Observation of Galactic Cosmic Rays and γ Rays with HAWC

Segev BenZvi
Department of Physics and Astronomy
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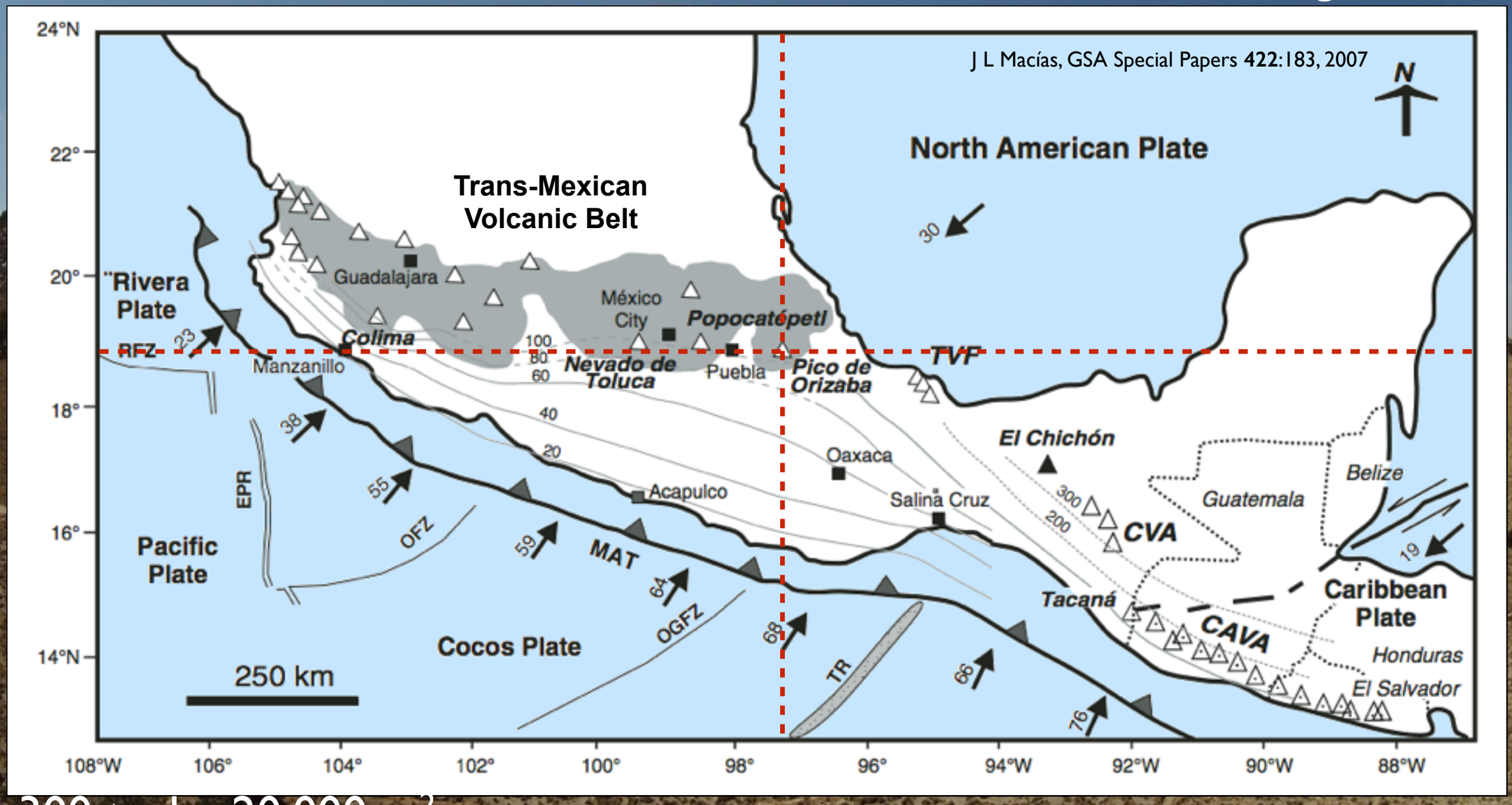
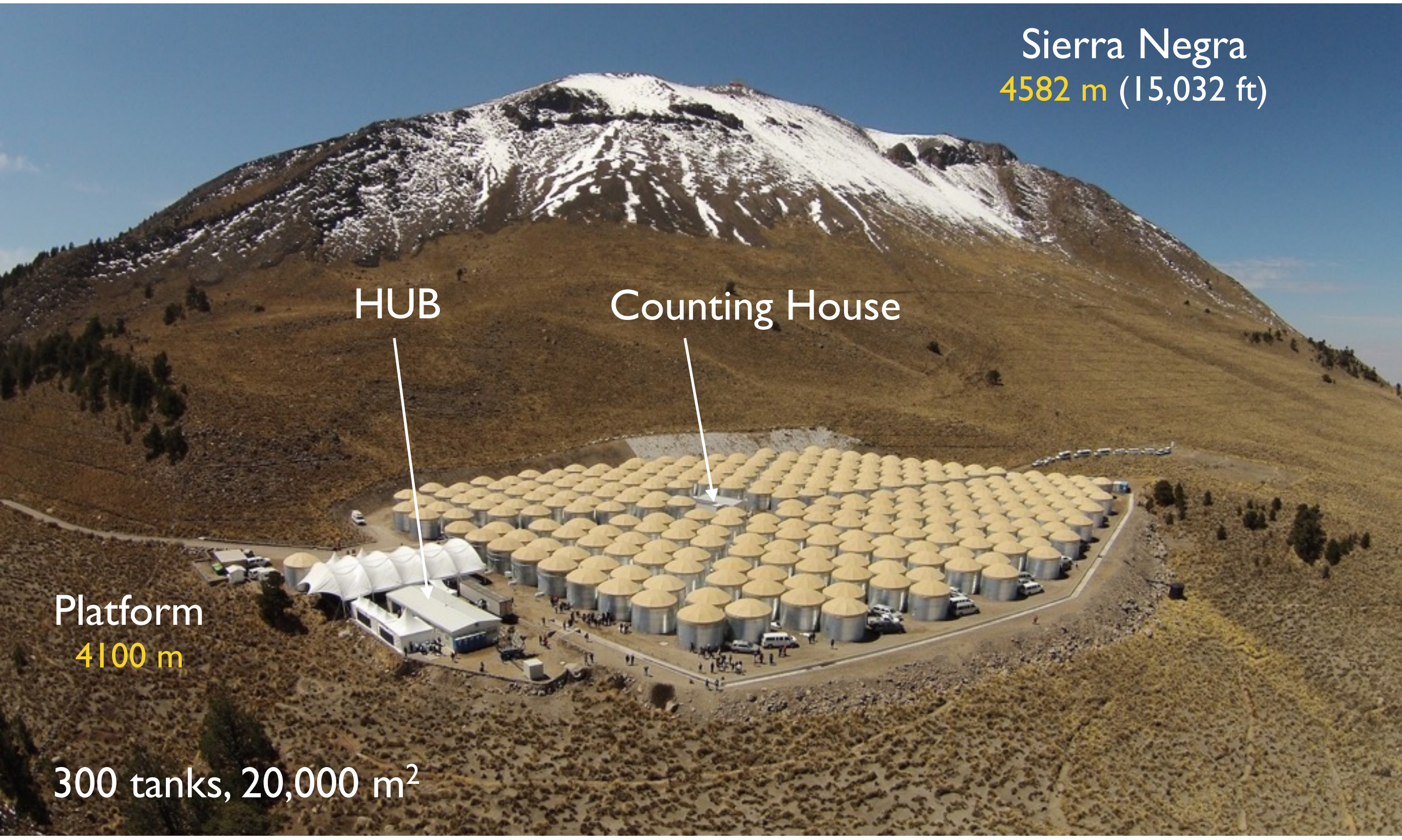
High Altitude Water Cherenkov Observatory

Sierra Negra

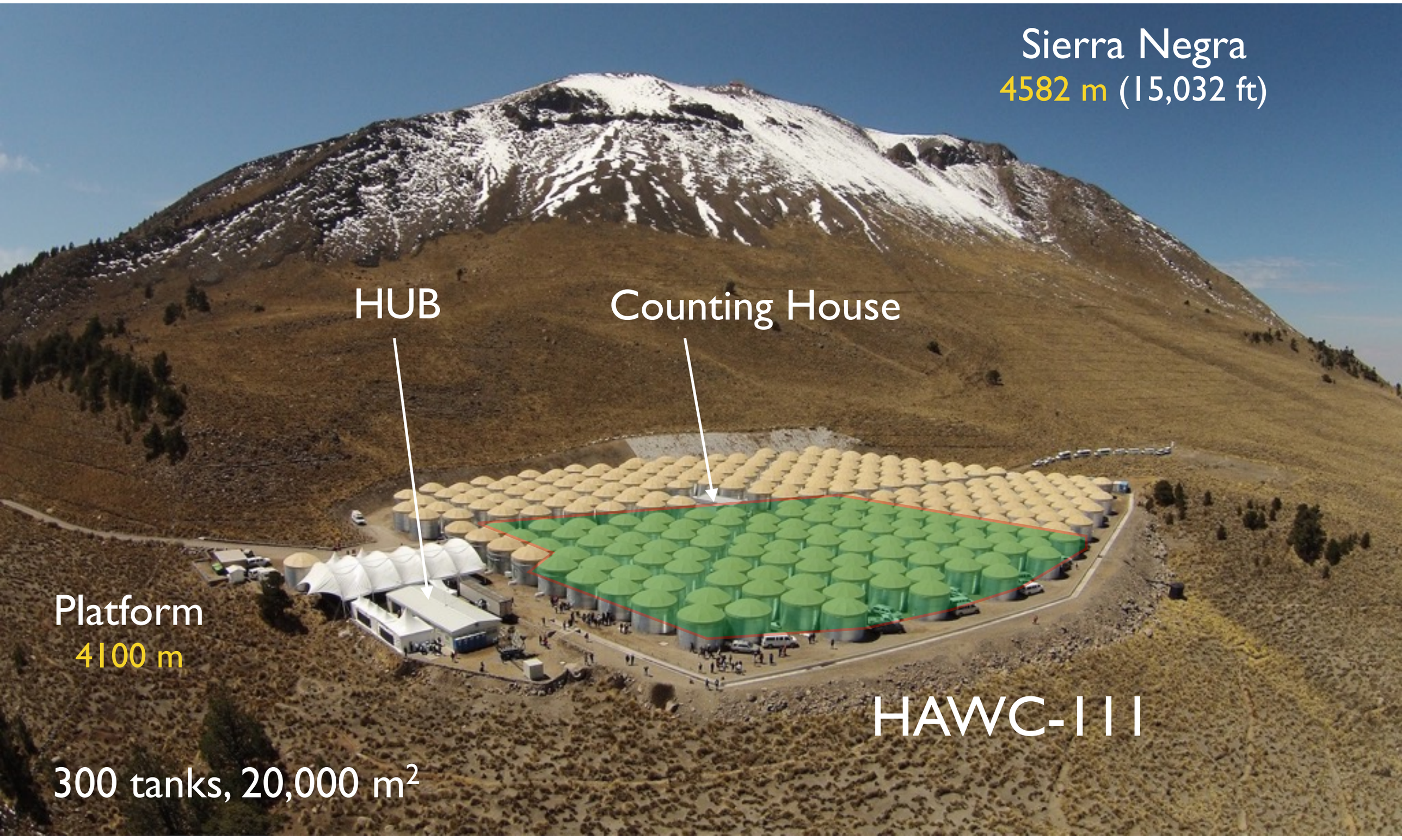


300 tanks, 20,000 m^2

High Altitude Water Cherenkov Observatory



High Altitude Water Cherenkov Observatory



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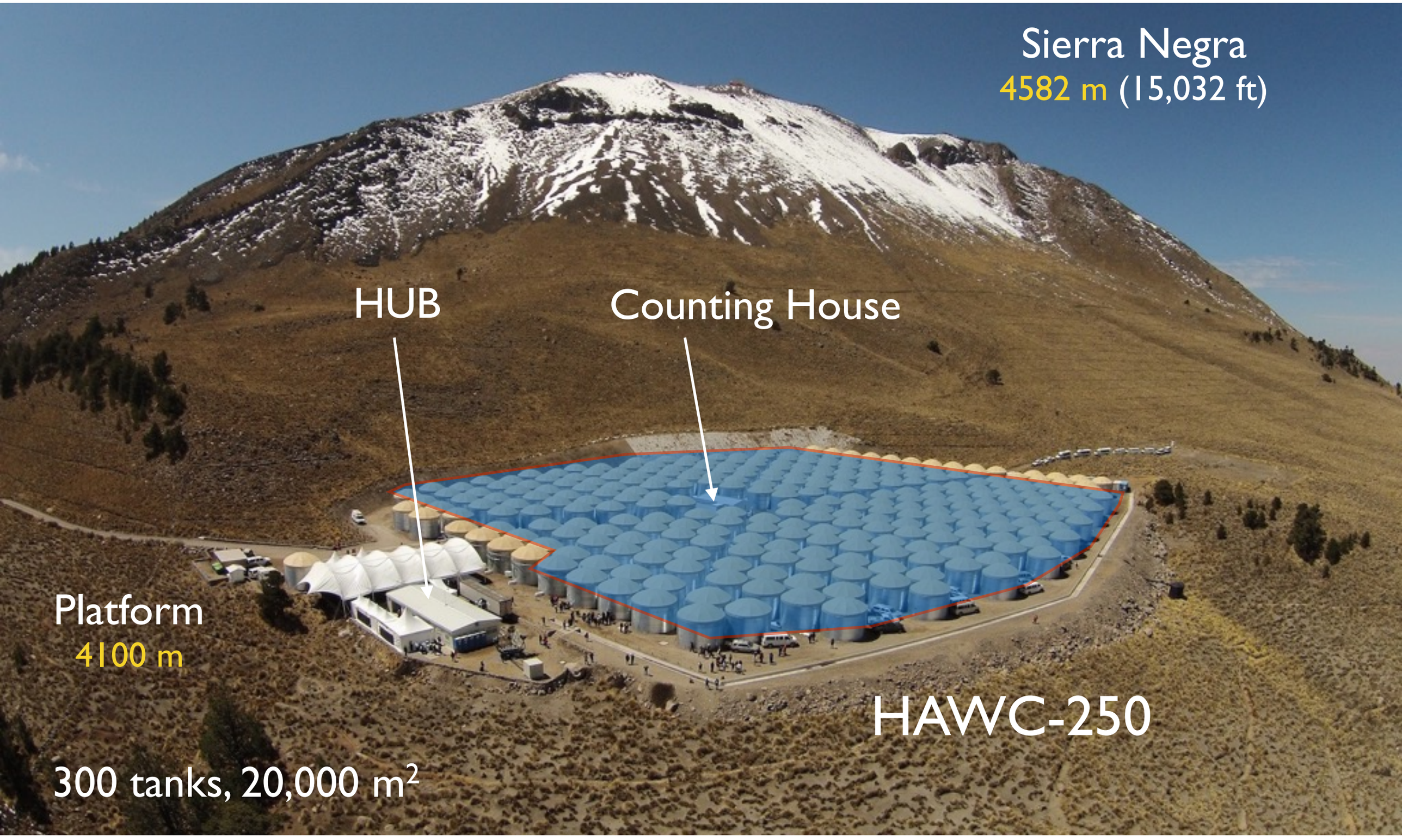
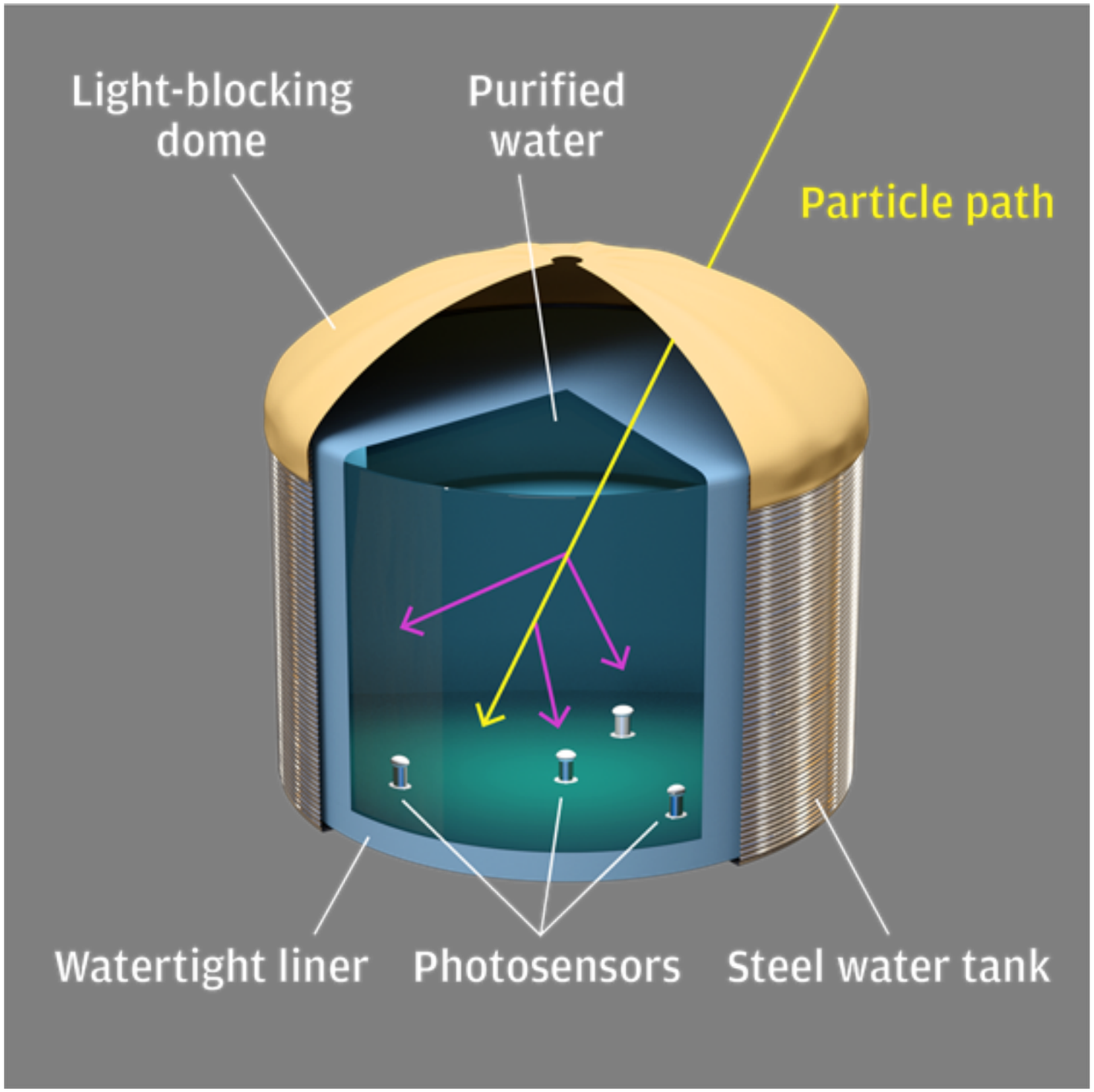


Water Cherenkov Detectors



Multi-messenger Physics

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

Multi-messenger Physics

- **Primary cosmic rays: ~100 GeV to 100 TeV**
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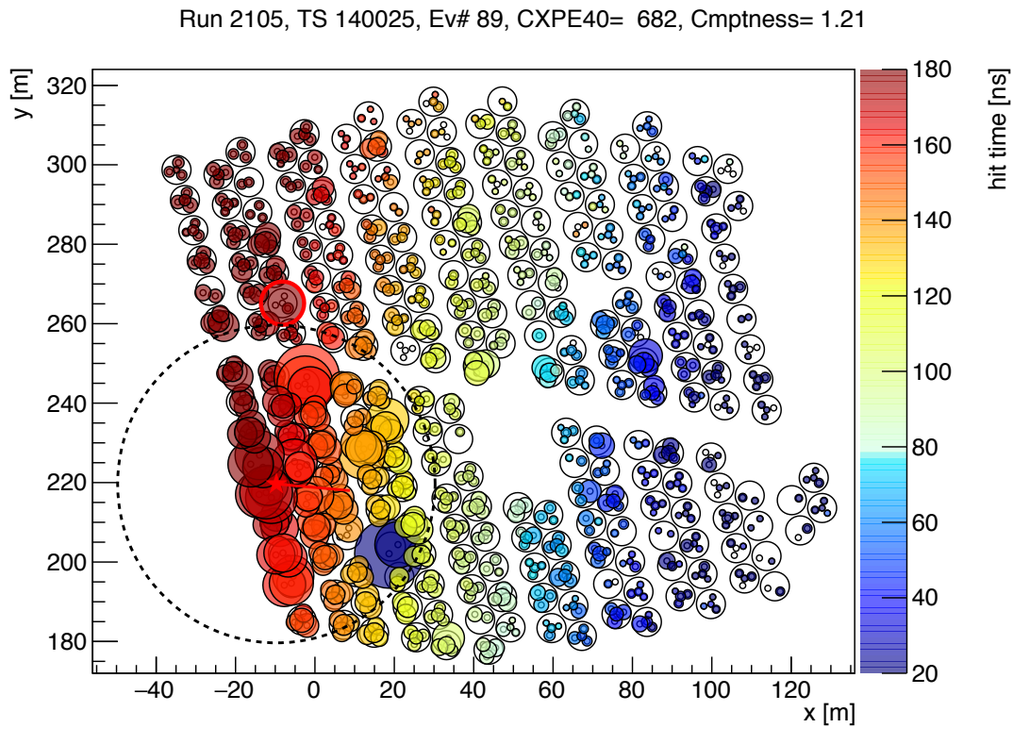
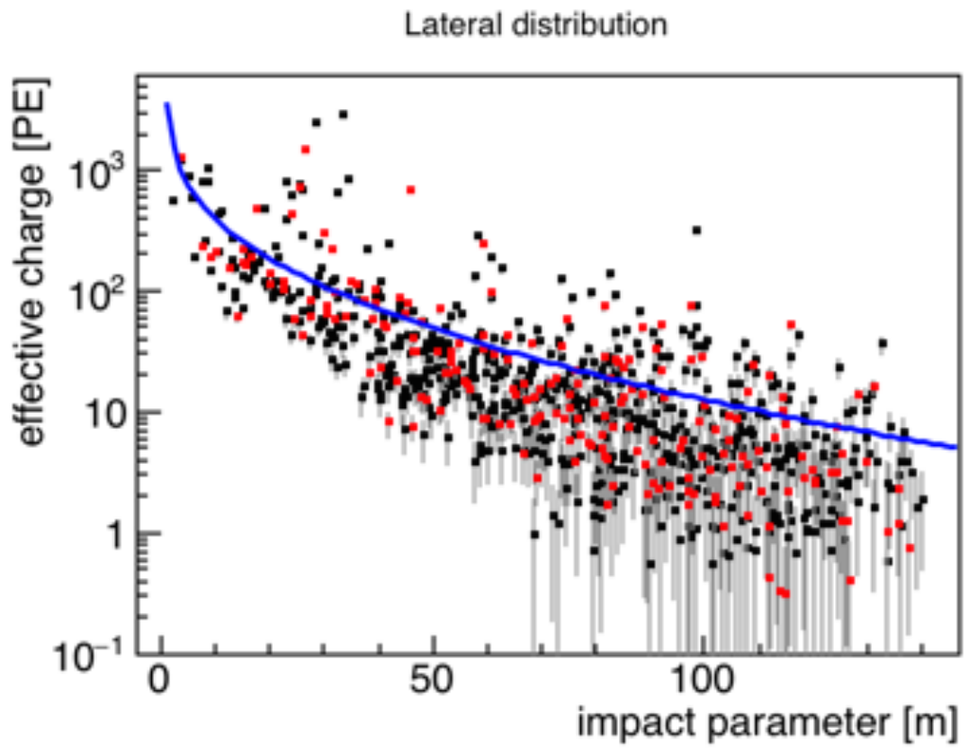
  - Lunar shadow: antiparticles (antiprotons, e+)
  - Solar shadow: heliospheric/coronal magnetic field
- **Galactic and extragalactic γ rays: ~1 TeV to 100 TeV**
  - Unbiased wide-FOV survey of Northern Hemisphere
  - Continuous observations (>90% total uptime): transient sources
  - High energies: distinguish IC from π^0 emission as Klein-Nishina effects become important
  - Galactic and extragalactic diffuse emission: neutrino origins
  - Distinguish "astrophysical" γ rays from Dark Matter (**K. Tollefson**)

