Research Overview Seminar

Physics of the Extreme Universe

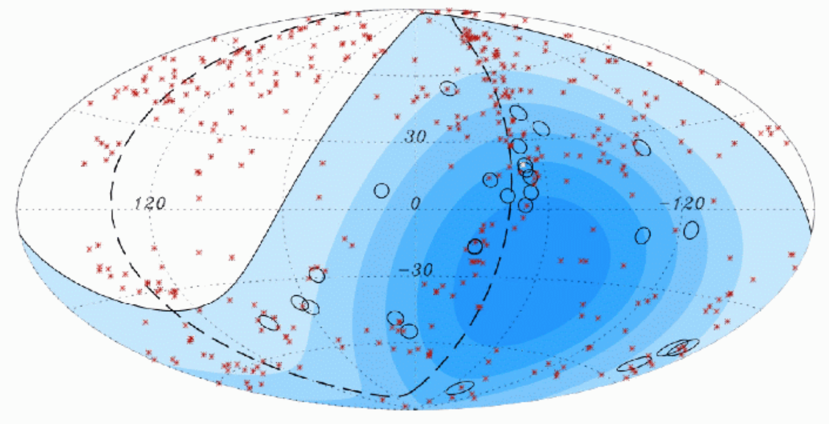
John A.J. Matthews

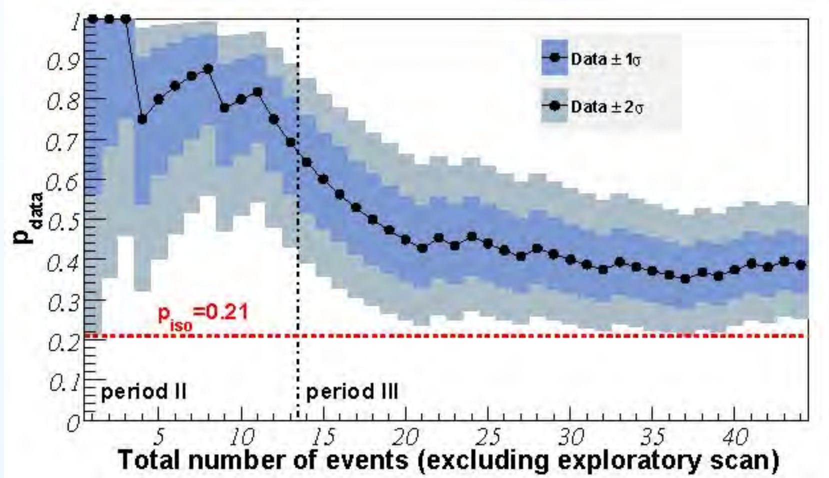
johnm@phys.unm.edu

University of New Mexico

Albuquerque, NM 87131

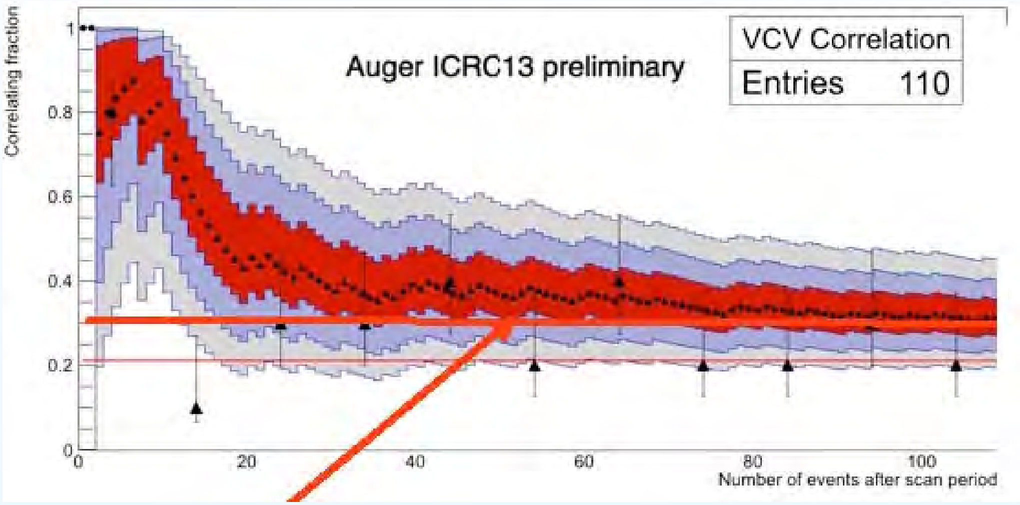
Several years ago ... in a country far away

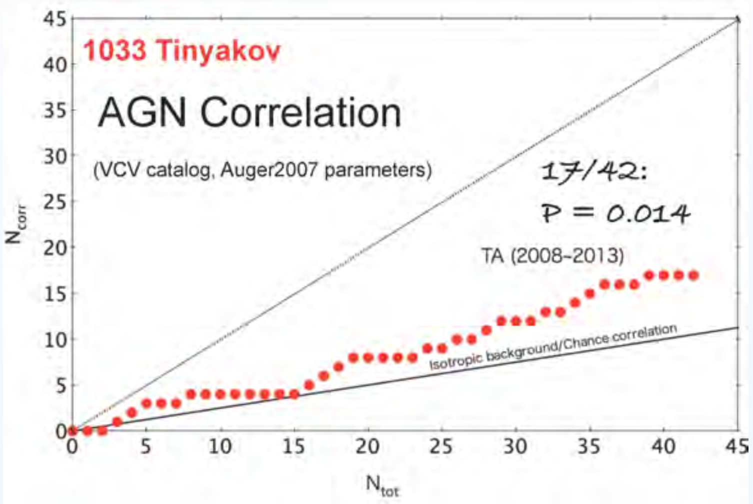




- We built the Pierre Auger Observatory (in Argentina) to study the highest energy cosmic rays (CRs):
  1. Is there a cutoff in the spectrum of the highest energy cosmic rays *... as expected from the interaction of CR protons with the cosmic microwave radiation*?
  2. And if there is a cutoff the highest 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!

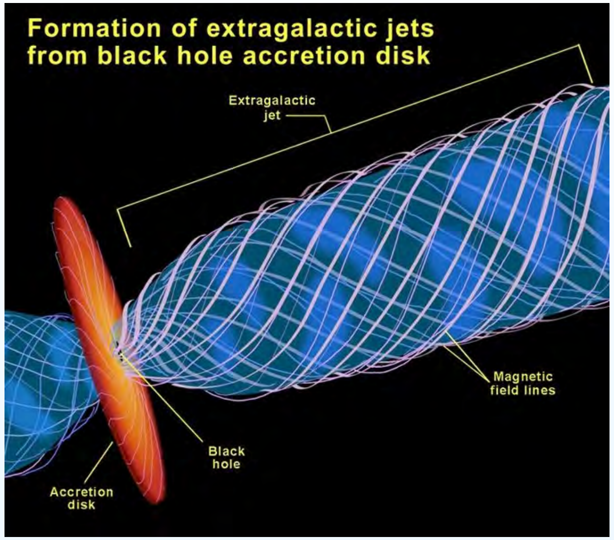
Today ... in a country far away





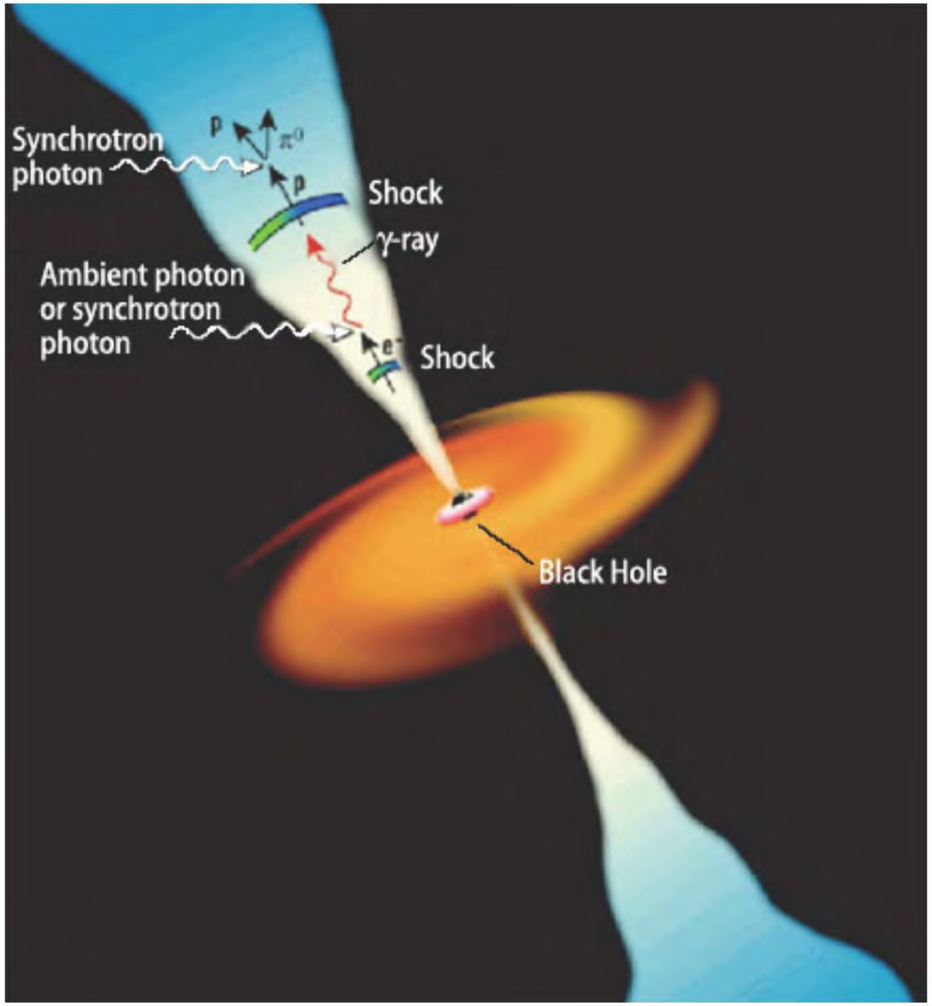
- (Left:) And while the initial magnitude of the CR:AGN correlation was over-estimated 5 years later are we observing a weak but stable signal?
- (Right:) And the Telescope Array experiment may also be observing a weak but non-zero signal!
- So maybe the AGNs are a (the?) source of the highest energy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



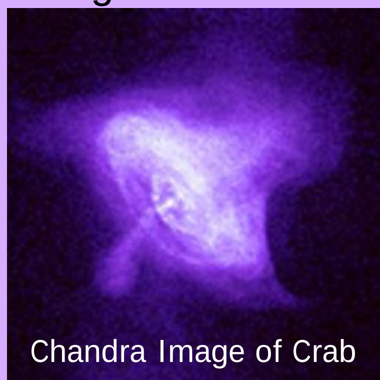
What physics in *e.g.* astrophysical jets could result in γ-rays to energies of 10^{15}eV or possibly cosmic rays to energies of 10^{20}eV?

- 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 ...

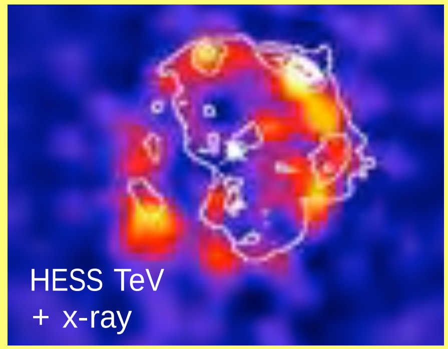
Nature's Particle Accelerators

Galactic

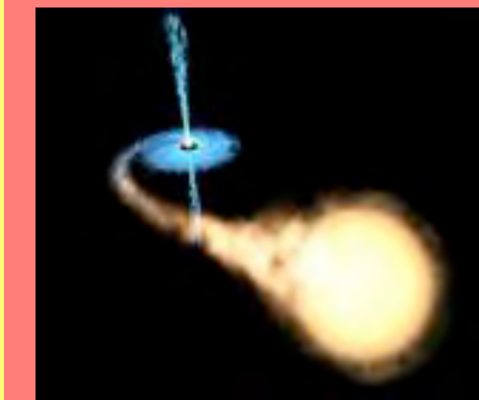
Pulsar Wind Nebula:
Spinning Neutron Star
powering *a* relativistic wind



Supernova
Remnant



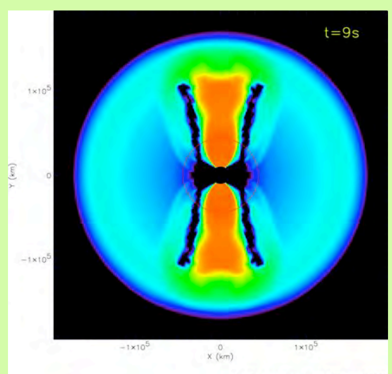
X-ray Binaries/
Microquasars



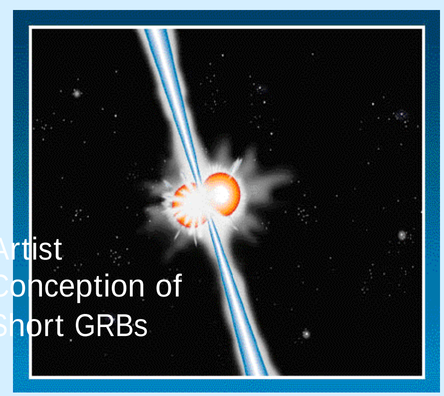
ExtraGalactic

Active Galactic Nuclei:
Black Hole producing
relativistic jet of particles

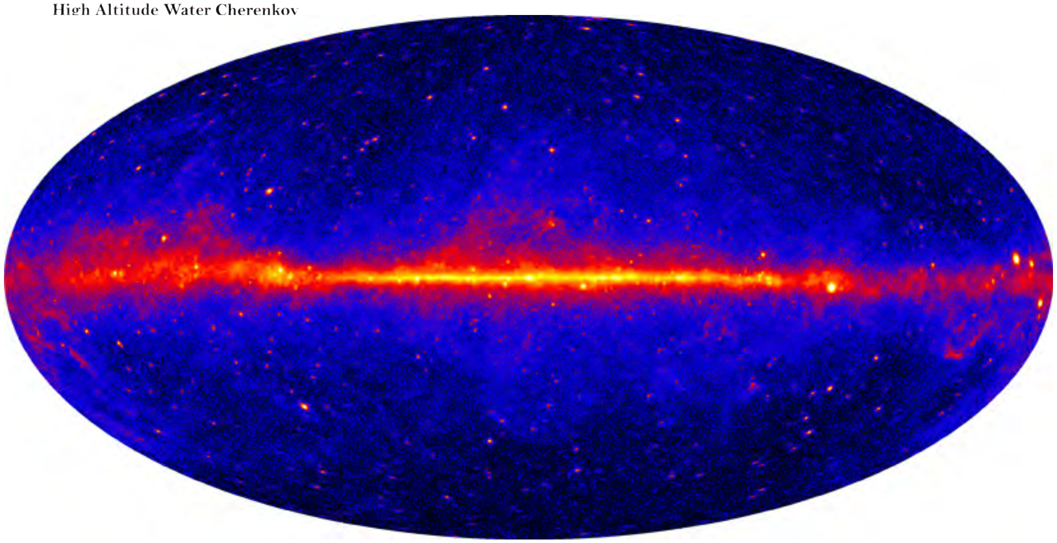
Long Gamma-Ray Burst:
Massive Star Collapsing
into a Black Hole



