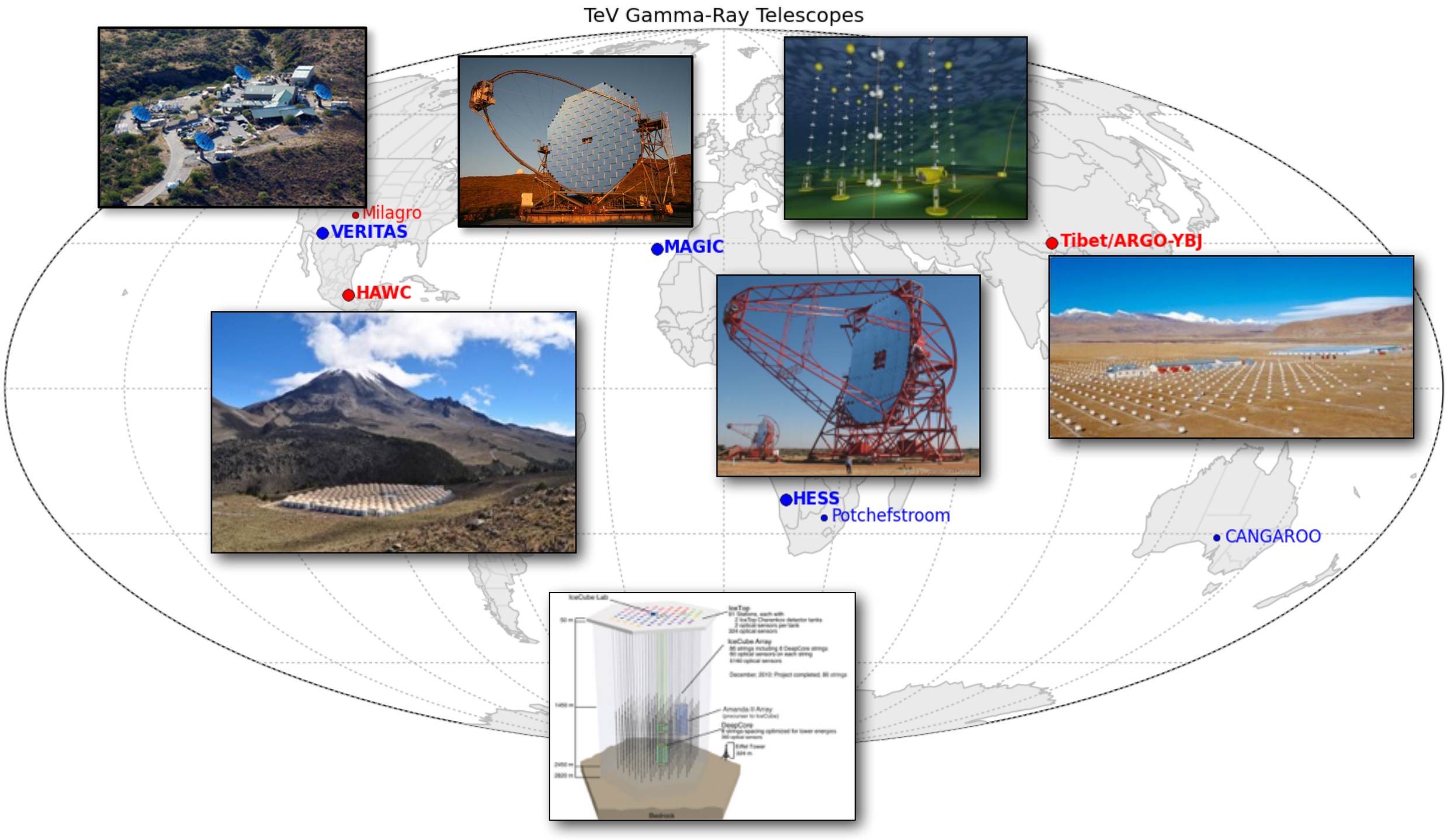
TeV Astrophysics at the HAWC Observatory

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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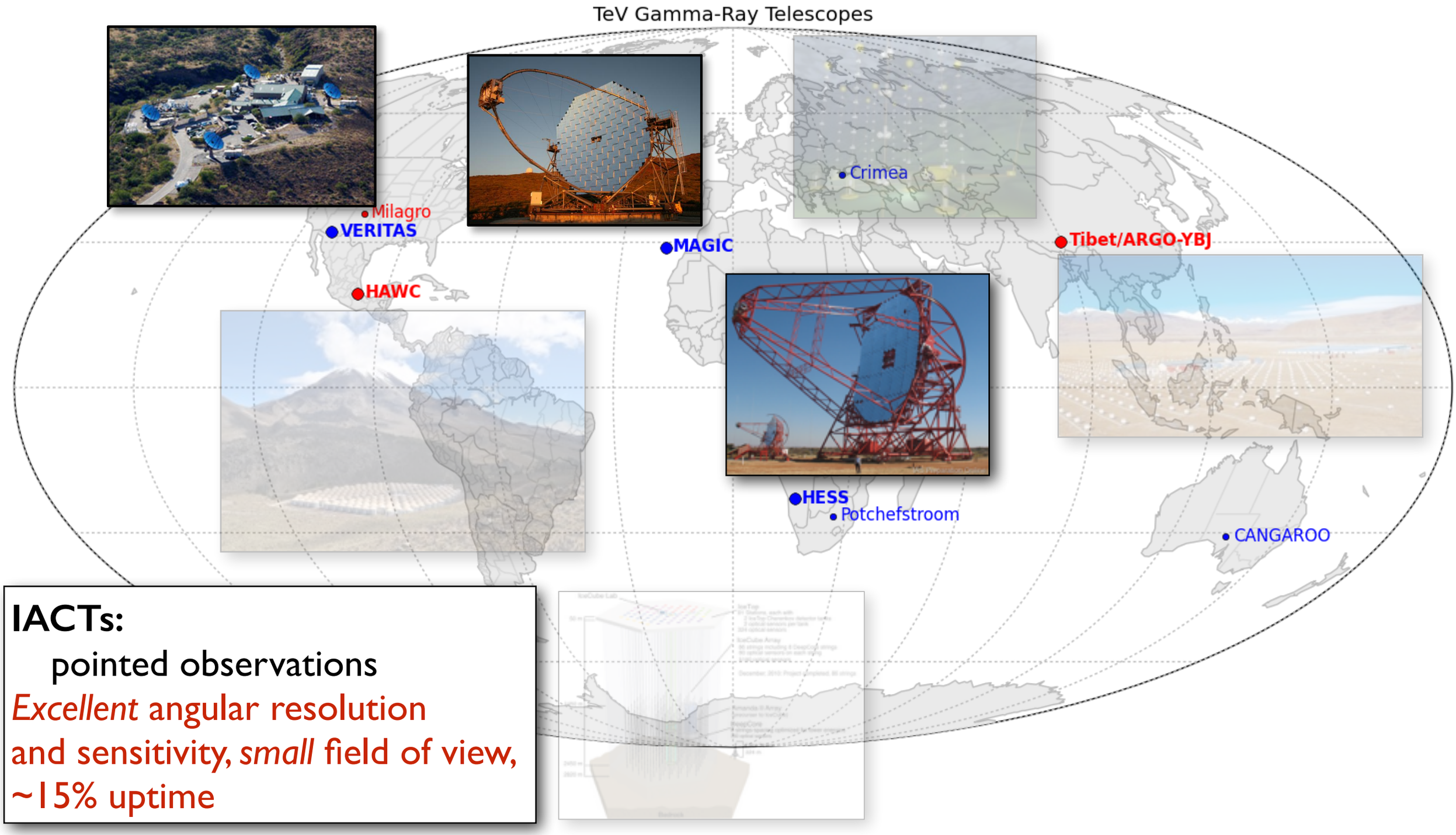


IACTs:

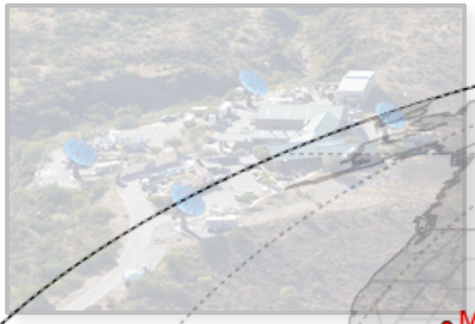
pointed observations

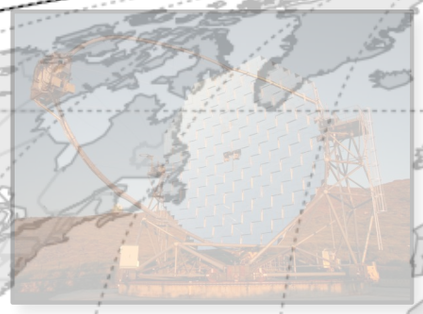
Excellent angular resolution and sensitivity, *small* field of view, ~15% uptime

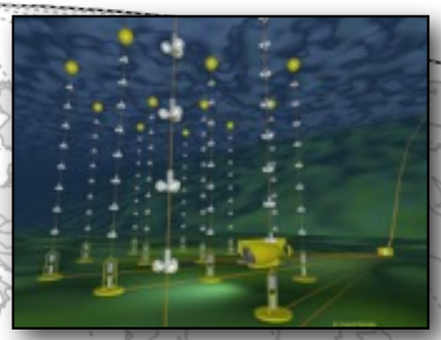
TeV Observatories

EGRET
AGILE
Fermi

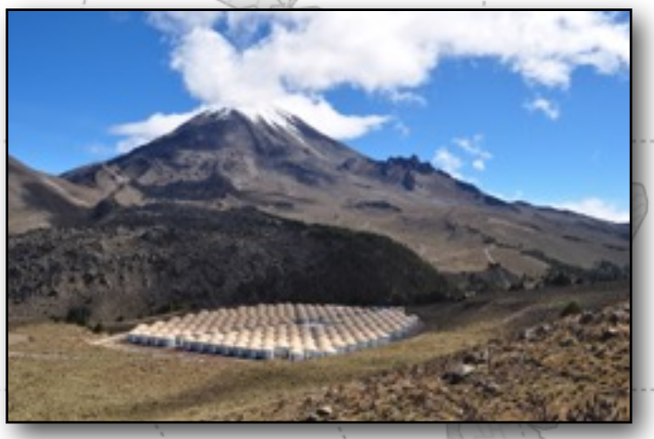
TeV Gamma-Ray Telescopes







Milagro
VERITAS
MAGIC
HAWC
Tibet/ARGO-YBJ



HESS
Potchefstroom
CANGAROO

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pointed observations
Excellent angular resolution
and sensitivity, *small* field of view,
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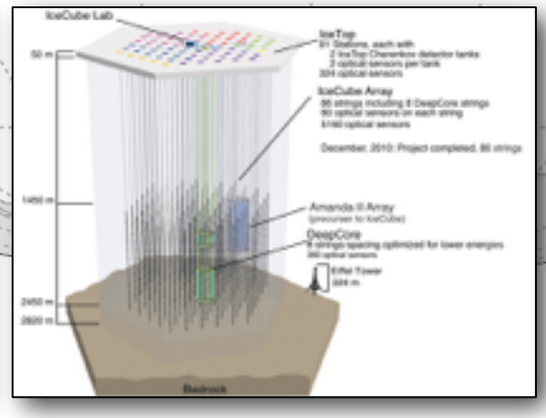


Space/Surface/Volume Detectors:
surveys
Moderate angular resolution,
large field of view (partial/all-sky),
continuous monitoring

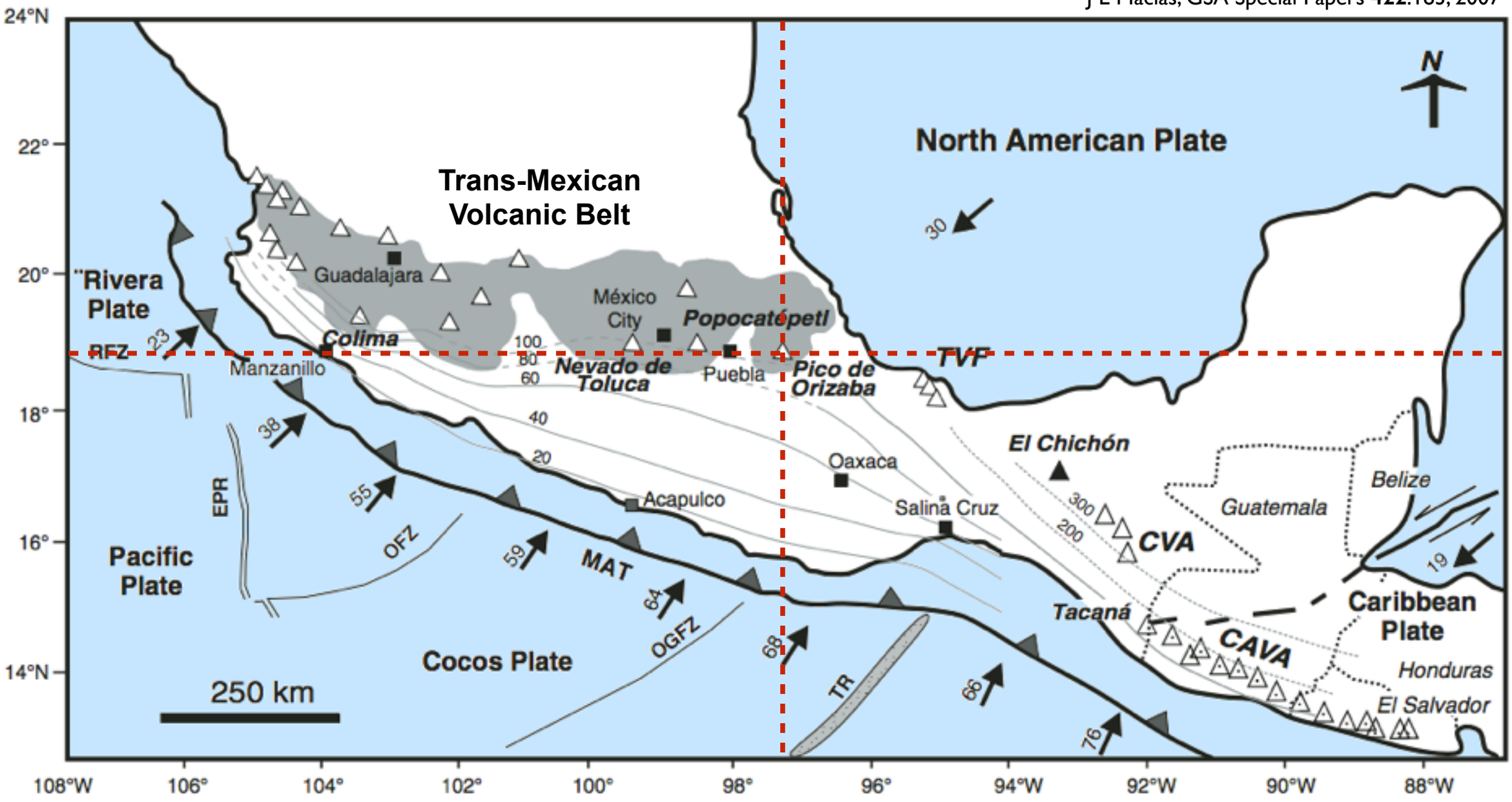
HAWC Observatory

- 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

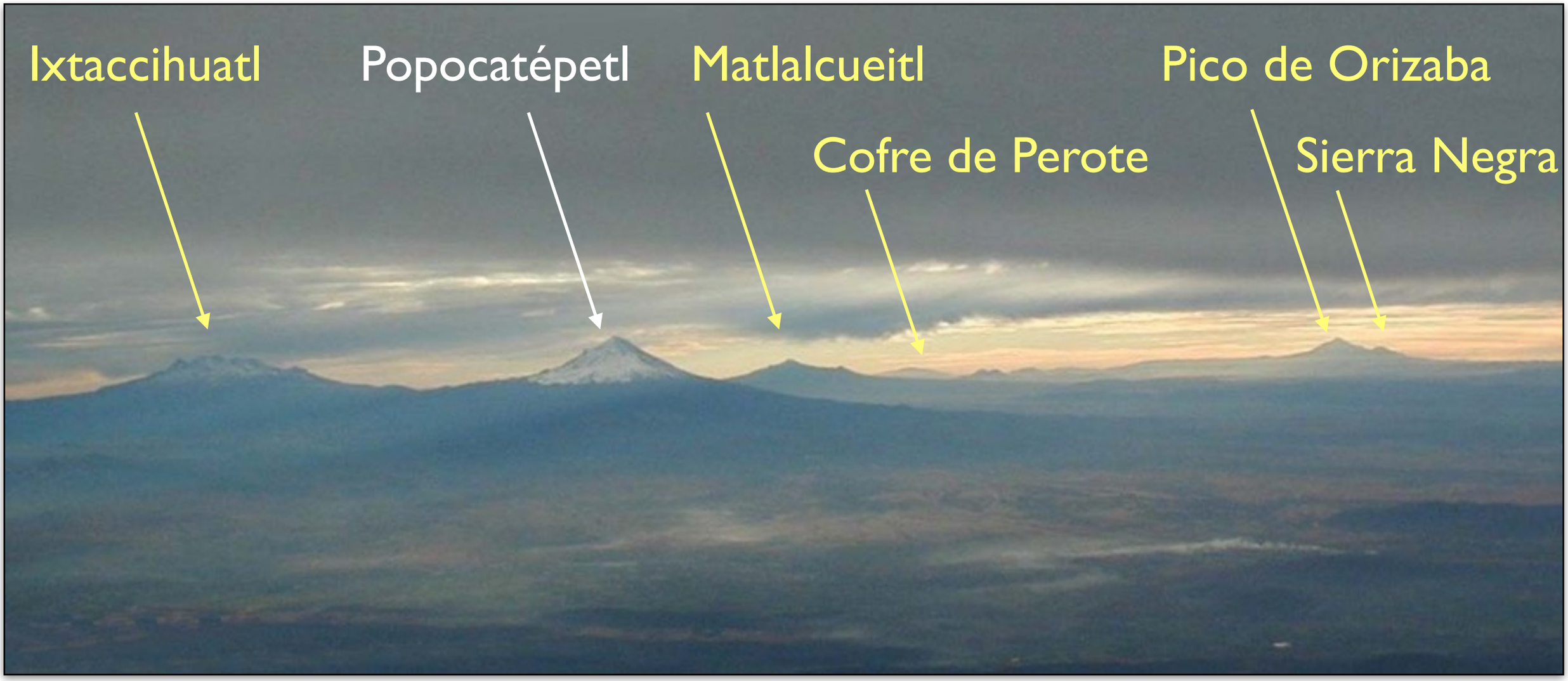
- Parque Nacional Pico de Orizaba: 97.5°W, 18.9°N