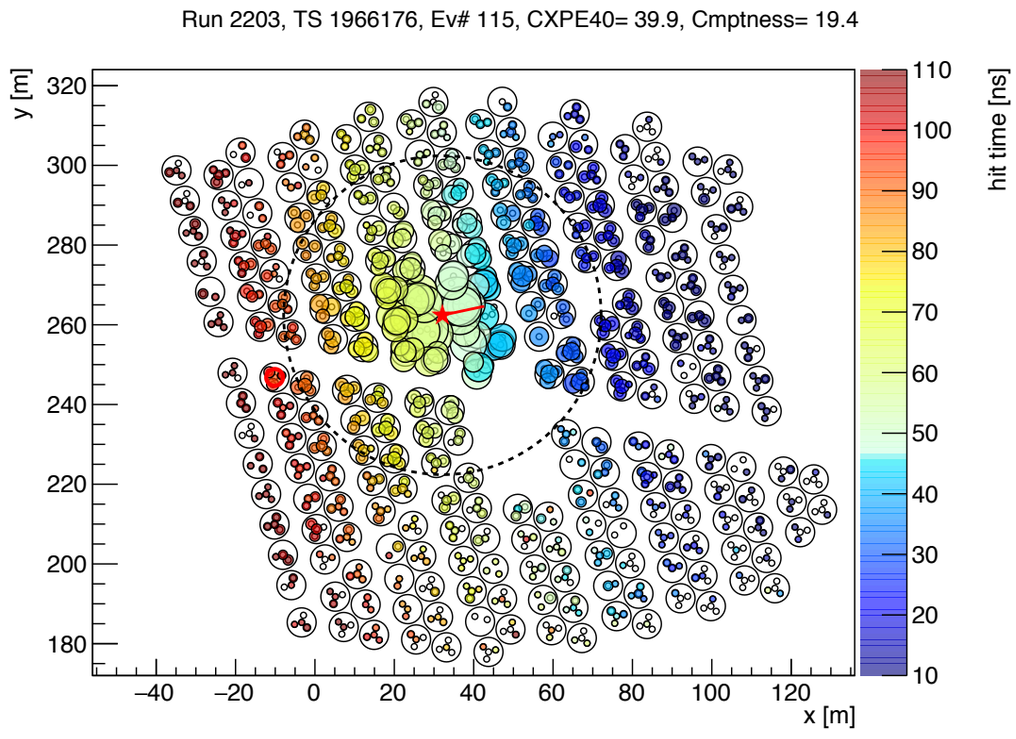
Background Suppression

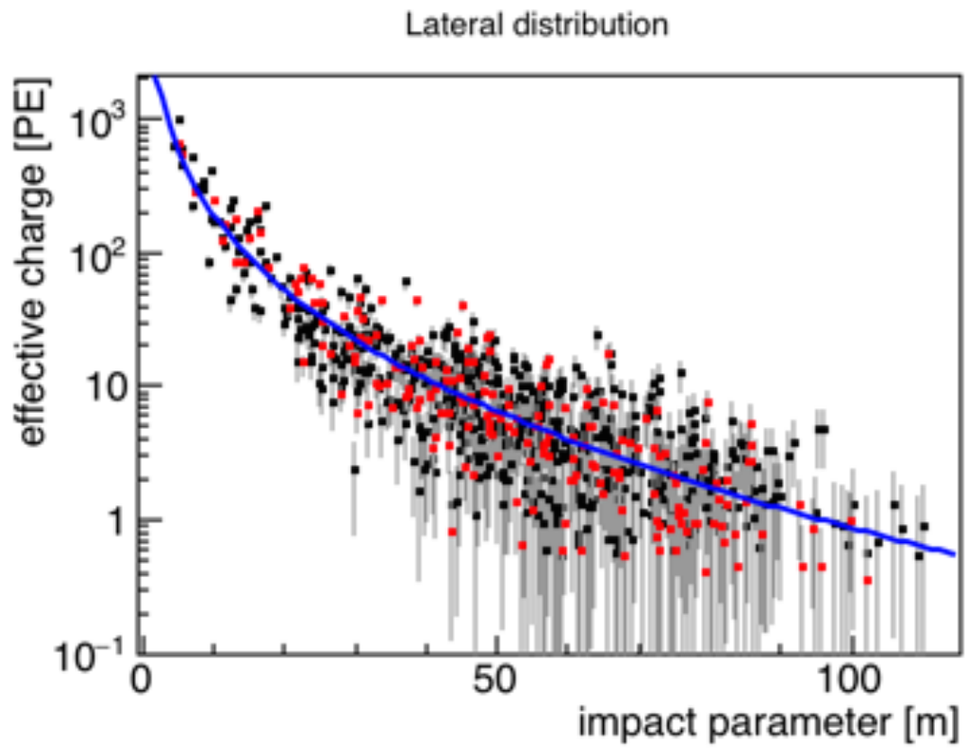




- Cosmic ray background: 25 kHz at trigger level
- Cosmic ray showers produce "clumpy" deposits of charge at large distances from the shower core
- Showers characterized by large variance in charge as a function of distance from shower core

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

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

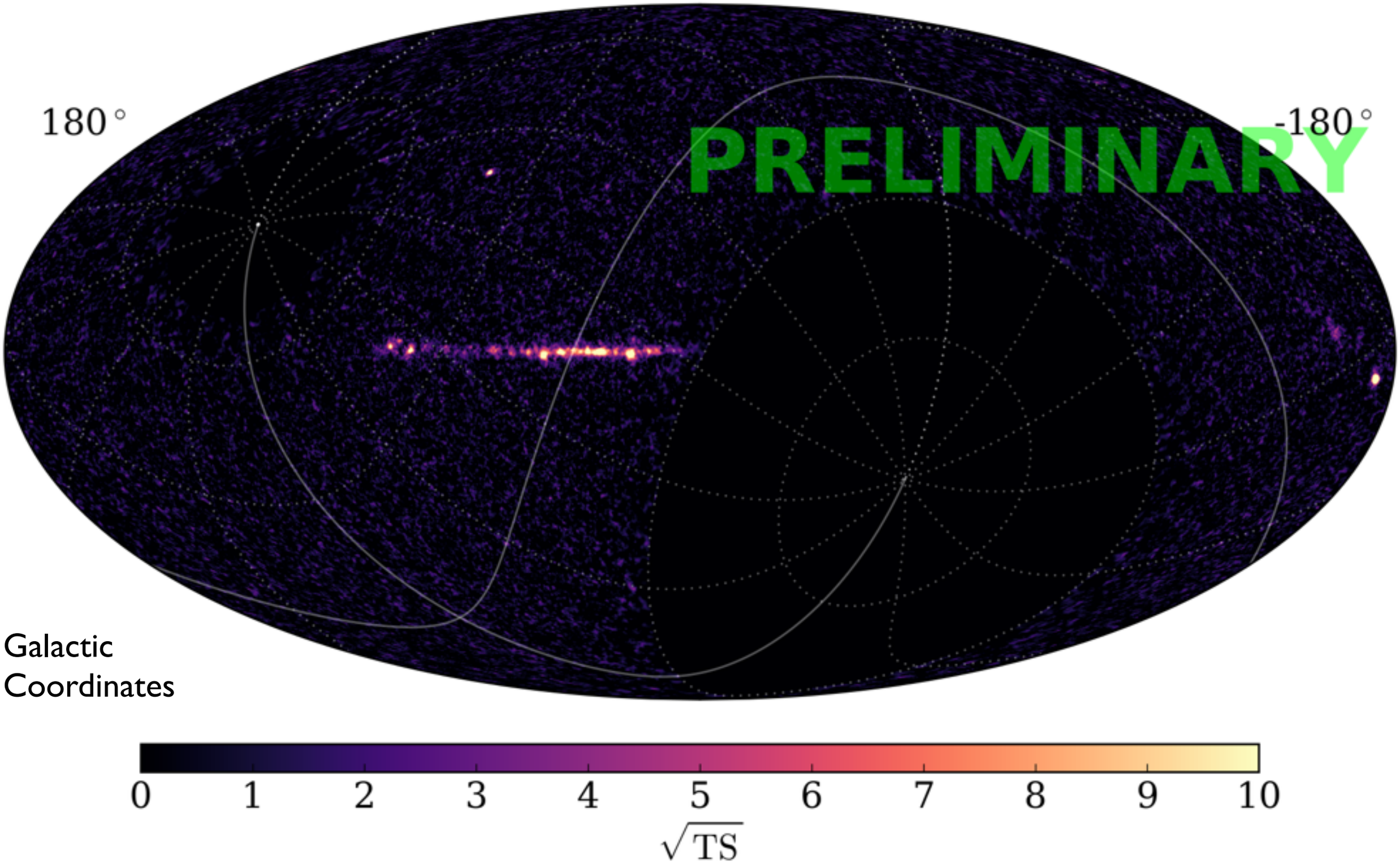
$$\ln \mathcal{L}(\vec{n} \mid \vec{\theta}) = \sum_{i=1}^{N_{\text{bin}}} \sum_{j=1}^{N_{\text{pix}}} n_{ij} \ln \lambda_{ij}(\vec{\theta}) - \lambda_{ij}(\vec{\theta}) - \ln n_{ij}!$$

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

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

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

γ-Ray Observations with HAWC



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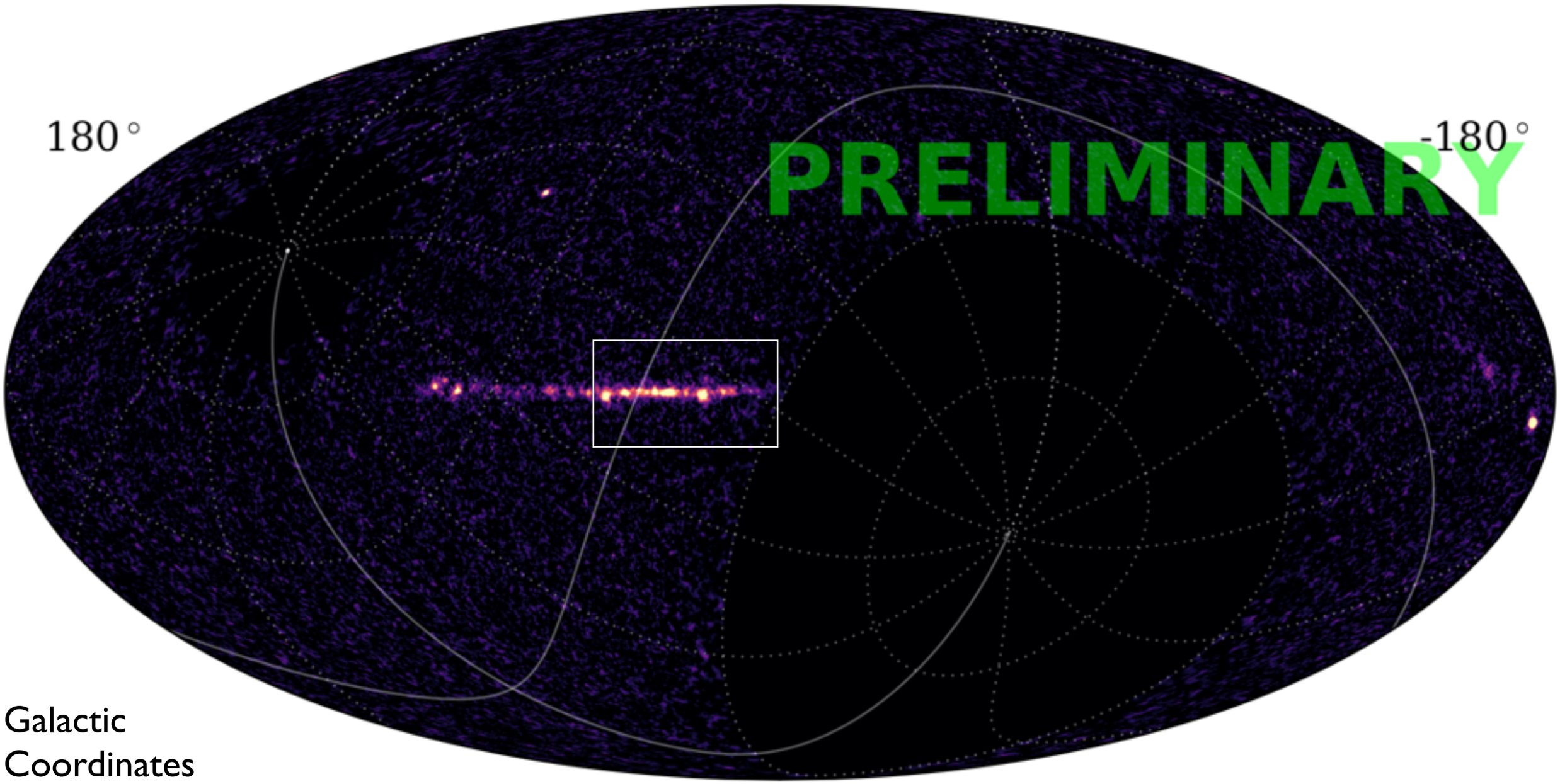

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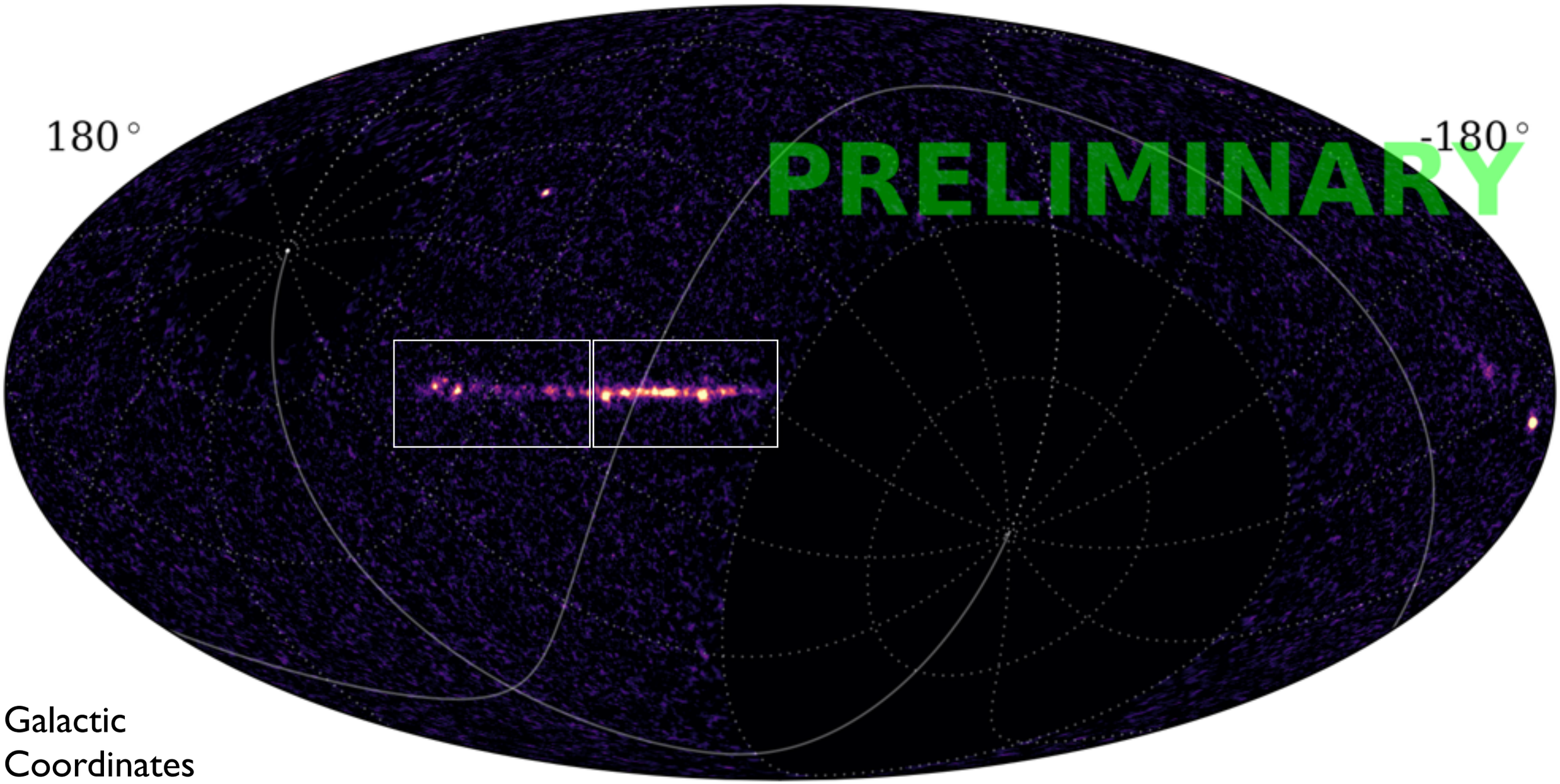

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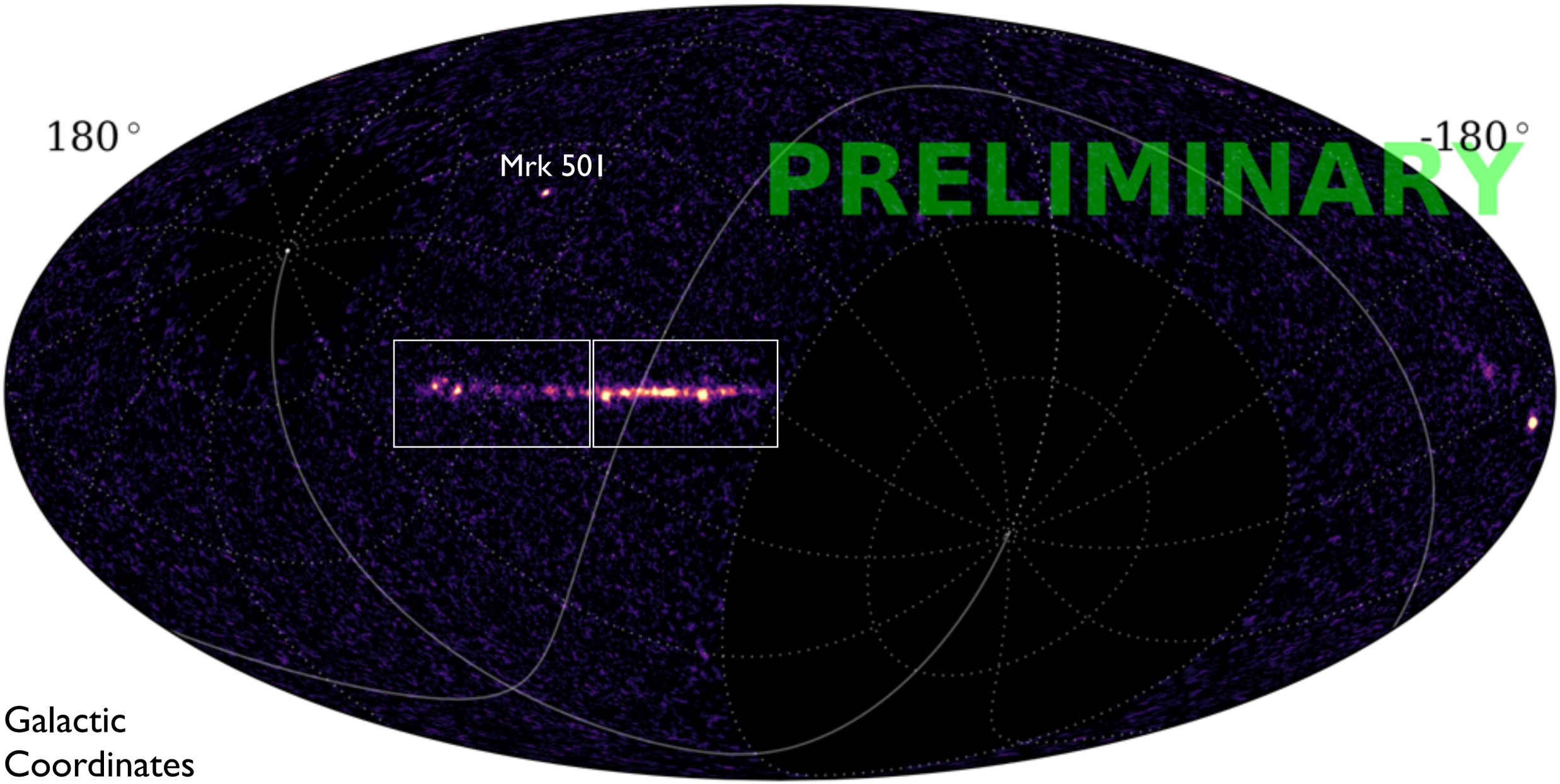

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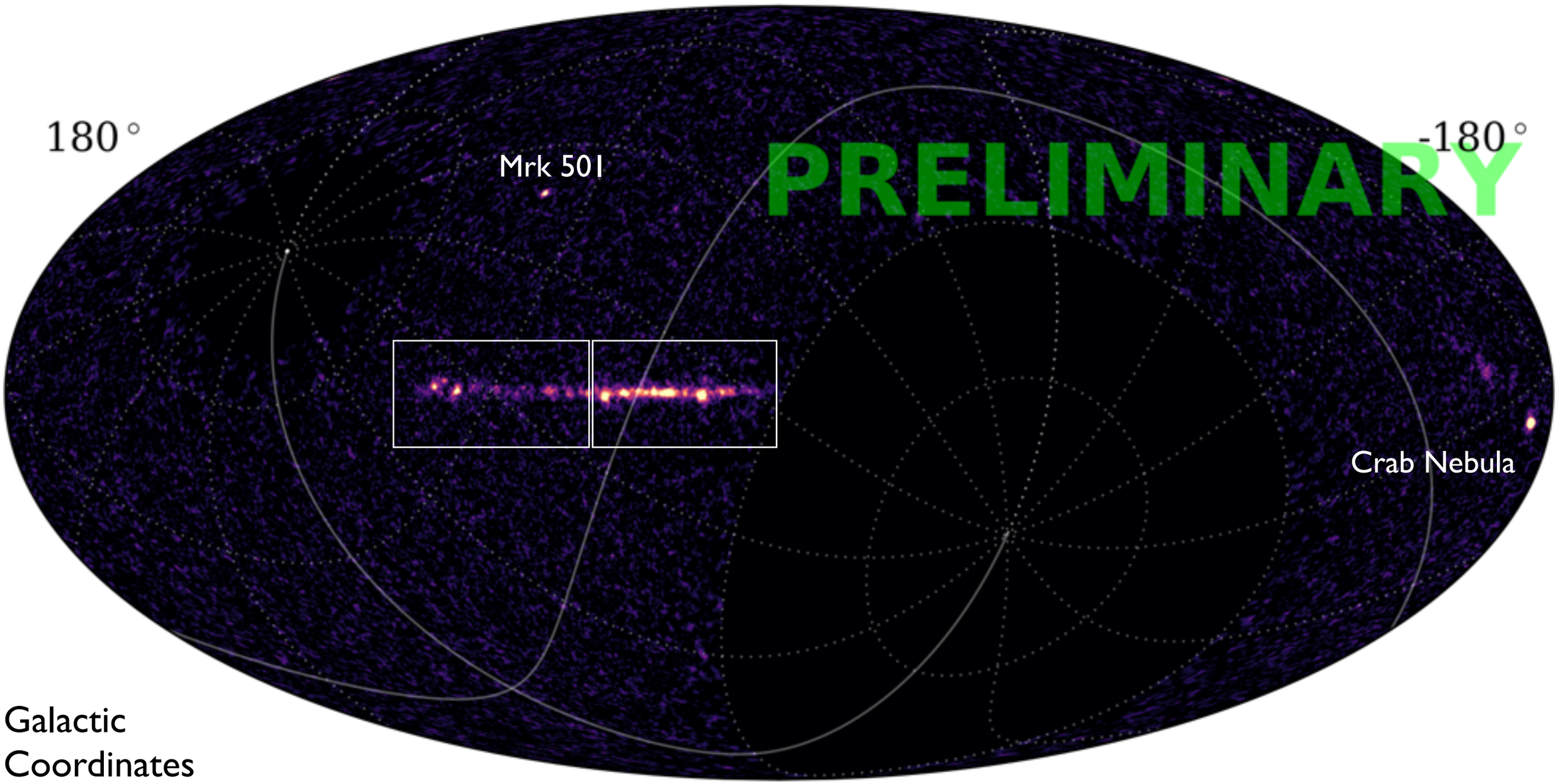

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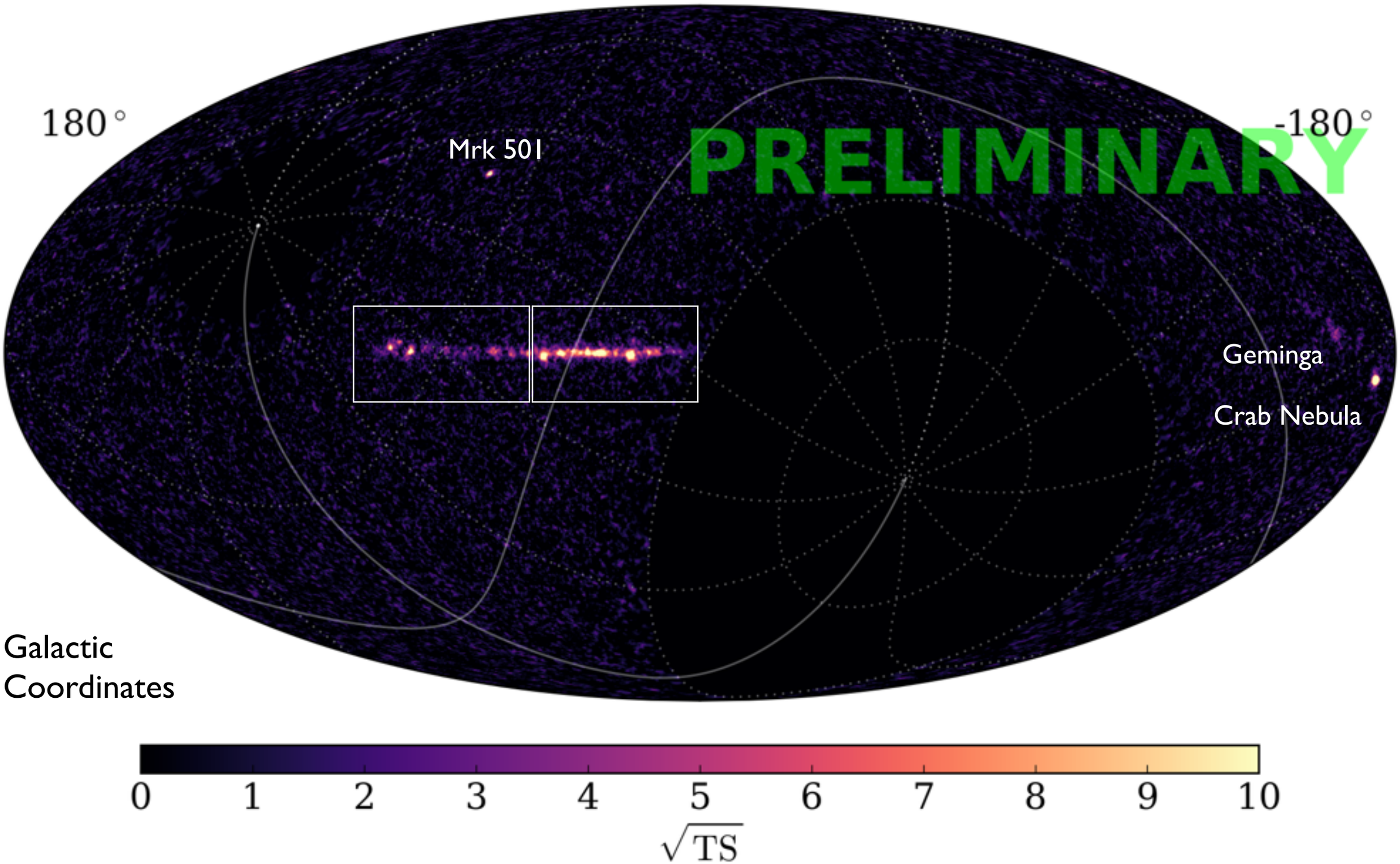
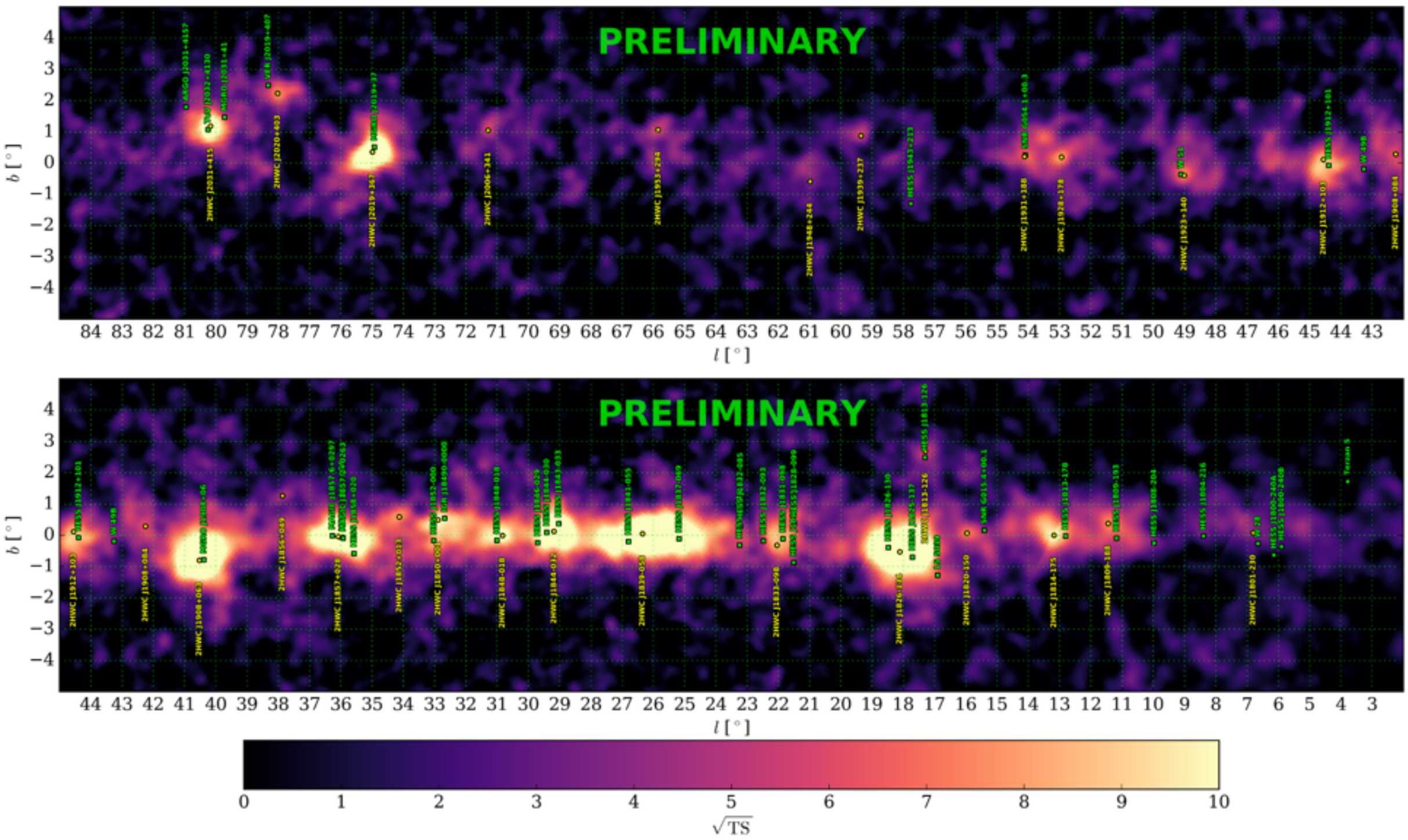


