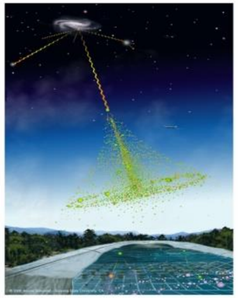


Imaging the Universe in a Big Bucket of Water
Results from Milagro
Prospects for HAWC

Jim Linnemann

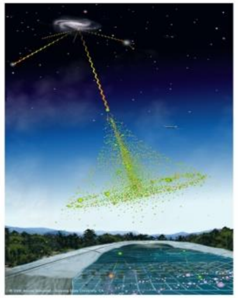
Michigan State University

AlbaNova & Nordita Colloquium

June 10, 2010

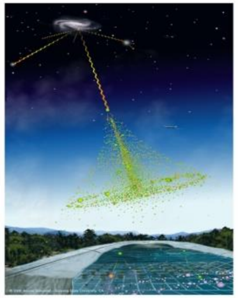
Outline:

High Energy Particle Astrophysics
Gamma Ray Observatories
Milagro Observations
High Altitude Water Cherenkov (HAWC) future



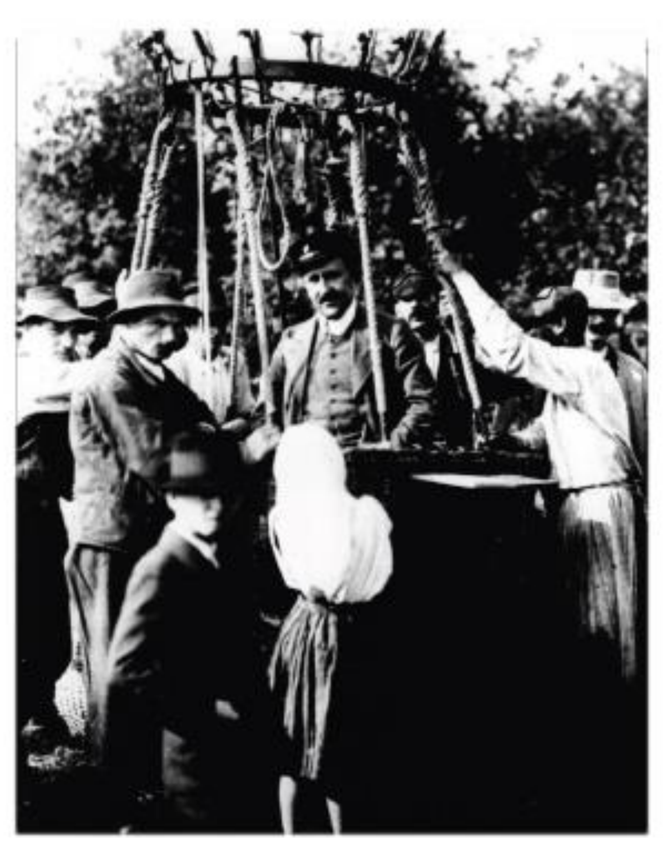
The Mystery of the Leaking Electroscope

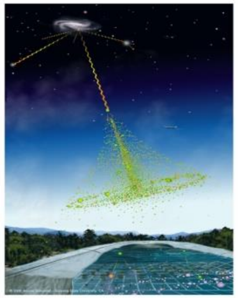
- Electroscopes measure static electricity: repulsion of like charges
- But they always discharge
- Why? What conducting medium carries away charge?
- How would you study it?
- Is it worse in a mine (thorium, radium)
- Does it get better farther away from the earth's surface?



Cosmic Rays Revealed

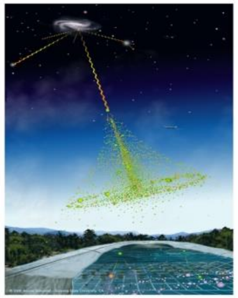
- In 1911-12 Victor Hess settled the question (Nobel '36)
- He measured rate of discharge in an electroscope in a balloon, ascending to 5000 meters
- The discharge got *faster* the further away from Earth
  - Not just decays on earth
  - Radiation from the cosmos
  - More evident outside shelter of earth's atmosphere





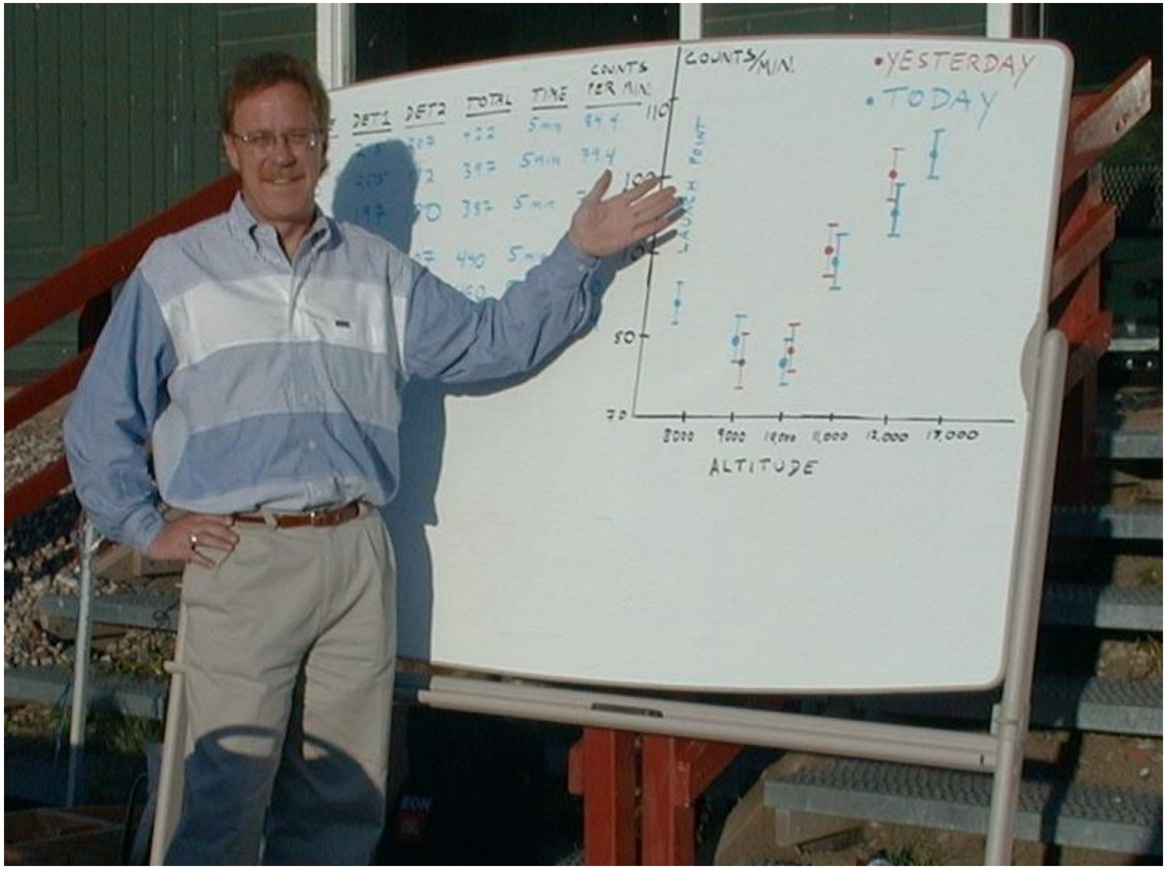
A Reprise in Aspen, 2001 (90 years later)

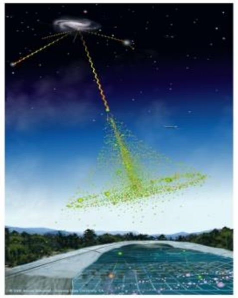
Jeff Wilkes as Victor Hess



Hey, somebody had to analyze the data!

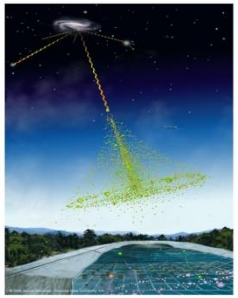
Note the altitude dependence





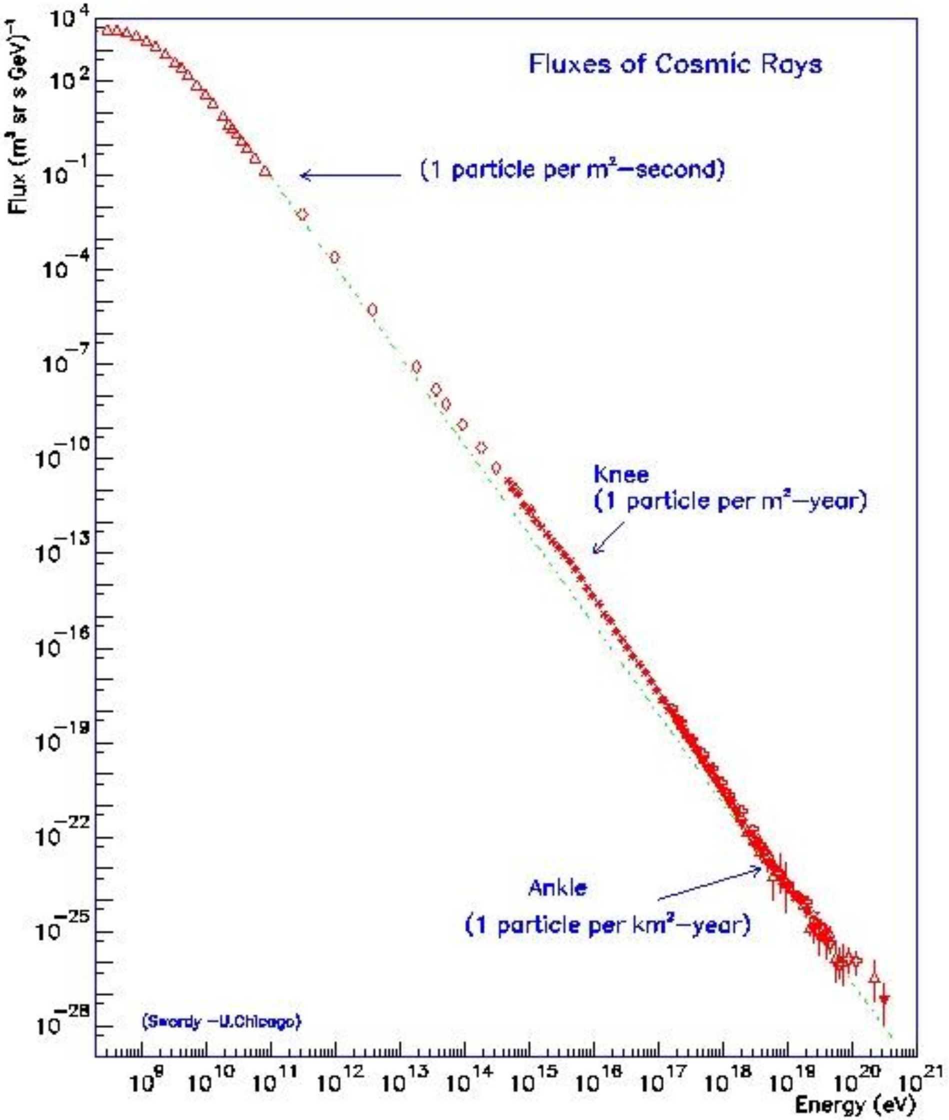
Other surprising effects of cosmic rays

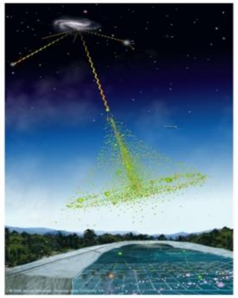
- The origins of High Energy Physics
  - Discovery of positron (antimatter), muon, pion, kaon
  - *Still* higher energy than any terrestrial accelerator
- One source of background genetic mutation rate
- Carbon 14 production
- Computer memory single bit soft errors
- Could limit manned Mars missions
- *May* be involved in nucleation of cloud droplets
- *May* be involved in forming ionized channels for lightning
- Significant in energy content of interstellar medium
  - Approximate equipartition with B fields, starlight



High Energy Particle Astrophysics

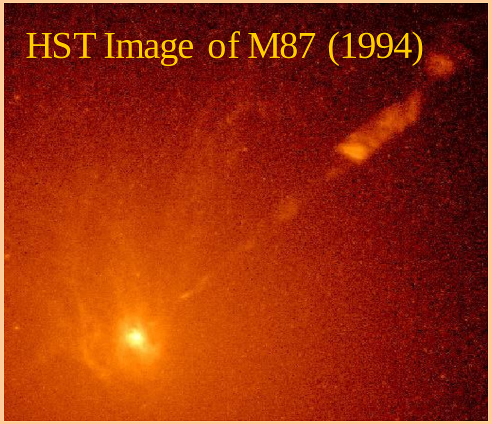
- **What do we know?**
  - Nature accelerates particles to >10^{20} eV
  - Gamma-ray sources accelerate particles to >10^{14} eV
- **What do we want to know?**
  - What astrophysical sources accelerate particles?
  - How do astrophysical sources accelerate particles?
  - What new high energy physics can we learn from astrophysics?
  - **γ rays point to their source (astronomy)**



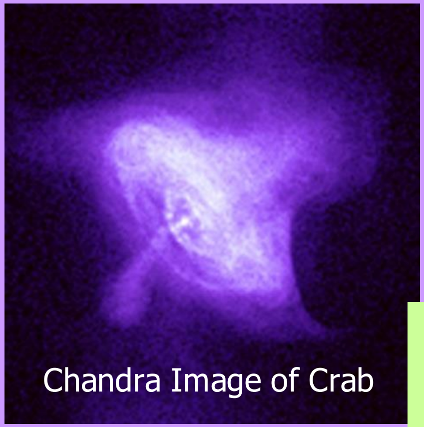


Producing Gamma Rays: Astrophysical Particle Accelerators

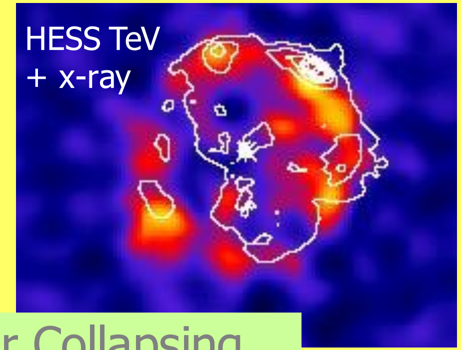
Black Hole producing relativistic jet of particles



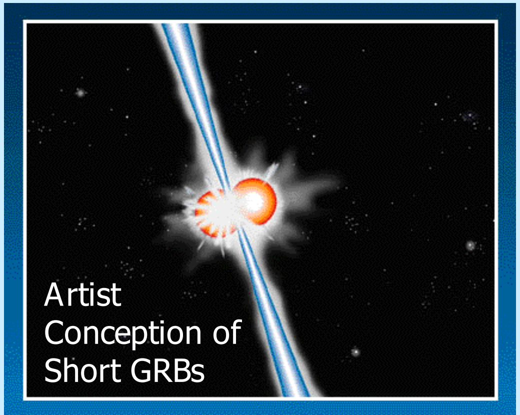
Spinning Neutron Star powering a relativistic wind



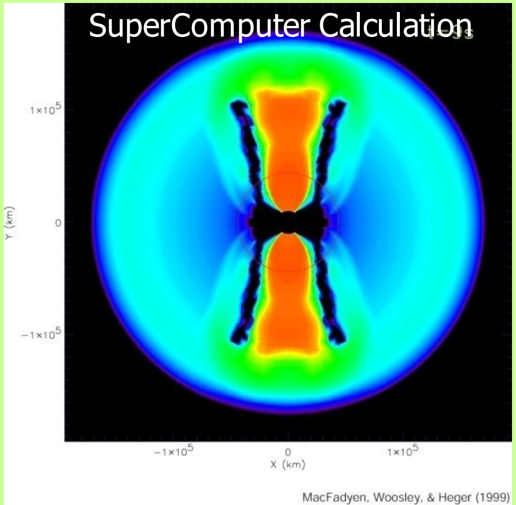
TeV image of Vela Jr. Supernova Remnant

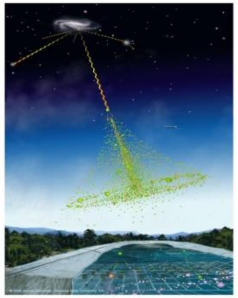


Binary Neutron Star Coalescing



Massive Star Collapsing into a Black Hole





Origins of Cosmic Rays: still not understood

Low E: Sun

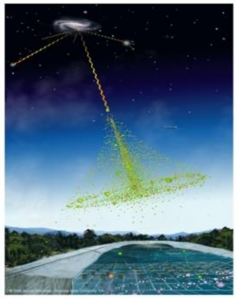
Galactic (up to knee?):

- Supernovae
  - Near neutron star: pulsed
  - No pulsing beyond ~ 100 GeV: nebula?
- Are electrons, or protons, the primaries?
  - $\pi^\circ \rightarrow \gamma\gamma$ if hadronic; look for ν coincidences with Ice Cube

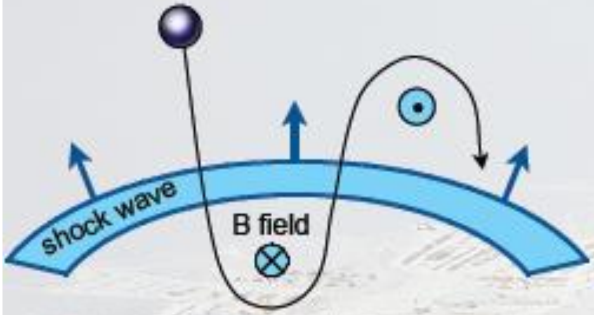
Extragalactic (highest energies? NIMBY)

- Composition change? (p/Fe)
- Active Galactic Nuclei
- Gamma Ray Bursts
- ???

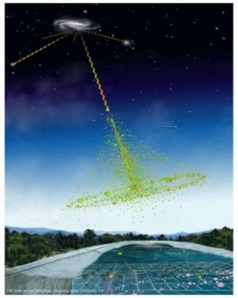
Attack by collecting sources: angular associations, shape, energy spectra, multiwavelength observations



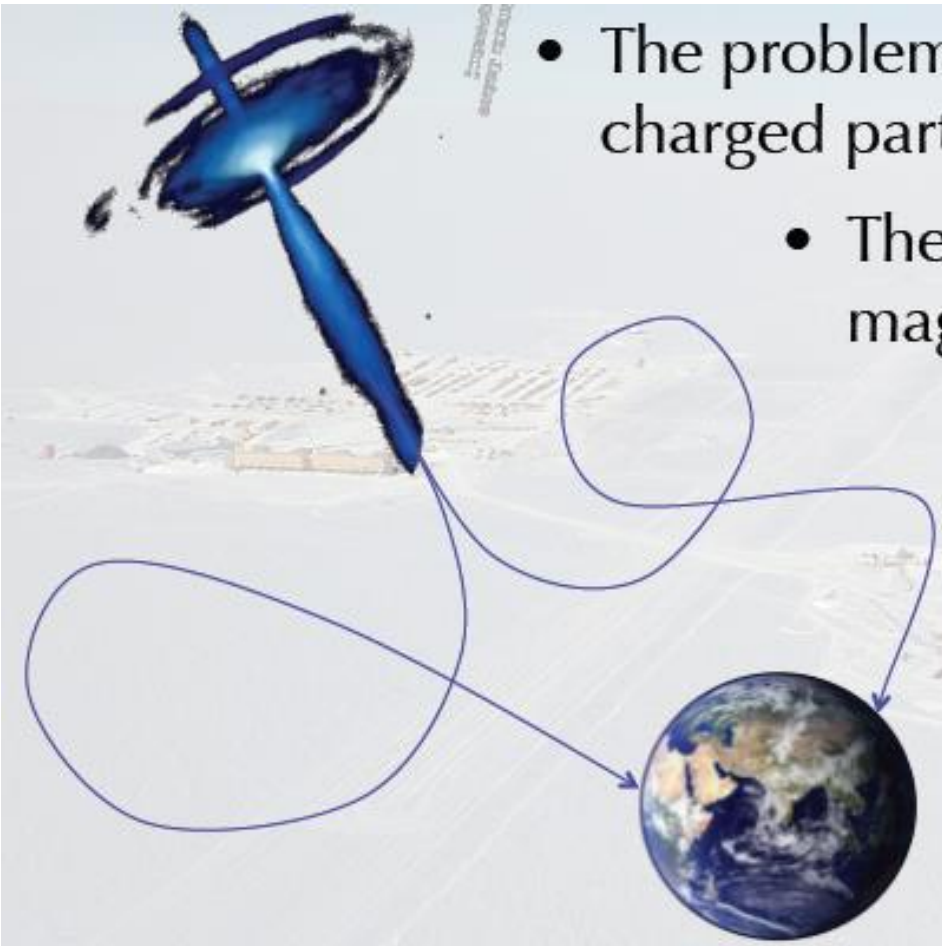
How do Cosmic Rays Get Accelerated?



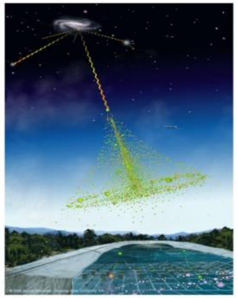
- General picture of particle acceleration by electromagnetic shock waves (Fermi acceleration)
  - Details not fully understood: complex MHD behavior
  - Particles gain energy scattering off relativistic shock wave
  - Probability to escape from the shock, depending on energy
  - Leads to a power law spectrum, $\frac{dN}{dE} \propto E^{-\Gamma}$
    - Γ the spectral index
    - For efficient acceleration, $\Gamma = 2$



Cosmic Rays Take a confused route!

