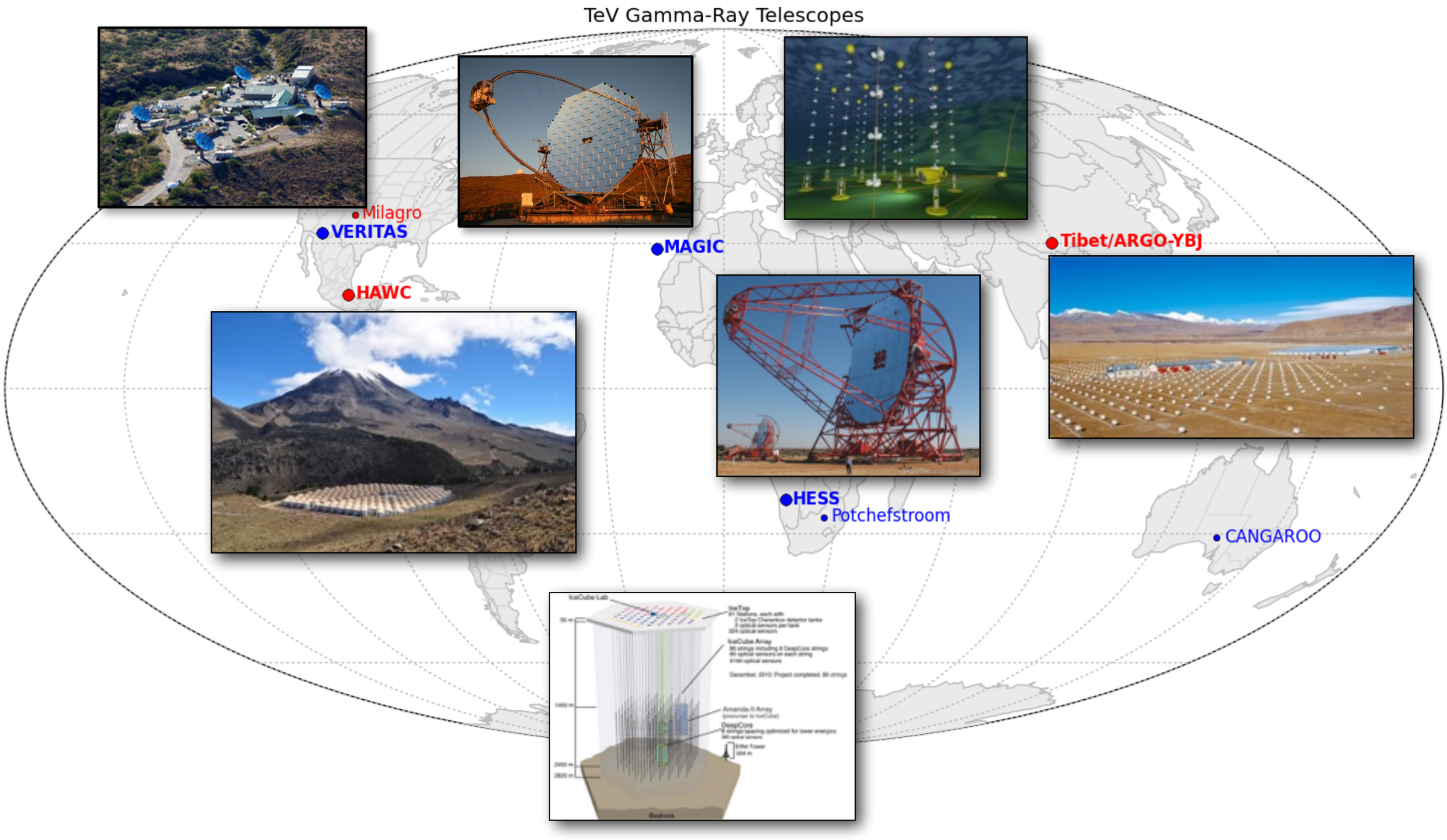
# TeV Astrophysics at the HAWC Observatory

**Segev BenZvi**
Department of Physics and Astronomy
University of Rochester

# HAWC Collaboration

- University of Maryland
- Los Alamos National Laboratory
- Univ. of Wisconsin-Madison
- University of Utah
- University of California, Irvine
- University of New Hampshire
- Pennsylvania State University
- University of New Mexico
- Michigan Technological University
- NASA/Goddard
- Georgia Institute of Technology
- Colorado State University
- Michigan State University
- University of Rochester
- Univ. of California, Santa Cruz
- Stanford University
- UNAM
  - Inst. de Fisica
  - Inst. de Astronomía
  - Inst. de Geofisica
  - Inst. de Cien. Nucl.
- Univ. Politecnica de Pachuca
- BUAP and INAOE (Puebla)
- Univ. Autónoma de Chiapas
- Univ. Aut. del Estado de Hidalgo
- Universidad de Guadalajara
- Universidad Michoacana de San Nicolás de Hidalgo
- Centro de Investigación de Estudios Avanzados (México, DF)
- Instituto Politécnico Nacional
- Centro de Investigación en Computación (IPN)
- IFJ-PAN, Krakow, Poland

# TeV Observatories



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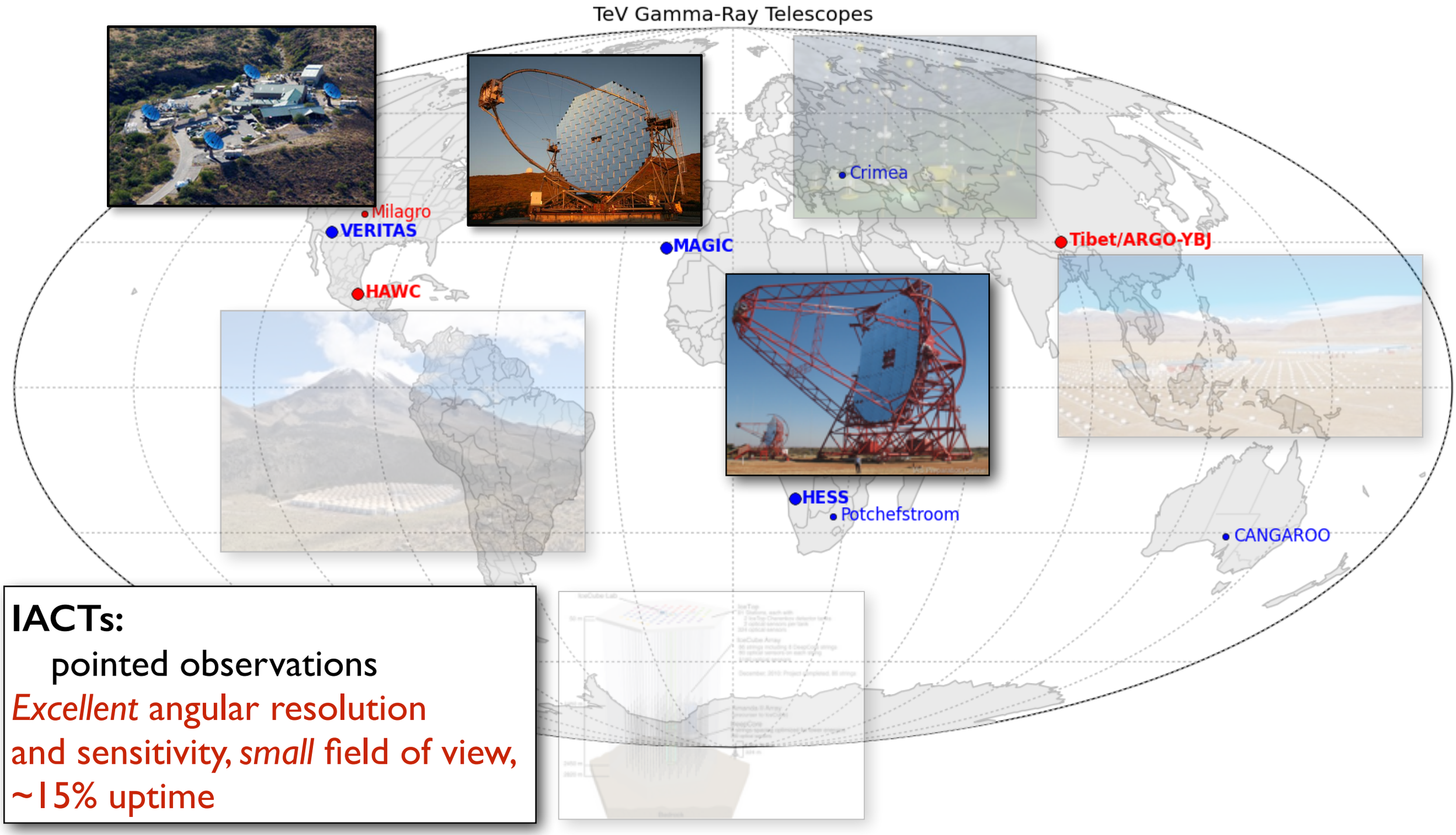



**IACTs:**

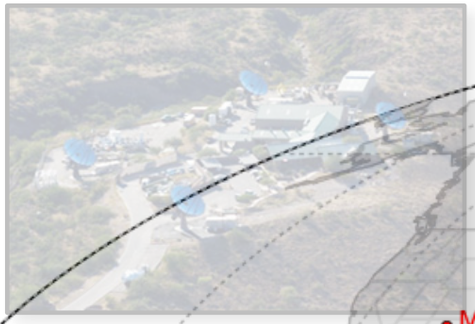
pointed observations

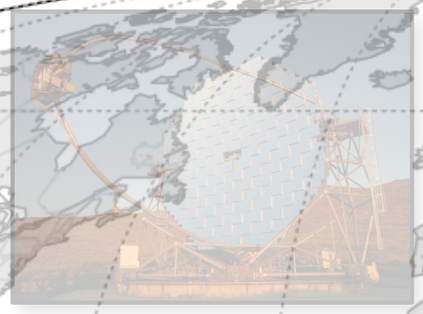
*Excellent* angular resolution and sensitivity, *small* field of view, ~15% uptime

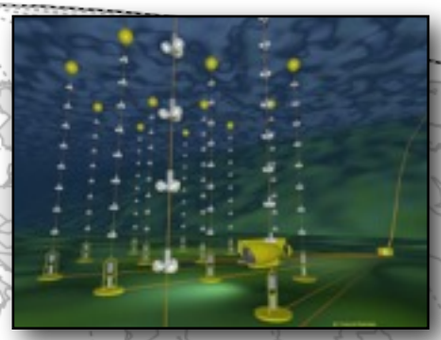
# TeV Observatories

EGRET
AGILE
Fermi

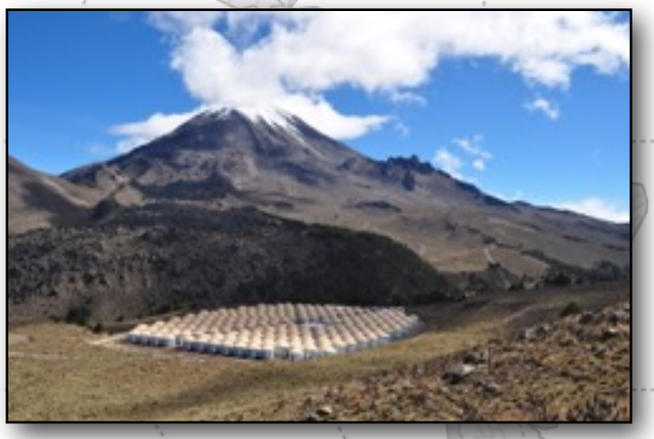
TeV Gamma-Ray Telescopes







Milagro
VERITAS
MAGIC
HAWC
Tibet/ARGO-YBJ



HESS
Potchefstroom
CANGAROO

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pointed observations
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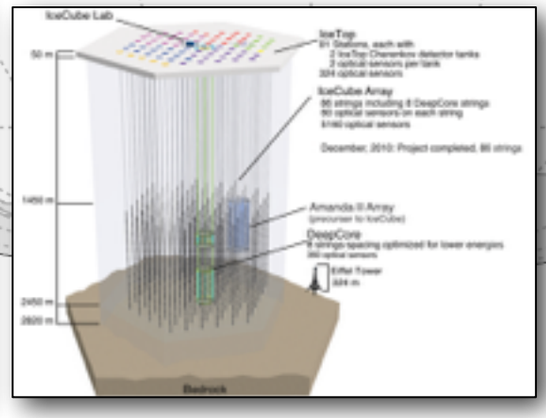



**Space/Surface/Volume Detectors:**
surveys
*Moderate* angular resolution,
*large* field of view (partial/all-sky),
*continuous* monitoring

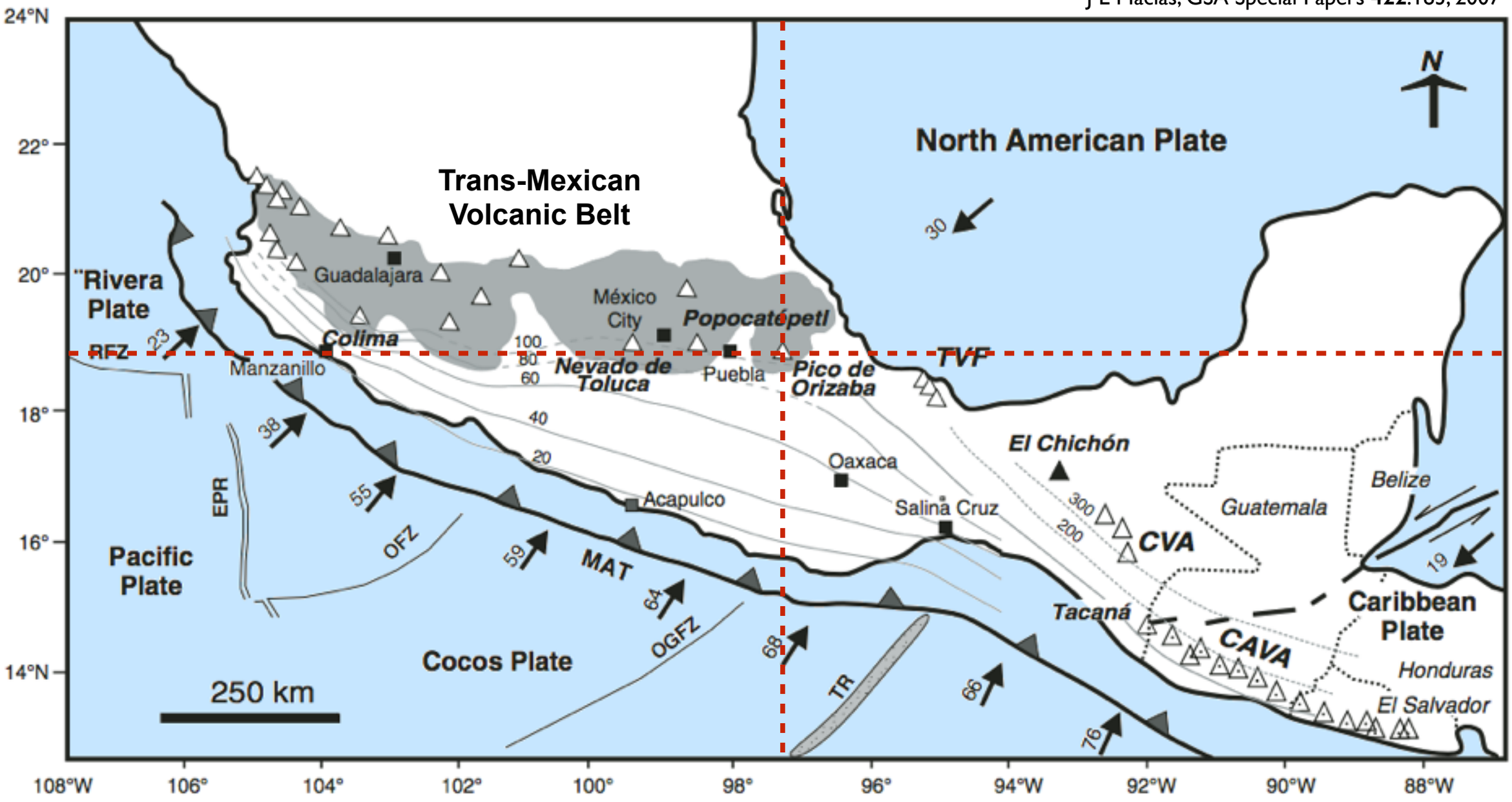
# HAWC Observatory

- The **H**igh **A**ltitude **W**ater **C**herenkov Gamma-ray Observatory (HAWC) is up and running
- Goals: observe gamma rays and cosmic rays from half the sky each day between 100 GeV and 100 TeV
  - 4100 meters above sea level
  - 19°N latitude (Galactic Center at 48° zenith)
  - 300 water tanks, 1200 large photocathode area PMTs
  - 1/6th of sky in instantaneous field of view
- Current status: tank construction and water filtration completed, final PMTs deployed. 270 tanks in DAQ

# Detector Location

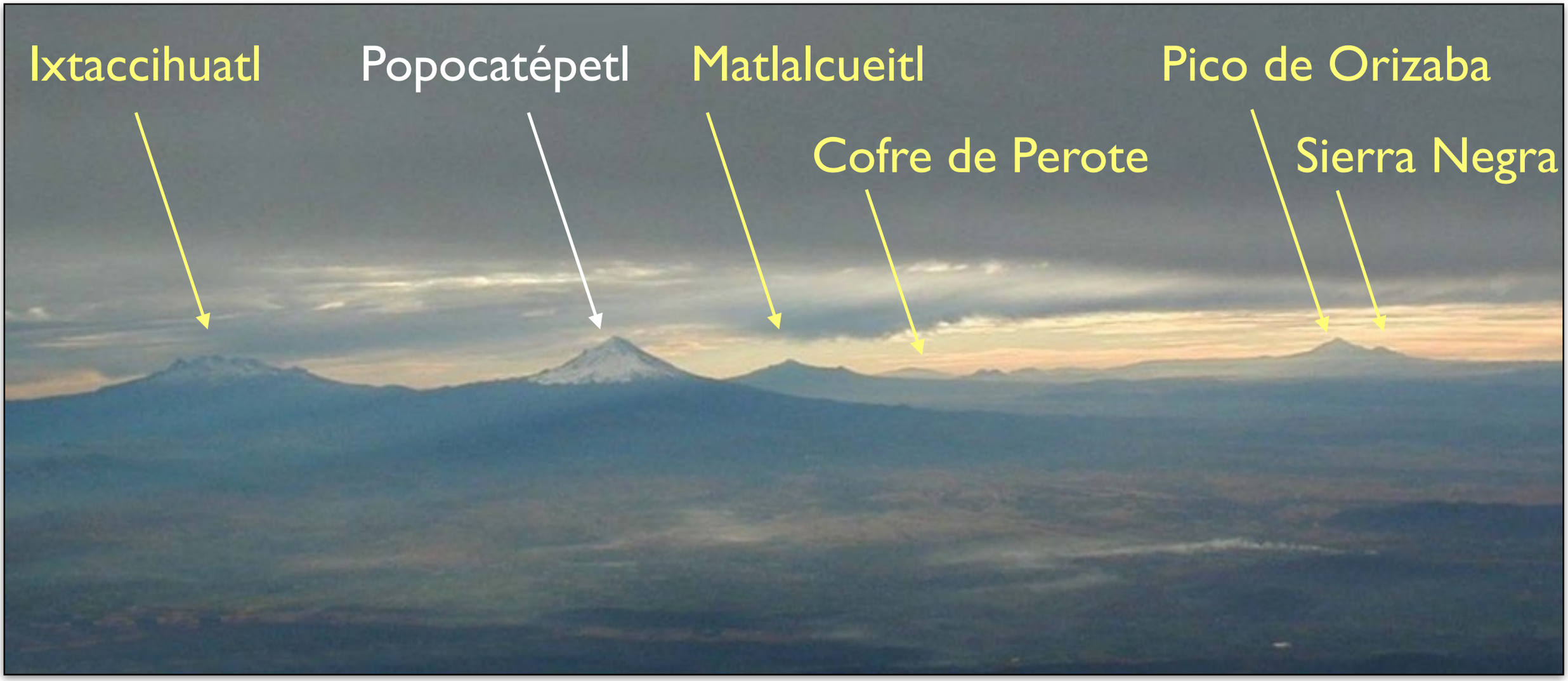
- Parque Nacional Pico de Orizaba: 97.5°W, 18.9°N

J L Macías, GSA Special Papers **422**:183, 2007



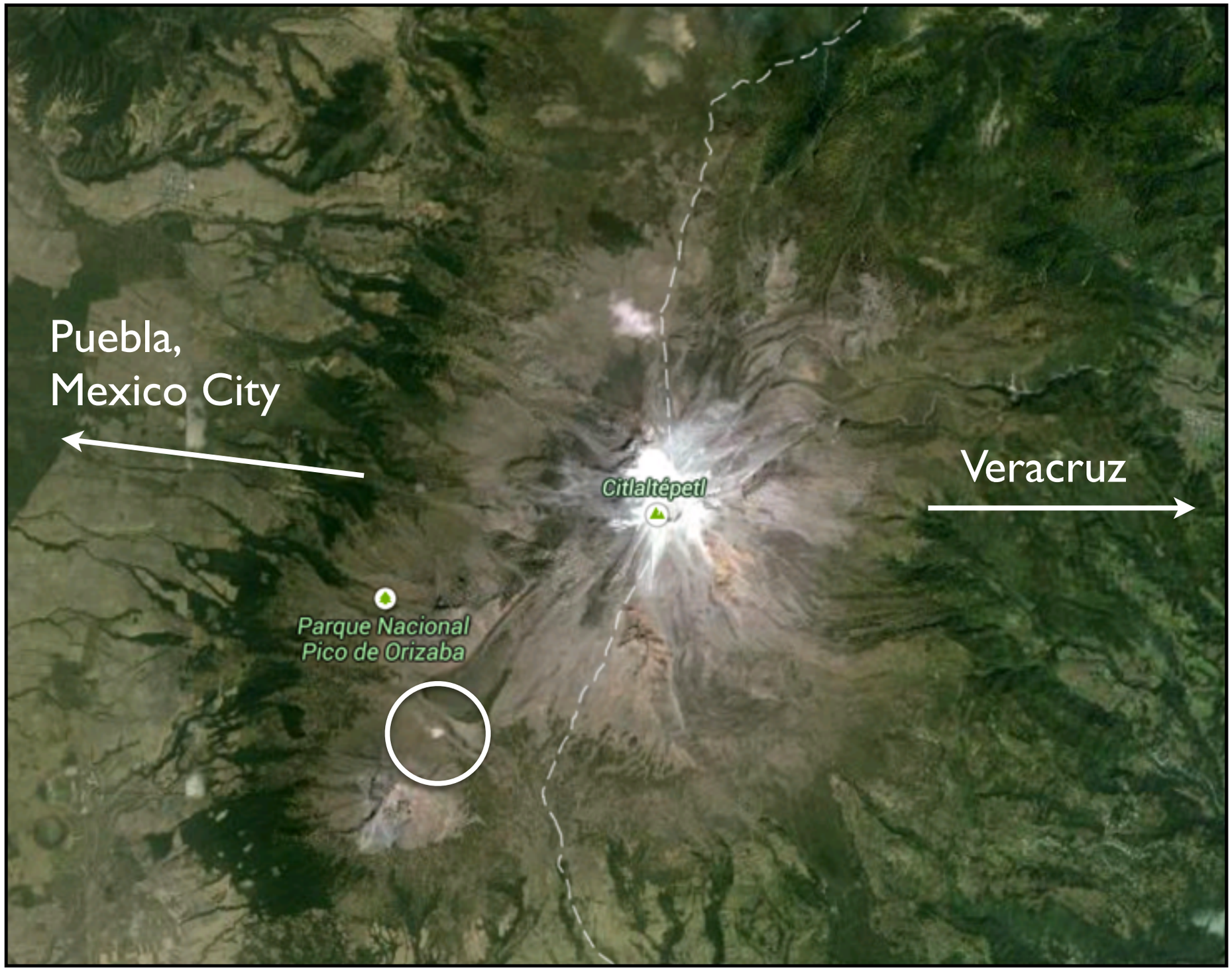
# HAWC Location

- 5 dormant volcanos, 1 active (Popocatépetl) east of Mexico City
- HAWC site: saddle between Sierra Negra and Pico de Orizaba




Credit: D. Tuggy

# HAWC Site


Puebla,
Mexico City
Veracruz
Citlaltépetl
Parque Nacional
Pico de Orizaba

# HAWC Site

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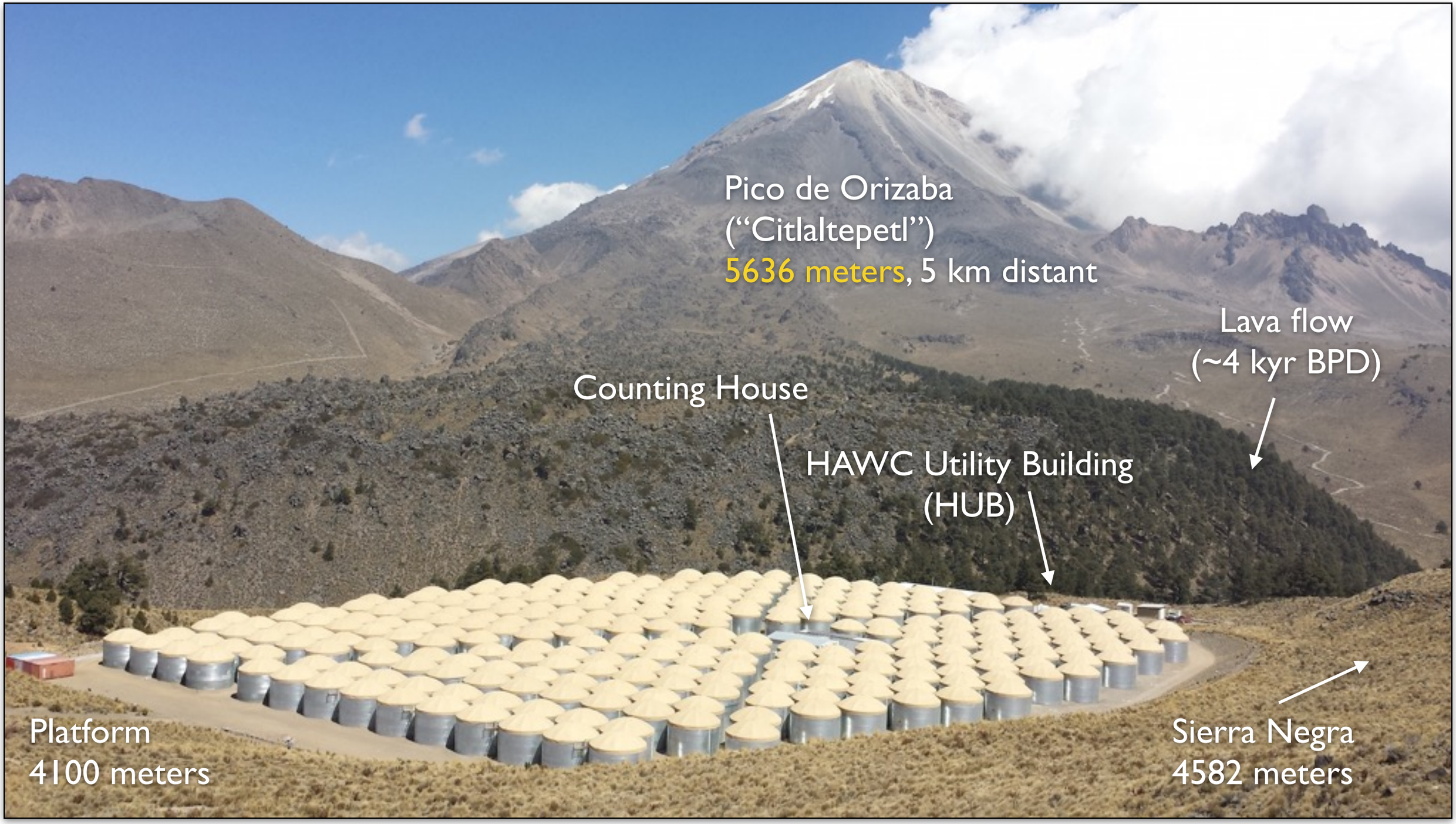
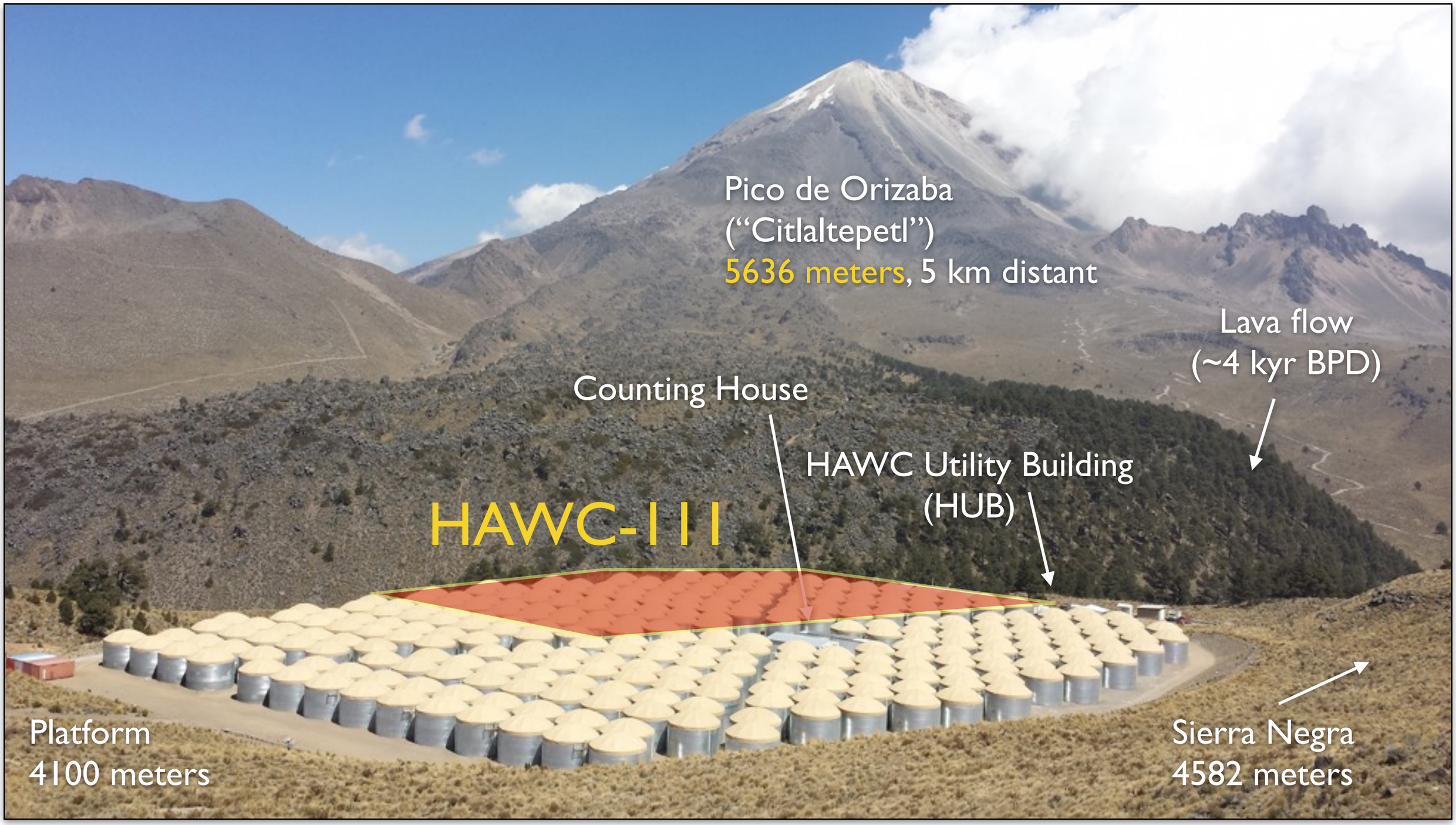

Pico de Orizaba
("Citlaltepetl")
5636 meters, 5 km distant
Lava flow
(~4 kyr BPD)
Counting House
HAWC Utility Building
(HUB)
Platform
4100 meters
Sierra Negra
4582 meters

