The High Altitude Water Cerenkov (HAWC) Project

Eduardo de la Fuente Acosta for the HAWC Collaboration.
(University of Guadalajara, México)

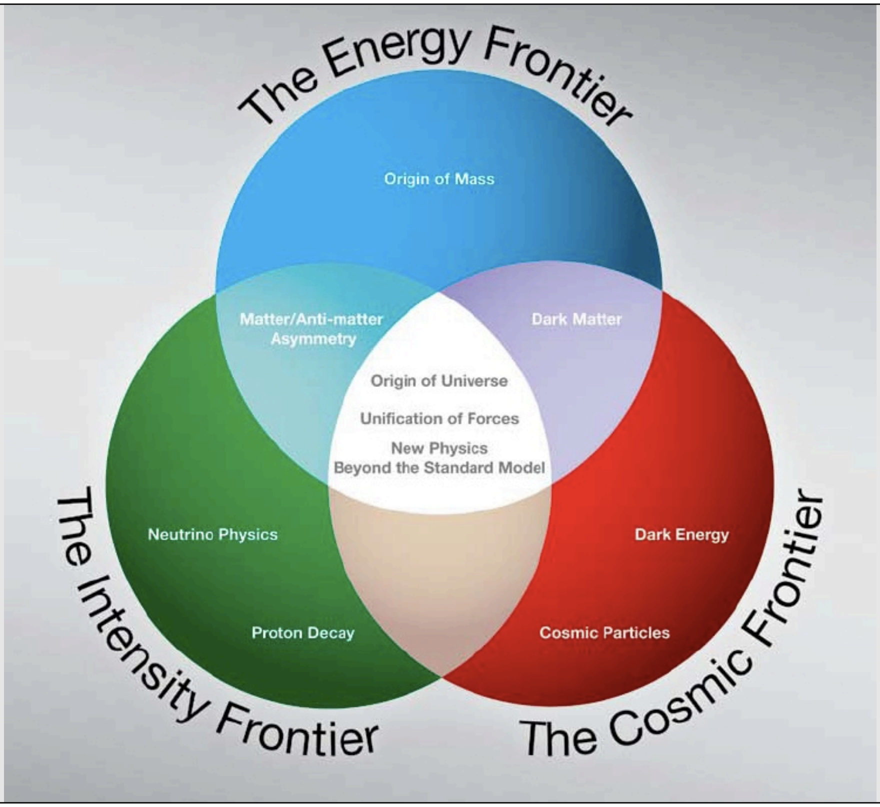
6th Winter Workshop and School on Astroparticle Physics (WAPP 2011), Darjeling, India

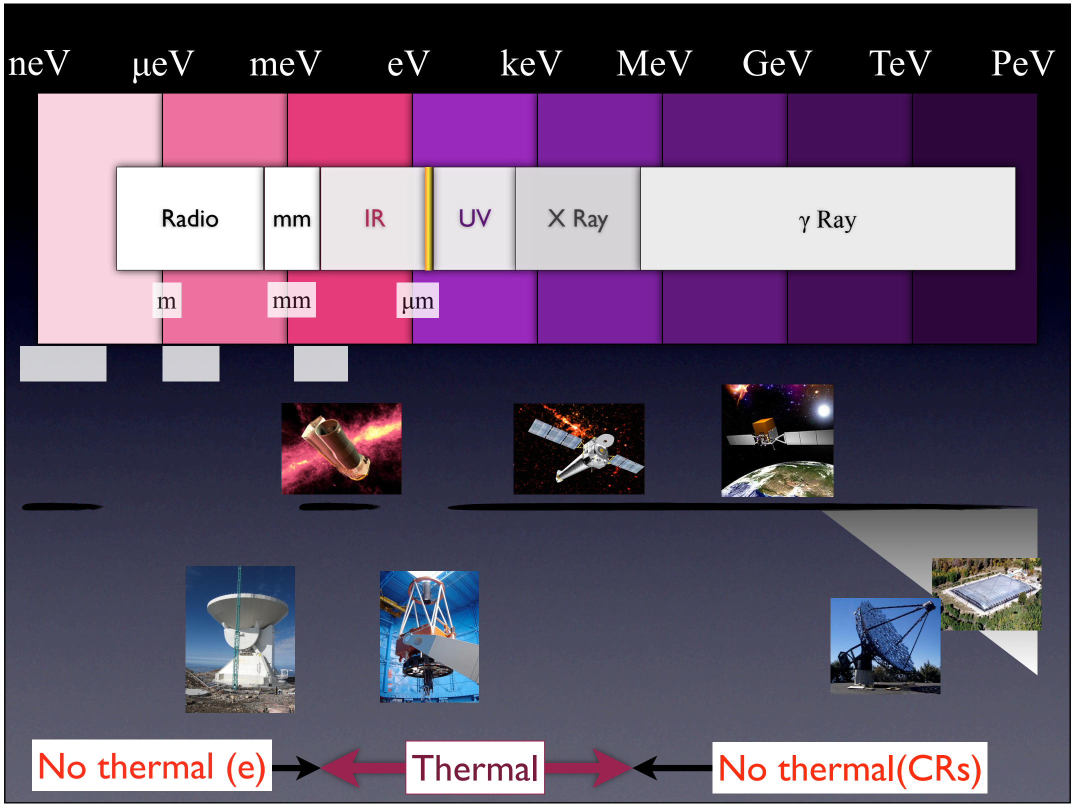
OUTLINE

- THE GAMMA RAY ASTRONOMY
- THE EARTH ATMOSPHERE AS DETECTOR
- CERENKOV RADIATION
- THE “WATER CERENKOV TECHNIQUE”
- THE HAWC PROJECT

OUTLINE

- **THE GAMMA RAY UNIVERSE**
- THE EARTH ATMOSPHERE AS DETECTOR
- CERENKOV RADIATION
- THE “WATER CERENKOV TECHNIQUE”
- THE HAWC PROJECT


The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Dark Energy
Proton Decay
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier



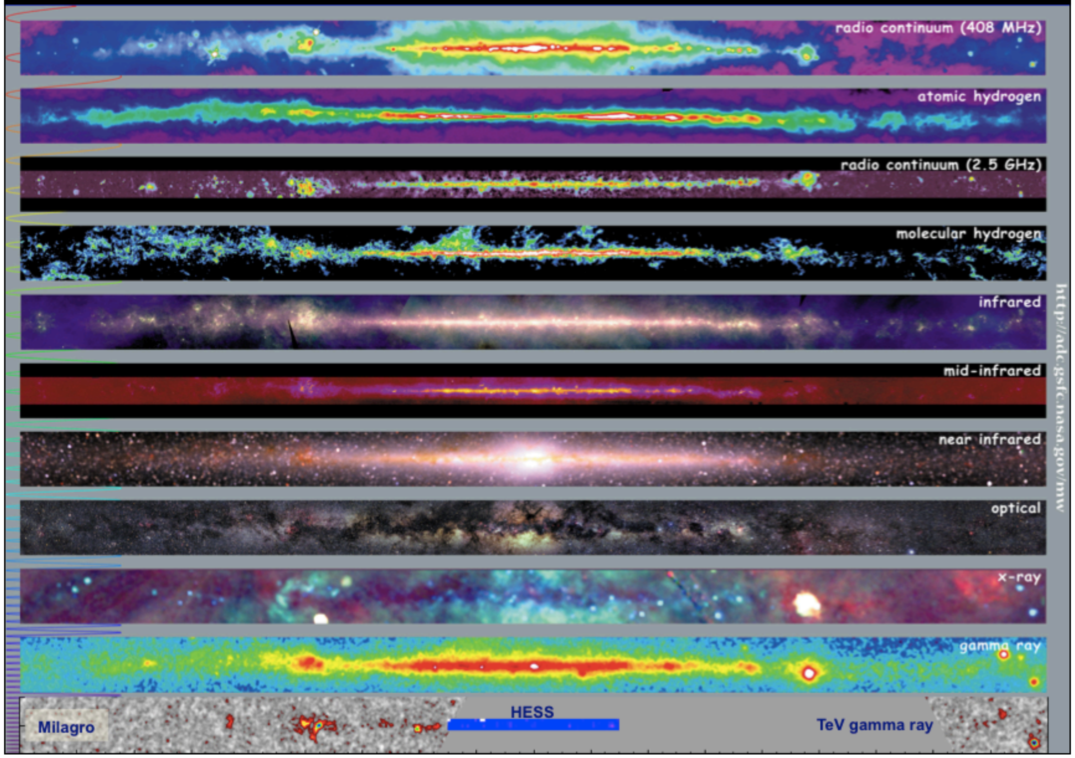
neV μeV meV eV keV MeV GeV TeV PeV

Radio | mm | IR | UV | X Ray | γ Ray

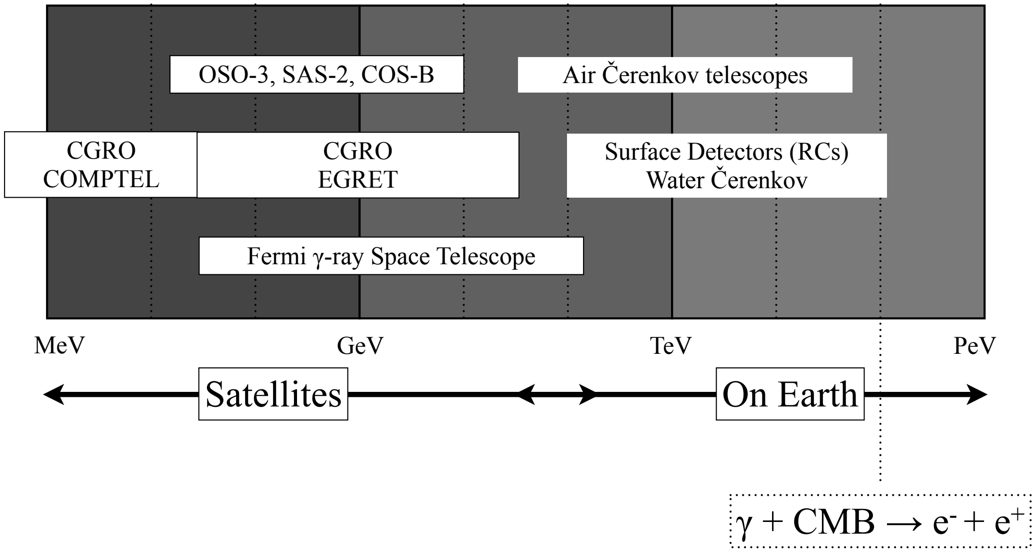
m mm μm

No thermal (e) → ← Thermal → ← No thermal(CRs)

Sky Maps at different Waveleghts



The Gamma Ray band



OSO-3, SAS-2, COS-B

Air Čerenkov telescopes

CGRO
COMPTEL

CGRO
EGRET

Surface Detectors (RCs)
Water Čerenkov

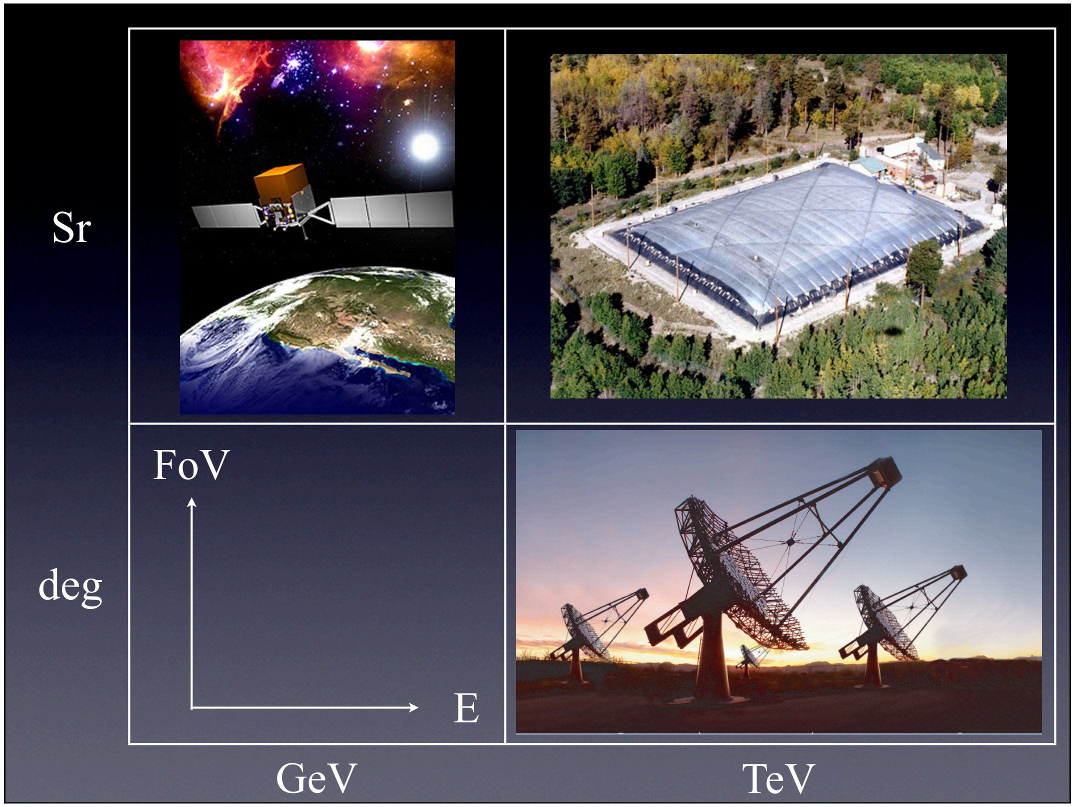
Fermi γ-ray Space Telescope

MeV GeV TeV PeV

Satellites

On Earth

$\gamma + \text{CMB} \rightarrow e^- + e^+$



Sr

deg

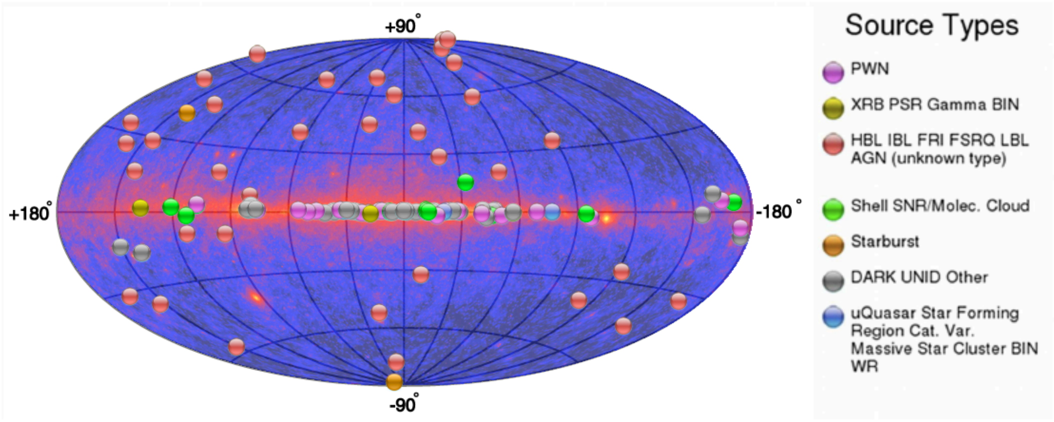
FoV

E

GeV

TeV

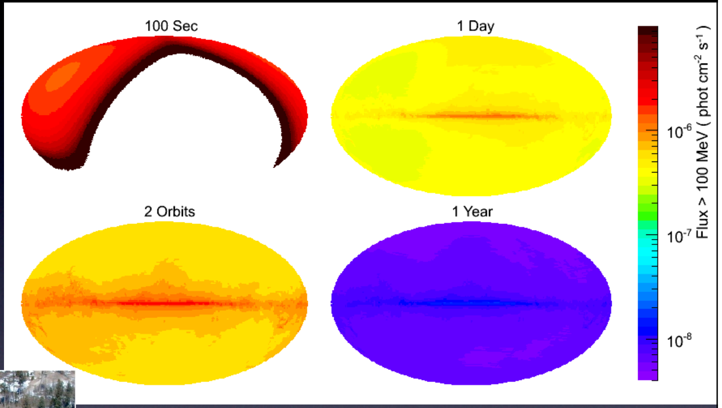
The Gamma-Ray Sky (TeV / GeV)



http://tevcat.uchicago.edu/

FγRST Operation

1 sky survey every 3 hours

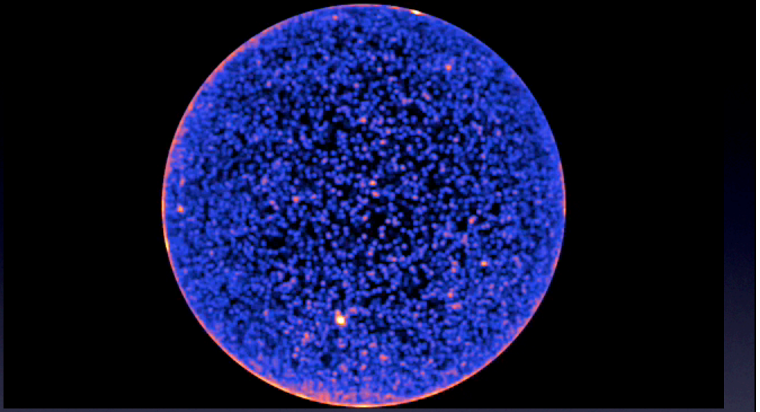


WČO Operation

1 partial sky survey evry 24 horas

Milagro = 55%; HAWC = 66%

11 months Fermi movie of N. Galactic hemisphere



1FGL Catalog	
Extragalactic = 658	
Bl Lac	292
FSRQ	278
AGN no blazar	25
AGN incierto	59
Galaxia starburst	2
Galaxia normal	2
Galactic = 85	
Pulsars	52
SNR	4
snr, pwn, psr	18
Globular Cluster	8
XRB	2
μ-cuasar	1
No association= 708	

