Research Overview Seminar

TeV Gamma Rays

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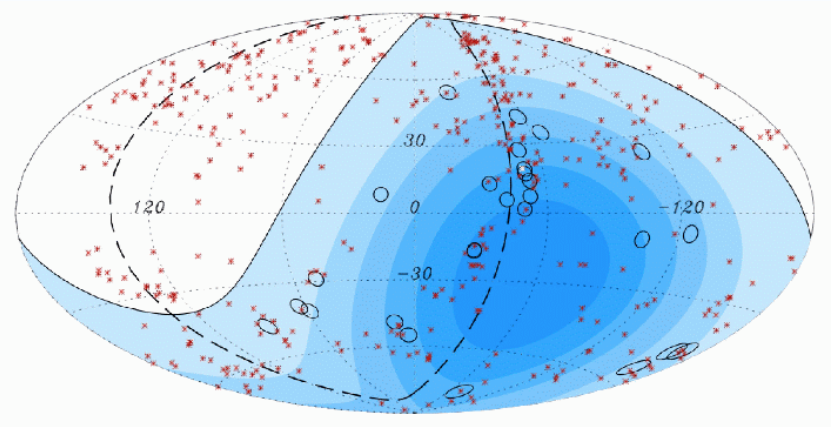
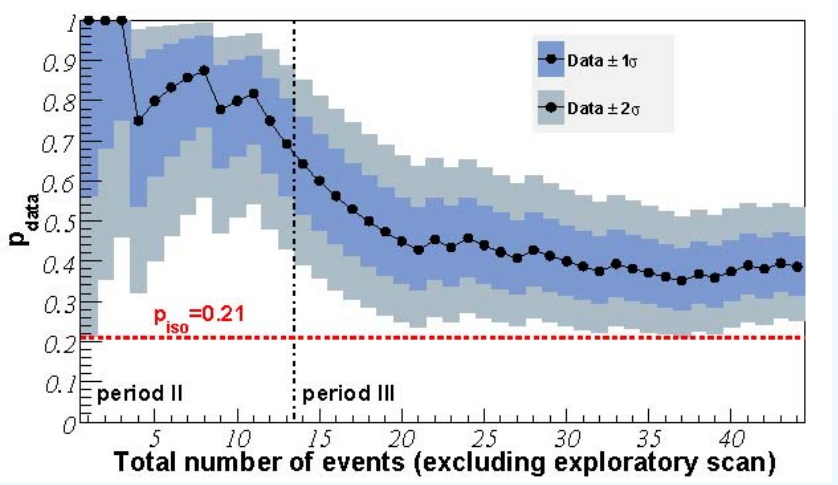
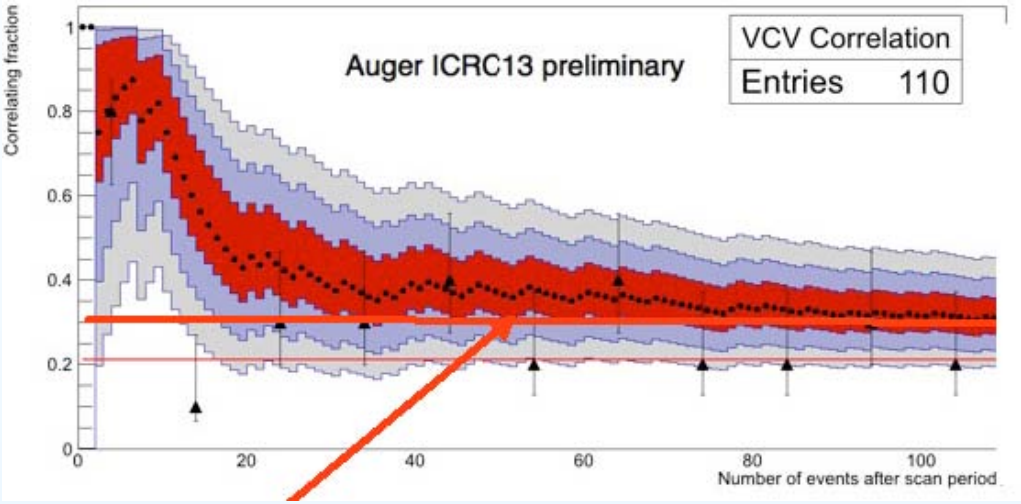
Several years ago ... in a country far away

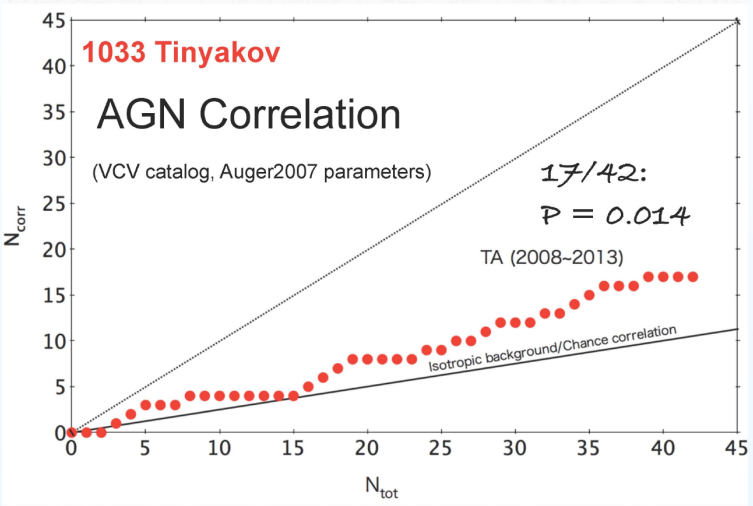




- We built the Pierre Auger Observatory (in Argentina) to study the highest energy cosmic rays (CRs):
  1. Is there a cutoff in the spectrum of the highest energy cosmic rays *... as expected from the interaction of CR protons with the cosmic microwave radiation*?
  2. And if there is a cutoff the highest energy CRs should have nearby sources ...
  3. And if magnetic deflections are not too large we might detect the sources ...
  4. And we *sort of* did!

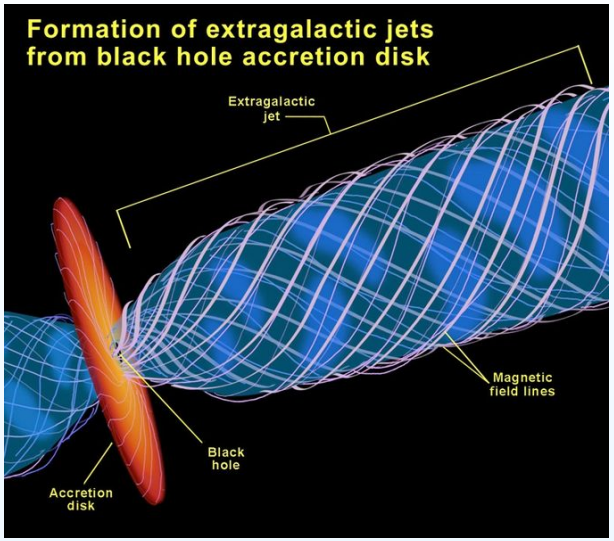
Today ... in a country far away





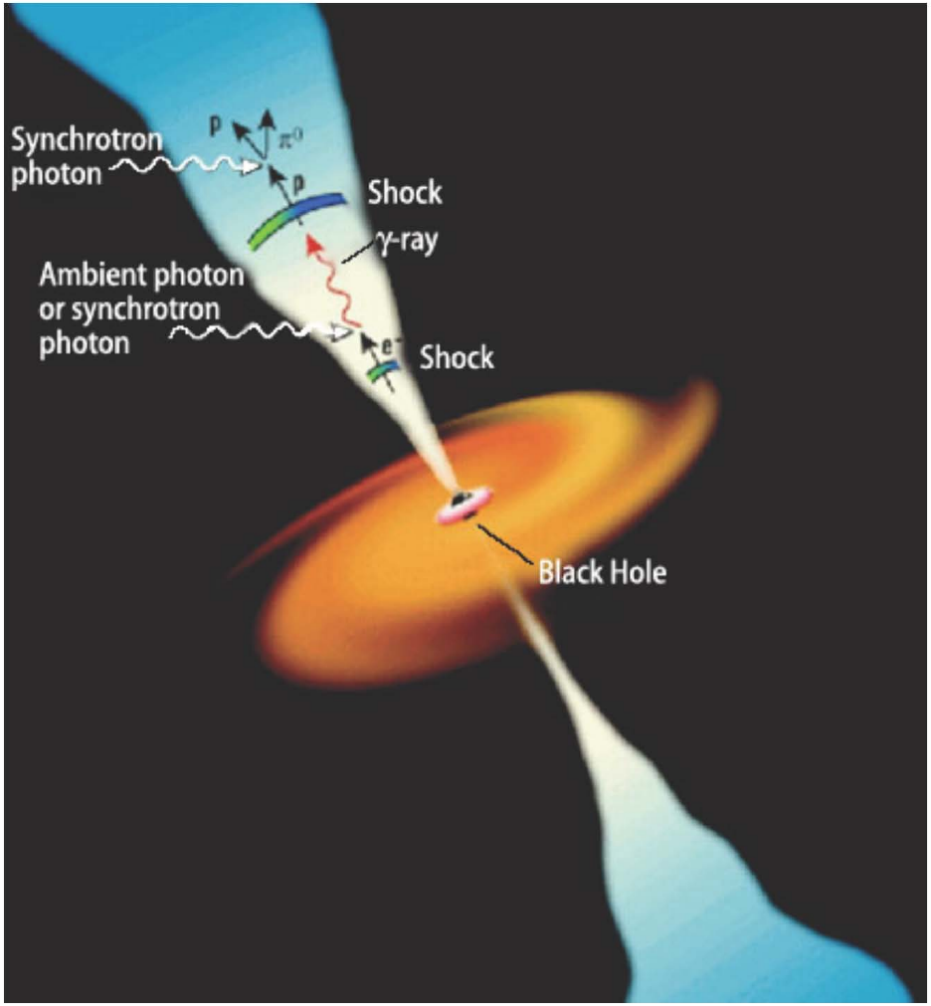
- (Left:) And while the initial magnitude of the CR:AGN correlation was over-estimated 5 years later are we observing a weak but stable signal?
- (Right:) And the Telescope Array experiment may also be observing a weak but non-zero signal!
- So maybe the AGNs are a (the?) source of the highest energy cosmic rays ...
- And if AGNs are the sources, how do they do it?

And while there are many models ...



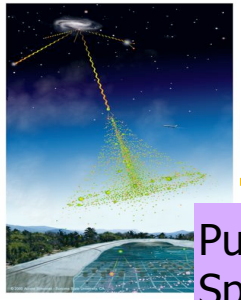
- *e.g.* extreme astrophysical sources: super-massive black holes/quasars/AGNs, GRBs, colliding galaxies, ...
- only experimental measurements will provide the clues to solve this puzzle

Many extreme sources are now known ...



What physics in *e.g.* astro-physical jets could result in γ-rays to energies of 10^{15}eV or possibly cosmic rays to energies of 10^{20}eV?

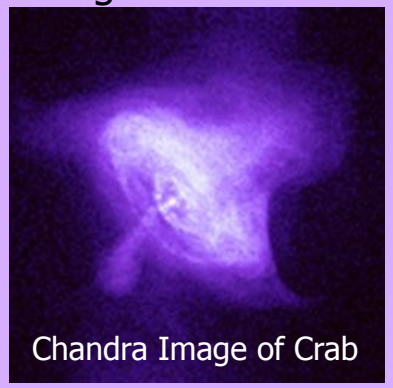
- Use light to make observations over the largest range of energies including: *radio, IR, visible, UV, X-ray and γ-rays*
- In addition use neutrino and cosmic ray telescopes ...



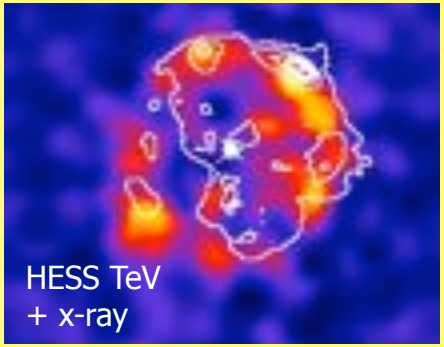
Nature's Particle Accelerators

Galactic

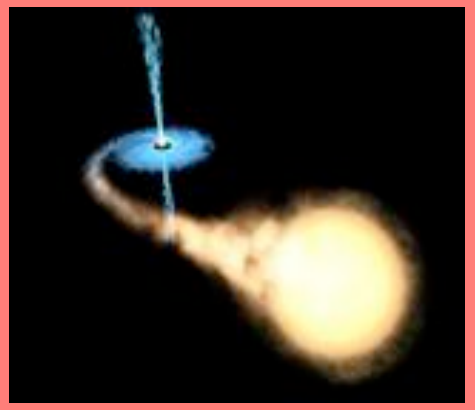
Pulsar Wind Nebula:
Spinning Neutron Star
powering *a* relativistic wind



Supernova
Remnant

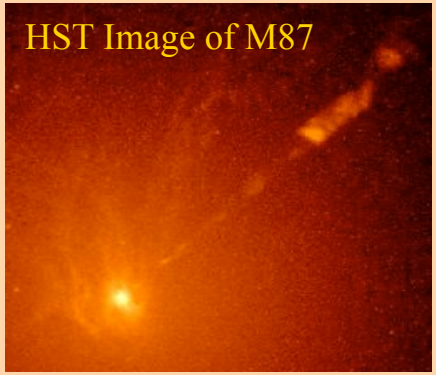


X-ray Binaries/
Microquasars

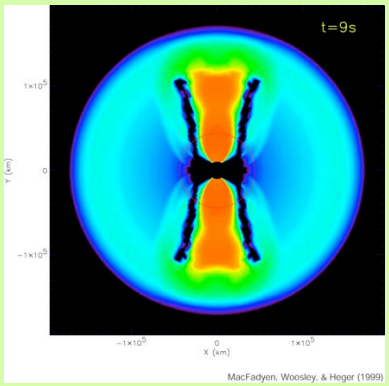


ExtraGalactic

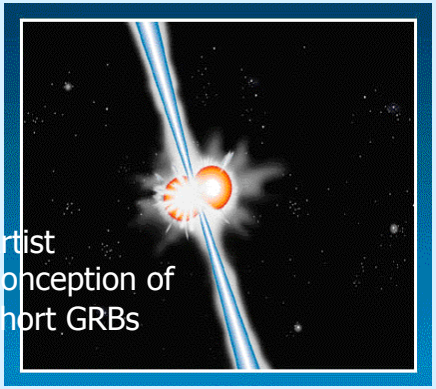
Active Galactic Nuclei:
Black Hole producing
relativistic jet of particles



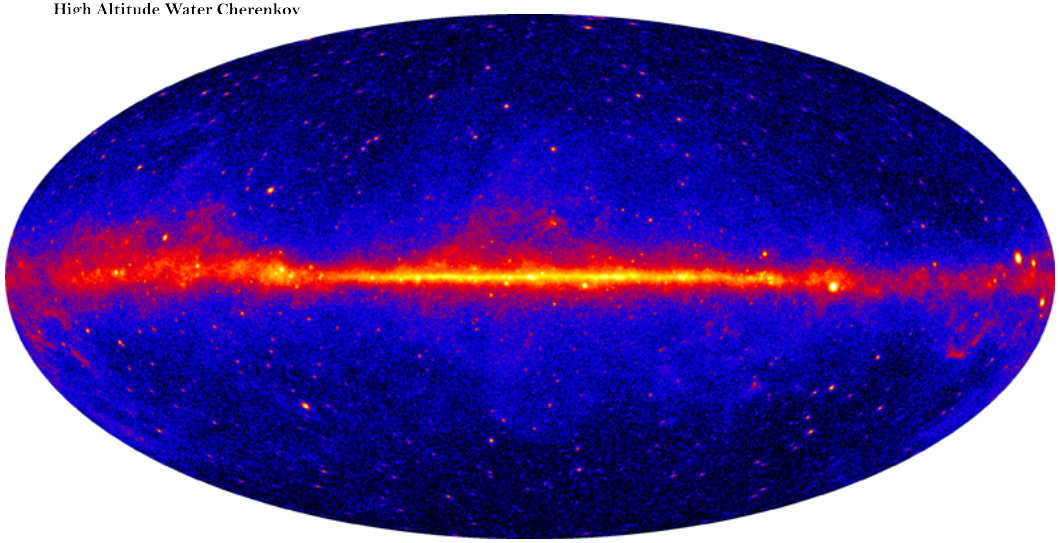
Long Gamma-Ray Burst:
Massive Star Collapsing
into a Black Hole



Short Gamma-Ray Burst:
Binary Neutron Star
Coalescing



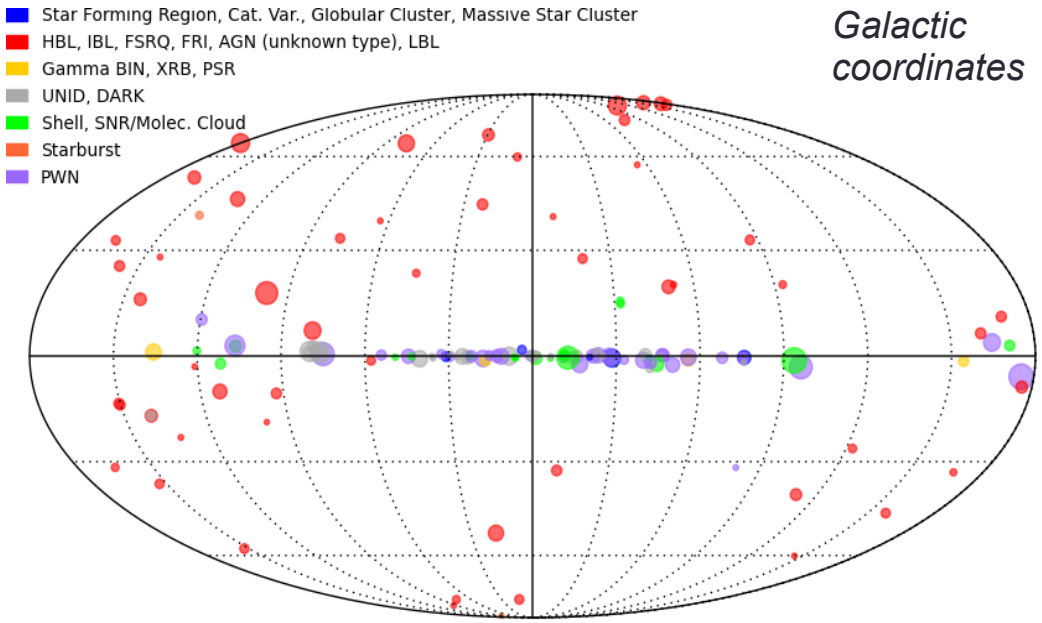
The GeV-TeV Sky



NASA's Fermi Gamma Ray Telescope

- Fermi-LAT 2-year all-sky survey at energies > 1GeV.
- ~2000 gamma-ray sources.

arXiv:1108.1435 (ApJ Supp.)



