# Air Showers and HAWC

**Pat Harding**

**Los Alamos National Laboratory**

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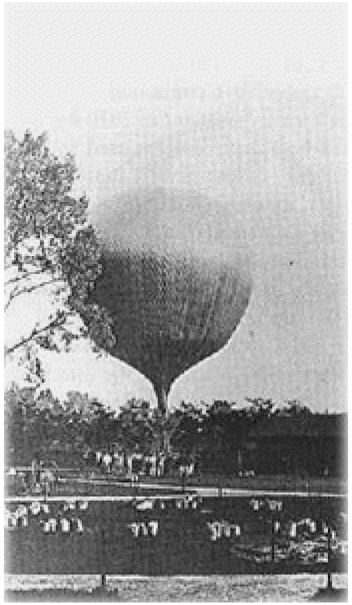
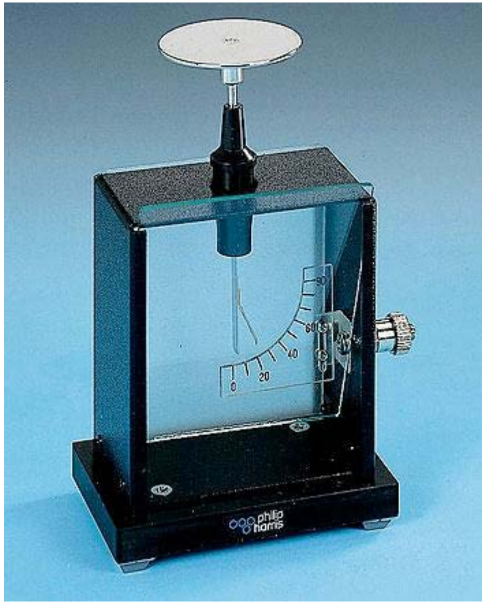
# Cosmic Rays Discovery

- **Physikalische Zeitschrift: "The results of these observations seem best explained by a radiation of great penetrating power entering our atmosphere from above."**

Victor Franz Hess

| Elevation | Rate |
|---|---|
| Ground | 12 |
| 1km | 10 |
| 2 km | 12 |
| 3.5 km | 15 |
| 5 km | 27 |