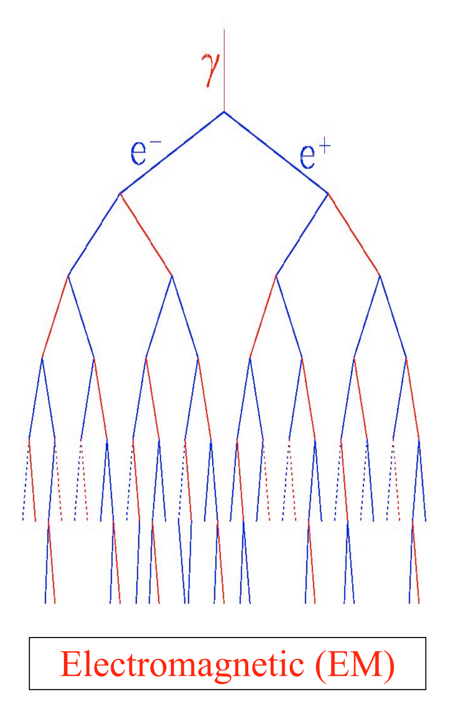
Normal galaxies	Starburst galaxies	Radio galaxies	Seyferts	FSRQ	Bl Lac
MW LMC SMC M31	M82, NGC 253 NGC 4945 (Sb or Sy 2?)	M87, Cen A, NGC1275, NGC1218, NGC 6251	PMN J0948+0022, PKS 1502+036, PKS 2004-447, NGC 6951	Classical EGRETs, 3C 454.3	EGRETs and TeV sources
SF cosmic rays interacting with ISM matter	Larger SF than normal galaxies, no variability found. Weak AGN in M82?	Variable, particle acceleration in mild jet, misaligned AGN	Narrow line Sy1 Sy 2 LINER Seyferts Maybe radio quiet	Highly variable, acceleration in relativistic jet	Steeper γ spectrum, highly variable, acceleration in relativistic jet

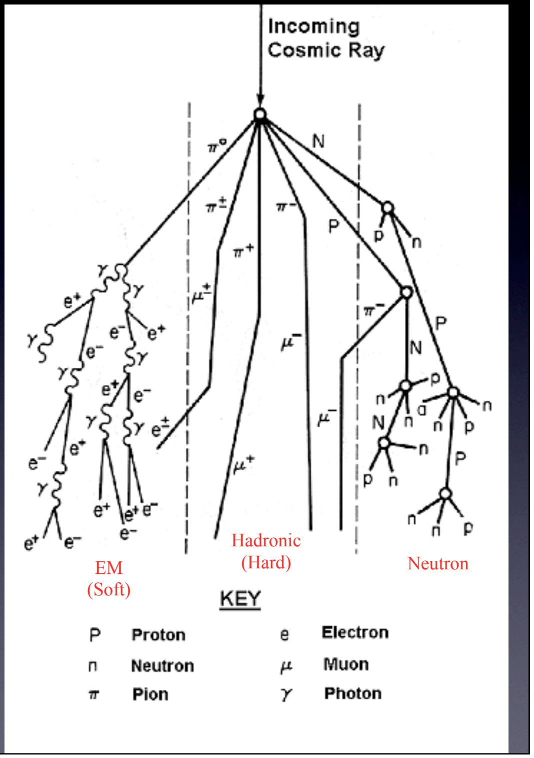
Accelerator power: SFR / Jet / AGN →

OUTLINE

- THE GAMMA RAY UNIVERSE
- **THE EARTH ATMOSPHERE AS DETECTOR**
- CERENKOV RADIATION
- THE "WATER CERENKOV TECHNIQUE"
- THE HAWC PROJECT

THE EARTH ATMOSPHERE AS DETECTOR: PARTICLES AIR SHOWER





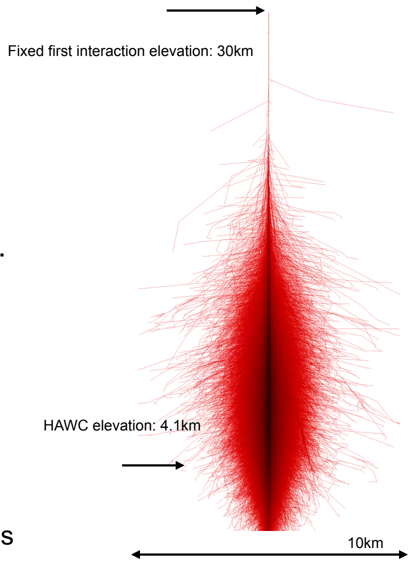
Atmospheric cascades

◆ Prior to shower maximum:

- Exponential growth in particle.
- Energy --> particle creation (pair,brems.)

◆ After shower maximum:

- Exponential decay in particle number.
- Particle energies fall below $E_{Critical}$ ($\sigma_{Compton} > \sigma_{Pair}$).
- Particle spectrum is independent of elevation.
- Energy deposited in atmosphere through ionization.
- For a 1 TeV shower, 100 GeV reaches HAWC observation level.



1 TeV gamma-ray shower Longitudinal Profile

From http://www.ast.leeds.ac.uk/~fs/photon-showers.html

OUTLINE

- THE GAMMA RAY UNIVERSE
- THE EARTH ATMOSPHERE AS DETECTOR
- **CERENKOV RADIATION**
- THE “WATER CERENKOV TECHNIQUE”
- THE HAWC PROJECT

Cherenkov Radiation

- Particle speed must be larger than the phase speed of light in the medium:

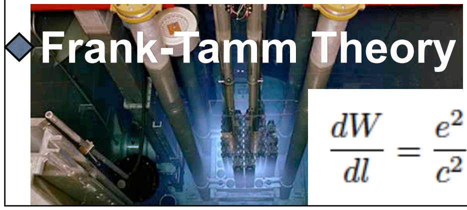
$$\beta > \frac{1}{n};$$

- Radiation with shorter wavelength are more intense:

$$\frac{d^2\mathcal{E}_\omega}{d\omega dz} \propto \omega;$$

- The emission angle of Cherenkov radiation with fixed frequency is also fixed:

$$\theta = \arccos(1/n(\omega)\beta).$$

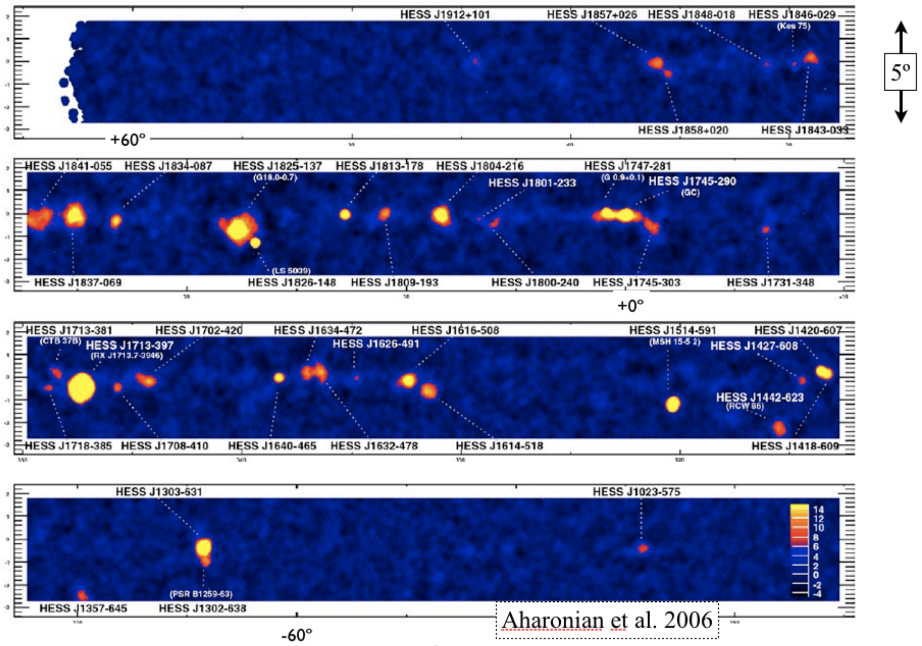


- **Frank-Tamm Theory (1937; Nobel in 1958):**

$$\frac{dW}{dl} = \frac{e^2}{c^2}\int_{\beta n>1}\left(1-\frac{1}{\beta^2 n^2}\right)\omega d\omega$$

HESS Galactic Plane Survey (Air)

Dec. 10: All four H.E.S.S. telescopes operational !

