The High Altitude Water Cherenkov (HAWC) TeV Gamma-Ray Observatory

Eduardo de la Fuente Acosta
for the HAWC Collaboration

Universidad de Guadalajara, México
edfuente@gmail.com

http://dti.cucea.udg.mx/

8th Workshop on Astroparticle Physics, Darjeeling, December, 2013

Outline

I.- INTRODUCTION

II.- GAMMA RAYS REMARKS

III.- MILAGRO OBSEVATORY: THE FIRST GENERATION OF WATER CHERENKOV DETECTORS (WCD)

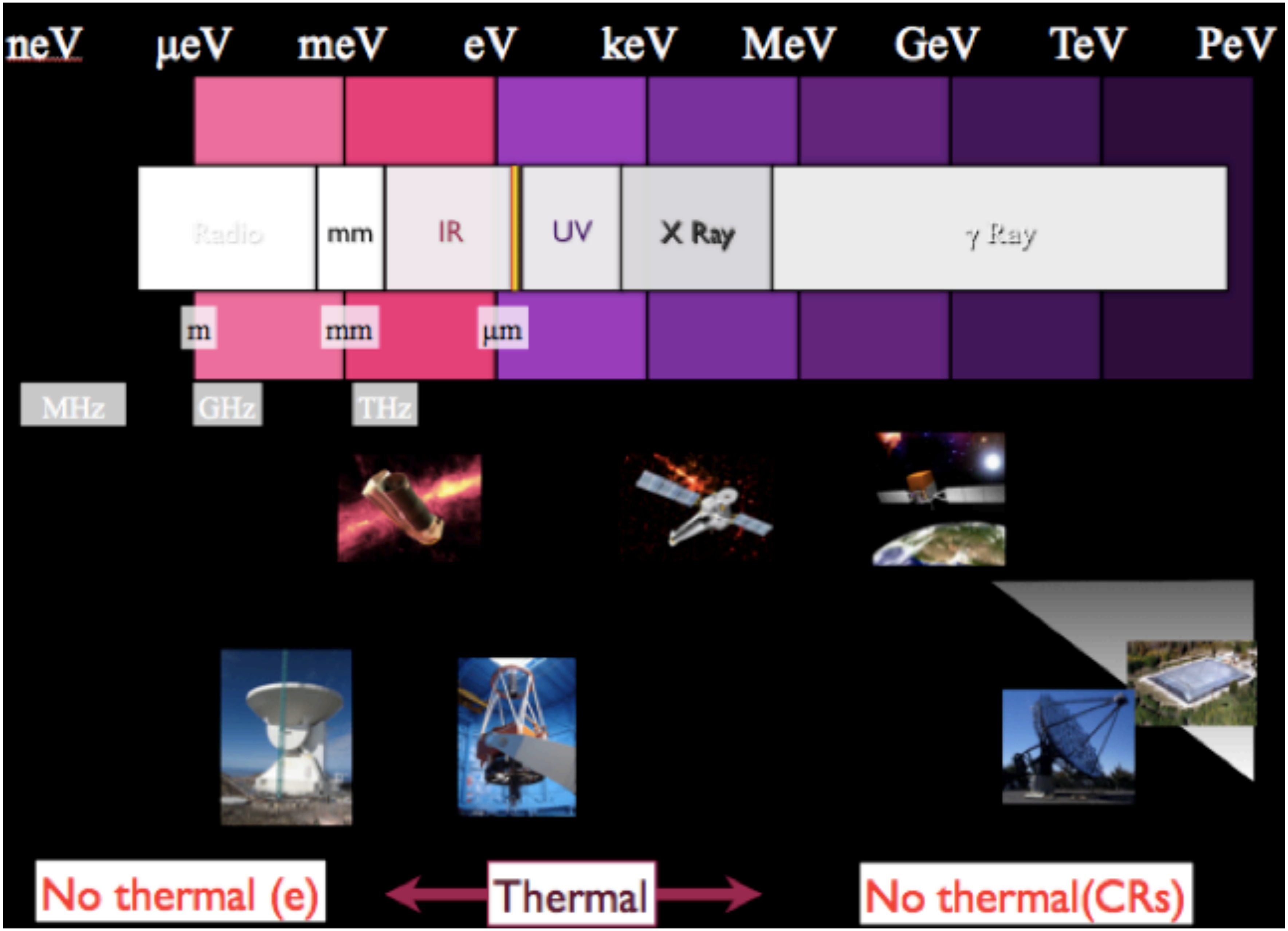
IV.- HIGH ALTITUDE WATER CERENKOV (HAWC); THE SECOND GENERATION OF WCD

V.- HAWC (DESIGN, COLABORATION, ELECTRONICS, DATES, PERFORMANCE, SCIENTIFIC CASE)

VI.- FIRST LIGHT AND PRELIMINARY RESULTS

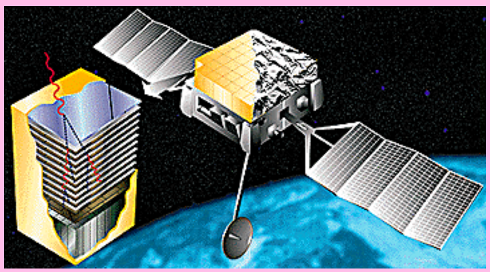
VII.- FUTURE

I.- INTRODUCTION



I.- INTRODUCTION

Wide Field of View, Continuous Operations



FERMI, AGILE, EGRET

Satellite Experiments

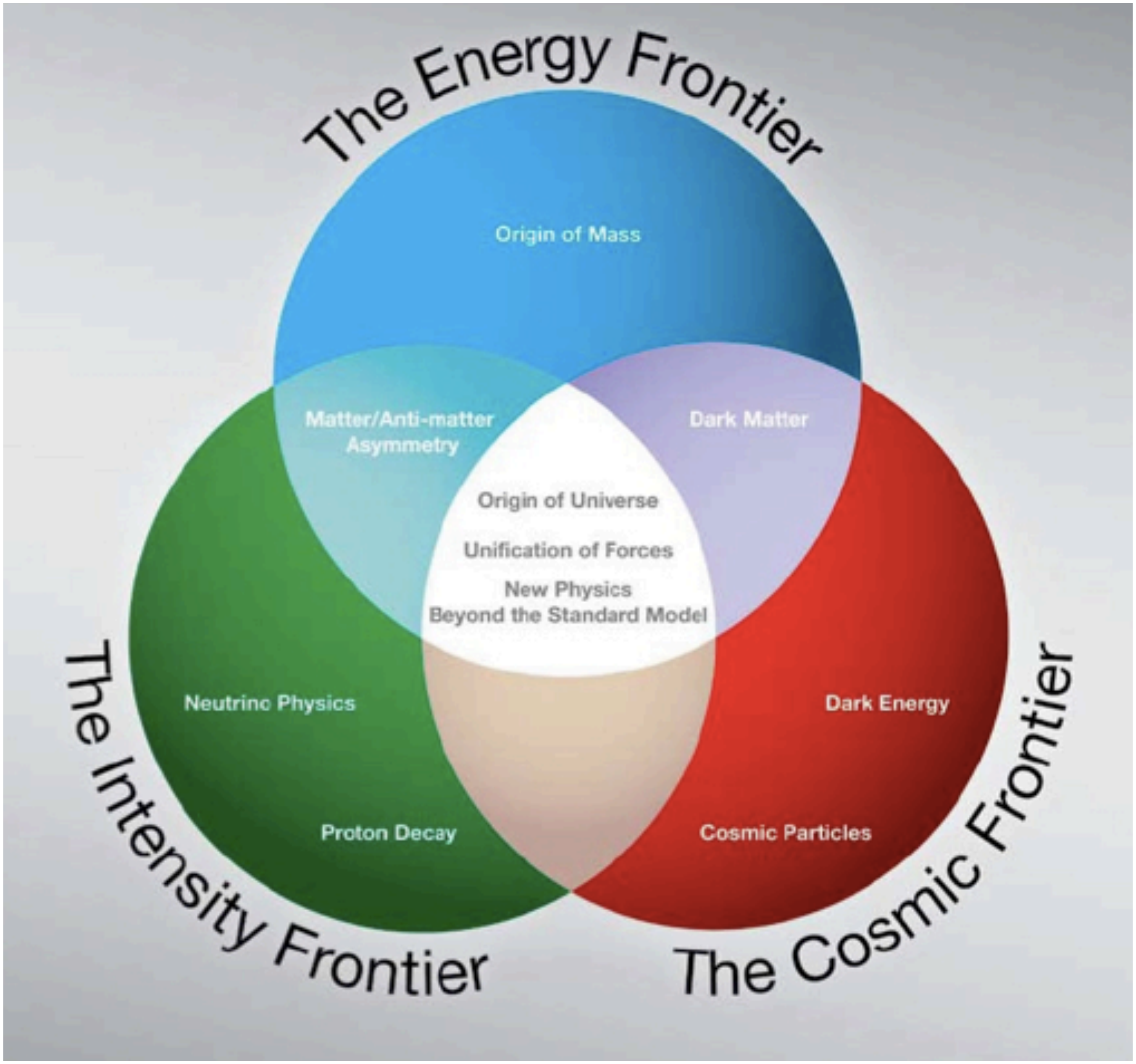
- high duty cycle ≈ 100 %
- large sky coverage LAT: ≈ 20 %
- sensitive to medium energies LAT: ≈ 30 MeV – 300 GeV

TeV Sensitivity

HAWC
ARGO
Milagro
Tibet ASγ

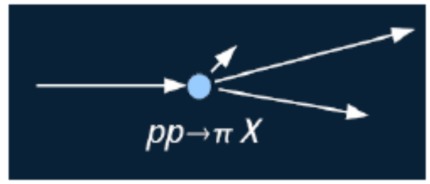
VERITAS
HESS
MAGIC

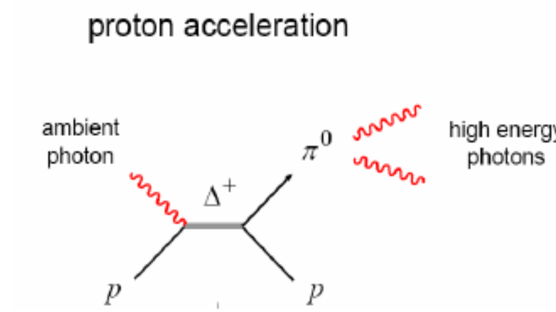
I.- INTRODUCTION



II.- Gamma Ray Emission Mechanism

By interaction with matter

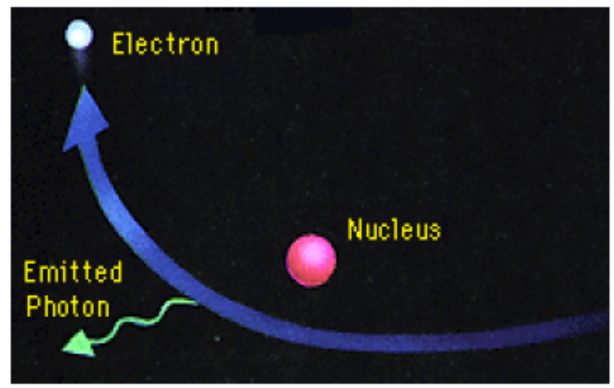




π° – decay:

In hadronic interactions produced neutral pions decay

Immediately: $\pi^0 \rightarrow \gamma + \gamma$ ($\tau = 8.4 \cdot 10^{-17}$ s)



Electron - Bremsstrahlung:

Deflected electrons in the coulomb field of nuclei emit radiation with the probability

$\phi \propto z^2 Z^2 E_e / m^2$

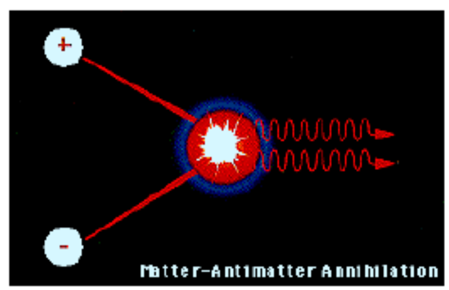
Annihilation and radioactive decay:

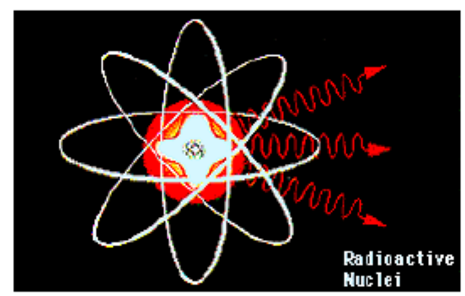
In dense matter annihilate electron-positron (proton-antiproton) pairs

$e^+ + e^- \rightarrow \gamma + \gamma$ ($\rightarrow E_\gamma = 511$ keV)

$p + \bar{p} \rightarrow \pi^+ + \pi^- + \pi^0$

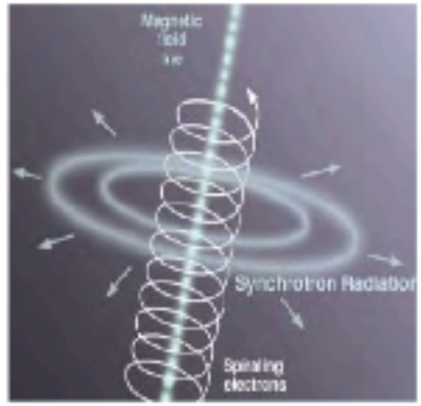
In elemental synthesis exist radioisotopes which have β – decay.





II.- Gamma Ray Emission Mechanism

By interaction with magnetic fields

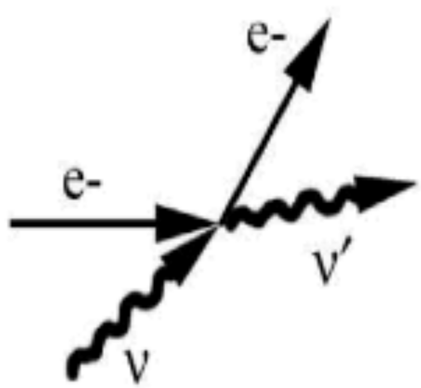


Synchrotron radiation

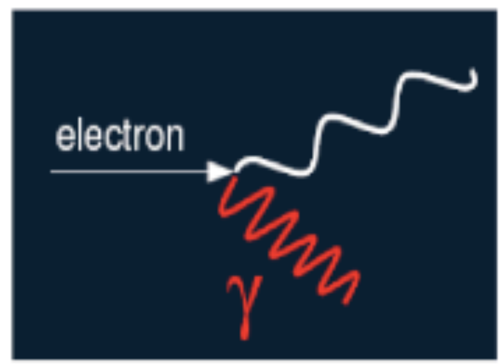
Synchrotron radiation:
Radiation of accelarated charged particles (electrons) in magnetic fields.
Power of the radiation: $P \propto E_e^{\,2} \cdot B^2$

Inverse Compton scattering

By interaction with photon fields



$\nu' > \nu$
High energy e- initially
e- loses energy



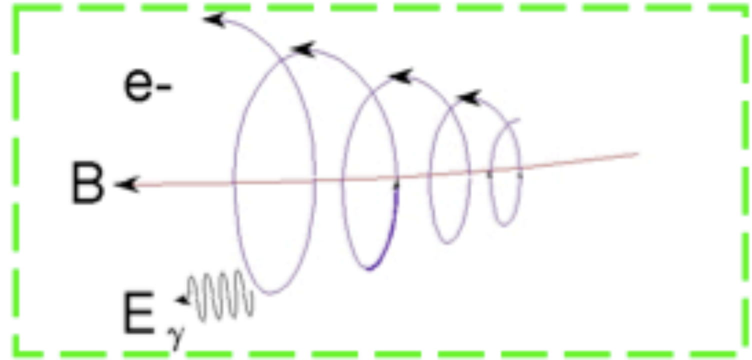
Inverse compton scattering:
fast electrons transfer energy on low energy photons
➔ Blue shifted photons

II.- Gamma Ray Probe Accelarated Particles

Electrons:

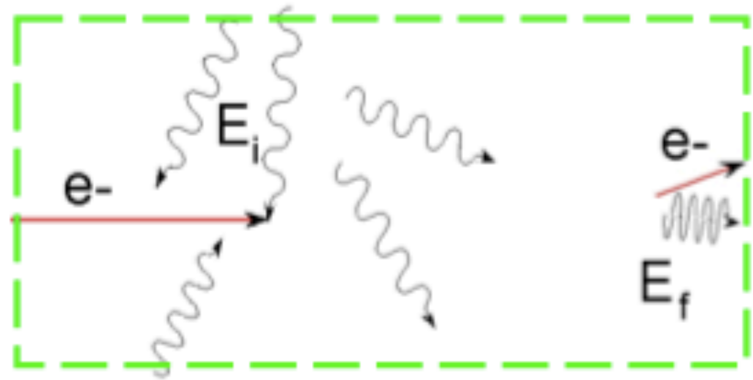
Synchrotron Emission

- Probes Magnetic Field, Electron Energy



Inverse Compton Scattering

- Probes Photon Field, Electron Energy



Synchrotron Self Compton

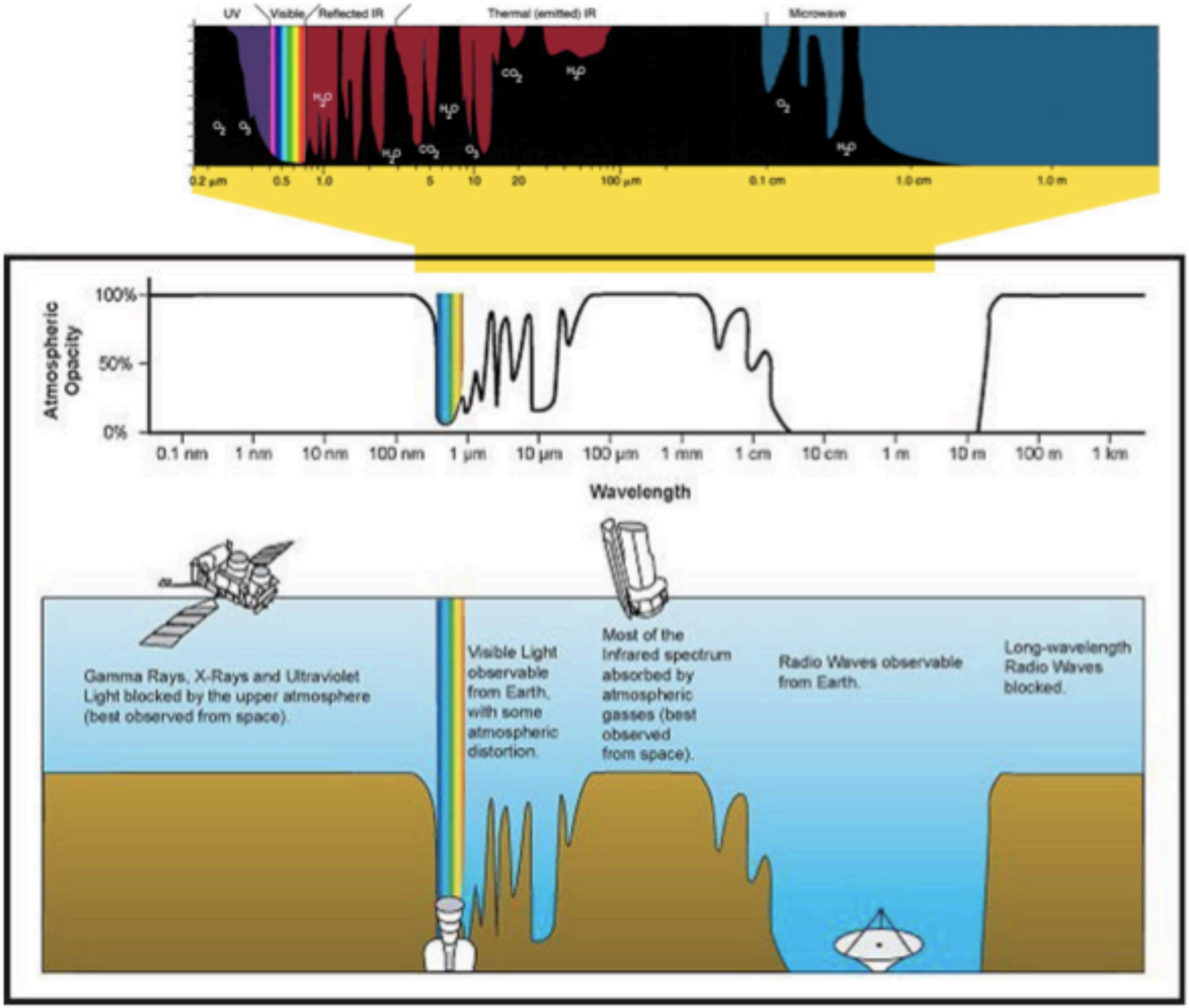
- If photon field is synchrotron, then Electron Energies & Magnetic Field are determined
- Quadratic relation between variability of TeV (IC) and X-rays (synch)

Hadrons:

$p + p \rightarrow \pi^+ + \pi^o + \ldots \rightarrow e + \nu + \gamma + \ldots$

$p + \gamma \rightarrow \pi^+ + \pi^o + \ldots \rightarrow e + \nu + \gamma + \ldots$

II.- Gamma Ray Observations on Earth ?



II.- Gamma Ray Observations on Earth ?

YES

Atmospheric Cascades

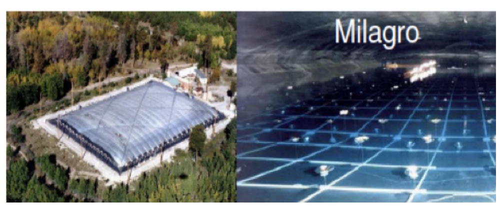
Cherenkov Effect

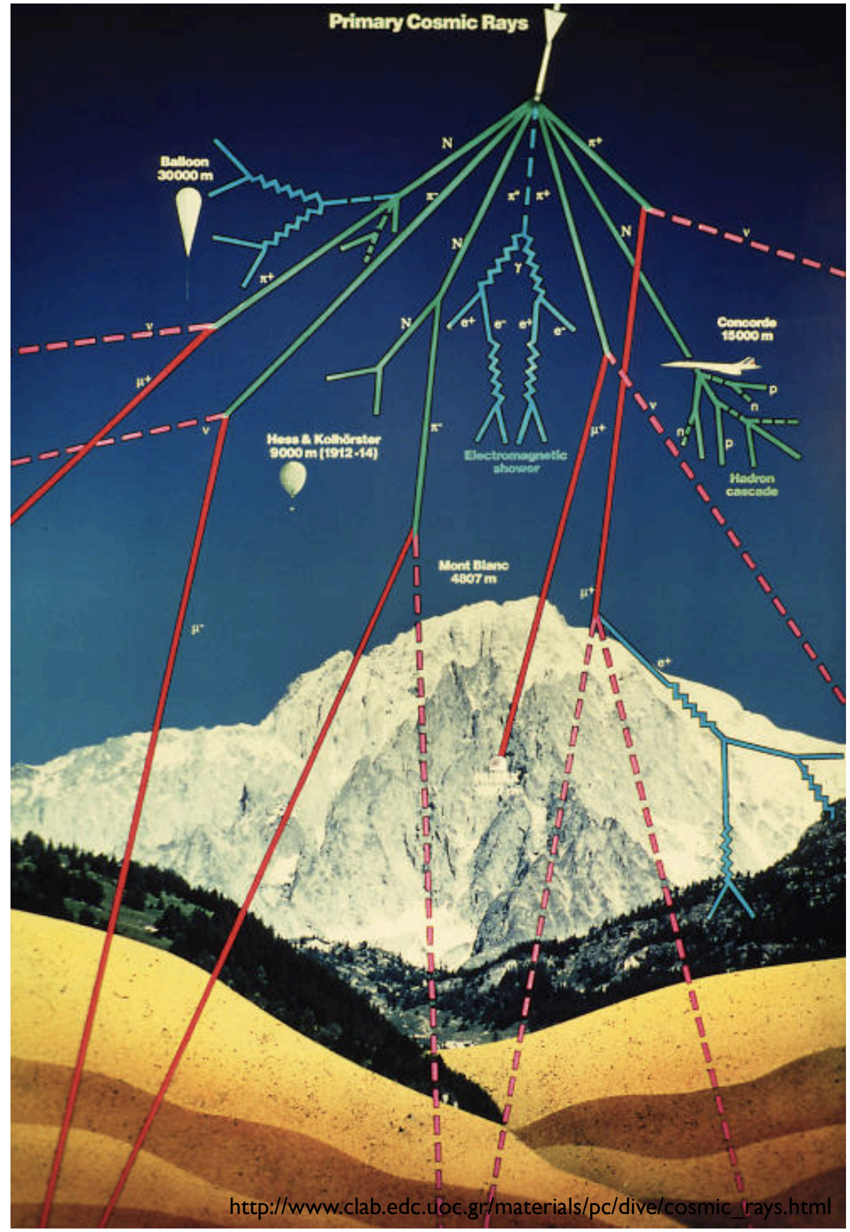
Air Cherenkov Telescopes

- very good angular resolution $\lesssim 0.2^\circ$
- large effective area $\mathcal{O}(10^5\,\mathrm{m}^2)$
- sensitive to very high energies $\approx 100\,\mathrm{GeV} - 50\,\mathrm{TeV}$

Water Cherenkov Detectors

- high duty cycle $\approx 95\,\%$
- large effective area $\mathcal{O}(10^4\,\mathrm{m}^2)$
- sensitive to very high energies





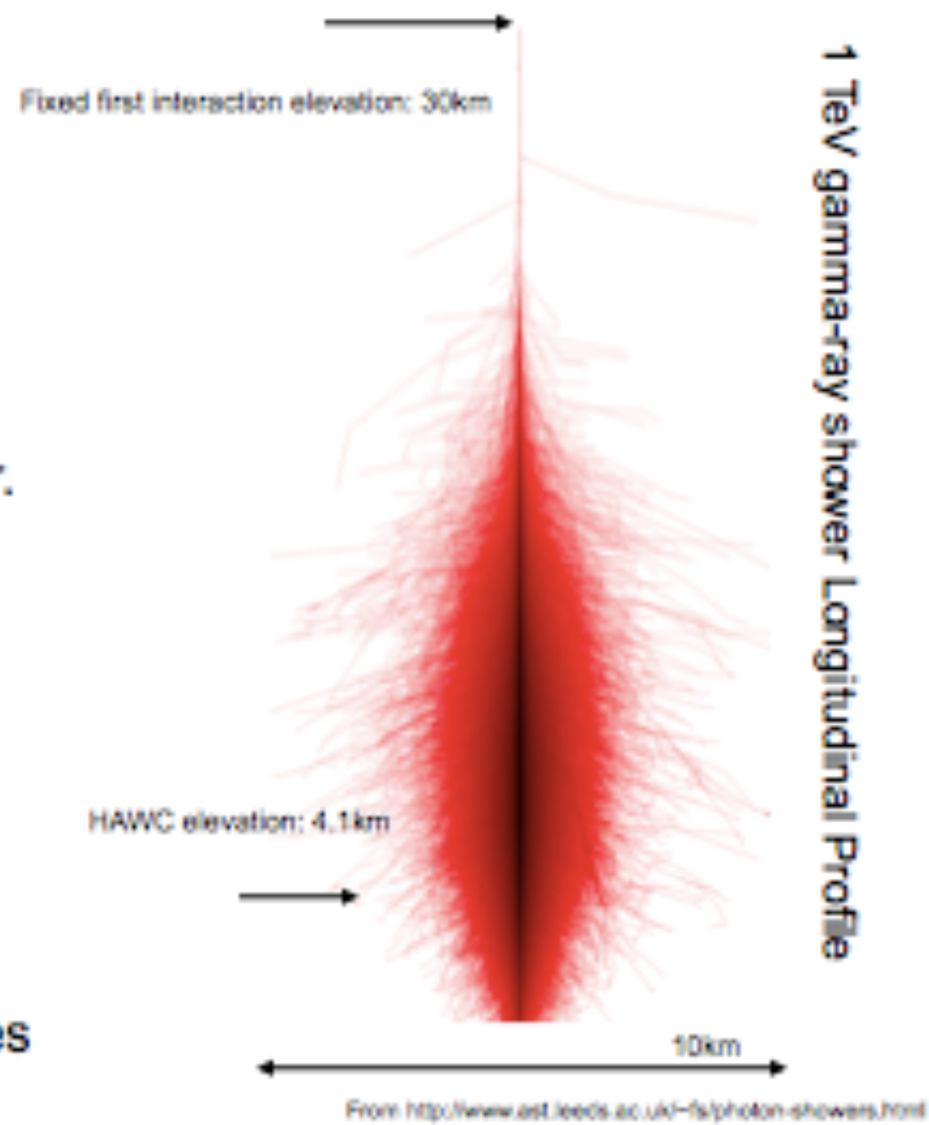
II.- Gamma Ray Observations on Earth ?
Atmospheric cascade

Prior to shower maximum:

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

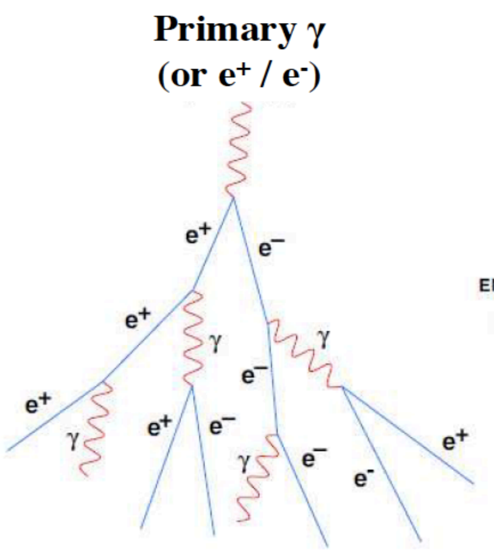
After shower maximum:

- 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.

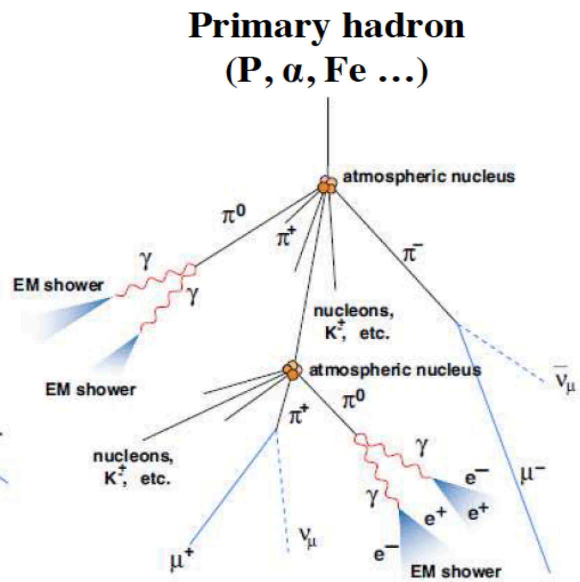


II.- Gamma Ray Observations on Earth ?