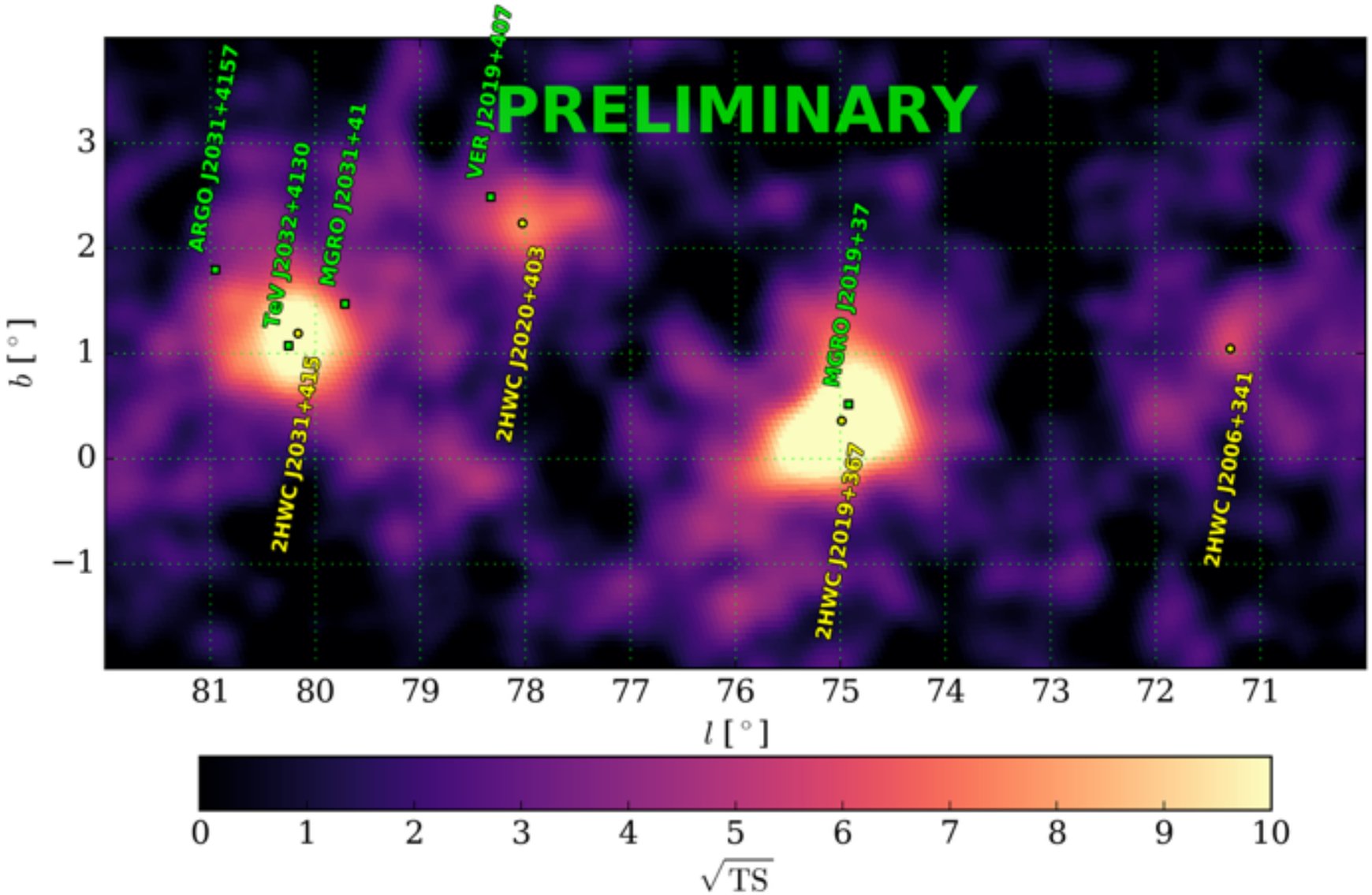
Galactic Plane

TeVCat Sources
HAWC Sources

C. Rivière, UMD



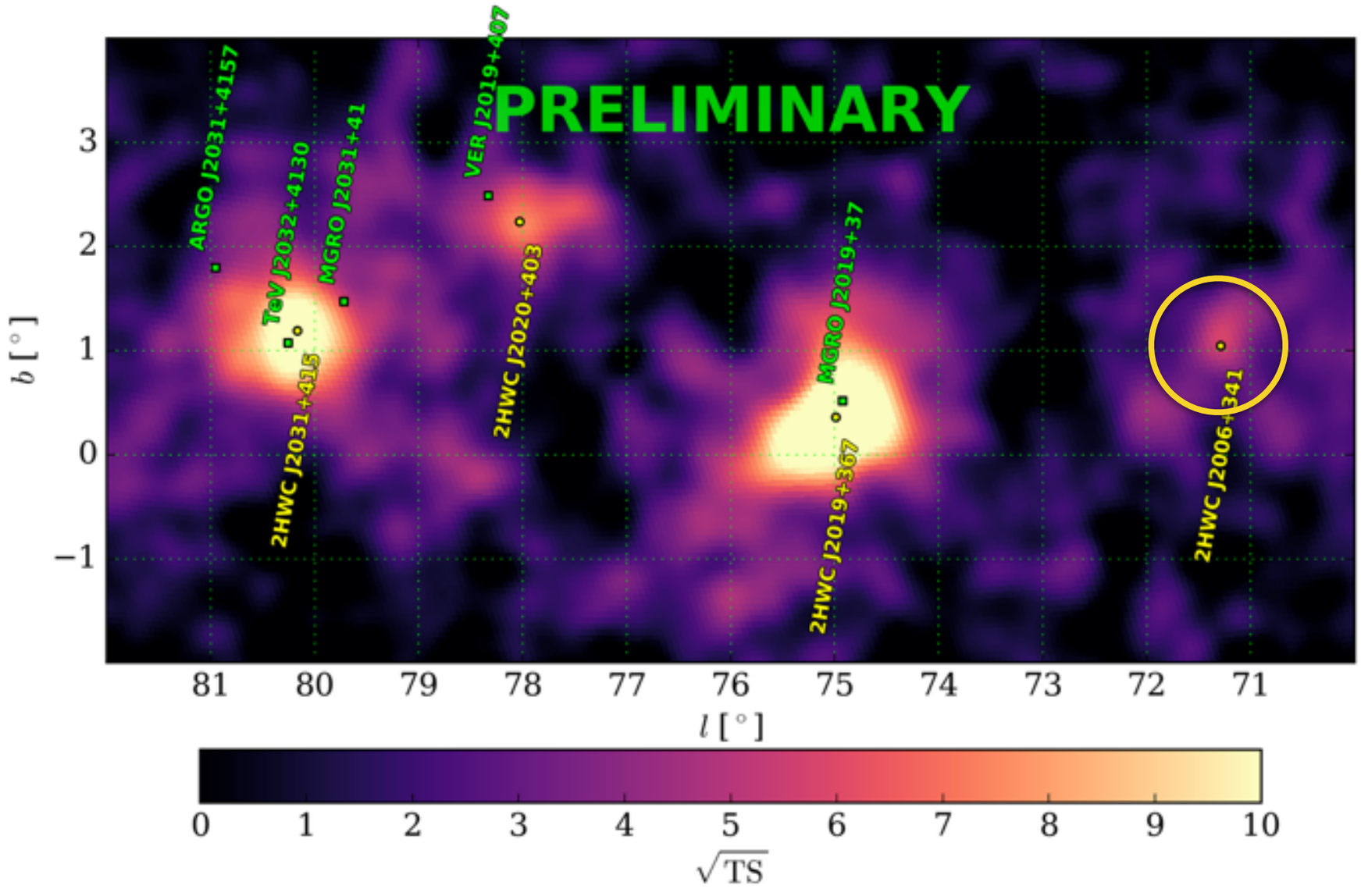
New Sources



C. Rivière, UMD

- Several new source candidates with no TeV counterpart; multiwavelength studies by IACTs in progress
- Note: 5σ post-trials corresponds to $\sqrt{TS} \sim 7$

New Sources



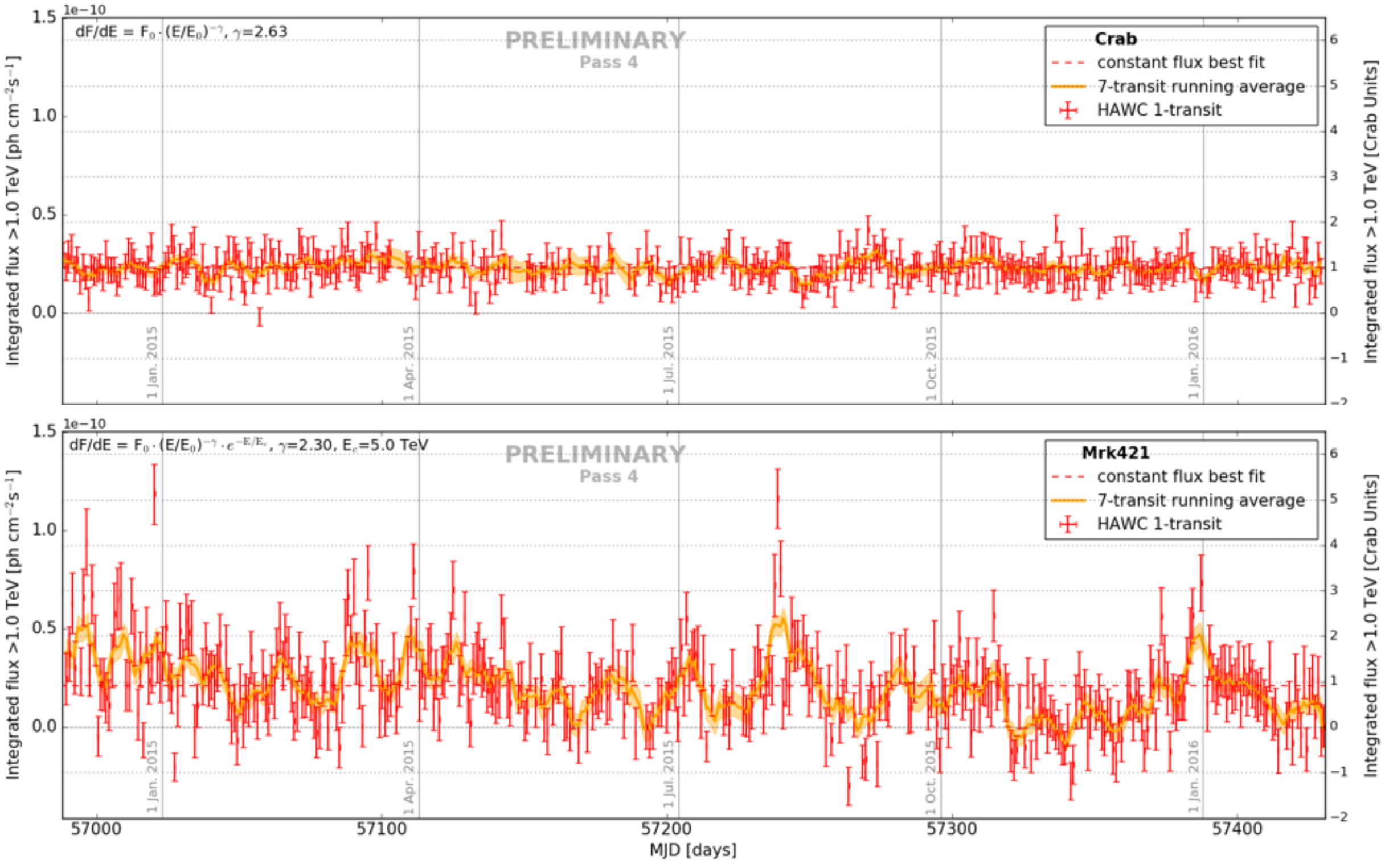
C. Rivière, UMD

Example:
2HWC J2006+341
$\sqrt{TS} \sim 6$

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

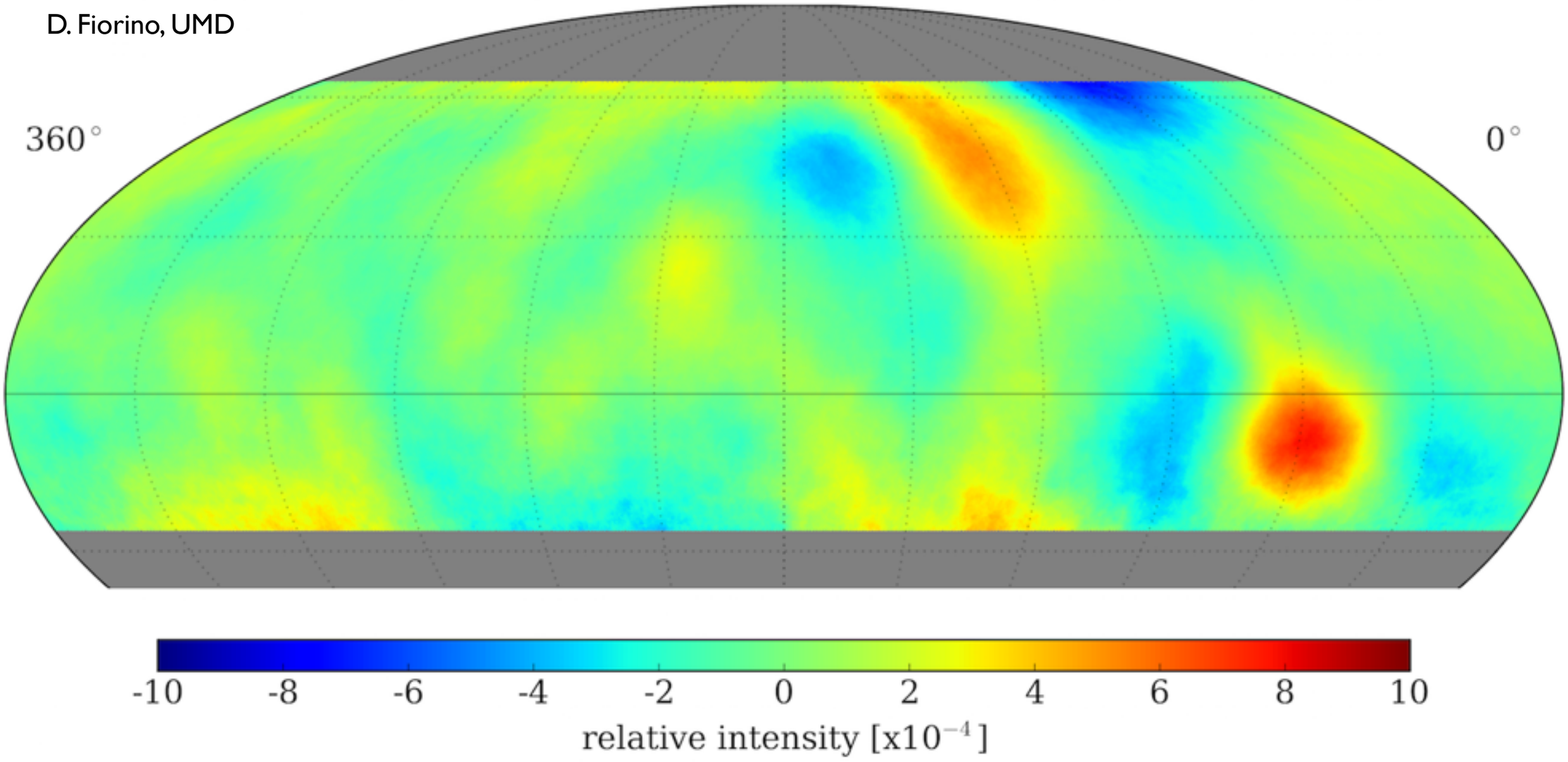
- Several new source candidates with no TeV counterpart; multiwavelength studies by IACTs in progress
- Note: 5σ post-trials corresponds to $\sqrt{TS} \sim 7$

Steady and Transient Emission



Cosmic Ray Anisotropy

D. Fiorino, UMD



- Anisotropy in cosmic-ray background seen at the 10^{-4} to 10^{-3} level. Signature of nearby accelerator(s)? Magnetic lensing? Exotic particle decay?

Cosmic Ray Anisotropy

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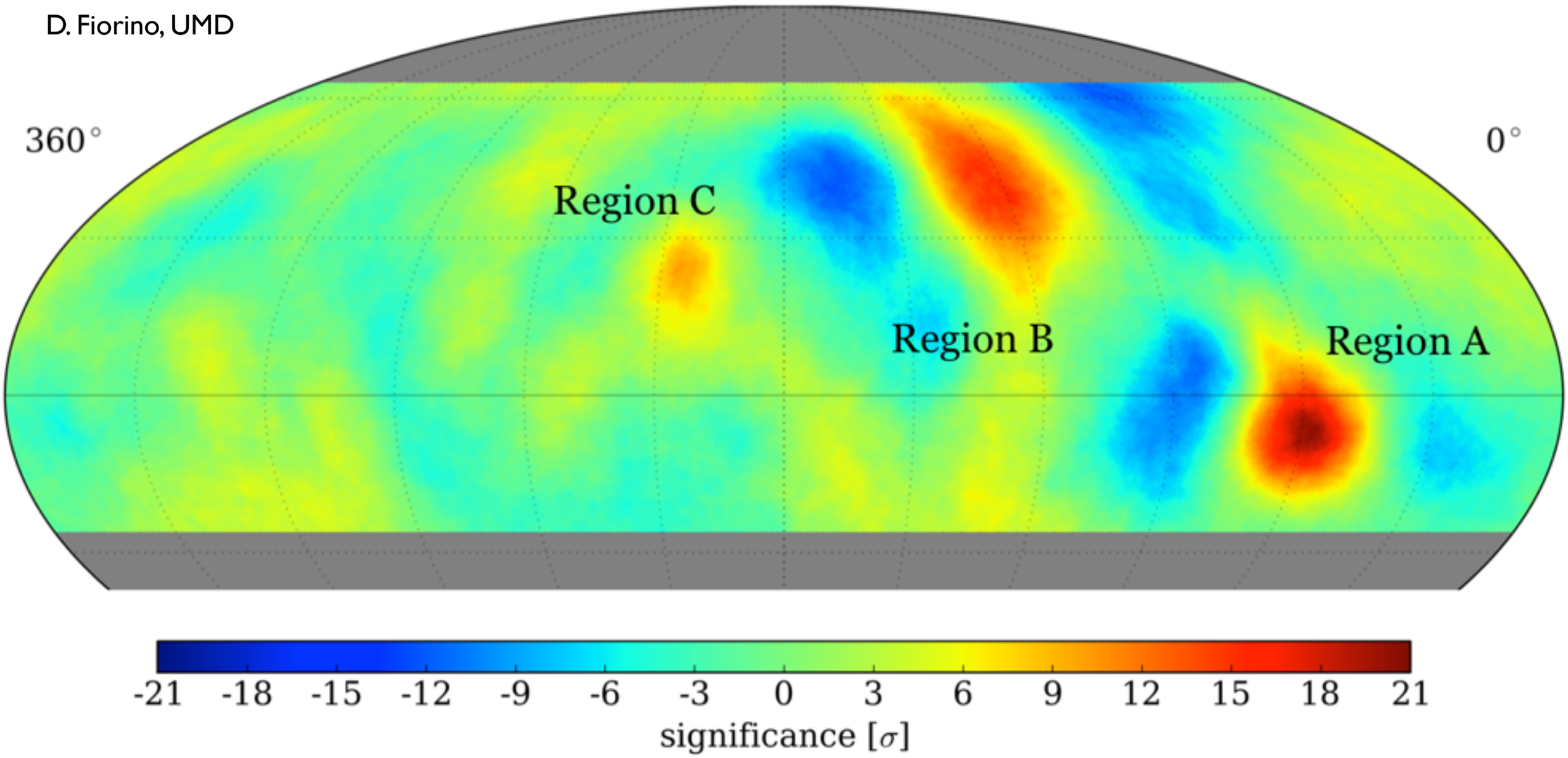
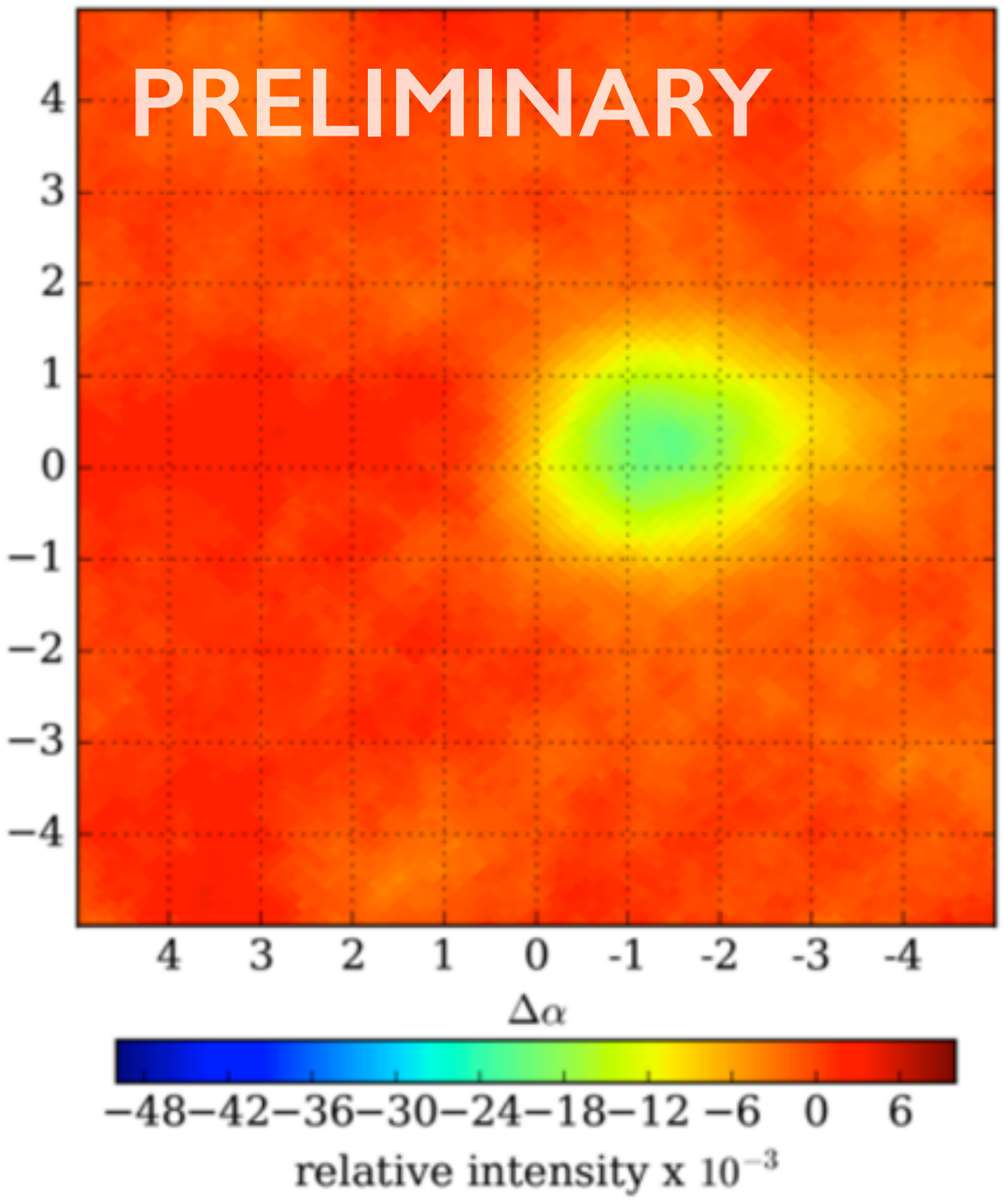