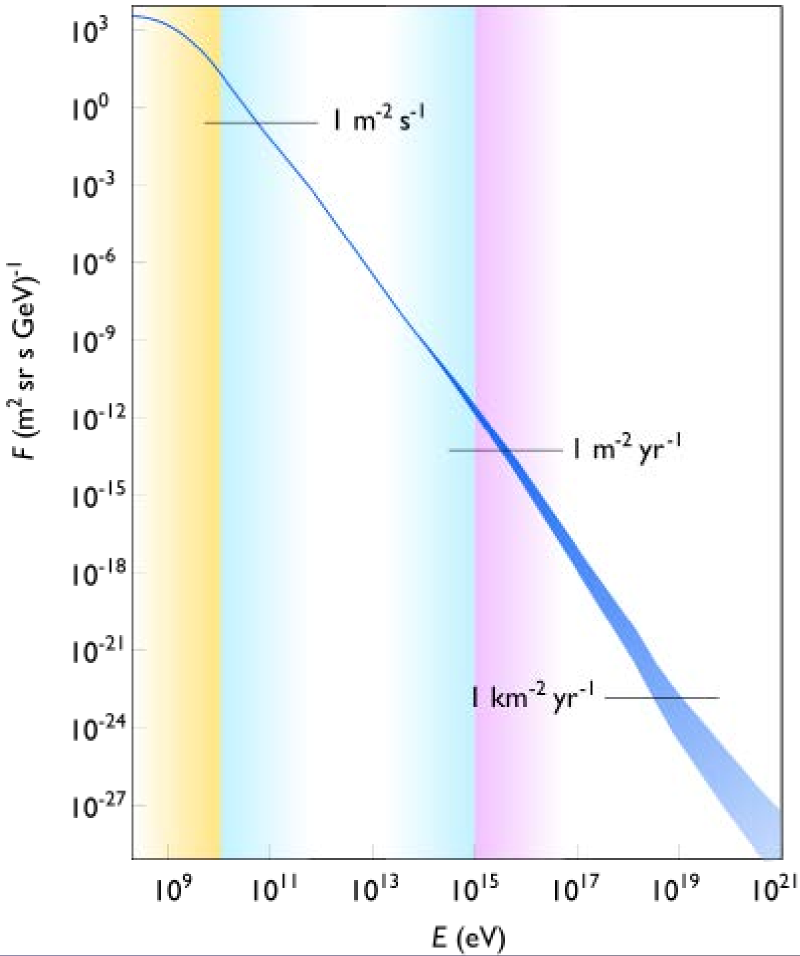




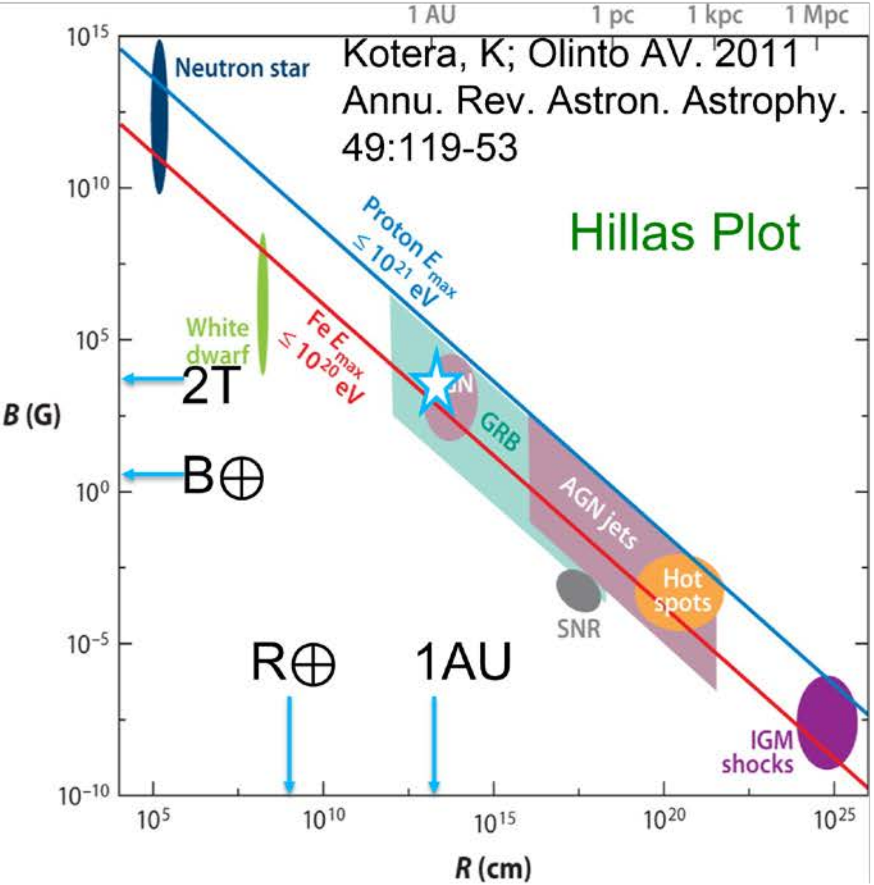
V. F. Hess. Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten. Physikalische Zeitschrift, 13:1084-1091, November 1912.

# Cosmic Rays

- **The flux charged cosmic rays follows nearly a single power law over:**
  - 10 decades in energy
  - 30 decades in flux
- **Single particles have been observed with energies above $10^{20}$eV!**
- **There are several “kinks” in the spectrum where the exponent changes, steepening at the “knee” and flattening at the “ankle”.**
- **The source of the high-energy cosmic rays remains elusive.**



