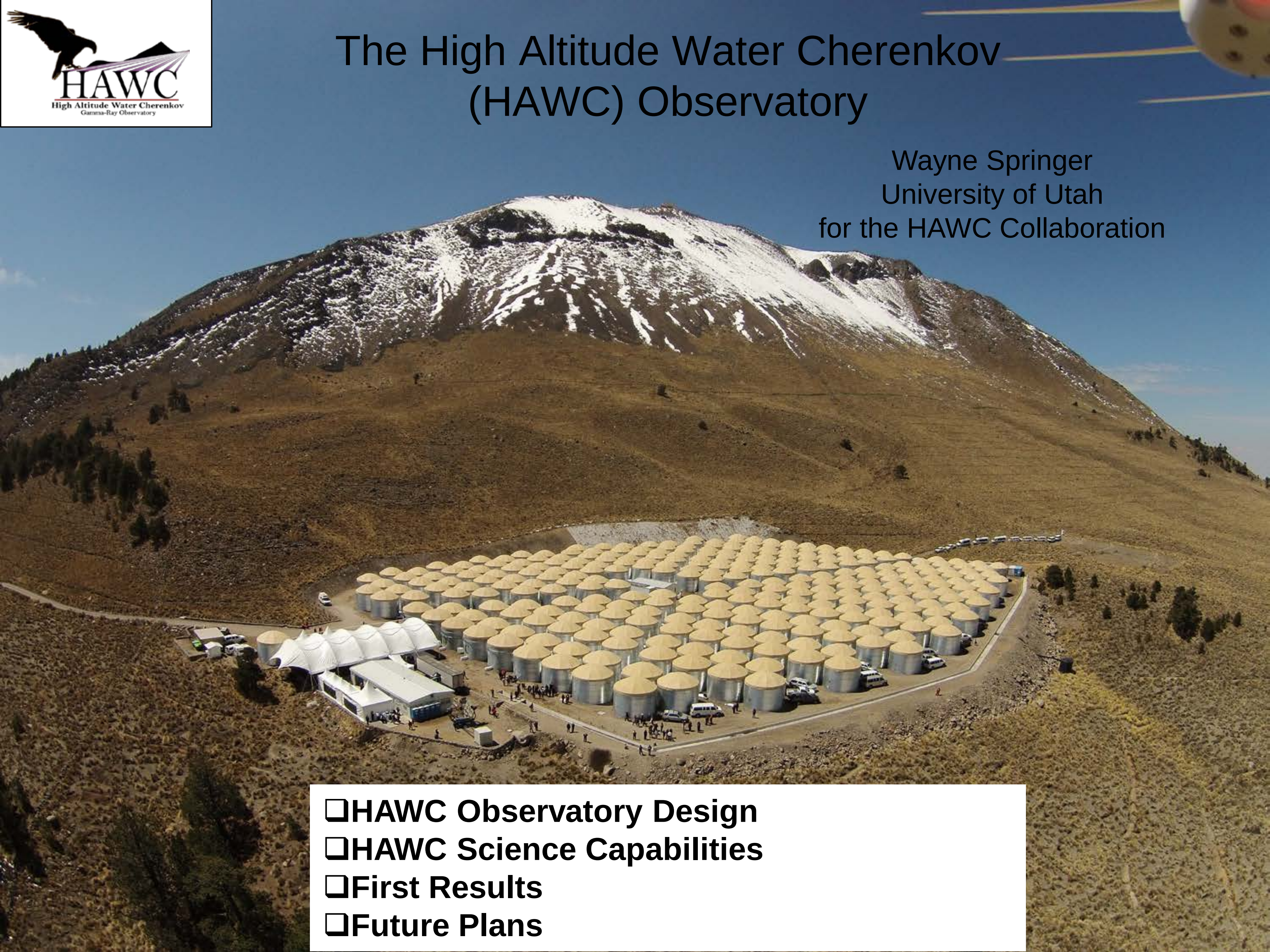
The High Altitude Water Cherenkov (HAWC) Observatory

Wayne Springer
University of Utah
for the HAWC Collaboration



- ❑**HAWC Observatory Design**
- ❑**HAWC Science Capabilities**
- ❑**First Results**
- ❑**Future Plans**

HAWC Collaboration

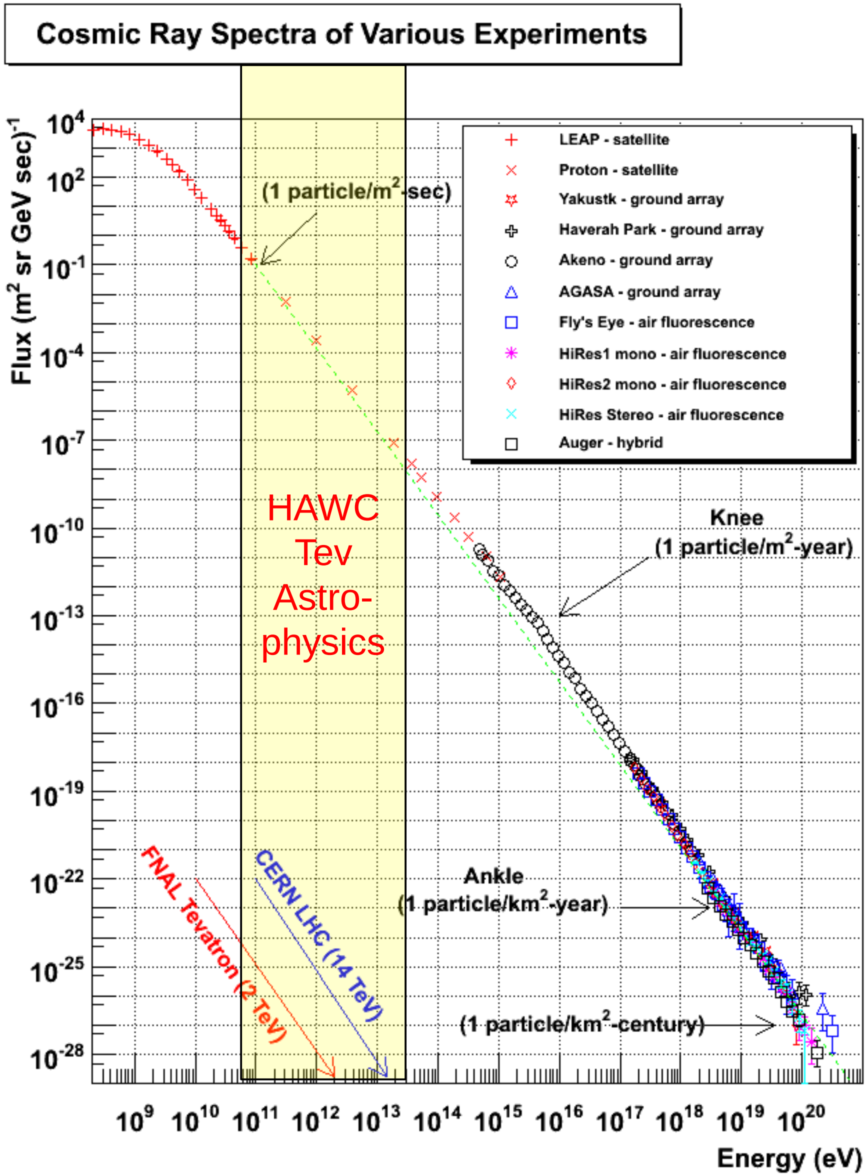
USA:
Pennsylvania State University
University of Maryland
Los Alamos National Laboratory
University of Wisconsin
University of Utah
Univ. of California, Irvine
University of New Hampshire
University of New Mexico
Michigan Technological University
NASA/Goddard Space Flight Center
Georgia Institute of Technology
Colorado State University
Michigan State University
University of Rochester
University of California Santa Cruz

Mexico:
Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma de México (UNAM)
Instituto de Física
Instituto de Astronomía
Instituto de Geofísica
Instituto de Ciencias Nucleares
Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapas
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional
Centro de Investigación en Computación - IPN

NSF Grants PHY1207595 and 1510504

Flux of Cosmic and Gamma Rays

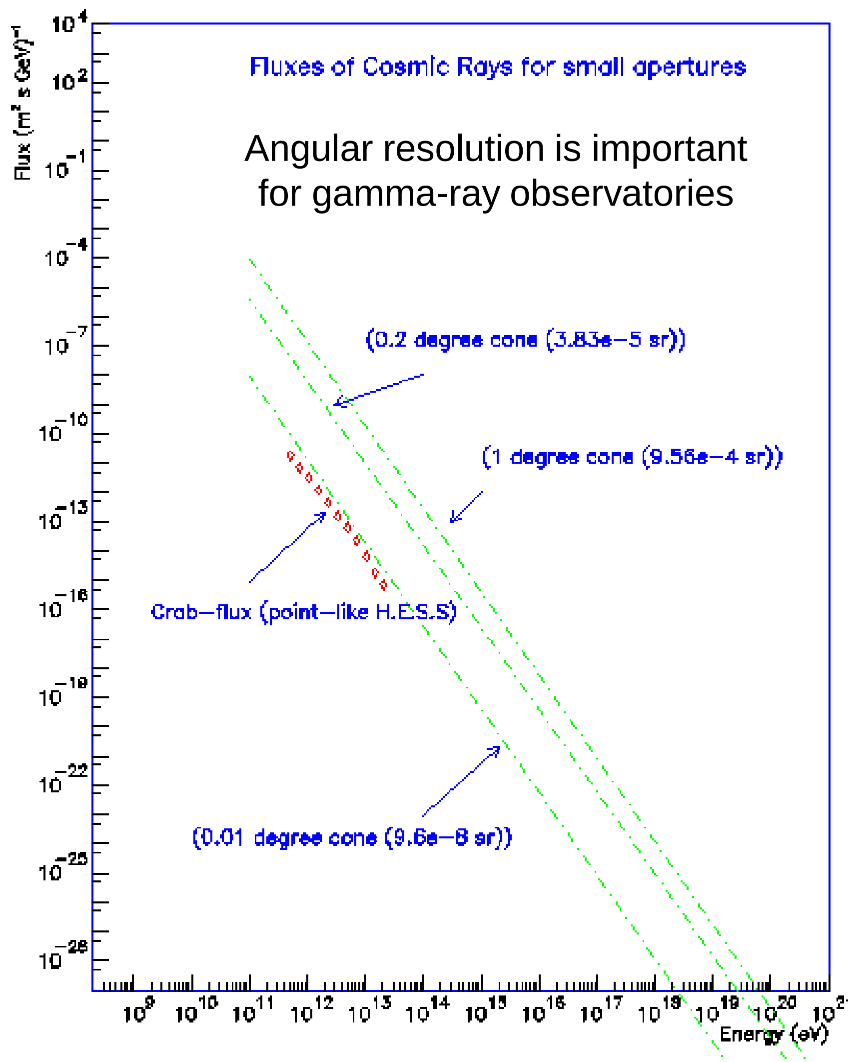
Cosmic Ray Flux is typically isotropic



http://www.physics.utah.edu/~whanlon/spectrum.html

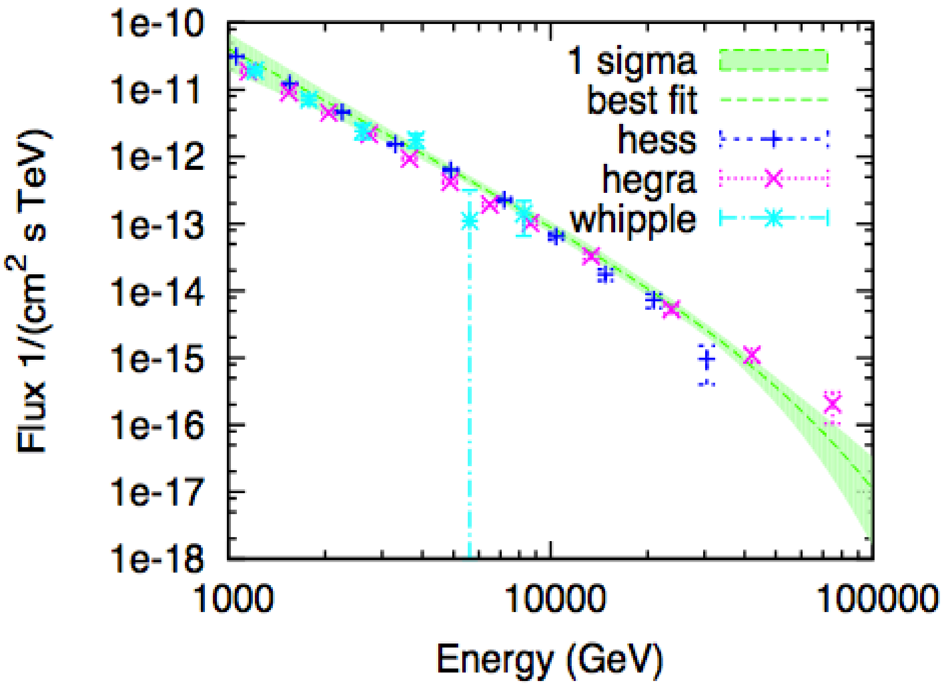
Gamma-Ray Flux is not isotropic

Comparison to γ-ray Flux from Crab Nebula

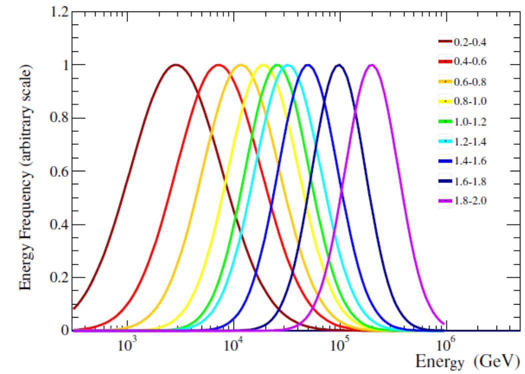


http://astroparticle.uchicago.edu/siteold/cosmic_ray_spectrum_picture.htm

Gamma Ray Spectral Fits



Milagro fit spectrum-dependent model of observable ("F-parameter") to determine spectral function.



The parameter $\mathcal{F}$ measures the size of an event and is defined as

$$\mathcal{F} = \frac{N_{\mathrm{AS}}}{N_{\mathrm{AS}}^{\mathrm{live}}} + \frac{N_{\mathrm{OR}}}{N_{\mathrm{OR}}^{\mathrm{live}}}, \quad (3)$$

where $N_{\mathrm{AS}}/N_{\mathrm{AS}}^{\mathrm{live}}$ is the fraction of live PMTs in the top layer (or air-shower layer) which participated in the event and $N_{\mathrm{OR}}/N_{\mathrm{OR}}^{\mathrm{live}}$

Milagro measurement of Crab Supernova Remnant Energy spectrum

$$\frac{dN}{dE} = (6.5 \pm 0.4) \times 10^{-14} (E/10\ \mathrm{TeV})^{-3.1 \pm 0.1} (\mathrm{cm}^2\ \mathrm{sec\ TeV})^{-1}$$

between ~1 TeV and ~100 TeV. When a finite E_{cut} is fit the result is

$$\frac{dN}{dE} = (2.5^{+0.7}_{-0.4}) \times 10^{-12} (E/3\ \mathrm{TeV})^{-2.5 \pm 0.4} \exp(-E/32^{+39}_{-18}\ \mathrm{TeV}) (\mathrm{cm}^2\ \mathrm{sec\ TeV})^{-1}$$

http://iopscience.iop.org/article/10.1088/0004-637X/750/1/63/pdf

Gamma-Ray Observatories
A Comparison of Techniques

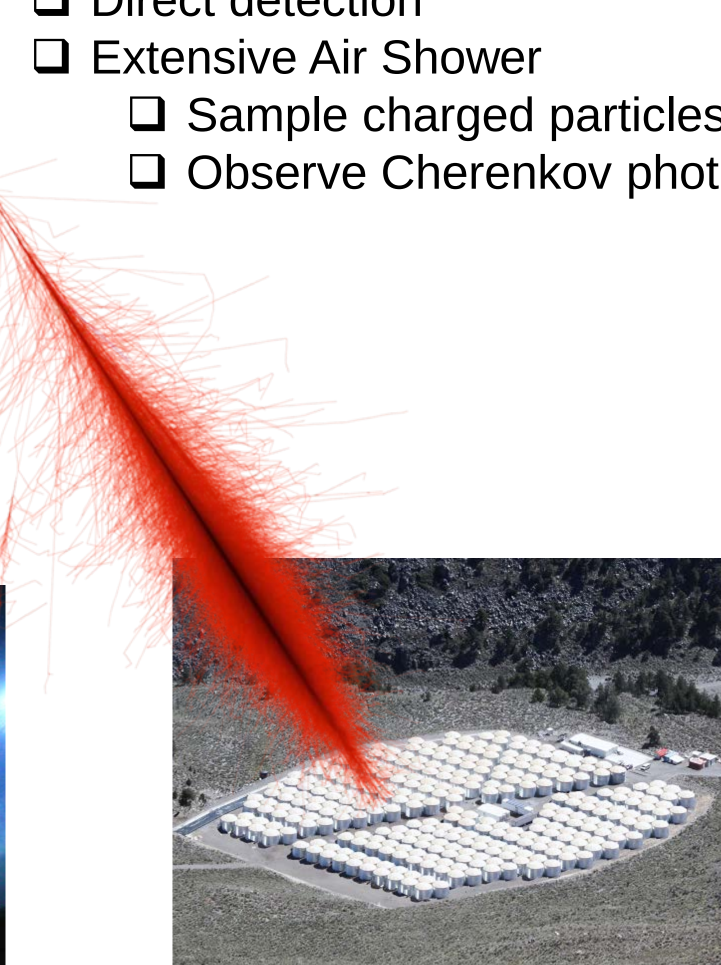
Satellite Based "HEP" detector

Complementary methods to observe Gamma Rays:

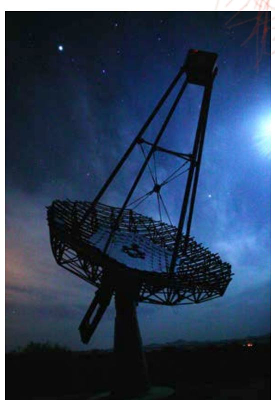
- ❑ Direct detection
- ❑ Extensive Air Shower
  - ❑ Sample charged particles at ground
  - ❑ Observe Cherenkov photons from EAS

Criteria

- ❑ Effective Area
- ❑ Field of View
- ❑ Hadron rejection
- ❑ Duty Cycle
- ❑ Resolution
- ❑ Energy Range



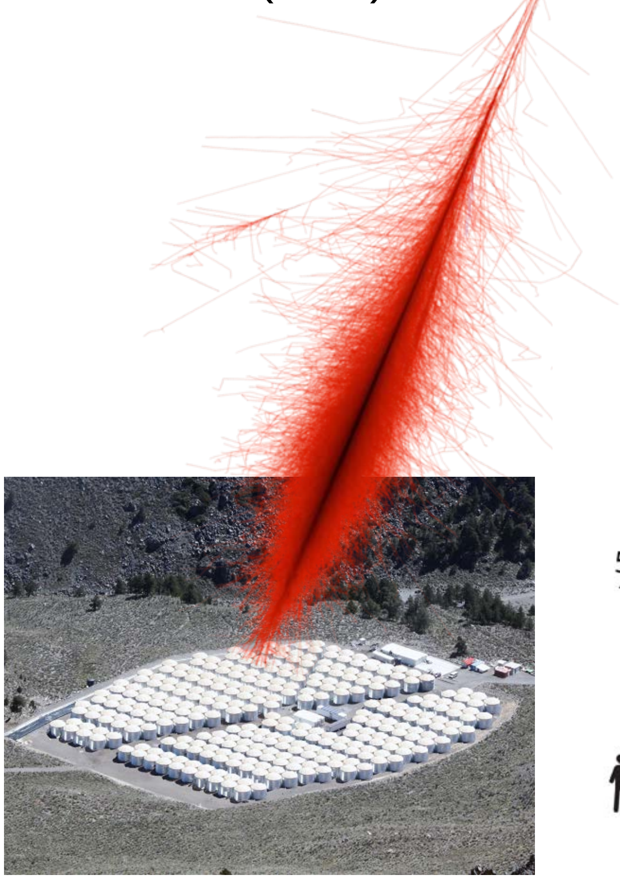
Imaging Atmospheric Cherenkov Technique



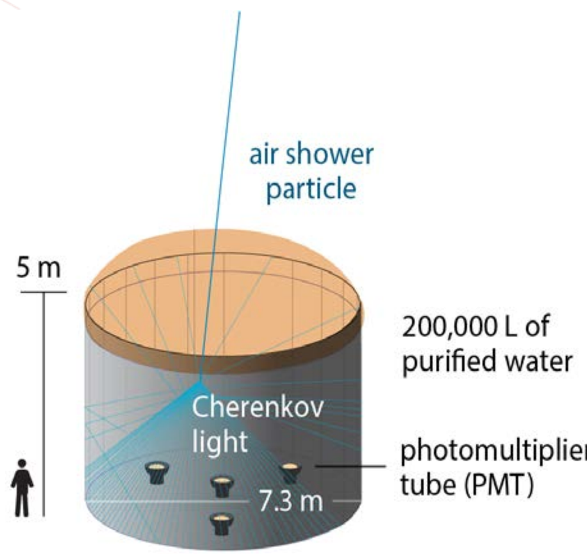
Surface Detector Array

HAWC Observatory Design Principles

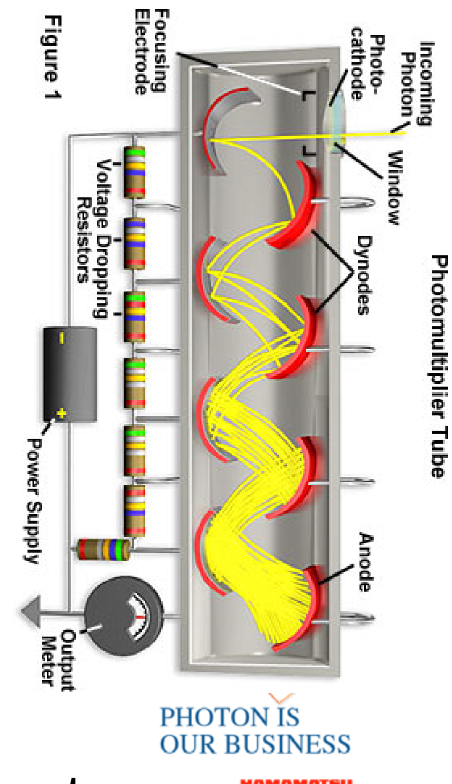
Atmosphere "converts" particle into an extensive air shower (EAS).



Water Cerenkov Detector Samples Extensive Air Shower particles by measuring their Cerenkov light emitted in water tank.



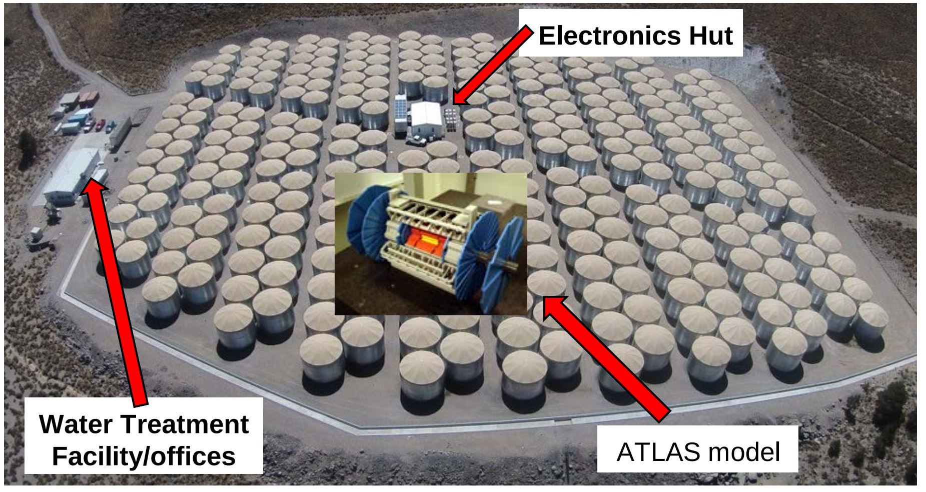
PMT Converts Cerenkov light into electrical signal.

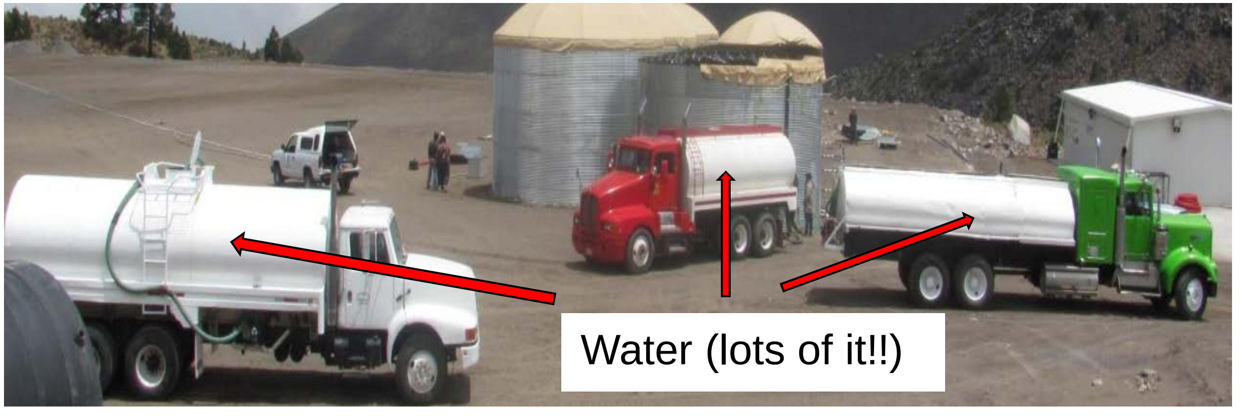


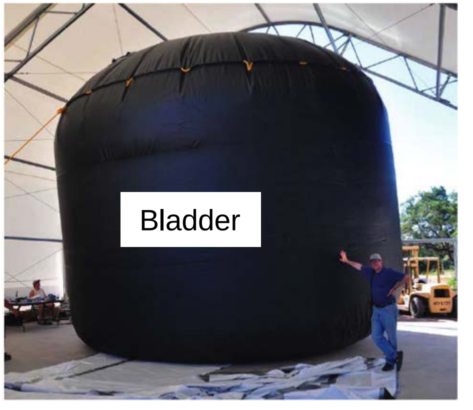
Based upon Milagro Experiment

HAWC Observatory Characteristics

- ❑ Based on Water Cerenkov Detector technique developed by Milagro Experiment
- ❑ Close packed array of 300 Water Cherenkov detectors
- ❑ Footprint covers ~180m x 140m ➔~22,500 m^2 effective area➔ Sensitive to higher energies
- ❑ Detector weight (300 tanks water only) 51,600 tons (ATLAS 7000 tons)
- ❑ Commercial water tanks 4.5m deep by 7.3m diameter
- ❑ Light-tight water bladder in steel support structure
- ❑ ~172,000 liters of treated water (4.1m depth, 172 tons)

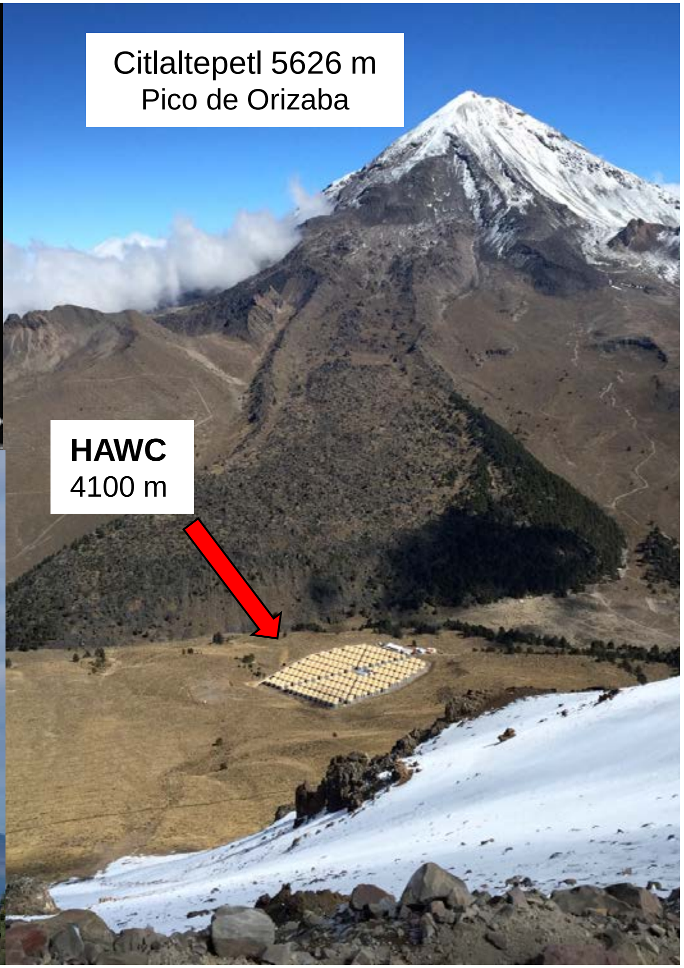


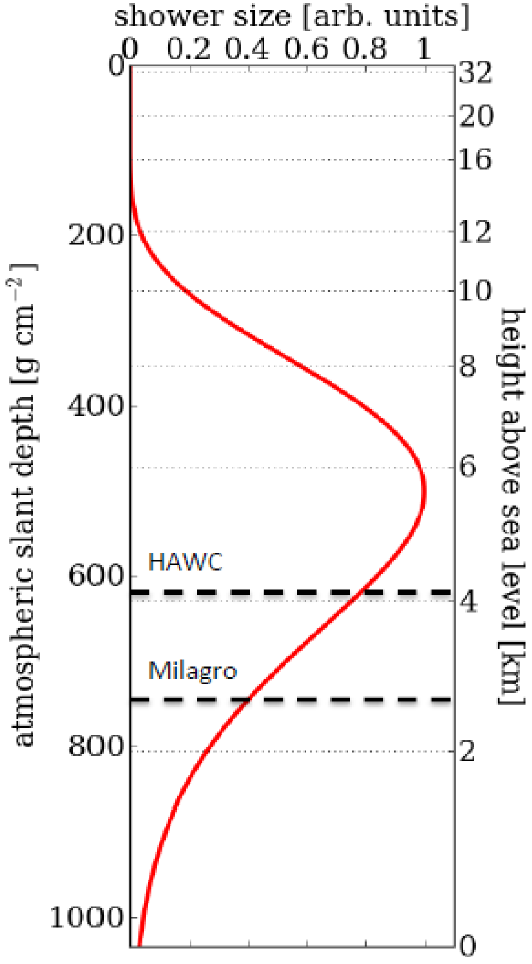




HAWC Observatory Characteristics

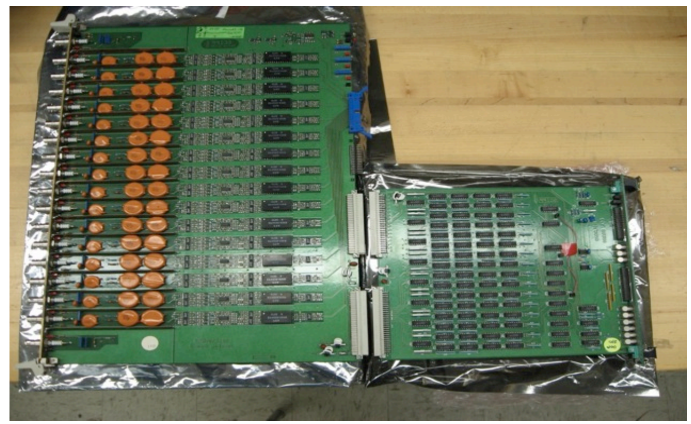
- Based on Water Cerenkov Detector technique developed by Milagro Experiment
- Close packed array of 300 Water Cherenkov detectors
- Footprint covers ~180m x 140m ➔~22,500 m^2 effective area➔ Sensitive to higher energies
- Sierra Negra, Mexico (18^0 59’ 41”N, 97^0 18’ 28” W)
- Altitude 4100 m a.s.l…~620 g/cm^2 ➔ Sample EAS closer to “shower max” for lower energies



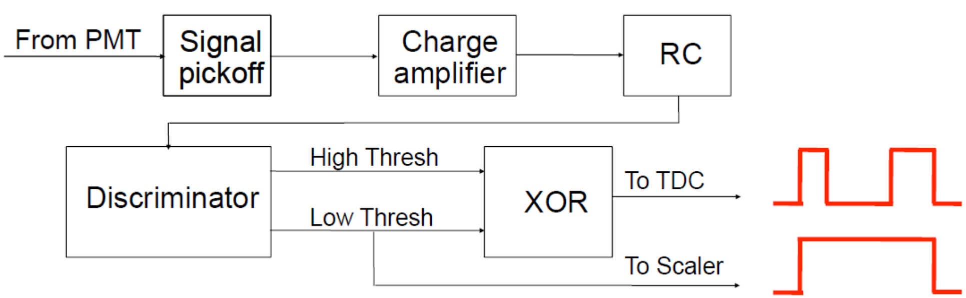


HAWC Observatory Characteristics
PMTs and Electronics

- ❑ Four Upward-Looking PMTs per tank
  - ❑ Three 8" Hamamatsu R5912 PMTs from Milagro
  - ❑ One 10" R-7081-MOD Hamamatsu in each tank
- ❑ Mix of refurbished Milagro electronics and new commercial electronics