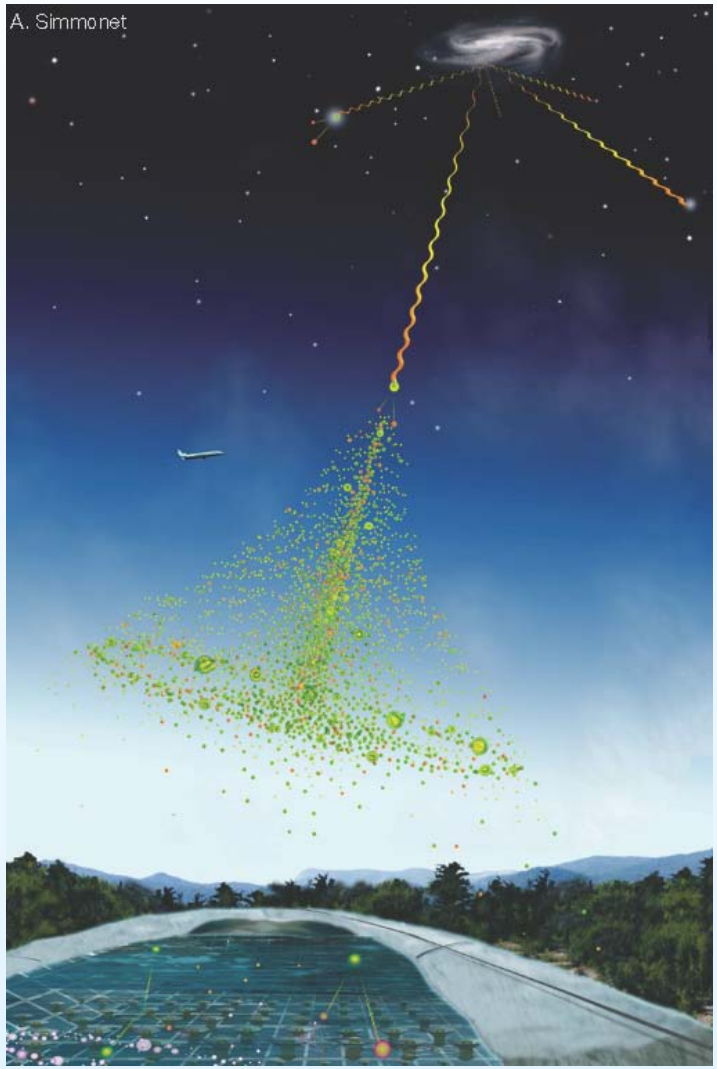
Galactic coordinates

TeV Catalog

- ~140 sources (~90 Galactic).
- Not an all-sky survey - catalog is strongly biased.

http://tevcat.uchicago.edu

γ-rays are the most recent frontier ...



Initial *sky surveys* must now move on to detailed measurements ...

- γ-ray directions must now be measured to an angular precision of $\lesssim 0.2^\circ$
- full duty cycle observing is critical to monitoring *short term variability*
- low particle flux (event rates) requires unconventional telescope(s) such as the new HAWC observatory in the Pico de Orizaba National Park in Mexico.

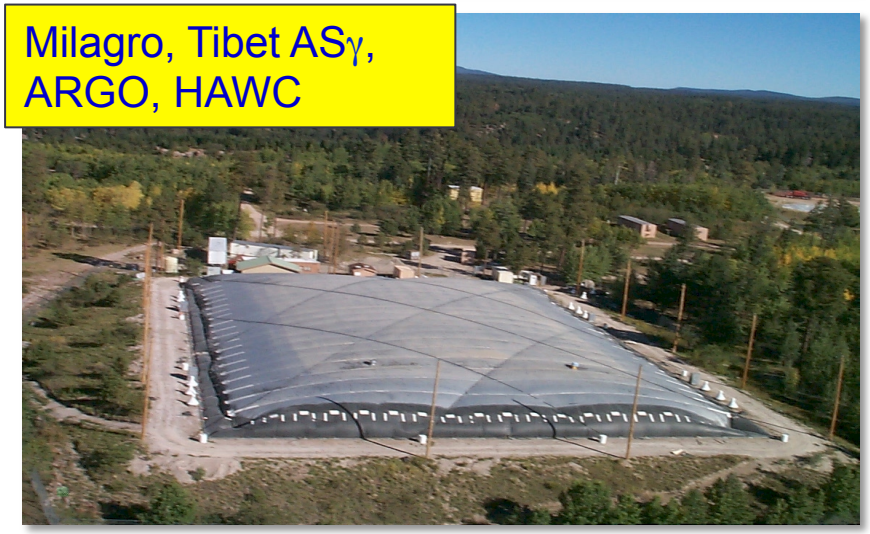
TeV Gamma-Ray Instruments

H.E.S.S., MAGIC, VERITAS, CTA

Air-Cherenkov Telescopes:

- Excellent sensitivity to point sources (1 Crab in ~minutes).
- Good angular resolution (~0.1°)
- Excellent background rejection.
- Limited duty cycle and field of view.

Milagro, Tibet ASγ, ARGO, HAWC



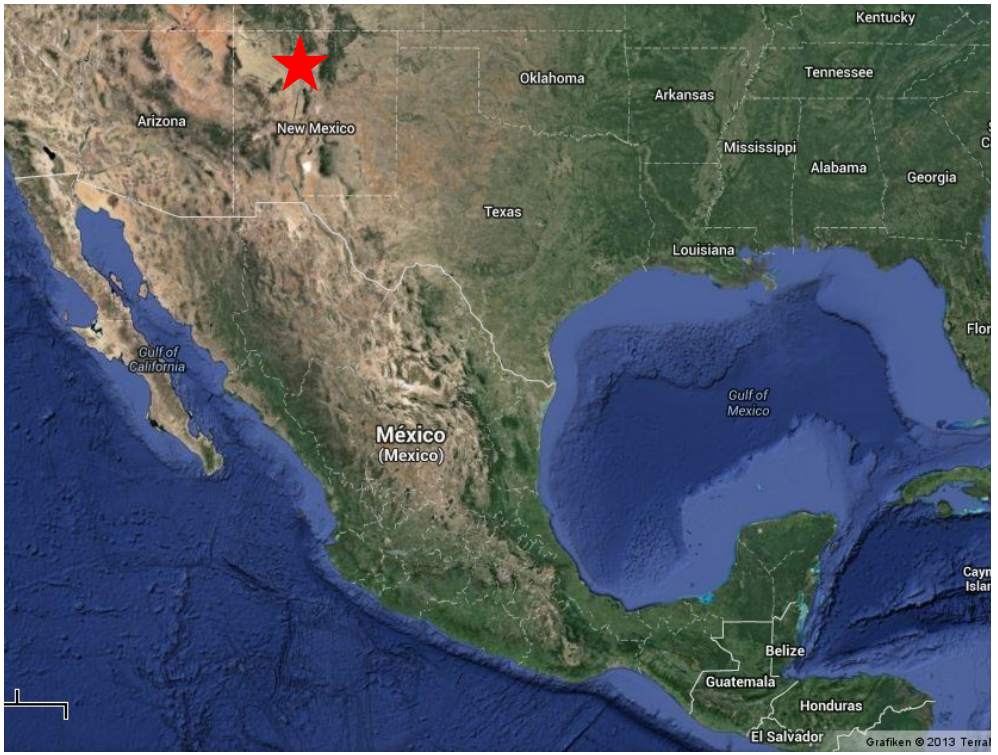
All-Sky Observatories:

- Large duty cycle (>95%), independent of weather and daylight.
- Large field-of-view (2 sr instantenous).
- Lower sensitivity to point sources.

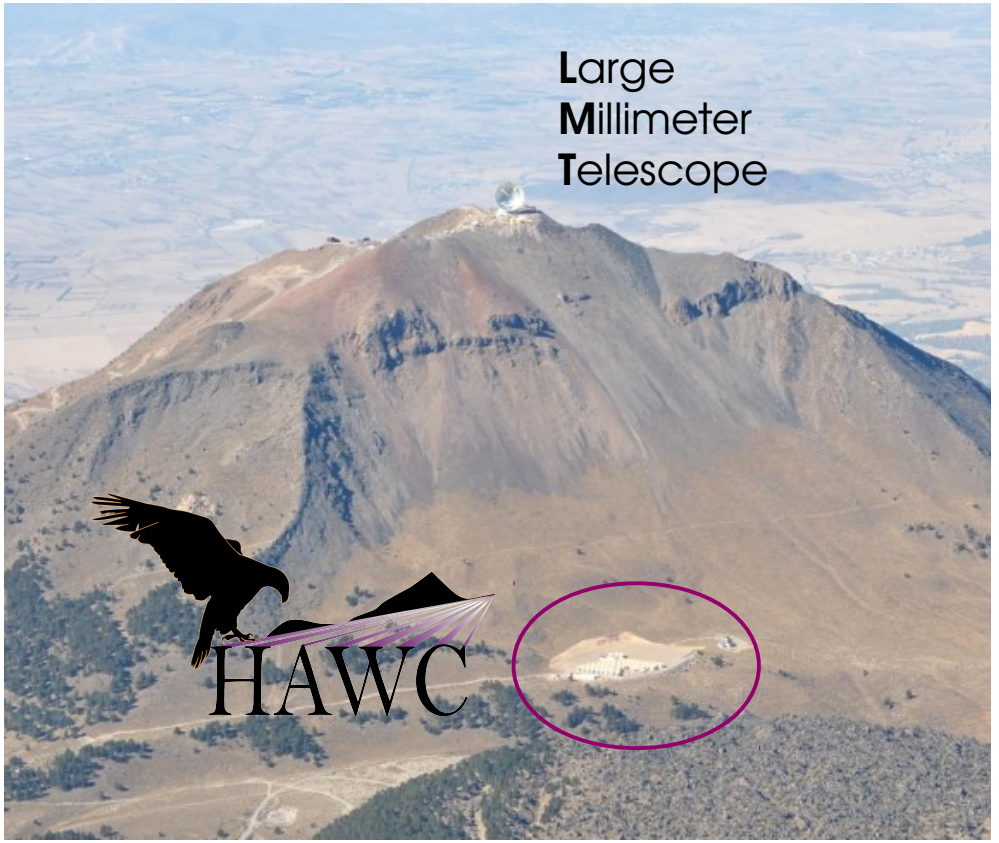
The two techniques are complementary.

1st Generation Water Cherenkov: Milagro

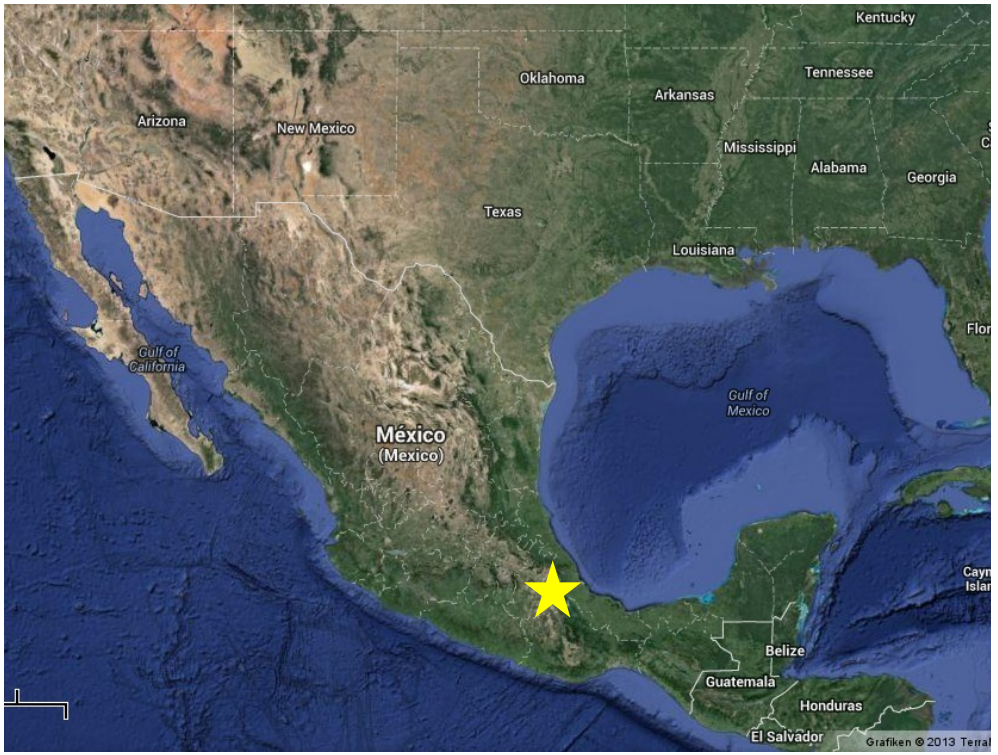
- Jemez Mountains, New Mexico
- 2350 m altitude
- operated between 2000 and 2008
- established gamma-ray water Cherenkov technique



2nd Generation Water Cherenkov: HAWC

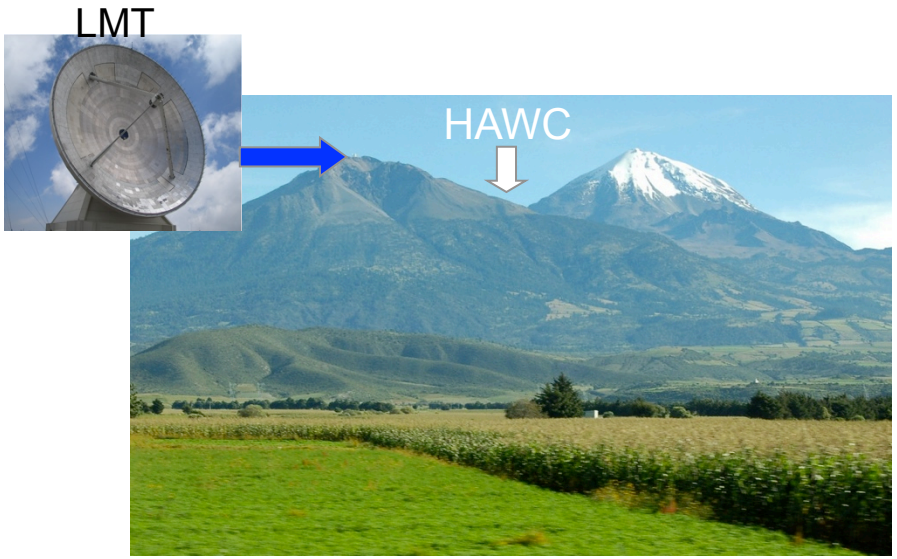


- Sierra Negra volcano near Puebla, Mexico
- High altitude site at 4100 m
- Temperate climate
- Existing infrastructure from LMT
- 17 radiation lengths of atm. Overburden (vs. 27 at sea level)



The HAWC Site

- Near ideal:
  - High elevation (4100m), but flat – Shoulder area between Mount Pico de Orizaba and Sierra Negra.
  - Just above tree line – not extreme climate.
  - Existing infrastructure from LMT.



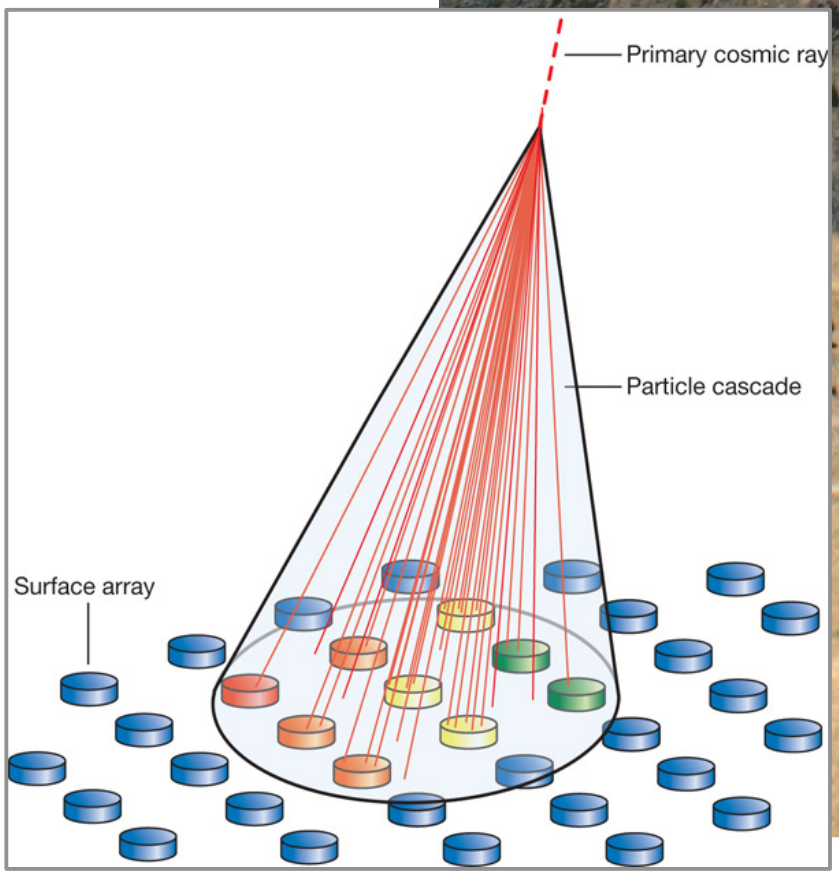
HAWC Observatory ...