# Candidate Accelerators





p=0.3 Br

p in Gev/c

B in Tesla

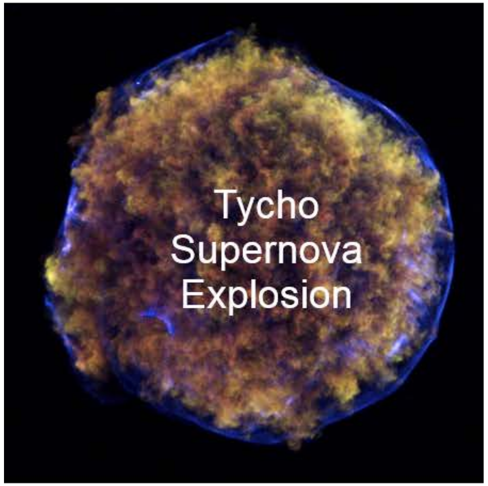
r in meters

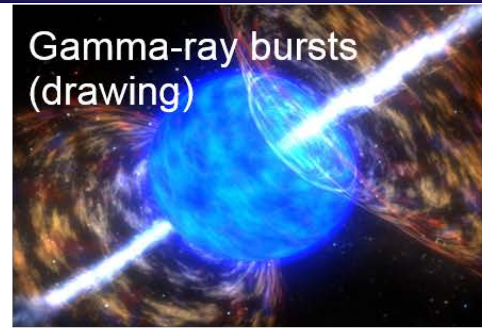
B=2T r=1.5x10$^{11}$m

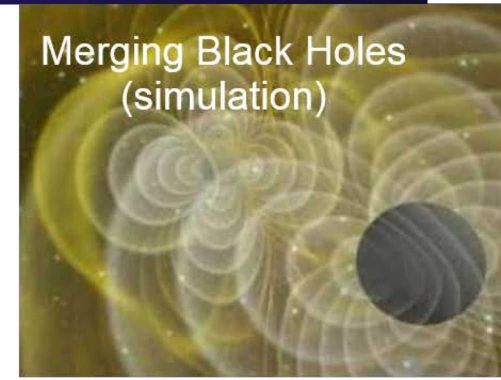
p=10$^{11}$ GeV/c

=10$^{20}$ eV/c

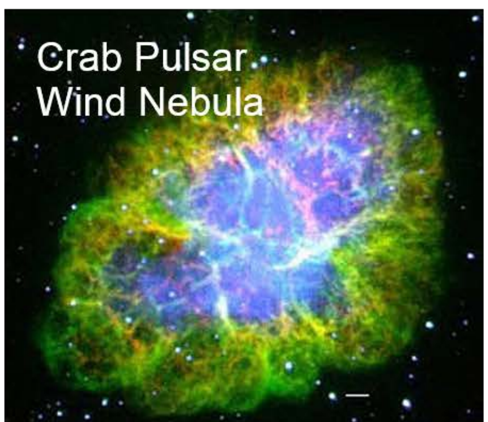
# Sources of the Highest-Energy Cosmic Rays and Gamma Rays

