Computing for the High Altitude Water Cherenkov Experiment (HAWC)

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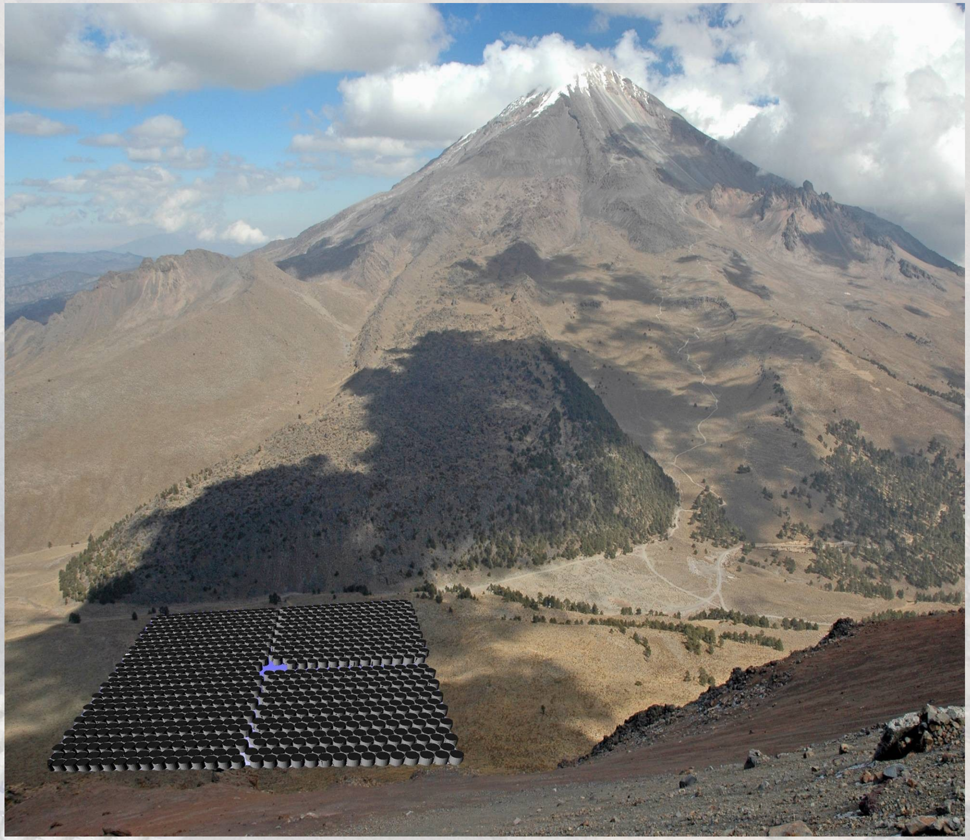
The High Altitude Water Cherenkov Experiment

- Water Cherenkov air shower array at 4100 meter site at Sierra Negra, Mexico
- 300 7.5m diameter, 5 meter high steel water tanks. Each with 200000 L of purified water and 3 Photomultiplier tubes.
- 150x150 meter area.
- Sensitive to gamma rays from 50 GeV to 100 TeV
- Successor to Milagro which operated in Jemez mountains from 2000 - 2008
- Overall 15x sensitivity improvement over Milagro.



HAWC Collaboration

USA:

- **Los Alamos National Laboratory** Brenda Dingus, John Pretz, Gus Sinnis, Asif Imran
- **University of Maryland** Jordan Goodman, Andrew Smith, Greg Sullivan, Brian Baughman, Jim Braun
- **University of Utah** Dave Kieda,
- **University of New Mexico** John Matthews
- **Michigan State University** Jim Linnemann, Kirsten Tollefson, Tilan Ukwatta
- **Pennsylvania State University** Ty DeYoung, Dmitry Zaborov
- **NASA/Goddard Space Flight Center** Julie McEnery, Elizabeth Hays
- **University of New Hampshire** James Ryan
- **Georgia Tech** Ignacio Taboada, Andreas Tepe
- **University of California, Irvine** Gaurang Yodh
- **Colorado State University** Miguel Mostafa
- **Michigan Technological University** Petra Huentemeyer, Brian Fick
- **University of Alabama** Pat Toale
- **University of Wisconson, Madison** Stefan Westerhoff, Teresa Montaruli, Segev Benzvi, Michael DuVernois, Juan Antonio Aguilar

Mexico:

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  - Alberto Carramiñana, Eduardo Mendoza, Ibrahim Torres
- **Universidad Nacional Autónoma de México (UNAM)**
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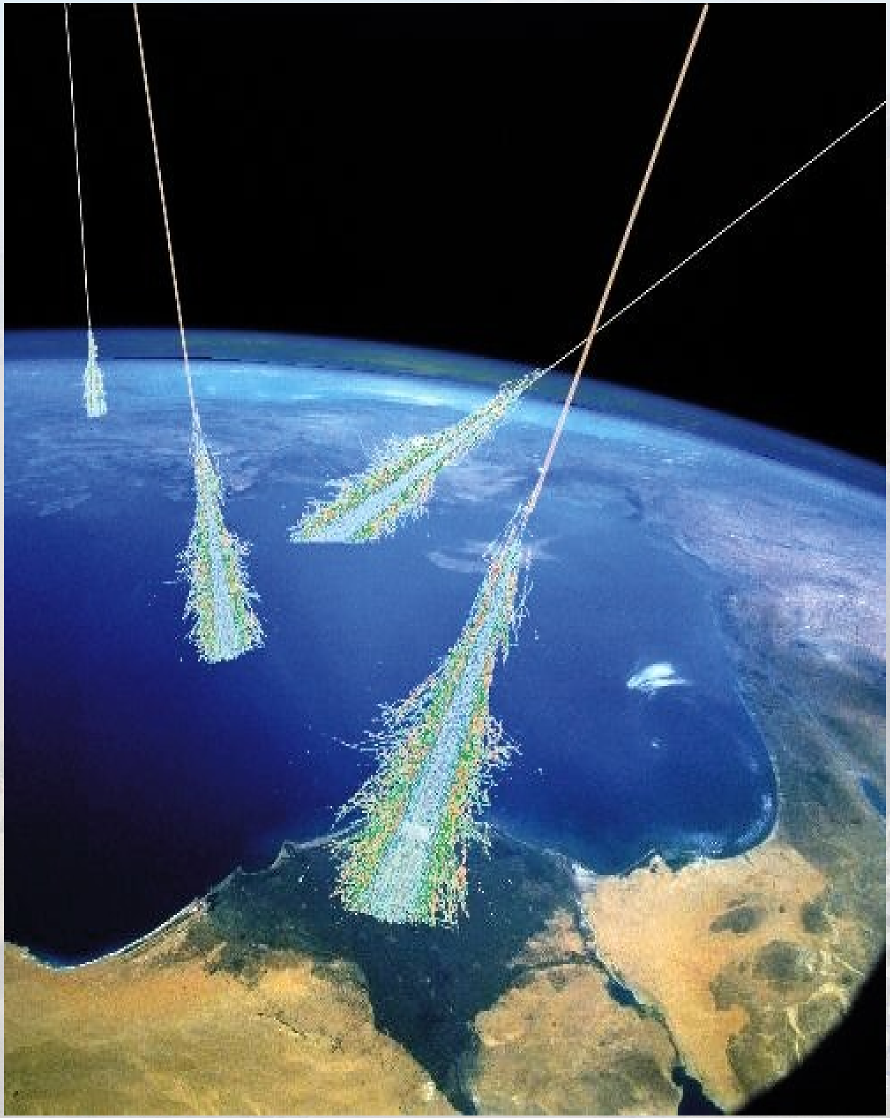
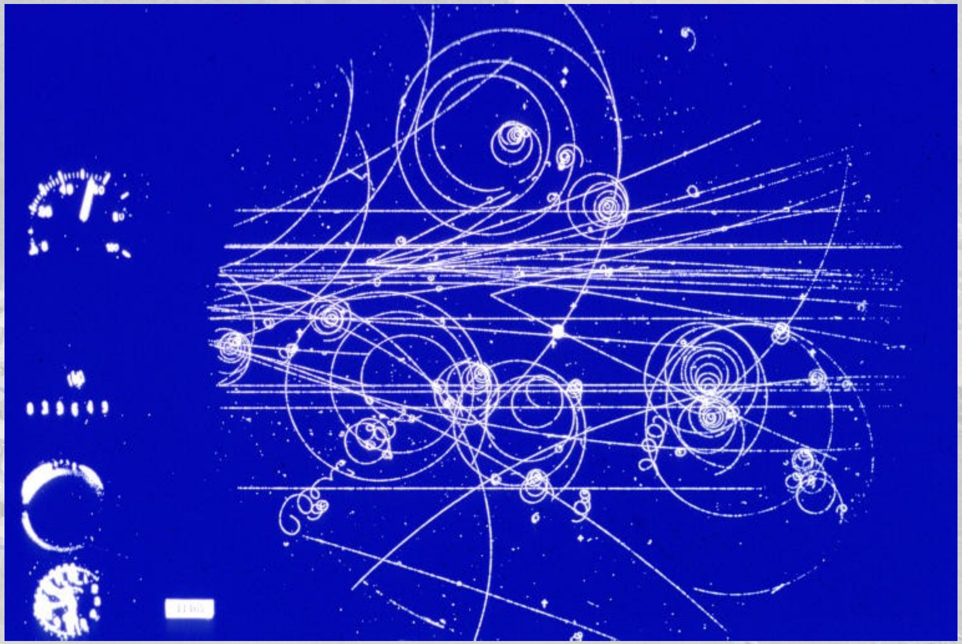
  - Instituto de Física: Arturo Menchaca, Rubén Alfaro, Andres Sandoval, Ernesto Belmont
  - Instituto de Ciencias Nucleares: Lukas Nellen, G. Medina-Tanco
  - Instituto de Geofísica: José Valdés Galicia, Alejandro Lara
- **Universidad Autónoma de Chiapas** Cesar Alvarez
- **Universidad de Guadalajara** Eduardo de la Fuente
- **Benemérita Universidad Autónoma de Puebla**
  - Humberto Salazar, Oscar Martínez, Cesar Álvarez, Arturo Fernández
- **Universidad Michoacana de San Nicolás de Hidalgo** Luis Villaseñor
- **CINVESTAV** Arnulfo Zepeda
- **Universidad de Guanajuato**
  - David Delepine, Gerardo Moreno, Marco Reyes, Luis Ureña, Victor Migenes