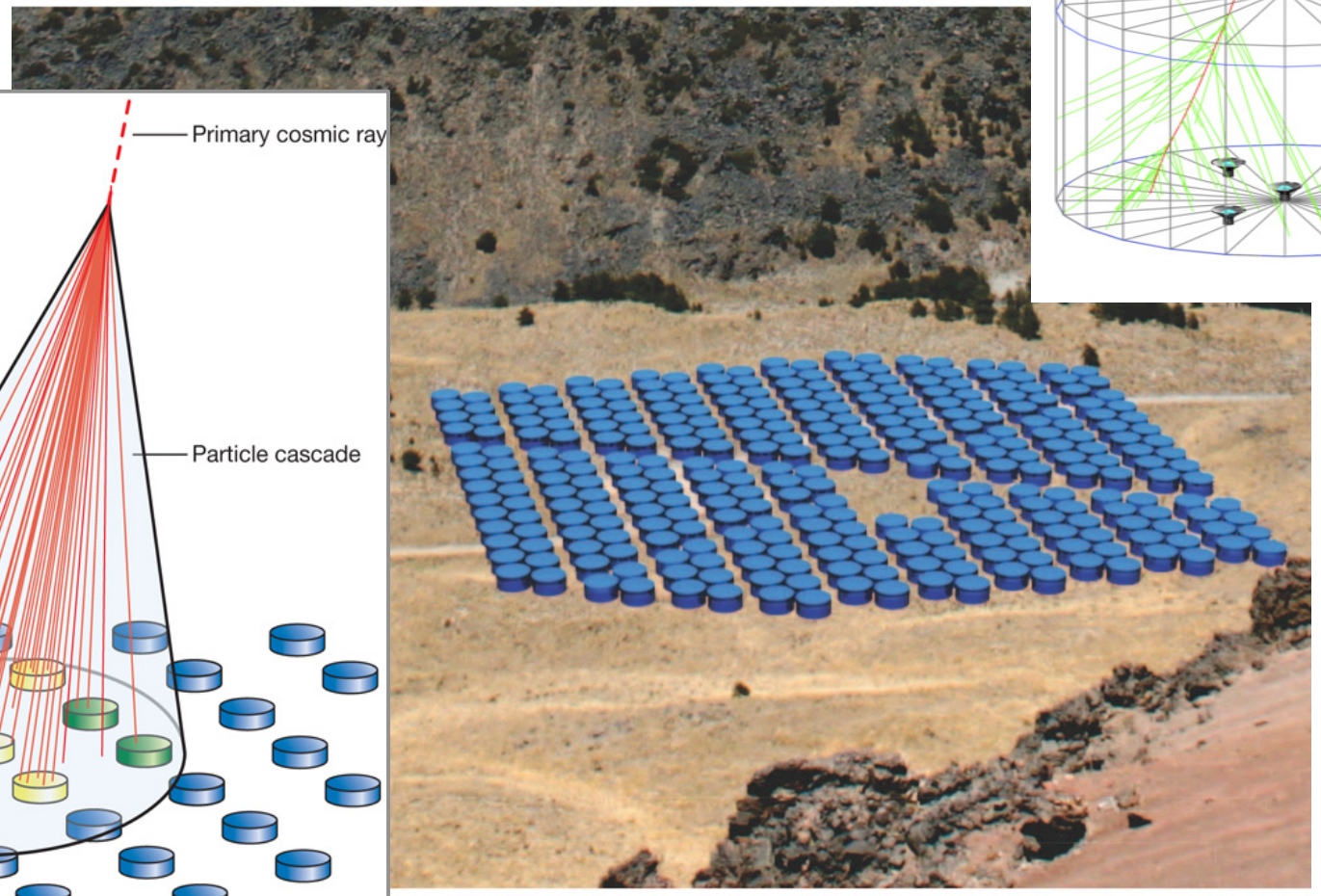
- 250 (of the final 300) water Cherenkov detectors (WCD) are installed
- instrumenting all the WCDs and filling with water is continuing
- as the detector is modular we are taking data using ~ 150 WCDs

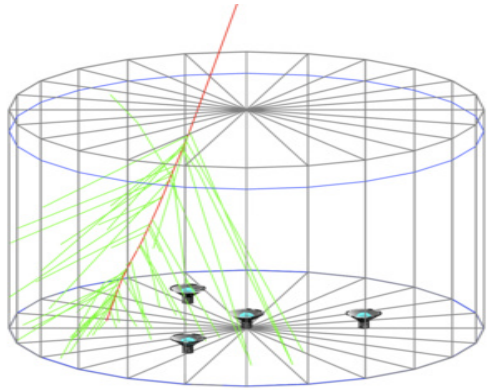
HAWC

How Does HAWC Work?

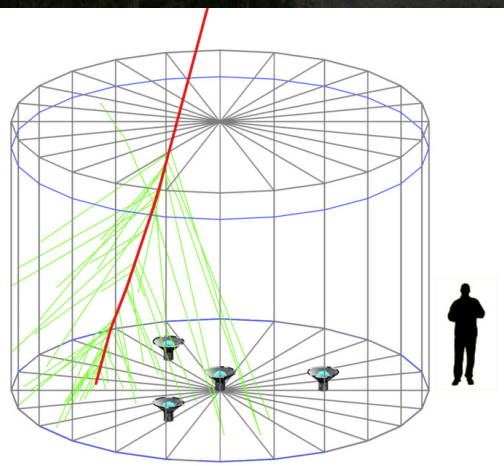
- Close-packed array of water-Cherenkov detectors, 20000 m^2



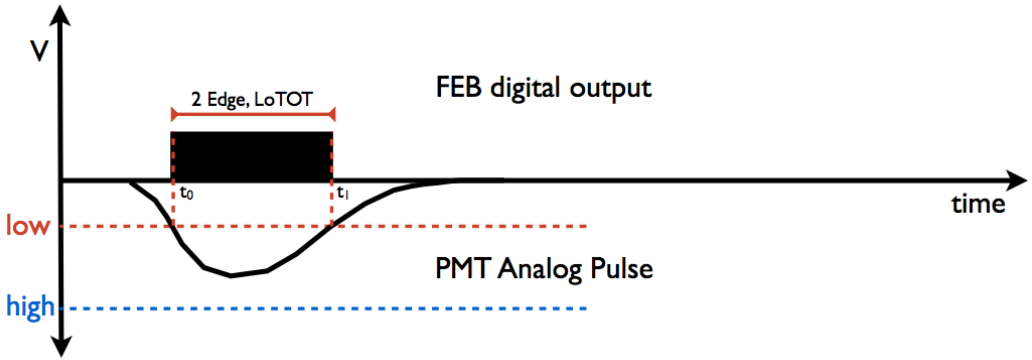




HAWC Data — Air Showers

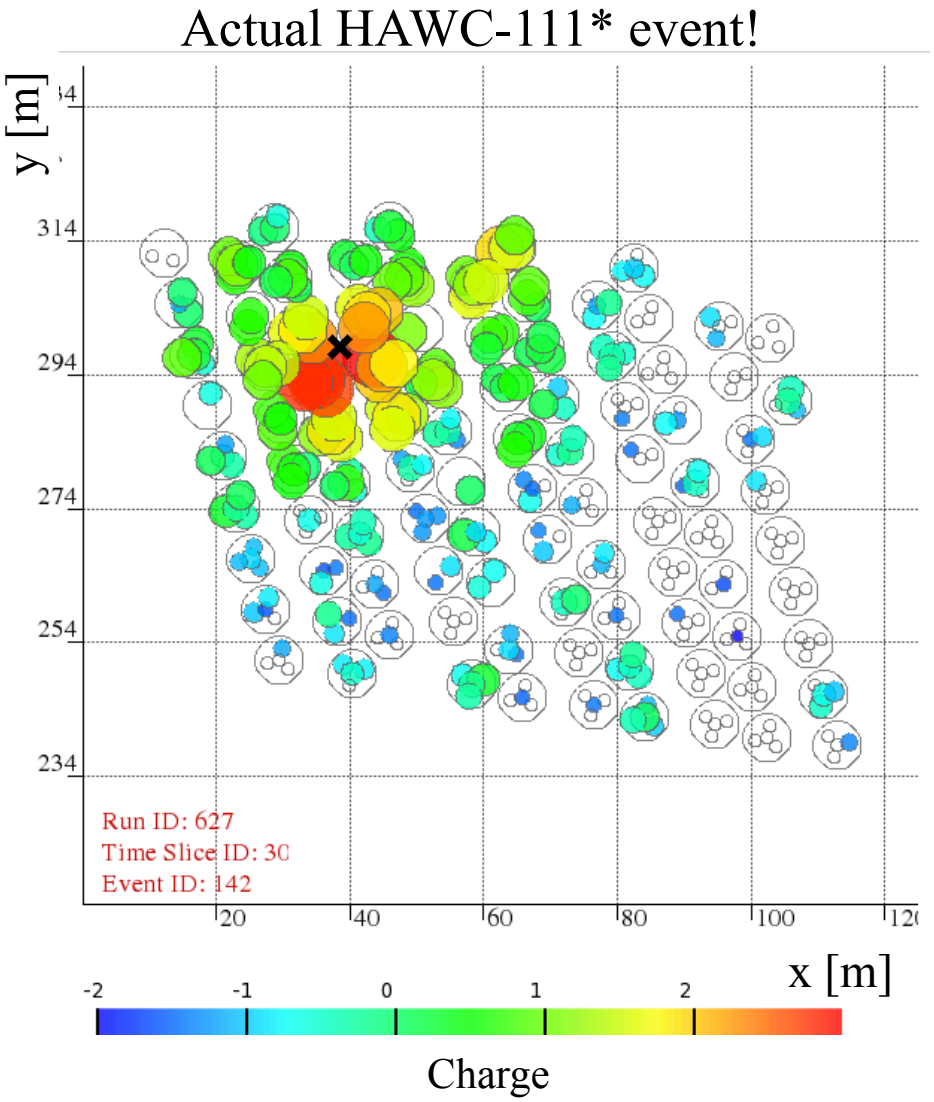


- **Triggered main DAQ**
  - Detects individual gamma ray air showers
  - Measures the arrival time and charge of PMT pulses



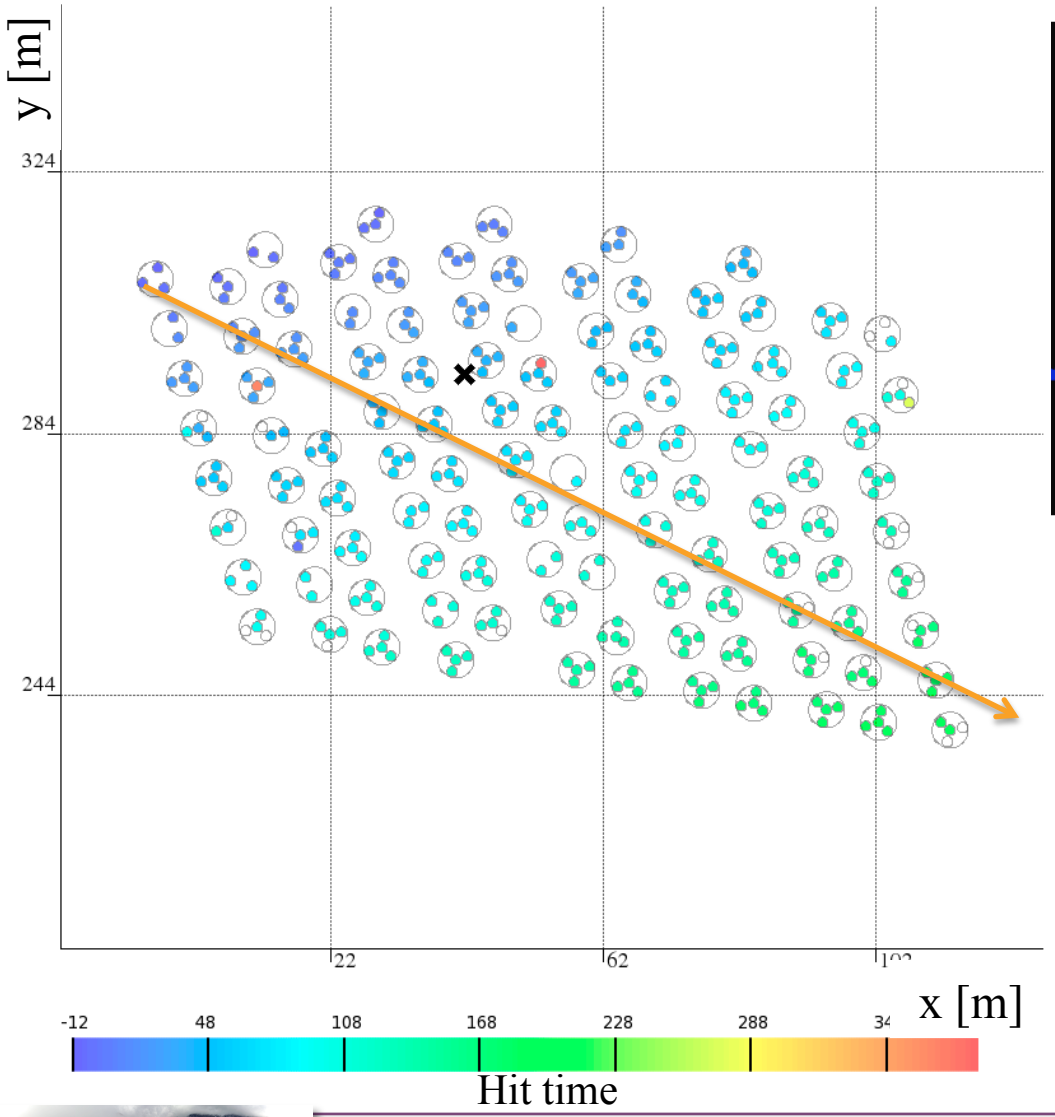
Air Shower Reconstuction

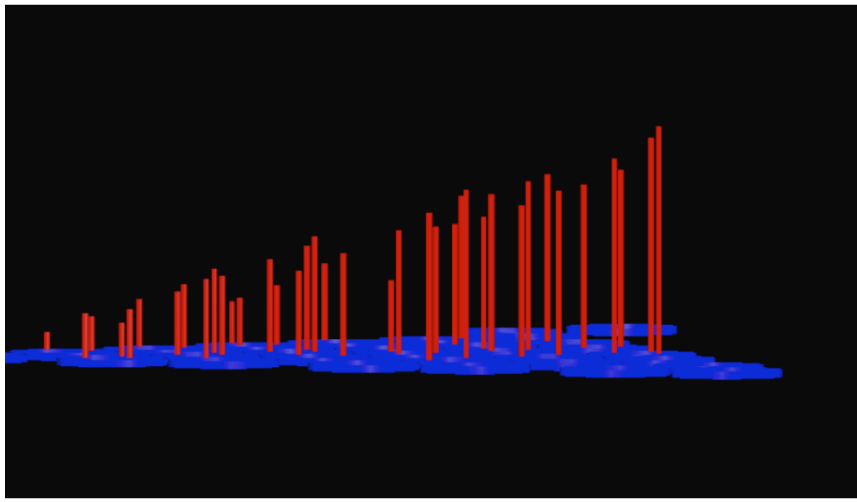
- Shower core location
  - Fit Gaussian to charge distribution