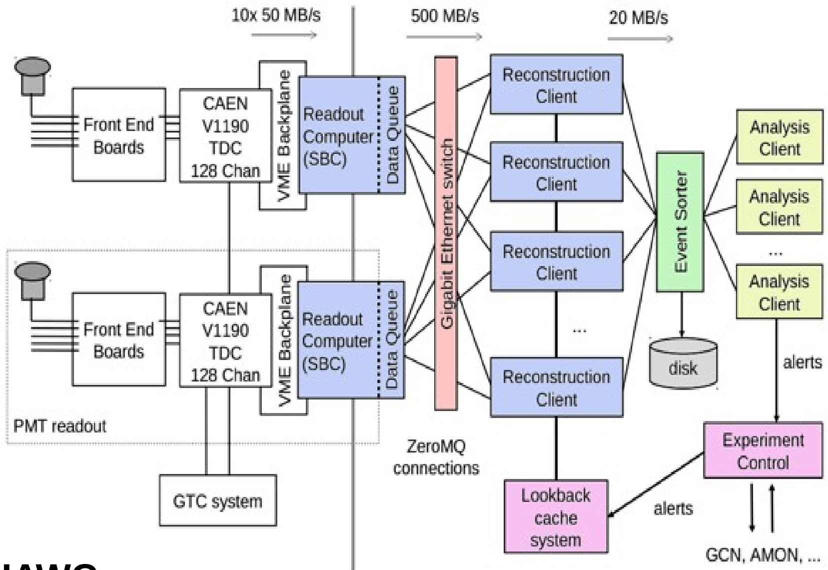


Time-Over-Threshold electronics

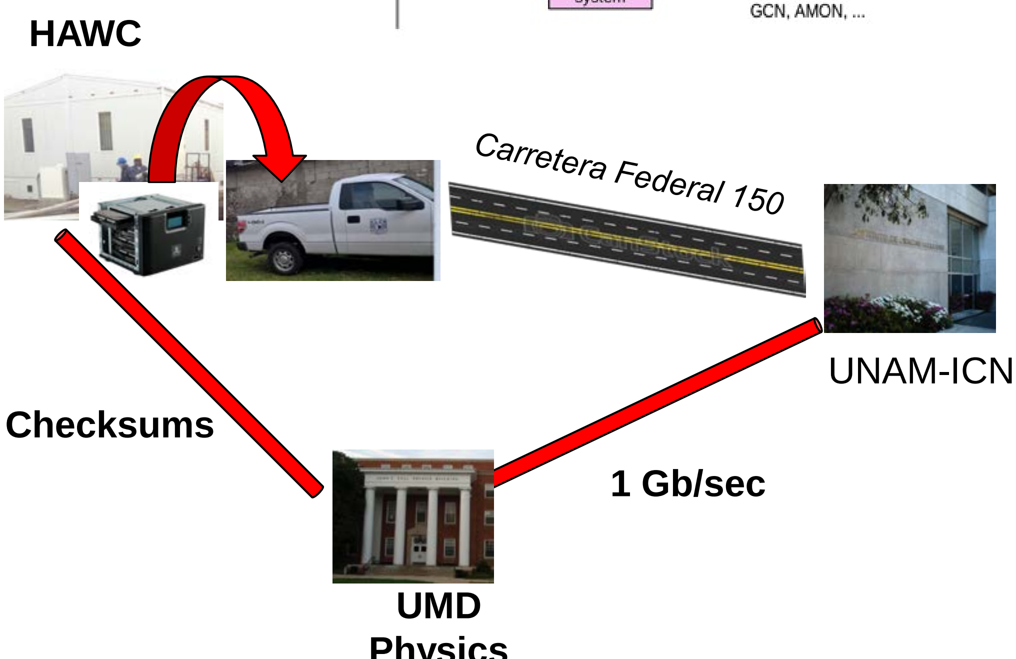


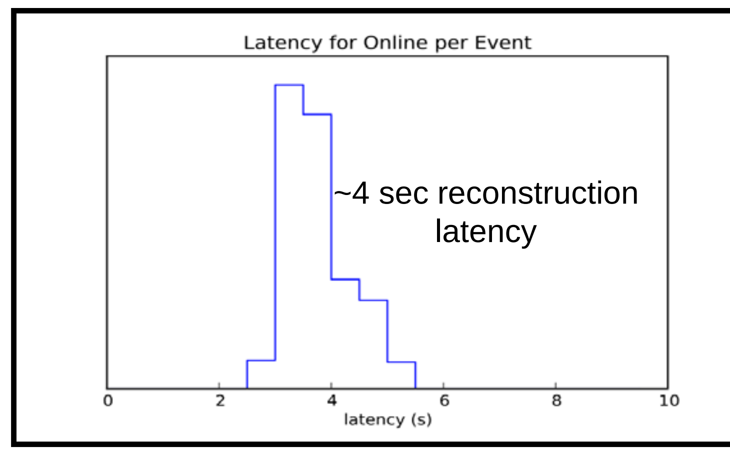
- ❑ Record data with CAEN VX1190 VME based TDCs
- ❑ Time over threshold proportional to charge
- ❑ Calibration using laser and fiber delivery to tanks
  - ❑ TOT→ charge
  - ❑ Timing offsets

HAWC Observatory Characteristics
DAQ/Data Handling

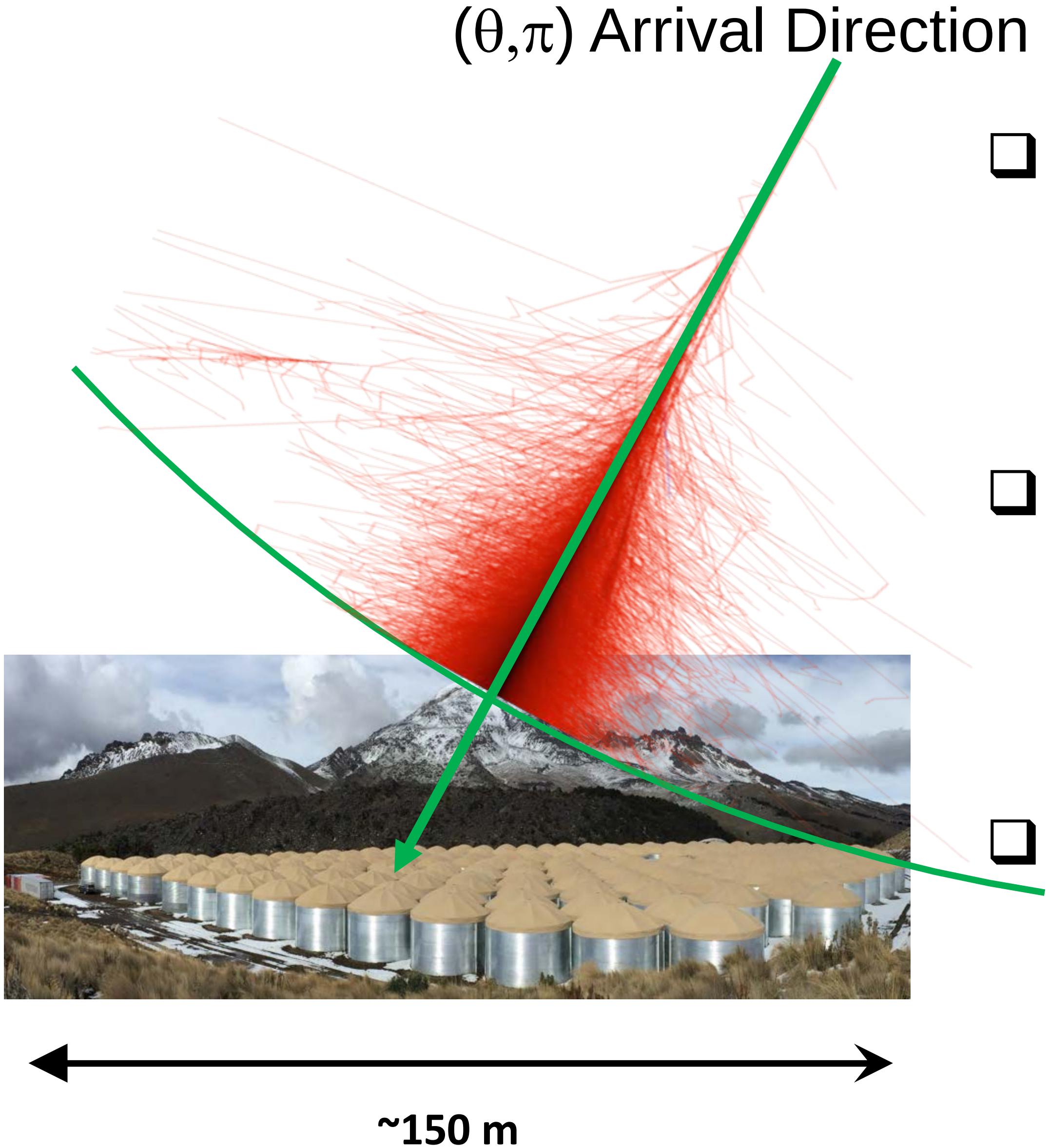


- ❑ 10-20 Khz data rate/PMT
  - ❑ ➔500 Mb/s for 300 tanks
- ❑ Triggerless DAQ:data processed entirely by software
  - ❑ Extract air-shower events
  - ❑ Measure rates
    - ❑ Single Muons
    - ❑ PMT rates
  - ❑ Reconstruction Latency 4 seconds
  - ➔ GRB trigger
- ❑ ~10-20 MB/sec stored ➔2TB /day
  ~Petabyte scale storage





HAWC Detector Event Reconstruction



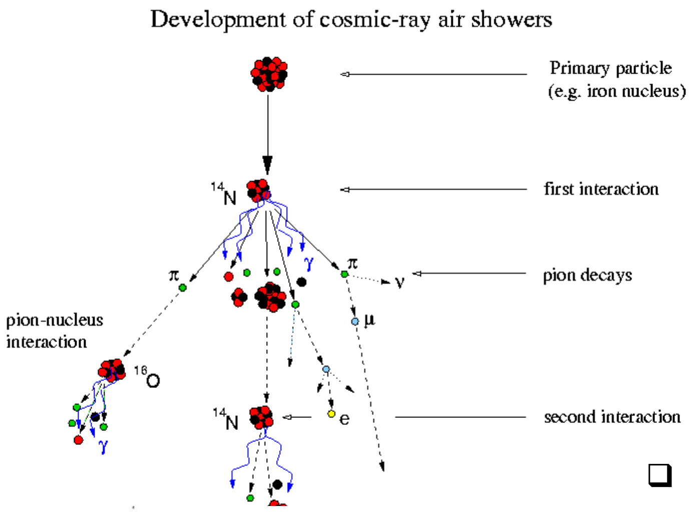
- ❑ **Shower Core Position**
  Location and Charge of PMT hits used to in Lateral Distribution fit (NKG function) to determine core location

- ❑ **Shower Axis Direction**
  Location and time of PMT hits used to determine shower front. Arrival direction is perpendicular to this “plane”.

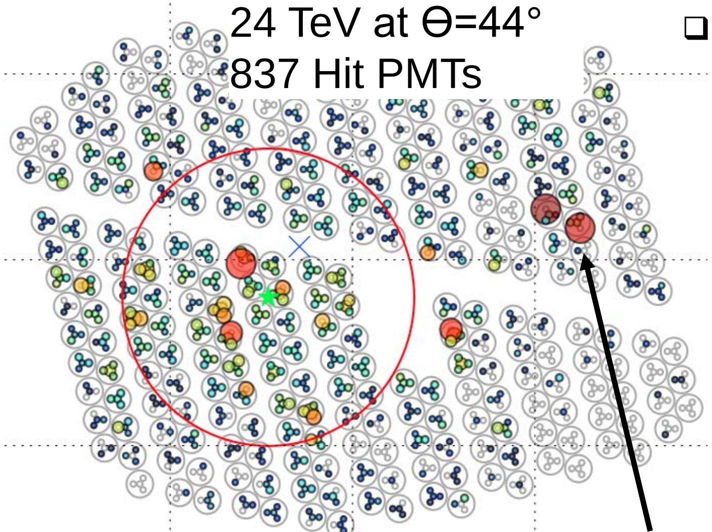
- ❑ **Shower Energy**
  Estimated from event size, PMT charges

HAWC Detector Performance
Hadron/Photon Separation

Hadrons



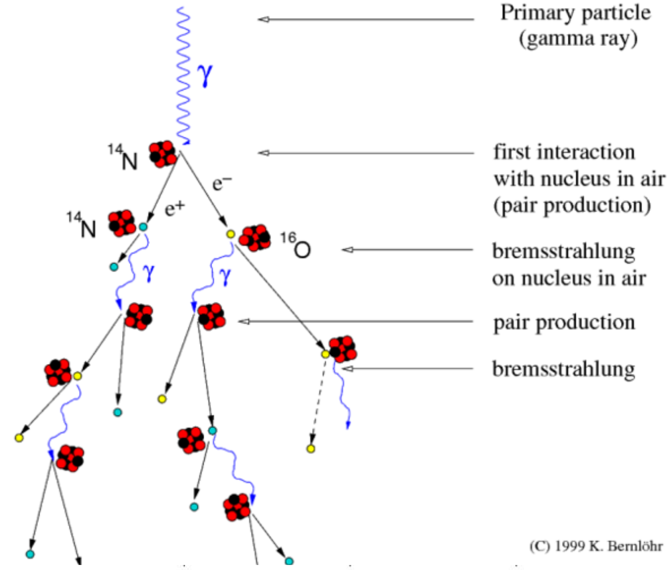
Simulated Proton
24 TeV at ϴ=44°
837 Hit PMTs

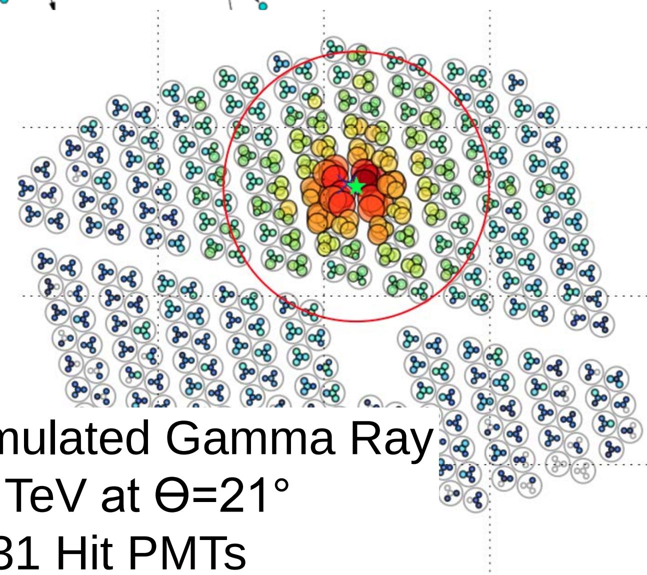


Energy deposited away from core

- One person's Signal….is another person's background!!!
- Hadron induced extensive air showers are "clumpier" than gamma induced EAS

Photons

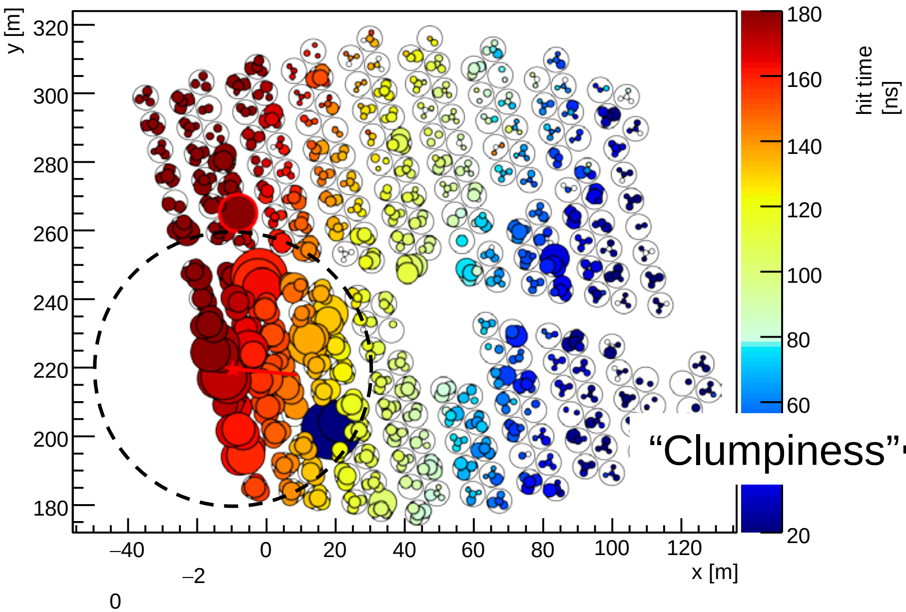




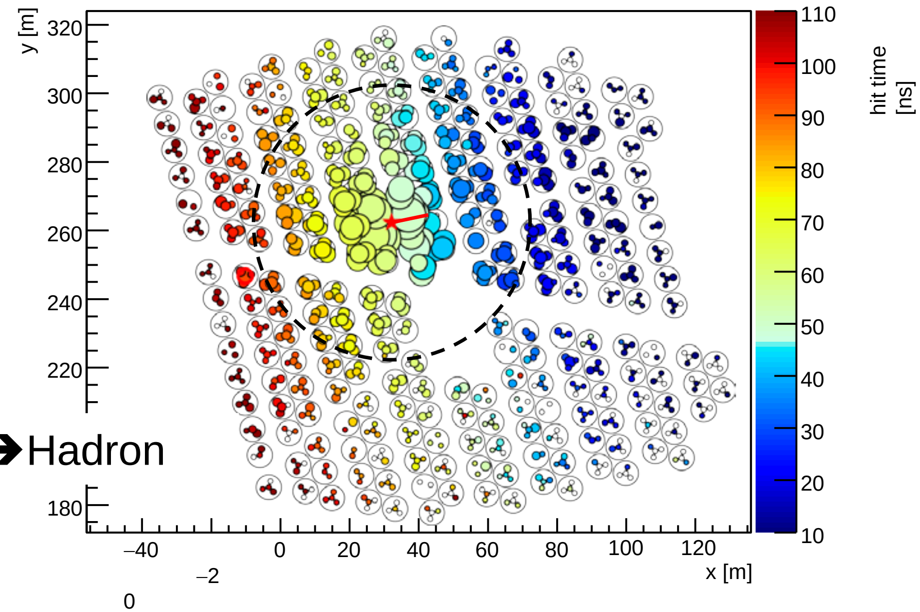
Simulated Gamma Ray
21 TeV at ϴ=21°
1131 Hit PMTs