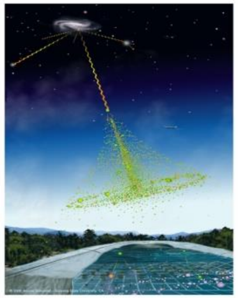


- The problem: cosmic rays are charged particles
  - The universe is filled with magnetic fields
    - Arrival direction is scrambled by random magnetic deflections
      - Except at the *very* highest energies (above ~10^{19} eV)



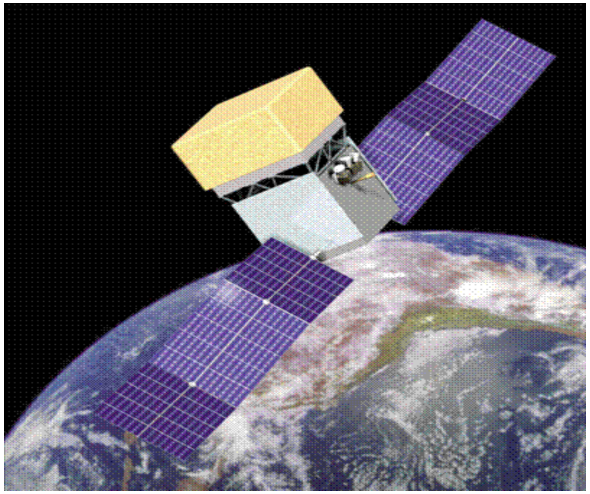
But there are also neutral cosmic rays

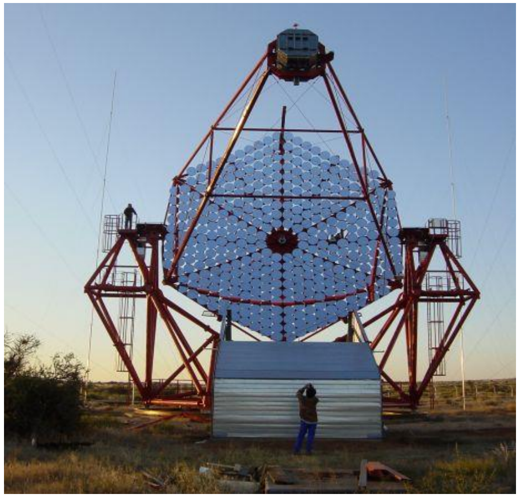
- Gamma rays   (very high energy photons)
- Because they are neutral, you can do astronomy with them
- That's because they travel in straight lines from their source
- Just like visible light reveals its sources to an optical telescope
- Neutrinos are also neutral, but harder to detect…
  - IceCube at the south pole…looks for sources in N hemisphere
- Neutrons exist also, but decay before arrival…



Comparison of Gamma-Ray Detectors

Low Energy Threshold	High Sensitivity	Large Aperture/High Duty Cycle
EGRET/Fermi LAT (May 08)	HESS, MAGIC, VERITAS	Milagro, Tibet, ARGO, HAWC





Space-based (Small Area)

"Background Free"

Large Duty Cycle/Large Aperture

- **Sky Survey (< 10 GeV)**
- **AGN Physics**
- **Transients (GRBs) < 100 GeV**

Large Effective Area

Excellent Background Rejection

Low Duty Cycle/Small Aperture

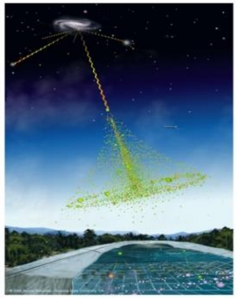
- **High Resolution Energy Spectra**
- **Studies of known sources**
- **Surveys of limited regions of sky**

Moderate Area

Good Background Rejection

Large Duty Cycle/Large Aperture

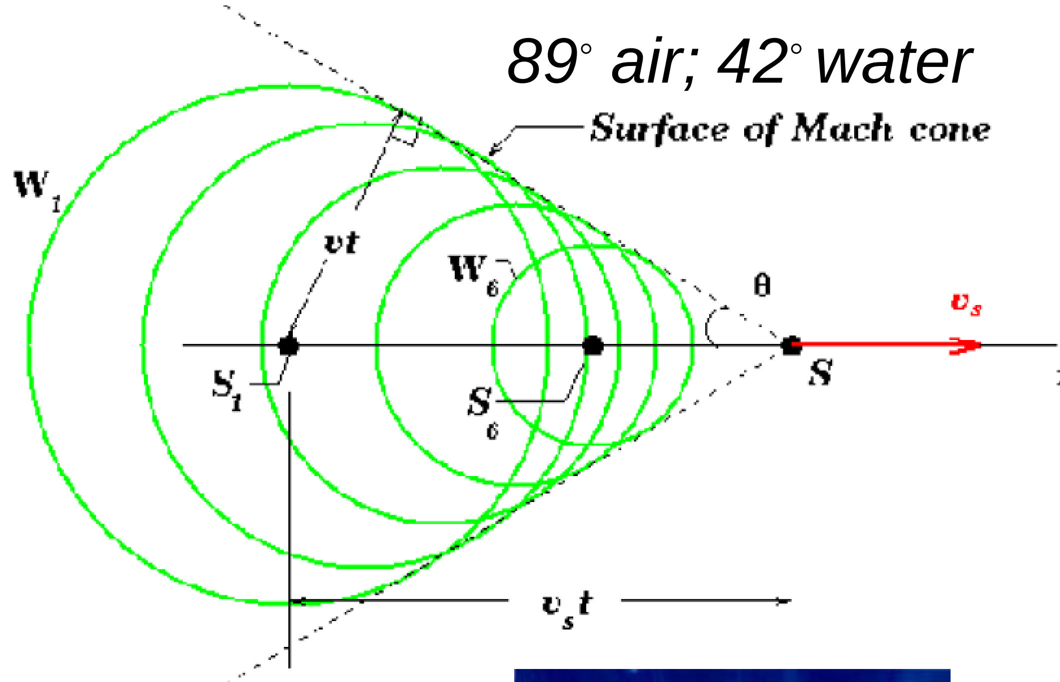
- **Unbiased Sky Survey**
- **Extended sources**
- **Transients (GRB's)**
- **Solar physics/space weather**

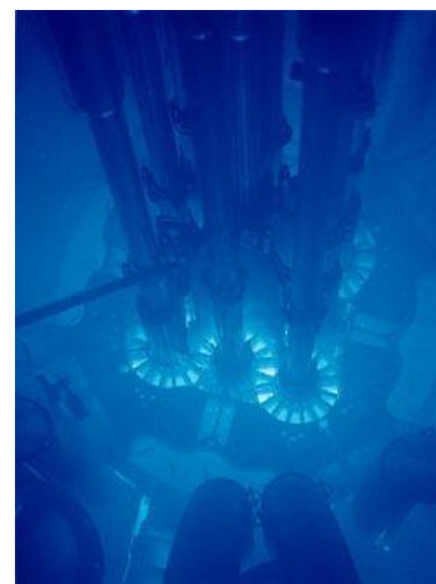


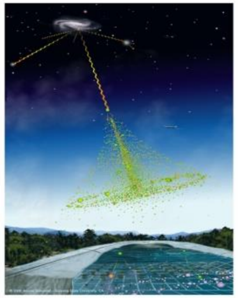
Cherenkov Radiation

- Source object moves to right at velocity v_S
- If source emits waves
  - Light or sound
- And it's moving faster than waves travel in the medium, a shock wave forms
- It travels perpendicular to the surface of the Mach cone
- Sonic boom, or Cherenkov light!

89° air; 42° water





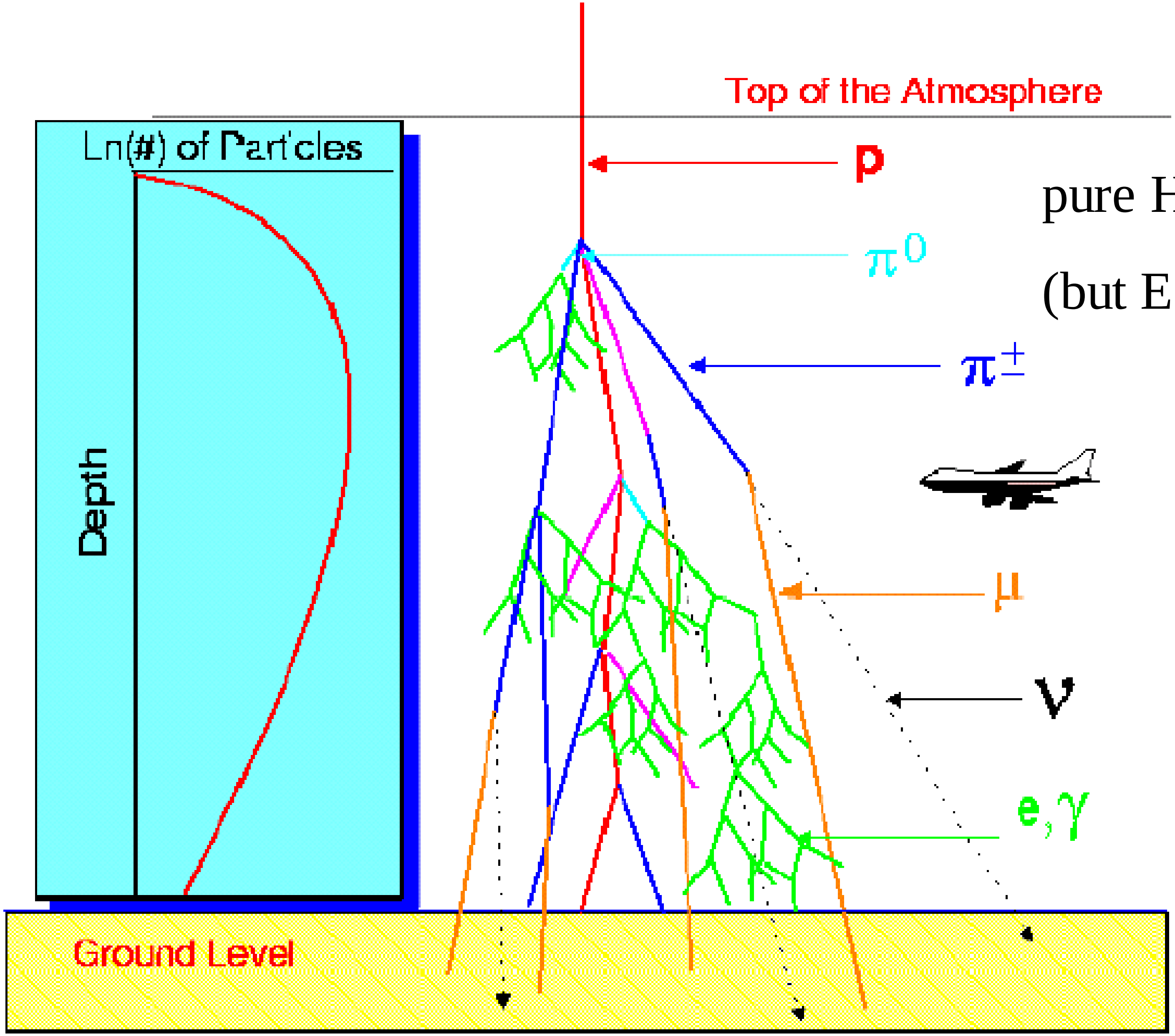


Atmospheric as Cosmic Ray Calorimeter

(Radiation and Interaction Lengths); atmosphere depth = Do $e^{-h/s}$; pressure = matter/area above your height

Check tire pressure !

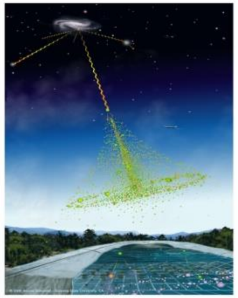
				Radiation and Interaction Lengths of Atmospheric Overbur			
				<--------------------units: **g/cm^2**-------------------->			
ATMOSPHERE	height	height			X0	Int Len	Coll Len
site	(m) a.s.l.	(m) a.s.l.	atmos	depth	36.66	90	62
Sea Level	0	0	100%	1030	28.1	11.4	16.6
Dugway (HighRes)	1372	4500	84%	870	23.7	9.7	14.0
Jemez Mtns (Milagro)	2630	8629	73%	750	20.5	8.3	12.1
Cerro Pachon(Soar)	2700	8858	72%	740	20.2	8.2	11.9
HAWC (Sierra Negra)	4100	13451	61%	623	17.0	6.9	10.0
Mauna Kea	4200	13780	60%	615	16.8	6.8	9.9
Tibet/Argo arrays	4300	14108	59%	606	16.5	6.7	9.8
LMT (Sierra Negra)	4600	15092	57%	586			
	5000	16404	54%	558	15.2	6.2	9.0
Cerro Toco	5600	18373	50%	518	14.1	5.8	8.4
Pico de Orizaba	5610	18406	50%	517			
Mt Everest	8848	29029	34%	348	9.5	3.9	5.6
	10000	32808	29%	302	8.2	3.4	4.9
	15000	49213	16%	164	4.5	1.8	2.6
	20000	65617	9%	89	2.4	1.0	1.4
	25000	82021	5%	48	1.3	0.5	0.8



pure HEP

(but E > ever measured)

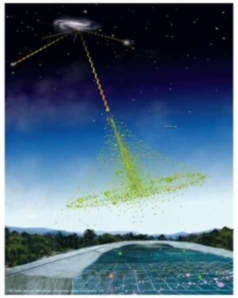
Extensive Air Showers



Jemez Mountains: rim of Valle Grande Caldera

We like volcanoes, as you will see…

The Milagro Site



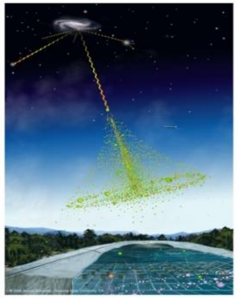
Water Cherenkov:
an Active Medium Calorimeter

WATER	atmospheres	depth	X0 36.08	Int Len 83.6	Coll Len 60.1
water: 1m	10%	100	2.8	1.2	1.7
water: 4m	39%	400	11.1	4.8	6.7
water: 5m	49%	500	13.9	6.0	8.3
water: 6m	58%	600	16.6	7.2	10.0
water: 8m	78%	800	22.2	9.6	13.3

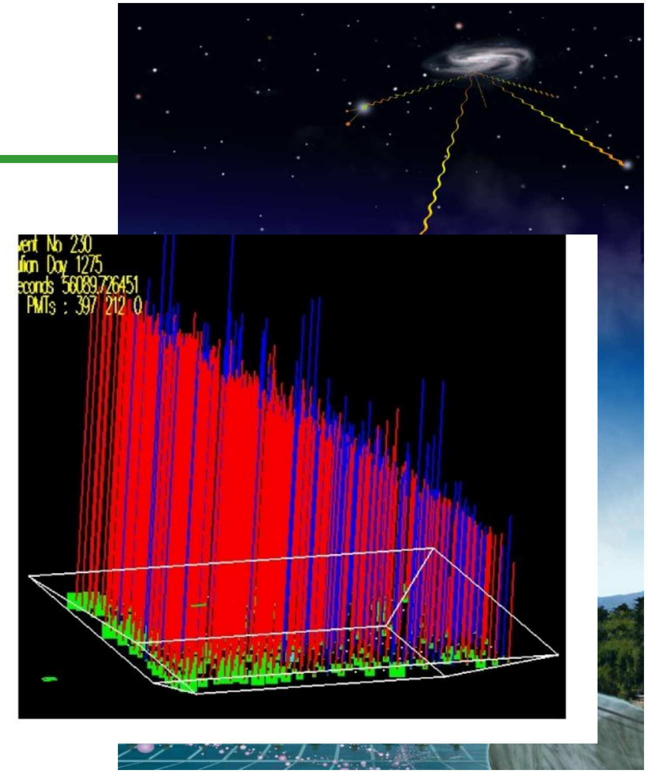
Much of EM shower in top meter or two

light: Cherenkov cone from e's

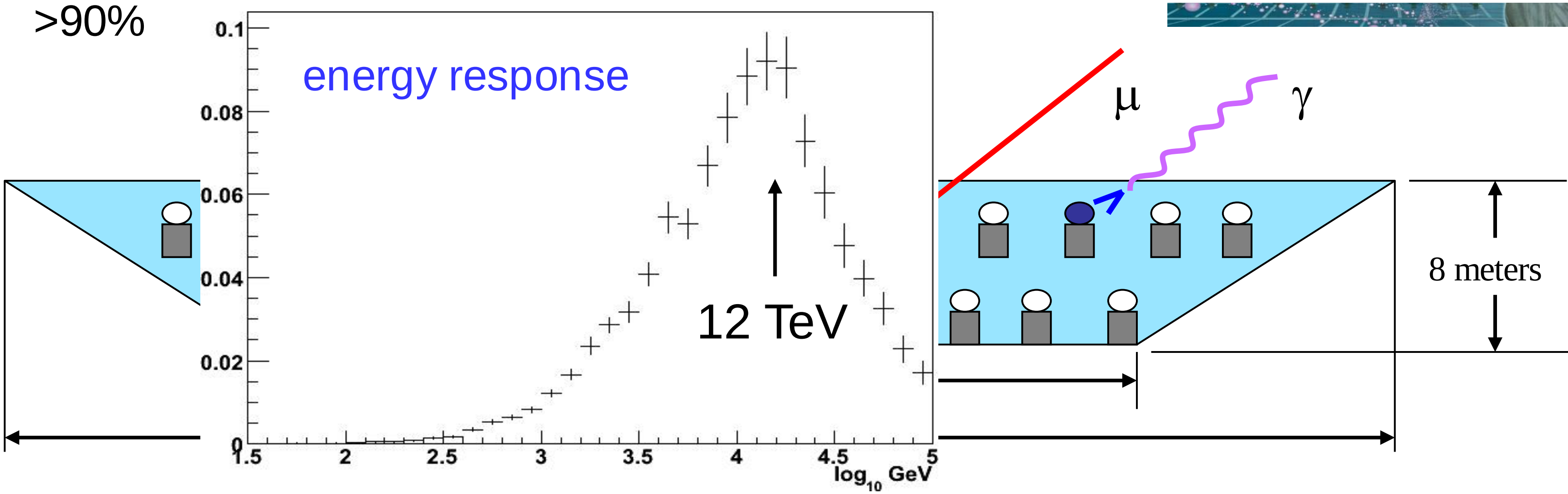
Hadrons and muons produce light nearer bottom tubes

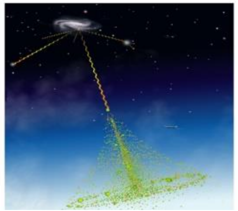


How Does Milagro Work?

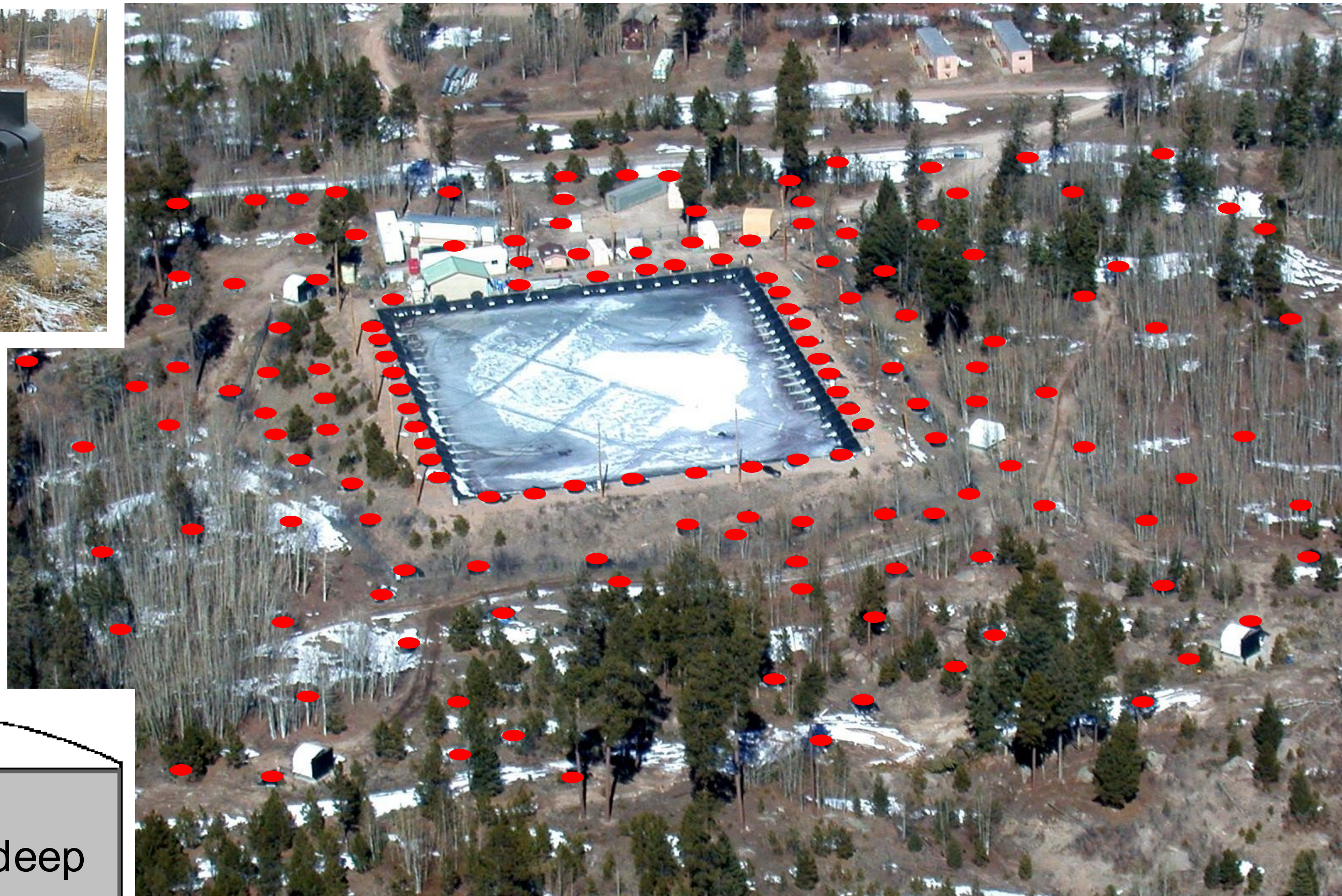


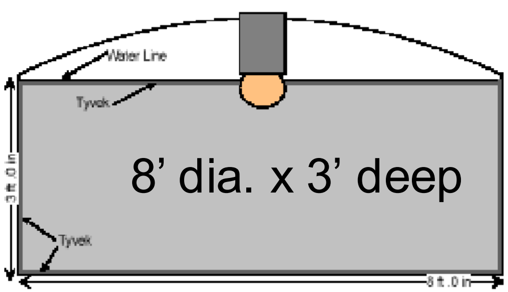
- Detect Particles in Extensive Air Showers from Cherenkov light created in 60m x 80 m x 8m pond containing filtered water
- Reconstruct shower direction to ~0.5° from the time different PMTs are hit
- 1700 Hz trigger rate mostly due to Extensive Air Showers created by cosmic rays
- Field of view is ~2 sr and the average duty factor is >90%





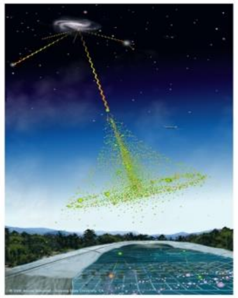
175 Outriggers: better rejection, resolution





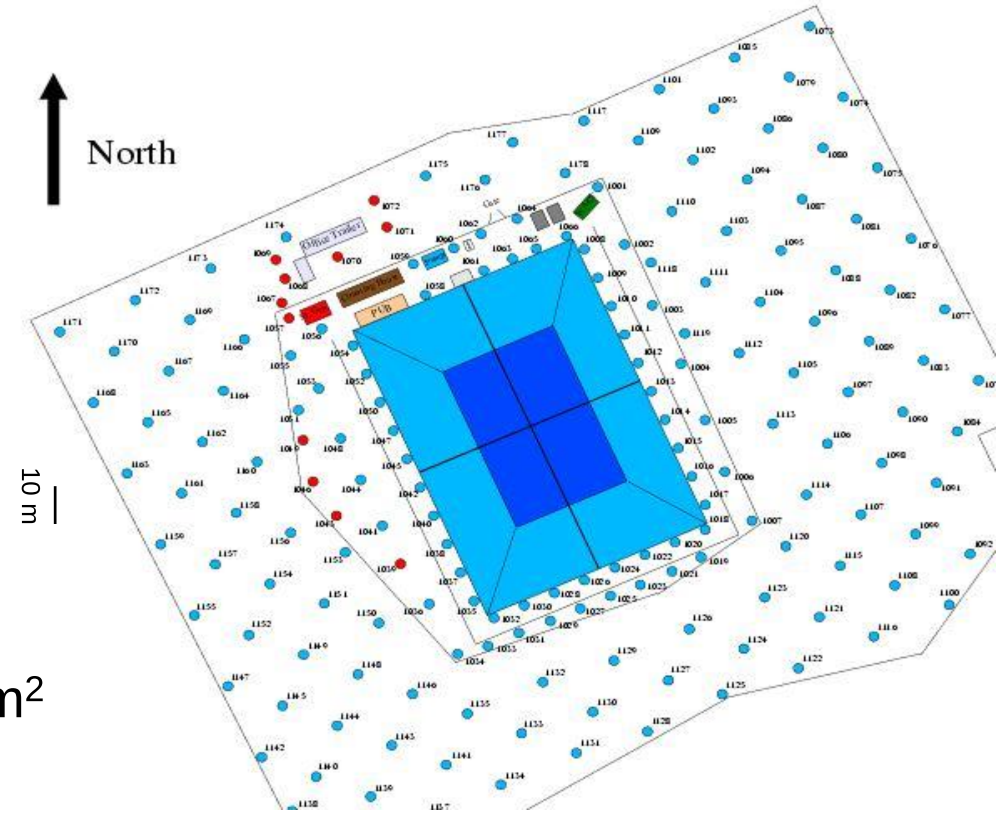
Area → Shower location → hadron rejection

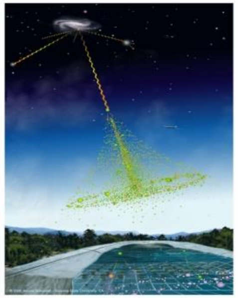
Width (lever arm) → Angular resolution



Milagro In a Nutshell

- Water Cherenkov Detector
- 2600m (8500’) elevation
- 898 photomultiplier tubes
  - 450 in top layer in pond
  - 273 in bottom layer in pond
  - 175 water tank outriggers
- Pond Area is 3600 m^2
  - Operational in January 2001
- Outrigger Array area is ~ 30000 m^2
  - Operational in June 2004
  - ~ 175 x 175 m
- Decommissioned June 2008