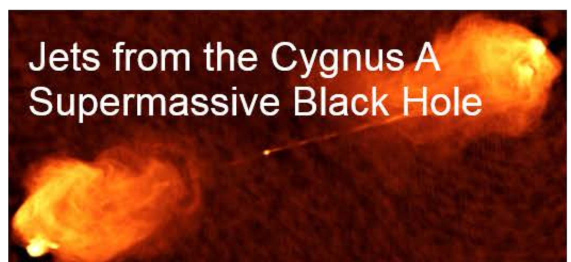


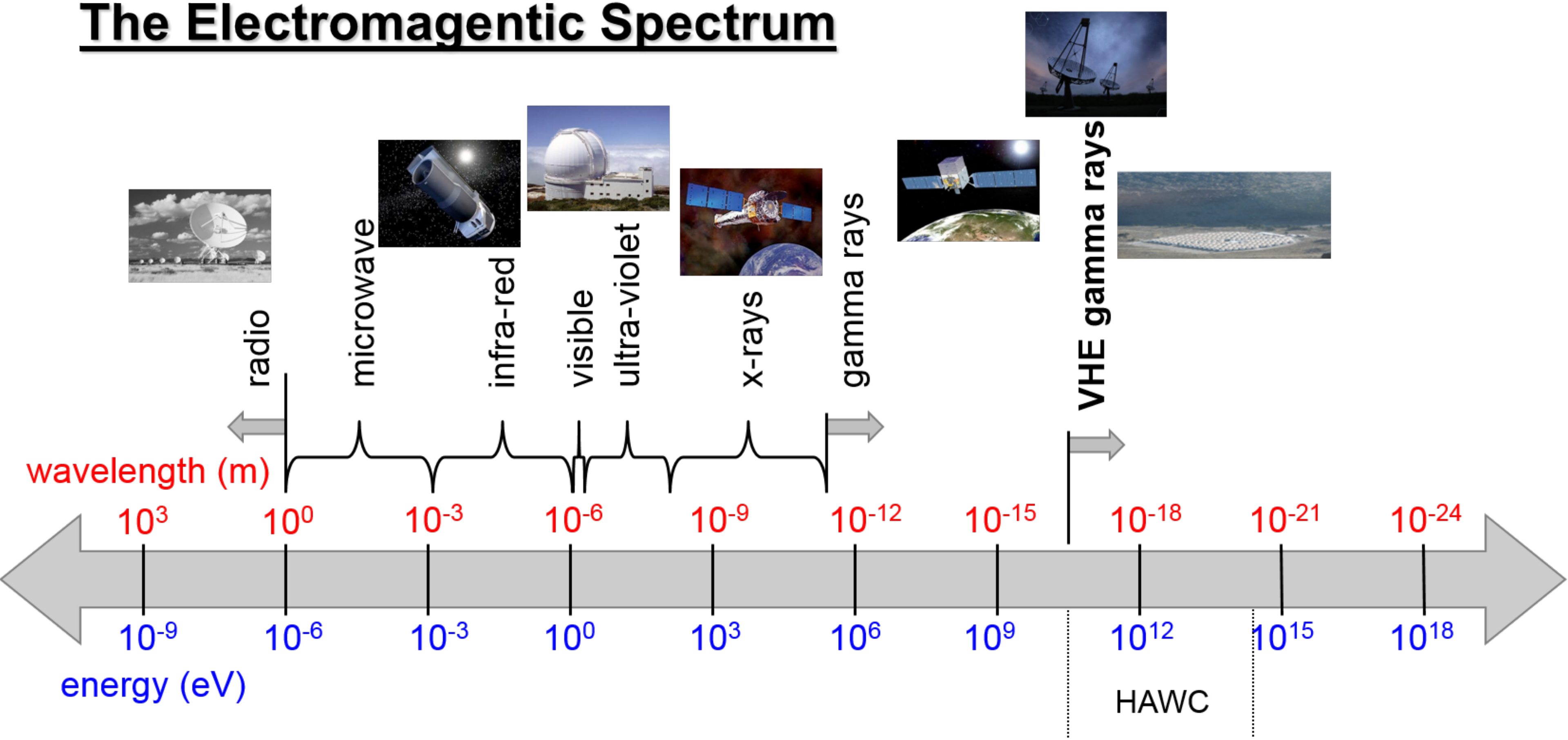

## The Most Violent Processes in the Universe



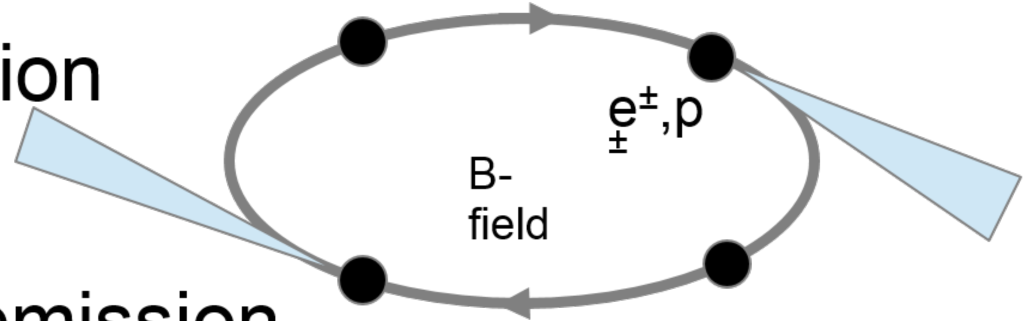

# Gamma Rays

## The Electromagentic Spectrum

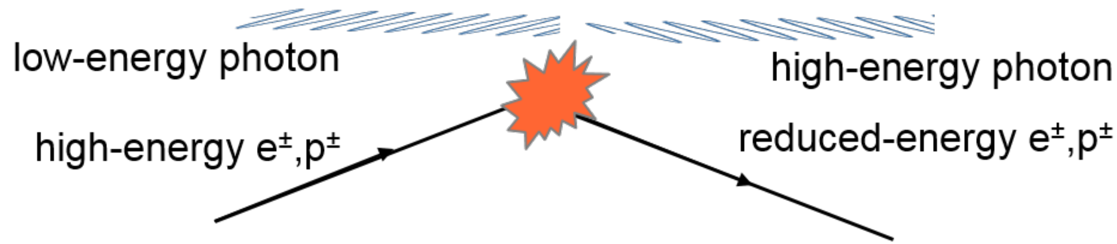


# Processes that Make TeV Gamma Rays

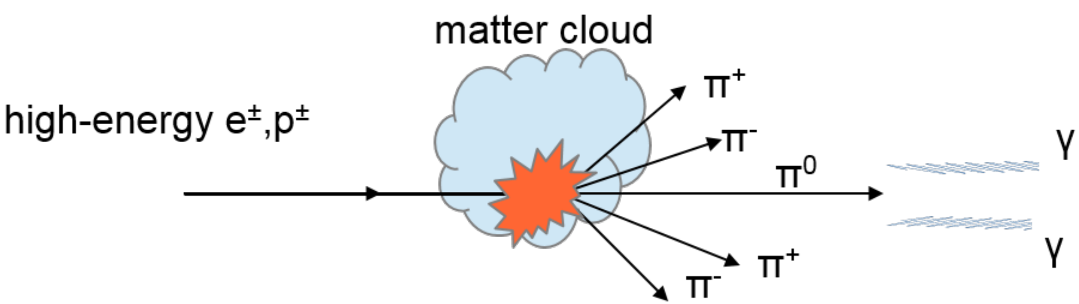
- Synchrotron emission




- Inverse Compton emission

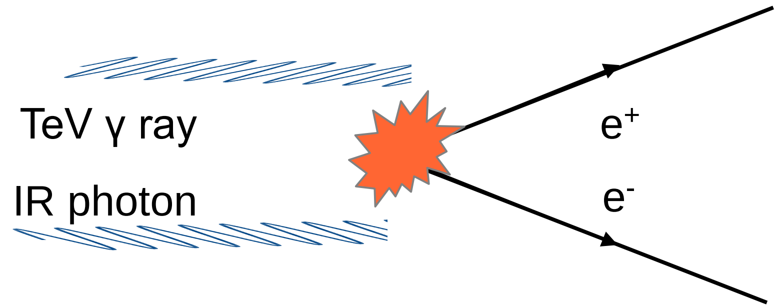