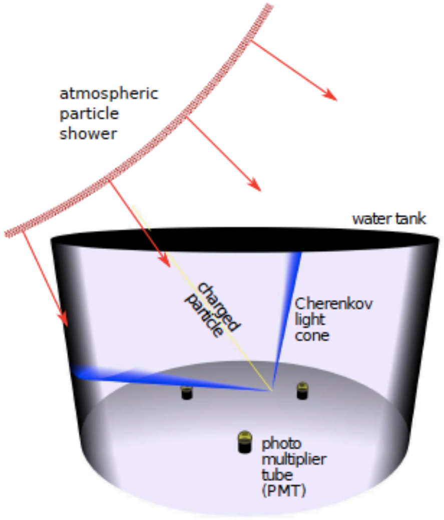


Aharonian et al. 2006

OUTLINE

- THE GAMMA RAY UNIVERSE
- THE EARTH ATMOSPHERE AS DETECTOR
- CERENKOV RADIATION
- **THE “WATER CERENKOV TECHNIQUE”**
- THE HAWC PROJECT

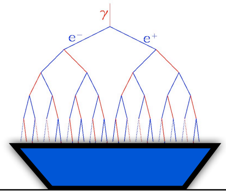
THE “WATER CERENKOV TECHNIQUE”

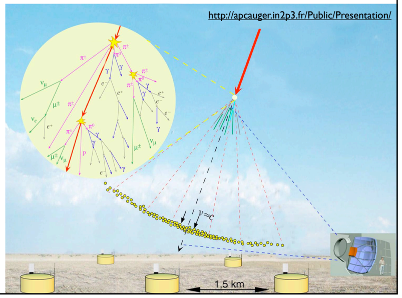


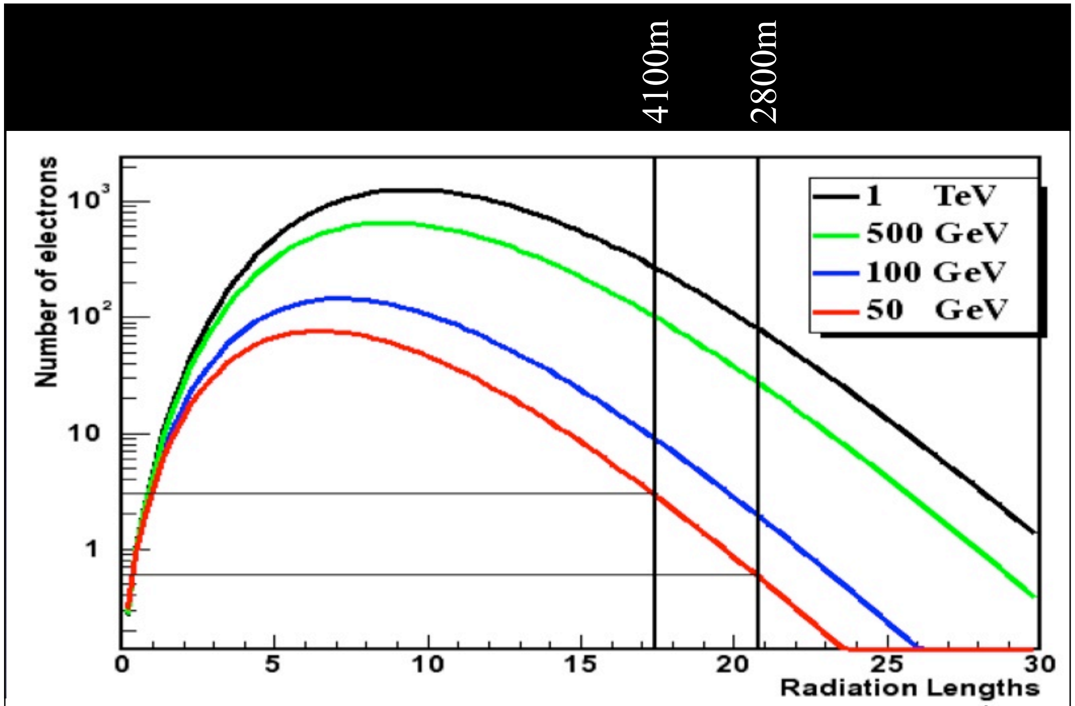
Why using the WC Technique?

Because of:

- large duty cycle ($\approx 95\,\%$)
  (independent of weather and day light)
- large field of view ($\approx 10\,\%$ of $4\,\pi$ sr)
- large effective area
- complementary energy band

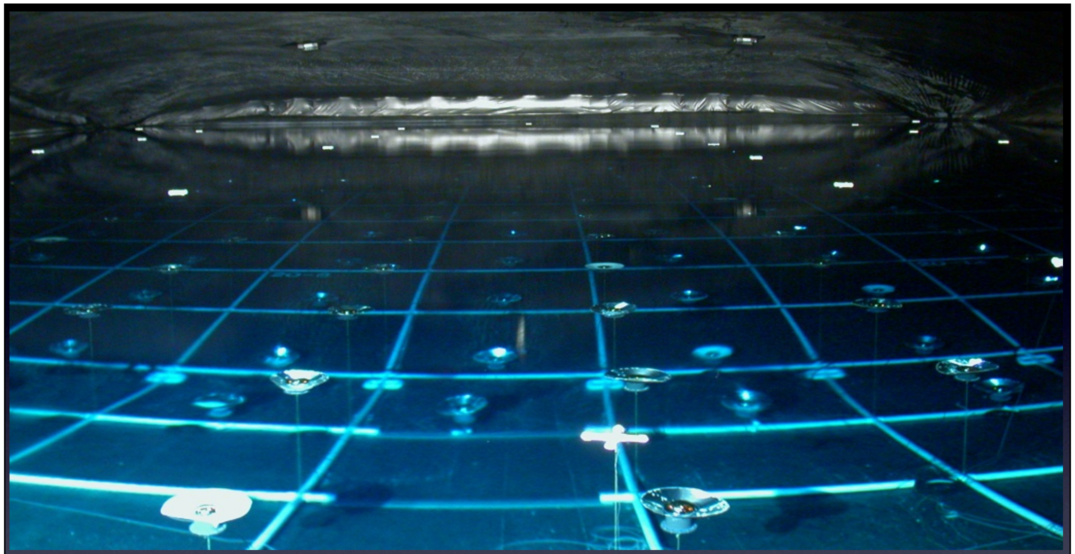


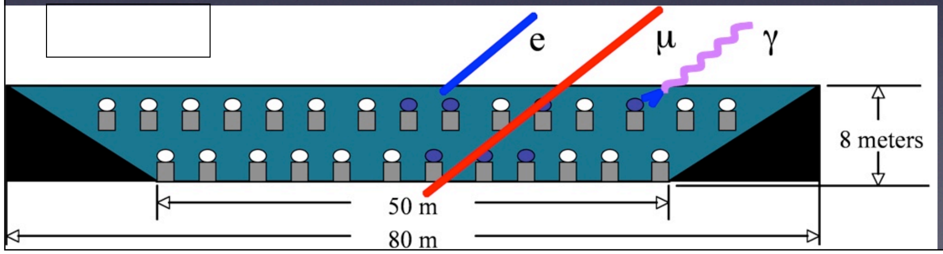


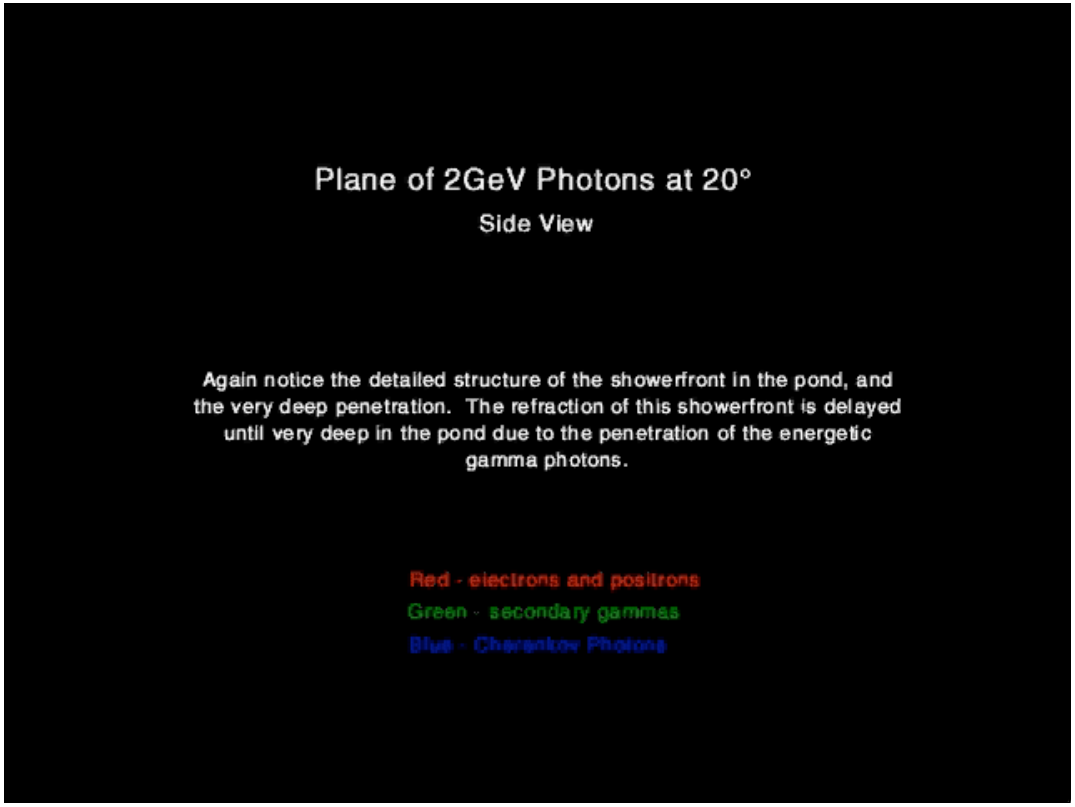


The scale lenght for the energy loss of e and photons when interacts with matter (gr cm-2)

