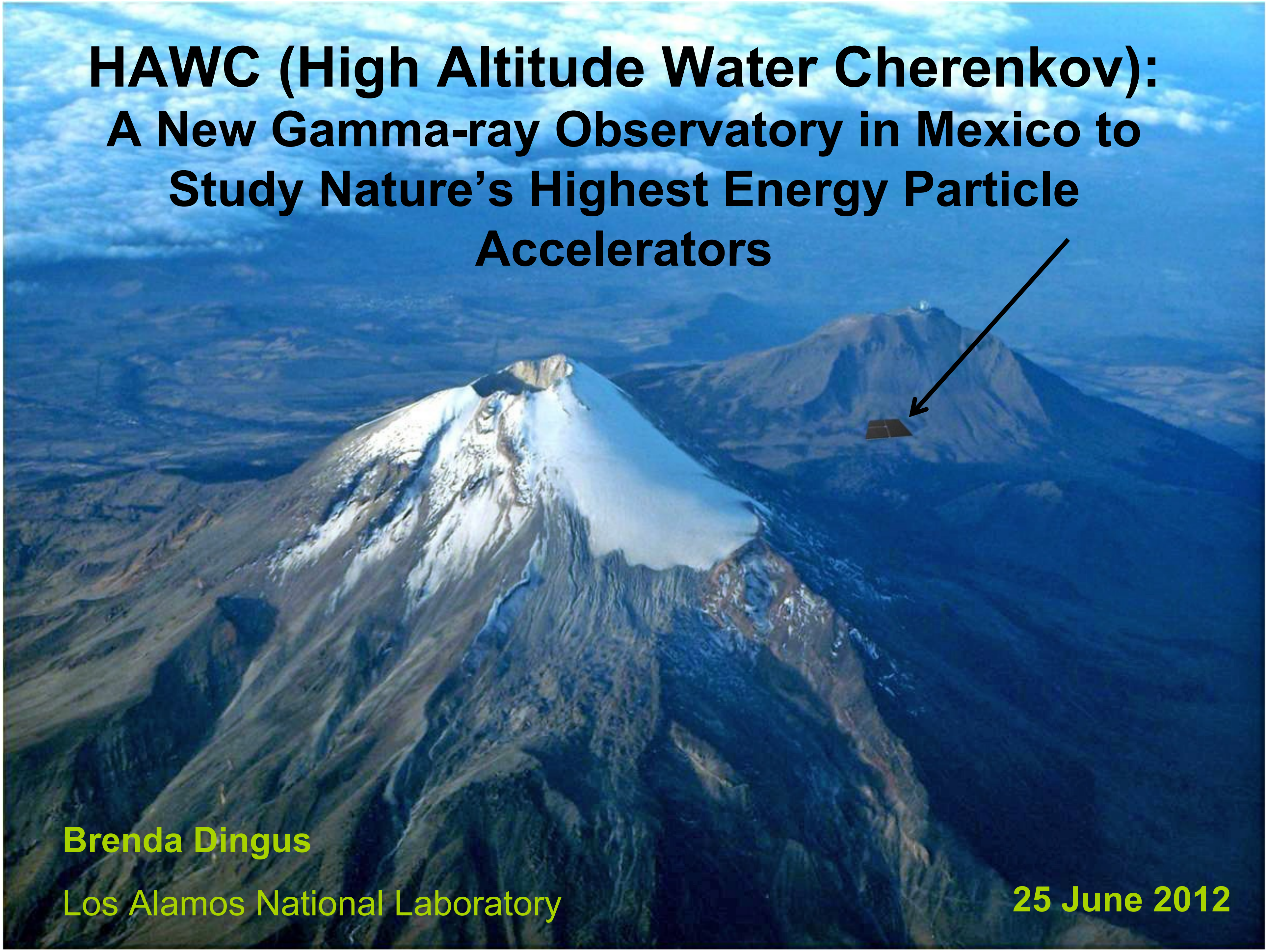
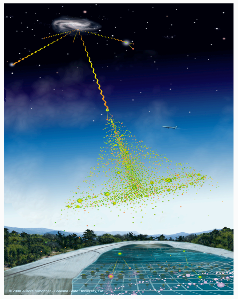
HAWC (High Altitude Water Cherenkov):
A New Gamma-ray Observatory in Mexico to Study Nature’s Highest Energy Particle Accelerators



Brenda Dingus

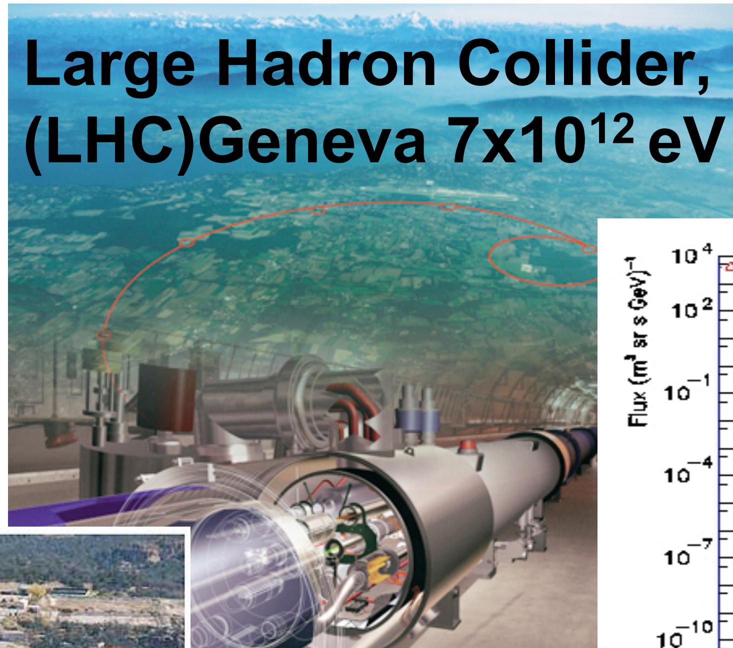
Los Alamos National Laboratory

25 June 2012



Particle Accelerators

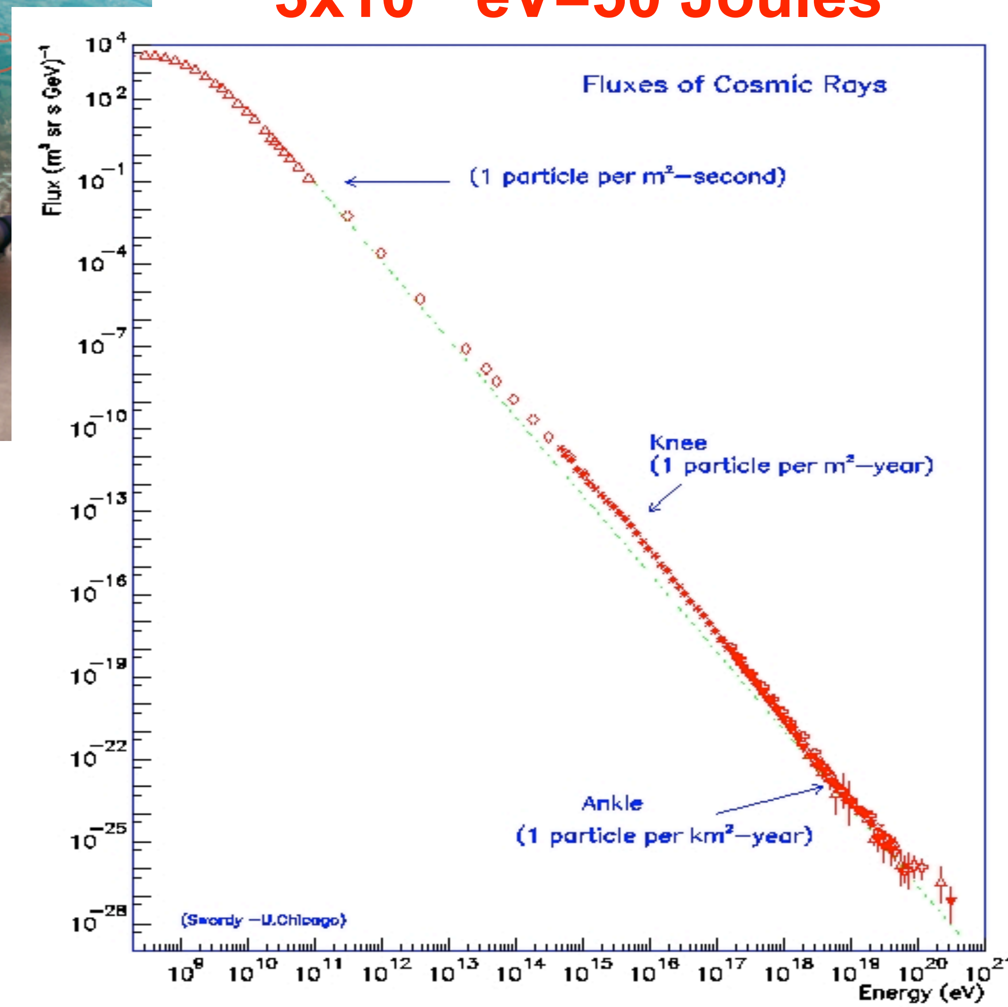
Large Hadron Collider, (LHC)Geneva 7×10^{12} eV

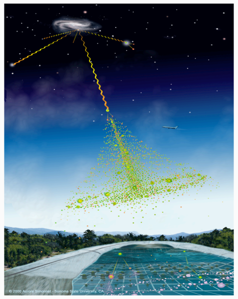


Nature accelerates cosmic rays to 3×10^{20} eV=50 Joules

LANL

8×10^{6}eV

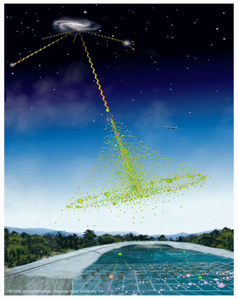




A Century Old Question: Where do cosmic rays come from?

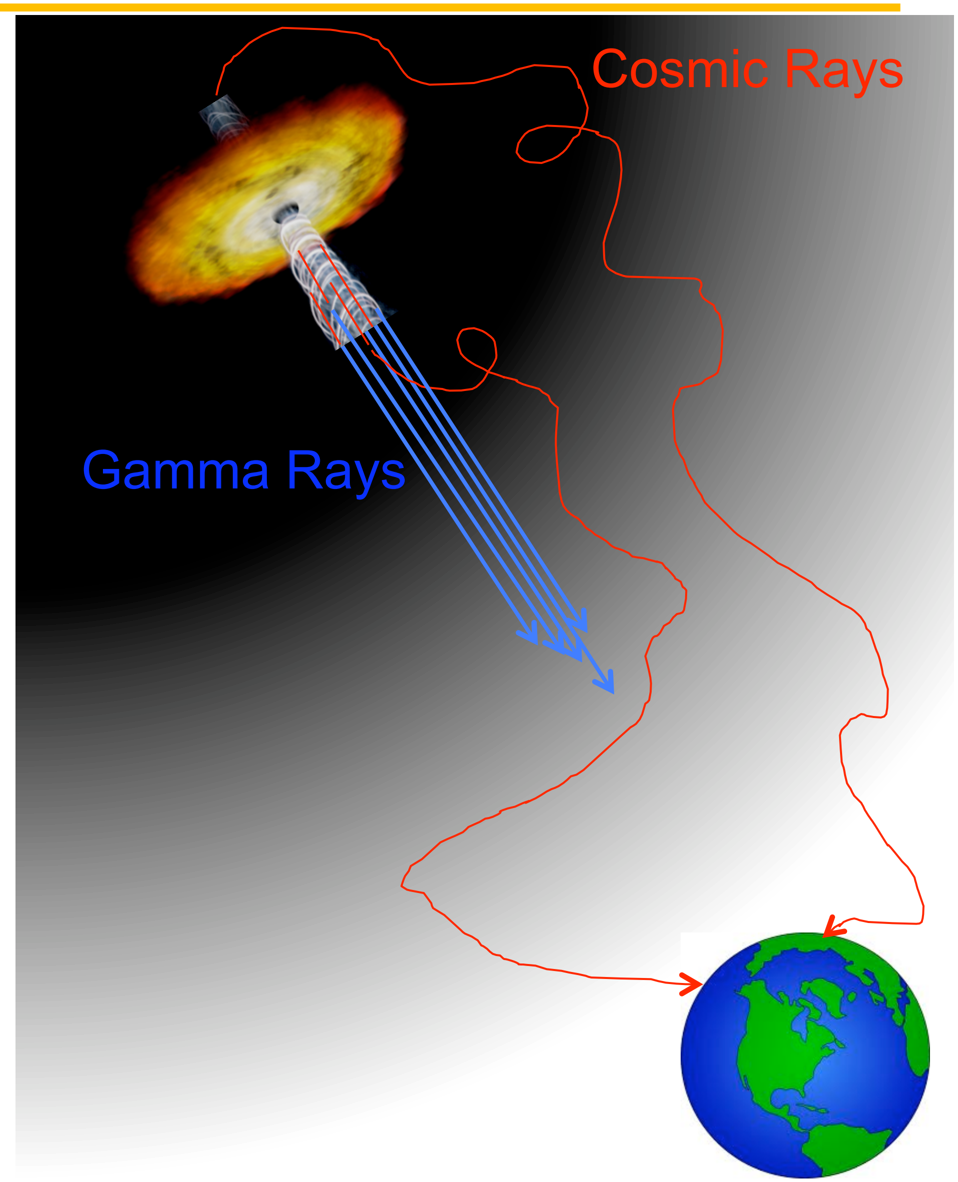
- Prediction was that radiation from Earth caused electroscope to discharge
- But in 1912 Hess observed more radiation at higher altitudes
- Cosmic Rays were discovered!

