Research Overview Seminar

Physics of the Extreme Universe

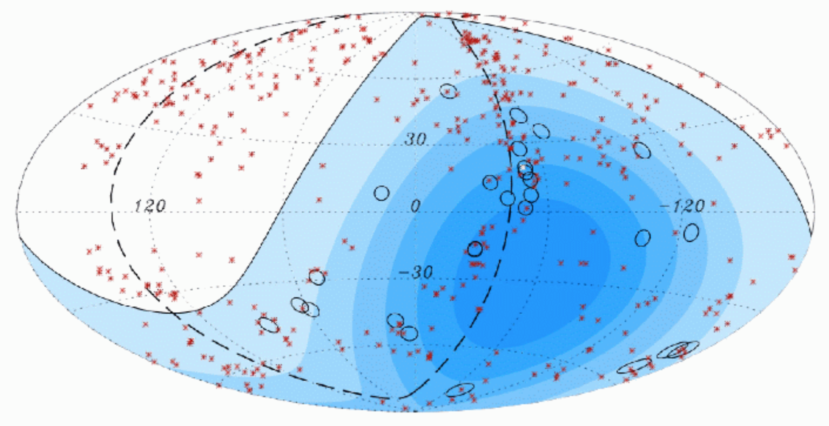
John A.J. Matthews

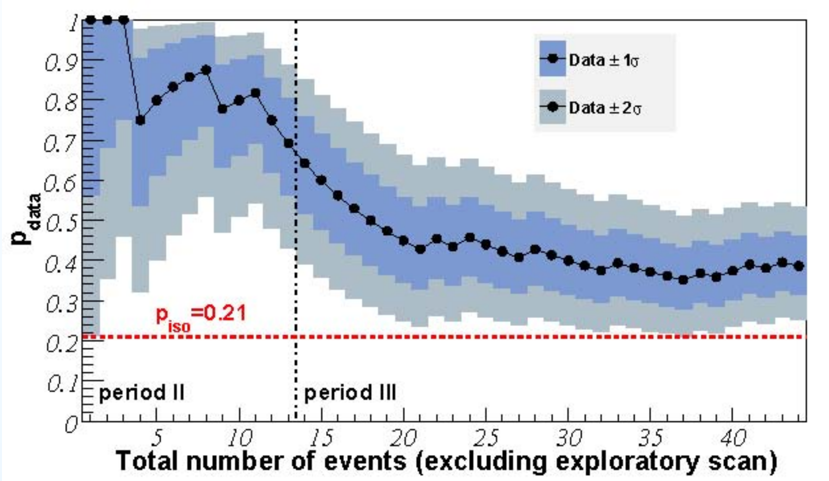
johnm@phys.unm.edu

University of New Mexico

Albuquerque, NM 87131

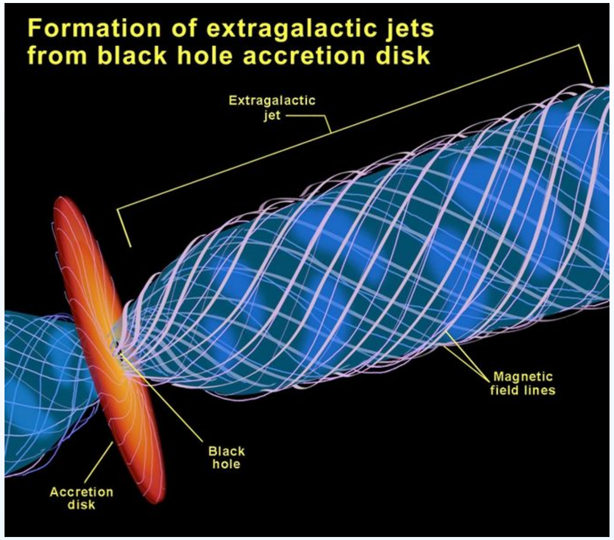
Several years ago ... in a country far away





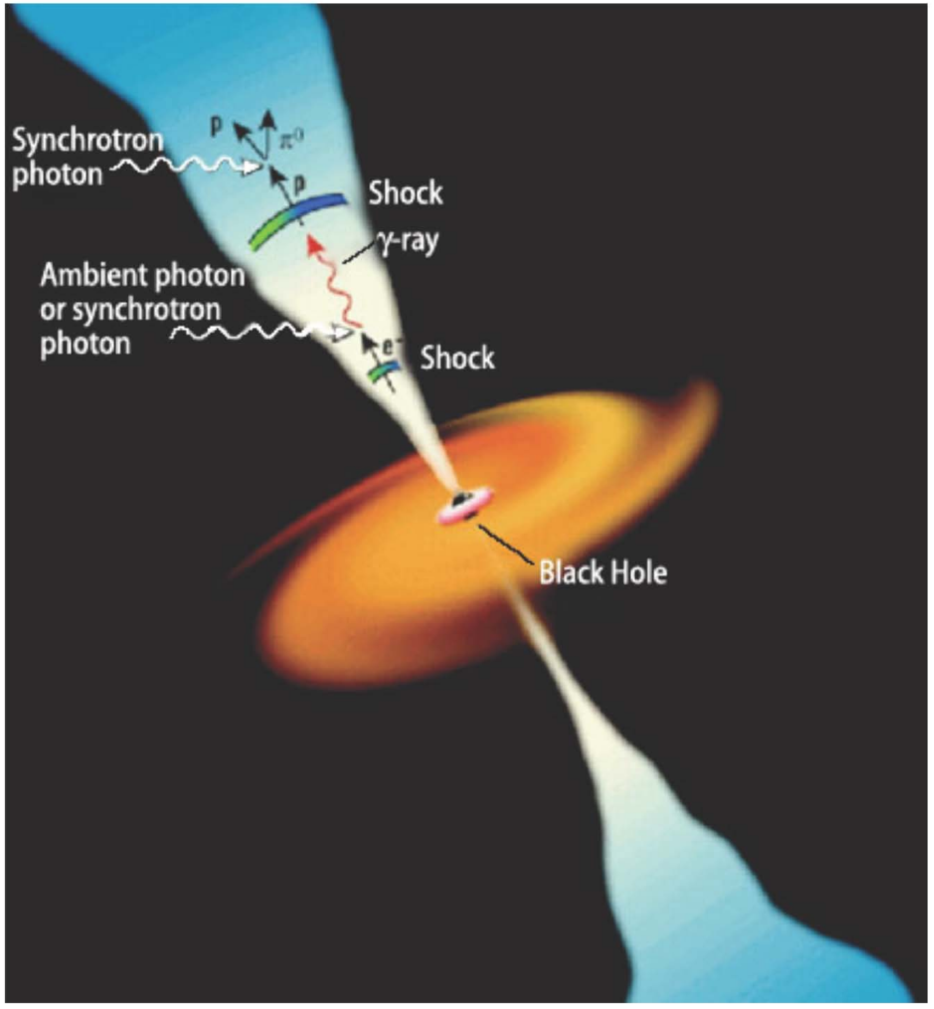
- We built the Pierre Auger Observatory (in Argentina) to study the highest energy cosmic rays (CRs):
  1. Is there a cutoff in the spectrum of the highest energy cosmic rays *... as expected from the interaction of CR protons with the cosmic microwave radiation*?
  2. And if there is a cutoff the highest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



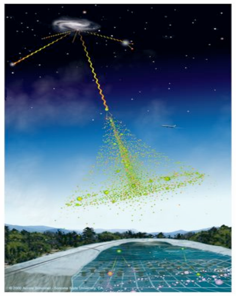
What physics in *e.g.* astro-physical jets could result in γ-rays to energies of 10^{15}eV or possibly cosmic rays to energies of 10^{20}eV?

- 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 ...

γ-rays are the most recent frontier ...

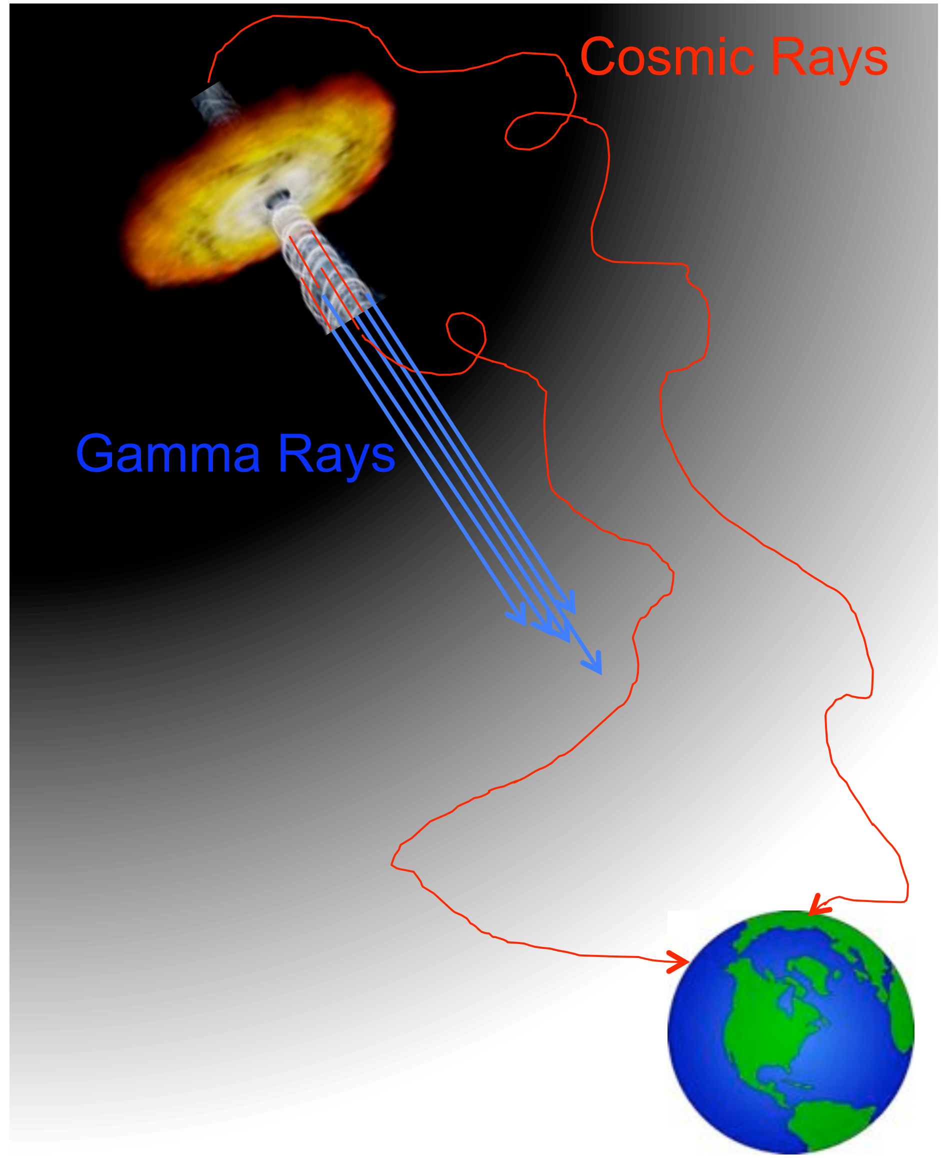
Initial *sky surveys* must now move on to detailed measurements ...

- γ-ray directions must now be measured to an angular precision of $\lesssim 0.2°$
- 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



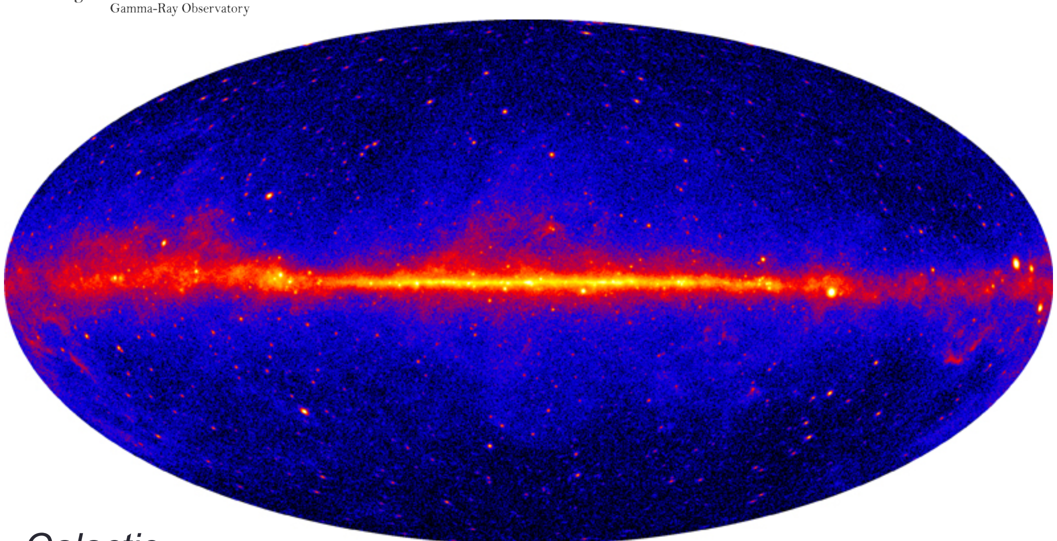
Gamma Rays Probe Cosmic Rays

- Cosmic rays are energetic particles that have electric charge => Directions are randomized by Magnetic Fields in the Universe
- Gamma rays are produced by cosmic rays near their accelerators => Directions point back to the Sources
- Therefore, gamma rays are unique probe of cosmic rays and their accelerators