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



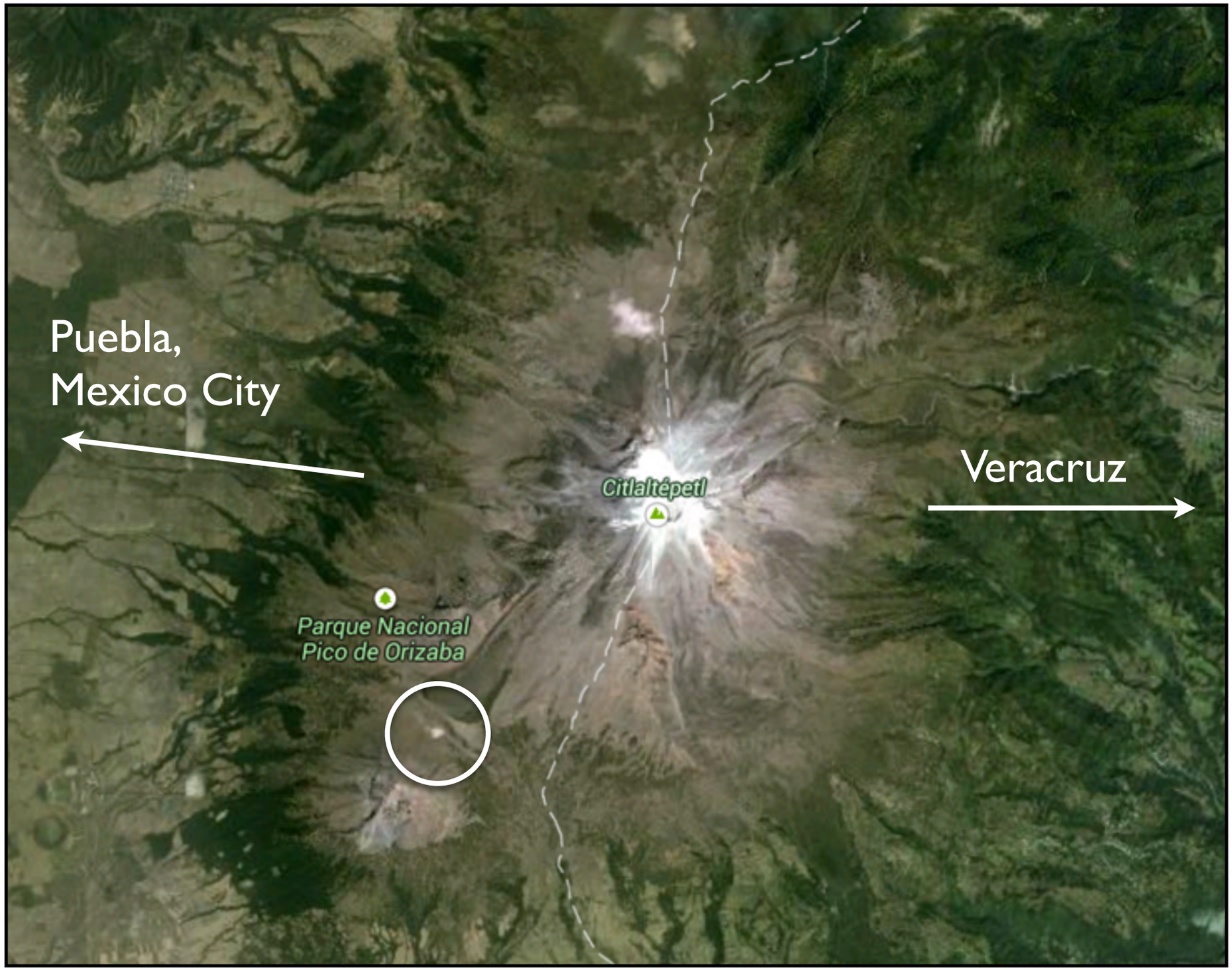
HAWC Location

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



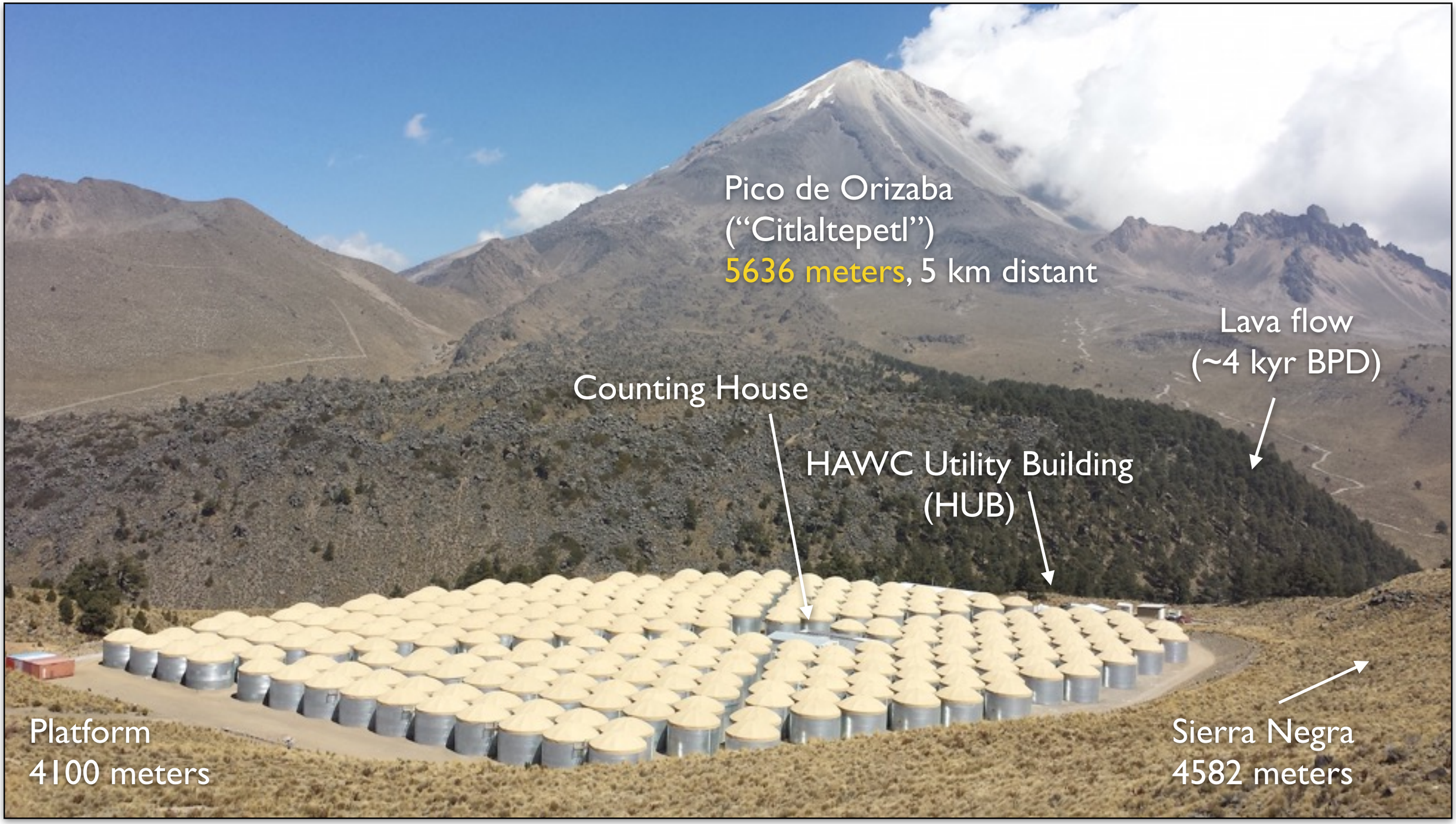
Credit: D. Tuggy

HAWC Site

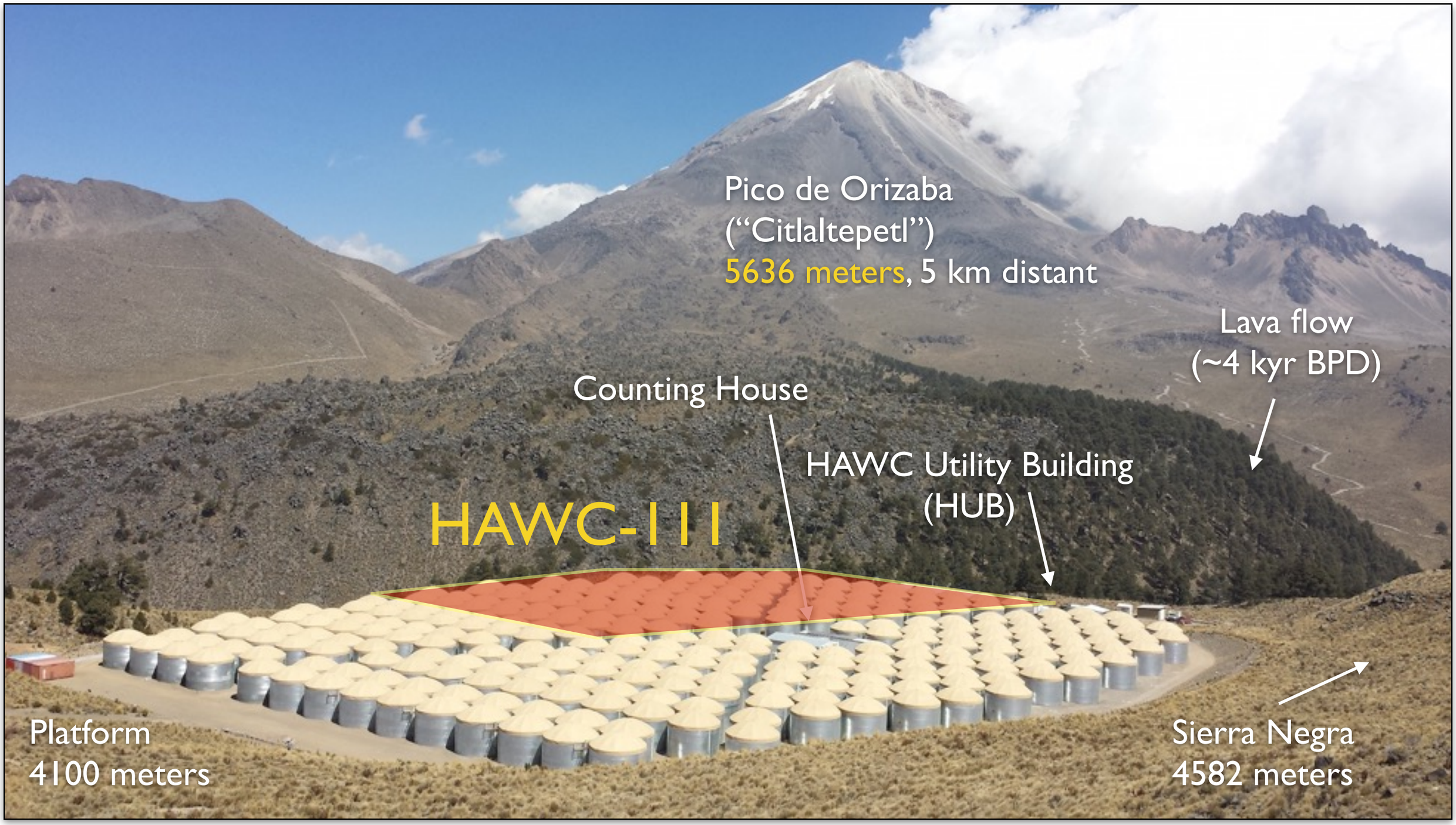

Puebla,
Mexico City
Veracruz
Citlaltépetl
Parque Nacional
Pico de Orizaba

HAWC Site

HAWC Site


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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4100 meters
Sierra Negra
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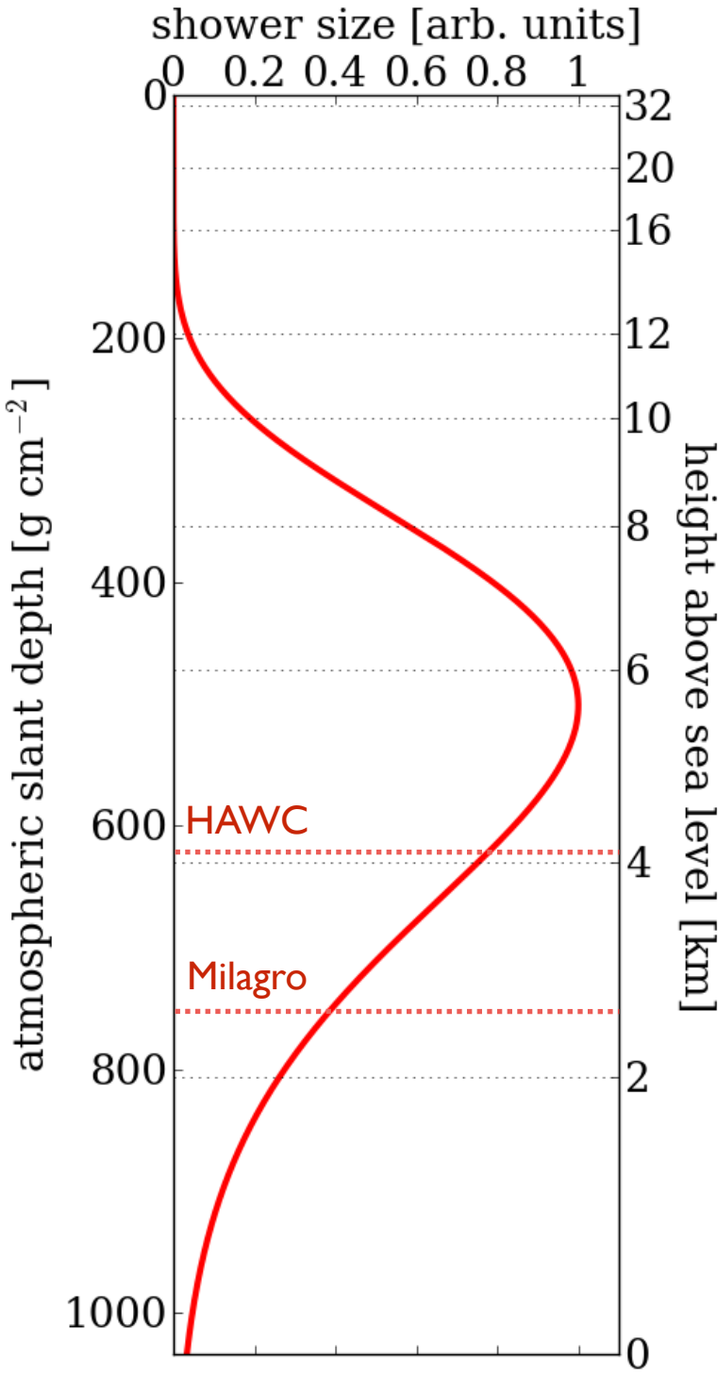
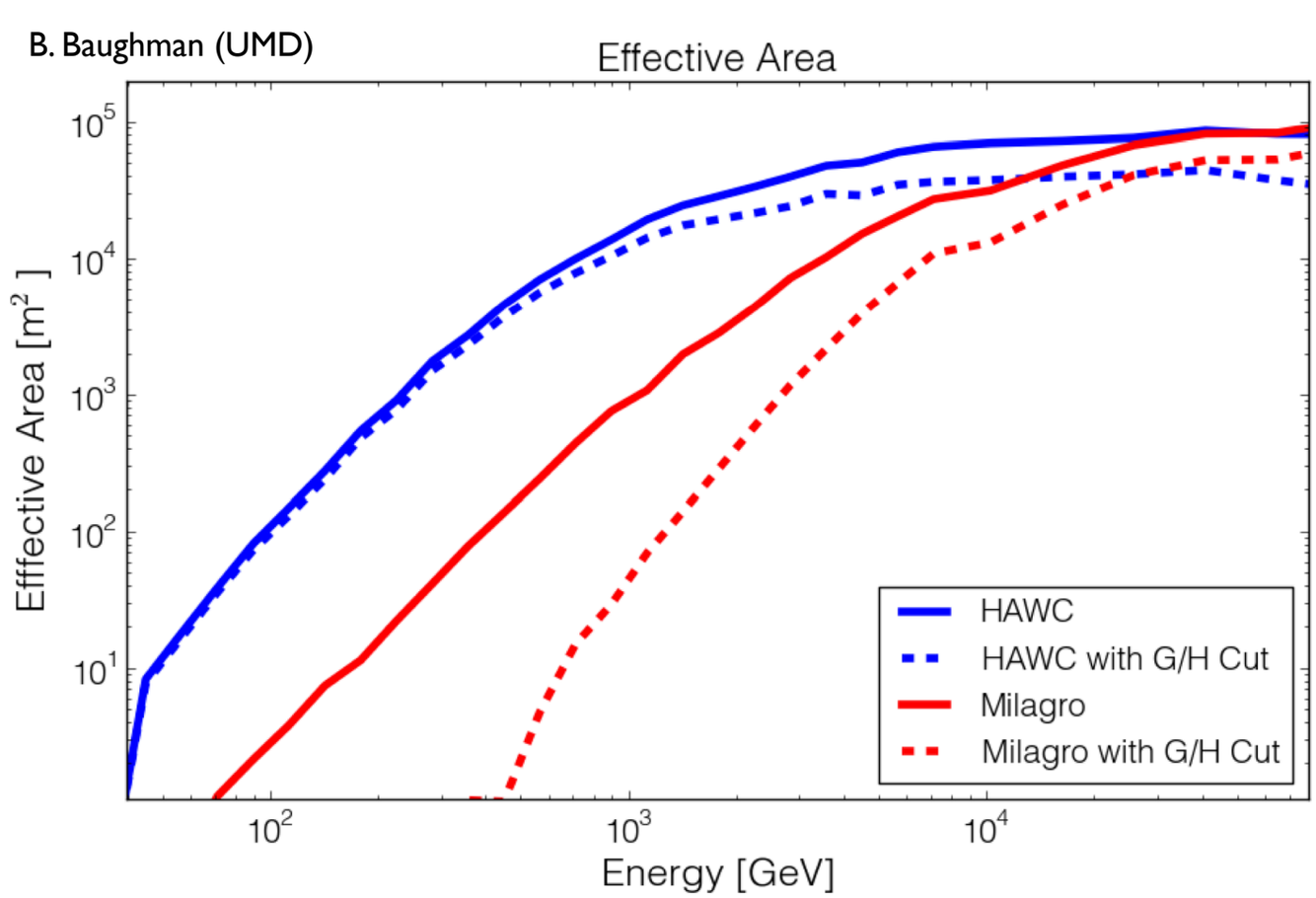
Why Deploy on a Volcano?



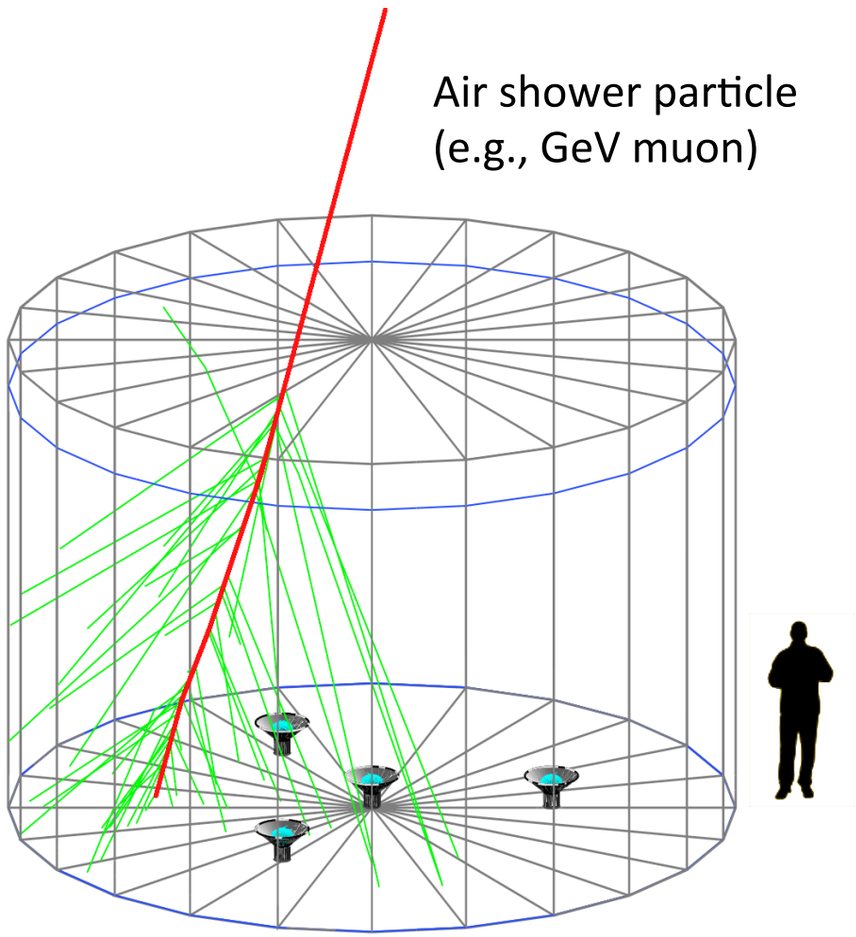
- At altitude, observe more particles in air shower; reduce energy threshold
- **Health/safety** fix for altitude-related illnesses: drive downhill



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

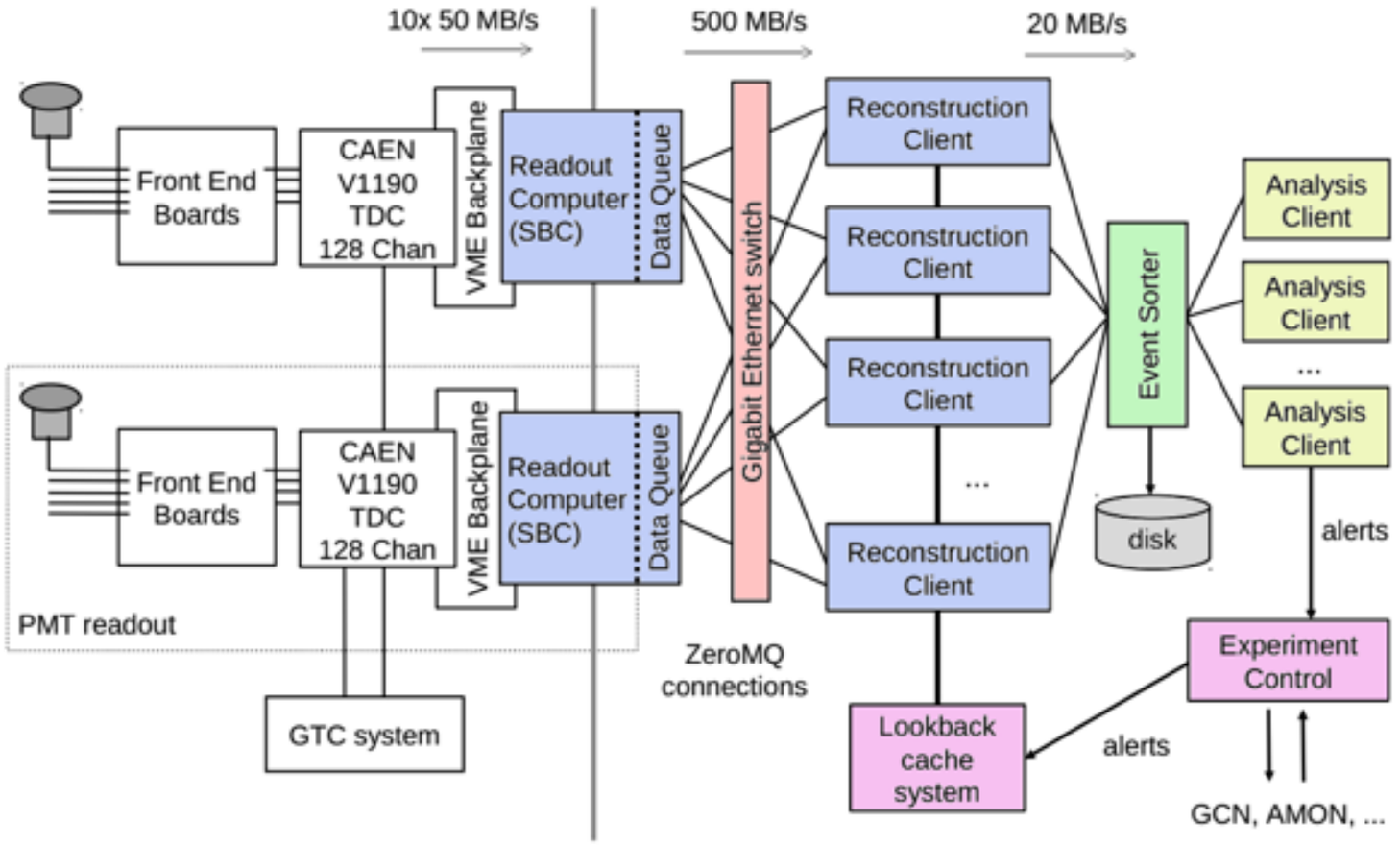
Cabling

- 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)

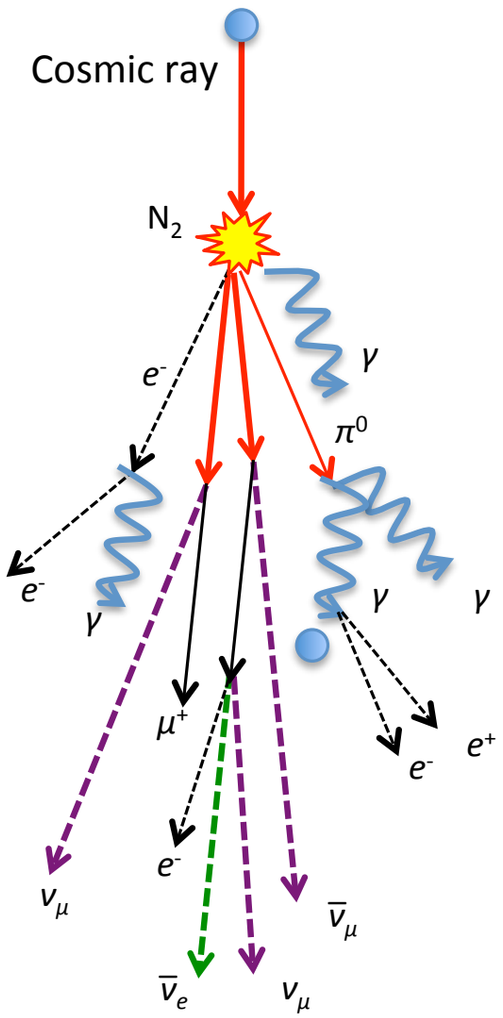
HAWC Data Transfer System

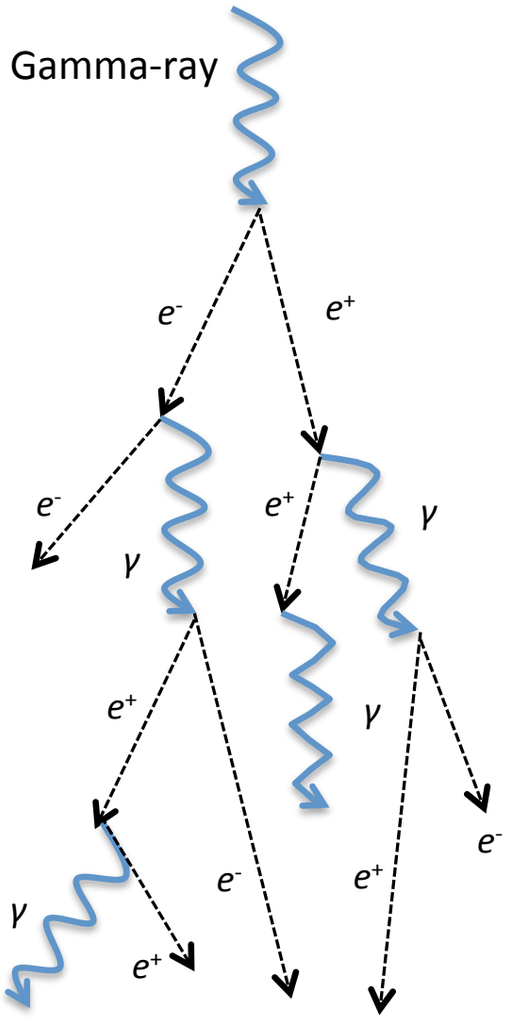
- Site network is sufficient for remote shifts and diagnostics, but not for sending 2 TB per day to UNAM and UMD