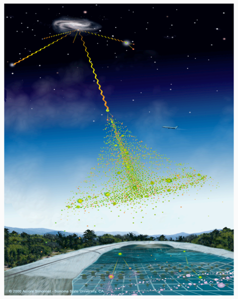
V. F. Hess. Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten. Physikalische Zeitschrift, 13:1084-1091, November 1912.



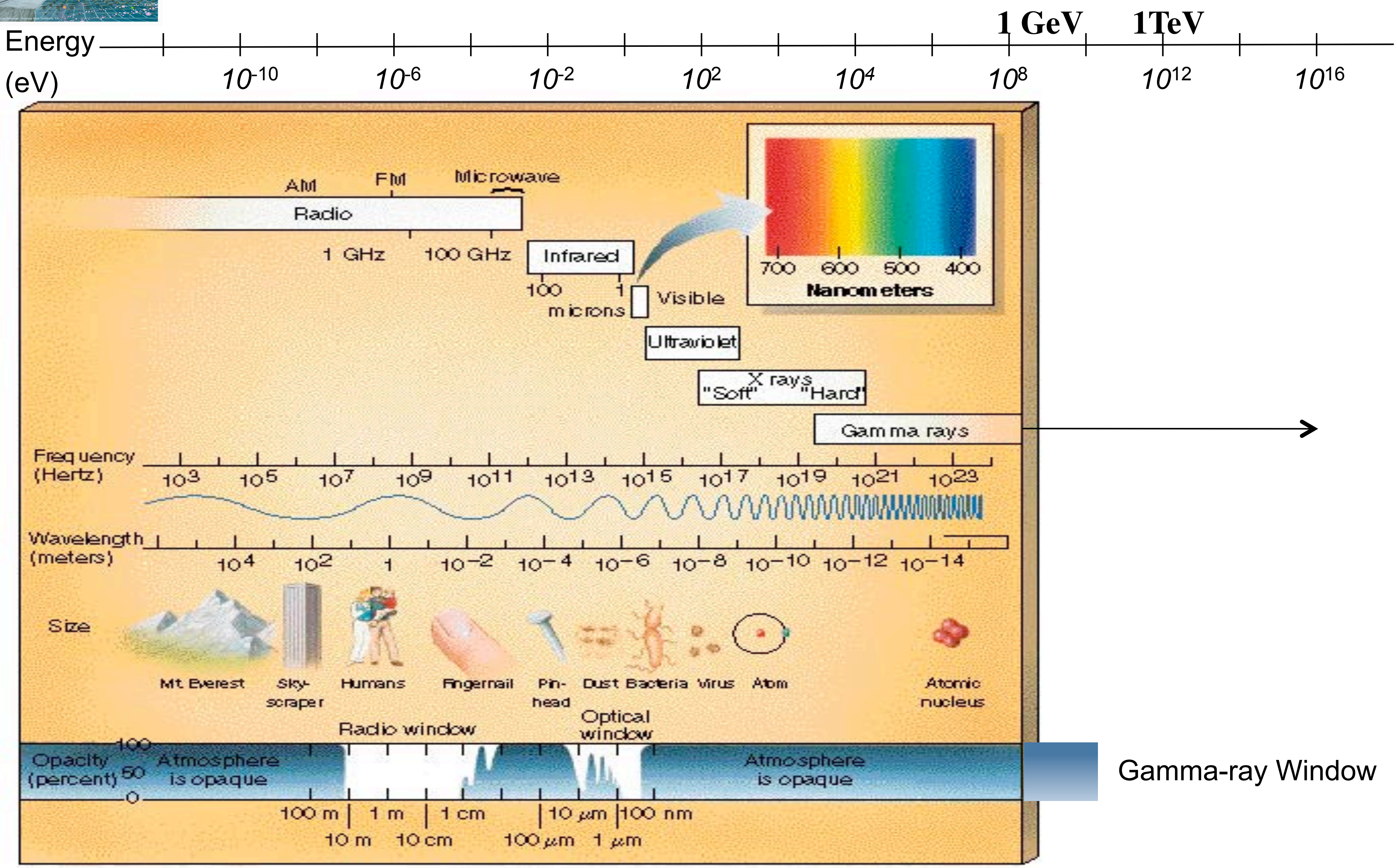
Gamma Rays Probe Cosmic Rays

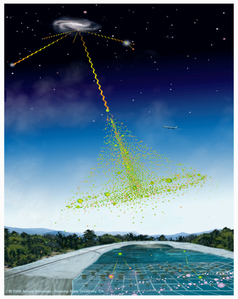
- Cosmic rays are energetic particles that have electric charge => Directions are randomized by Magnetic Fields in the Universe
- Gamma rays are produced by cosmic rays near their accelerators => Directions point back to the Sources
- Therefore, gamma rays are unique probe of cosmic rays and their accelerators





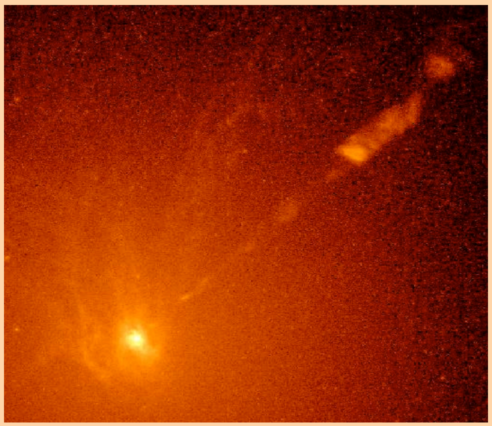
- Cosmic Rays are Particles (primarily protons)
- Gamma Rays are the highest energy light



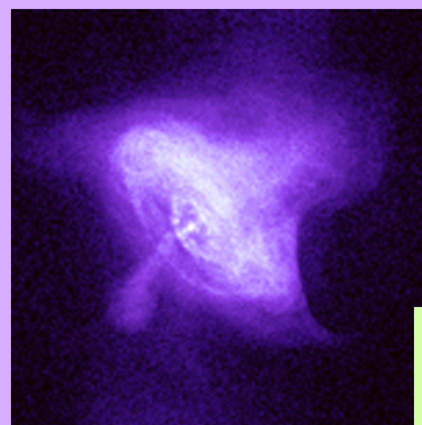


Gamma Ray Sources are Astrophysical Particle Accelerators

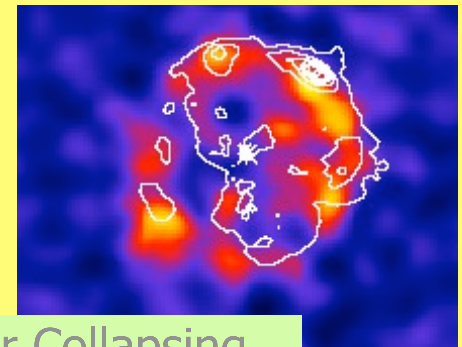
Black Hole producing relativistic jet of particles



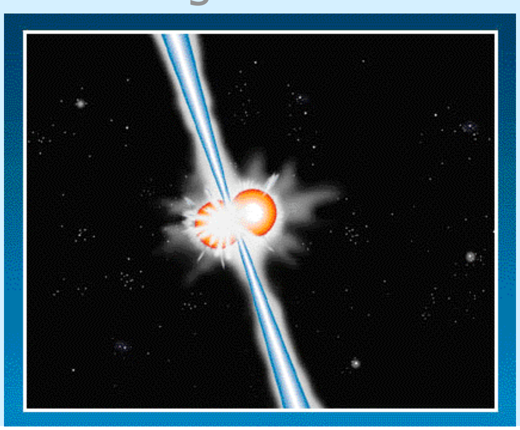
Spinning Neutron Star powering a relativistic wind



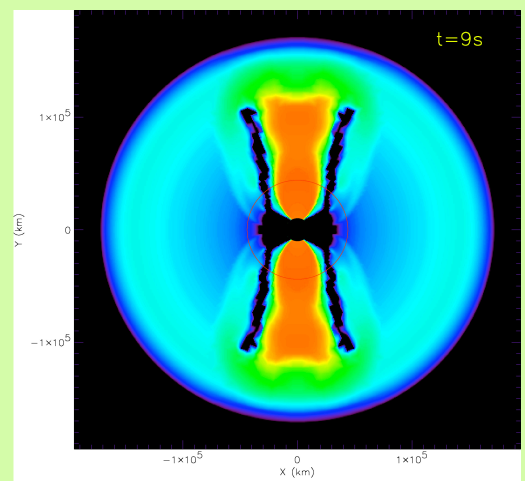
TeV image of Vela Jr. Supernova Remnant



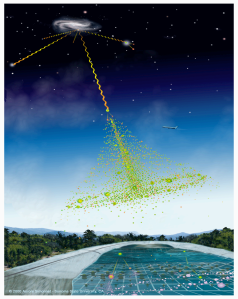
Binary Neutron Star Coalescing



Massive Star Collapsing into a Black Hole

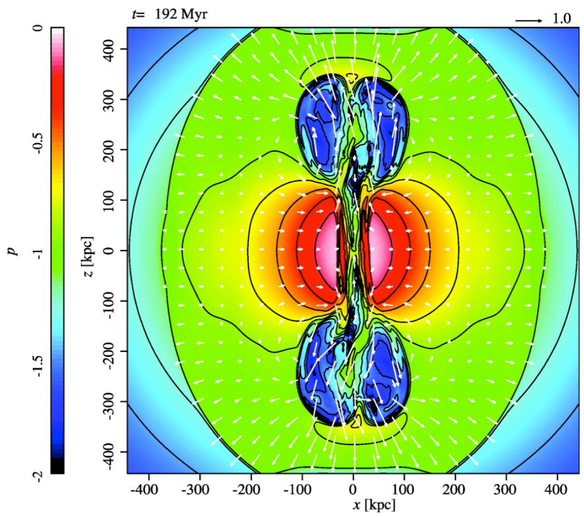


MacFadyen, Woosley, & Heger (1999)

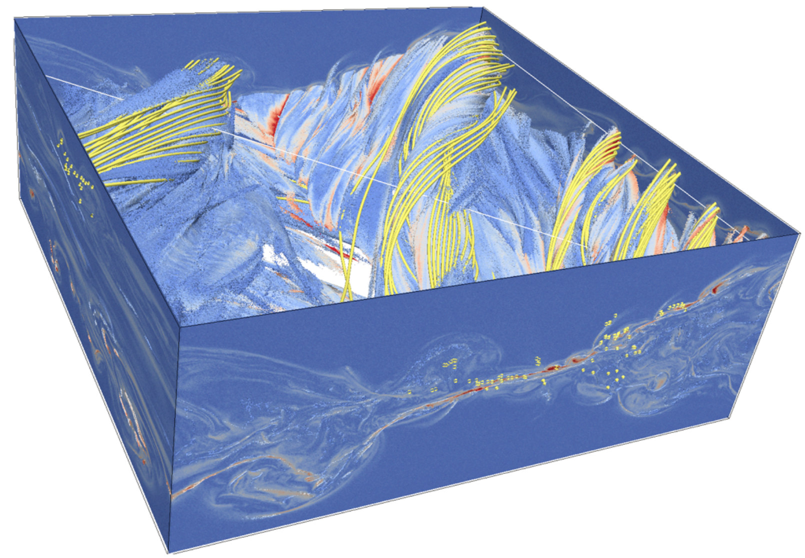


LANL Computation Simulations of Astrophysical Particle Acceleration

- Hui Li, Bill Daughton, Chris Fryer, Sterling Colgate

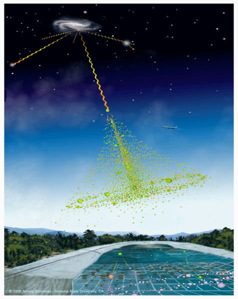


Relativistic Magneto Hydro Dynamic Simulation of fluids (of plasma and electromagnetic fields) ejected in 2 jets from a supermassive black hole