Short Gamma-Ray Burst:
Binary Neutron Star
Coalescing



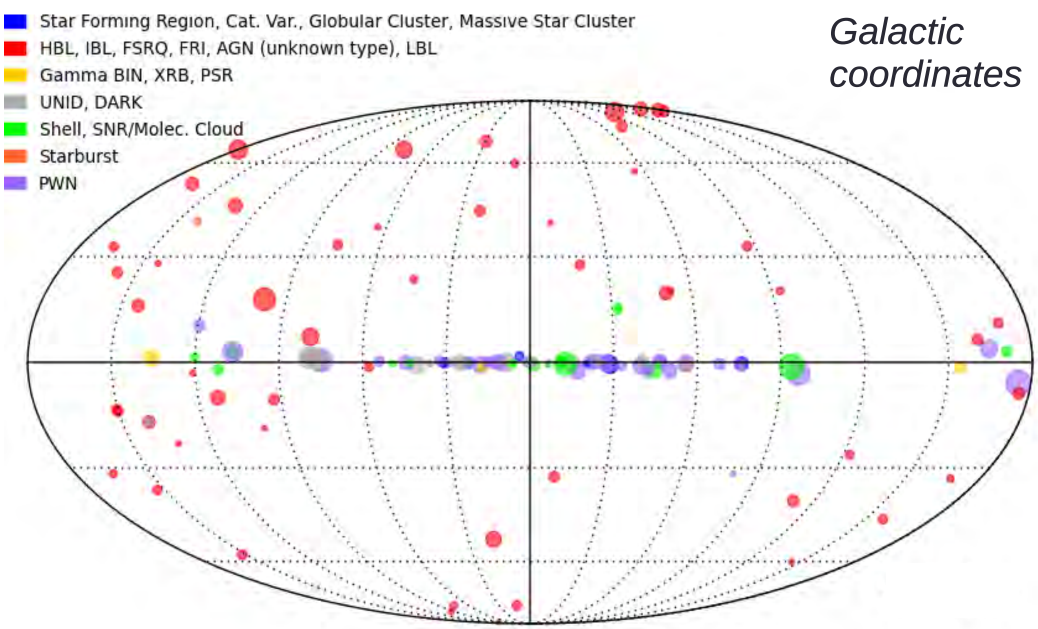
The GeV-TeV Sky



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.)



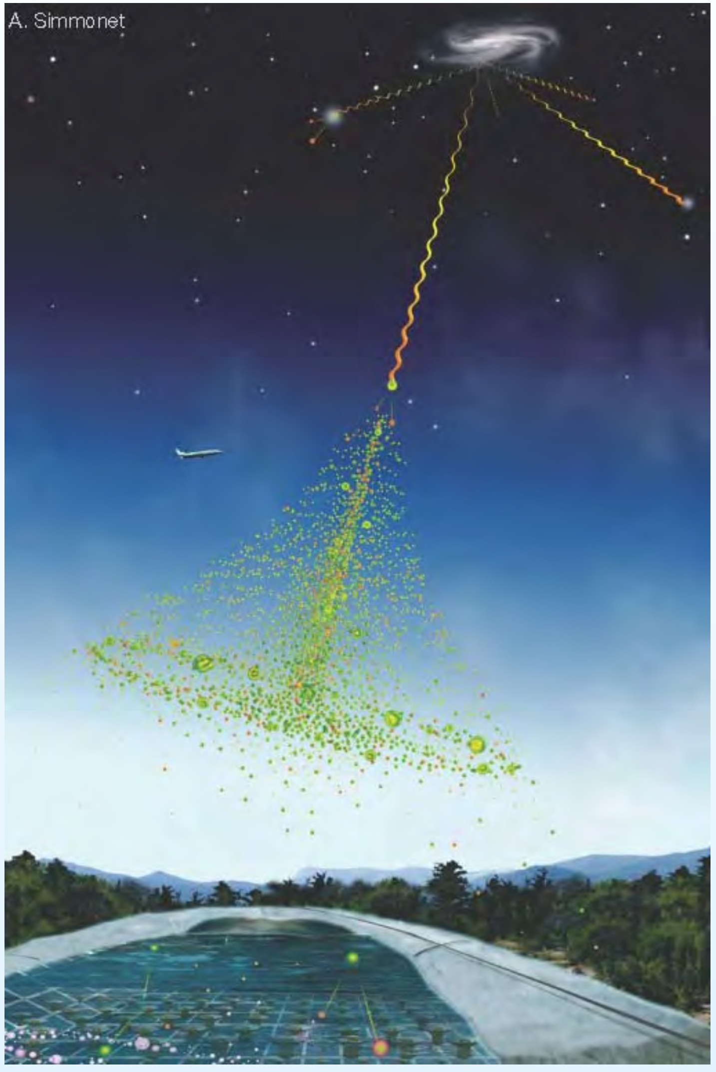
Galactic coordinates

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


HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

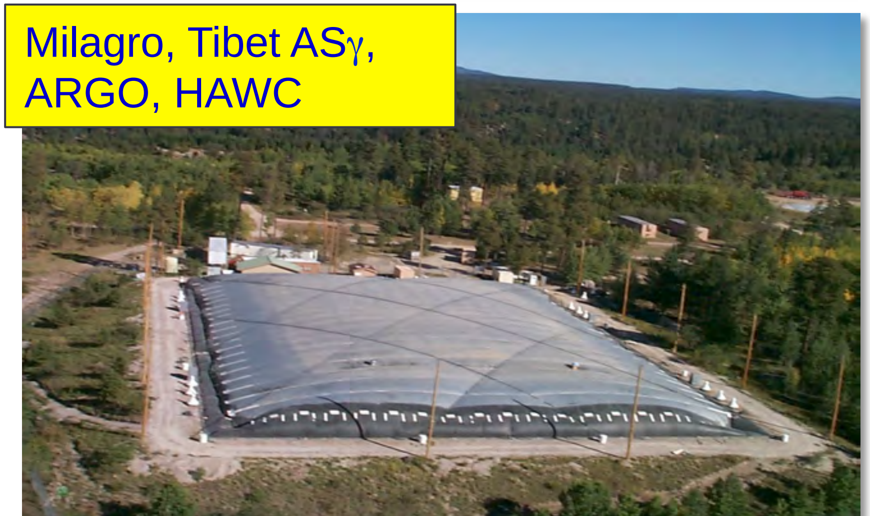
TeV Gamma-Ray Instruments

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:

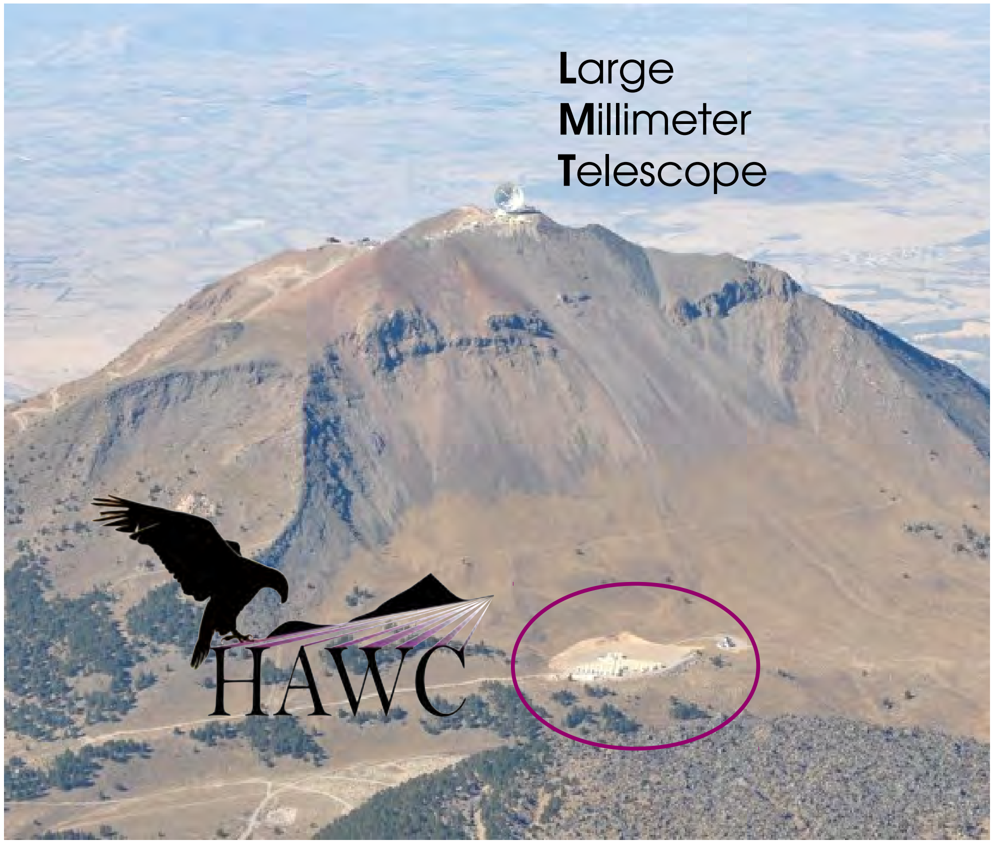
- Large duty cycle (>95%), independent of weather and daylight.
- Large field-of-view (2 sr instantenous).
- Lower sensitivity to point sources.

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

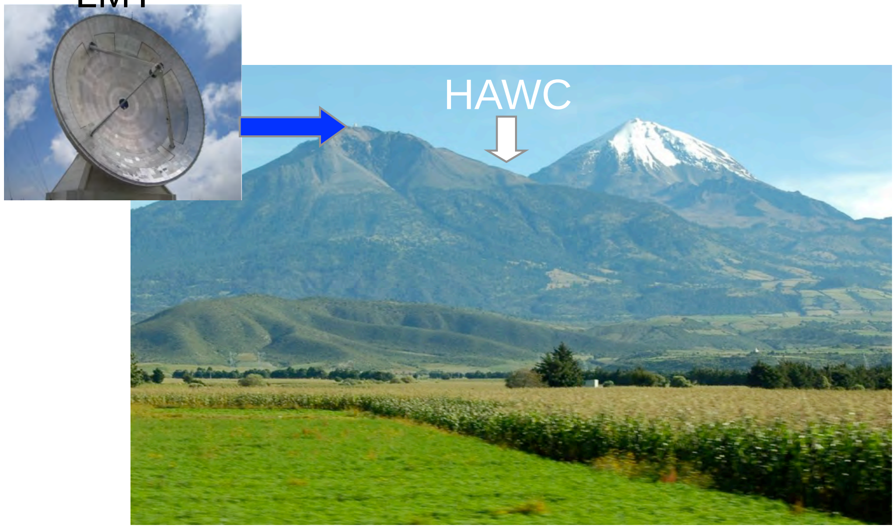
2nd Generation Water Cherenkov: HAWC



- 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)