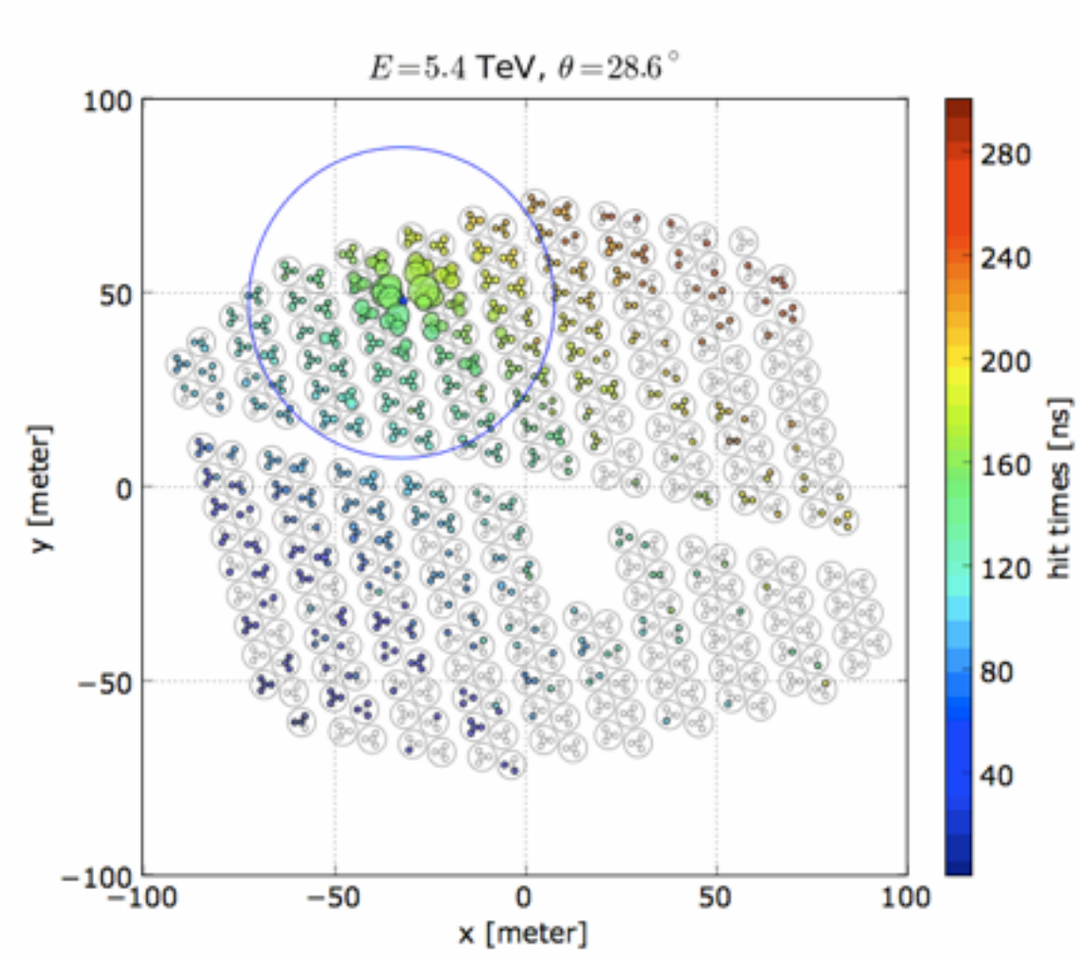
- *"Never underestimate the bandwidth of a ~~station wagon~~ Dodge Durango full of tapes hurtling down the highway."*
  — A. Tannenbaum

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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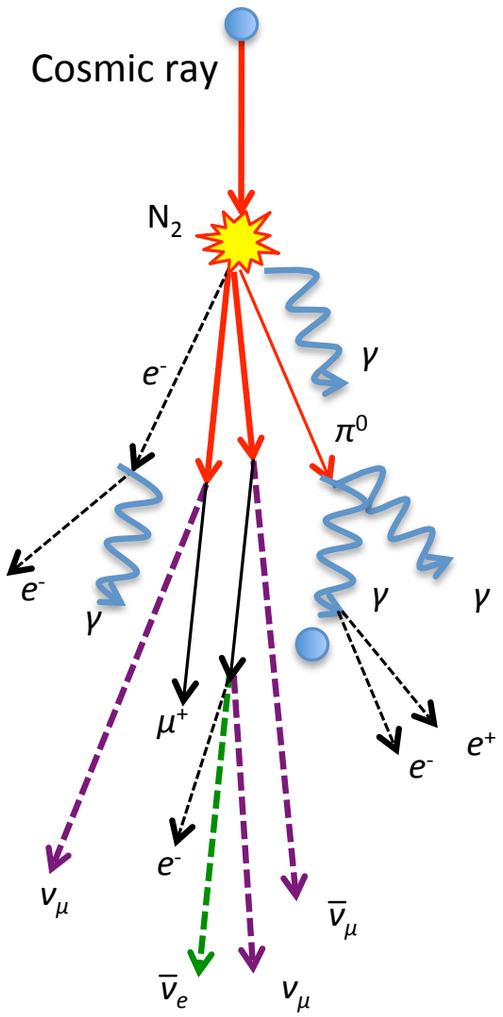

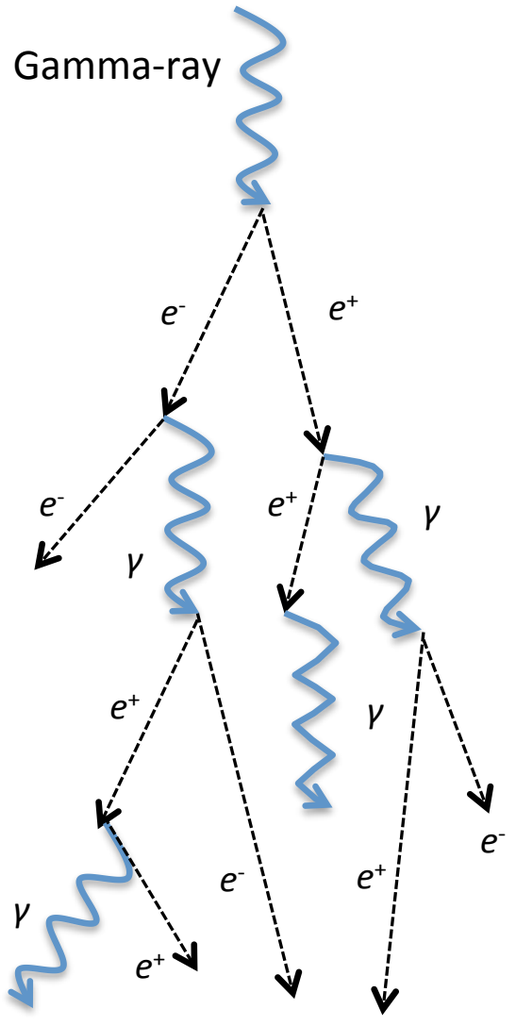

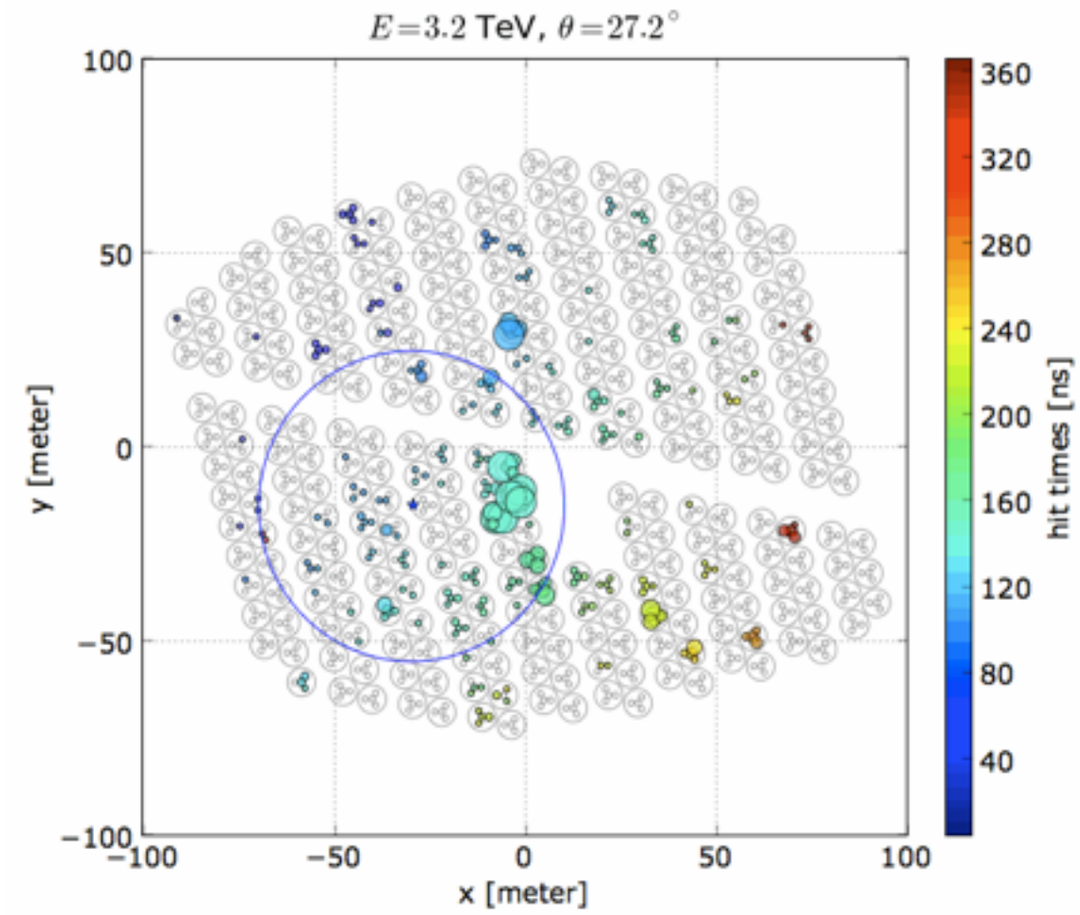

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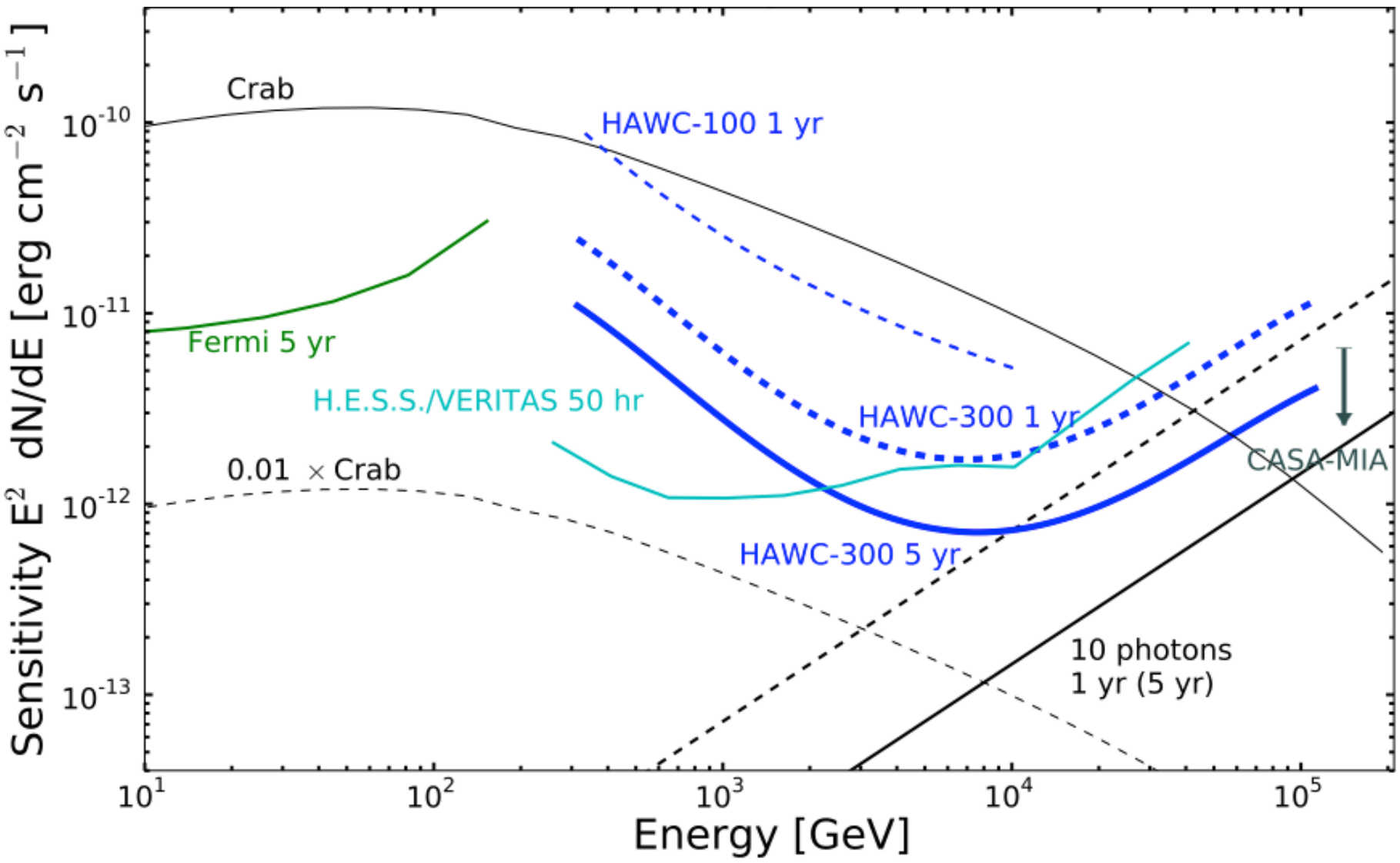
HAWC Differential Sensitivity

B. Baughman (UMD)

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

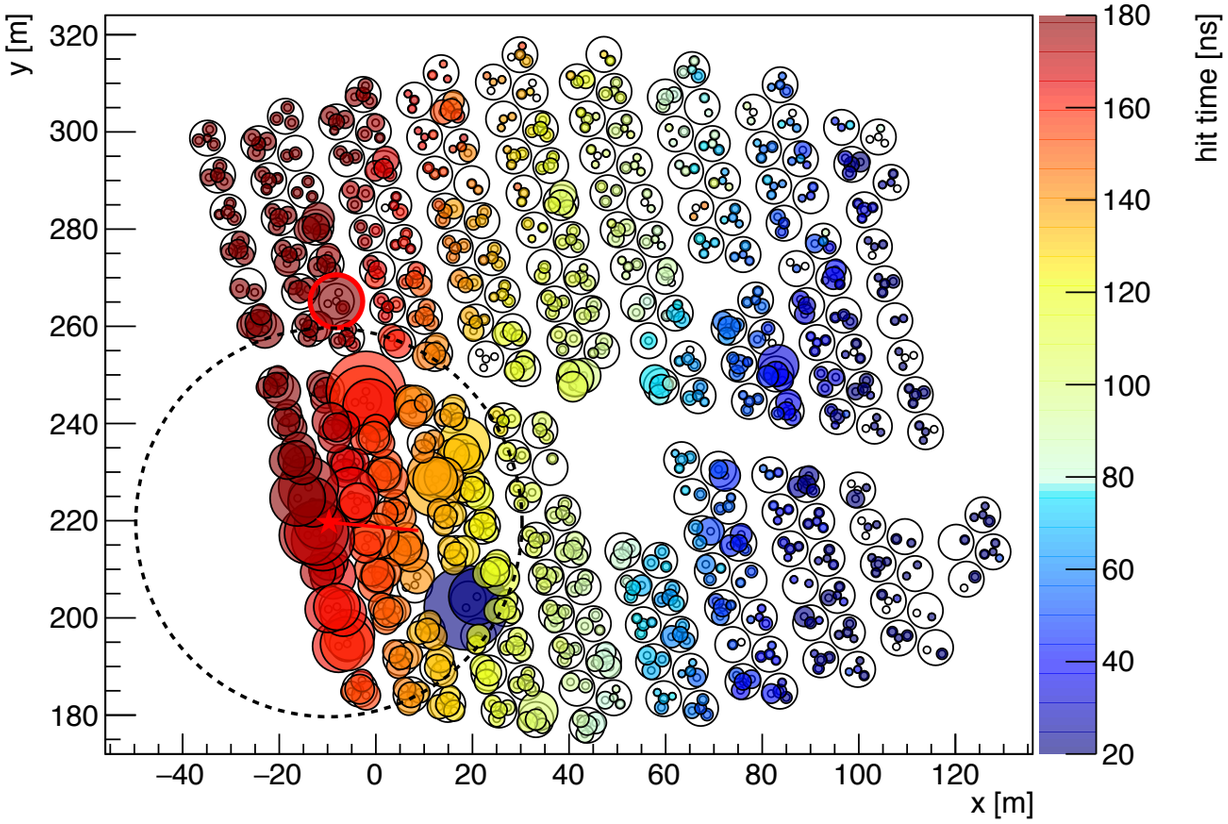


- 5 years of HAWC @ 10 TeV ~ 50 hr IACT @ 1 TeV
- Remember: HAWC is a *survey* instrument, not a pointing instrument