3 Dimensional Simulation of Particle Acceleration by Magnetic Reconnection using Particle in Cell techniques

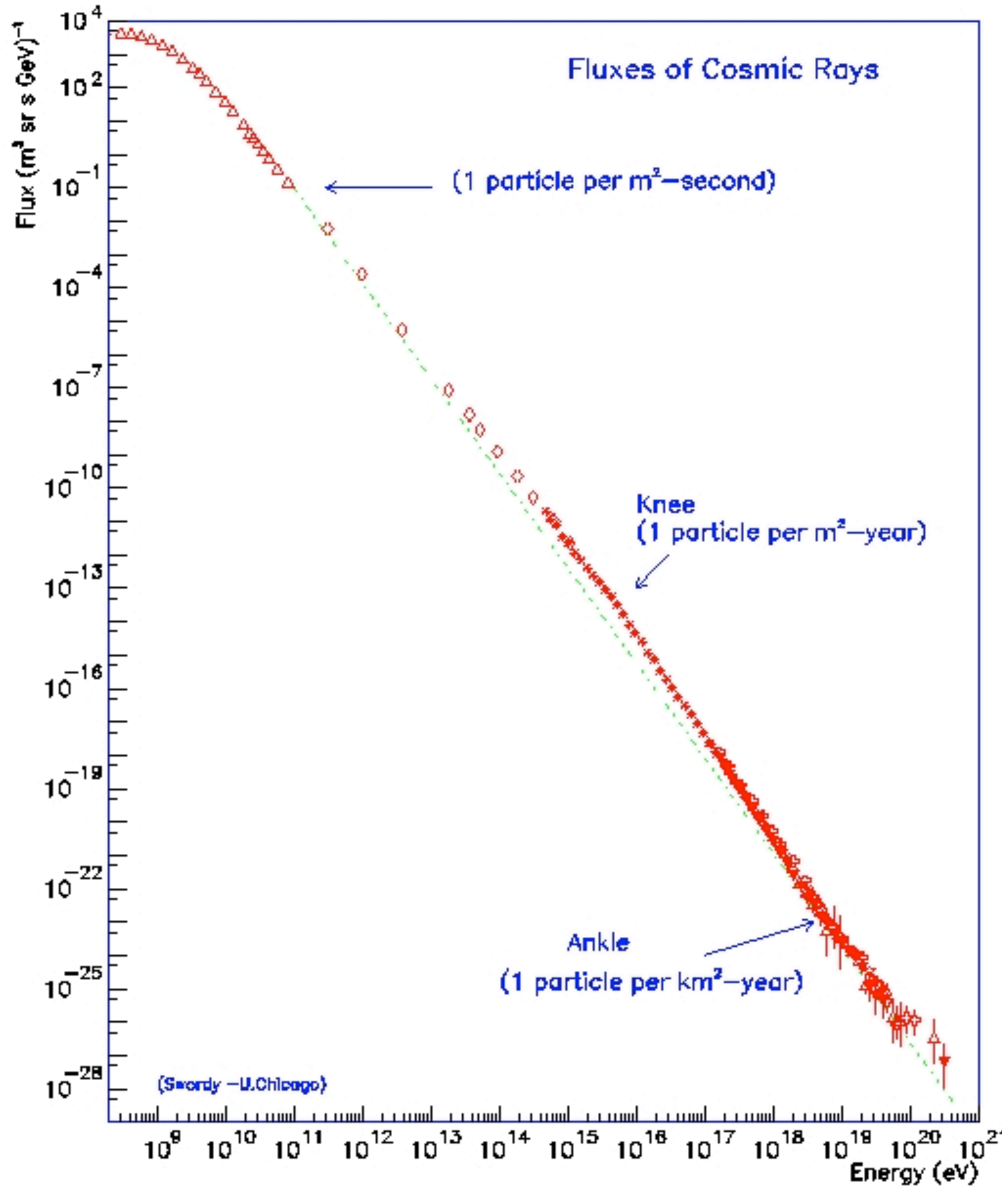
LANL astrophysics simulations test super computers with non classified problems.



High Energy Astrophysics

- **What do we know?**
  - Nature accelerates particles to $>10^{20}$ eV (> 1Joule)
  - Gamma-ray sources accelerate particles to $>10^{14}$ eV

- **What do we want to know?**
  - What astrophysical sources accelerate particles?
  - How do astrophysical sources accelerate particles?
  - What new high energy physics can we learn from astrophysics?



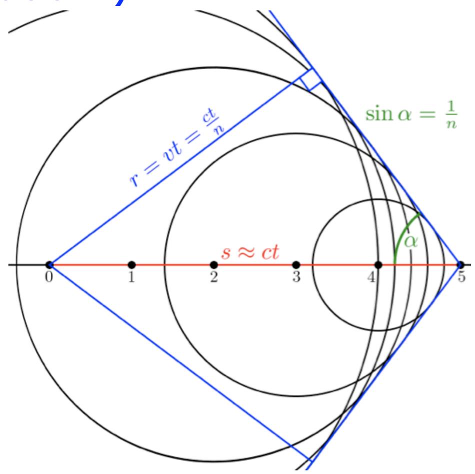
Showers of Particles in the Atmosphere

- Relativistic particles are created when gamma-rays or cosmic-rays impact Earth's atmosphere

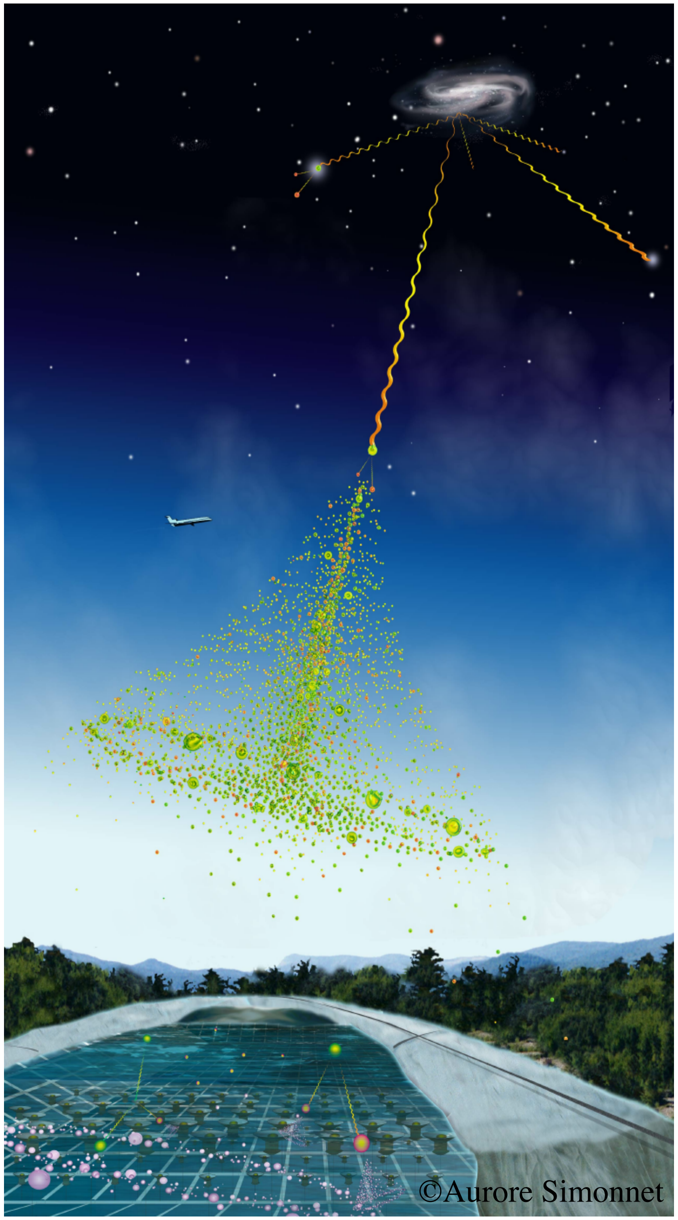
- Relativistic Particles in this "extensive air shower" emit light

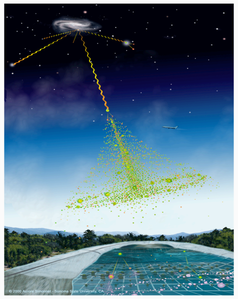
Cherenkov Light

Exceeding the wave speed in a medium produces a shock wave (similar to sonic boom)

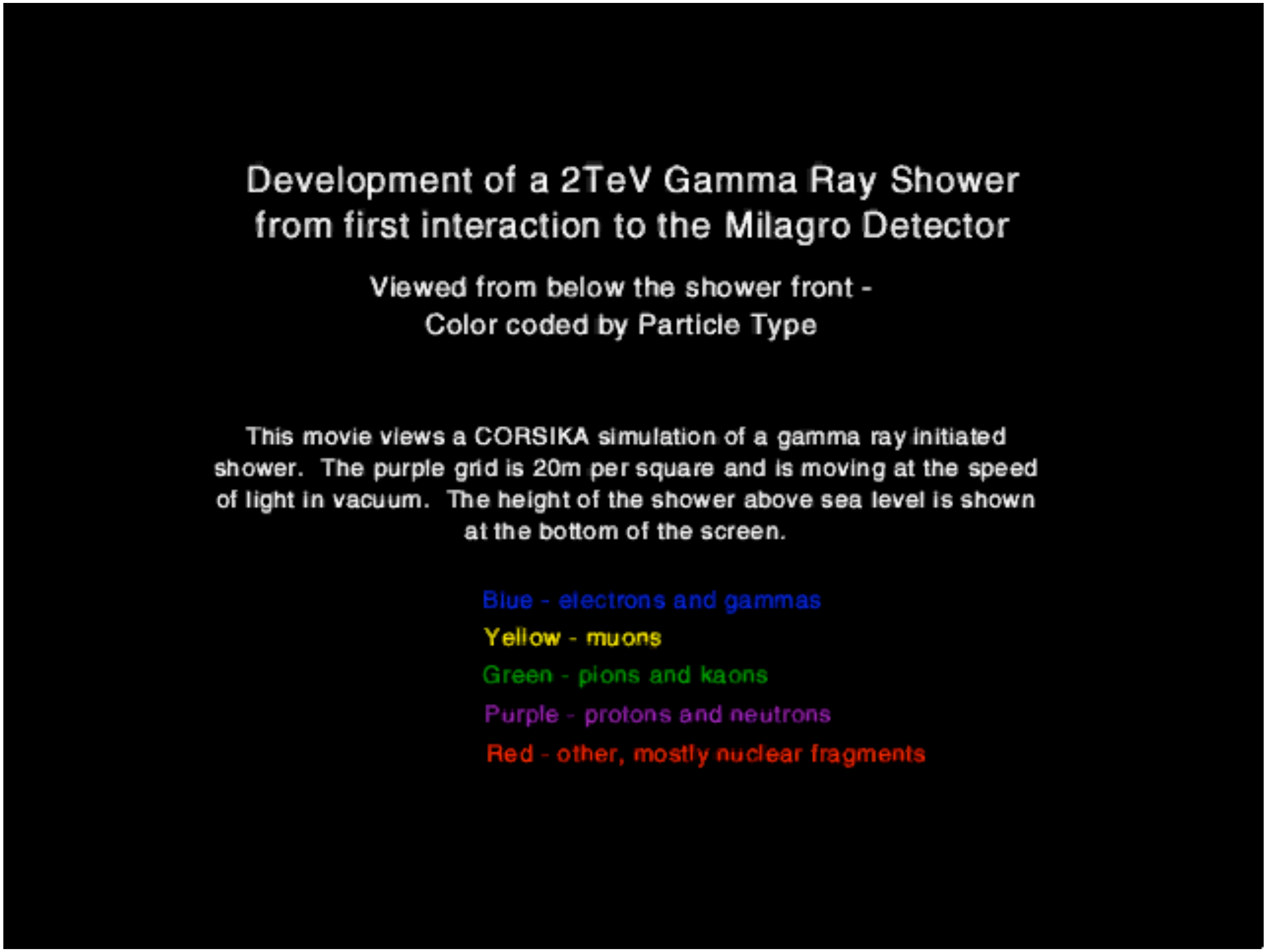


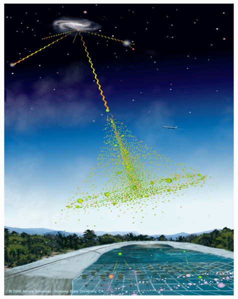
- Cherenkov angle in air is ~1°
- Cherenkov angle in water is ~ 40°