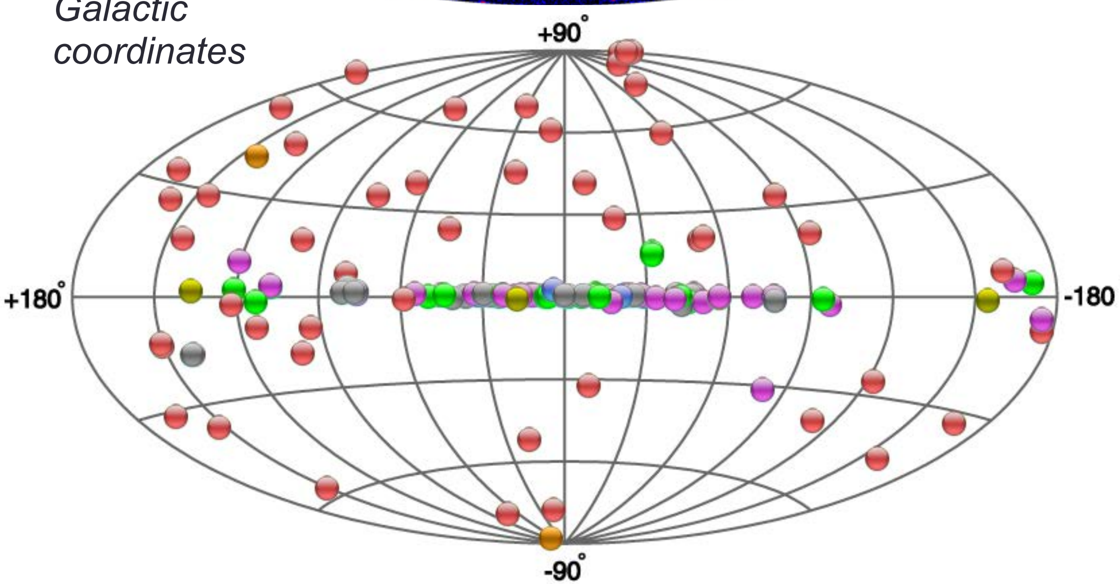


HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

The GeV-TeV Sky



Galactic coordinates



NASA's Fermi Gamma Ray Telescope

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

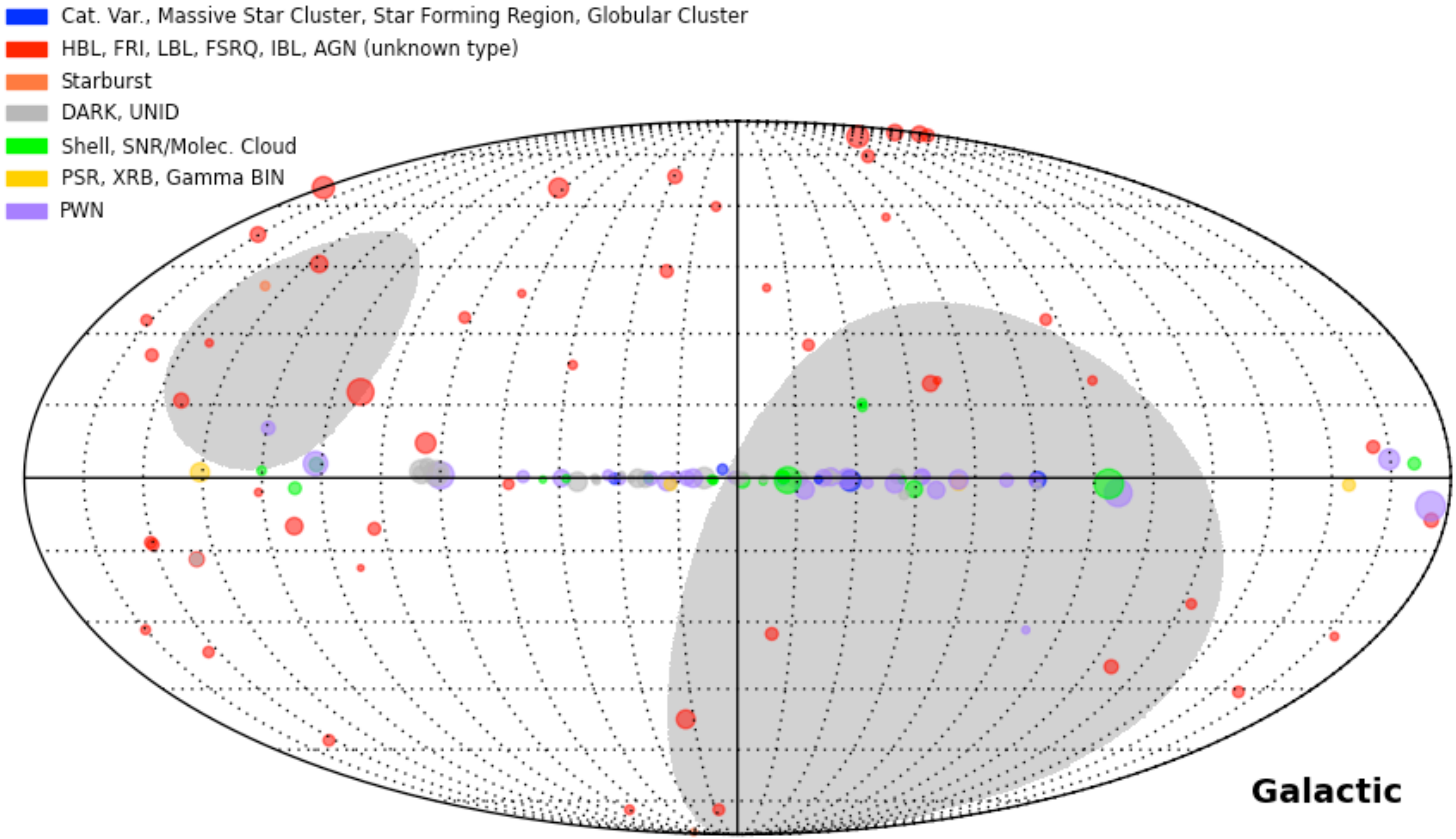
arXiv:1108.1435 (ApJ Supp.)

TeV Catalog (as of June 2012)

- 136 sources (85 Galactic, 51 extragalactic).
- Not an all-sky survey - catalog is strongly biased.

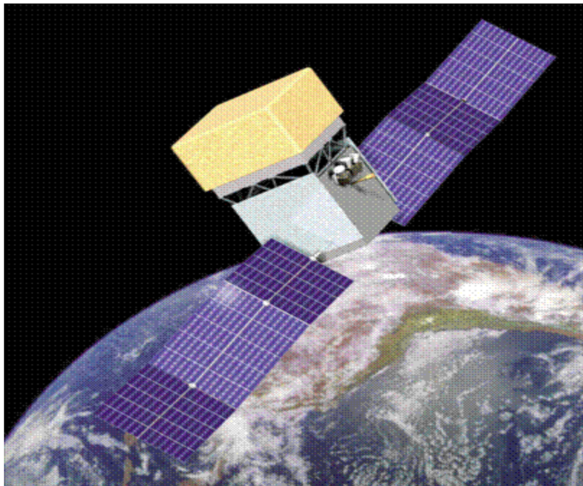
http://tevcat.uchicago.edu

Galactic TeV gamma sources



- About half the known sources visible to HAWC

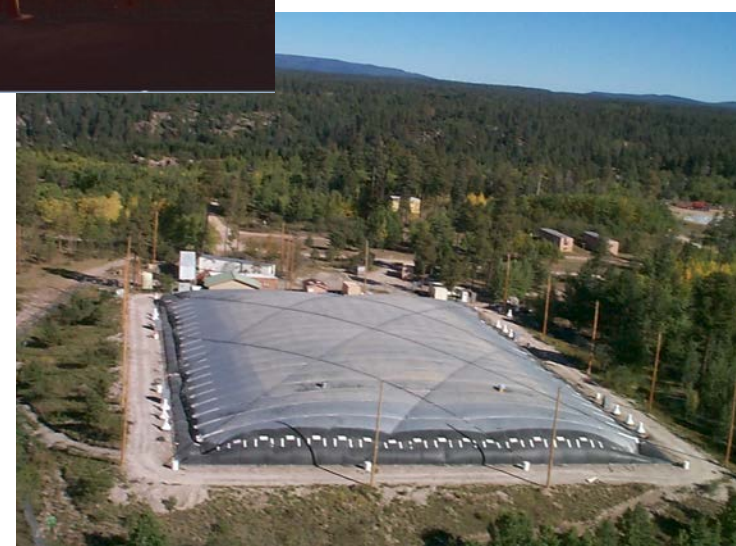
Gamma Ray Instruments



EGRET/Fermi
1 GeV to 100 GeV, large duty cycle, all-sky, background-free, small area.

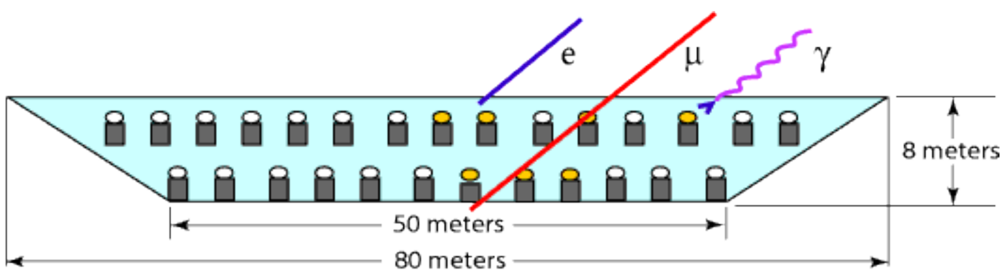
HESS, MAGIC, VERITAS, CTA
low duty cycle, limited region of sky, excellent background rejection.

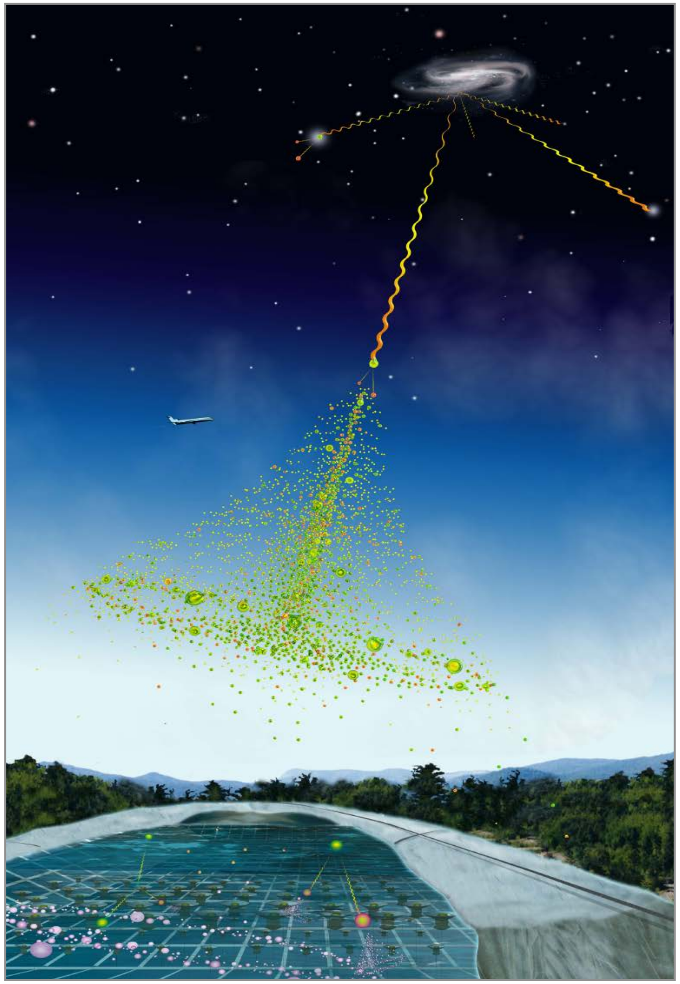
Milago, Tibet, ARGO, HAWC
Large duty cycle, half-sky, good background rejection.



Water Cherenkov Technique

- Particles of extensive air shower move through water volume and generate Cherenkov light that is captured by PMTs.
- Air shower photons can pair-produce in the water and produce Cherenkov light, too, so a large part of the electromagnetic component of an air shower can be detected.
  - Large duty cycle (>90%), independent of weather and daylight.
  - Large field-of-view (2 sr, or 16% of 4π), with a sky coverage of 2π sr daily.
  - Large effective area.