HAWC-250 Data Events

Likely Cosmic-Ray Event

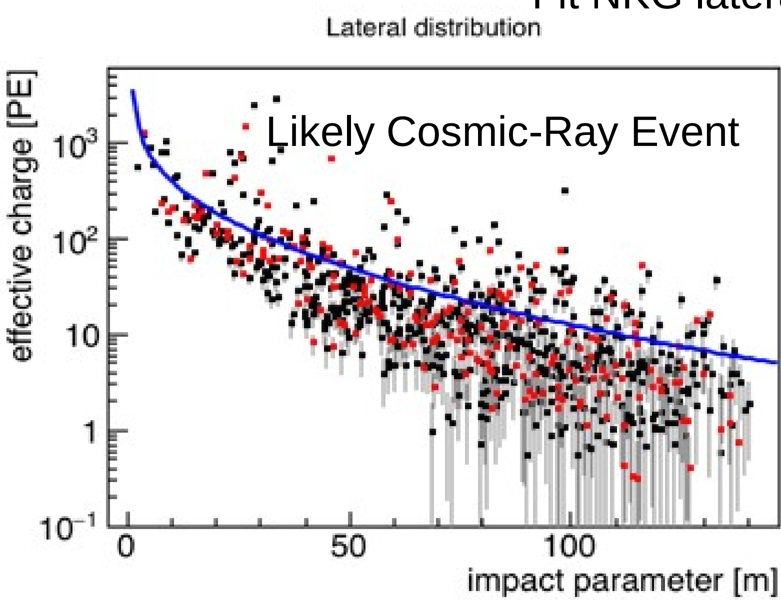


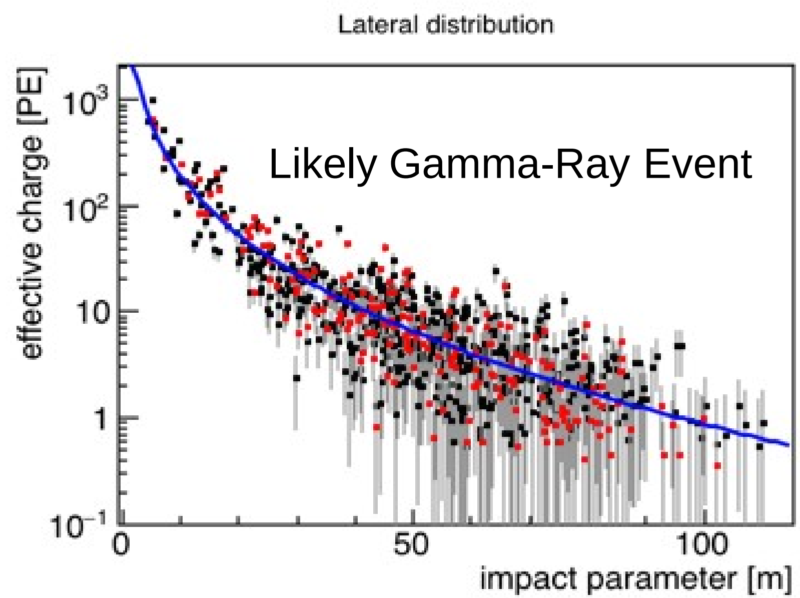
Likely Gamma-Ray Event



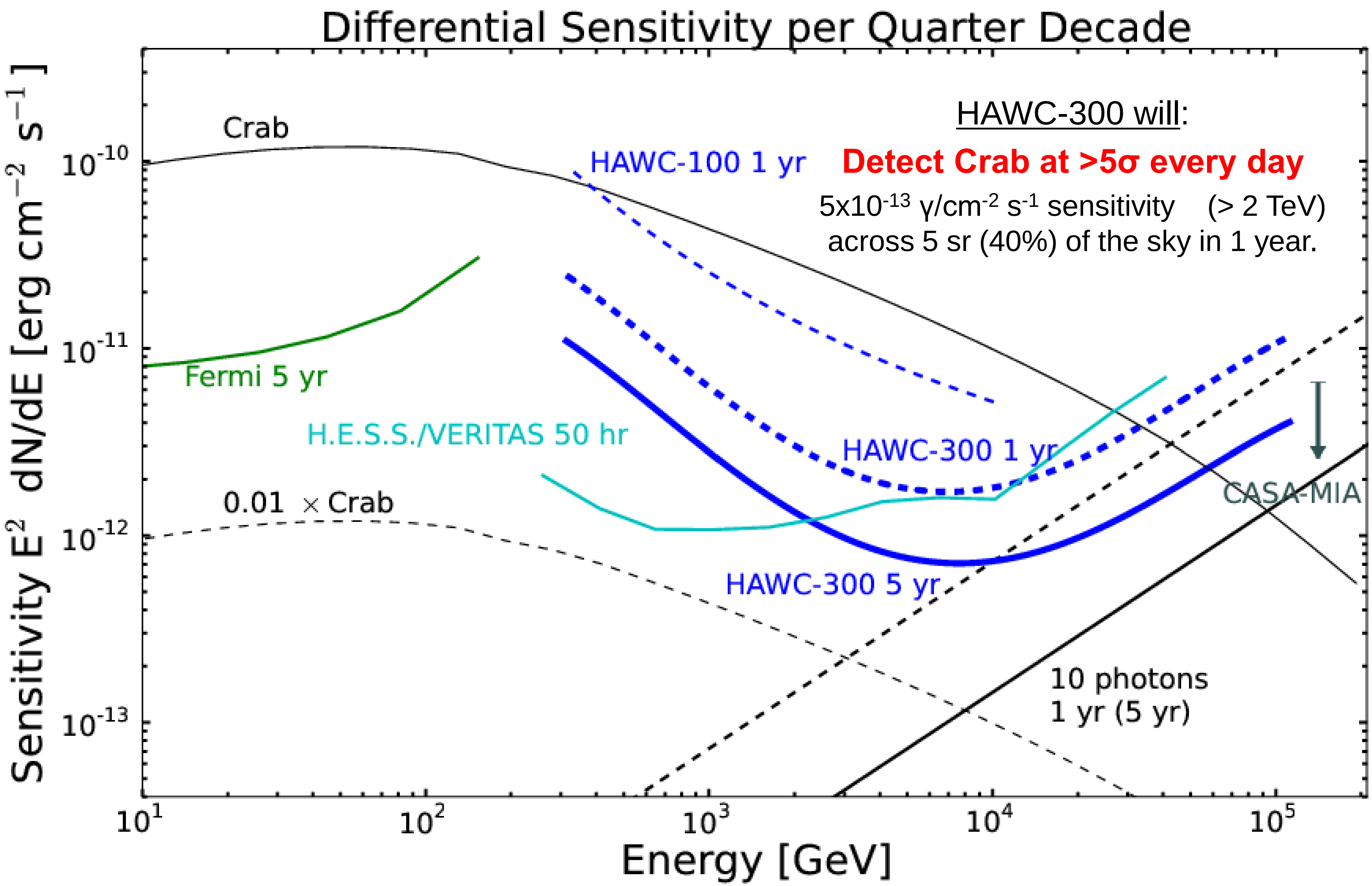
“Clumpiness”➔Hadron

Fit NKG lateral –distribution function





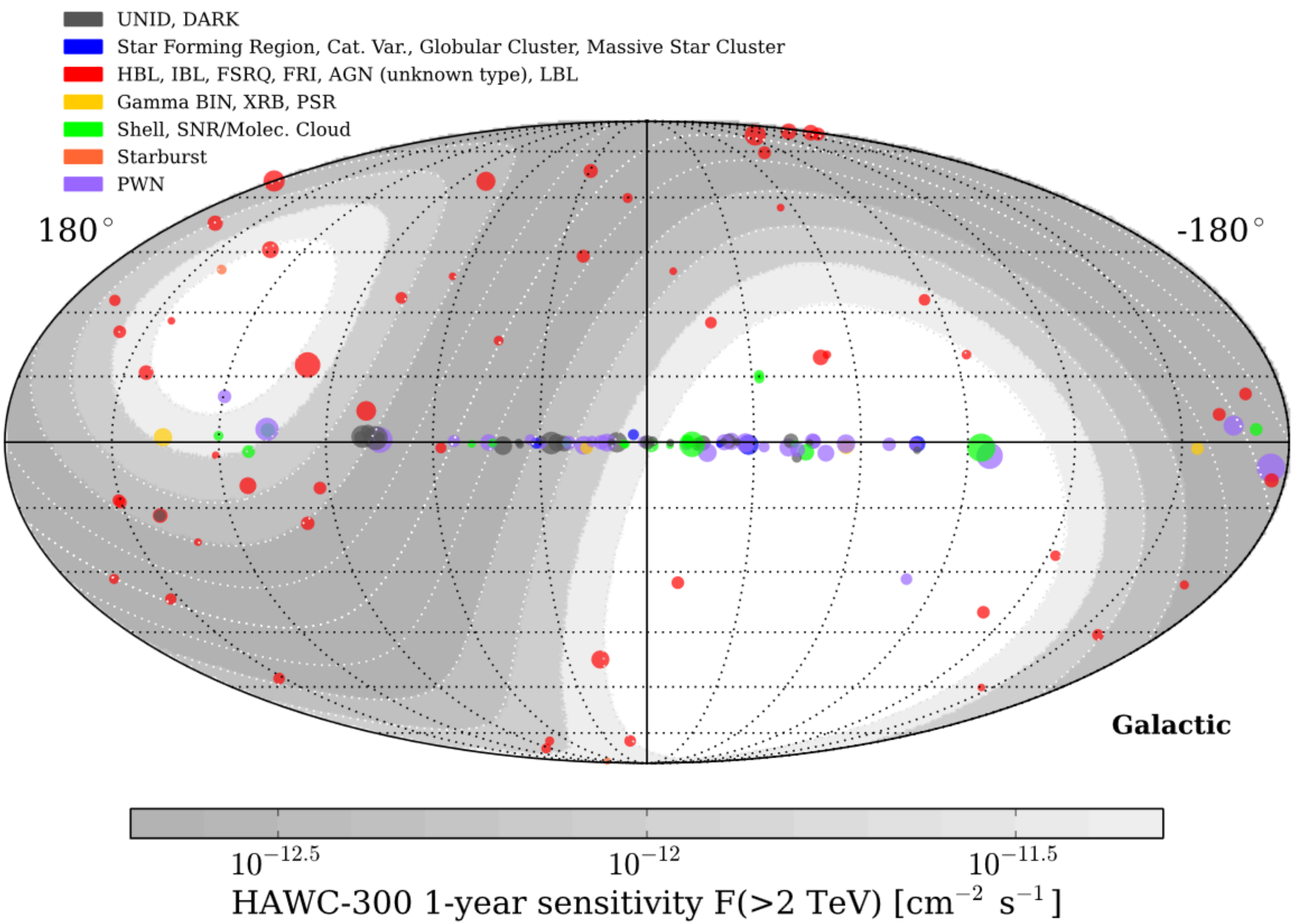
HAWC Detector Performance
Sensitivity to Point-Like Sources



[Astropart. Phys. 50-52 (2013), arxiv:1306.5800]

HAWC Detector Performance
Observable Sky

Known sources are shown, but much of the high latitude sky has not been observed deeply at TeV energies



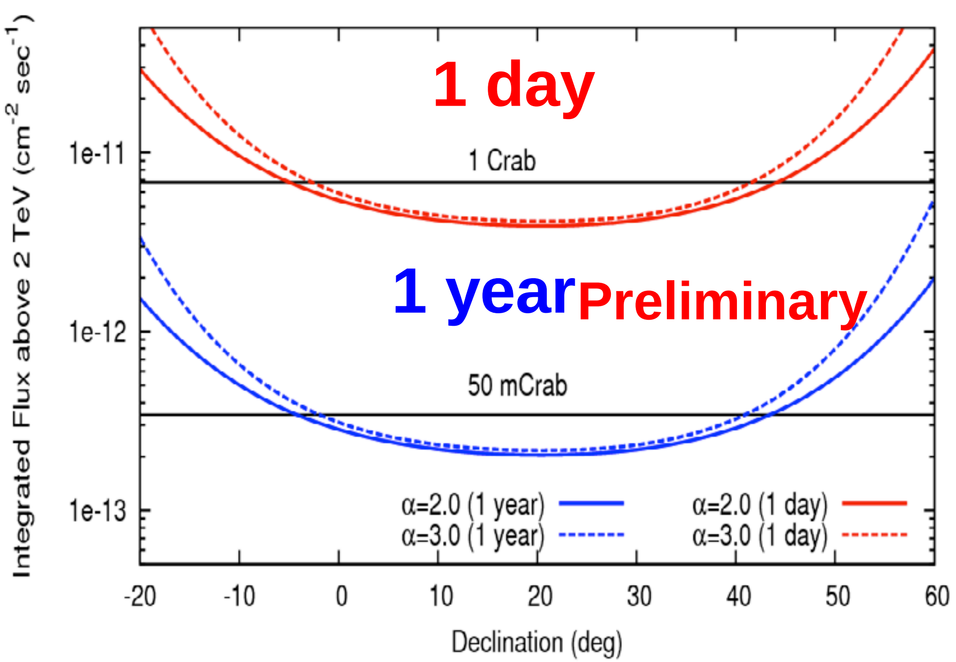
HAWC Capabilities

All-Sky Survey

- A major goal of HAWC is to perform a complete, unbiased TeV survey of the gamma-ray of the sky.
- HAWC has wide FOV and ~100% duty cycle
- Sky survey (20 mCrab in 5 years)
- ~6 σ on the Crab in 1 transit (Milagro 120 days)
- 40% overlap with HESS galactic plane
- 90% overlap with ICE-CUBE sky
- Spatial/Temporal overlap VERITAS
- Galactic Center at 48^0 from zenith, about 10% of Crab

Detect Crab at >5σ every day

$5x10^{-13}$ γ/cm^{-2} s^{-1} (sensitivity > 2 TeV) across 5 sr (40%) of the sky in 1 year.



HAWC Capabilities

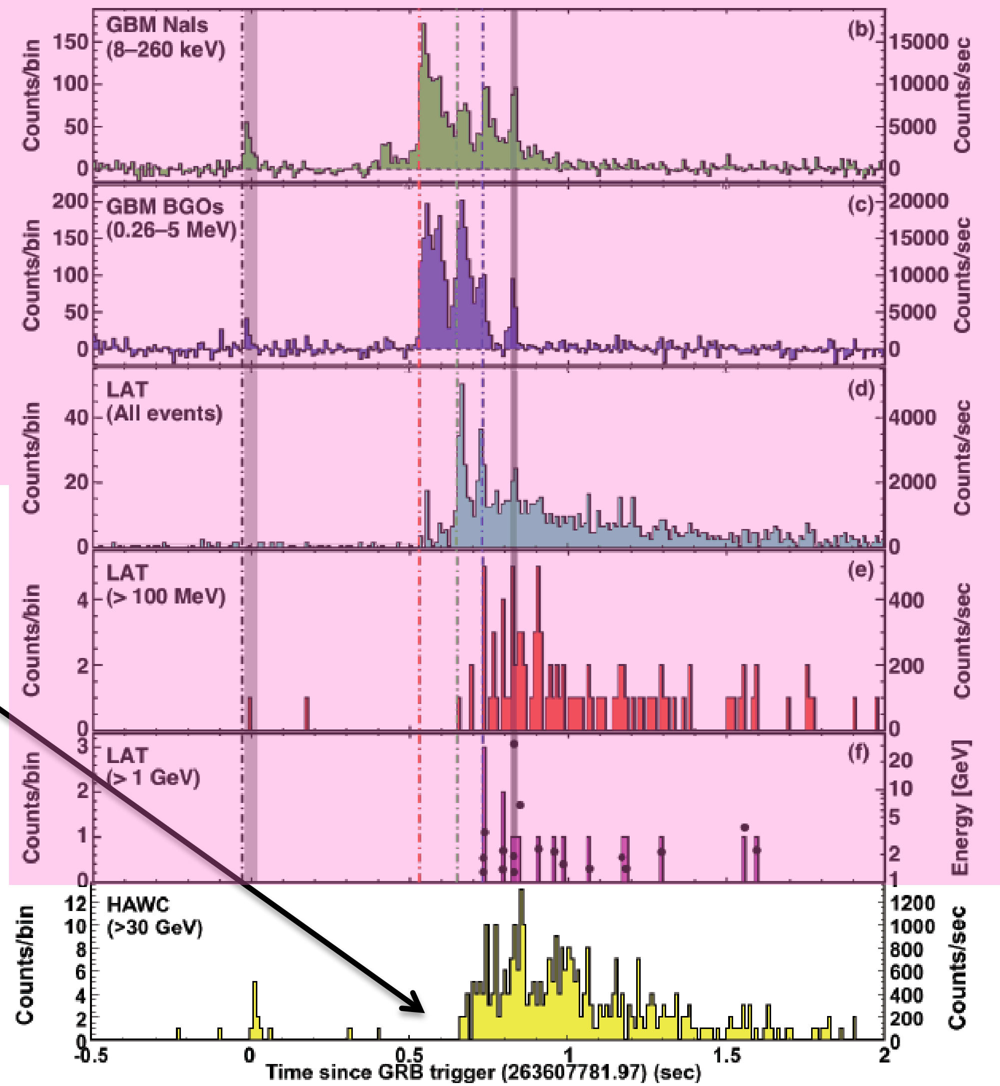
Sensitive to Transient Sources

Fermi observation of GRB090510, z=0.9

- Highest Observed Energy was 33 GeV with 16 γ-rays >1 GeV
- Constrained Lorentz Invariance at the Plank Mass scale

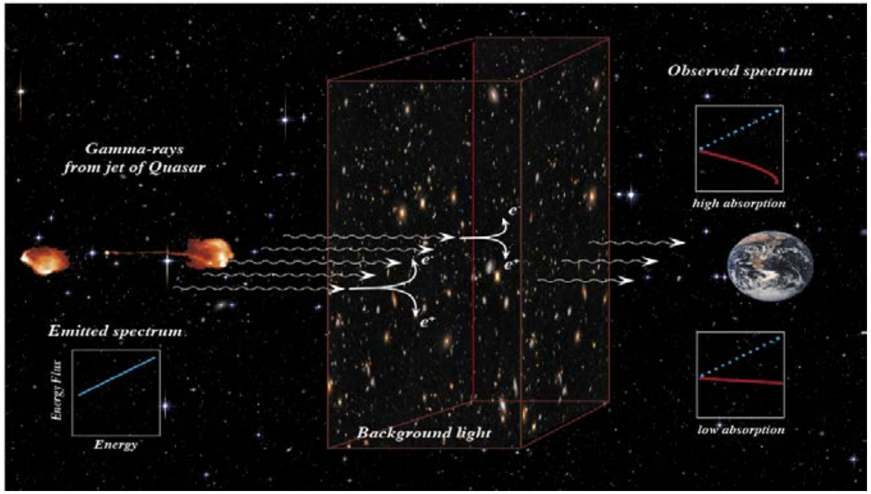
HAWC would detect this GRB if it occurred in FOV.