- **MILAGRO**: The First Water Cerenkov Gamma Ray Observatory
- Los Alamos National Laboratory, NM, at 2650m (1999 to 2008)




e
μ
γ
8 meters
50 m
80 m



Plane of 2GeV Photons at 20°

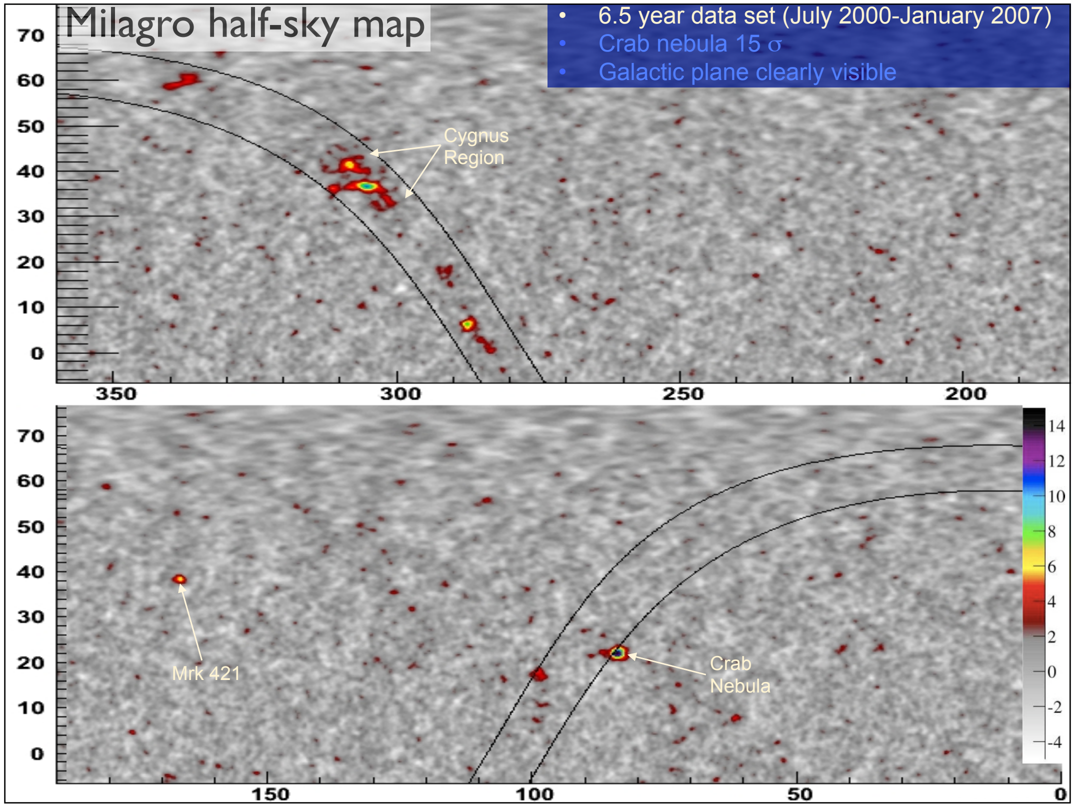
Side View

Again notice the detailed structure of the showerfront in the pond, and the very deep penetration. The refraction of this showerfront is delayed until very deep in the pond due to the penetration of the energetic gamma photons.

Red - electrons and positrons
Green - secondary gammas
Blue - Cherenkov Photons

Milagro half-sky map

- 6.5 year data set (July 2000-January 2007)
- Crab nebula 15 σ
- Galactic plane clearly visible



OUTLINE

- THE GAMMA RAY UNIVERSE
- THE EARTH ATMOSPHERE AS DETECTOR
- CERENKOV RADIATION
- THE “WATER CERENKOV TECHNIQUE”
- **THE HAWC PROJECT**

THE HAWC PROJECT

100 GeV and 100 TeV

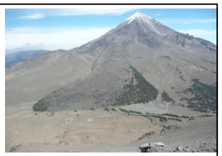
FOV: 15% of the sky.

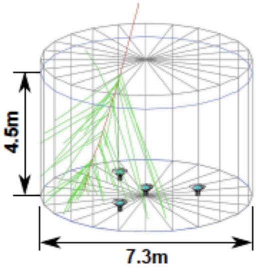
Exposed to half of the sky: 24-hour

Effective Area: 22,000 m2

Water per tank: 200,000 liters

PMT: Hamamatsu R5912 20 cm





- ◆ location: Sierra Negra, Mexico (3.5 h east of Mexico City)
- ◆ 4100m above MSL
- ◆ 300 water filled tanks
- ◆ 4 PMTs per tank
- ◆ main DAQ system: CAEN TDC VME modules (Mod. VX1190)
- ◆ scaler DAQ system: Struck scaler VME modules (Mod. SIS3820)

$\approx 15\times$ Milagro sensitivity!

HAWC

The High-Altitude Water Cherenkov Gamma-Ray Observatory

The HAWC Collaboration (México-USA)

USA

- George Mason University
- Georgia Institute of Technology
- Harvey Mudd College
- Los Alamos National Laboratory
- Michigan State University
- Michigan Technical University
- NASA/Goddard Space Flight Center
- Ohio State University at Lima
- Pennsylvania State University
- Univ. of California, Irvine
- University of Maryland
- University of New Hampshire
- University of New Mexico
- University of Utah
- University of Wisconsin

México

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

HAWC TIME SCALE AND FUNDING

HAWC Time Scale:

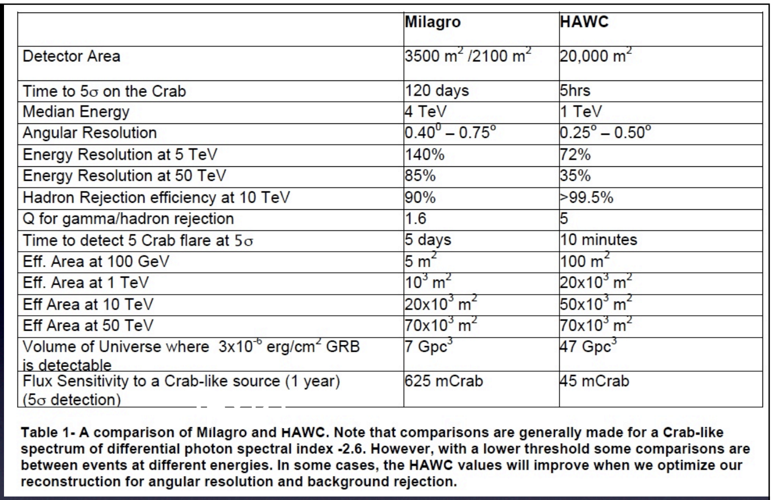
- Fall 2011: VAMOS collects 1-3 months of data
  (scaler sensitivity $\gtrsim$ Milagro scalers)
- Spring 2012: HAWC-30
  (main DAQ sensitivity $\gtrsim$ Milagro)
- Spring 2013: HAWC-100
  (Begin of regular science operations)
- Fall 2014: HAWC-300, end of construction
  (main DAQ $\approx$ 15$\times$ and
  (scaler DAQ $\approx$ 30$\times$
  more sensitive then Milagro)

Funding:

- $\approx$ 7 M USD from NSF (University of Maryland)
- $\approx$ 3 M USD DOE (LANL)
- $\approx$ 3 M USD CONACyT (UNAM and INAOE)
- $\approx$ 3 M USD LANL LDRD funding for 4th PMT

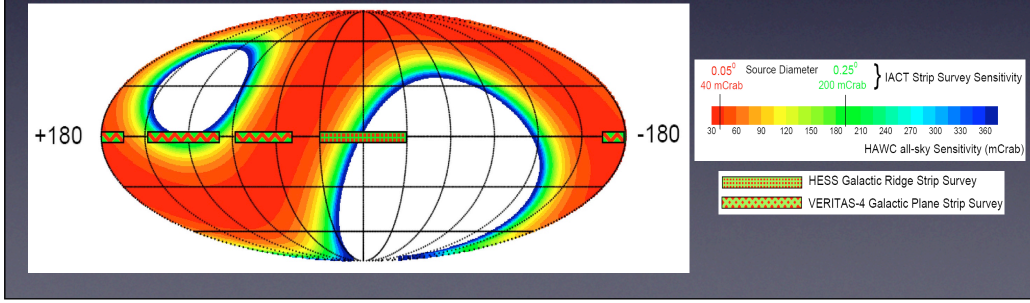
The HAWC Collaboration (México-USA)