*HAWC with 111 tanks

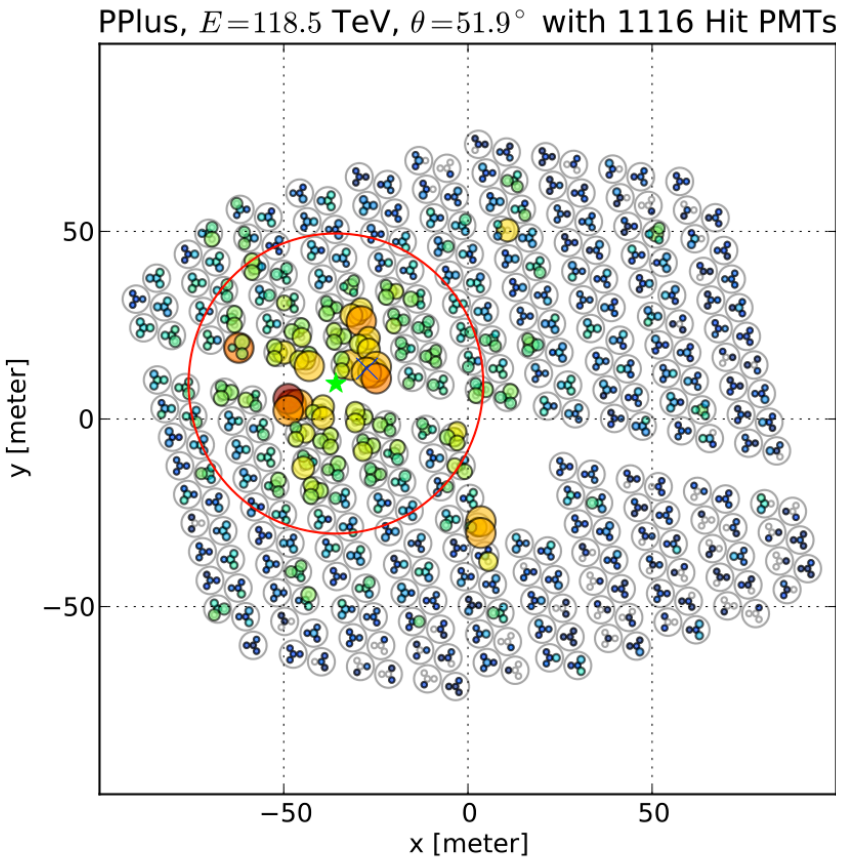
Air Shower Reconstuction

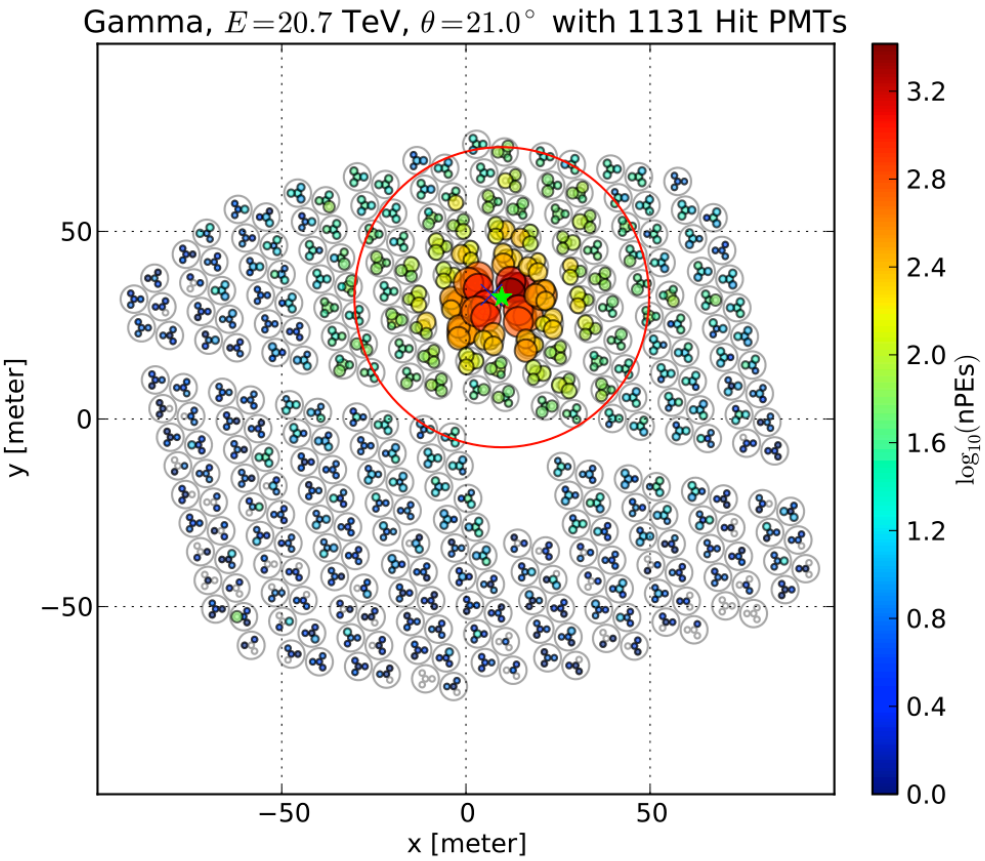




- Incoming shower angle
  - Fit hit arrival times

Background Rejection

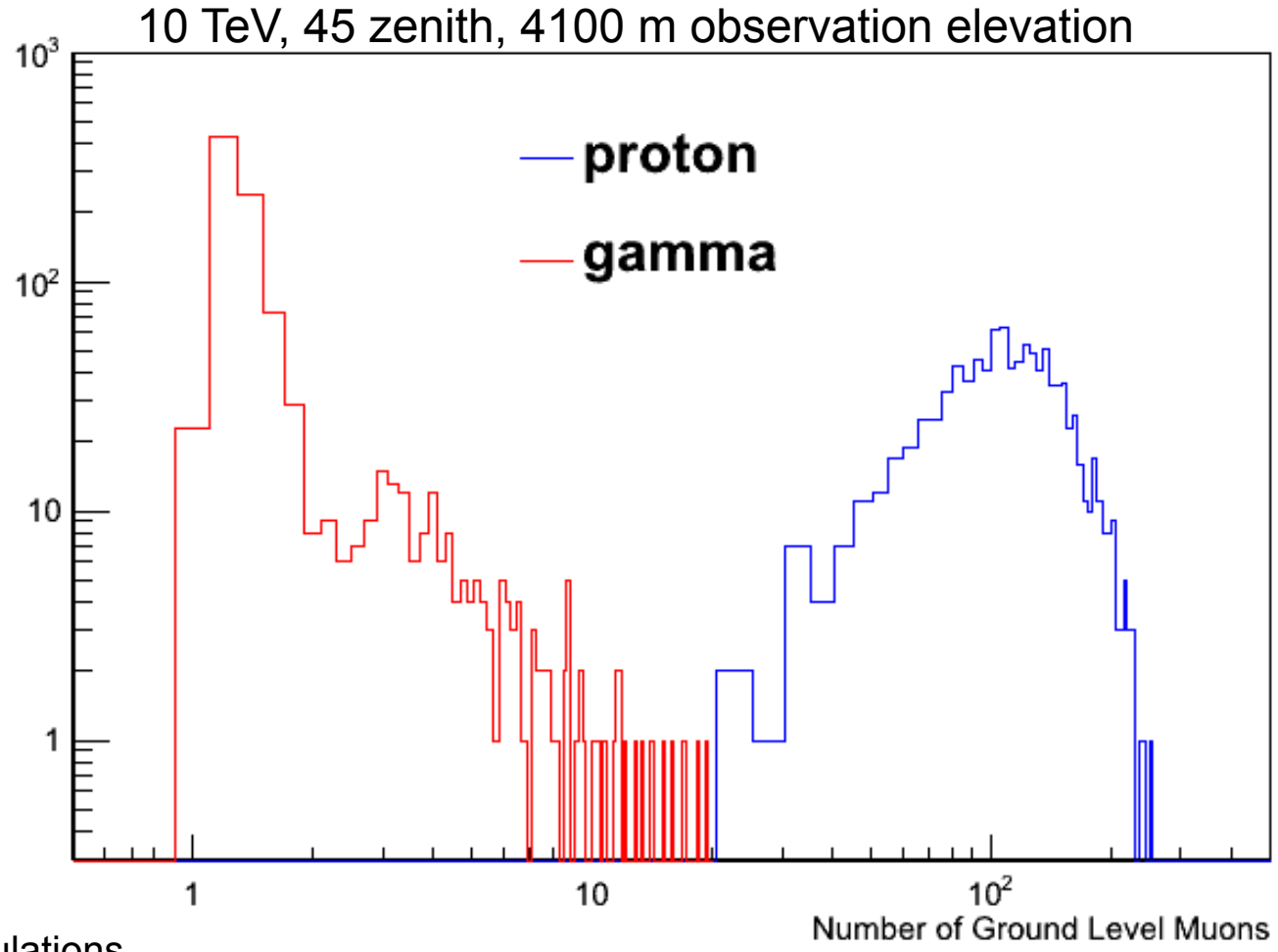




- **Hadron showers:** muons and high energy particles far from core, *"spotty."*
- **Gamma showers:** electromagnetic, *smooth*.

Gamma/Hadron Separation

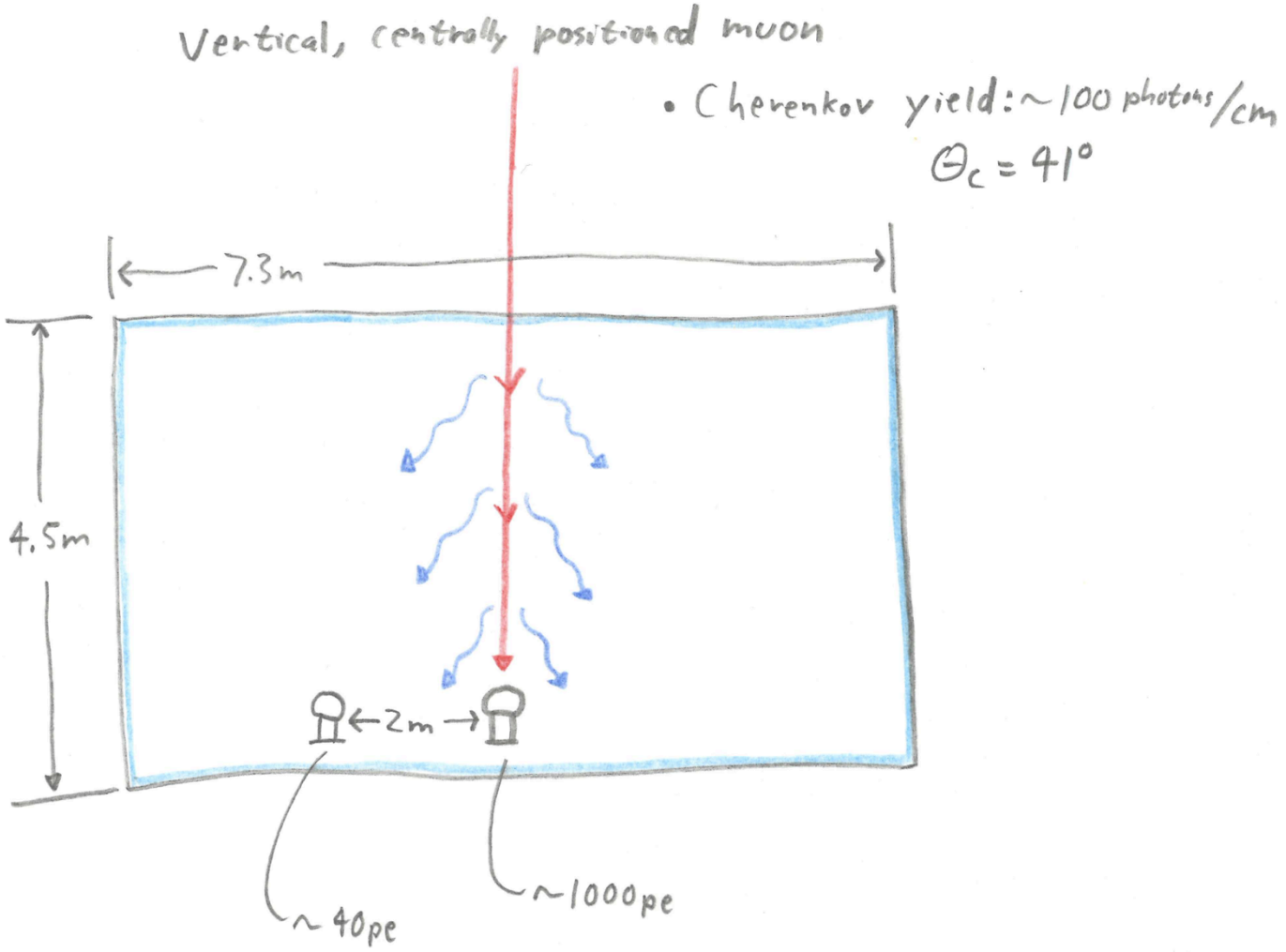
- Ground Level Muons are a powerful Gamma/ Hadron Discriminate



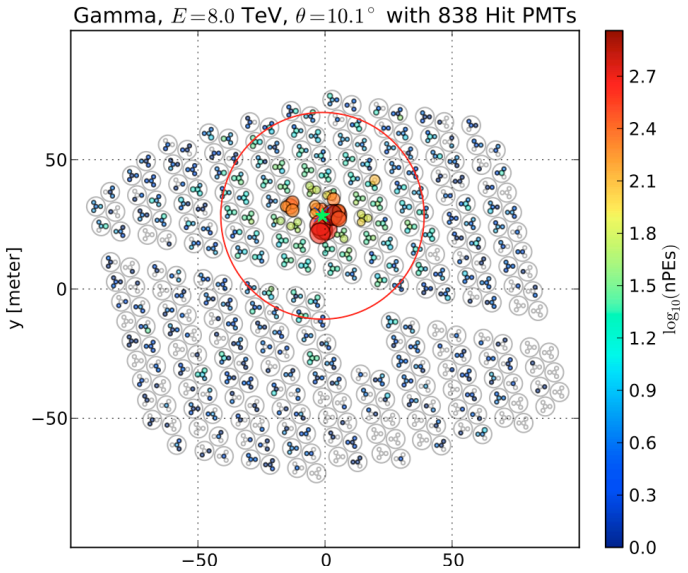
Conex-Sibyll 2.1 Simulations

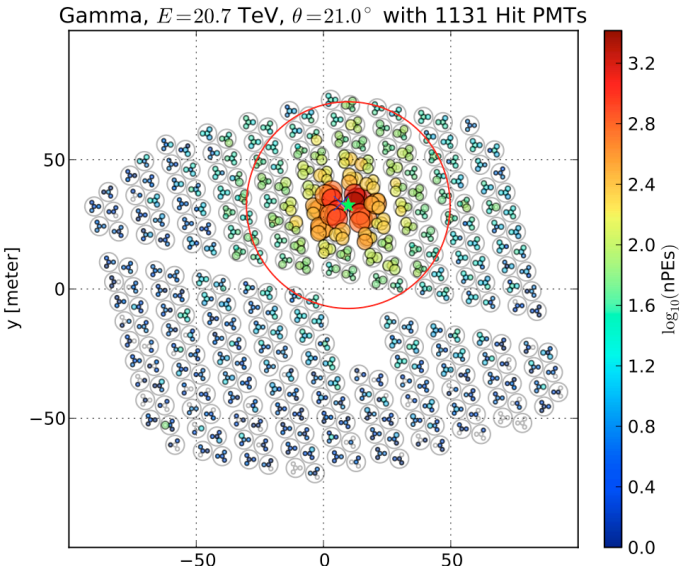
Gamma/Hadron Separation

- Muons deposit their energy lumpy.....