Gilmore& Taboada, (arXiv:1306.1127), predict 1.65 GRB/yr detected by HAWC



HAWC Capabilities
Sensitive to Distant Sources

- ~40 known TeV AGN, yet most of the
  extragalactic sky has not been surveyed.
- TeV spectra from distant sources probes:
  - Cosmology of Extragalactic Background Light
  - Sources of UHECR
  - Intergalactic Magnetic Field
  - Axion Like Particles
  - $\gamma \rightarrow a \rightarrow \gamma$ (Hooper & Serpico, PRL 2007)



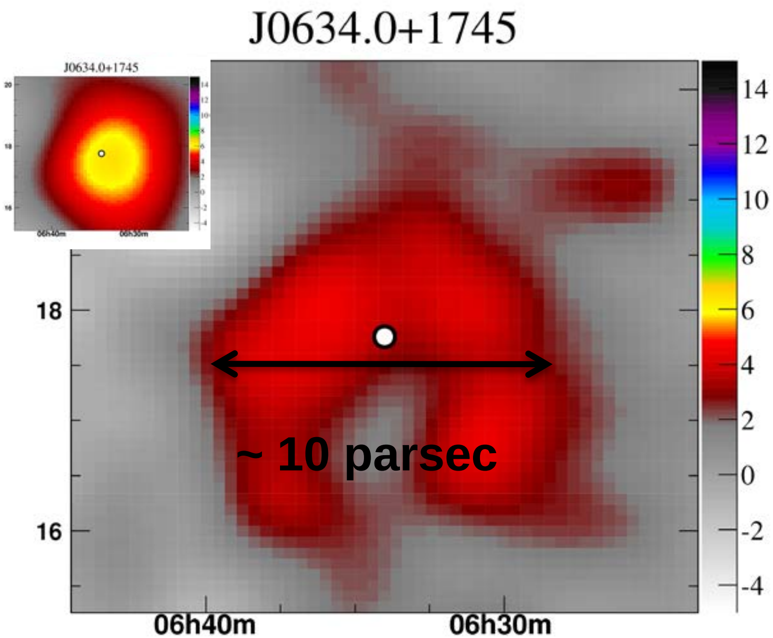
Essey, Kalashev, Kusenko, Beacom, PRL 2010

HAWC will survey the extragalactic sky, measure multi-TeV spectra and it's variability, and enable multimessenger observations through prompt notification of flaring activity.

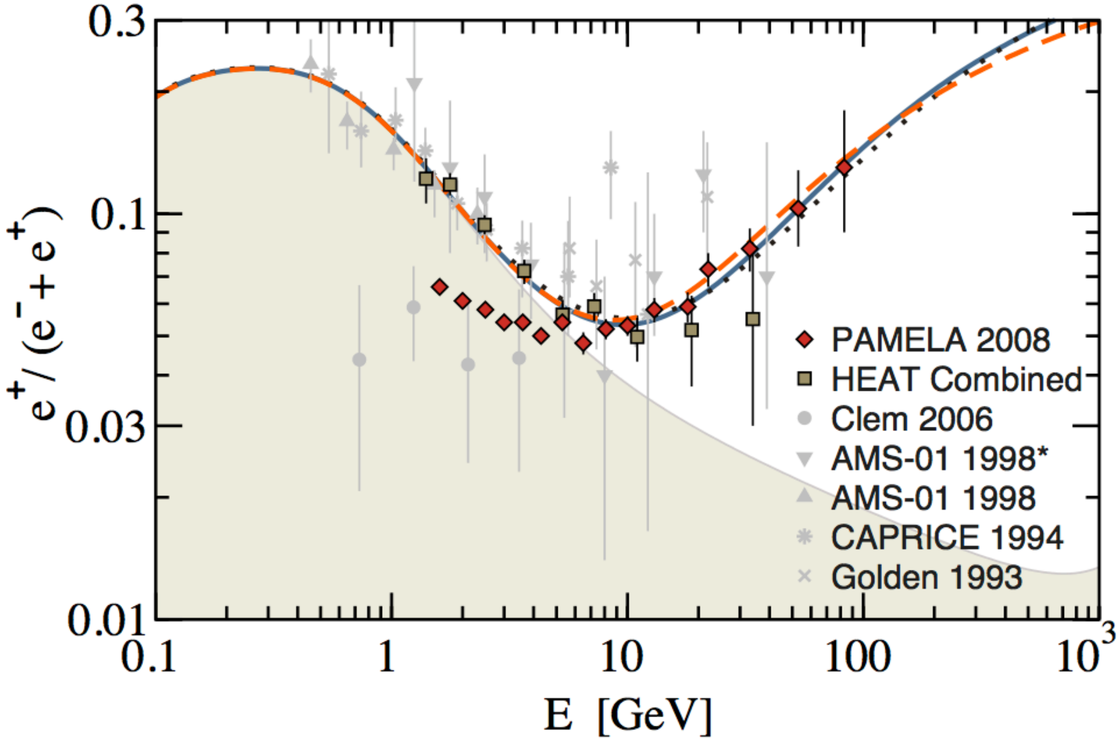
HAWC Capabilities

Sensitive to Extended Sources

Milagro's Detection of an extended excess coincident with Geminga



PAMELA's positron excess is well fit given Milagro's flux from Geminga



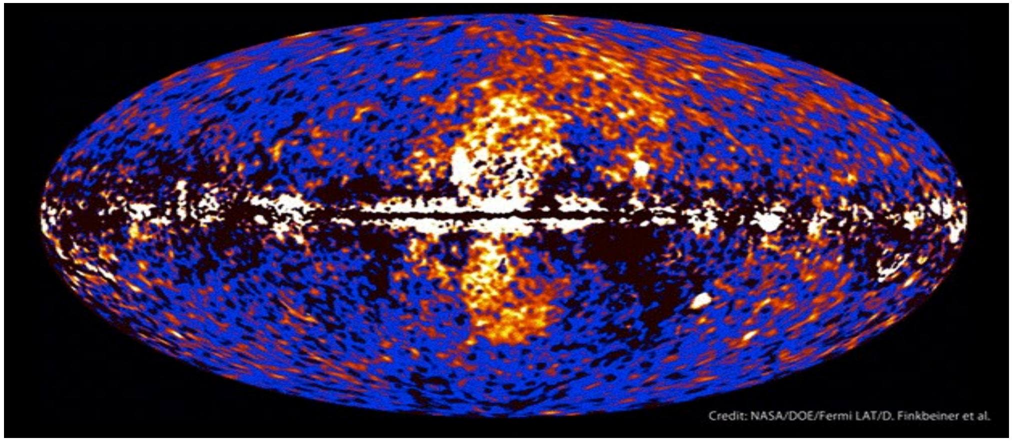
Yüksel, Kistler, Stanev PRL 2009

HAWC will detect Geminga with >50σ to measure spectra and map diffusion near source.

HAWC Capabilities

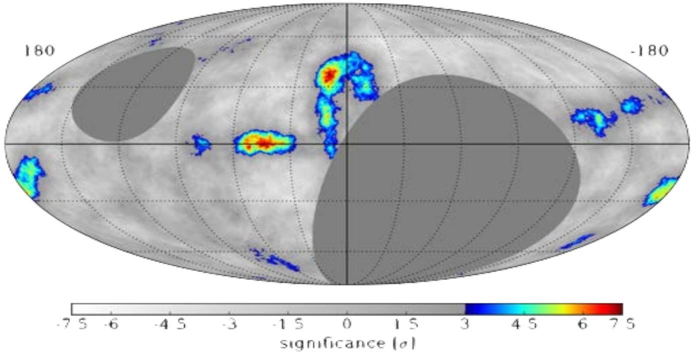
Sensitive to Diffuse Emission

Fermi observation of Diffuse Emission Lobes from Milky Way

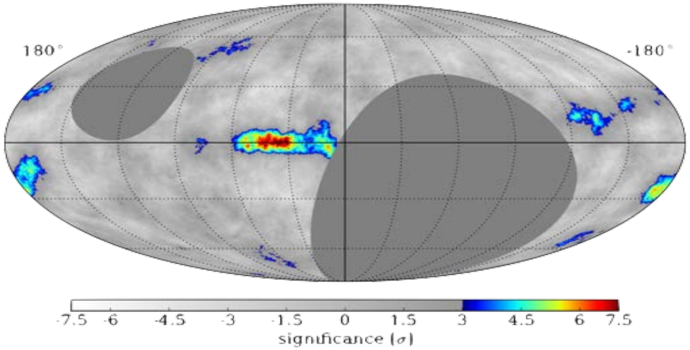


Simulation of 3 years of HAWC data

H. Ayala Solares (MTU), ICRC 2013



No Spectral Cutoff

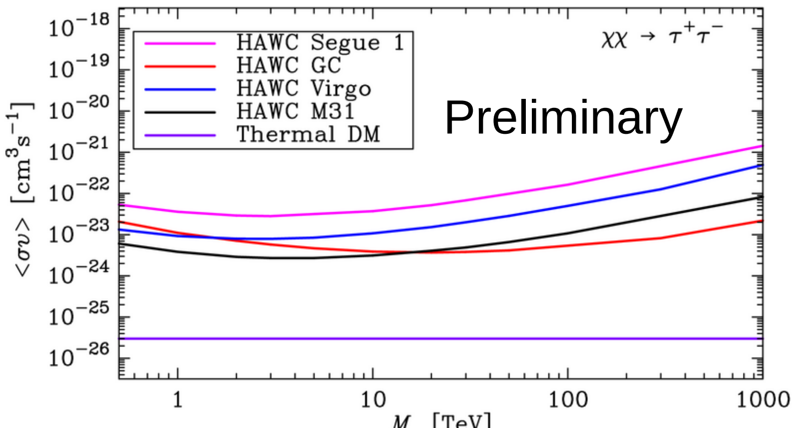


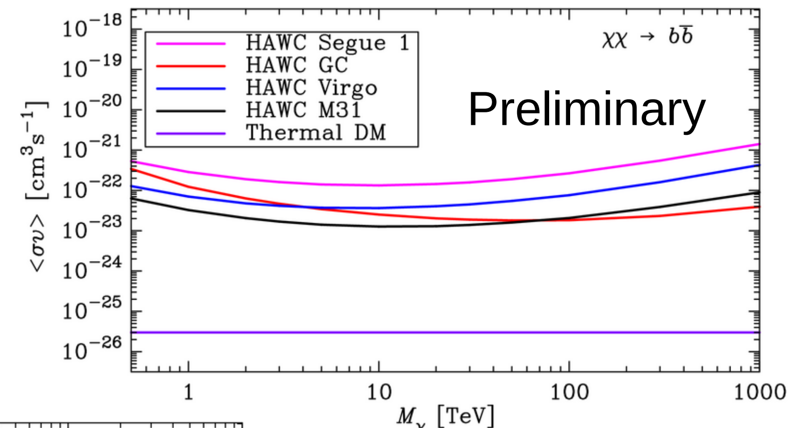
150 GeV Spectral Cutoff

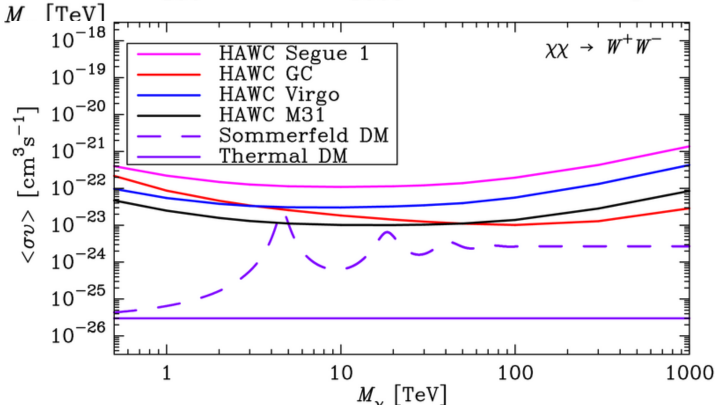
HAWC Capabilities

Sensitive to Dark Matter Annihilation

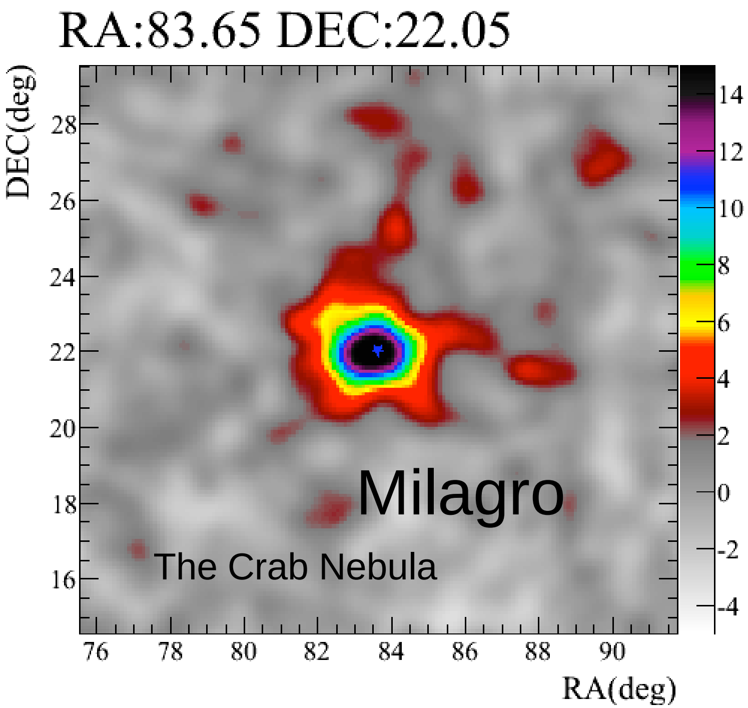
- Beyond the Standard Model of Particle Physics
- Satellite galaxies have large Mass, but small Luminosity and are thus dark matter rich
  - HAWC has sensitivity to higher mass WIMPS
  - Recently higher M/L galaxies have been found by Sloan Deep Survey
  - HAWC will observe all M/L galaxies in half the sky, *even if L=0*





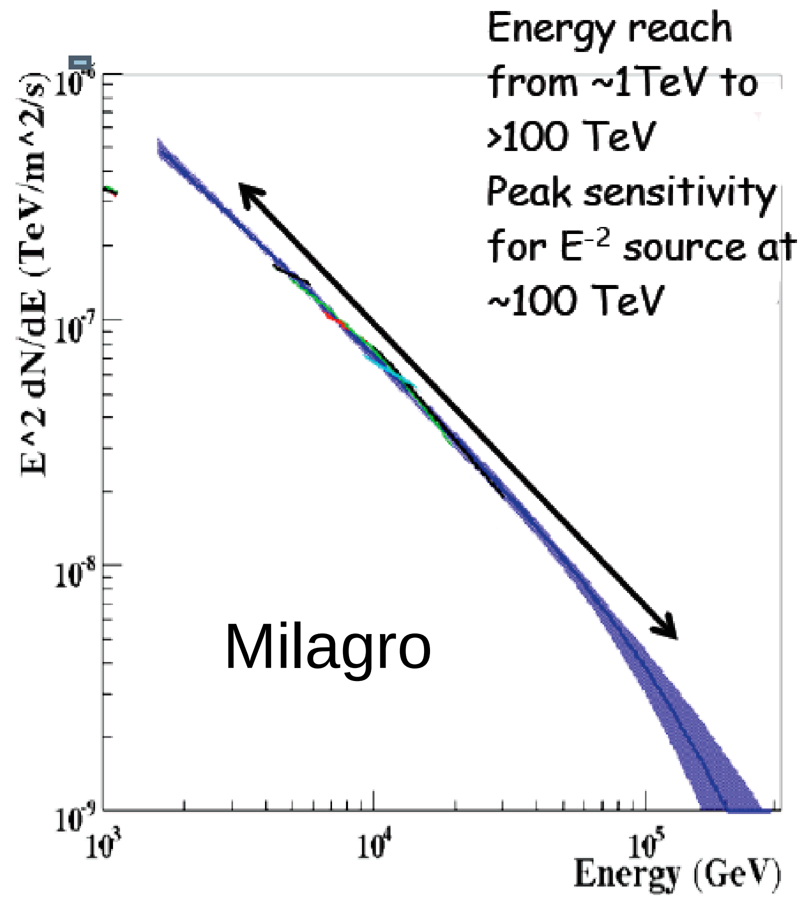


HAWC Capabilities
Energy Spectrum Measurements

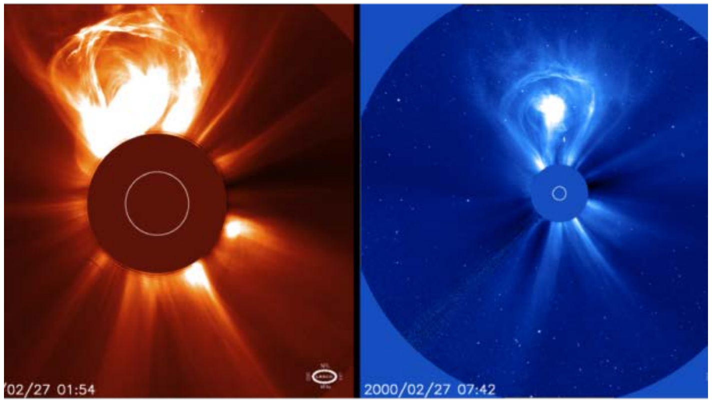


HAWC will be able to measure spectra to energies beyond 100 TeV for a source as bright as the Crab Nebula….

Peak Sensitivity for E^{-2} source at ~100 TeV



HAWC Capabilities
Solar/Heliosphere Physics



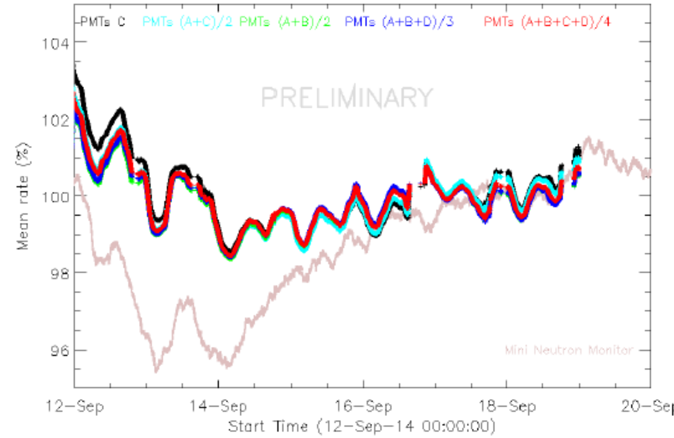


Figure 2: Forbush Decrease observed by HAWC and a mini neutron monitor located at HAWC's site on September 14, 2014.