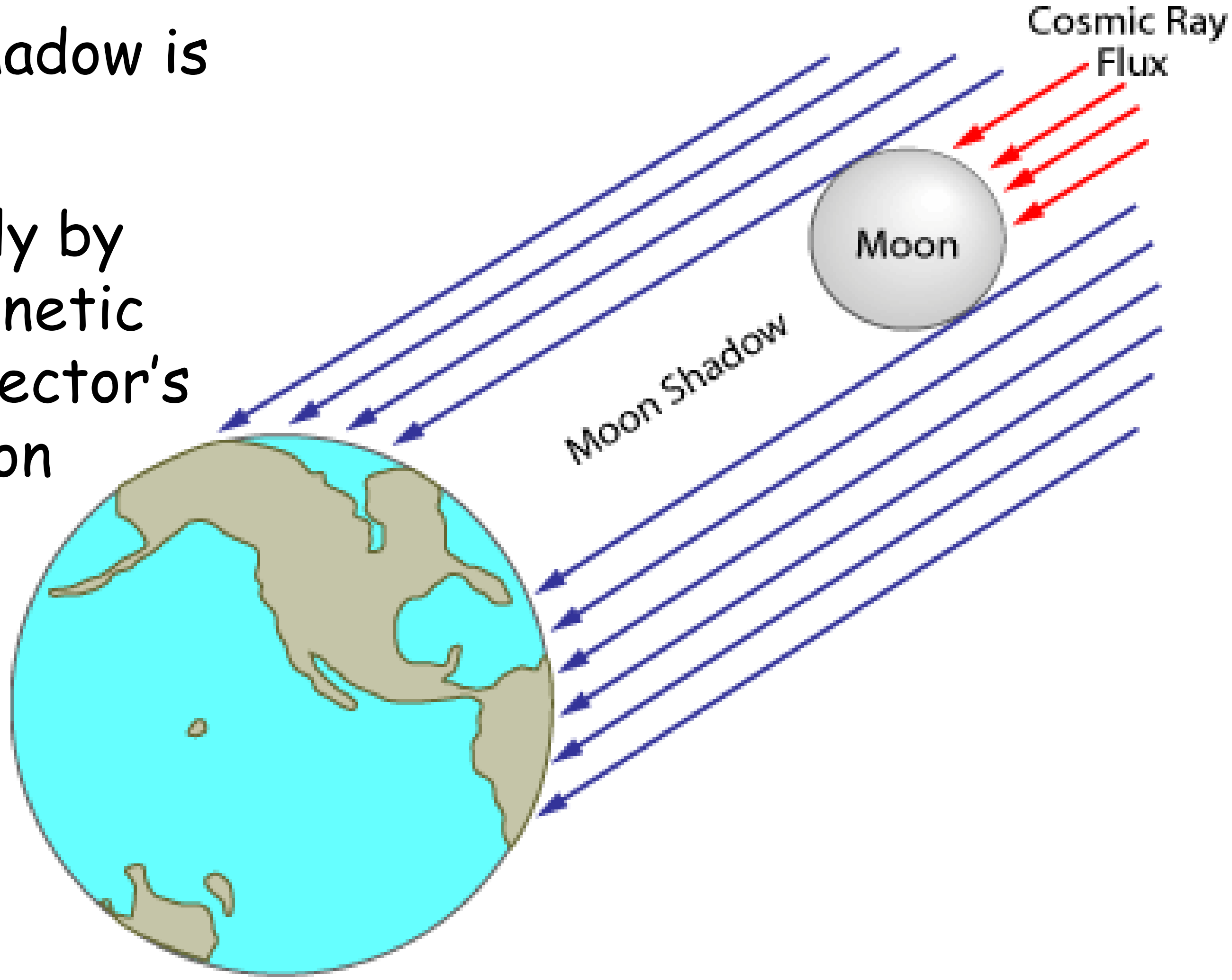


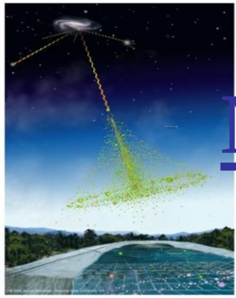


Moon Shadow seen in Cosmic Rays

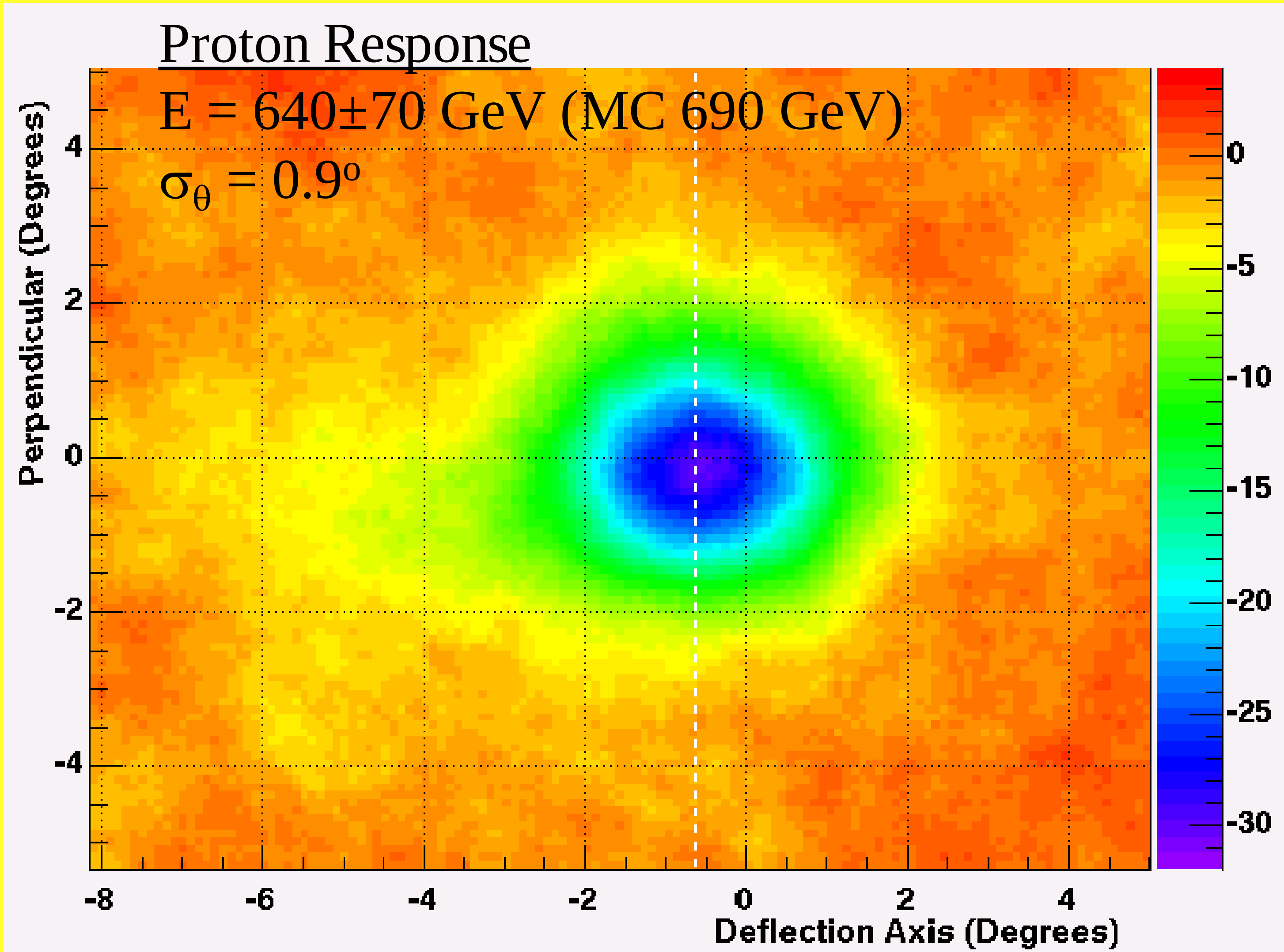
The moon's shadow is sharp:

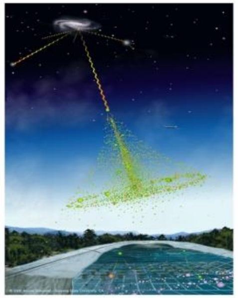
blurred only by earth's magnetic field and detector's resolution





Moon Shadow: Energy Scale Calibration





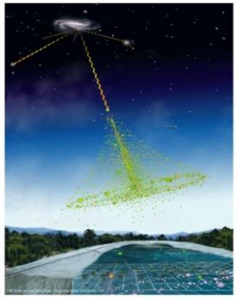
Mission Improbable

Hadronic background **~ 10^3 to 10^4** > gamma signal

On the other hand, gammas point back at the source

So one tool is angular resolution

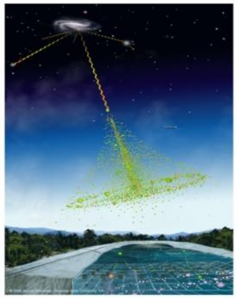
The second is seeing the difference in shower tails at ground level (20Xo or 8λ_I into the calorimeter)



Simulation of 2 TeV γ-ray in Atmosphere

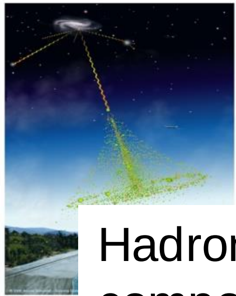
[..\Videos\GShower2TeVPart.mov](..\Videos\GShower2TeVPart.mov)

Video by Miguel F. Morales, U Santa Cruz (now U Washington)



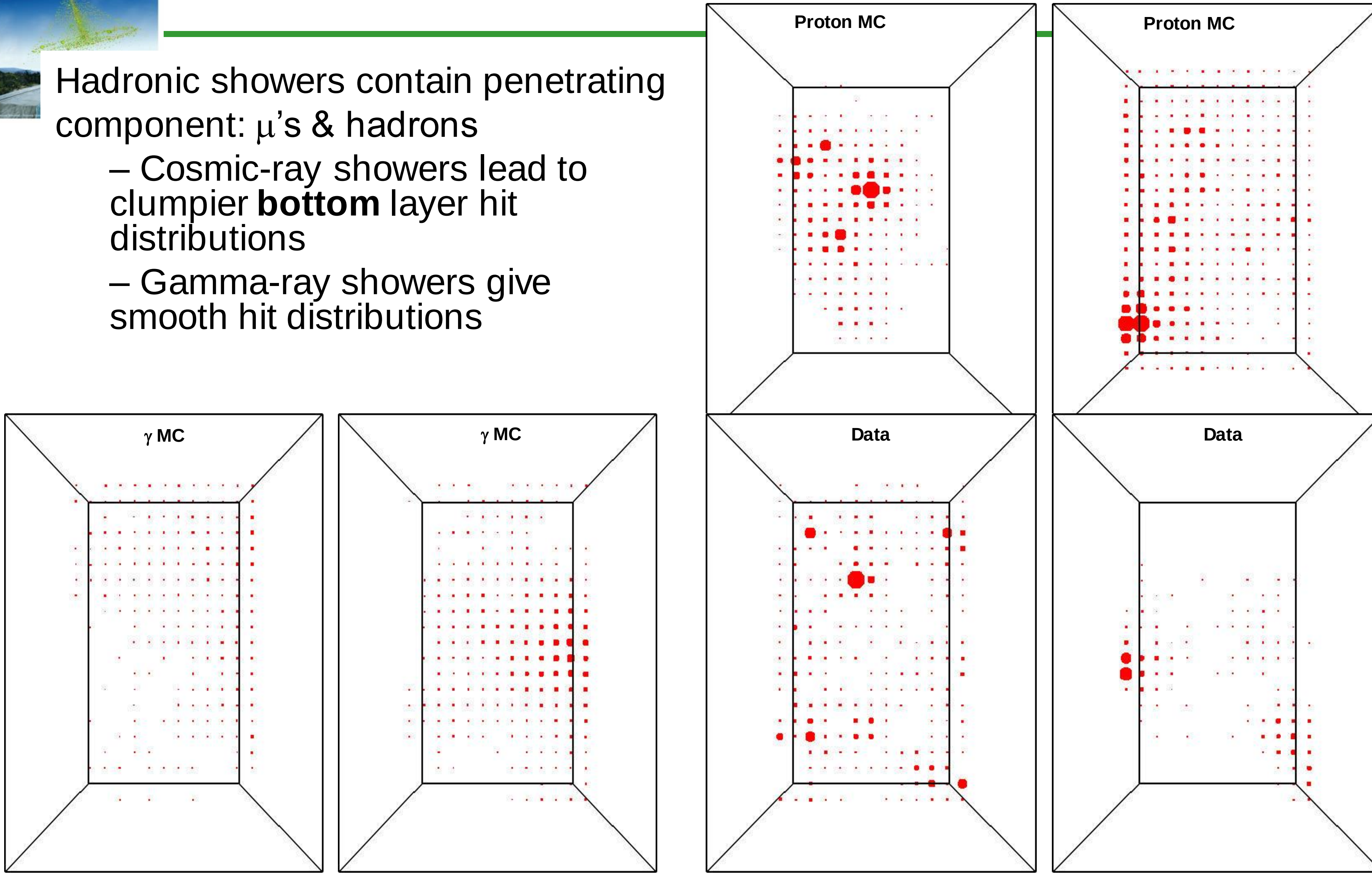
Simulation of 2 TeV Proton in Atmosphere

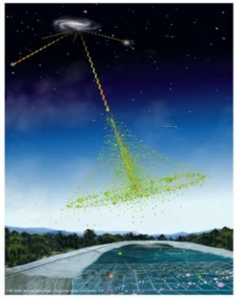
..\Videos\PShower2TeVPart.mov



Background Rejection in Milagro

- Hadronic showers contain penetrating component: μ's & hadrons
  - Cosmic-ray showers lead to clumpier **bottom** layer hit distributions
  - Gamma-ray showers give smooth hit distributions

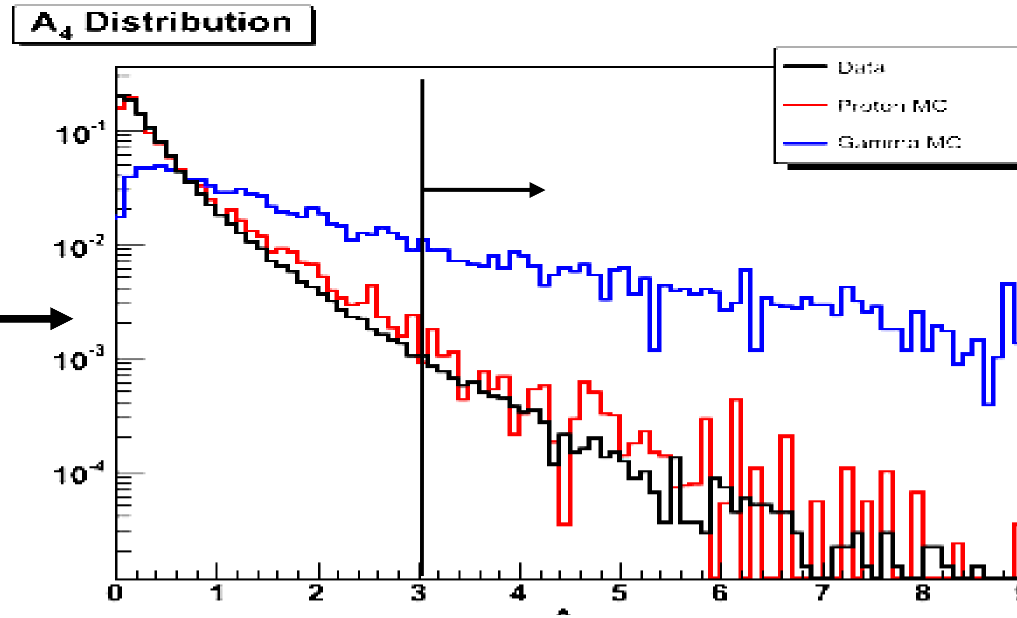




Milagro Background Rejection (Cont'd)

Background Rejection Parameter

$$A_4 = \frac{\left(fTop + fOut\right) * nFit}{mxPE}$$



mxPE: maximum # PEs in **bottom** layer PMT

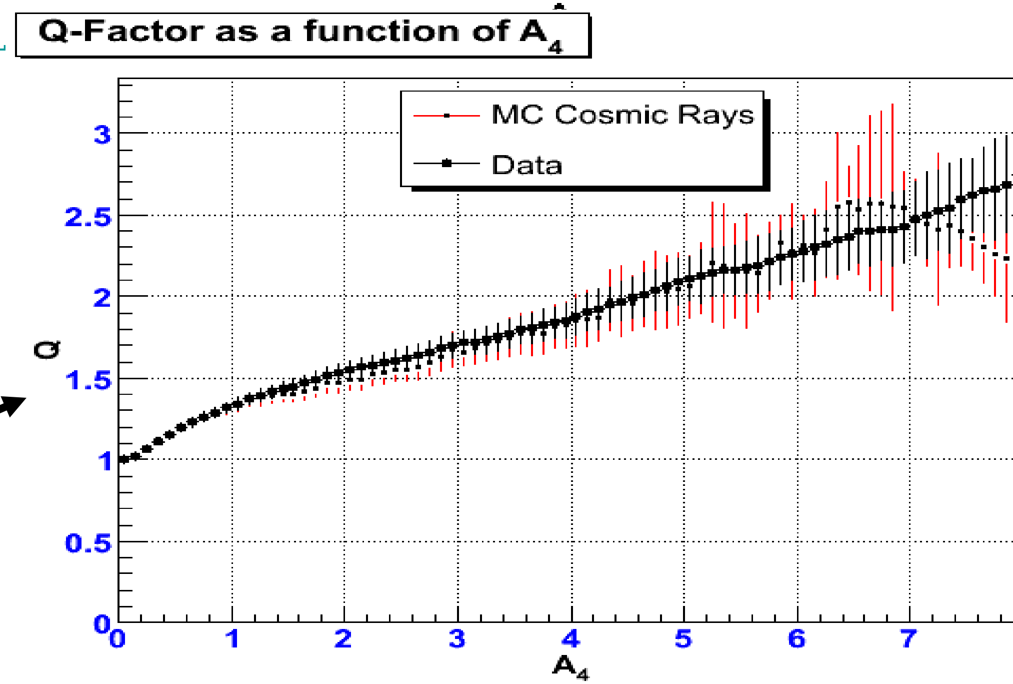
fTop: fraction of hit PMTs in **Top** layer

fOut: fraction of hit PMTs in **Outriggers**

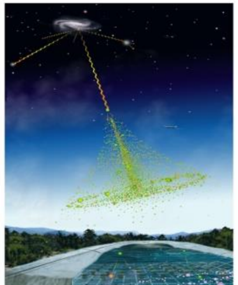
nFit: # PMTs used in the angle reconstruction

mxPE large with muon: drives A4 low for hadrons

S/B increases with increasing A_4 so analysis weights events by S/B as determined by the A_4 value of the event

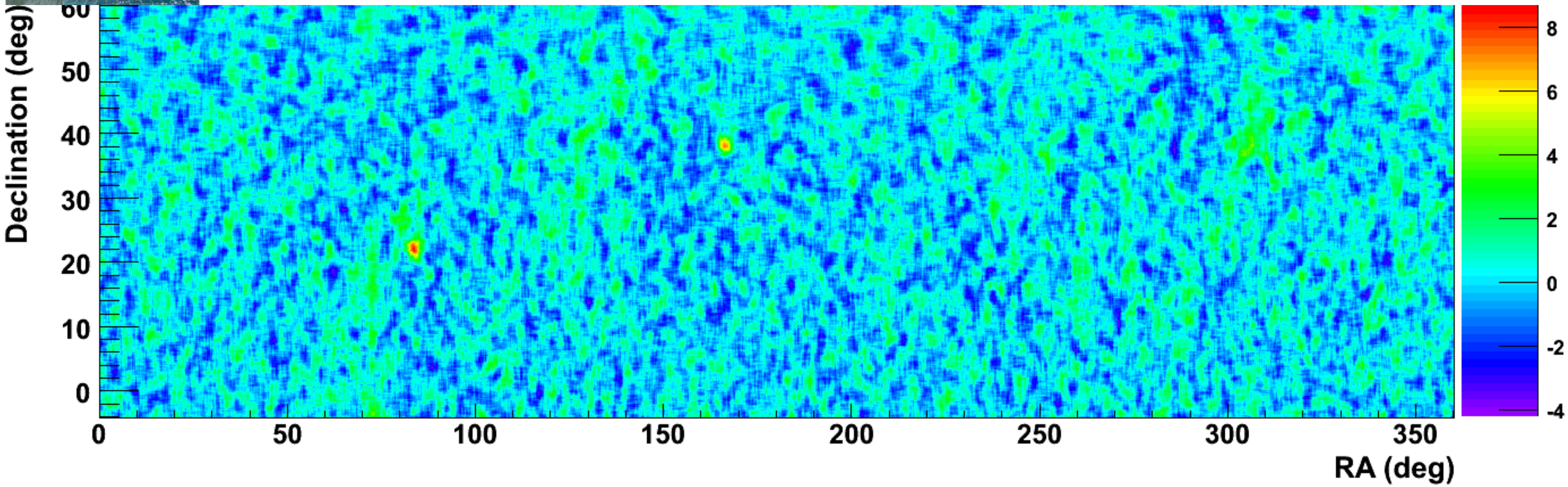


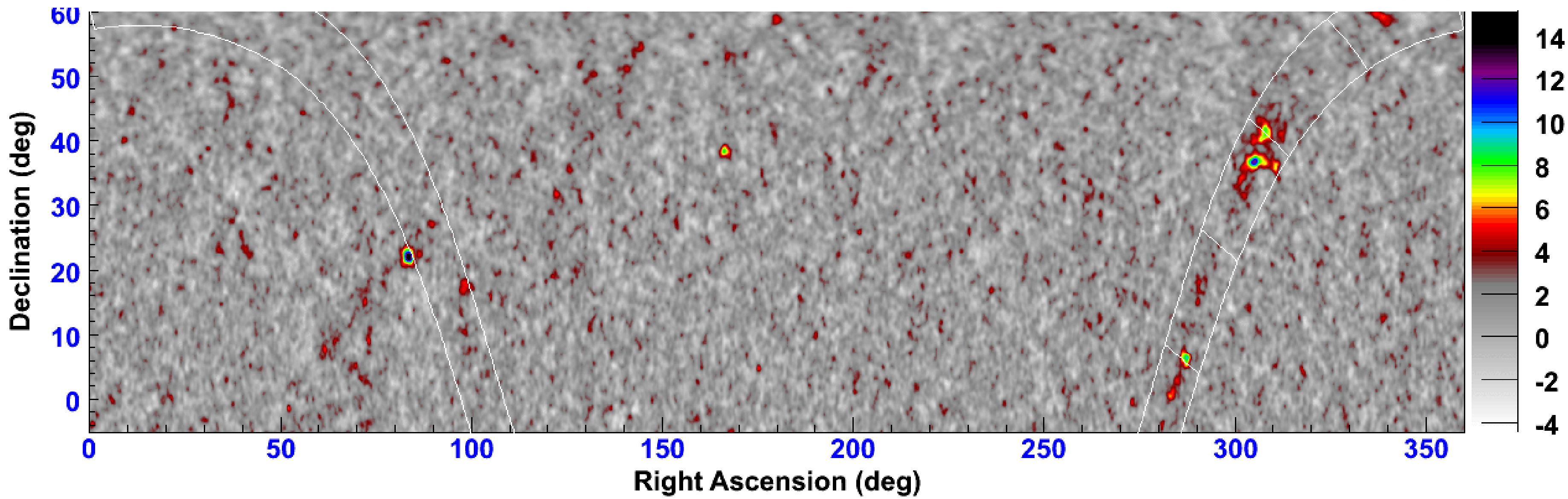
Improves sensitivity by ~2x (Aous Abdo Ph.D. thesis)



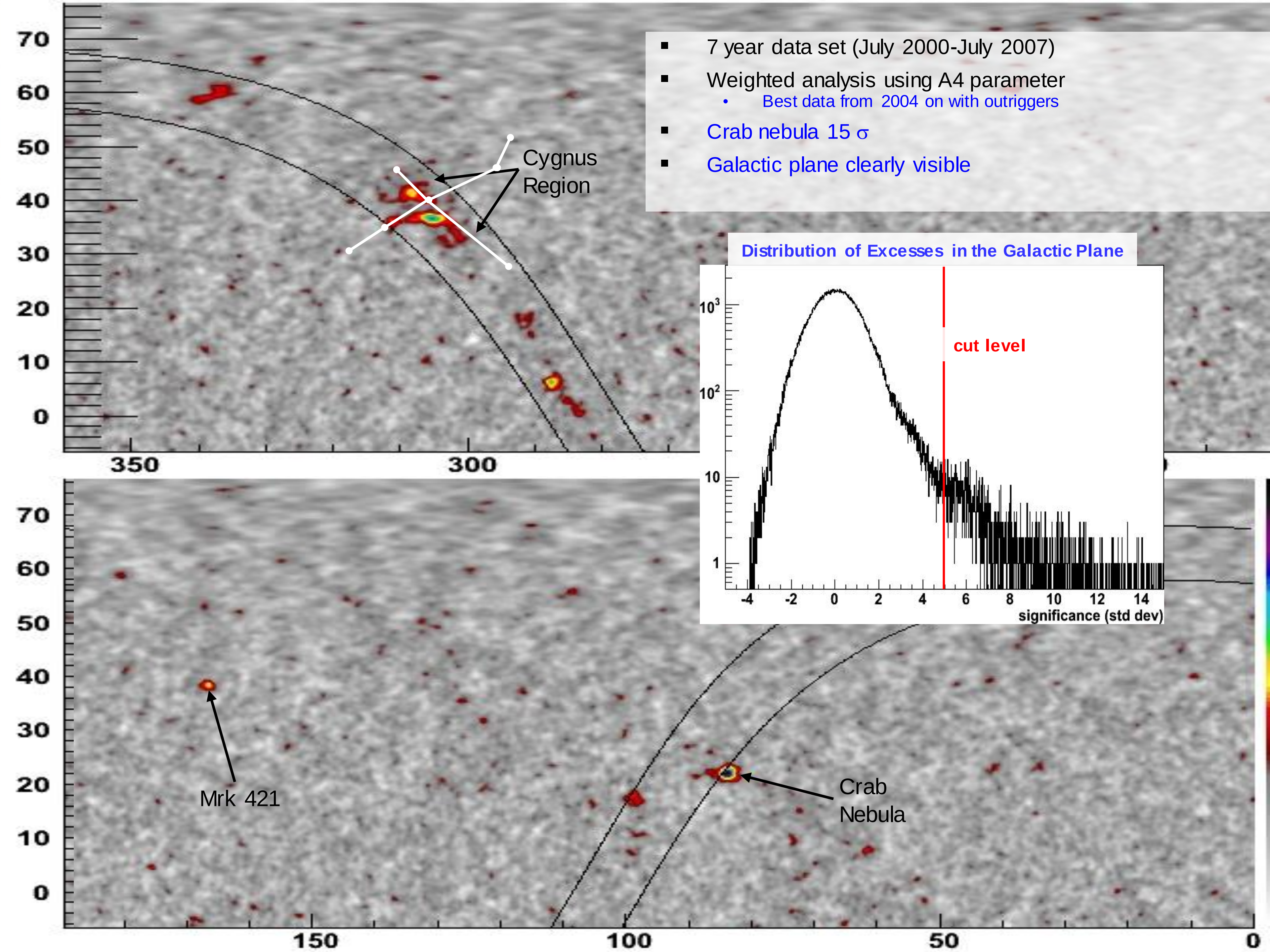
Before: Ntop / mxPE   mxPE sensitive to muons
After: A4 (nonlinear)