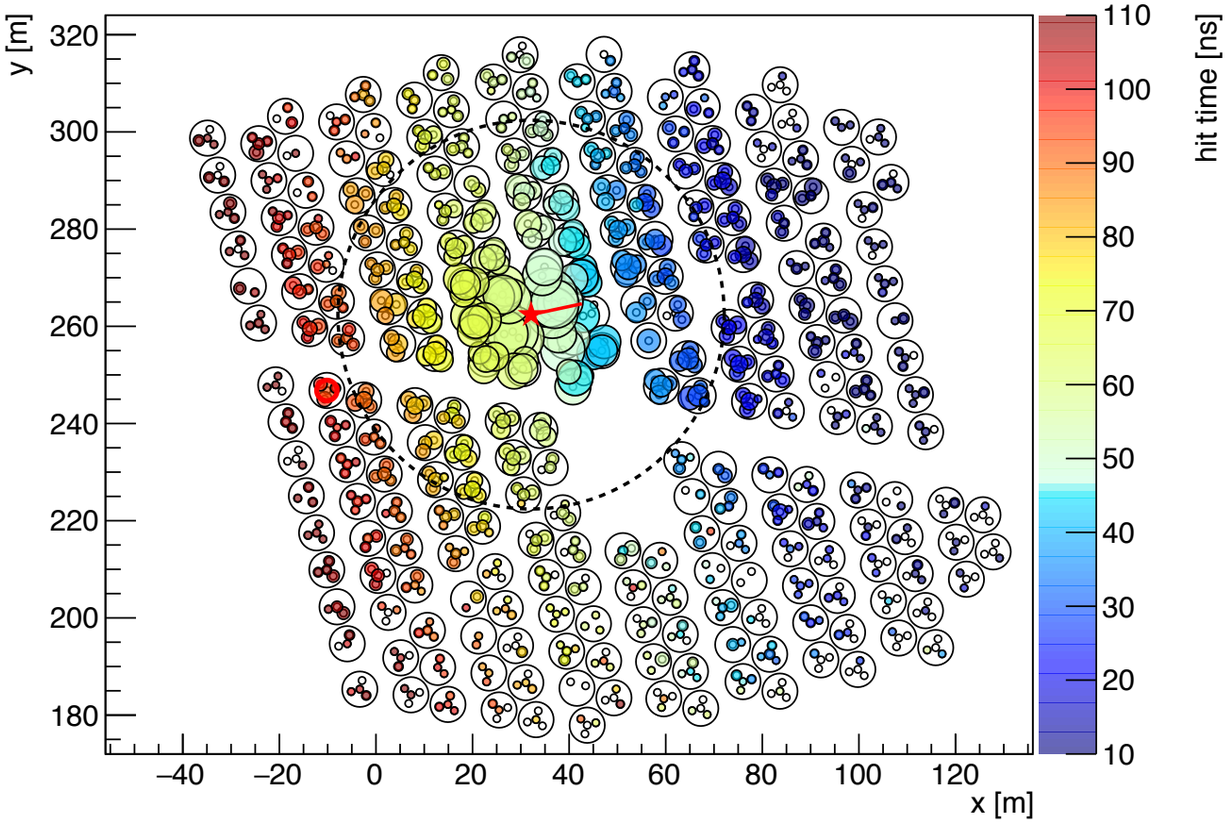
HAWC-250 Data

- 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

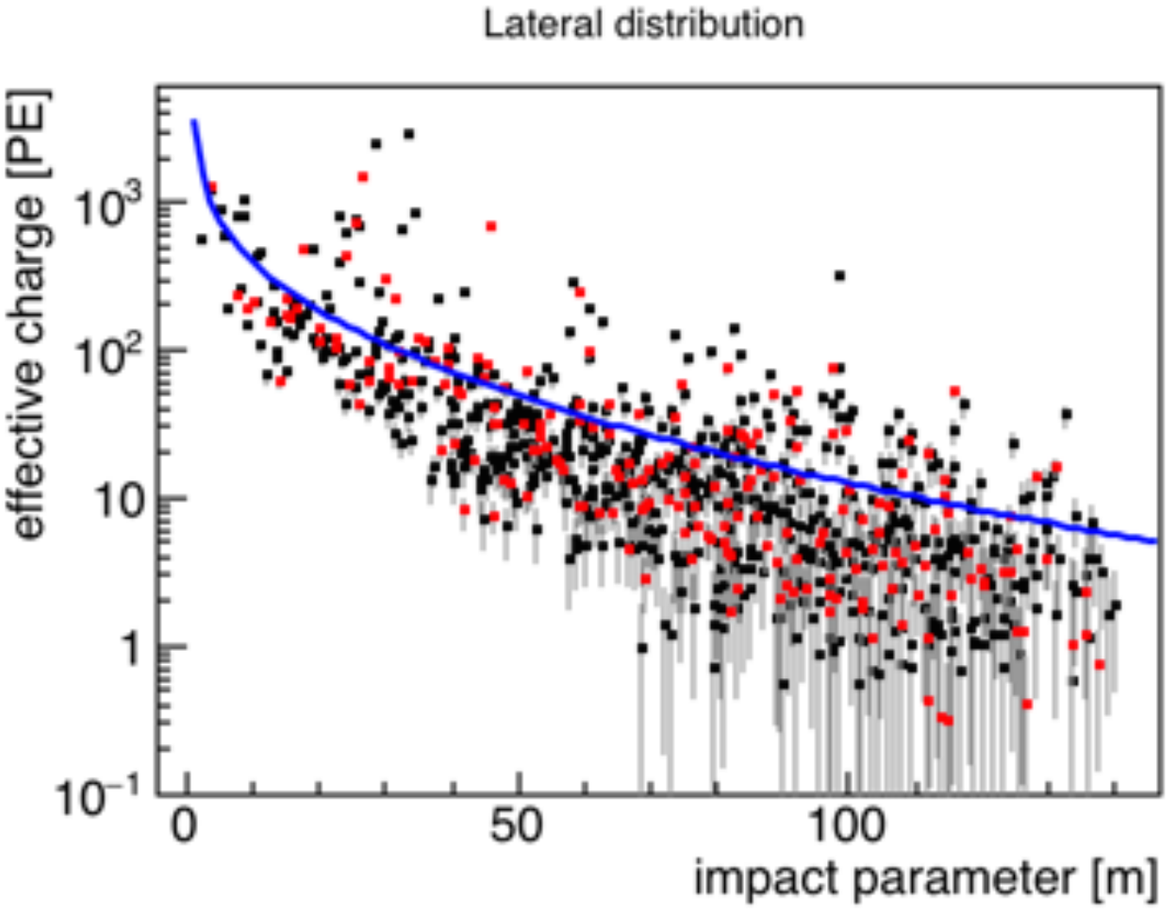


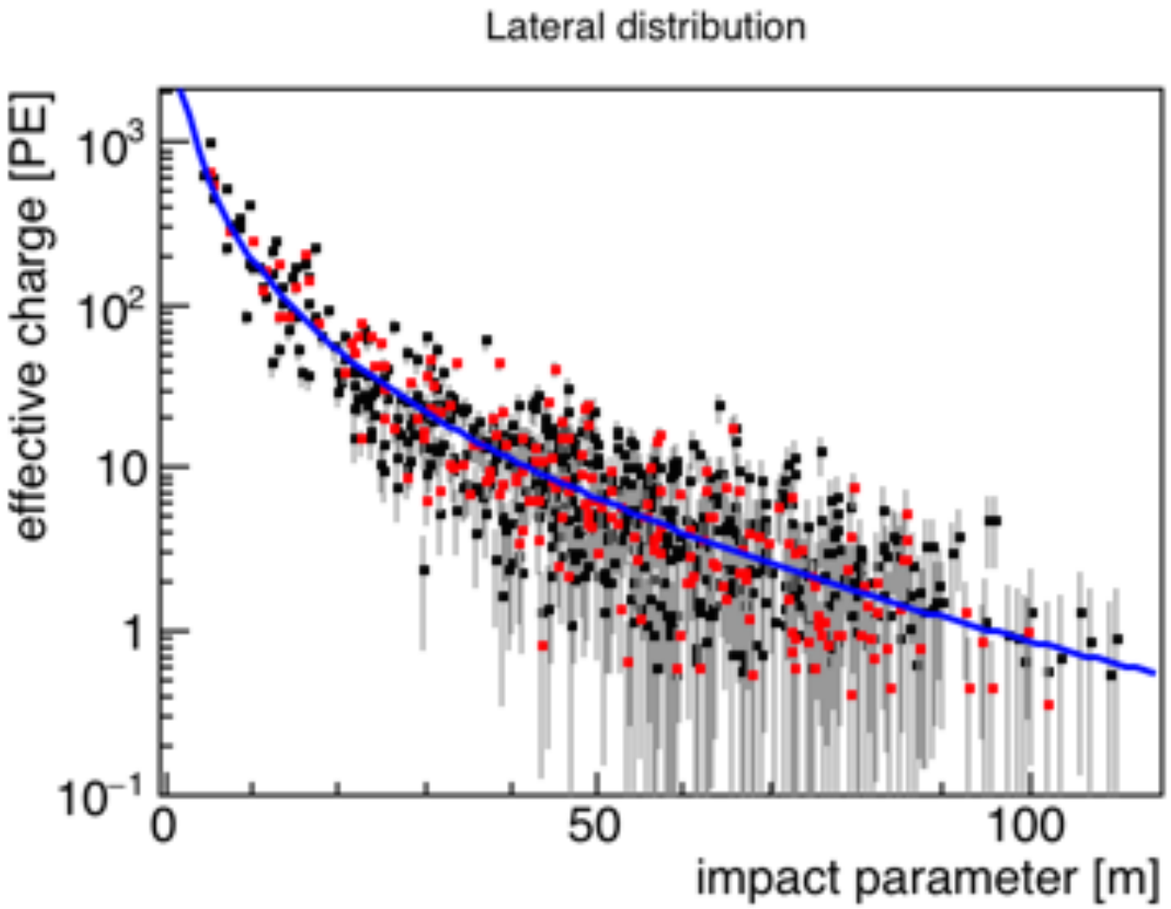
Run 2203, TS 1966176, Ev# 115, CXPE40= 39.9, Cmptness= 19.4



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

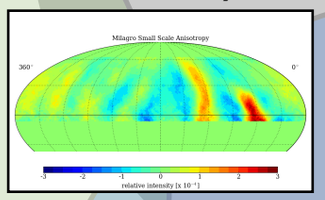
Dark Matter

Cosmic electron spectrum

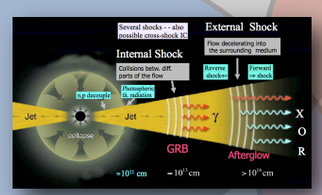
e^+/e^- ratio

Indirect DM Searches

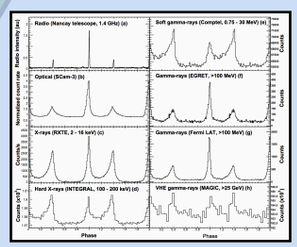
Cosmic Rays



GRBs



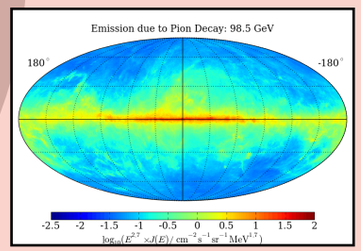
Lorentz Invariance Violation



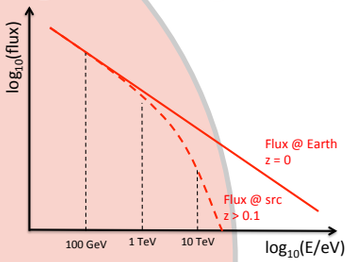
Exotic Particles

Cosmology

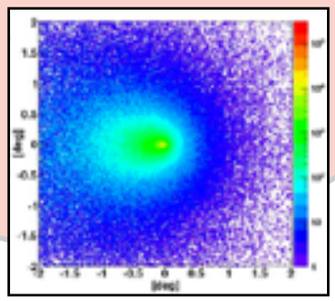
Diffuse Emission



Extragalactic Background Light (IR)



Intergalactic Magnetic Fields



Monopoles, Axions, Q-balls, etc.

Fundamental Physics

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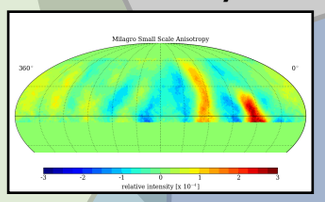
Cosmic Rays



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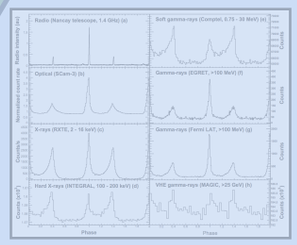

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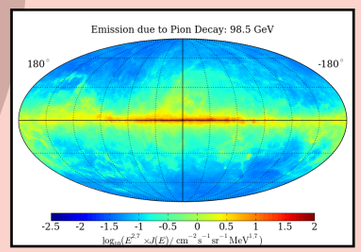

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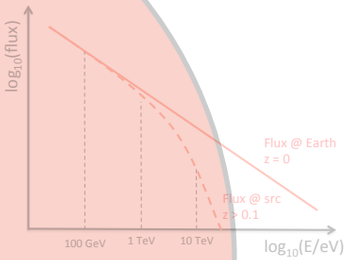

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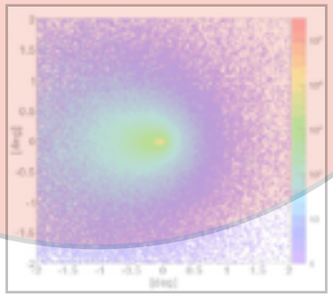
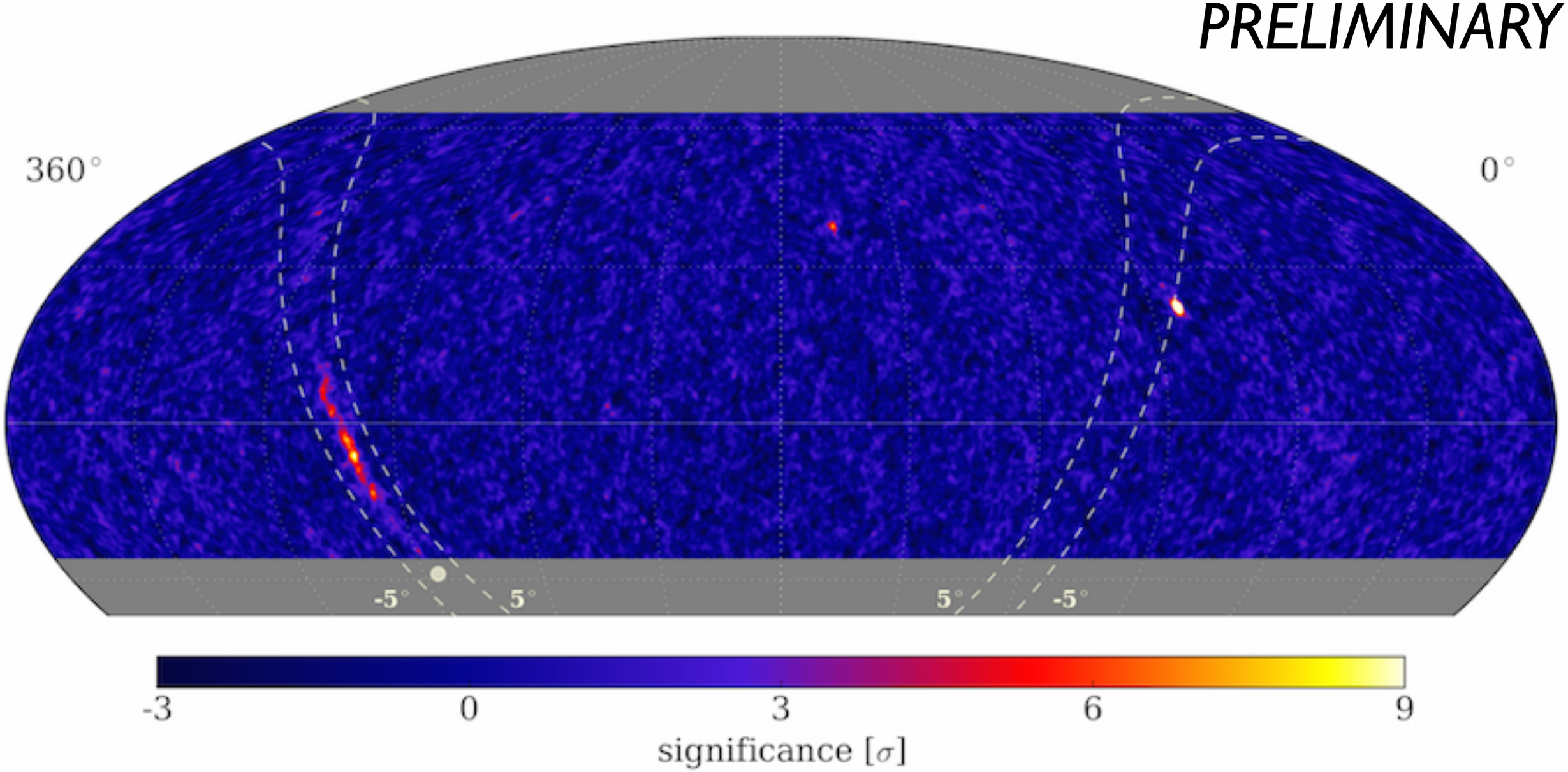


Fundamental Physics

HAWC-250 γ-Ray Map

PRELIMINARY



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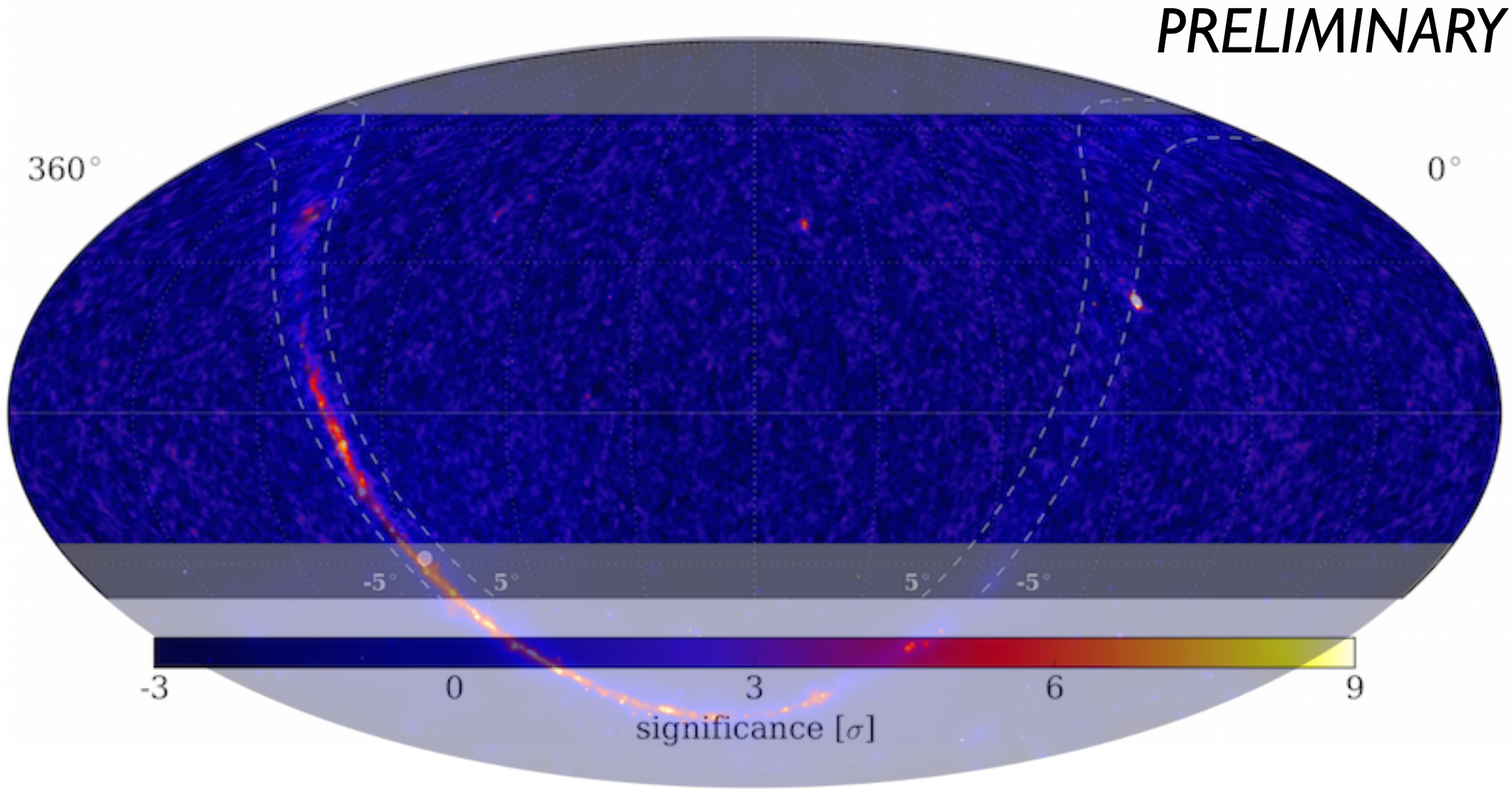

Fermi LAT: *E* > 50 GeV (M. Ajello)

HAWC-250 γ-Ray Map

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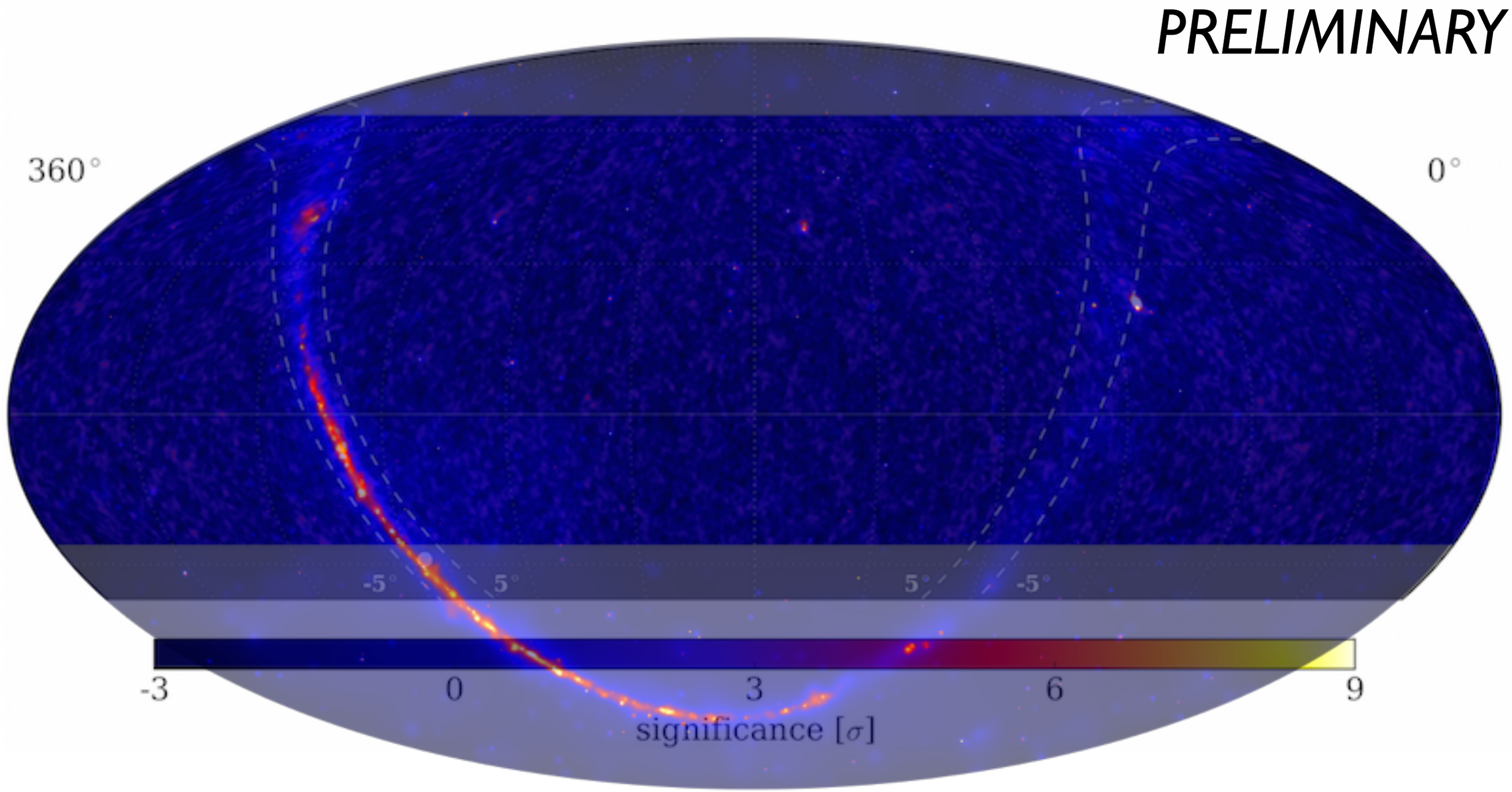