Extensive Air Showers



Source: nasa.gov

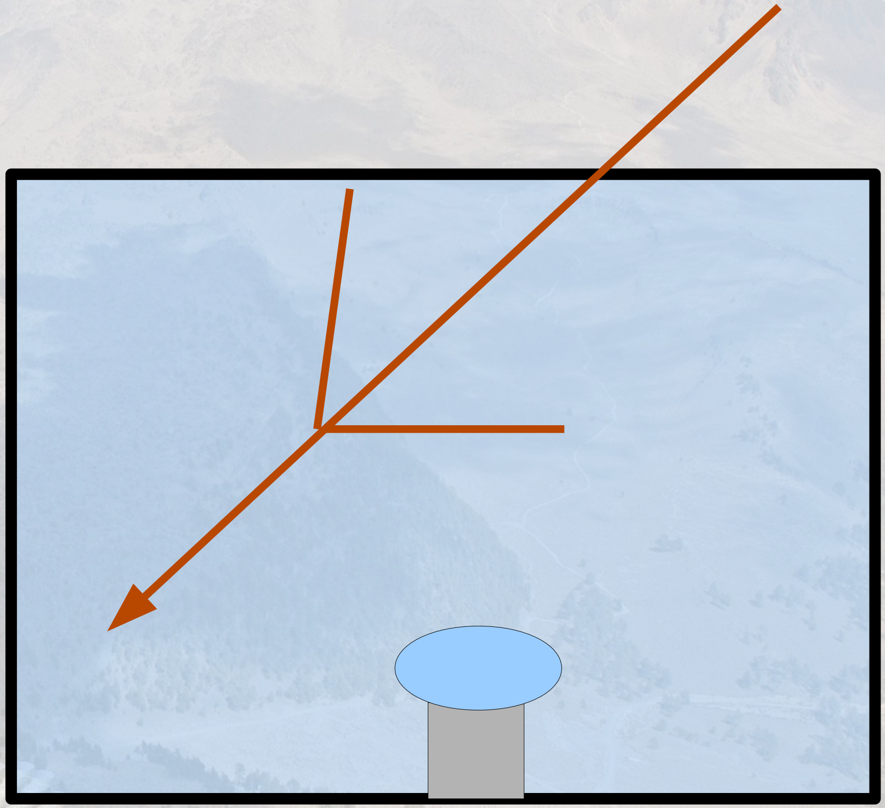
- Earth continuously bombarded with particles from outer space.
- Cosmic rays (ionized nuclei)
  - Hadronic air shower, a mess of π^0 ,$\pi^\pm$, $K^\pm$,γ, ν, $e^\pm$,$\mu^\pm$
- Gamma rays
  - A pure electromagnetic air shower.
- Detected with ground-based arrays or viewing the light from the shower development directly
- Particle physics born in cosmic ray air showers.



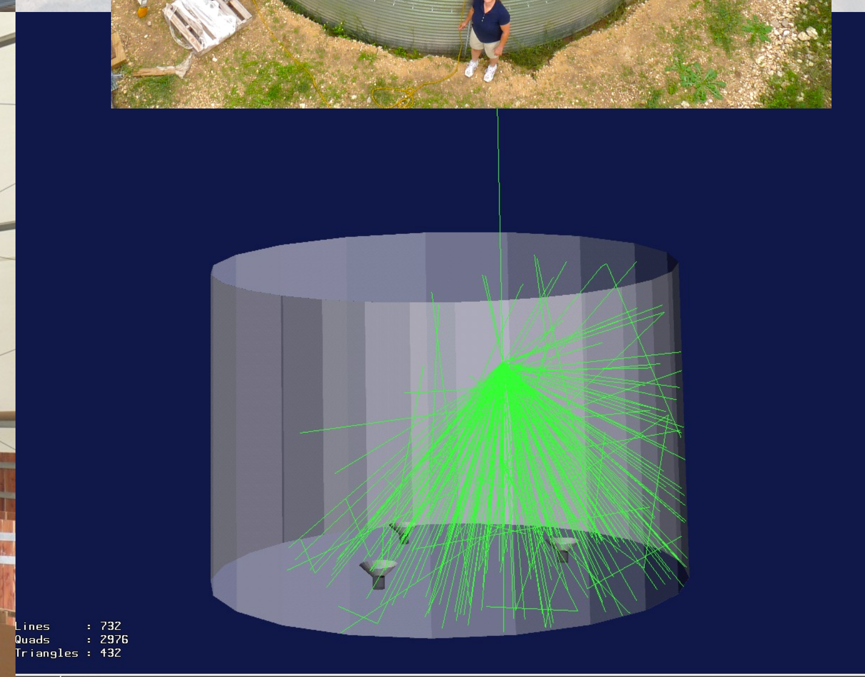
Source: cern.ch

Water Cherenkov Detection of (gamma ray and cosmic ray) Air Showers

- Instrument a volume of water with Photo-Multiplier Tubes
- Detect Cherenkov light from high-energy particle passage through the water.
- Technique used by Super Kamiokande, IceCube, SNO to name a few.
- Why Water?
  - Clear Cherenkov medium.
  - Inexpensive and abundant.
- Instrument a large flat area to see air showers.
- Reconstruct primary particle direction from PMT timing

