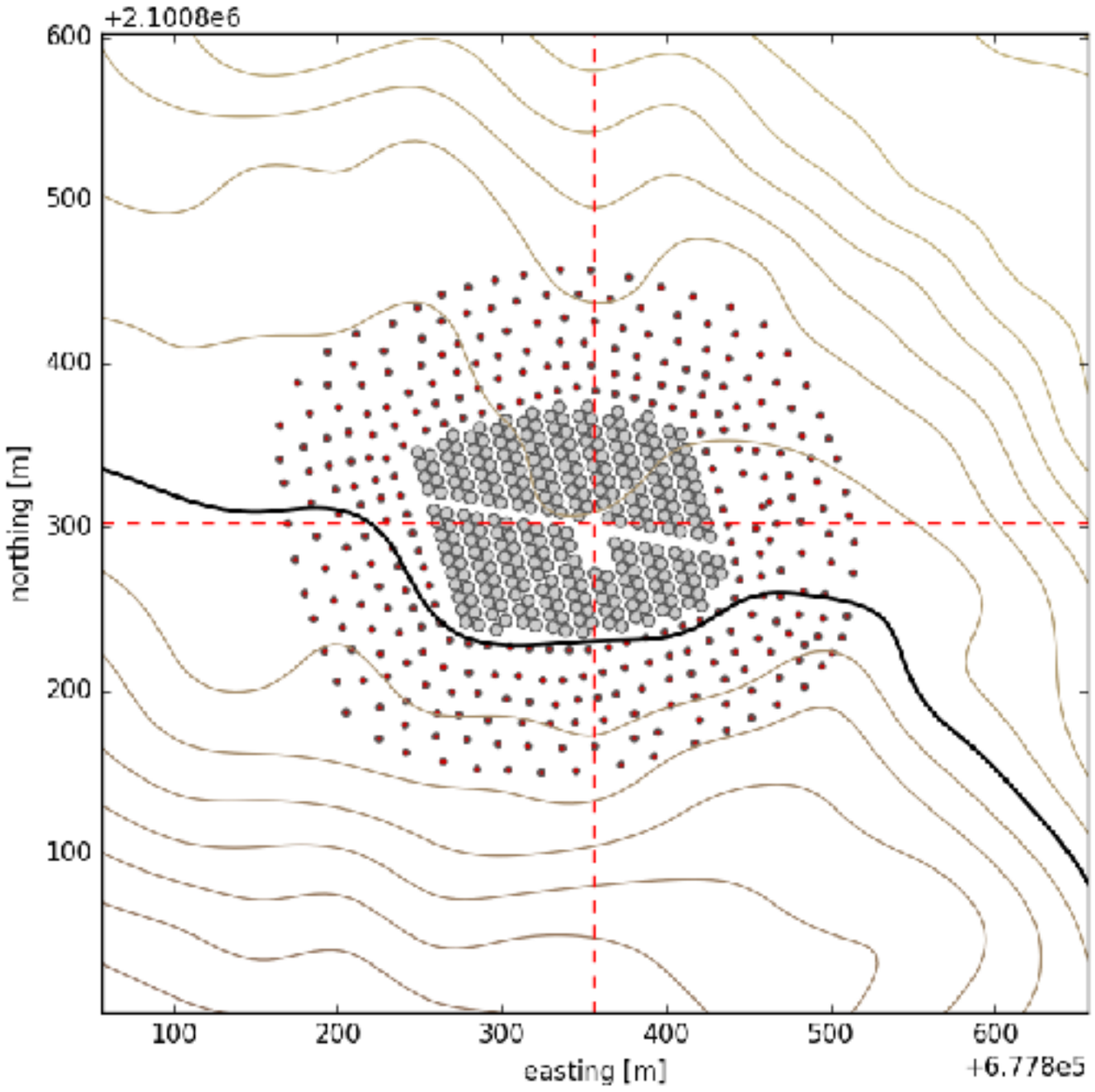
- HAWC is sensitive to π^0+IC+bremsstrahlung emission from the Galaxy above 1 TeV
- Study Galactic CR environment? Or a component of the IceCube astrophysical ν flux?
- Right: 3-year simulation using π^0 + IC flux scaled to match the Milagro diffuse measurement
- Caution: much of the Milagro diffuse emission was likely due to unresolved sources. So this is probably an overestimate…