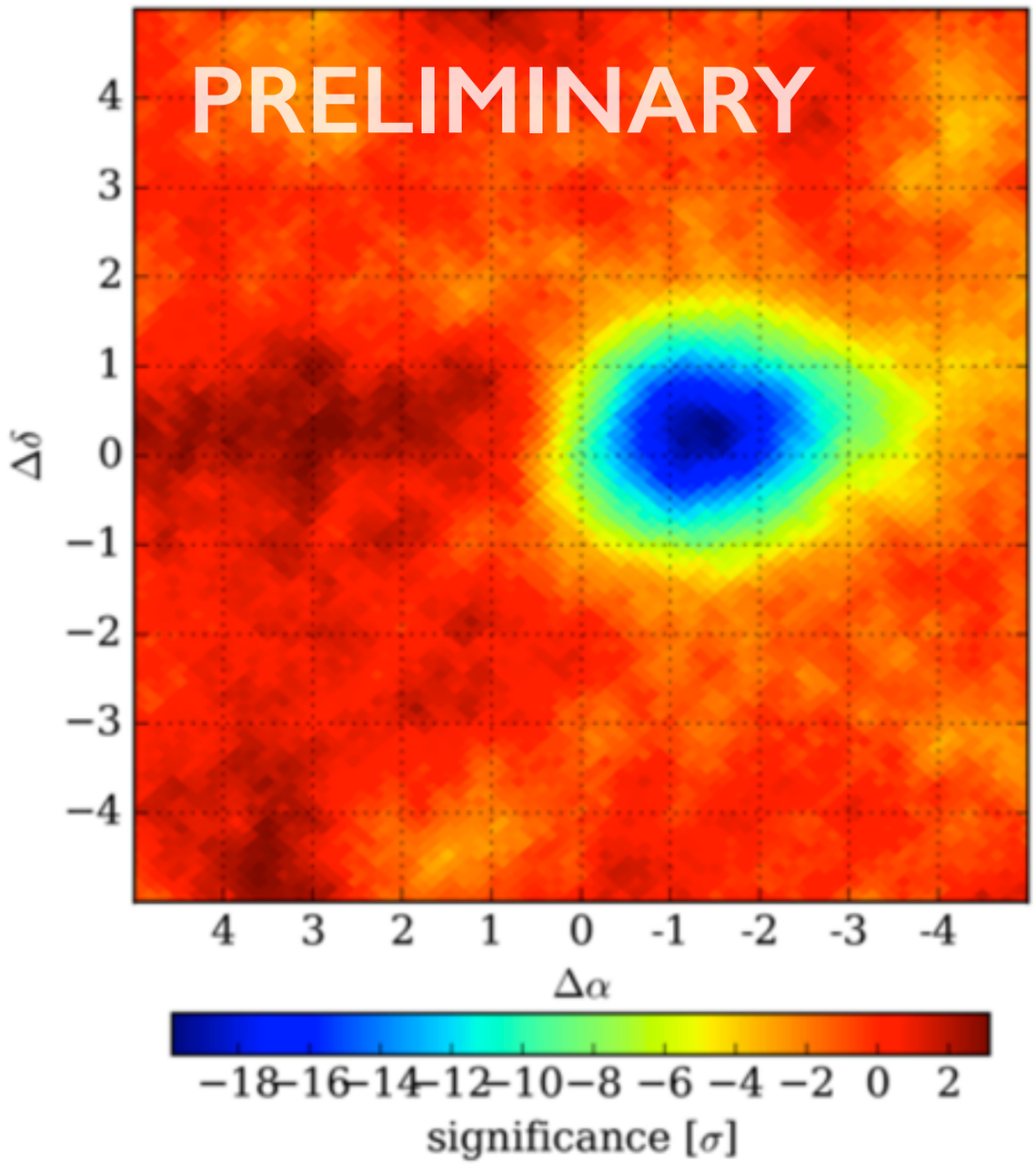
- Anisotropy in cosmic-ray background seen at the 10^{-4} to 10^{-3} level. Signature of nearby accelerator(s)? Magnetic lensing? Exotic particle decay?

Lunar Shadow

Median Energy: 0.6 TeV

Z. Hampel-Arias
UW-Madison





Lunar Shadow

Median Energy: 1.3 TeV

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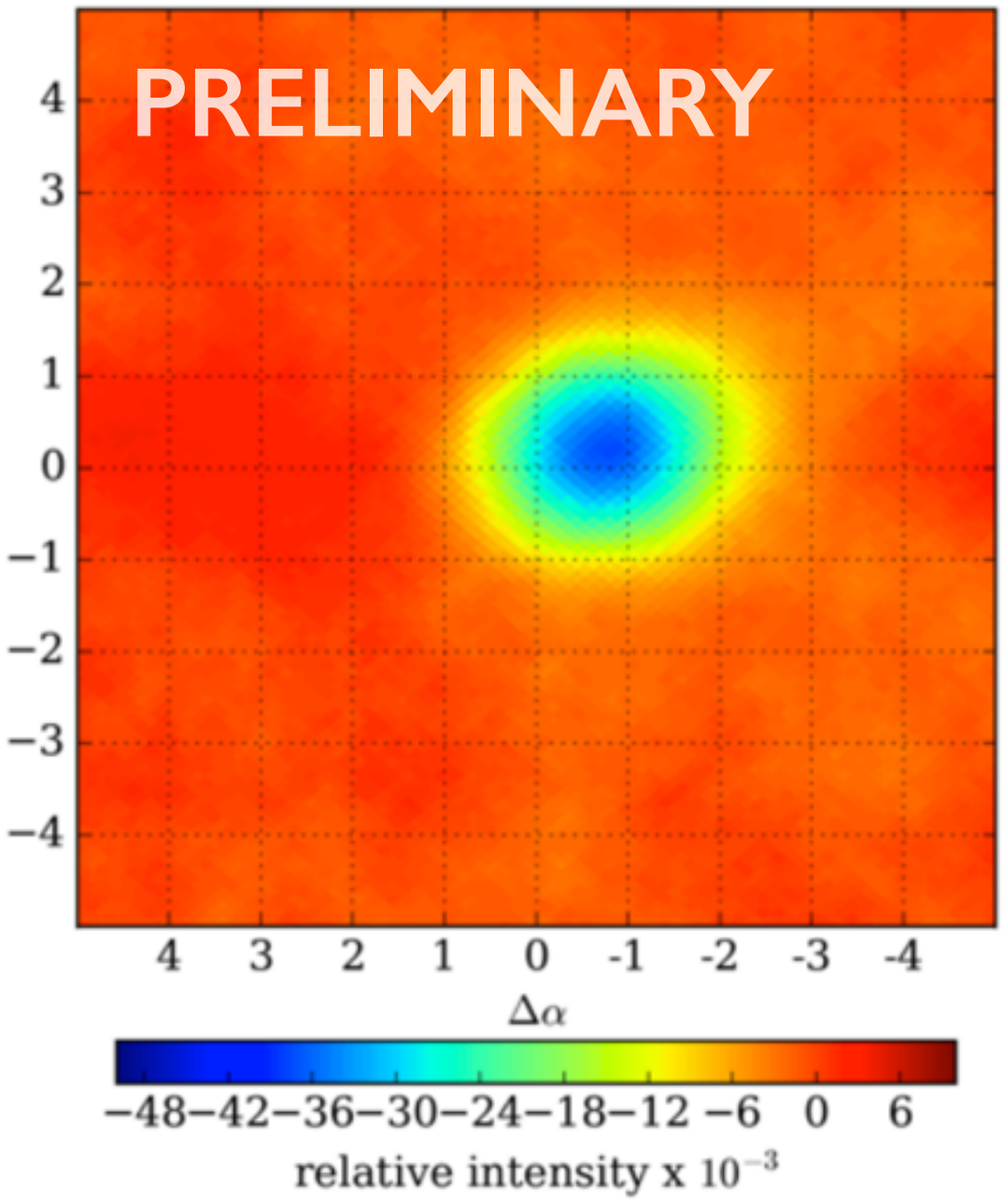
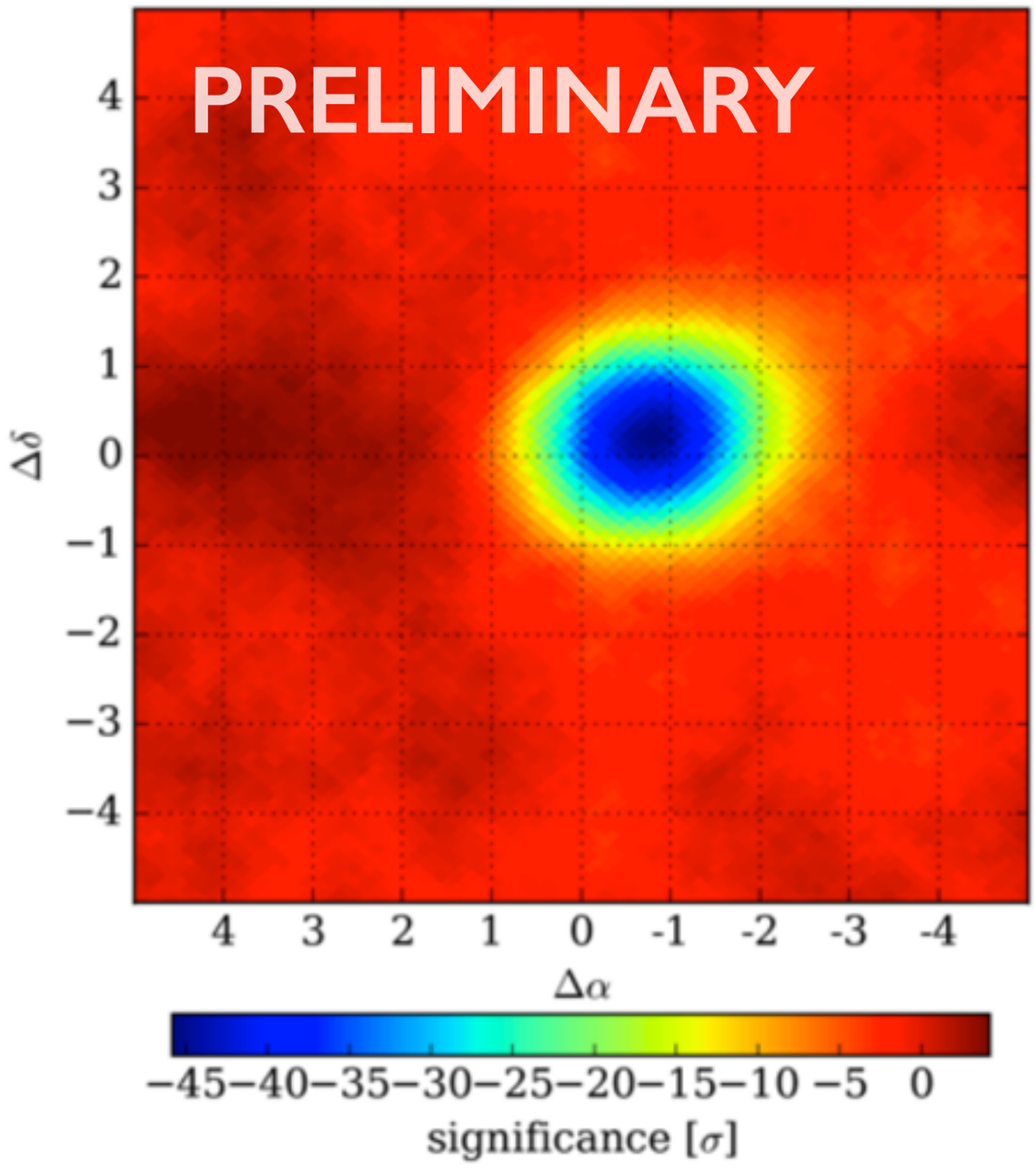
UW-Madison





Lunar Shadow

Median Energy: 5.0 TeV

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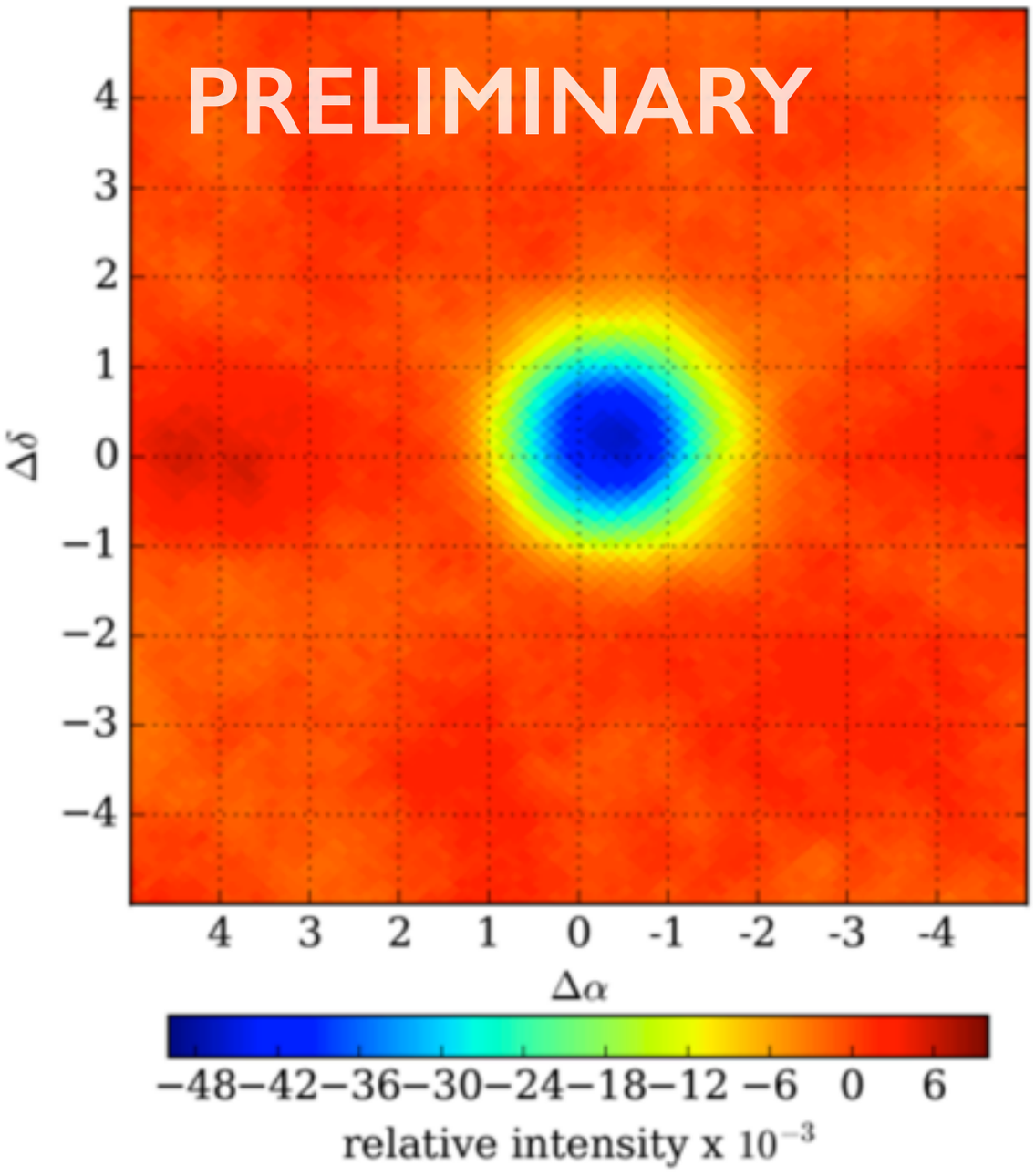
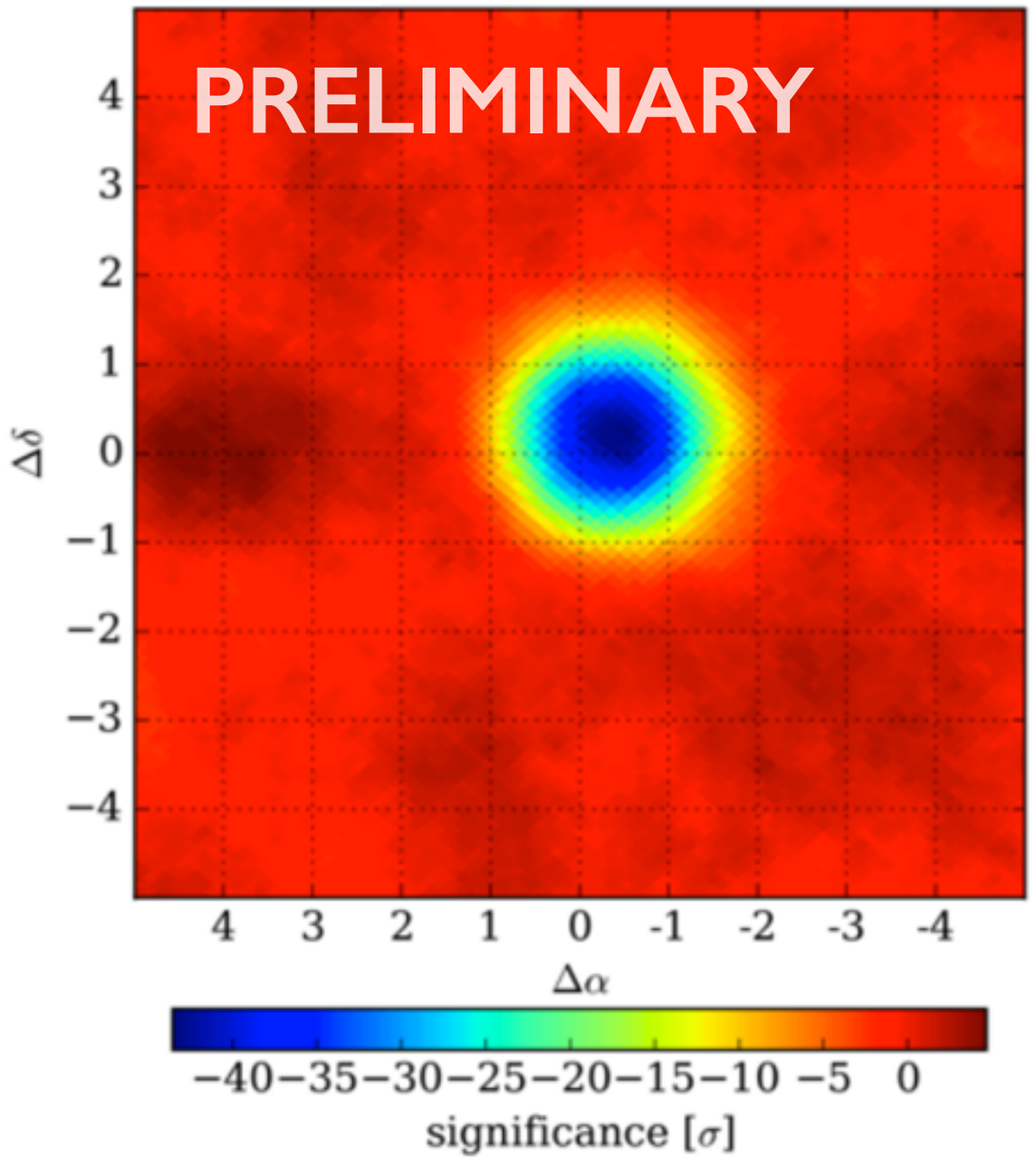
UW-Madison





Lunar Shadow

Median Energy: 17.2 TeV

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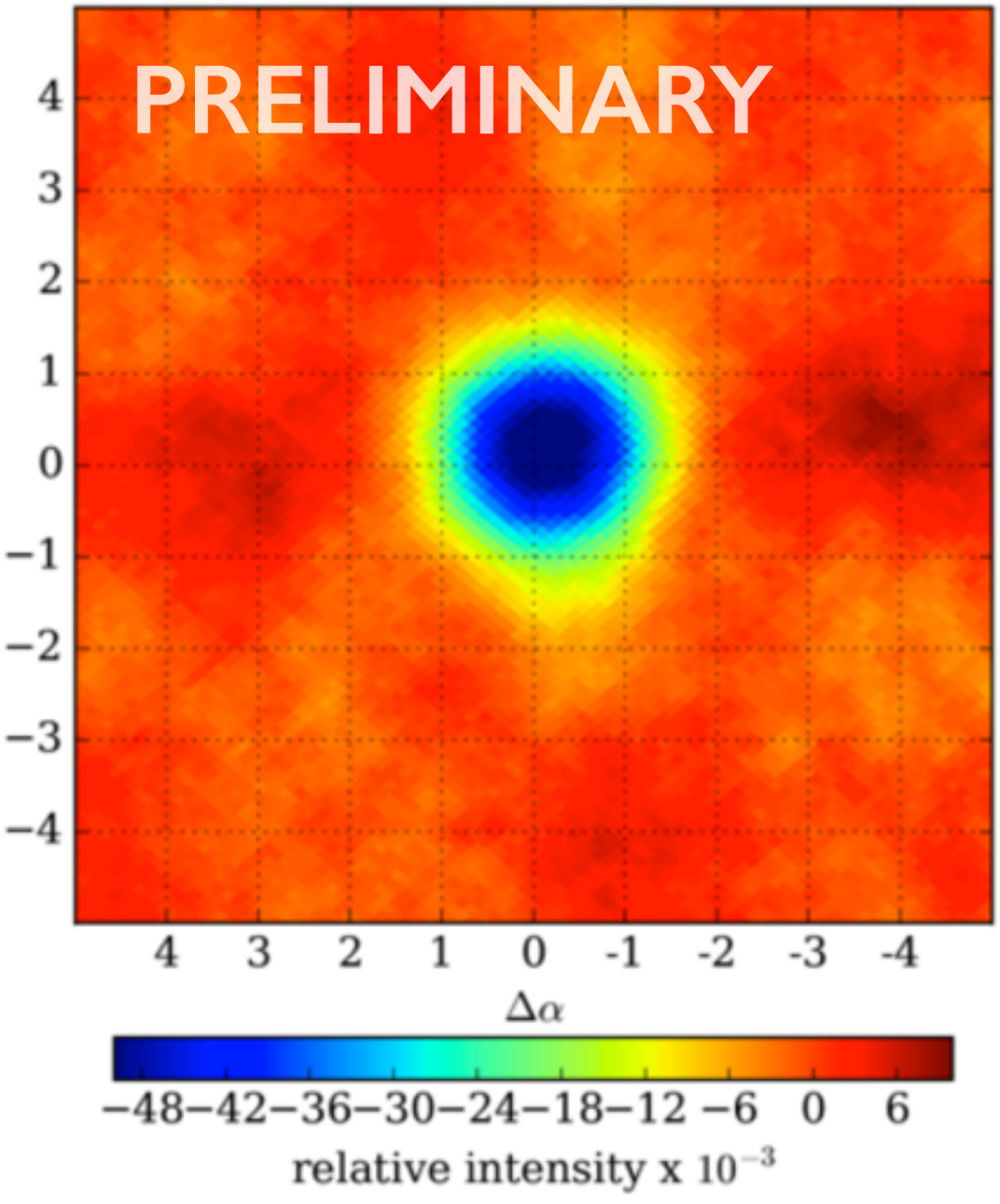