# HAWC Site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HAWC Utility Building
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HAWC-111
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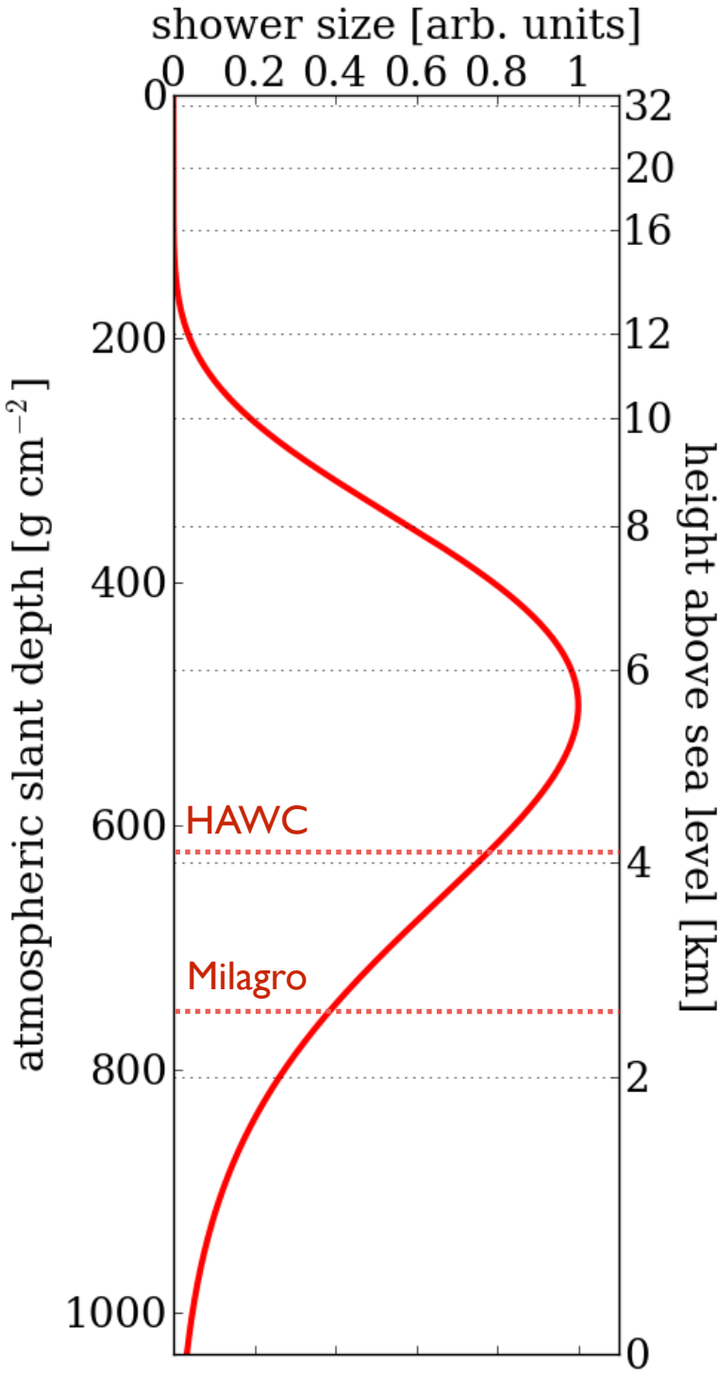
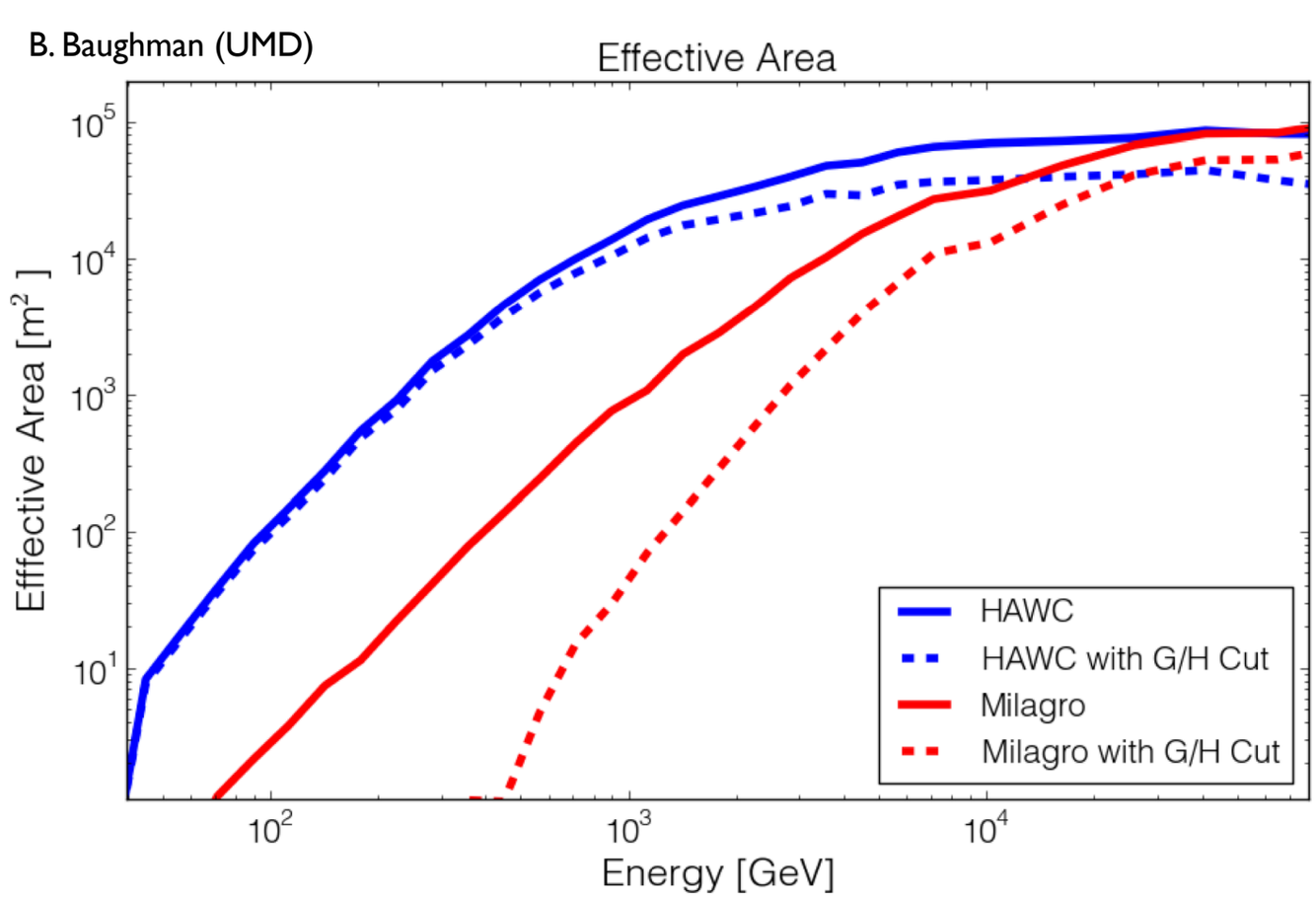
# Why Deploy on a Volcano?



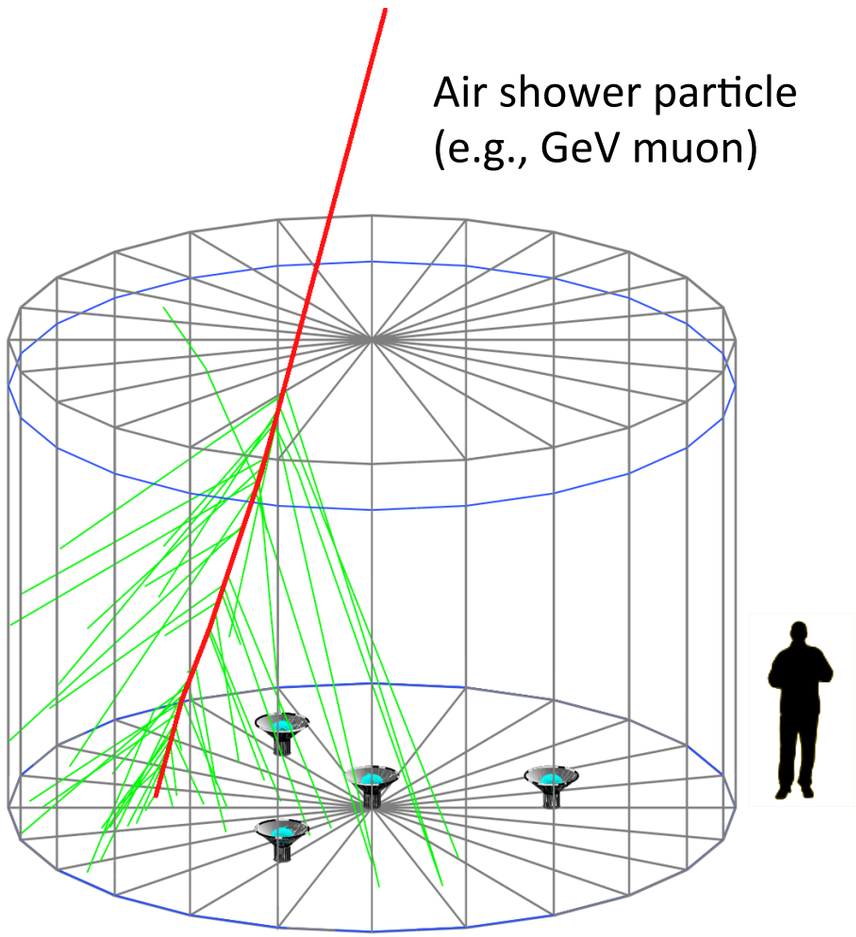

- At altitude, observe more particles in air shower; reduce energy threshold
- **Health/safety** fix for altitude-related illnesses: drive downhill



# Why Deploy on a Volcano?

# Water Cherenkov Method

- Robust and cost-effective surface detection technique
- Water tanks: 7.3 m radius, 5 m height, 185 kL purified water
- Tanks contain three 8” R5912 PMTs and one 10” R7081-HQE PMT looking up to capture Cherenkov light from shower front




# Tank Deployment

- Tanks built using 5 "rings" of curved steel panels and capped with an opaque military-grade canvas roof

Final tank deployed: December 15, 2014

Water filtration system in HUB, Sierra Negra

- Next: bladder installation, water delivery, wet PMT deployment
- 55 million L (55 kT) water delivered: 3900 tanker truck trips

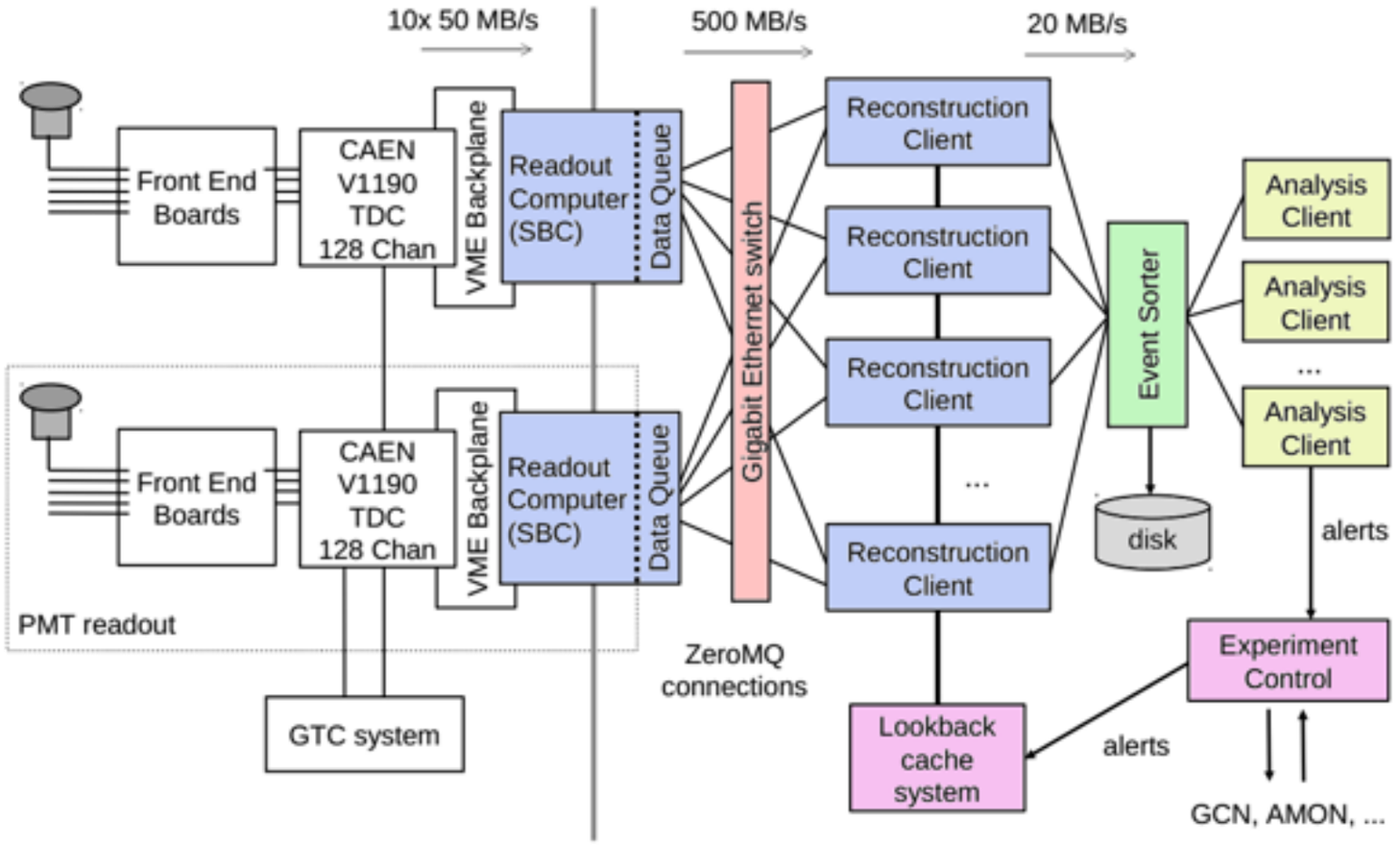
# Cabling

- Buried coaxial cables used to connect PMTs to HV supply and front-end electronics in the Counting House

- Total length of cable used: 180 km

# Software Trigger

- A computing farm in the Counting House is used to apply a simple multiplicity trigger to the data in software. No topological cuts are applied at trigger level.




D. Zaborov, G. Kunde

- After the the trigger, the event rate is reduced to ~10 kHz, or a data rate of ~0.02 GB/s (2 TB/day)

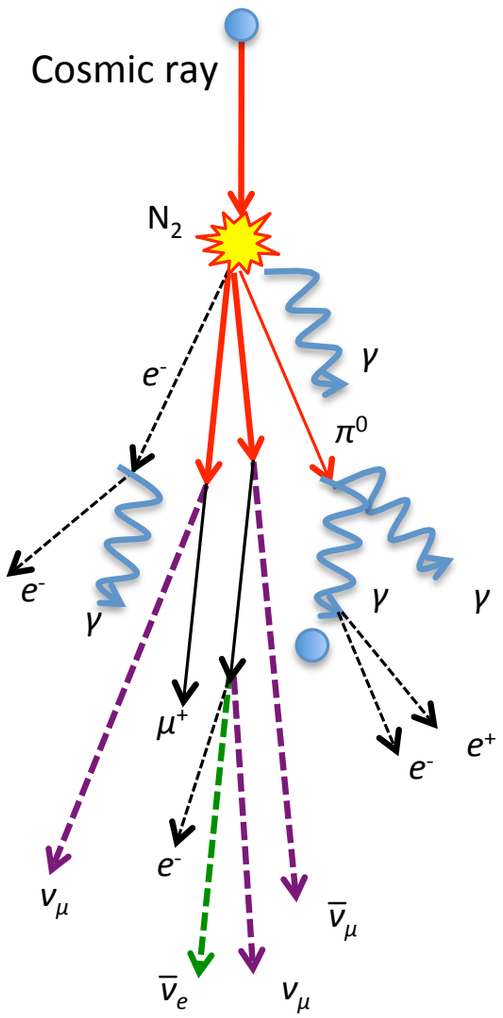
# HAWC Data Transfer System

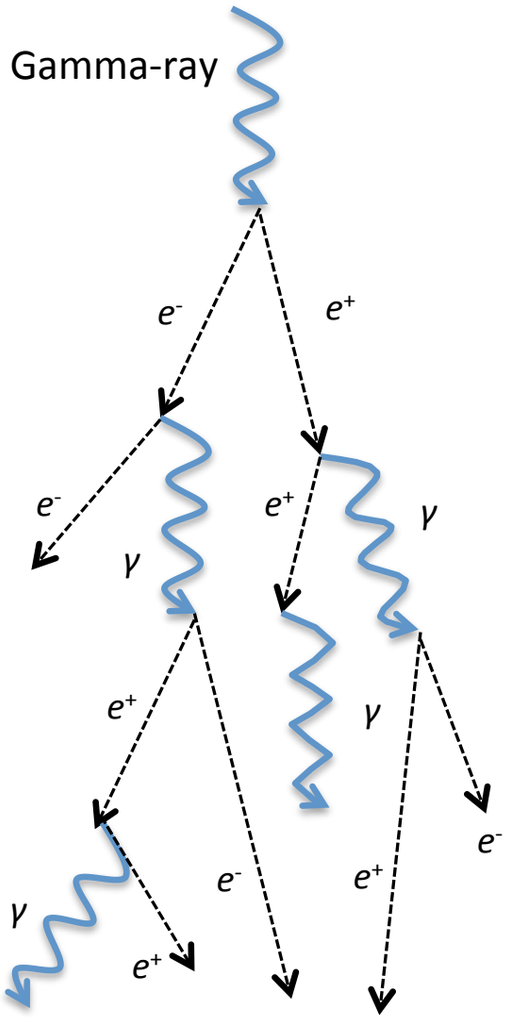
- Site network is sufficient for remote shifts and diagnostics, but not for sending 2 TB per day to UNAM and UMD

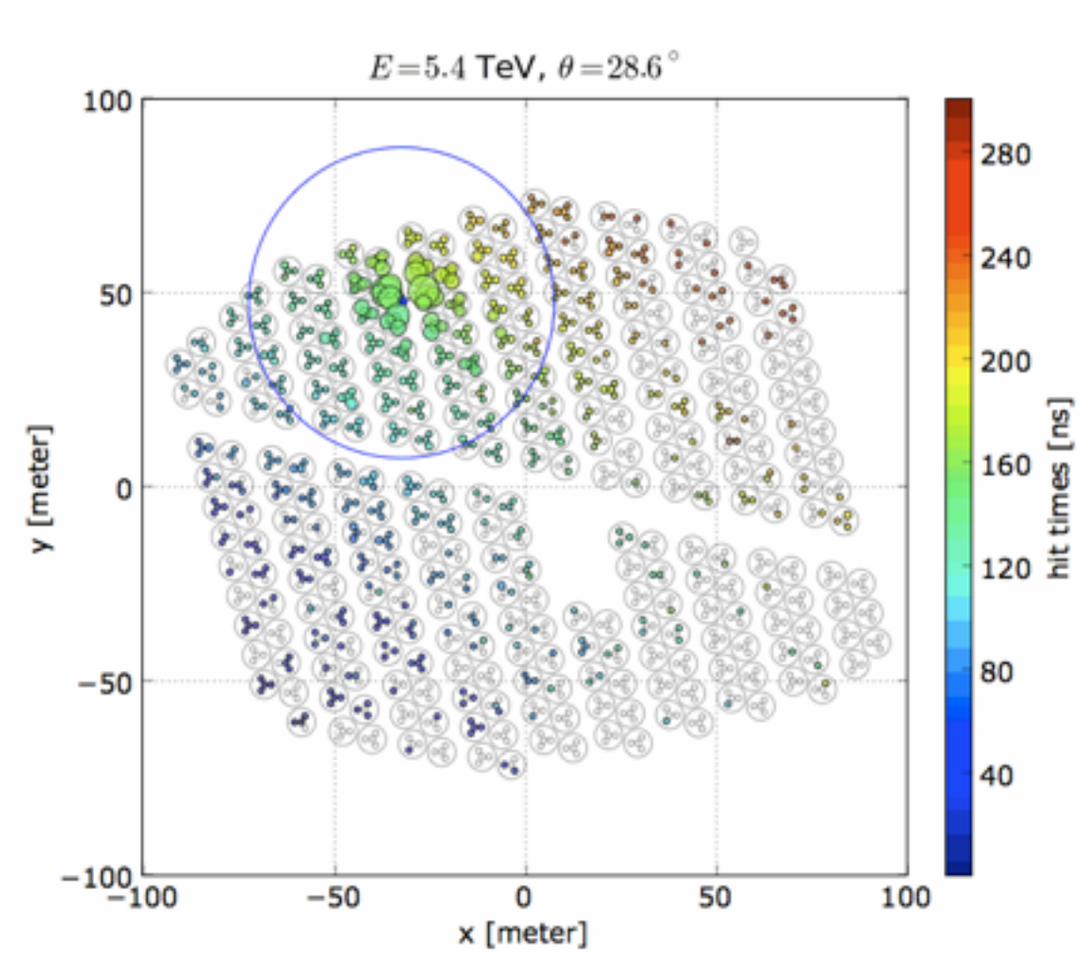
- *"Never underestimate the bandwidth of a ~~station wagon~~ Dodge Durango full of tapes hurtling down the highway."*
  — A. Tannenbaum

# Background Rejection

- CR rejection using topological cut in hit pattern




- Requires sufficient number of triggered channels (>70) to work well. Q-value ($\epsilon_\gamma/\sqrt{\epsilon_{CR}}$) is ~5 for point sources

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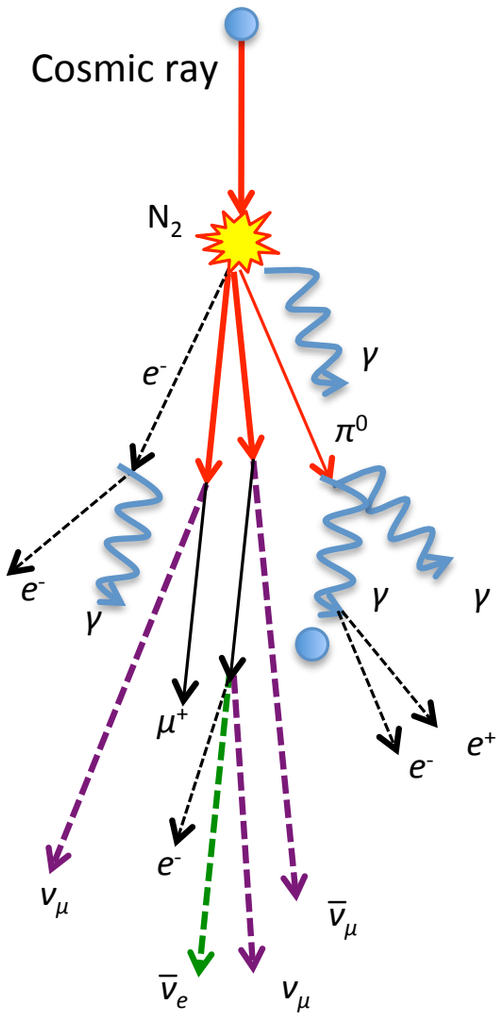


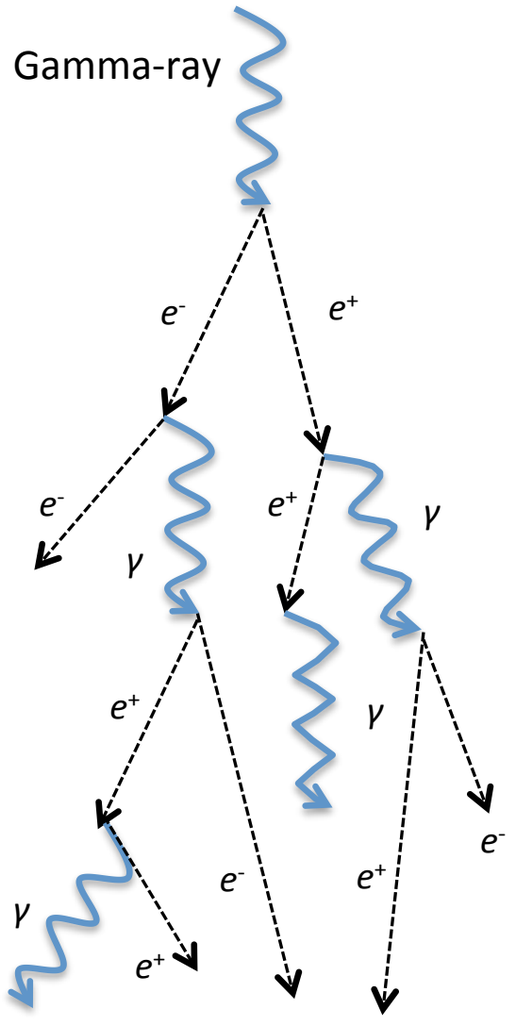


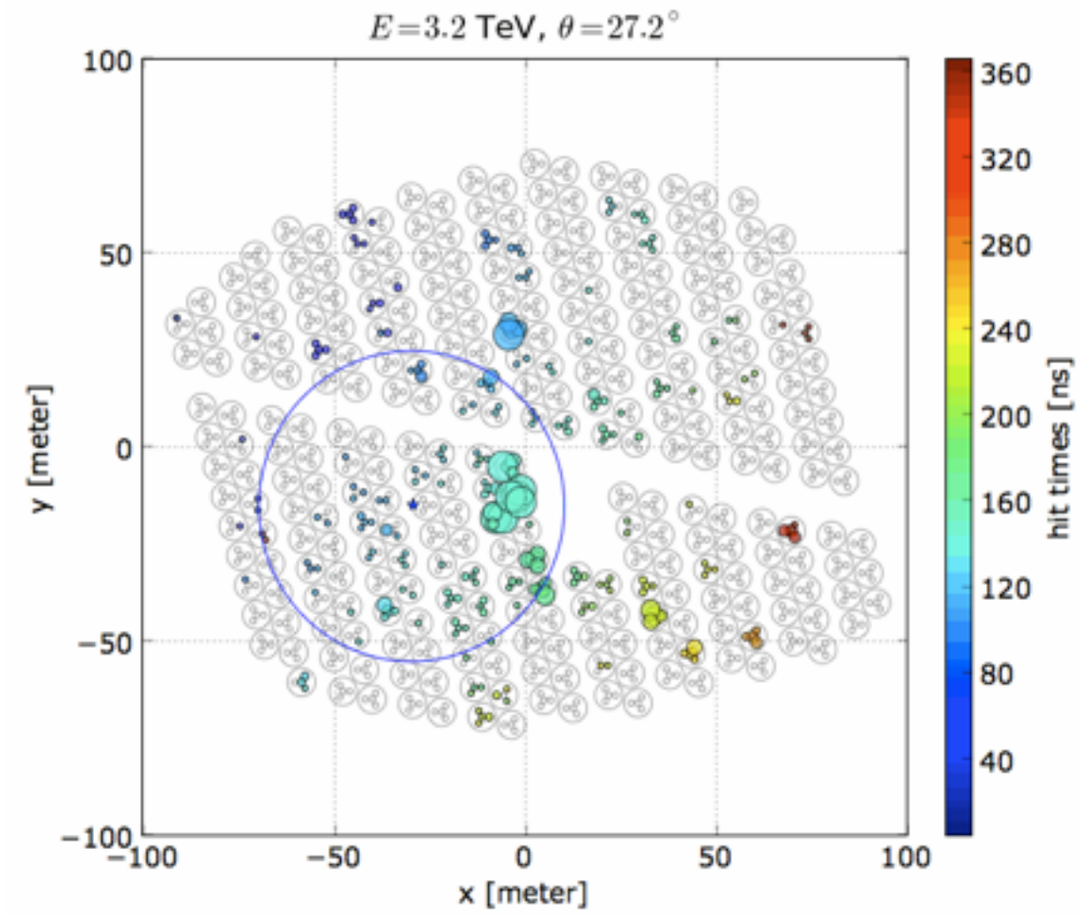


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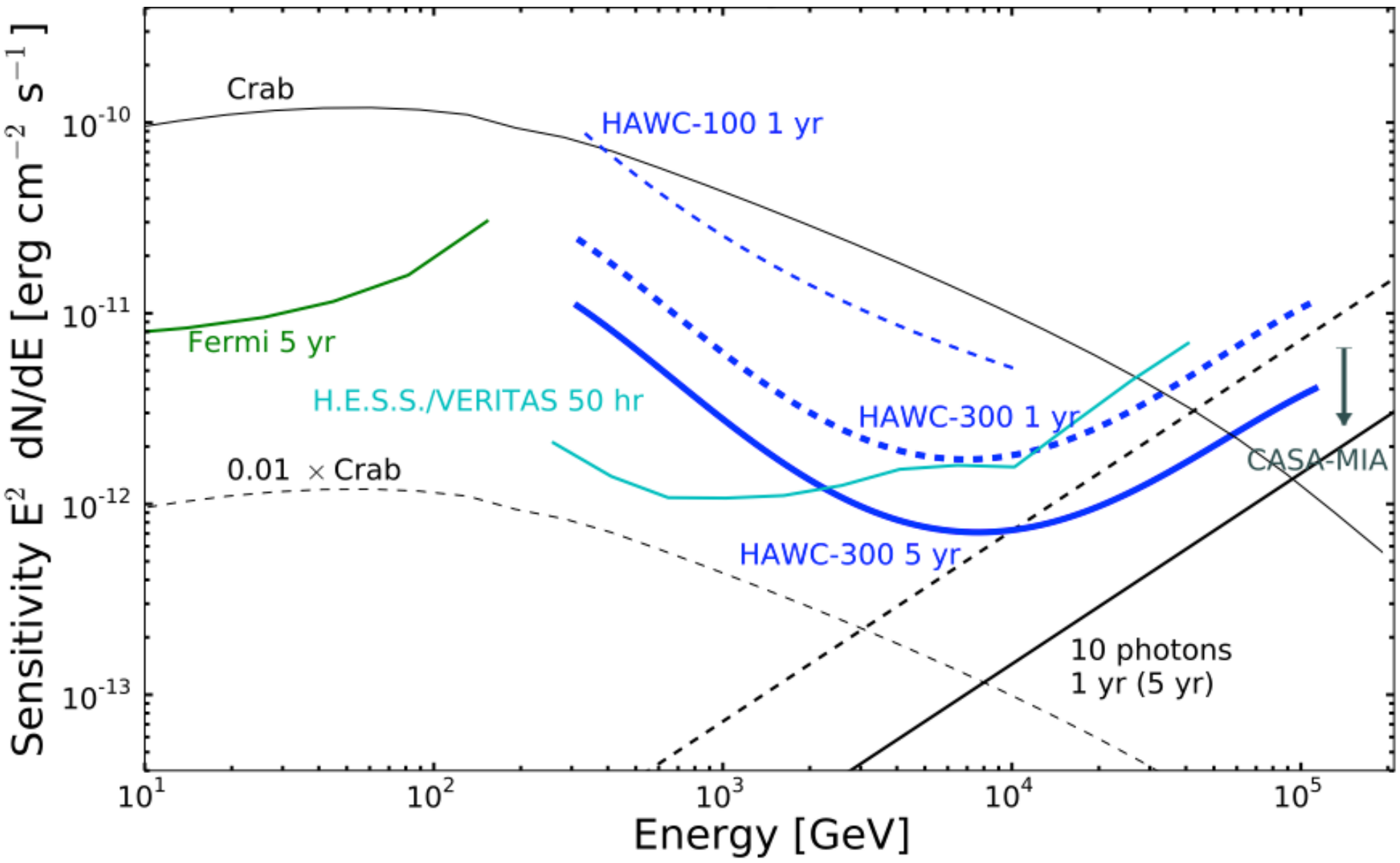
# HAWC Differential Sensitivity

B. Baughman (UMD)

A. Abeysekara et al., Astropart. Phys. **50-52**:26, 2013

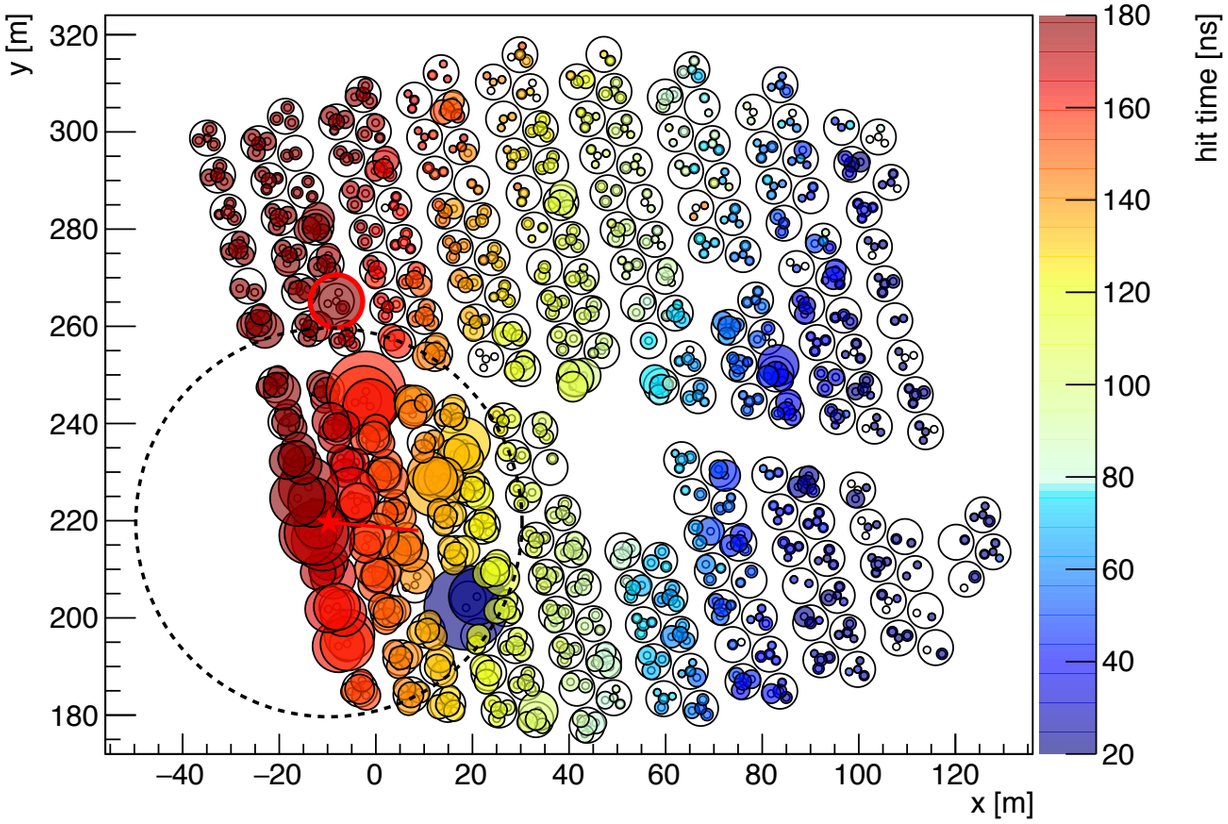



- 5 years of HAWC @ 10 TeV ~ 50 hr IACT @ 1 TeV
- Remember: HAWC is a *survey* instrument, not a pointing instrument