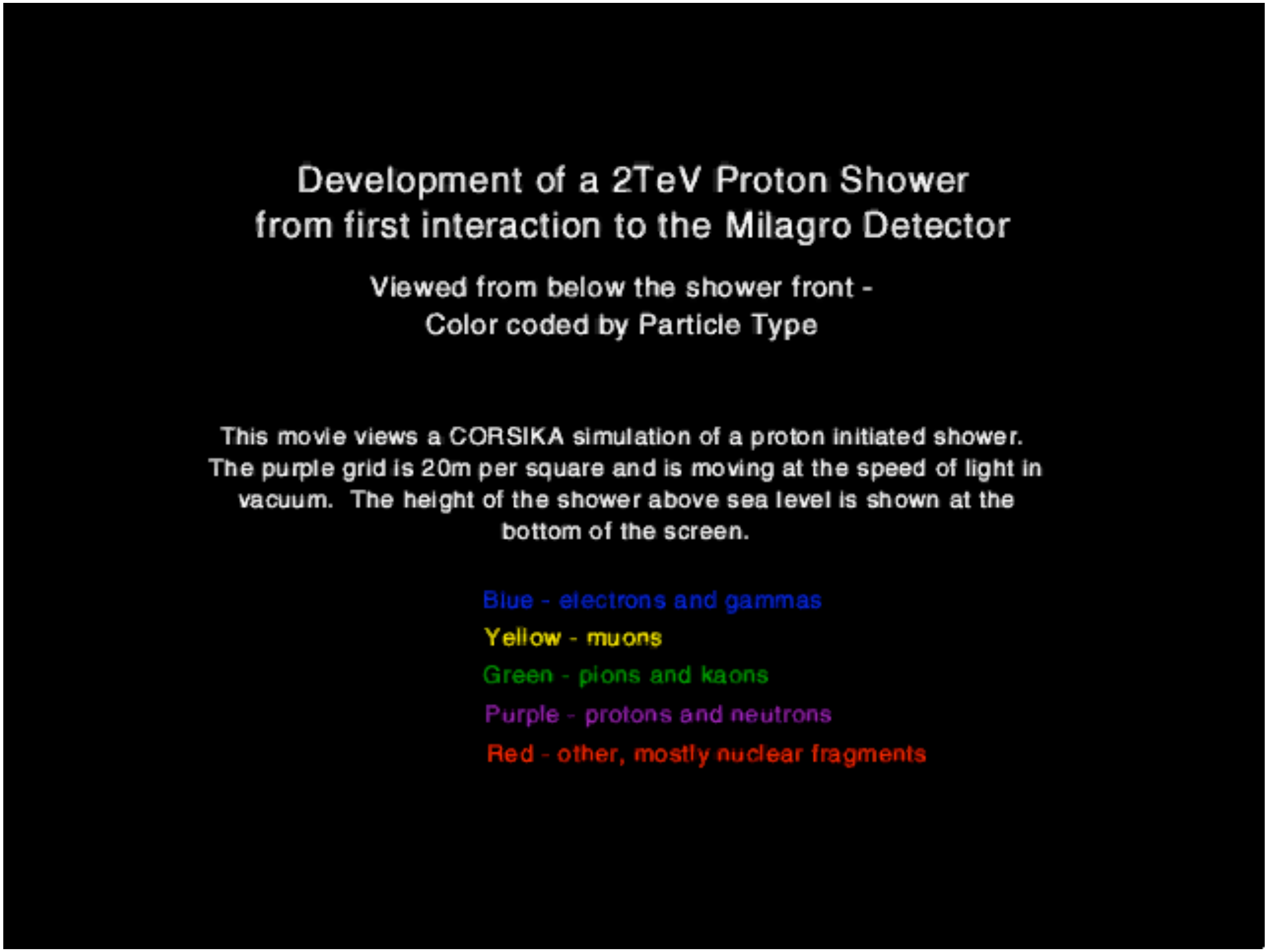


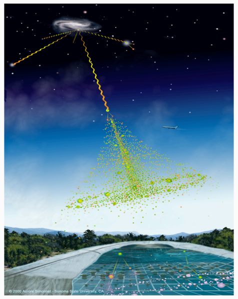
Detecting High Energy Gamma-Rays



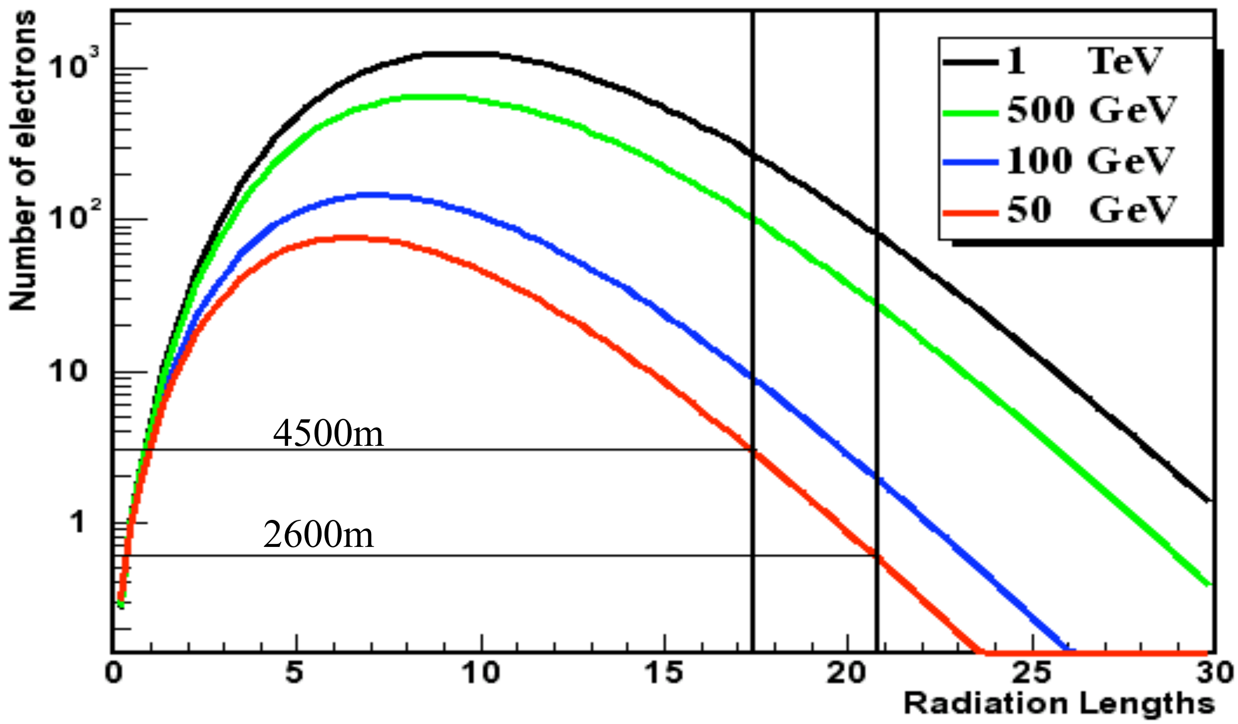


Detecting High Energy Cosmic-Rays





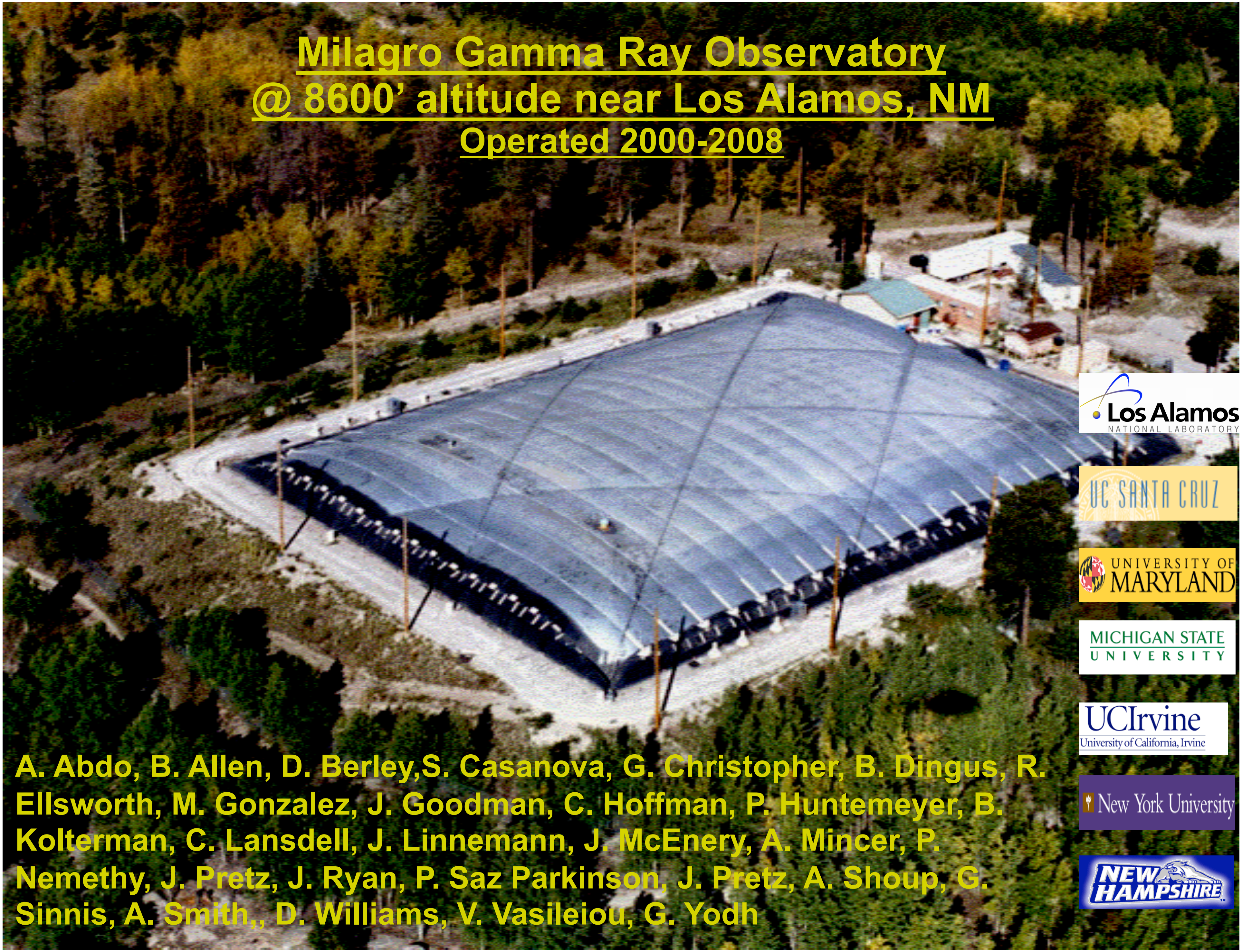
Higher Altitude is Closer to Shower Max.



Difference between 2600m (Milagro) and 4500m (HAWC):

~ 6x number of particles

~ 2x lower energy threshold



Milagro Gamma Ray Observatory
@ 8600’ altitude near Los Alamos, NM
Operated 2000-2008

A. Abdo, B. Allen, D. Berley,S. Casanova, G. Christopher, B. Dingus, R. Ellsworth, M. Gonzalez, J. Goodman, C. Hoffman, P. Huntemeyer, B. Kolterman, C. Lansdell, J. Linnemann, J. McEnery, A. Mincer, P. Nemethy, J. Pretz, J. Ryan, P. Saz Parkinson, J. Pretz, A. Shoup, G. Sinnis, A. Smith,, D. Williams, V. Vasileiou, G. Yodh

Los Alamos NATIONAL LABORATORY
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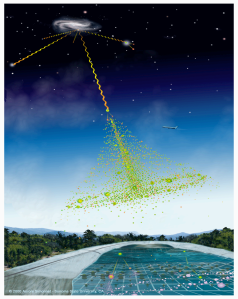
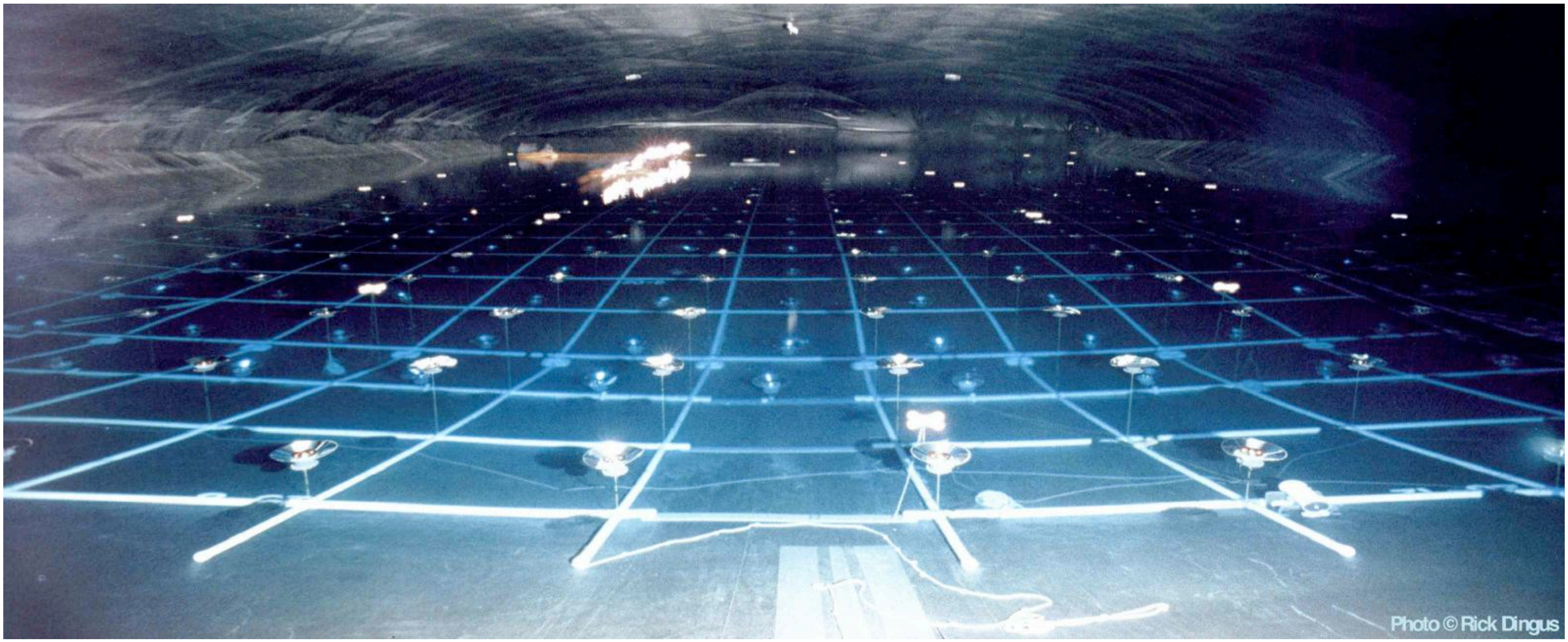
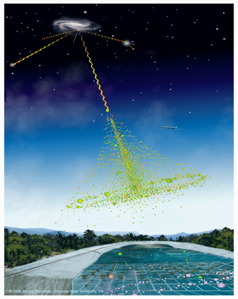
UNIVERSITY OF MARYLAND
MICHIGAN STATE UNIVERSITY
UCIrvine University of California, Irvine
New York University
NEW HAMPSHIRE