THE ASTROPHYSICAL JOURNAL, 801:5 (8pp), 2015 March 1

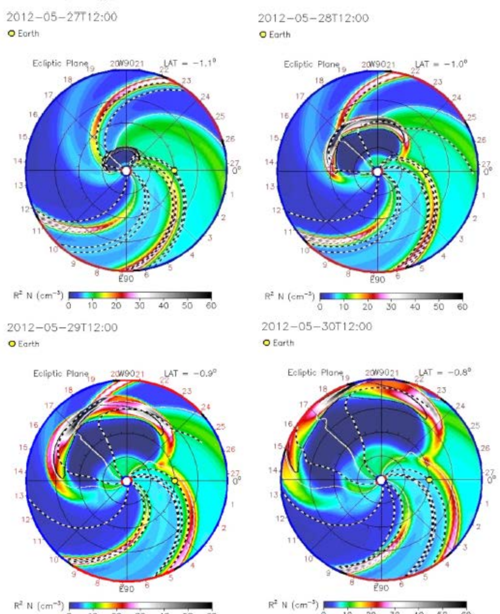
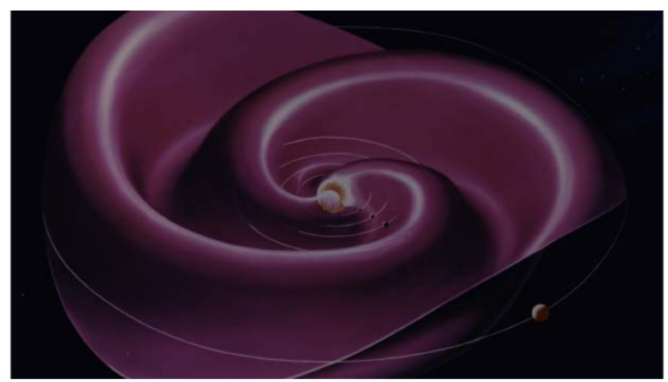


Figure 4. Snapshots of the Enlil model run at four times during the 2012 May 30 CME's propagation through the inner heliosphere. The dates shown are for 12 UT on 27 (top-left), 28 (top-right), 29 (lower-left), and 30 (lower-right). Blue colors represent low proton density and red, white and gray represent very high density. Earth is marked as the yellow circle and the Sun is the white circle.

Coronal Mass Ejections and variability of Magnetic Field of the Heliosphere modify the measured flux of cosmic rays on Earth.

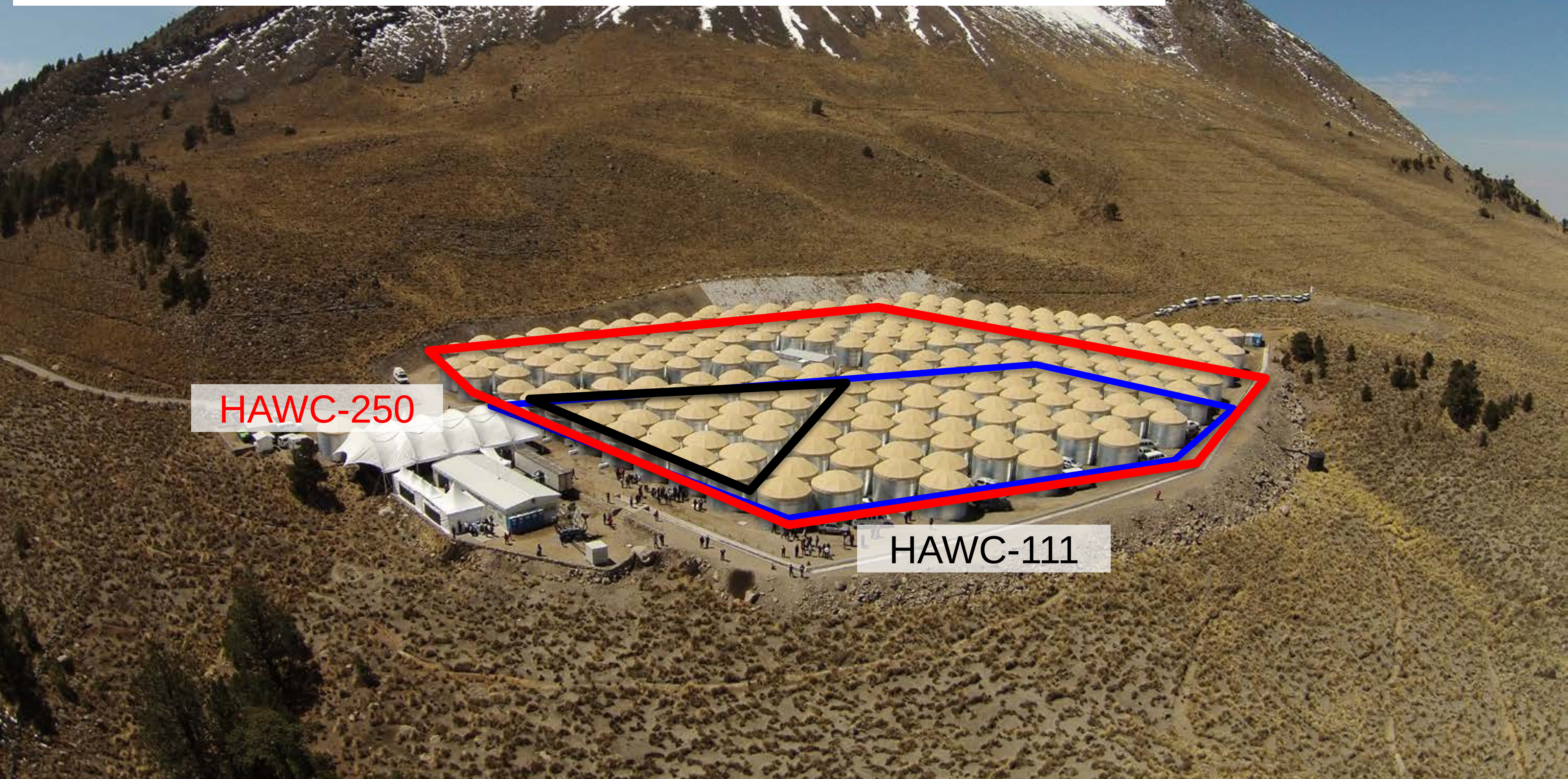


http://omniweb.gsfc.nasa.gov/

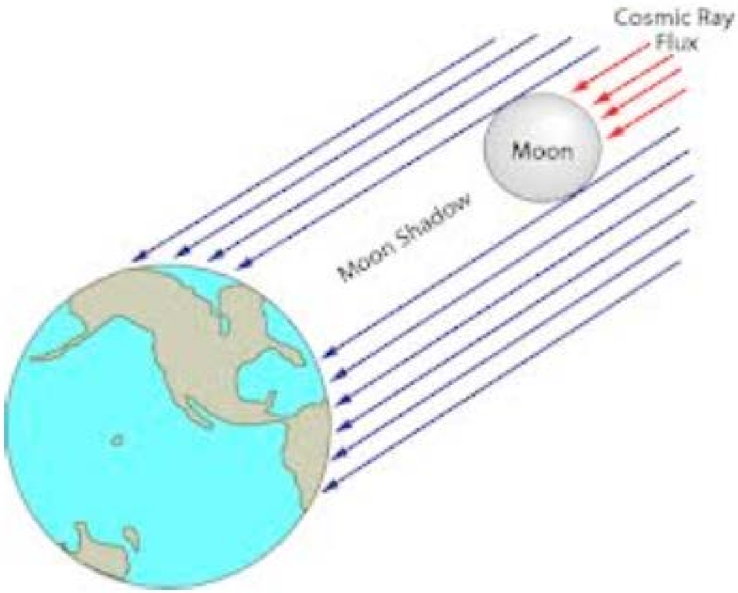
http://iopscience.iop.org/article/10.1088/0004-637X/801/1/5/pdf

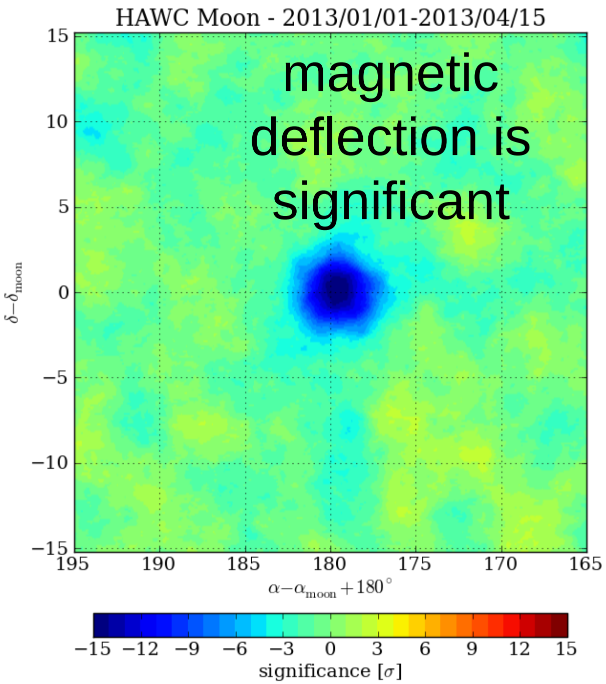
HAWC Construction

- HAWC Funding Starts: February 2011
- HAWC-30: August 2012.
- HAWC-111: Operations Begins: August 2013
- HAWC-250: November, 2014
- HAWC Inauguration, HAWC-300: March, 2015
- HAWC expansion plans (outrigger array) have been funded

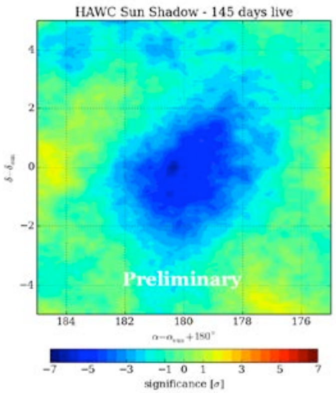


HAWC Observations
Shadow of Moon and Sun

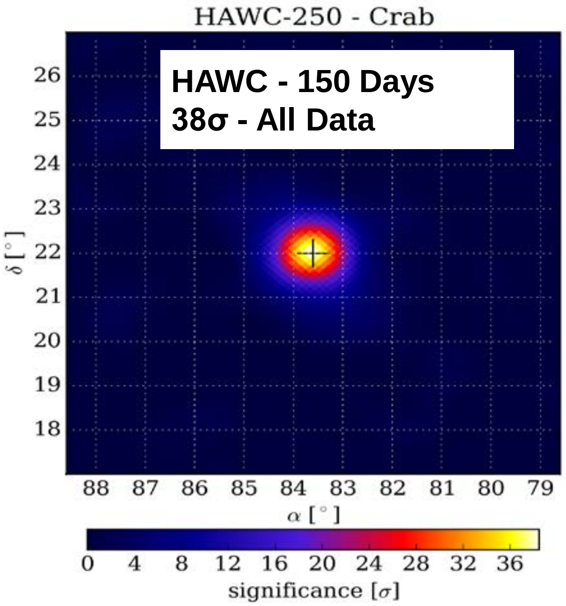


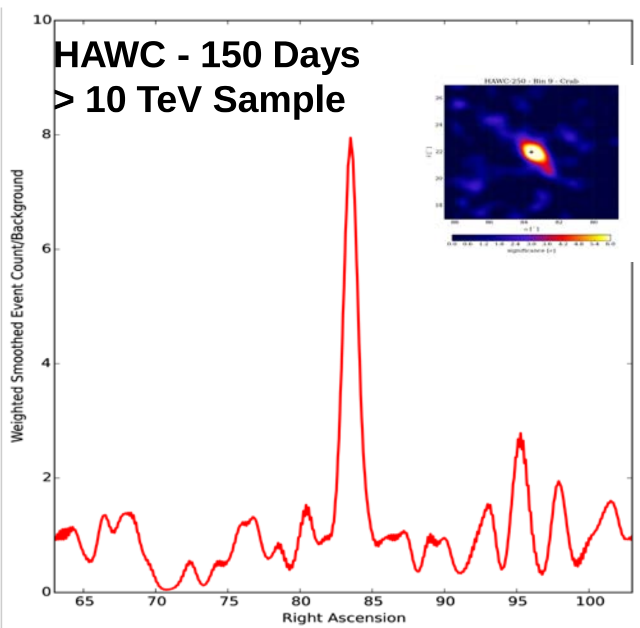


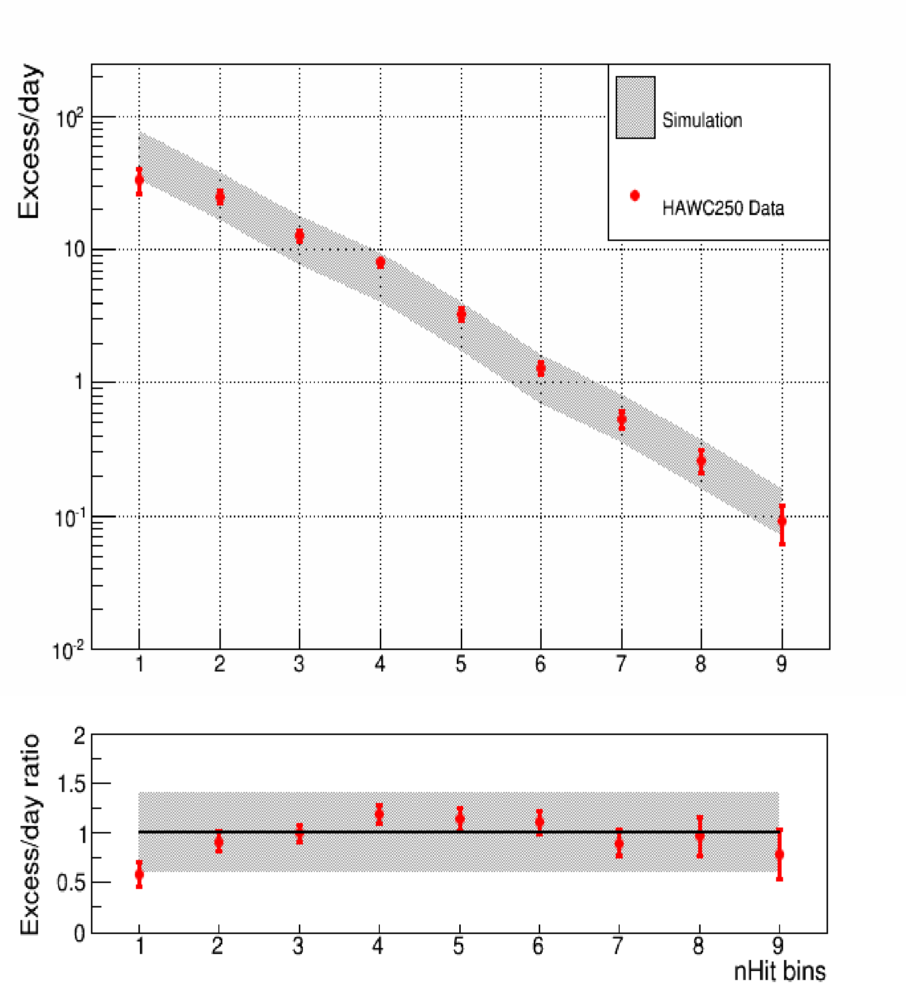
Useful for calibration, the expected angular shift due to earth's magnetic field can be used to study energy calibration and pointing.