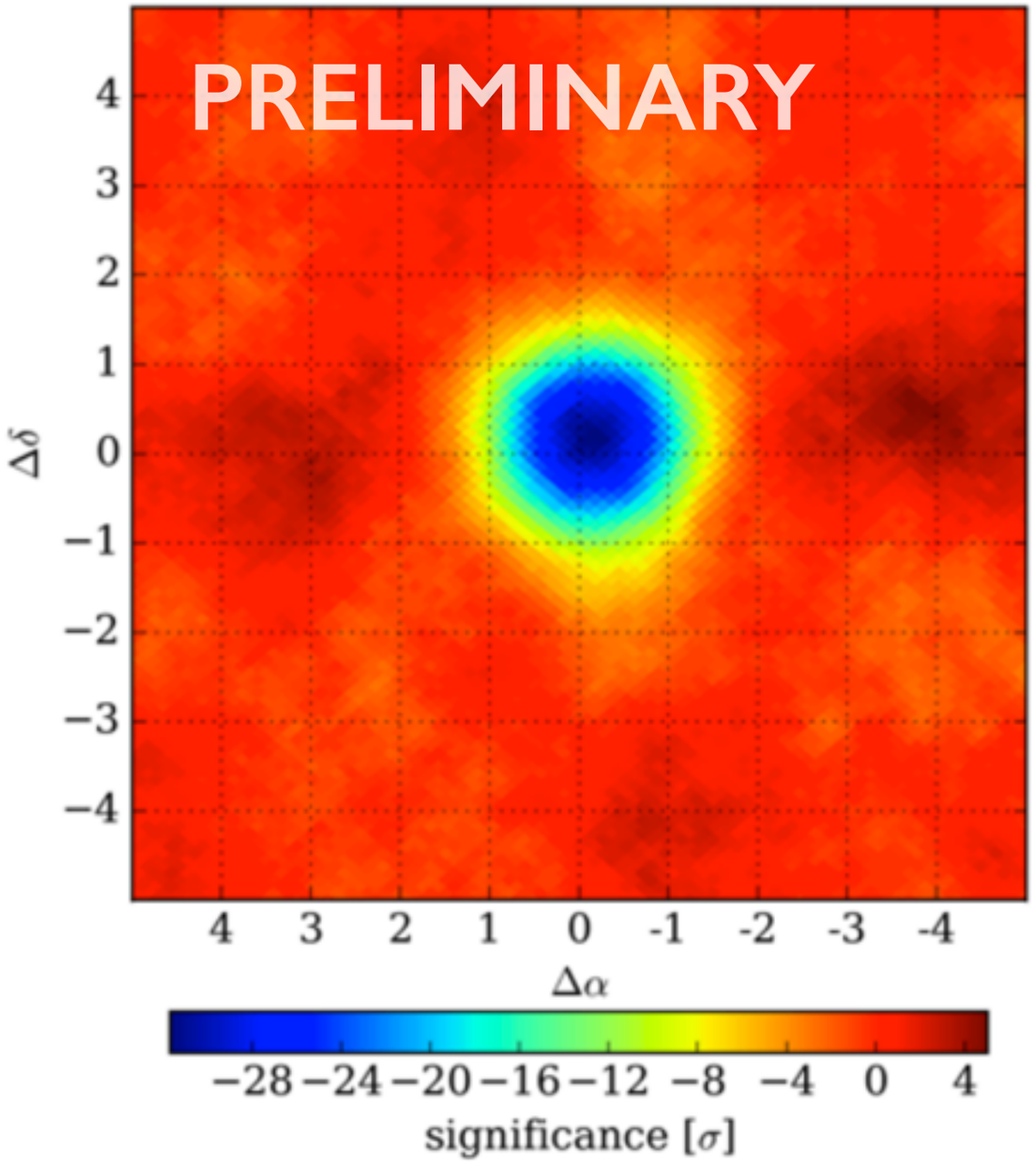

Lunar Shadow

Median Energy: 51.0 TeV

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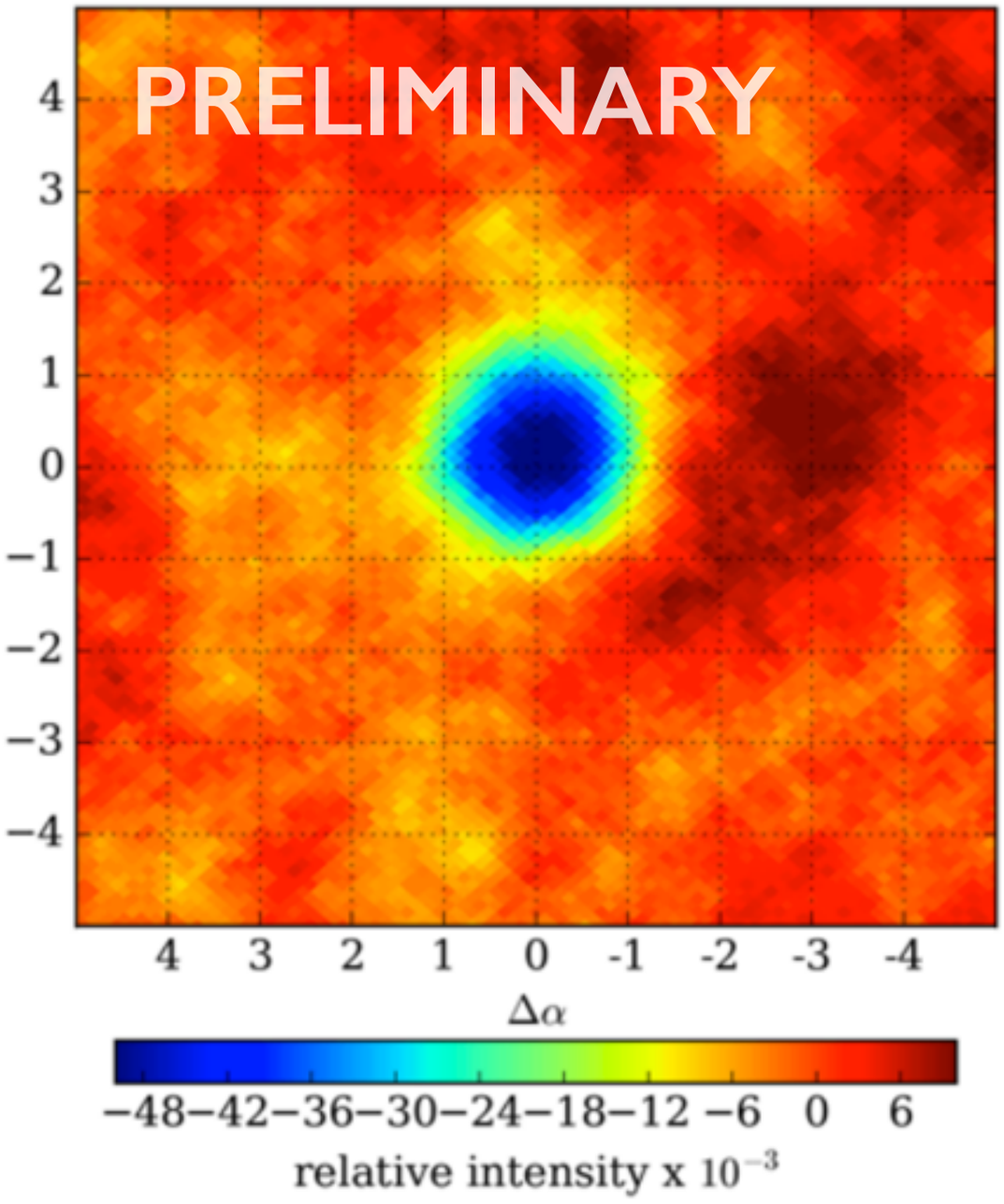

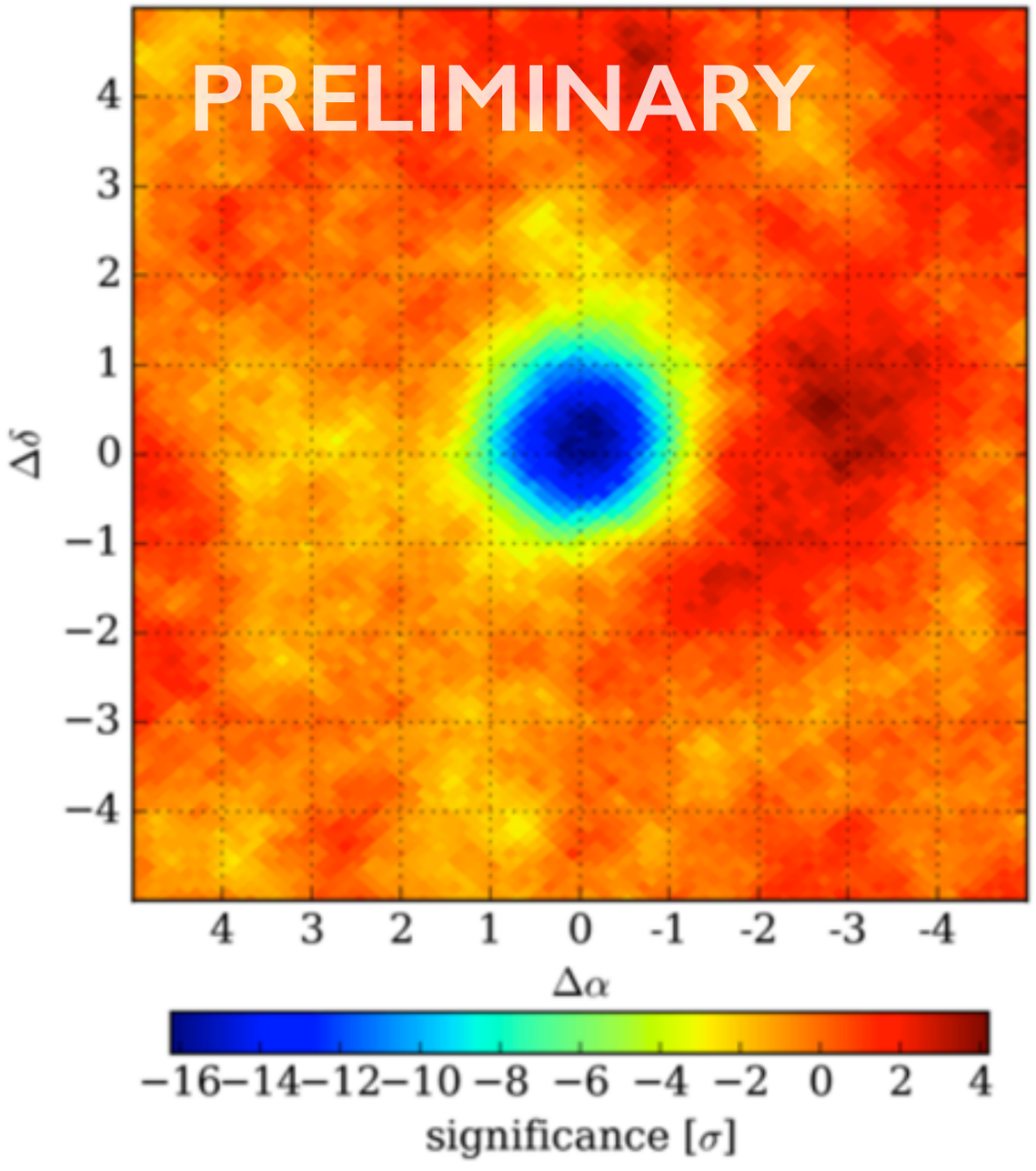

Lunar Shadow

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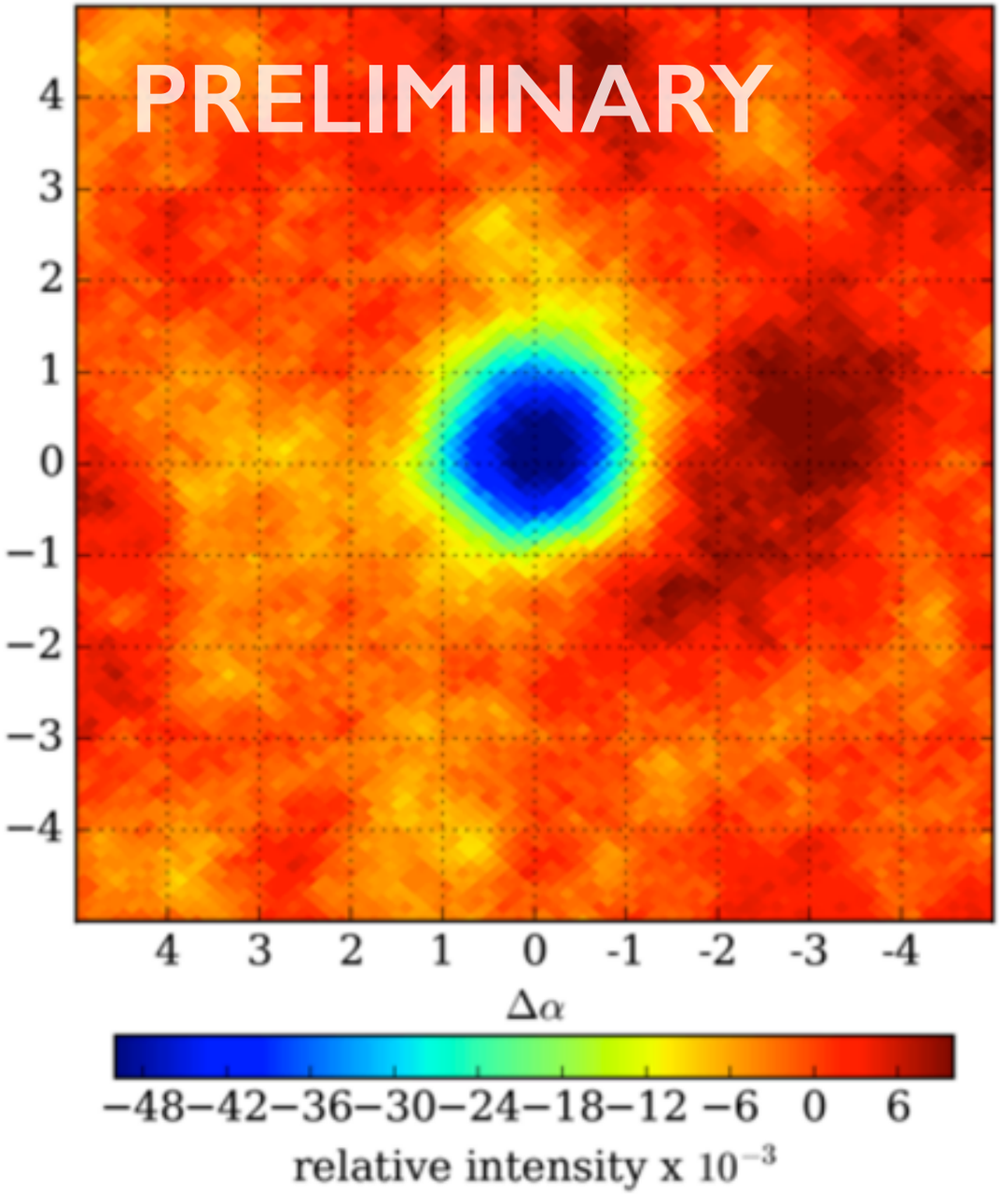
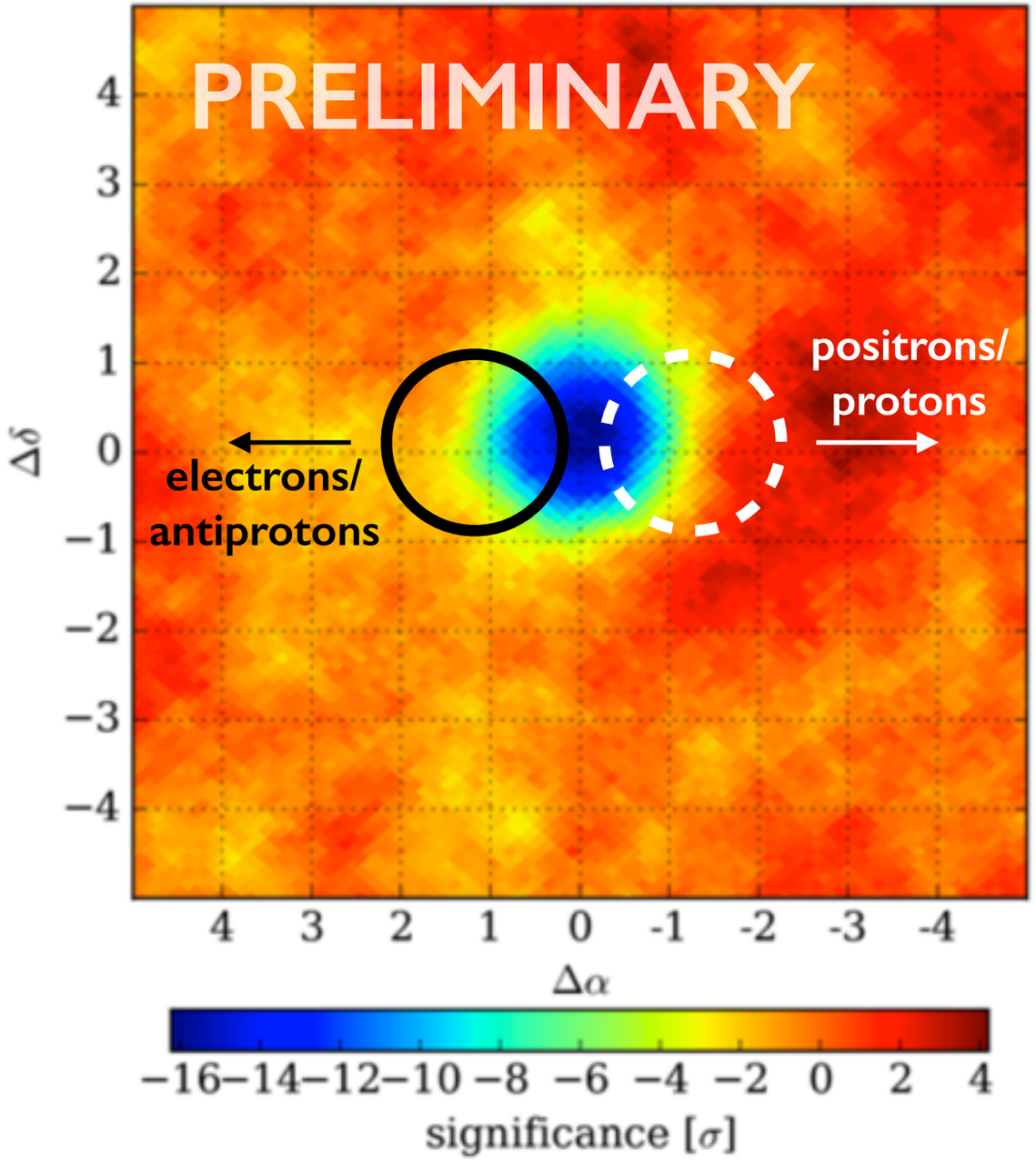
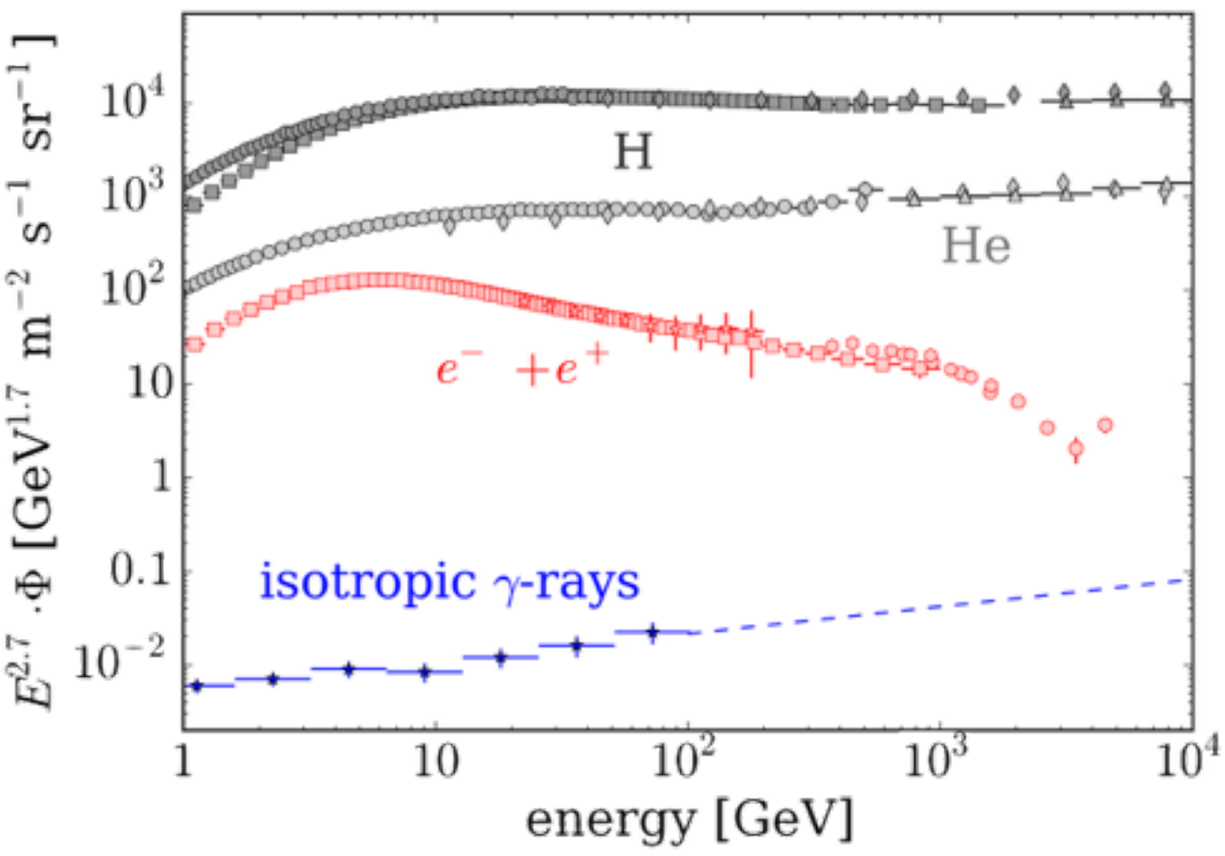
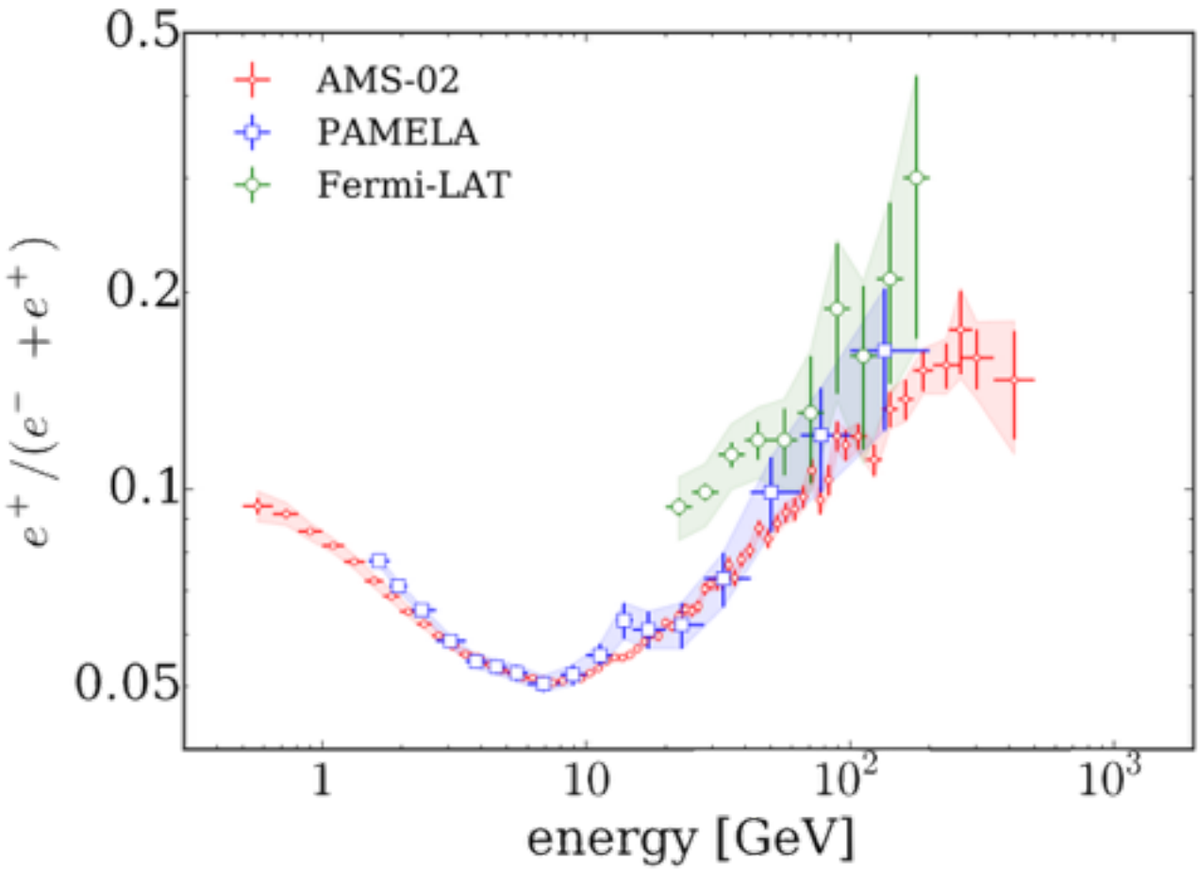




Direct Observation of e^+e^-?

- Can we extend e+ measurements above 1 TeV using the Earth-Moon system as a geomagnetic spectrometer?