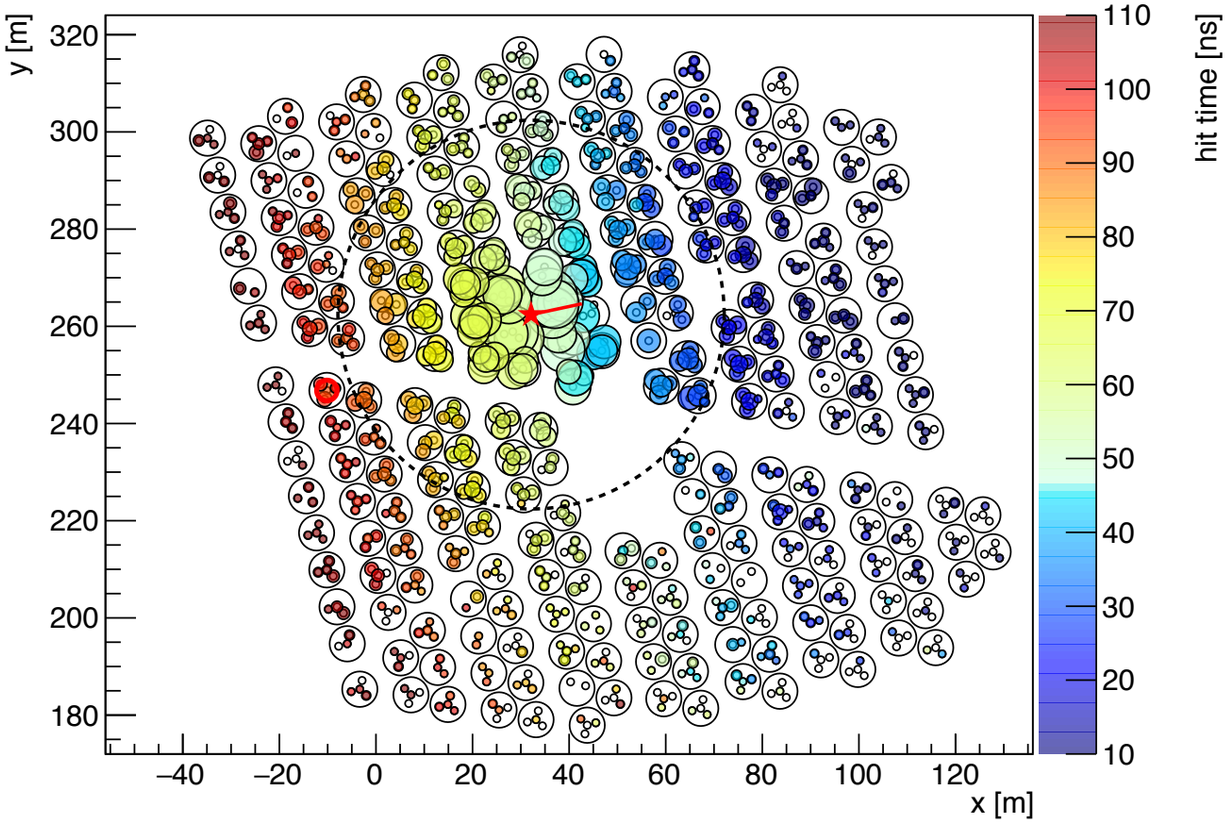
# HAWC-250 Data

- Left: successful fit of a cosmic-ray event
- Right: successful fit of a gamma-ray event (Crab)
- Clumpiness of shower = "hadron-ness"

Run 2105, TS 140025, Ev# 89, CXPE40= 682, Cmptness= 1.21

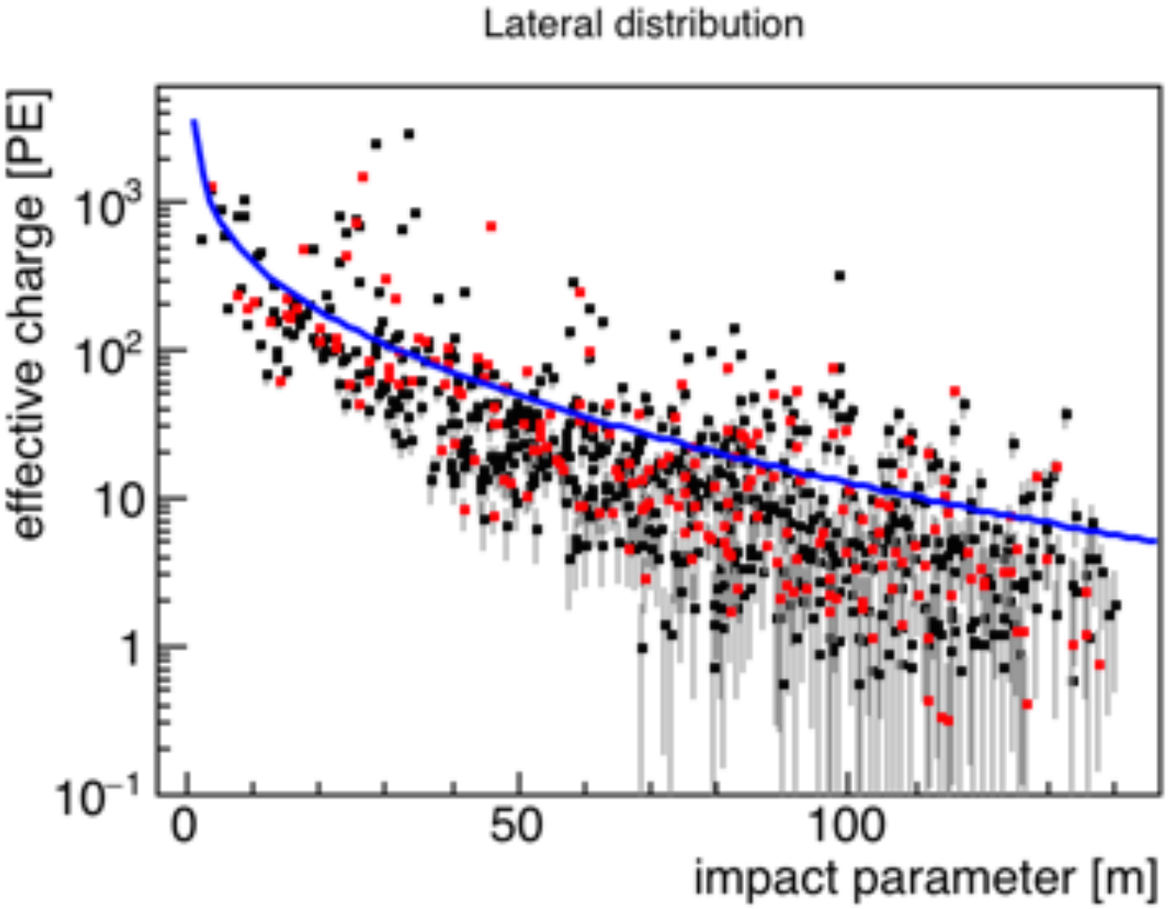


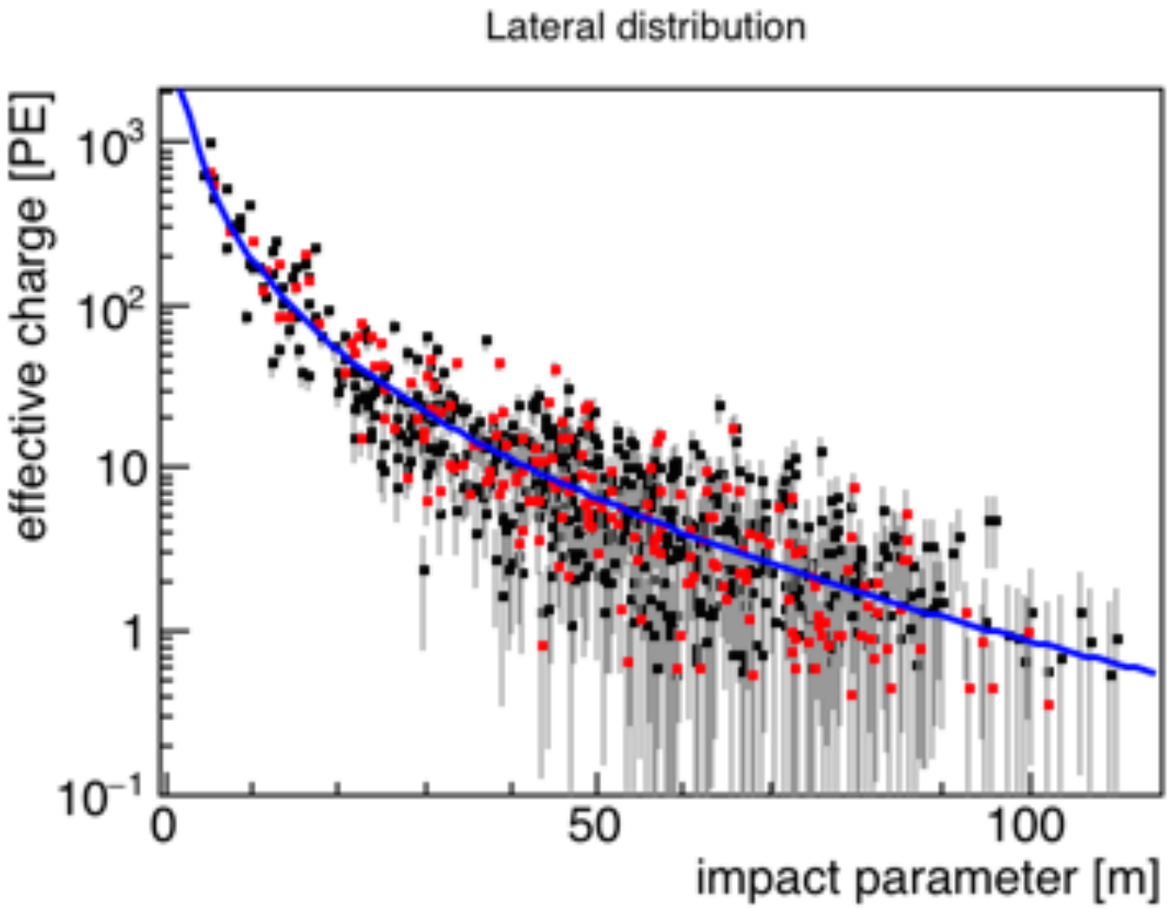

Run 2203, TS 1966176, Ev# 115, CXPE40= 39.9, Cmptness= 19.4



# HAWC-250 Data

- NKG fits to lateral distribution of observed charge
- Cosmic ray (left): poor NKG fit. In addition, observe much more scatter in the charge distribution



# HAWC Is Complete!

- E. Cabrero (CONACyT) and F. Córdova (NSF) pushing the "start button" at the HAWC Inauguration, March 20, 2015

# HAWC Physics Program

## Astrophysics

SNRs, Pulsars, *Binaries*, etc.

*AGN Flares*

## Dark Matter

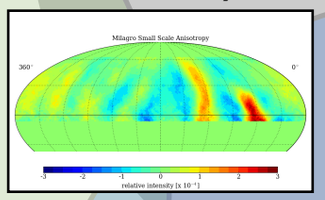
*Cosmic electron spectrum*



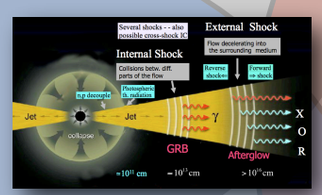
*$e^+/e^-$ ratio*

Indirect DM Searches

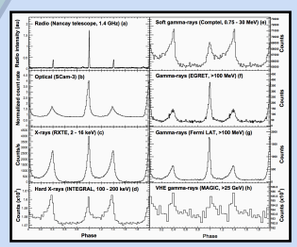
*Cosmic Rays*




*GRBs*



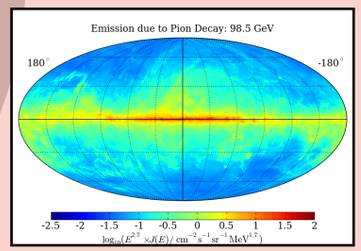

Lorentz Invariance Violation



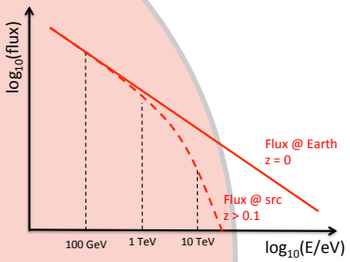
Exotic Particles

## Cosmology

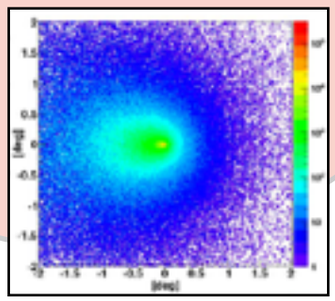
*Diffuse Emission*




*Extragalactic Background Light (IR)*




Intergalactic Magnetic Fields



Monopoles, Axions, Q-balls, etc.

## Fundamental Physics

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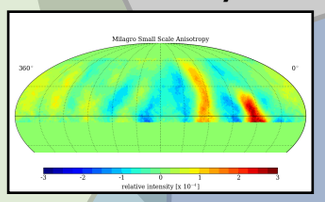


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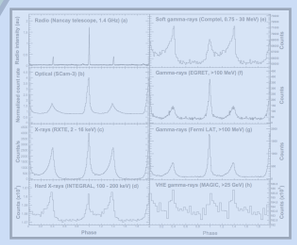

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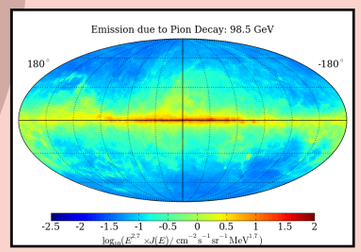


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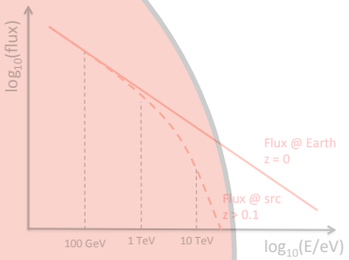


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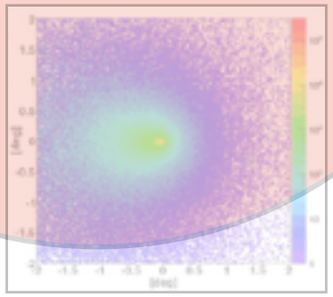
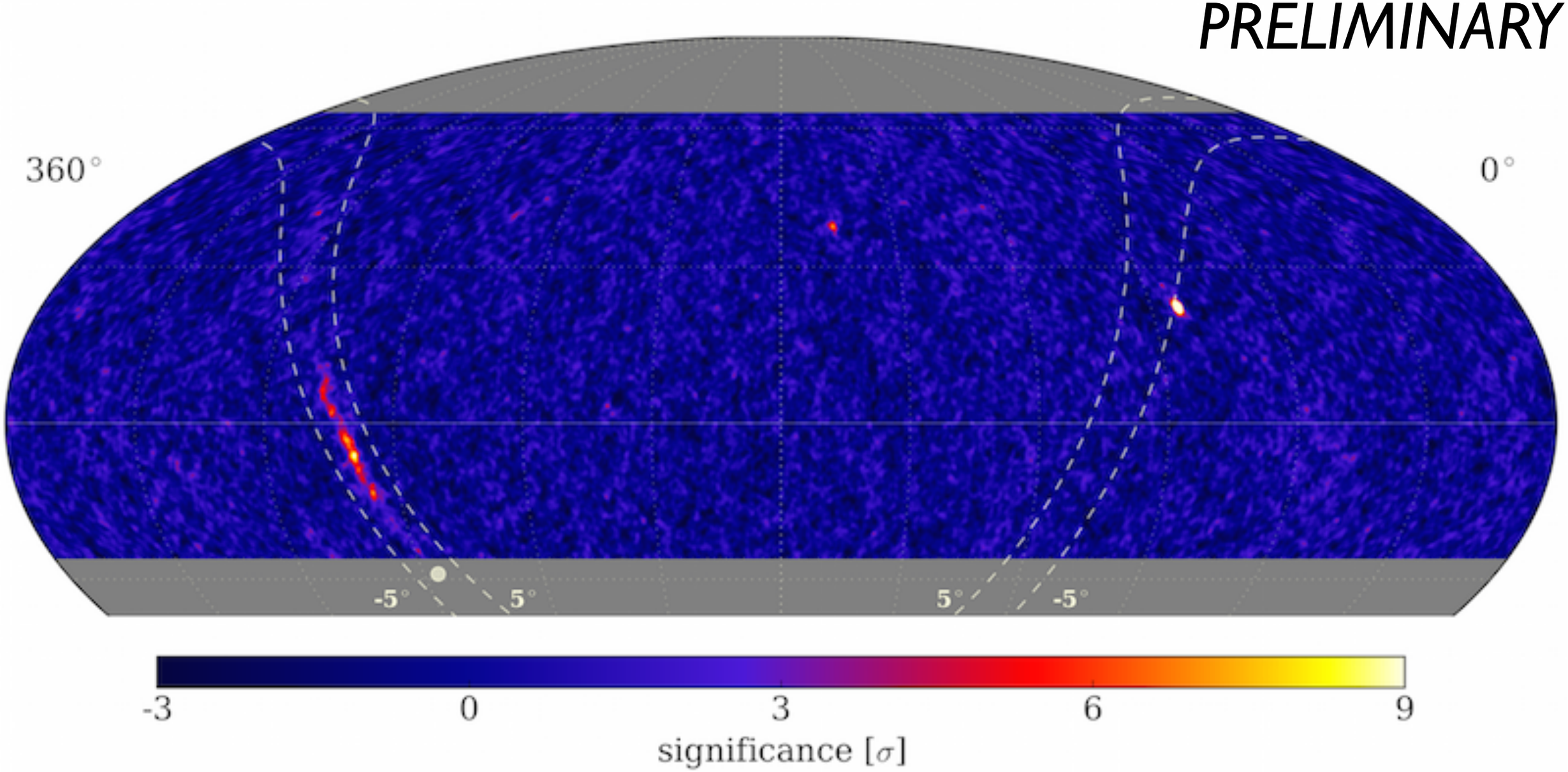


## Fundamental Physics

# HAWC-250 γ-Ray Map

*PRELIMINARY*



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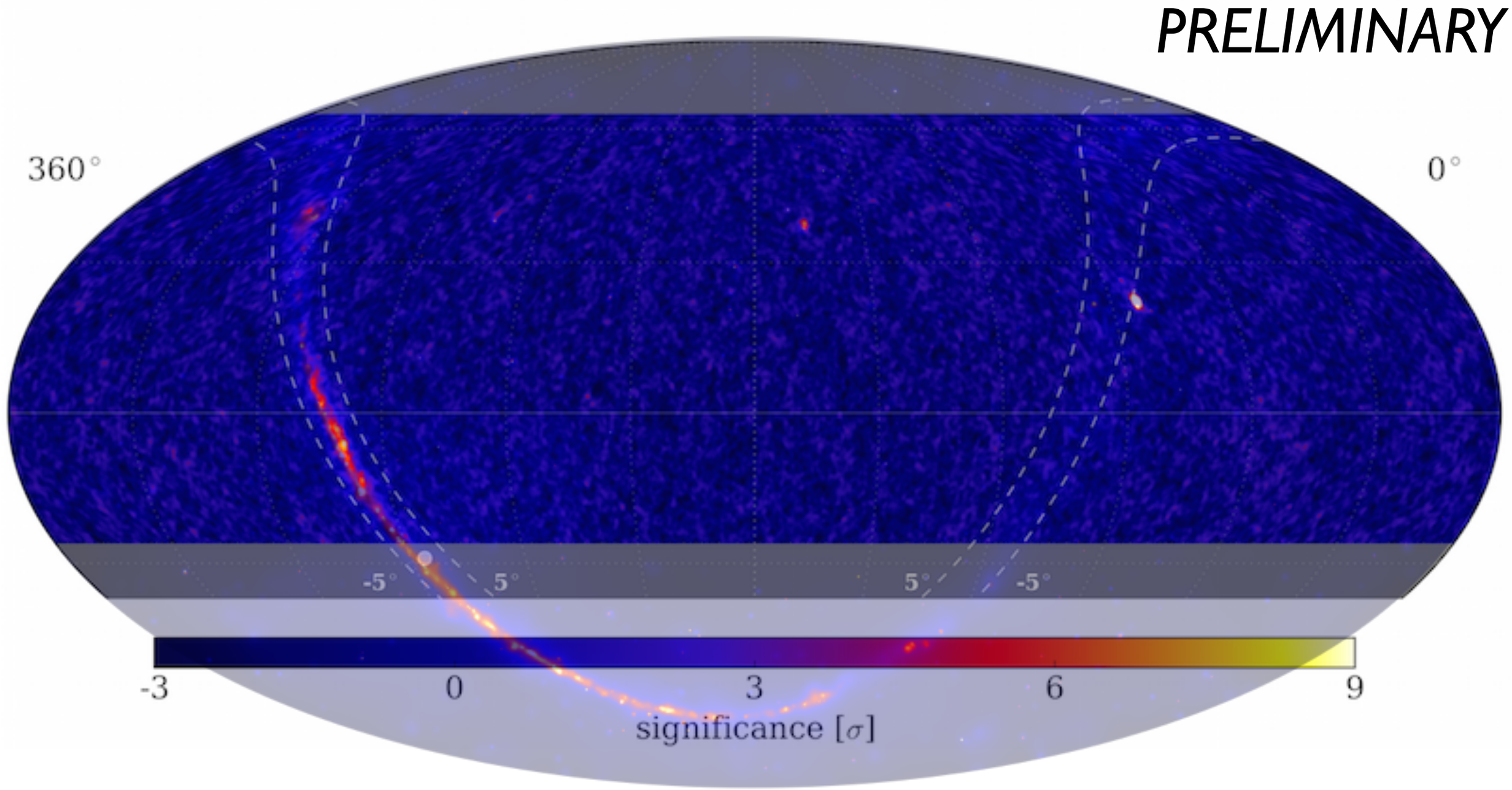


Fermi LAT: *E* > 50 GeV (M. Ajello)

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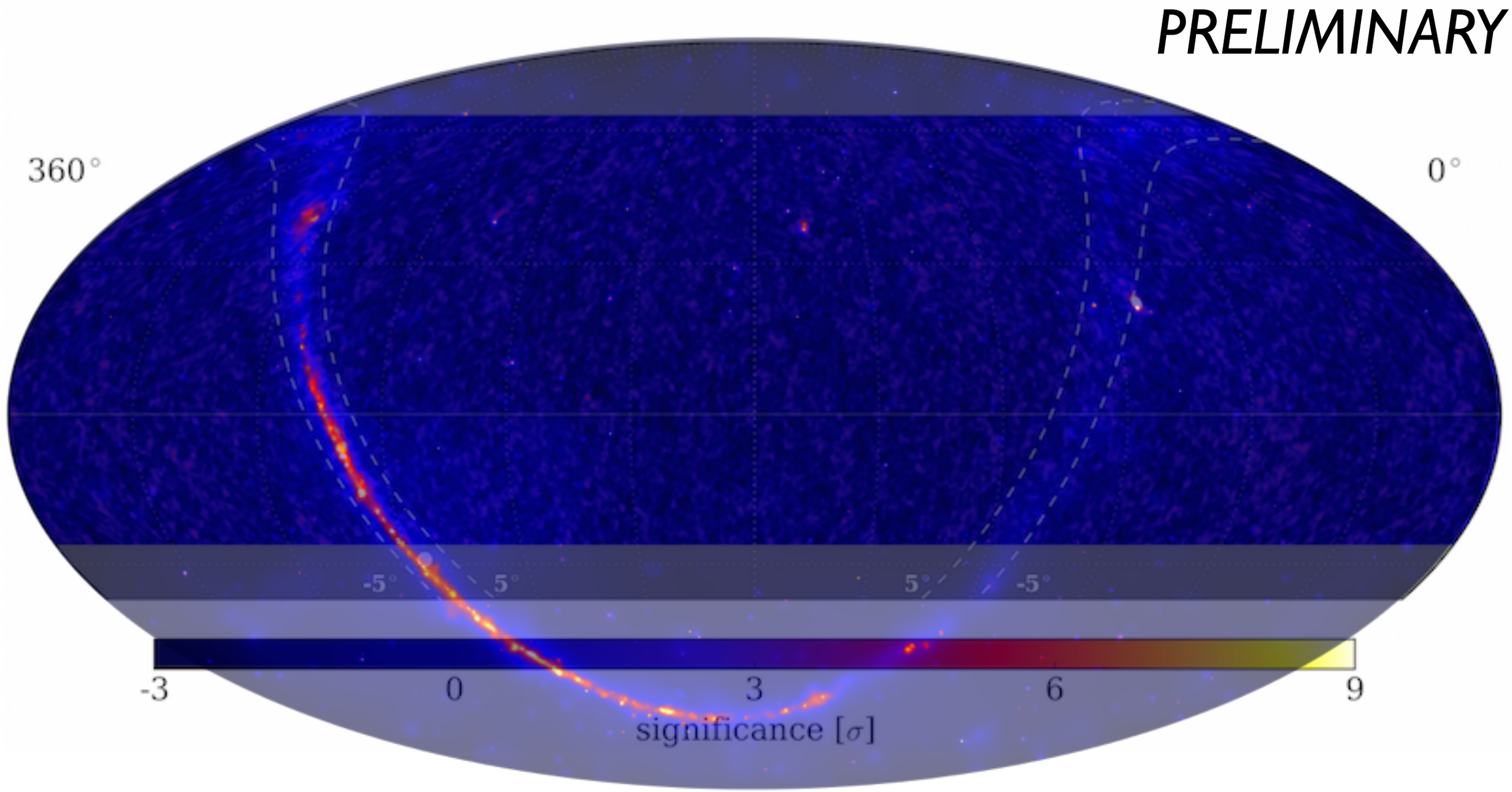


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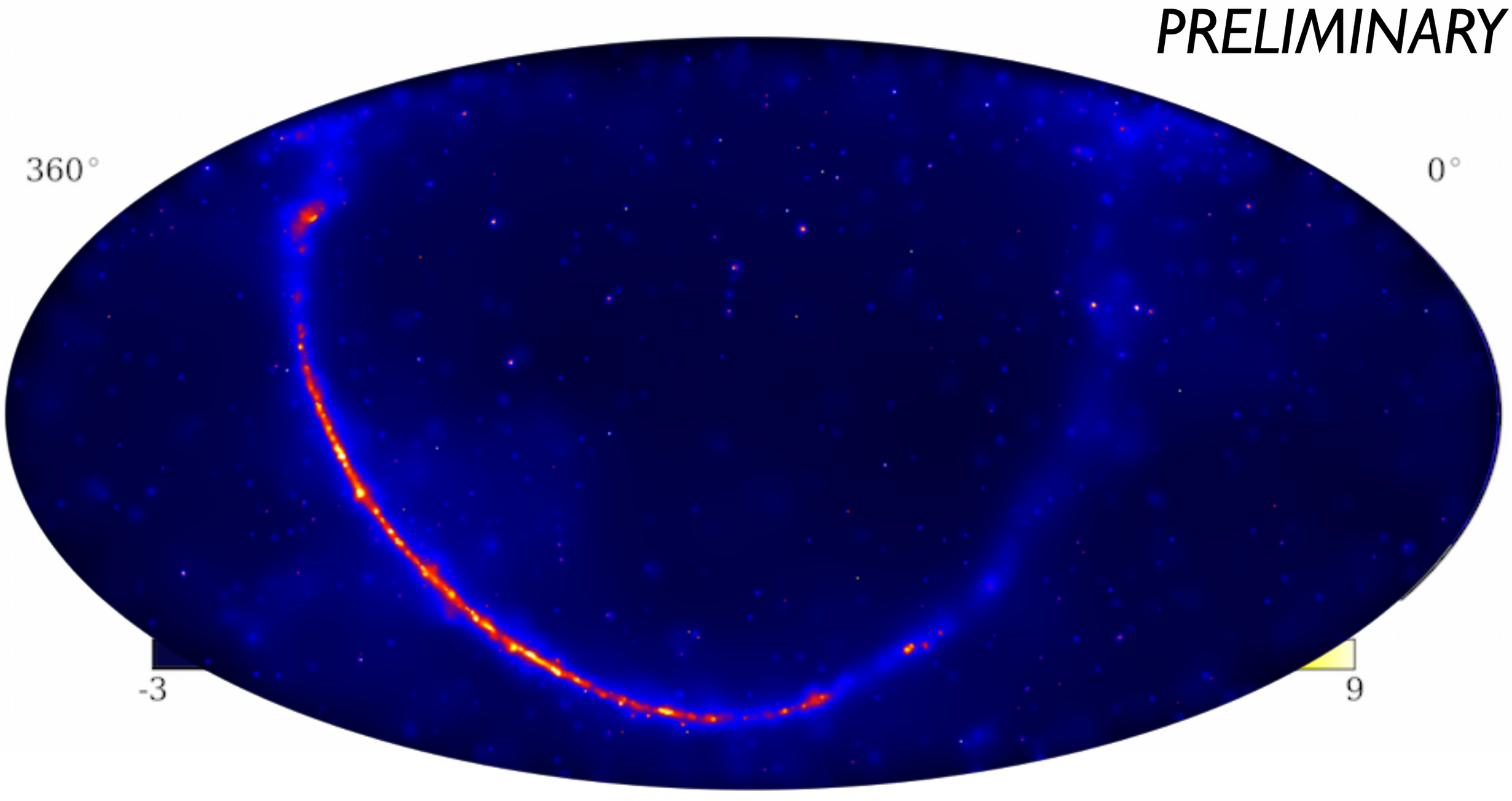


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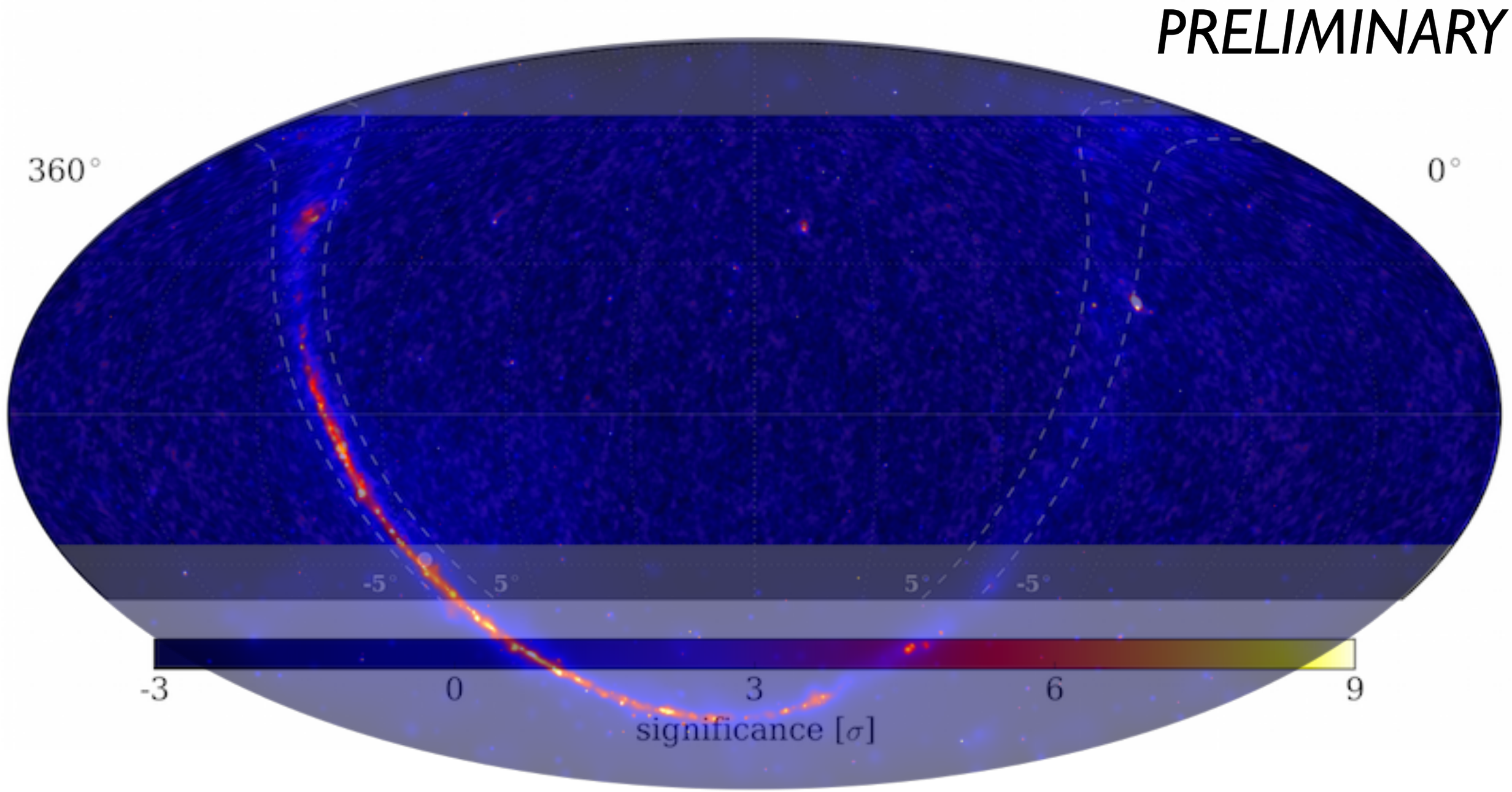