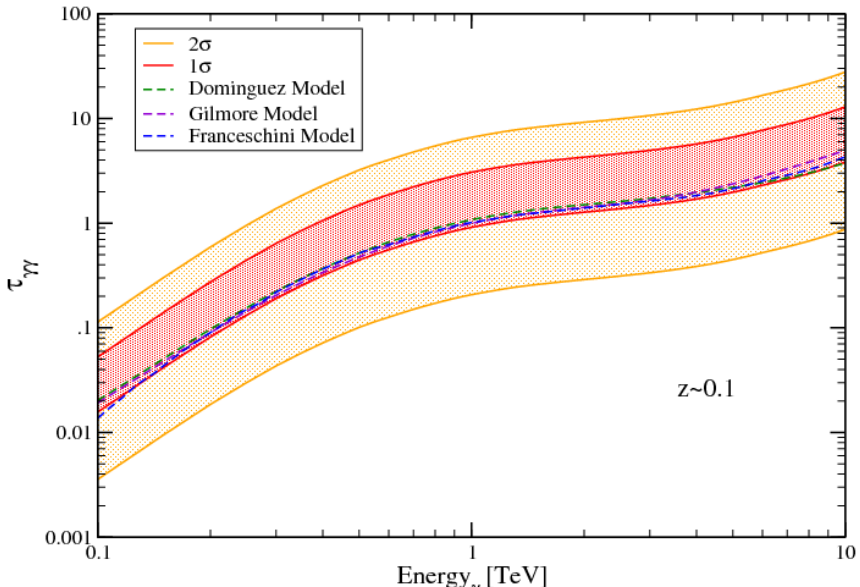

- Hadronic pions



# Gamma-Ray Attenuation

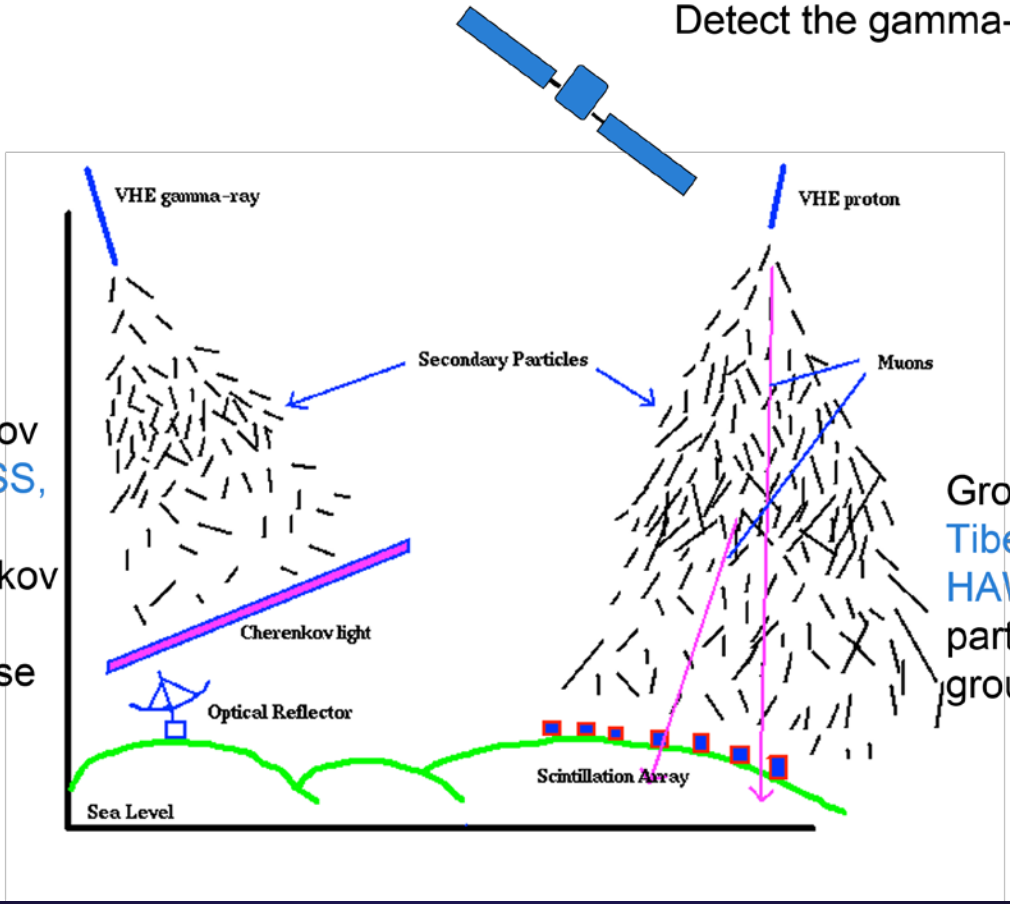
- Gamma rays can interact with photons from the IR background or CMB to produce electron-positron pairs
- For extragalactic gamma rays, this sets a horizon beyond which we cannot observe sources
- The optical depth τ increases with increasing gamma-ray energy and increasing distance