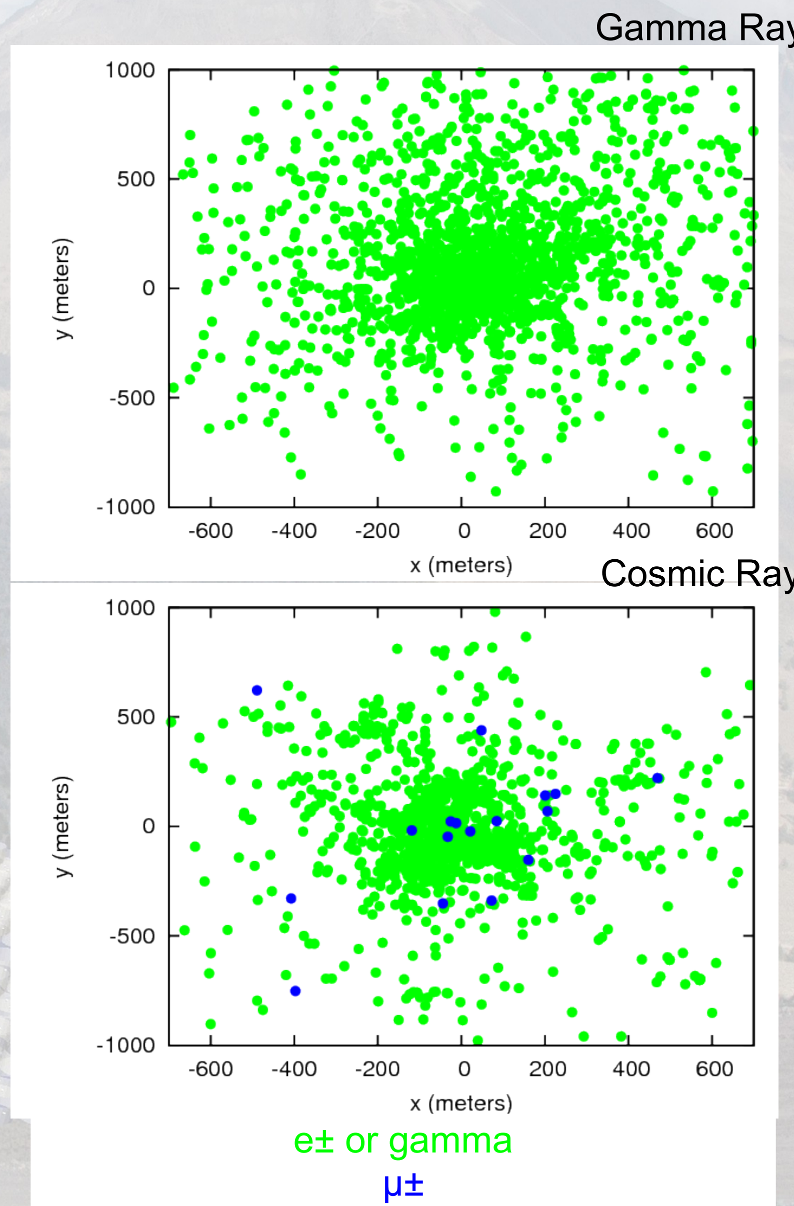


HAWC Tanks

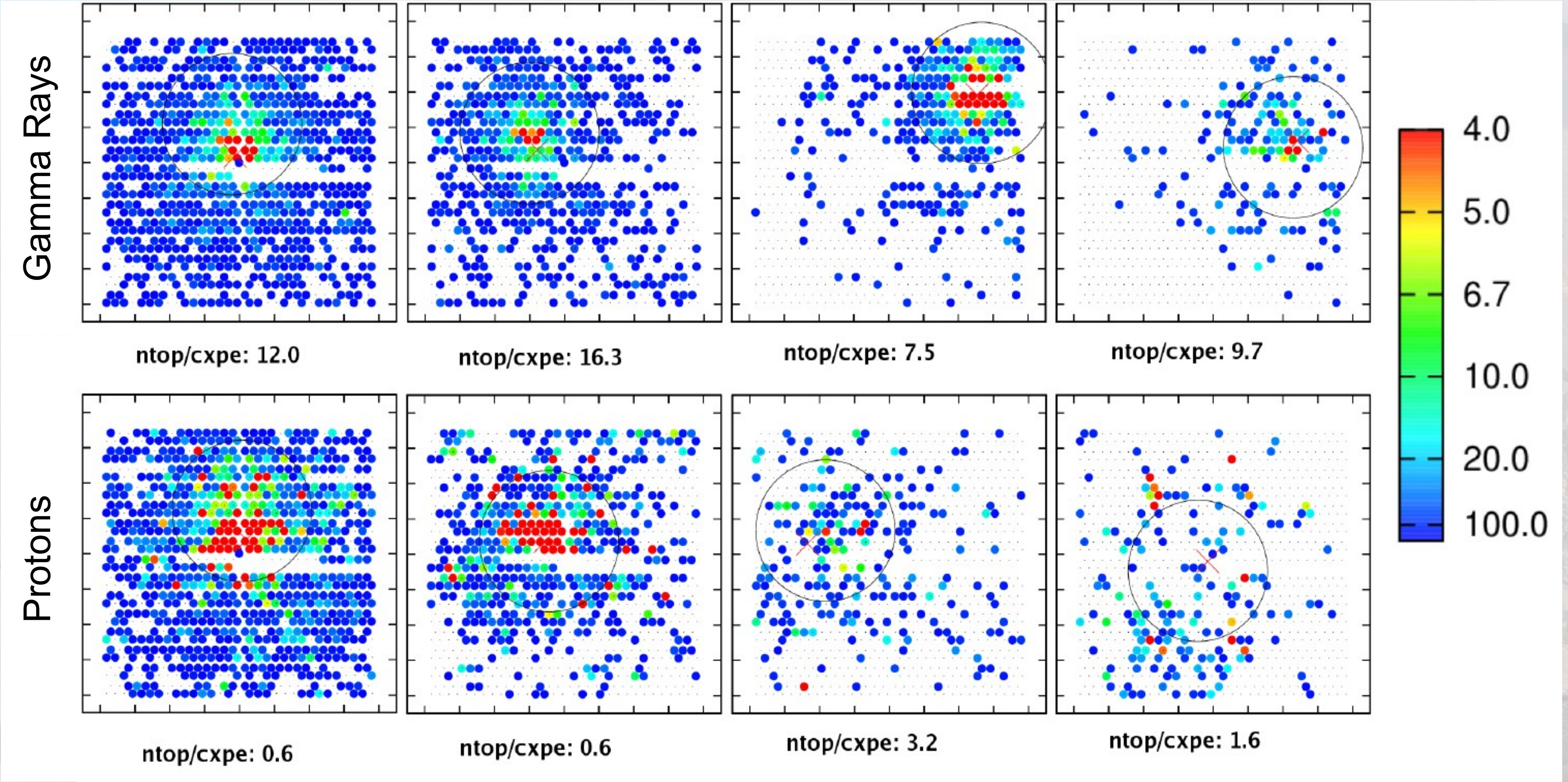


Gamma Ray vs Cosmic Ray Air Shower

- Gamma-ray events are pure electro-magnetic processes.
    - Pair-production, Bremsstrahlung, Compton scattering are dominant processes
    - Pure e±, gamma particles (mostly)
- Cosmic-ray events produce hadronic air showers
    - π±, K± result in μ at ground level
    - Clumpy distribution on the ground from jets in the shower.