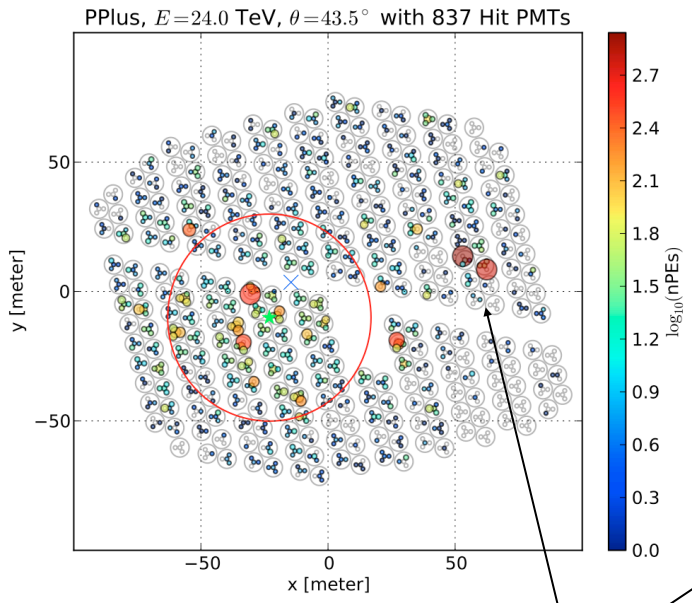


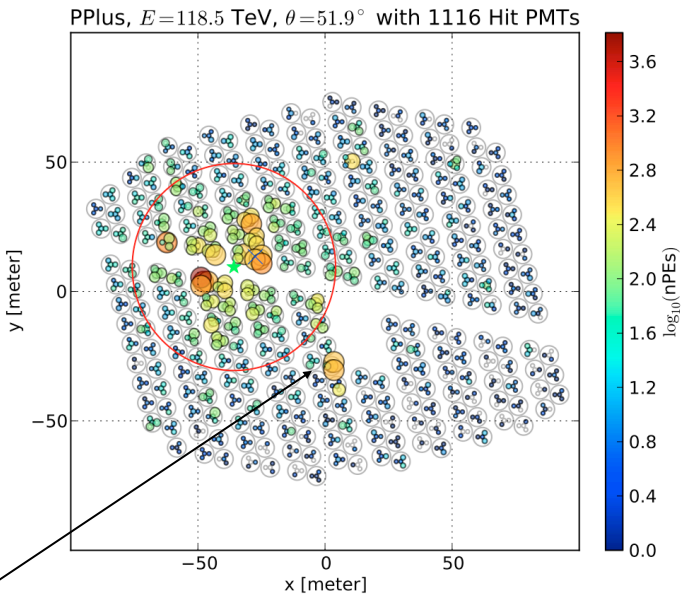
Gammas





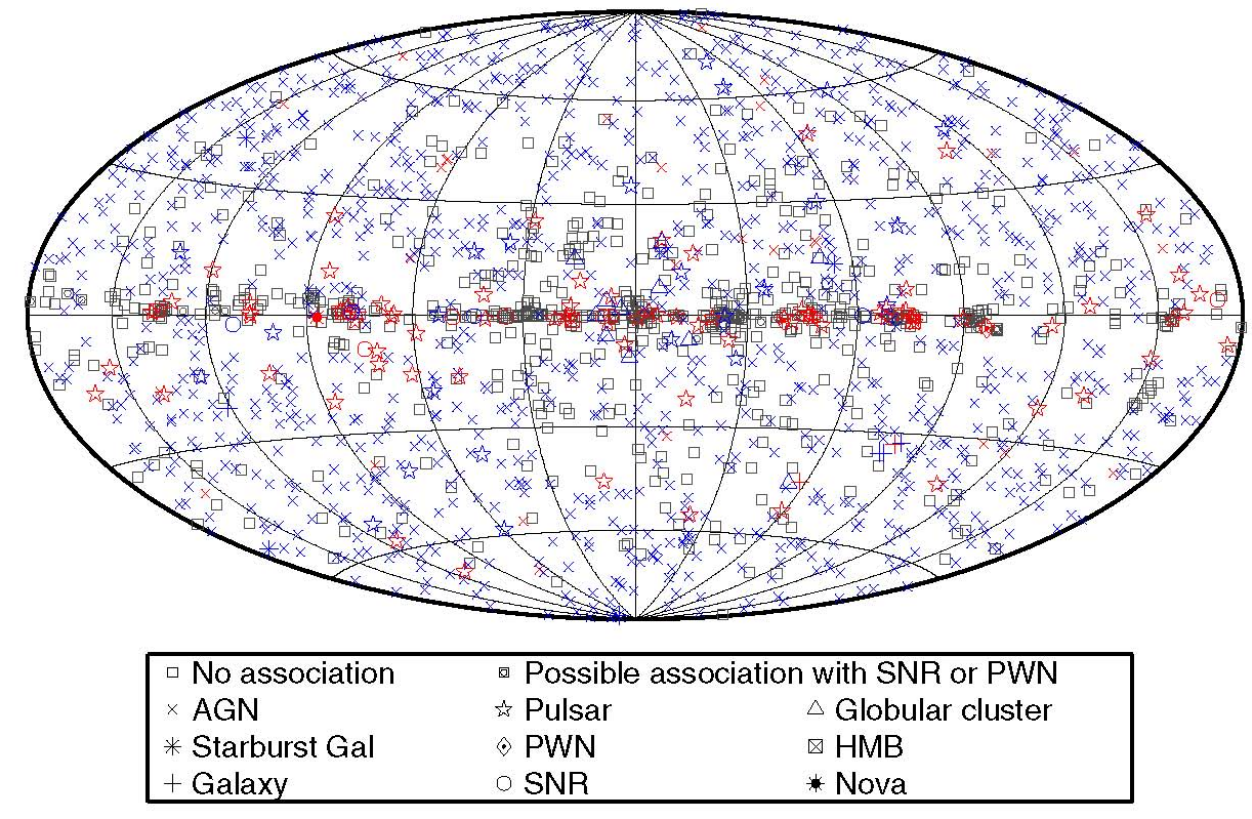
Protons





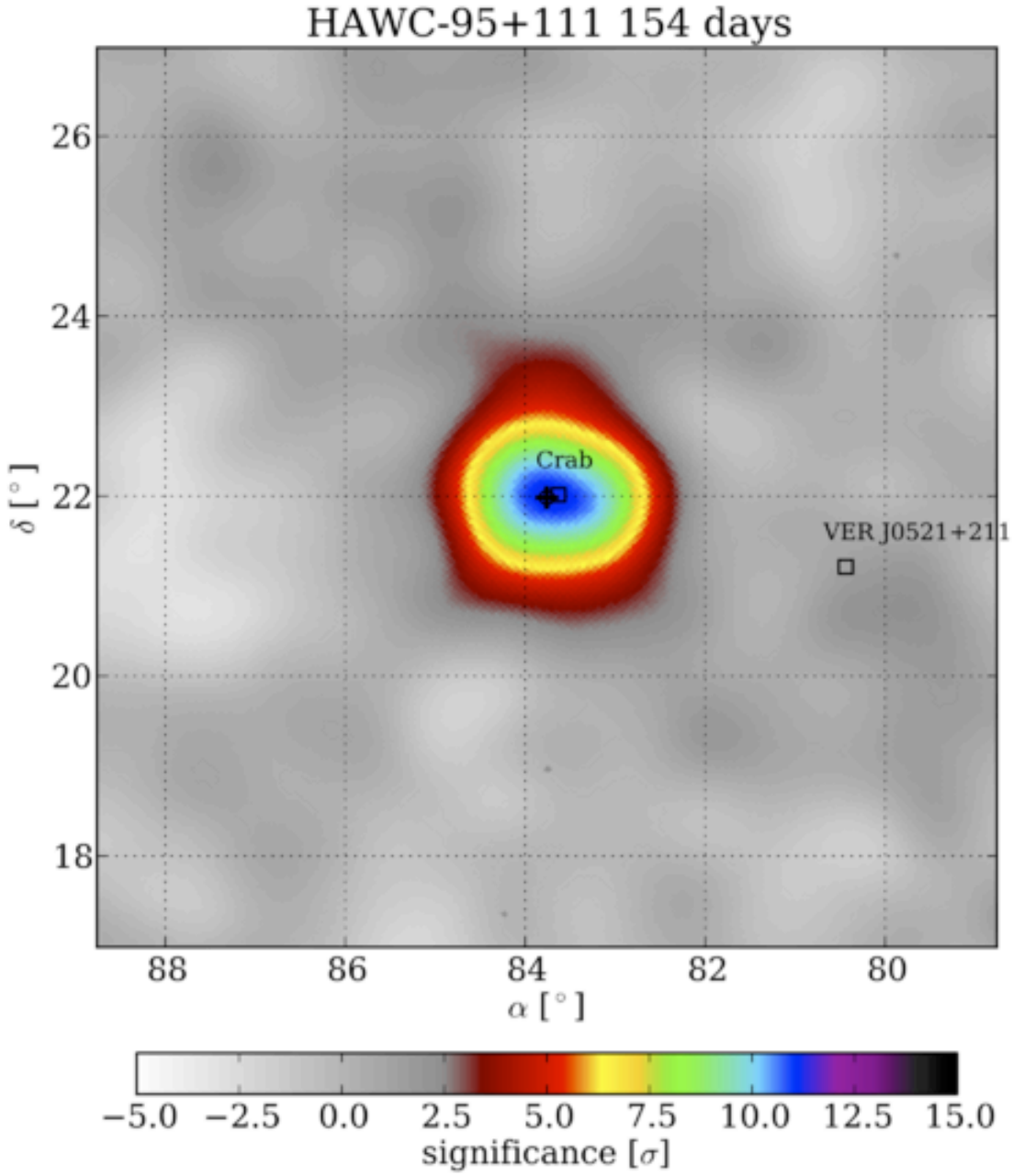
Energy deposited away from core

HAWC Physics ...

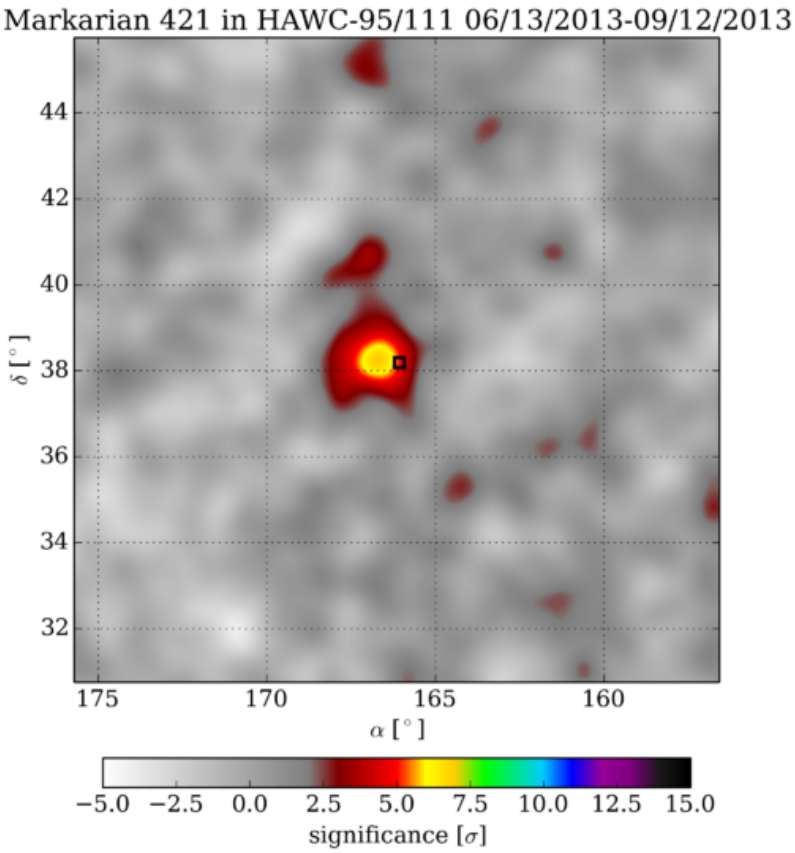


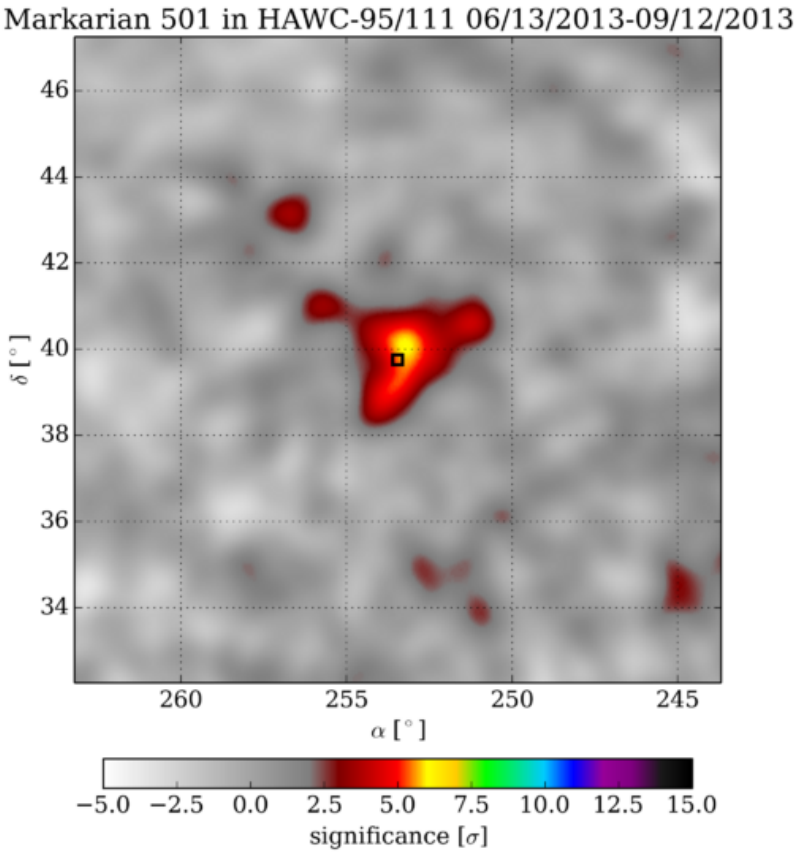
- the Fermi satellite has identified hundreds of super-massive black holes (AGNs)
- HAWC is the unique instrument to extend Fermi measurements, at GeV energies, to the highest (TeV) energies
- combined Fermi and HAWC data will greatly restrict source physics models

The Crab

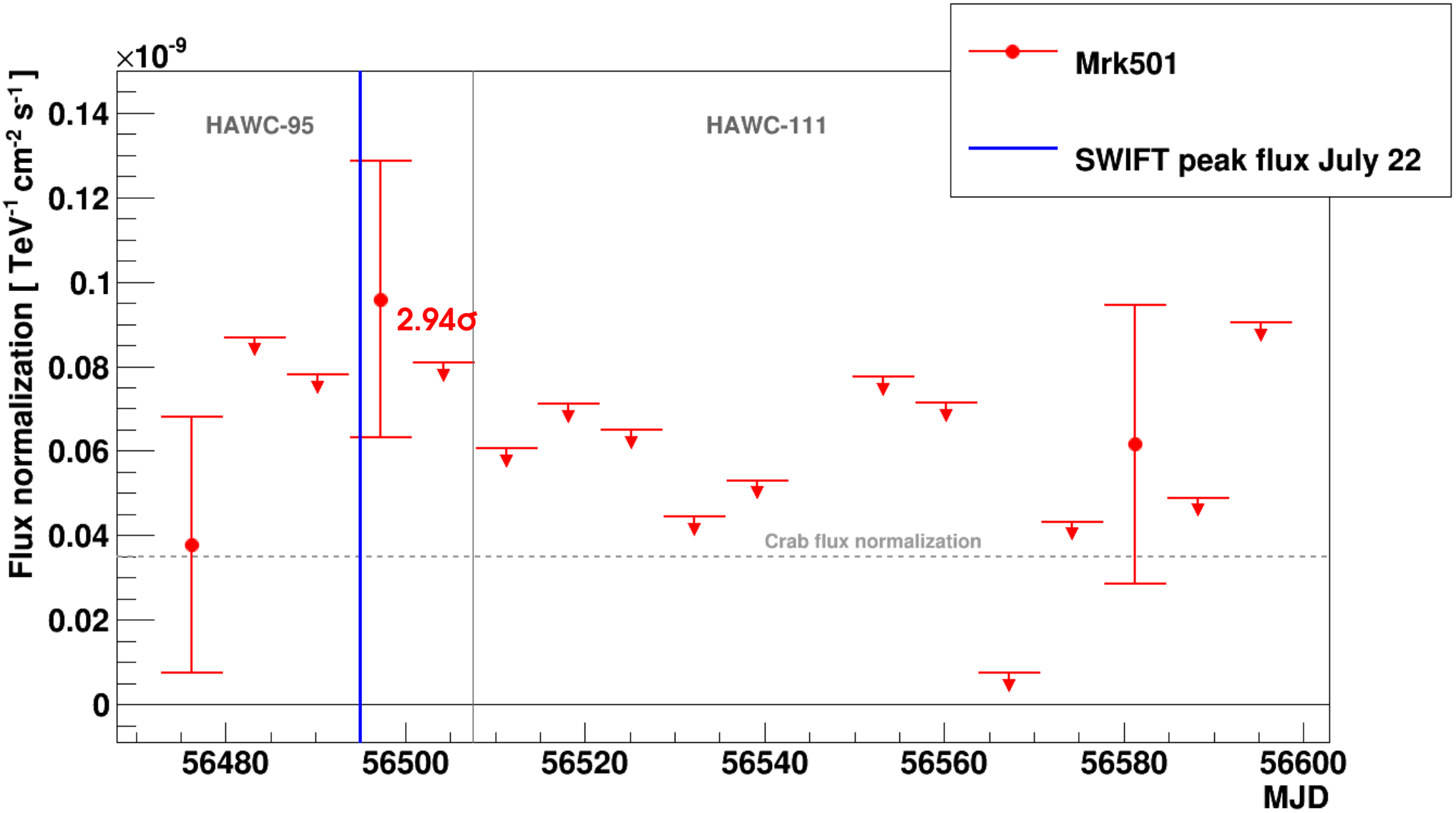

HAWC-95+111 154 days
26
24
22
20
18
δ [°]
Crab
VER J0521+211
88
86
84
82
80
α [°]
−5.0 −2.5 0.0 2.5 5.0 7.5 10.0 12.5 15.0
significance [σ]

The Markarians





Mrk501 Light Curve



México

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University of Maryland
University of New Hampshire
University of New Mexico
University of Utah
University of Wisconsin-Madison

http://www.hawc-observatory.org

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Summary

- Super-massive black holes (AGNs) and Gamma-ray bursts (GRBs) are of great current interest both theoretically and experimentally.
- New instruments, and in particular the High Altitude Water Cherenkov (HAWC) experiment, are needed to truly advance our understanding of the physics.
- The UNM group in HAWC is well positioned (as leader of the precision (timing) calibration system and one of the co-developers of the HAWC maximum likelihood analysis framework) to play a major role in HAWC physics.
- HAWC, already in routine data-taking and over 2/3 completed, provides an ideal opportunity for students.
- The HAWC experiment also benefits from close collaboration with nearby LANL
- So: many opportunities and no lack of challenges!