- By observing this cutoff in source spectra, we can determine the nature of the extragalactic background light



# Techniques for Gamma-Ray Detection

Satellite (Fermi, AGILE, EGRET…) Detect the gamma-rays directly.



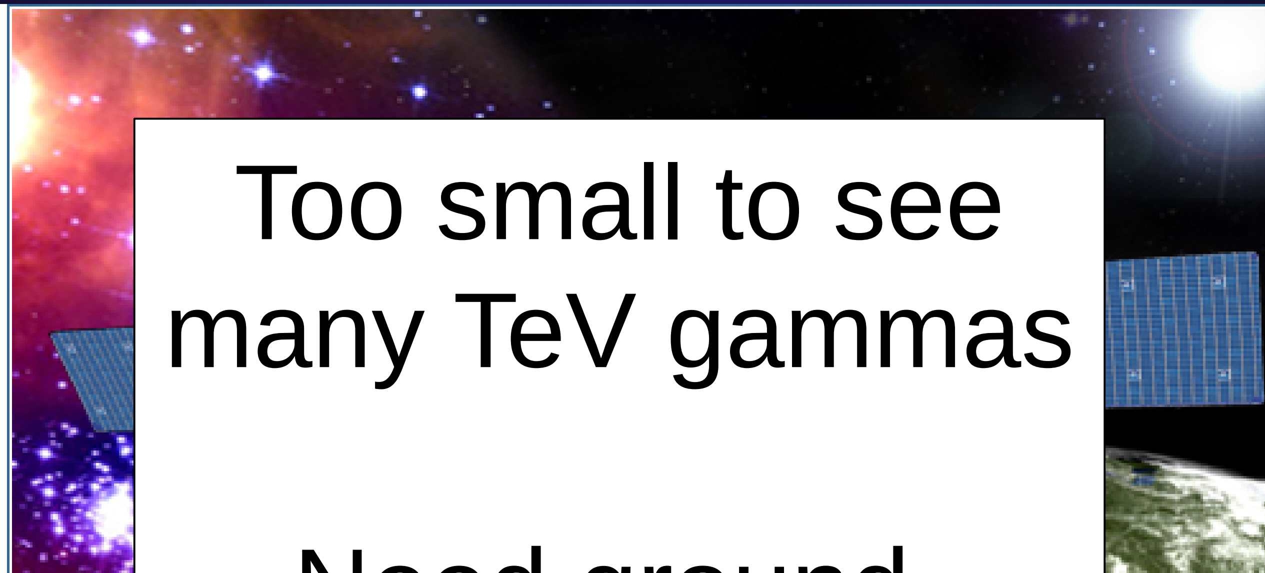

Atmospheric Cherenkov Telescope Array (HESS, MAGIC, VERITAS, CTA..) Detect Cherenkov light from air-shower particles as the traverse the atmosphere.