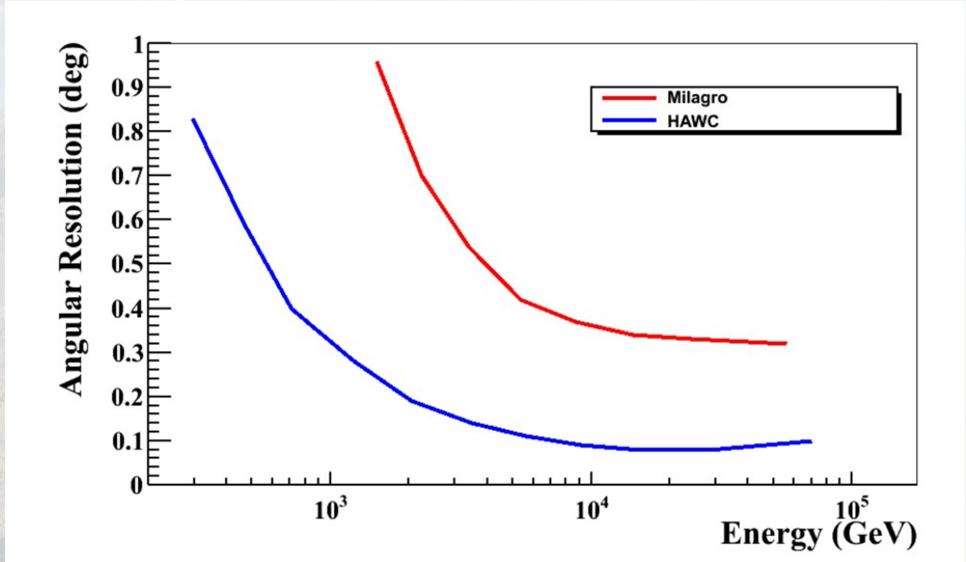


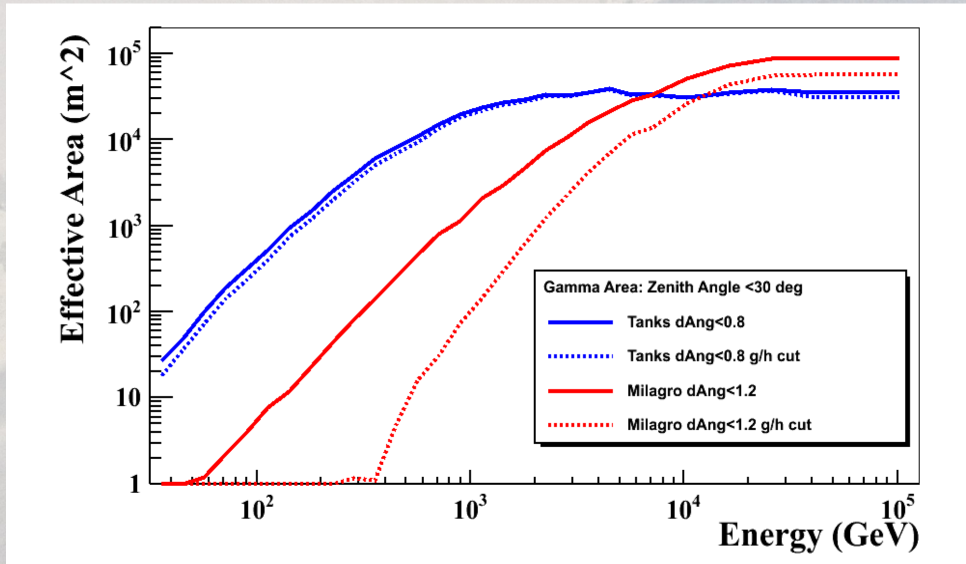
Gamma/Hadron Discrimination in HAWC

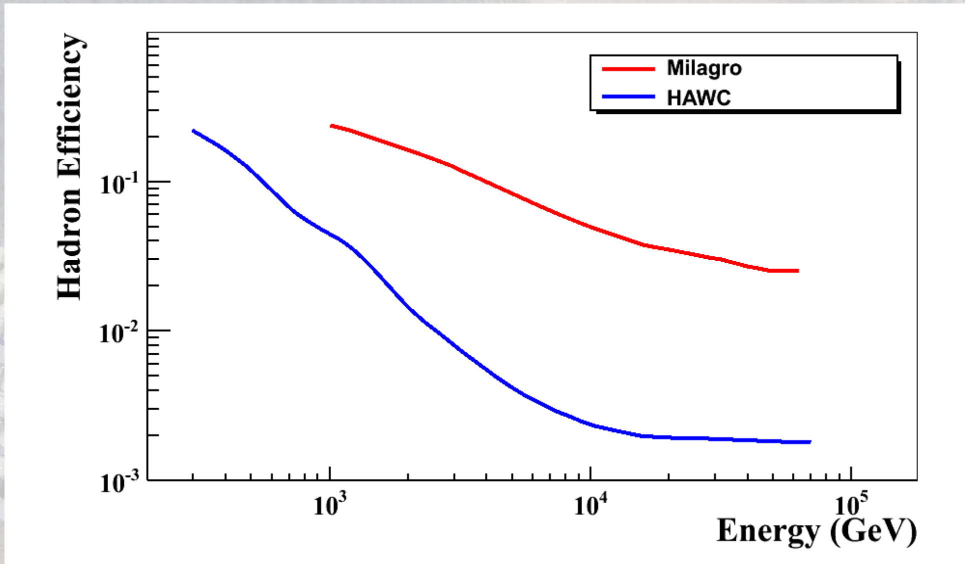


HAWC Performance

- Increased altitude gives large effective area at 50-100 GeV and better angular resolution.
- Large muon-sensitive area improves gamma/hadron discrimination