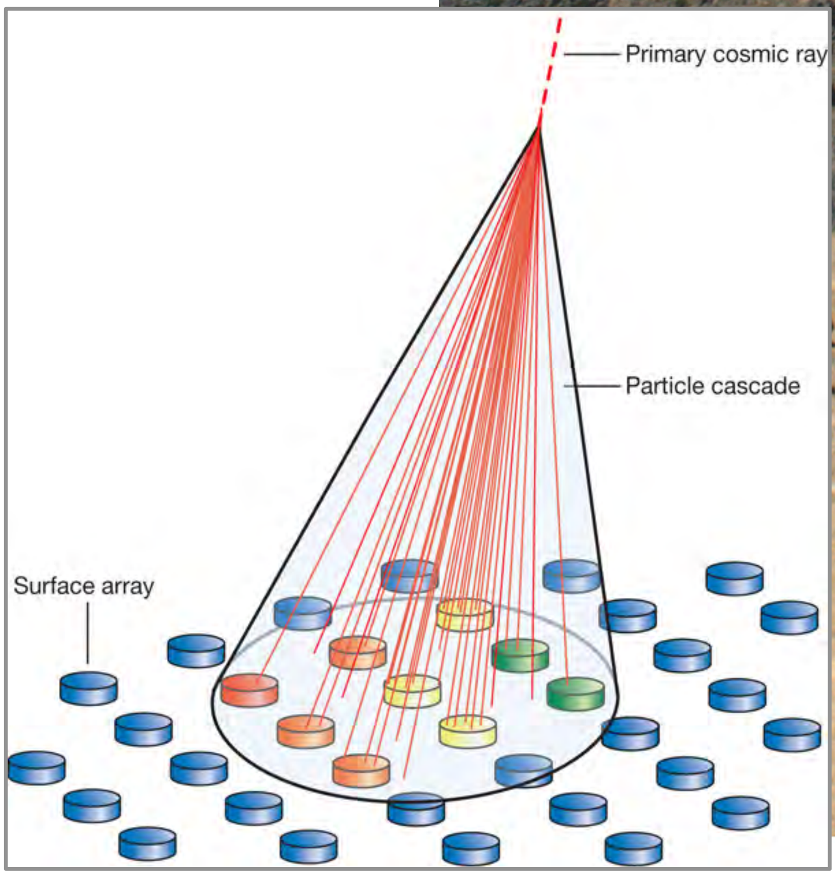
The HAWC Site

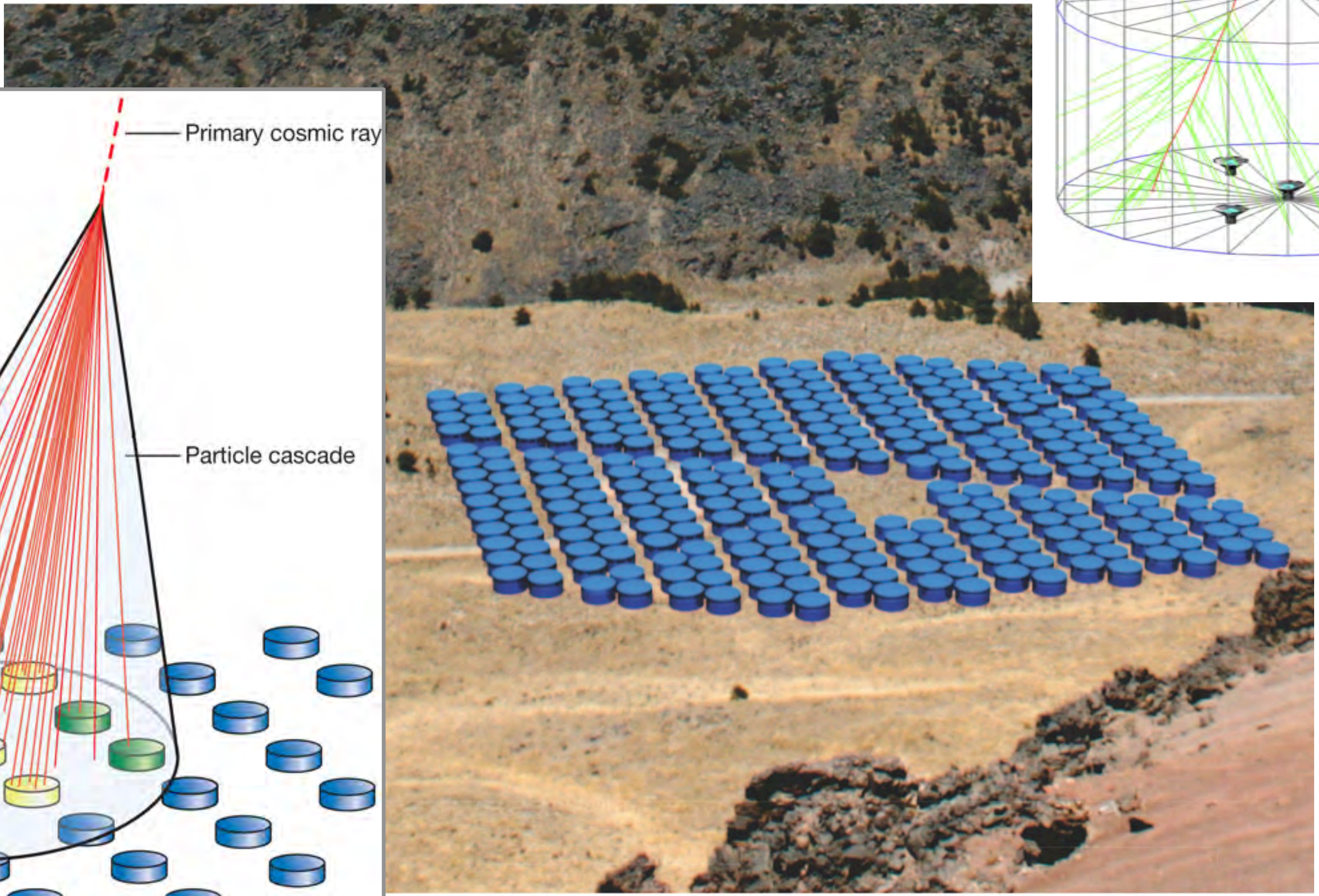
- Near ideal:
  - High elevation (4100m), but flat – Shoulder area between Mount Pico de Orizaba and Sierra Negra.
  - Just above tree line – not extreme climate.
  - Existing infrastructure from LMT.

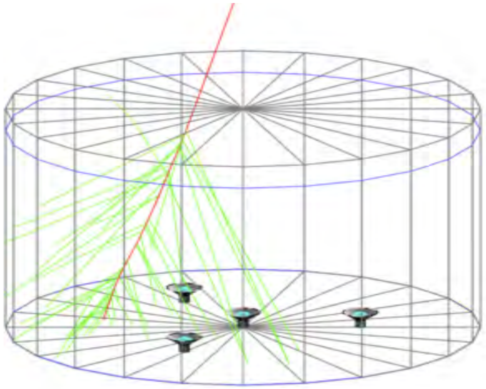


How Does HAWC Work?

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



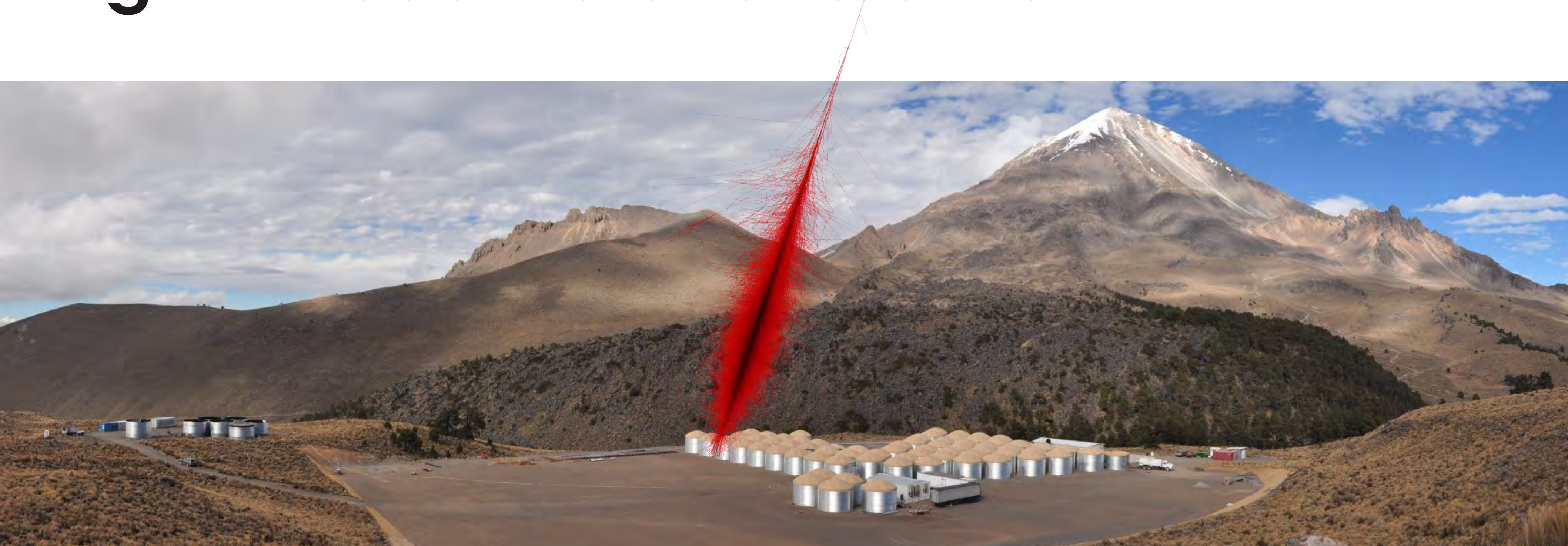




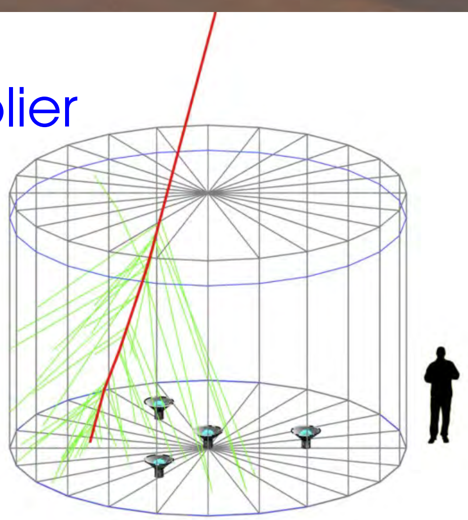
The HAWC Array

- **20,000 m^2** covered with water Cherenkov detectors (WCDs)
- **200,000 liters** of purified water
- **1200 PMTs** (900 from Milagro + 300 central high QE PMT)
- **300 WCDs** at completion (summer 204), **95 are operational now**
- Ongoing **data taking during construction** (started October 2012)

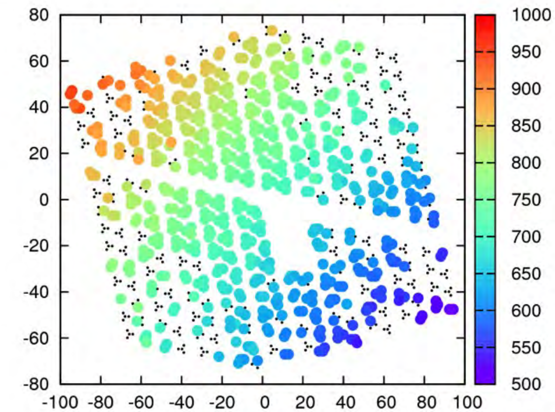
High Altitude Water Cherenkov



4 Photo Multiplier Tubes (PMTs) per Tank to detect Cherenkov Light from secondary air shower particles



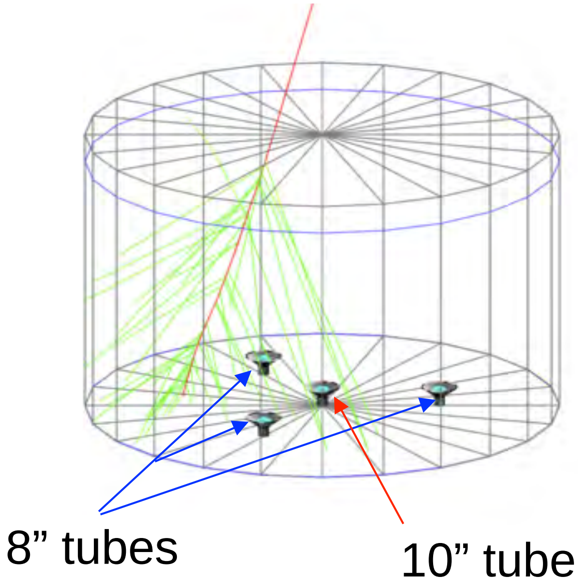
Use PMT hit times and charges to reconstruct air showers



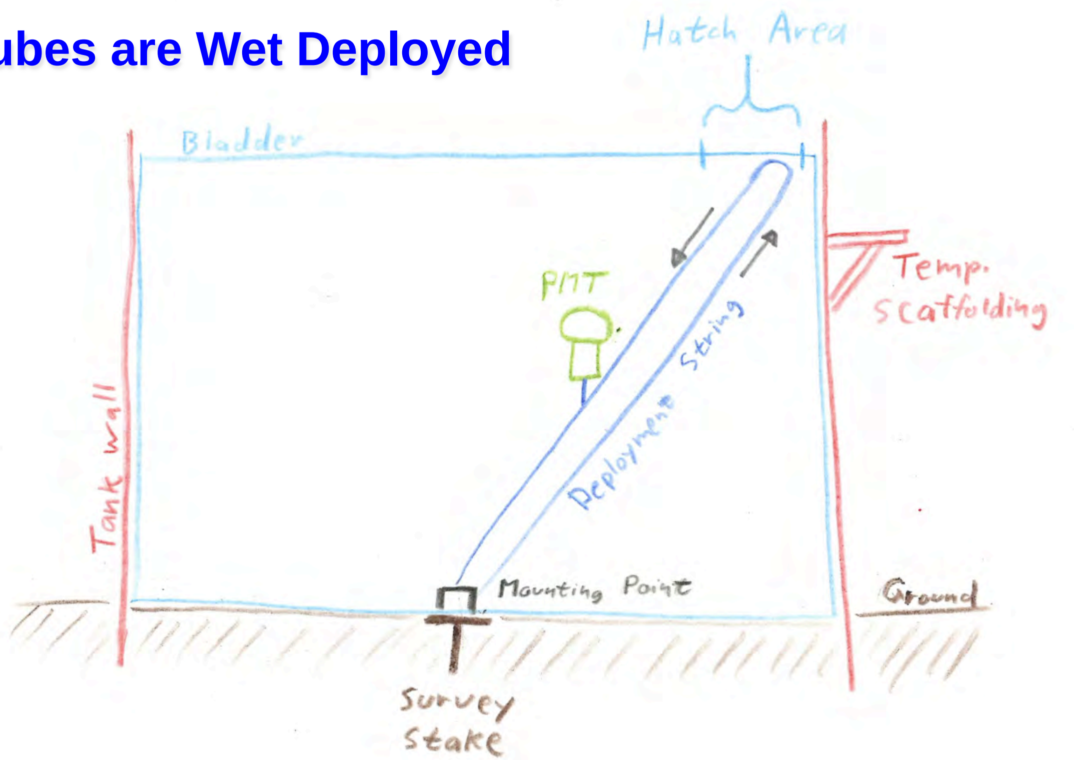
HAWC
High Altitude Water Ch
Gamma-Ray Observato

Water Cherenkov Detector: The Photomultiplier Tubes

- Four PMTs: Three Hamamatsu 5912 (8”), One Hamamatsu R7081 HQE (10”).
  - Tubes look up to see Cherenkov light directly – ~1pe per 30 MeV deposited.