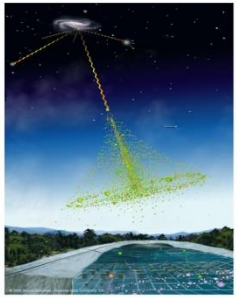
better variable: like 4x more data



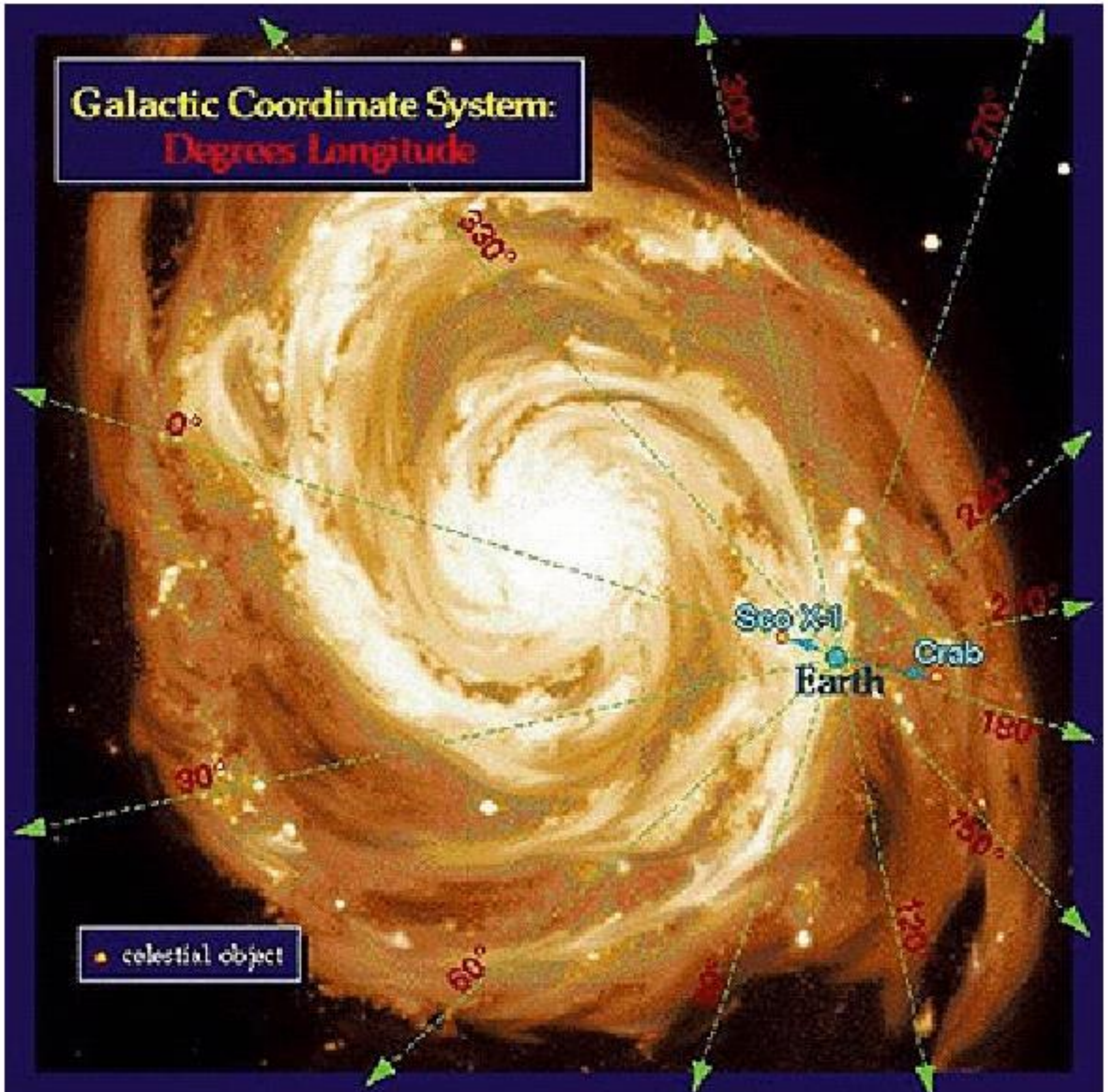


- 7 year data set (July 2000-July 2007)
- Weighted analysis using A4 parameter
  - Best data from 2004 on with outriggers
- Crab nebula 15 σ
- Galactic plane clearly visible

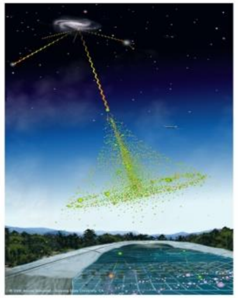


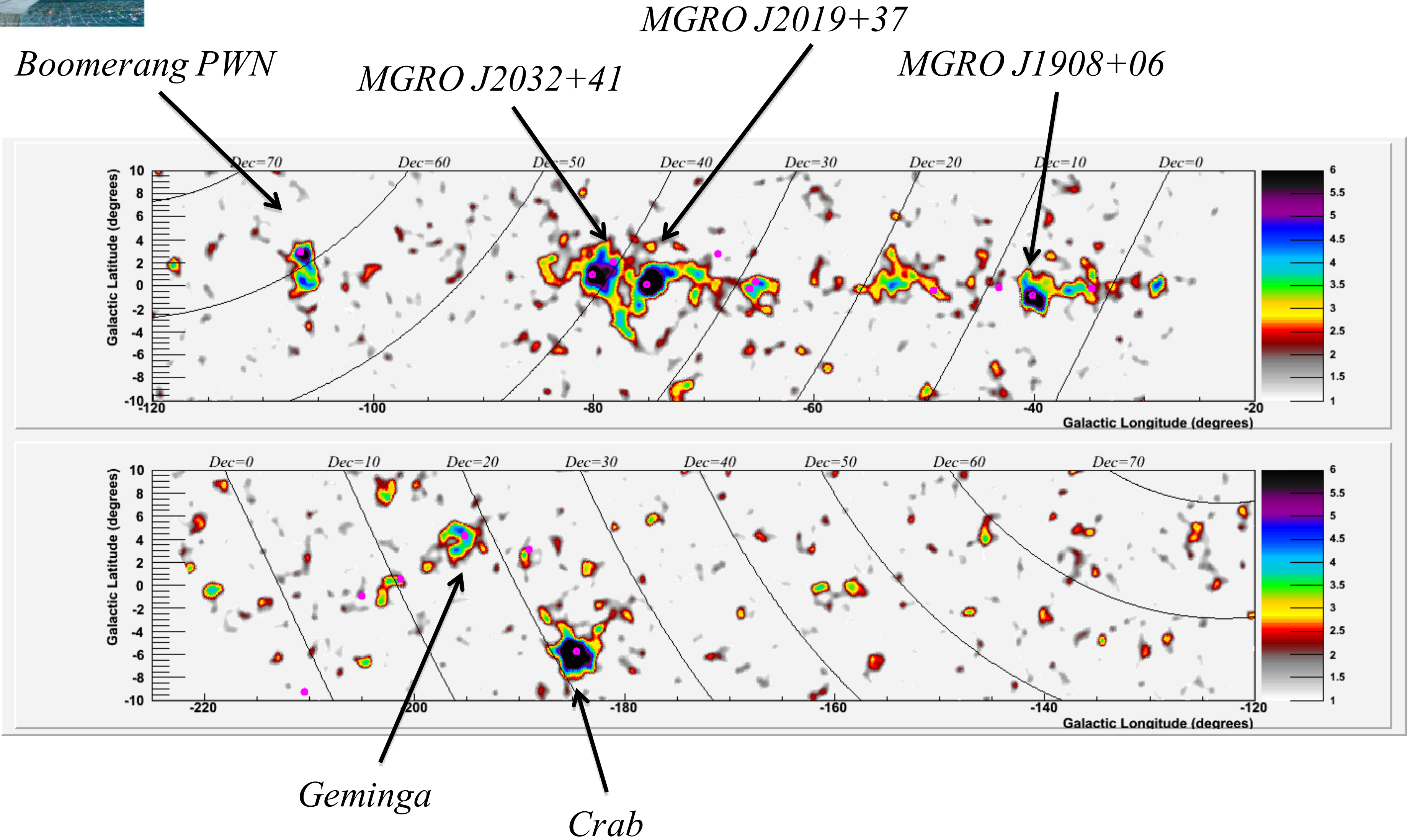


"Once you have sources, you need astrophysicists" For fellow particle physicists, here's a map

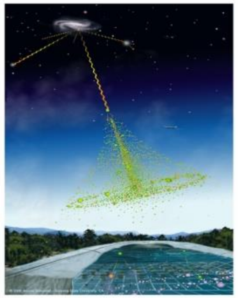


Survey of the Galactic Plane



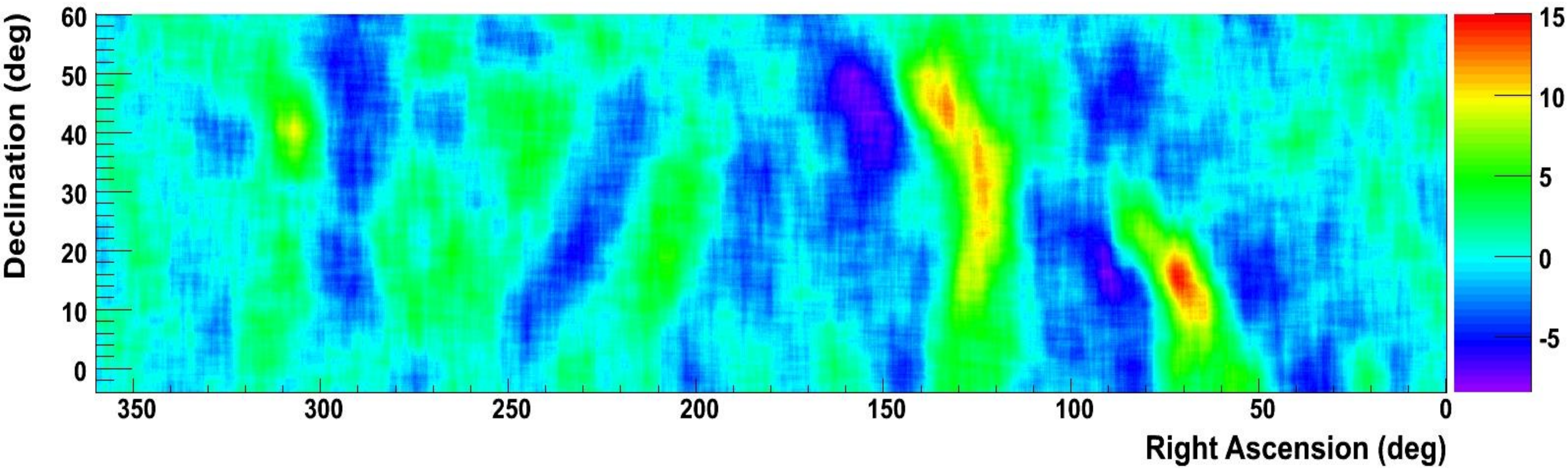


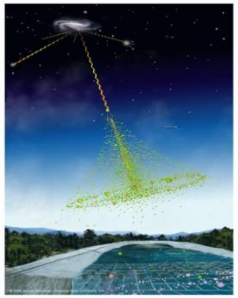
*Abdo et al. ApJL **700** (2009) L127-131*



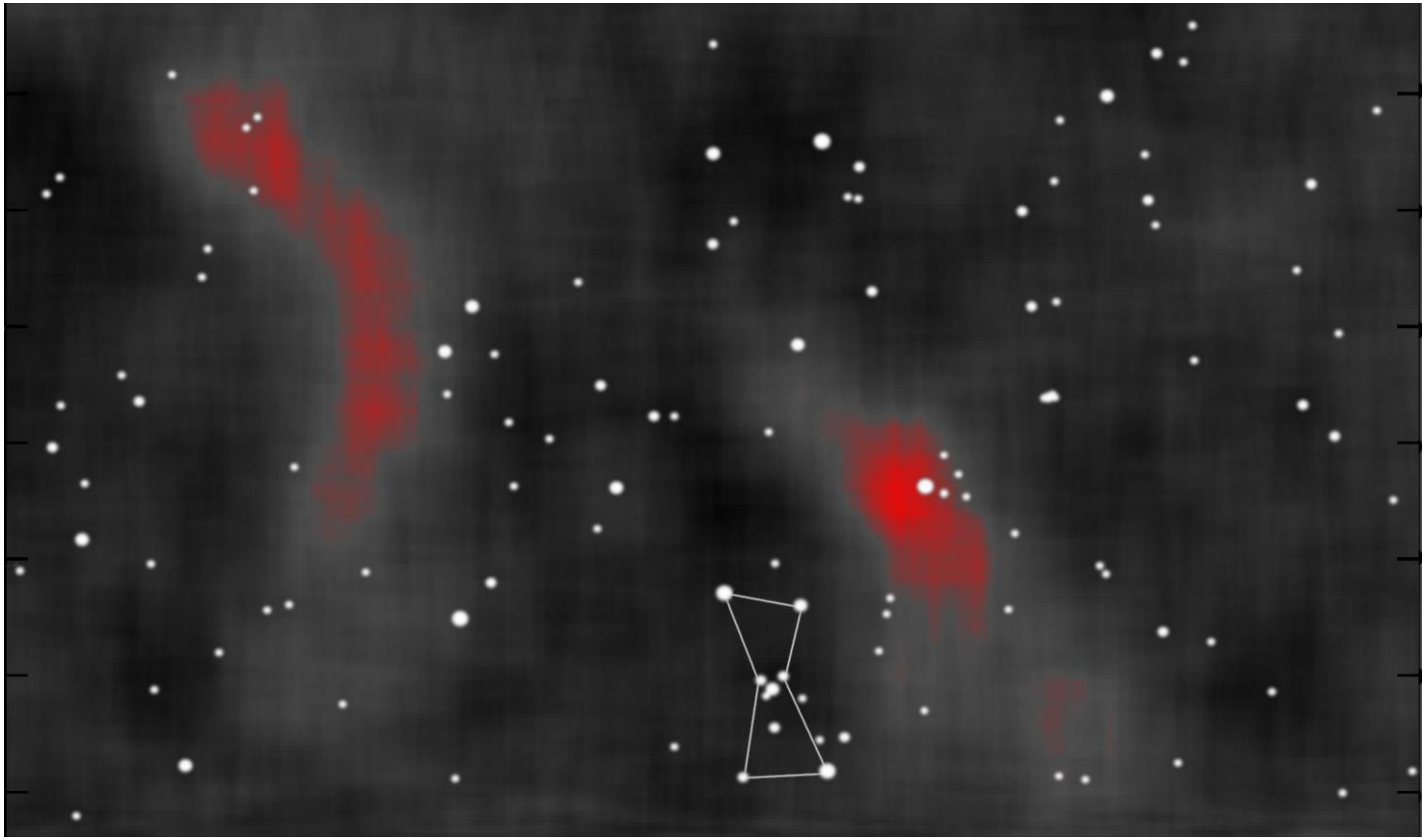
Milagro's Unexpected Cosmic Ray Anisotropy Observation

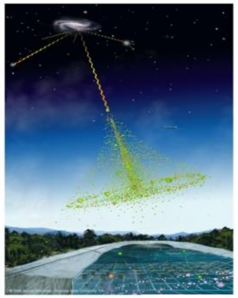
- Anisotropy on 10 deg size scale with a fractional excess of 7e-4 above the cosmic ray background (15 σ)
- Excess is not gamma rays, but charged cosmic rays (11σ)
- Largest excess is not consistent with the locally measured cosmic ray energy spectrum (4 σ), but is harder with a cut off of ~10 TeV
- Explanations are difficult because the gyroradius of a 10 TeV proton in a 1 μG field is 0.01 parsecs=2000 AU
- Possibly a nearby source?



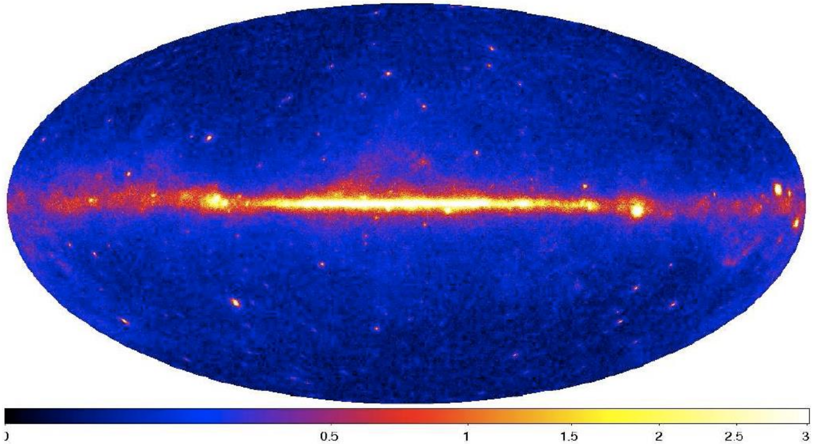


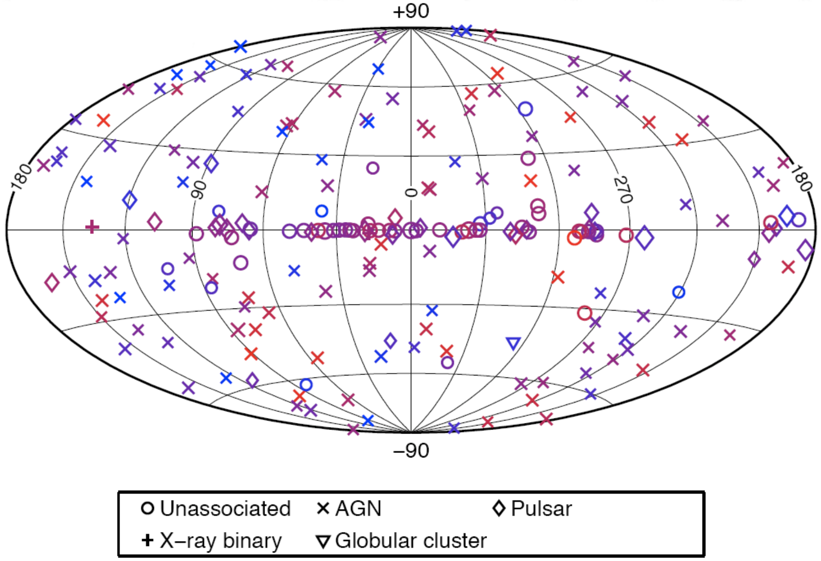
This is anisotropy on a large scale





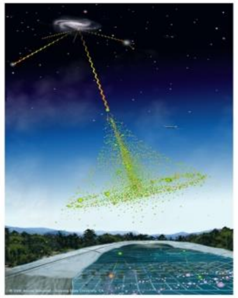
Fermi-LAT Bright Source List





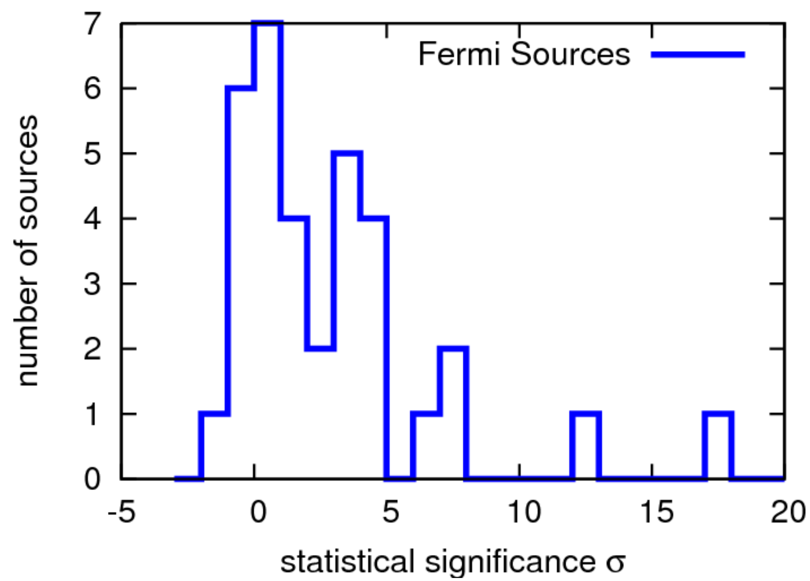
*Abdo et al. ApJS **183**:46-66,2009*

- *Sensitivity from 100 MeV to hundreds of GeV*
- *205 10σ sources in 3 months of data*
- *Blazars, pulsars identified by their variability.*
- *Several new pulsars (pulsations discovered in the GeV first)*
- *Deeper survey than entire EGRET dataset*
- *Angular resolution < 0.1^o at the higher energies*



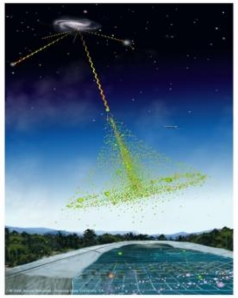
Milagro Search for TeV emission from Galactic sources

- 34 / 205 BSL sources are possibly Galactic and in Milagro's field of view ($\delta > -5^o$)
  - 16 pulsars
  - 1 x-ray binary
  - 5 SNR
  - 12 unknown
- 14/34 are observed at 3σ or more in Milagro data
- Probability of a single 3σ detection in 34 trials is only 4%
- 6/14 have been reported by Milagro before
- 9/14 are pulsars (all 6 previous Milagro sources are now associated with pulsars)
- 3/14 are SNR

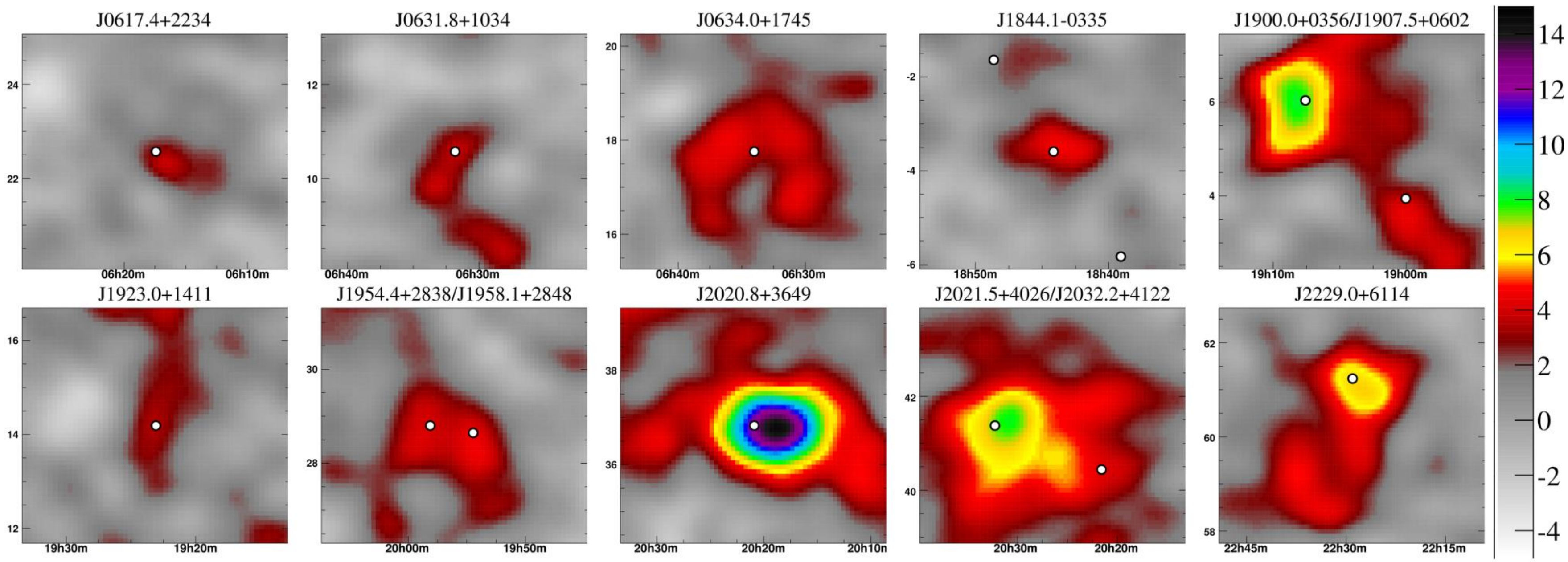


- *'Most' of the 3σ sources are true TeV detections, but cannot be claimed individually*
- *All of these will be observable with 3 months of HAWC data*