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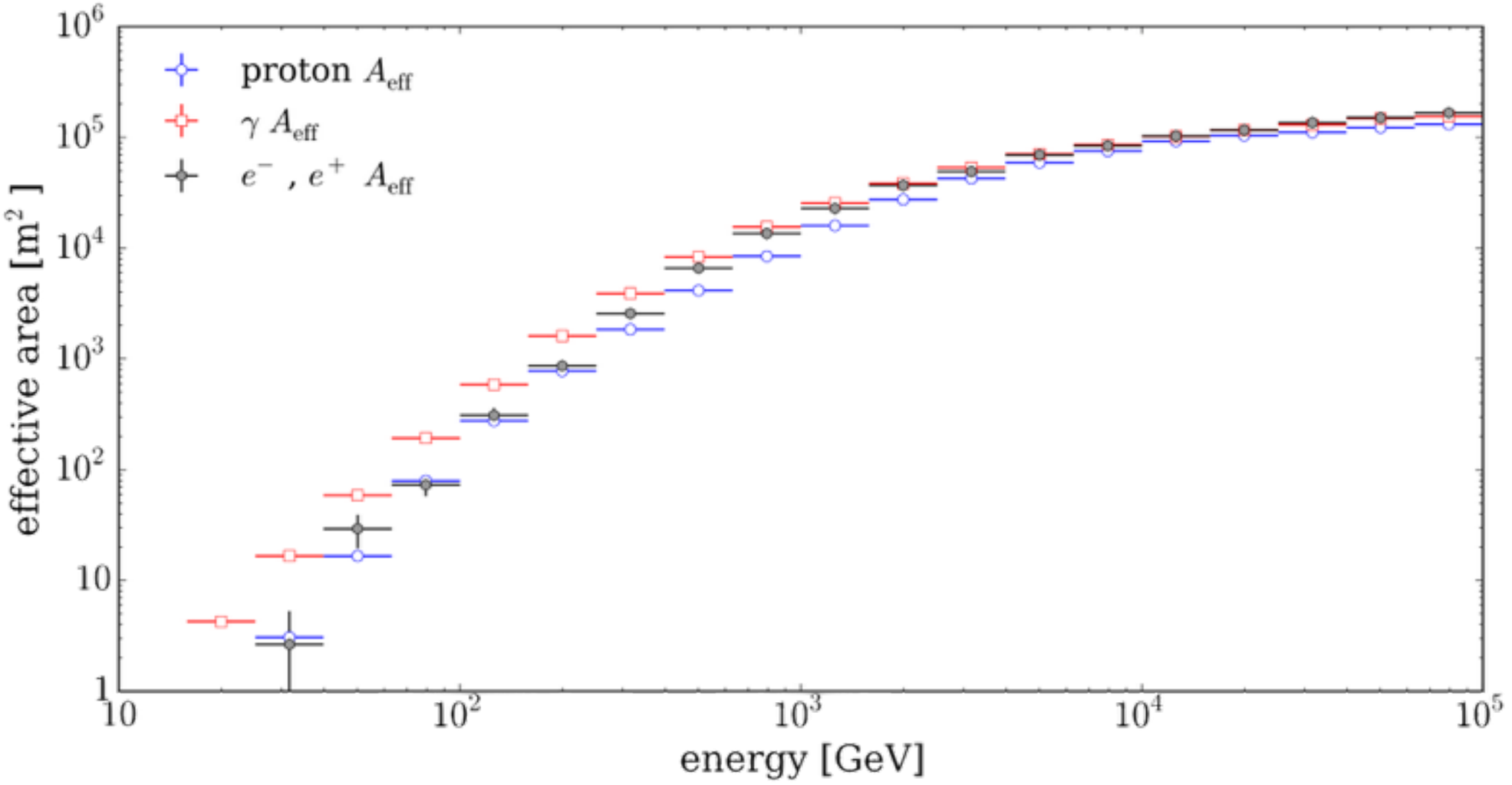

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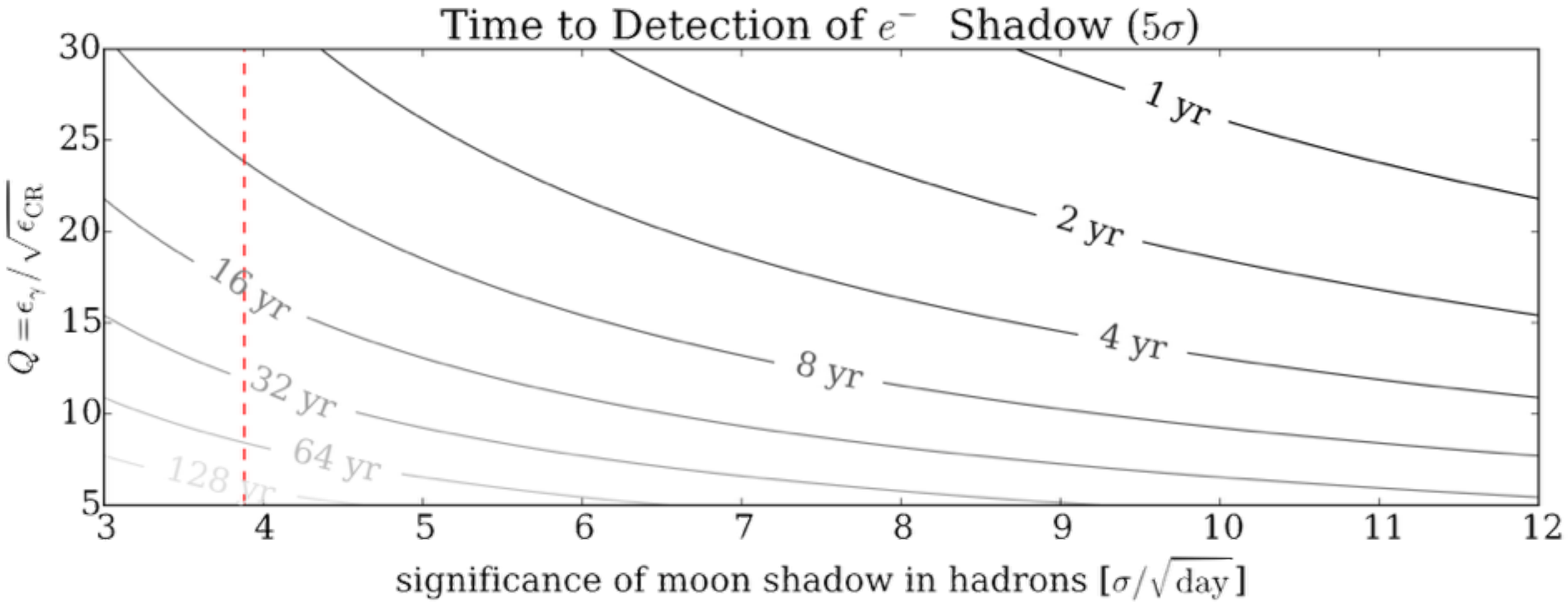
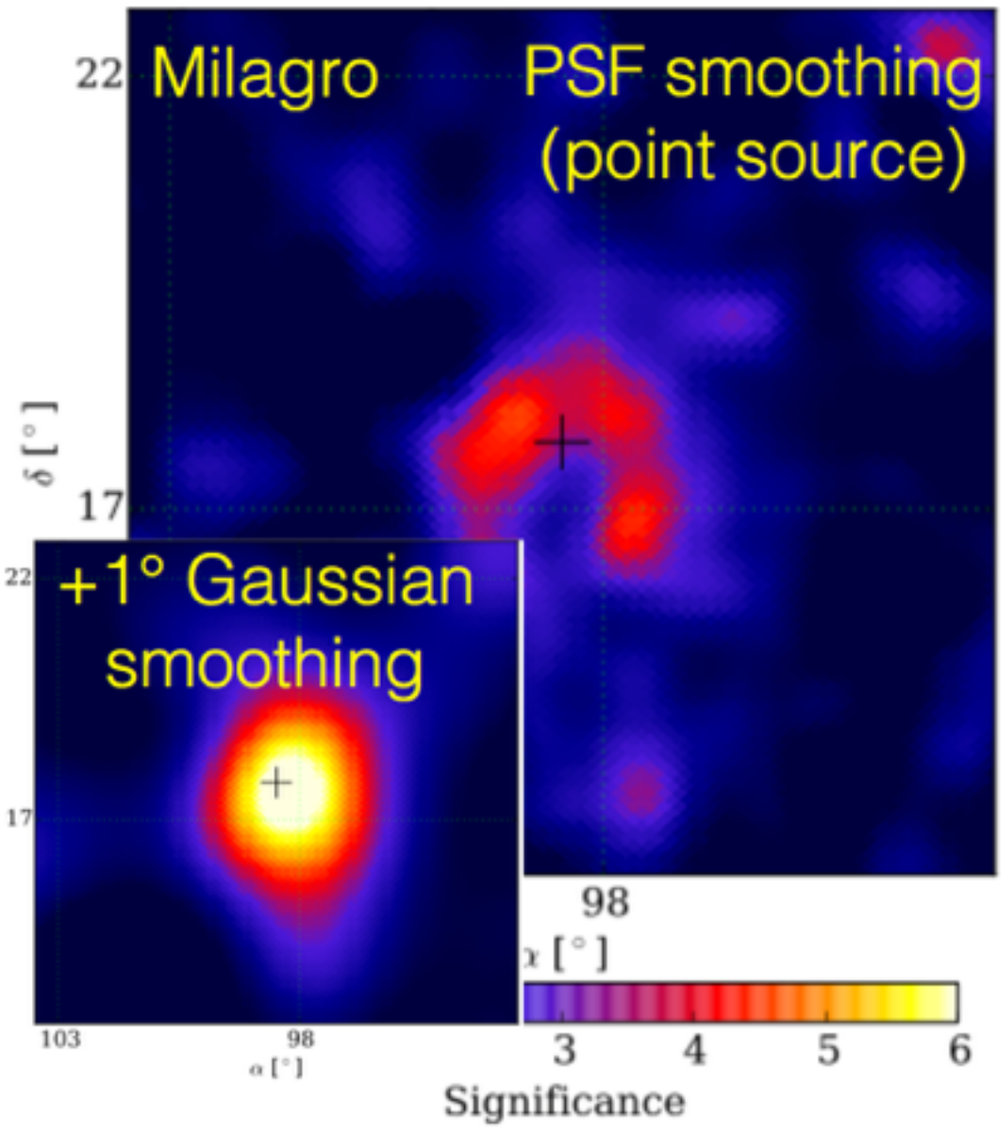


- At 2-3 TeV "sweet spot" we are fighting against the very steeply falling $e^{\pm}$ flux. A very challenging analysis for HAWC!

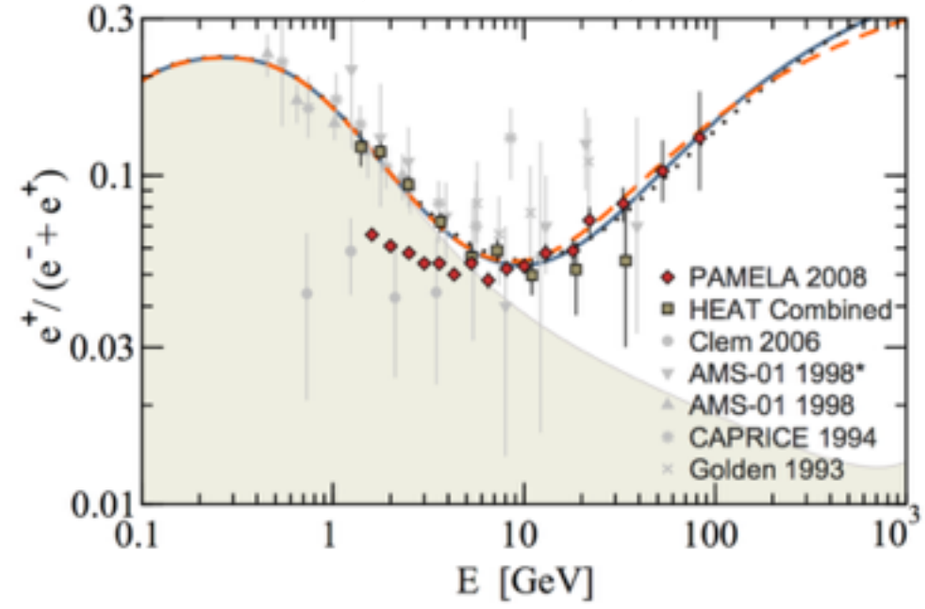
Indirect Observation of e^+e^-

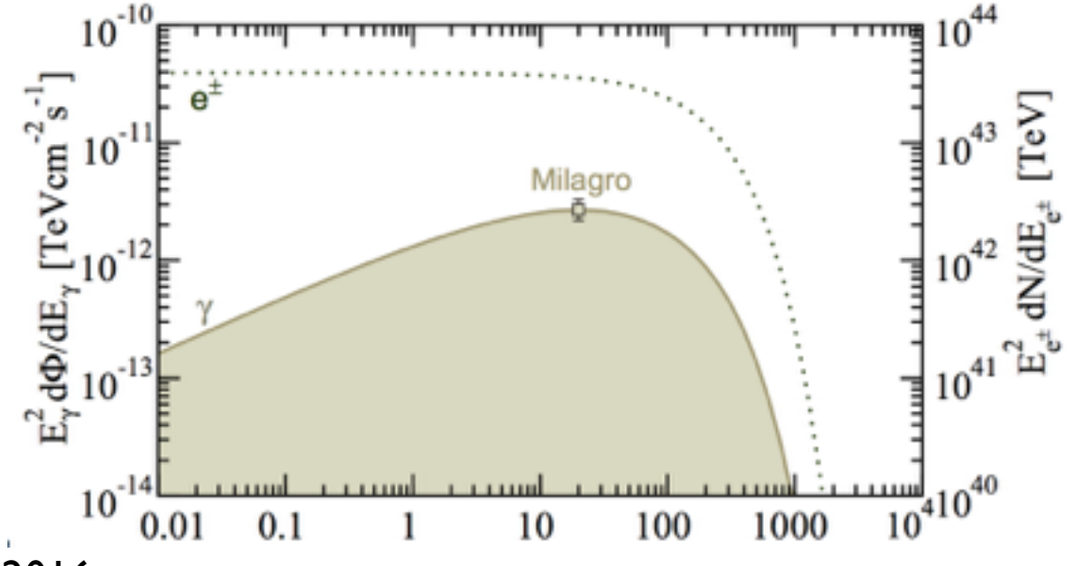
- Positron excess at Earth; created by nearby middle-aged pulsar?
- Geminga could be that pulsar. 300 kyr old, ~250 pc distant

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

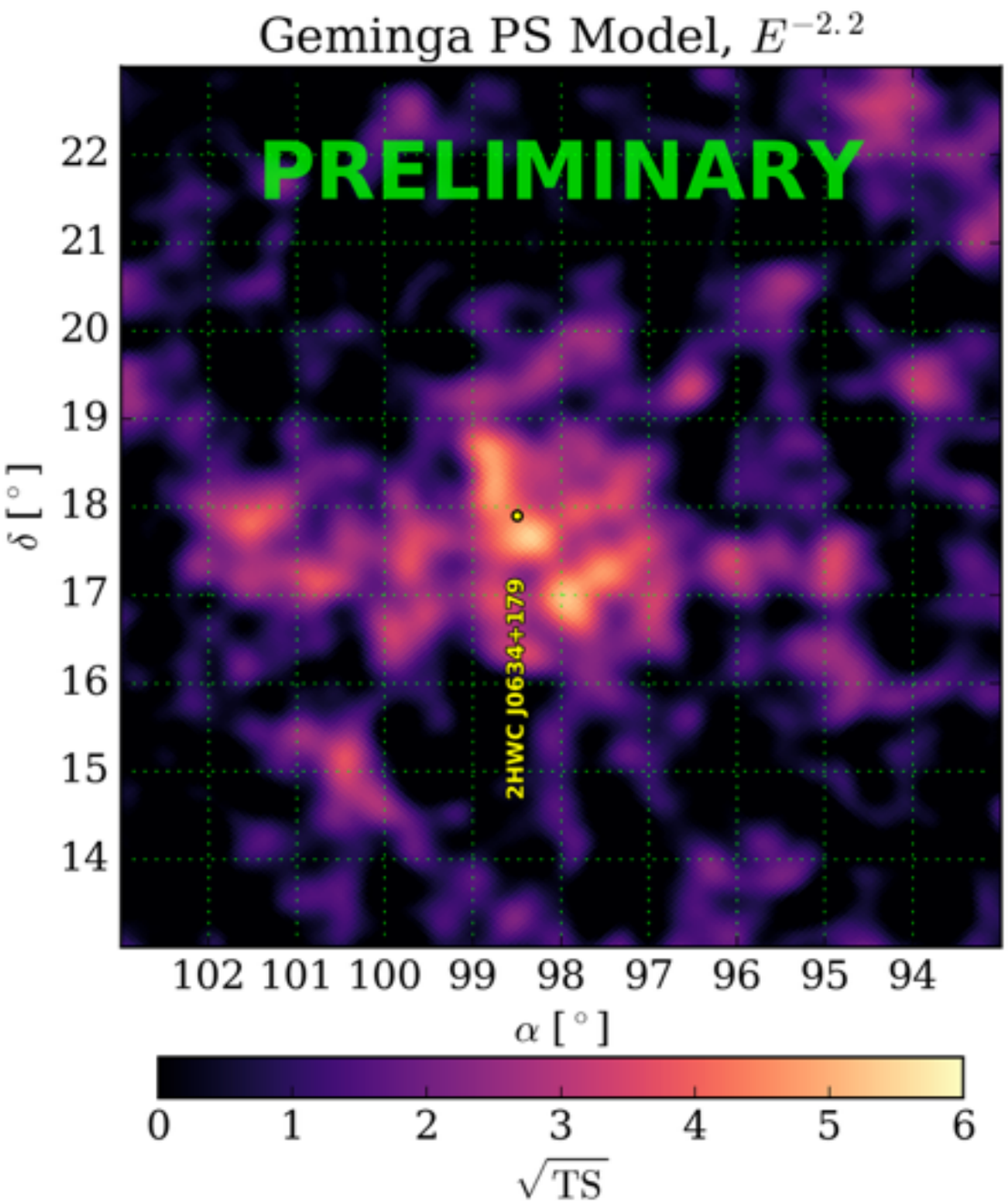


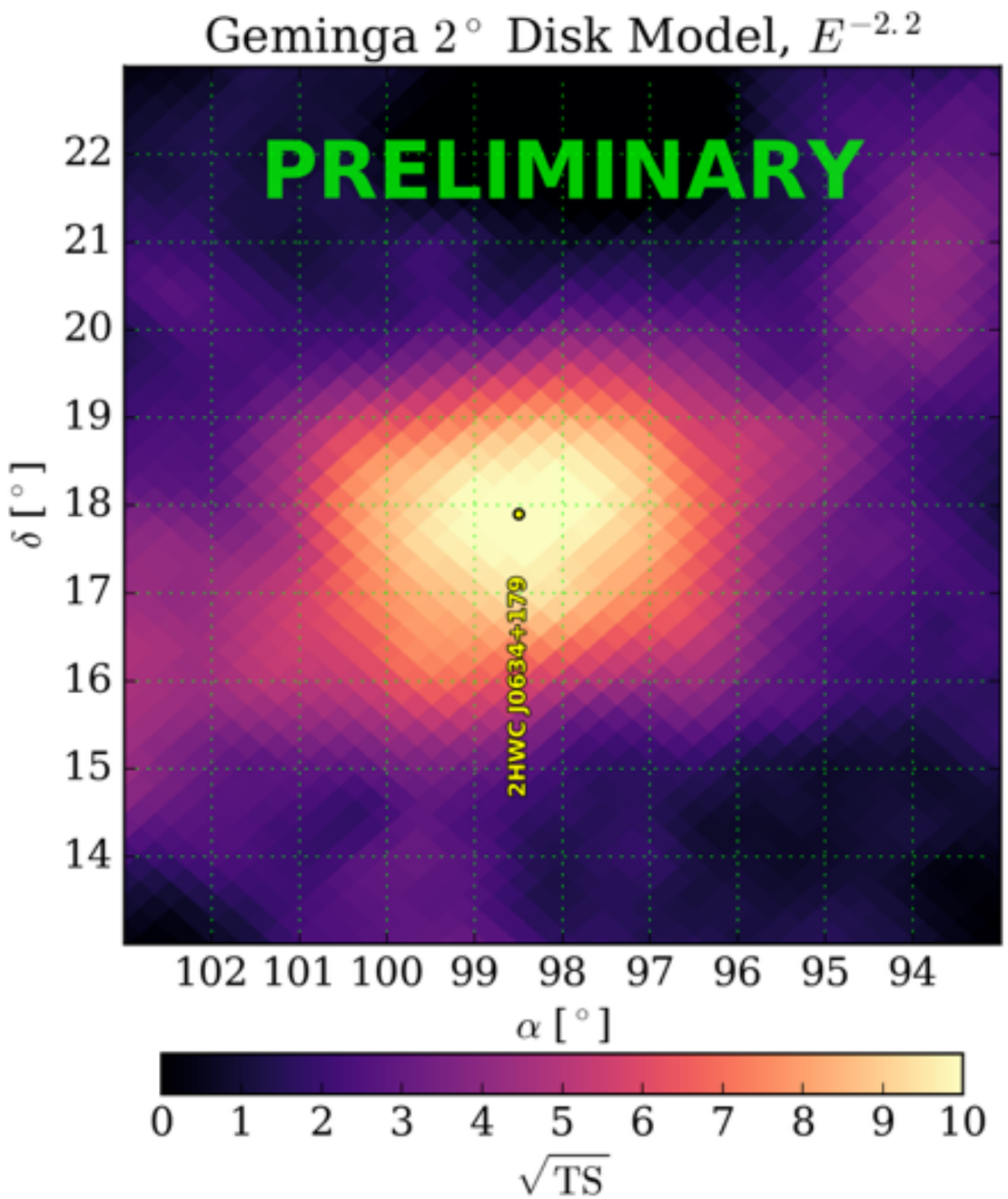
H. Yüksel et al., PRL **103**:0511101, 2009