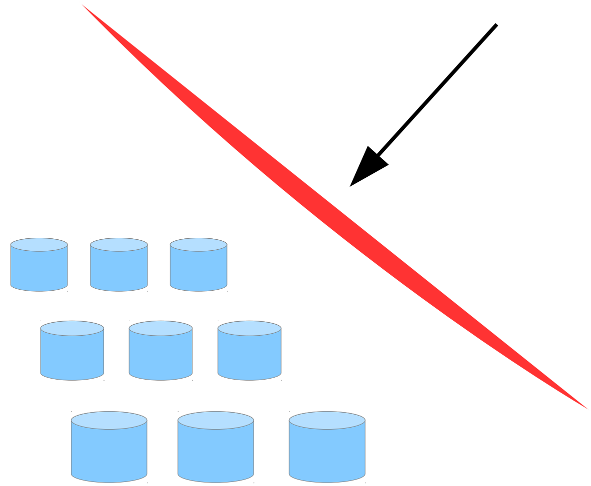


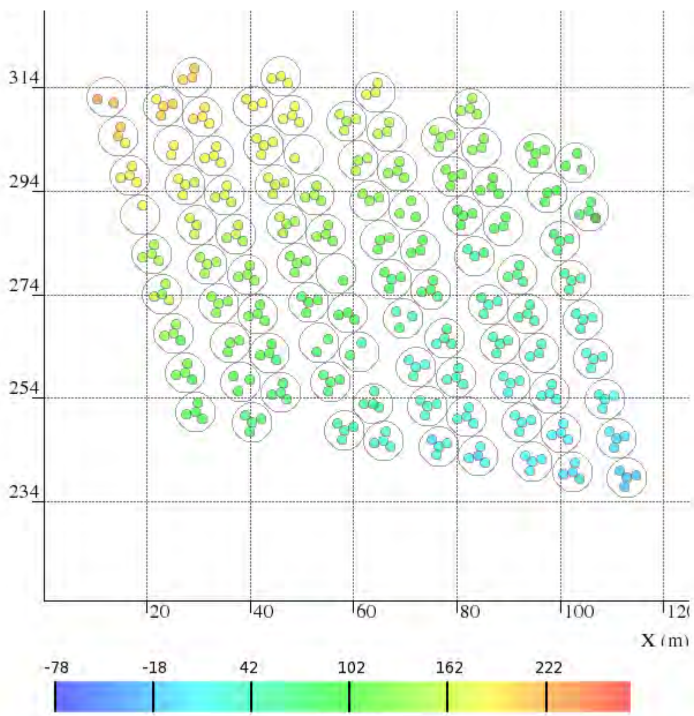
Tubes are Wet Deployed



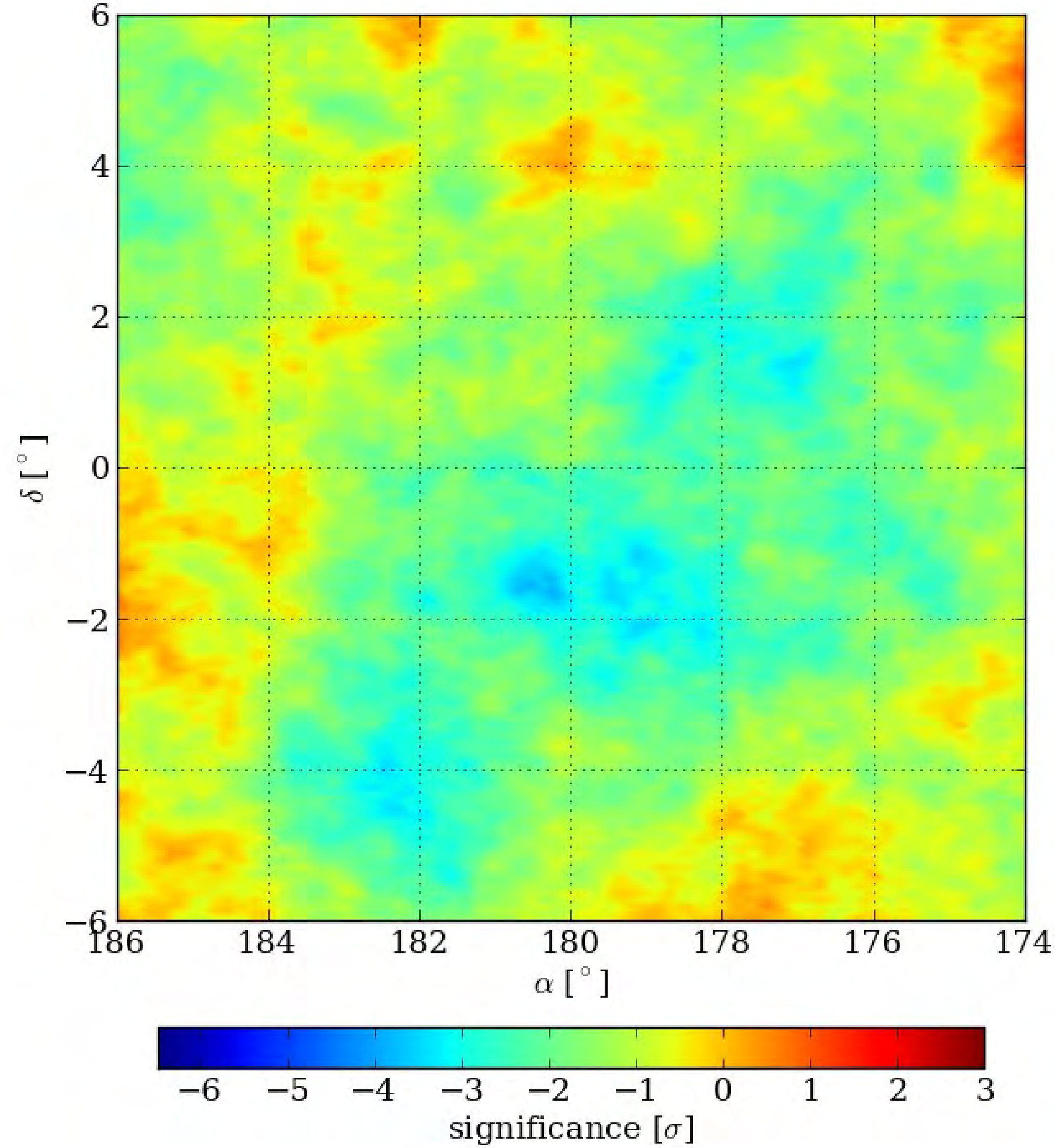
First 10” tube glued into enclosure

Air Shower Reconstruction

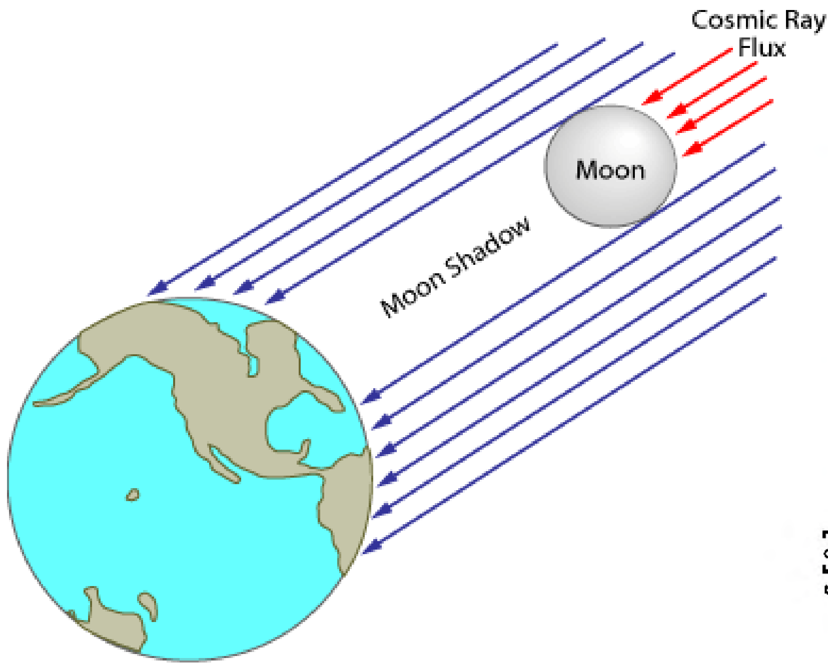




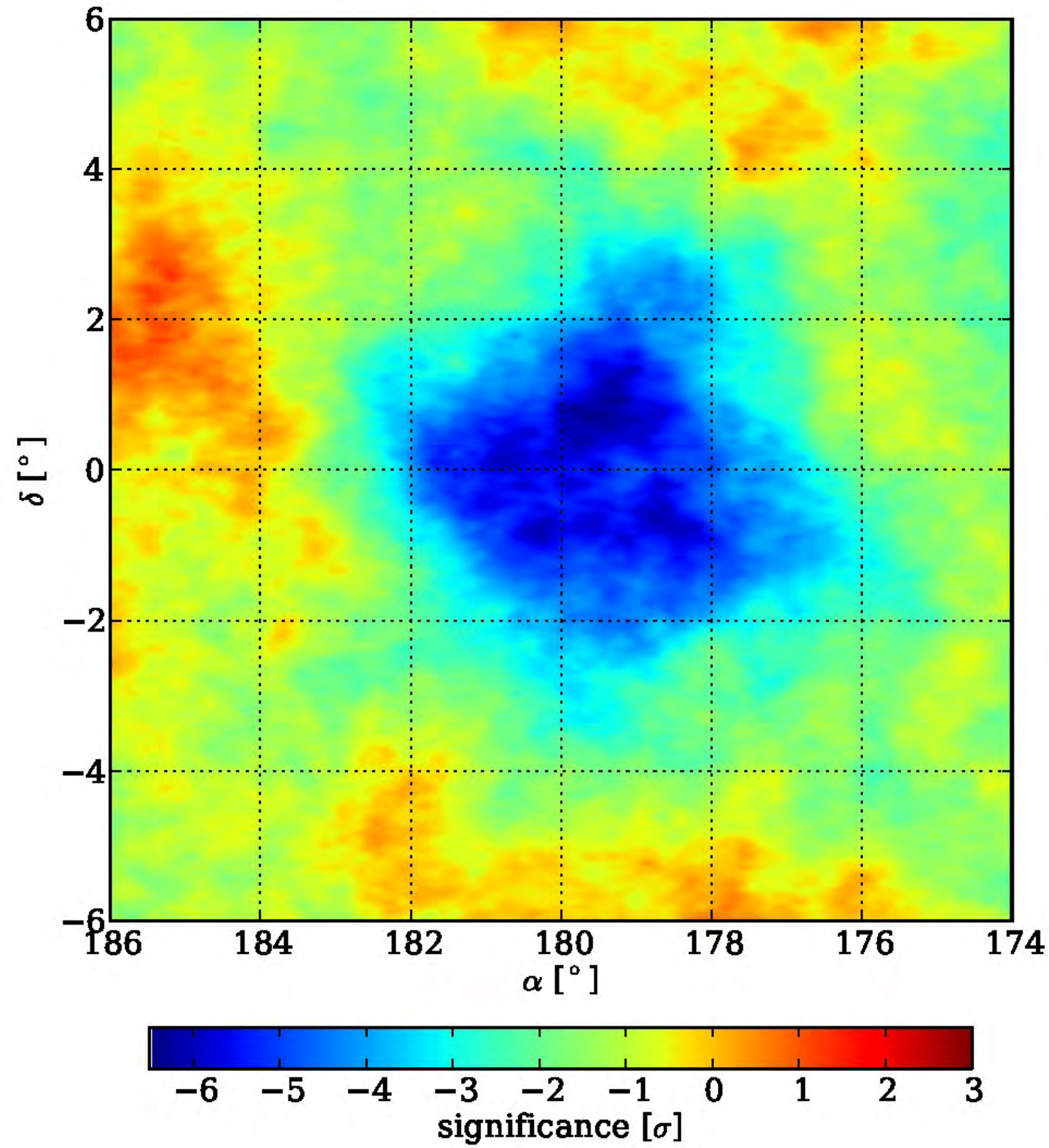
before calibration:



Air Shower Reconstruction

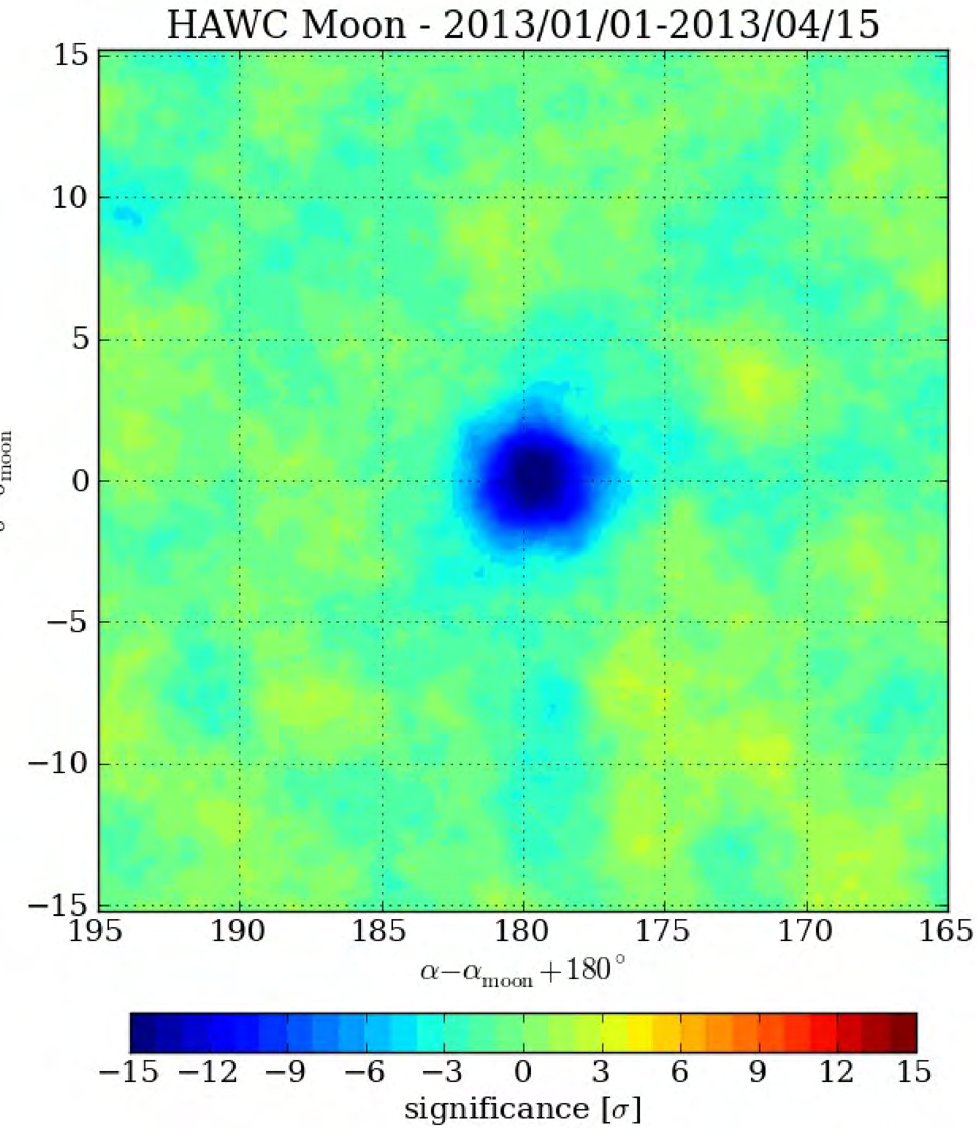


after calibration:

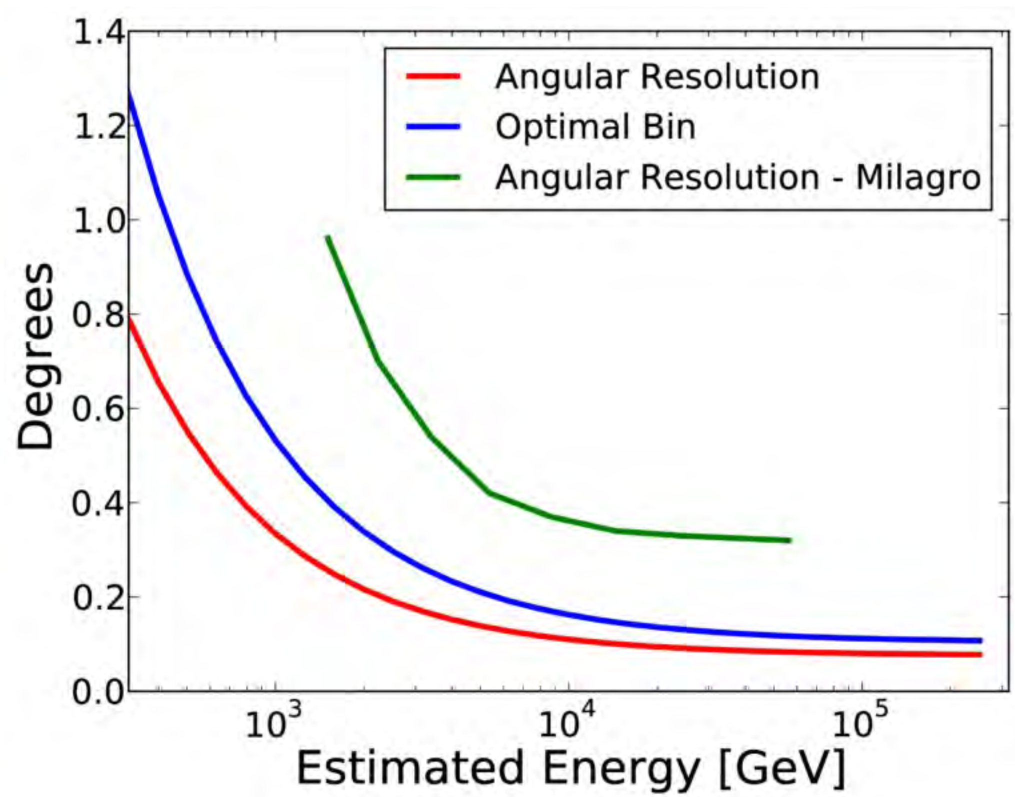


Event reconstruction based on fitting the shower core and shiwer front:
Calibration of PMT charge and timing via laser system is crucial.