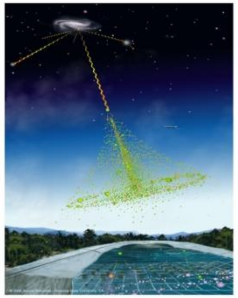
*Abdo et al. ApJL **700** (2009) L127-131*



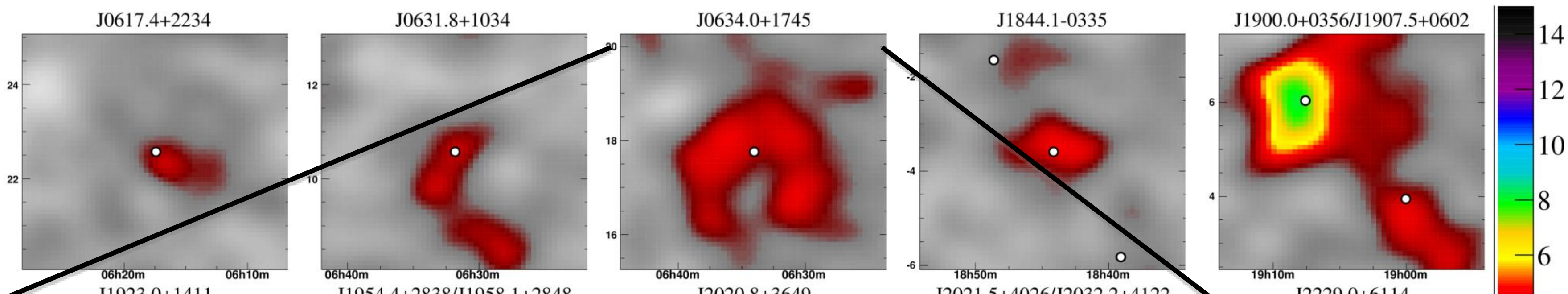
The 3σ Locations

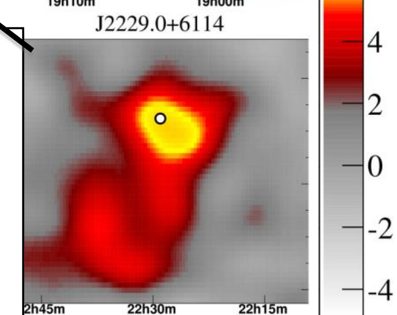


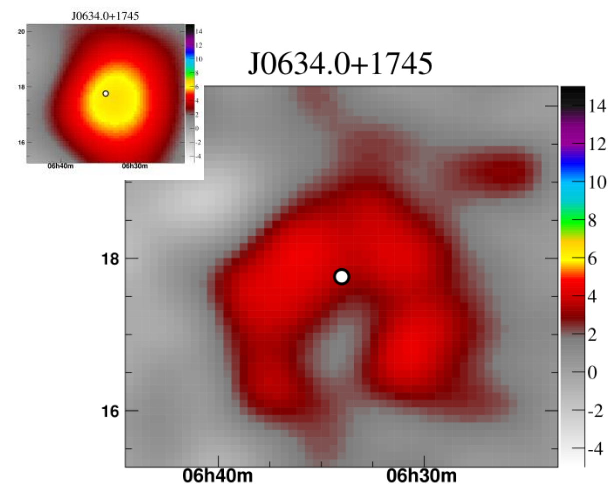
Abdo et al. ApJL ***700*** *(2009) L127-131*



The 3σ Locations

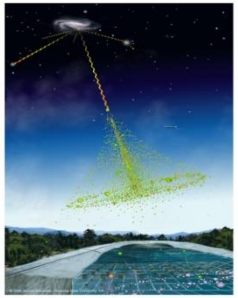




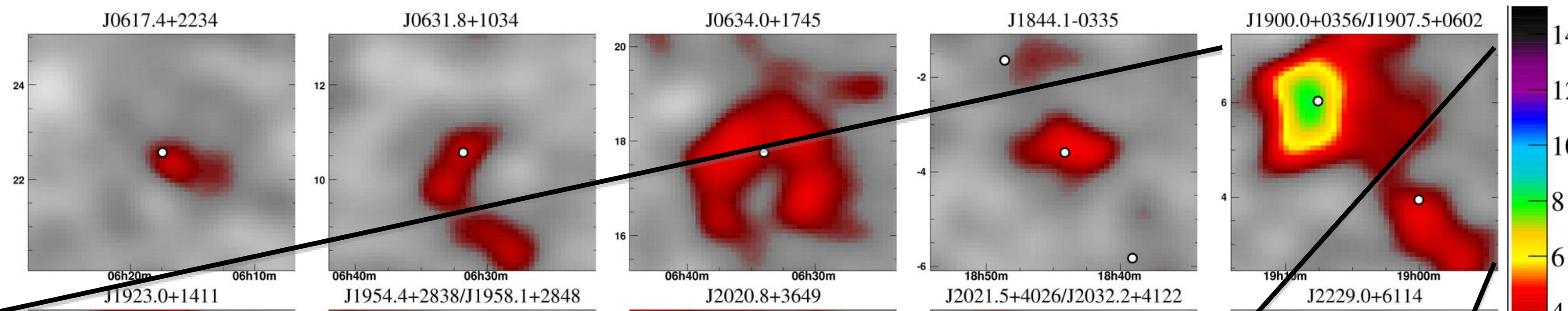


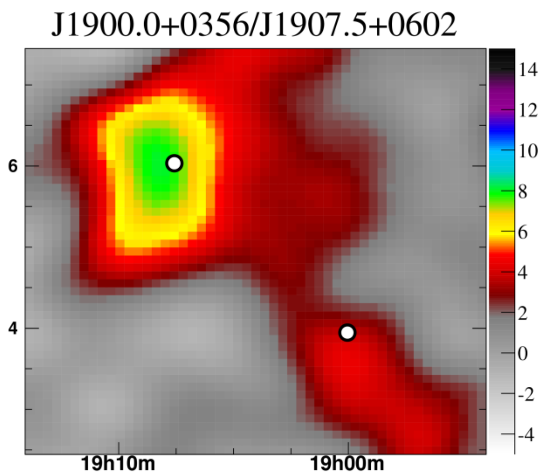
- Most Significant source in BSL
- Old (300 kyr) and nearby (169 pc)
- 3.5σ at the location of Geminga
- 6.3σ when assuming 1º extended source
- 1º extent, consistent with IACT size of distant PWN

*Abdo et al. ApJL **700** (2009) L127-131*



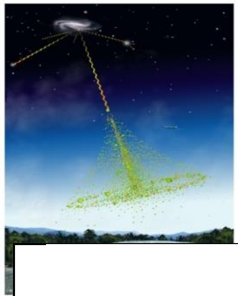
The 3σ Locations



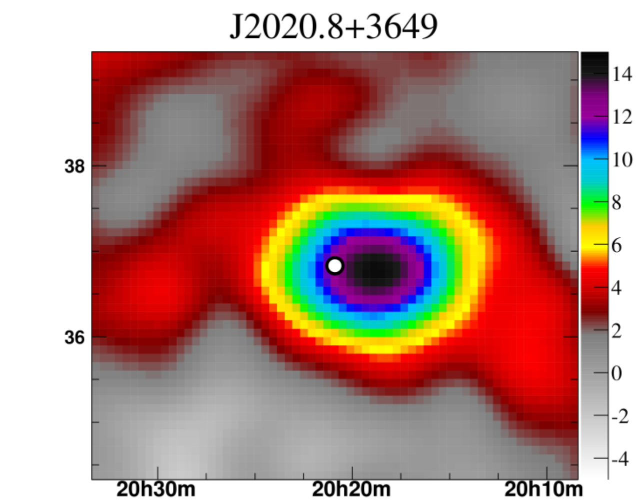


- 7.4σ at pulsar location. 8.1σ at local maximum.
- Pulsar discovered by the LAT.
- Verified by HESS and Veritas.
- Extended by 0.21^{o} in HESS data

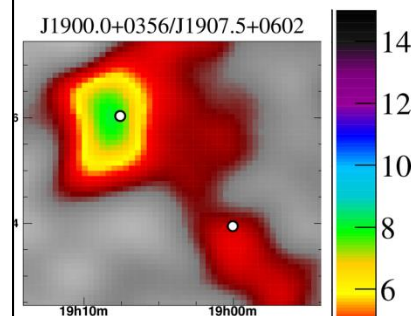
Abdo et al. ApJL 700 (2009) L127-131

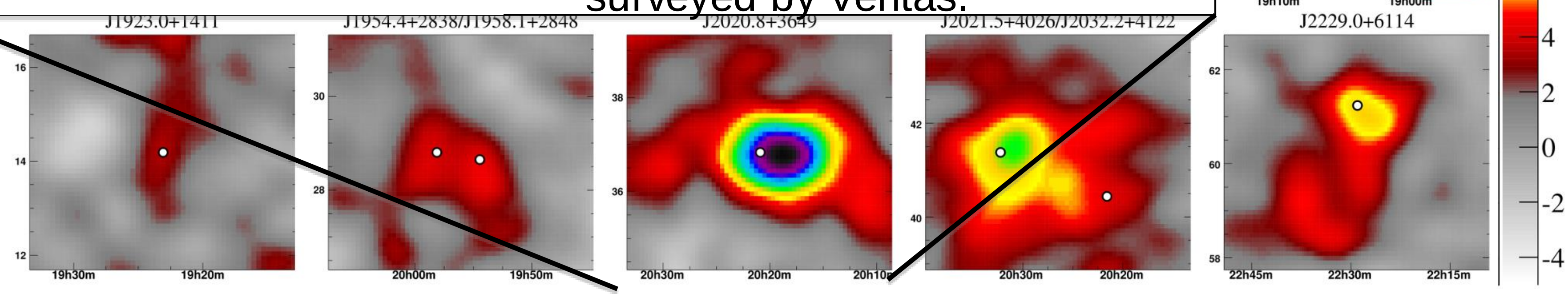


The 3σ Locations

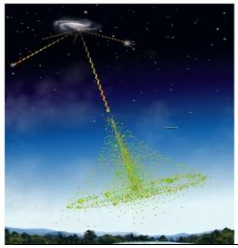


- Most significant source for Milagro after the Crab. 12.4σ at the pulsar location. 14.5σ at peak.
- Identified as a young pulsar by AGILE.
- Milagro peak is separated from pulsar by 0.3^o with a 1σ error of 0.1^o.
- In the Cygnus region being surveyed by Veritas.

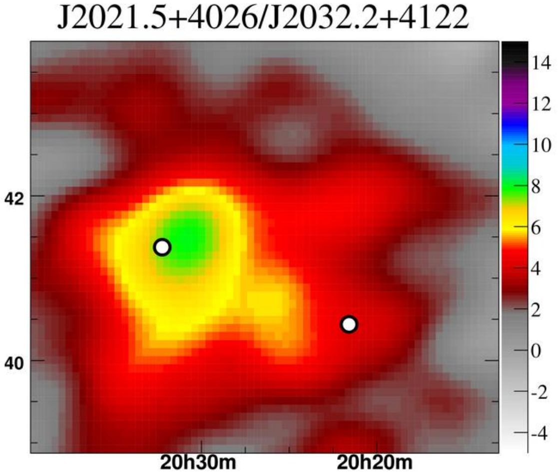




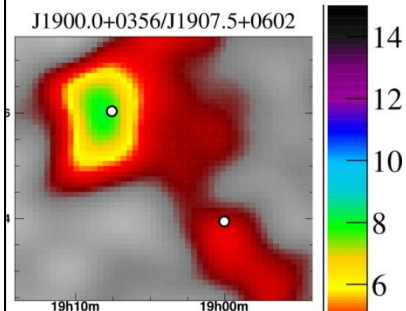
*Abdo et al. ApJL **700** (2009) L127-131*

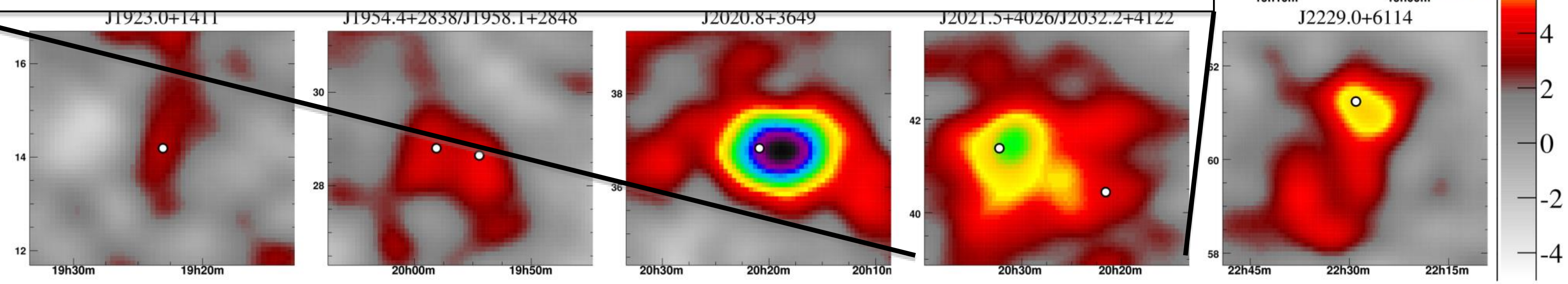


The 3σ Locations

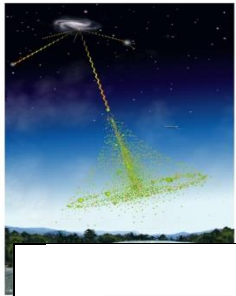


- Associated with LAT-identified pulsar
- Originally reported by Milagro as an 3º extended source.
  - Source confusion with 0FGL J2021.5+4026?

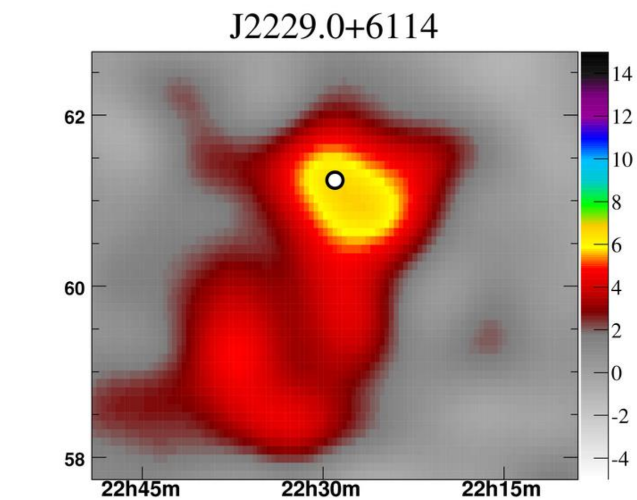




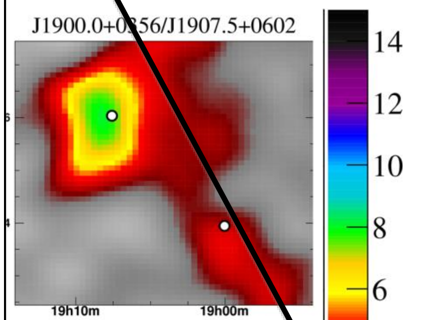
*Abdo et al. ApJL **700** (2009) L127-131*

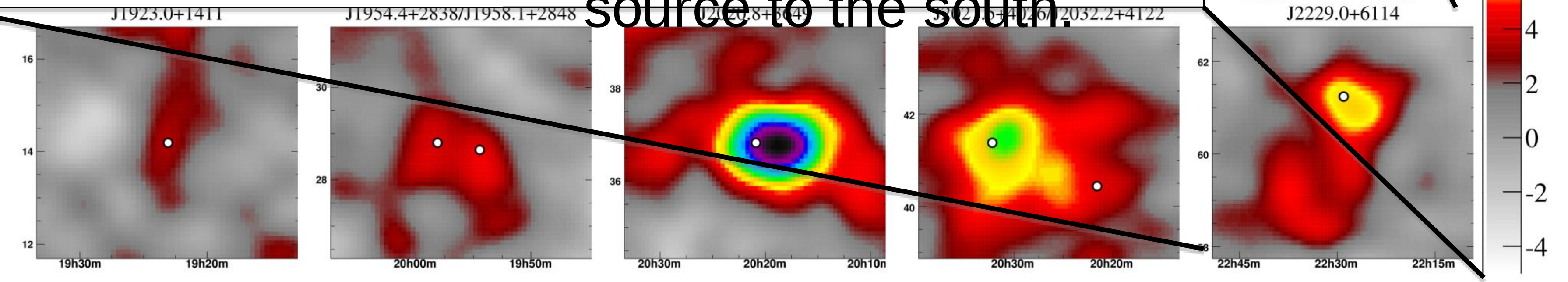


The 3σ Locations

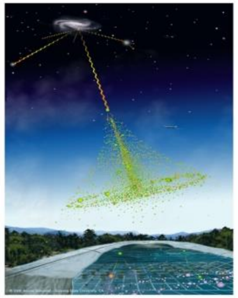


- Boomerang PWN
- 6.6σ at the pulsar location 6.8σ.
- Associated with radio pulsar J2229+6114
- Additional new Fermi source to the south.



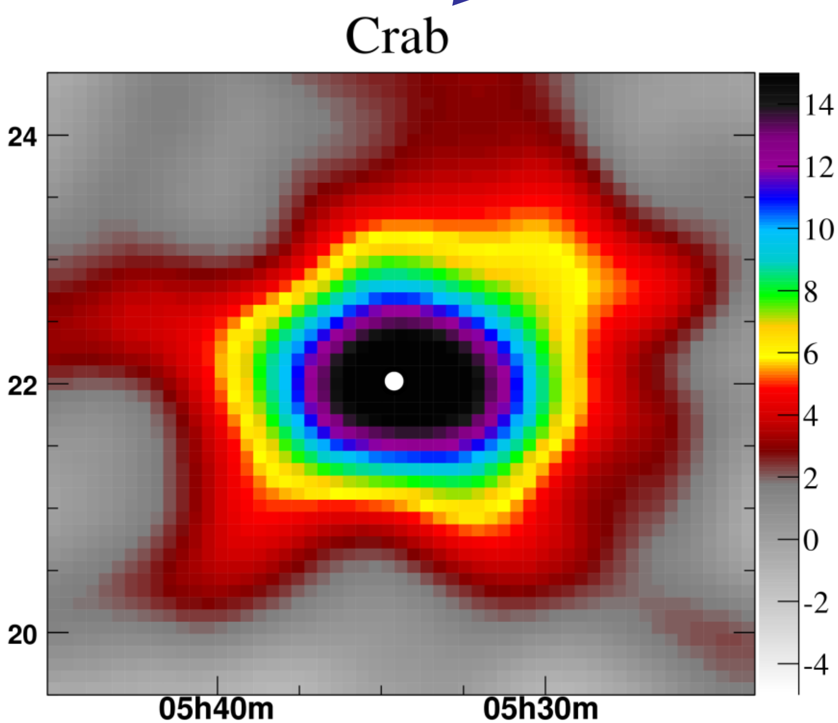


*Abdo et al. ApJL **700** (2009) L127-131*

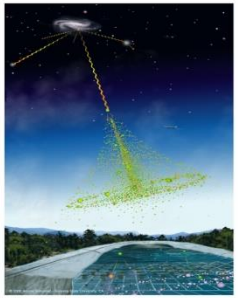


Milagro Gamma-Ray Sources

Our favorite blowtorch



- Milagro's strongest sources are very likely TeV PWN. Typical TeV source is a PWN.
- TeV emission is quite commonly associated with MeV-GeV Pulsars.
- Spectrum to connect Milagro measurements to Fermi measurements are universally softer than 2.3.



From Milagro to HAWC

Altitude 2650 m to 4100 m

Area 22,000 m^2

from 4,000 m^2 (top)

or 2,200 m^2 (bottom)

or 30,000 m^2 outrigger field

Reuse 900 tubes

& FE electronics

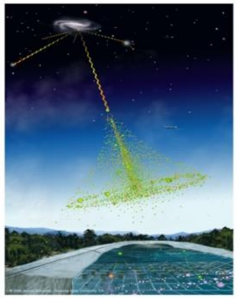
Cost ~$10M

HAWC 10 – 15 x Sensitivity :

HAWC: (5σ) Crab in ~ 1 day

Milagro: (5σ) Crab in 3 mo

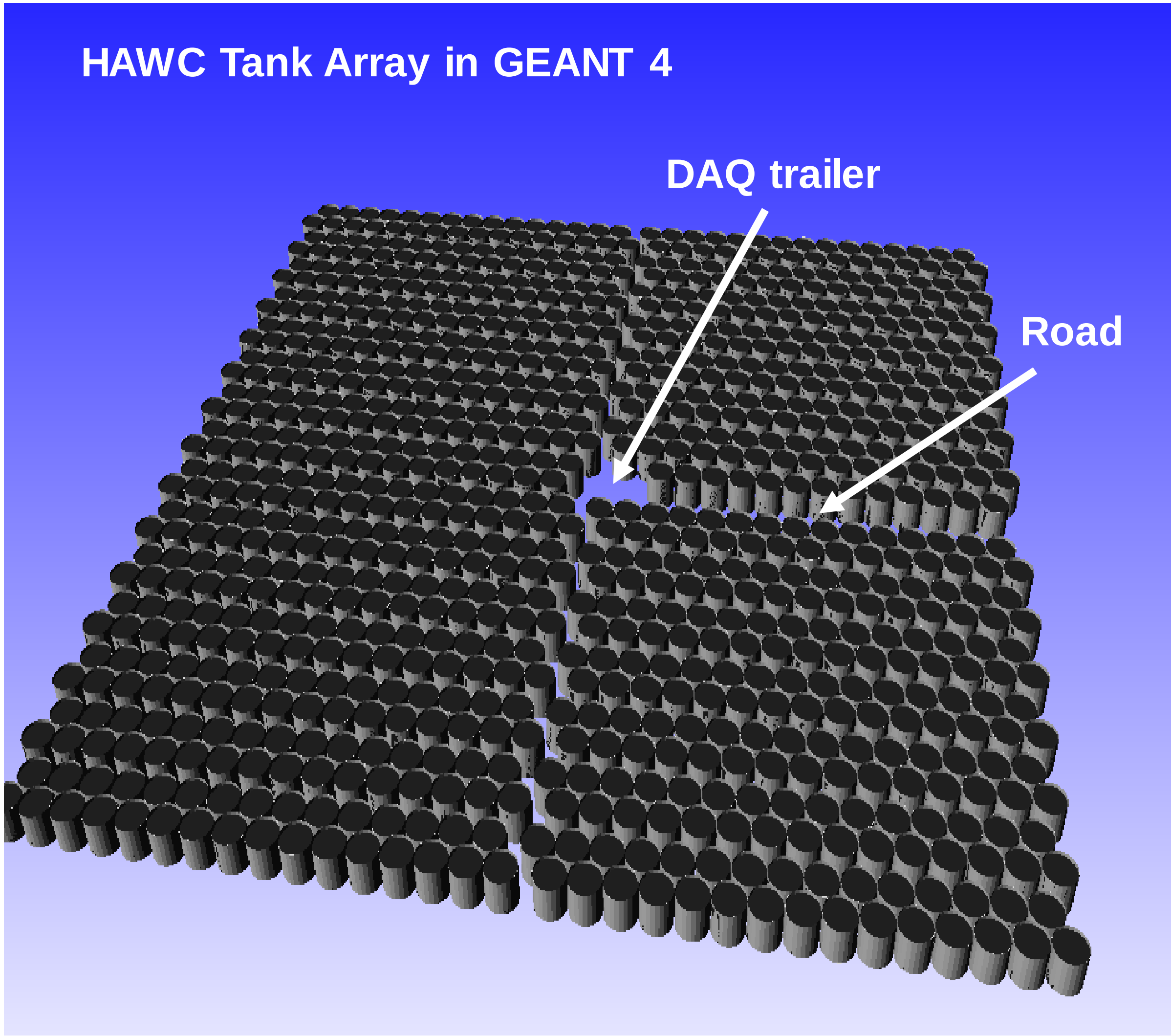
http://umdgrb.umd.edu/hawc/index.php

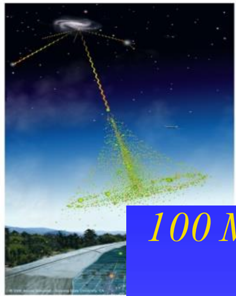


HAWC Detector Design

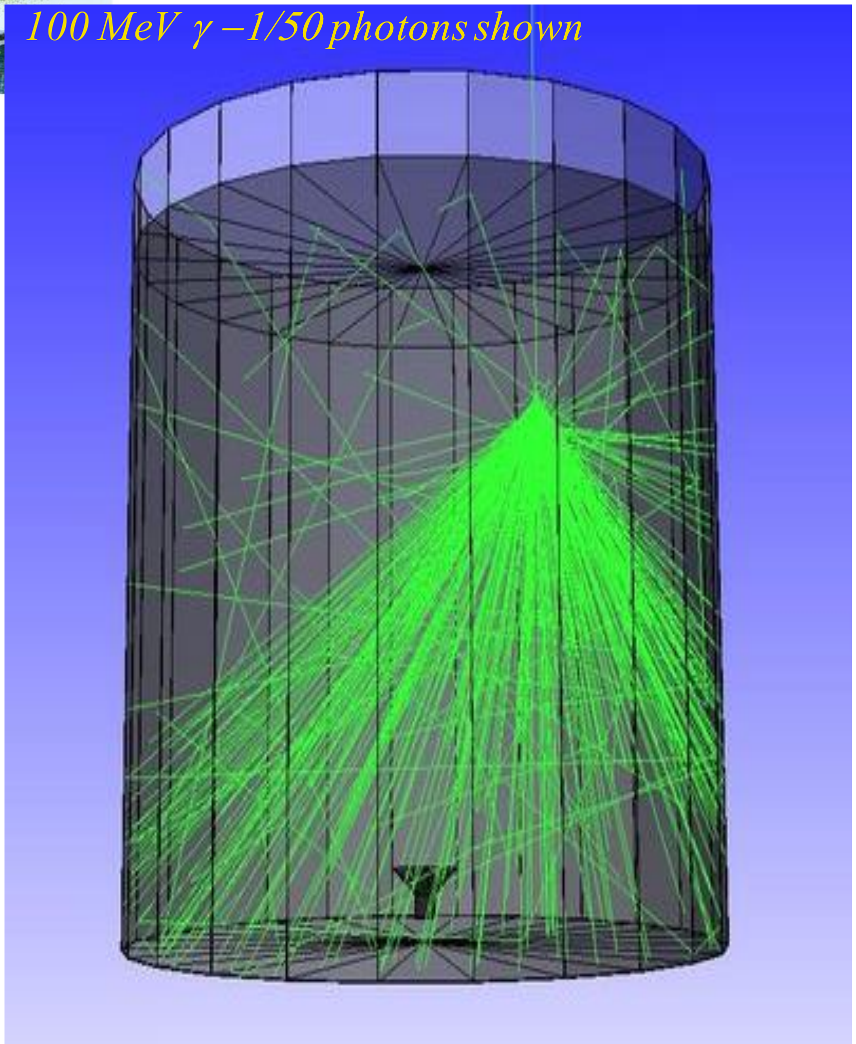
- 300 water tanks
- Tanks 7.5m diameter and 4.3m deep
- Build tanks on site
- Three 8” PMT/tank
- 150m x 150m array