HAWC vs. Milagro

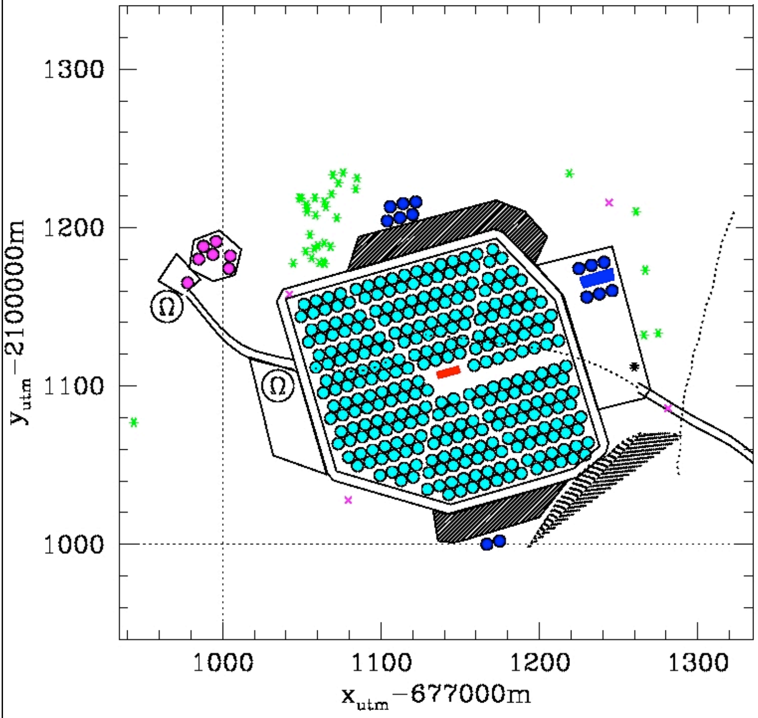


	Milagro	HAWC
Detector Area	3500 m^2 /2100 m^2	20,000 m^2
Time to 5σ on the Crab	120 days	5hrs
Median Energy	4 TeV	1 TeV
Angular Resolution	0.40^{0} – 0.75°	0.25° – 0.50°
Energy Resolution at 5 TeV	140%	72%
Energy Resolution at 50 TeV	85%	35%
Hadron Rejection efficiency at 10 TeV	90%	>99.5%
Q for gamma/hadron rejection	1.6	5
Time to detect 5 Crab flare at 5σ	5 days	10 minutes
Eff. Area at 100 GeV	5 m^2	100 m^2
Eff. Area at 1 TeV	10^3 m^2	20x10^3 m^2
Eff Area at 10 TeV	20x10^3 m^2	50x10^3 m^2
Eff Area at 50 TeV	70x10^3 m^2	70x10^3 m^2
Volume of Universe where 3x10^{-6} erg/cm^2 GRB is detectable	7 Gpc^3	47 Gpc^3
Flux Sensitivity to a Crab-like source (1 year) (5σ detection)	625 mCrab	45 mCrab

Table 1- A comparison of Milagro and HAWC. Note that comparisons are generally made for a Crab-like spectrum of differential photon spectral index -2.6. However, with a lower threshold some comparisons are between events at different energies. In some cases, the HAWC values will improve when we optimize our reconstruction for angular resolution and background rejection.

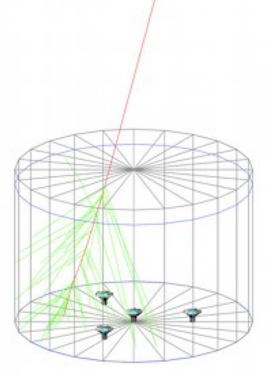


THE HAWC ARRAY LAYOUT AND TANKS



Water:
$n \approx 1.33$
$\Rightarrow \gamma m_e c^2 \approx 0.775$ MeV
$\Rightarrow \theta_c = \cos(1/n) = 41°$

Air:
$n \approx 1+3\times10^{-4}$
$\Rightarrow \gamma m_e c^2 \approx 21$ MeV
$\Rightarrow \theta_c = \cos(1/n) = 1.4°$

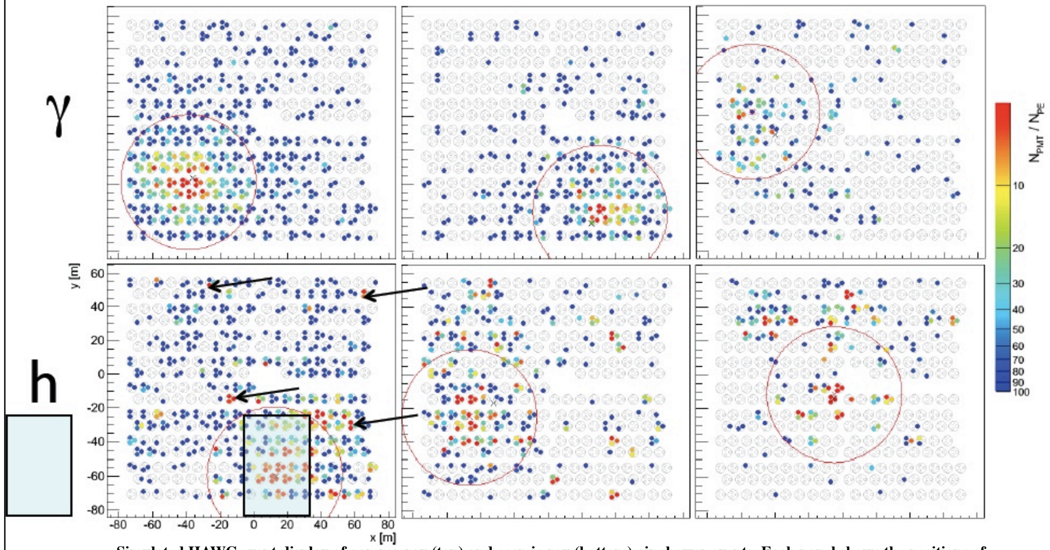


Because the Cherenkov cone in water is so large, nearly every charged particle that enters the tank should be observed by at least one of the four PMTs

HAWC Gamma Hadron Separation

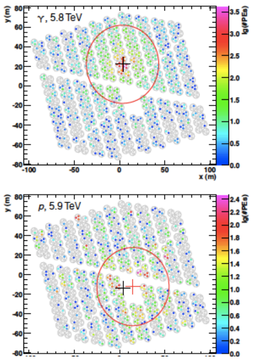
The reconstruction algorithm identifies the PMT with the highest measured number of PEs at a radial distance of at least 40 m from the reconstructed core. This number is denoted CxPE40 .

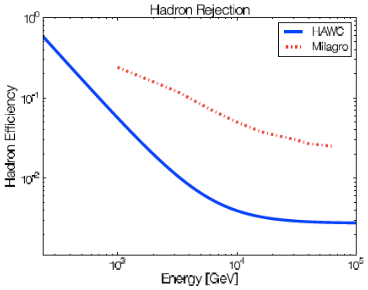
$$S = \frac{N_{\text{hit}}}{\text{CxPE}_{40}}$$



Simulated HAWC event display of gamma-ray (top) and cosmic-ray (bottom) air shower events. Each panel shows the positions of PMTs and hits for an event, where the hits are color coded according to the ratio of total number of hits in the event to the number of photoelectrons in the given hit. Red coloring indicates hits with a larger fraction of the total event charge. A circle with a 40 m radius is drawn, centered on the position of the shower core. Colors: How hard a channel was hit in the photoelectrons (PE) scaled to the number of hit channels in the ful event

HAWC PERFORMANCE: G/H cont.





G/H separation is done by using the granularity of the shower foot print in the detector.

$$S = \frac{N_{\mathrm{hit}}}{\mathrm{CxPE}_{40}}$$

Given a fixed N hit, a large value of S implies a more gamma–like shower, while a smaller S is considered to be more hadron–like.

◆ The optimal value on which to cut S (separator) is determined by maximizing the signal to noise ratio for a given range of N hit values while keeping at least 50% of the gamma rays.

◆ Events with S above the optimal value are treated as gamma rays while those below are treated as hadrons.

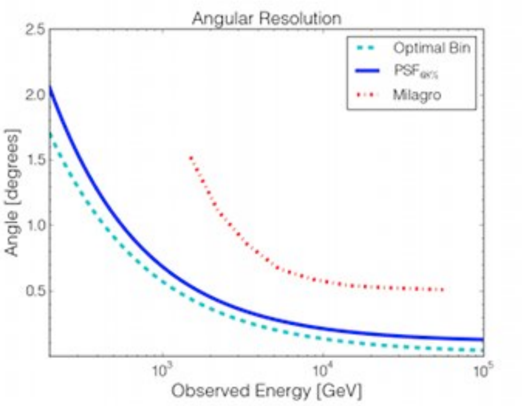
◆ The Figure shows the resulting efficiency for hadrons to pass the optimized cut on S for a given energy.

As the energy increases the efficacy of the cut improves, eliminating an increasing fraction of hadrons from observations.

HAWC PERFORMANCE: Angular Resolution

The angular resolution is defined as the typical error made when reconstructing the arrival direction of an air shower.