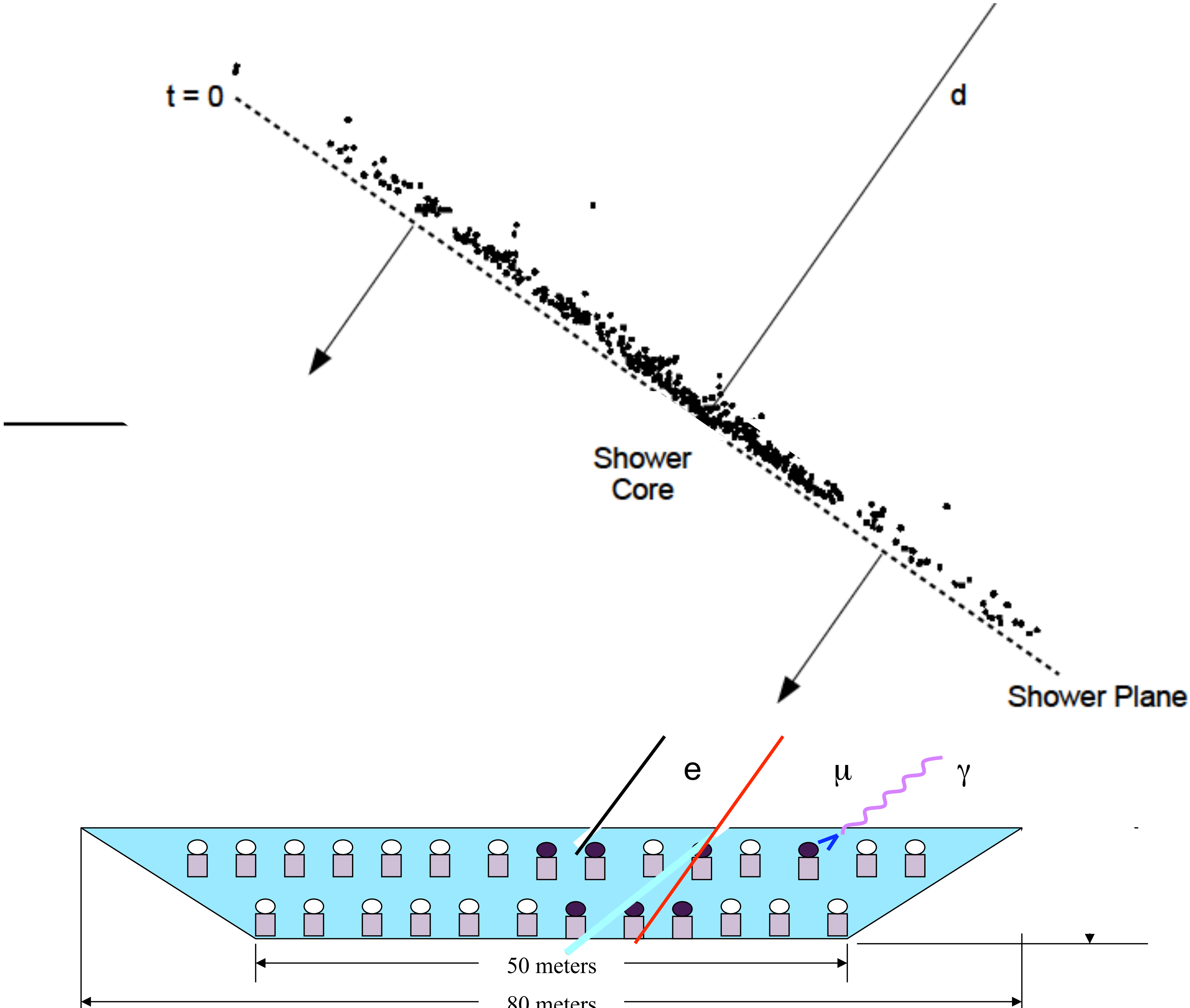


Precursor: Milagro Gamma Ray Observatory @ 2650m altitude near Los Alamos, NM

2000-2008

Inside the Milagro Detector

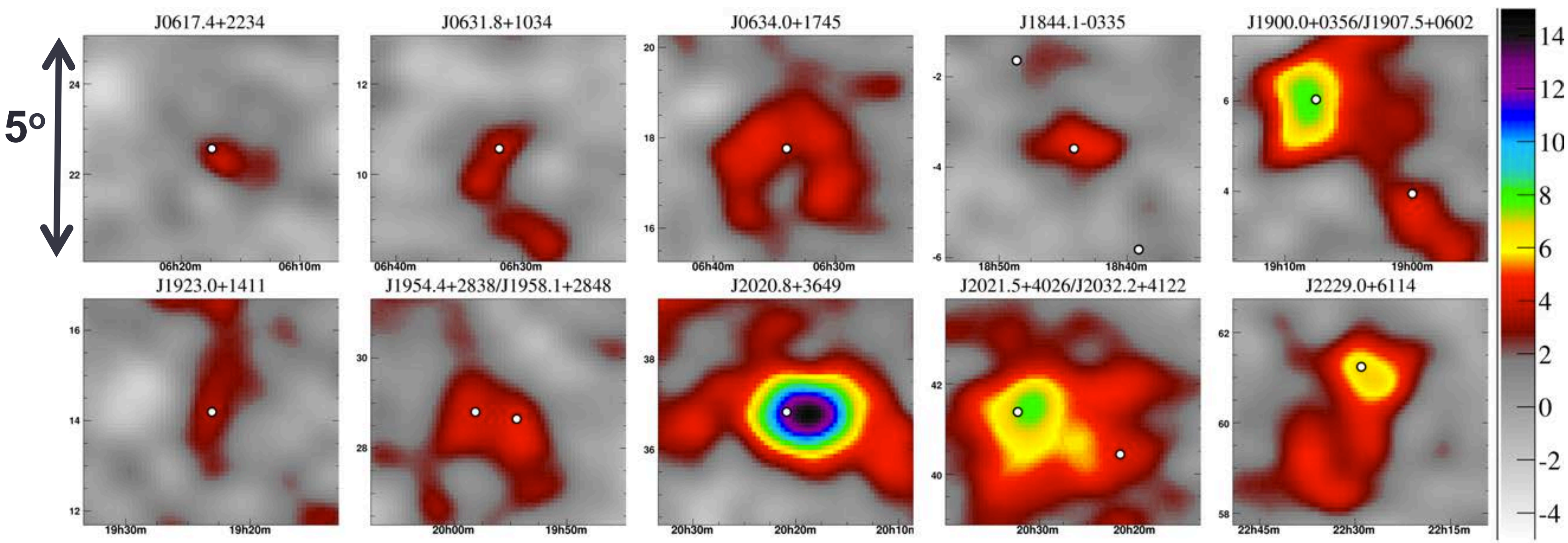
80m x 60m, 8m deep



t = 0
d
Shower Core
Shower Plane
e
μ
γ
50 meters
80 meters

Associations with Fermi Bright Source List

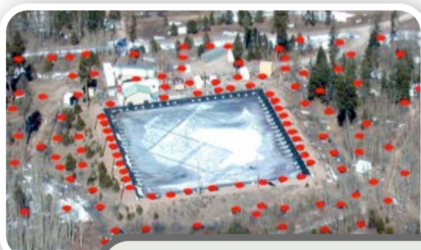
- 34 out of 205 Fermi BSL objects are possibly Galactic and in Milagro's field of view.
- 14/34 are observed at 3σ or more in Milagro data.
- Strong evidence for multi-TeV emission associated with Galactic LAT BSL sources "as a class."



From Milagro to HAWC

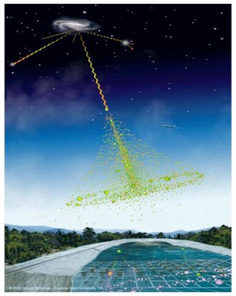
- Lesson from analysis of Fermi BSL with Milagro: there are potentially many TeV gamma ray sources right below the Milagro detection threshold.

- The water Cherenkov technique is working, but we need a detector that is more sensitive than Milagro. Possible ways to improve sensitivity:
  - Move to higher altitude to decrease the energy threshold.
  - Improve optical isolation.
  - Increase detector area.

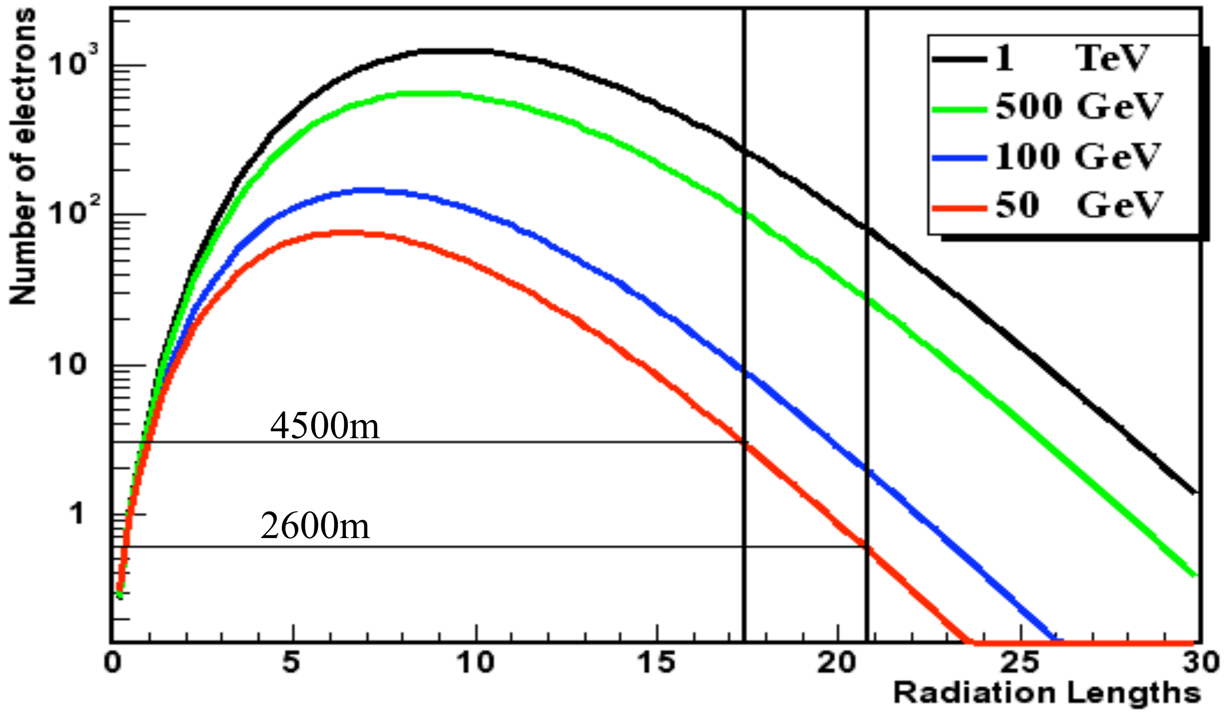


Milagro
- 2630 m asl
- Pond
- Pond area ~4,000 m^2

HAWC
- 4100 m asl
- Individual tanks
- Array area ~22,000 m^2



Higher Altitude is Closer to Shower Max.

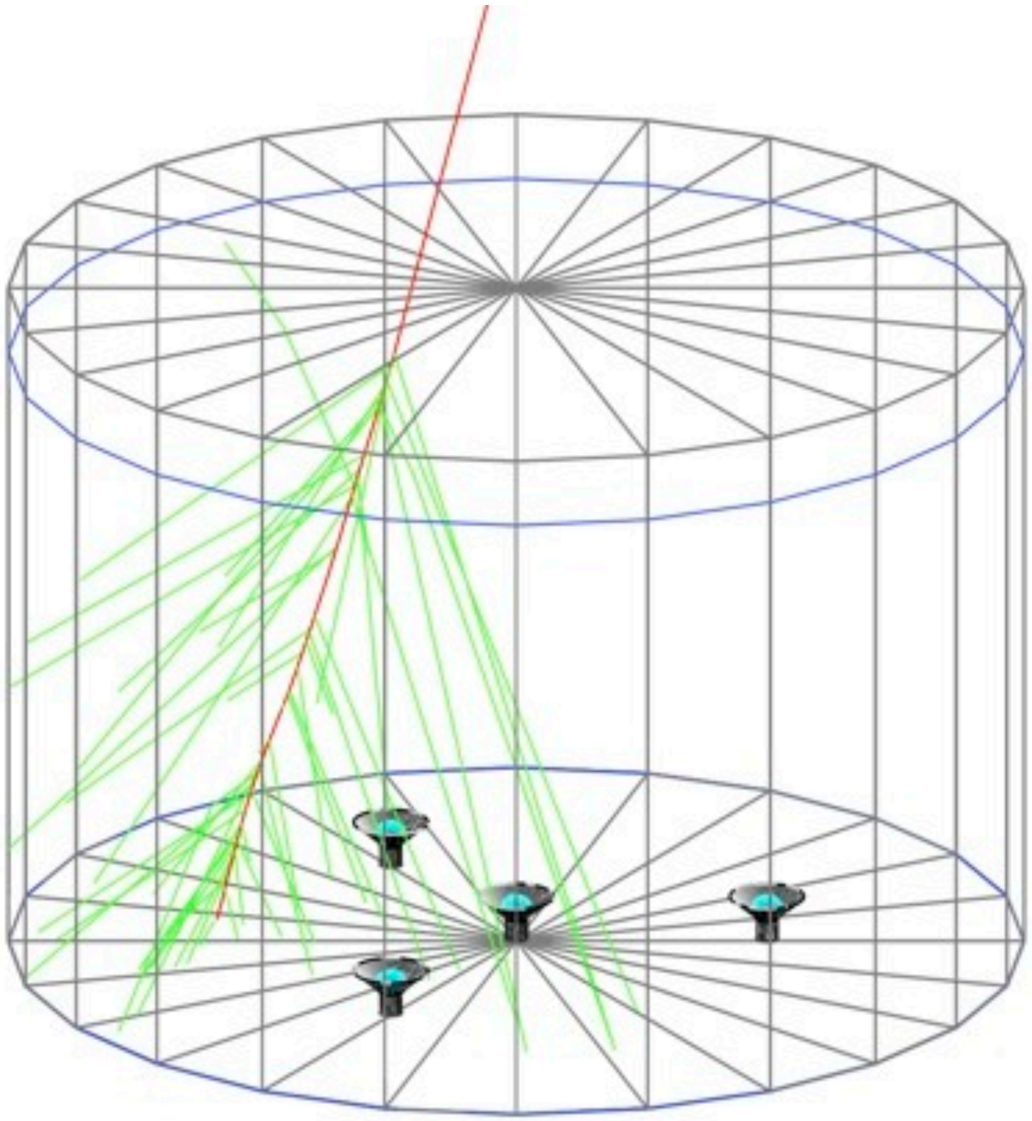


Difference between 2600m (Milagro) and 4100m (HAWC):