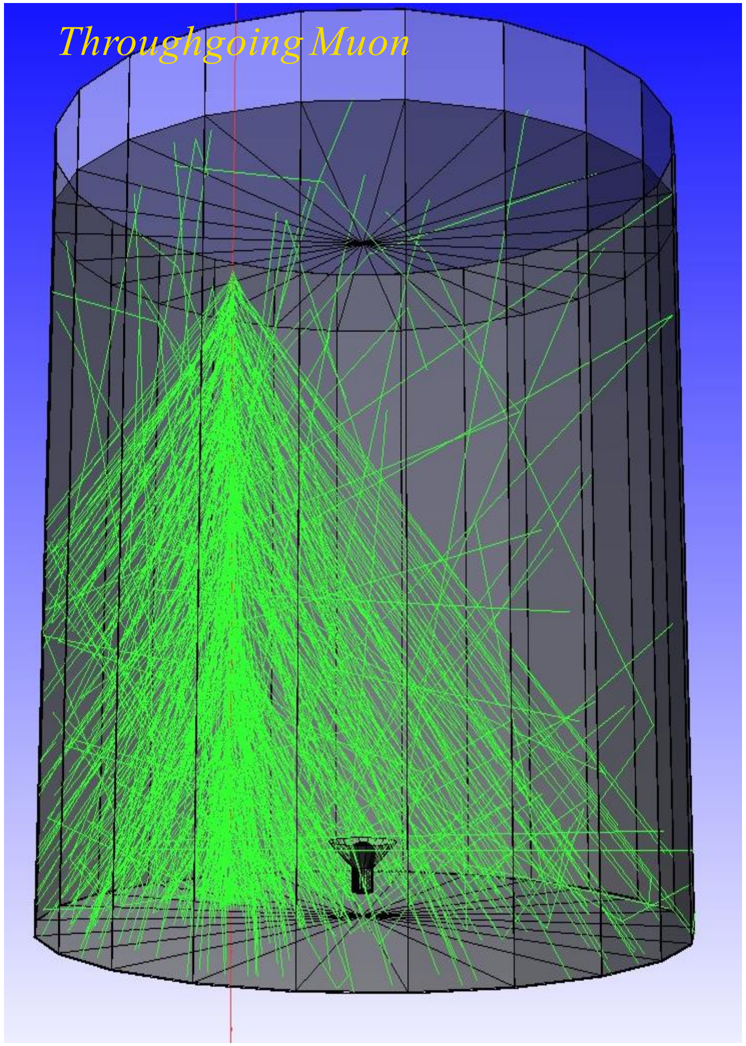
  78% coverage

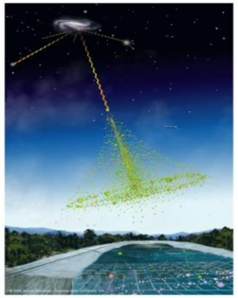




Tank Simulation

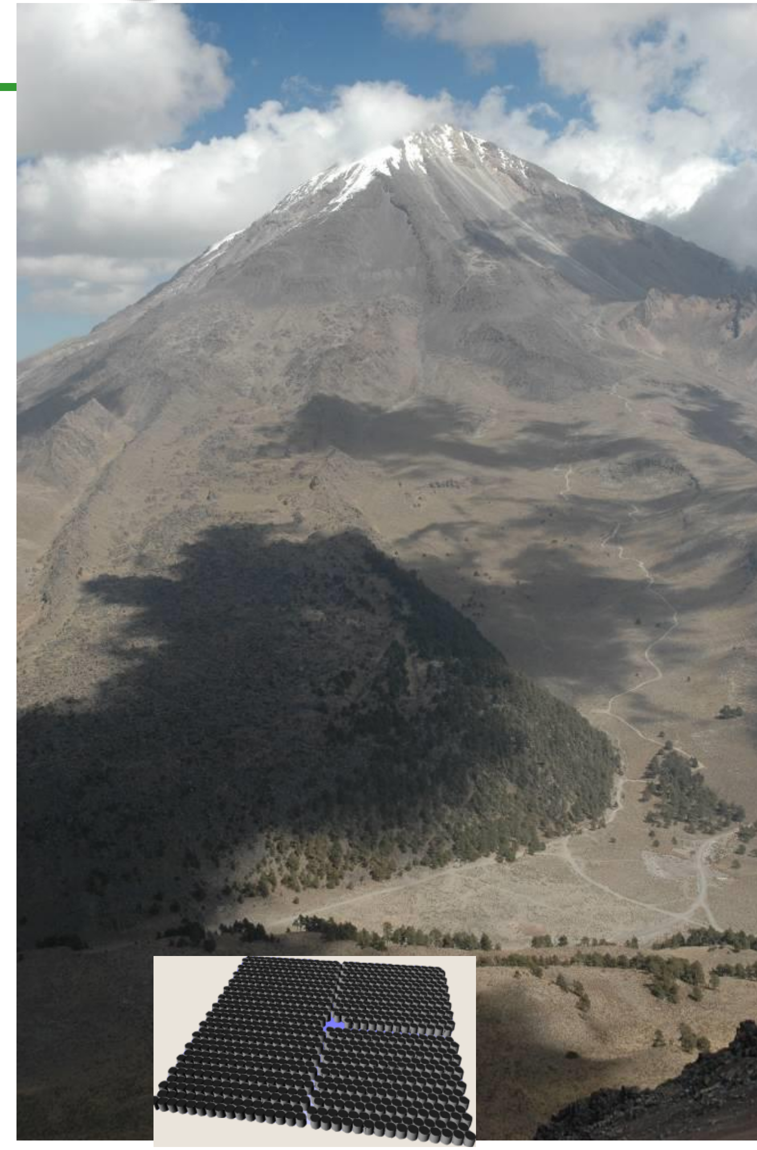




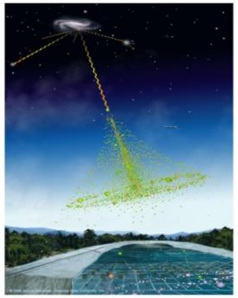


Site Location is Sierra Negra, Mexico

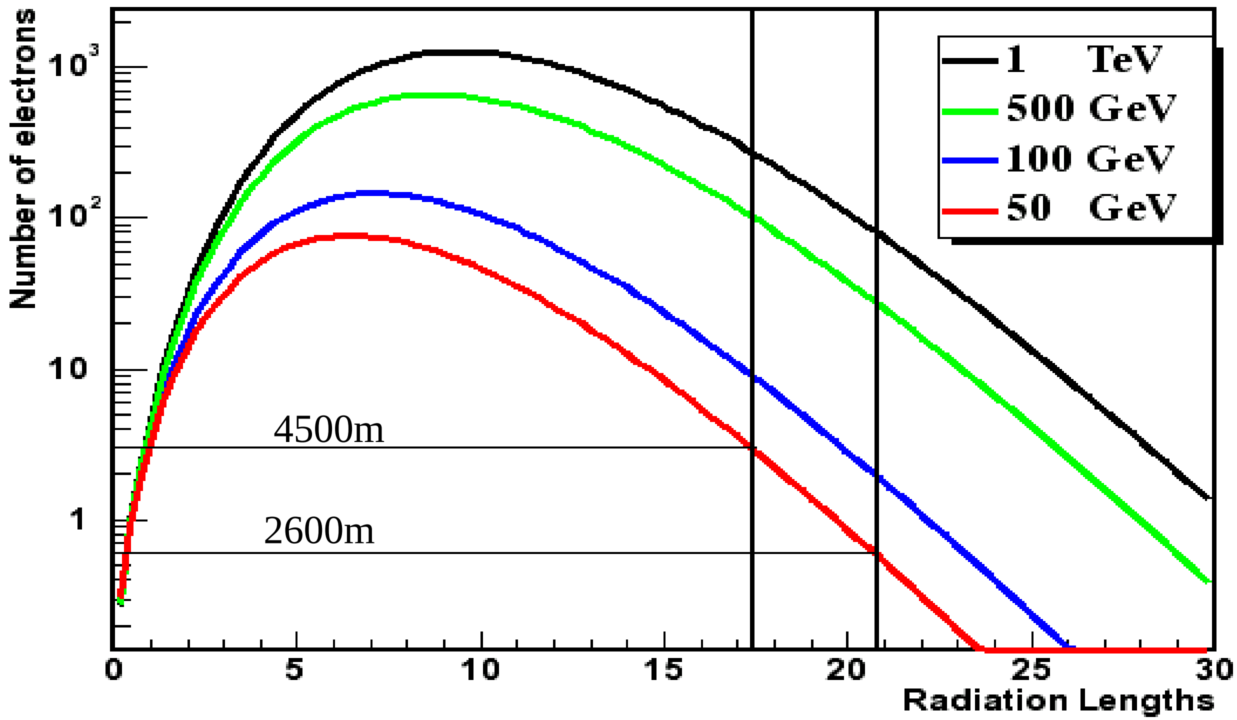
- 4100 m above sea level
- Latitude of 19 deg N
- Easy Access
  - 2 hr drive from Puebla
  - 4 hr drive from Mexico City
- Existing Infrastructure
  - Few km from the US/Mexico Large Millimeter Telescope
  - Power, Internet, Roads
  - Sierra Negra Scientific Consortium
    ~7 projects
- Excellent Mexican Collaborators
  - ~15 Faculty at 7 institutions have submitted proposal to CONACYT for HAWC
  - Experience in HEP, Auger, and astrophysics (including TeV)



"Don't worry: the lava flow predates the conquistadors"



Higher Altitude is Closer to Shower Max.

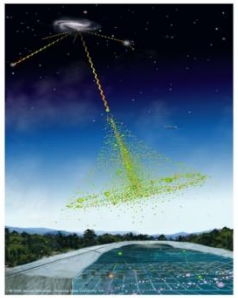


Difference between 2600m (Milagro) and 4500m (Tibet):

~ 6x number of particles

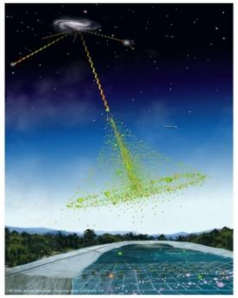
~ 2x lower energy threshold

Result: 15-20 x Milagro sensitivity



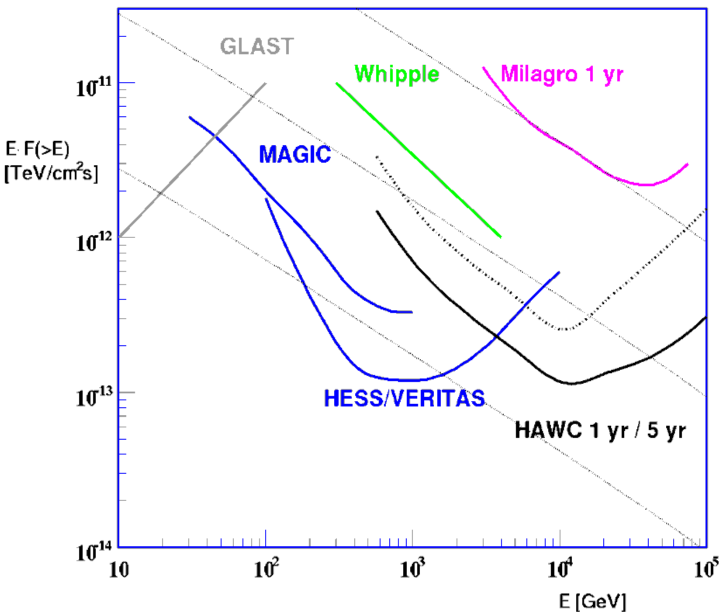
HAWC Science Objectives

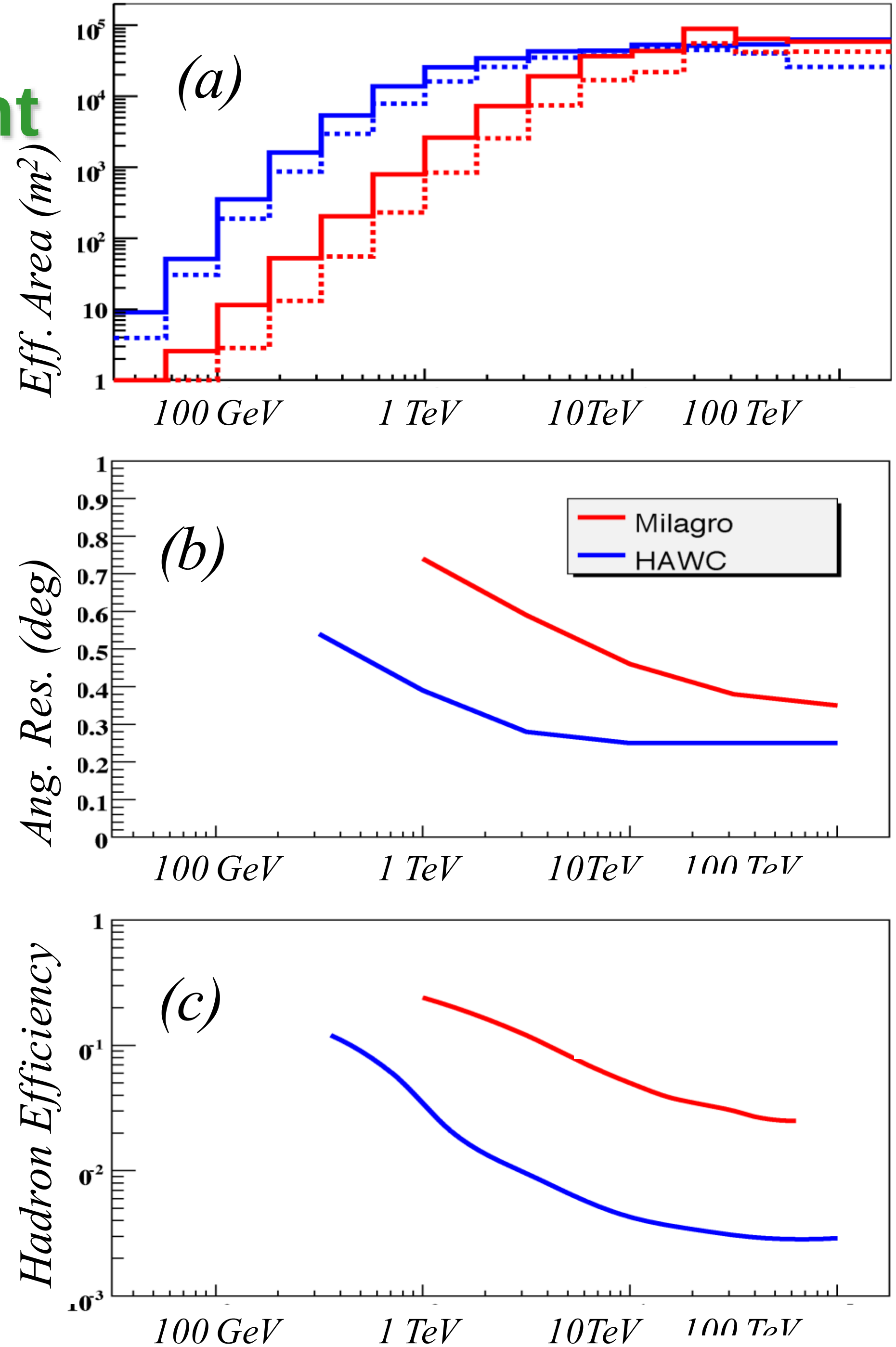
- Constrain the origin of cosmic rays via HAWC's observations of γ-rays up to 100 TeV from discrete sources and the Galactic plane.
- Probe particle acceleration in extreme magnetic and gravitational fields via HAWC's observations of transient TeV sources, such as gamma ray bursts and supermassive black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

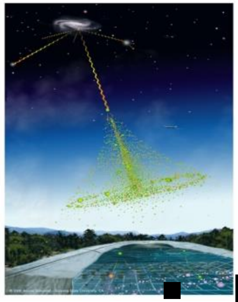


HAWC Improvement over Milagro

- Larger effective area at low energies
- Better angular resolution
- Better Gamma/Hadron Separation
- Overall 15x improvement over HAWC
- Preserve all the raw data
  - Better Calibration Sensitivity
- See the Crab at 5σ every day
  - Precise tuning of gamma-ray MC and stability

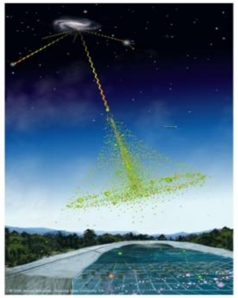






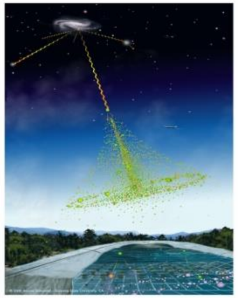
MSU projects

- Hadron rejection: improve sensitivity x 2 (~ x 4 data)
  - Abdo PhD   Both Milagro and Fermi/Lat are Abdo et al.
- Shifts: at LANL, or comfort of MSU offices
- Sr Thesis on Fermi GeV sources off galactic plane
  - Ahren Barber
- Unfolding of energy spectrum
  - Energy estimator is fraction of tubes hit (variant of A4 variable)
    - Not pulse height! (PH is done by time over threshold)
  - Current method fits spectrum to estimator, but no E spectrum
    - Udara Abesekaya (grad student)
- HAWC Electronics
  - Jim: head of HAWC electronics
  - Dan Edmunds (help from Udara, postdoc)
    - re-optimization of front end boards for new TDCs, HAWC tanks
    - GPS absolute time scale for experiment
    - Interface to scalers, trigger, TDCs, DAQ
    - Design of replacement front end board (layout: an upgrade grant)

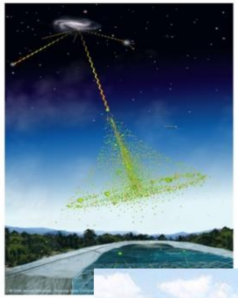


Status of HAWC

- ~1M USD from NSF, UMD, and INAOE, UNAM, CHIAPAS, CONACyT
  - Tank development
  - Prototype array at the HAWC site
  - Development of the HAWC site
- Road to the Site
- Tanks at the Site
- Successful data runs with the prototype array.

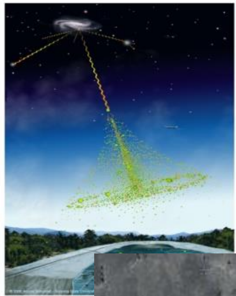


Tank Development

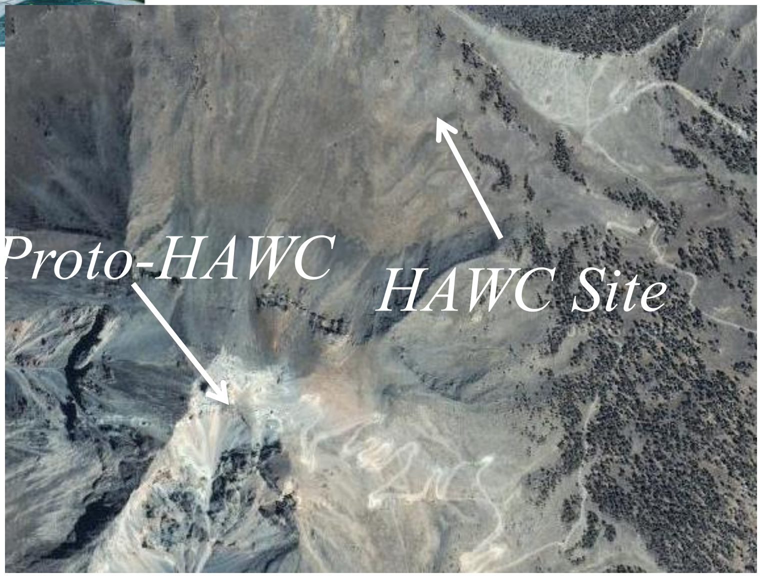


Proto-HAWC

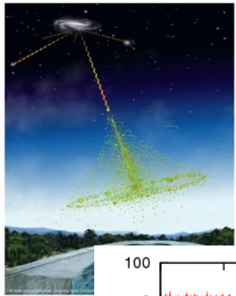
- Simple array near HAWC site (by LMT)
- Testing
  - Infrastructure
  - Site workability
  - Initial scientific tests
  - Test bench for calibration, DAQ, and other preparation
  - Tank designs



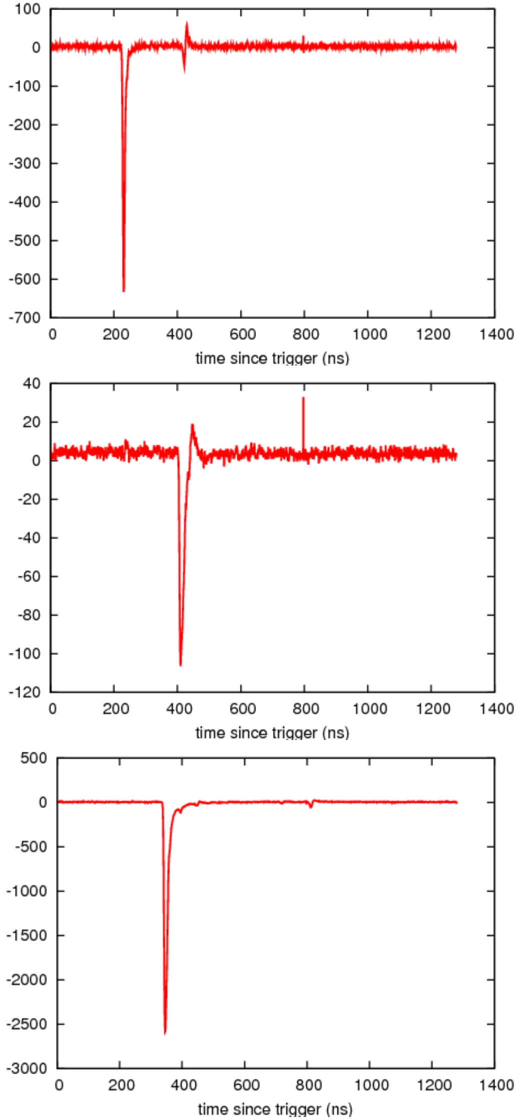
Proto-HAWC

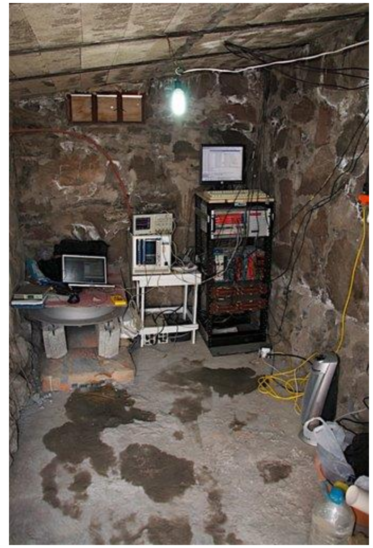


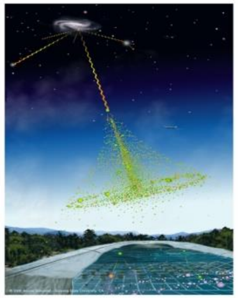
- 3 3.0–meter black plastic water tanks at the LMT site (4600 meters)
- Tanks operated in triple-coincidence
- 3 channels of 12 μs FADC sampling every 0.5 ns
- 16 Hz Rate