Additional/backup slides

The University of New Mexico

Additional slides

First Results From HAWC

Monitoring the TeV Gamma-Ray Sky

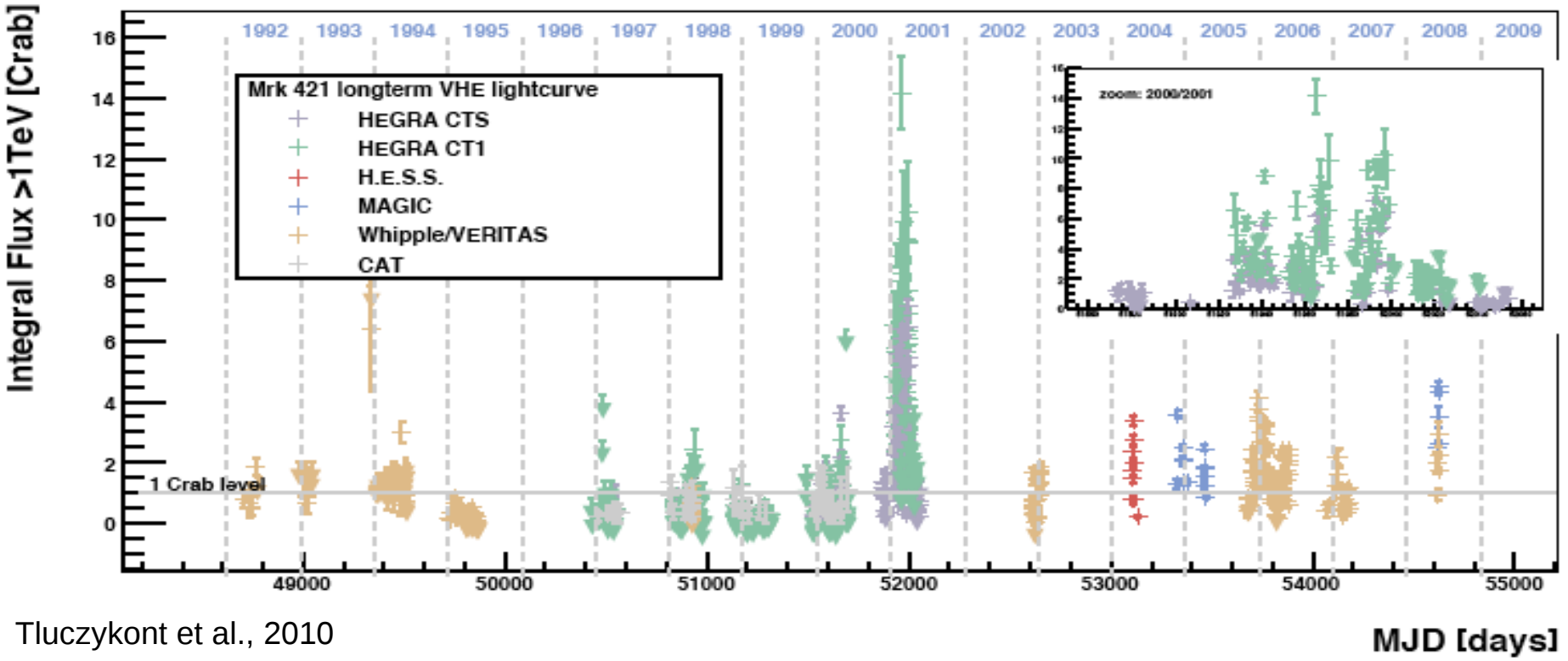
Robert J. Lauer

IAU Symposium 313
Galapagos Islands
September 15, 2014

THE UNIVERSITY of NEW MEXICO

TeV Monitoring of Extra-Galactic Jets

- ~40 known TeV AGN
- Imaging Air Cherenkov telescope observations with
  < 0.1% duty cycle per AGN
- many **biased flare observations**, e.g. X-ray triggered



Tluczykont et al., 2010

TeV Monitoring of Extra-Galactic Jets

- ~40 known TeV AGN
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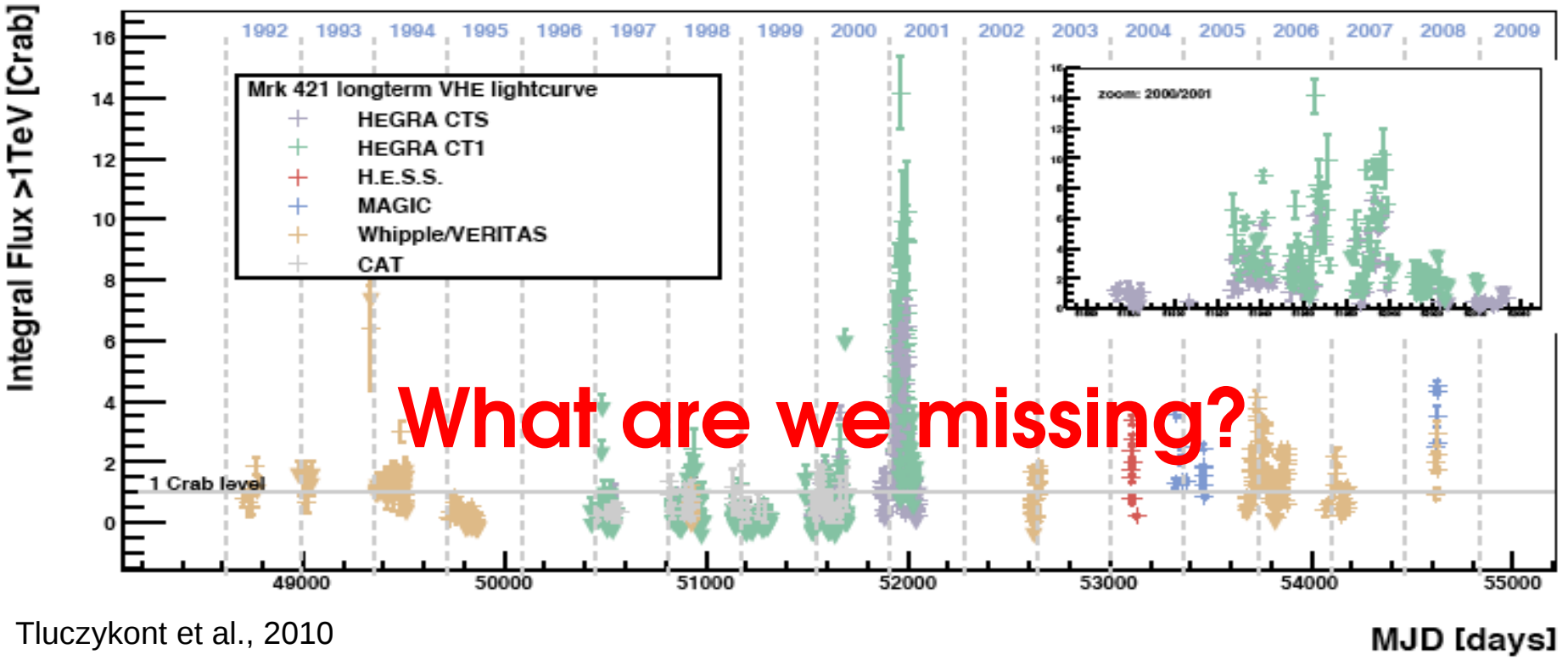
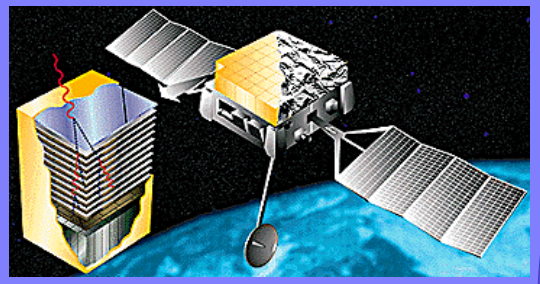


Tluczykont et al., 2010

Gamma-Ray Detectors

Wide Field of View, Continuous Operations



Fermi
AGILE
EGRET

TeV Sensitivity

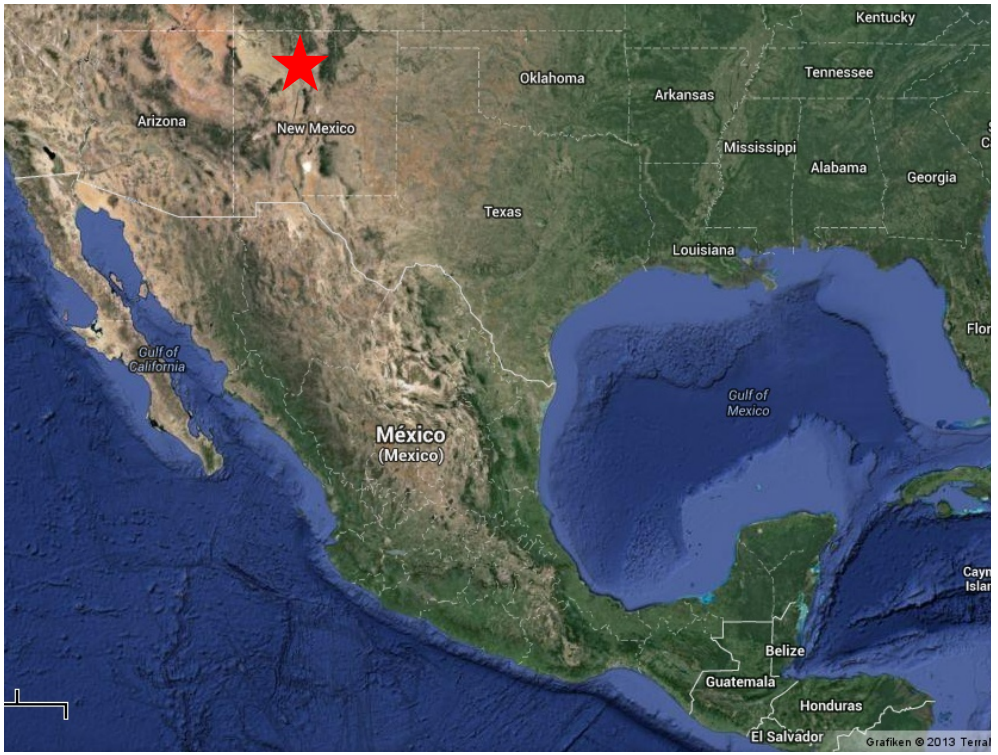
HAWC
Milagro
ARGO
Tibet ASγ

VERITAS
HESS
MAGIC

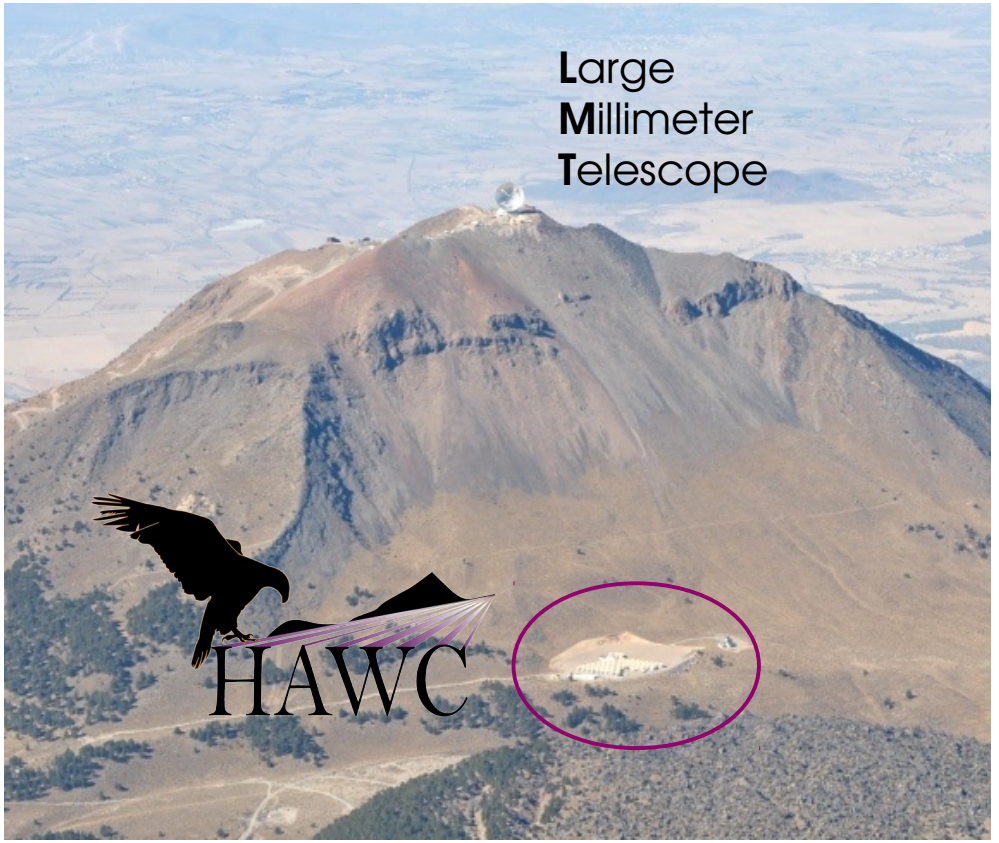
The HAWC Collaboration

1st Generation Water Cherenkov: Milagro

- Jemez Mountains, New Mexico
- 2350 m altitude
- operated between 2000 and 2008
- established gamma-ray water Cherenkov technique

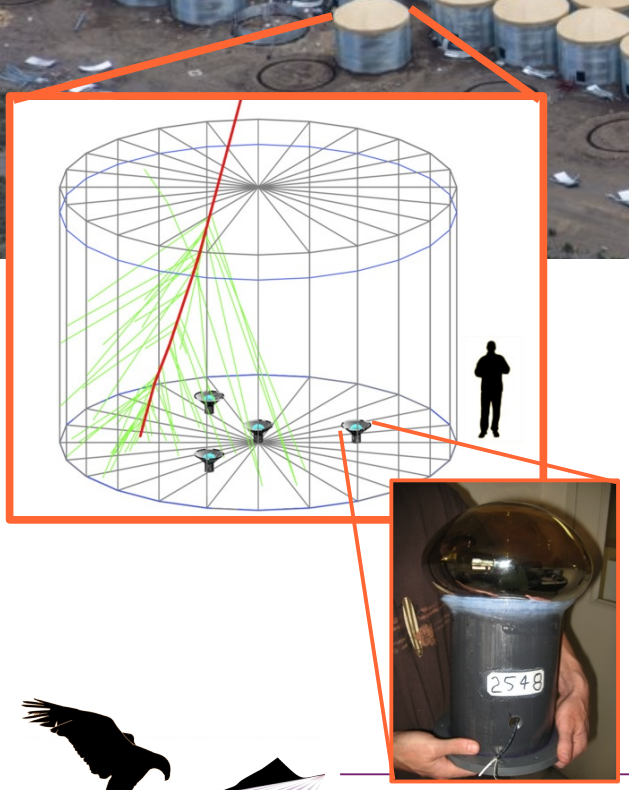


2nd Generation Water Cherenkov: HAWC



- Sierra Negra volcano near Puebla, Mexico
- High altitude site at 4100 m
- Temperate climate
- Existing infrastructure from LMT
- 17 radiation lengths of atm. overburden (vs. 27 at sea level)

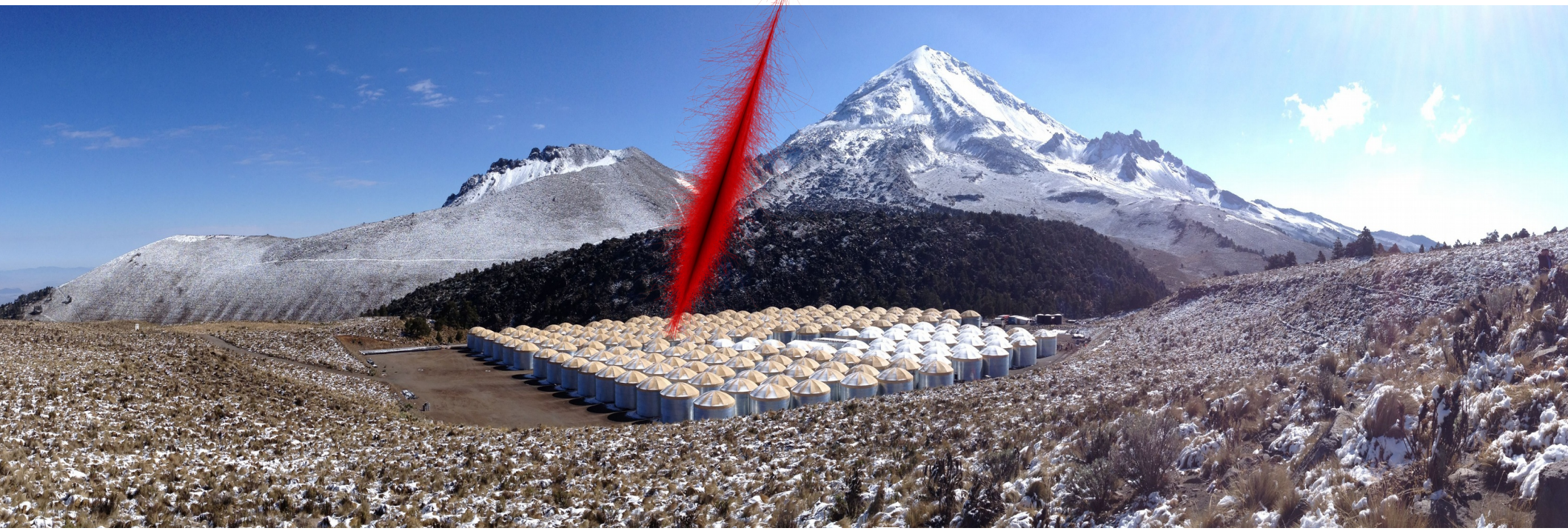
The HAWC Array



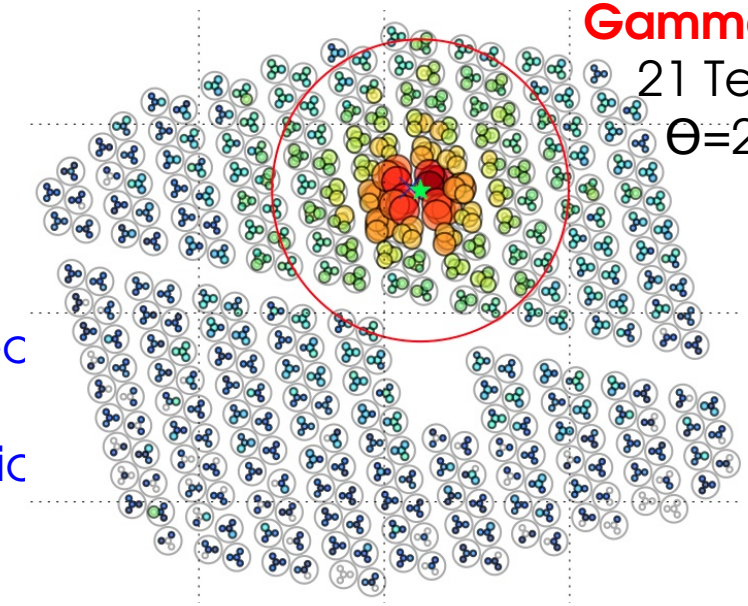
- **22,000 m^2** water Cherenkov detector (WCD) array
- **300 WCDs** at completion (early 2015)
- **200,000 liters** of purified water **per WCD**
- **1,200 PMTs** (900 from Milagro + 300 high QE PMT)
- Ongoing **data taking during construction:**
  111 tanks have been operated **since August 2013**