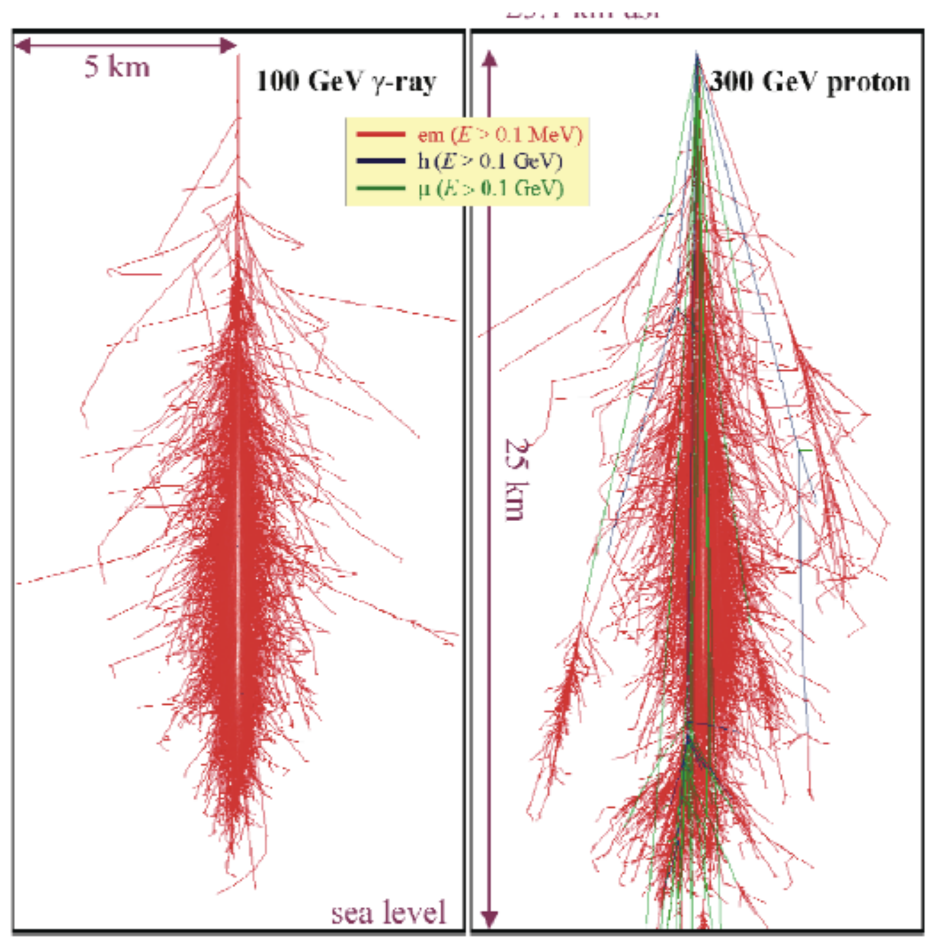
Atmospheric cascade components (Gamma rays, Cosmic rays, Neutrons):



Pure electromagnetic Cascade



Hadronic Cascade:
- **⅓ electromagnetic (π°)**
- **⅔ "lost" (π± → μ± + ν)**



Hadronic Component dominates in emission over the Electromagnetic Component, therefore for gamma rays observations, a good Gamma/Hadron rejection is needed

II.- Gamma Ray Observations on Earth ?

Cherenkov Effect

- In a material with refractive index, n, a charged particle emits if its velocity is greater than the local phase velocity of light .

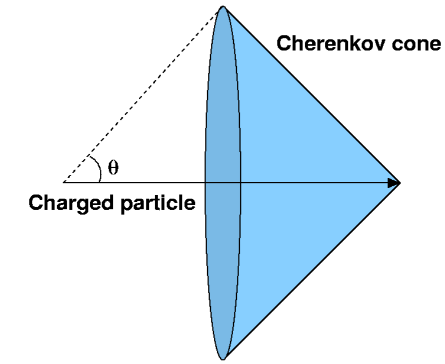
- The charged particle polarizes the atoms along its trajectory

- These time dependent dipole emit electromagnetic radiation

- If v < c / n, the dipole distribution is symmetric around the particle position, and the sum of all dipoles vanishes

- If v > c / n, the distribution is asymmetric and the total time dependent dipole is not null, thus radiates.

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

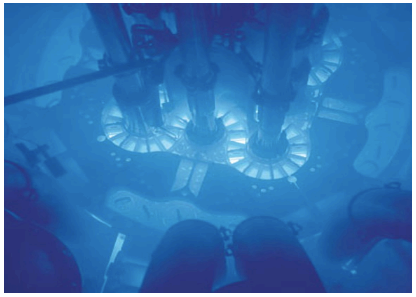


$$\frac{d^2\mathcal{E}_\omega}{d\omega dz} \propto \omega;$$

Shorter wavelenghts, more intense

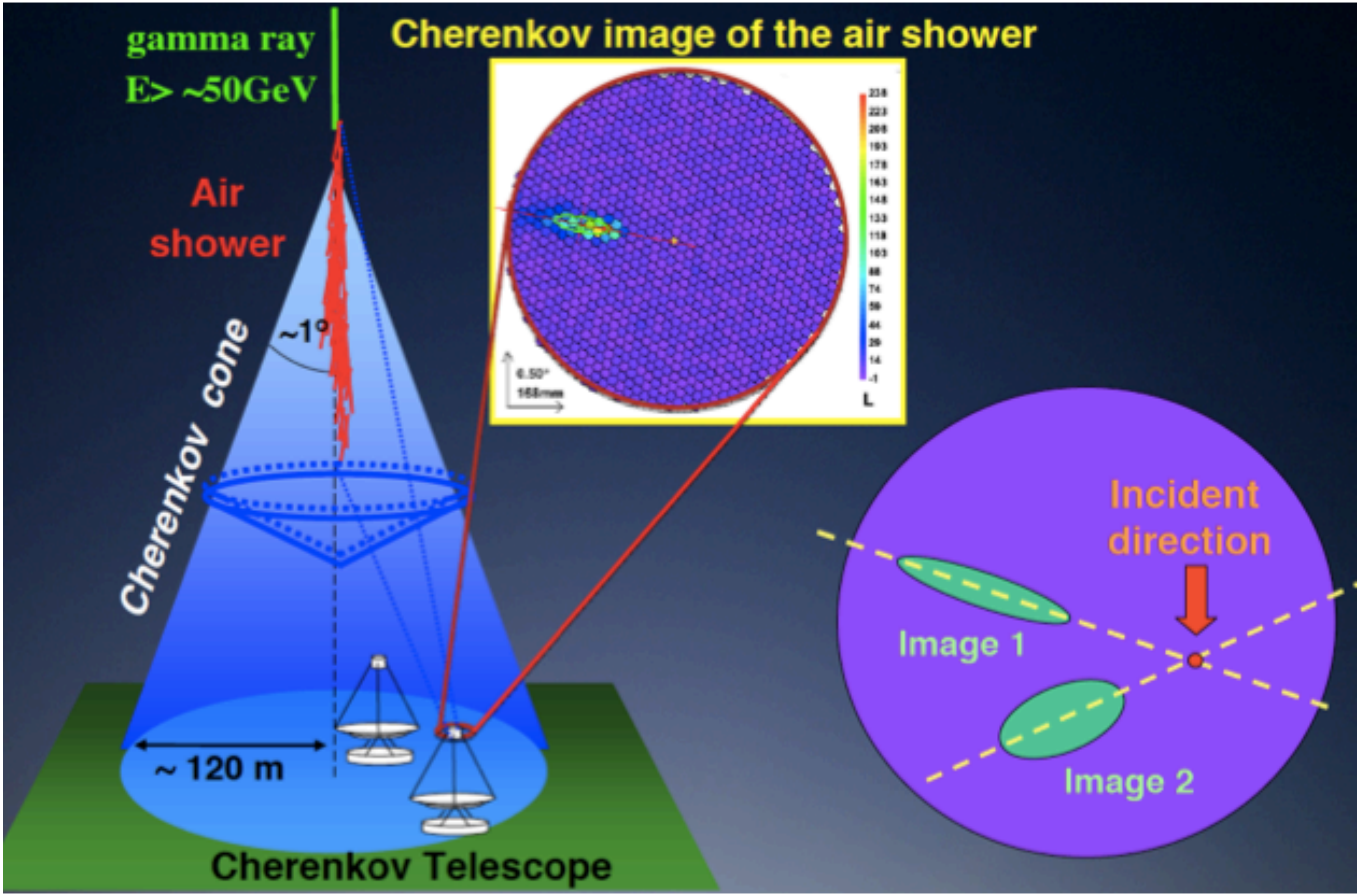
Frank-Tamm Theory (1937, Nobel 1950)

$$\frac{dE}{d\ell} = \frac{2\pi e^2 \nu}{c^2}\left[1 - \frac{1}{\beta^2 n^2(\nu)}\right]$$



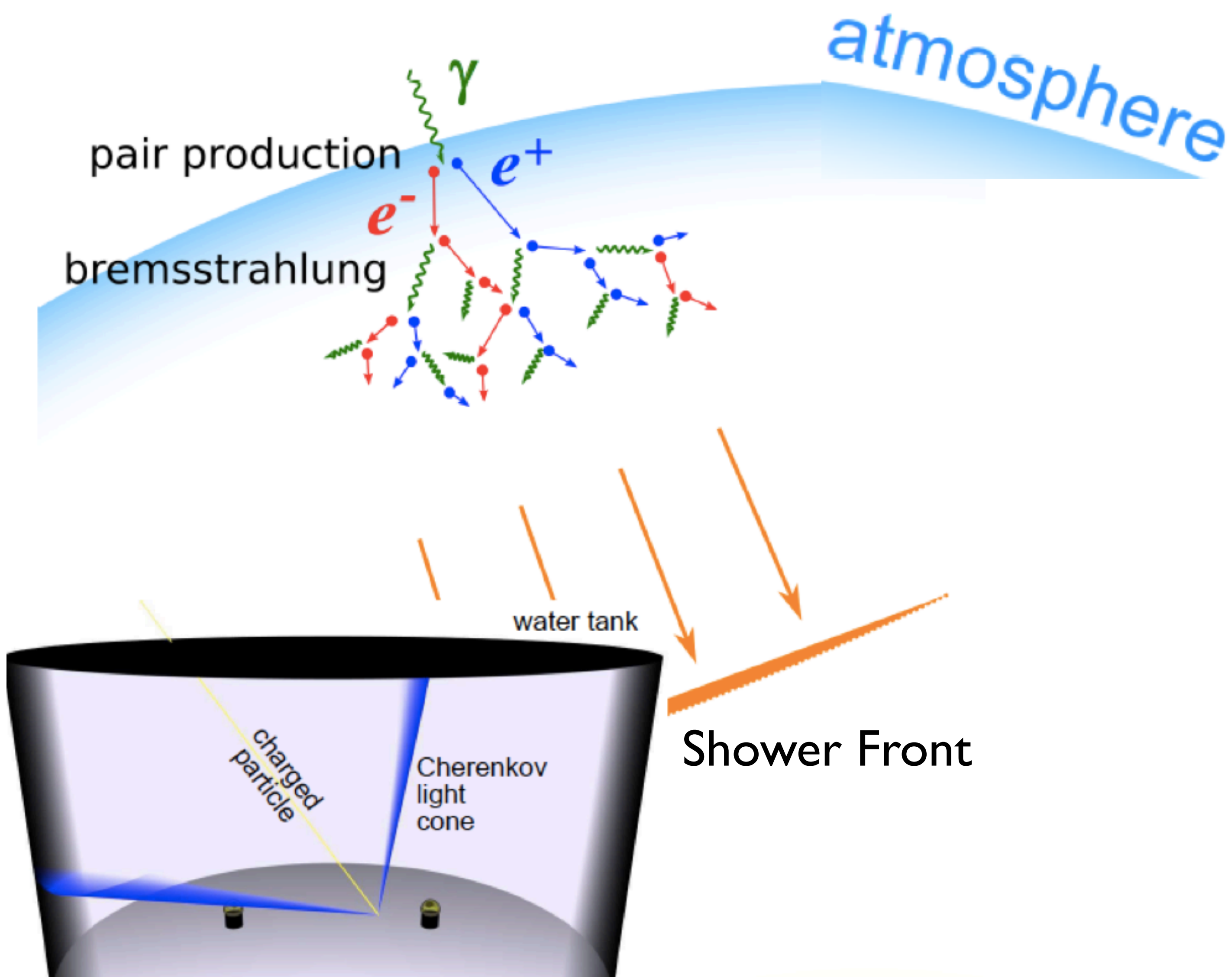
II.- Gamma Ray Observations on Earth ?

Air Cherenkov Detectors



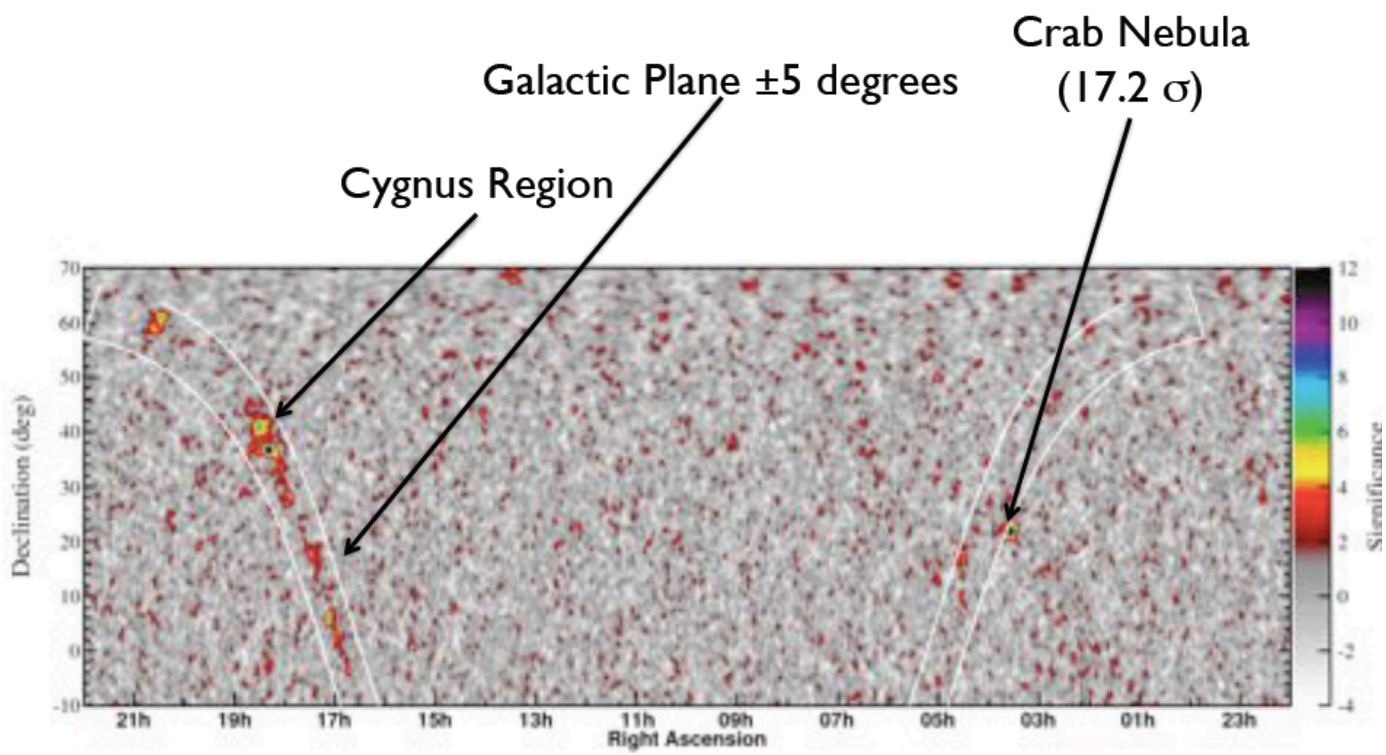
II.- Gamma Ray Observations on Earth ?