- **The angular resolution of HAWC is a significant improvement over that of Milagro. This is primarily due to its larger deep–water area and the optical isolation of the detectors, which will improve the accuracy of the reconstruction of the air-shower frony**



- **PSF68% is the 68th percentile of the distribution of opening angles between the true and reconstructed directions of simulated events.**

- **The optimal bin size describes the angular scale on which the signal to noise ratio is maximized for a given source and background. Here an object with a Crab–like spectrum transiting at 30○ from zenith is assumed for the source.**

- **The angular resolution of the HAWC observatory is about 0.1° for energies >10 TeV (0.35° E ~ 1 TeV). It improves with energy because the number of triggers increases with energy, in turn increasing the information available to the shower track fit. This resolution is a tremendous improvement over the Milagro detector, in which the best angular resolution was about 0.5°.**

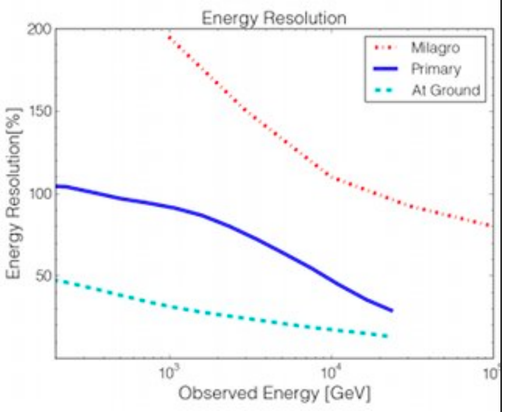
  The optimal bin size falls below 1○ at ~500 GeV while Milagro attained a similar angular resoluction only for showers ~3 TeV

HAWC PERFORMANCE: Energy Resolution

- **The number of PEs recorder by the WCD is a good estimator of the enrgy of the EM shower at ground level. The signal can be converted to an estimate of the energy of the primary particle.**

- **The energy resolution refers to the typical error made when estimating the energy of the primary particle which initiated an air shower. A small energy resolution is an advantage because it allows for an unbiased estimate of the energy spectra of observed sources.**

- **The expected energy resolution of HAWC has been calculated with simulated events. Above 10 TeV the energy resolution is below 50% — i.e., the energy of the particles observed above this threshold will by reconstructed to within 50% of the true energy. This is a major improvement over the energy resolution of Milagro, which was >100% for nearly all energies.**

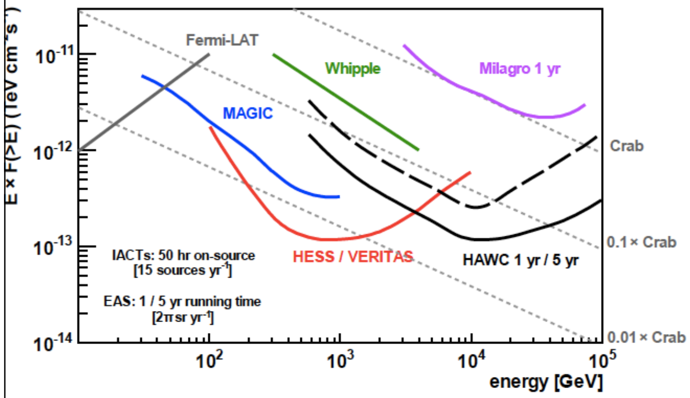


- **The Figure shows the energy resolution for gamma–ray induced air showers arriving well within the instrumented area of the detector and less than 45° from zenith for both HAWC and Milagro.**

  Resulting resolution of the primary gamma–ray energy is about 100 % below 2 TeV and falls gradually with increasing energy

HAWC PERFORMANCE; SENSITIVITY

Because the flux of gamma rays from all sources drops rapidly as a function of energy, observations of sources require a large effective area and long integration times, especially if the goal is to observe gamma rays above 10 TeV.



ACTs typically observe sources for < 50 hours, and survey observations last for about 10 hours. At energies above roughly 6 TeV, the HAWC single-year sensitivity is better than the sensitivity of 50 hours of observation of a single source with VERITAS or HESS.

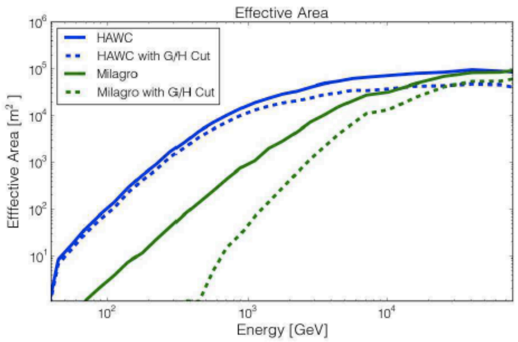
An IACT can only spend up to about 200 hours per year observing a single interesting source due to ambient light and weather. Above 10 TeV, the sensitivity of HAWC is better than the current generation of IACTs.

10 TeV is an important threshold because gamma-ray emission due to electron scattering of low-energy photons is expected to become inefficient at high energies. Sources with hard spectra above 10 TeV could the best candidates for acceleration of protons and other cosmic ray particles. With HAWC differentiate a hadronic gamma-ray spectrum from a leptonic spectrum with an exponential cutoff at 40 TeV is possible. HAWC is able to measure 20 gamma rays above 100 TeV from a source with a spectral index of -2.3 and 20% of the flux of the Crab

HAWC PERFORMANCE; EFFECTIVE AREA

$$A_{eff}(E,\theta) = A_{thrown}\frac{N_{observed}(E,\theta)}{N_{thrown}(E,\theta)}$$

where A_{thrown} is the area over which simulated events are thrown, $N_{observed}$ is the number of events passing some specified cuts and N_{thrown} is the number of events thrown in the simulation.



- Effective area of HAWC along with the effective area of the predecessor experiment Milagro for comparison. Above about 1 TeV, the effective area approaches the geometrical footprint of the experiment and at lower energies the effective area is reduced due to the tendency of lower energy air showers to result in few energetic particles on the ground
- **Obtained by selecting events with more than 70 PMTs hit and by insisting that events are well-reconstructed and within the optimal analysis bin of a source of a hypothetical source.**

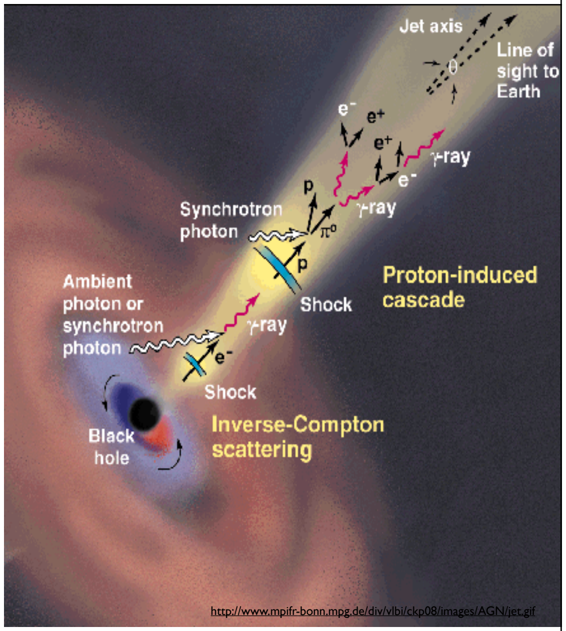
HAWC Science Objectives

One of the primary goals of HAWC is to identify new TeV gamma-ray sources and extend measurements of known sources to higher energies

- Observation of sources in the galactic plane at high energies
  - verification of galactic CR accelerators
  - measurement of source energy spectra up to 100 TeV
- Measurement of the galactic diffuse gamma-ray flux
  - diffuse spectrum above 10 TeV
  - spacial resolution of diffuse emission at TeV energies
  - extending diffuse gamma-ray measurements to higher energies (→ protons)
- Active galactic nuclei (AGN) transient emission
- Observation of large and medium scale cosmic ray anisotropies
- Gamma-ray burst (GRB) observation
- Fundamental physics

Active Galactic Nuclei

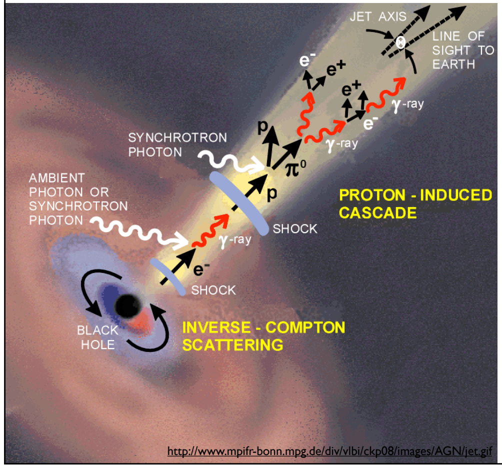
- Open questions
  - Protons or electrons?
  - Plasma Bulk Lorentz factor?
  - B-field?
  - Location of γ-ray production?
  - Acceleration mechanism?
- HAWC observations
  - Flares from known TeV AGN
  - New TeV AGN
  - Spectra > 1 TeV
  - Multiwavelength Observations with other wide field observatories & rapid notification
- HAWC science
  - Average Flux & Spectra
  - Duty Cycle
  - Unbiased Survey
  - Constraints on Extragalactic Background Light (EBL)