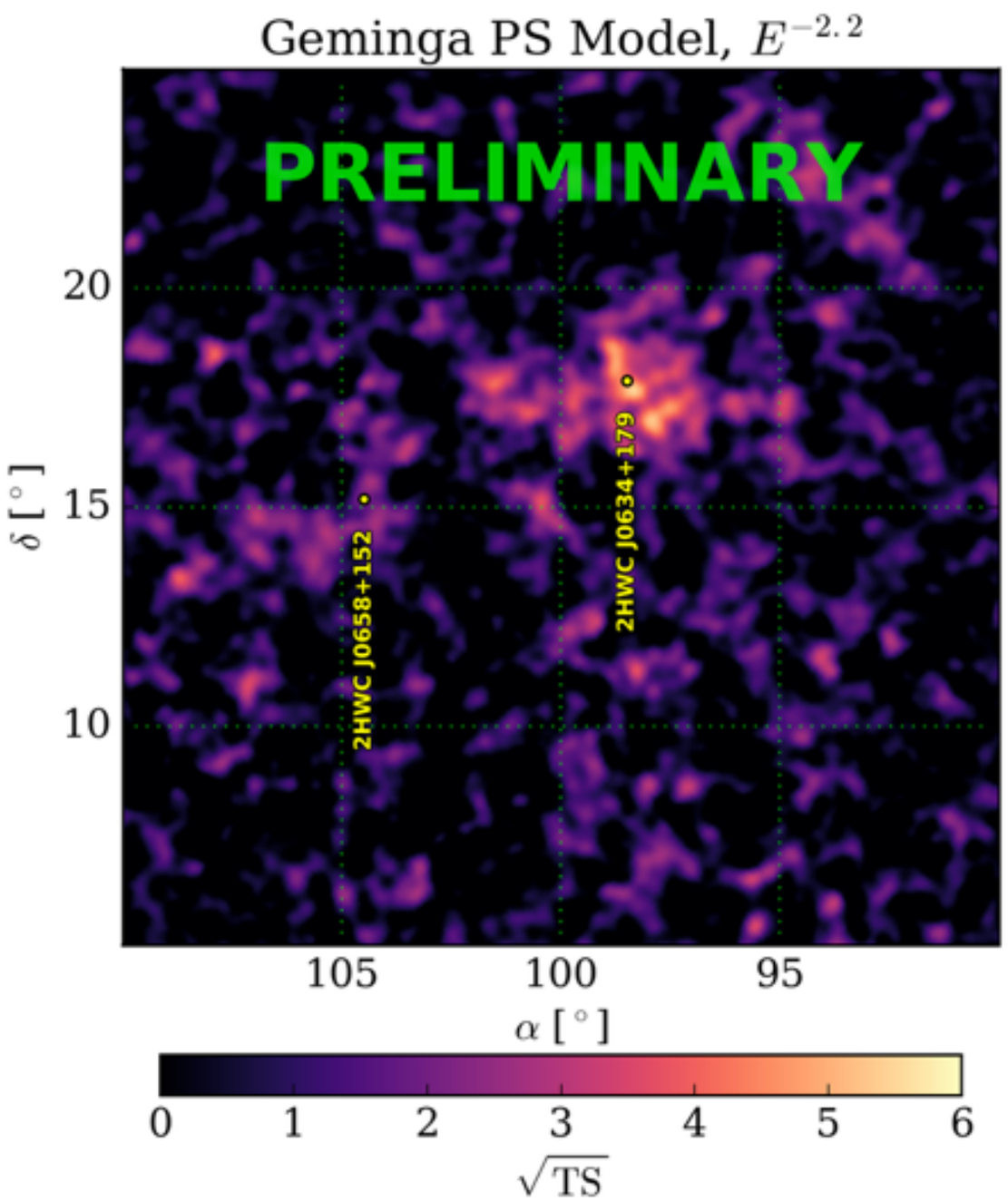
Observation with HAWC

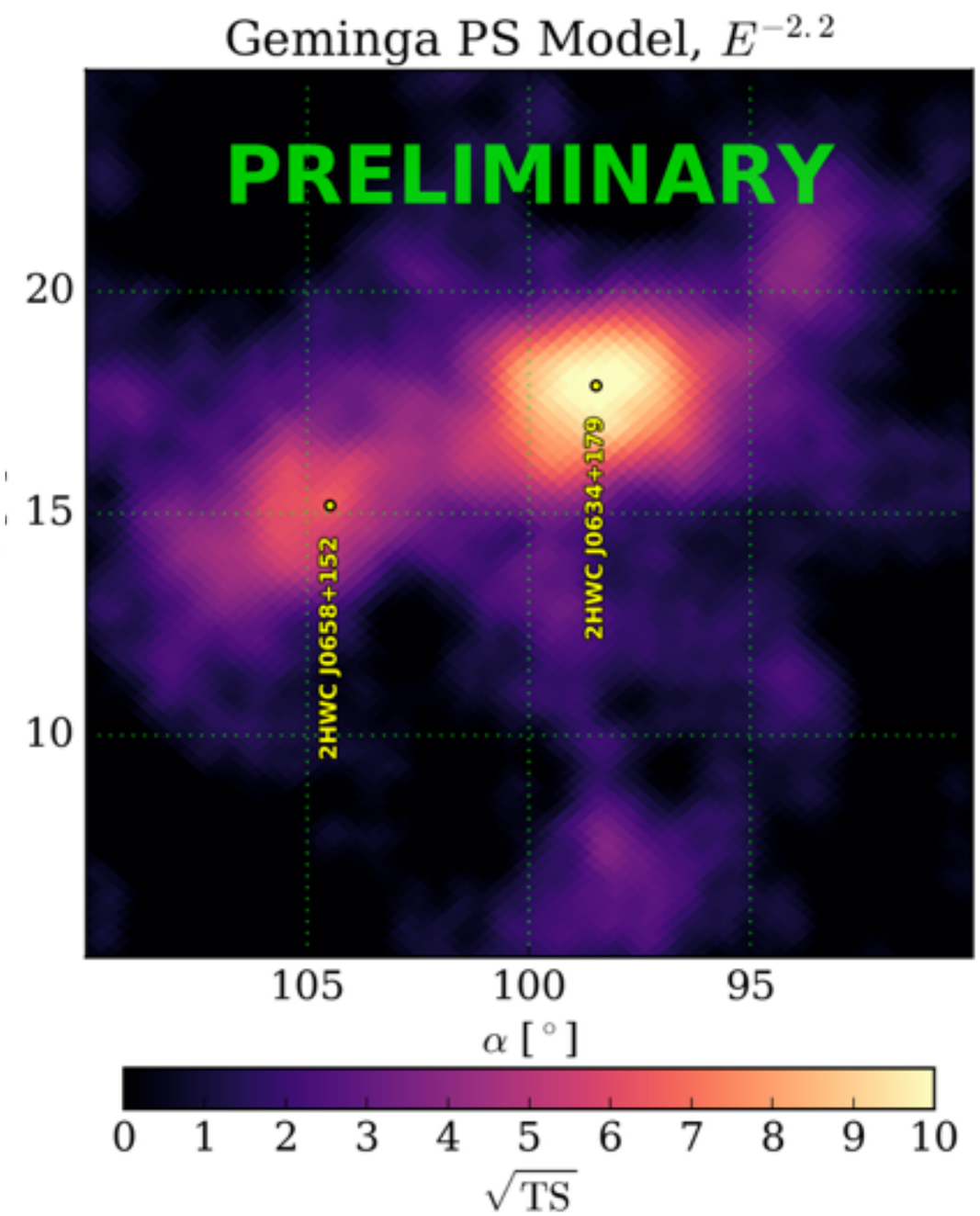




P. Salesa-Greus, IFJ-PAN

Geminga and PSR J0659+14

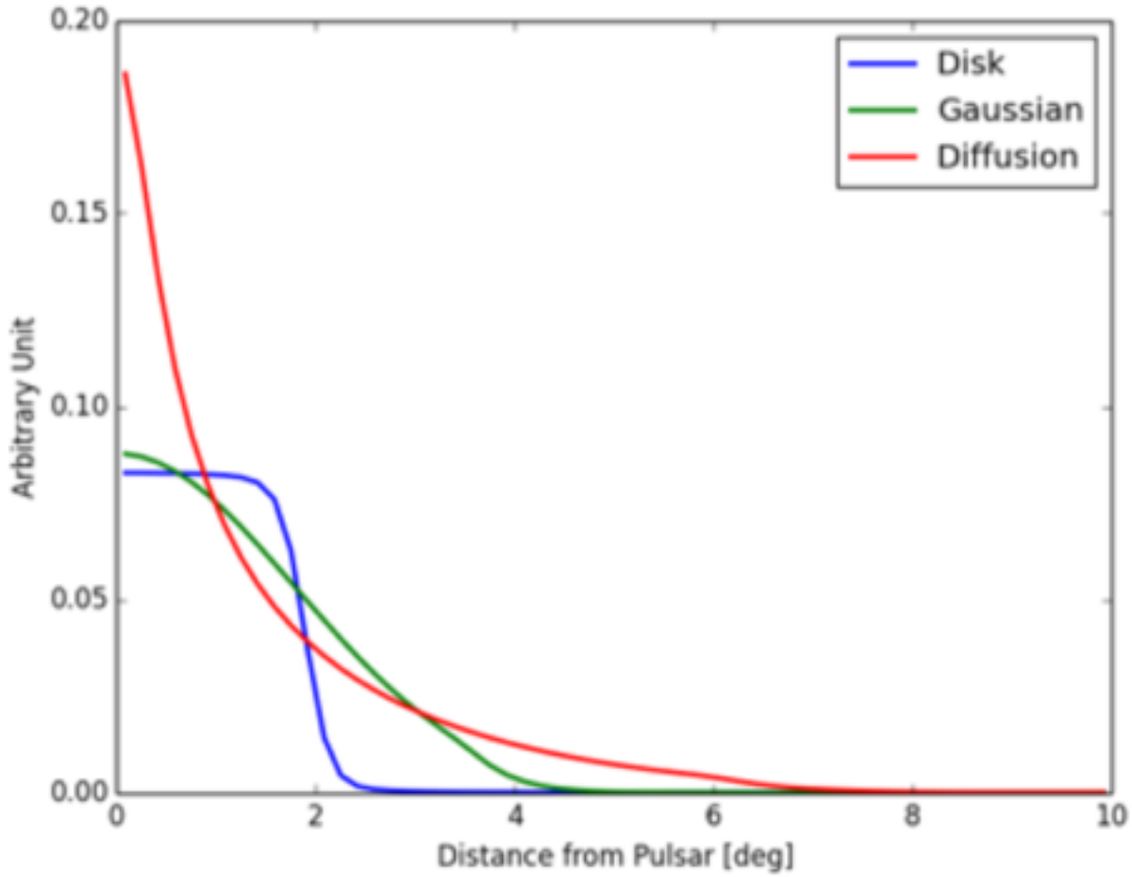




P. Salesa-Greus, IFJ-PAN

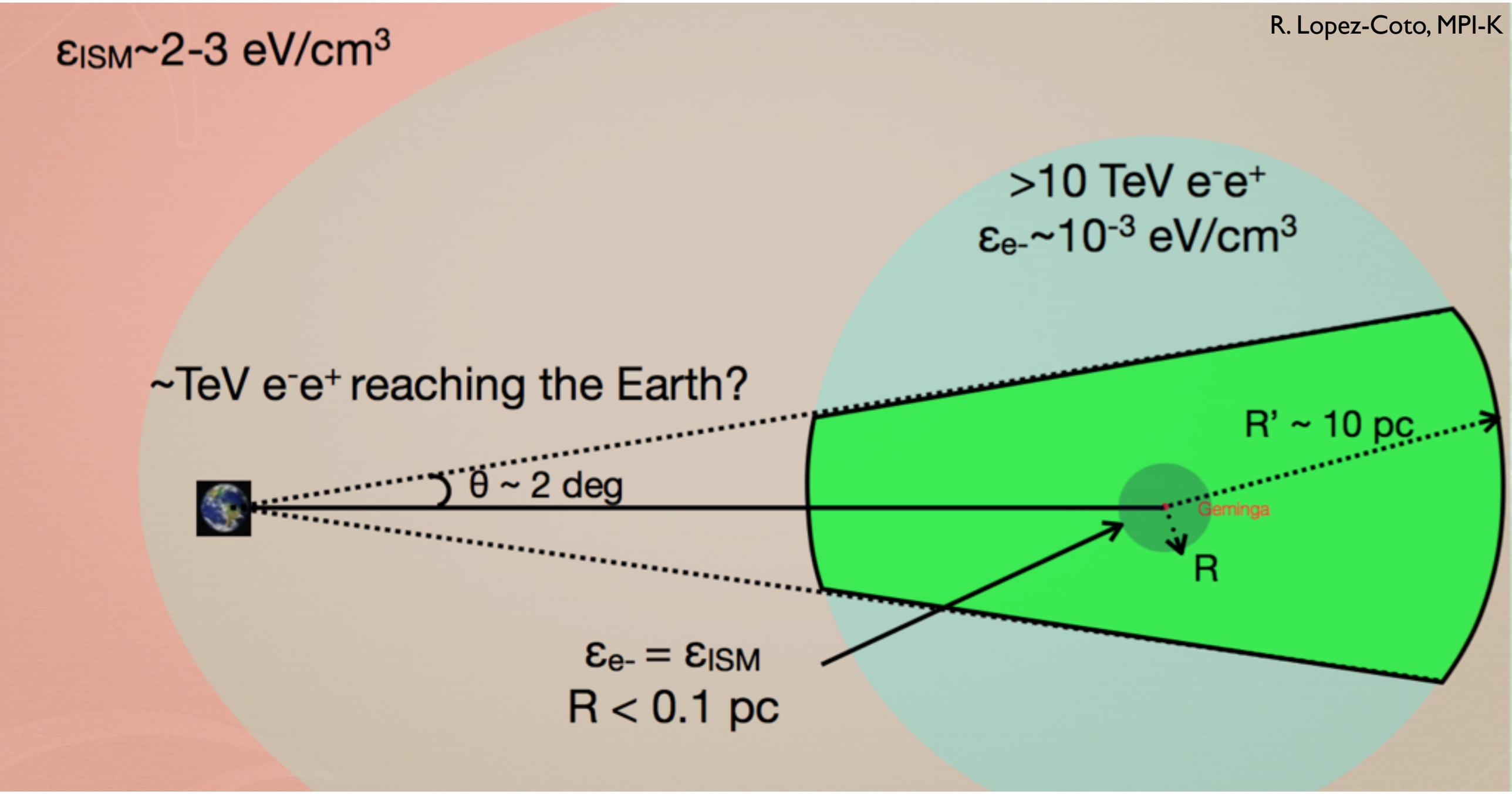
Morphology and $e^{\pm}$ Flux

- Morphological fits to disk, Gaussian, and particle diffusion models. Results soon!
- Using spectrum + morphology, we can infer the diffusion coefficient and *identify* or *rule out* these close pulsars as the source of $e^{\pm}$ at Earth



- Note: no other TeV observations; limits on emission from the pulsar and surrounding nebula by MAGIC (arXiv:1603.00730). Angular extent makes observations tricky for IACTs
- Note: large nebula is also not observed at other wavelengths: ~2' tails seen in X-ray, Caraveo et al., Science **301**:2003, 1345

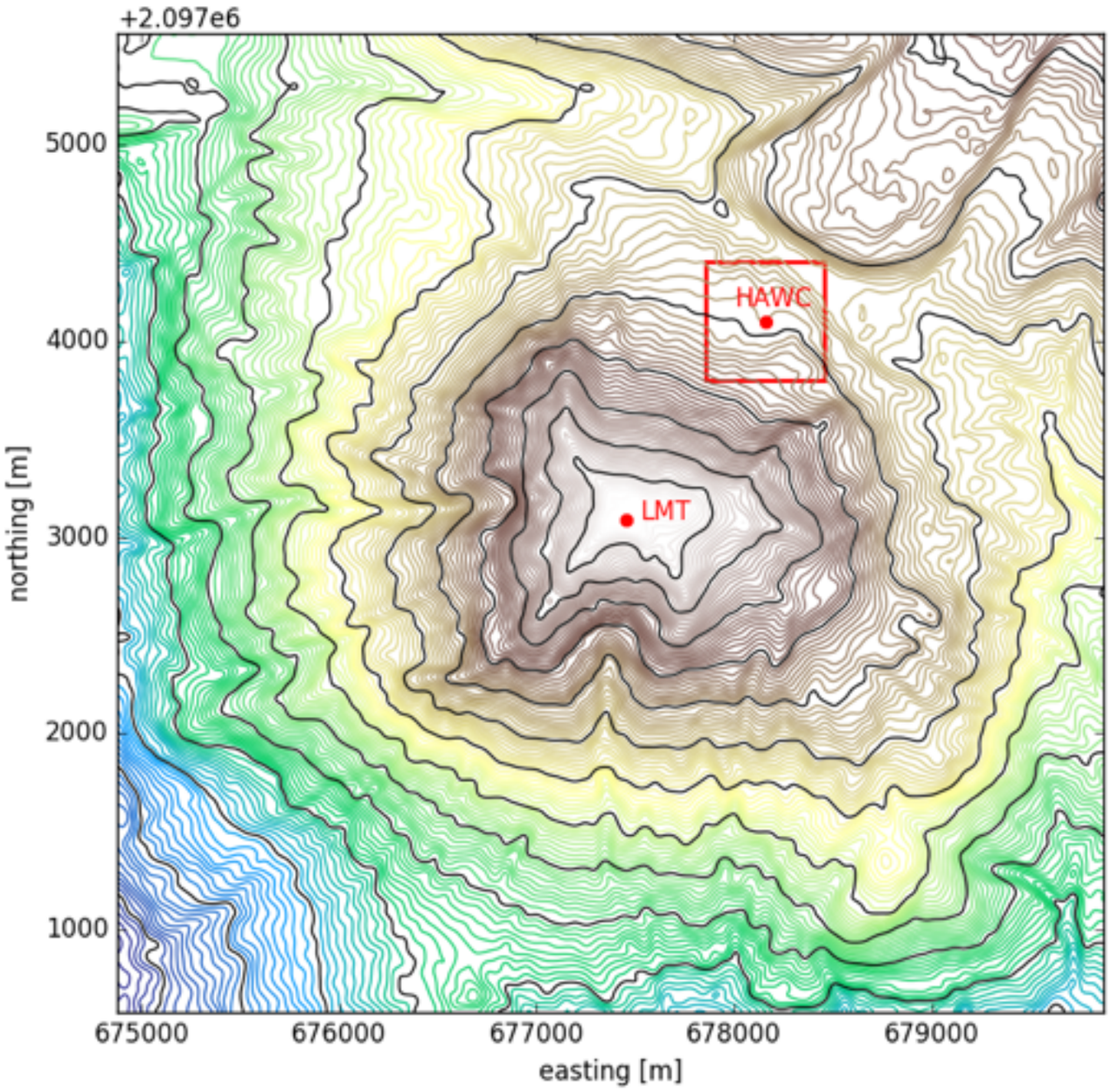
Spectrum + Angular Profile

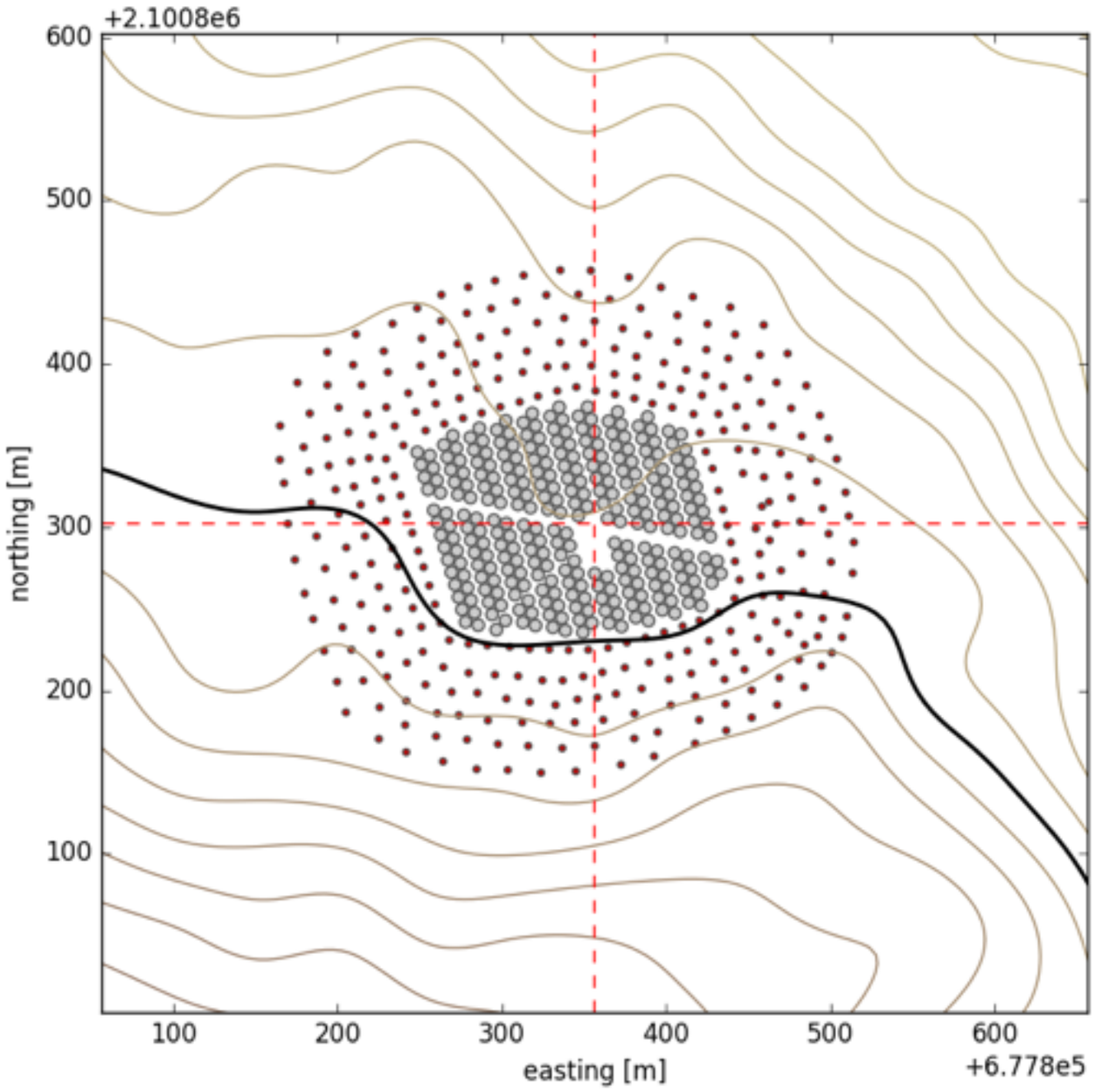


- Are we seeing emission from electrons diffused into the ISM?

HAWC Upgrades

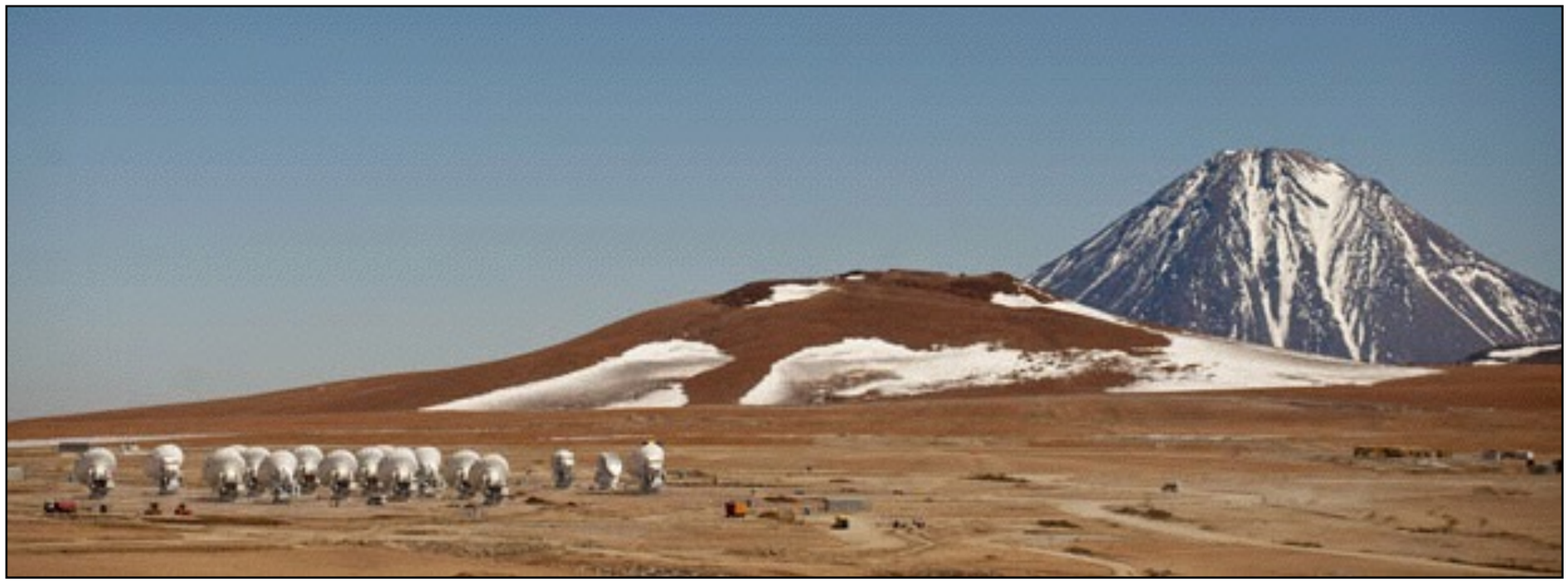
- High-energy extension: outrigger tanks funded (LANL LDRD)
- Test tanks deployed; PMT tests underway; FLASHCAM electronics





Southern Gamma-Ray Survey Observatory

- A high altitude site (4800-5000 m a.s.l.) in the Southern Hemisphere is under discussion. See presentation on August 6 by **M. DuVernois**

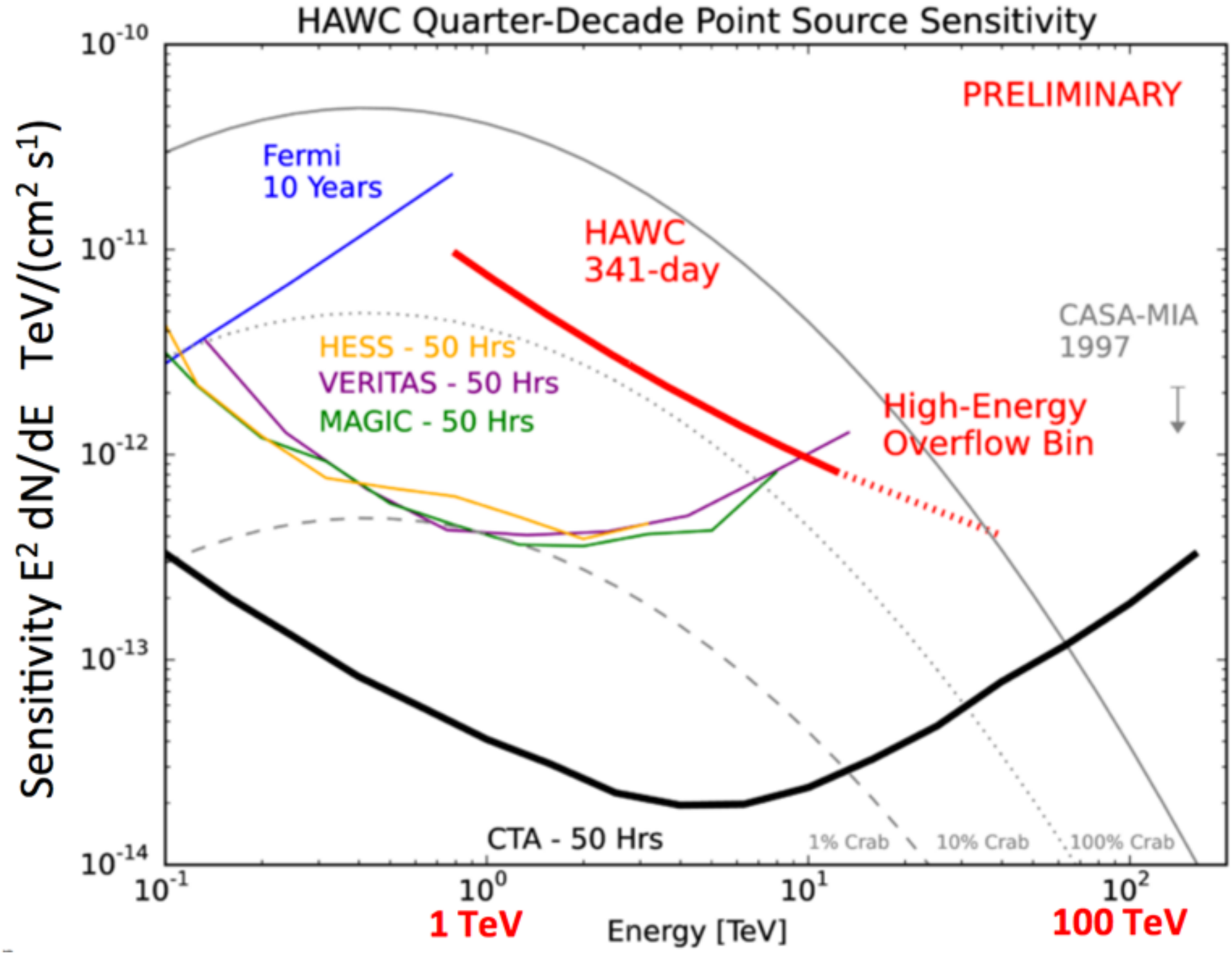


- Goals: improved sensitivity <1 TeV, exposure to Galactic Center, about 8 sr daily sky coverage, early warning system for CTA
- **SGSO Workshop**: Puebla, Mexico, Nov. 11-12. For details, see http://events.icecube.wisc.edu/conferenceDisplay.py?confId=81