Angular Resolution

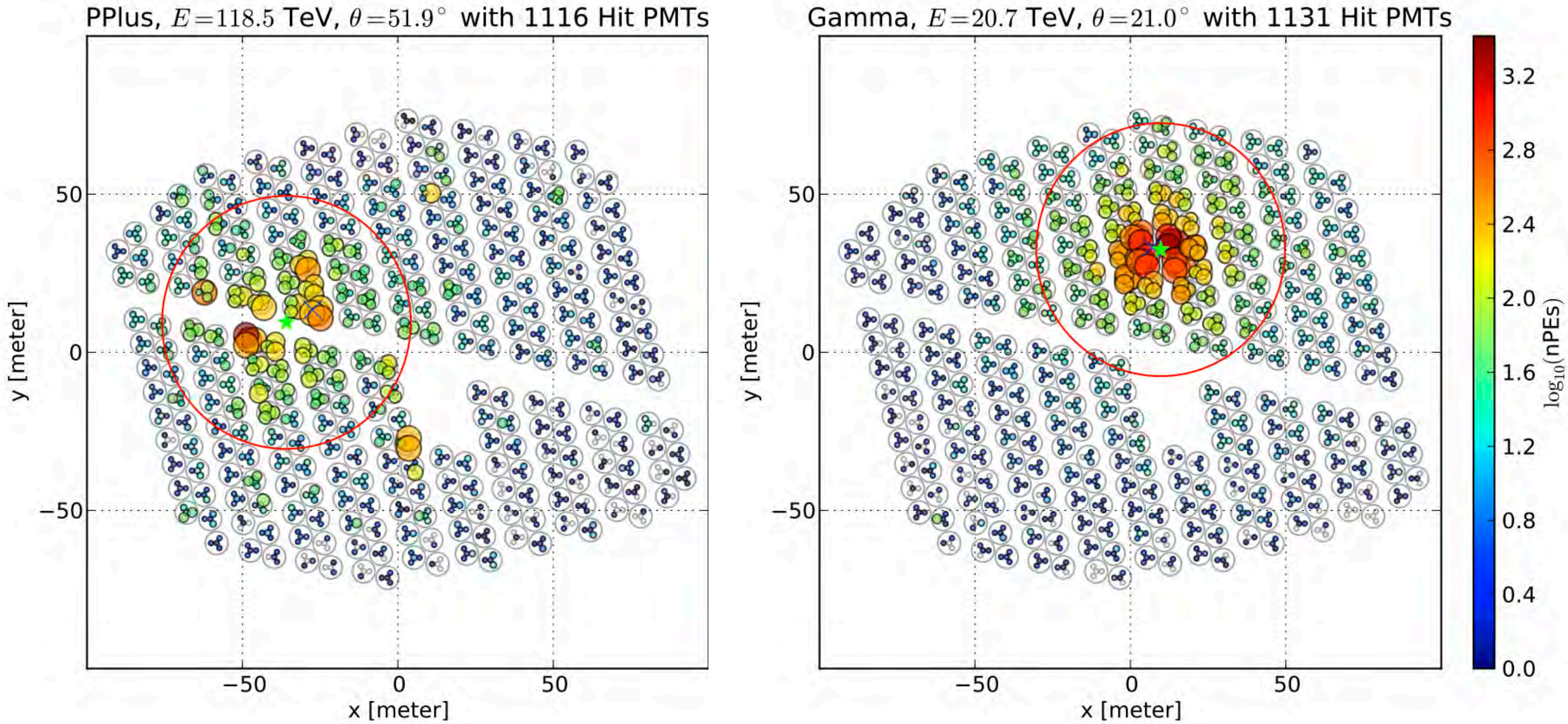


Moon shadow in cosmic rays allows early resolution and pointing verification



Angular resolution approaches ~0.1° for energies above 10 TeV

Background Rejection

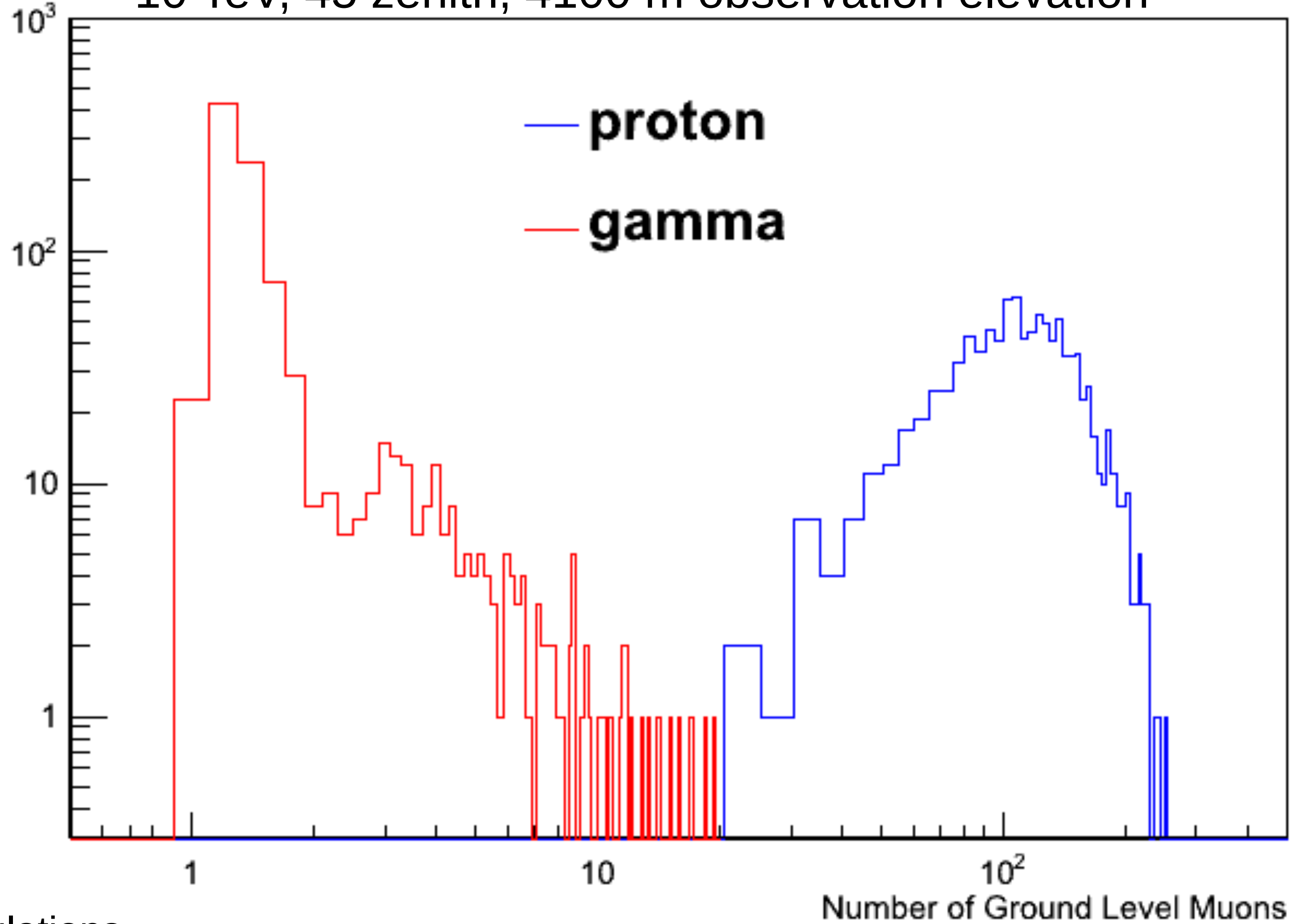


- **Hadron showers:**
  muons and high energy particles far from core, *"spotty."*
- **Gamma showers:**
  electromagnetic, *smooth*.

Gamma/Hadron Separation

- Ground Level Muons are a powerful Gamma/ Hadron Discriminate

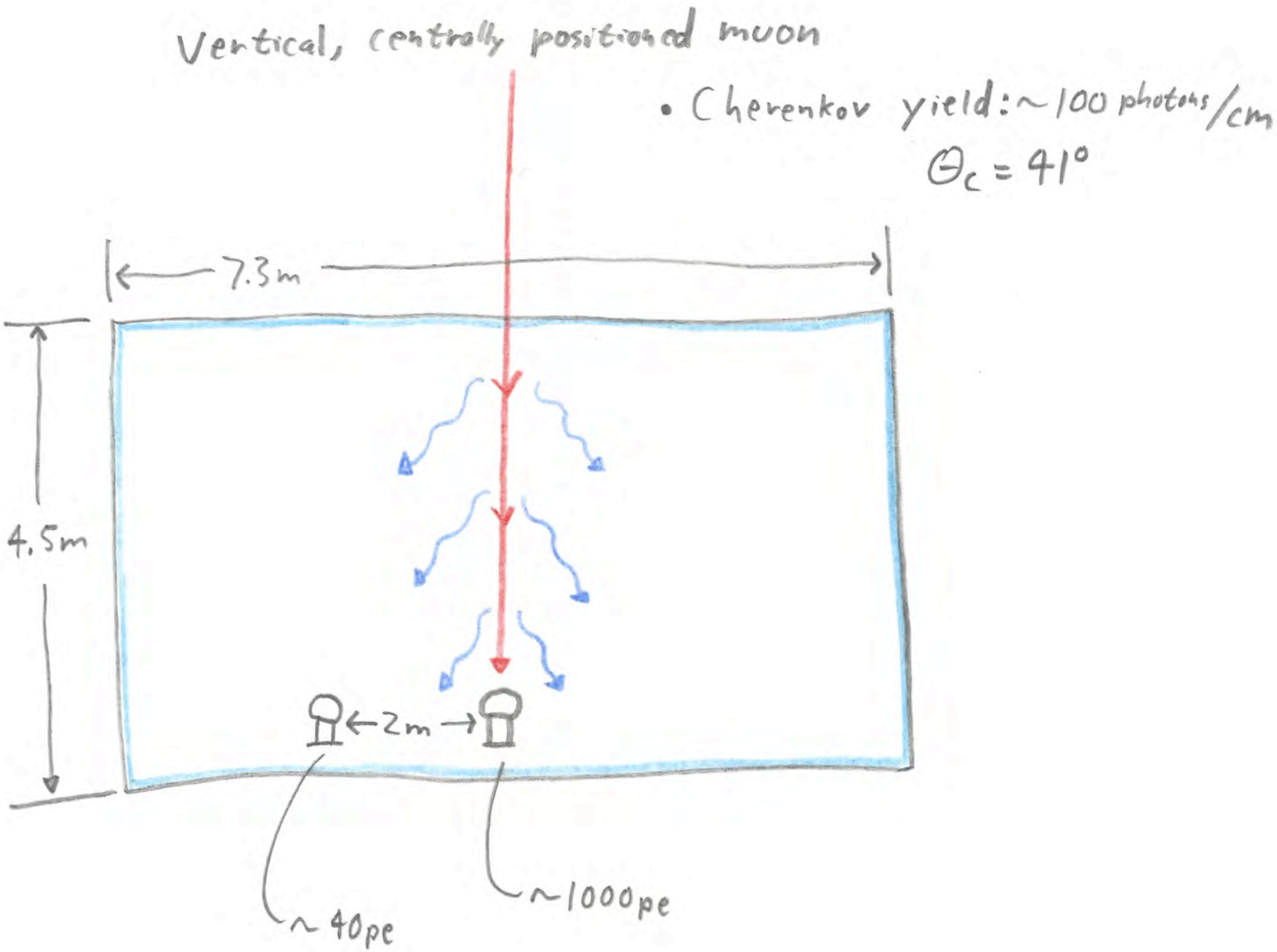
10 TeV, 45 zenith, 4100 m observation elevation



Conex-Sibyll 2.1 Simulations

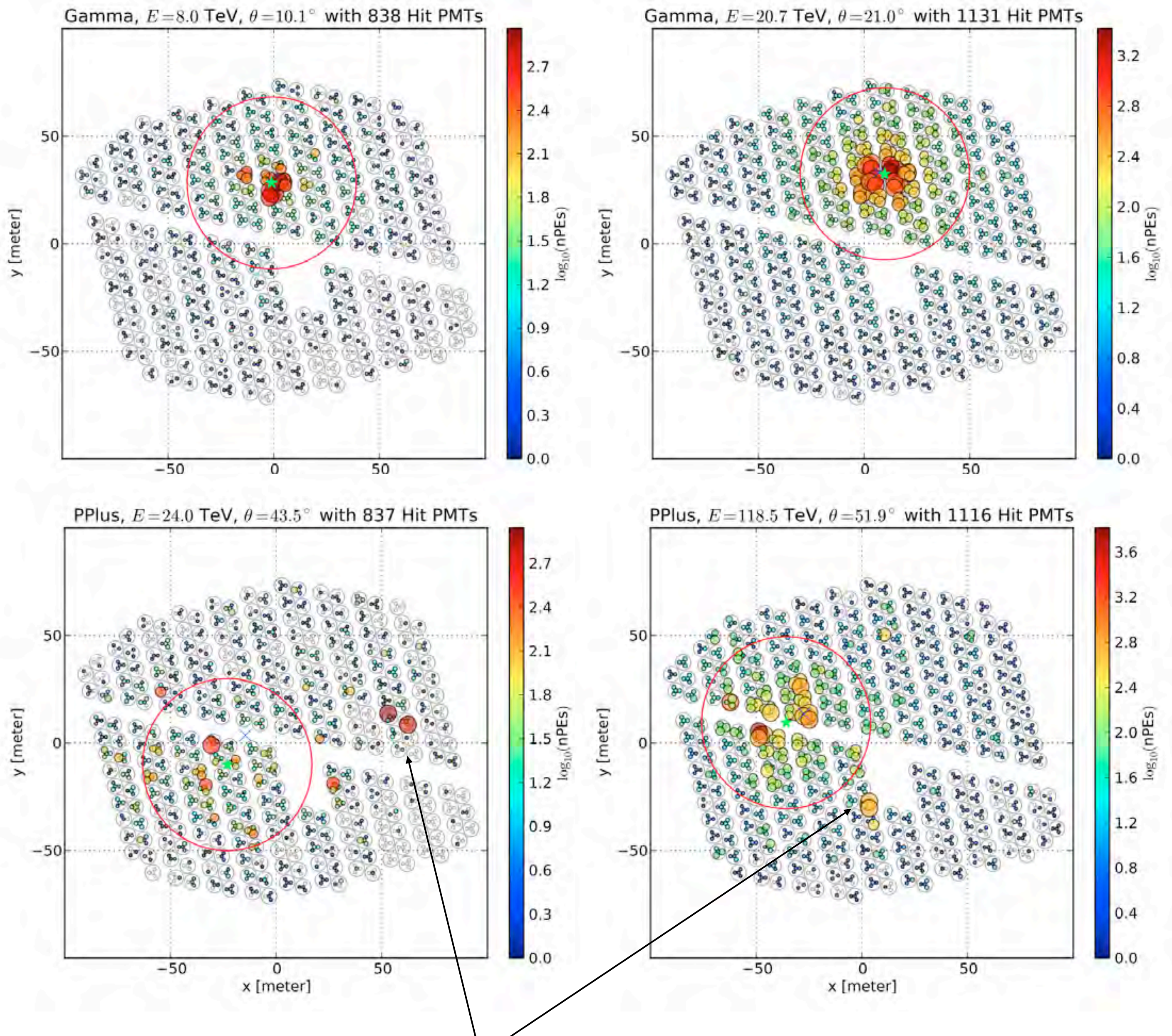
Gamma/Hadron Separation

- Muons deposit their energy lumpy.....