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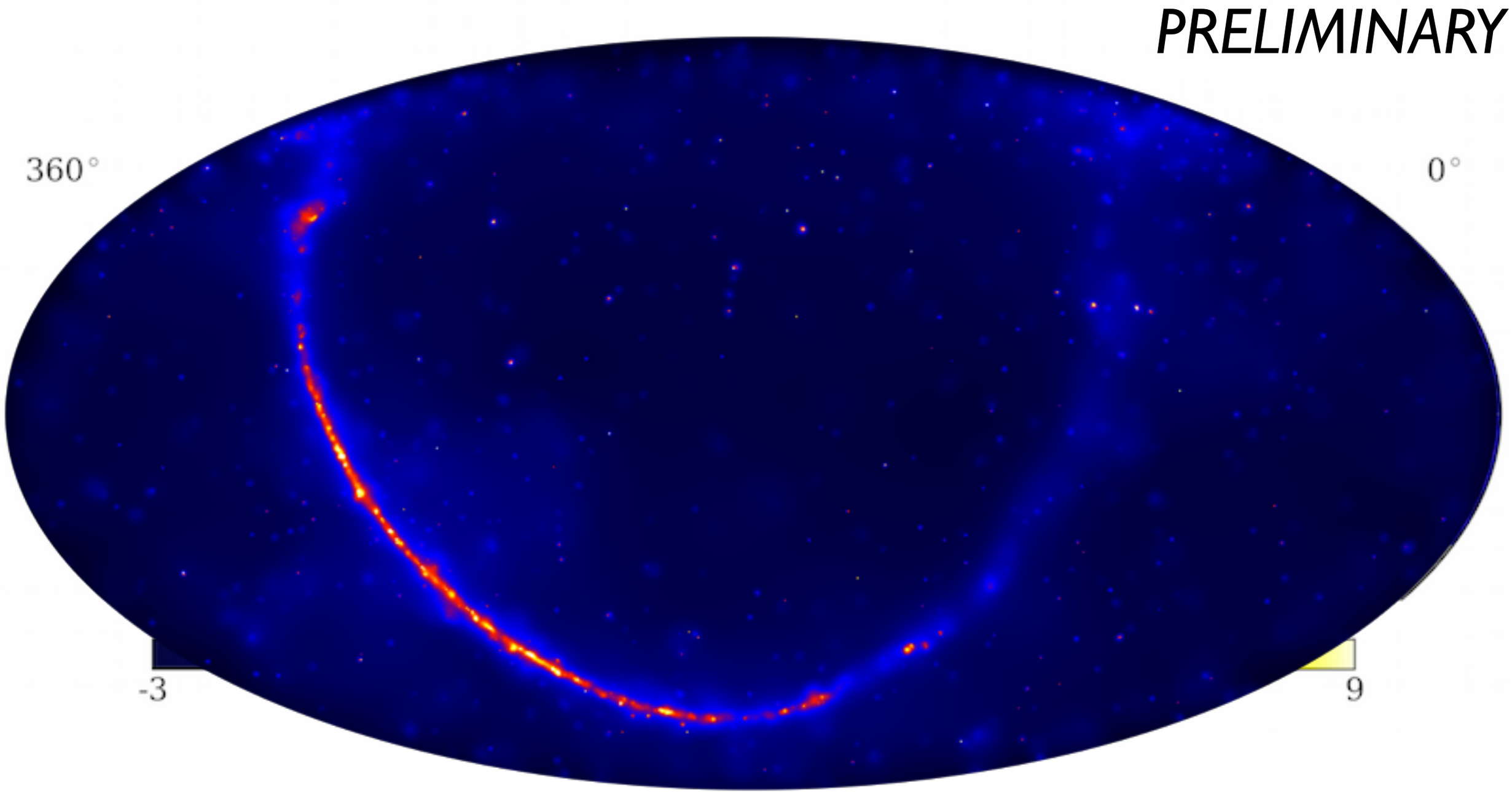

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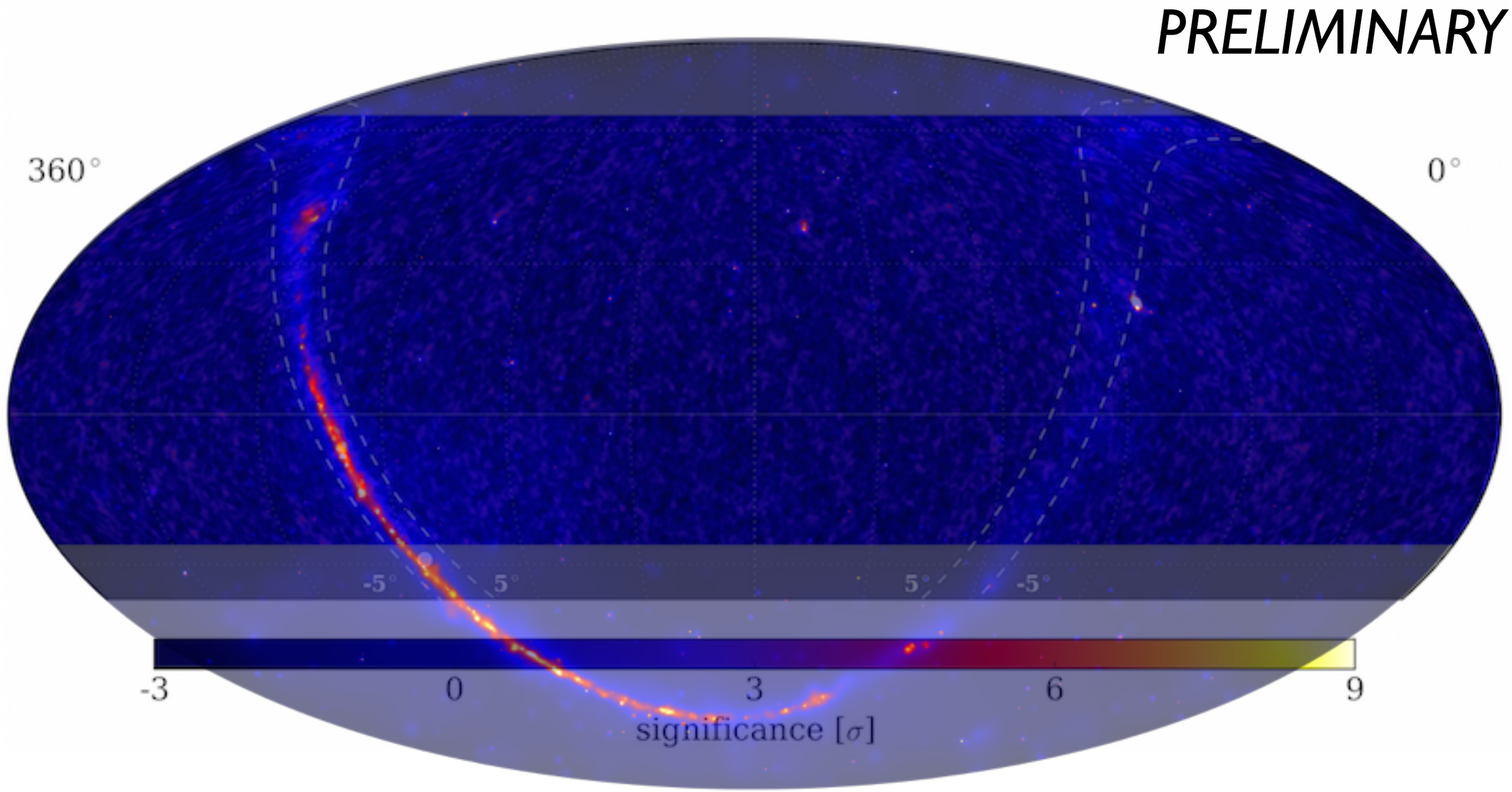

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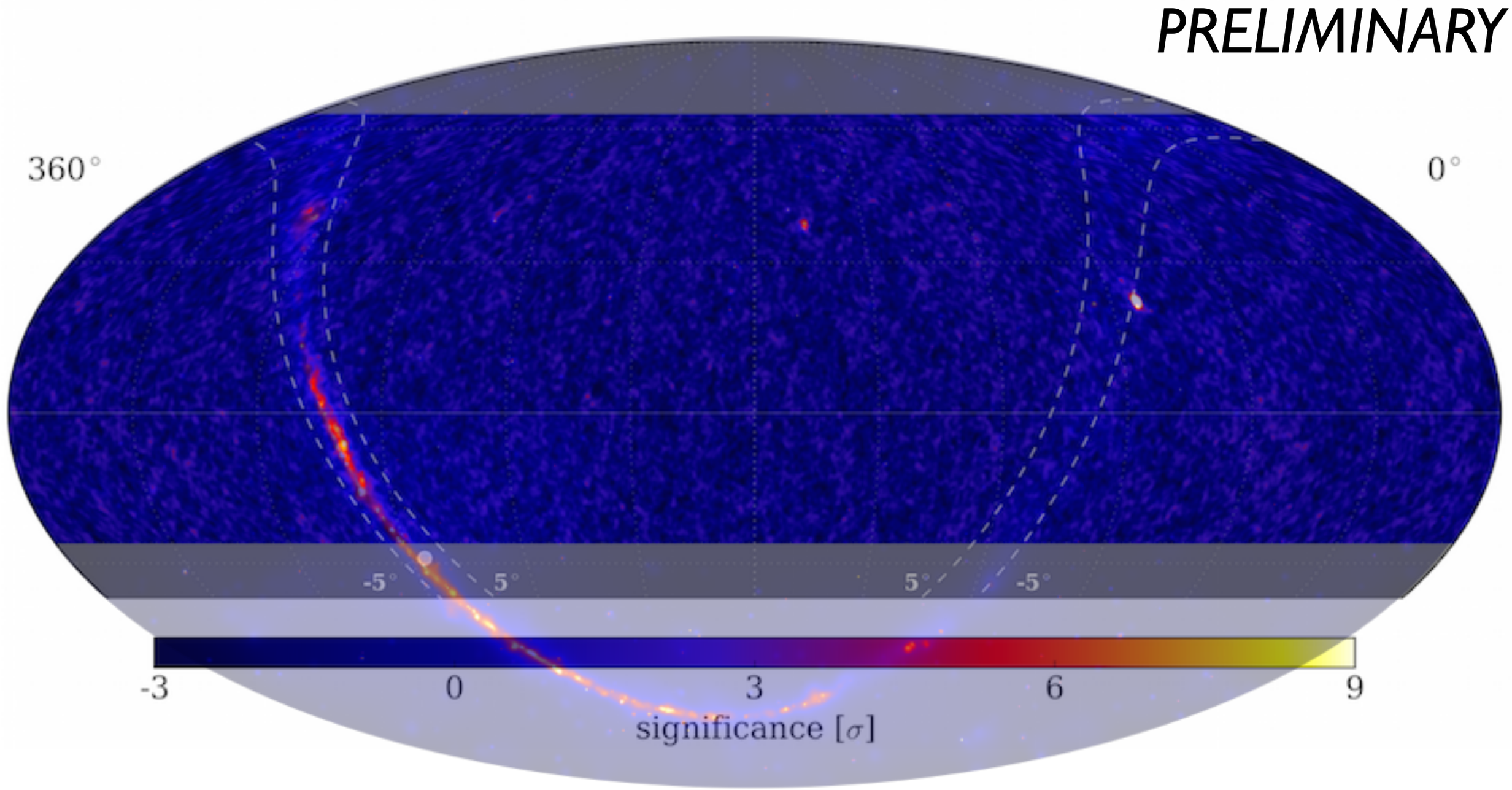

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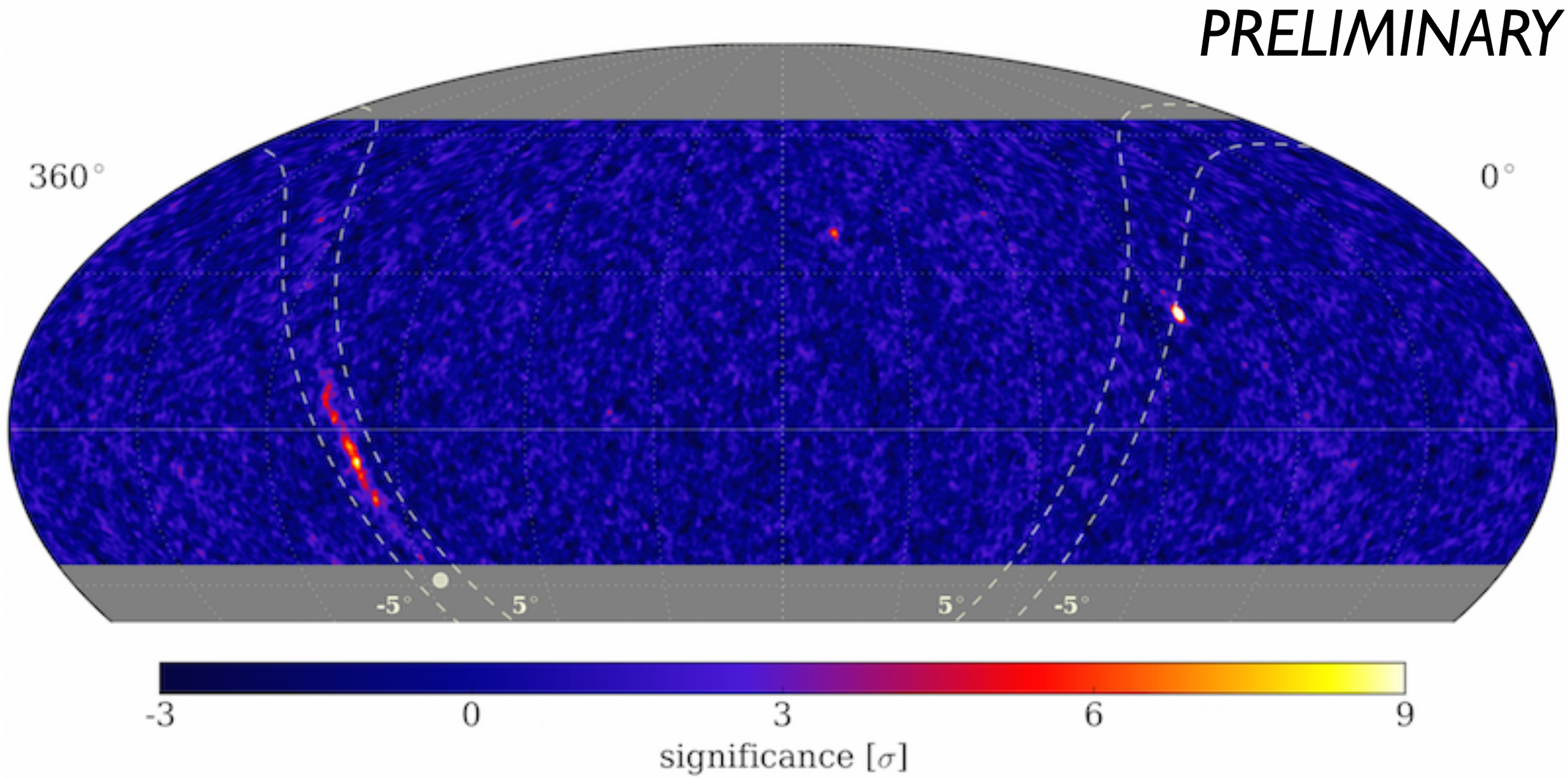

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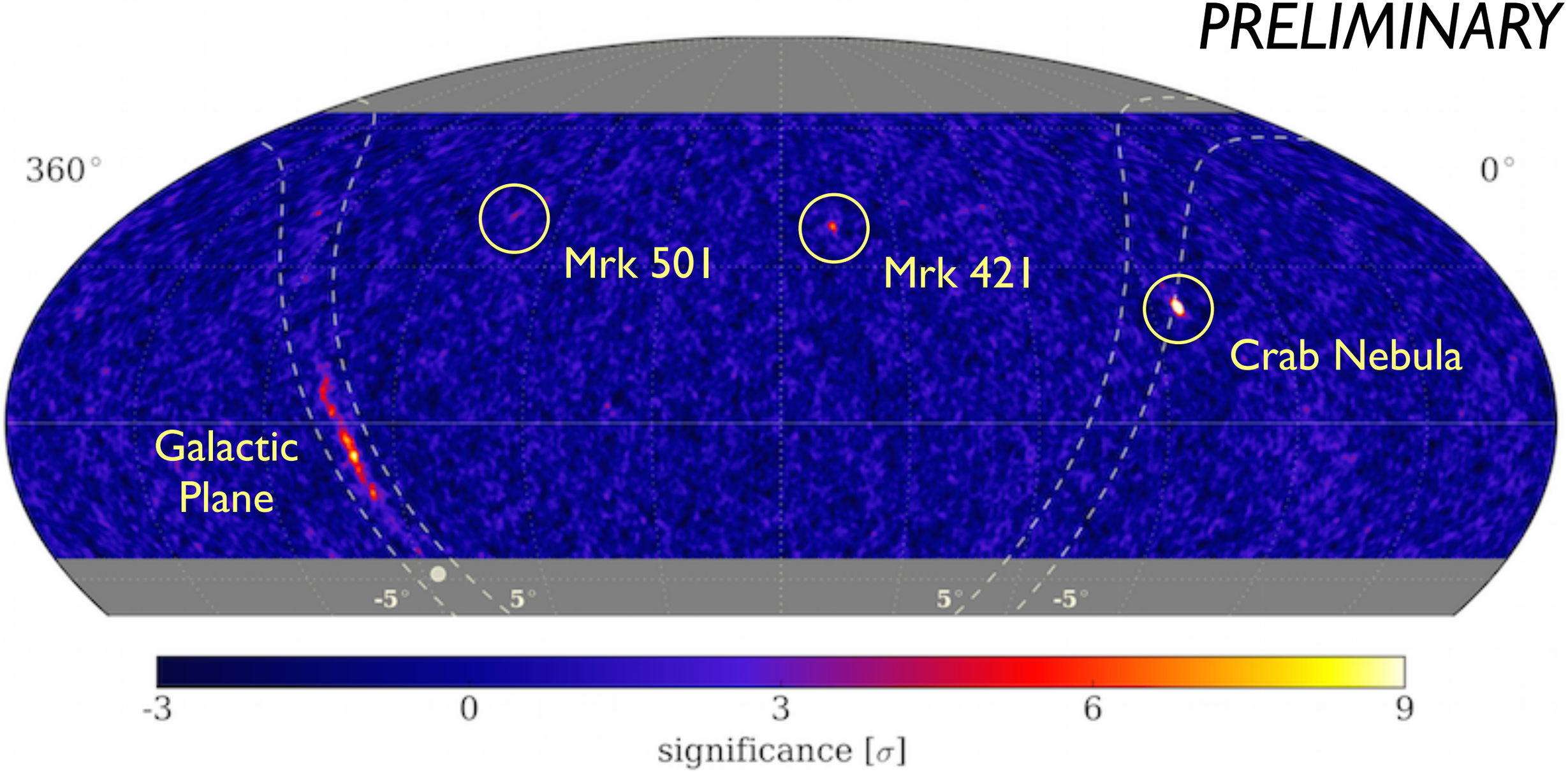
HAWC-250 γ-Ray Map