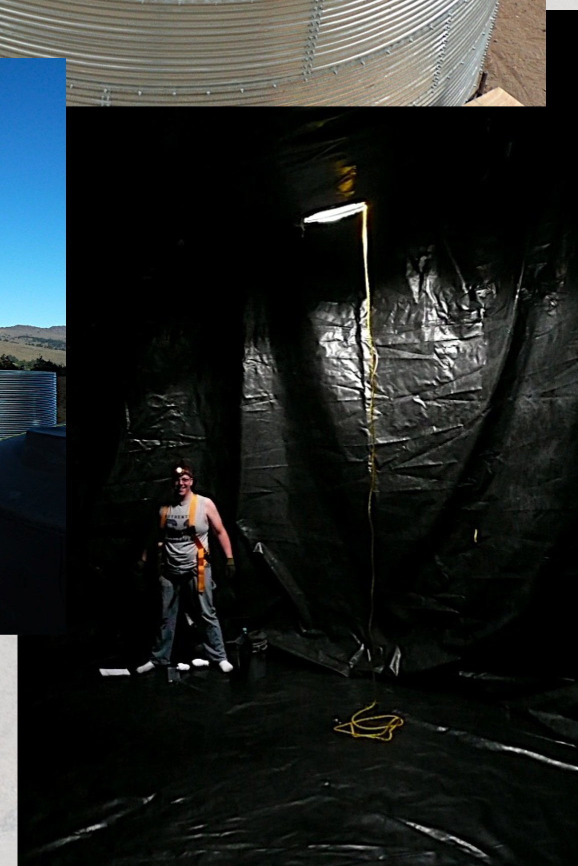




Current Status

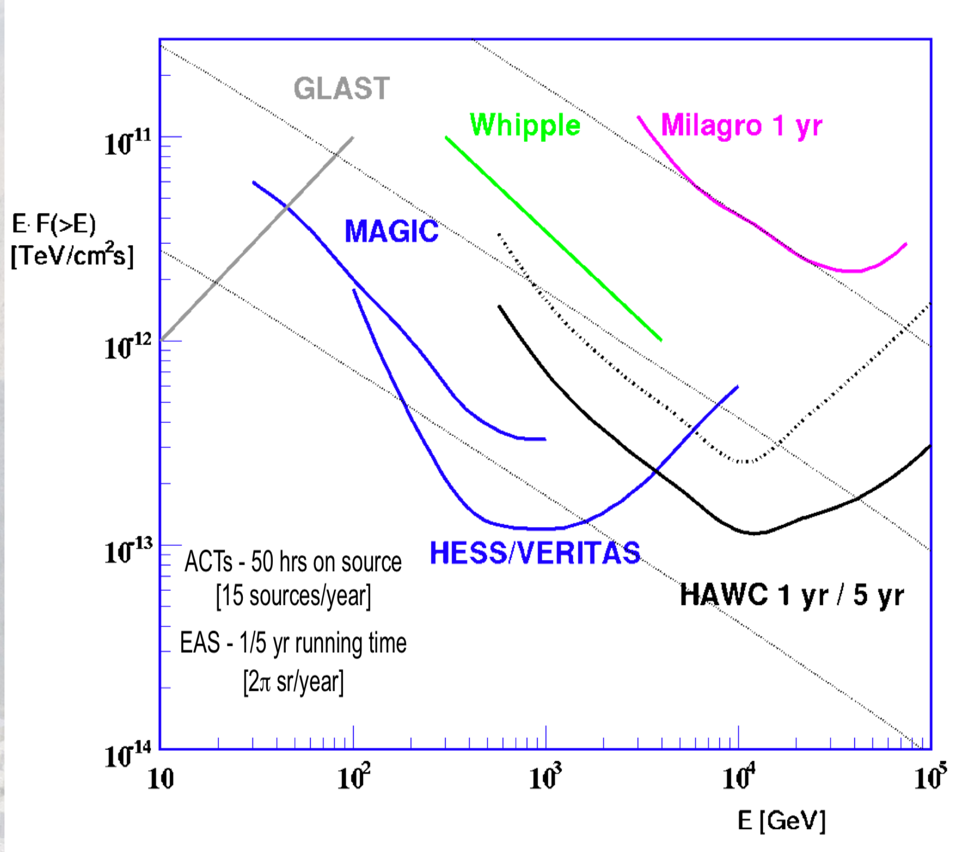
- Funded!
- ~8.5 M USD in construction funds from NSF, NSF MRI, DOE, Conacyt and High Energy Network (Red FAE) funds
- NSF MRI for construction of VAMOS (Verification Assessment Measuring Observatory Subsystems) an engineering development array of 7 Cherenkov detectors of final HAWC design.
- VAMOS construction is nearly complete (awaiting water)

VAMOS



Timeline

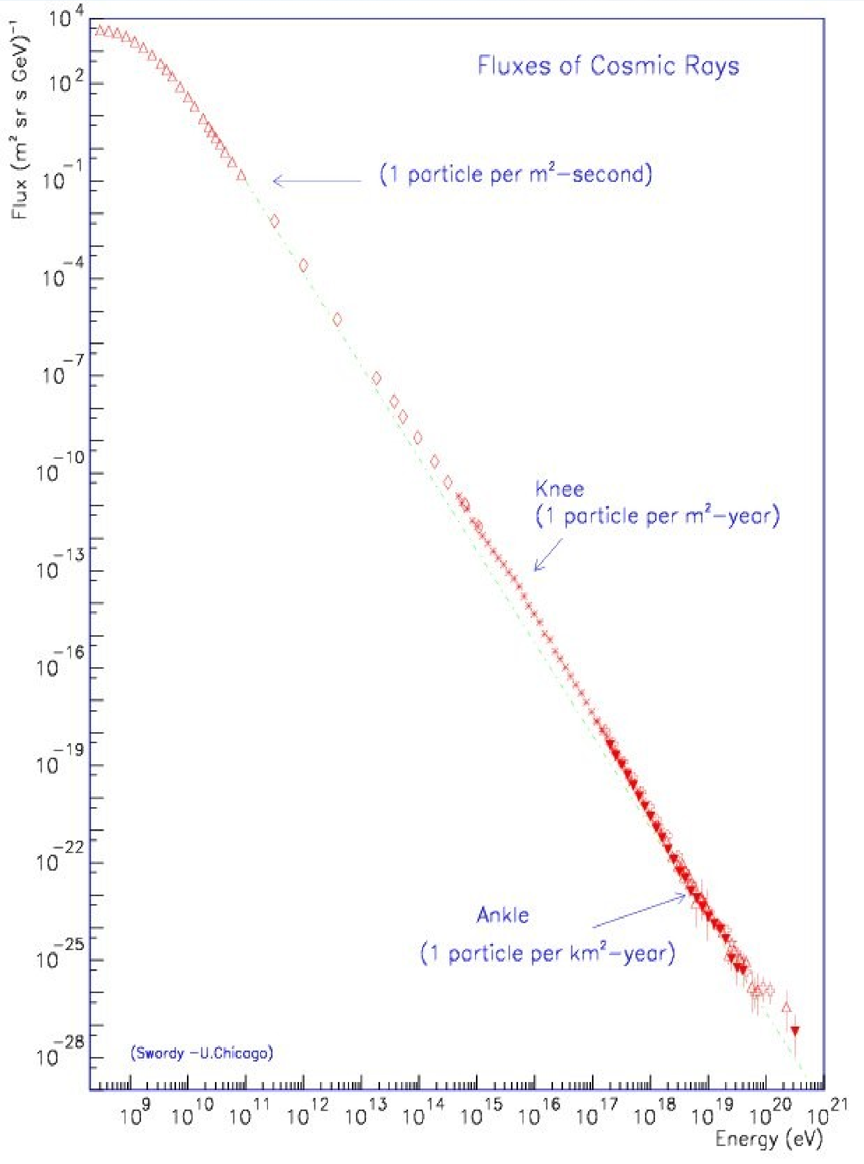
- Now: Operation of VAMOS. Sensitivity to the shadow of the Moon.
- 2012: 30 Tanks / 90 PMTs. Approaching Milagro Sensitvity. Sensitive to gamma ray bursts.
- 2013: 100 Tanks / 300 PMTs. Surpass Milagro sensitivity. New surveys of the sky. Continuous operation.
- 2014: Completed detector. 300 tanks / 900 PMTs.