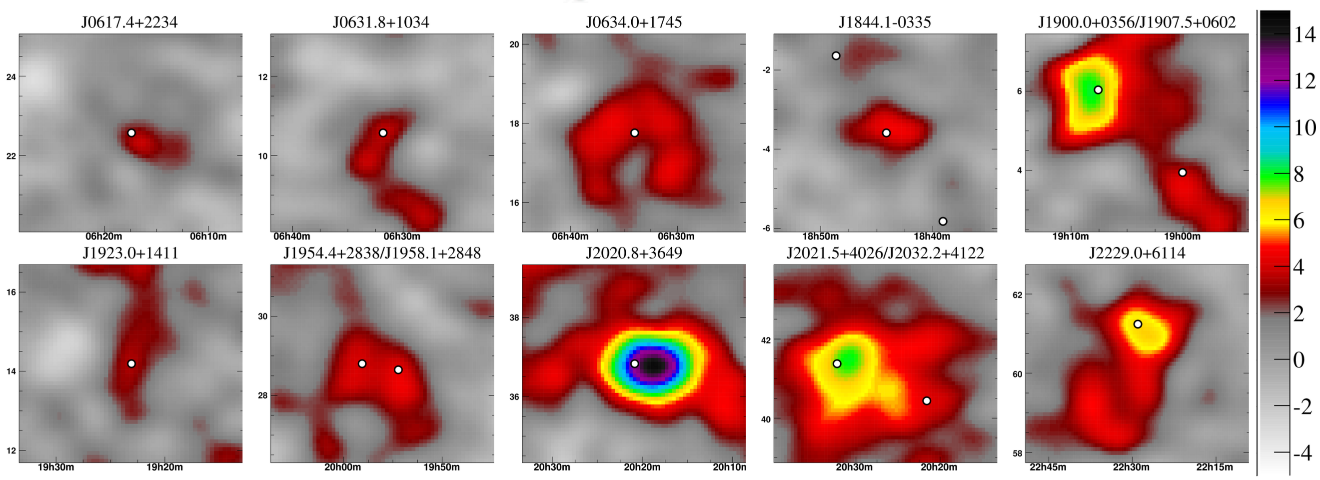
Water Cherenkov Detectors



III.- First Generation on WCD

III.- First Generation on WCD





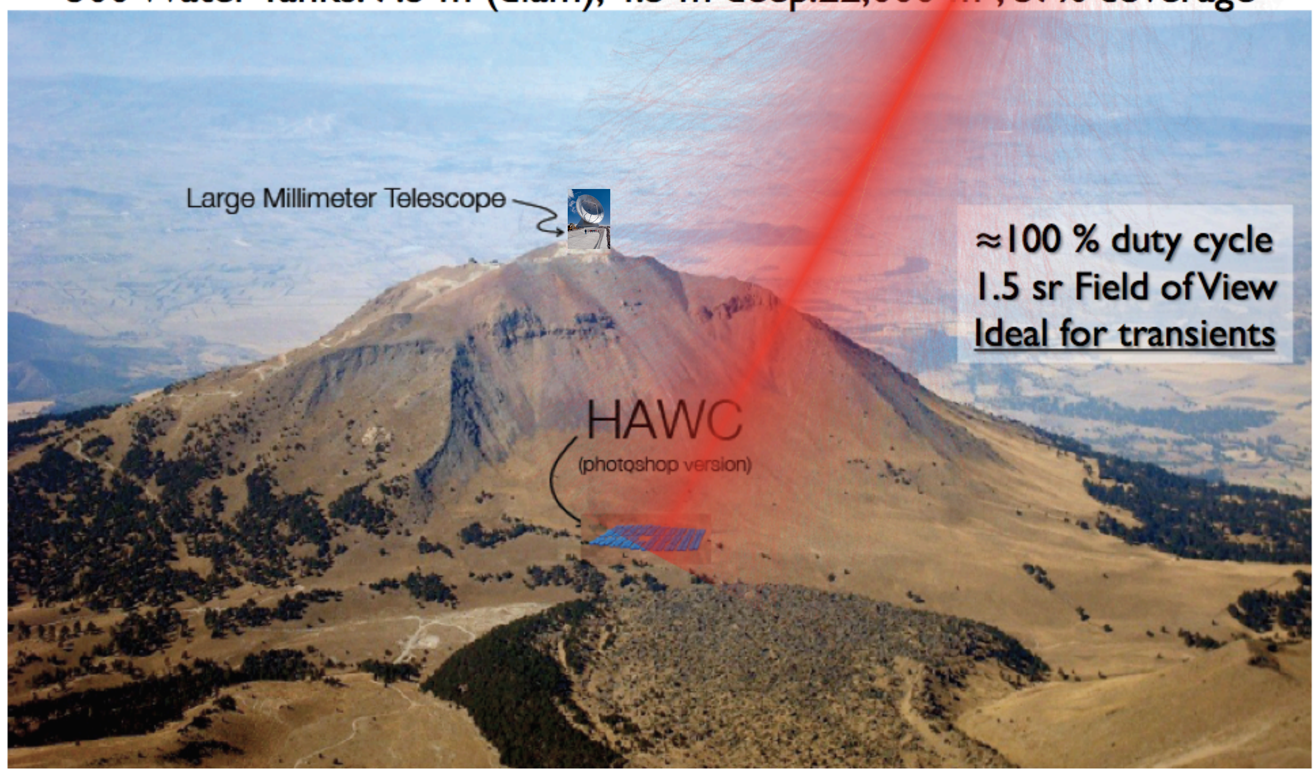
See MILAGRO (LANL; 60 x 80 x 8 m; Abdo et al., 2007, 2009, for details. Threshold: 500 GeV. 6.5 years of data (Jul 2000 – Jan 2007); crab nebula 15 sigmas, GP clearly visible

Abdo et al., ApJ Lett 2009

IV.- High Altitude Water Cherenkov (HAWC) Observatory: Second Generation (WCD)

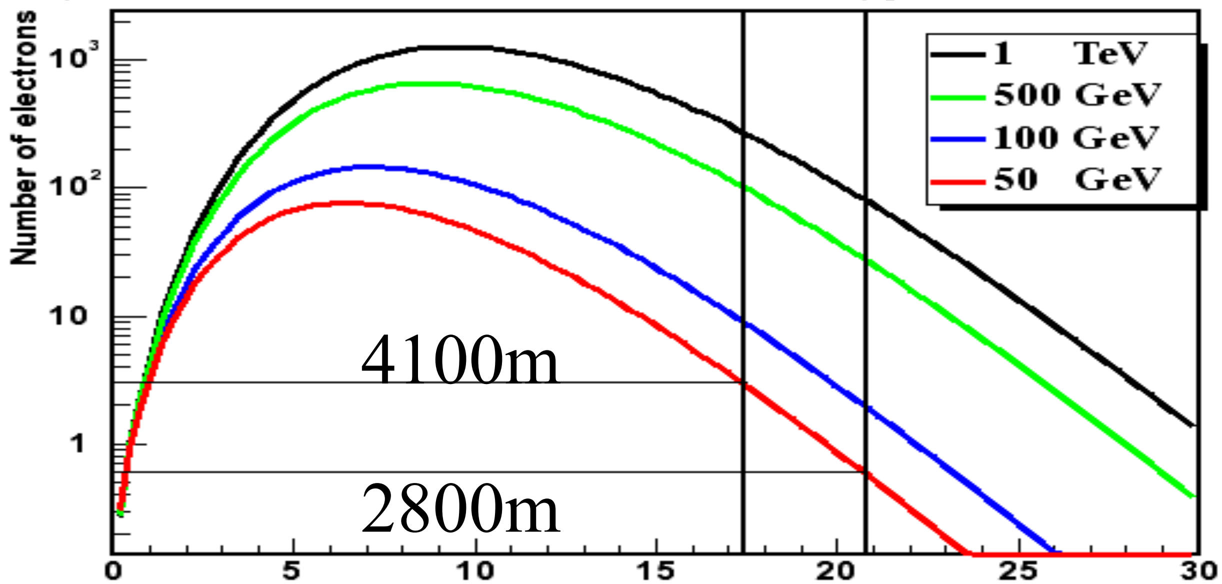
15 times Milagro Sensitivity

Saddle point between Pico Orizaba (5636 m), and Sierra Negra (4640 m)
Site: 4100m, 18°58'N 97°16'W. Central Mexico
300 Water Tanks. 7.3 m (diam), 4.5 m deep. 22,000 m^2, 57% coverage



IV.- High Altitude Water Cherenkov (HAWC) Observatory: Second Generation (WCD)

High Altitude lowers energy threshold



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

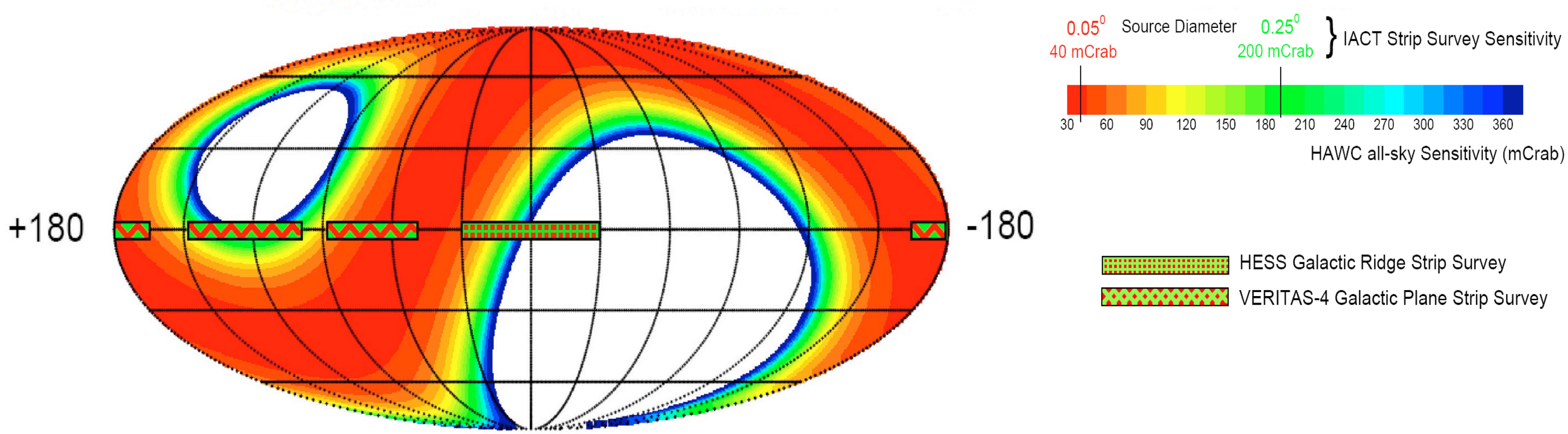
- **Higher Altitude means fewer radiation lengths and more particles**

- **Fluctuations in first interaction means more particles**

- **For example 5% of events (e^{-3}=5%) will have 5 x more particles**

IV.- High Altitude Water Cherenkov (HAWC) Observatory: Second Generation (WCD)

	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	$0.40^0 – 0.75^o$	$0.25^o – 0.50^o$
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



IV.- High Altitude Water Cherenkov (HAWC) Observatory: Second Generation (WCD)

HAWC Large field of view, continously operating high energy gamma ray observatory (100 GeV to hundreds TeV). One of the primary goals of HAWC is to identify new TeV gamma-ray sources and extended measurements of known sources to higher energies. Spectra studies up to 10 TeV (e.g., SEDs), Monitoring (Transients, GRB, AGN), Large Scale (Anisotropy), Diffuse emission.

AIMS

- Provide an unbiased map of the TeV sky (2.5π sr/day)
- Study transient emission from sources like AGNs
- Search for 100 GeV emission from GRBs
- Measure the energy spectrum of Galactic sources up to the highest energies
- Measure diffuse emission between 1 and 100 TeV
- Study small and large scale anisotropy of cosmic rays at energies > 1 TeV
- Search for new physics at TeV energies
- Provide TeV alerts for other instruments

V.- High Altitude Water Cherenkov (HAWC)

The HAWC Collaboration

- University of Maryland
- Los Alamos National Laboratory
- University of Wisconsin
- University of Utah
- Univ. of California, Irvine
- Michigan State University
- George Mason University
- University of New Hampshire
- Pennsylvania State University
- University of New Mexico
- Michigan Technological University
- NASA/Goddard Space Flight Center
- Georgia Institute of Technology
- University of Alabama
- The Ohio State University
- Colorado State University
- University of California Santa Cruz

USA

Instituto Nacional de Astrofísica ” ptica y Electrónica (INAOE)

Universidad Nacional Autónoma de México (UNAM)

Instituto de Física
Instituto de Astronomía
Instituto de Geofisica
Instituto de Ciencias Nucleares

Benemérita Universidad Autónoma

Universidad Autónoma de Chiapas

Universidad Autónoma del Estado de Hidalgo

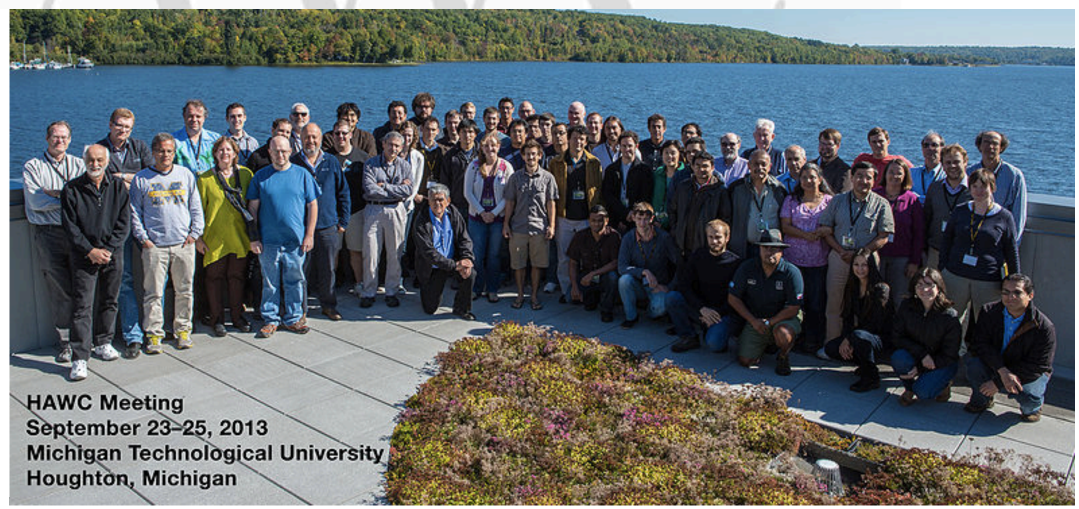
Universidad de Guadalajara

Universidad Michoacana de San Nicolás de Hidalgo

Centro de Investigacion y de Estudios Avanzados

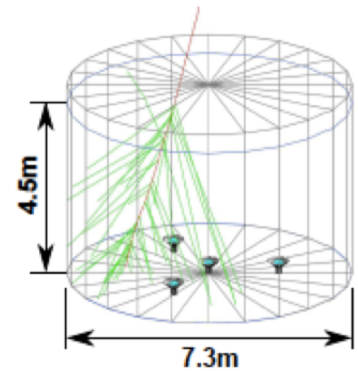
Universidad de Guanajuato

Mexico



V.- High Altitude Water Cherenkov (HAWC); Design

300 hundred tanks (detectors) at completion, covering 20,000 m^2, 4100 m asl.