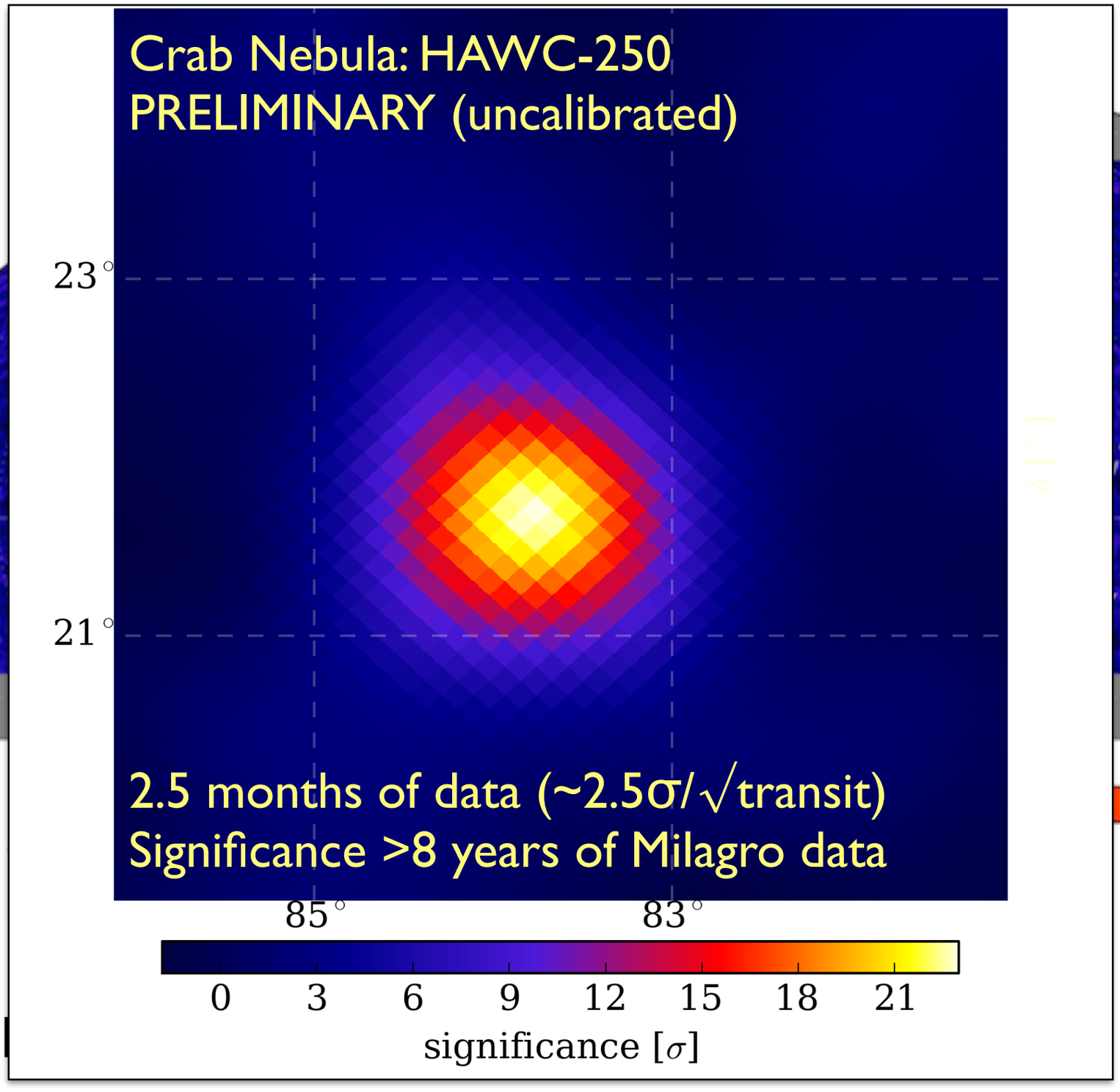
PRELIMINARY



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

HAWC-250 γ-Ray Map

C. Riviere (UMD)

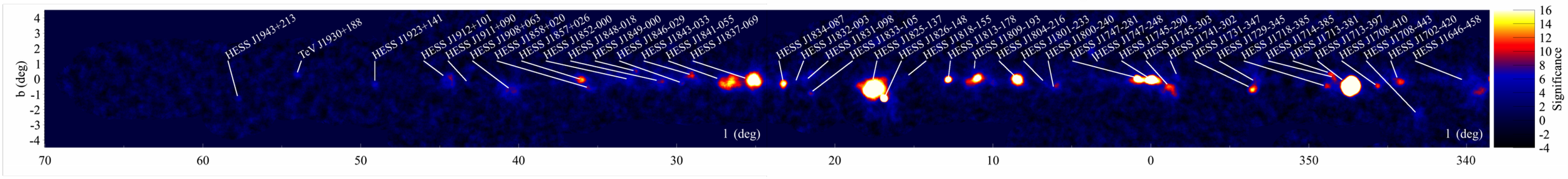


Fermi

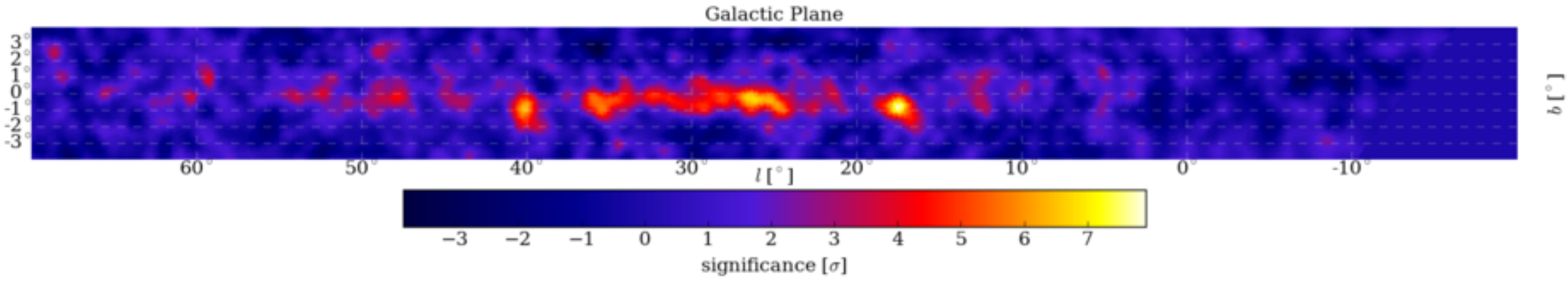
The Galaxy in TeV γ Rays

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

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



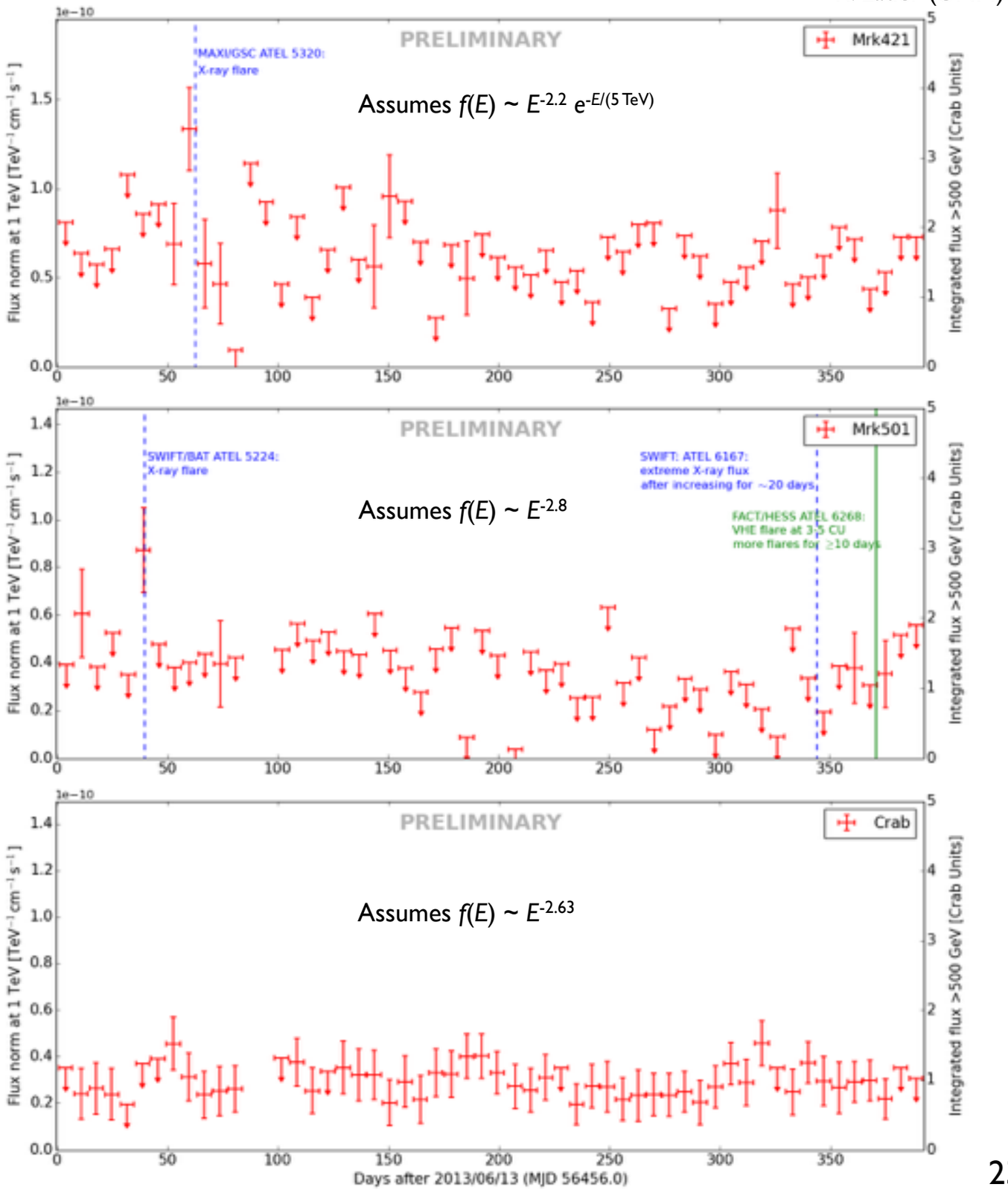
- HAWC view of the Galactic Plane (PRELIMINARY)



Observations of AGN

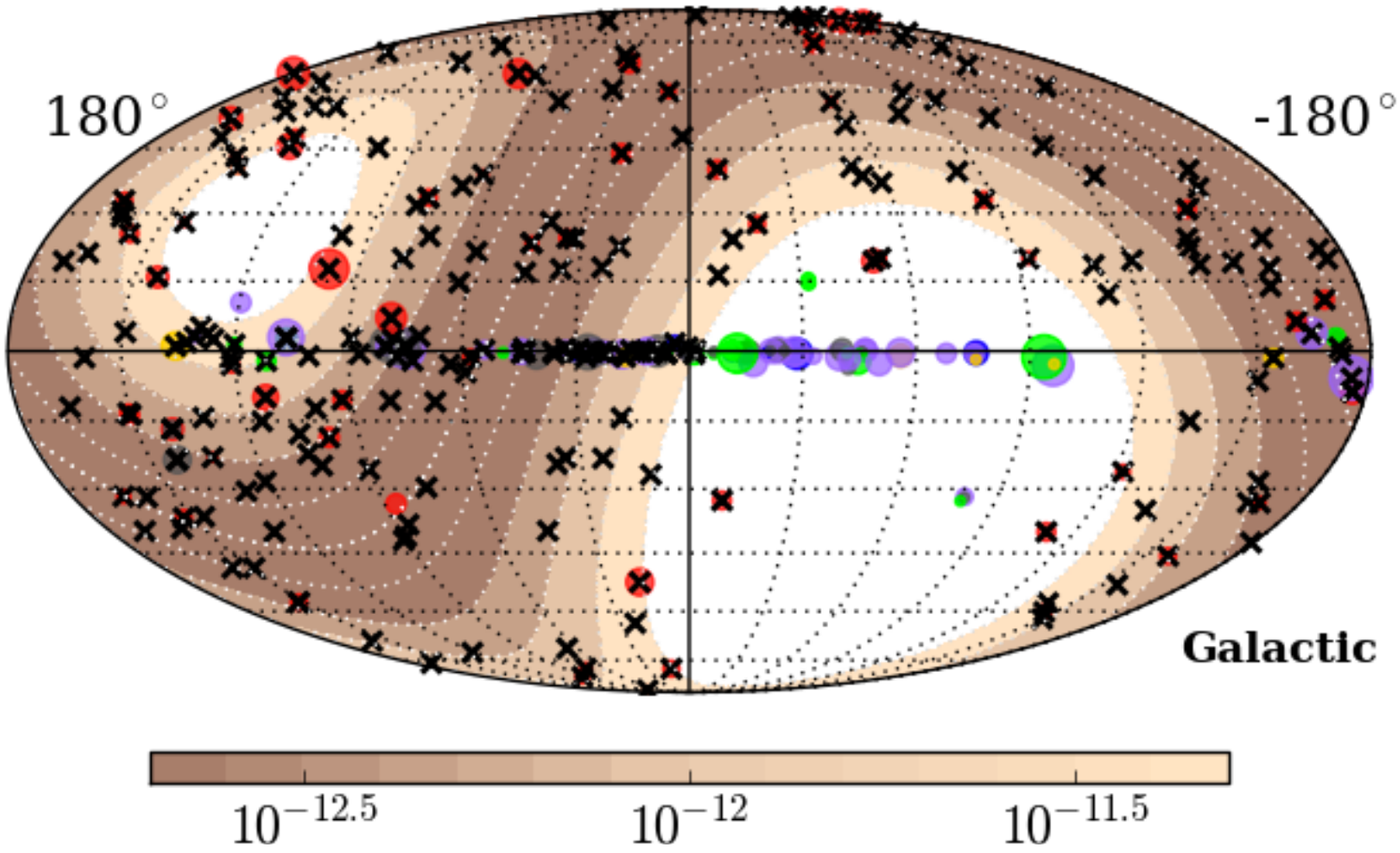
R. Lauer (UNM)

- 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)



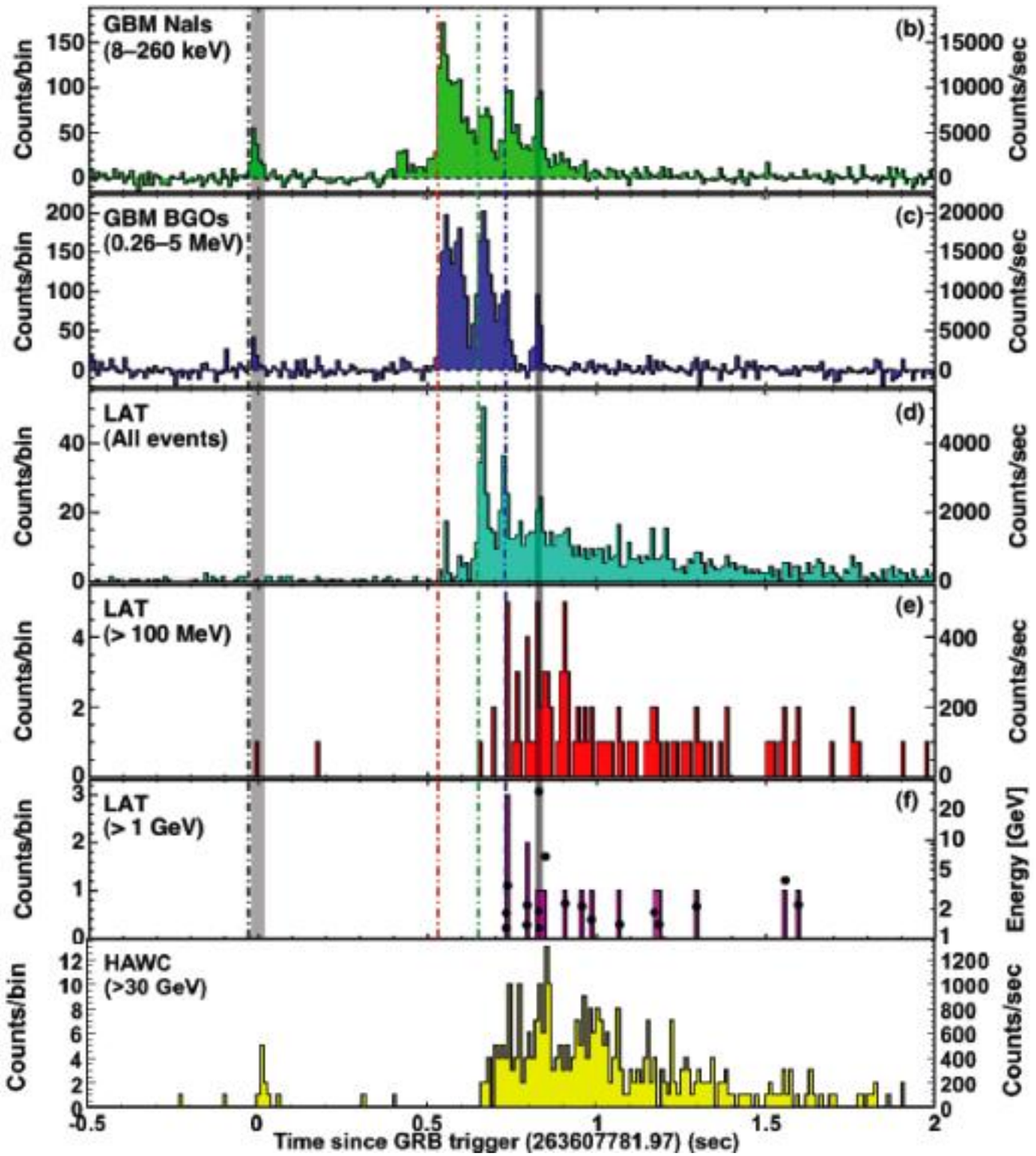
- Current HAWC performance: 95% uptime
- Crab duty cycle: 20%
- Mrk 421 duty cycle: 15%

- 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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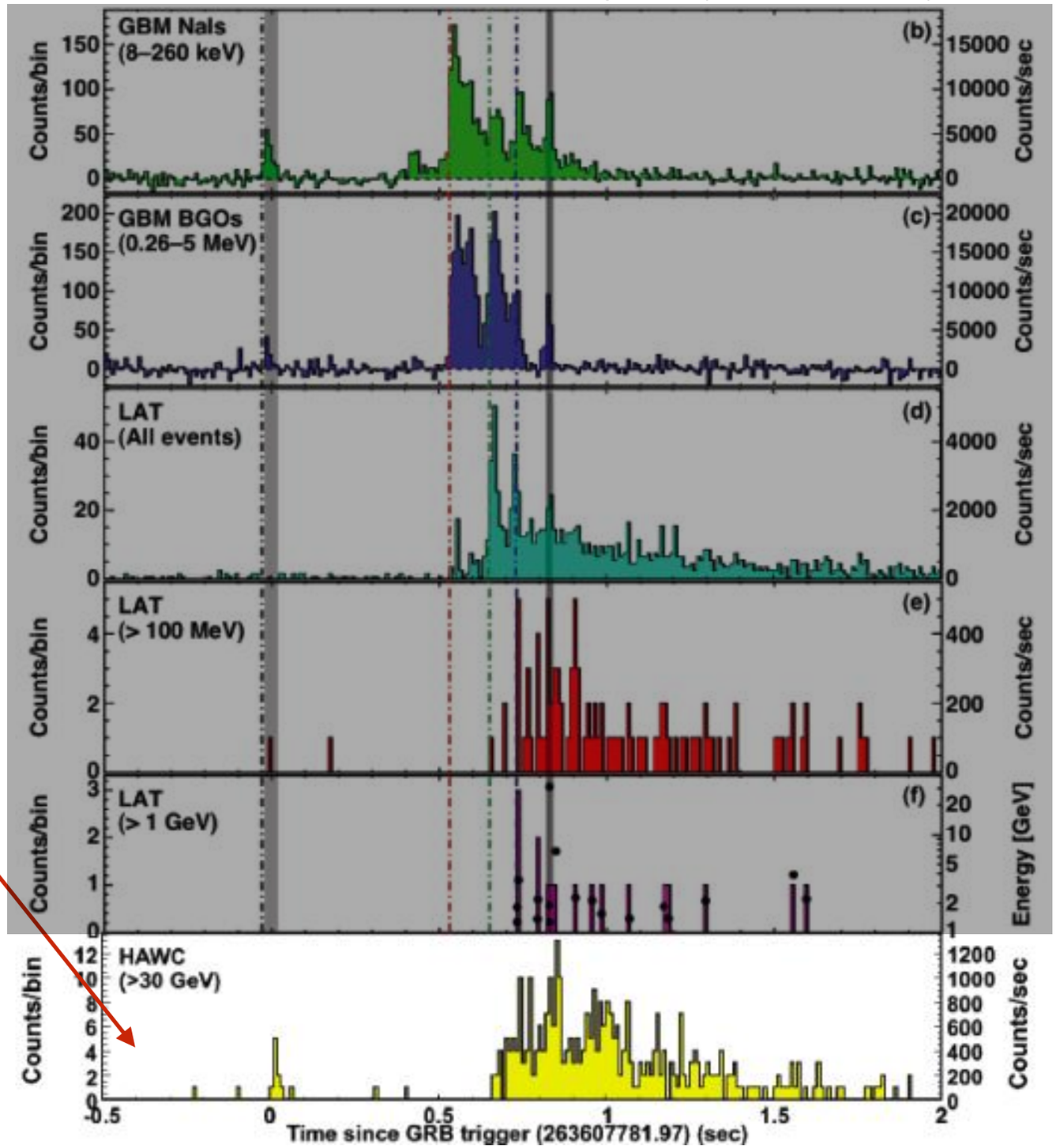
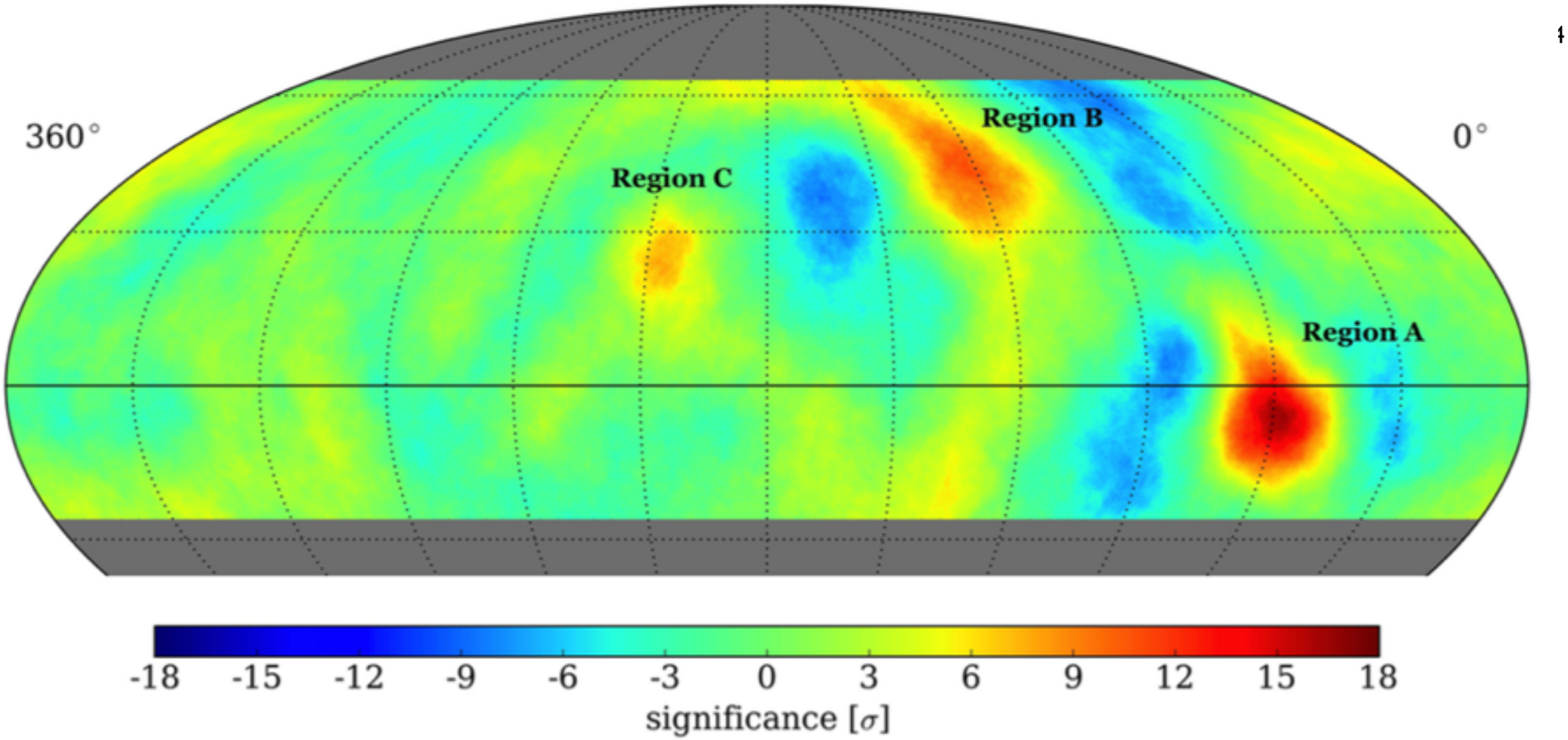


Observations of Cosmic Rays

- 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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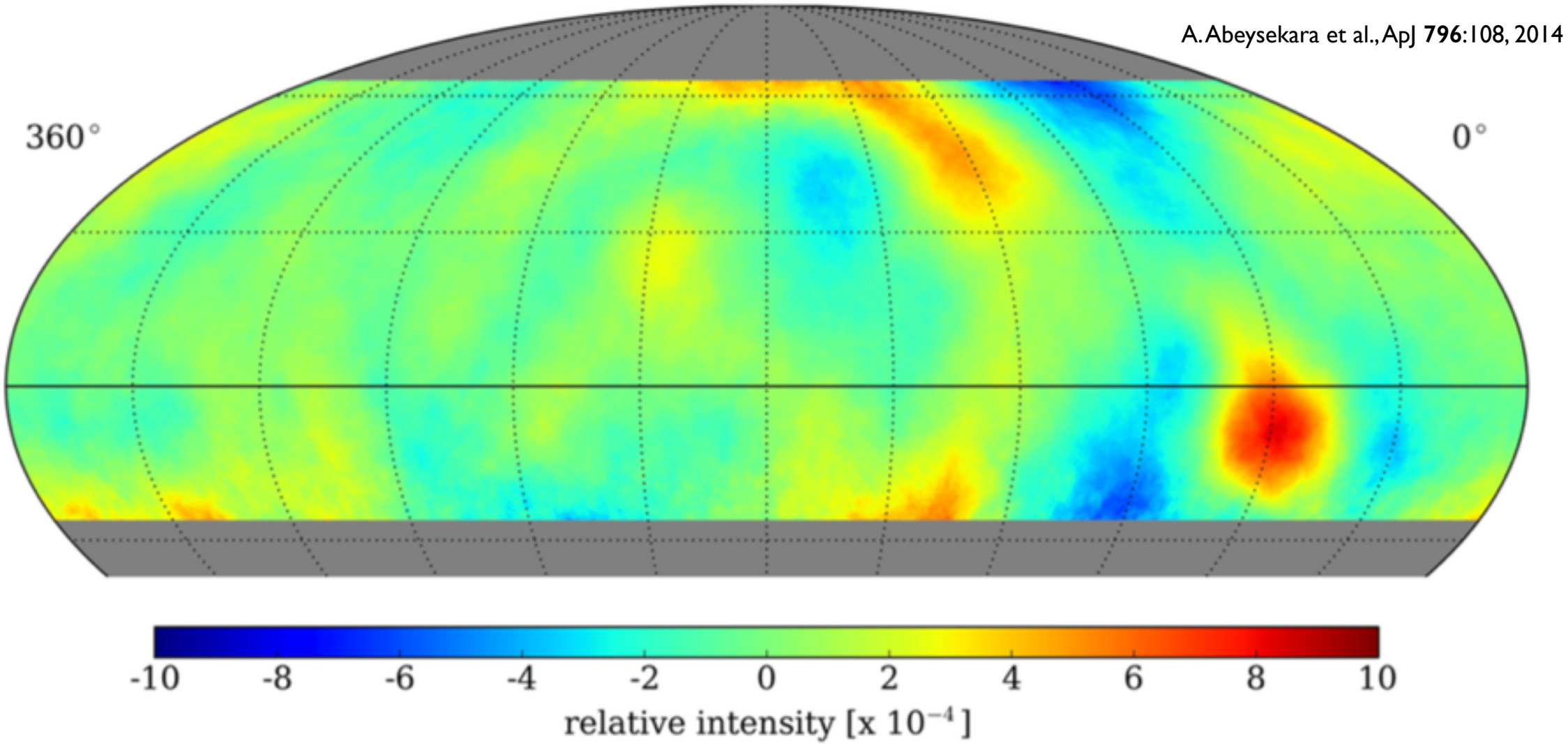