~ 4x number of particles

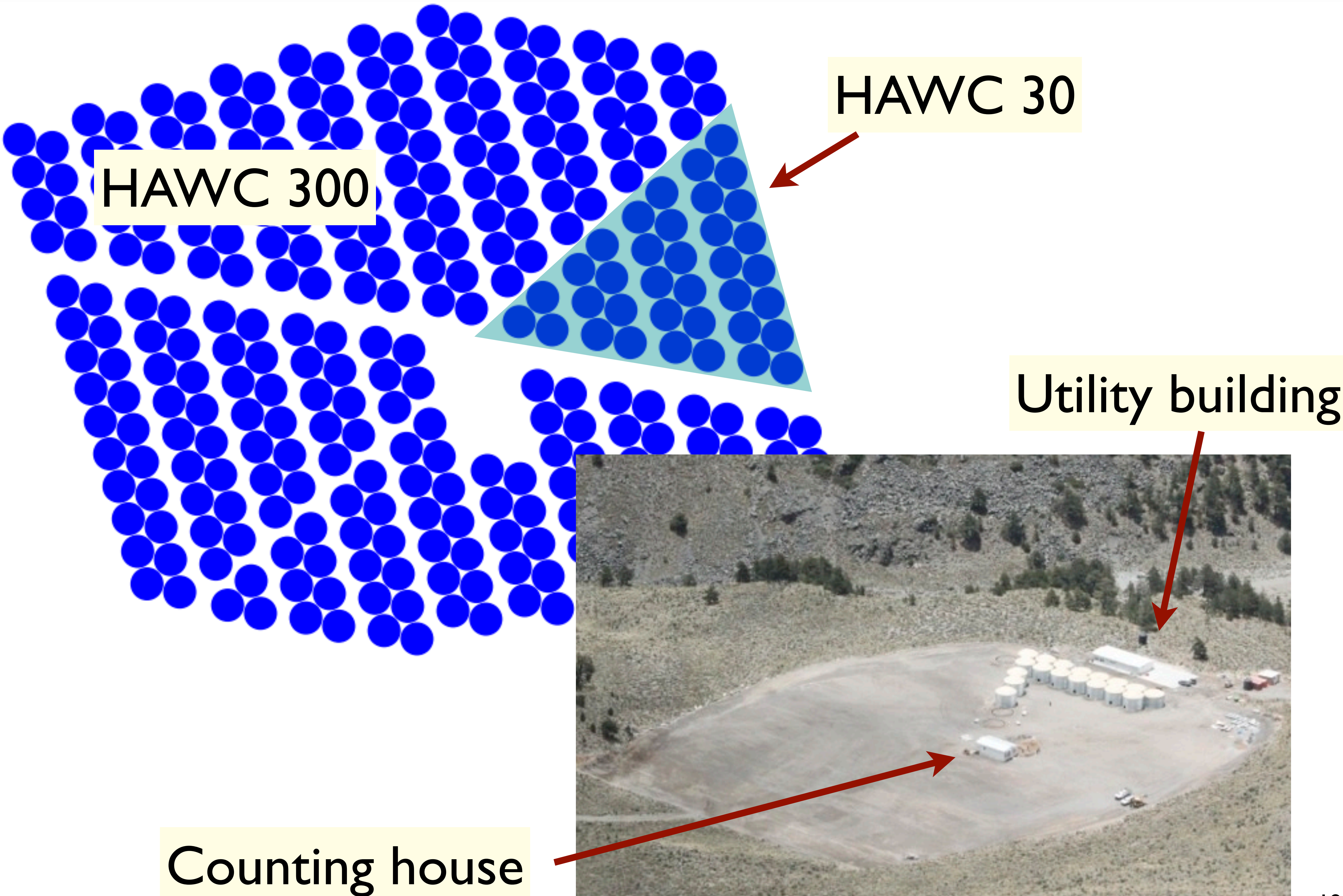
~ 2x lower energy threshold

Individual WCD

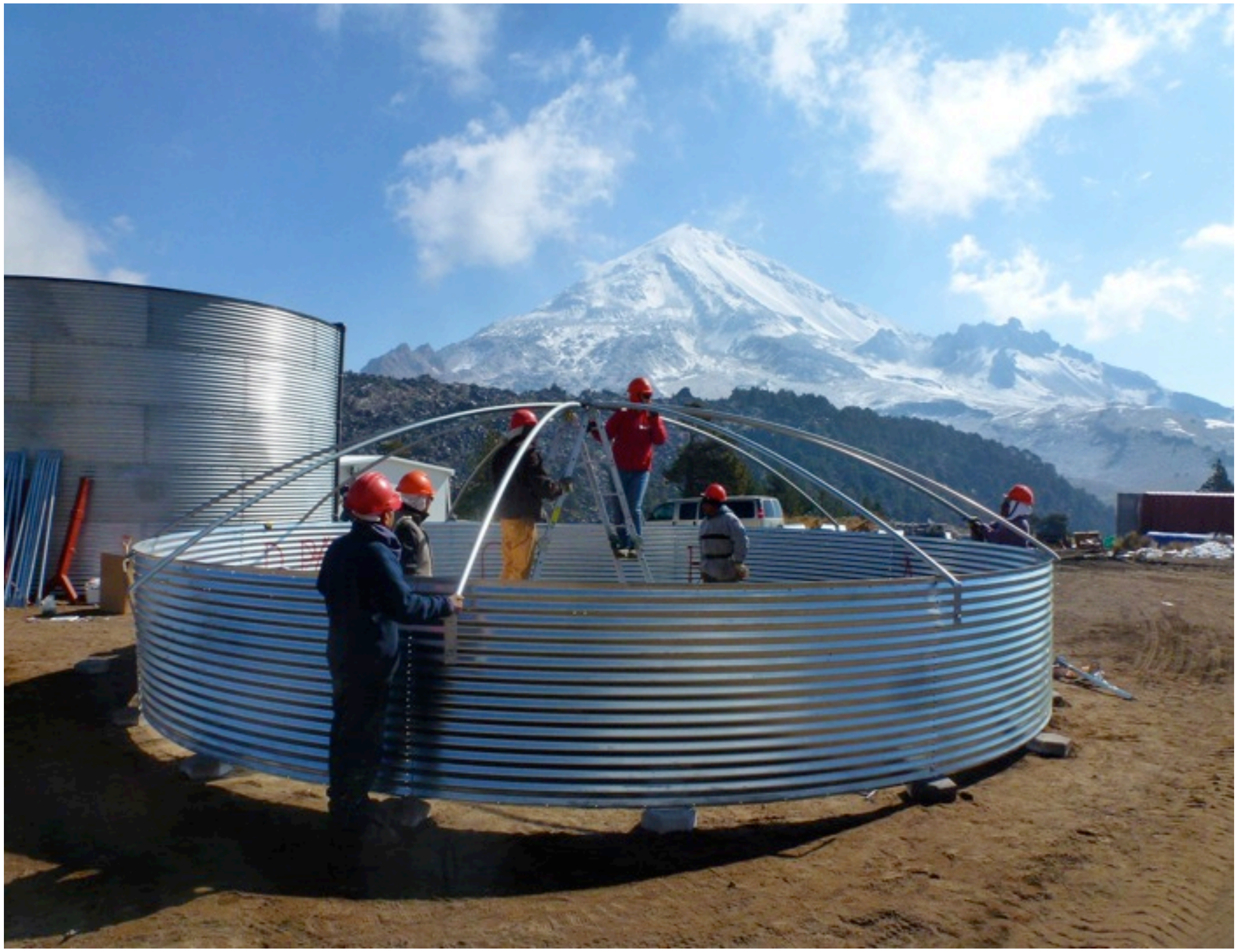


- ◉ Steel body
- ◉ Plastic liner to contain water
- ◉ 4.5 m tall, 7.3 m diameter
- ◉ 3 + 1 Photomultipliers

Layout and construction status



The metal tanks are constructed from the top down



Top down tank construction

Light-tight Bladder

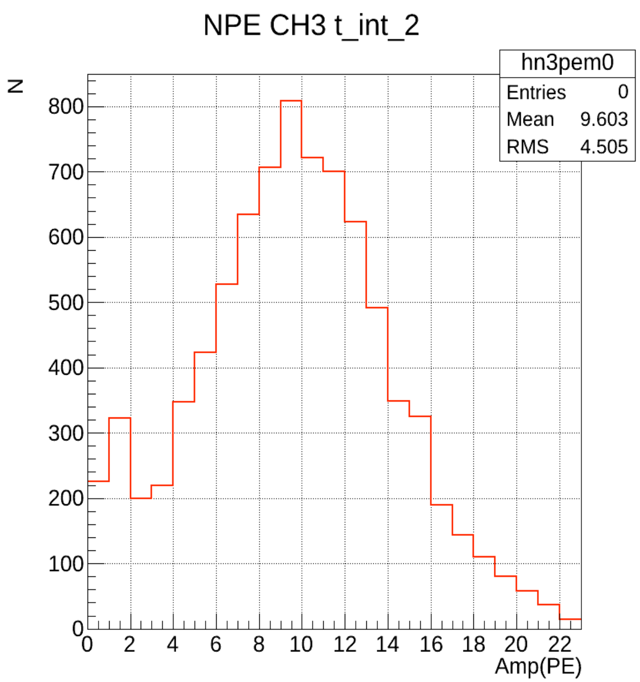
Made by Colorado State University.

Each bladder weighs < 300 lbs. and fits in 30”x9’ tube.

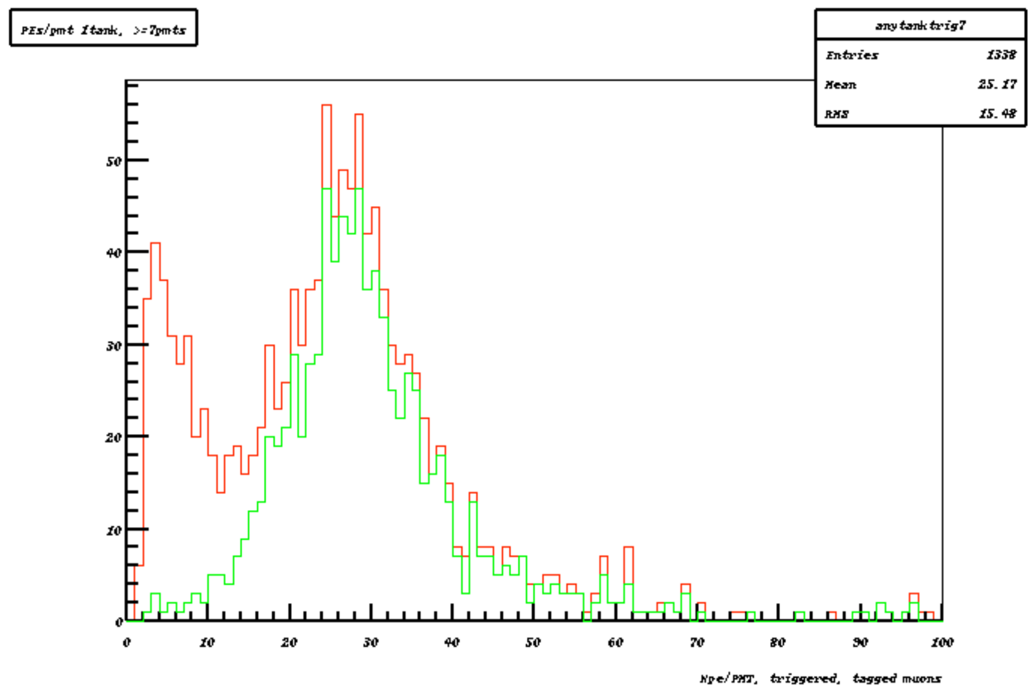
Water treatment plant makes clean water (λ_{abs}>15m)

Vertical muon signature compared to simulation

4 PMT in 2 ns
coincidence



Monte Carlo simulation
red all particles
green muons



HAWC Collaboration

México

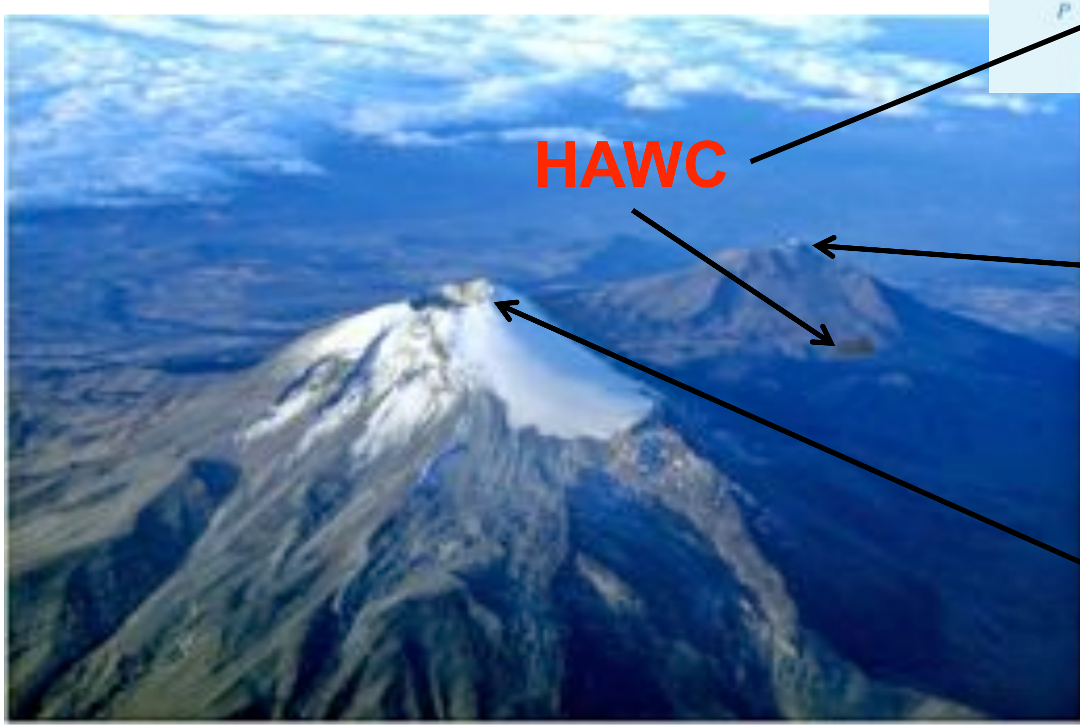
Benemérita Universidad Autónoma de Puebla
Centro de Investigación y de Estudios Avanzados
Instituto Nacional de Astrofísica Óptica y Electrónica
Universidad Autónoma de Chiapas
Universidad de Guadalajara
Universidad de Guanajuato
Universidad Michoacana de San Nicolás de Hidalgo
Universidad Nacional Autónoma 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