Modular Construction, actual 111 detectors are operational

Each tank with 200,000 liters of ultra-pure water and 4 PMTs

V.- High Altitude Water Cherenkov (HAWC); Design

Important Dates

12M USD project funding began Feb 2011

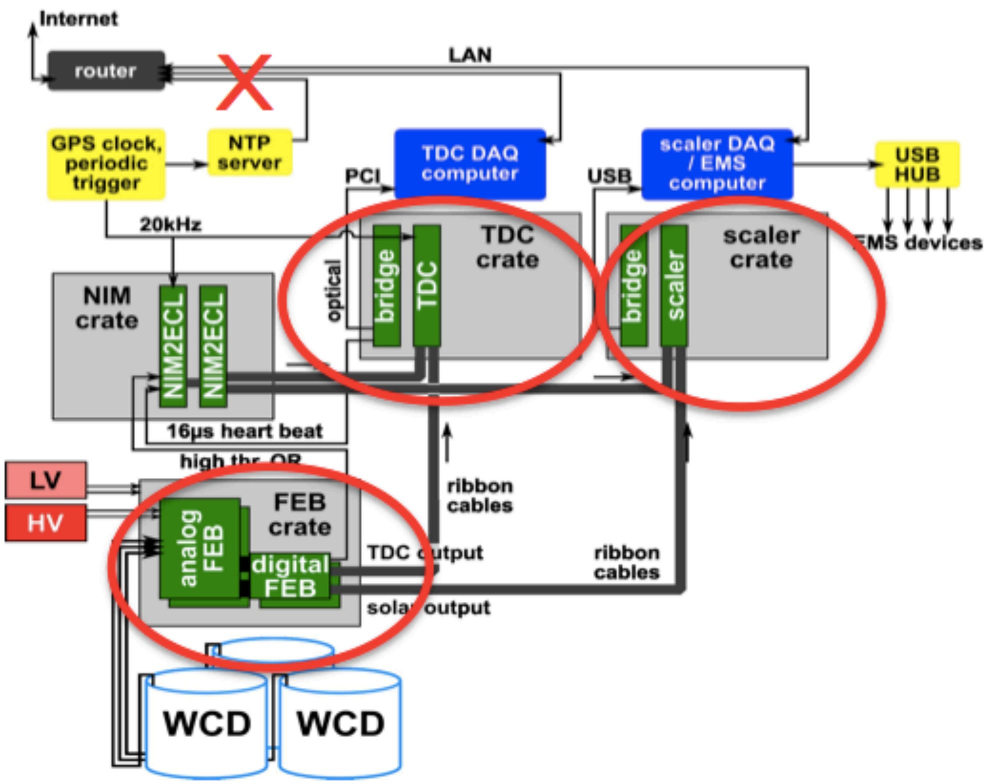
Operations with 100 water Cherenkov detectors in Aug 2013

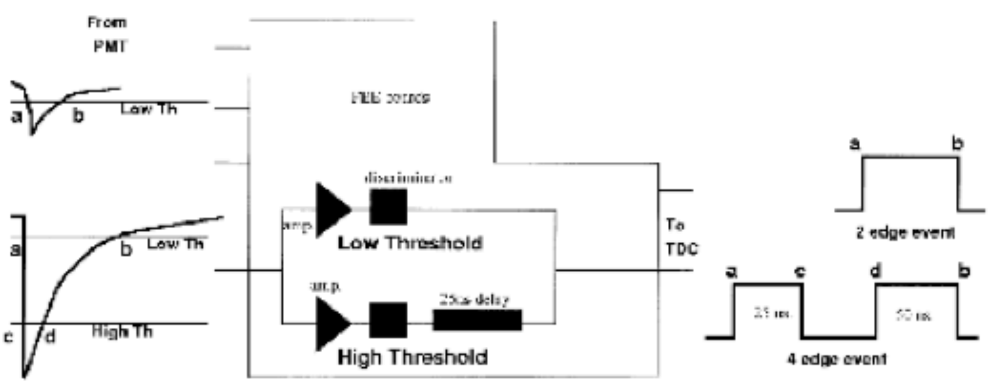
Observatory complete in Aug 2014

Adding 4th PMT in center of each Water Cherenkov Detector

- Higher quantum efficiency of 1.3x Milagro's PMTs
- Larger 10" diameter or 1.5x area of Milagro's PMTs
- Effectively 1.3x1.5=2x Milagro's PMT

V.- High Altitude Water Cherenkov (HAWC); Electronics





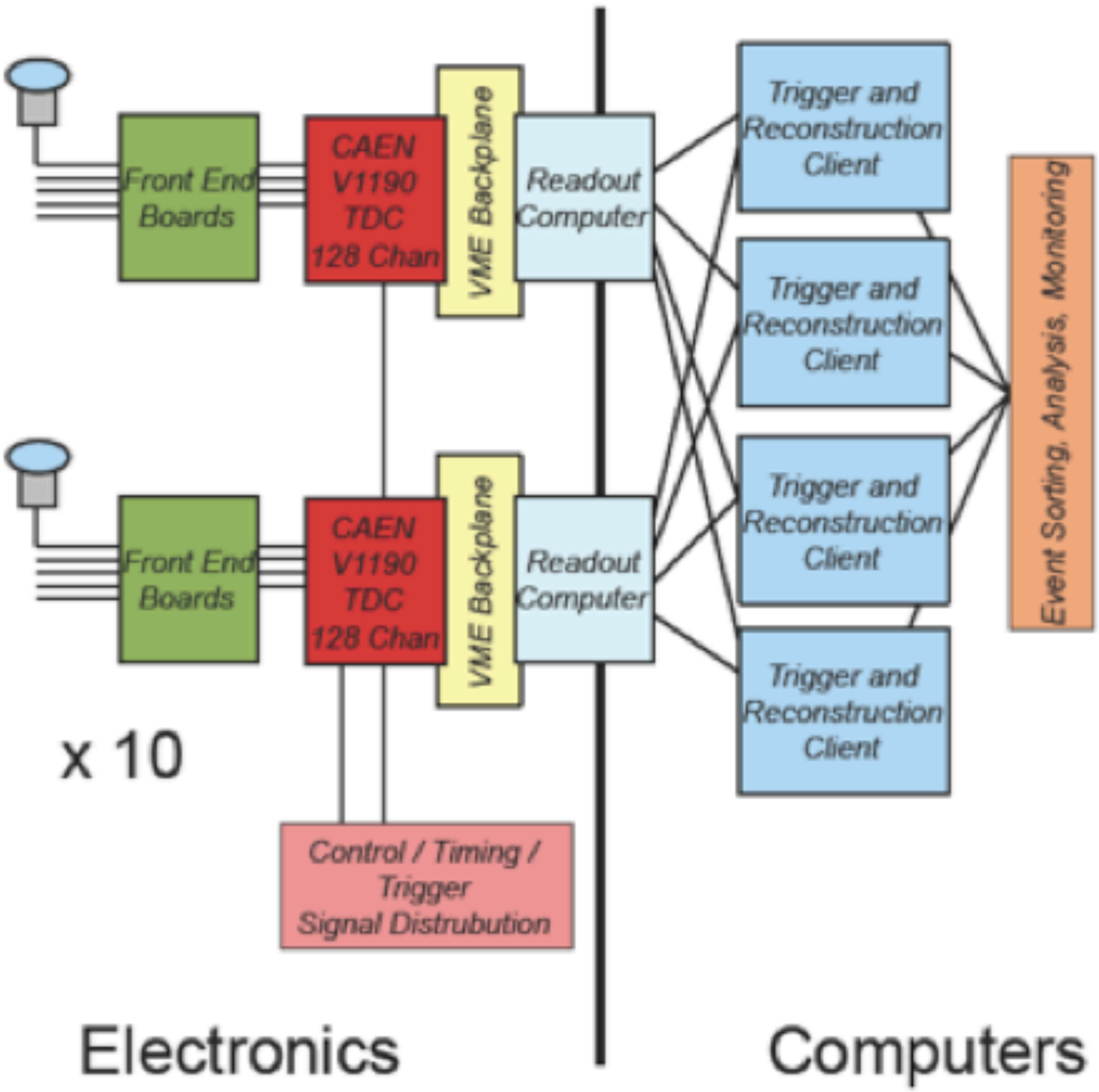
EMS records pressure, temp, water level

Scalers take single rates and are readout every 10 ms

TDC record the ToT
of every signal above
¼ and 5 single photo electrons
~30 kHz/PMT
11 MB/s to disk

Data stored in 8 TB portable disk arrays
they are transported to UNAM
read into the ICN cluster and mirrored to UMD
26 TB recorded during October

V.- High Altitude Water Cherenkov (HAWC); Electronics



Recording all photoelectrons in all 1200 PMTs is 500 MB/sec = 40 TB/day

Requires distributed DAQ with events built in software.

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

V.- HAWC; How it works

The WCDs measure the timing and density of air shower particles reaching the ground.

Custom front-end electronics partially re-used from the Milagro experiment are used to record the leading-edge time and total charge seen by each PMT during an air shower.

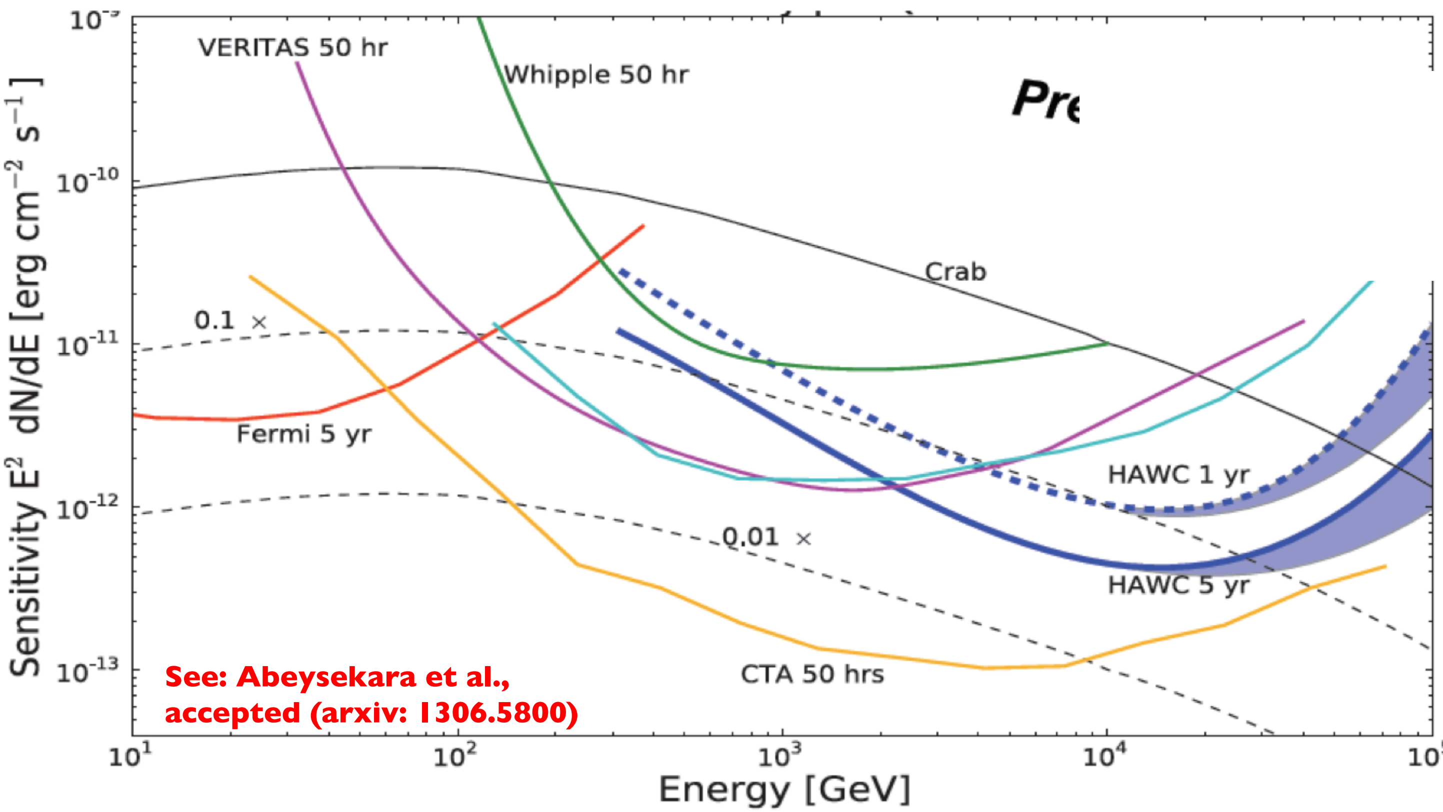
The particles from an air shower arrive in a thin planar sheet propagating at the speed of light which washes over the instrument and the arrival time of light is used to determine the direction of the original primary particle.

Air showers are modeled using the CORSIKA program developed for the KASCADE experiment.

The ground detector components are modeled using a Geant 4 simulation.

The simulation was validated against data from the Milagro experiment and comparison to early HAWC data suggests the simulation is sufficient to estimate the sensitivity of the whole instrument. Reconstruction algorithms developed for Milagro are applied to the simulated output.

V.- High Altitude Water Cherenkov (HAWC); Performance



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.

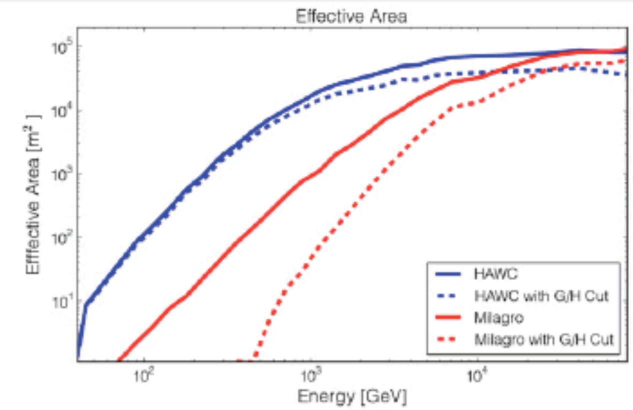
V.- HAWC (HAWC); Performance

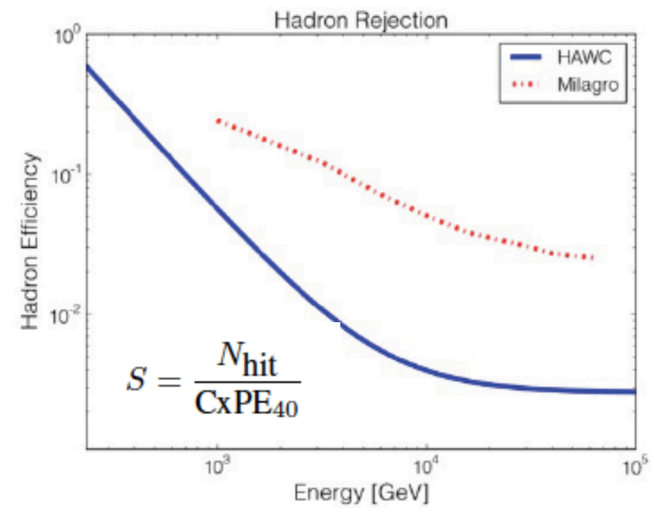
Effective Area: Rises with energy up to 1 TeV. This rise is due to the increasing probability for a particle to produce a detectable number of particles at the ground.

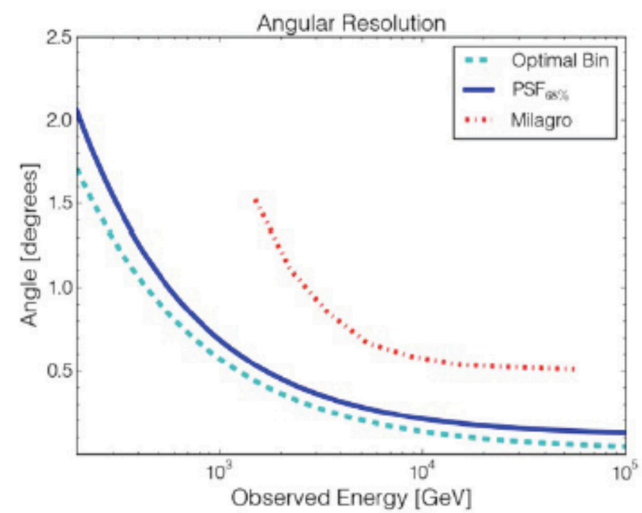
Angular Resolution is defined as the typical error made when reconstructing the arrival direction of an air shower.

Hadron Rejection: 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.