Ground Array (Milagro, Tibet, ARGO, HAWC…) Detect particles reaching ground level.

# Gamma Rays with Satellites

- **Direct detection of particles in space**
- **Good sensitivity**
  - Large field-of-view
- **Small (~1 $m^2$)**
  - Rare TeV photons will not hit in large quantity

# Gamma Rays with Satellites

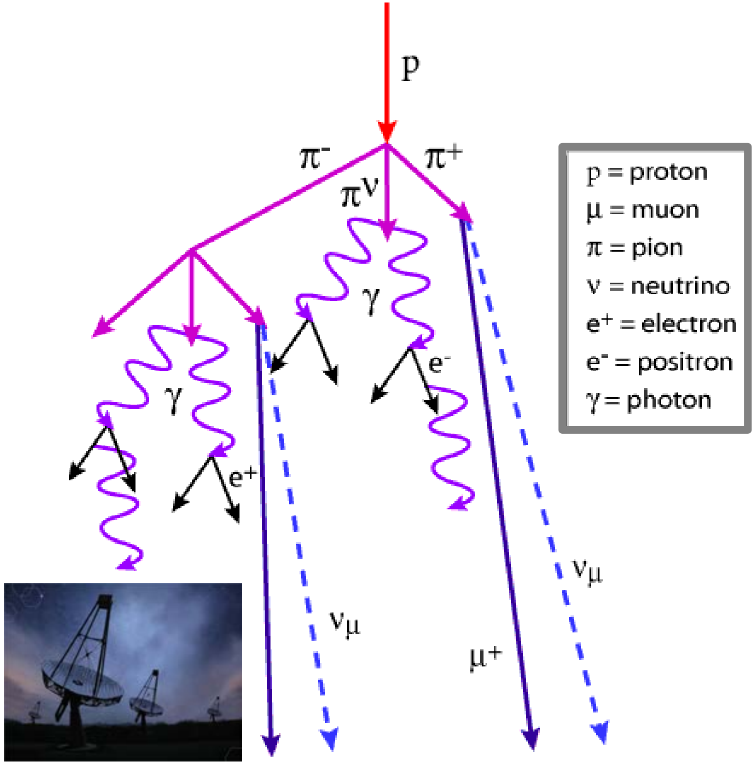


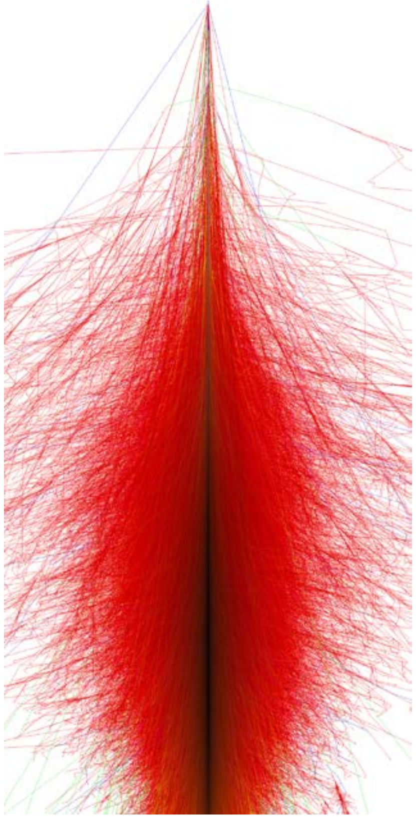
Too small to see many TeV gammas

Need ground-based experiments

- **Direct detectio**
- **Good sensitivi**
  - Large field-of-v
- **Small (~1 m²)**
  - Rare TeV photons will not hit in large quantity