HAWC Site Location in Mexico

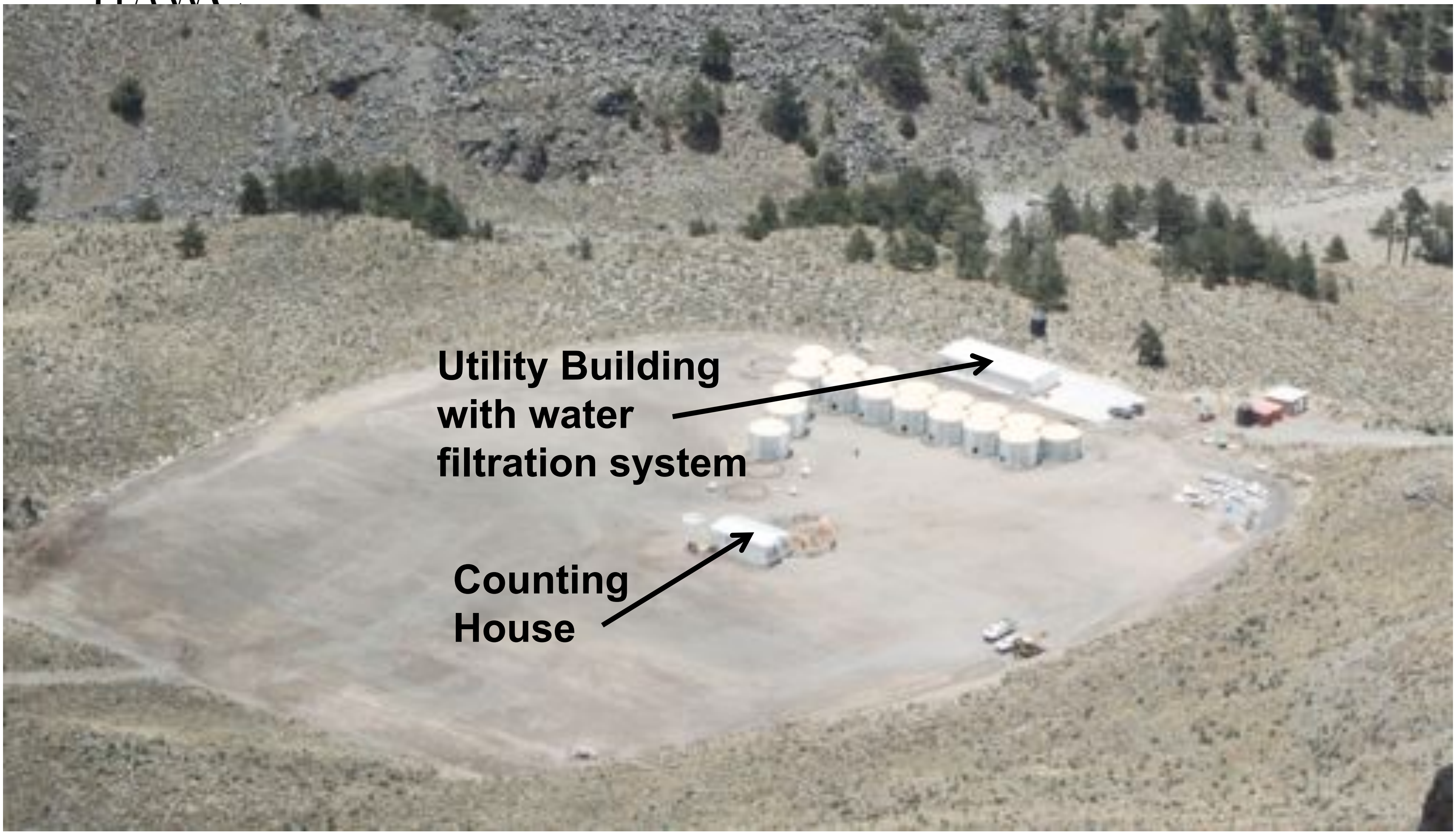
- 4100 m (13,500’) above sea level
- Latitude of 19 deg N
- Temperature 2-5^{o}C
- Existing Infrastructure
  - 1 km from >$100M US/Mexico Large Millimeter Telescope
  - Power, Internet, Roads



Large Millimeter Telescope (50m dia. dish)

Pico de Orizaba 5600 m (18,500’)

Platform for 300 WCDs is leveled.

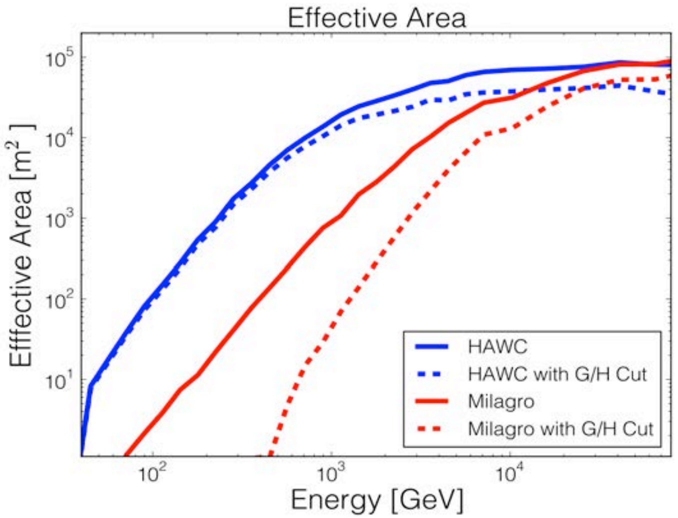


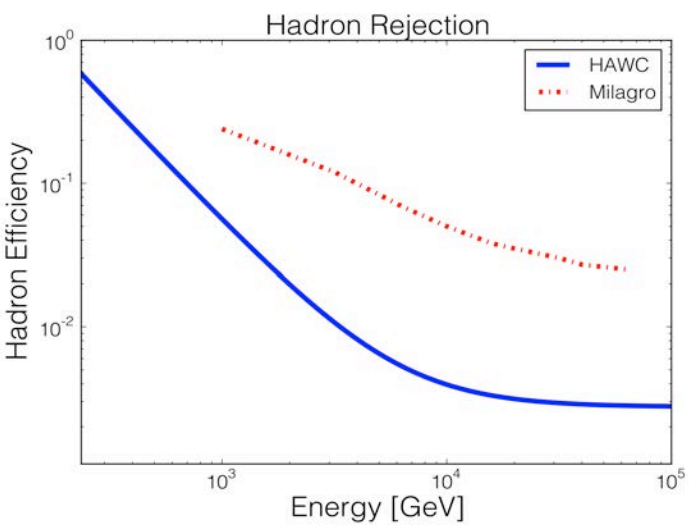
New discoveries await!

Milestones

- VAMOS 7 Summer 2011
- <u>HAWC 30 Summer 2012</u>
- HAWC 100 Summer 2013
- HAWC 300 Fall 2014

Performance





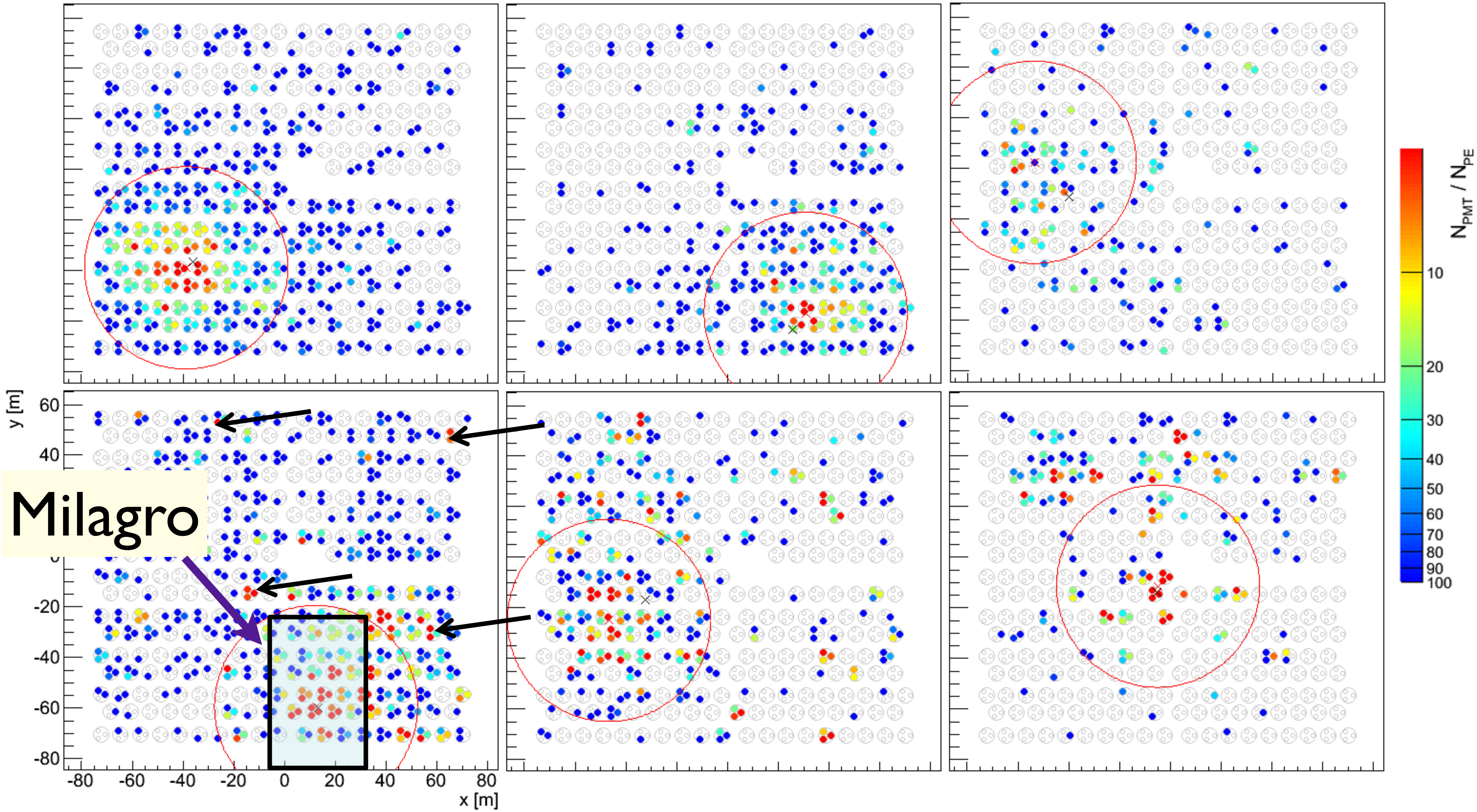
Effective area:

- HAWC has a lower threshold and a much better low energy response than Milagro.
- HAWC and Milagro have a similar effective area at high energy.
- Effective area at 100 GeV is still about ~100 m^2.
- At 2 TeV, the effective area of HAWC is ~7 times larger than Milagro.

Hadron rejection:

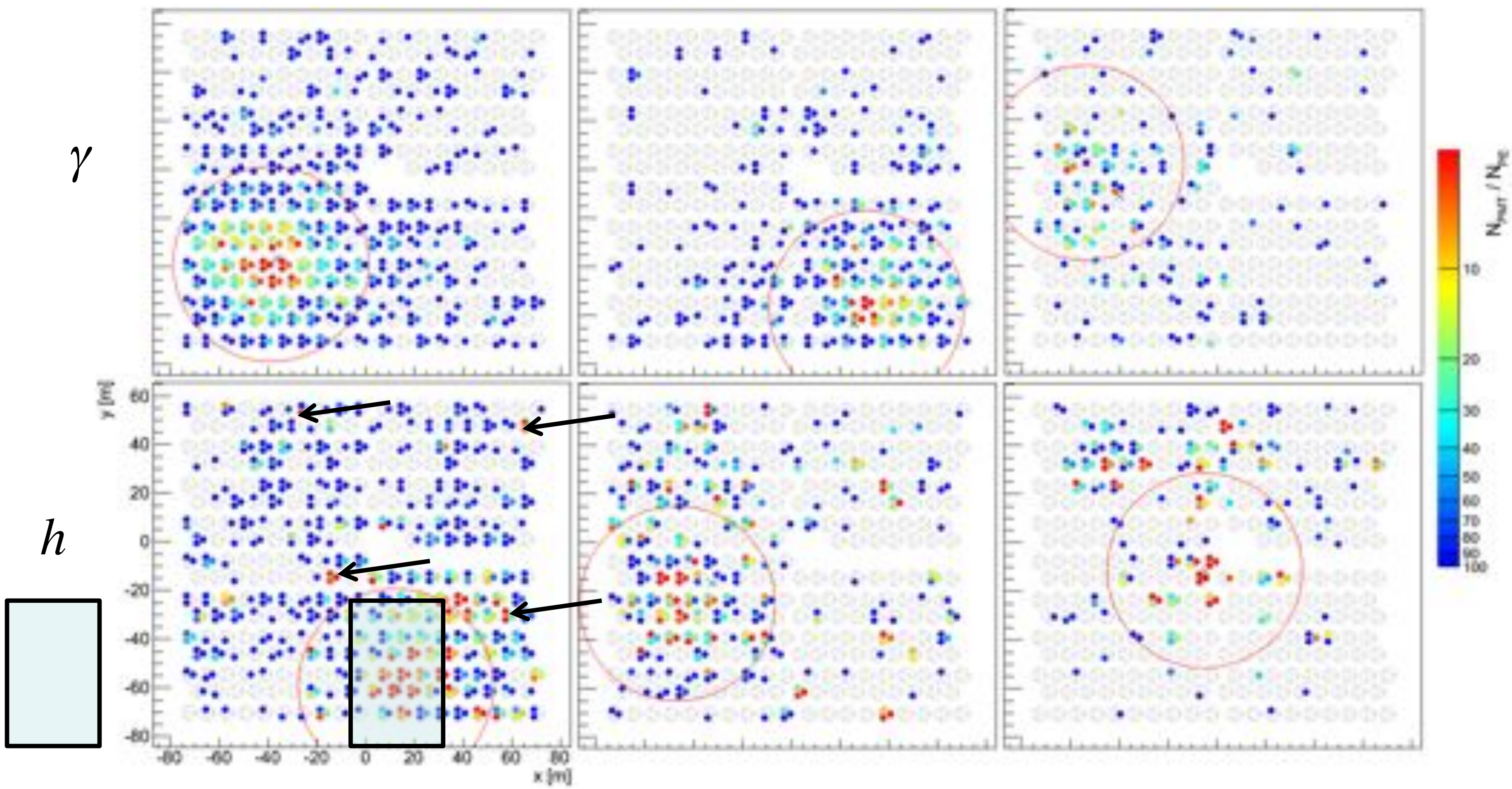
- Plot shows hadron efficiency for a 50% gamma efficiency.
- At 2 TeV, hadron rejection is ~10 times better than Milagro.