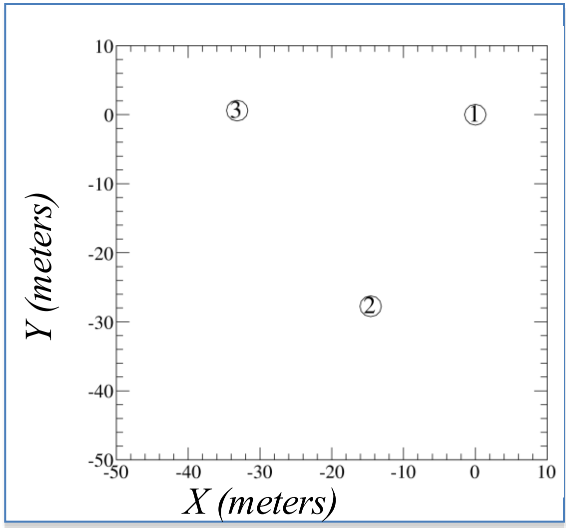
Proto-HAWC First Event



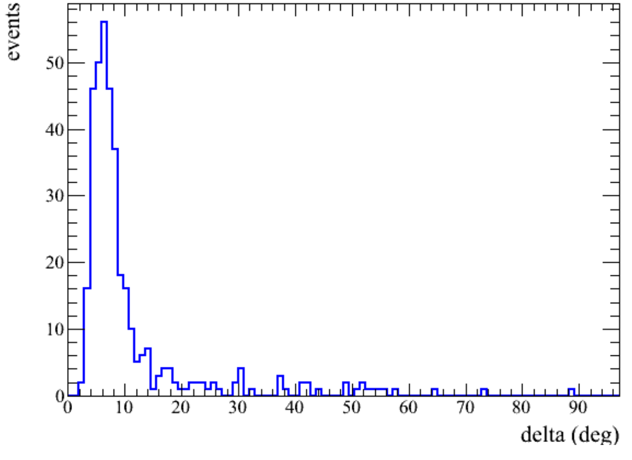


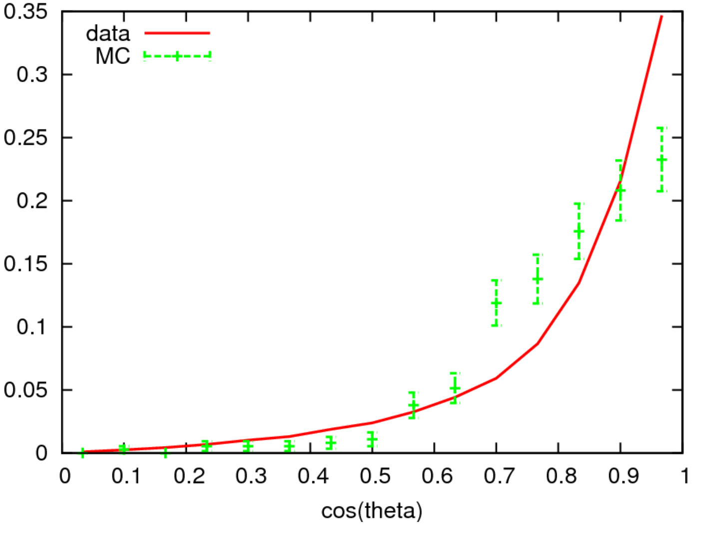


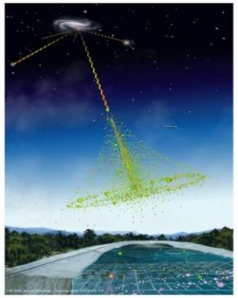
Initial Reconstruction



- Fit is the plane consistent with all 3 hit times
- Simple fit not representative of HAWC performance
  - No correction for shower curvature, core location, etc

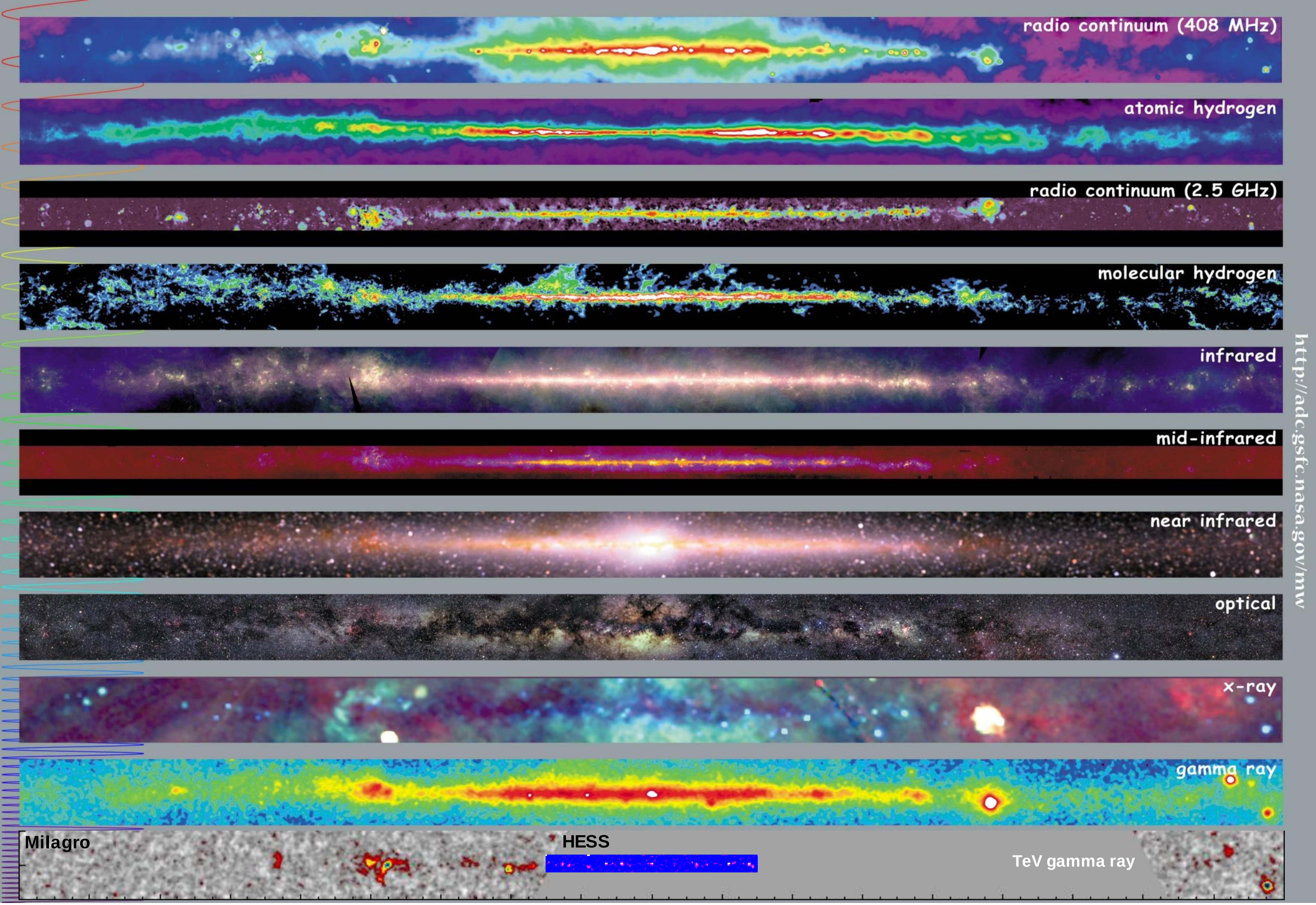




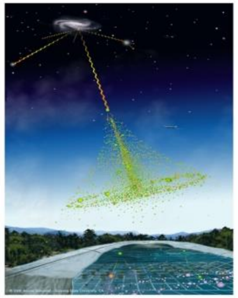


We are actively developing HAWC Site

- Road to the Site
  - Drainage coming in
- Purchased tanks in US and shipped to Mexico
- Now have tanks at the HAWC Site (not the LMT site)
- Pursuing a test well and power to the site.



TeV γ-rays: A New Window on the Sky



Conclusion

- Milagro has demonstrated success of the water Cherenkov technique for gamma rays
  - Discovery of TeV emission from the Galactic plane
  - Image of TeV emission from the Cygnus region
  - 7 New Candidate TeV Sources; more with Fermi/LAT
- Future Plan is HAWC
  - Building on expertise with Milagro
  - Design improvements in Size, Altitude, Tanks. . .
  - 15 x Milagro sensitivity
- HAWC: Synergistic Component of Particle Astrophysics Portfolio
  - Identify which of Fermi/LAT 1000s of sources extend to TeV energies and monitoring these sources daily
  - Determine targets for the Atmospheric Cherenkov Telescopes to use their enhanced angular and energy resolution
  - Improve IceCube sensitivity x10 by identifying flaring sources
  - "Fund under all scenarios"
    - by HEPAP Particle Astrophysics Advisory Group

HAWC Sensitivity
15x Milagro's

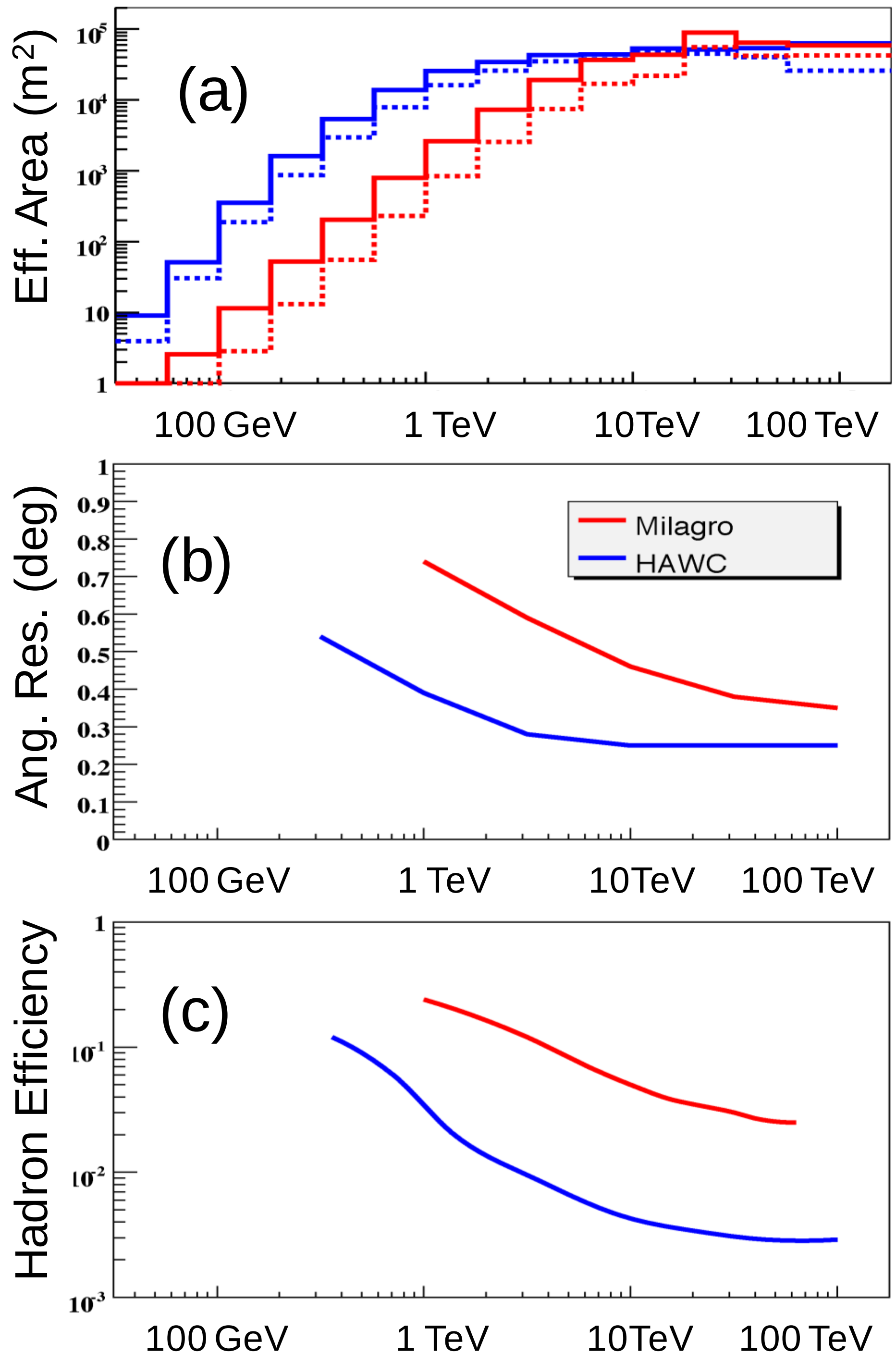
Larger Effective Area at Lower E

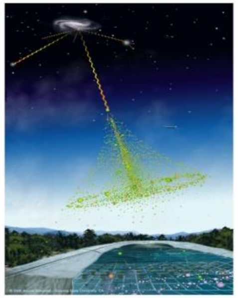
Better Angular Resolution

Improved Background Rejection

→ 10-15 x improvement in flux sensitivity

→ $(10\text{-}15)^2$ = 100-200 x faster to observe same flux



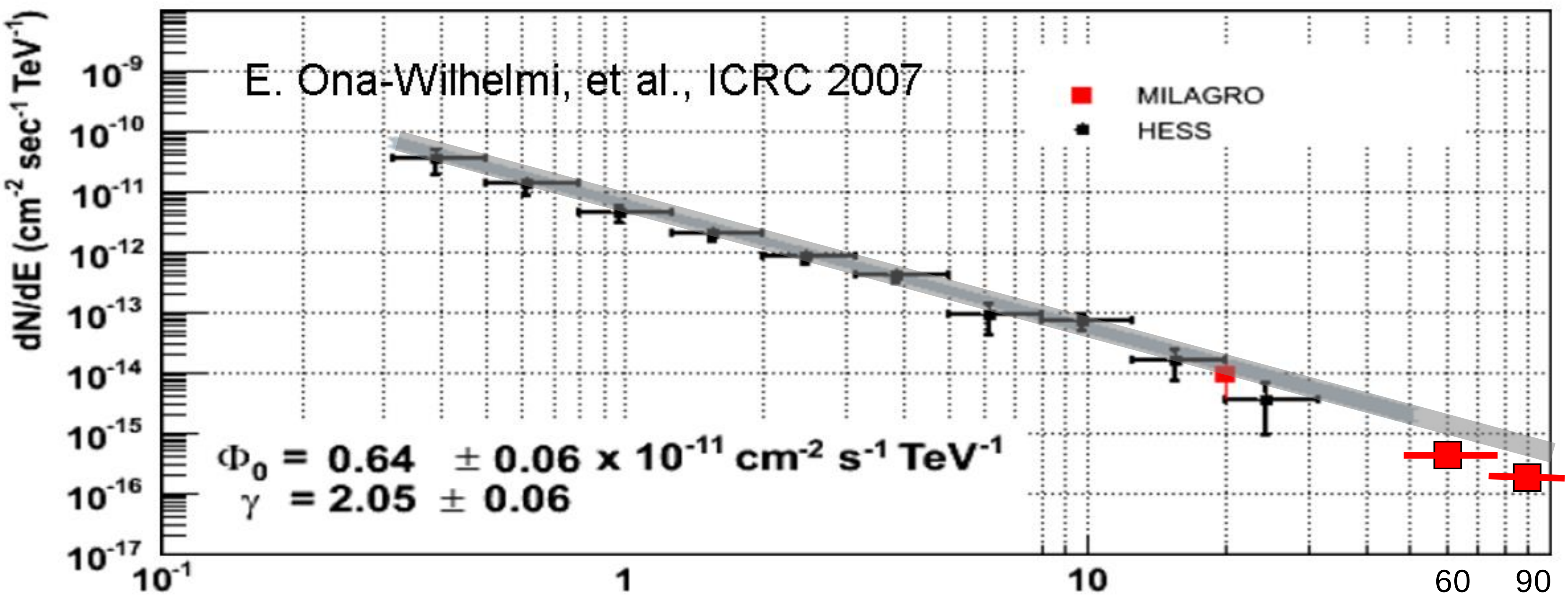


Milagro Extension of TeV spectrum of MGRO J1908+06 – *Preliminary*

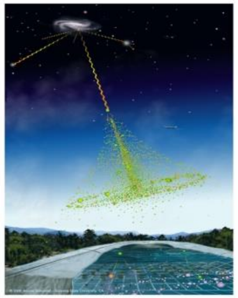
full E scale still in progress

A4 is correlated with Energy of Gamma-Ray Initiating Shower

Harder A4 cut give median detected energy of 90 TeV and 6 sigma detection significance

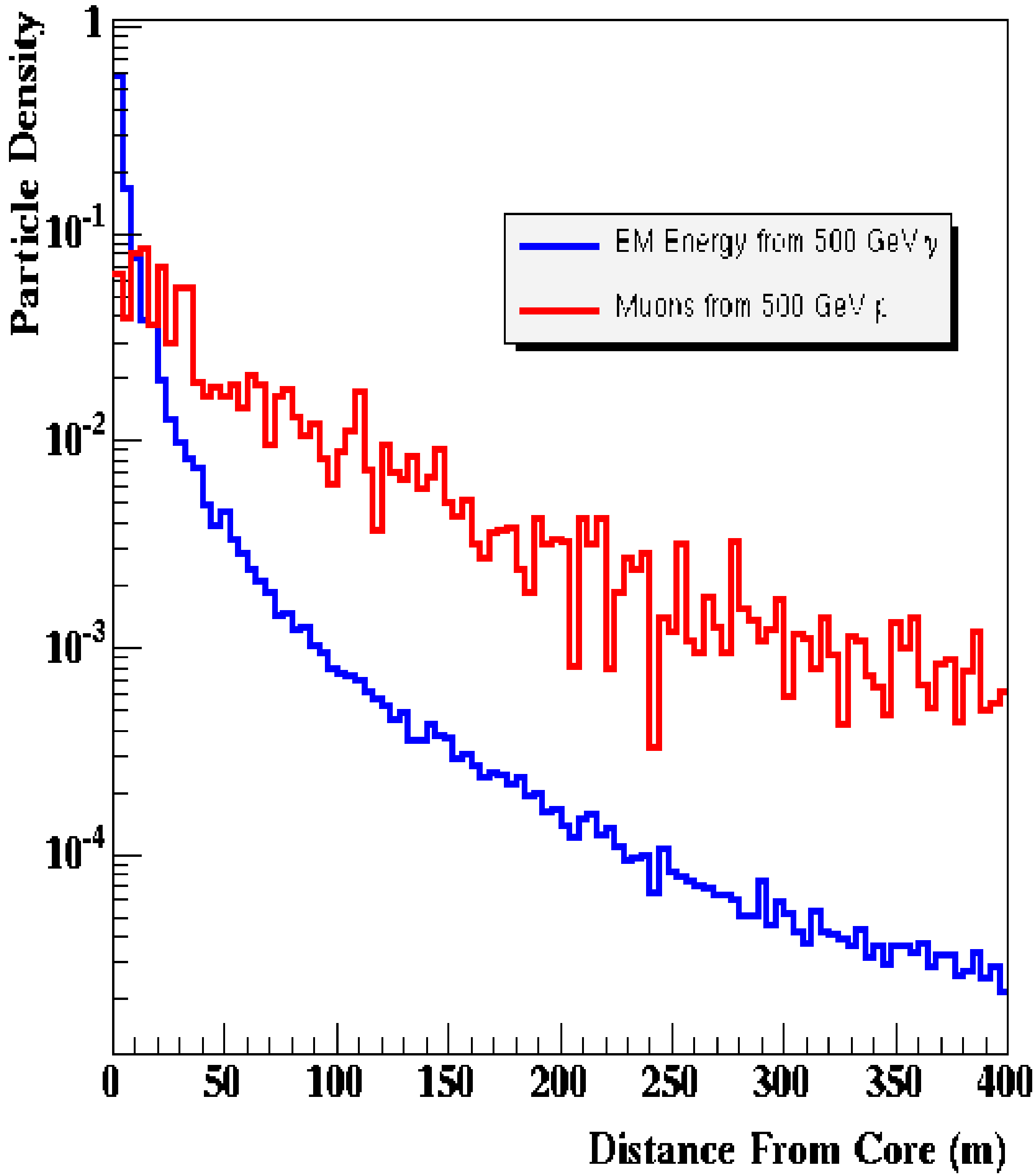


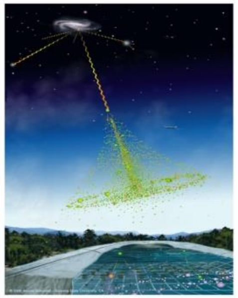
Lateral Distribution of Extensive Air Showers



- Gammas have NARROW lateral distribution of electrons

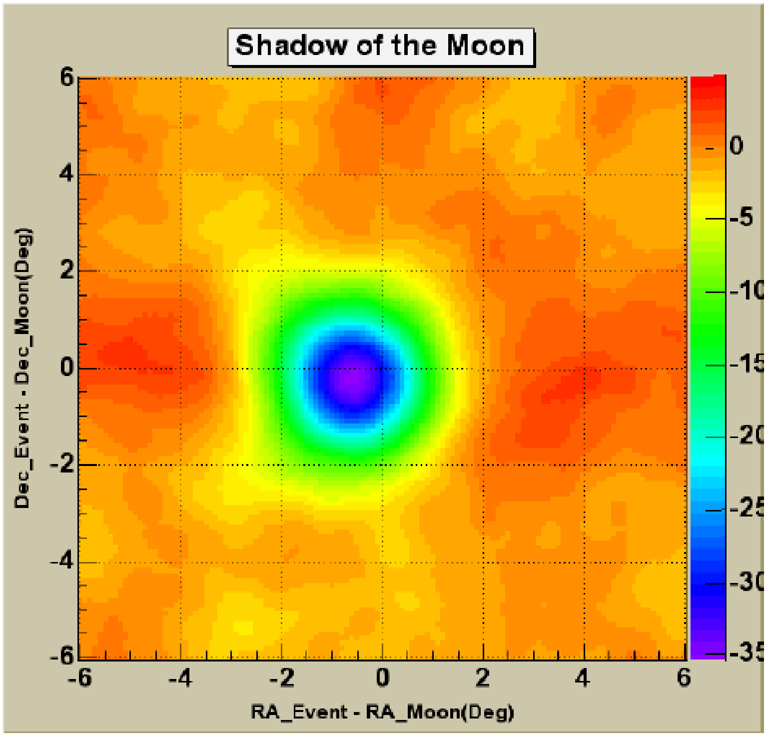
- Protons have BROAD lateral distribution of muons (decays high in atm)



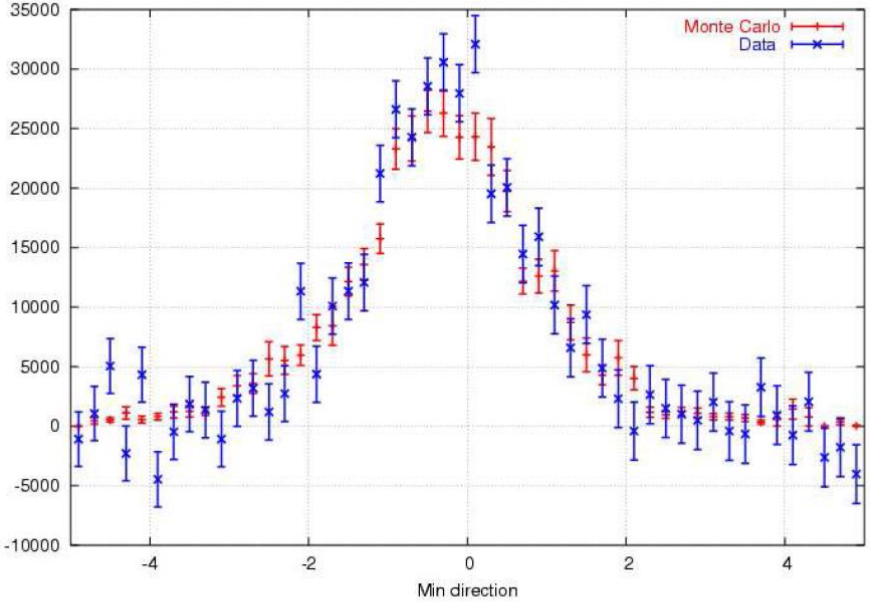


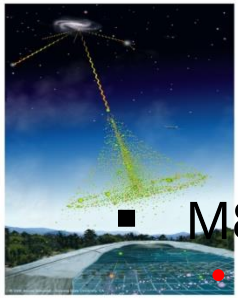
Moon for Monitoring

- Cosmic Rays are Shadowed by the Moon (0.5° dia.)
- Shadow is deflected by Earth's magnetic field at low energies
- 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