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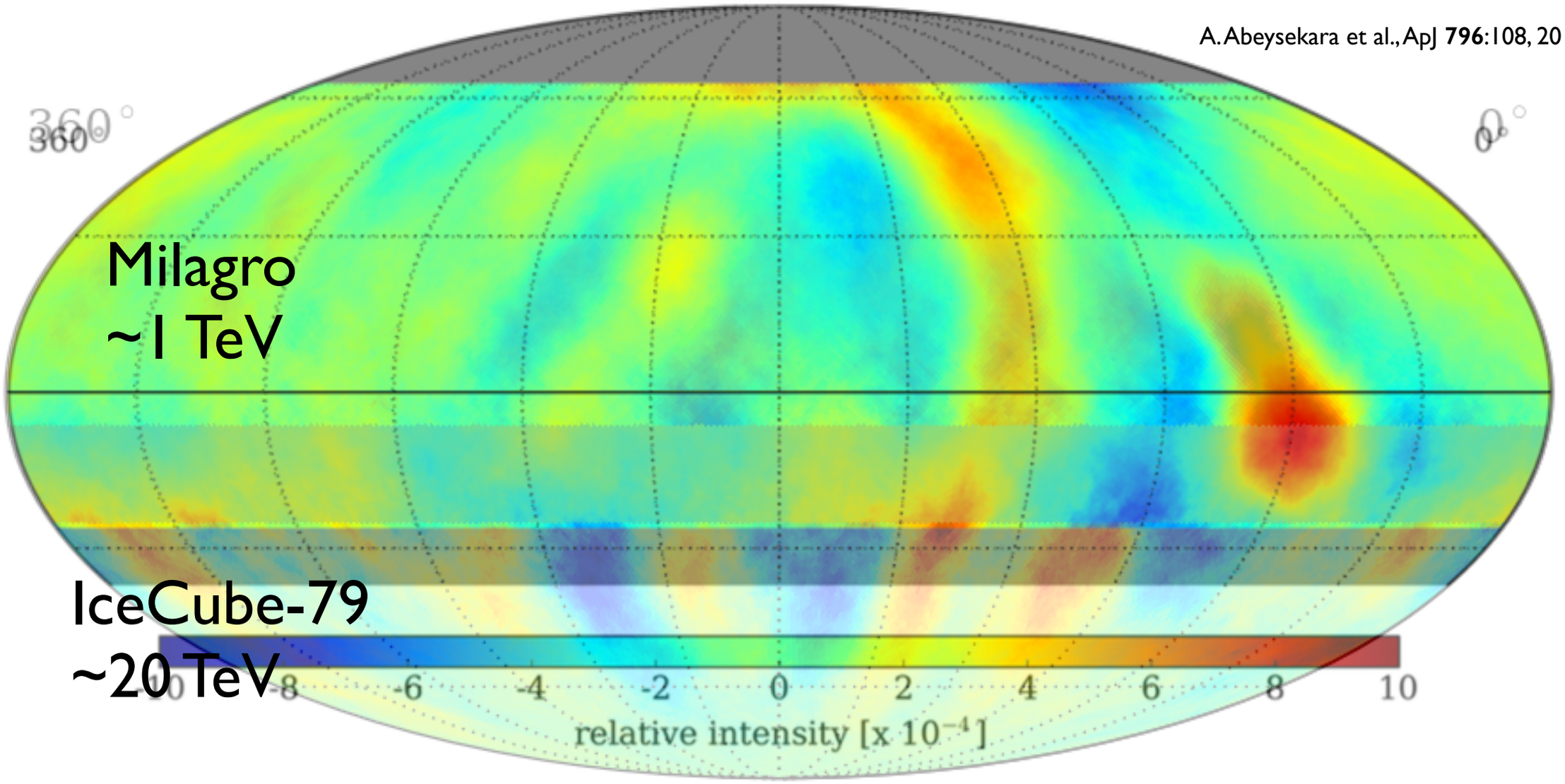

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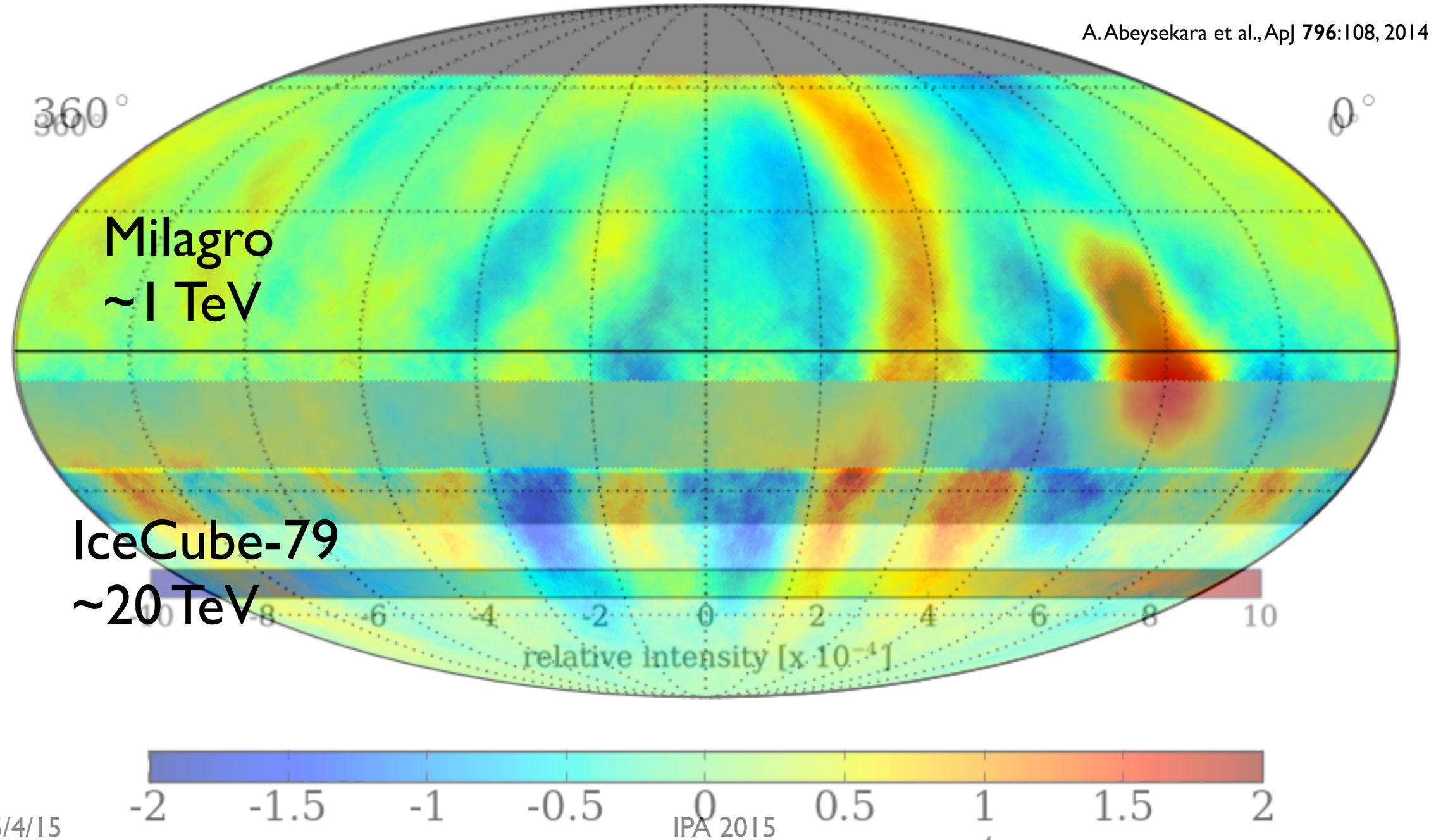

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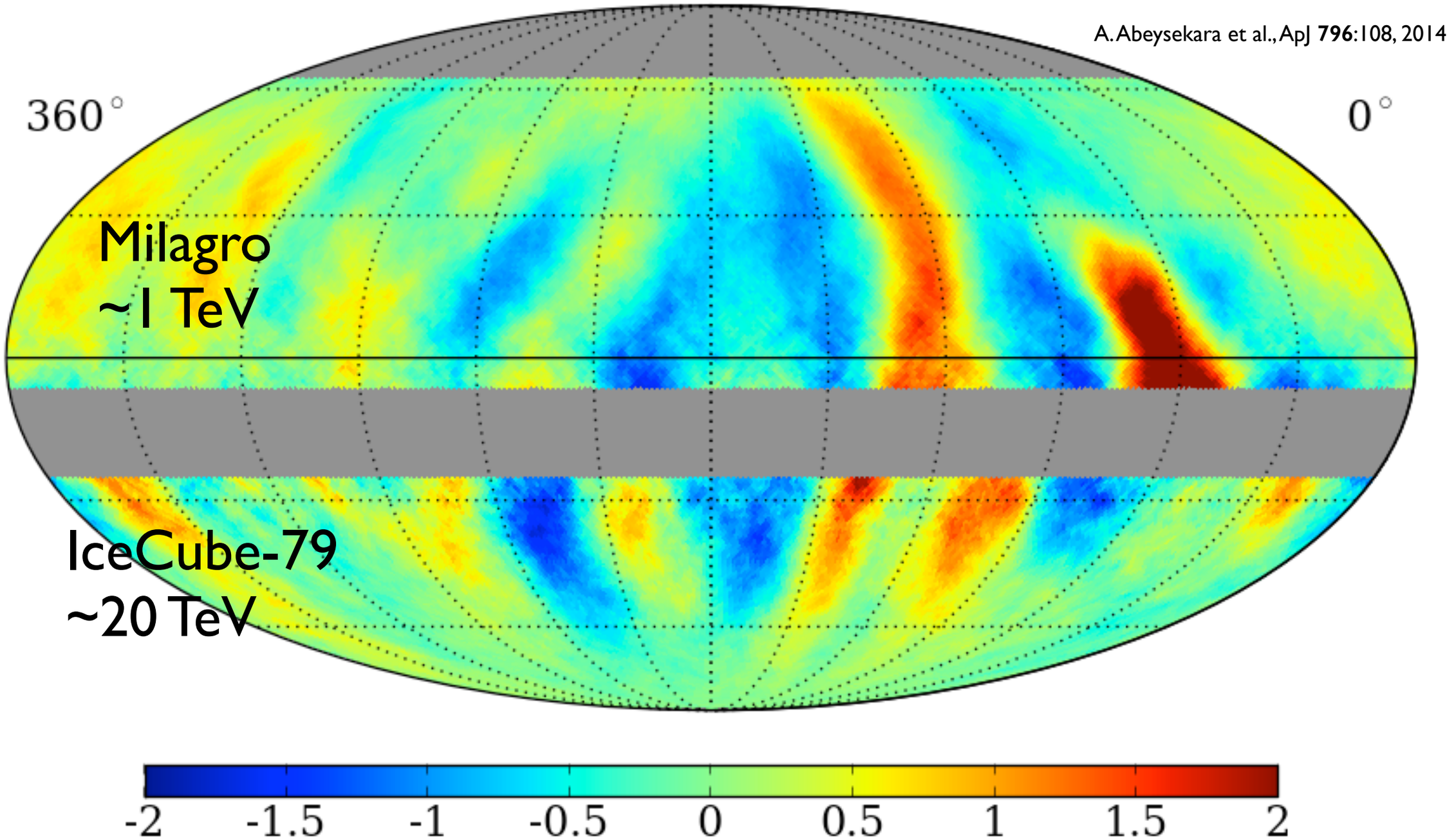

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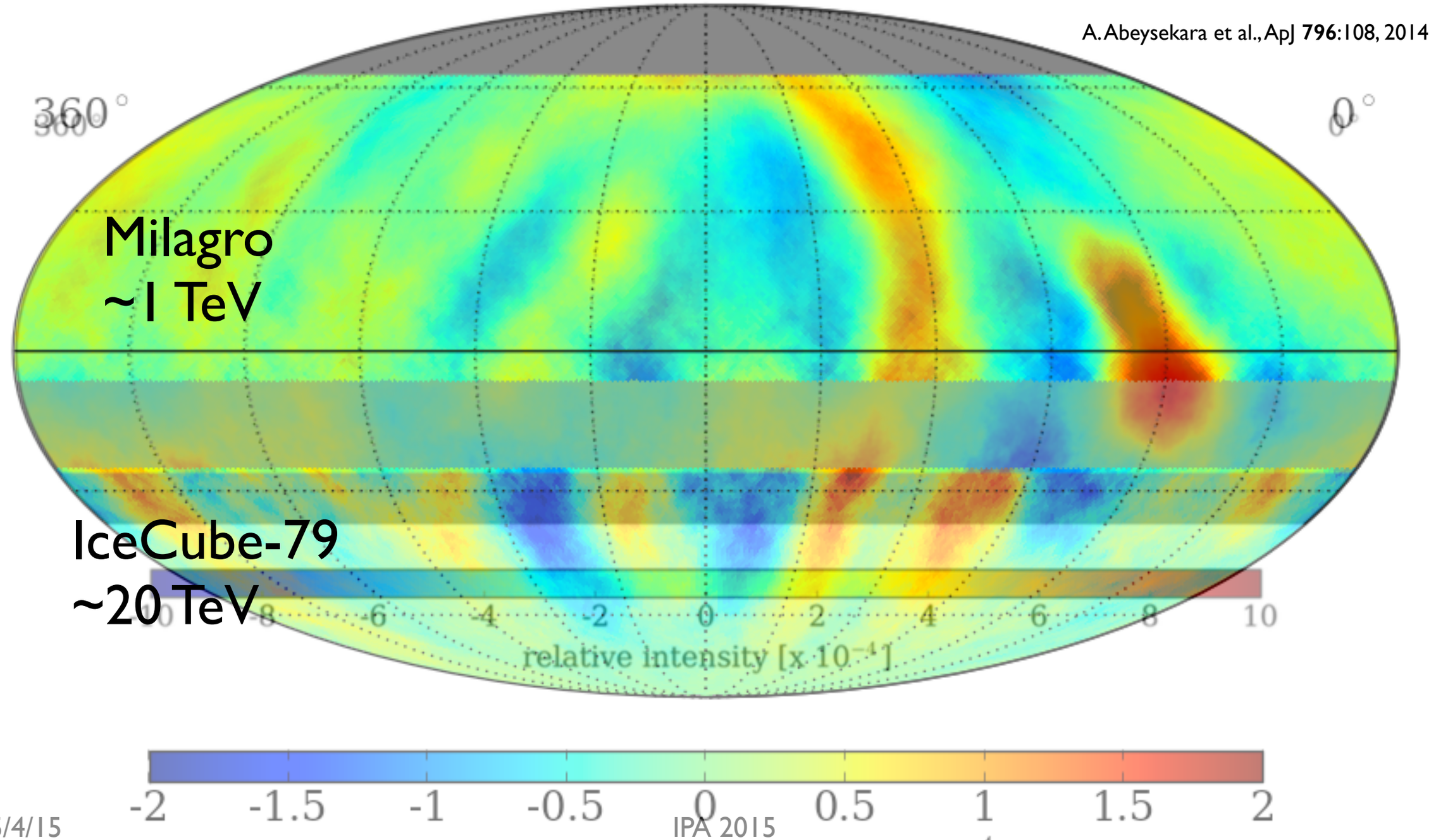

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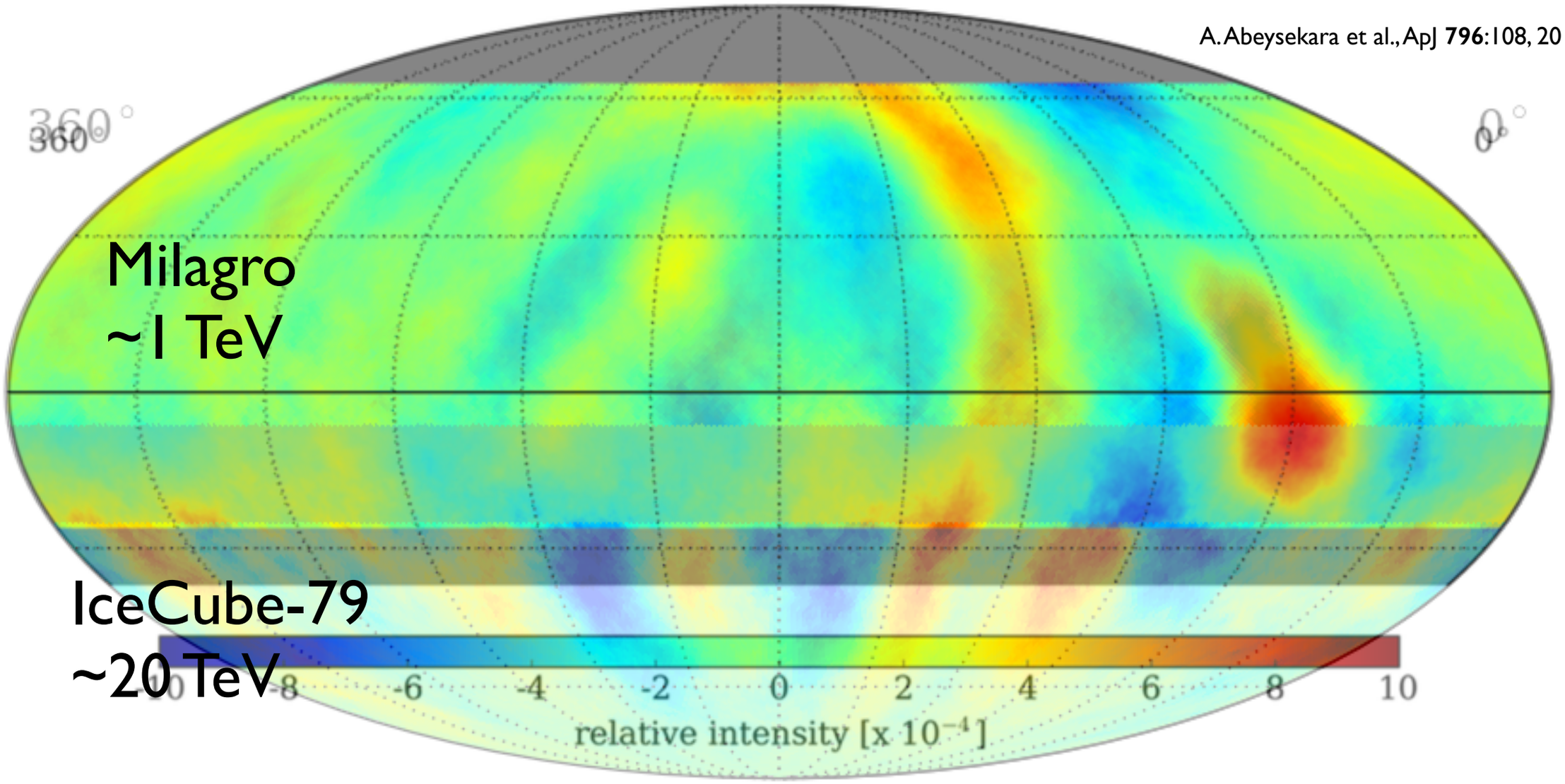