Gamma/hadron separation



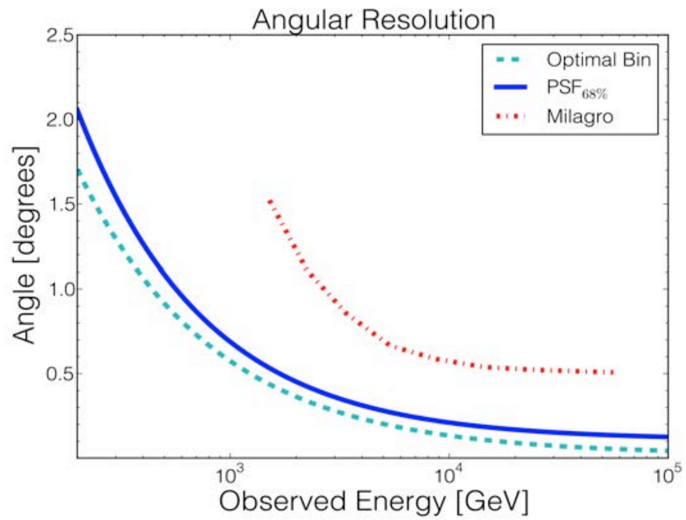
- Criterium: strong signal outside 40m circle around core
  - selects "clumpy" nature of hadron showers

HAWC Gamma Hadron Separation



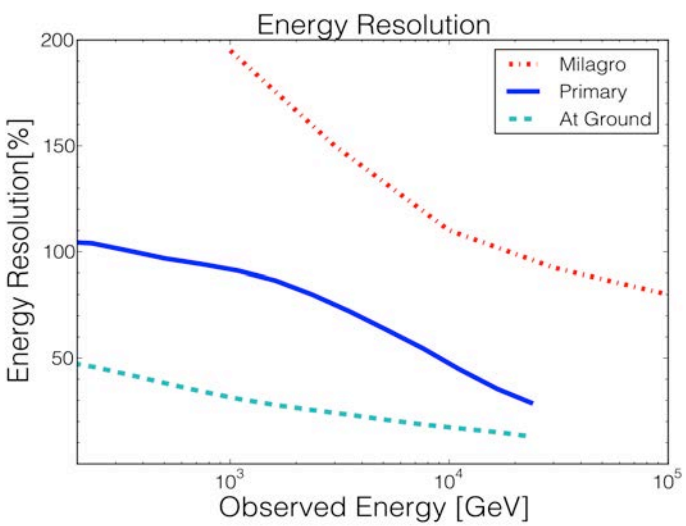
Play the game at http://www.hawc-observatory.org/observatory/ghsep.php

Performance



Angular resolution:

- Resolution is <0.5° above TeV.
- Even at low energies, the resolution is better than 2°.
- At 2 TeV, the angular resolution is ~2 times better than Milagro.



Putting it all together:

- HAWC will be ~15 times more sensitive than Milagro and will observe the Crab at a significance of ~5σ each day.
- HAWC has a promising effective area even at energies as low as 100 GeV.

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Key Goals

- 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, …).

Summary

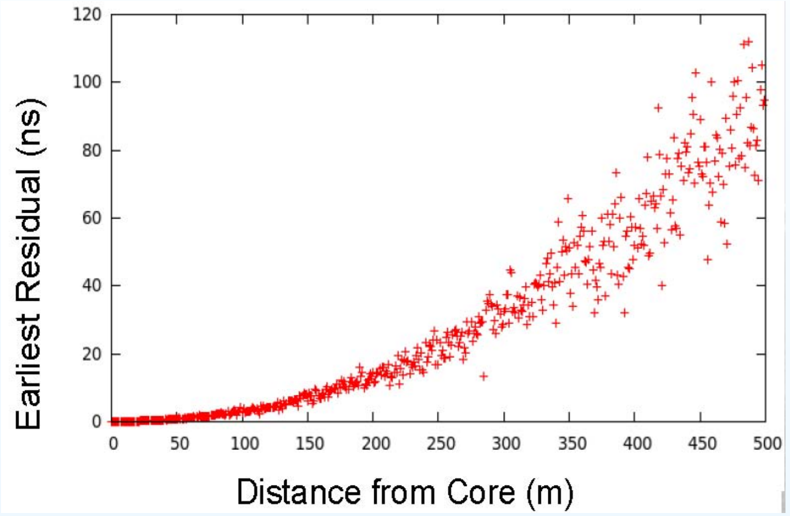
- The extreme universe is of great current interest both theoretically and experimentally
- New instruments, and in particular the High Altitude Water Cherenkov (HAWC) experiment, are needed to truly advance our understanding of the physics
- The UNM group in HAWC is well positioned (as leader of the precision (timing) calibration system) also to play a major role in HAWC physics
- HAWC, now in construction, provides an ideal opportunity for student involvement
- The HAWC experiment also benefits from close collaboration with nearby LANL
- Funding is available for RAs ...
- **So: many opportunities and no lack of challenges!**

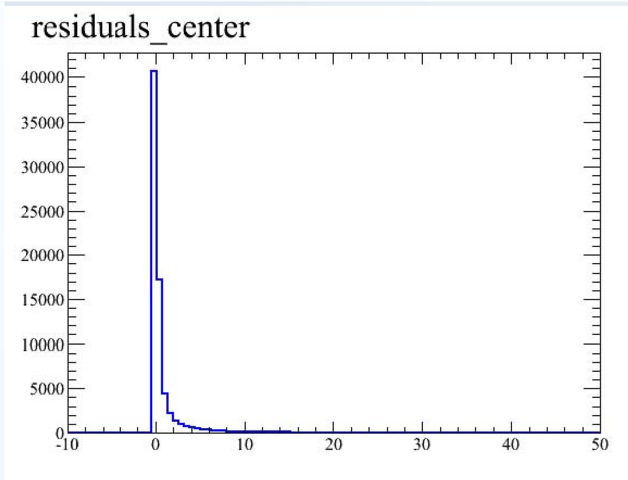
Additional/backup slides

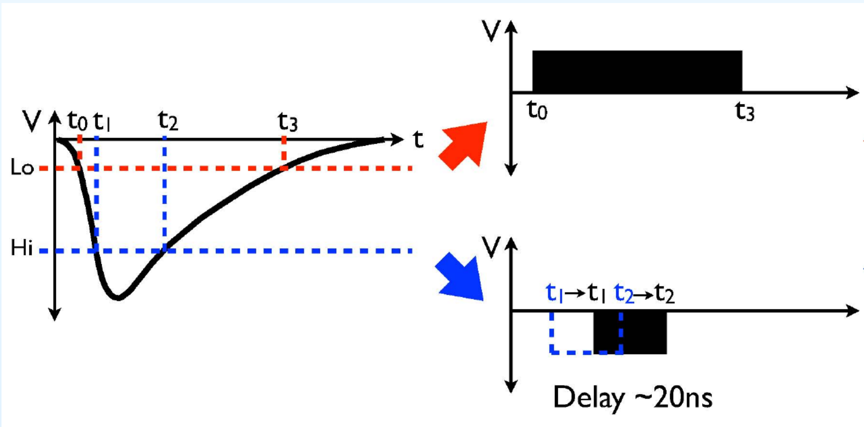
The University of New Mexico

Additional slides

HAWC challenges ...

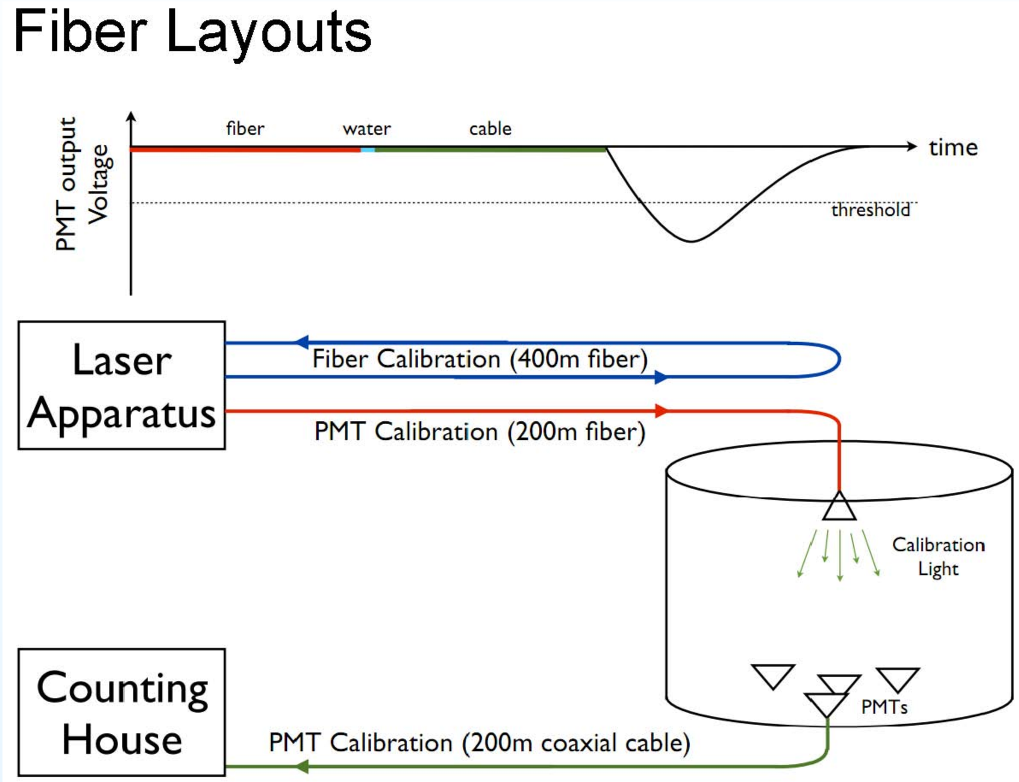






- (Top Left) Shower front timing residuals *vs* distance from shower core; (Top Right) Timing residuals (nsec) near the shower *core*.
- Precision angular reconstruction then needs the PMT timing offsets (errors) to be < 1ns.
- DAQ emphasis on precision timing (Bottom Left) results in the signal amplitude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

HAWC calibration *design* ...