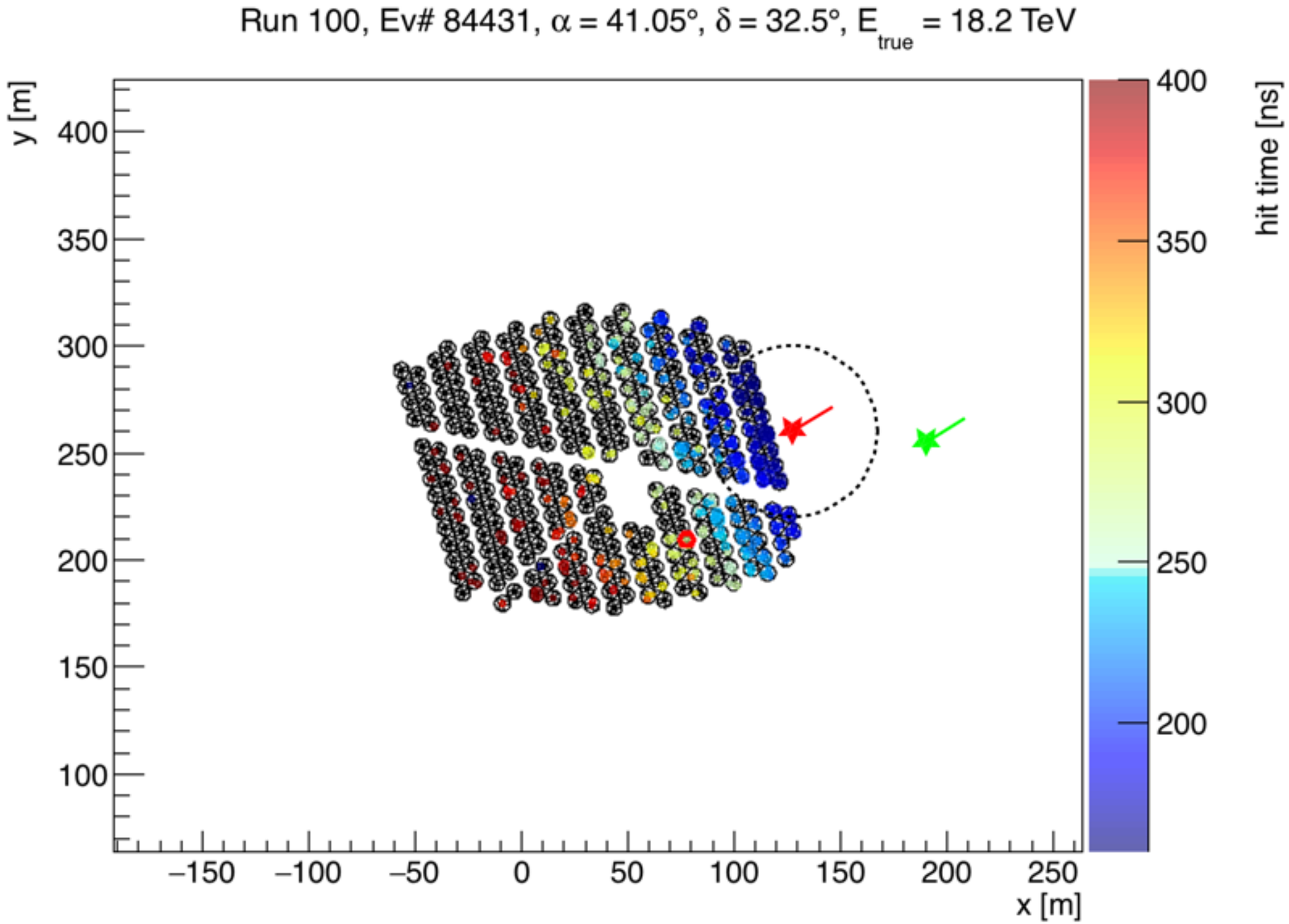
HAWC Upgrades

- High-energy extension: outrigger tanks funded (LANL LDRD)
- Test tanks deployed; PMT tests underway; FLASHCAM electronics