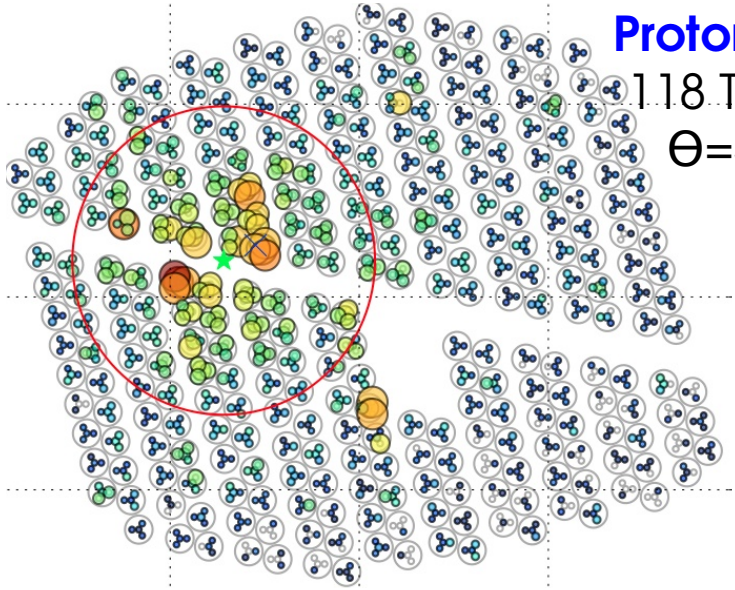
HAWC

Extended Air Shower Detection Technique

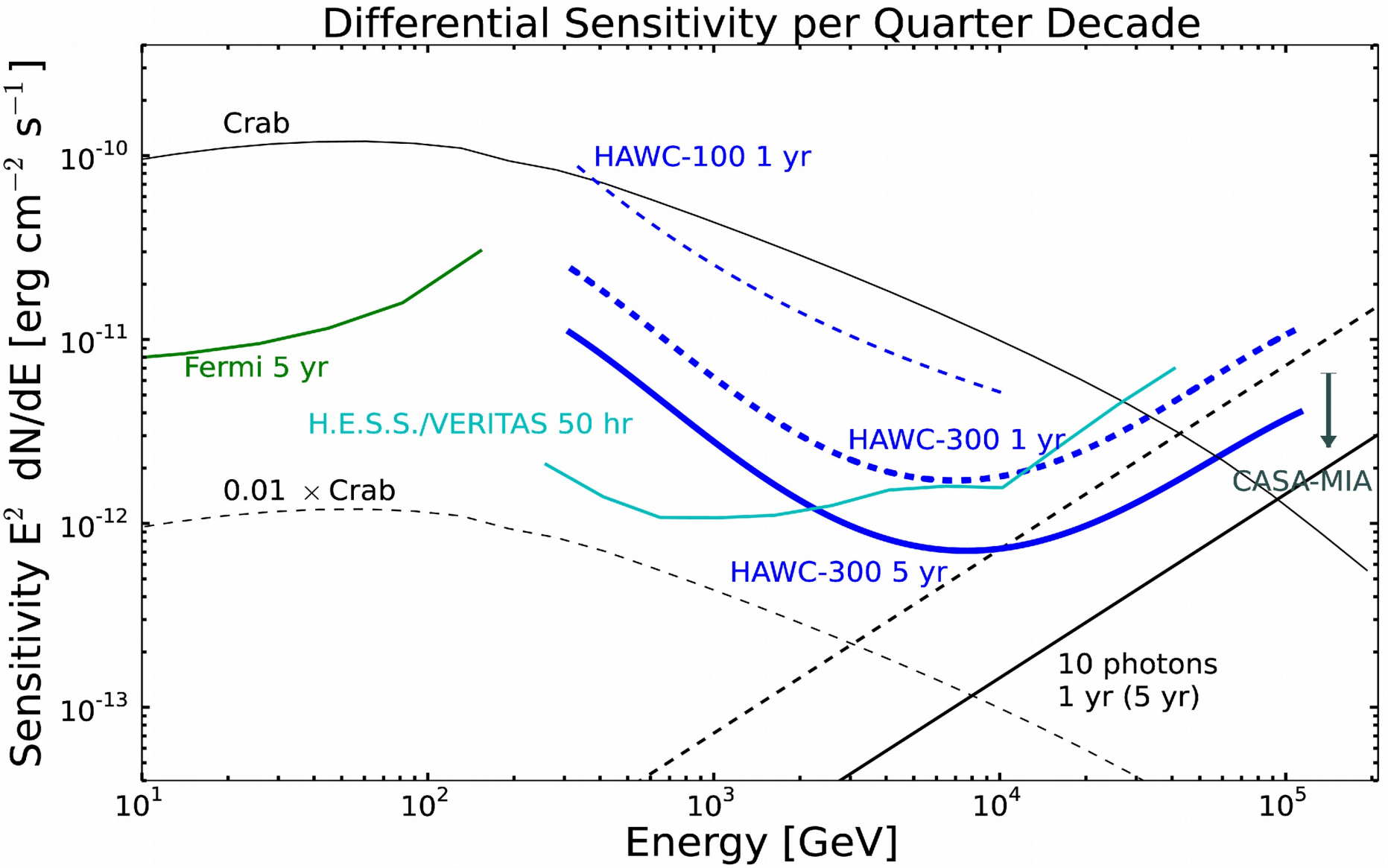


1) Reconstruct air showers based on PMT hit times and charges
2) Reject charged primaries via bright hits outside the core





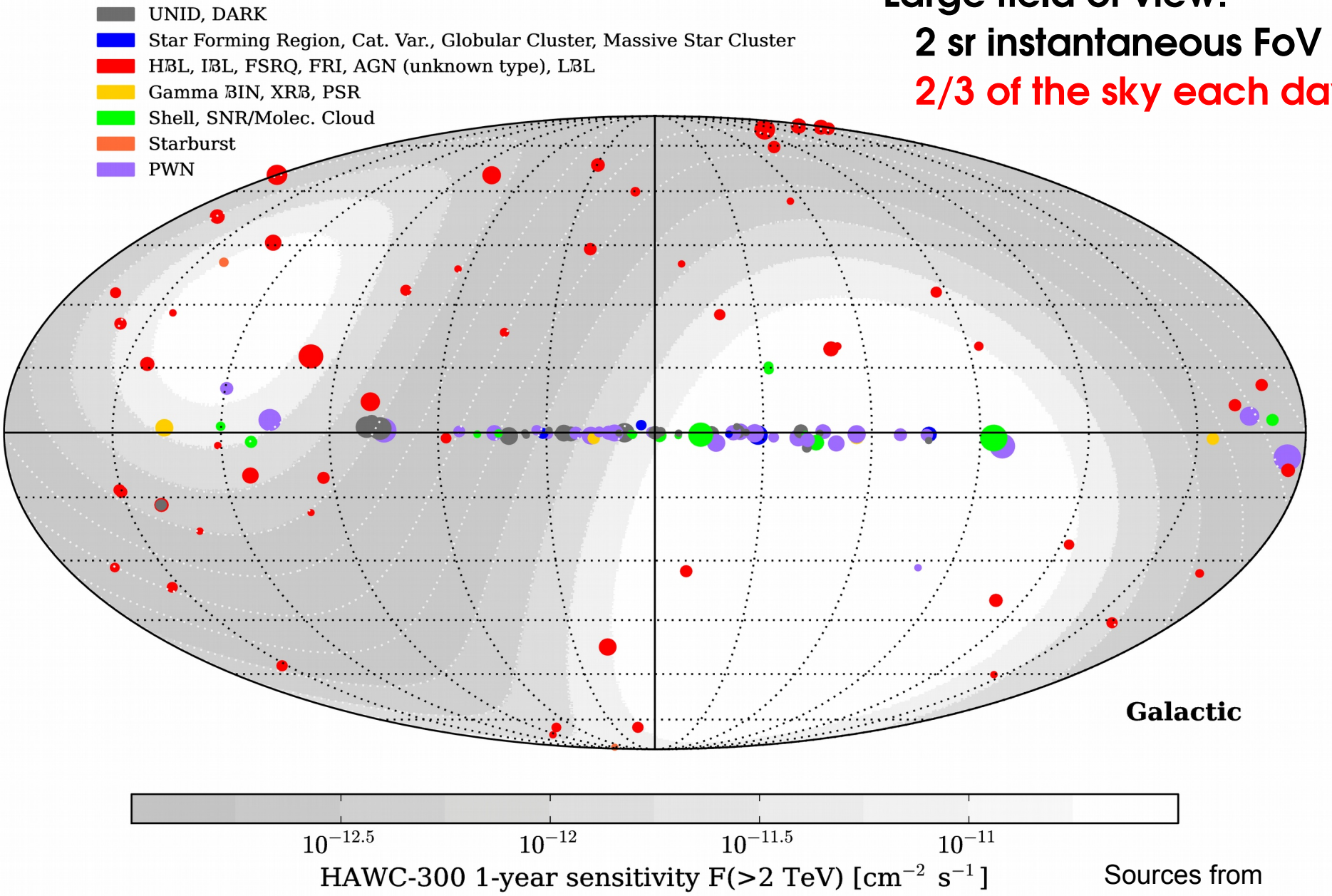
HAWC Sensitivity



Abeysekara et al. (HAWC Collab.)
Astropart. Phys., 50-52 (2013)

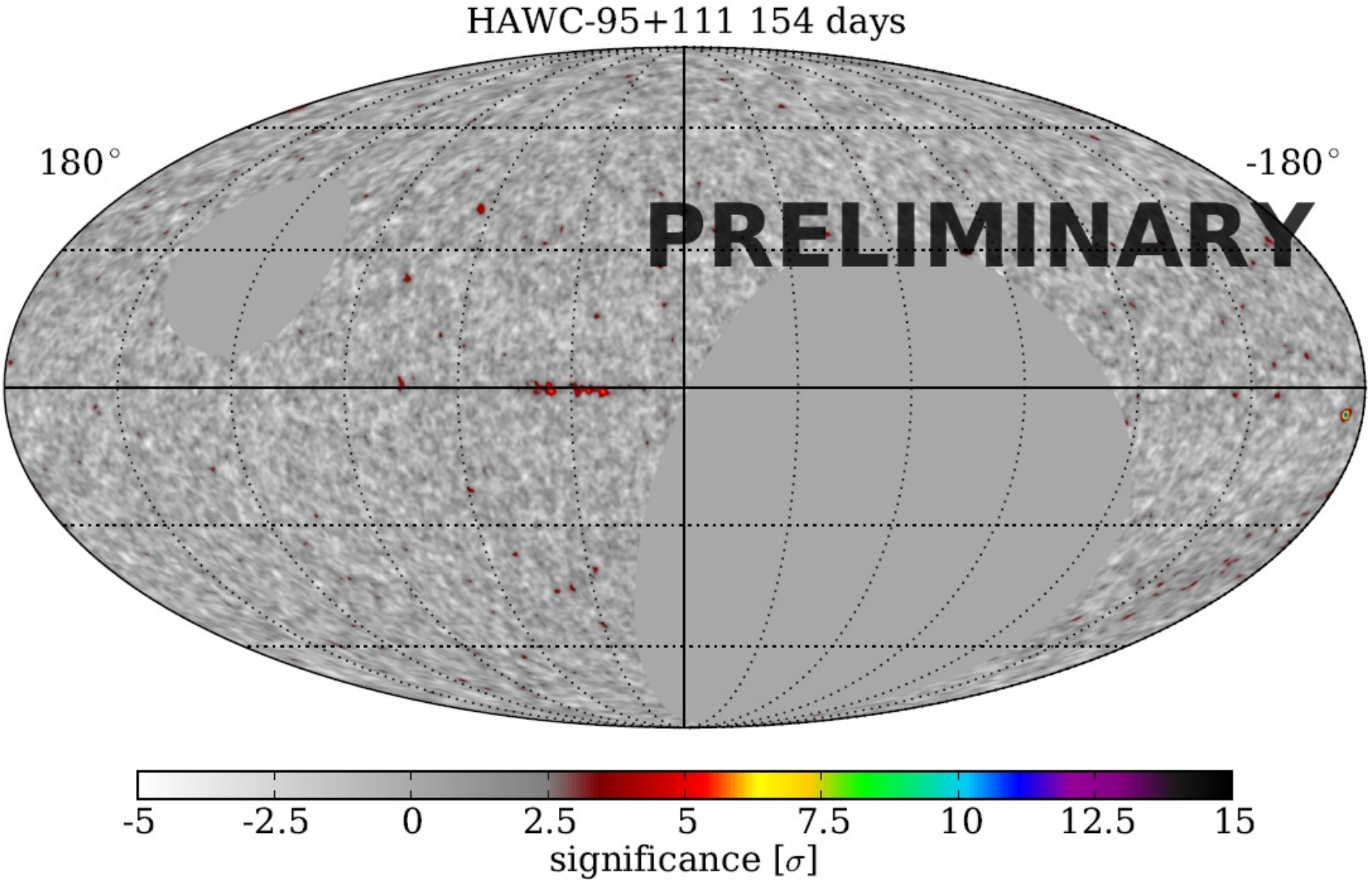
HAWC Field Of View

Large field of view:
2 sr instantaneous FoV
2/3 of the sky each day



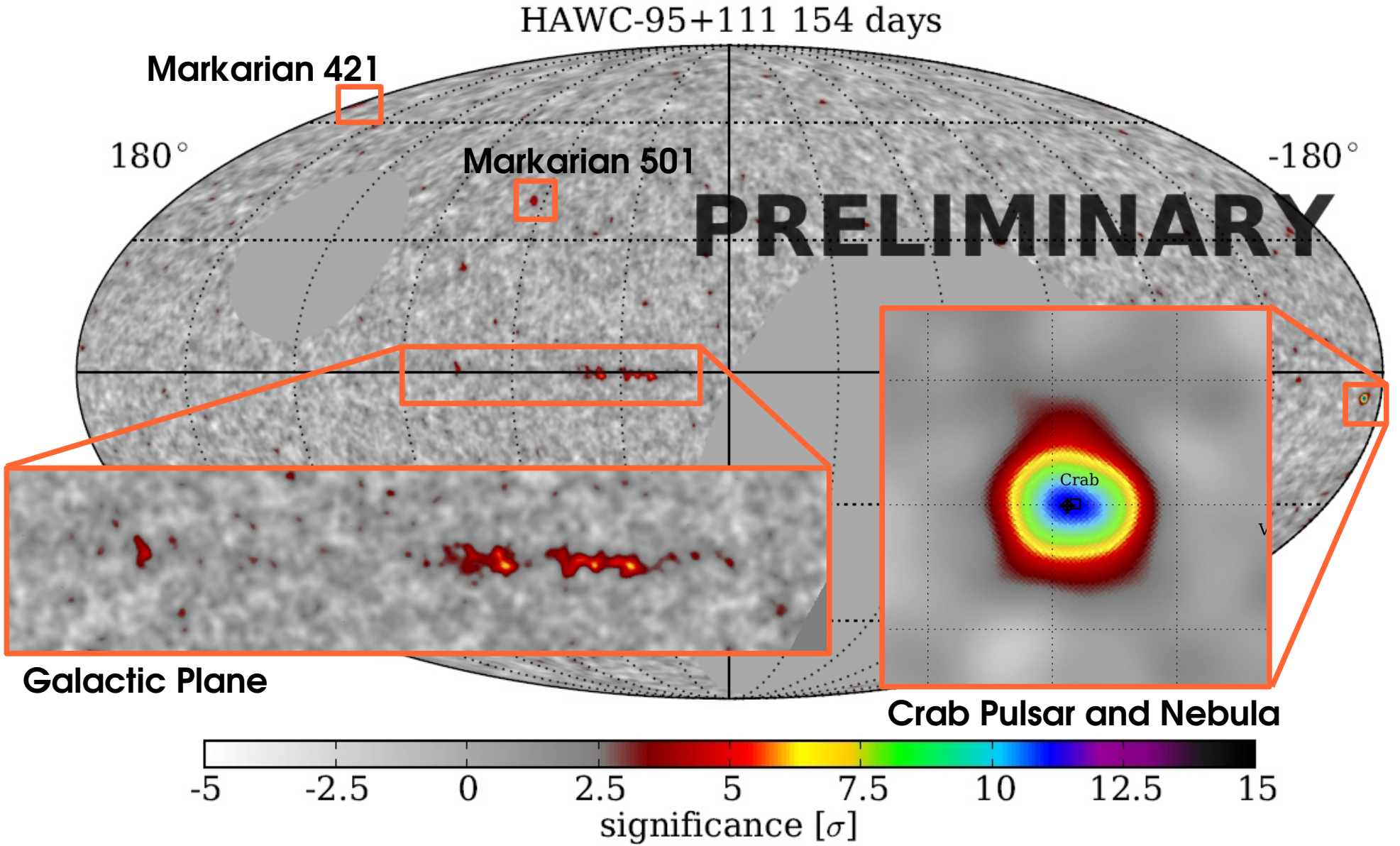
Sources from
TeVCAT.uchicago.edu

HAWC Gamma-Ray Sky Map



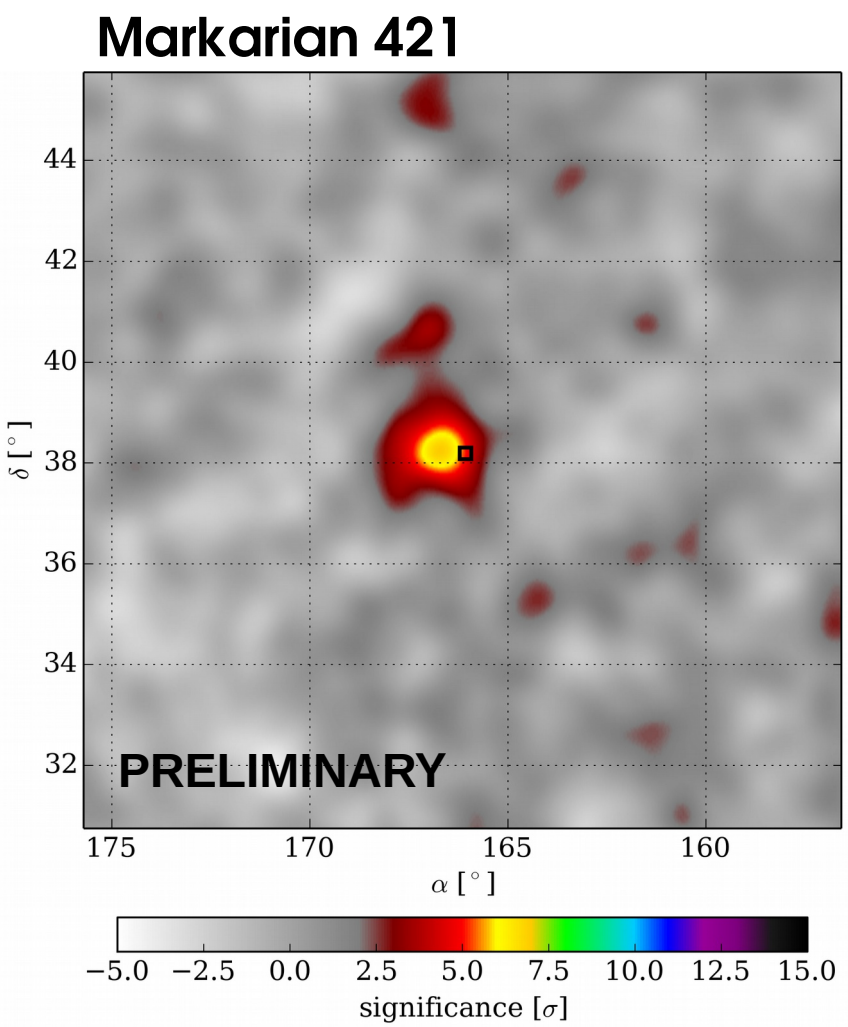
Caveats: Absolute pointing uncertainties, preliminary calibration, high-energy data omitted, and subset of data reconstructed online