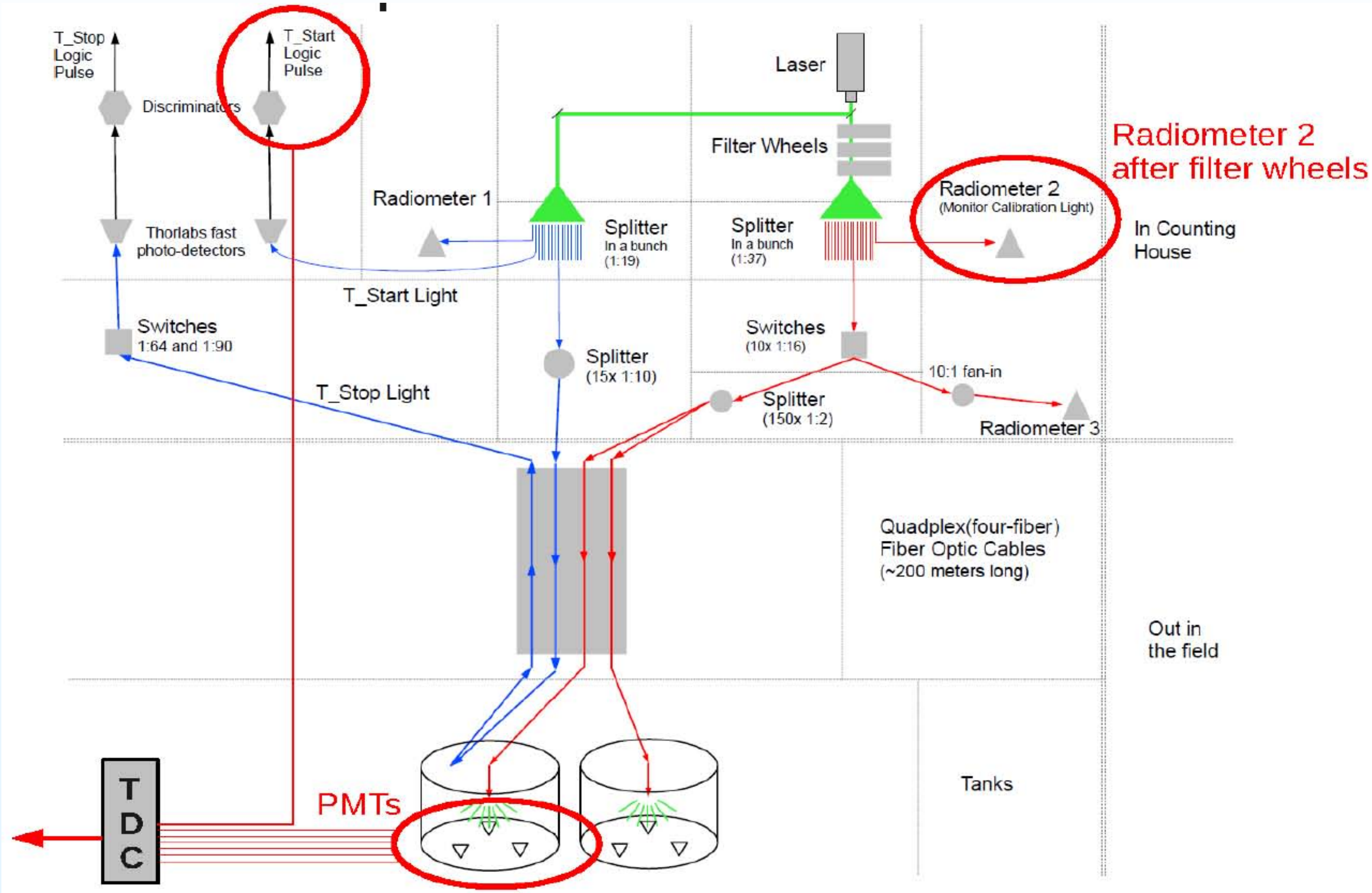


- Use a pulsed (300ps, 532nm laser) light source of known intensity and with known light transit time to the PMTs.
- Adjust the source intensity (using neutral density filters) over the (required) PMT dynamic range of ~ 0.1PE to $\sim 10^4$PEs.
- Repeat 300 times (for 300 WCDs). Begin with the HAWC WCD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

HAWC calibration *calibration at CSU WCD* ...

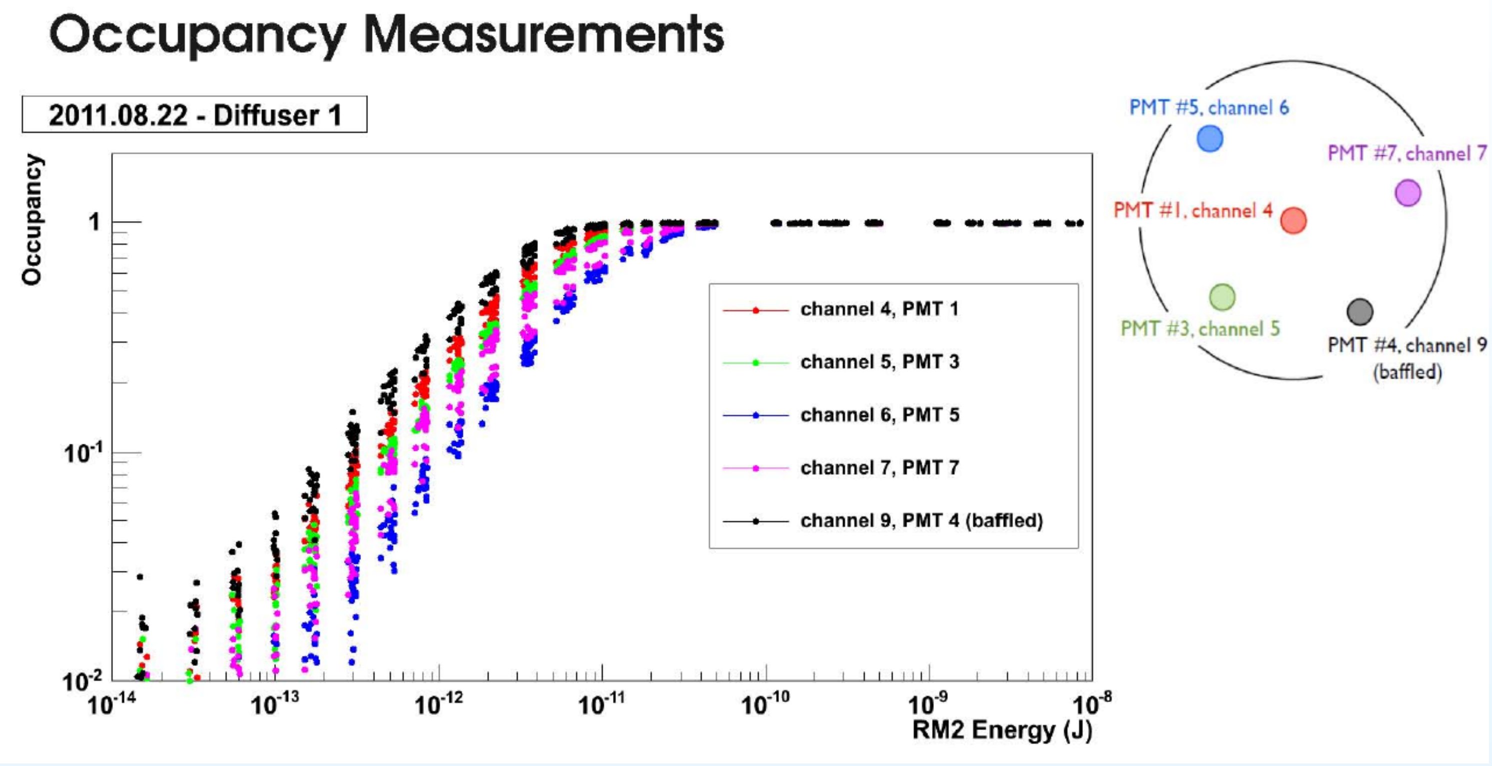
- The prototype HAWC WCD at CSU has allowed R&D on all components (hardware, control software and analysis) of the calibration system.
- Major group calibration responsibilities include:
  1. CSU: calibration data analysis, muon calibration
  2. George Mason U: muon calibration
  3. LANL: DAQ for TDCs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

HAWC calibration *schematic* ...



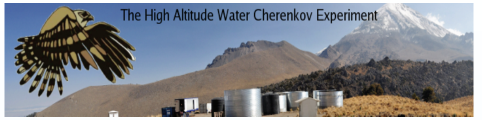
- The *ingredients* for a calibration include: the light-to-WCD Intensity (Radiometer 2), and digitization of the laser pulse time (T_{start}) and the PMT (time and ToT).

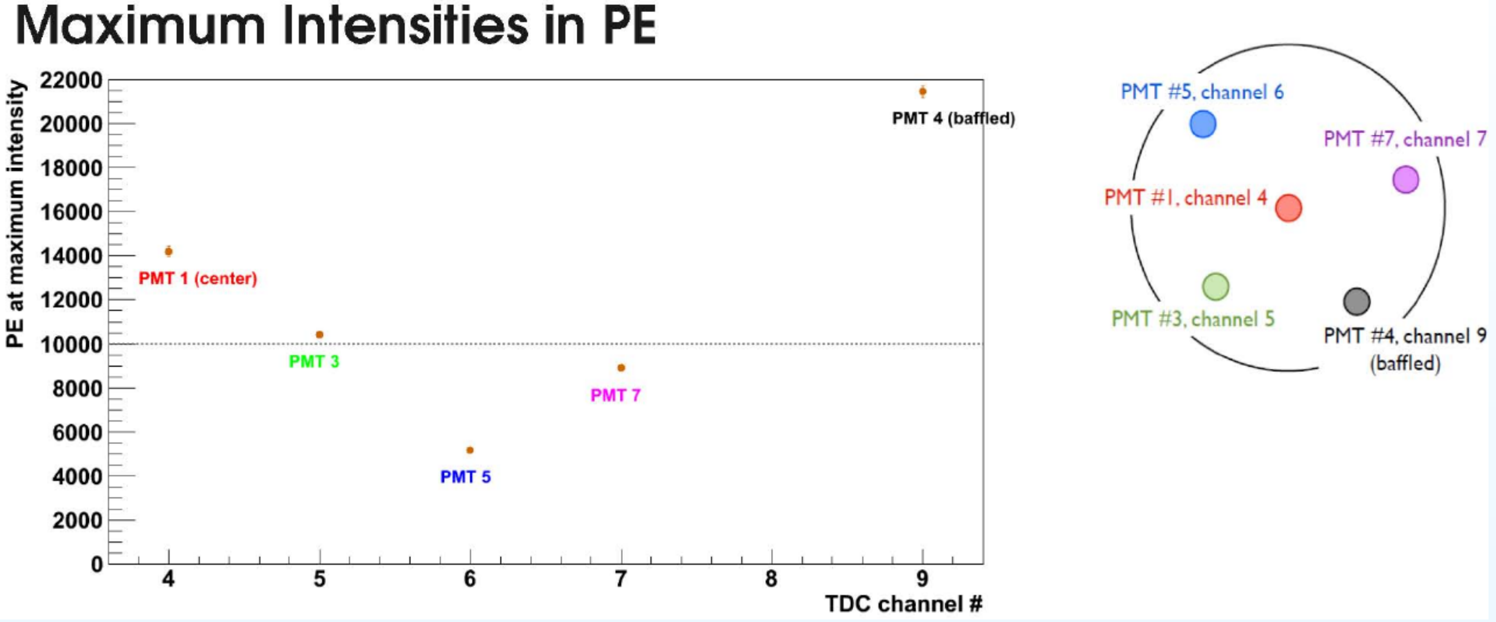
HAWC calibration *cycle* ...



- 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.

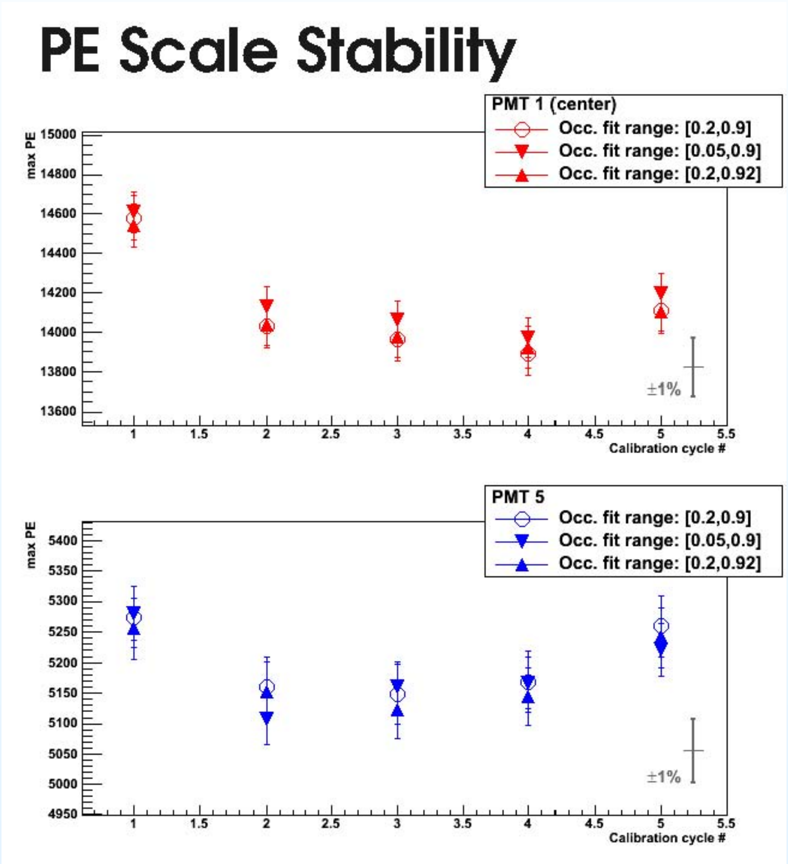
HAWC calibration *“Maximum PEs” at CSU* ...

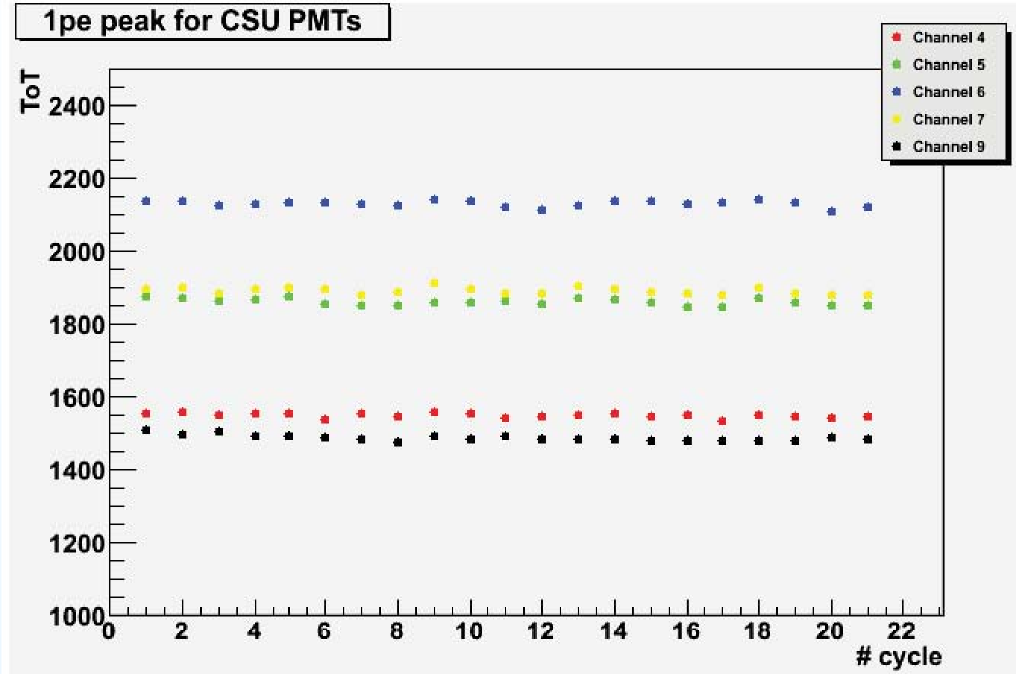




- The CSU prototype HAWC WCD has been in routine data taking for calibration R&D since spring 2011.
- This tank includes 5 (4 plus one with reflective baffle) PMTs and 4 selectable calibration light diffusers.
- Maximum PMT calibration signals (PEs), temporarily reduced by $\sim 4\times$, meet the design goal of $\sim 10,000$ PEs (dotted line in plot).