Cosmic Rays

- Discovered by Victor Hess in 1912 (Nobel Prize in 1936)
- Increase in radiation at high altitudes
- Radiation is cosmic in origin
- Became clear later that we were seeing secondaries from nuclear primaries.

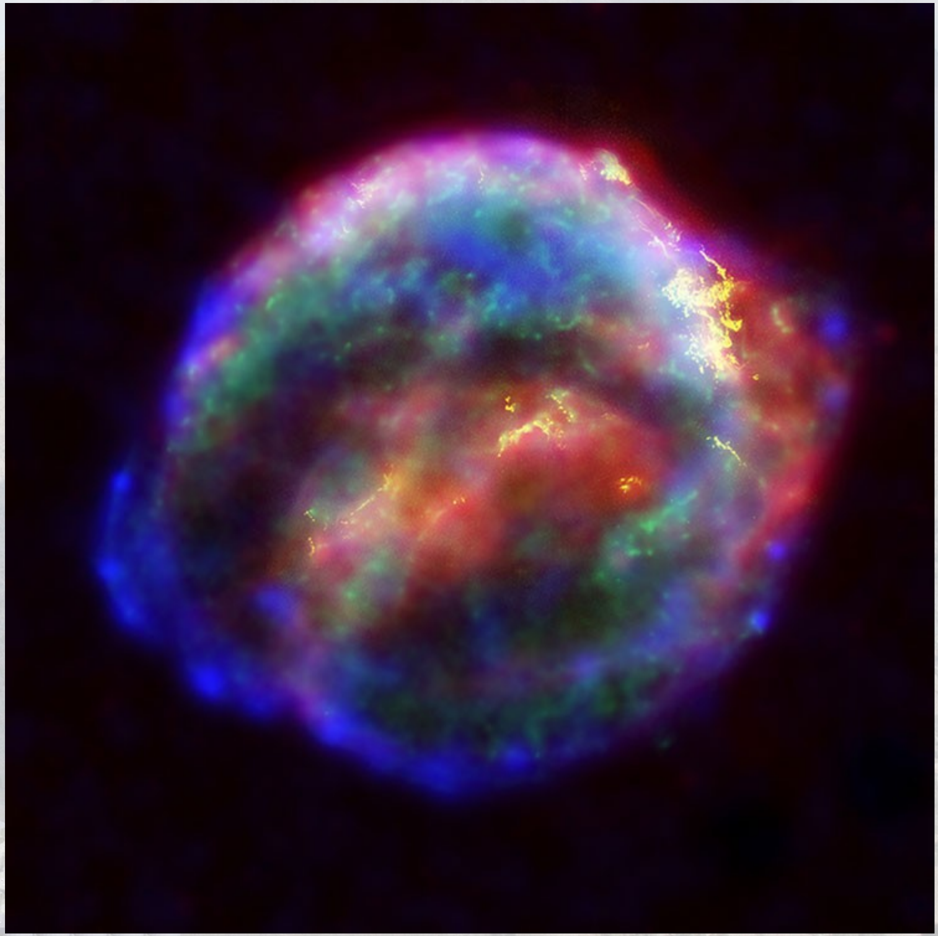
Cosmic Ray Knowns and Known Unknowns



- Very nearly isotropic.
- Energy spectrum ~$E^{-2.7}$
- Huge range of fluxes and energies
- Highest energy > 10^{20} eV
- Low-energy composition matches solar system abundances (with important differences)
- 'Ankle' is apparent transition to extra-galactic cosmic rays.
- Energy density comparable to energy density in photons.
- Consistent model for galactic CR of acceleration in supernova shocks.

Acceleration Mechanism?

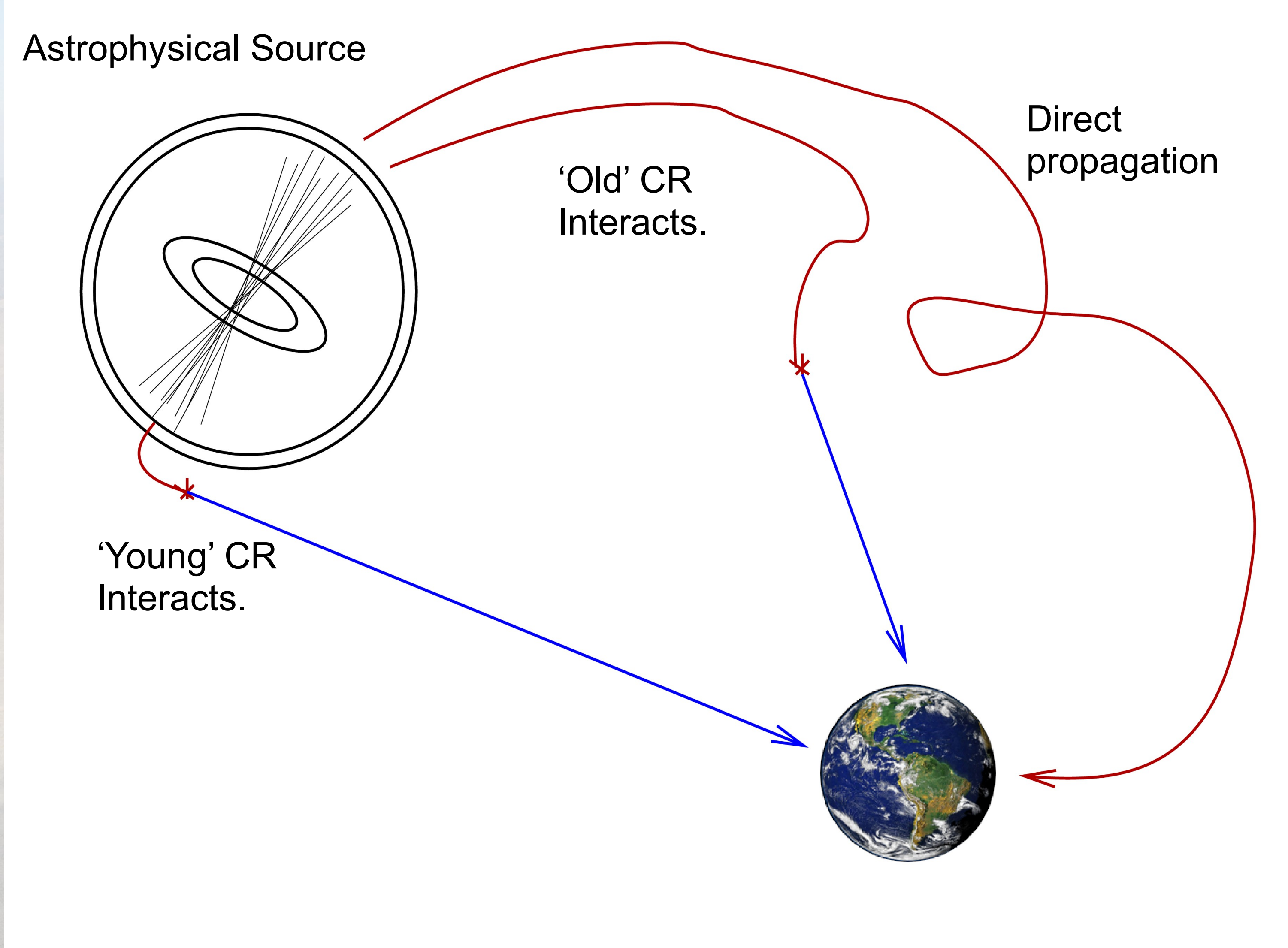
- Fermi Acceleration at shock fronts.
- Particles ping-pong back and forth across the shock gaining energy at each crossing.
- Requires accelerated particles to be contained.
- Predicts universal E^{-2} energy spectrum