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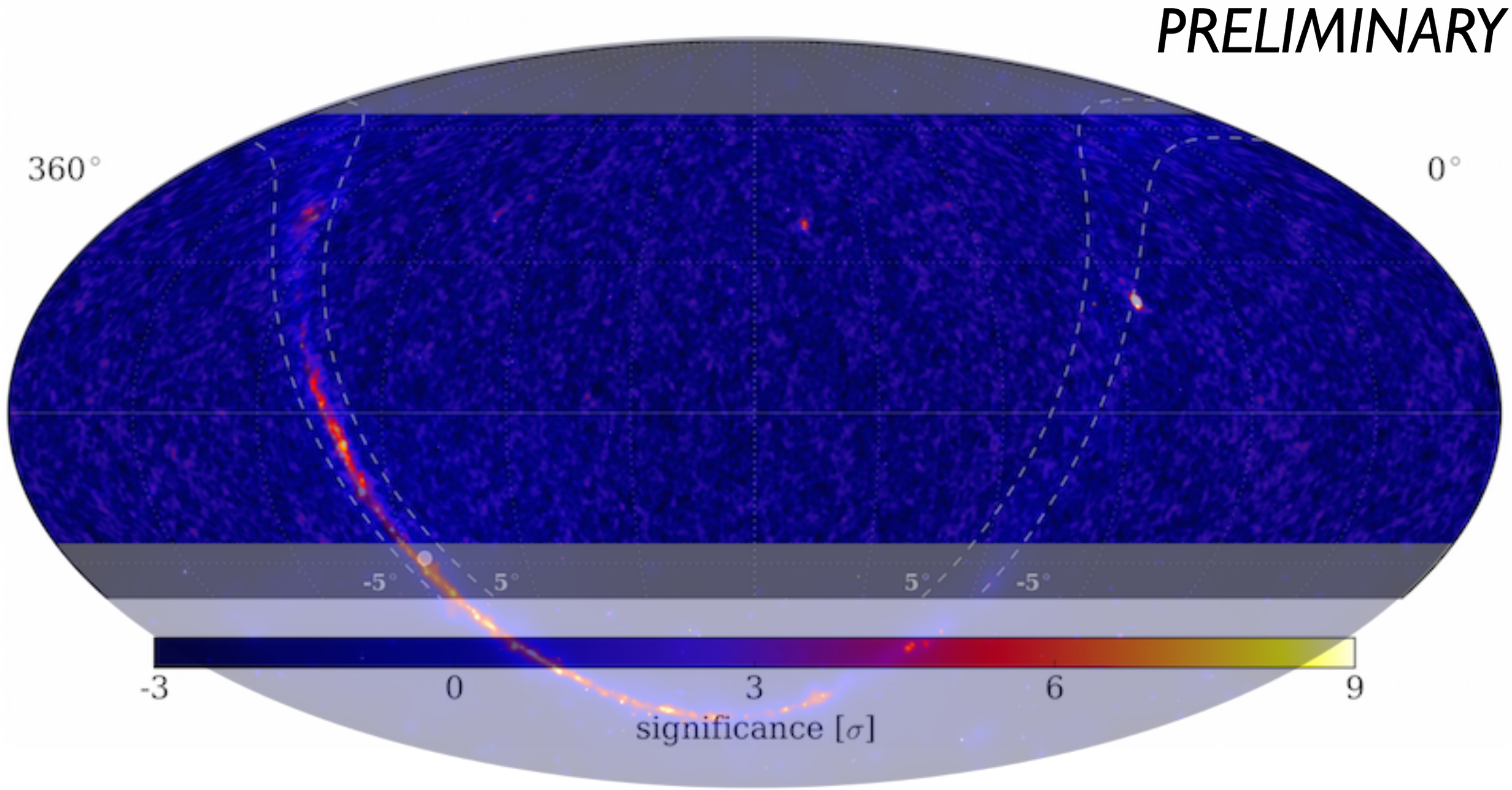


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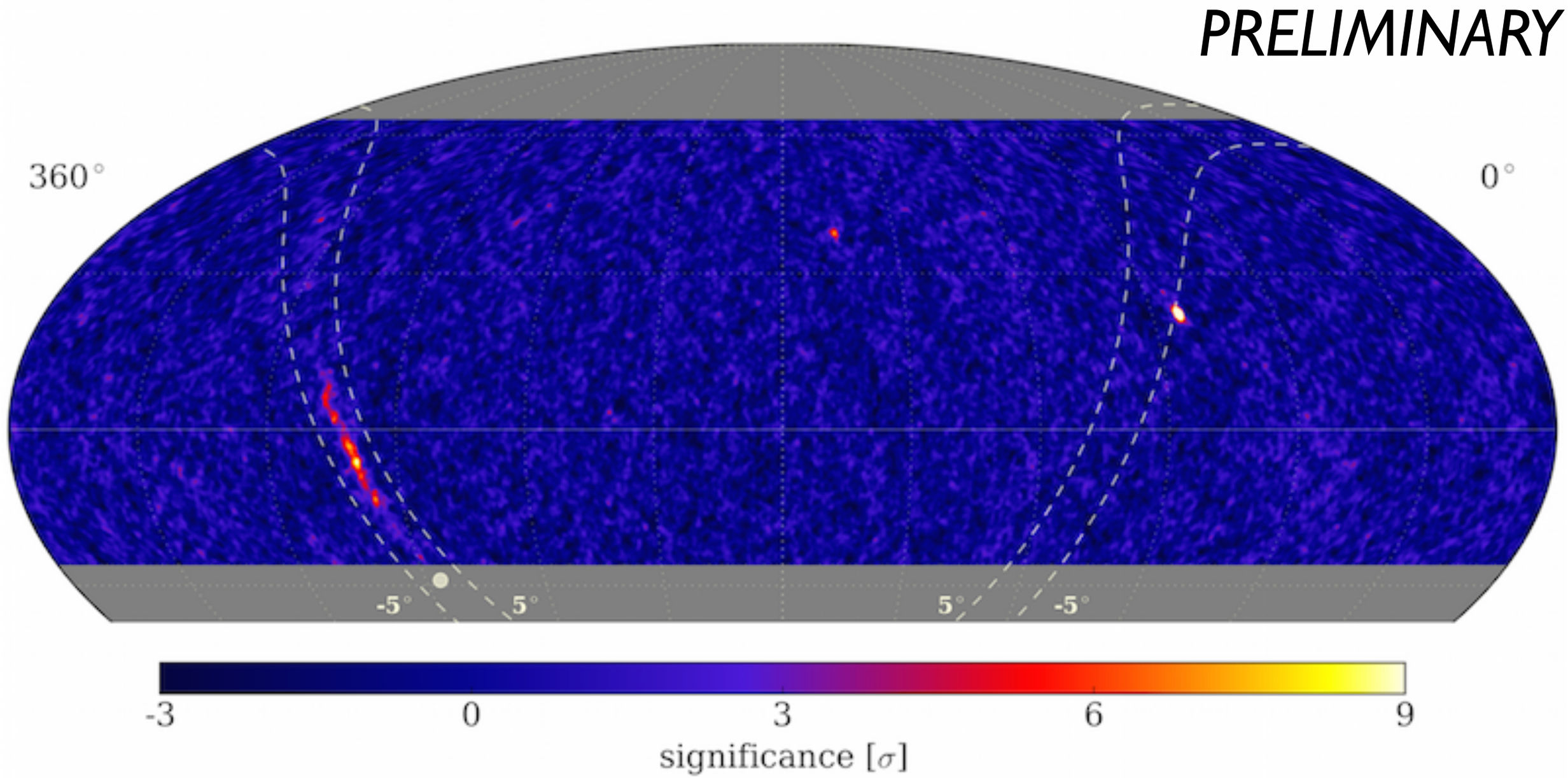
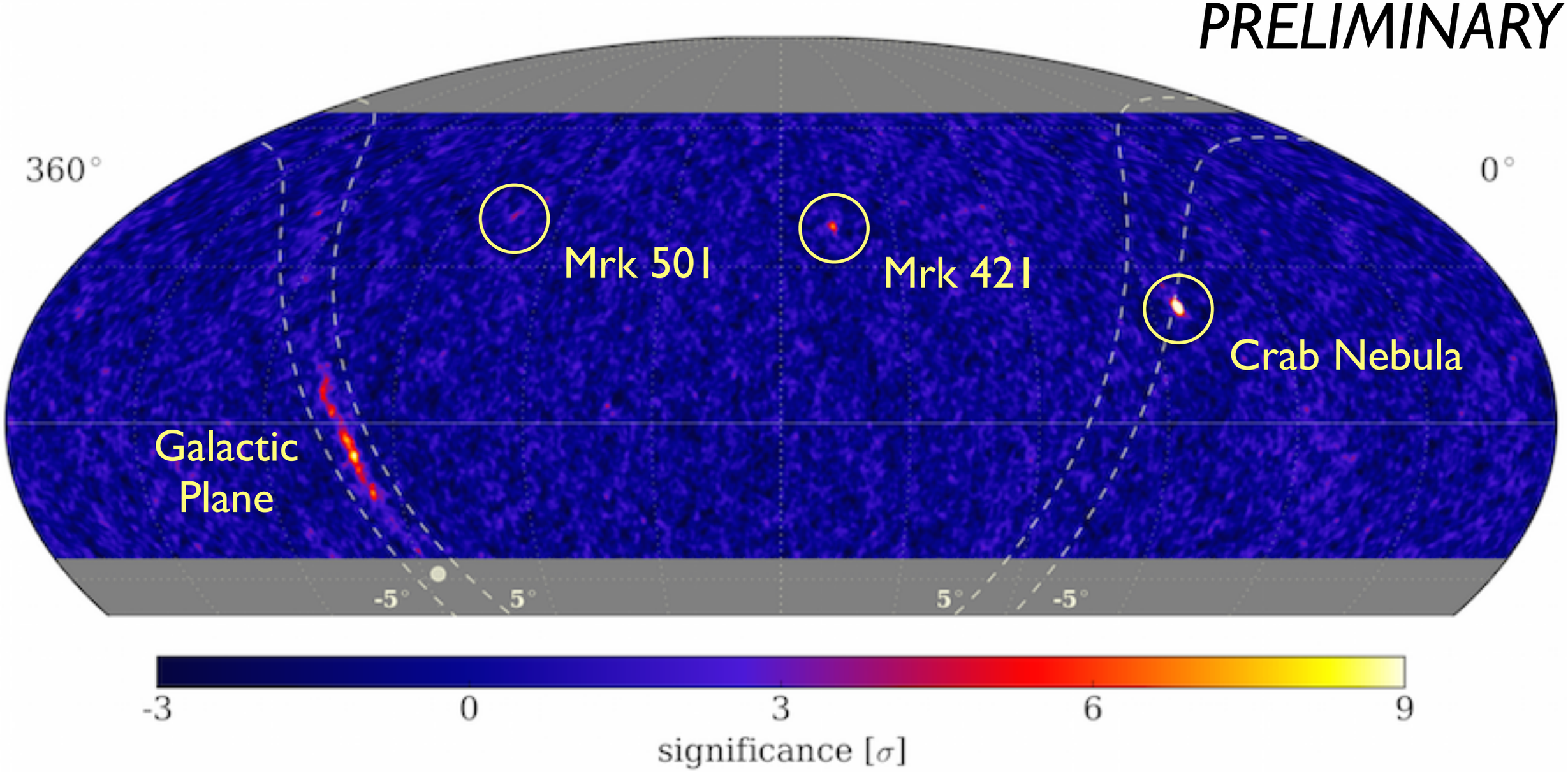



Fermi LAT: *E* > 50 GeV (M. Ajello)

# HAWC-250 γ-Ray Map

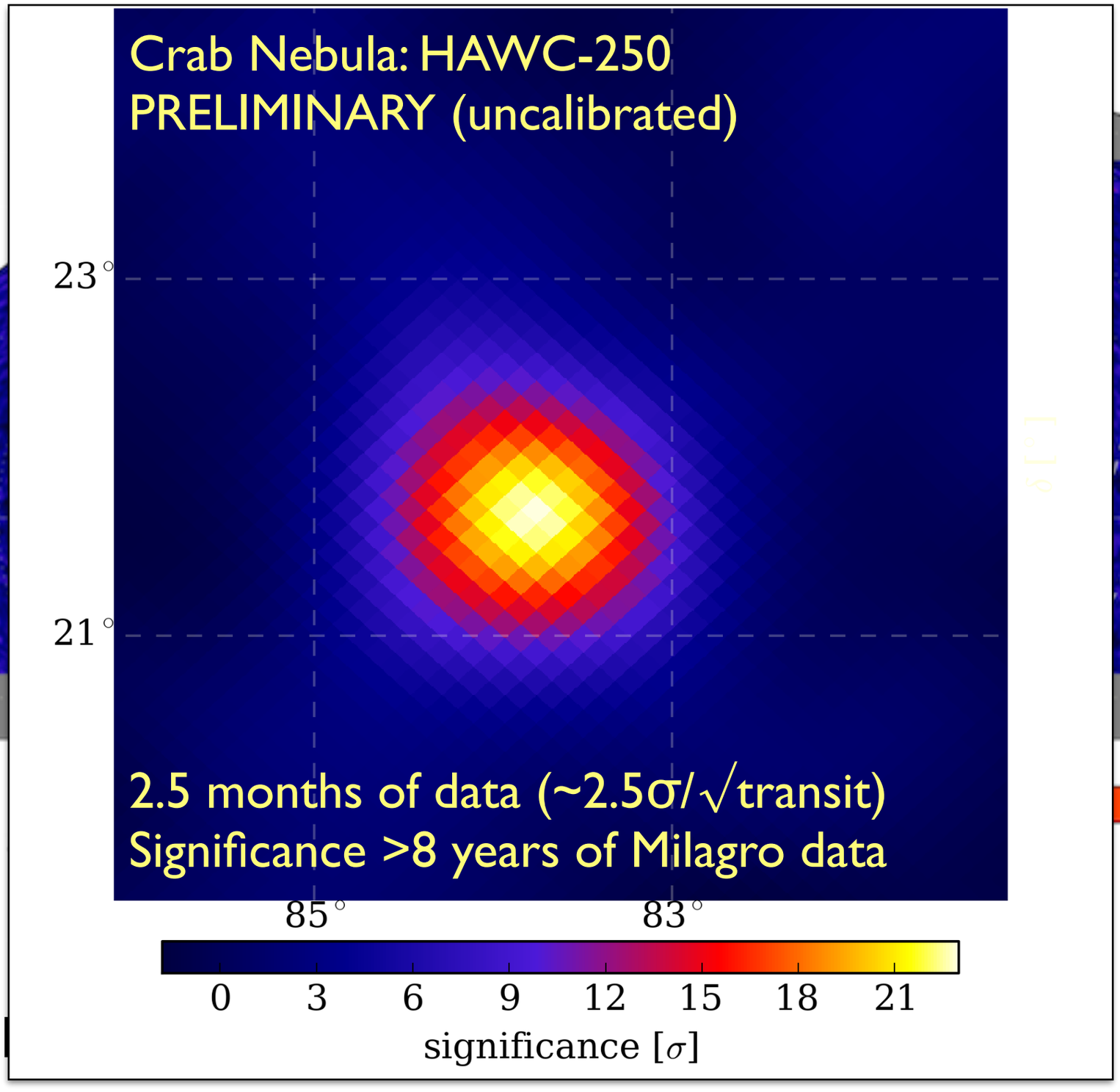
*PRELIMINARY*




Fermi LAT: *E* > 50 GeV (M. Ajello)

# HAWC-250 γ-Ray Map

C. Riviere (UMD)





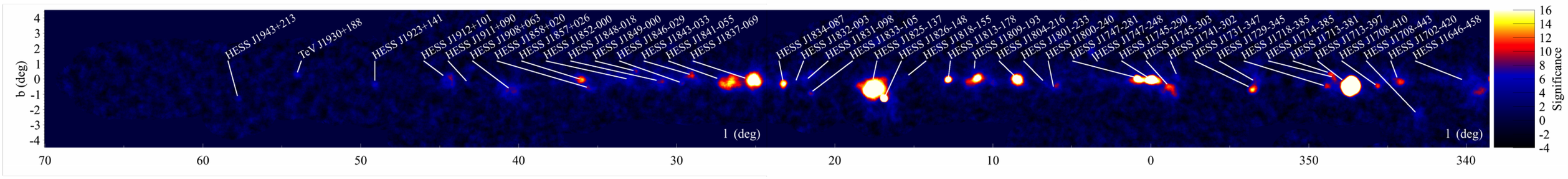


Fermi

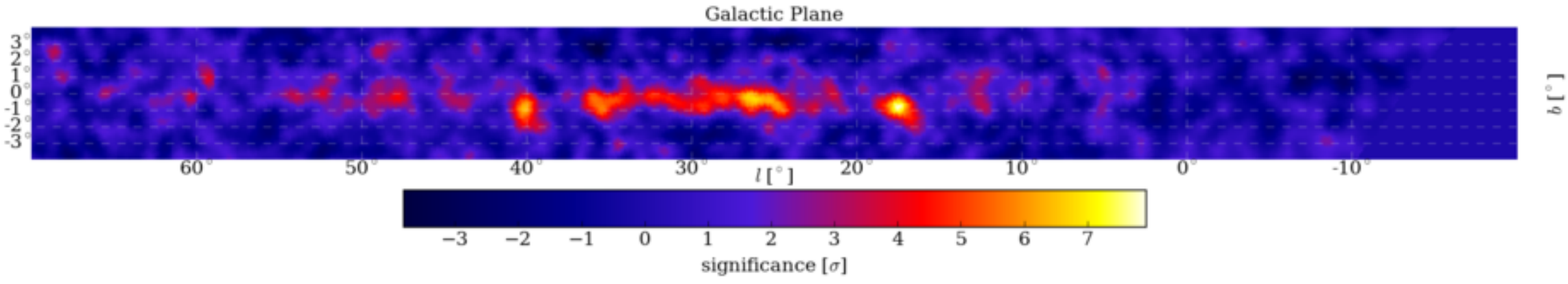
# The Galaxy in TeV γ Rays

- HESS survey of the Galactic Plane showing only the region of overlap with HAWC

S. Carrigan et al., Proc. 48th Recontres de Moriond, 2013



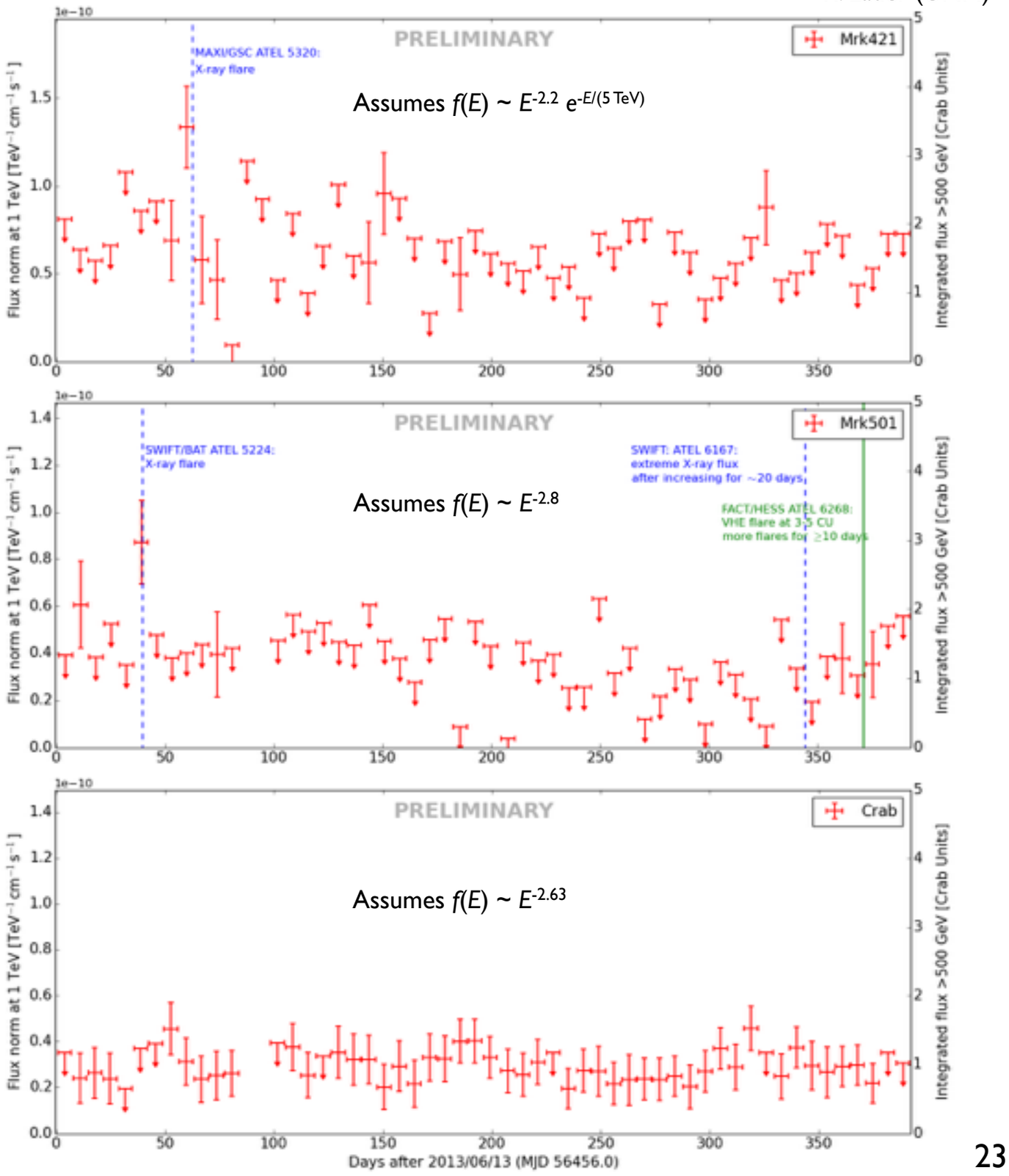

- HAWC view of the Galactic Plane (PRELIMINARY)



# Observations of AGN

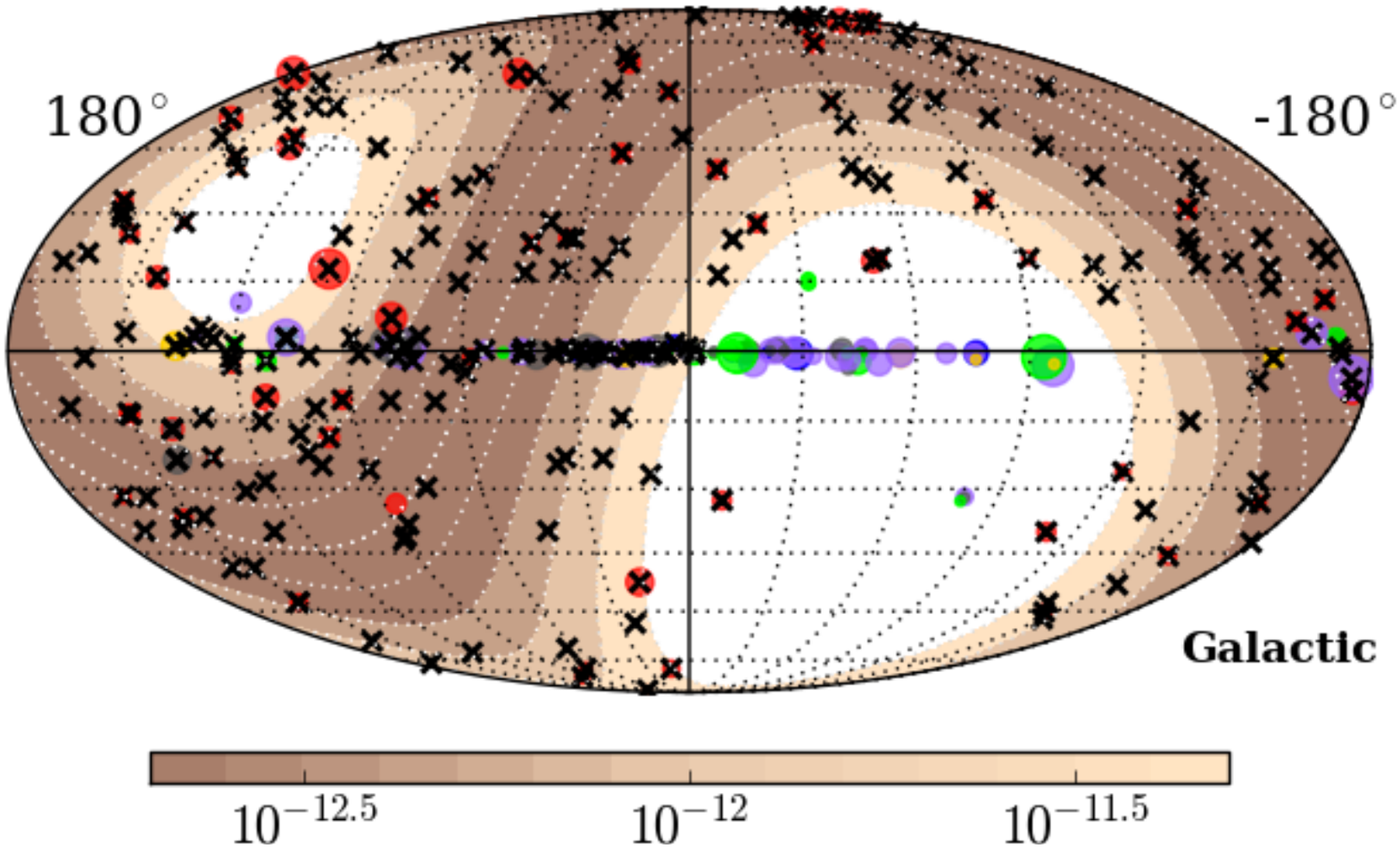
R. Lauer (UNM)

- Preliminary light curves from HAWC-111
- Data are binned in one week intervals
- Mrk 421, 501: some flaring behavior
- Crab: consistent with steady flux



# High-Uptime Flare Monitoring

I. Wisher (UW-Madison)



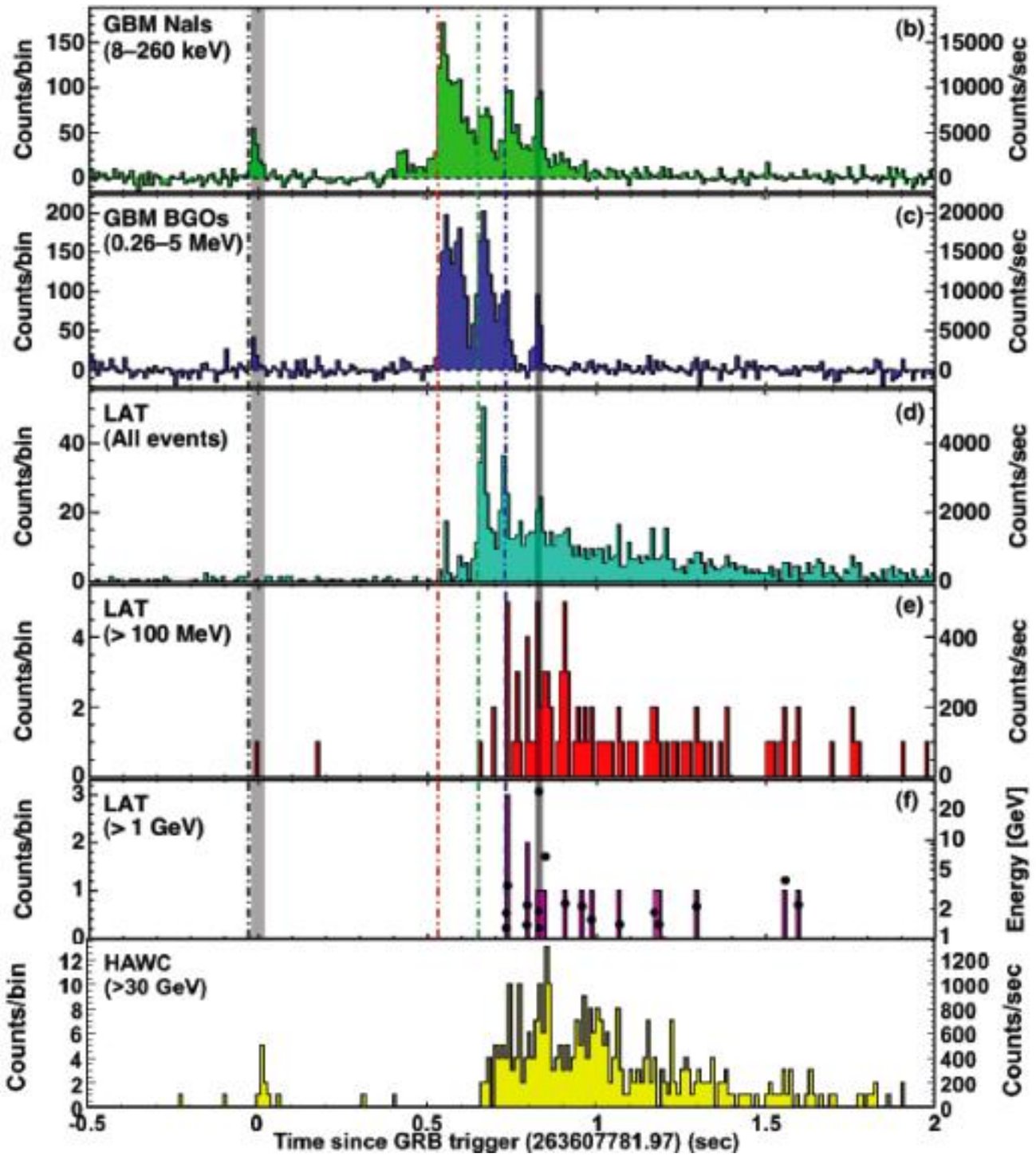

- Current HAWC performance: 95% uptime
- Crab duty cycle: 20%
- Mrk 421 duty cycle: 15%

- Monitoring extragalactic sources in TeVCat + 2FGL blazars with $z \leq 1$ + 30 Galactic TeV binary candidates (240 objects). **See talk by Ian Wisher this afternoon**

# Gamma-Ray Bursts

- Fermi observation of GRB090510, $z$=0.9
  - $E_{max}$ = 33 GeV
  - Constrained Lorentz Invariance Violation at $M_{Planck}$ scale
- Would be observed by HAWC if in FOV
- Expectation: HAWC will detect $\leq$1.6 GRB $yr^{-1}$ (mainly short GRBs: see NIM A **742**:276, 2014)