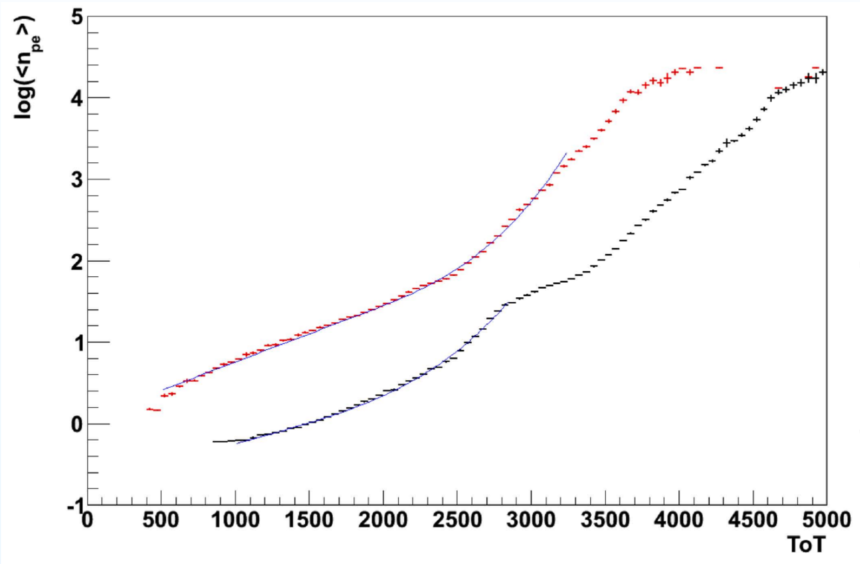
HAWC calibration *stability at CSU* ...

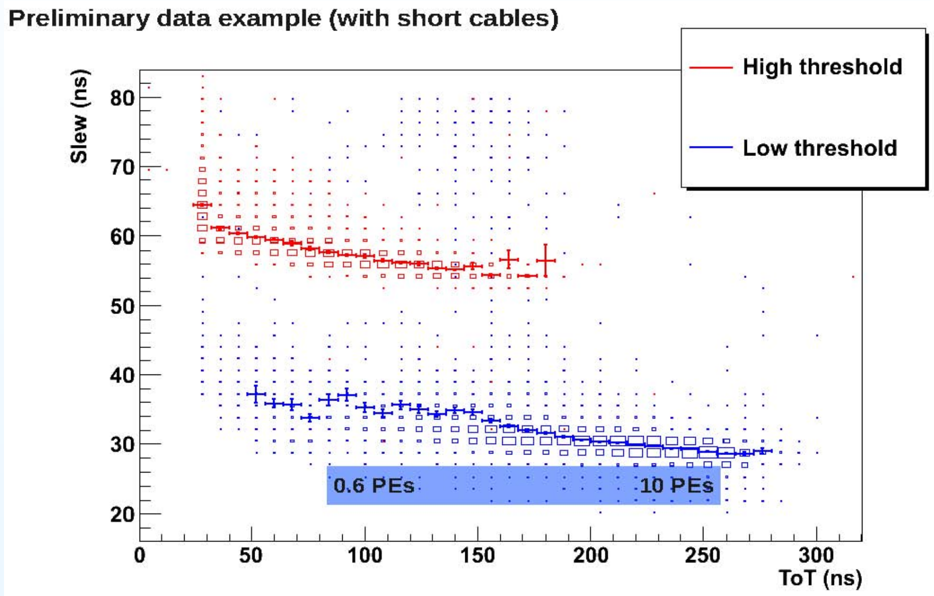




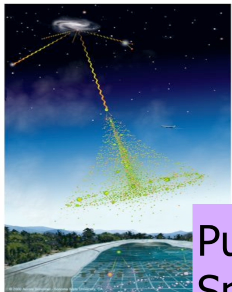
- (Left plots): Variation in the Maximum PE values for different analysis *fit ranges* and for two different PMTs *vs* calibration cycle.
- (Top plots): Variation in the 1PE→ToT values for all 5 PMTs *vs* calibration cycle.
- Both Maximum PE and 1PE calibration results show variations of $1 \sim 2\%$.

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





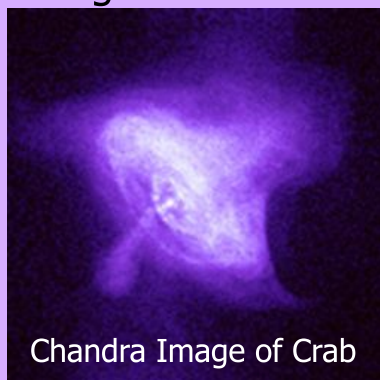
- (Top Left) Relation between what HAWC measures: PMT ToT and the PMT signal in PEs. The PMT signal in PEs is needed for shower plane reconstruction and γ-hadron separation.
- (Top Right) Time slewing correction (nsec) *vs* the measured PMT signal in ToT. The slewing correction is needed for shower plane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



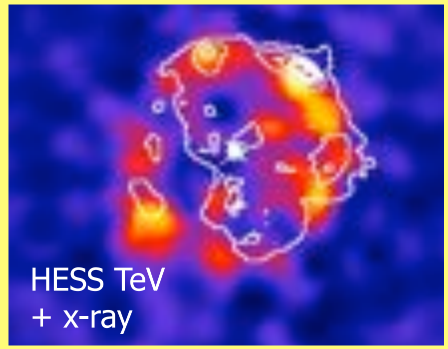
Nature’s Particle Accelerators

Galactic

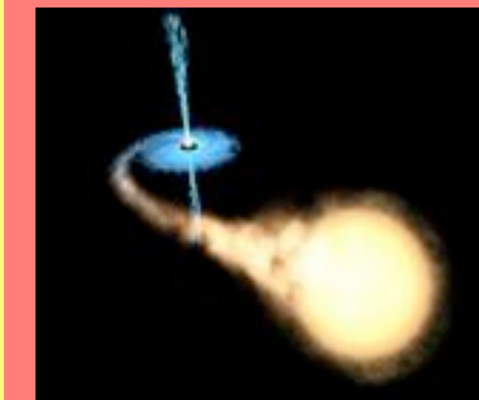
Pulsar Wind Nebula:
Spinning Neutron Star
powering *a* relativistic wind



Supernova
Remnant



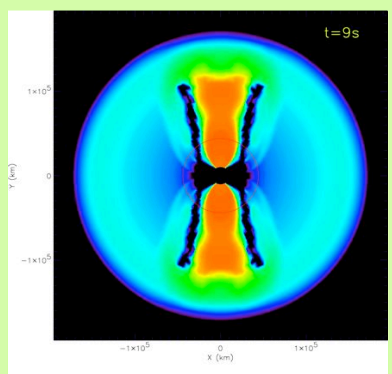
X-ray Binaries/
Microquasars



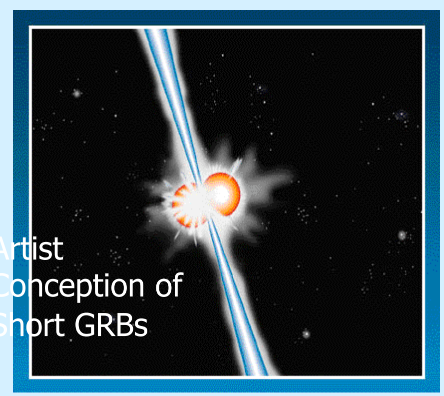
ExtraGalactic

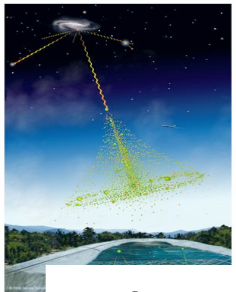
Active Galactic Nuclei:
Black Hole producing
relativistic jet of particles

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



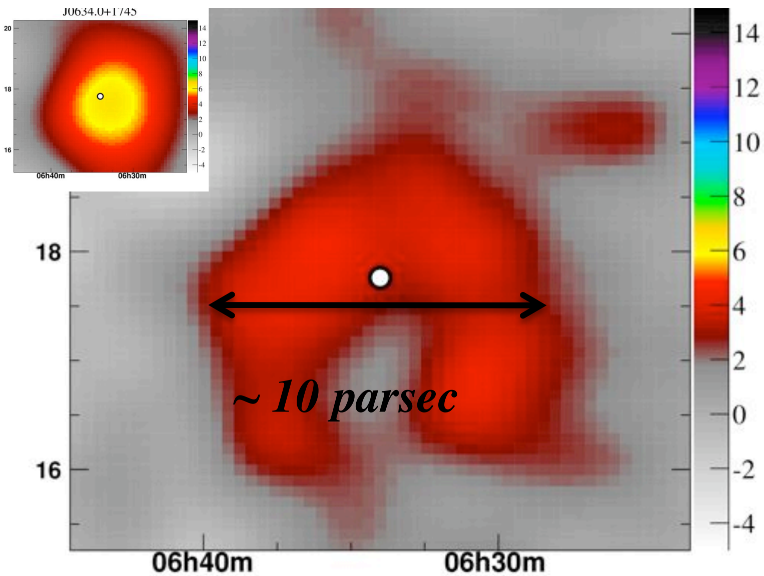
Short Gamma-Ray Burst:
Binary Neutron Star
Coalescing



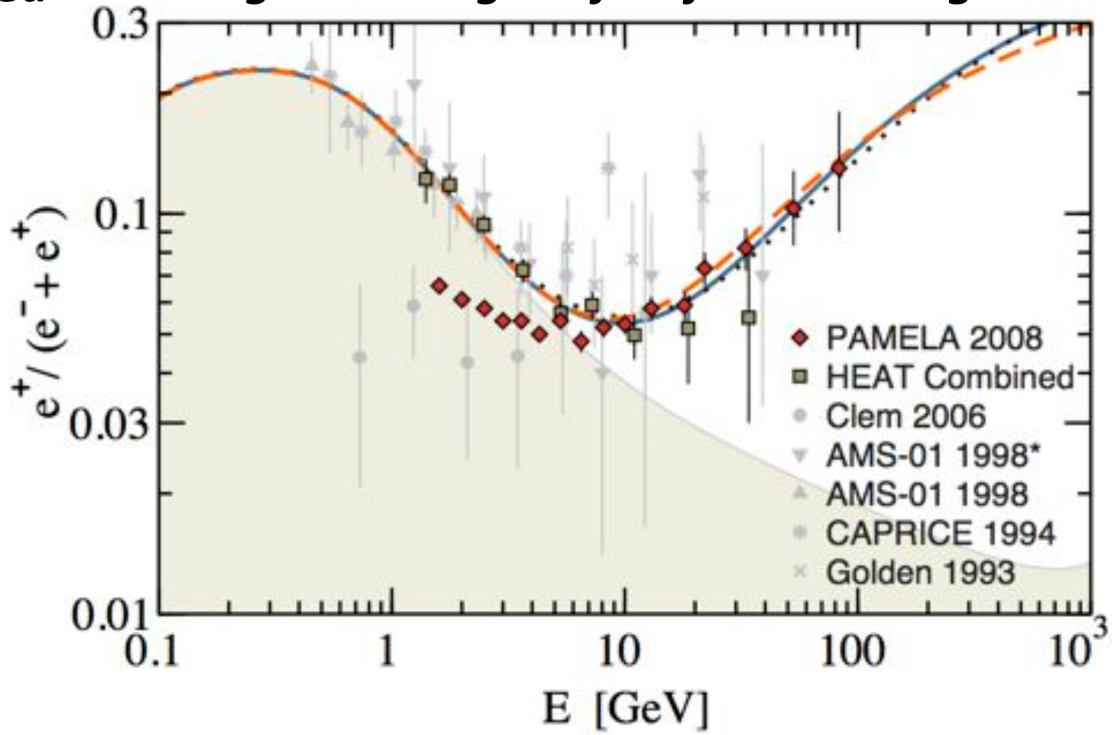


Geminga: a Nearby Positron Source

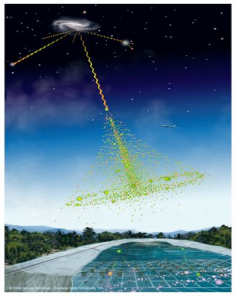
Milagro's Detection of an extended excess coincident with Geminga



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



The confirmed presence of a nearby, ancient source of high-energy electrons and positrons immediately suggests an explanation for the positron excess. -Yüksel, Kistler, Stanev Phys Rev Lett 200



Milagro Detects Extragalactic Source Mrk421

- Mrk 421 is a bright, variable, TeV emitting, active galactic nuclei
- Milagro constrains average flux and spectrum
- Continuous monitoring of the TeV and x-ray correlation, but need better sensitivity to constrain theories