Better because the larger deep–water area and the optical isolation of the detectors, which will improve the accuracy of the reconstruction of the air-shower front

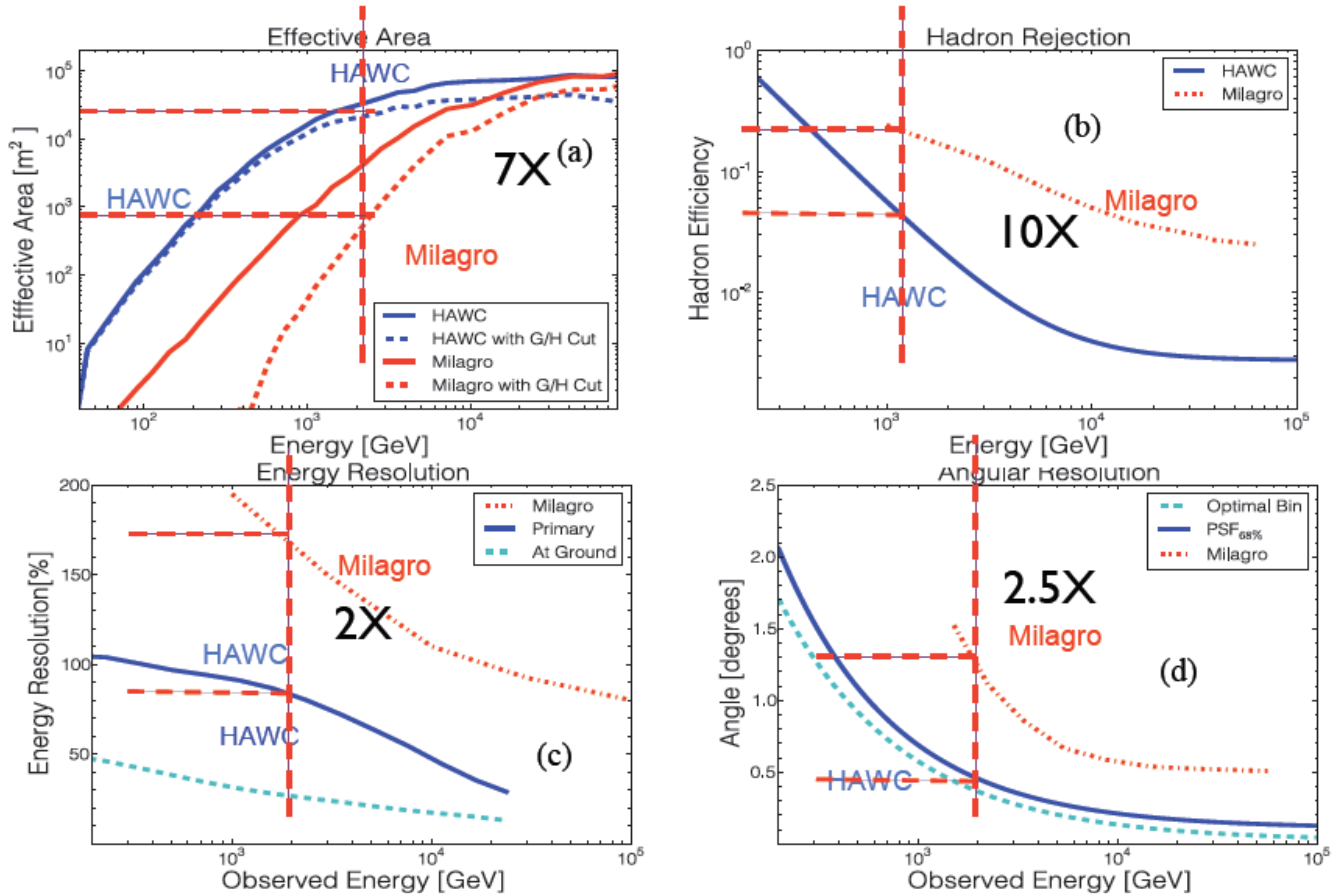






V.- HAWC; Performance Summary

HAWC Performance at 2 TeV



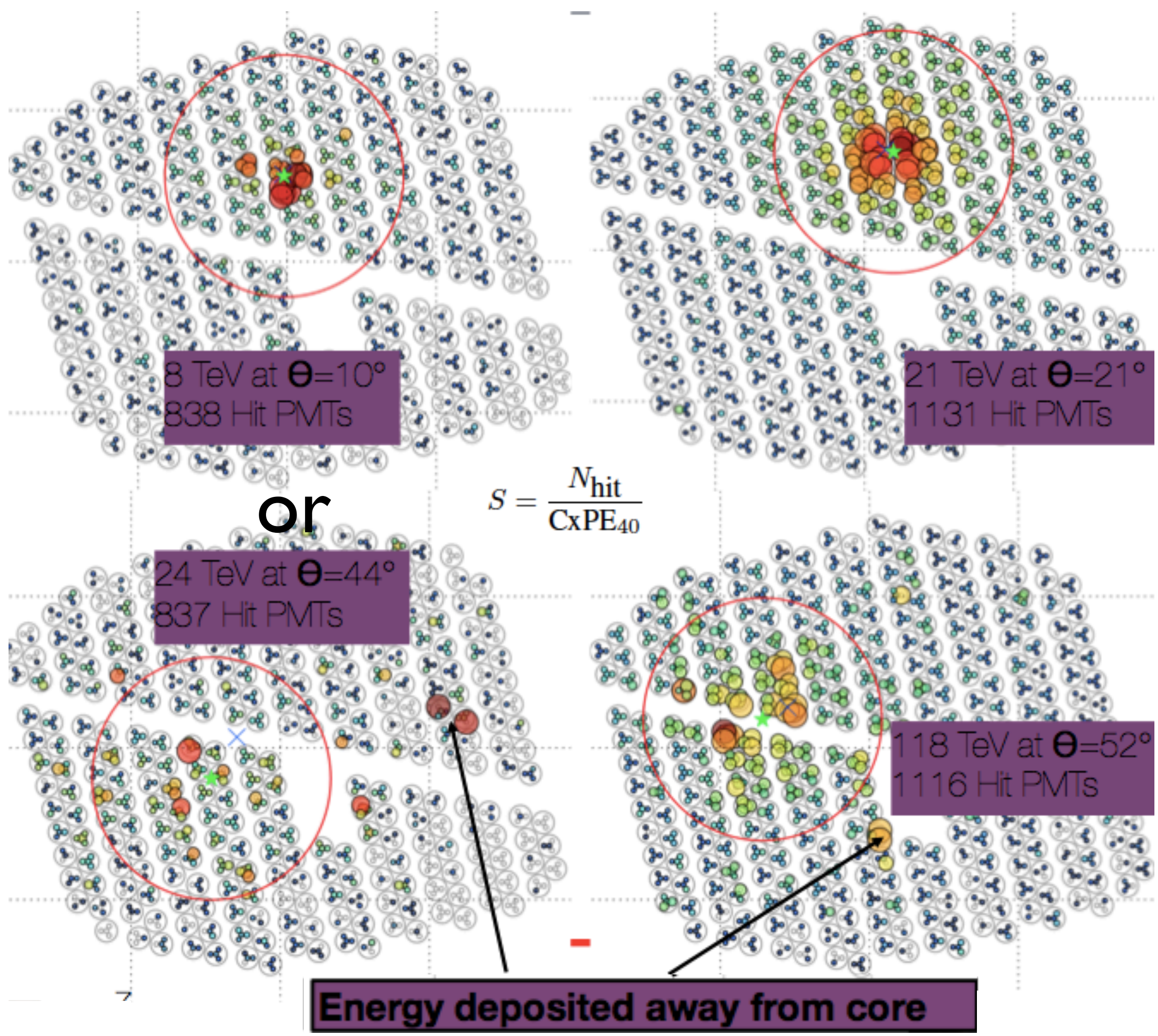
V.- High Altitude Water Cherenkov (HAWC); Performance

Better Gamma /Hadron Rejection than Milagro and ARGO- YBJ. Very important issue.

Main Parameter:
The compactness

N_{hit} = total number of PMTs participating in an event

$CxPE_{40}$ = number of PEs recorded in the hardest-hit channel outside of a radius of 40 meters from the shower core



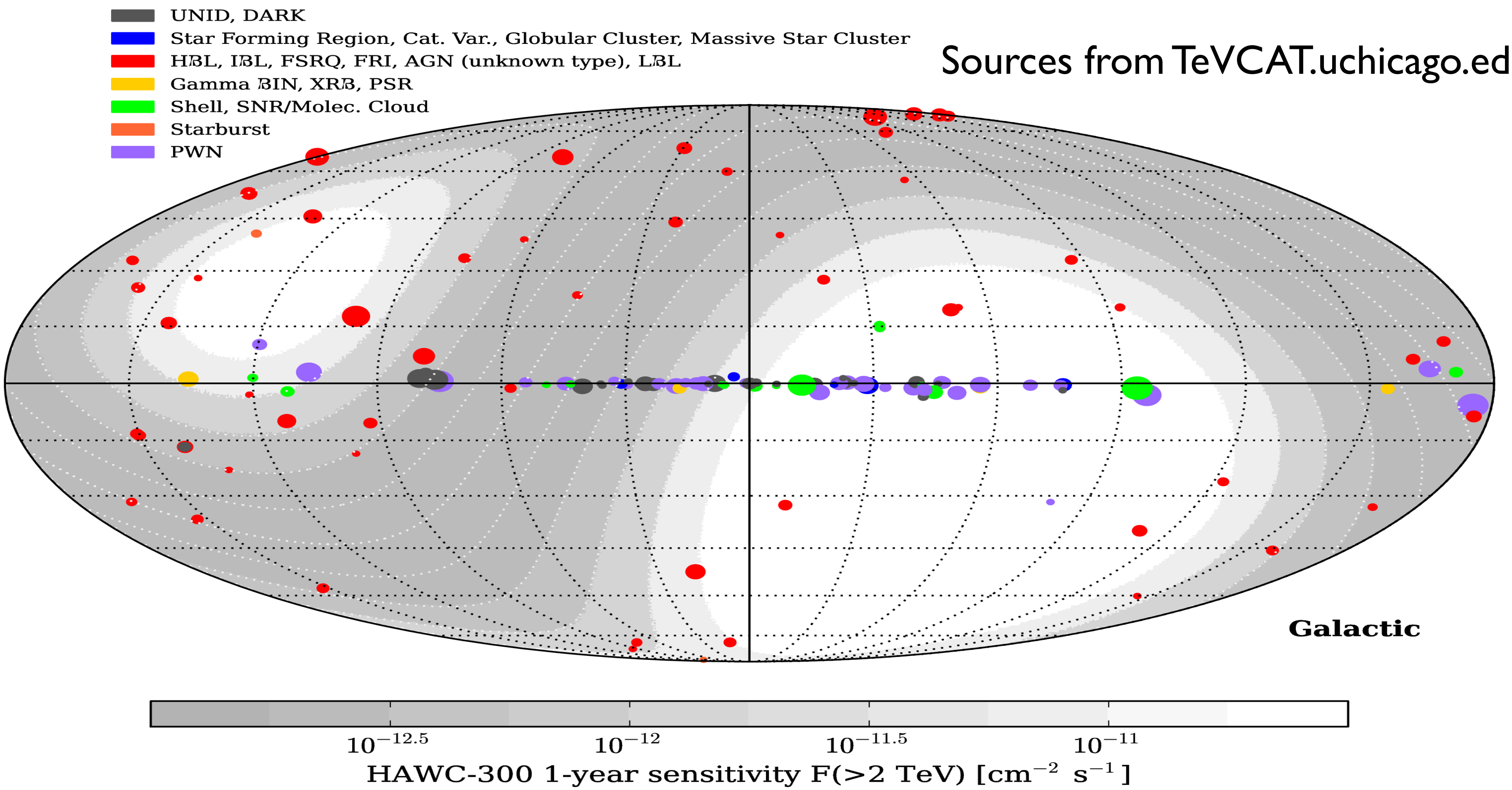
$$S = \frac{N_{hit}}{CxPE_{40}}$$

Goodman & Pretz 2013, Proceedings of the ICRC in Rio de Janeiro, Brasil, for details

V.- HAWC FIELD OF VIEW

Known sources are shown, but most of the high latitude sky has not been observed at TeV energies.

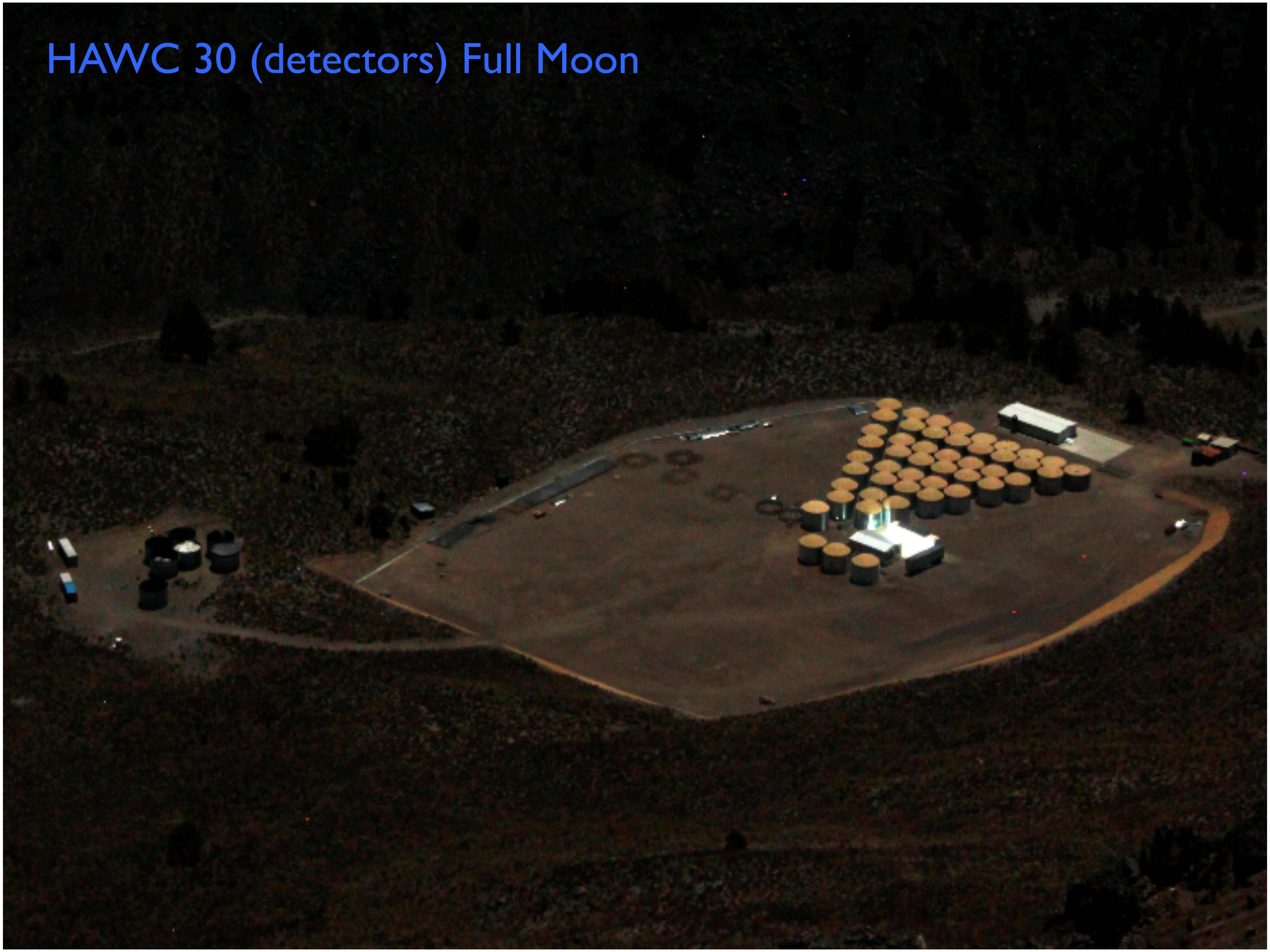
Sources from TeVCAT.uchicago.edu



VI.- HAWC NOW

- HAWC is detecting gamma rays now
- Science operations with 111 tanks began 1 Aug 2013
- Currently, 165 tanks constructed with 4 more per week
- Full detector complete in 2014

VI.- First Light and Preliminary Results



VI.- First Light and Prelimary Results

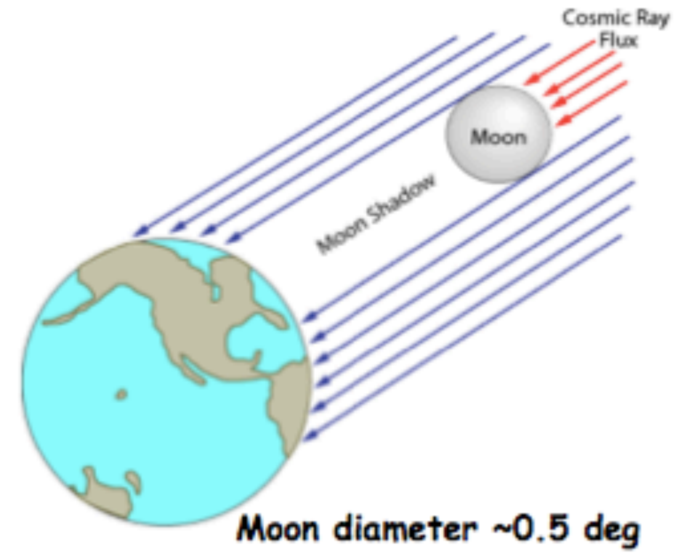
Cosmic rays are hampered by the Moon → Deficit of cosmic rays in the direction of the Moon

- Size of the deficit → Angular Resolution
- Position of the deficit → Pointing Error

Geomagnetic Field: positively charged particles deflected towards the West and negatively charged particles towards the East.