J. Braun (UMD/UW-Madison)



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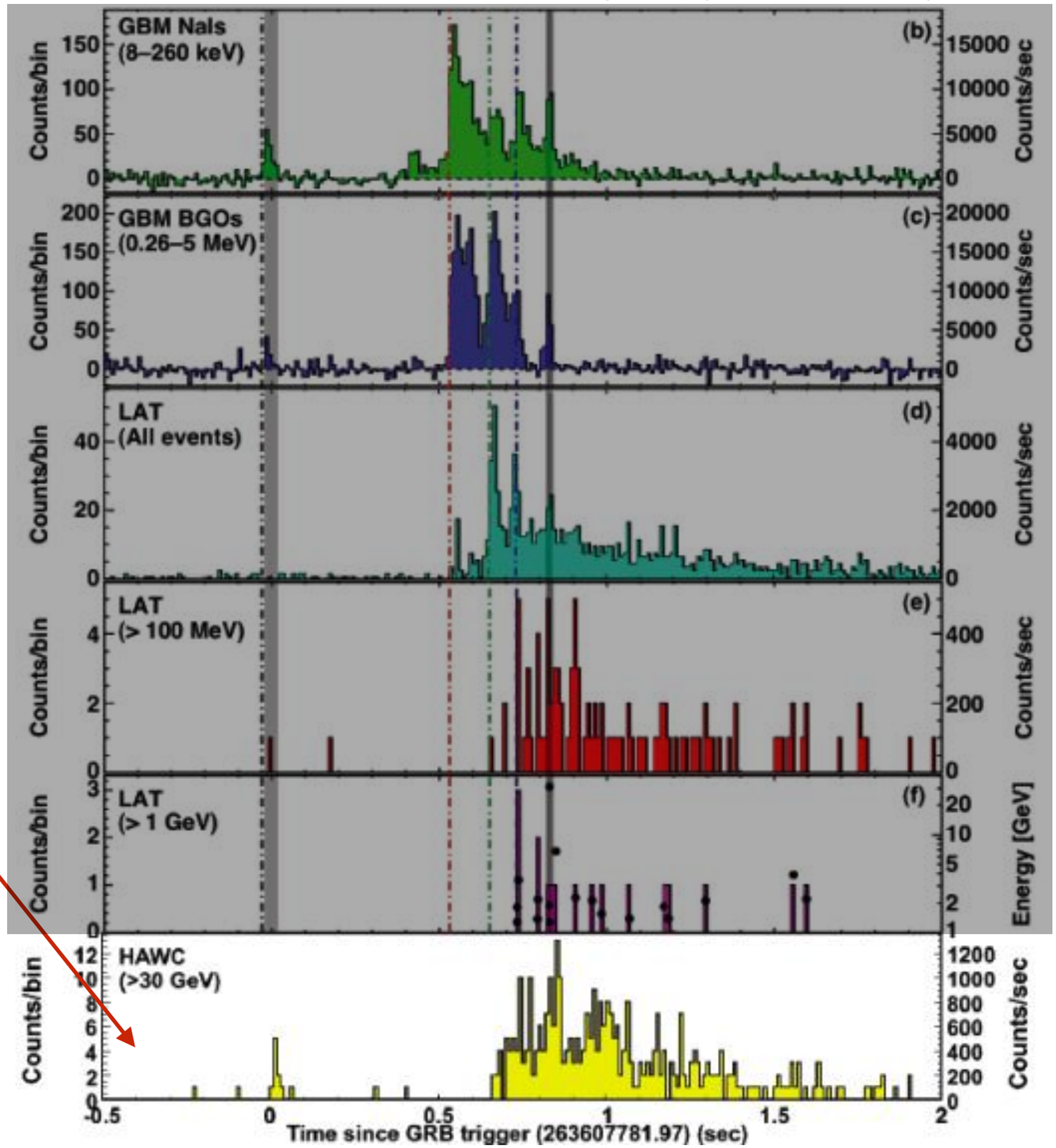
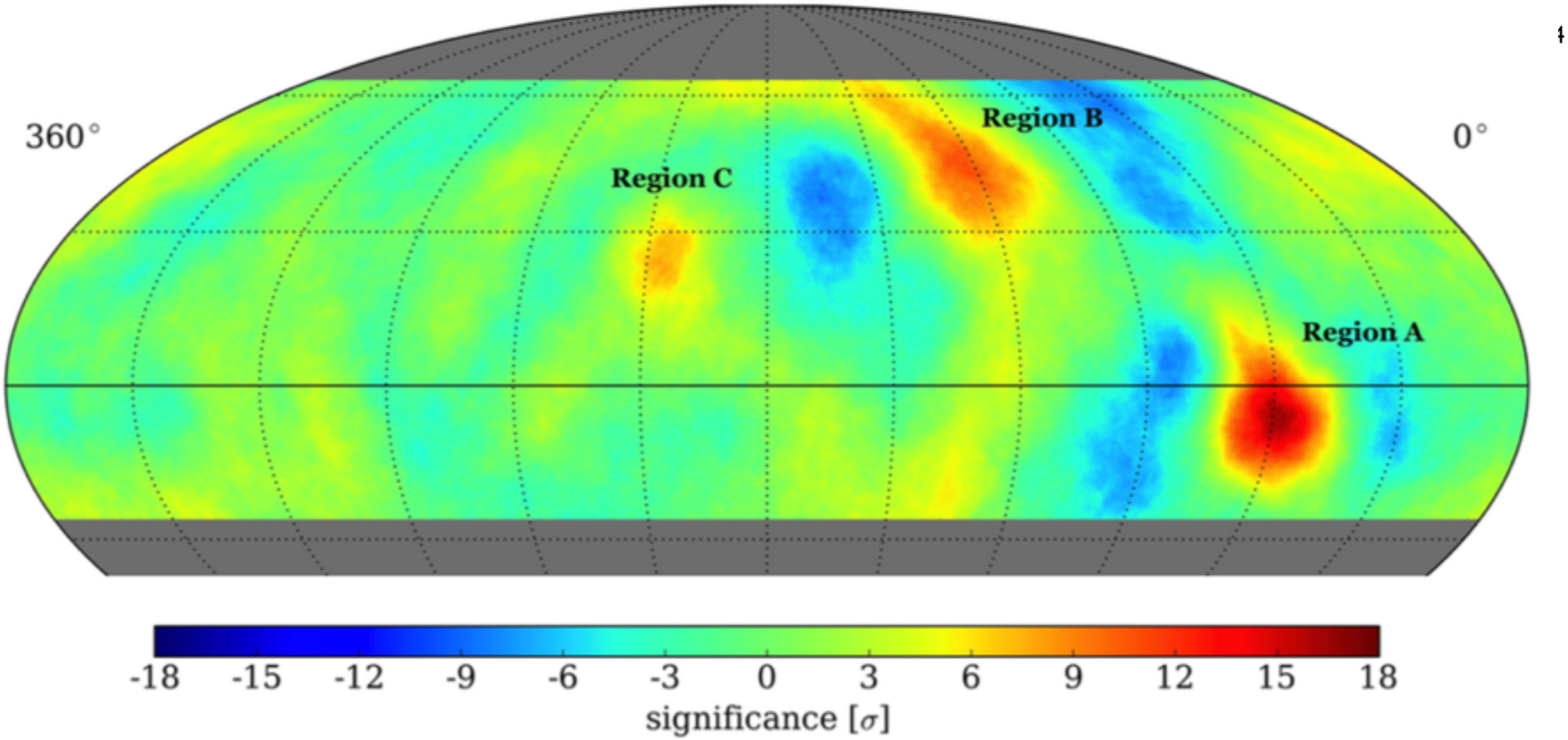


# Observations of Cosmic Rays

- Very high statistics observations of cosmic rays (recall: 10 kHz event rate)
- Angular resolution for cosmic-ray reconstruction ranges from >1° below 1 TeV to <0.5° above 10 TeV
  - Easily sufficient for study of "small-scale" anisotropy of cosmic rays
- First results:
  - Observation of the lunar shadow in cosmic rays
  - Observation of $10^{-4}$ anisotropy in CR intensity

# Cosmic-Ray Anisotropy

- 3 significant hotspots at 2 TeV. Evidence for nearby Galactic sources? Magnetic lensing? Something more "exotic?"



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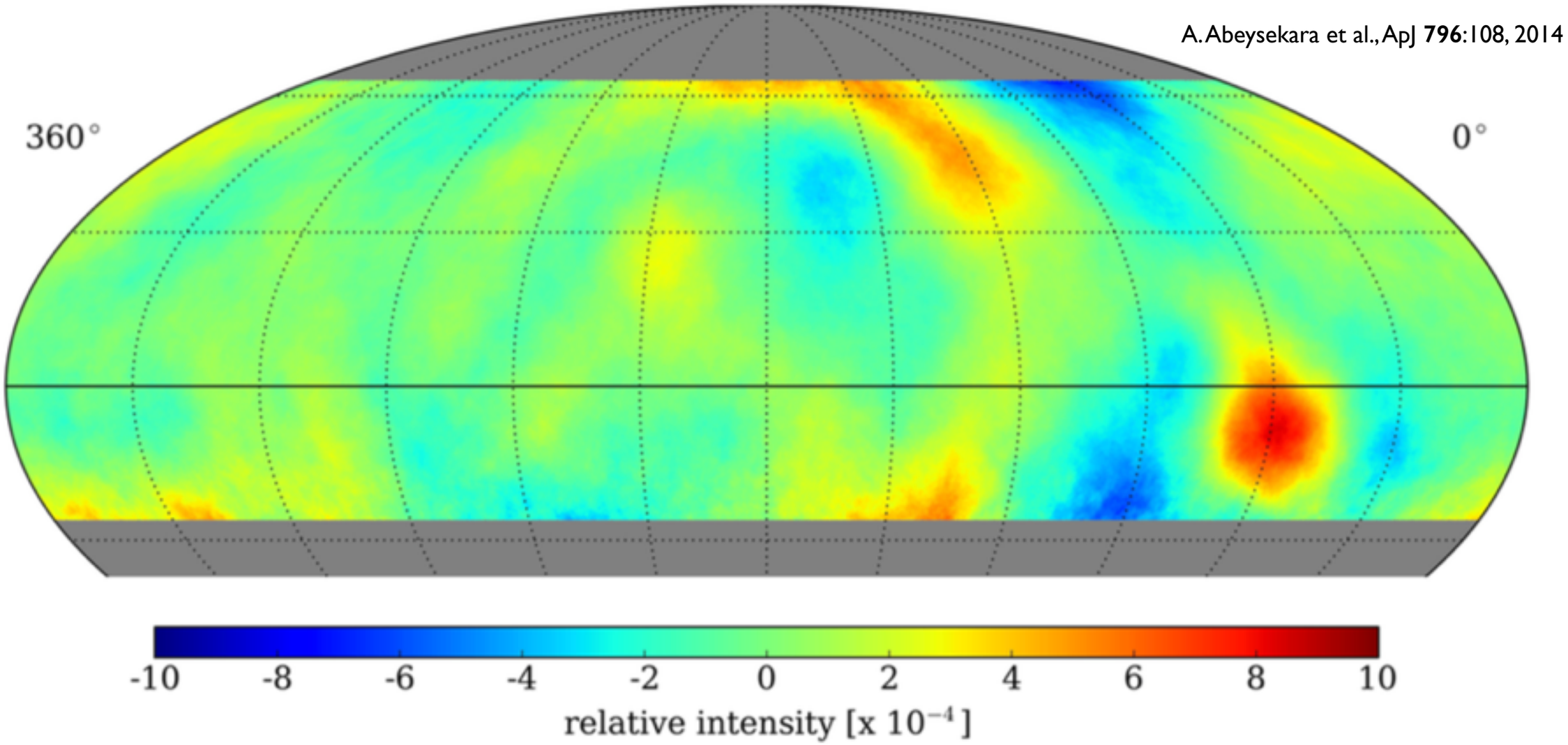

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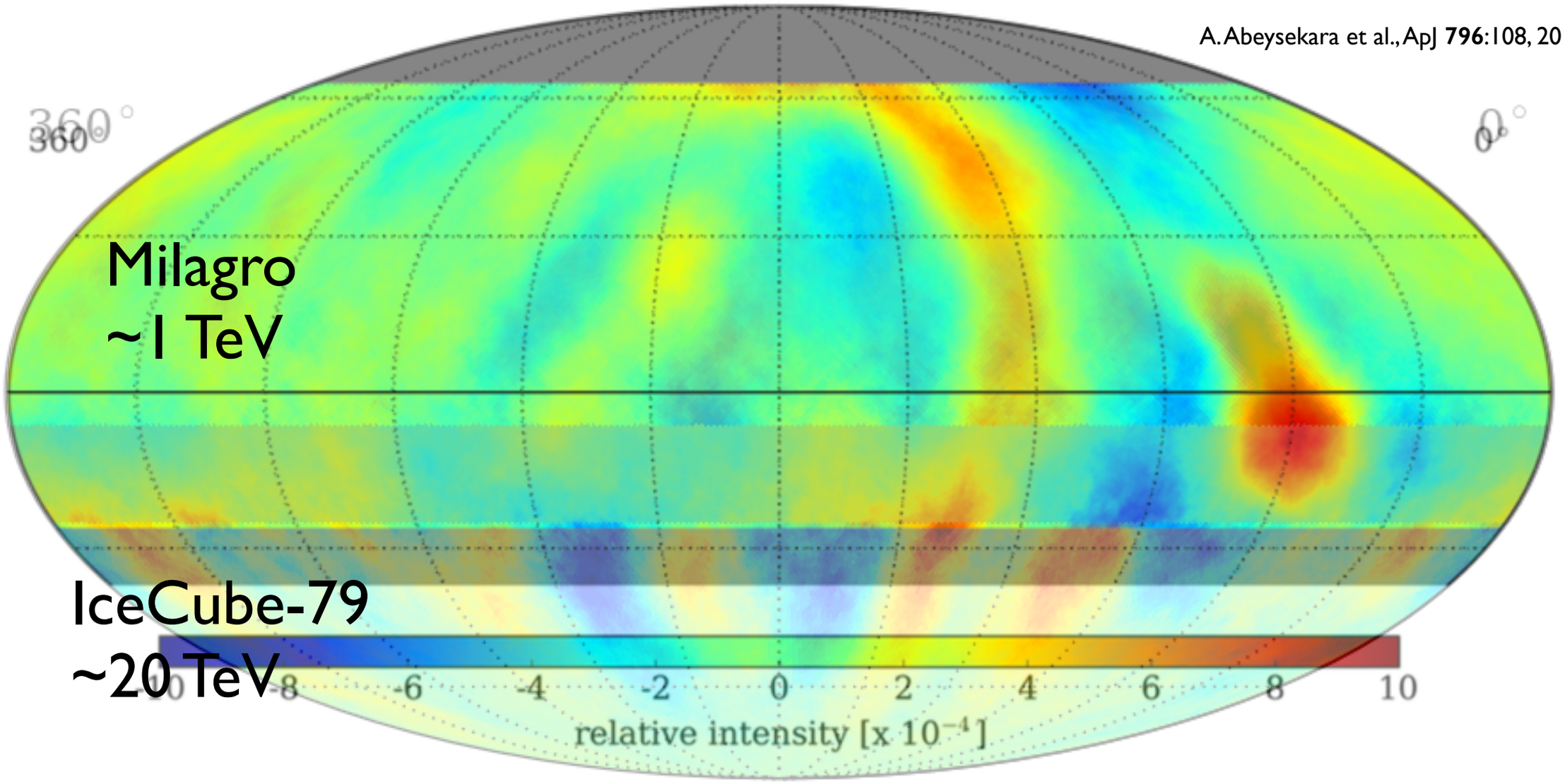

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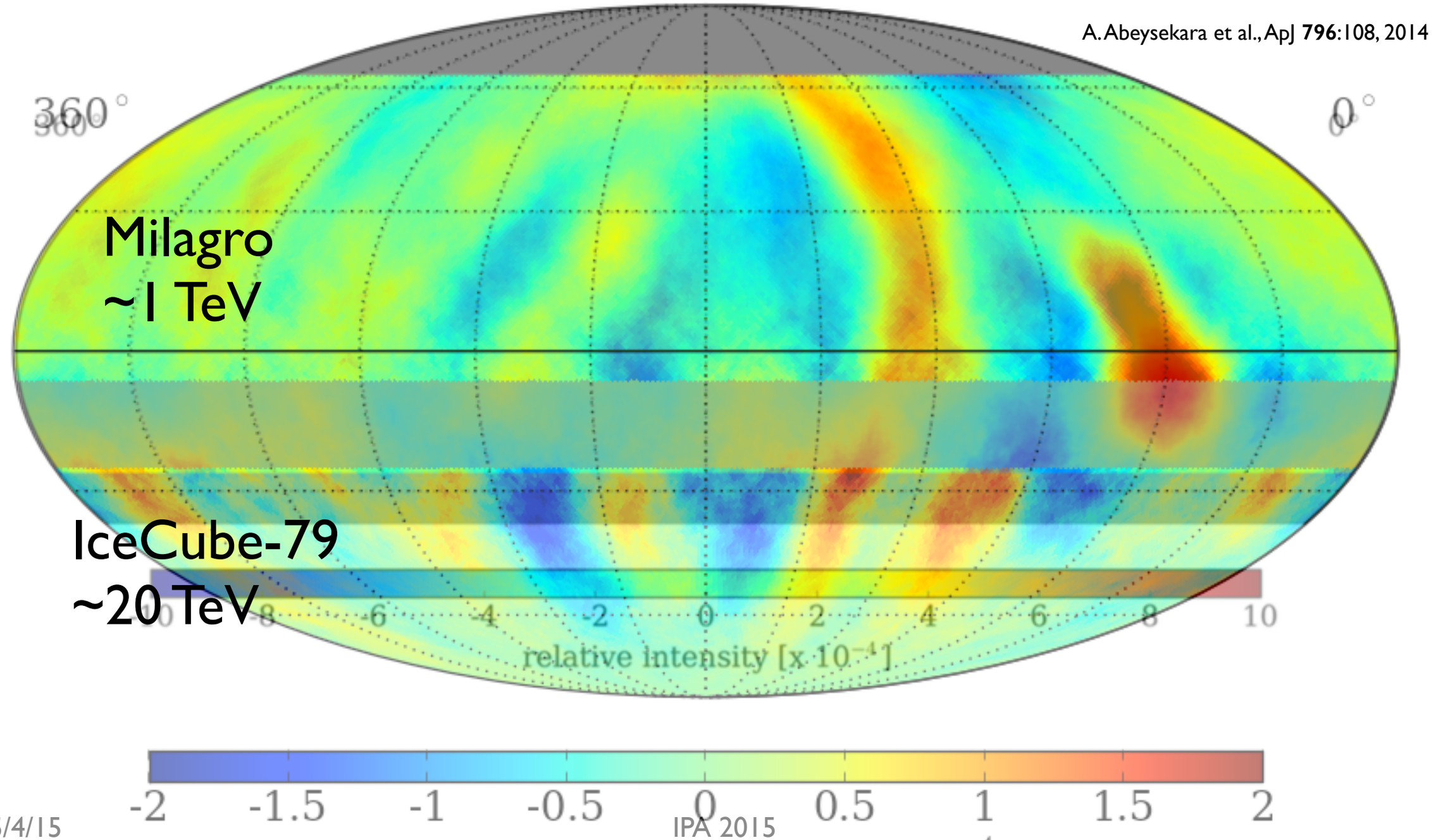

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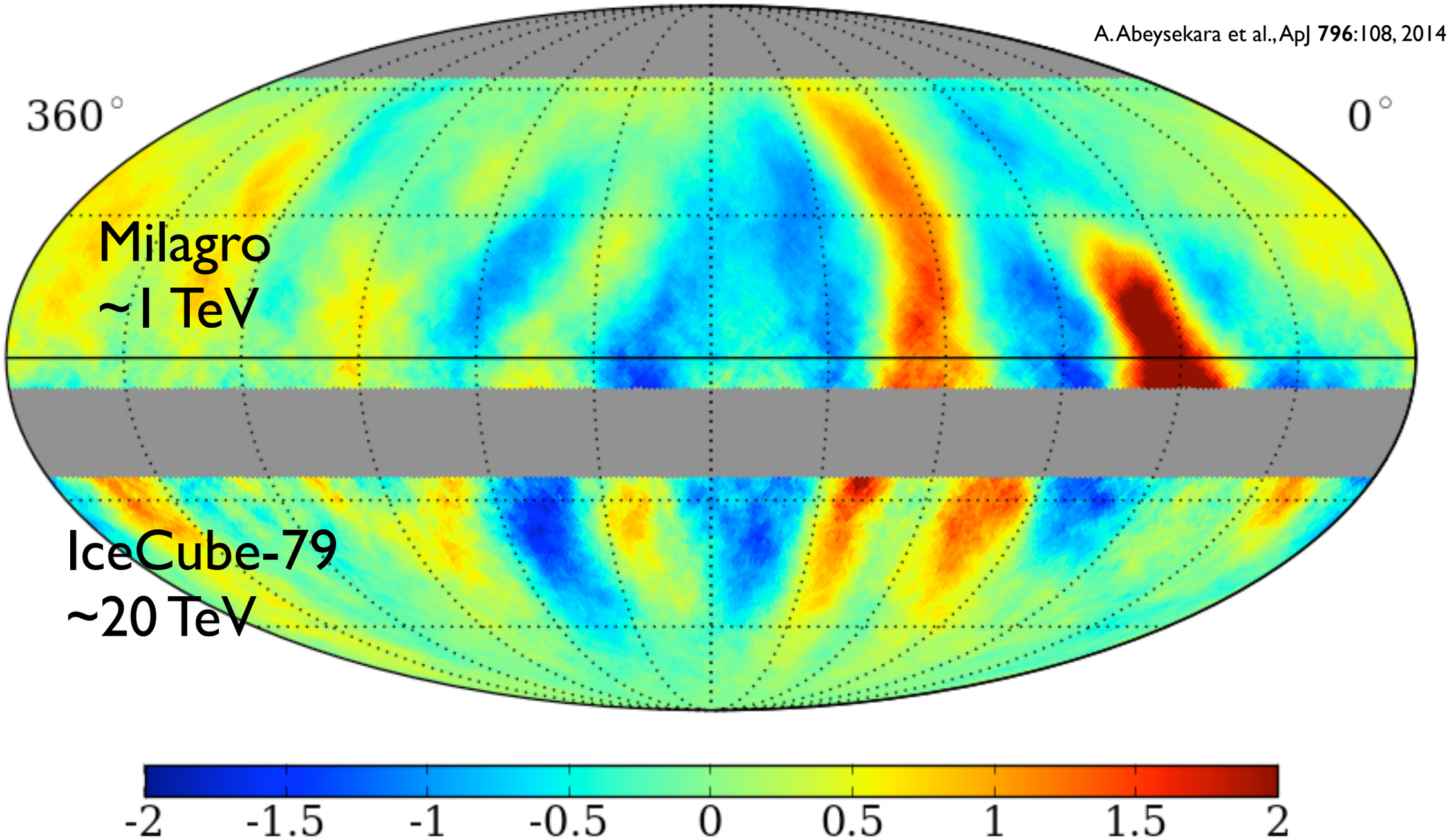

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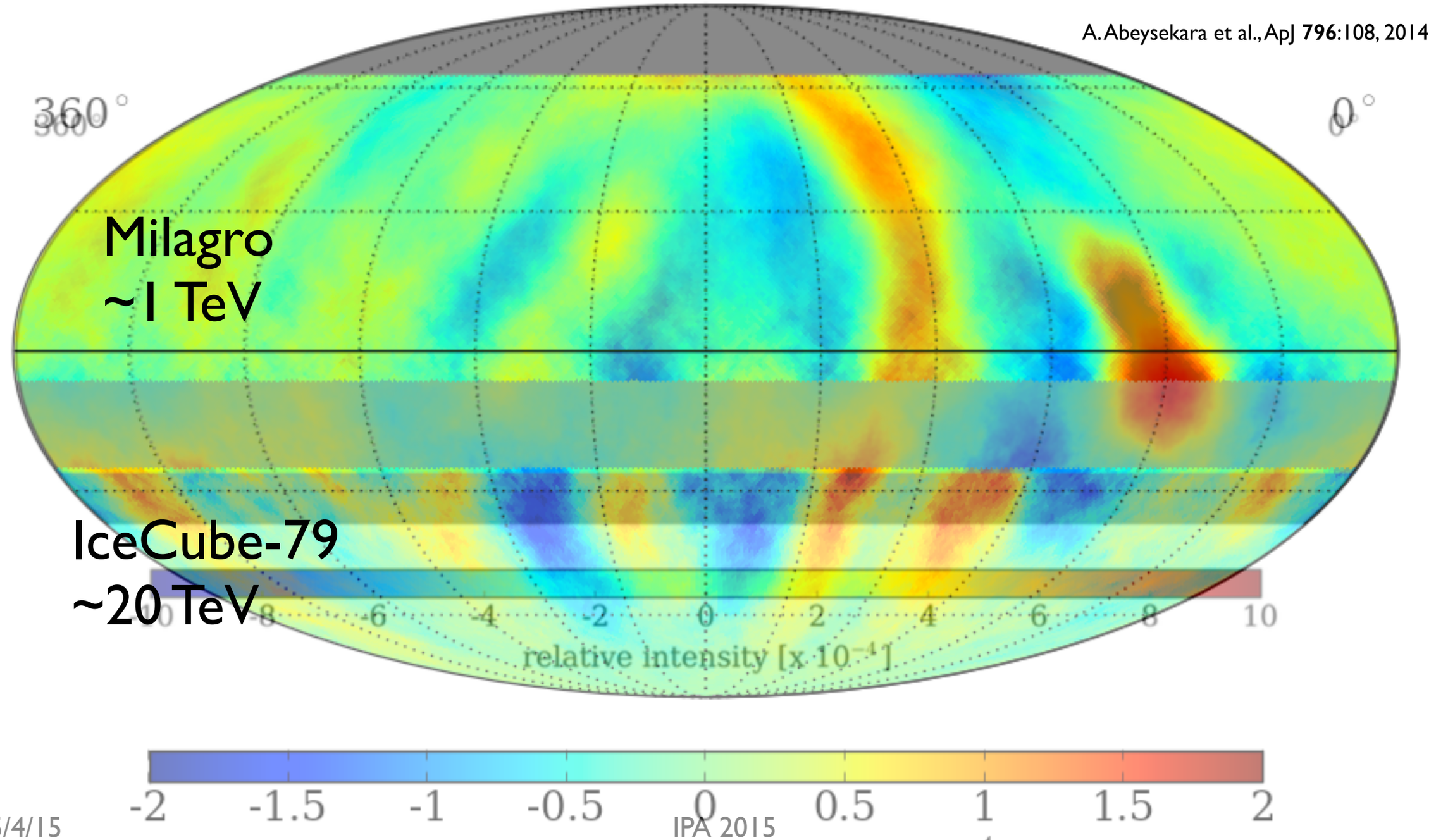

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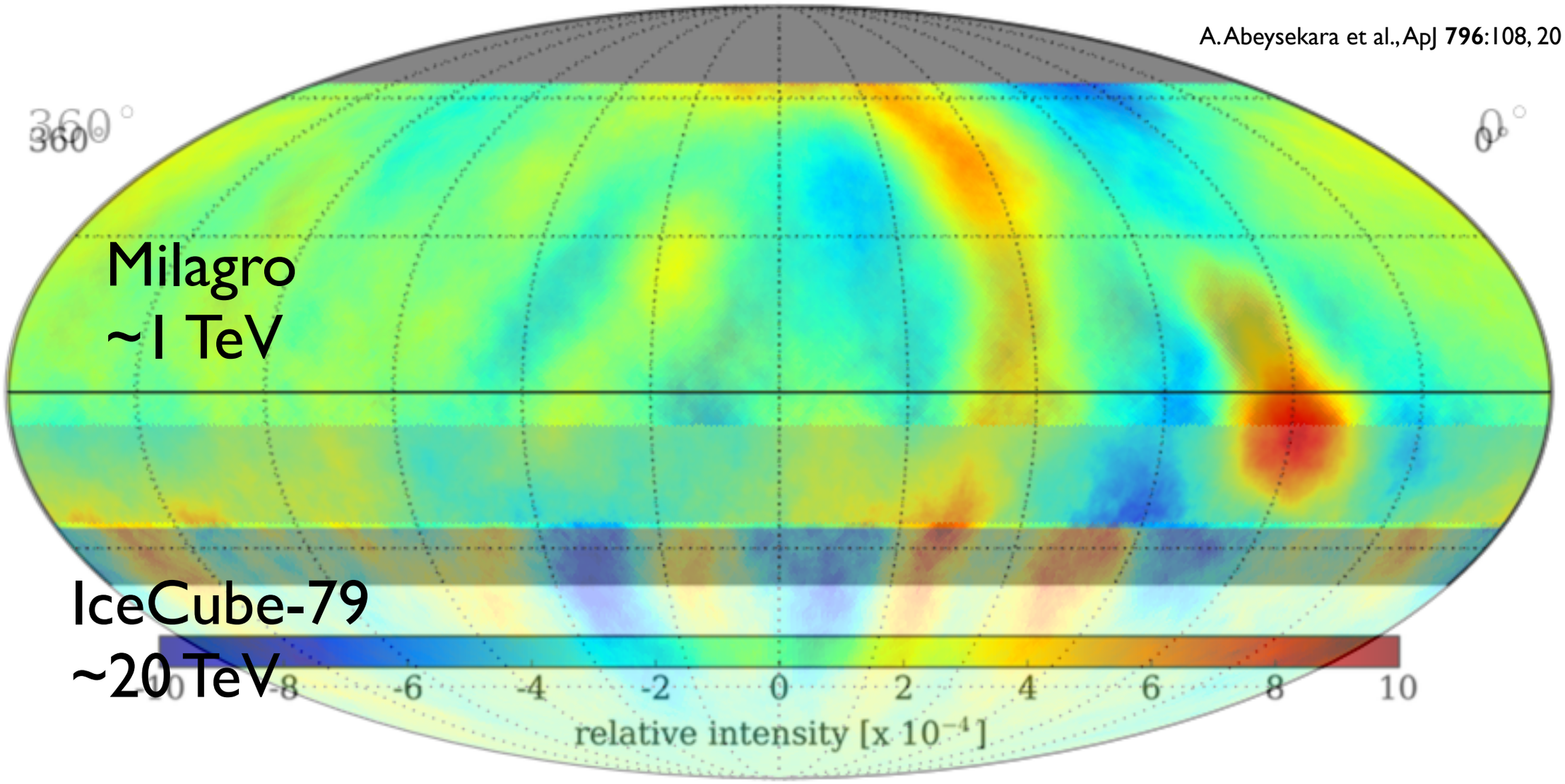

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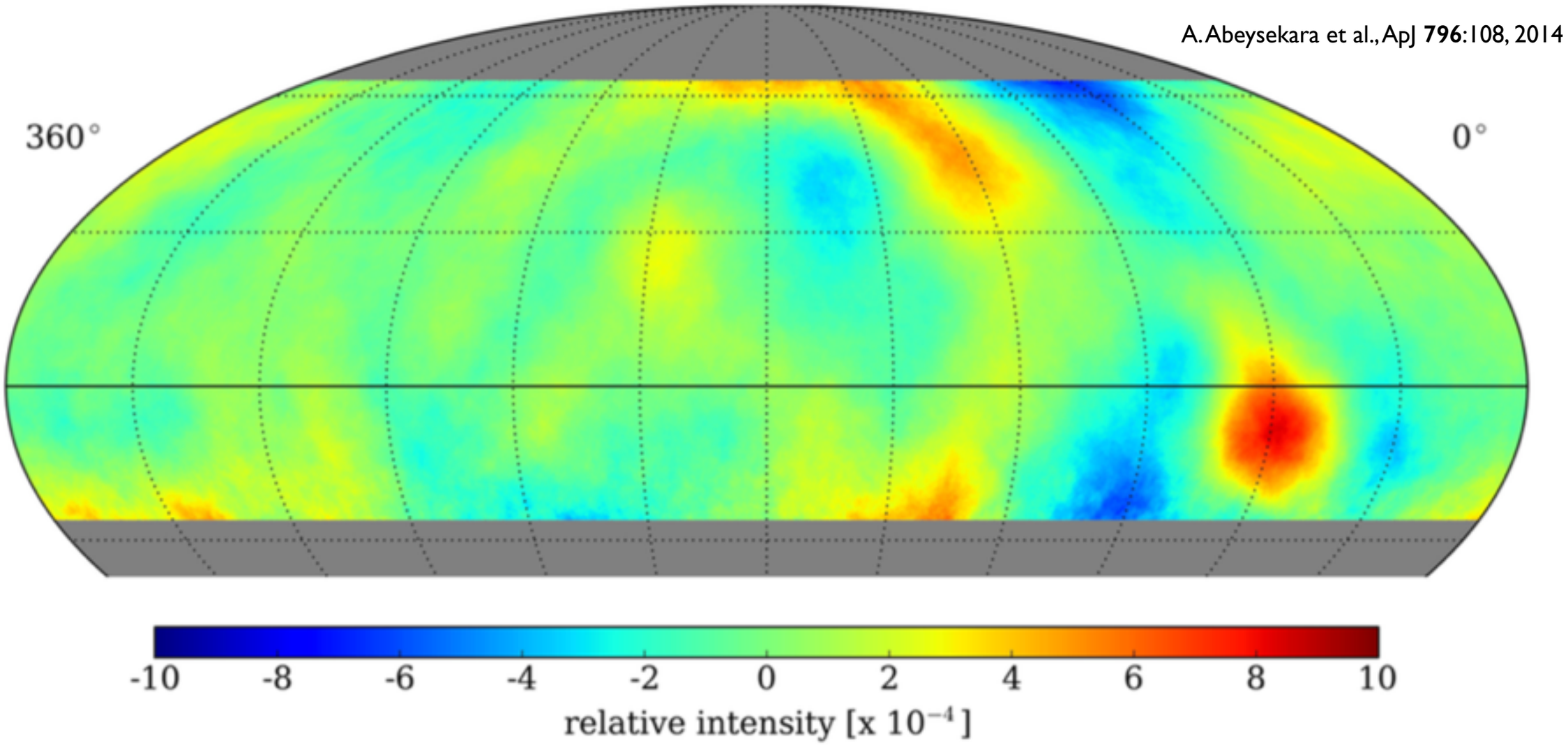
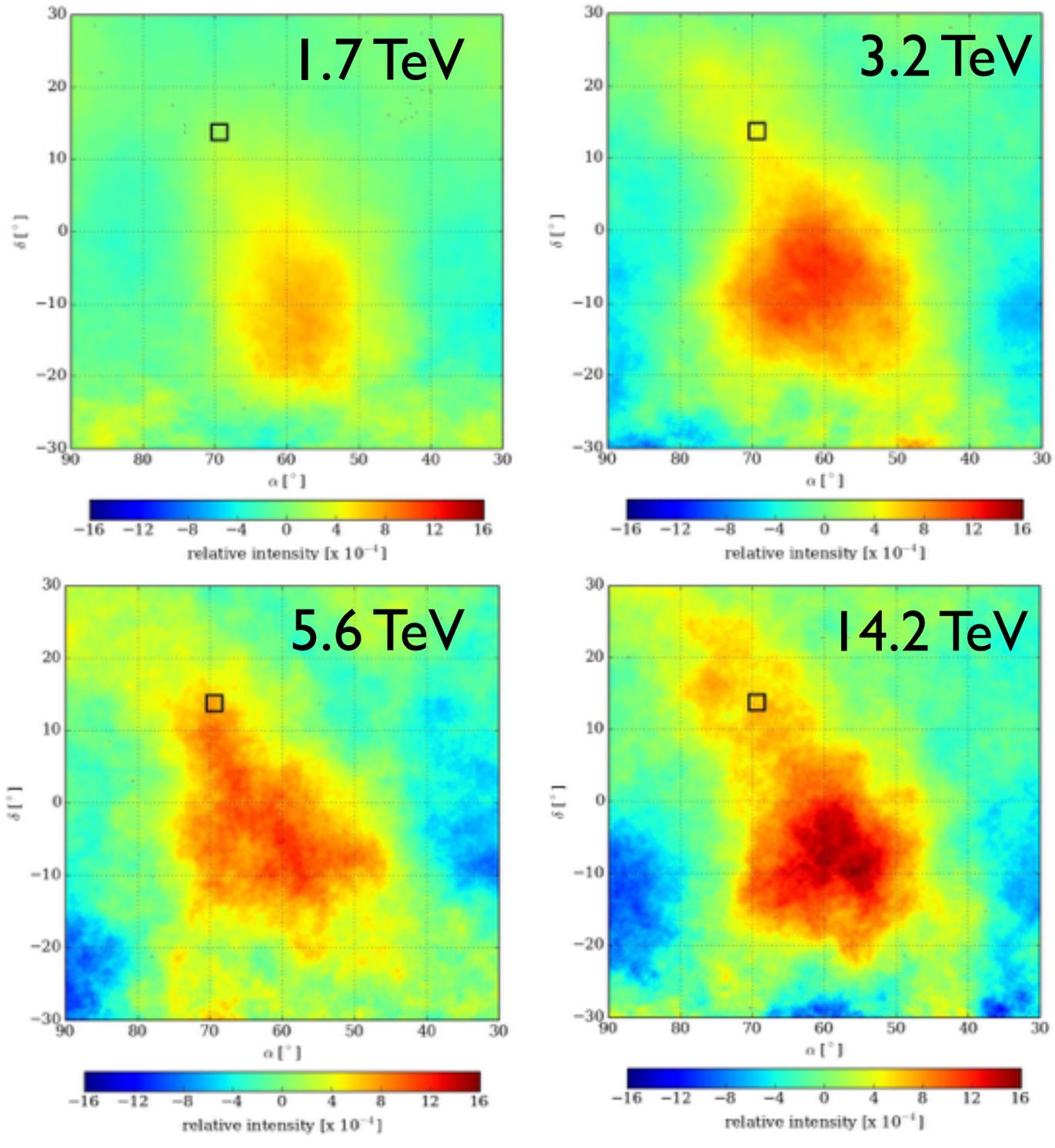