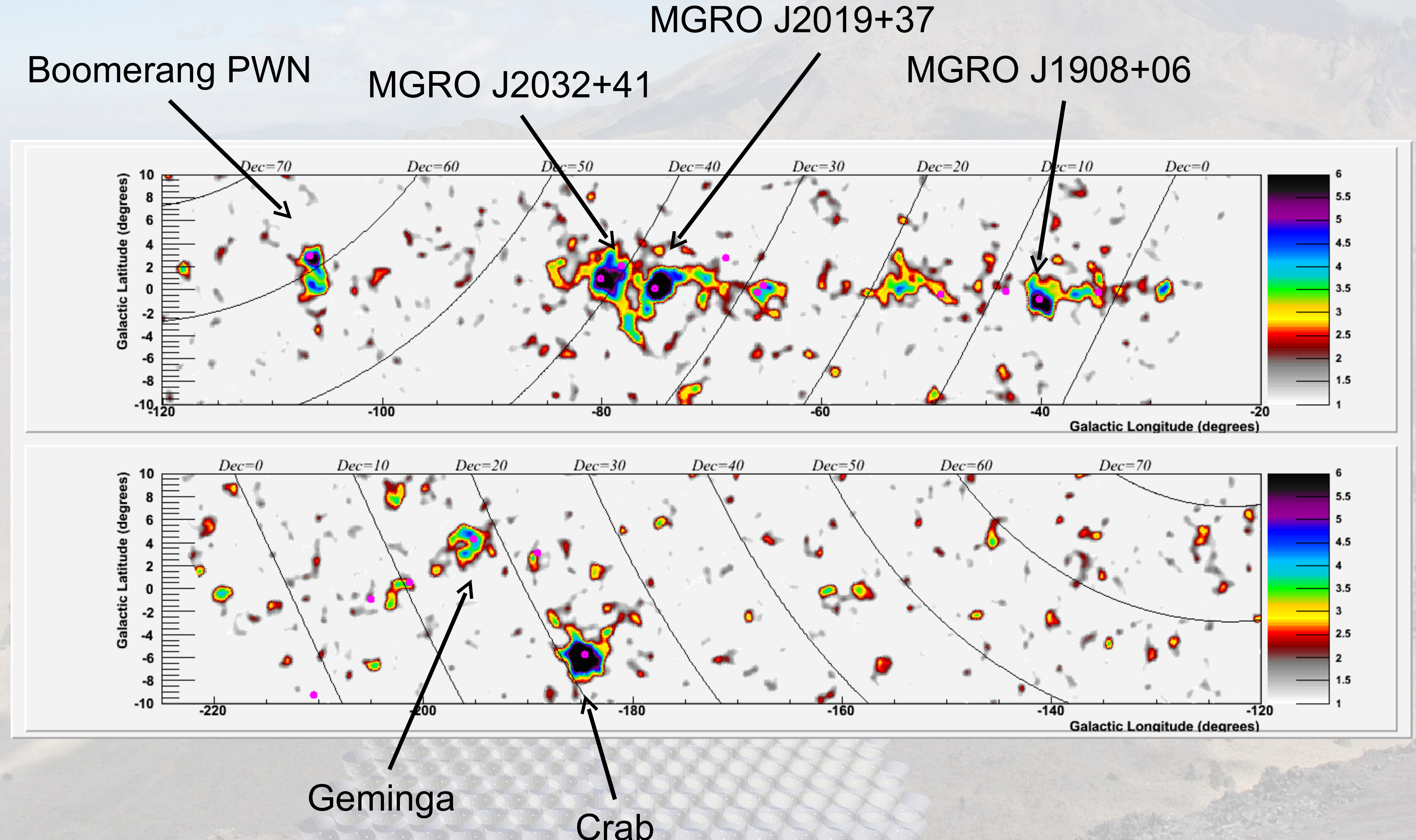
SN1604 in X-Ray (Chandra X-Ray Telescope)

Big Picture of Cosmic Radiation

and the role of gamma rays....



Milagro Survey of the Galactic Plane



Science with HAWC

- Galactic Sources
  - Highest energy emission in the Galaxy. Sources of cosmic rays.
  - Diffuse emission and propagation.
- Extra-Galactic Sources
  - Wide field of view and continuous observation is essential for extra-Galactic transients.
  - AGN
    - Measure long-term light curves from active galaxies. Catch flares when they happen.
    - Trigger lower-energy observations. Catch 'orphan flares'.
    - Measure integral flux over long durations.
  - GRB
    - Catch GRBs when they happen.
    - Potential for first ground-based observation of gamma rays from a GRB.
- Cosmic Ray Anisotropy
  - Milagro identified curious small-scale anisotropy in the cosmic ray arrival directions and HAWC will bring better energy resolution and more vents to this effort.
- Solar Physics
  - Scalers are sensitive to solar events by observing an overall increase in the cosmic ray rate.