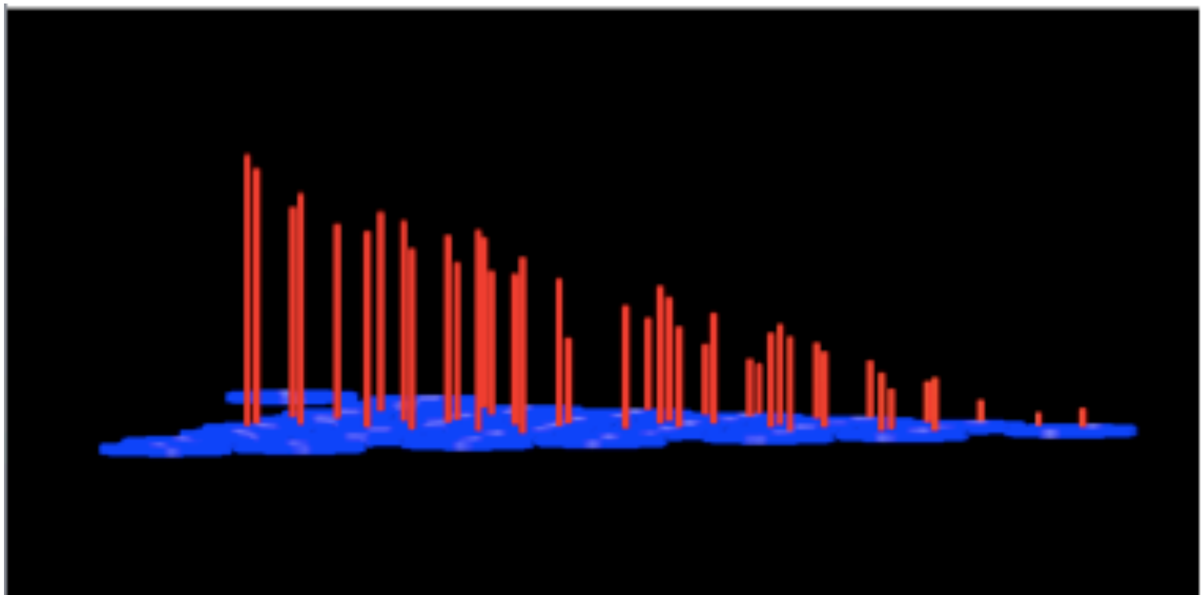
→ Ion spectrometer

$$\Delta\vartheta \approx \frac{1.6^0}{E(TeV)}$$



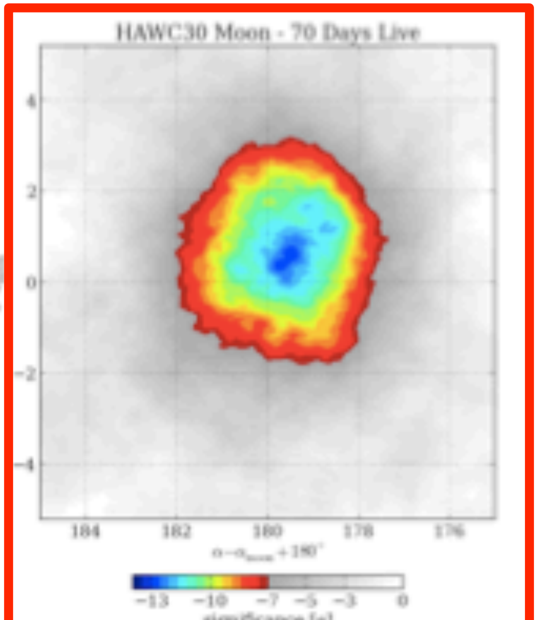
The observation of the Moon shadow can provide a direct check of the relation between size and primary energy: ➔ Energy Calibration

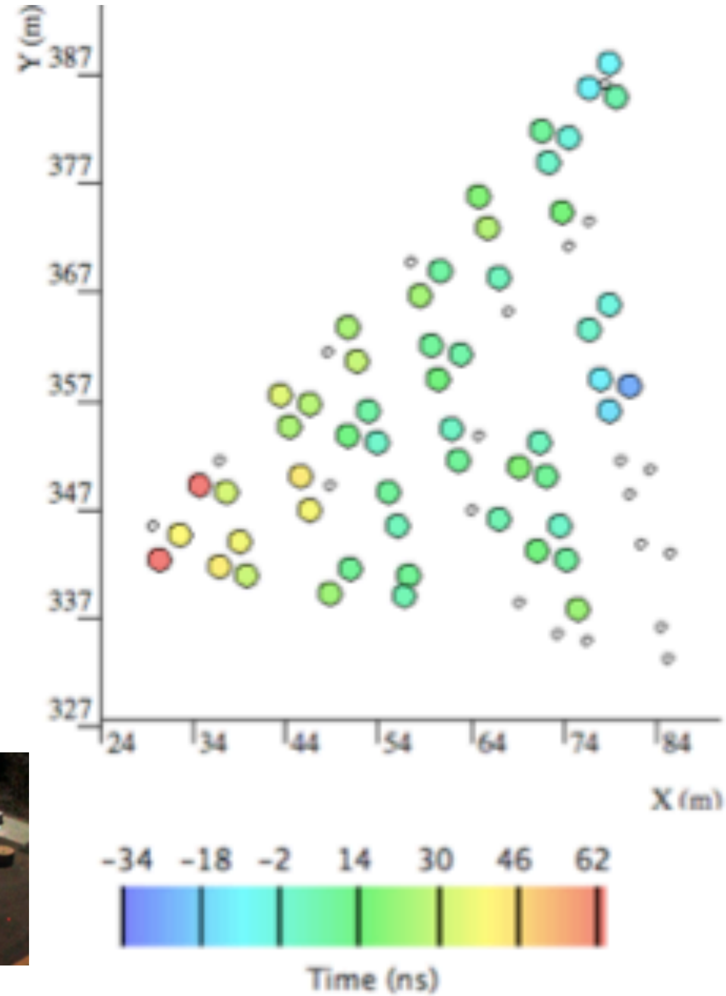
VI.- First Light and Prelimary Results



Median Energy ~ 1.6 TeV (protons) nChannel ≥ 32

Recall: 1° offset per 1.58 TeV for protons

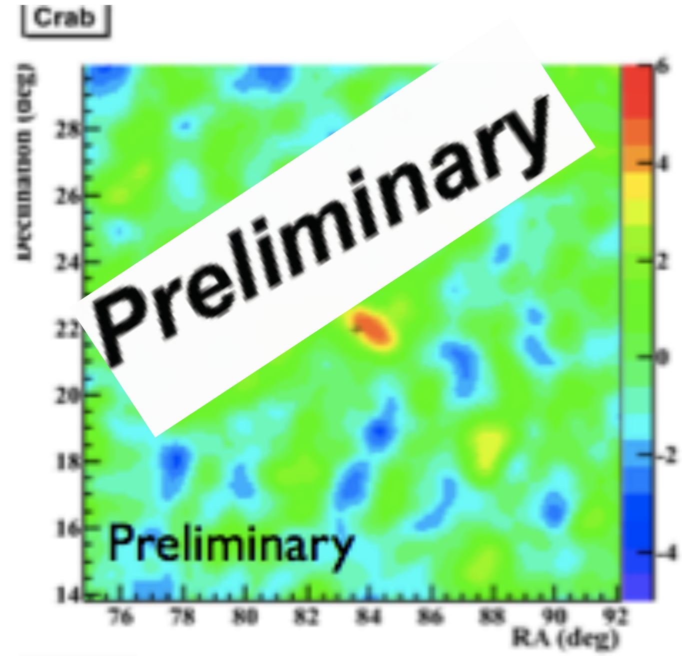


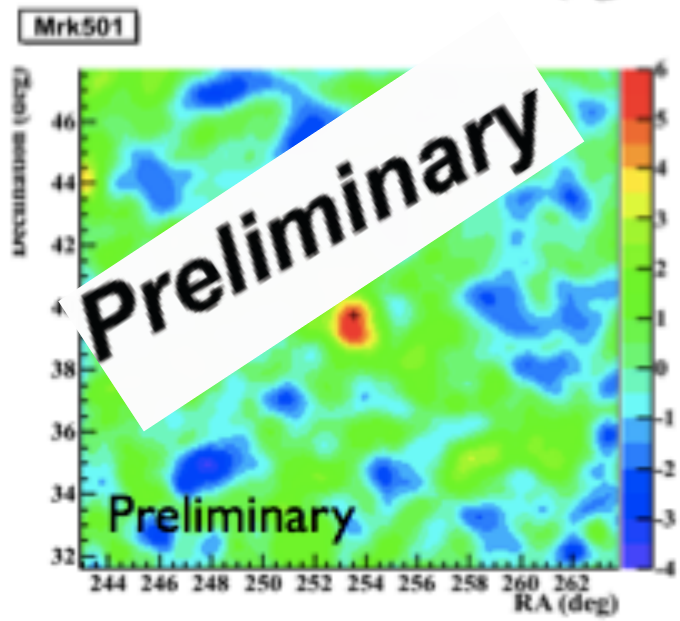


HAWC 30 Events and Observation of cosmic-ray shadow of Moon with 70 days of data

VI.- Prelimary Results

- HAWC science operations began Aug 1, 2013
- All data is reconstructed on site
- Site data shows evidence of gamma rays
  - 3.3 σ at Crab, 4.6 σ nearby
  - 5.4 σ at Mrk501, 5.7 σ nearby
- Triggered data being transferred via internet to UMD now
- Offline reconstruction beginning
- Full calibration soon
- Expect 111 WCDs have ~5x sensitivity of Milagro and ~1/3 the full HAWC sensitivity



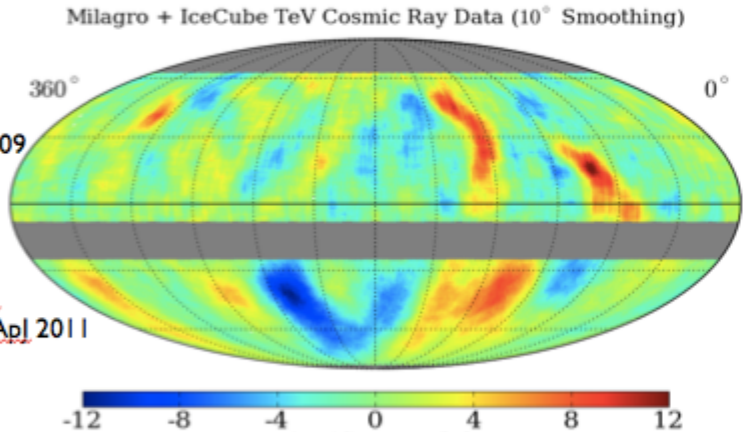


VI.- Prelimary Results

Unexpected Anisotropy of 10 TeV Cosmic Rays; Gyroradius of 10TeV proton in 2μG field is 1000 AU

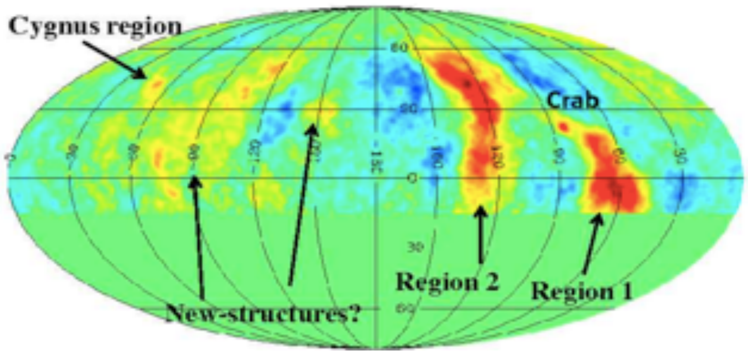
Milagro:
Abdo, et al. PRL, 2009

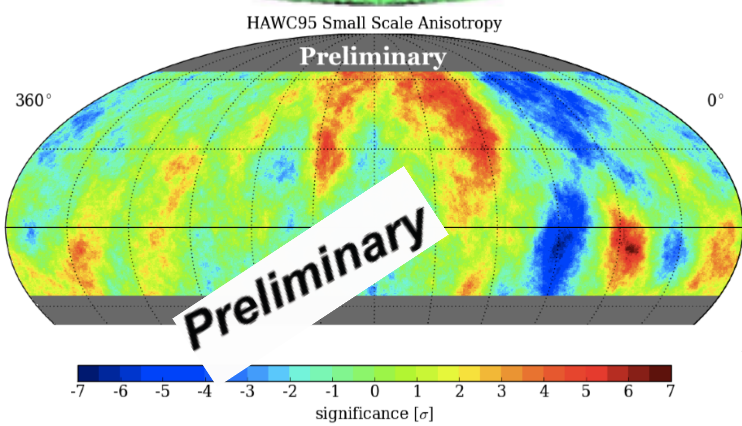
IceCube
R. Abbasi, et al., ApJ 2011



ARGO-YBJ

S. Vernetto et al., Proc. 31st ICRC, 2009





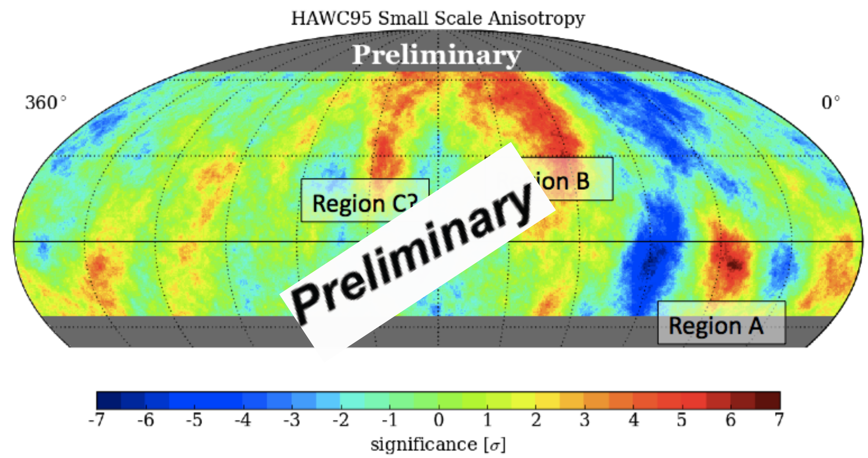
nCh ≥ 32

Direct integration

2hr ≥ dt ≥ 1hr

10° smoothing

Li/Ma signif.