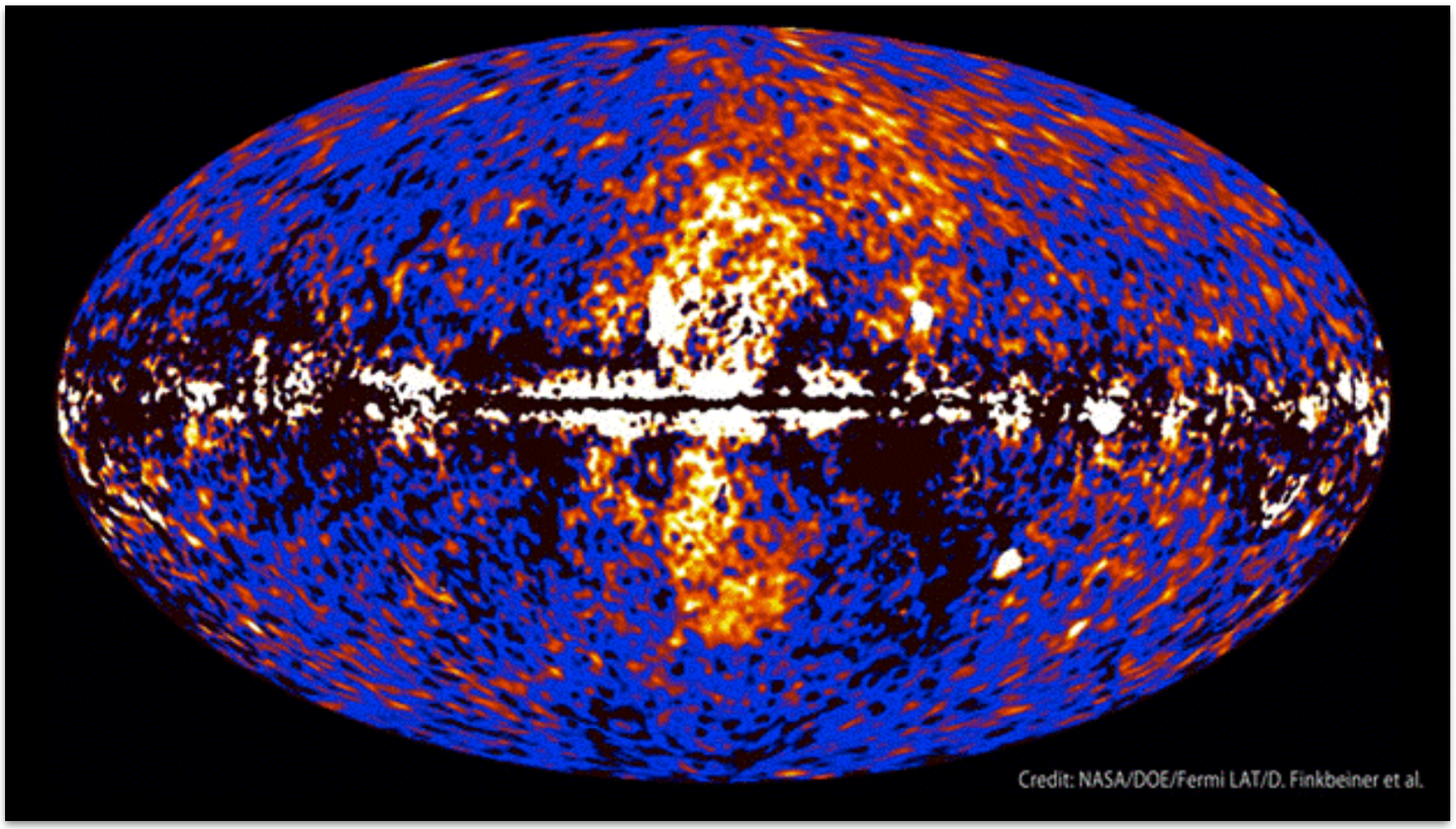
# Energy Dependence

- Region A as a function of energy cut
- Box: centroid of Region A observe with Milagro
- Note: significant overlap between energy bands
- Only a wide-field instrument can study a region this large

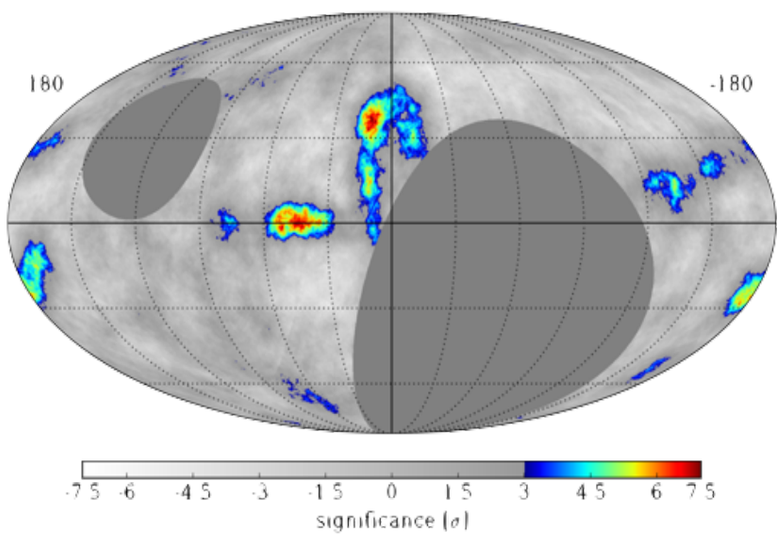


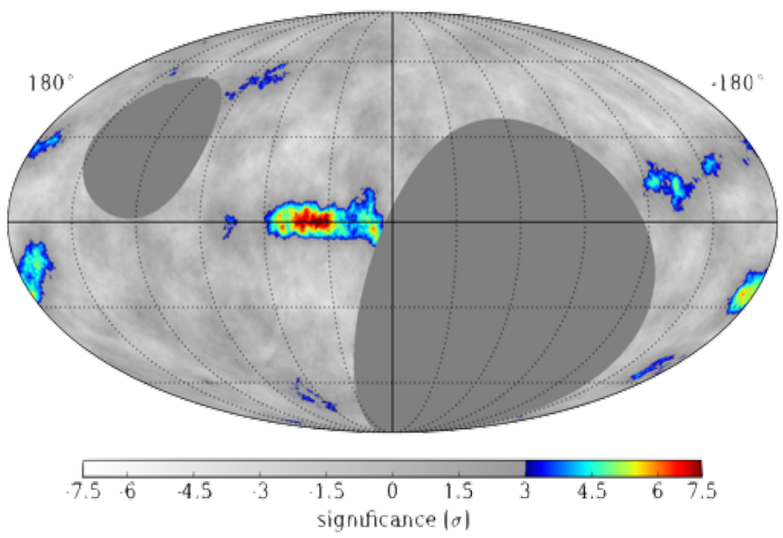
# Diffuse Emission

- Simulation of 3 years of data from HAWC-300
- Diffuse emission from Galactic Plane
- Fermi bubbles:
  - Lower left: no spectral cutoff
  - Lower right: 150 GeV cutoff
- Can constrain extension of bubble spectrum



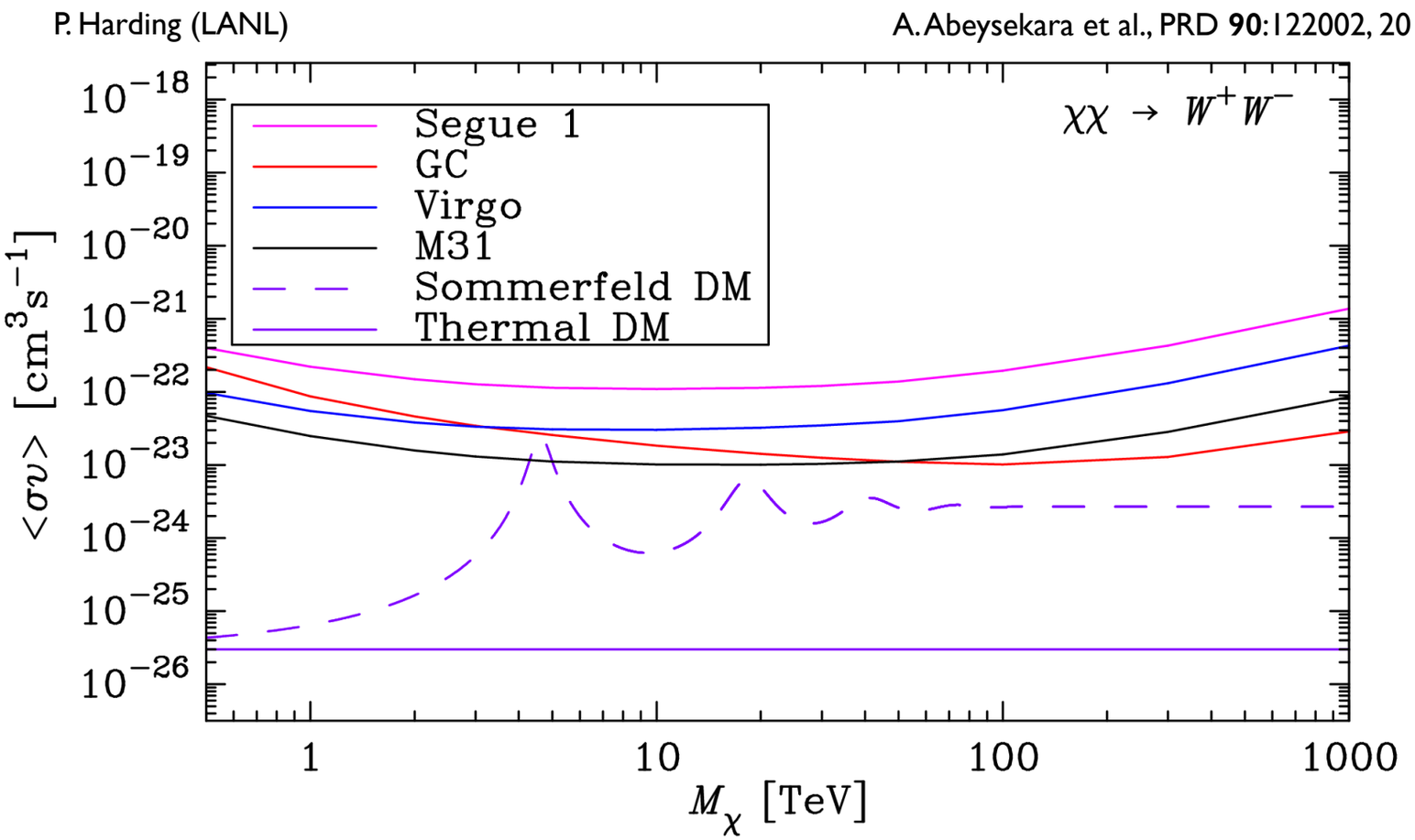

H. Ayala Solares (MTU), ICRC 2013



# Beyond the Standard Model

- Sensitivity to TeV WIMP annihilation in high *M/L* satellite galaxies:



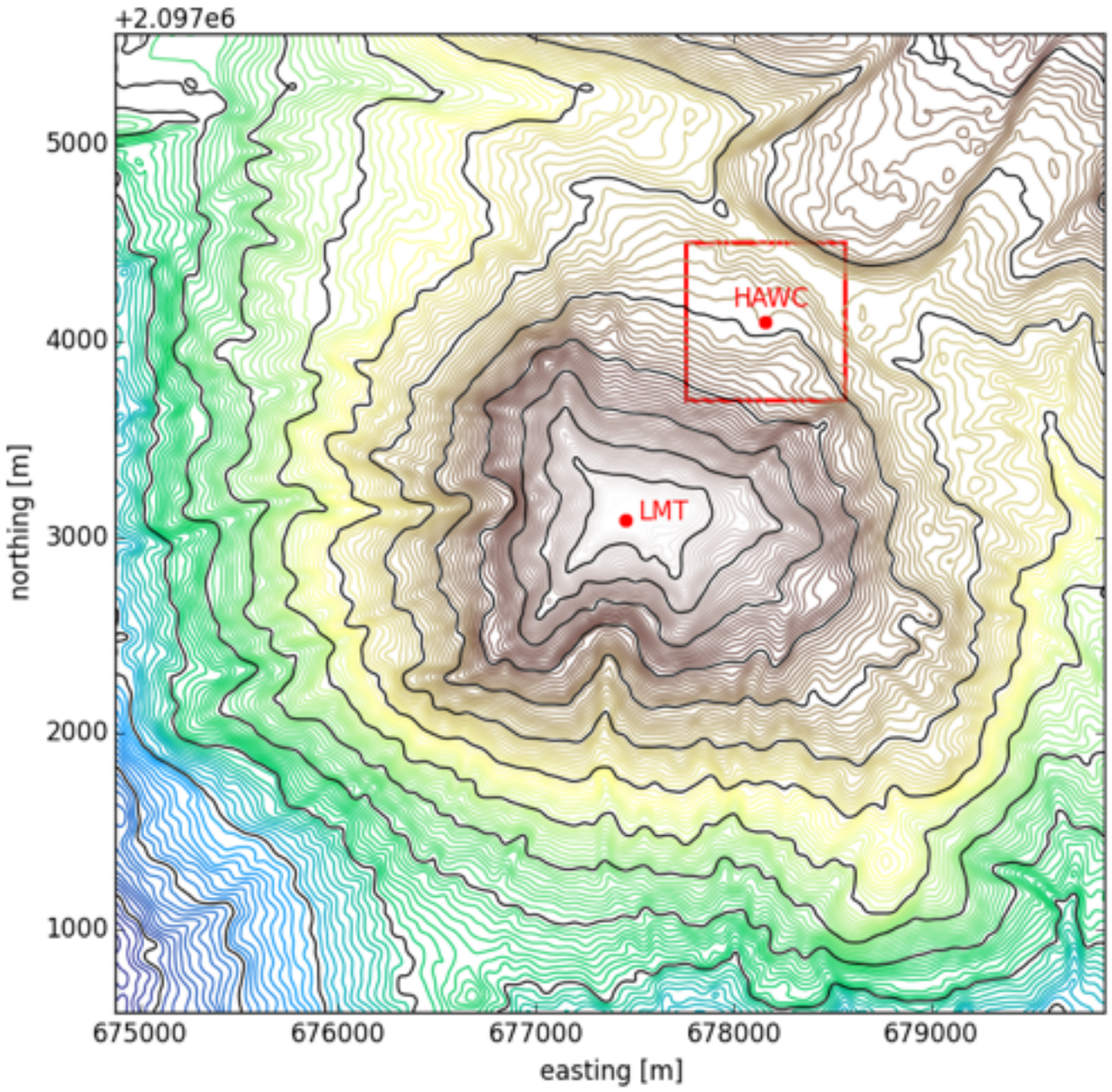

- Cosmological simulations: too few satellites observed
- HAWC: observations of high *M/L* satellites, even when *L*=0

# Next 5 Years…

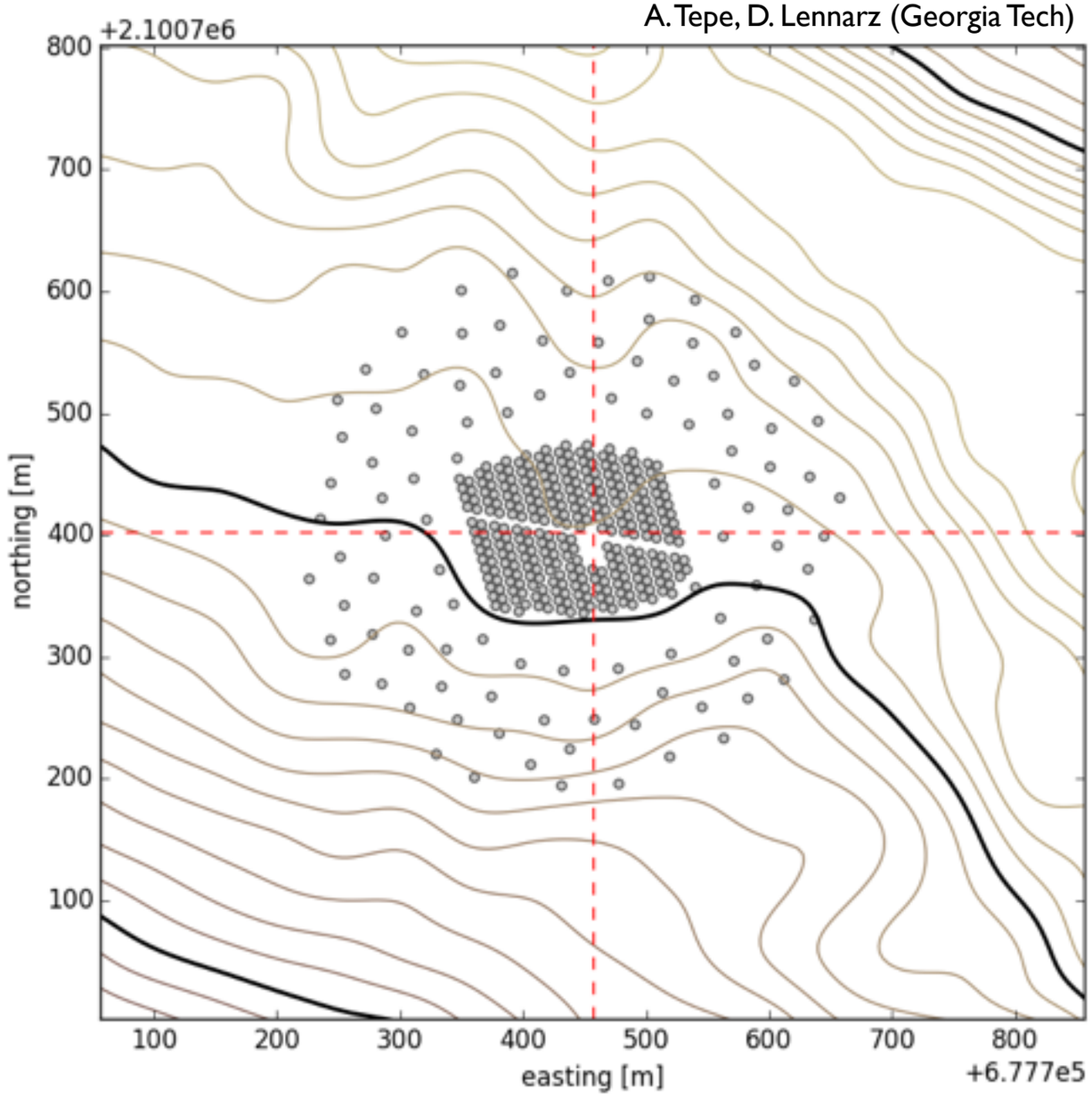
- One year of HAWC-300:
  - Unbiased measurements of AGN; observations of significant flares
  - Extended galactic sources (e.g., Cygnus region)
- Years 2-3 of HAWC-300:
  - Diffuse Galactic emission at TeV. Fermi bubbles if no spectral cutoff
  - Galactic and extragalactic transients (binaries, GRBs)
  - Measurements of hadronic & leptonic cosmic rays
- Five years of HAWC-300:
  - Cosmology: IGMF, extragalactic background light (far IR), …
  - Beyond the Standard Model: dark matter limits, primordial black hole evaporation, Q-balls, Lorentz Invariance violation, …

# Next 5 Years…

- High-energy extensions and other plans: Outriggers? A site in the Southern Hemisphere?



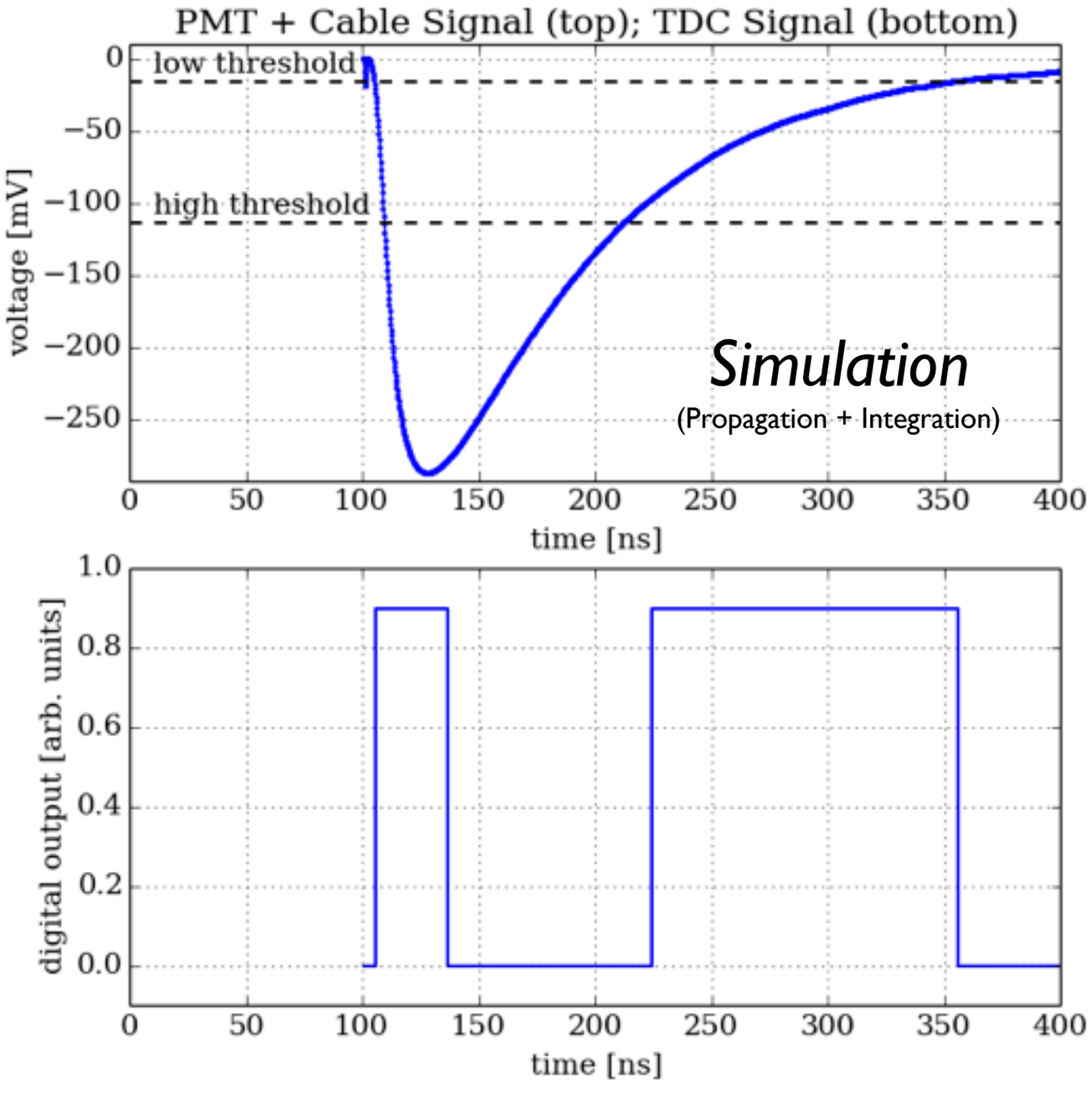

A. Tepe, D. Lennarz (Georgia Tech)



# Summary

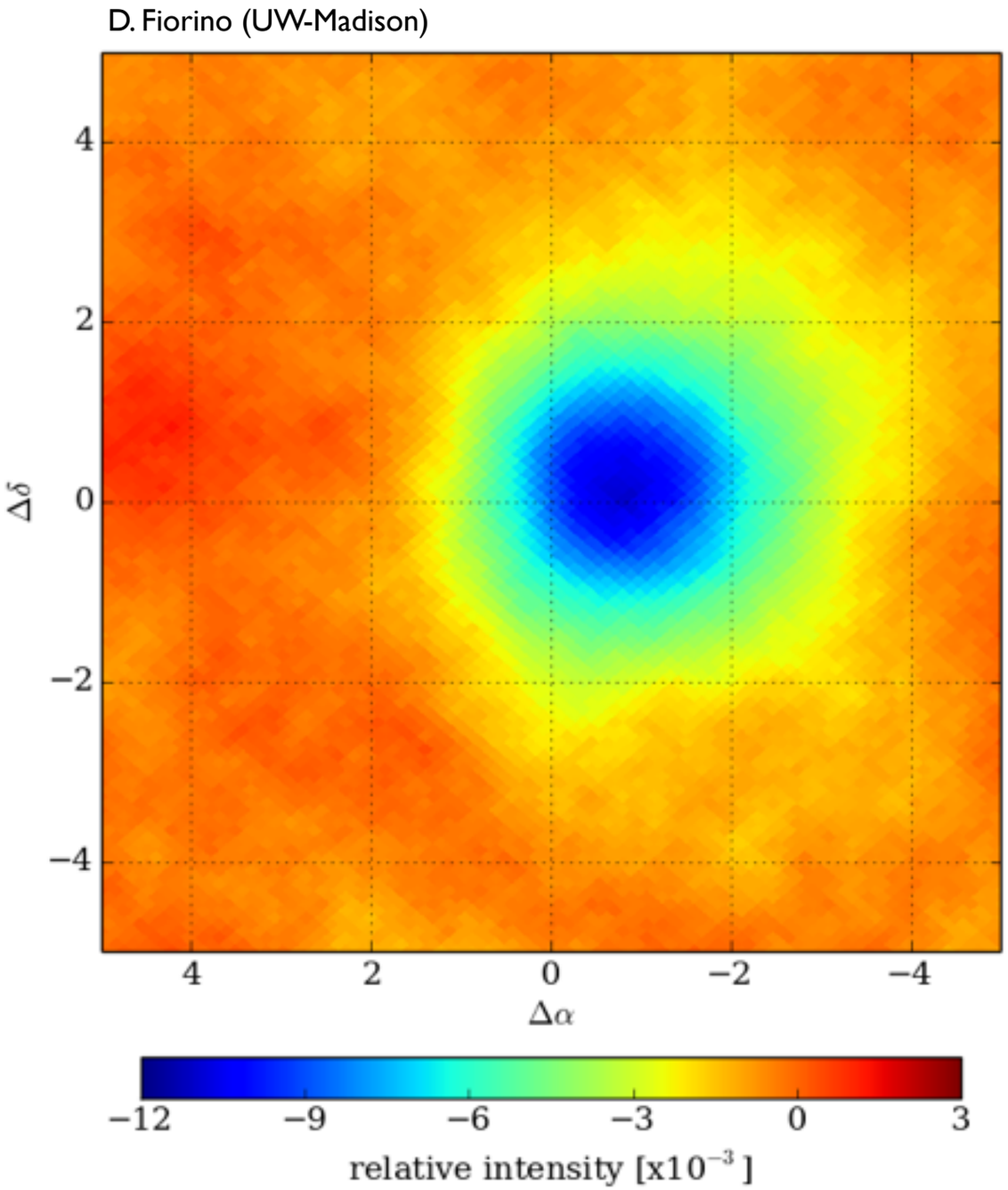
- New era of complementary observations at GeV and TeV
  - Continuous coverage of 1/2 of the sky
  - HAWC has (or is completing) data-sharing MoUs with all major TeV facilities. Plan follow ups of HAWC measurements with IACTs
  - Considerable physics overlap with IceCube
- Construction of HAWC ended on schedule and on budget. We are ready to deliver results!
- Stay tuned for **official** results (calibrated, not *a posteriori*) at summer conferences

# Signal Processing




- Compression achieved using V1190 TDCs from CAEN
- PMT $V(t)$ → logic pulse with 2 or 4 "edge" transitions; 100 ps resolution per edge
- Charge-TOT absolute calibration performed at LANL. HV gain-matching during PMT deployment
- Detector drift: weekly laser shots, plus long-term water clarity measurements
- Rate from 1200 PMTs after TDC compression: 0.5 GB/s

# Moon Shadow: HAWC-111




- 181 transits, -32.5σ
- Significance:
  - 2.4σ /√transit
- deflection: -0.91°±0.04°, ($E_{median}$ = 2 TeV)

$$\delta\theta \simeq 1.6^\circ \cdot Z \left(\frac{E}{\mathrm{TeV}}\right)^{-1}$$

- Relative intensity:
  - (-11.3±0.4)×10$^{-3}$

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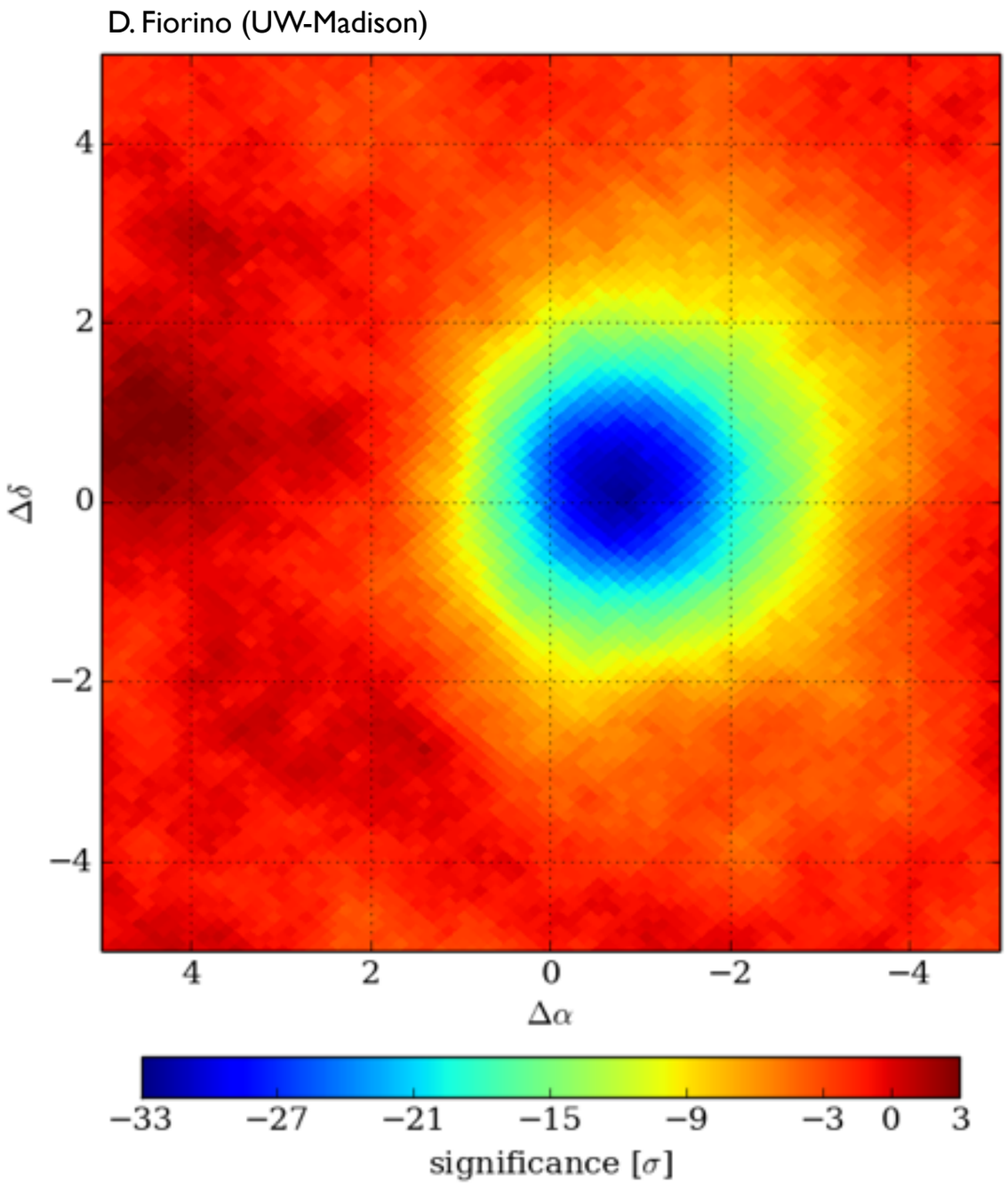