Crab Nebula: Performance Benchmark
HAWC Signal







Seeing the Right Number of Gamma Rays…

HAWC First Results
as reported at 34th ICRC

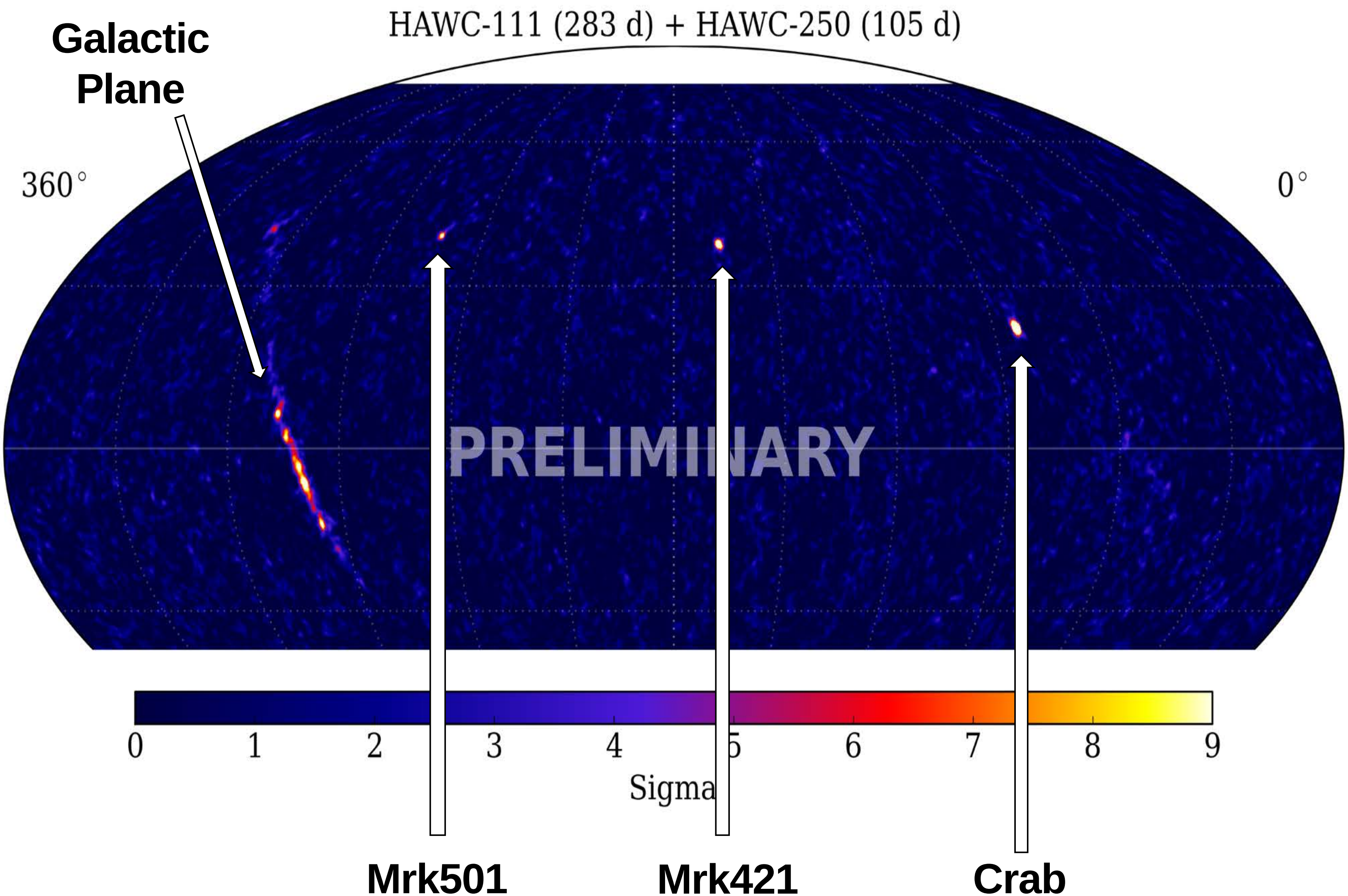
- 31 Contributions

  - Extra-Galactic Physics: 6 Contributions
  - Galactic Physics: 7 Papers
  - Cosmic-Ray Physics: 5 Papers
  - Fundamental Physics: 5 Papers
  - General Detector: 8 Papers

http://arxiv.org/html/1508.03327

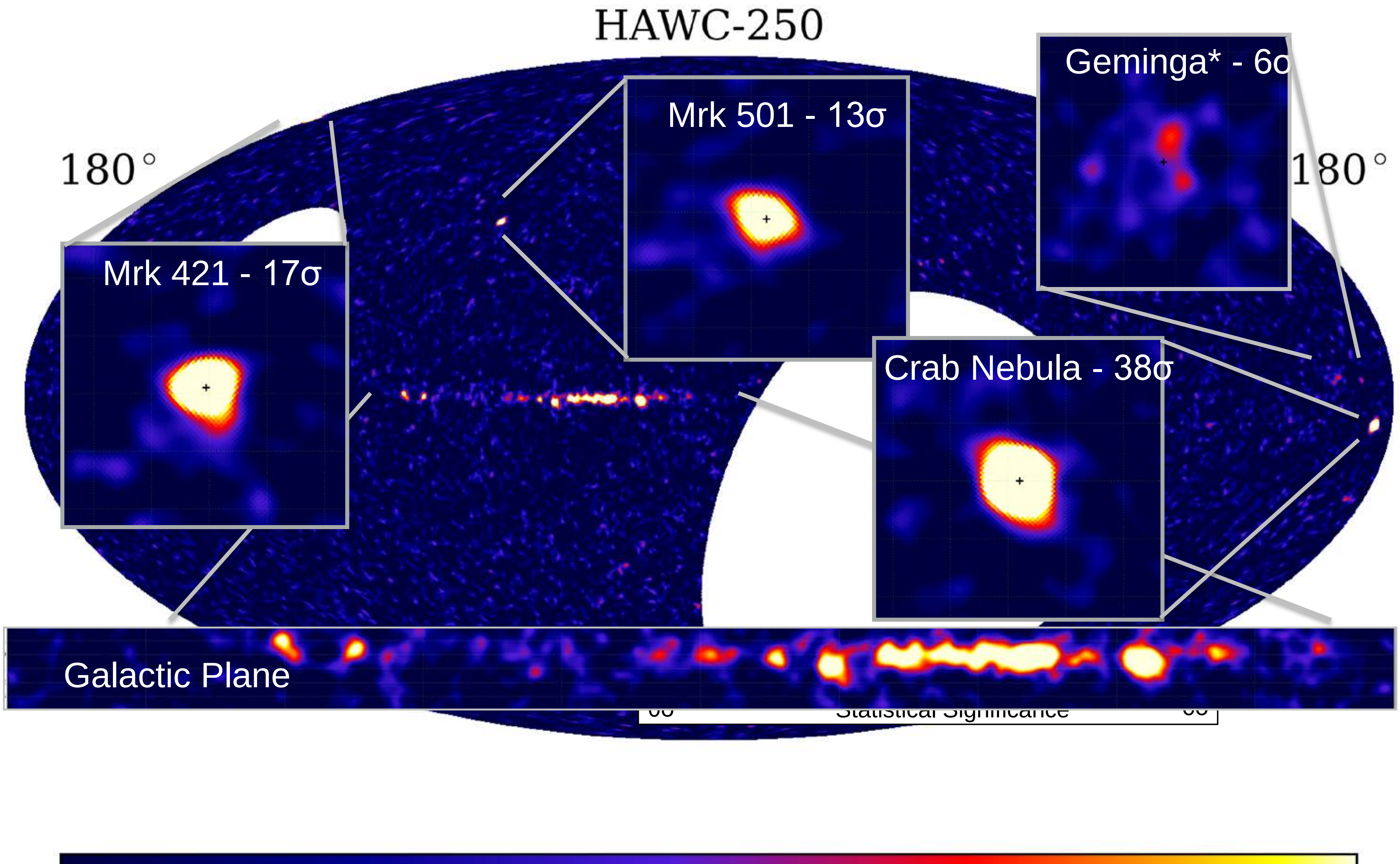
HAWC-250 Gamma Ray Sky Map

Equatorial Coordinates

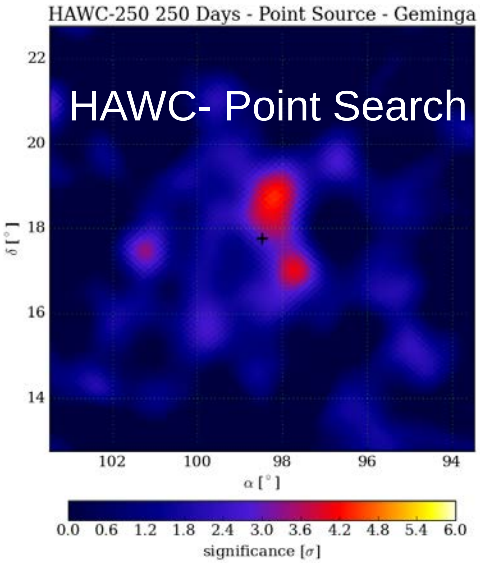


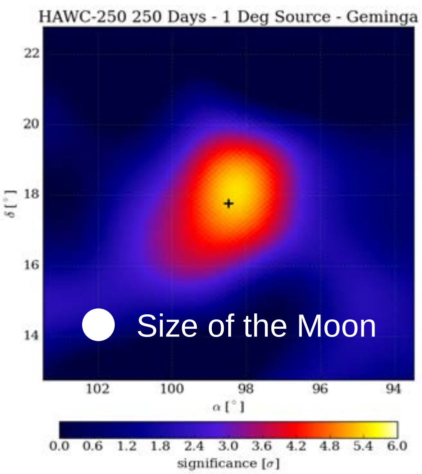
HAWC-250 150-Day TeV Sky Survey

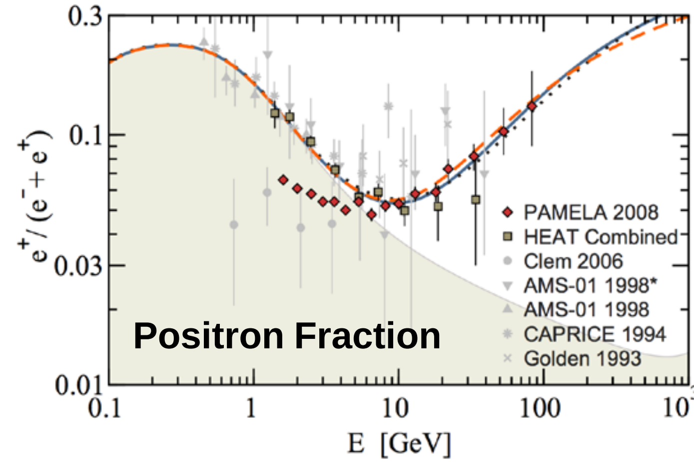
(Galactic Coordinates)

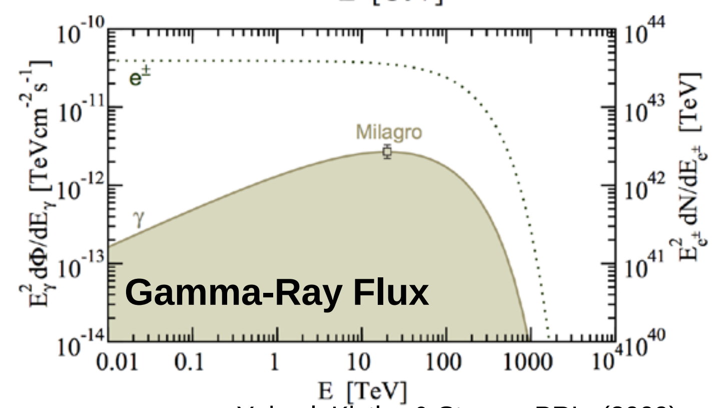


Geminga: A Nearby Particle Accelerator
Contributor to the Positron Excess?



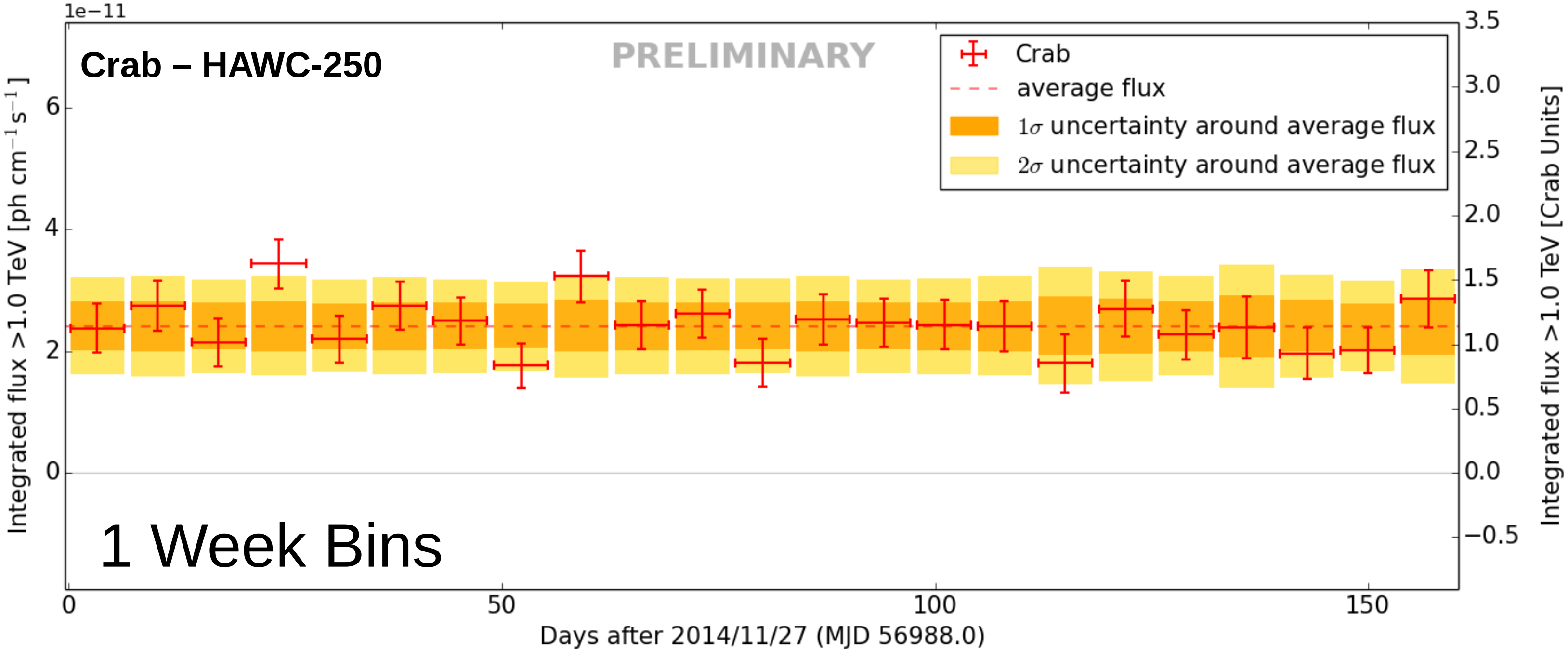




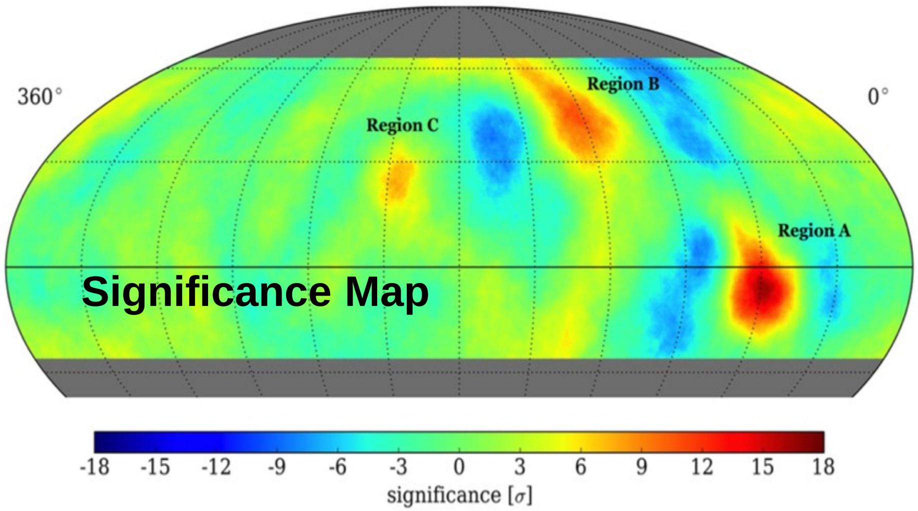


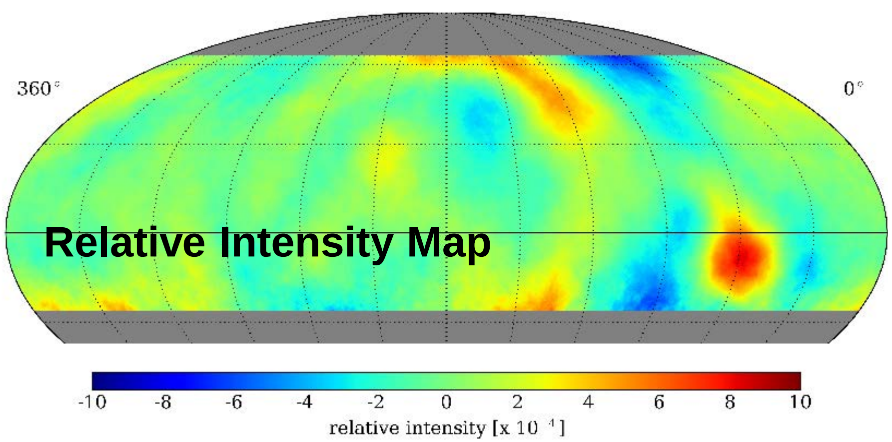
Yuksel, Kistler & Stanev. PRL. (2009).