Gammas

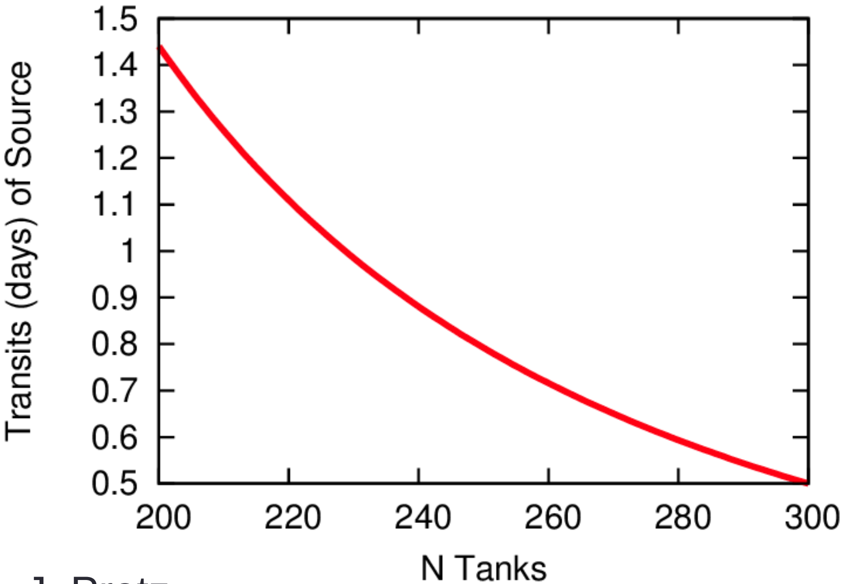
Protons



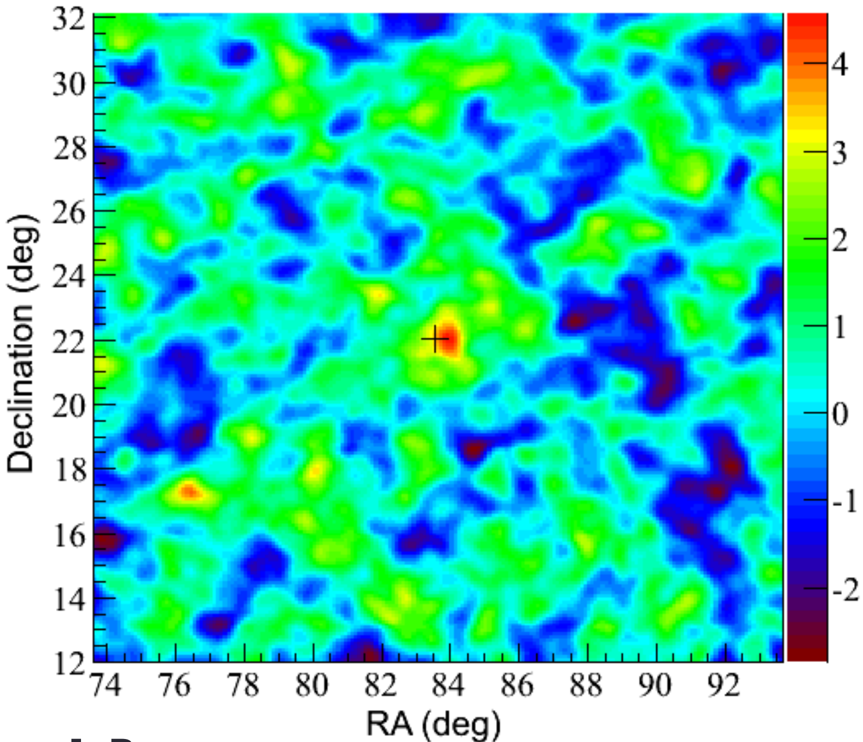
Energy deposited away from core

Crab Nebula

HAWC-30	Fall 2012	
HAWC-111	Summer 2013	14 transits
HAWC-250	Summer 2014	2.5 hours



J. Pretz

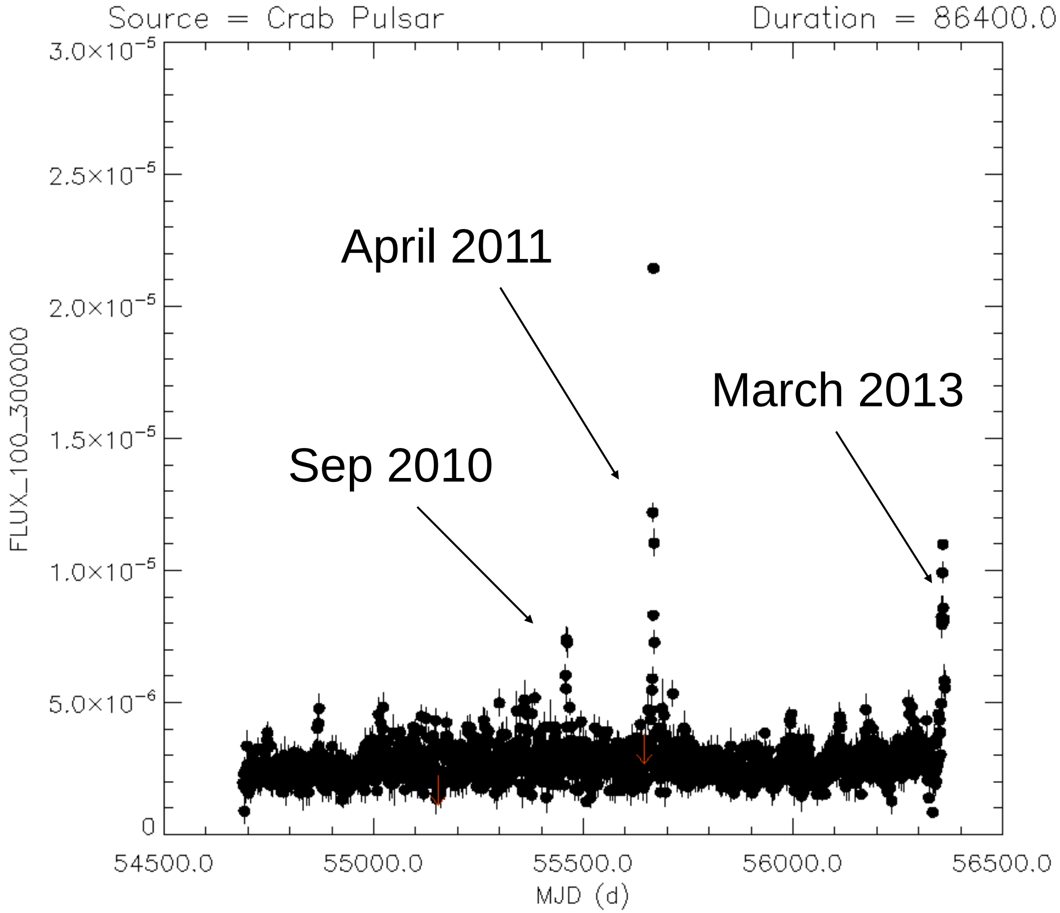


J. Braun

Transients: The Crab

- Considered a reference source
- **Sep. 2010:** Fermi and AGILE observe a 3x flare at > 100 MeV
- **April 2011:** Fermi and AGILE observe a 30x flare!
- **Mar. 2013:** Fermi and AGILE observe a 4-5x flare

Fermi-LAT >100 MeV



Transients: The Crab

- **Flares show structure at 12-hour time scales**

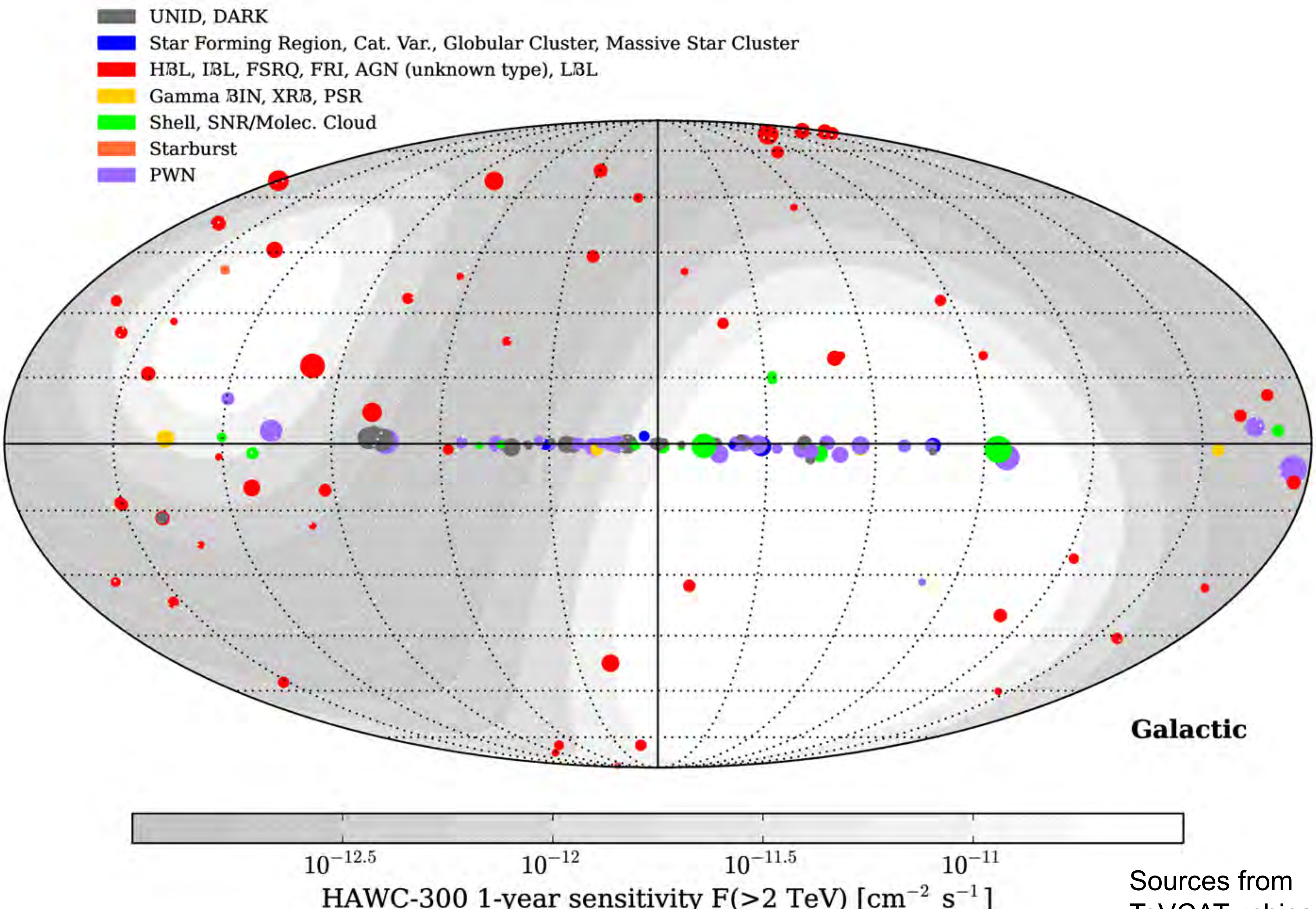
- **Flares are likely synchrotron emission from freshly accelerated ~PeV electrons that rapidly cool**
  - Acceleration mechanism is not understood
  - Implies TeV – PeV inverse Compton emission

  → TeV observations probe Lorentz factor of acceleration region

- **ARGO-YBJ reports an excess during September 2010 and April 2011 flares**

- **Perfect science for HAWC:**
  - Crab transits overhead; sensitivity: 8σ per day
  - Difficult for IACTs