Region A : 7.0 sigma
Region B: 5.5 sigma
Region C: 4.9 sigma

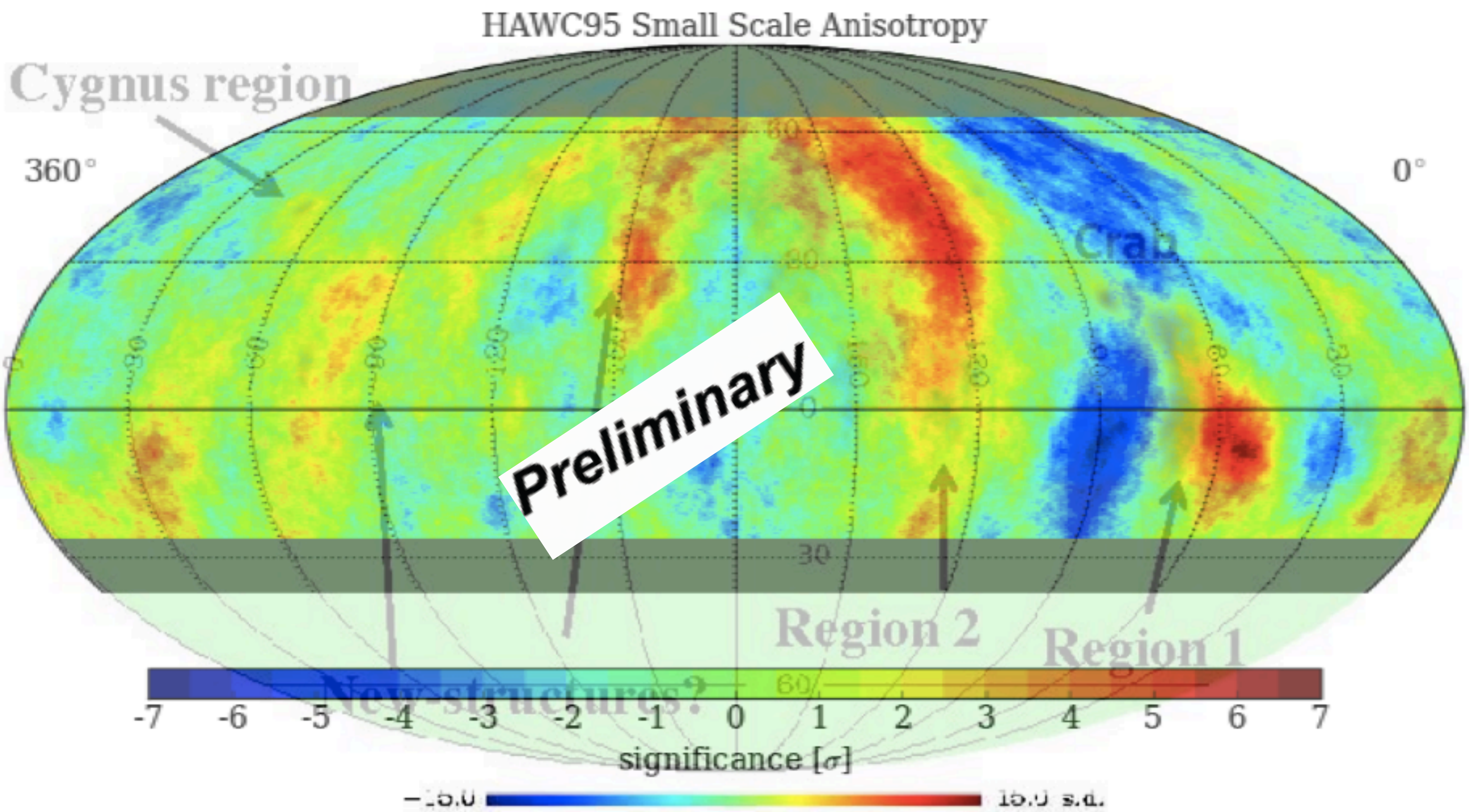
Pre-trial will be greater than 7 with another month of data.

Find post-trial with random data sets.

Astroparticle Physics, in preparation
Point of Contact: Segev Benzvi and Dan Fiorino; Univesity of Wisconsin, Madison

VI.- Prelimary Results

ARGO-YBG vs. HAWC 95



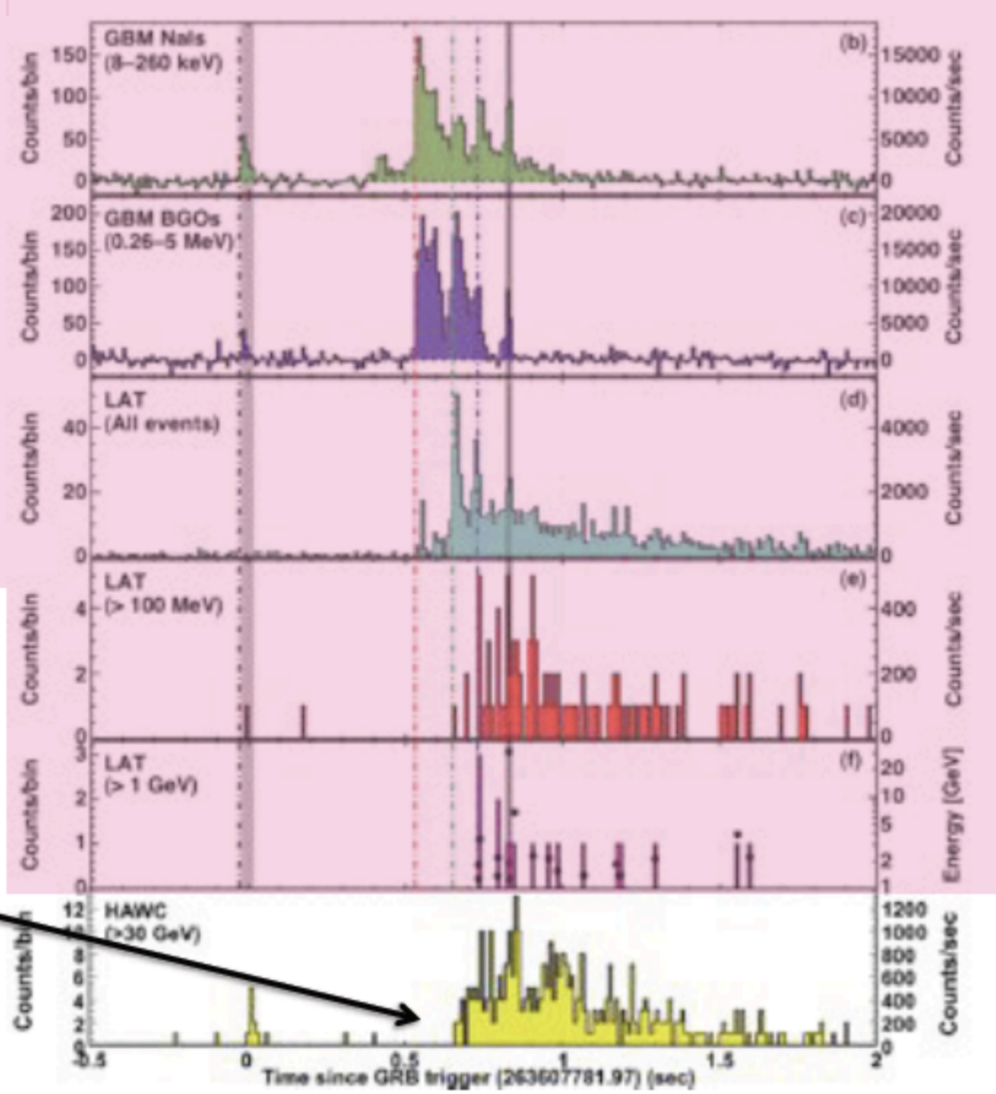
Astroparticle Physics, in preparation
Point of Contact: Segev Benzvi and Dan Fiorino; Univesity of Wisconsin

VI.- Prelimary Results

Fermi observation of GRB090510, z=0.9

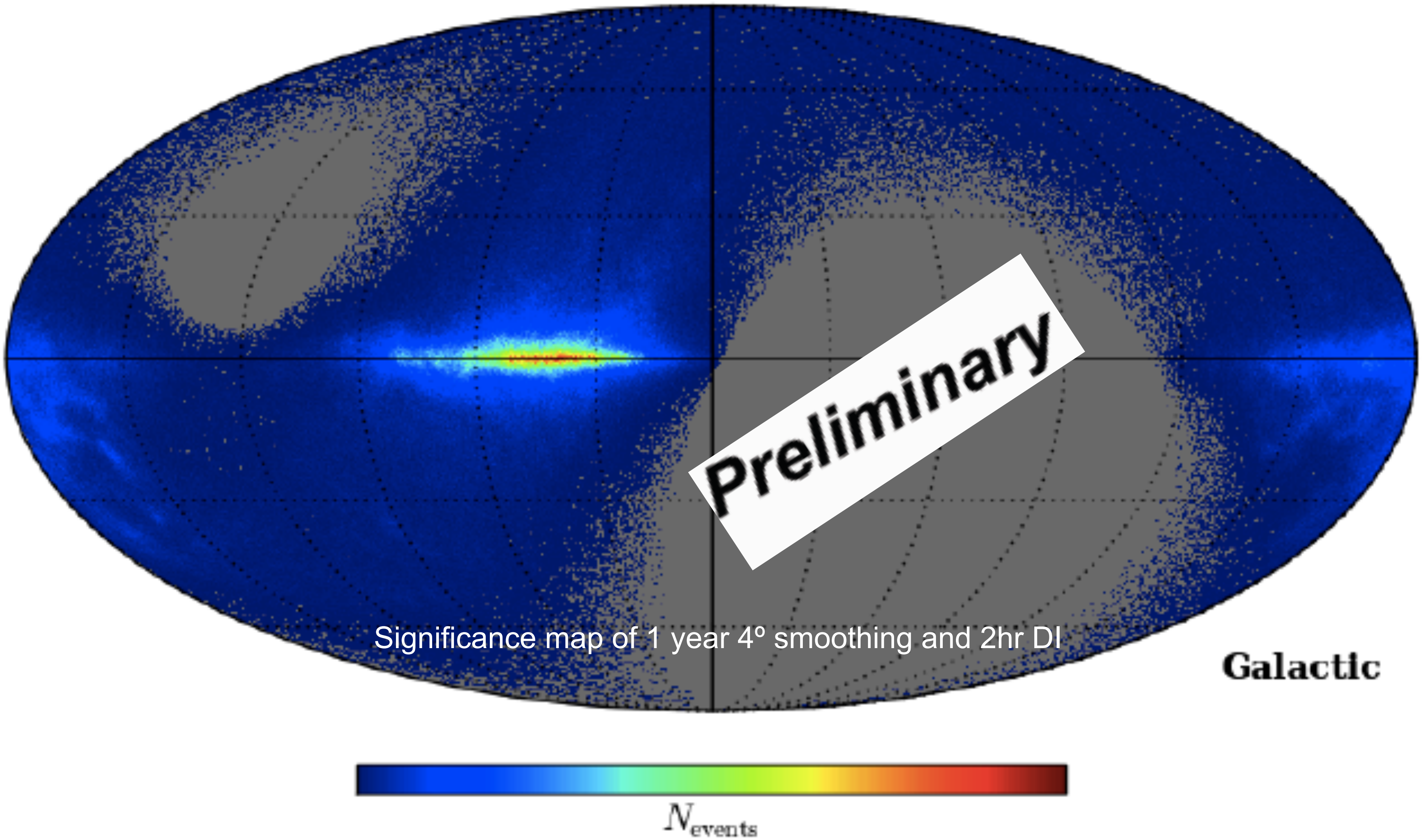
- Highest Observed Energy was 33 GeV with 16 γ-rays >1 GeV
- Constrained Lorentz Invariance at the Plank Mass scale

HAWC would detect this GRB if it occurred in FOV



See also: Dmitry Lennarz (PSU); ICRC2013 (Katherine Sparks).
Paper in preparation, see also Abeysekara et al., Astropart.Phys. 35 (2012) 641-650. Also arXiv: 1108.6034

VII.- Preliminary Results (Diffuse Emission)



Paper to be published, See Huntemeyer et al., 2013, Proceedings of the ICRC 2013
Point of Contact: Petra Huntemeyer, Michele Hui, and Hugo Ayala (Michigan Tech, Houghton)

VII.- Sinergy of HAWC with other experiments

Complements TeV atmospheric Cherenkov telescopes (which have <3 degree field of view and <10% duty factor)

- Identifies new and flaring sources for follow up observation of morphology and sub TeV spectra
- Extends TeV spectra to higher energies

Complements GeV All Sky Survey

- Monitors 1000s of Fermi GeV sources at higher energies

Complements TeV neutrino observations

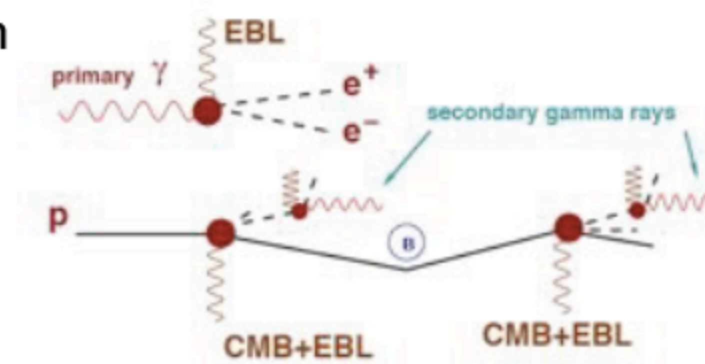
- Identifies new and flaring TeV sources to improve the sensitivity and interpretation of blind searches

Complements Advanced LIGO

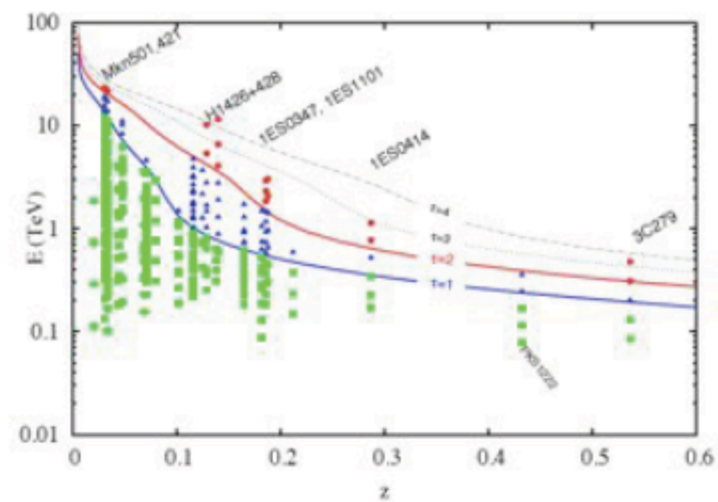
- Simultaneous observations of nearby, short GRBs from ns-ns inspiral

VII.- Near future (AGNs): Distant Universe

- TeV γ-rays are attenuated by pair production
- TeV spectra from distant sources probe:
  - Cosmology of Extragalactic Background Light
  - Sources of UHECRs
  - Intergalactic Magnetic Field in Voids
  - Axion Like Particles $\gamma \rightarrow a \rightarrow \gamma$ (Hooper & Serpico, PRL 2007)



Essey, Kalashev, Kusenko, Beacom, PRL 2010



TeV spectra extend beyond pair production threshold for many sources (Horns&Meyer 2012)

HAWC will survey sky for new TeV AGN, measure multi-TeV spectra and variability, and enable multimessenger observations through prompt notification of flaring activity.

VII.- Near Future (Pulsar Wind Nebulae)

1.- Are the most common Galactic source of TeV gamma rays.

2.- The central pulsar drives a flow of energetic electrons into the surrounding material lighting it up with syncrotron radiation.

Further acceleration is possible in shocks created when the flow interacts with surrounding material.

3.- Perhaps the most intriguing current topic in PWN science is the detection of flares from the Crab Nebula, challenging our understanding of these objects.

It is currently unknown how high in energy these flares go or whether any other PWN flares.

4.- Electrons and positrons accelerated in PWN constitute a background to dark matter searches.

5.- Developing an unbiased high-sensitivity survey of PWN is crucial to understanding energetic particle backgrounds for more exotic searches.

VII.- Near Future (Supernova Remnants)

1.- SNR accelerate particles at shock boundaries by Fermi mechanism.

2.- To date, the strongest positive evidence that SNR are responsible for the Galactic cosmic-ray population is due to TeV emission near SNR coincident with molecular clouds with which the SNR is interacting.

4.- More recently, evidence of characteristic spectral features from pion decay has been seen in these objects, strengthening the case they are hadron accelerators.

Nevertheless, while we have a few demonstrated examples of hadron accleration in SNR, we still have not yet seen evidence of PeV hadron acceleration to fully account for the believed Galactic cosmic ray population.

HAWC's unbiased survey out to 100 TeV will help identify or constrain instances of PeV hadron accleration.

5.- Points on SED's at TeV range. Very important to determine if pion decay, IC, or Bremmstranlung dominates

VII.- Near Future (Supernova Remnants)

Mexican Group (IA-UNAM, UAEH, U de G, ICN-UNAM) created to study supernova remnants (plerions and Pulsar Wind Nebula).

Focus in those Supernova Remants reported by MILAGRO

Perform optical (Polarimetry and Fabry-Perot), X-Ray, and Gamma-Ray with HAWC. Contrasting between observations

Polarization can be produced by anisotropic radiation processes (Light scattering, Zeeman effect, Synchrotron emission, Dichroic absorption, birefringence); A more direct way to investigate the magnetic field configuration.

Multi-Wavelenghts (MW) observations are useful to detect structures and bright features associated with the PWN, to confirm theoretical models associated with the nature of the emission, and determine regions of diferent emission (e.g., Radio; Syncrotron, and Gamma Rays; accelerated protons interacting with molecular clouds) in Supernova Remnants.

THANK YOU!

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