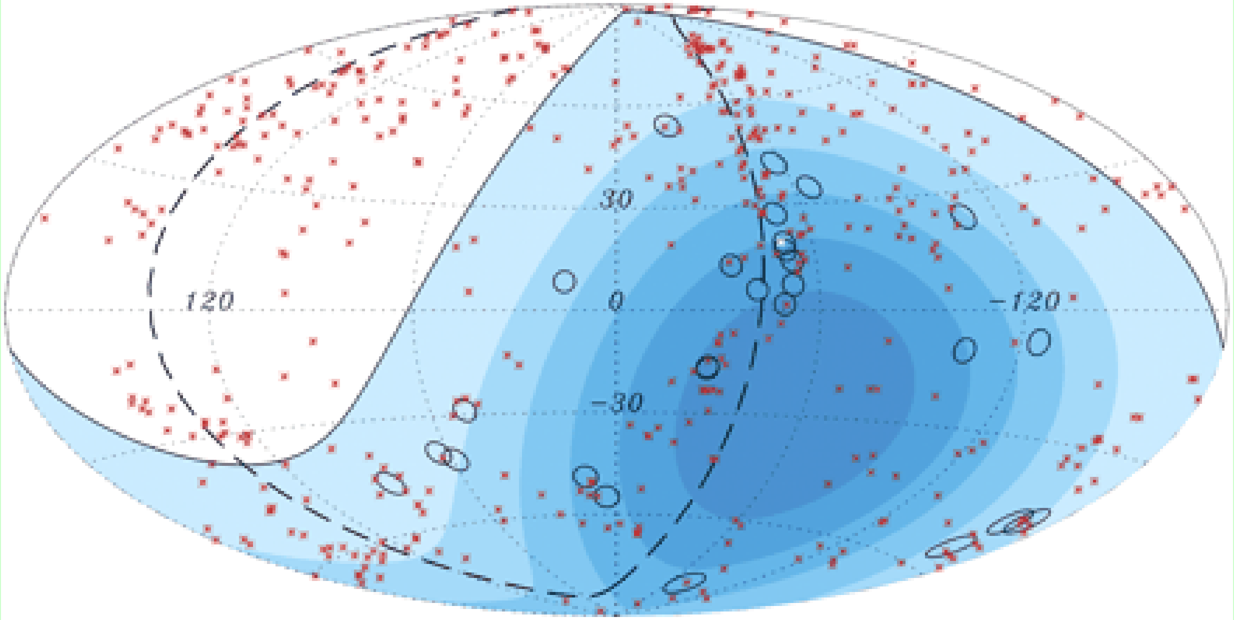


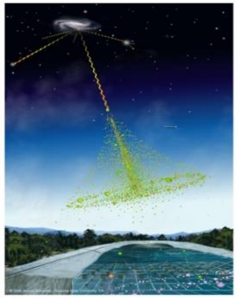


Nearby AGN

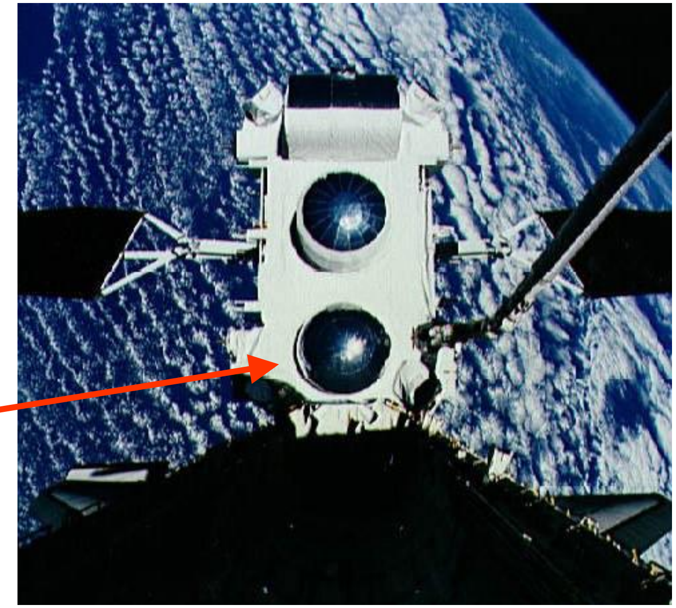
- M87 is a known, variable source of TeV γ-rays
  - HAWC will detect average flux at 5.8σ extending spectra to highest energies & monitoring variability
- Auger's evidence for a correlation of UHECR with AGN point to other nearby particle accelerators
  - UHECR directions are deflected by several degrees, so individual sources can't be determined
  - However, UHECR will produce TeV gamma-rays near the sources due to interactions with the CMB & infrared
  - HAWC can search the 100s of nearby AGN to find UHECR emitters

Auger's 27 UHECRs (black circles) > 6e19eV & nearby, z<0.018, AGN (red *) plotted in Galactic coordinates with the SuperGalactic plane indicated by the dashed line



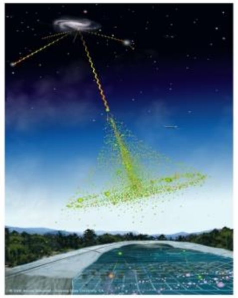


Satellite γ-ray Observatories >30 MeV



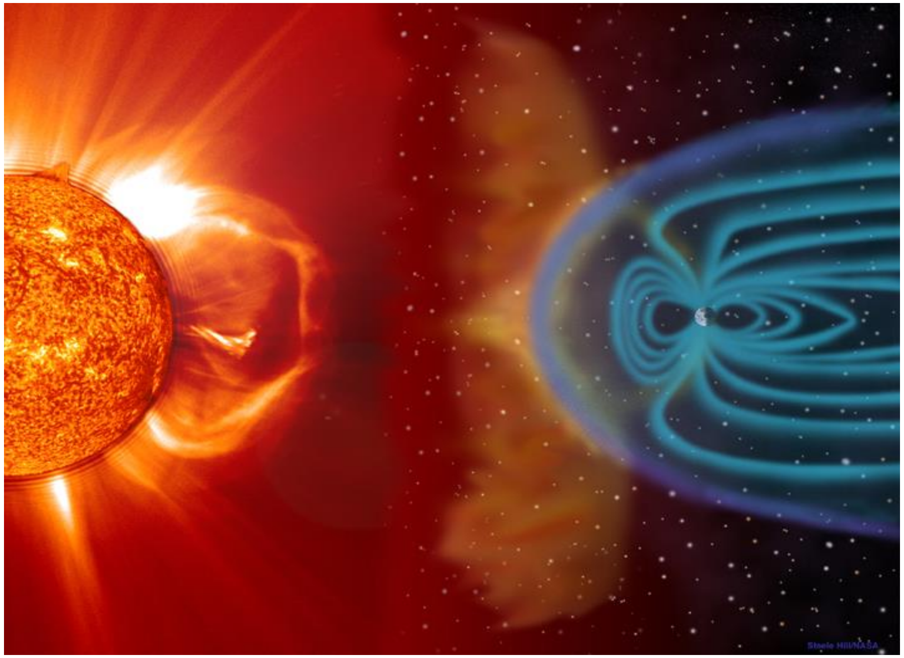
- Pre Compton Observatory
  - SAS2
  - CosB
- EGRET on the Compton Gamma-Ray Observatory (1991-2000)
- GLAST = Fermi Lat

  (May 2008-2018)

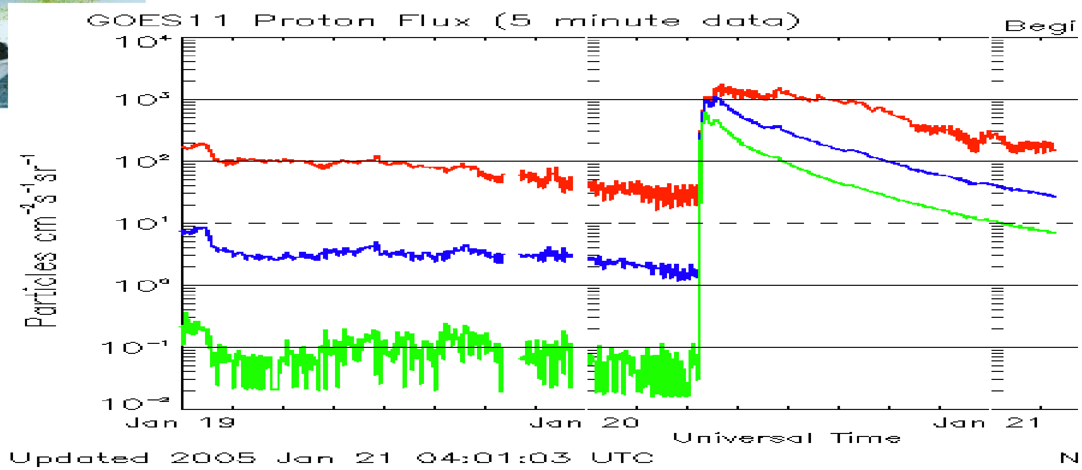


Solar Physics

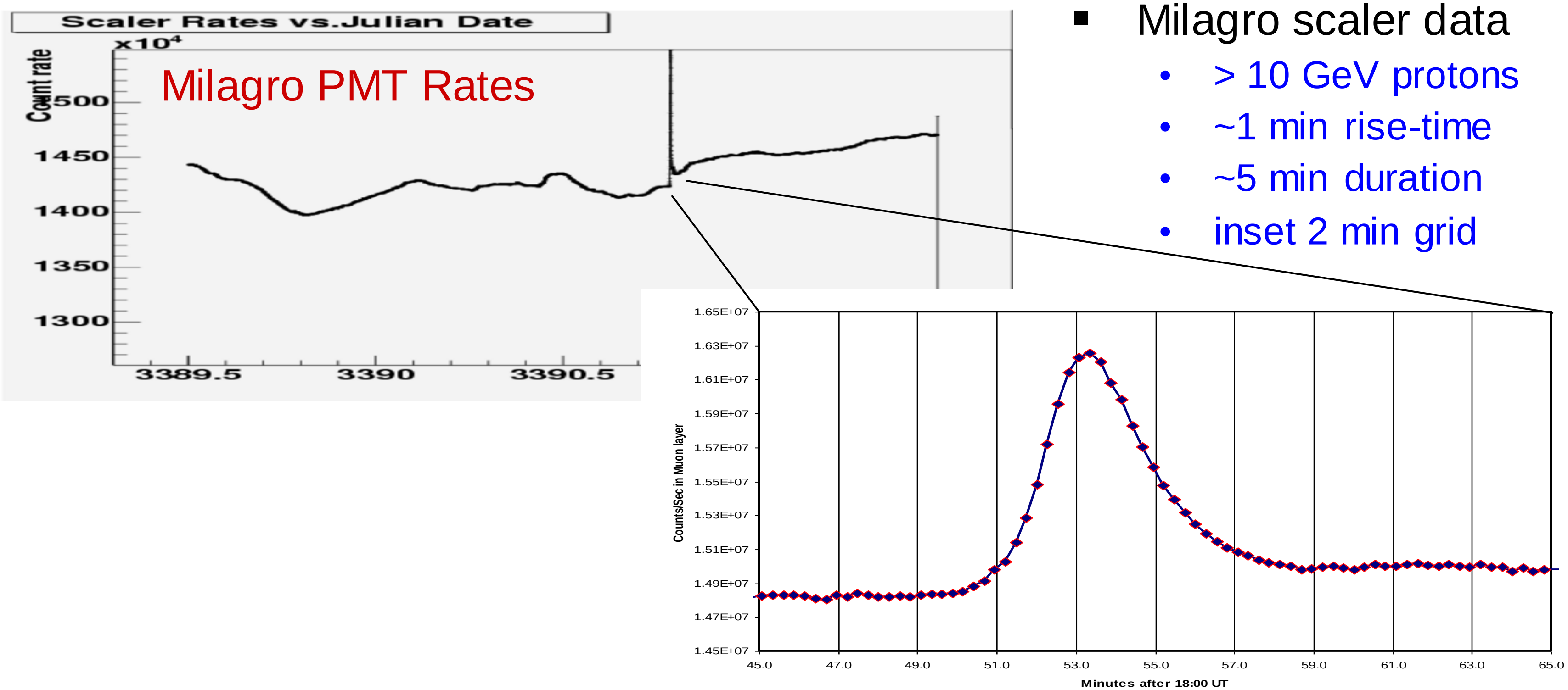
- Coronal mass ejections are an ideal laboratory to study particle acceleration
- By monitoring the singles rates in all PMTs we are sensitive to “low”-energy particles (>10 GeV)
- Milagro has detected 4 outbursts from the Sun with >10 GeV particles



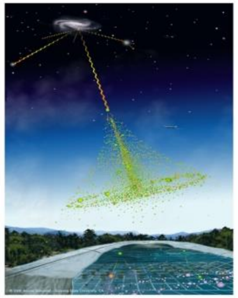
X7-Class flare Jan. 20, 2005



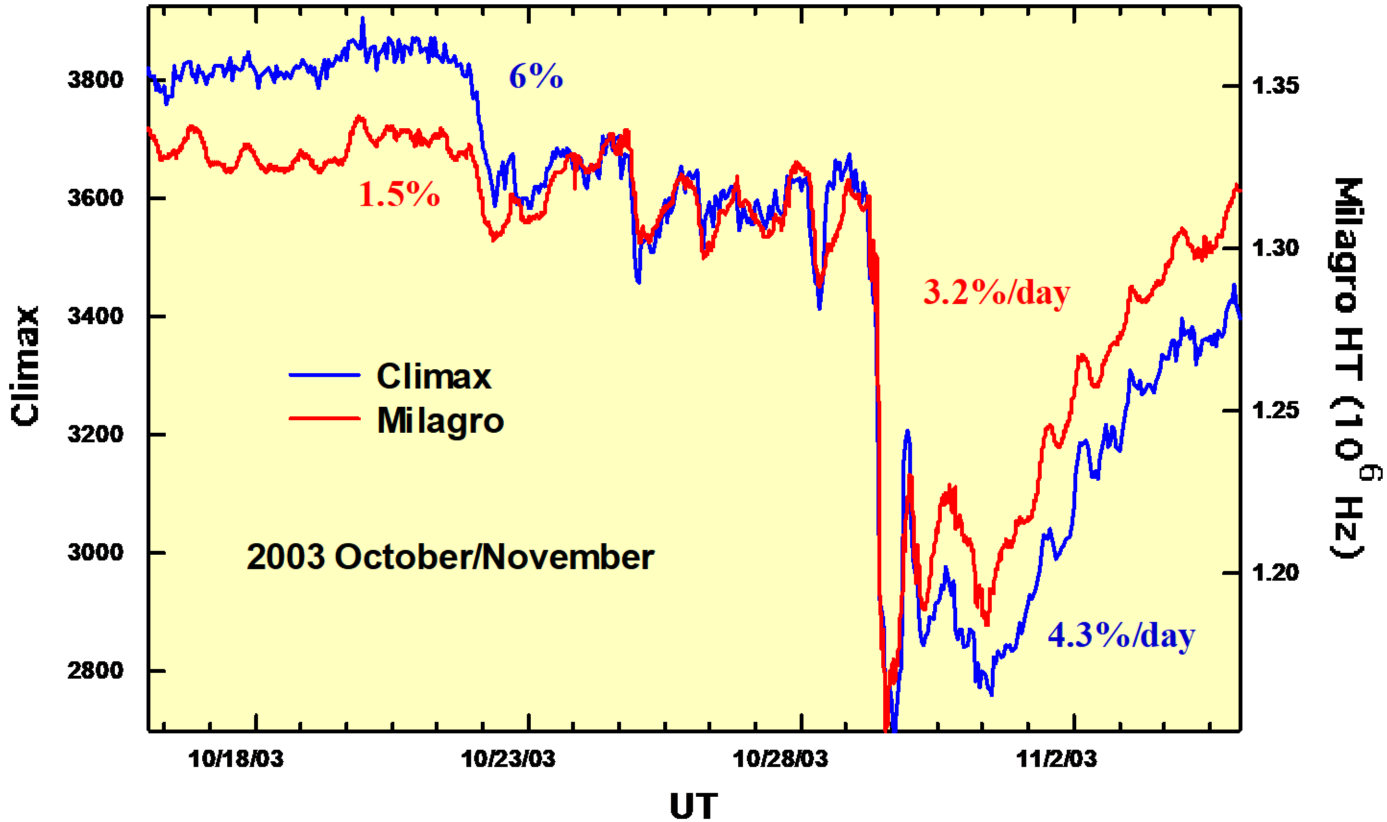
- GOES proton data
  - >10 MeV
  - >50 MeV
  - >100 MeV

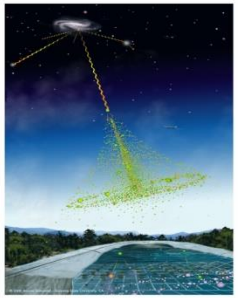


- Milagro scaler data
  - > 10 GeV protons
  - ~1 min rise-time
  - ~5 min duration
  - inset 2 min grid

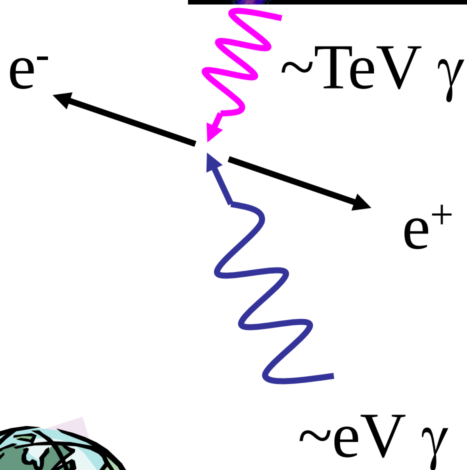


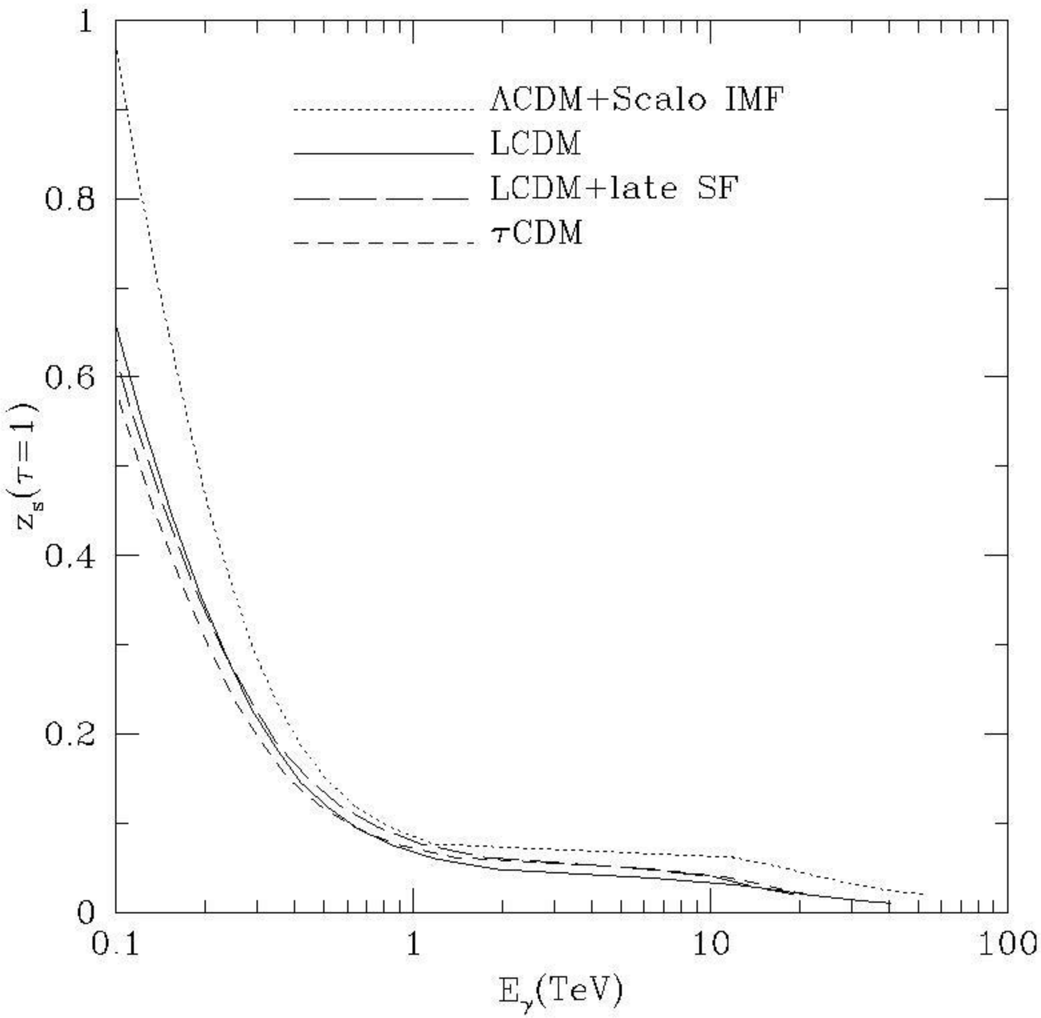
Forbush Decreases – The interplanetary field

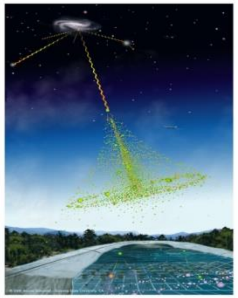




Absorption of TeV Photons

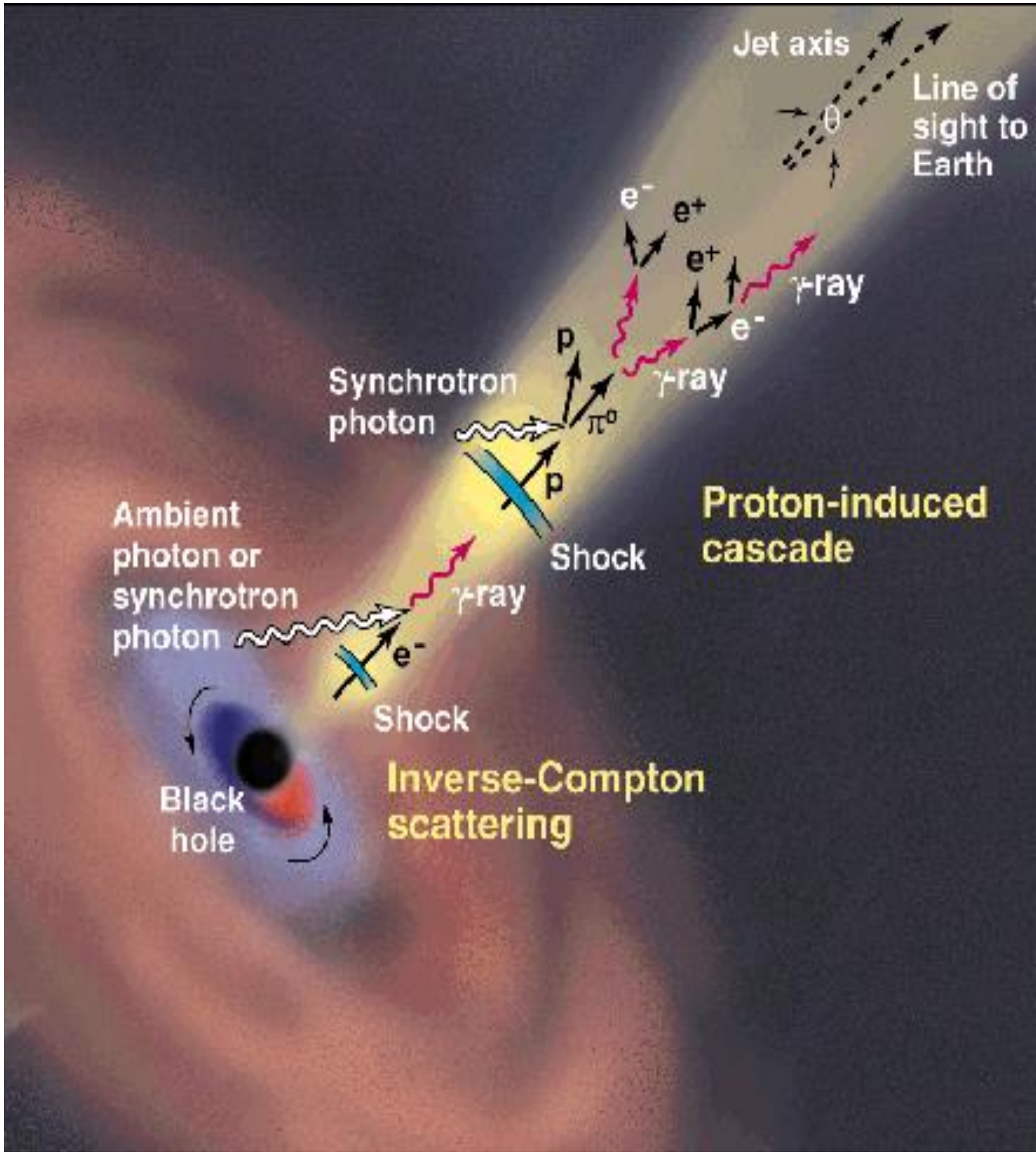






Active Galactic Nuclei

- Open questions
  - Protons or electrons?
  - Plasma Bulk Lorentz factor?
  - B-field?
  - Location of γ-ray production?
  - Acceleration mechanism?
- HAWC observations
  - Many flares from known TeV AGN
  - New TeV AGN
  - Spectra > 1 TeV
  - Multiwavelength Observations with other wide field observatories & by rapid notification



Milagro Observation in Galactic Coordinates