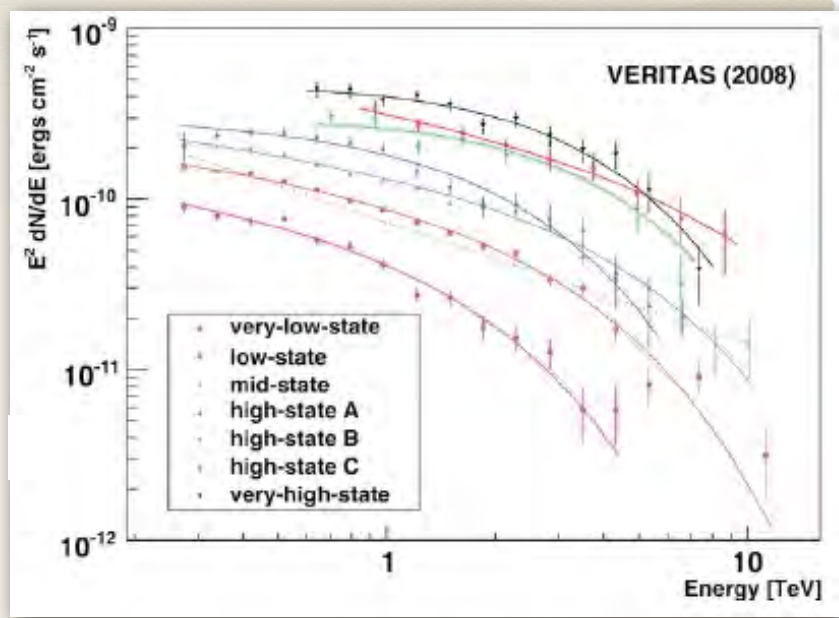
HAWC Field Of View

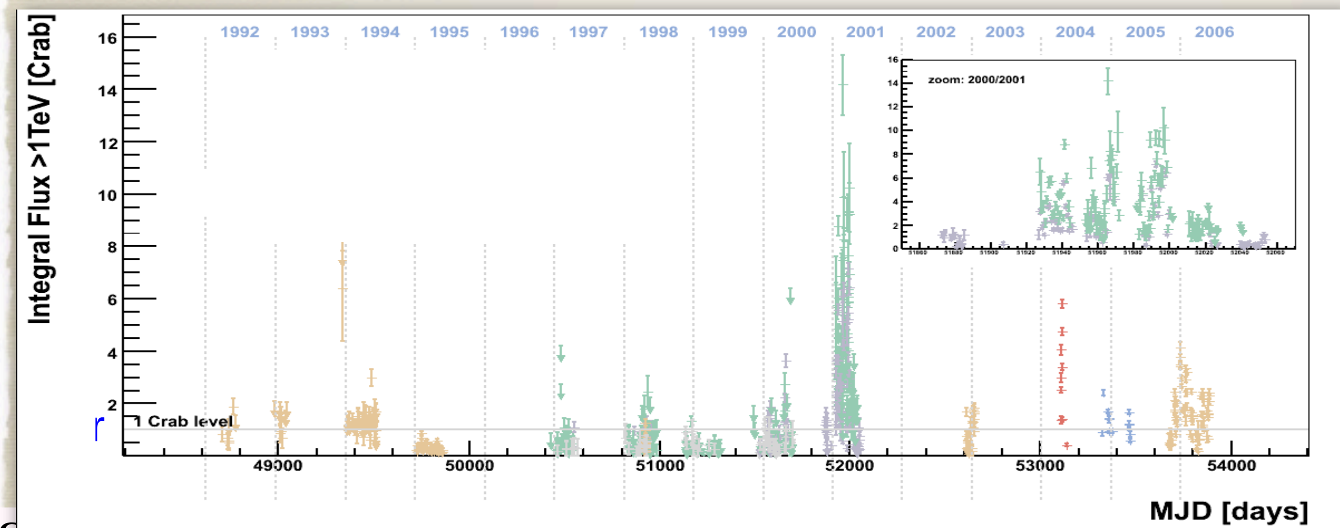


Sources from TeVCAT.uchicago.edu

Active Galactic Nuclei

- >50 AGN detected at TeV energies
- HAWC will observe all northern hemisphere AGN for ~5 hours/day
- Mrk 421 “very-high-state” detectable (8σ) in 30 minutes
- Mrk 421 “high-state-A” detectable in 1 day
- Mrk 421 “very-low-state” 1 month



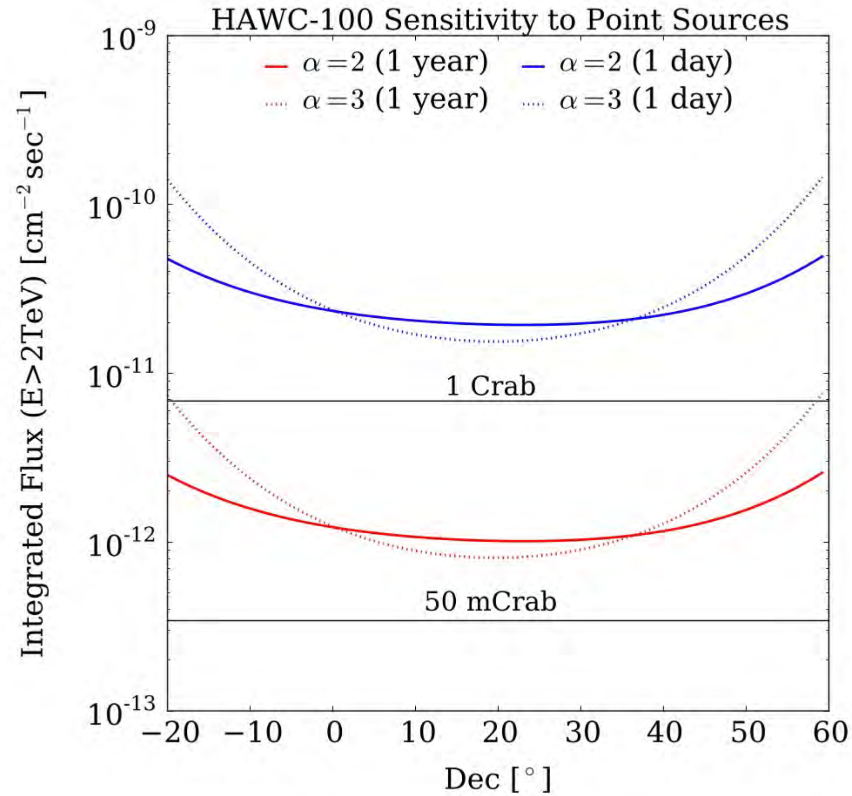


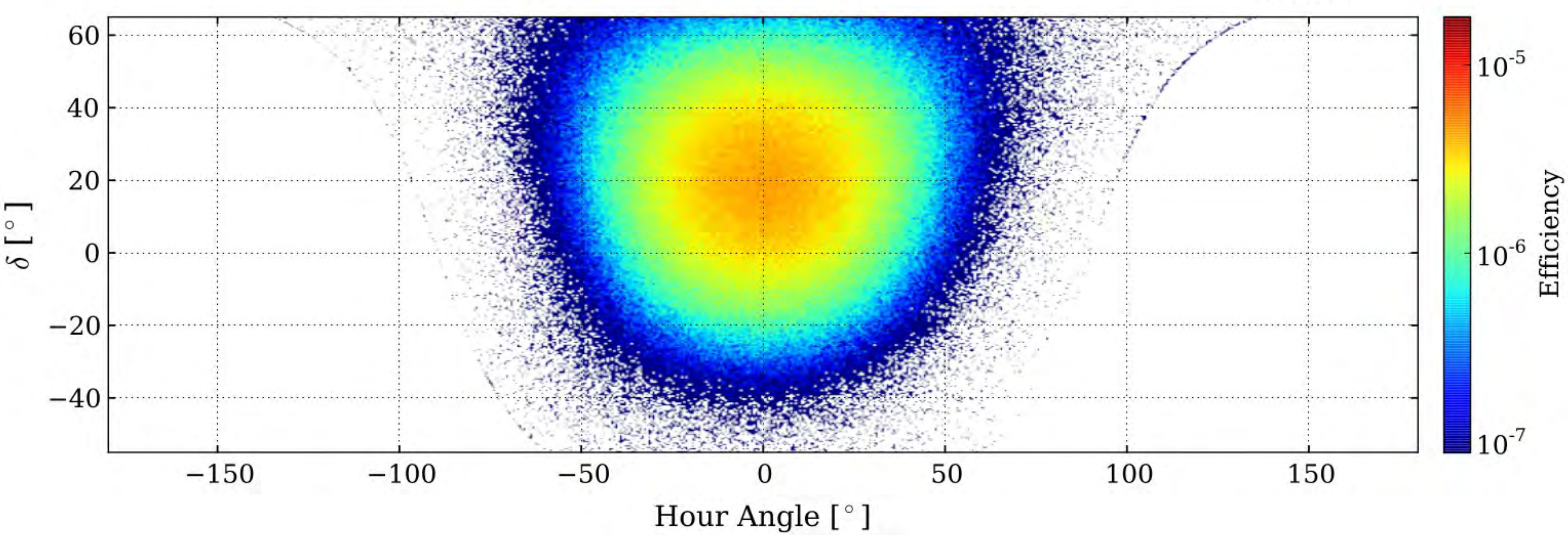
AGN Follow Up

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

HAWC's 5σ sensitivity is:
(10, 1, 0.1) Crab in (3 min, 5 hrs, 1/3 yr)

System to send flare alerts for IACTs under development.





Science Agenda

- Provide an *unbiased map* of the TeV sky (2π sr daily).
- Search for the *sources of cosmic rays:*
  - Measure the energy spectrum of Galactic sources up to the highest energies.
  - Measure diffuse gamma-ray emission between 1 TeV and 100 TeV and search for regions with emission above that expected from the observed matter density.
  - Map the arrival direction distribution of cosmic rays at energies > TeV and study the large- and small-scale anisotropy.
- Search for *transient sources:*
  - Search for >30 GeV emission from GRBs.
  - Study transient emission from sources like AGN.
- Probe density of extragalactic background light (*EBL*) in the IR waveband.
- Search for *new physics* at TeV.
- Provide *TeV alerts* for other instruments (IACTs, IceCube, …).

México

Benemérita Universidad Autónoma de Puebla
Centro de Investigación y de Estudios Avanzados
Instituto Nacional de Astrofísica Óptica y Electrónica
Universidad Autónoma de Chiapas
Universidad de Guadalajara
Universidad de Guanajuato
Universidad Michoacana de San Nicolás de Hidalgo
Universidad Nacional Autónoma de México
- Instituto de Astronomía
- Instituto de Física
- Instituto de Ciencias Nucleares
- Instituto de Geofísica

USA

Colorado State University
George Mason University
Georgia Institute of Technology
Harvey Mudd College
Los Alamos National Laboratory
Michigan State University
Michigan Technological University
NASA/Goddard Space Flight Center
Ohio State University at Lima
Pennsylvania State University
University of California, Irvine
University of California, Santa Cruz
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

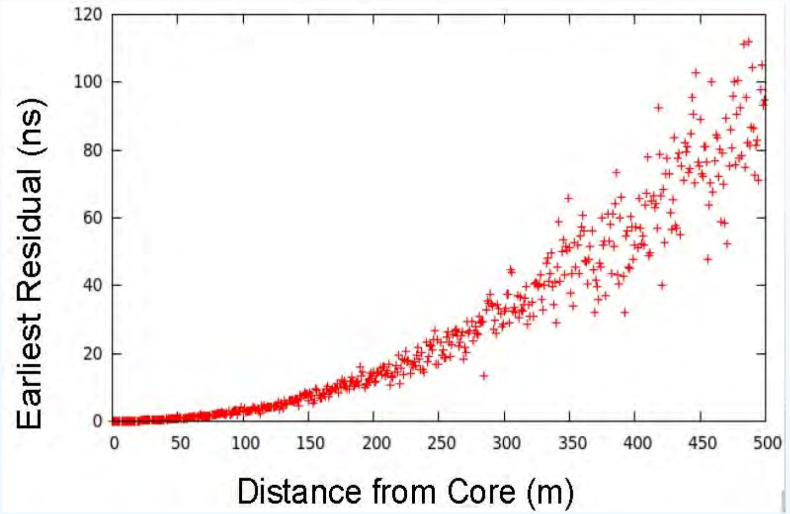
Summary

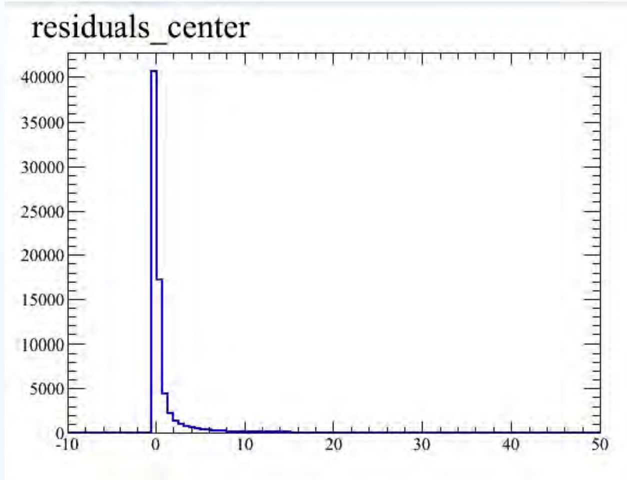
- The extreme universe is of great current interest both theoretically and experimentally.
- New instruments, and in particular the High Altitude Water Cherenkov (HAWC) experiment, are needed to truly advance our understanding of the physics.
- The UNM group in HAWC is well positioned (as leader of the precision (timing) calibration system) to play a major role in HAWC physics.
- HAWC, already in routine data-taking and over 1/3 completed, provides an ideal opportunity for students.
- There are also good Auger analysis opportunities for students.
- So: many opportunities and no lack of challenges!

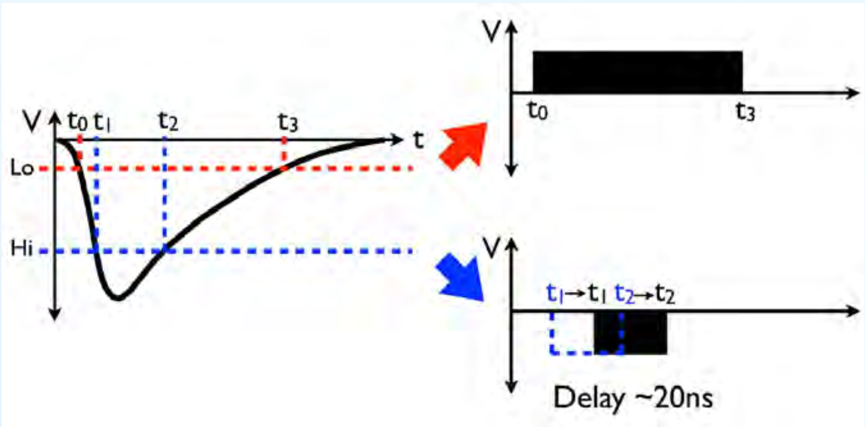
Additional/backup slides

Additional slides

HAWC challenges ...