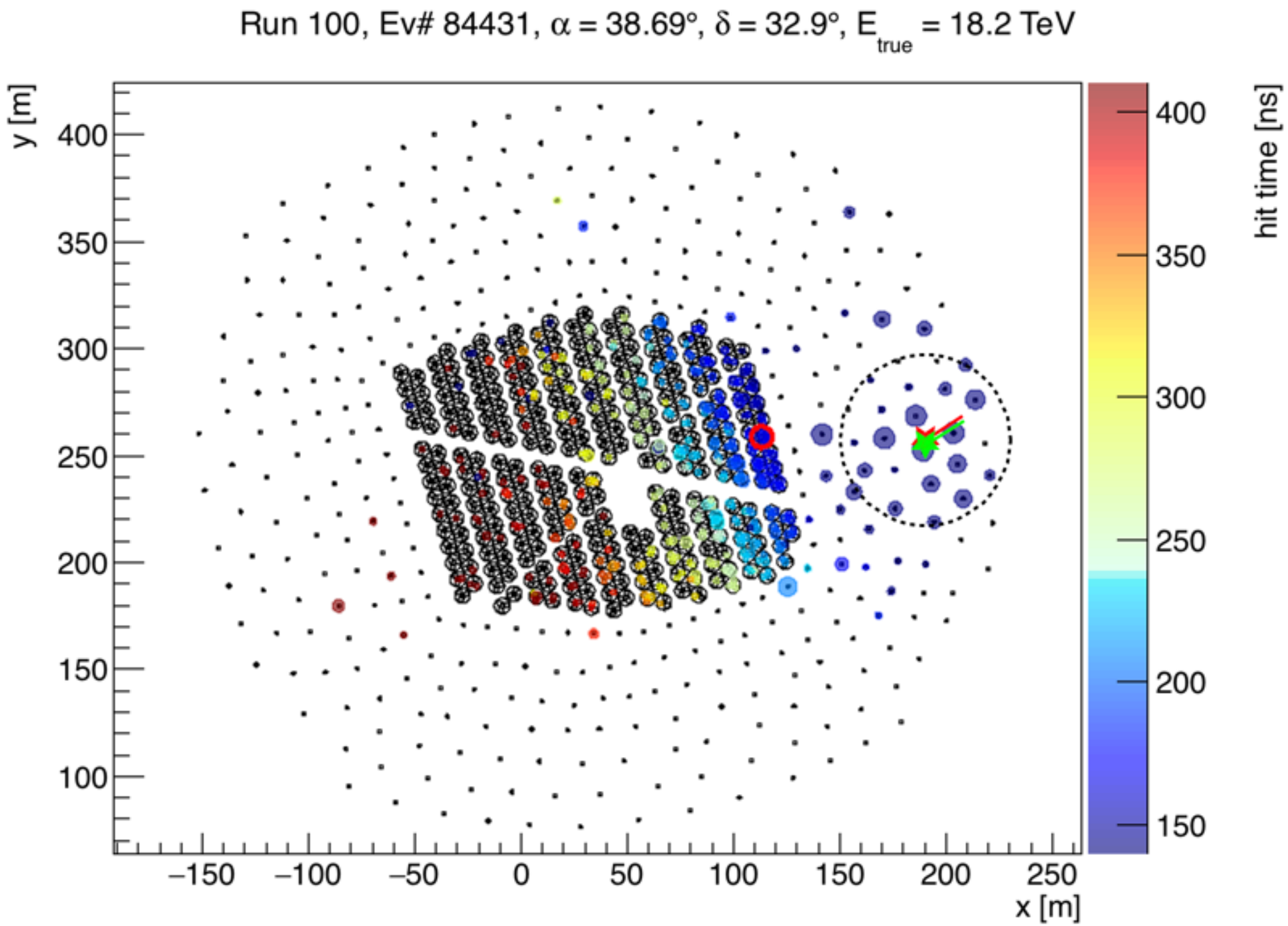




Outrigger Upgrade



Outrigger Upgrade



Southern Gamma-Ray Survey Observatory

- A high altitude site (4800-5000 m a.s.l.) in the Southern Hemisphere is under discussion

- Goals: improved sensitivity <1 TeV, exposure to Galactic Center, about 8 sr daily sky coverage, early warning system for CTA
- **SGSO Workshop**: Puebla, Mexico, Nov. 11-12. For details, see http://events.icecube.wisc.edu/conferenceDisplay.py?confId=81

Summary

- Construction of HAWC ended in December 2014
  - Stable operation: live time >95%, excluding planned shutdowns
- Detailed observation of inner Galaxy has yielded several previously unknown TeV source candidates. Multi wavelength follow-ups in progress (MAGIC, VERITAS, H.E.S.S., IceCube)
- High-statistics observations of hadronic cosmic rays: anisotropy, lunar shadow, solar shadow
- New measurements of very extended regions of TeV emission, not observed at other wavelengths. Study of connection to local $e^{\pm}$ flux is being completed
- Upgrades: high energy extension underway, southern hemisphere site under discussion, workshop November 11-12