Time Variability: Crab Nebula (HAWC-250 Teaser)

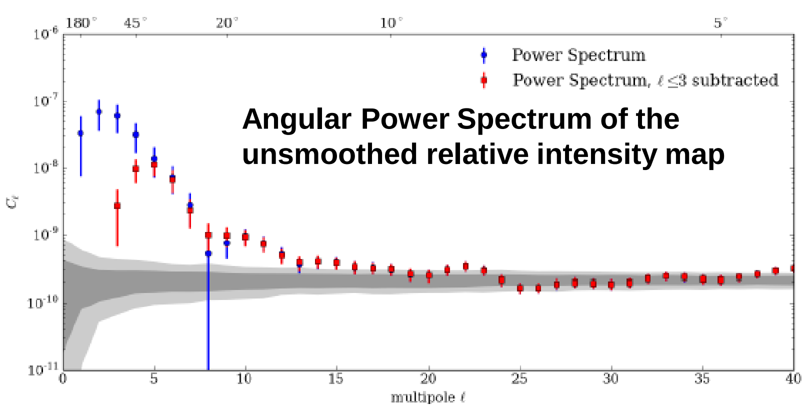


HAWC Small-Scale Cosmic Ray Anisotropy

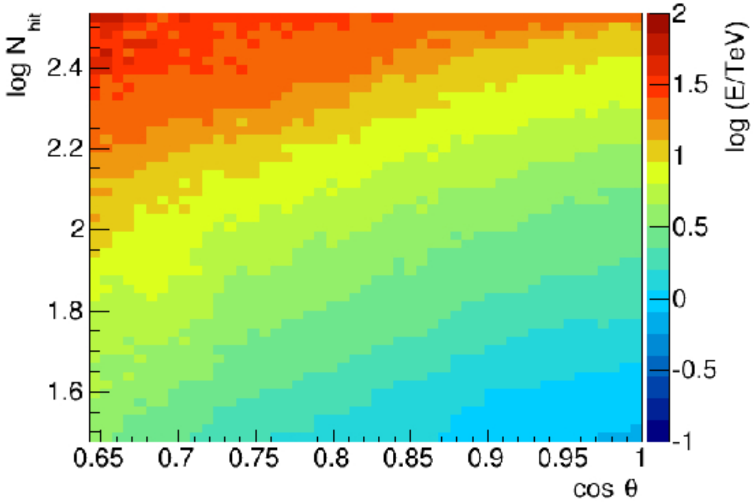




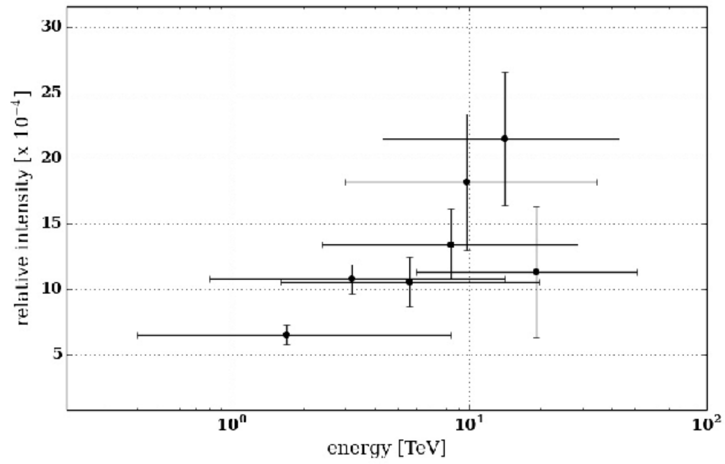
- 86 Billion events in 181 days
- Large-scale anisotropy removed (dipole,quadrupole+octupole)
- 10^0 Smoothing
- Small Angular Scales $<60^0$.
- Region A: Most Significant
- Region B: Most Extended
- Region C: Confirms Argo-YBJ
- Energy Dependent
- Astrophys.J. 796 (2014) 108



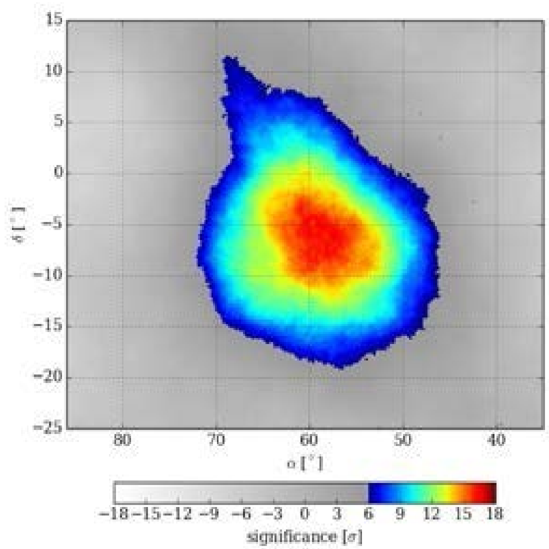
HAWC Small-Scale Cosmic Ray Anisotropy
Region A Energy Dependence



Median Energy v. Npmt v. cos θ

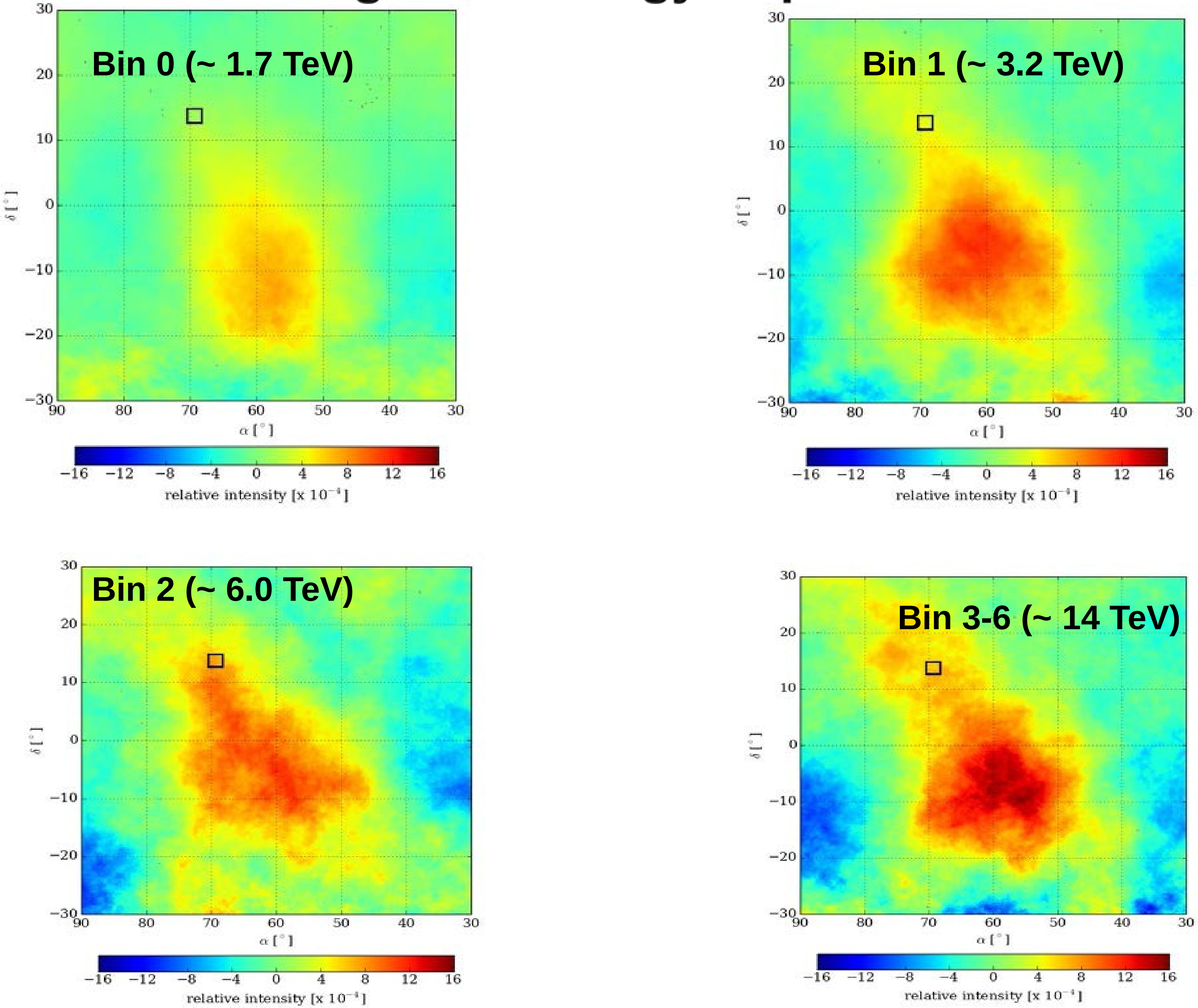


Relative Intensity v. Median Energy

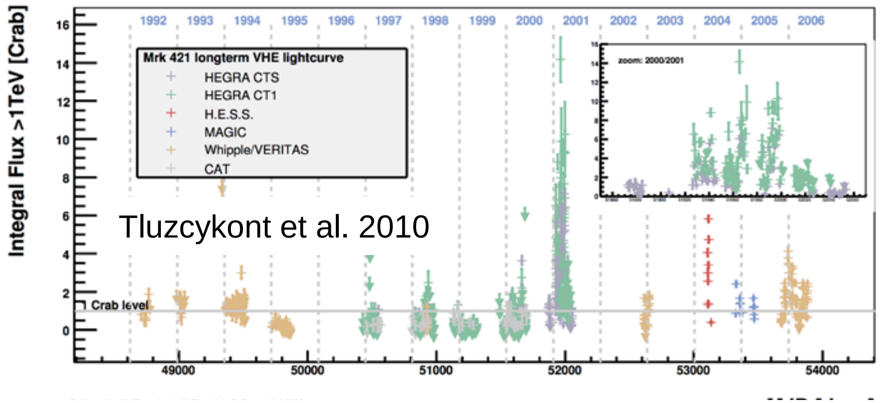


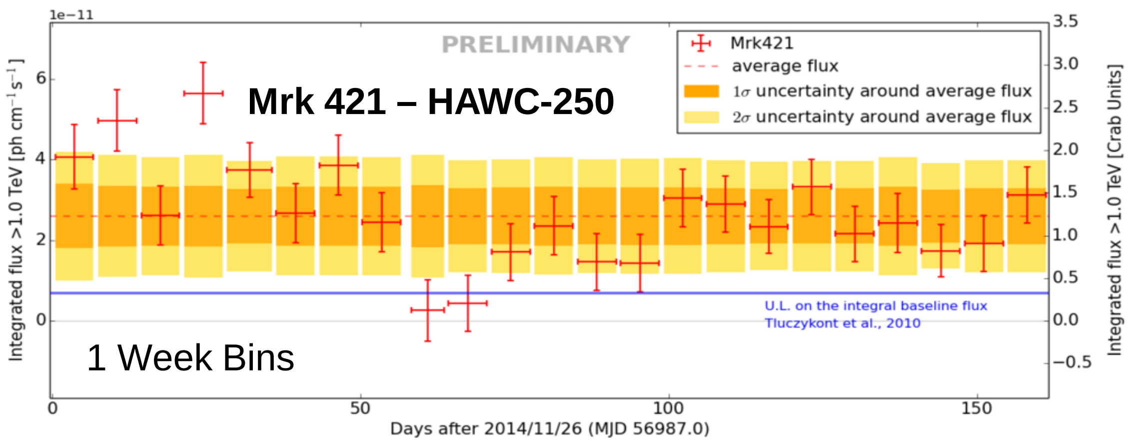
Region A significance- all energies

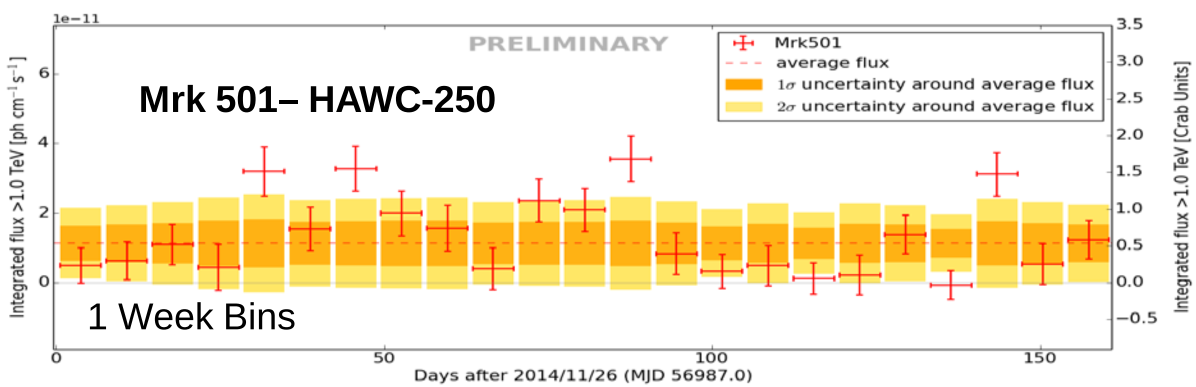
HAWC Small-Scale Cosmic Ray Anisotropy Region A Energy Dependence



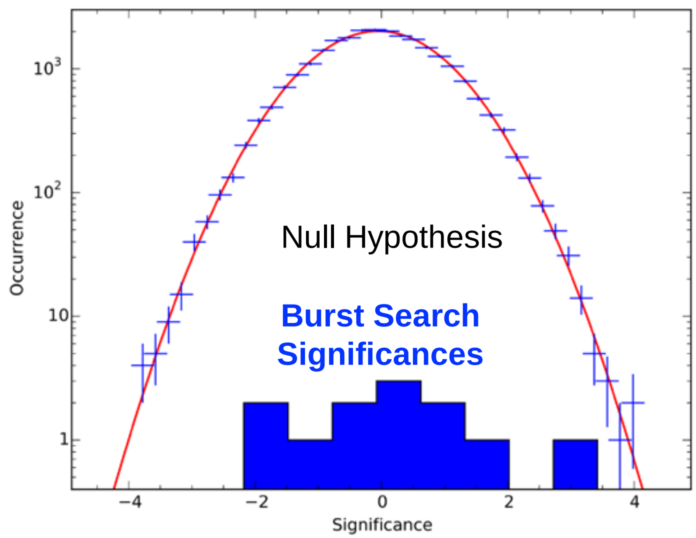
Blazar Light Curves with HAWC

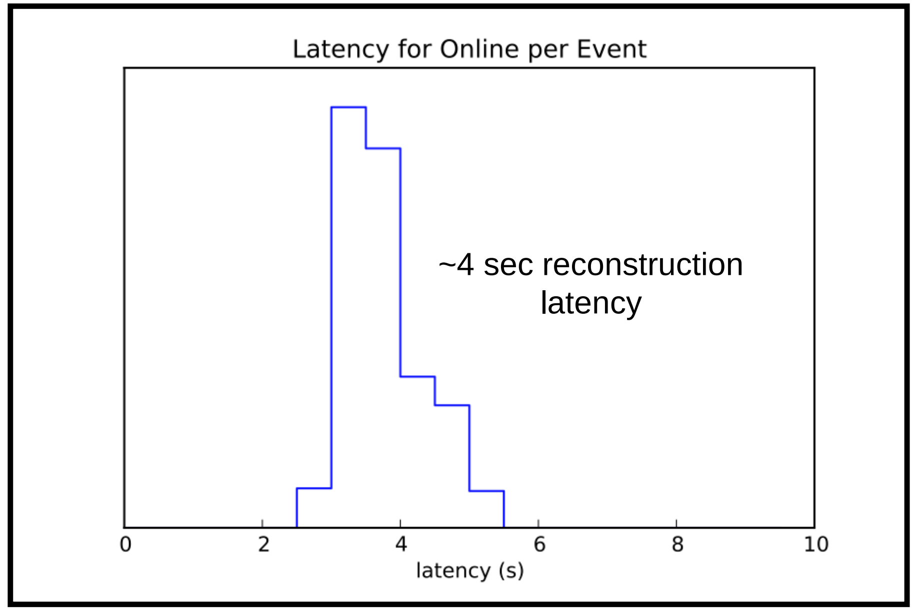






HAWC: GRB Searches





- ❑ Expect 1-2 visible GRB Per Year in HAWC-300 (extrapolating from Fermi)
- ❑ Constrain Fermi Rising Component
- ❑ Issue GRB alerts to other observatories
- ❑ Perform "triggered" searches prompted by other observations
- ❑ Flurry of MOUs with other experiments..

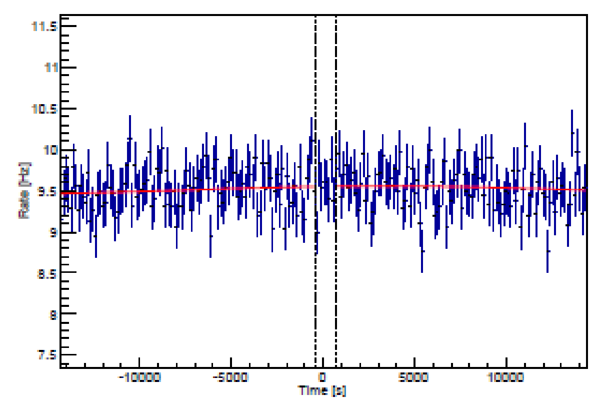
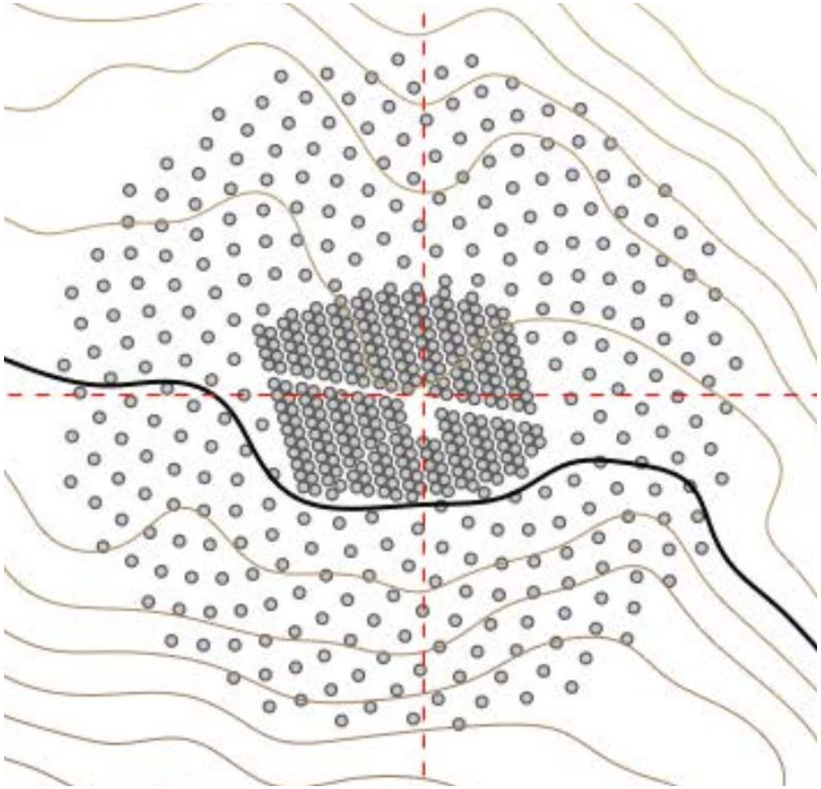


Figure 3: Event rate for on-observation (at zero) and off-observations before and after the trigger time of GRB 140423A. The red line shows the background model that is created by scaling the allsky event rate fit. The horizontal dashed lines show the region where data is not used for the scaling of the background model.

The Future of HAWC



- **HAWC**
  - Public transient alerts this year
  - Public data release of all-sky data
- **Outrigger Array**
  - Enhance Sensitivity above 10 TeV
  - Funded and Going Forward.
- **Southern Hemisphere Detector**
  - Southern complement for CTA
  - No wide-field TeV survey of the Southern Sky … yet

Summary

- ❑**HAWC Observatory Status**
  - ❑Construction Complete
  - ❑Acquiring Science Data
- ❑**HAWC Science Objectives**
  - ❑Study the origin of cosmic rays
  - ❑Study particle acceleration in astrophysical jets
  - ❑Explore new physics via HAWC's unbiased survey.
- ❑**First Results**
  - ❑Galactic Plane Survey in HAWC-111
  - ❑Flaring Blazars in HAWC-111/250
  - ❑Geminga in HAWC-250
  - ❑Multi-Wavelength/Messenger Activities
- ❑**Future**
  - ❑Outrigger Array Expansion
  - ❑Pursue science objectives

For more information please visit
http://www.hawc-observatory.org