Data Analysis

Raw Data

5-10 kHz
Times of PMT Hits

Reconstructed Data

Direction,
Gamma/Hadron-likeness
Energy

Skymap Production

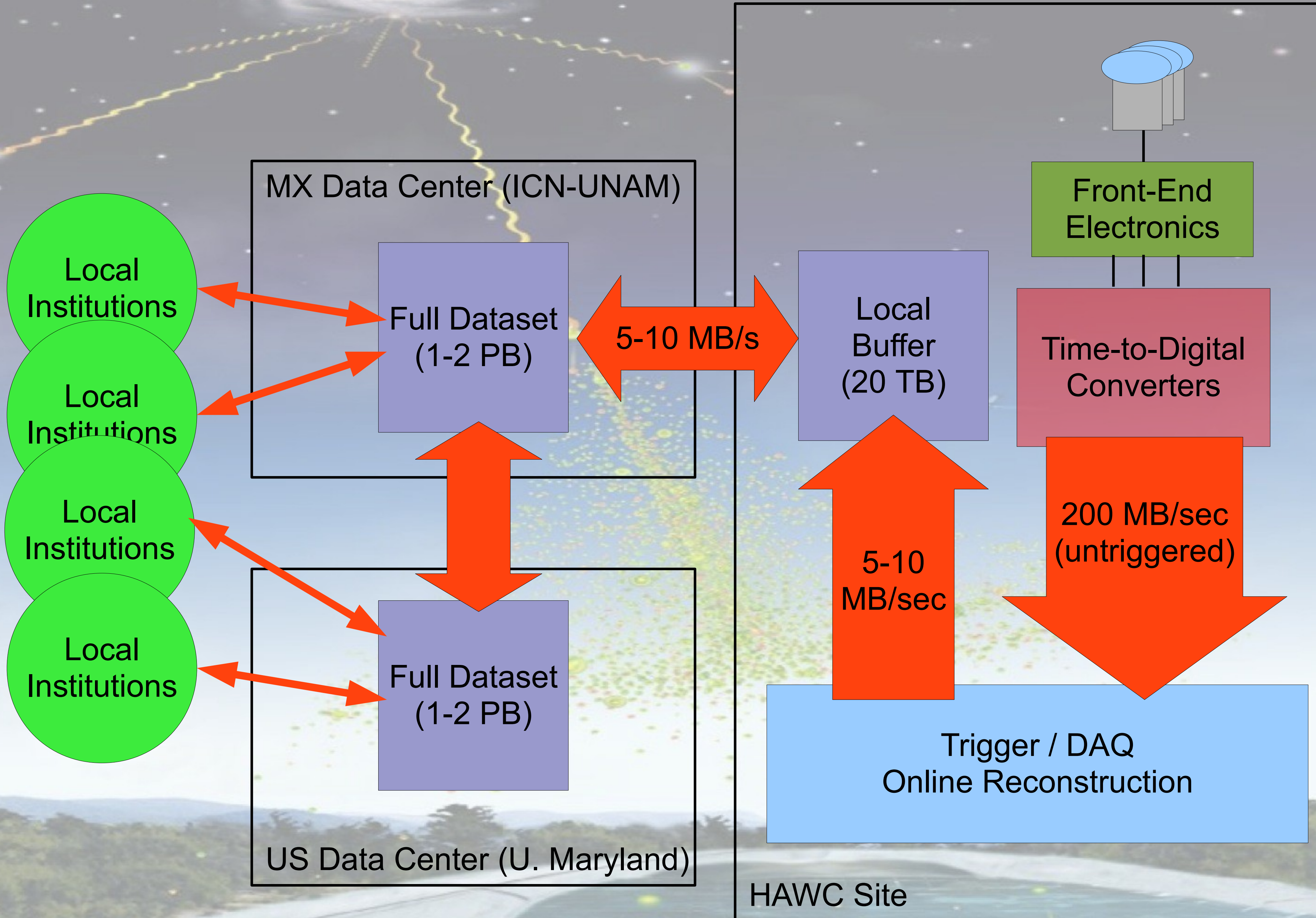
Background Estimation
and Subtraction

Source Identification and Characterization

Significance calculated, flux, spectrum estimated, transient search.

- Raw Data consisting of PMT times is reconstructed.
  - First pass at the HAWC site for quick analysis and data health.
  - Subsequent passes at each data center.
  - CPU budget for a 'few' reprocessings.
- Skymap Production is fast and is done over and over again depending on needs.

Data Flow

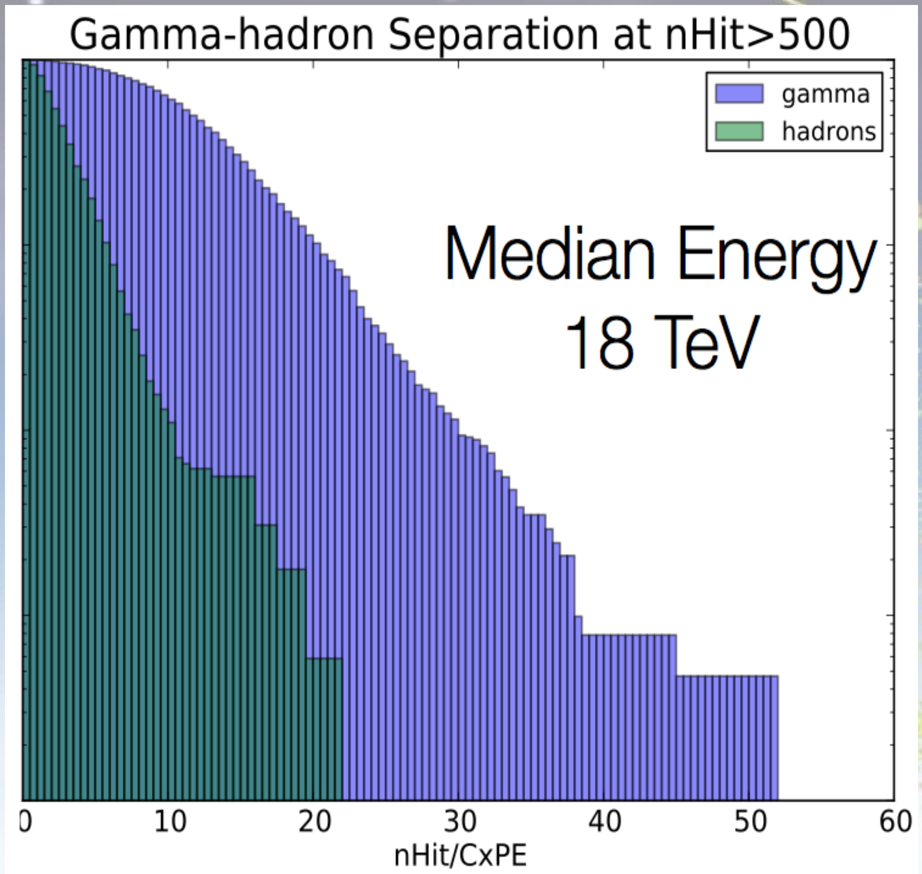


MX Data Center (ICN-UNAM)
Full Dataset (1-2 PB)
5-10 MB/s
Local Buffer (20 TB)
Front-End Electronics
Time-to-Digital Converters
200 MB/sec (untriggered)
5-10 MB/sec
Trigger / DAQ Online Reconstruction
HAWC Site
Local Institutions
Local Institutions
Local Institutions
Local Institutions
Full Dataset (1-2 PB)
US Data Center (U. Maryland)

Responsibilities

- US and MX Data Centers
  - Redundant copies of Raw data and Simulation
  - Reconstruction of Raw data
  - Generation of high-level data products (sky maps)
  - Generation of Monte Carlo
  - Analysis center for smaller institutions
  - "Tier 0/1" in LHC Language
- Local Institutions
  - Varying commitment to generate simulation (depending on institution resources)
  - Analysis of high-level data products (sky maps)
  - Development of production code on small datasets

A Note on Simulation



- At the highest energies our background subtraction is quite good.
  - CxPE = PEs in the hardest hit channel more than 40 meters from the core.
  - Very simple. New parameters may be better.
- Difficulty estimating the optimal acceptance because we don't have enough gamma-like hadrons. The separation is too good.
- More (much more) simulation is needed (60x current dataset at least)
- Not simply a case of 'more is better'. Science at the highest energies depends critically on large simulation sets.

Summary of Requirements

Need	Requirement
Transmission of Site Data to UNAM	5-10 MB/sec (sustained for 5 yrs)
Mirroring of Site Data between ICN-UNAM and UMD data centers	5-10 MB/sec sustained data transfer between sites
Storage at ICN-UNAM data center	1-2 PB (5-8 years from now)
Storage at UMD data center	1-2 PB (5-8 years from now)
Generation of Simulation - Mexico	150+ 1.6 GHz Cores (Bare minimum. Continuous usage for a year)
Generation of Simulation - UMD	150+ 1.6 GHz Cores (Bare minimum. Continuous usage for a year)
Reconstruction of Raw Data / User Analysis at ICN-UNAM Data Center	200 1.6 GHz Cores
Reconstruction of Raw Data / User Analysis at UMD Data Center	200 1.6 GHz Cores
Support User Analysis at ICN-UNAM Data Center	Reliable Moderate-Speed Access to Institutions in Mexico

Conclusions

- HAWC is funded and is coming to Mexico.
  - Premier instrument for high-energy wide-field gamma ray astronomy
  - Construction underway.
  - 3.5 years till completion.
  - Data begins flowing in earnest after ~ 1 year.
- HAWC plans for 2 redundant data centers, one at ICN-UNAM and one at U. Maryland.
  - Full PB-scale facilities.
  - CPU for reconstruction of data. End user analysis.
  - Mission critical
  - No technological hurdles. Not trivially handled.
- Synergy with efforts on ALICE and Auger at UNAM.
  - We all benefit from improved network within Mexico.