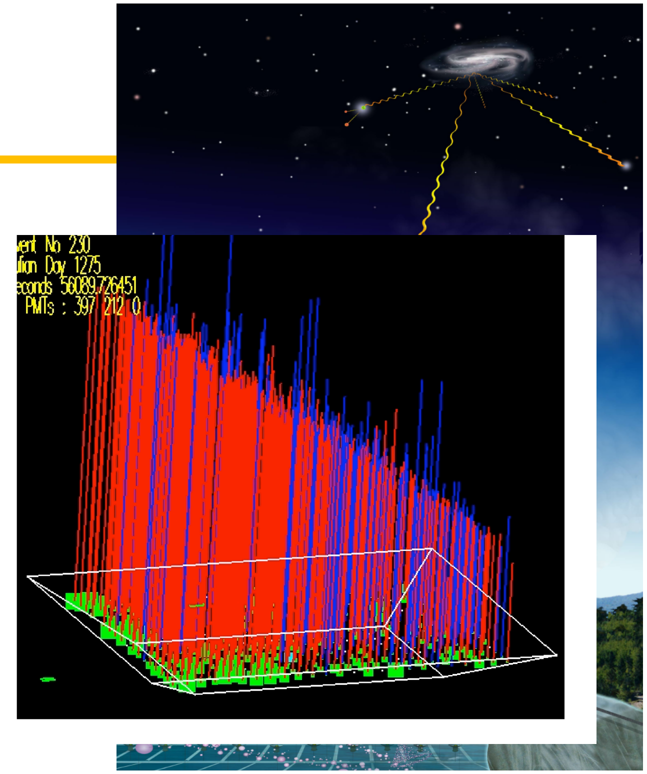


The Milagro Water Cherenkov Detector

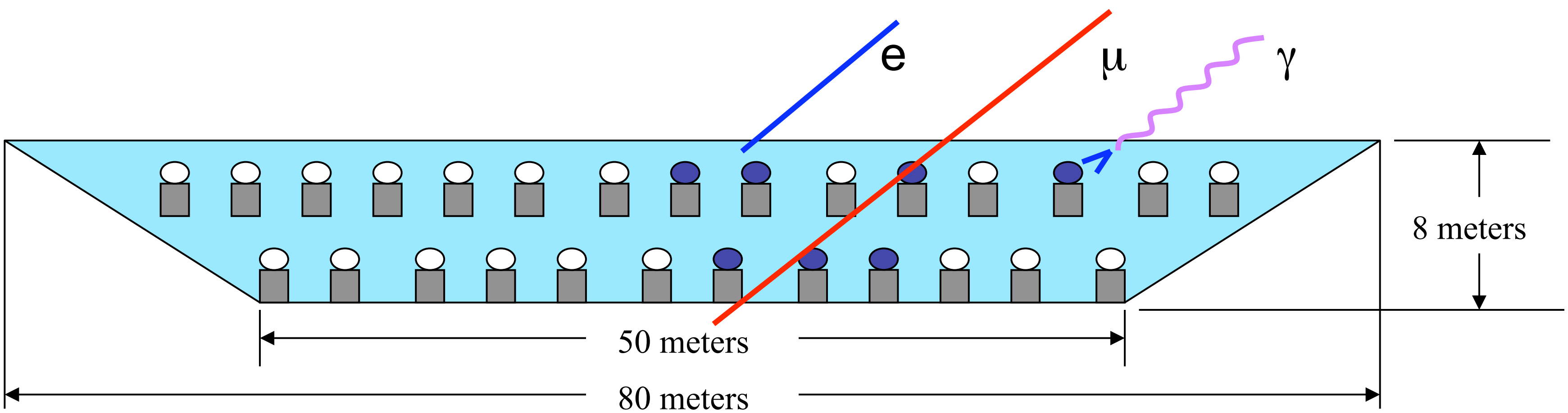


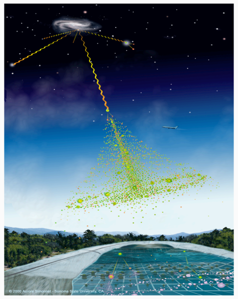


How Did Milagro Work?



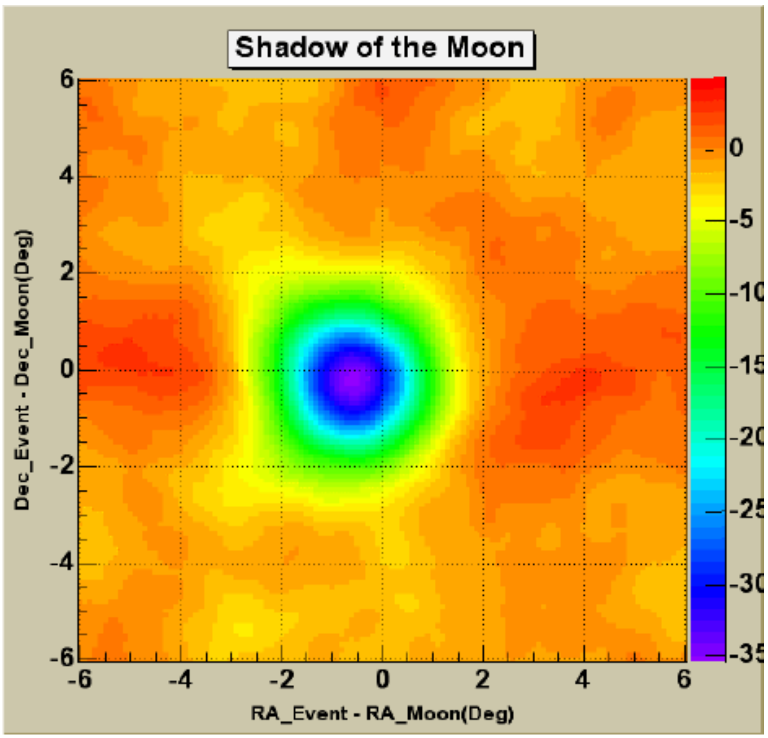
- Detected Particles in Extensive Air Showers from Cherenkov light created in 60m x 80 m x 8m pond containing filtered water
- Reconstructed shower direction to ~0.5° from the time that different photodetectors are hit
- Field of view was ~2 sr and duty factor >90%
- 1700 Hz trigger rate mostly due to Extensive Air Showers created by cosmic rays
- > 100 billion air showers were recorded



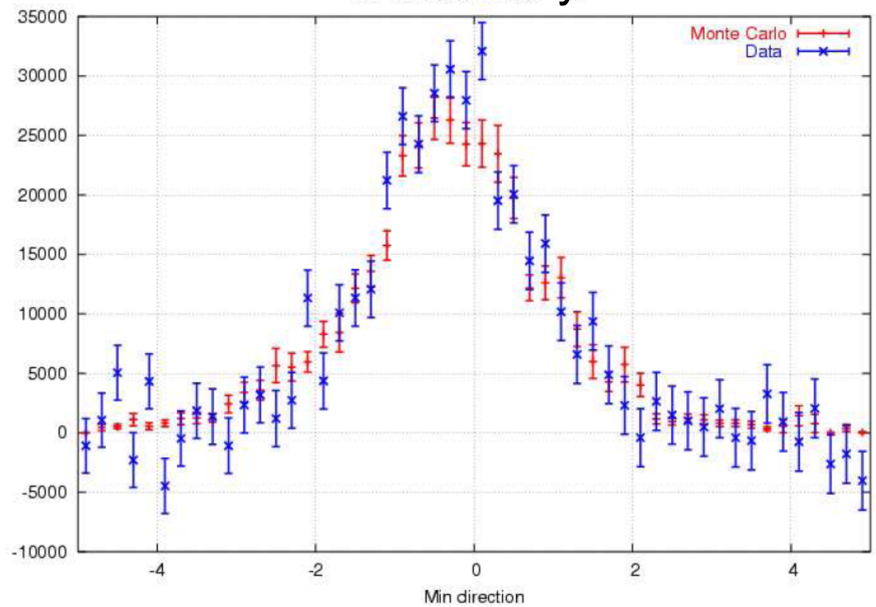


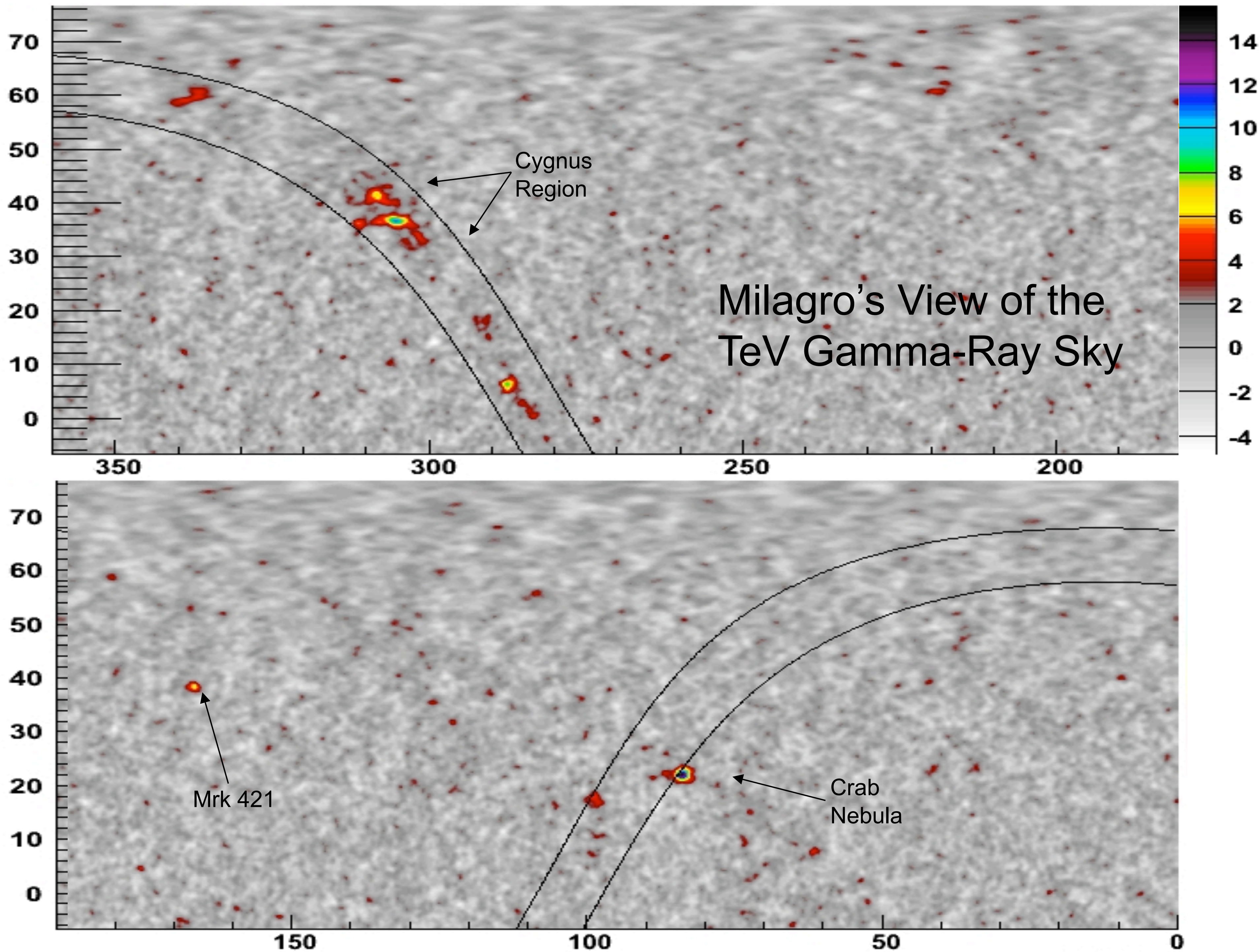
Moon for Monitoring

- Cosmic Rays are Shadowed by the Moon (0.5^o dia.)
- Shadow is deflected by Earth's magnetic field
- Deflection measures Milagro's energy scale for protons
- Shadow size measures Milagro's angular resolution for protons