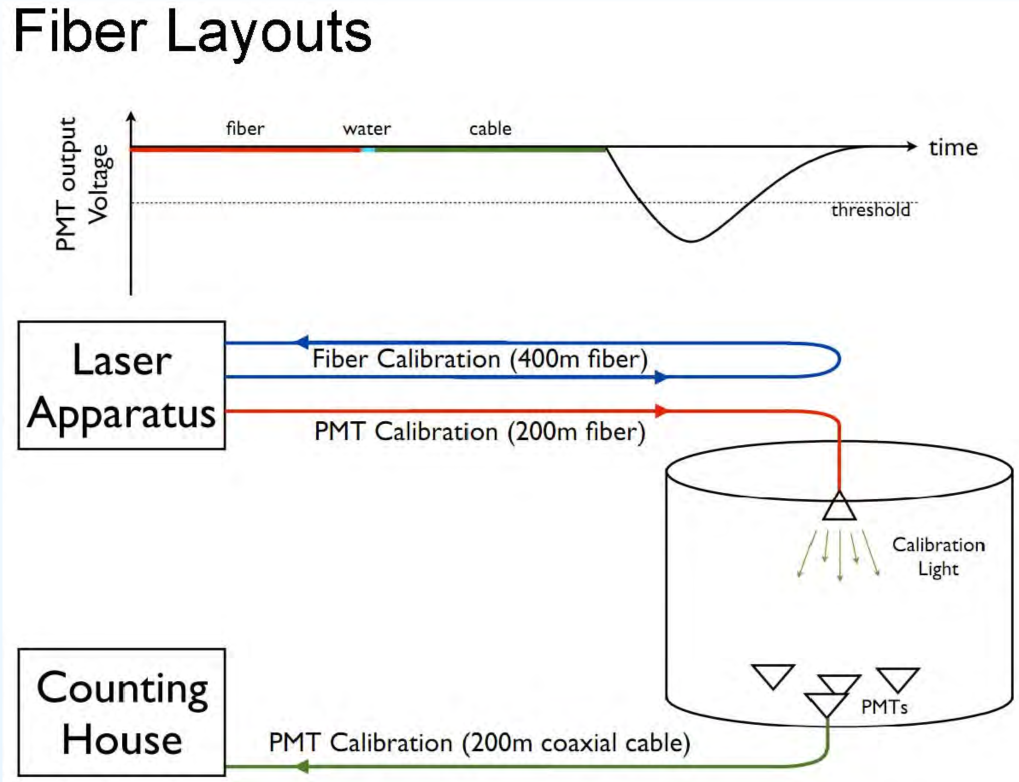






- (Top Left) Shower front timing residuals *vs* distance from shower core; (Top Right) Timing residuals (nsec) near the shower *core*.
- Precision angular reconstruction then needs the PMT timing offsets (errors) to be < 1ns.
- DAQ emphasis on precision timing (Bottom Left) results in the signal amplitude being *coded* as Time over Threshold (ToT).

HAWC calibration *design* ...

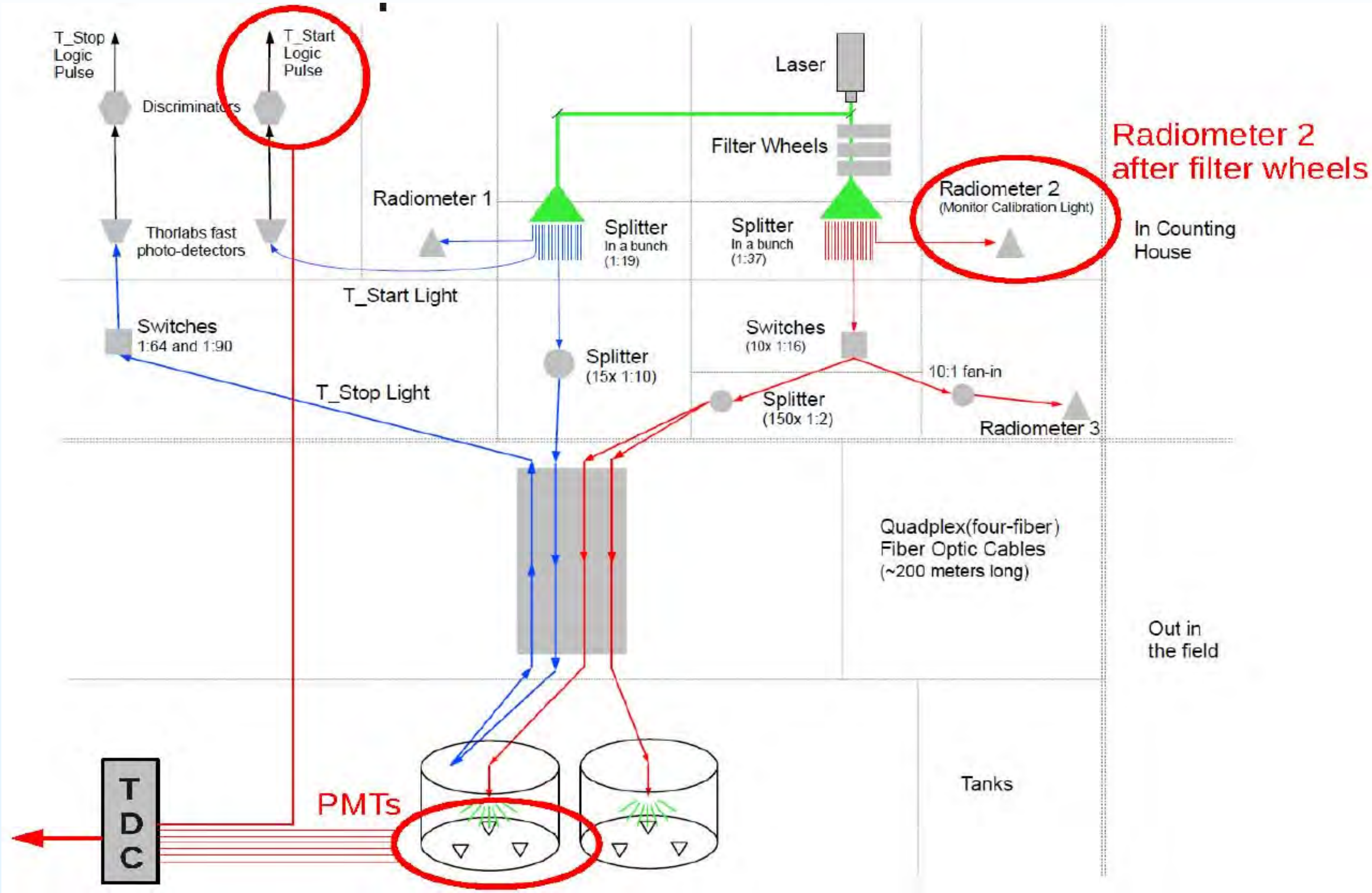


- Use a pulsed (300ps, 532nm laser) light source of known intensity and with known light transit time to the PMTs.
- Adjust the source intensity (using neutral density filters) over the (required) PMT dynamic range of ~ 0.1PE to $\sim 10^4$PEs.
- Repeat 300 times (for 300 WCDs). Begin with the HAWC WCD prototype at CSU

HAWC calibration *calibration at CSU WCD* **...**

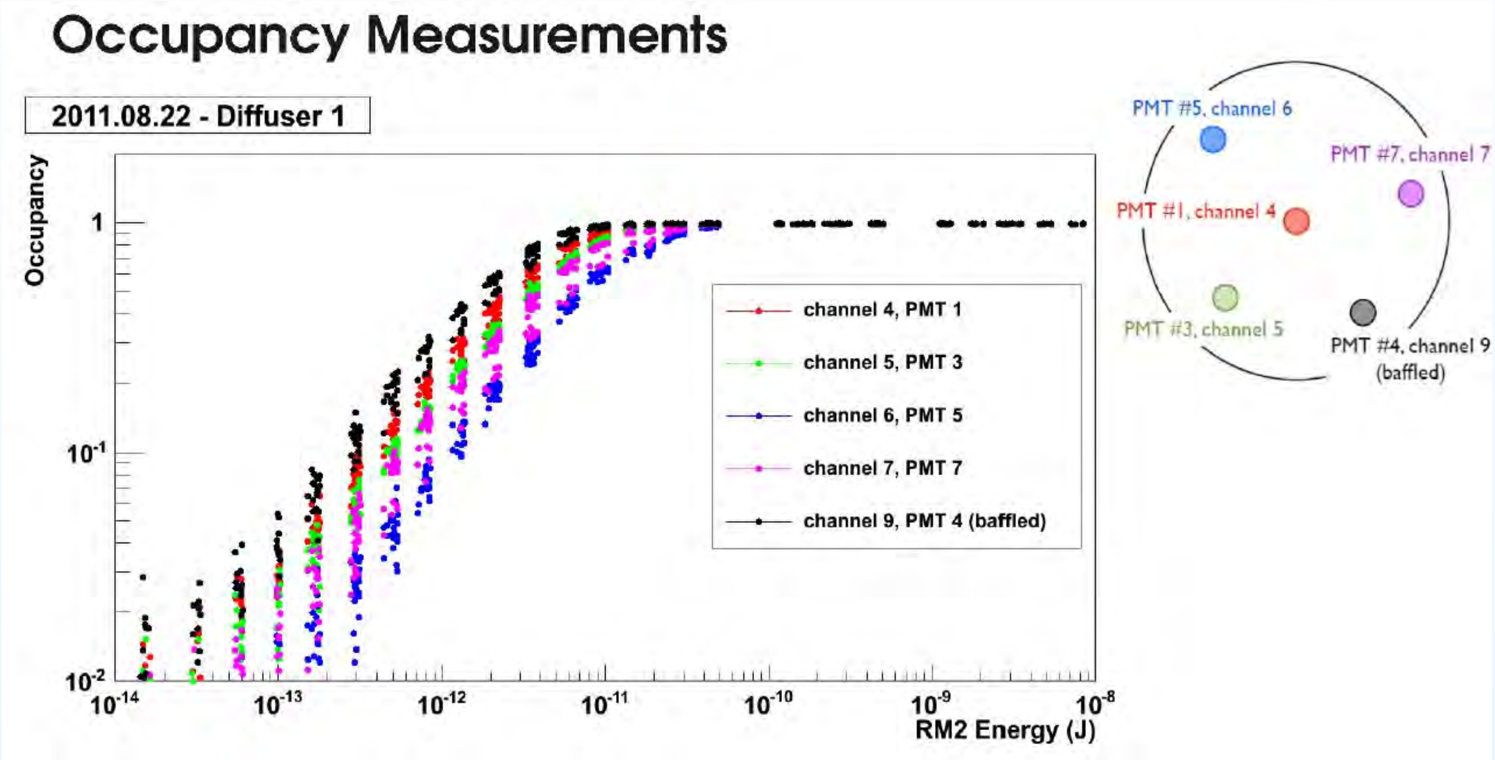
- The prototype HAWC WCD at CSU has allowed R&D on all components (hardware, control software and analysis) of the calibration system.
- Major group calibration responsibilities include:
  1. CSU: calibration data analysis, muon calibration
  2. George Mason U: muon calibration
  3. LANL: DAQ for TDCs
  4. MTU: calibration control software and data analysis
  5. UNM: calibration hardware, control software and data analysis

HAWC calibration *schematic* ...



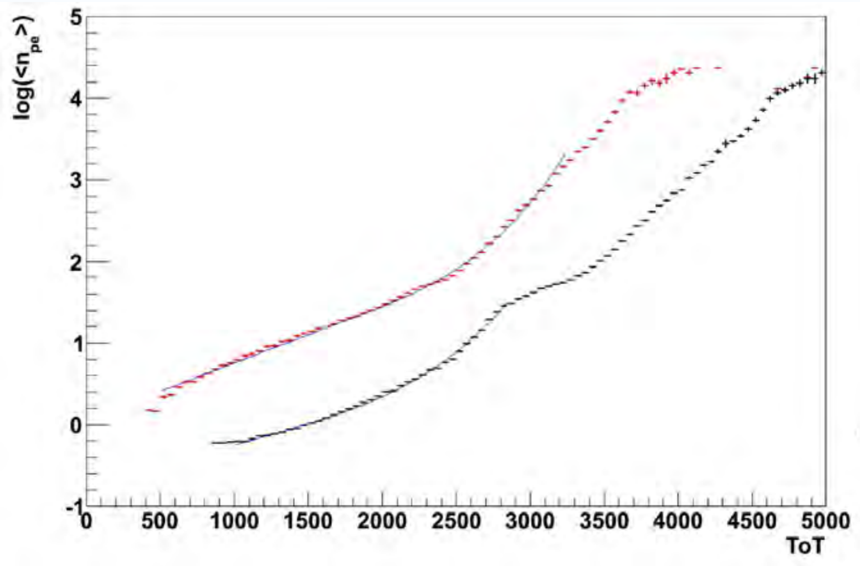
- The *ingredients* for a calibration include: the light-to-WCD Intensity (Radiometer 2), and digitization of the laser pulse time (T_{start}) and the PMT (time and ToT).

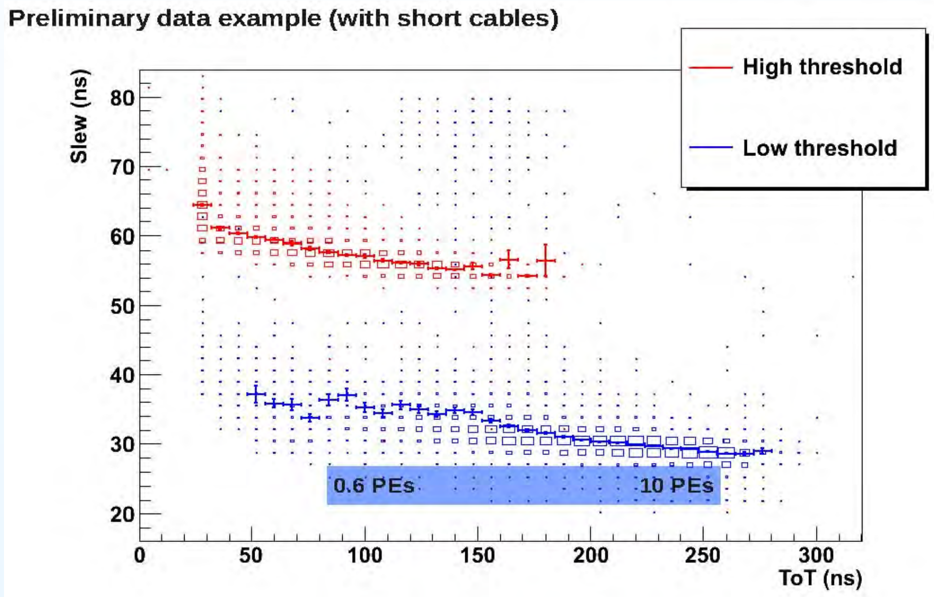
HAWC calibration *cycle* ...



- A calibration cycle involves ~ 2000 light pulses/intensity at 150 discrete intensities.
- The PMT occupancy (*i.e.* fraction of laser pulses with PMT signal $> V_{Lo}$) is related to the average number of PEs, $< n_{PE} >$, at that intensity (RM2 energy (J)).
- This is merged with the distribution of ToT (at that RM2 energy (J)) to obtain: ToT $\rightarrow n_{PE}$ for each of the PMTs (5 in this data from CSU) in the WCD.

HAWC calibration *deliverables (from CSU) (I)* ...





- (Top Left) Relation between what HAWC measures: PMT ToT and the PMT signal in PEs. The PMT signal in PEs is needed for shower plane reconstruction and γ-hadron separation.
- (Top Right) Time slewing correction (nsec) *vs* the measured PMT signal in ToT. The slewing correction is needed for shower plane reconstruction.
- Note: Time slewing $\equiv$ time between laser and PMT pulses; ToT(ns) = ToT/10.24.