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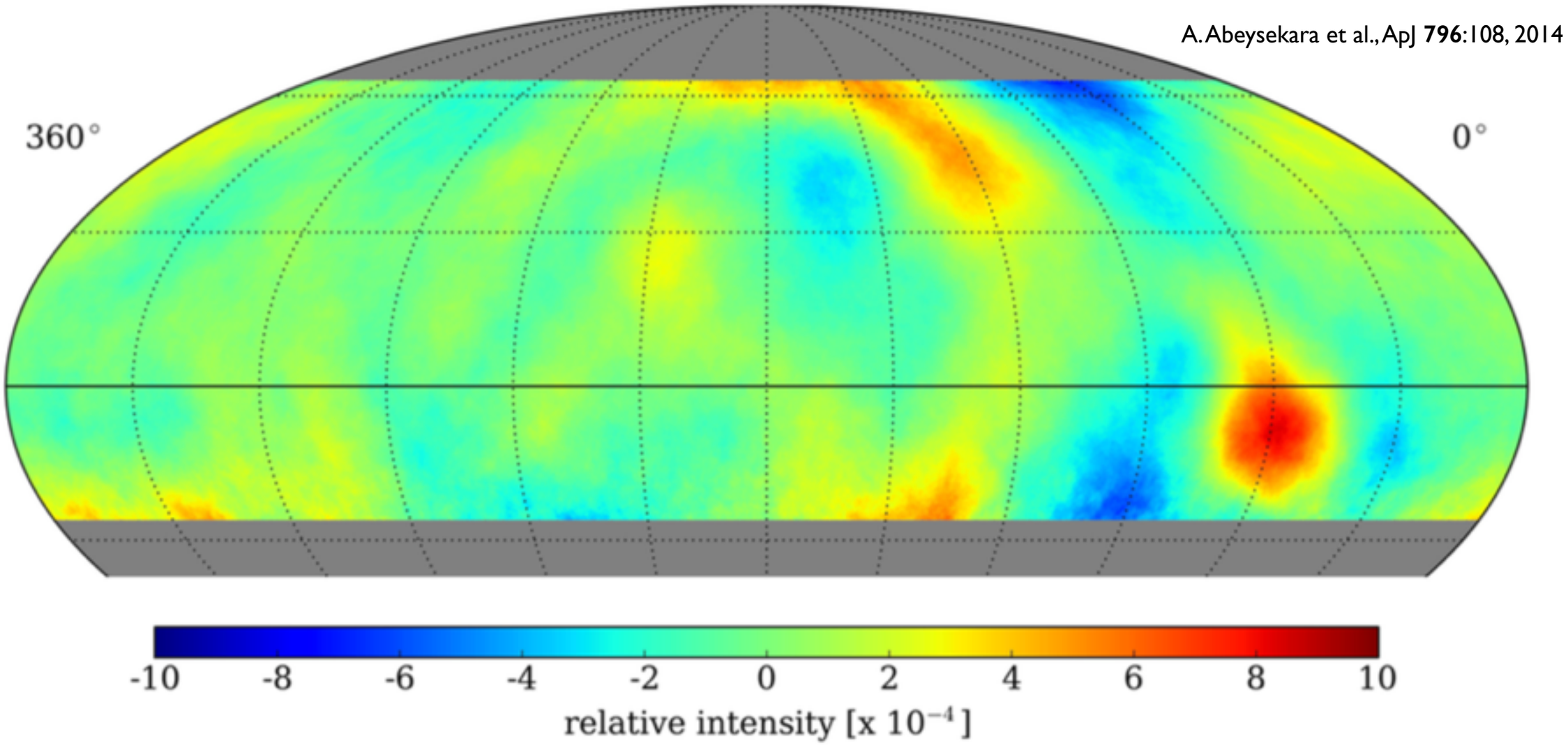
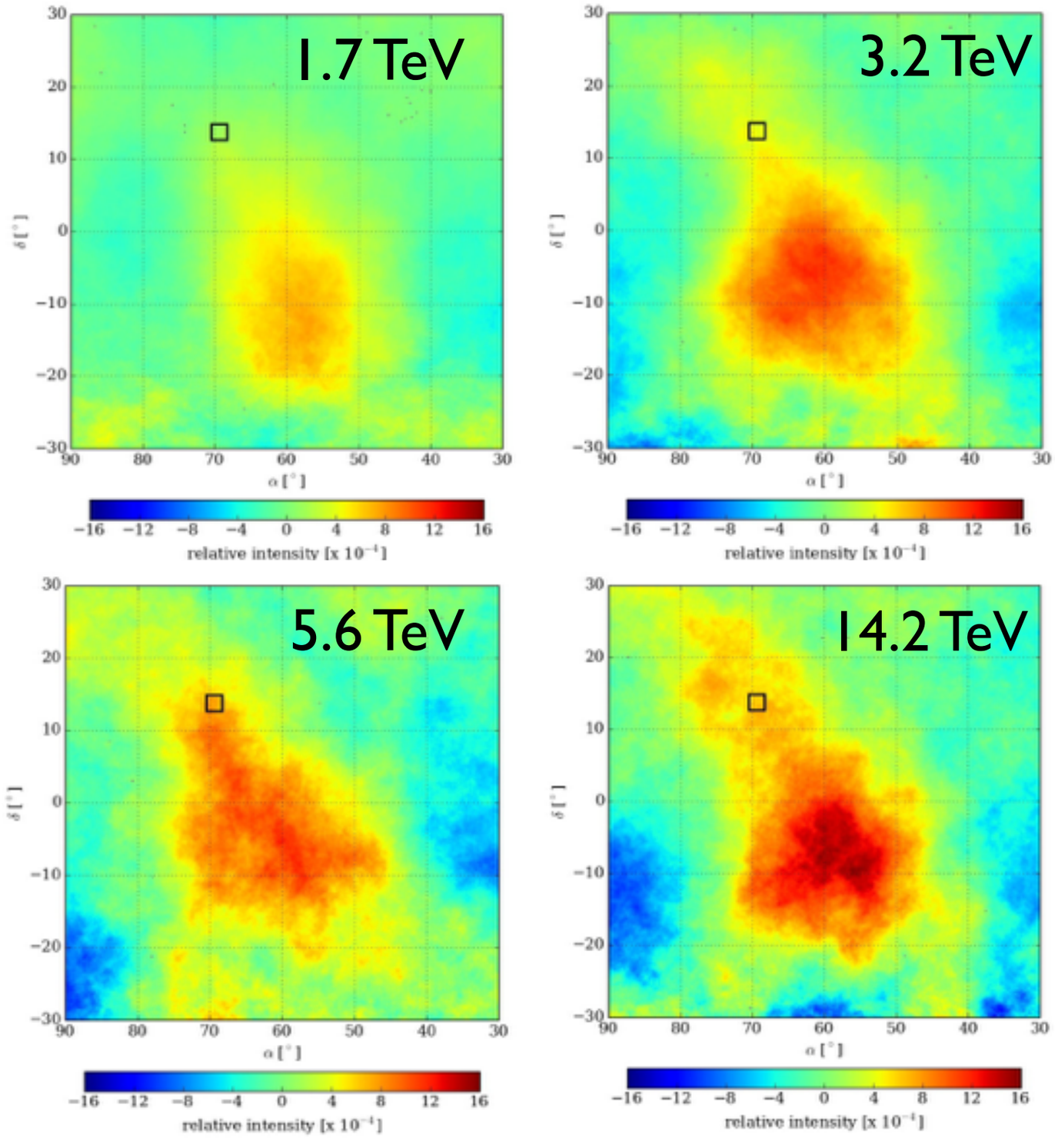


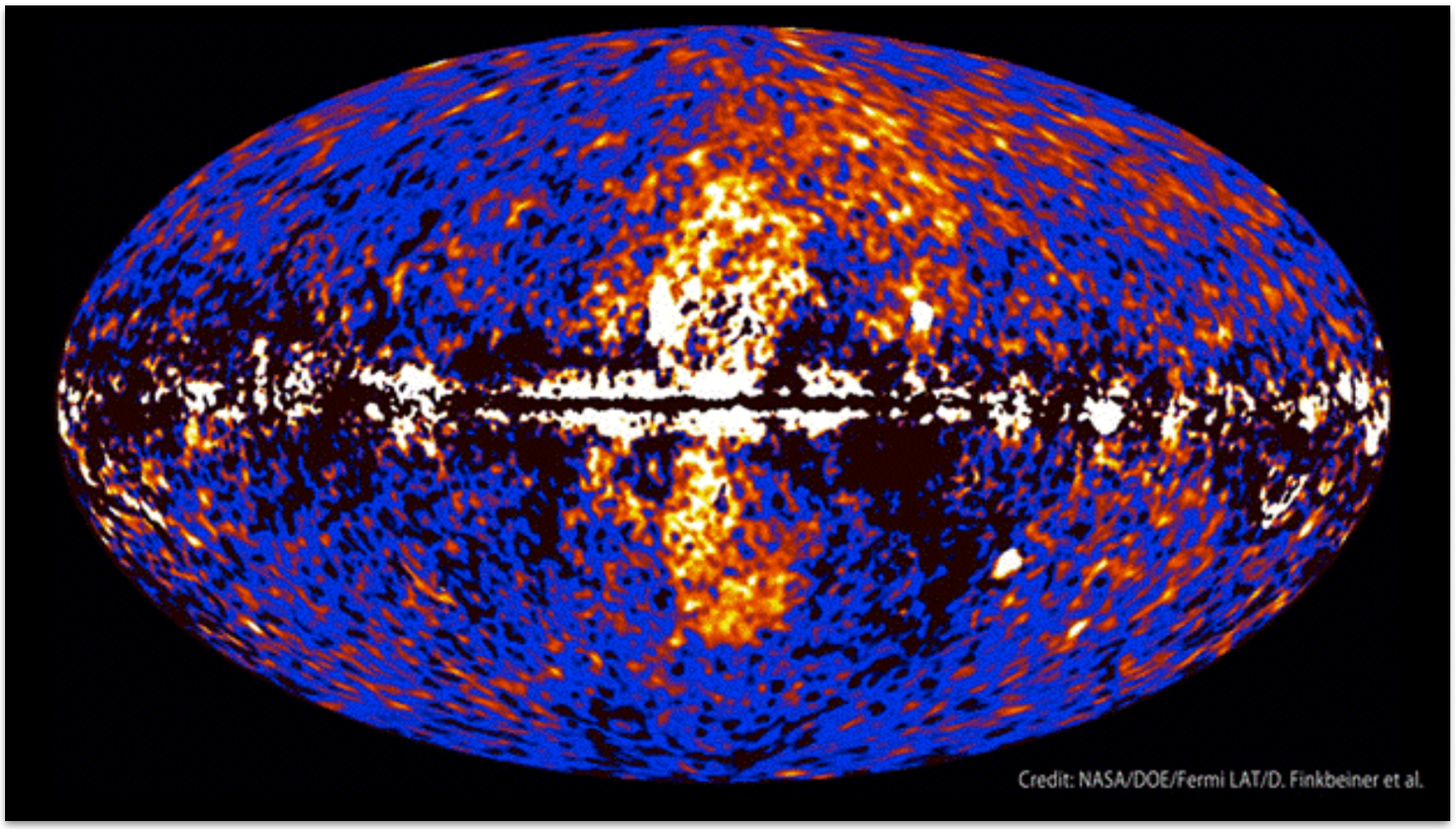
Energy Dependence

- 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

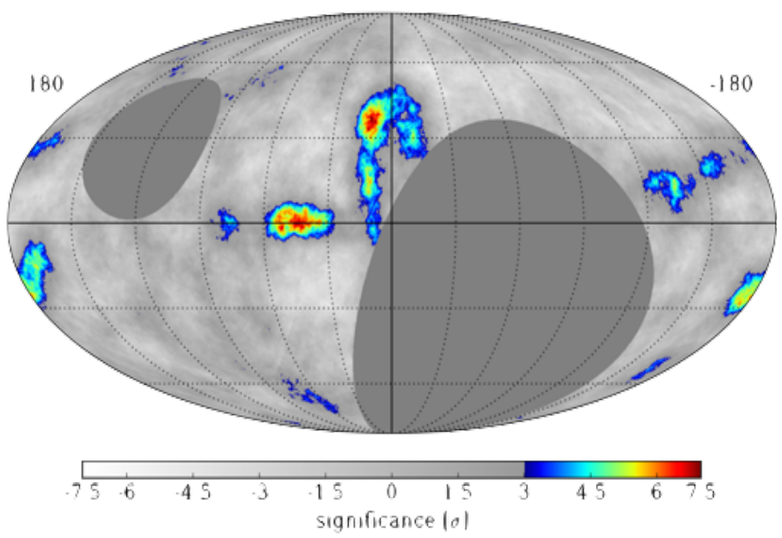


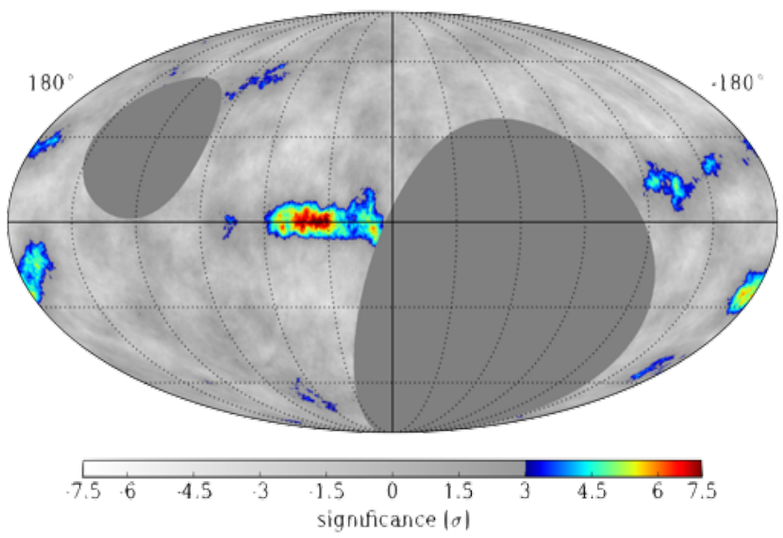
Diffuse Emission

- 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



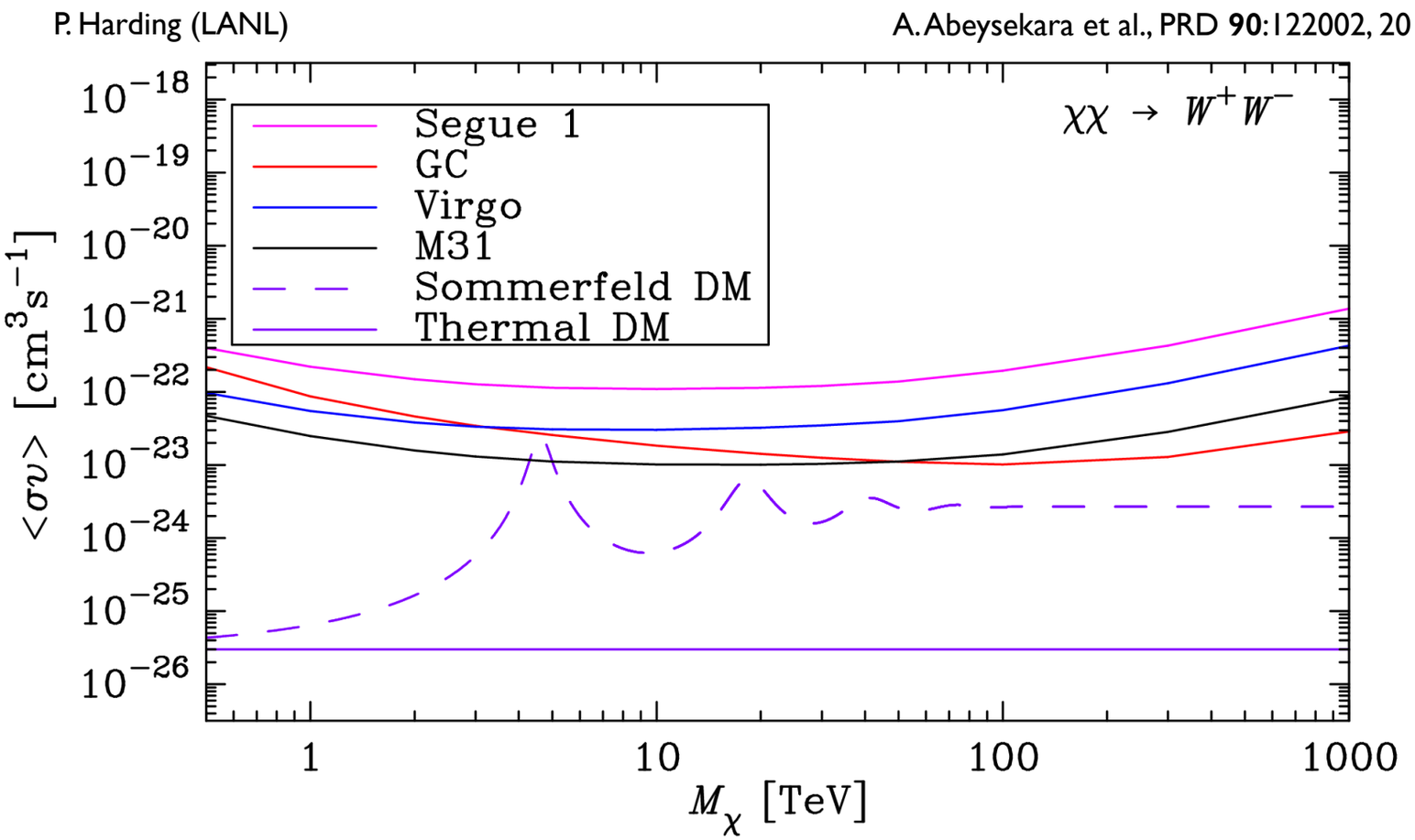
H. Ayala Solares (MTU), ICRC 2013





Beyond the Standard Model

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



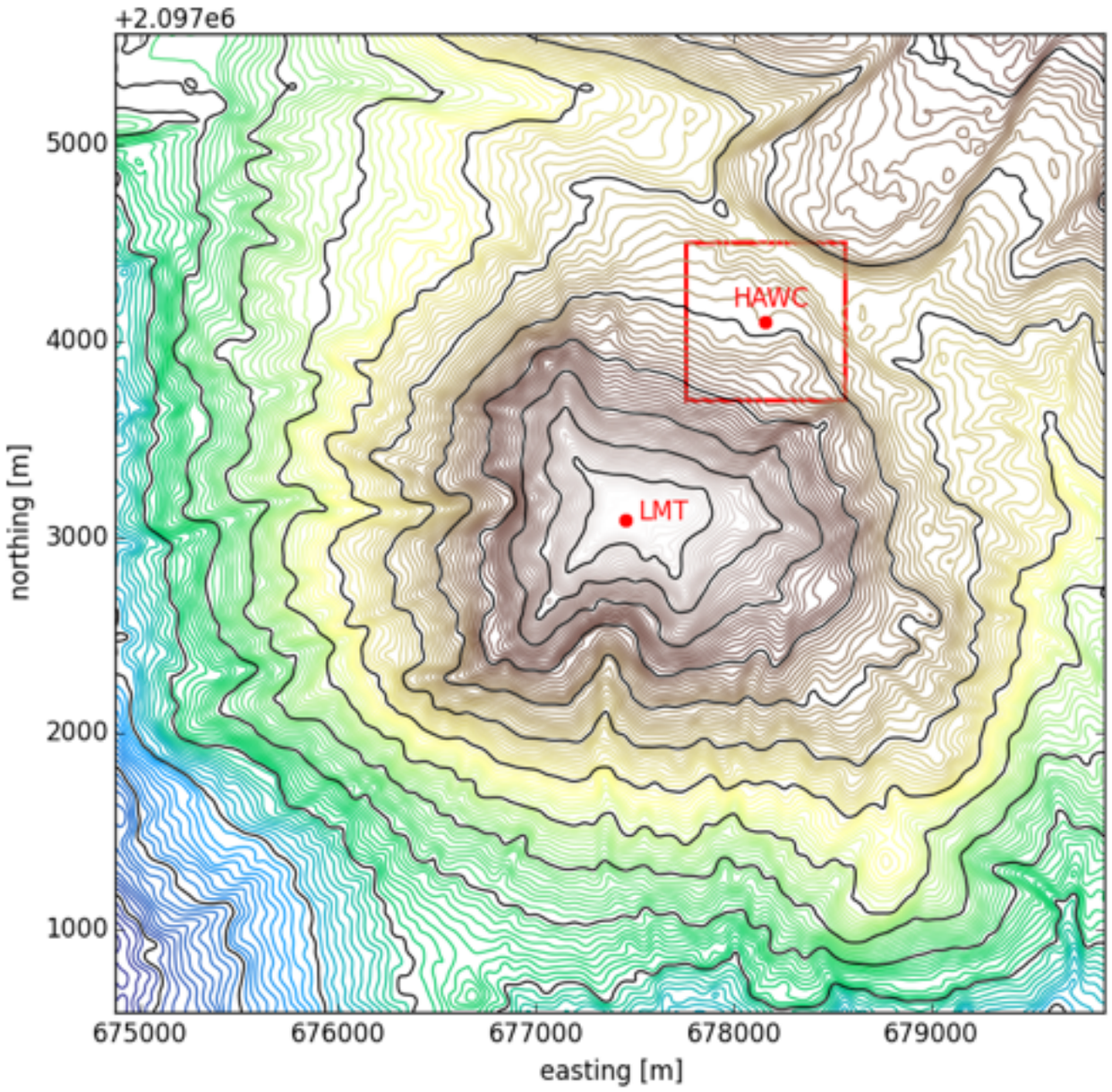
- Cosmological simulations: too few satellites observed
- HAWC: observations of high *M/L* satellites, even when *L*=0

Next 5 Years…

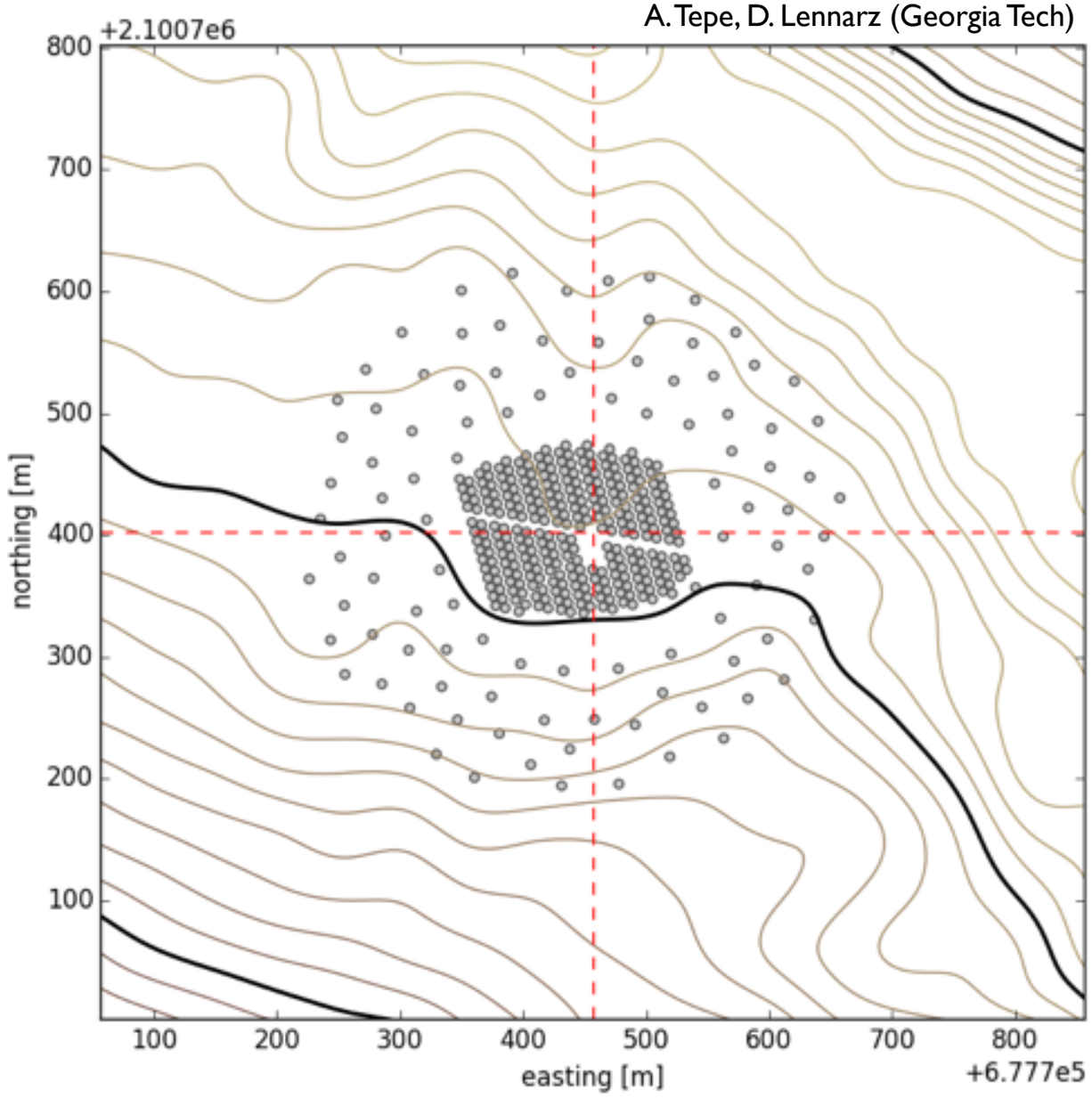
- One year of HAWC-300:
  - Unbiased measurements of AGN; observations of significant flares
  - Extended galactic sources (e.g., Cygnus region)
- Years 2-3 of HAWC-300:
  - Diffuse Galactic emission at TeV. Fermi bubbles if no spectral cutoff
  - Galactic and extragalactic transients (binaries, GRBs)
  - 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