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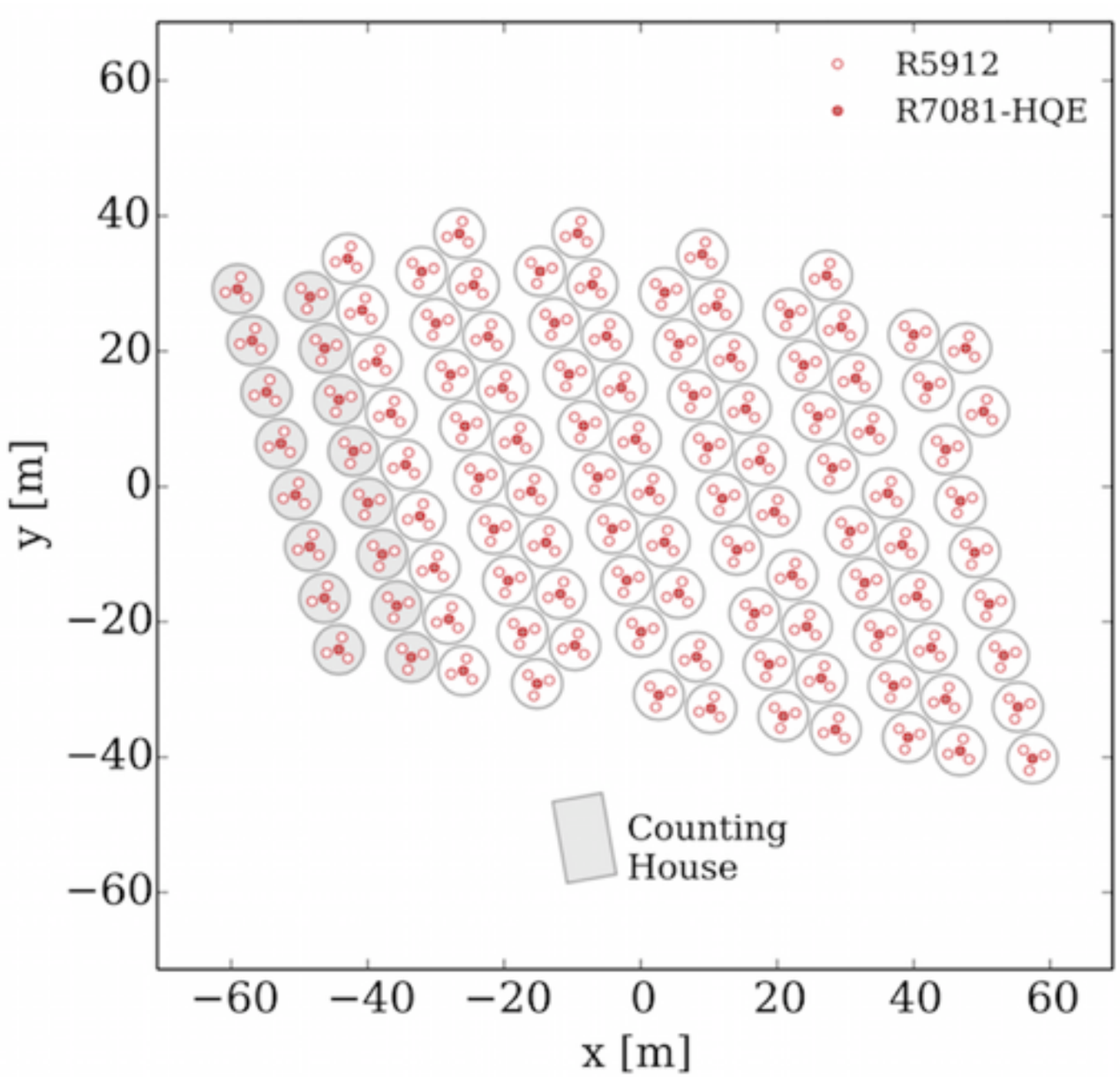
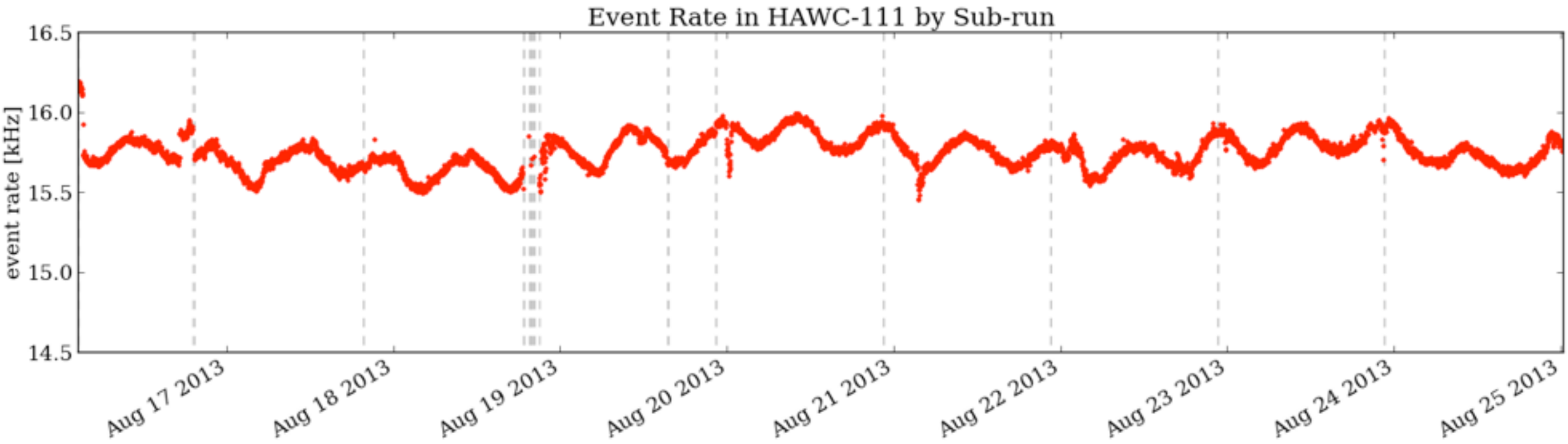
# Detector Configuration

- Cosmic-ray results from HAWC-95 and HAWC-111
- 12 Jun 2013 to 8 Jul 2014
- 181 days (4332.1 hr)
- 85.6 billion events
- Event selection:
  - Full runs: contiguous 24 hr periods of observation
  - Successful angle fit
  - $N_{ch} \geq 30$
- 113 days, 49 billion events



# Background Estimation

- Effect of atmosphere, detector drift on event rate:




- Use data from interval *dt* to get the expected counts

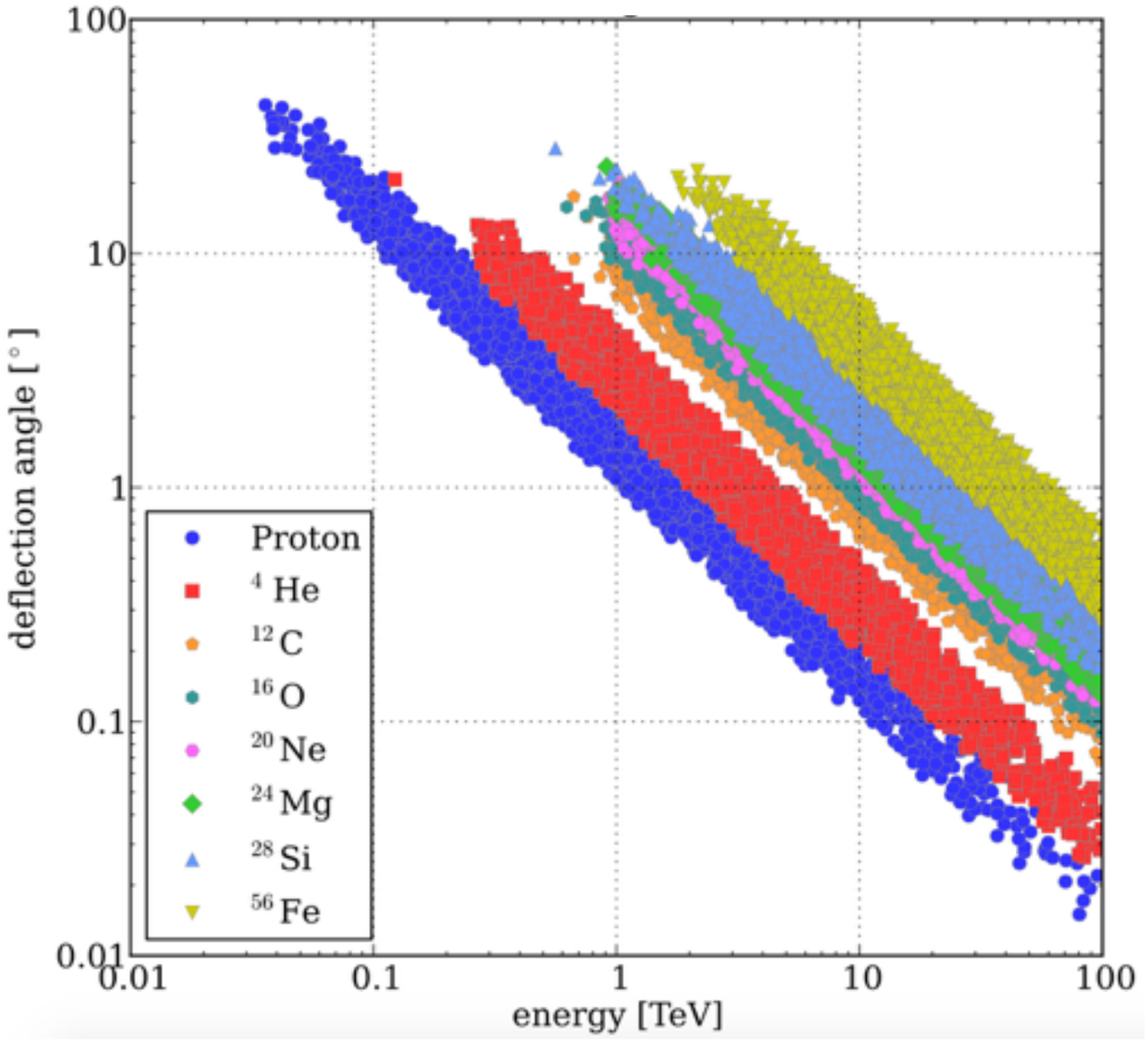
$$\langle N(\alpha,\delta)\rangle = \int dt \int d\Omega\ A(ha,\delta)\cdot R(t)\cdot \epsilon(ha,\alpha,t)$$

Event rate

Detector acceptance

Selection function: 1 if *ha*, α, *t* in same bin

# Geomagnetic Smearing



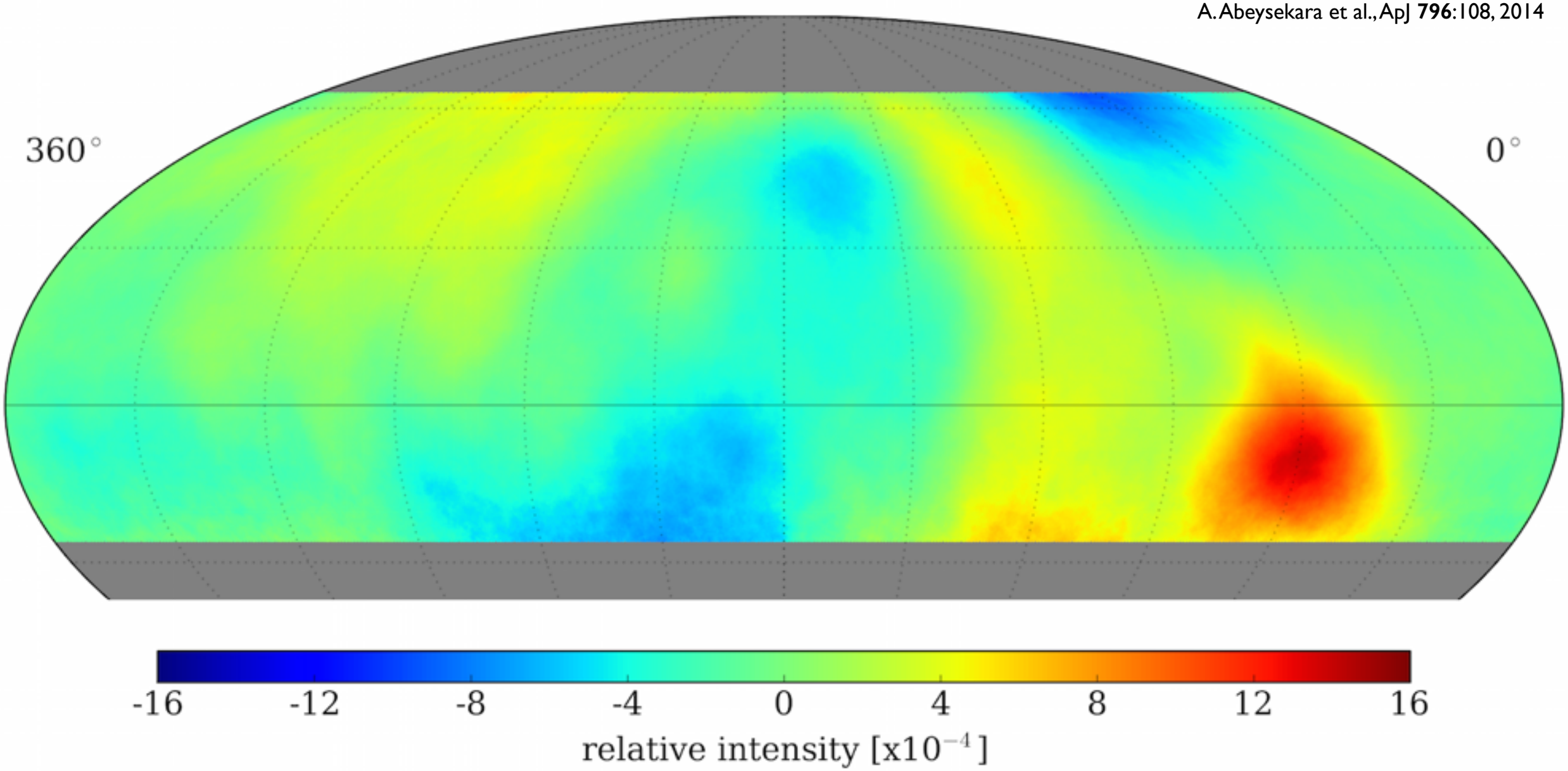

- At and below ~2 TeV, the deflection of cosmic rays in the geomagnetic field is larger than the angular resolution of the detector
- Left: simulated deflection per species at location of HAWC using IGRF11 field
- Best fit for cosmic-ray deflection at HAWC site:

$$\delta\theta \simeq 1.6^{\circ} \cdot Z \left( \frac{E}{\mathrm{TeV}} \right)^{-1}$$

# Relative Intensity Map

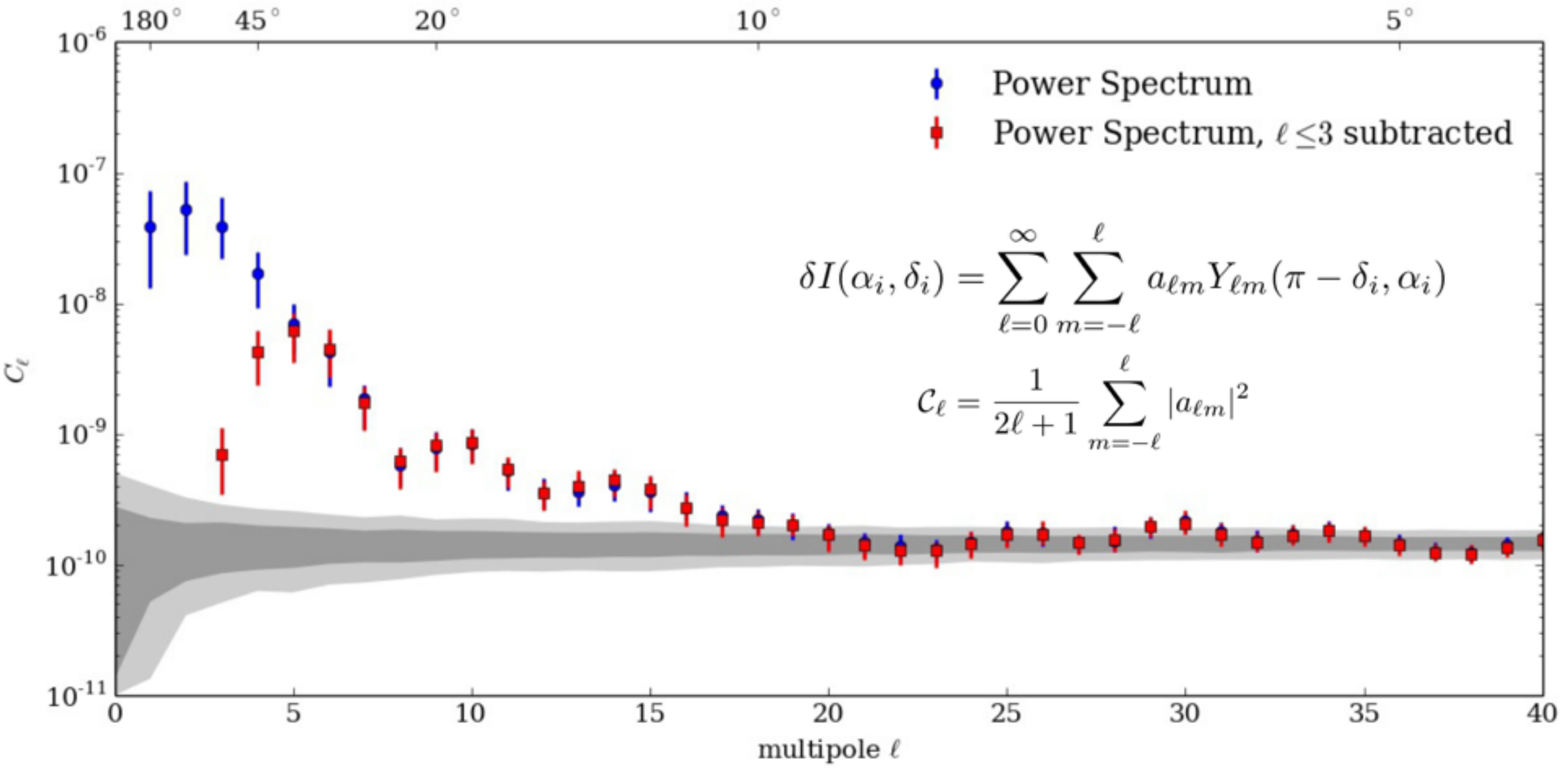
- Binned skymap, *dt*=24 hr, 10° smoothing filter applied:

A. Abeysekara et al., ApJ **796**:108, 2014



# Cosmic Ray Power Spectrum

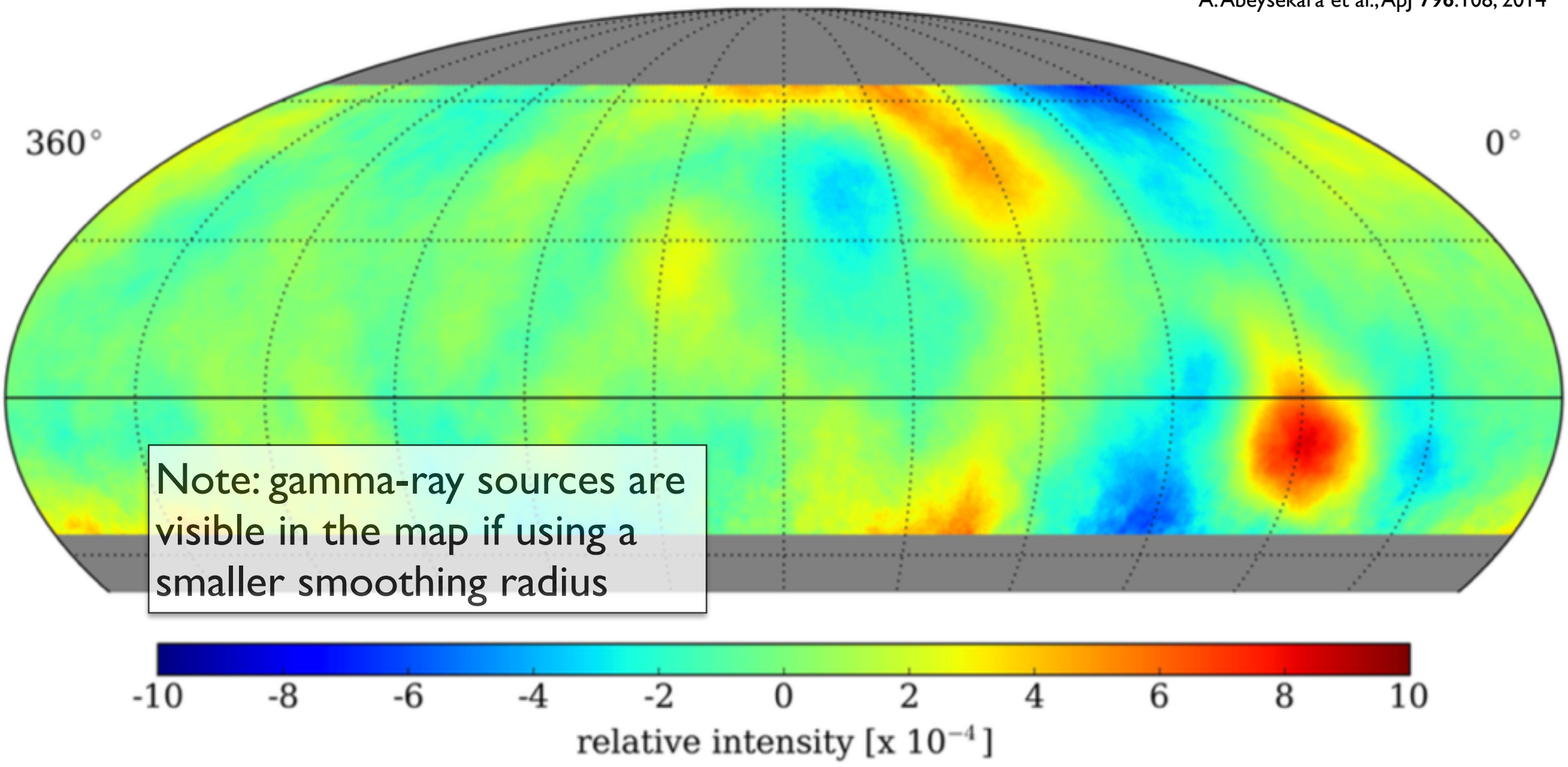
- Power spectrum indicates presence of structure at small scales. *Not* a partial sky effect, which we correct for.



# Small-Scale Anisotropy

- Sky map after subtraction of largest features:

A. Abeysekara et al., ApJ **796**:108, 2014



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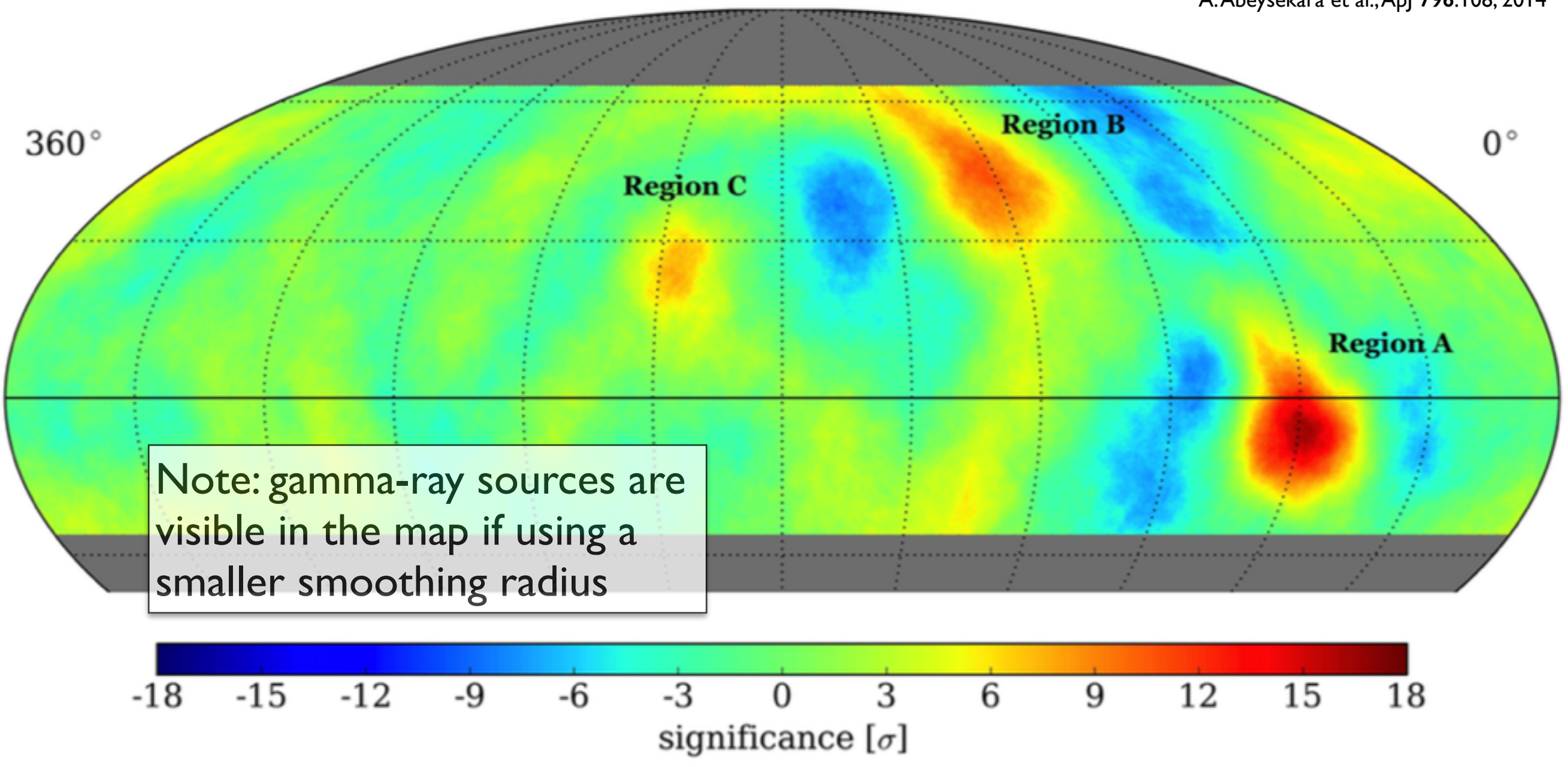
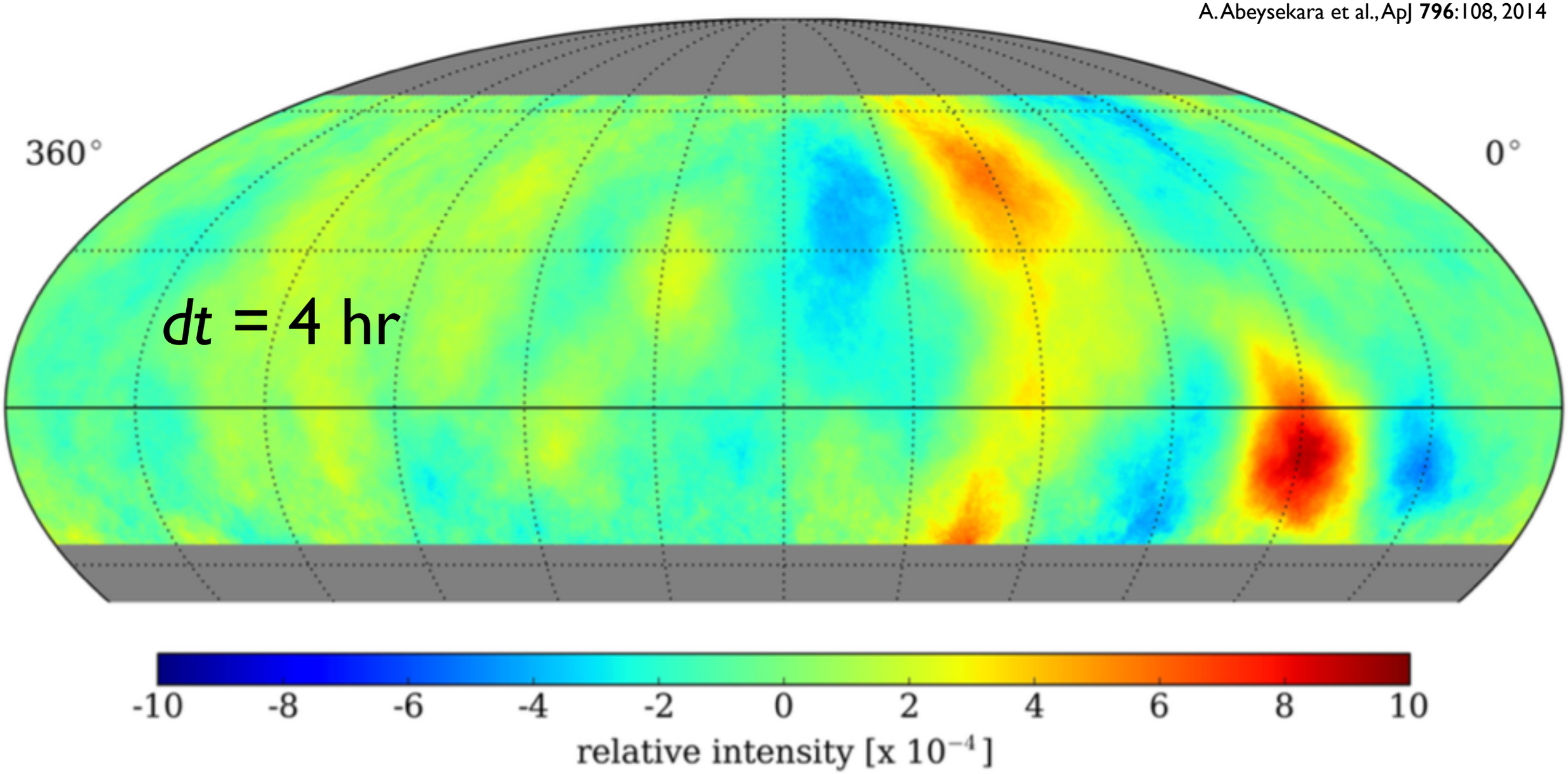



Note: gamma-ray sources are visible in the map if using a smaller smoothing radius

# Systematic Check

- Binned skymap, *dt*=4 hr, 10° smoothing filter applied:

A. Abeysekara et al., ApJ **796**:108, 2014



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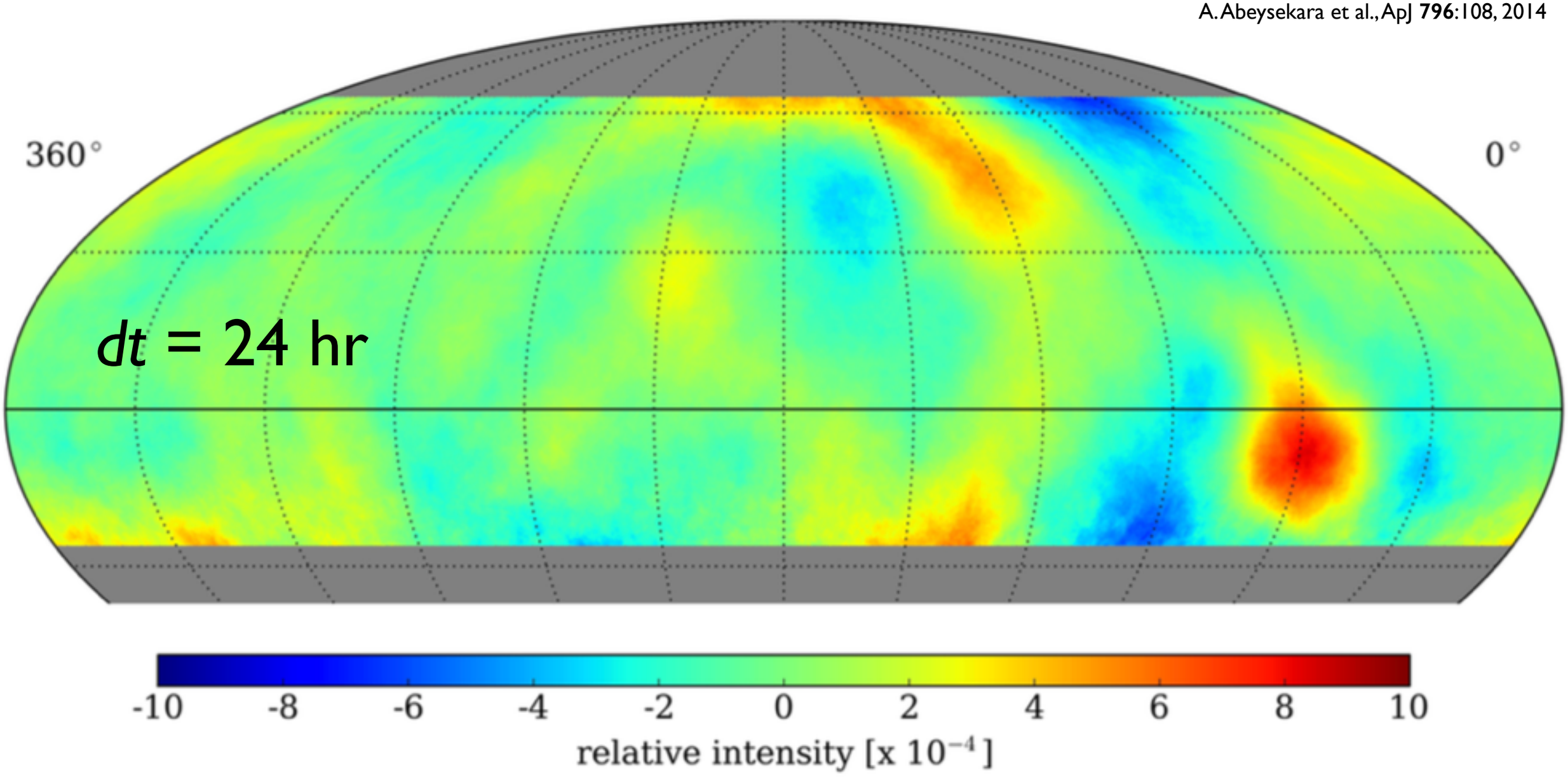
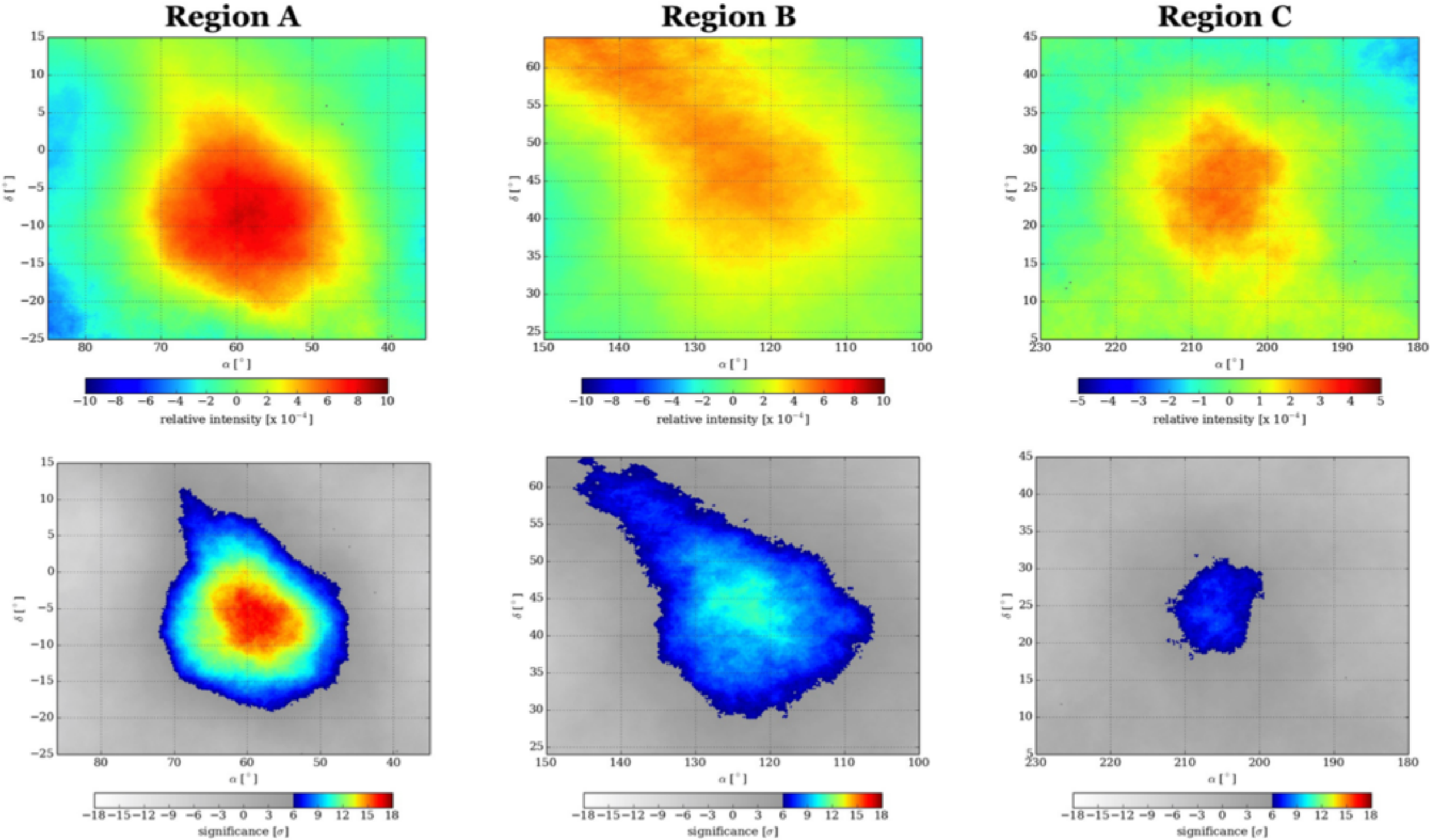


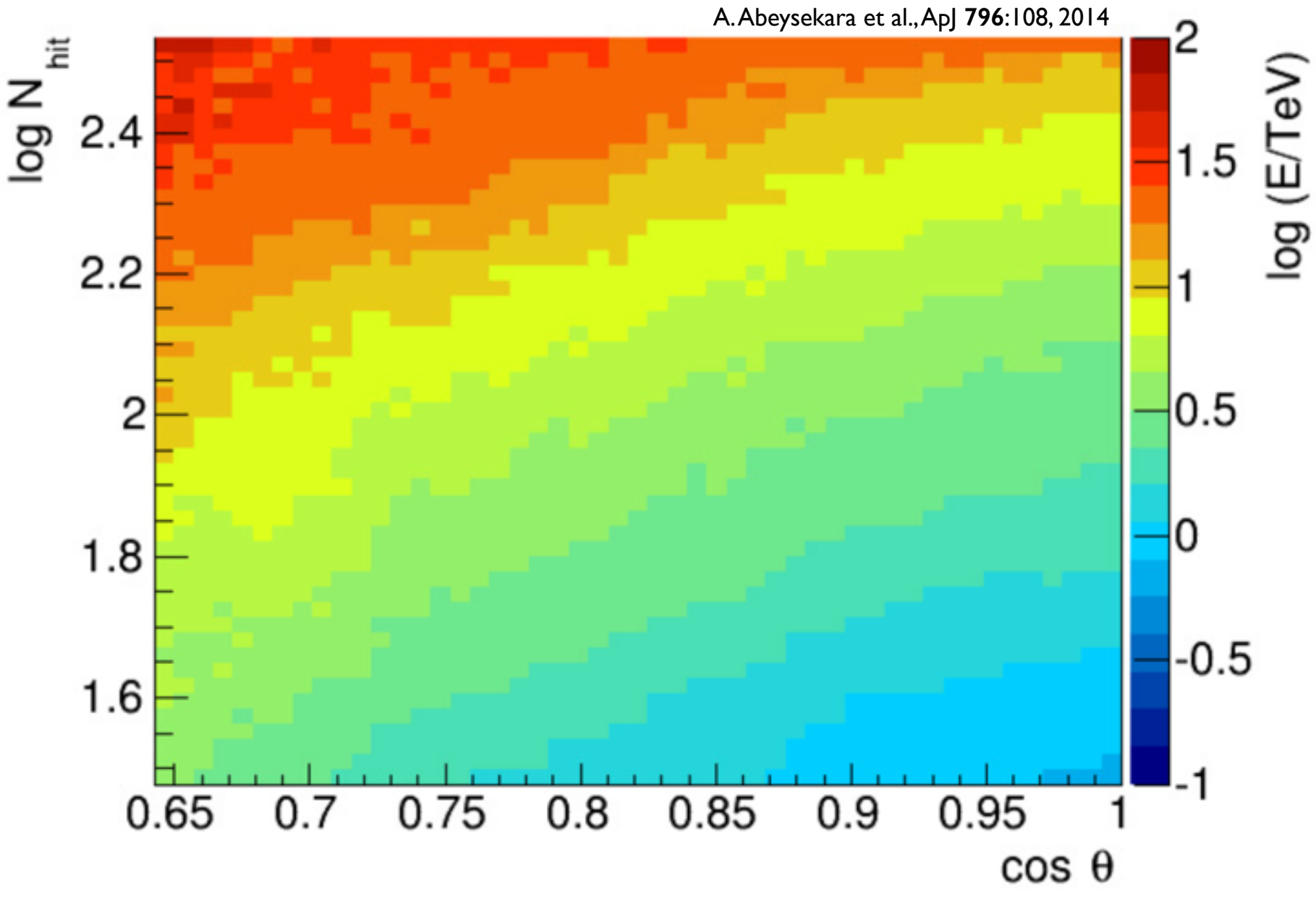
# Hotspots

A. Abeysekara et al., ApJ **796**:108, 2014



# Energy Dependence

- Energy proxy: binning of median energy based on 2D slices in simulated $N_{ch}$ and cos $\vartheta$, similar to IceCube analysis

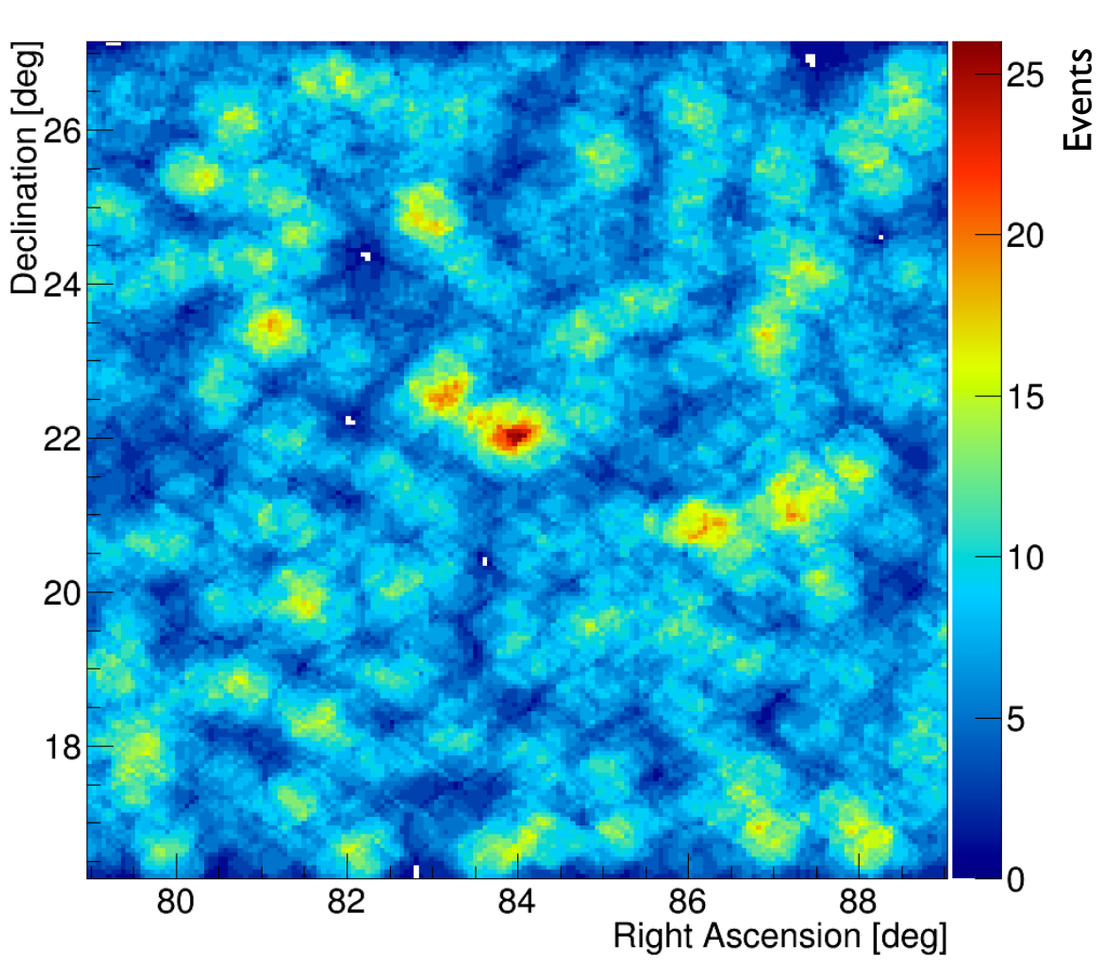


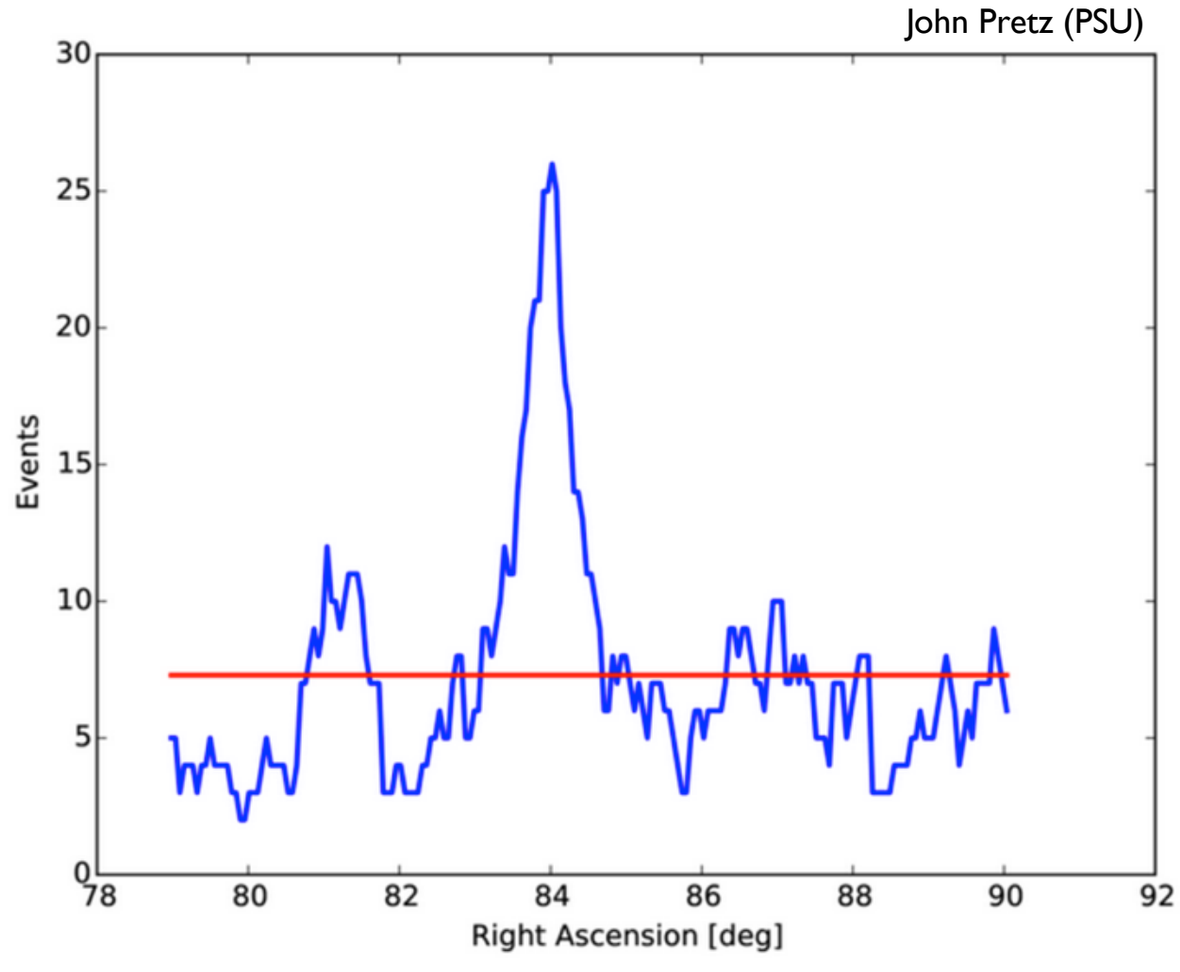
# Cosmic Ray Anisotropy

- Large scale anisotropy: diffusion from over-density of sources in direction of GC. <1% effect, flips in orientation (observed in data)
  - Erlykin & Wolfendale (2006), Blasi and Amato (2011), Sigl and Giacinti (2012), Streshnikova et al. (2013)
- Small scale structure (<10°):
  - Distortion of "dipole" in turbulent fields (caustics): Giacinti and Sigl (2012), Ahlers (2014)
  - Unusual interstellar magnetic field configuration: Aharonian (2008), Salvati and Sacco (2009), …
  - Heliospheric effect: Desiati and Lazarian (2013), Schwadron (2014)
  - Beyond the Standard Model: DM annihilation (Harding, 2013), strangelets (Perez-Garcia, 2014)

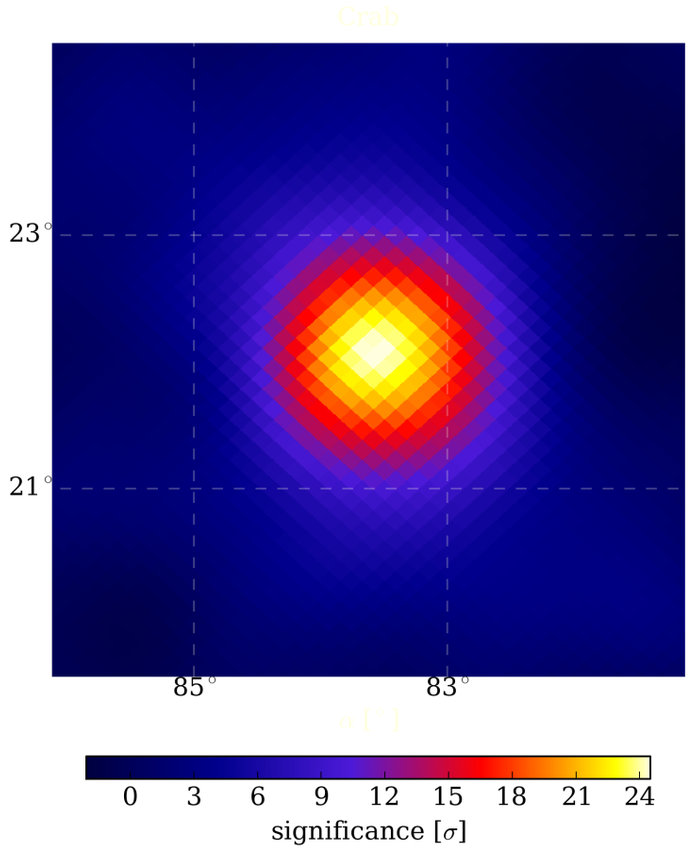
# γ-Rich Sample from the Crab

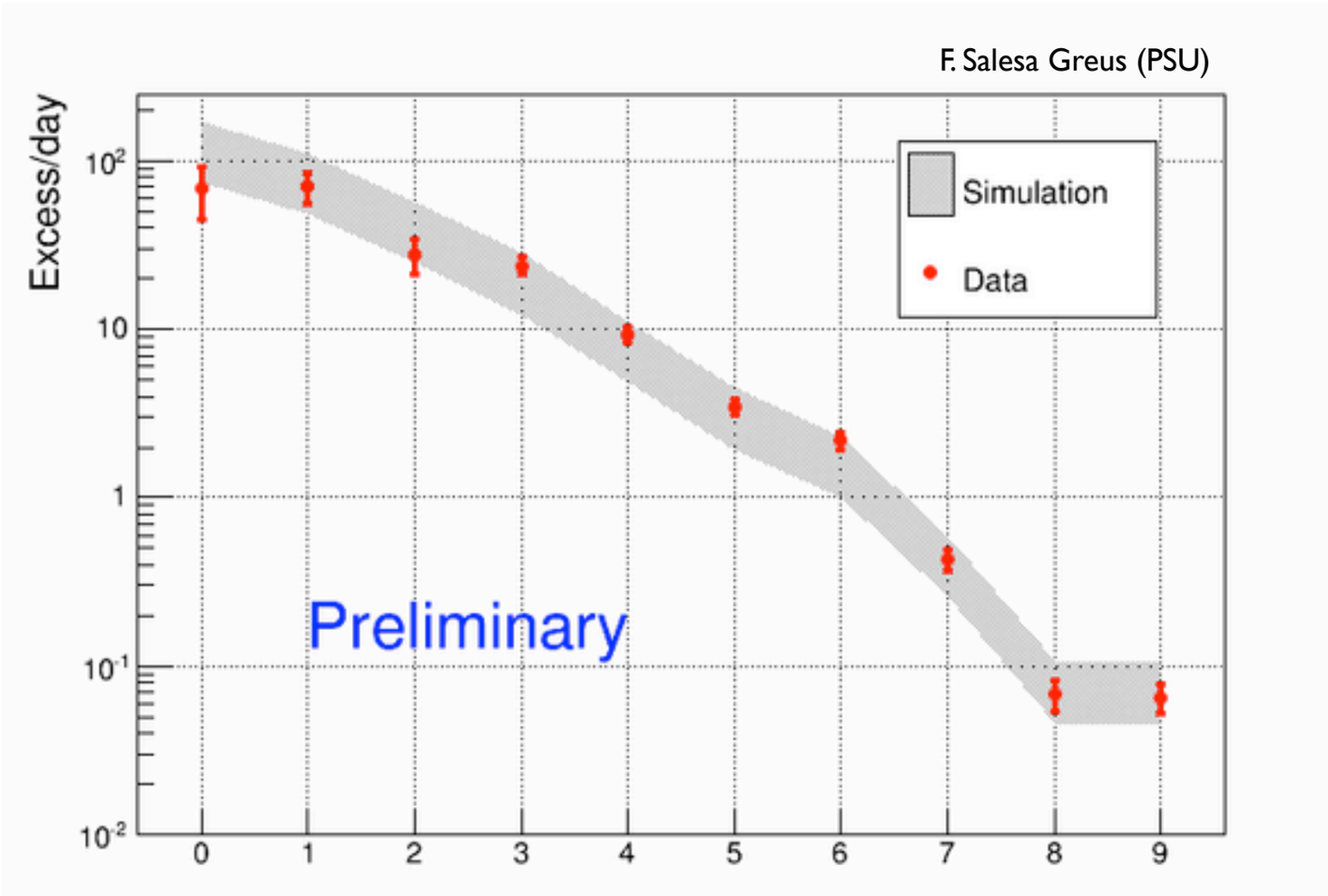
- Trigger rate: 10 kHz, >99.9% cosmic rays
- Roughly 400 gammas/day from the Crab Nebula
- Tight cuts on high-energy sample: signal/background ~ 3

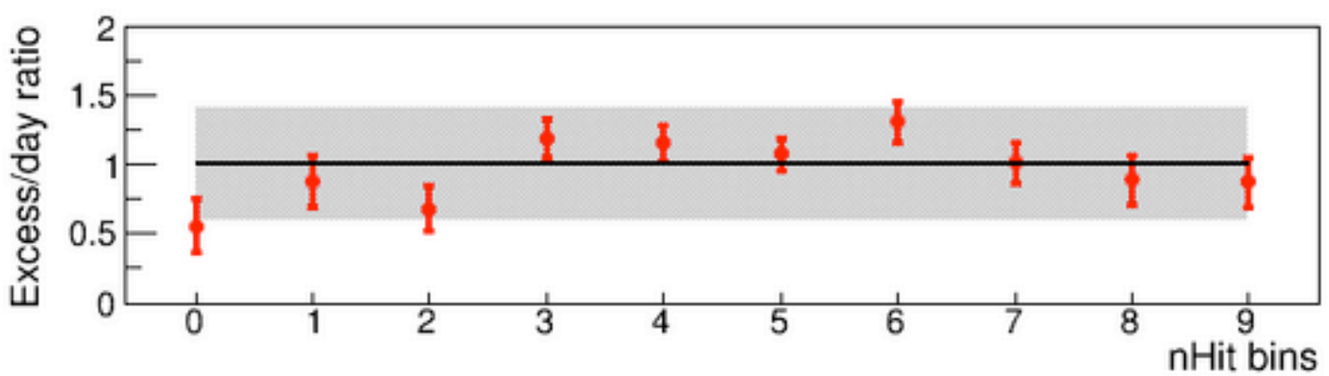


# Crab Nebula: HAWC-111




- Excess counts from Crab Nebula: data vs. simulation
- 9 analysis bins in $N_{hit}$
- Bin 0: ~300 GeV median
- Bin 9: ~10 TeV median

# Tank Construction

- Tanks built using 5 "rings" of curved steel panels; then capped with an opaque military-grade canvas roof

- Next: bladder deployment, water delivery, and PMT deployment. Work: local crew of about 25 people

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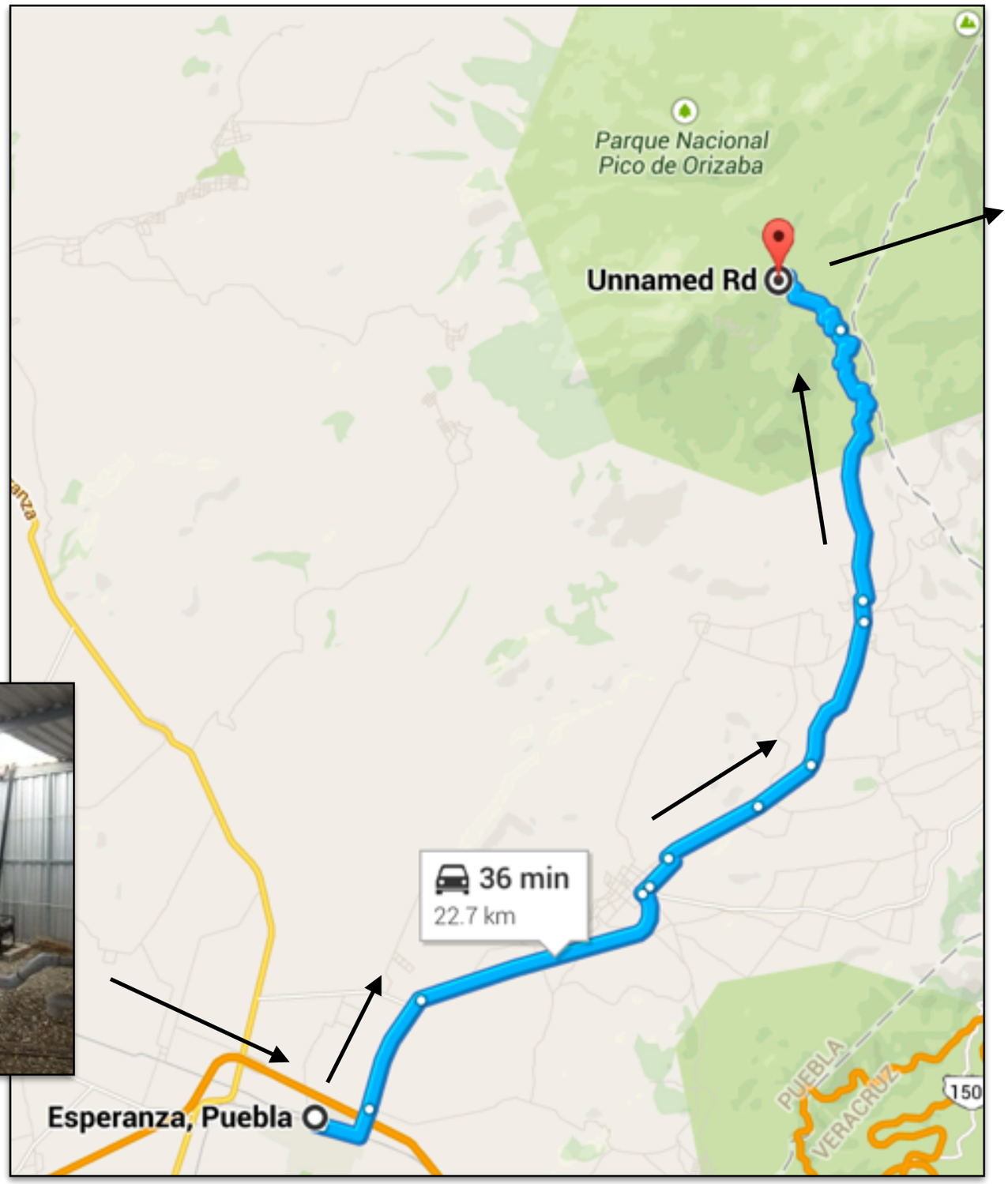
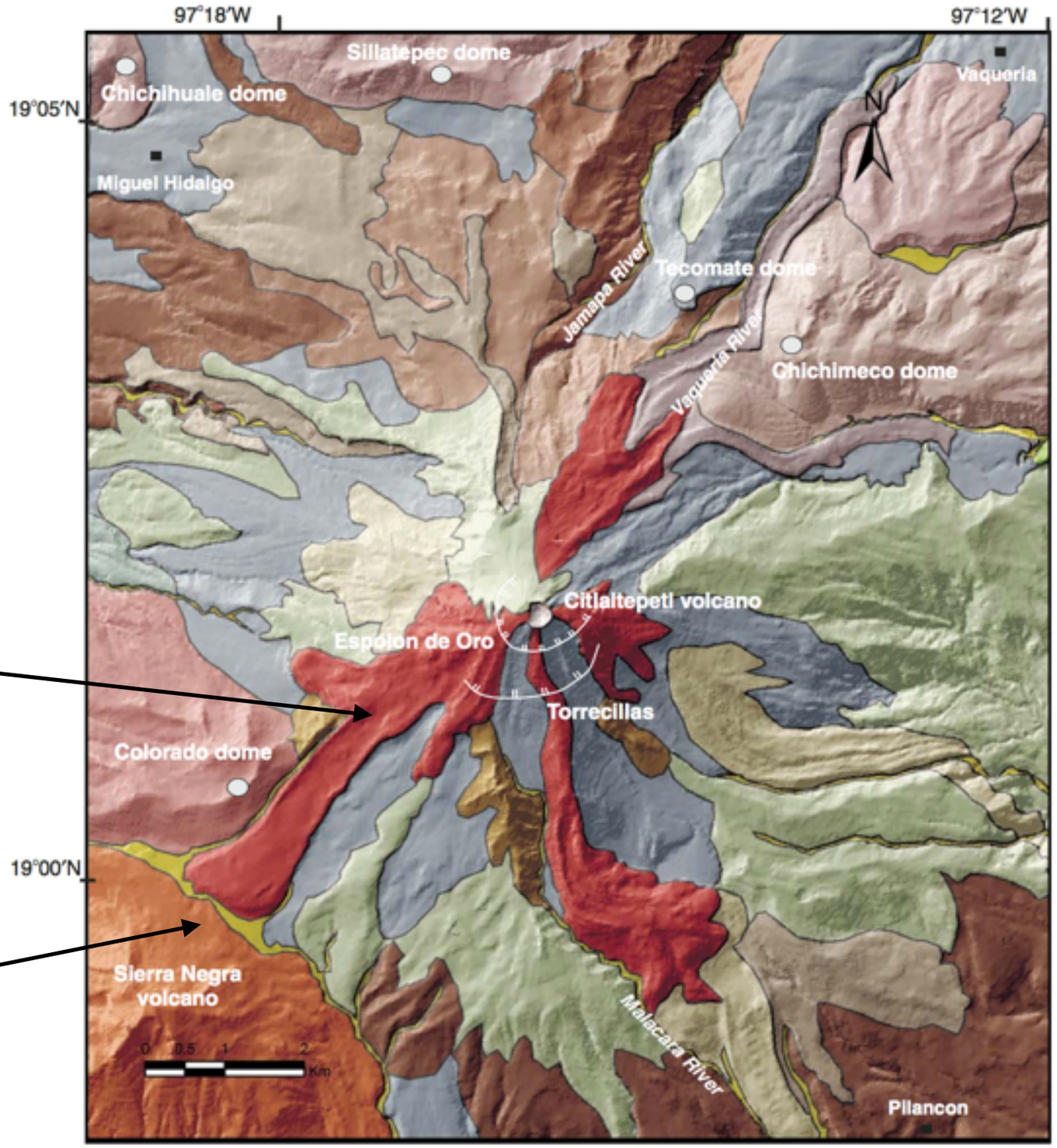
# Water Delivery

Water was filtered at Esperanza and trucked to the site. 13 trips needed per tank




# Local Geology




J L Macías, GSA Special Papers **422**:183, 2007

Lava Flows
2100 B.C.

HAWC

Recent Eruptions:
1613, 1687, 1846