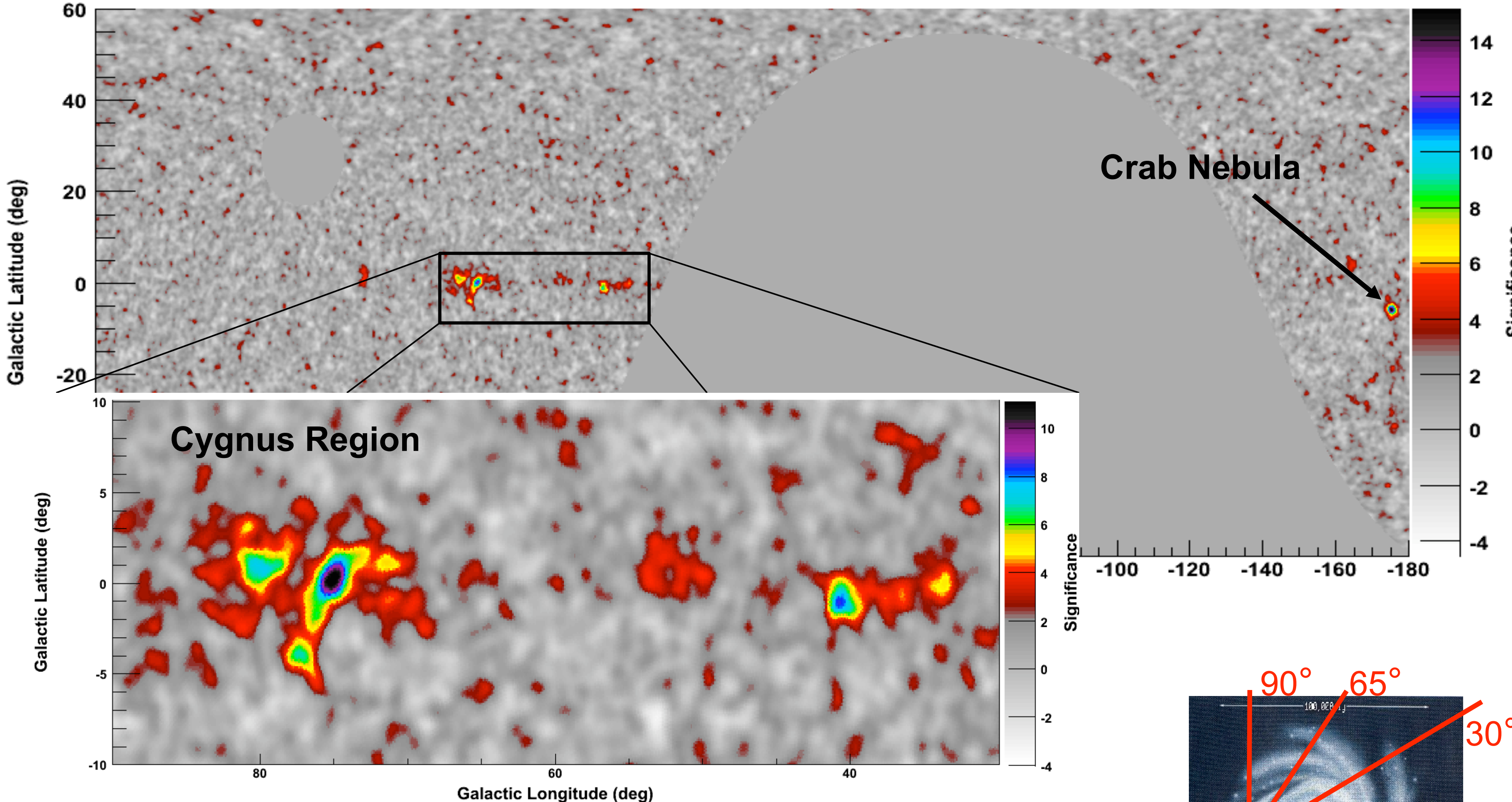


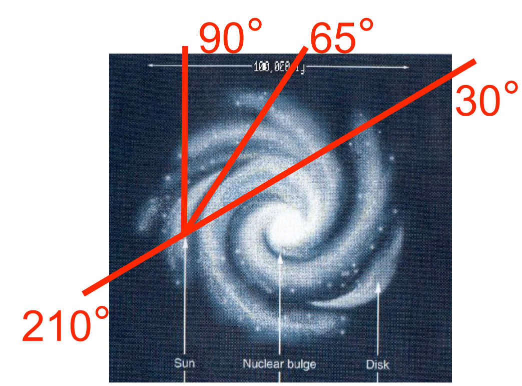
Moon Shadow in direction with minimum deflection by Earth's B



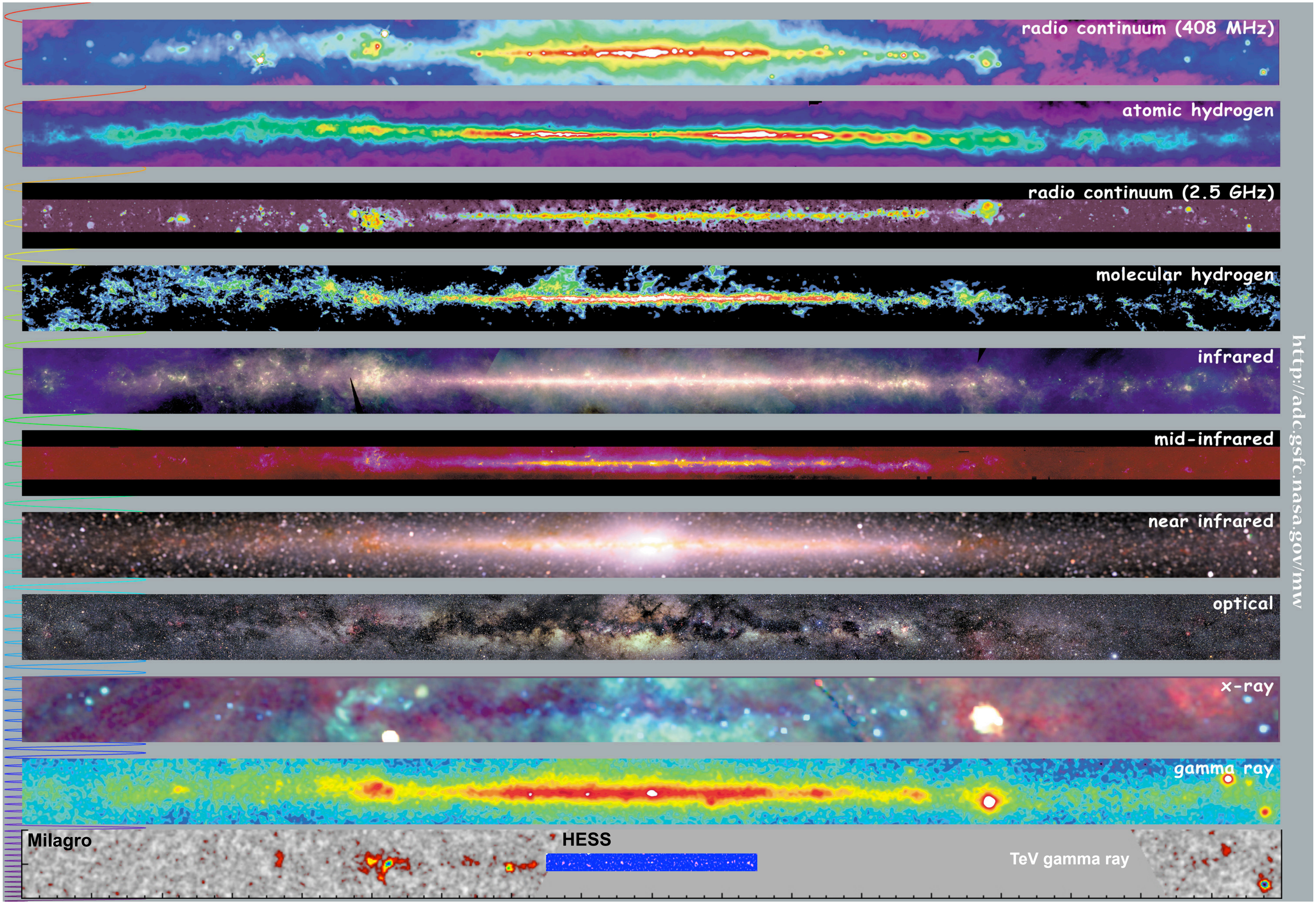

Milagro's View of the TeV Gamma-Ray Sky
Cygnus Region
Mrk 421
Crab Nebula
70
60
50
40
30
20
10
0
350
300
250
200
150
100
50
0
14
12
10
8
6
4
2
0
-2
-4

Milagro Observation in Galactic Coordinates

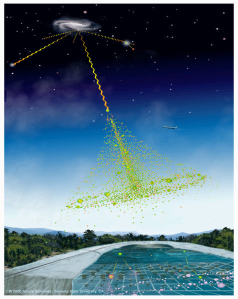




- Galactic emission visible from l=25° to l=90°
- Cygnus Region shows extended excess
- $\mathrm{Flux}_{\mathrm{Cygnus}} \sim 2 \times \mathrm{Flux}_{\mathrm{crab}}$



TeV γ-rays: A New Window on the Sky



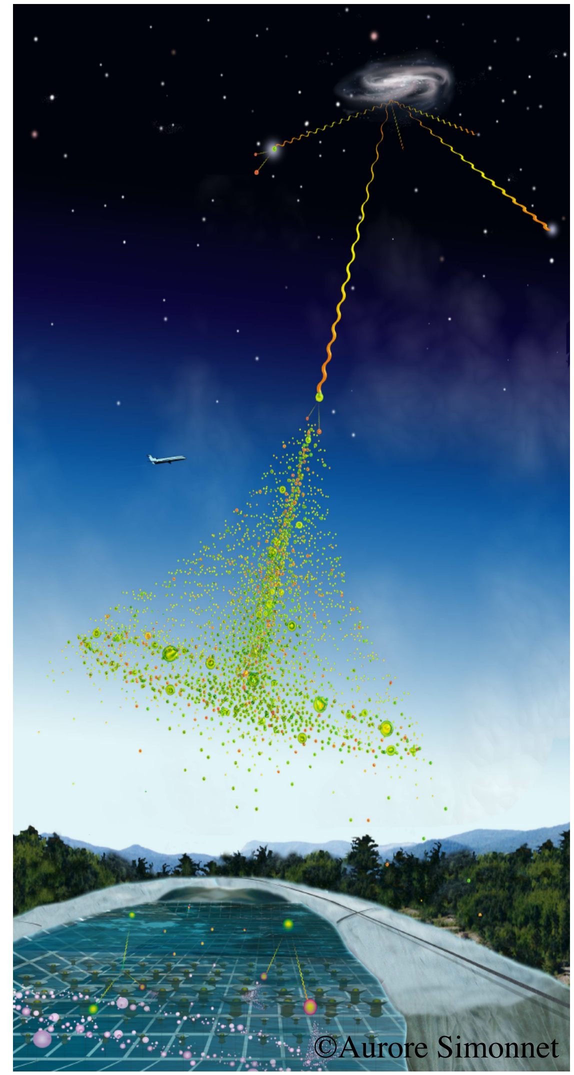
HAWC Design builds on the success of Milagro

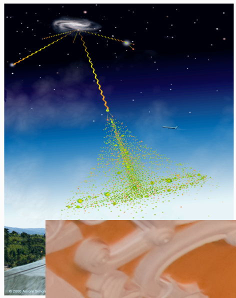
Milagro "1st Generation" Water Cherenkov gamma-ray detector

- 2650m (8600') elevation at Fenton Hill, NM
- Covered pond of 4000 m^2
- Operated 2000-2008

HAWC "2nd Generation" Water Cherenkov gamma-ray detector

- 4100m (13500') elevation near Puebla, Mexico
- 300 water tanks spread over 25000 m^2
- Construction 2010-14, Operation 2013-19
- 15 x Milagro's sensitivity with 10 x lower energy threshold