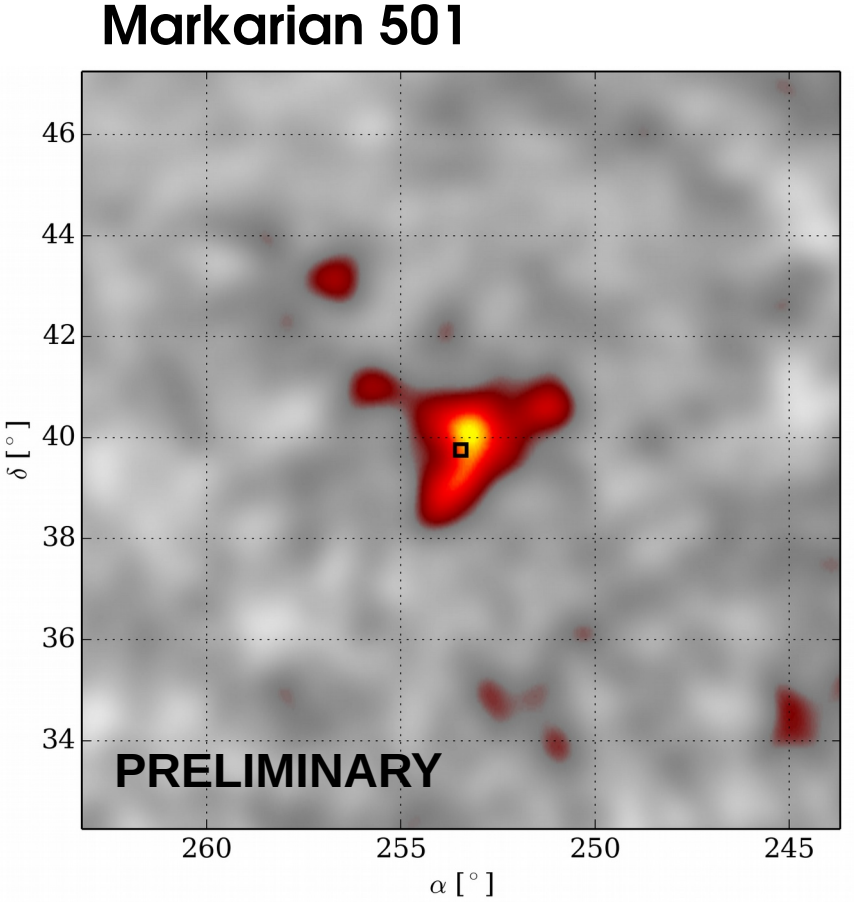
HAWC Gamma-Ray Sky Map



Caveats: Absolute pointing uncertainties, preliminary calibration, high-energy data omitted, and subset of data reconstructed online

AGN Observations





The two Mrk blazars detected at > 5σ

A likelihood analysis will provide **AGN light curves of daily measurements.**

We already have **1 year of data** from 1/3 of the array
with several known strong AGN flares to be analyzed with HAWC.

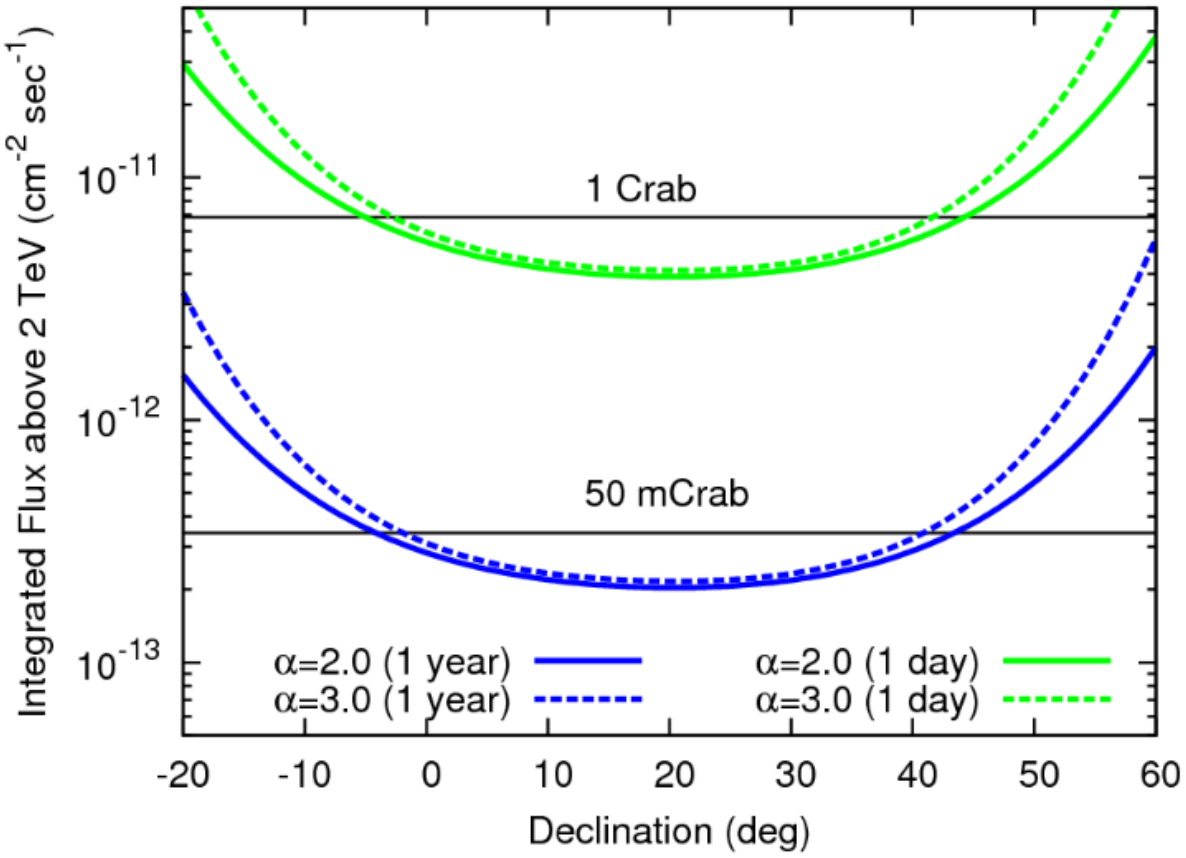
AGN Monitoring

HAWC will monitor all Northern AGN with **20% duty cycle/day** (5 hrs) regardless of sun, moon, or weather.

With the full HAWC detector we will be able to detect

(10, 1, 0.1) Crab Units in (3 min, 5 hrs, 1/3 yr)

at 5σ significance.



Automated online system for detecting AGN flares is being tested.

→ HAWC will be able to promptly alert **Imaging Air Cherenkov Telescopes** And other observatories to obtain **prompt follow-up observations.**

A detailed online analysis of HAWC data is possible within 24 h.

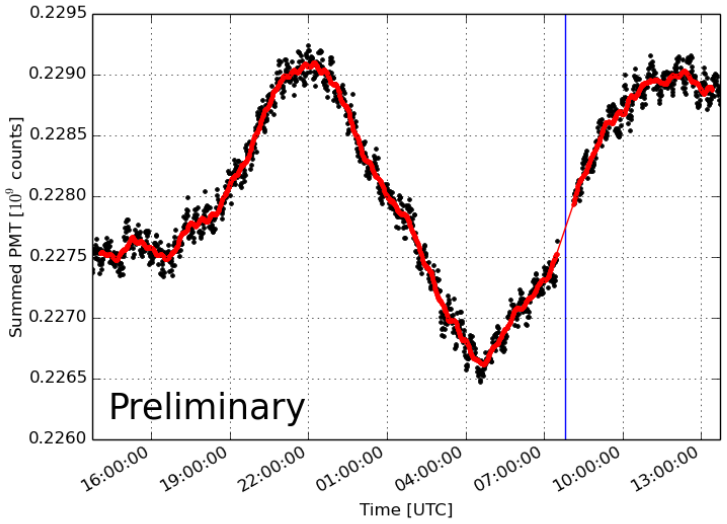
First HAWC Gamma-Ray Burst Limits

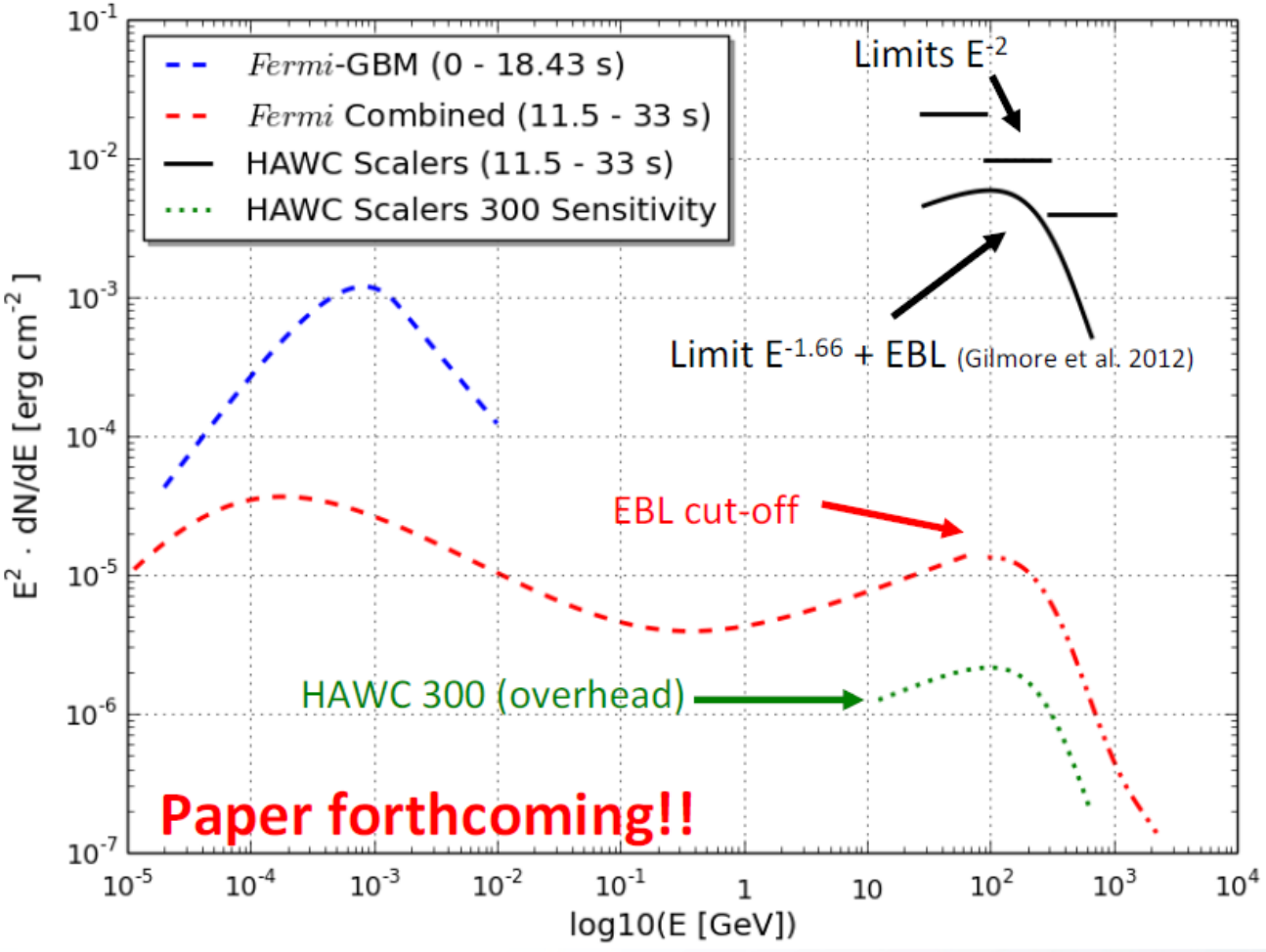
HAWC data for several GRBs has been analyzed. **No detection so far.**

- Abeysekara et al. (HAWC Collab.) Astropart. Phys. 35 (2012)
- ICRC Proceedings arXiv:1310.0071

GRB 130427A:
94 GeV photon in Fermi data

Main HAWC DAQ offline, but scaler* system running
→ first HAWC GCN circular.

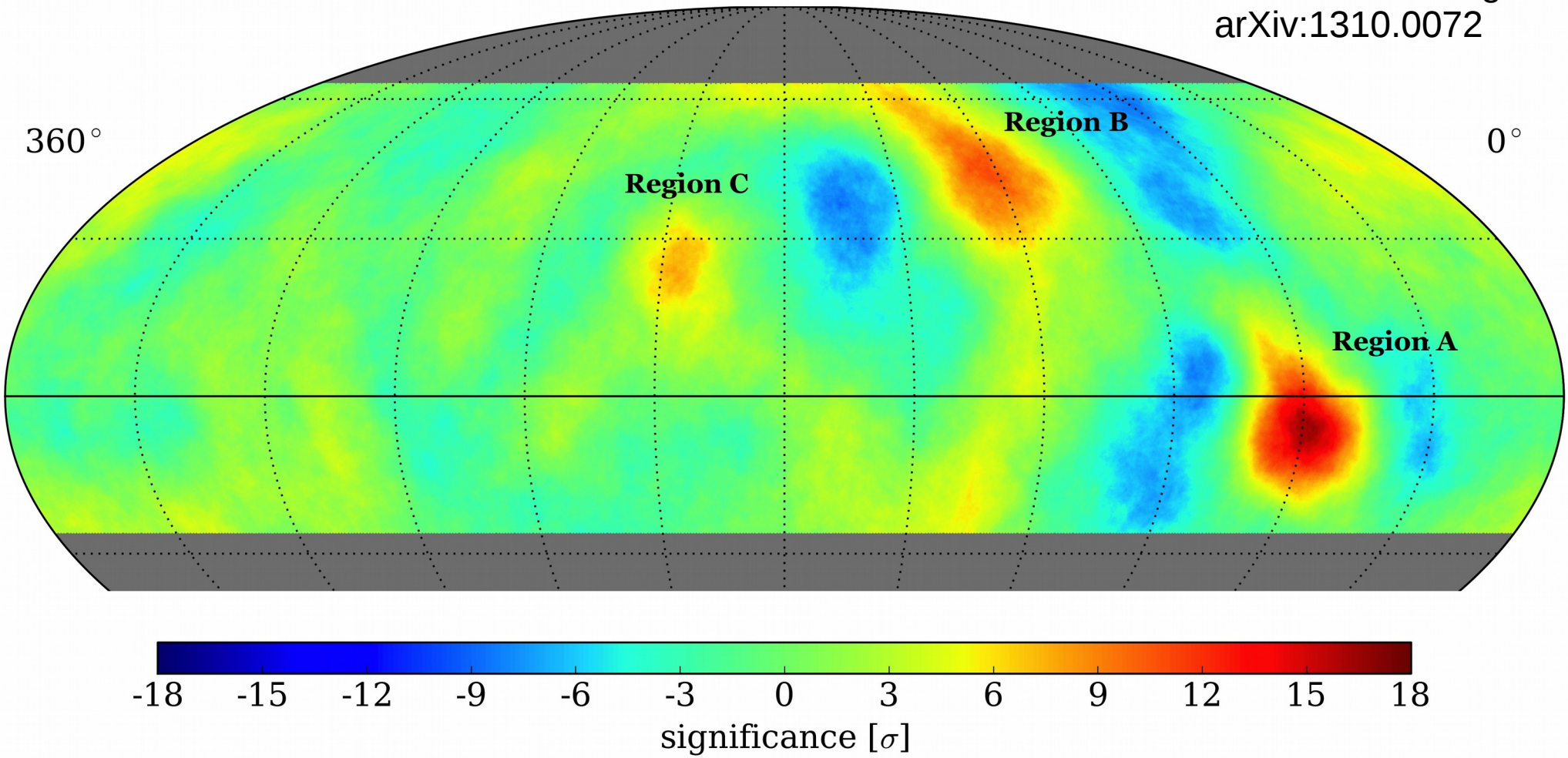




*Scalers: Search for excess over moving average at time of GRB.

Cosmic Ray Physics: Anisotropy

ICRC Proceedings:
arXiv:1310.0072



10° radial smearing and multipole subtraction of large scale anisotropy

49 billion events, collected over 113 sidereal days with ~1/3 of the array

Summary

- **HAWC** has started to **survey and monitor 2/3 of the sky** to observe gamma-ray sources and other TeV phenomena.
- **HAWC** has **detected the Crab** Pulsar/Nebula at > 10σ **and Mrk 421 and Mrk 501** at > 5σ.
- **HAWC** will provide **continuous AGN light curves** of daily measurements
- **HAWC** data on past **GRBs and AGN flares are being analyzed.**
- **HAWC will alert other telescopes** in case of transient events and perform prompt online analyses.