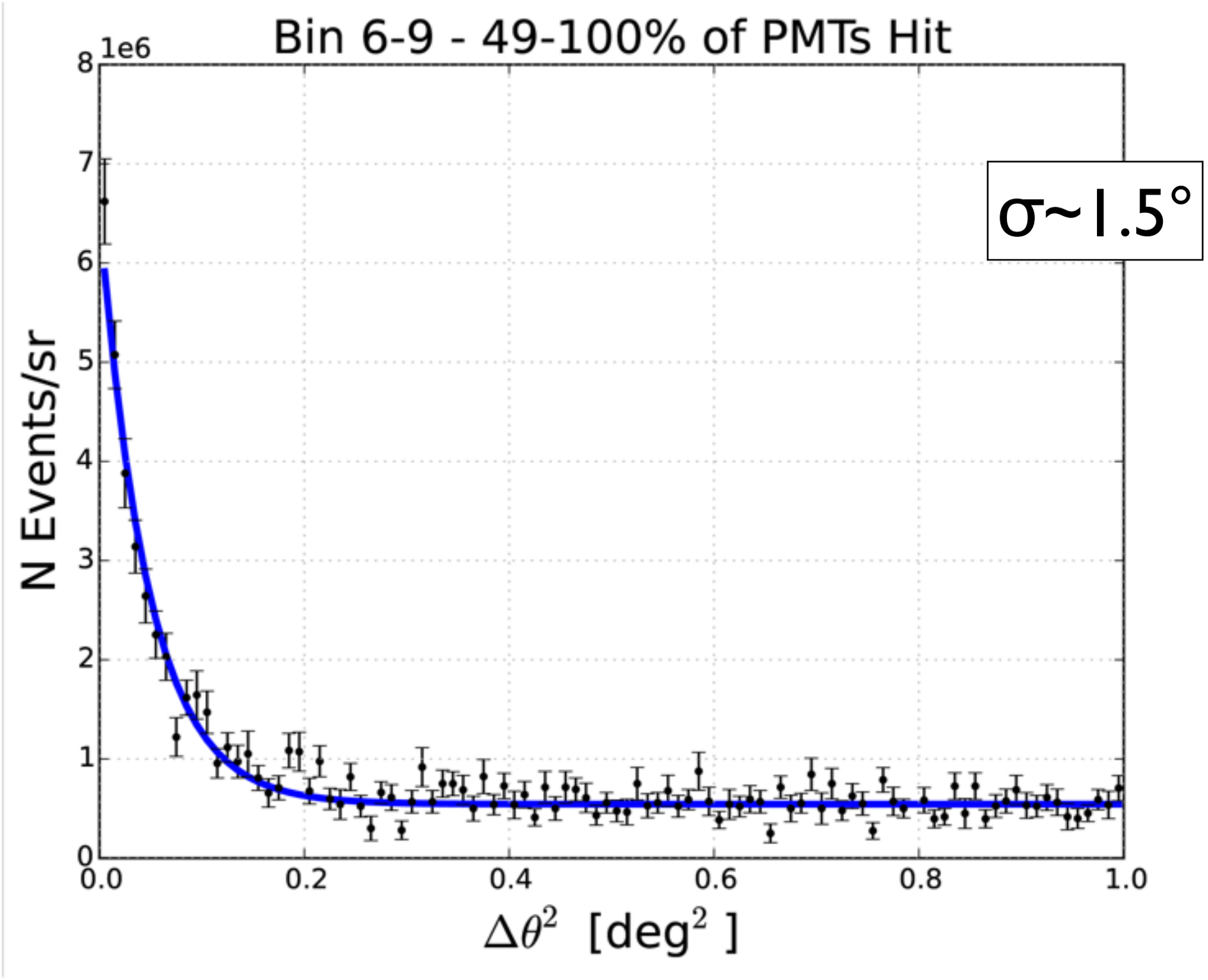
Summary

- 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

Differential Sensitivity

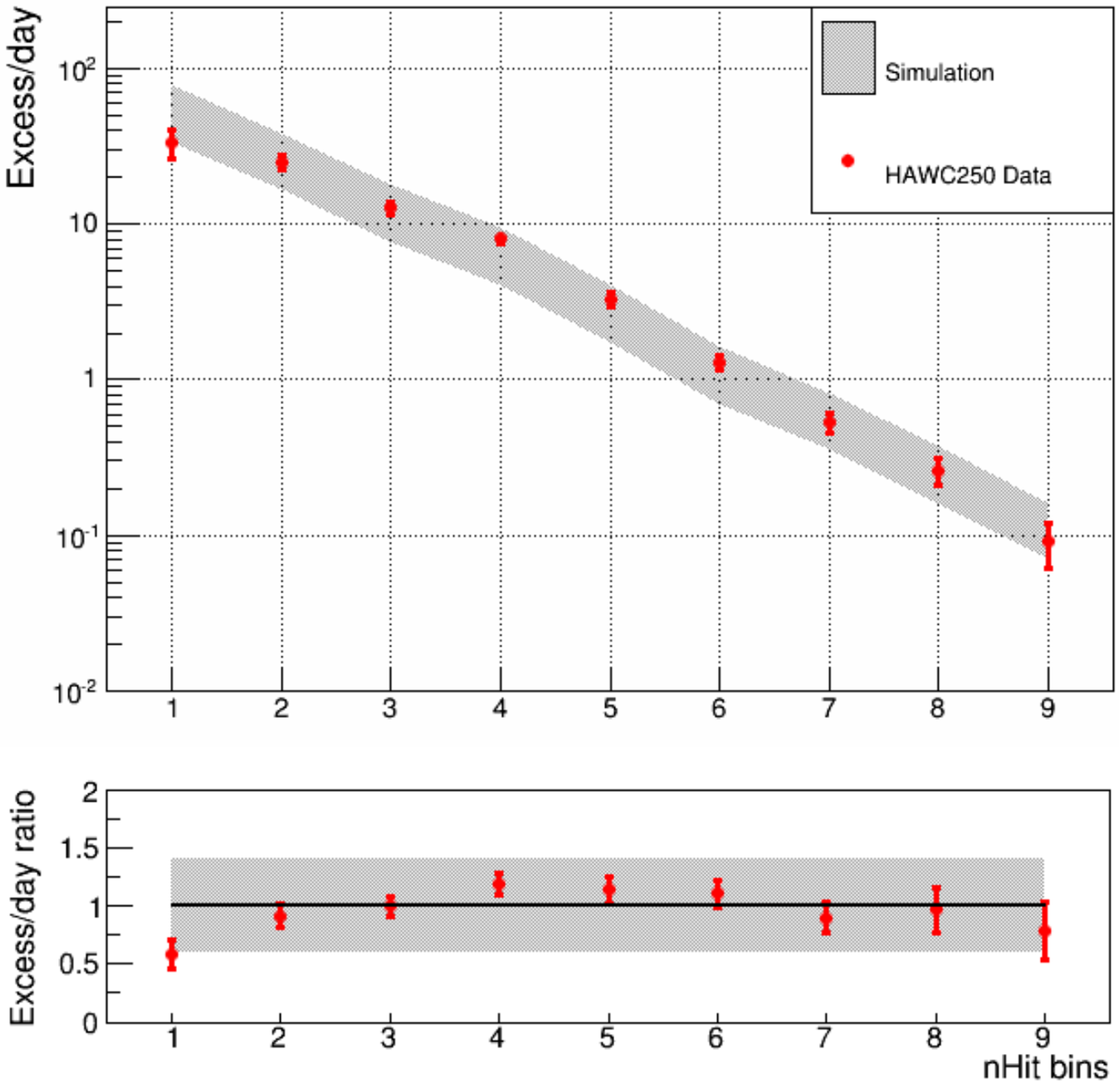


Angular Resolution

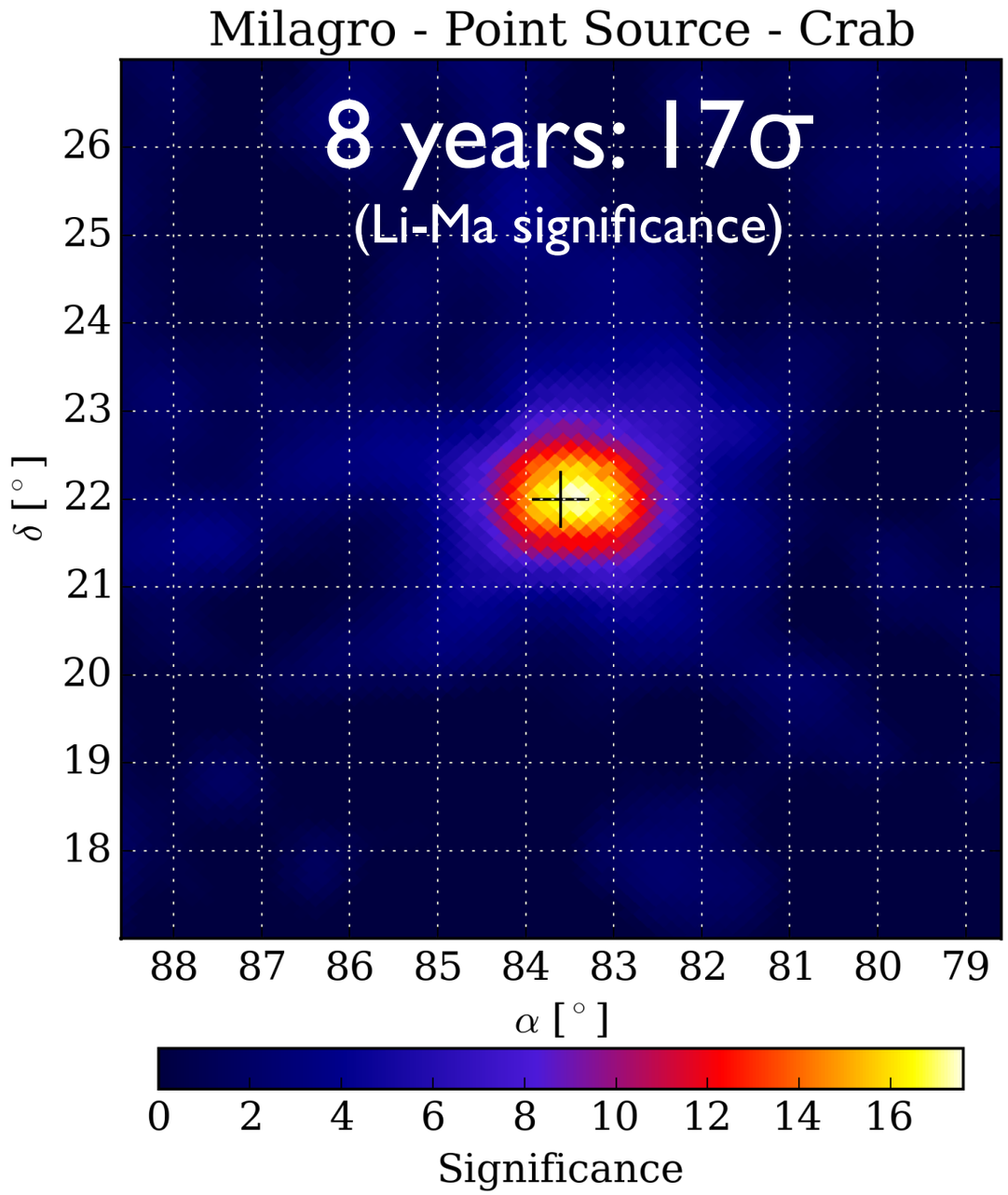


Verification: Crab Nebula

F. Salesa Greus, ICRC 2015

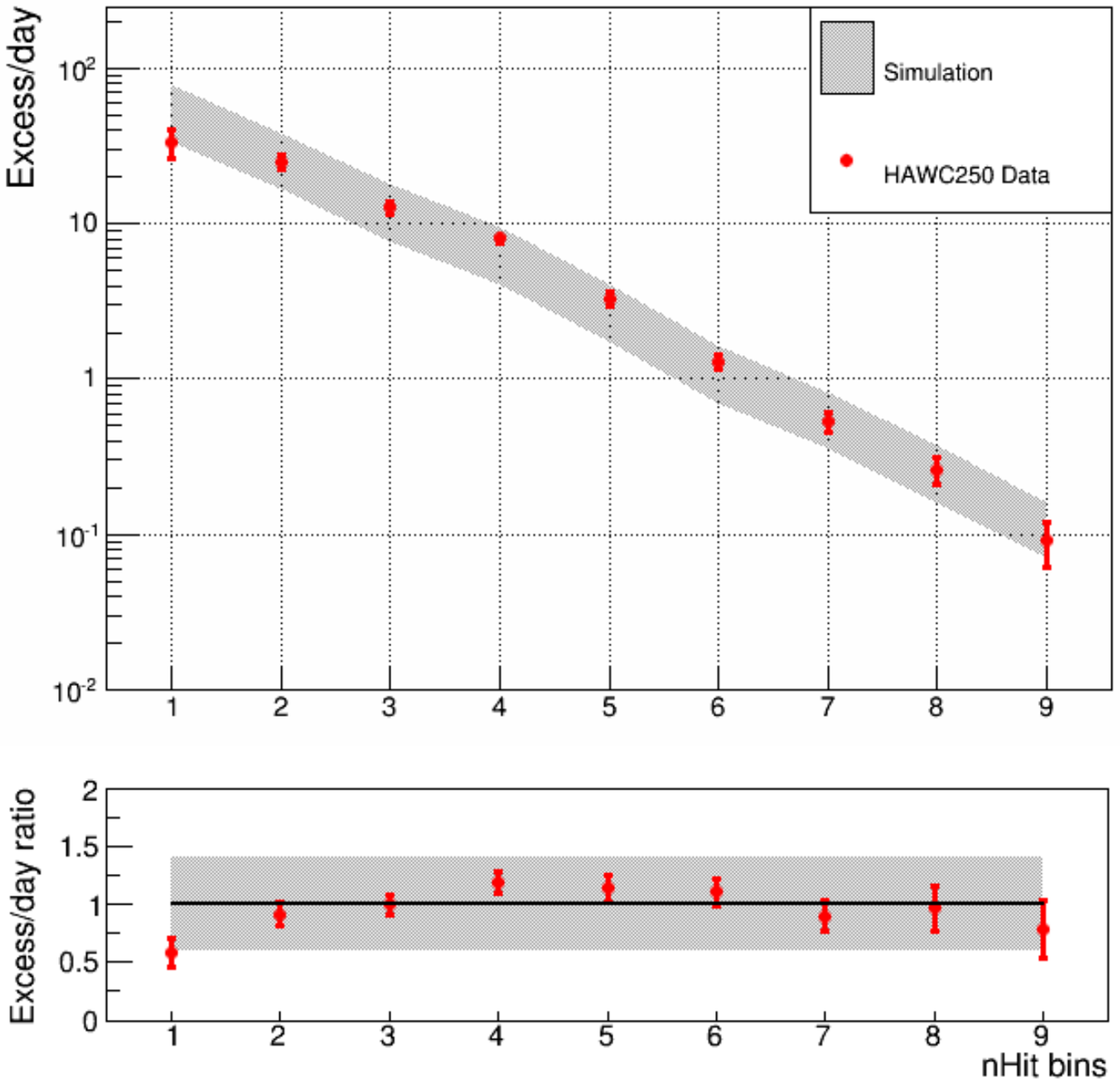


Larger Event:
Higher Energy →



Verification: Crab Nebula

F. Salesa Greus, ICRC 2015



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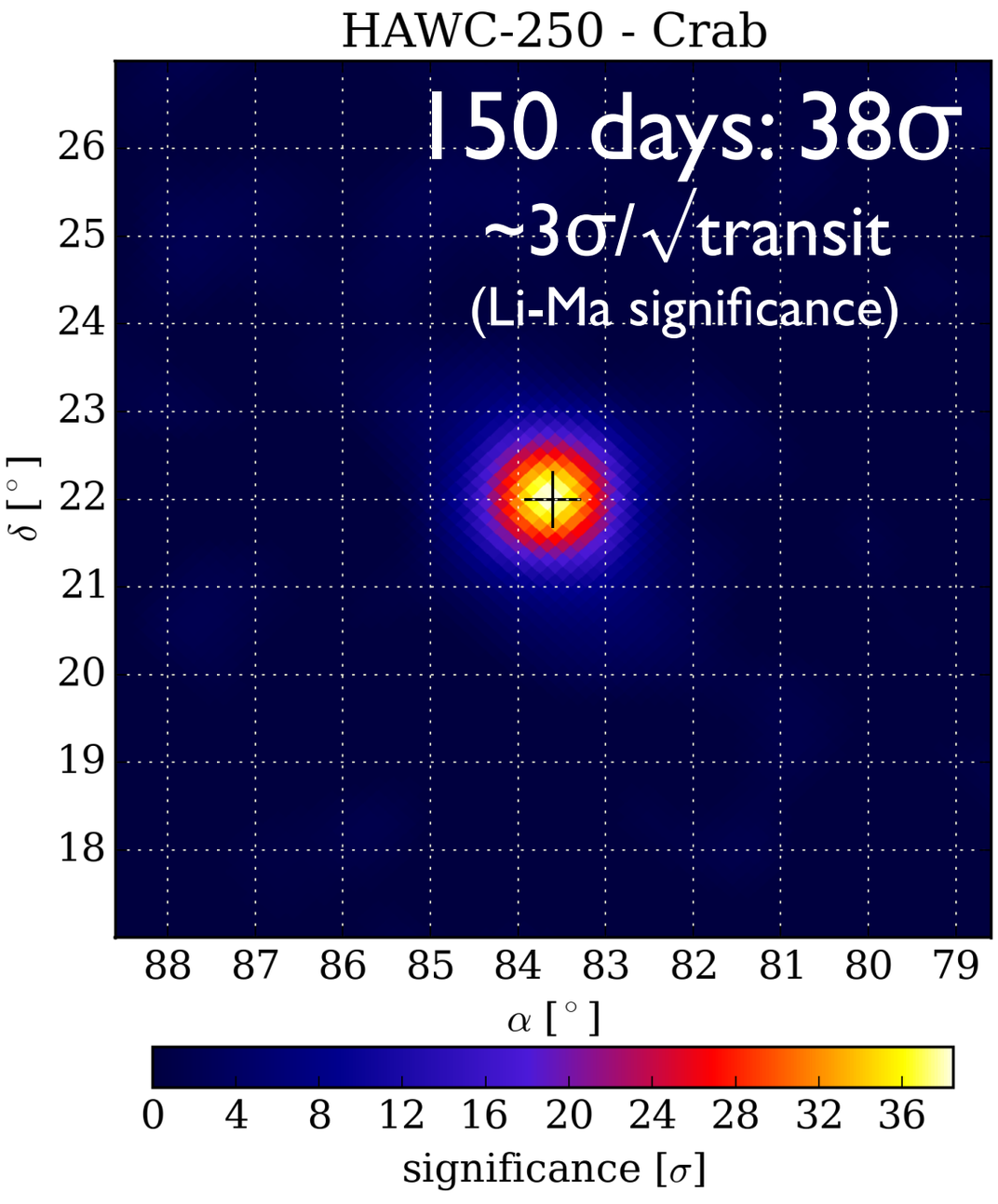
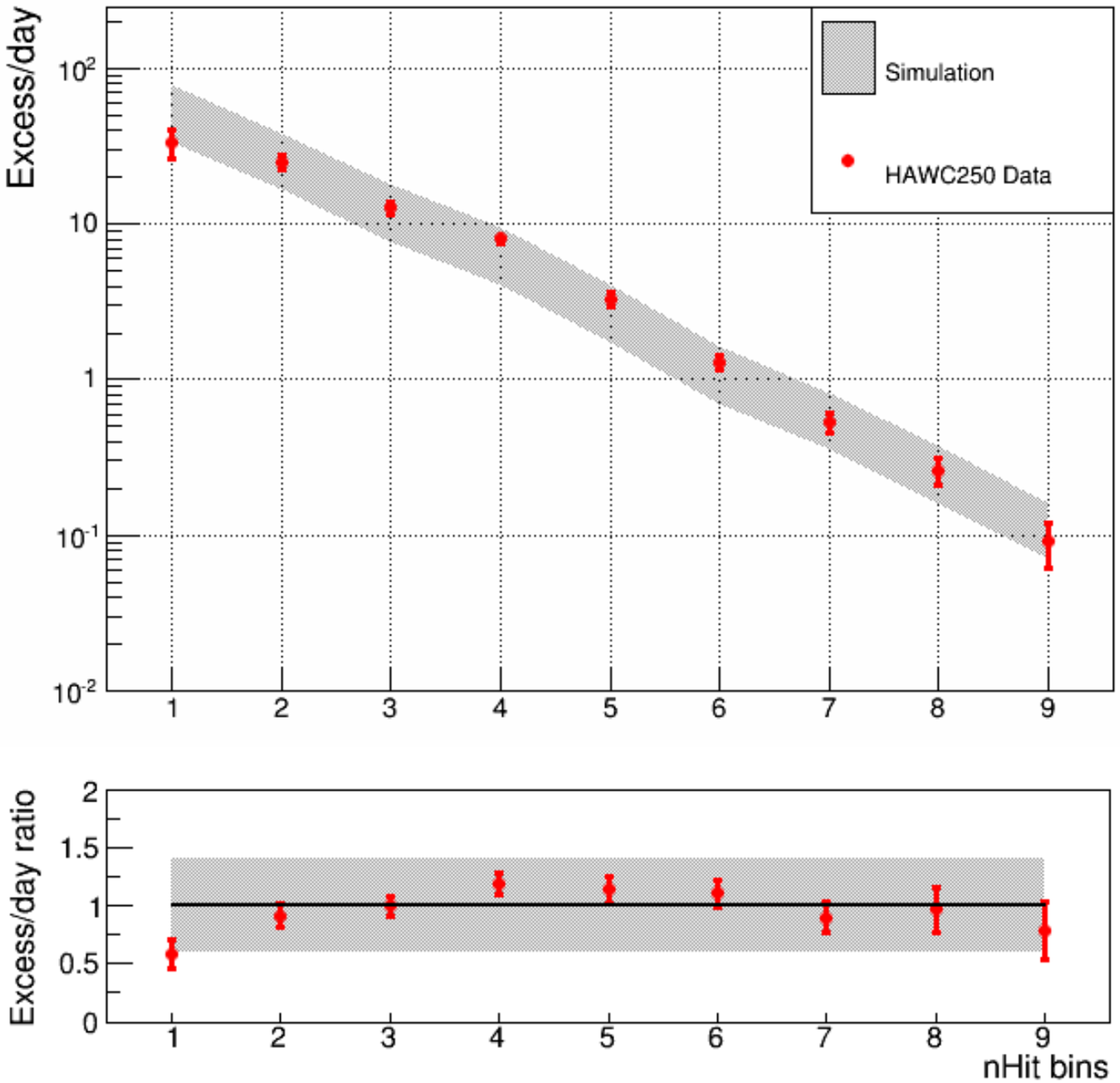
Higher Energy →

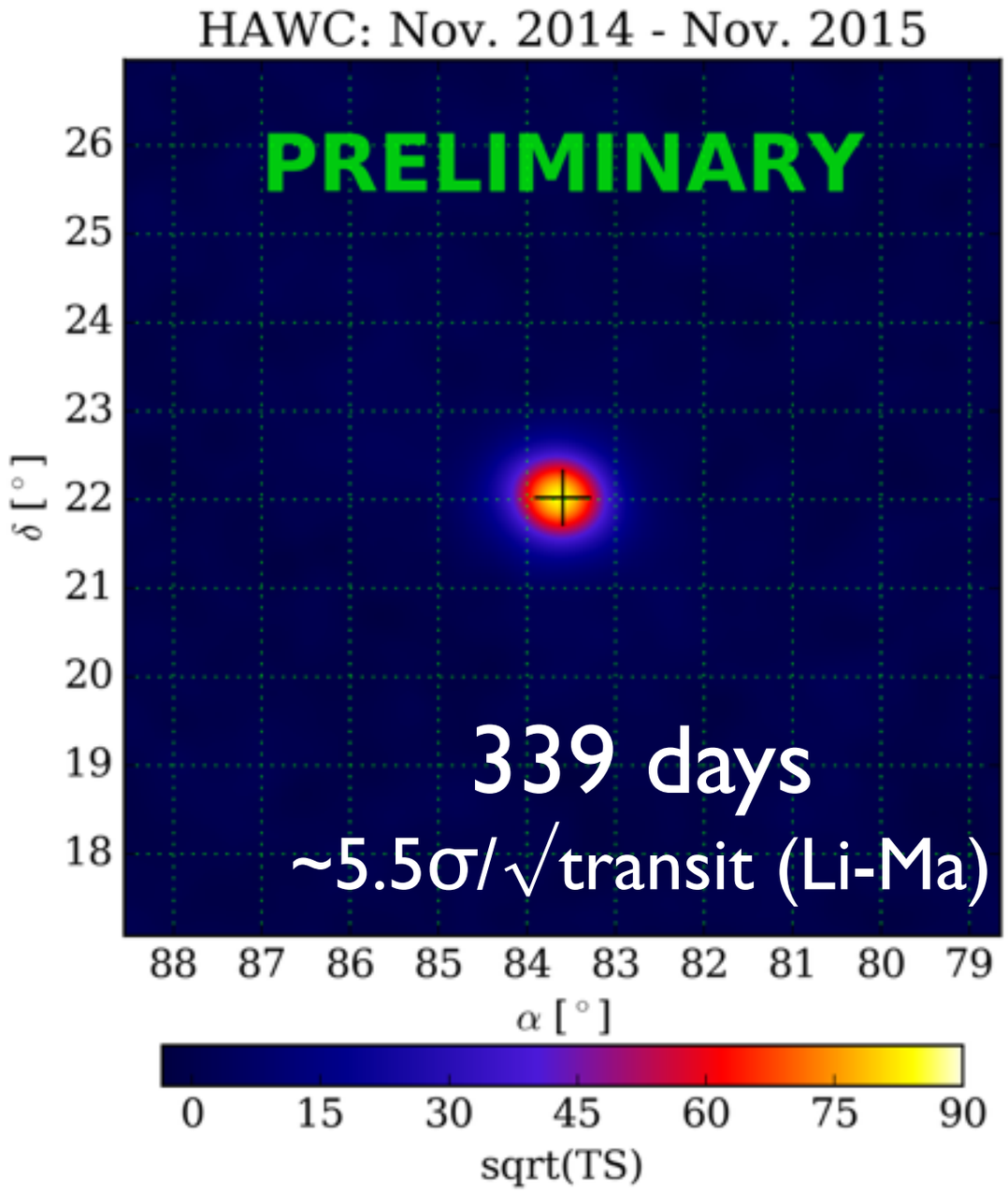


Verification: Crab Nebula

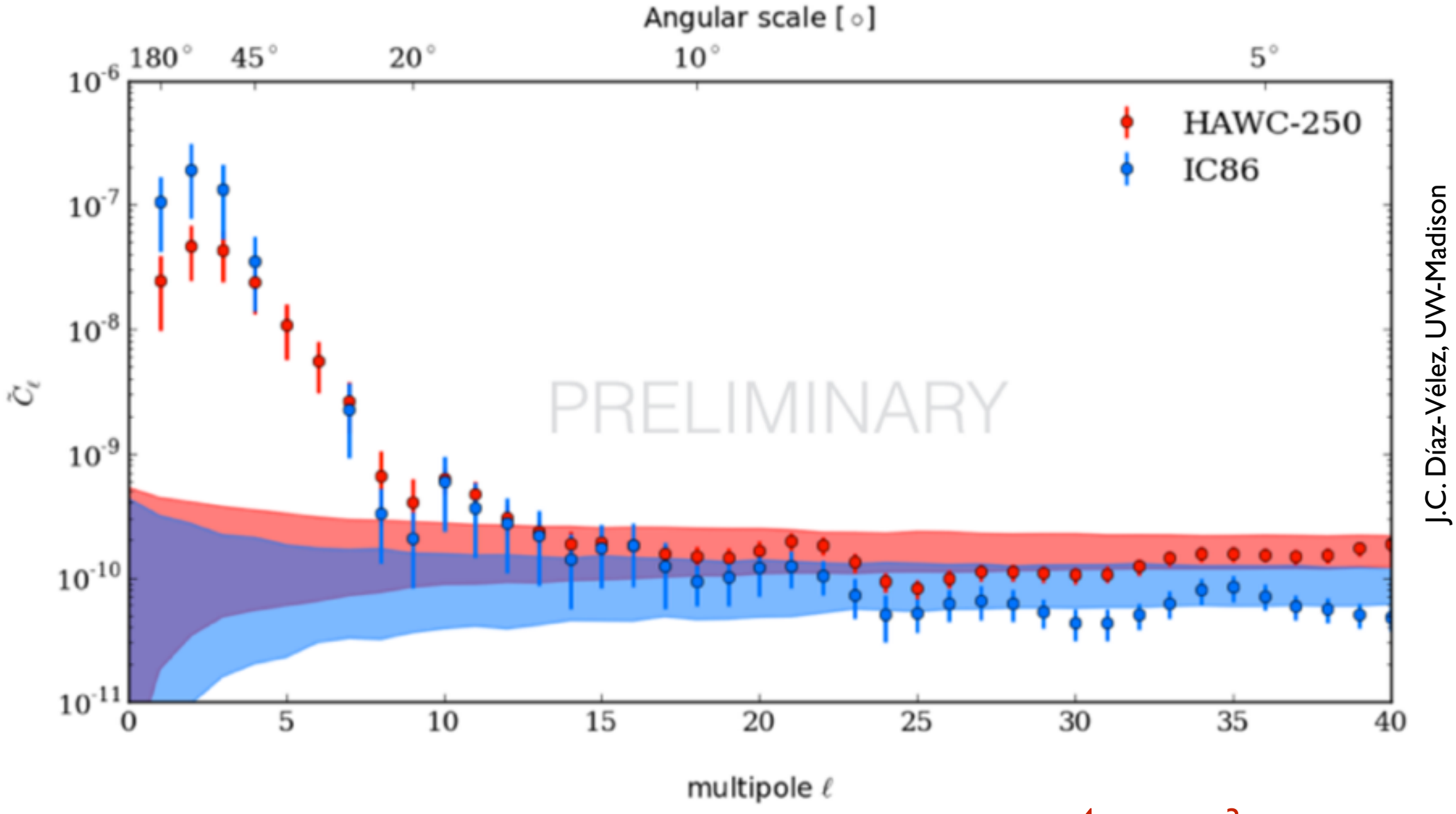
F. Salesa Greus, ICRC 2015



Larger Event:
Higher Energy →



Cosmic Ray Anisotropy



- Anisotropy in cosmic-ray background seen at the 10^{-4} to 10^{-3} level. Signature of nearby accelerator(s)? Magnetic lensing? Exotic particle decay?

Diffuse Sensitivity

- Sensitivity to CR acceleration in different parts of the Galaxy
- Sensitivity to Galactic component of high-energy neutrino flux
- Reduced systematics in study of gamma-ray sources and dark matter annihilation