The HAWC Collaboration

The HAWC Collaboration

Los Alamos National Laboratory: Brenda Dingus (US spokesperson), : Gus Sinnis, John Pretz, Asif Imran
University of Maryland: Jordan Goodman, Andrew Smith, Jim Braun, David Berley, Brian Baughman
University of Wisconsin: Teresa Montaruli, Stefan Westerhoff, Segev Ben Zvi, Juanan Aguilar, Mike Duvernois, Zig Hampel-Arias, Dan Fiorino, Ian Wisher
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Michigan State University: Jim Linnemann, Kirsten Tollefson, Dan Edmunds, Udara Abeysekara, Tilan Ukwatta
Ohio State University at Lima: Anthony Shoup
George Mason University: Robert Ellsworth
Colorado State University: Miguel Mostafa, Dave Warner, Megan Longo, Paco Salesa Grues,Michael Gussert
University of New Hampshire: James Ryan, Peter Bloser
Pennsylvania State University: Tyce DeYoung, Cmitry Zaborov, Kathryne Sparks
University of Alabama: Patrick Toale
University of New Mexico: John Matthews, Robert Lauer
Michigan Technical University: Petra Hüntemeyer, Emanuele Bonamente, Nathan Kelley-Hoskins
NASA/Goddard Space Flight Center: Julie McEnery, Elizabeth Hays, Vlasios Vasileiou
Georgia Institute of Technology: Ignacio Taboada, Andreas Tepe
HAWC Technical Staff: Michael Schneider, Scott Delay

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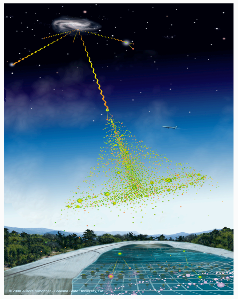
Centrode Investigacion y de Estudios Avanzados: *Arnulfo Zepeda*
Universidad de Guanajuato: *David Delepine, Gerardo Moreno, Edgar Casimiro Linares, Marco Reyes, Luis Ureña, Mauro Napsuciale, Victor Migenes*
CIC Instituto Politécnico Nacional: *Jesus Martinez*

USA:
16 institutions,
52 people

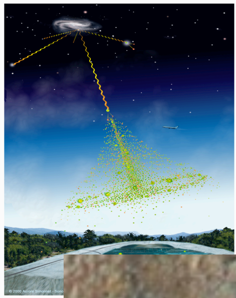
Mexico:
15 institutions,
54 people



HAWC Site Location in Mexico

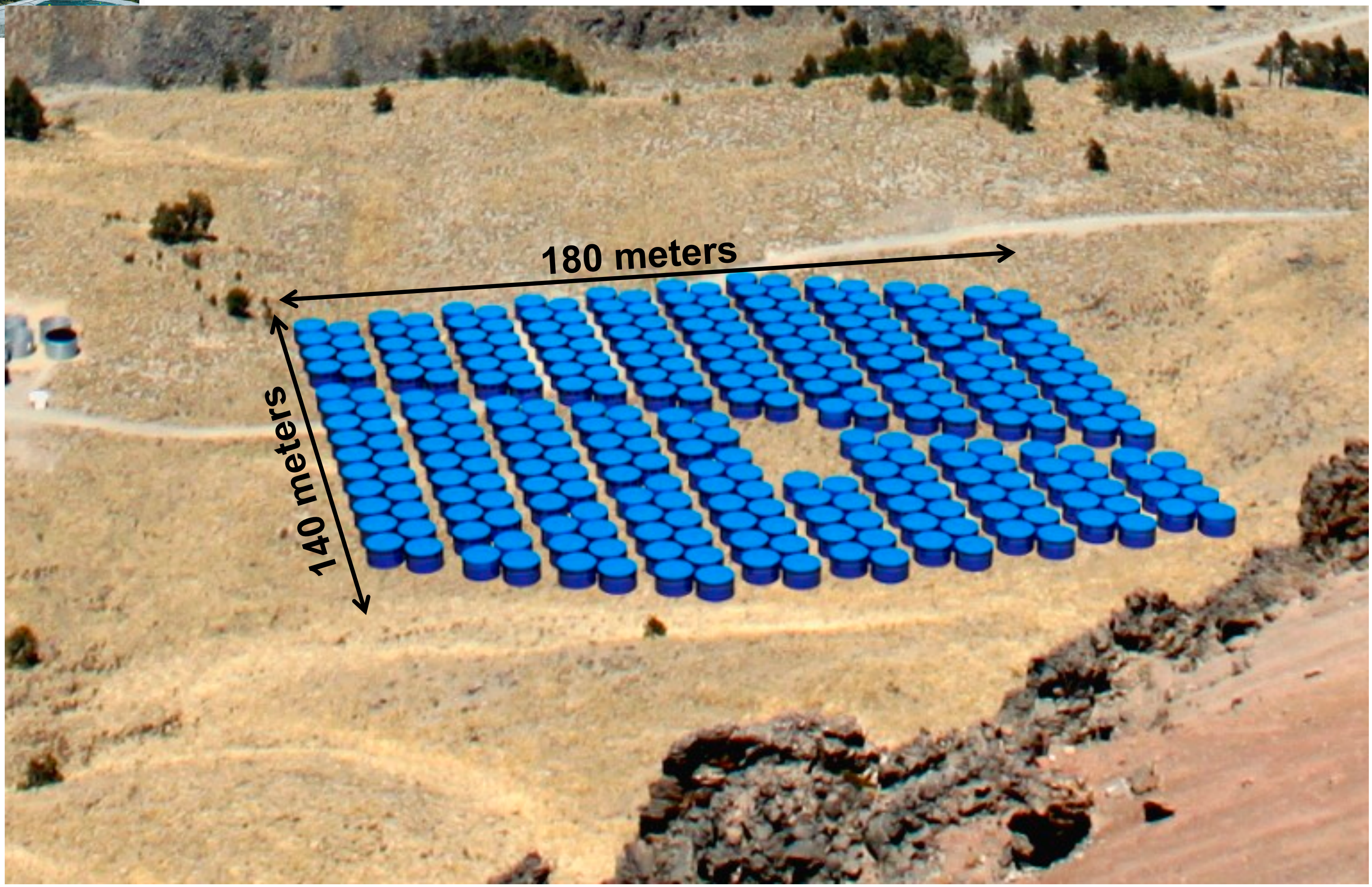
- 4100 m (13,500’) above sea level
- Latitude of 19 deg N
- Temperature 2-5^{o}C
- Existing Infrastructure
  - 1 km from >$100M US/Mexico Large Millimeter Telescope
  - Power, Internet, Roads

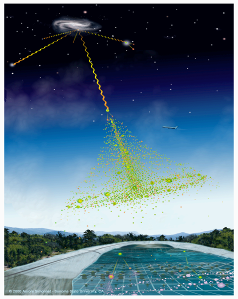
Pico de Orizaba
5600 m (18,500’)



HAWC Design

300 – 24’ diameter water tanks



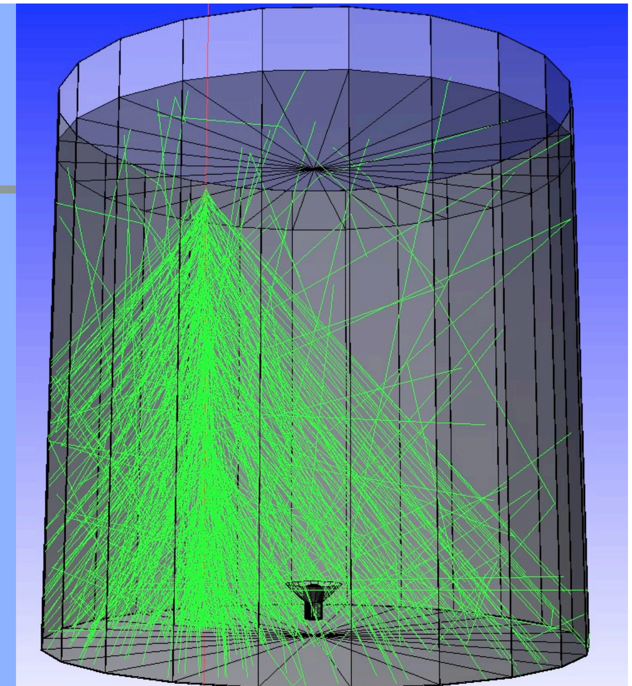


Tanks vs Pond

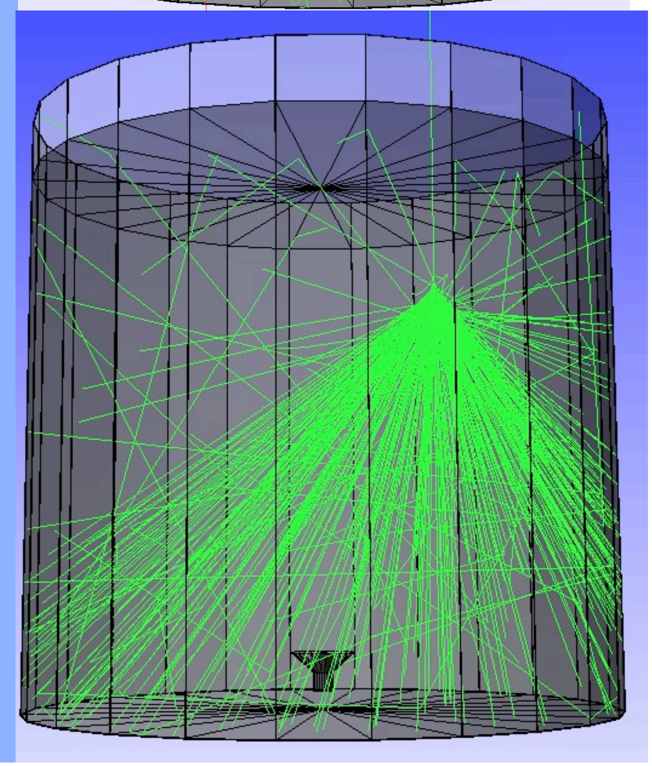
- Less expensive
- Build incrementally
  - Develop & debug as we are building
  - Within 2 yrs HAWC will have 4x Milagro sensitivity
- Expandable & upgradeable