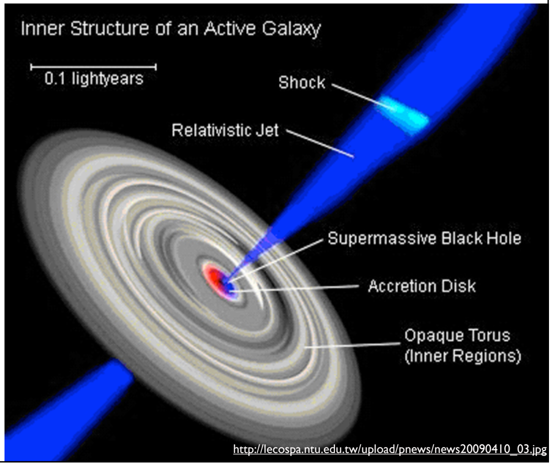
http://www.mpifr-bonn.mpg.de/div/vlbi/ckp08/images/AGN/jet.gif

AGN Monitoring

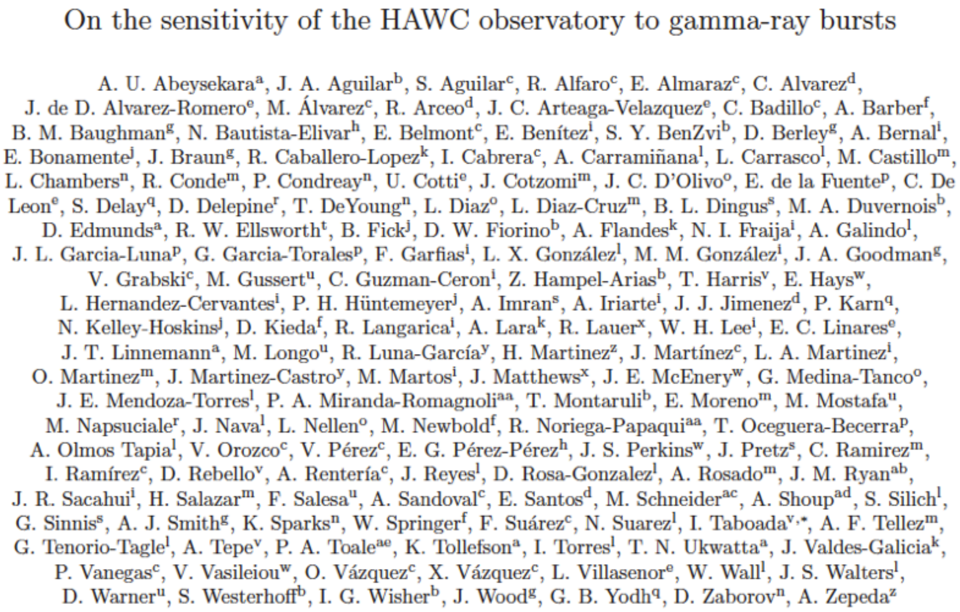
- HAWC will obtain duty factors and notify multiwavelength observers of flaring AGN in real time.
- All sources within ~ 3π sr would be observed every day for ~ 5 hrs.
- HAWC's continuous observations would not have gaps due to weather, moon, or solar constraints.
  - HAWC's 5 σ sensitivity is (10,1,0.1) Crab in (3 min, 5 hrs, 1/3 yr)



http://www.mpifr-bonn.mpg.de/div/vlbi/ckp08/images/AGN/jet.gif



http://lecospa.ntu.edu.tw/upload/pnews/news20090410_03.jpg



◆

On the sensitivity of the HAWC observatory to gamma-ray bursts

A. U. Abeysekara[a], J. A. Aguilar[b], S. Aguilar[c], R. Alfaro[c], E. Almaraz[c], C. Alvarez[d],
J. de D. Alvarez-Romero[e], M. Álvarez[c], R. Arceo[d], J. C. Arteaga-Velazquez[e], C. Badillo[c], A. Barber[f],
B. M. Baughman[g], N. Bautista-Elivar[h], E. Belmont[c], E. Benítez[i], S. Y. BenZvi[b], D. Berley[g], A. Bernal[i],
E. Bonamente[j], J. Braun[g], R. Caballero-Lopez[k], I. Cabrera[c], A. Carramiñana[l], L. Carrasco[l], M. Castillo[m],
L. Chambers[n], R. Conde[m], P. Condreay[n], U. Cotti[e], J. Cotzomi[m], J. C. D'Olivo[o], E. de la Fuente[p], C. De
Leon[e], S. Delay[q], D. Delepine[r], T. DeYoung[n], L. Diaz[o], L. Diaz-Cruz[m], B. L. Dingus[s], M. A. Duvernois[b],
D. Edmunds[a], R. W. Ellsworth[t], B. Fick[j], D. W. Fiorino[b], A. Flandes[k], N. I. Fraija[i], A. Galindo[l],
J. L. Garcia-Luna[p], G. Garcia-Torales[p], F. Garfias[i], L. X. González[l], M. M. González[i], J. A. Goodman[g],
V. Grabski[c], M. Gussert[u], C. Guzman-Ceron[i], Z. Hampel-Arias[b], T. Harris[v], E. Hays[w],
L. Hernandez-Cervantes[i], P. H. Hüntemeyer[j], A. Imran[s], A. Iriarte[i], J. J. Jimenez[d], P. Karn[q],
N. Kelley-Hoskins[j], D. Kieda[f], R. Langarica[i], A. Lara[k], R. Lauer[x], W. H. Lee[i], E. C. Linares[e],
J. T. Linnemann[a], M. Longo[u], R. Luna-García[y], H. Martinez[z], J. Martínez[c], L. A. Martinez[i],
O. Martinez[m], J. Martinez-Castro[y], M. Martos[i], J. Matthews[x], J. E. McEnery[w], G. Medina-Tanco[o],
J. E. Mendoza-Torres[l], P. A. Miranda-Romagnoli[aa], T. Montaruli[b], E. Moreno[m], M. Mostafa[u],
M. Napsuciale[r], J. Nava[l], L. Nellen[o], M. Newbold[f], R. Noriega-Papaqui[aa], T. Oceguera-Becerra[p],
A. Olmos Tapia[l], V. Orozco[c], V. Pérez[c], E. G. Pérez-Pérez[h], J. S. Perkins[w], J. Pretz[s], C. Ramirez[m],
I. Ramírez[c], D. Rebello[v], A. Rentería[c], J. Reyes[l], D. Rosa-Gonzalez[l], A. Rosado[m], J. M. Ryan[ab],
J. R. Sacahui[i], H. Salazar[m], F. Salesa[u], A. Sandoval[c], E. Santos[d], M. Schneider[ac], A. Shoup[ad], S. Silich[l],
G. Sinnis[s], A. J. Smith[g], K. Sparks[n], W. Springer[f], F. Suárez[c], N. Suarez[l], I. Taboada[v,*], A. F. Tellez[m],
G. Tenorio-Tagle[l], A. Tepe[v], P. A. Toale[ae], K. Tollefson[a], I. Torres[l], T. N. Ukwatta[a], J. Valdes-Galicia[k],
P. Vanegas[c], V. Vasileiou[w], O. Vázquez[c], X. Vázquez[c], L. Villasenor[e], W. Wall[l], J. S. Walters[l],
D. Warner[u], S. Westerhoff[b], I. G. Wisher[b], J. Wood[g], G. B. Yodh[q], D. Zaborov[n], A. Zepeda[z]

Submitted to Astroparticle Physics (astro-ph/1108.6034)

The HAWC Observatory has promising potential in the study of > 30 GeV emission by GRBs. Approximately ~ 40 GRBs/yr will be simultaneously in the field of view of HAWC.

◆ **Synergy with Fermi-Lat: many GeV emitters could be TeV emitters: Many TeV sources have yet to be discovered**

◆ **Undetection of MGRO J2019+37 by IACTs: finite spatial extent? or hard spectral Index pushing into energies where HAWC has much better sensitivity?**

◆ **The CRAB as standard candle in the TeV regime**

VAMOS RESULTS ON END 2012

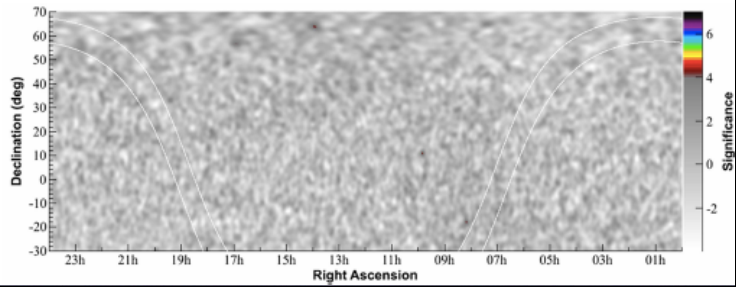
◆ **Starting of HAWC 30**

Verification and Assessment Measuring of Observatory Subsystems (VAMOS) TEST ARRAY

VAMOS

- 7 tanks
  (6 instrumented)
- finished: June 2011

24 h main DAQ sky map→
(equatorial coordinates)



THE SITE

END OF 2011

THANK YOU!