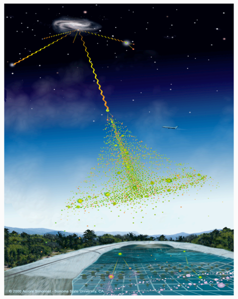
GEANT4 Simulation

Muon (thinned 1/50) produces up to 100s of pes depending on impact parameter

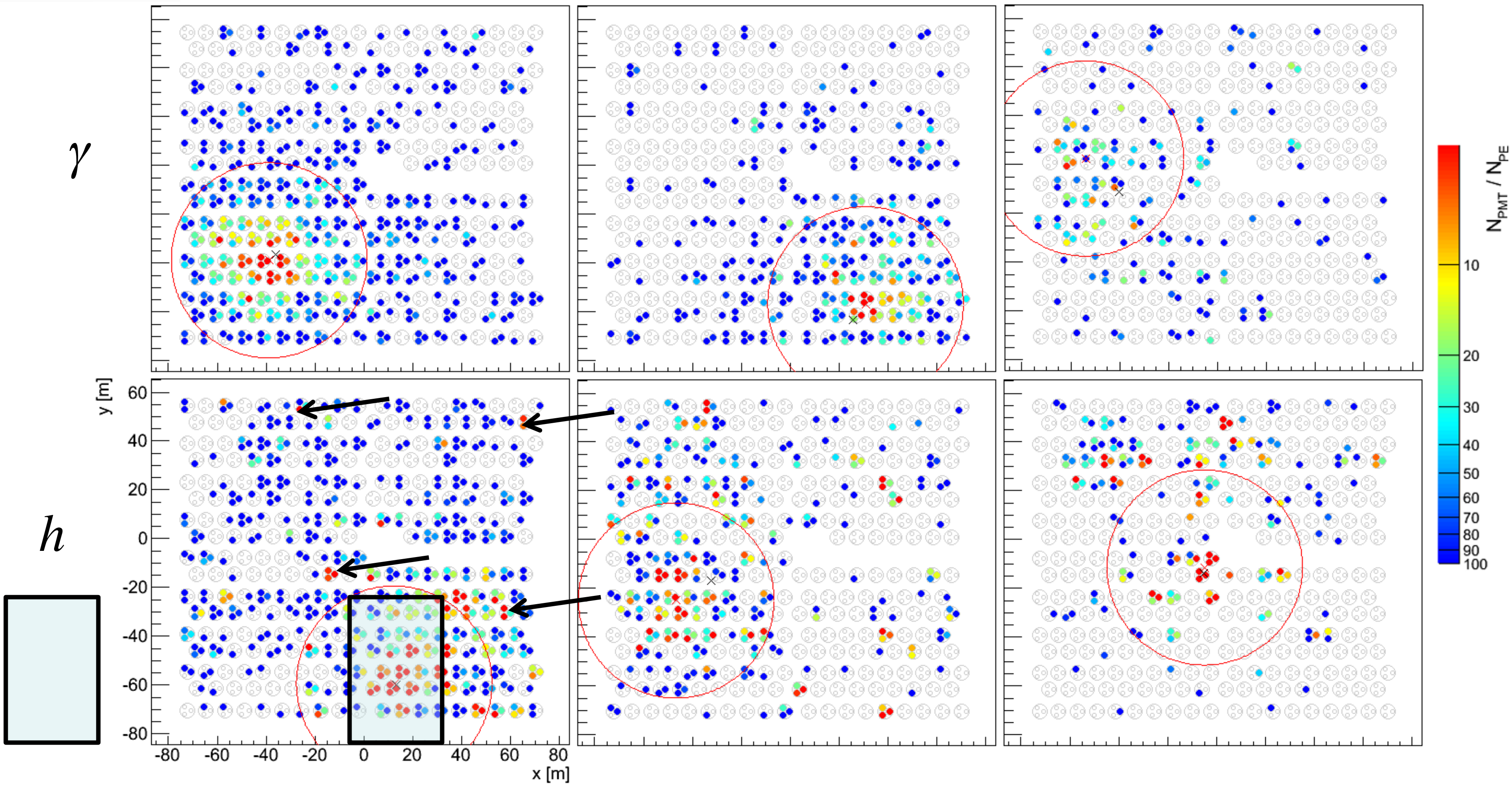


100 MeV γ-ray (thinned 1/200) produces 1pe/ 60 MeV *independent* of impact parameter

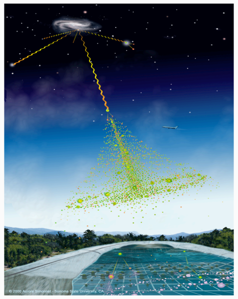




HAWC Gamma Hadron Separation

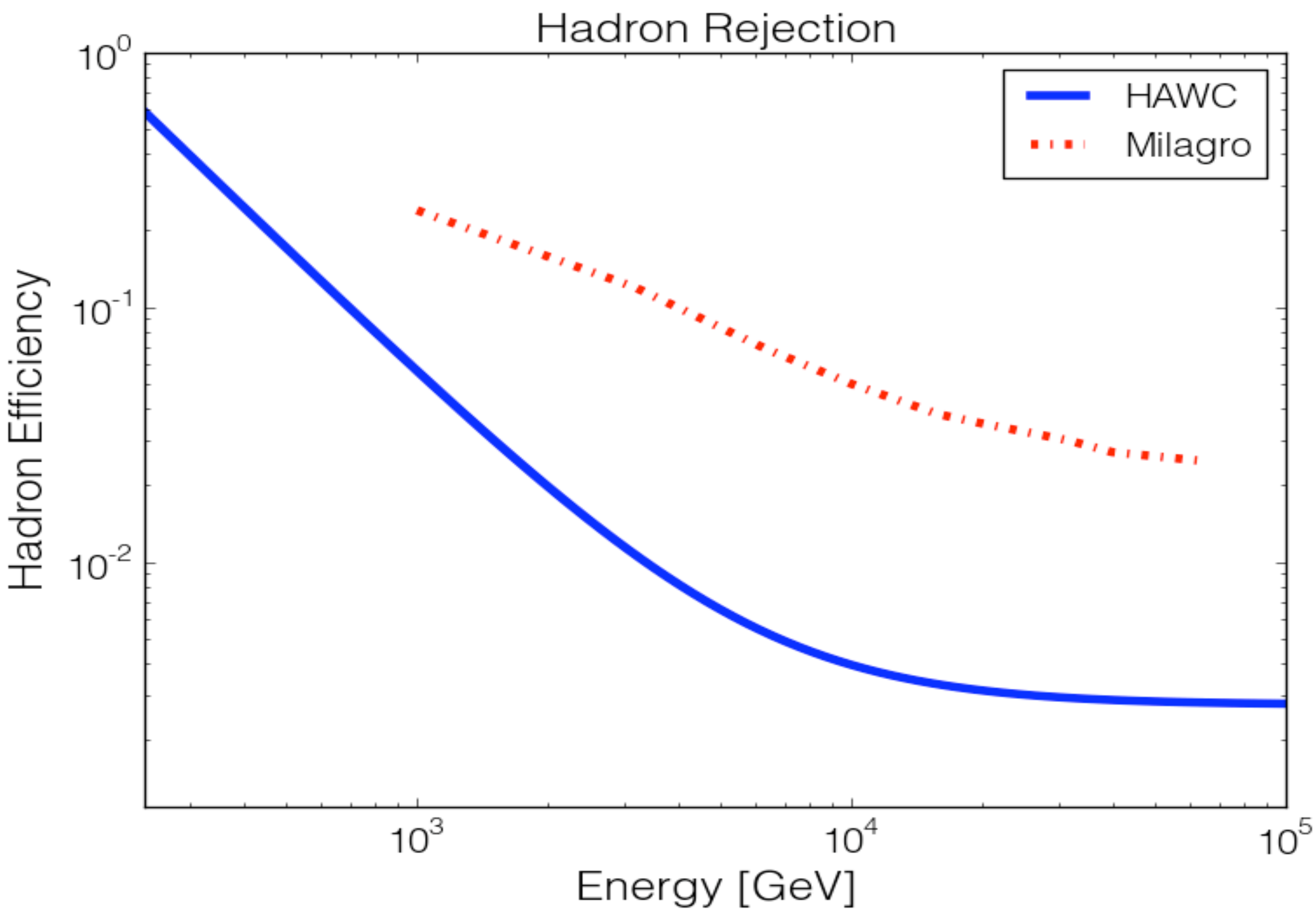


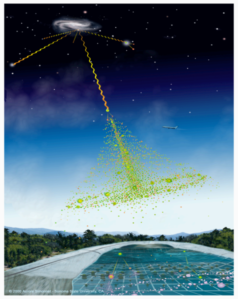
Play the game at http://www.hawc-observatory.org/observatory/ghsep.php



HAWC Simulated Performance vs Milagro

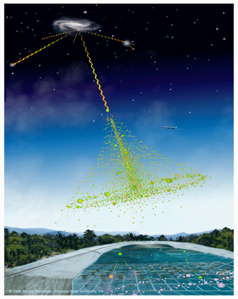
Background Rejection Efficiency (while maintaining 50% of gammas) improves especially at high



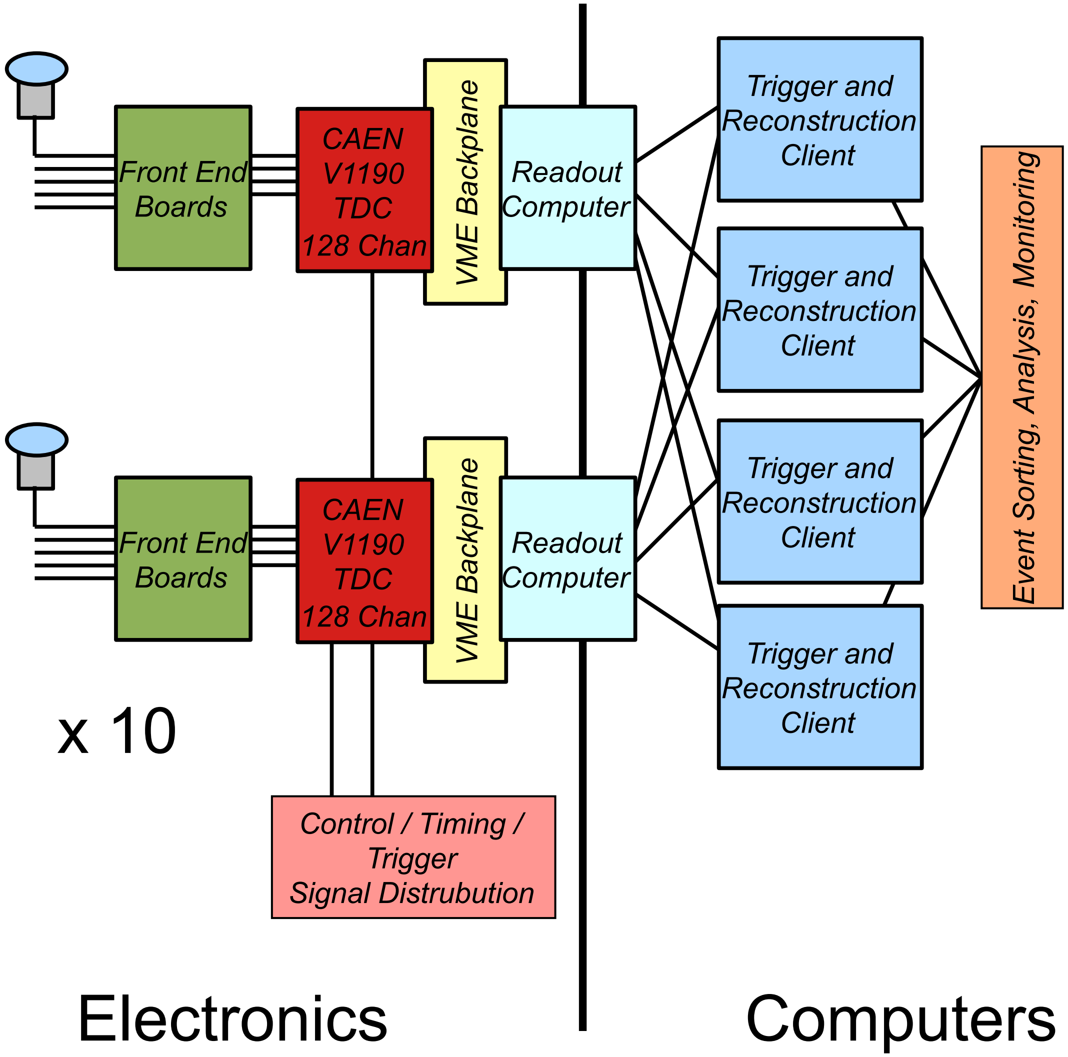


300 Water Cherenkov Detectors (WCDs) each containing 4 sensitive photodetectors.

The 900 Photomultiplier tubes from Milagro are being refurbished and 300 new tubes have been procured.



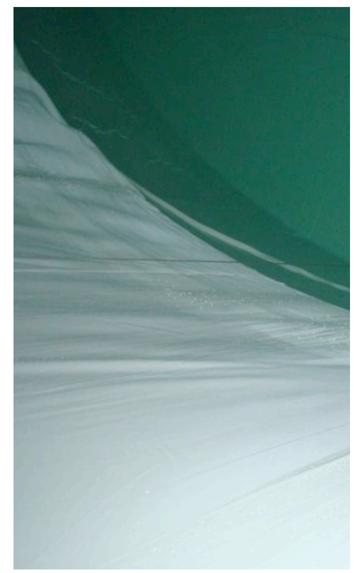
500 MB/sec data acquisition system

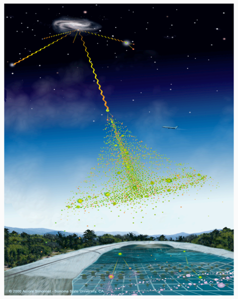


Raw data rate is
500 MB/sec
= 40 TB/day
= 15 PB/year

So we process and compress data to 20MB/sec within 1 day to create dataset of 3 PB after 5 years of operation

Commercial Water Storage Solution

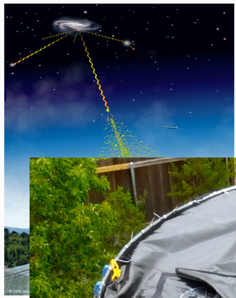




Light-tight Bladder

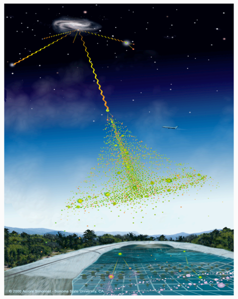
Made by Colorado State University.

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



Full size prototype in US

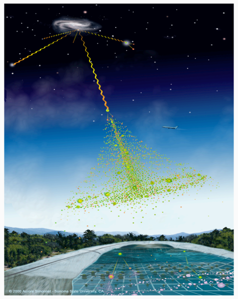
First deployed in Austin TX, but now located at Colorado State University, Fort Collins where we are testing HAWC calibration system and new installation techniques.



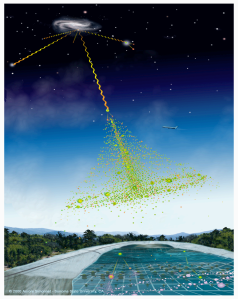
HAWC Construction in Mexico

Verification and Measuring of Observatory Systems (VAMOS) Prototype Array

First 7 full size water Cherenkov detectors at HAWC site July 2011

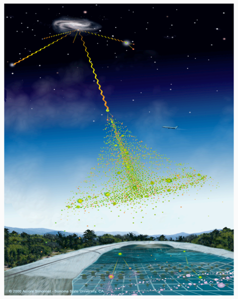



HAWC
VAMOS



HAWC Construction underway

- Funding of 12M USD split between NSF, DOE, and CONACYT began Feb 2011
- 30 of 300 Water Cherenkov Detectors to be installed Sept 2012
- 100 will be continuously operating August 2013 (with 5 x sensitivity of Milagro)
- Construction of 300 should be completed in August 2014 (with 15 x sensitivity of Milagro)



HAWC Science Objectives

- Constrain the origin of cosmic rays via HAWC's observations of γ-rays up to 100 TeV from discrete sources and the Galactic plane.
- Probe particle acceleration in extreme magnetic and gravitational fields via HAWC's observations of transient TeV sources, such as gamma ray bursts and supermassive black holes.
- Explore new TeV physics via HAWC's unbiased sky survey with a detection threshold of ~30 mCrab in two years.