# Air Showers



Corsika simulation of the shower from a 100 TeV proton

# Gamma Ray Energy Loss Mechanisms

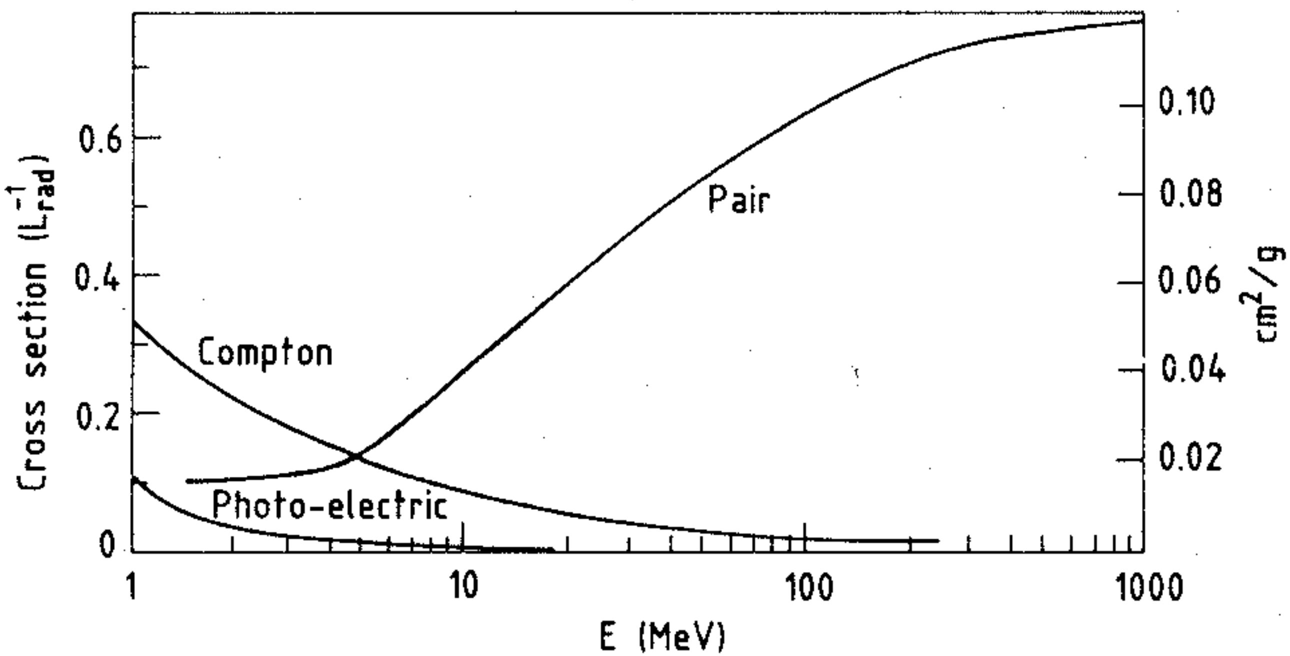
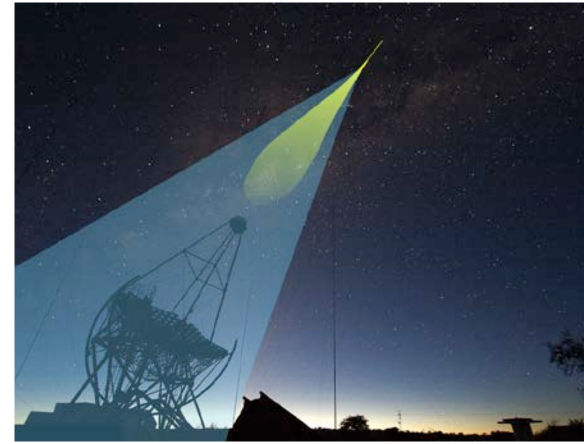


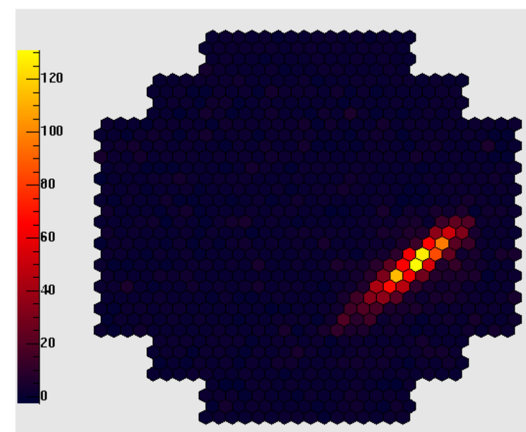

**Fig. 2:** Photon cross-section $\sigma$ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

# Imaging Air Cherenkov Telescopes



- **Observe the Cherenkov radiation from charged air shower particles traveling through the atmosphere**
- **Properties:**
  - Effective area: ~$10^5$ $m^2$ ✓
  - Energy resolution: ~15% ✓✓
  - Angular Resolution: ~0.1° ✓
  - Field-of-view: ~ ~2° - 5° ✗
  - Duty cycle: ~ ~10% ✗
- **Excellent for pointed observations**
- **Not survey instruments**



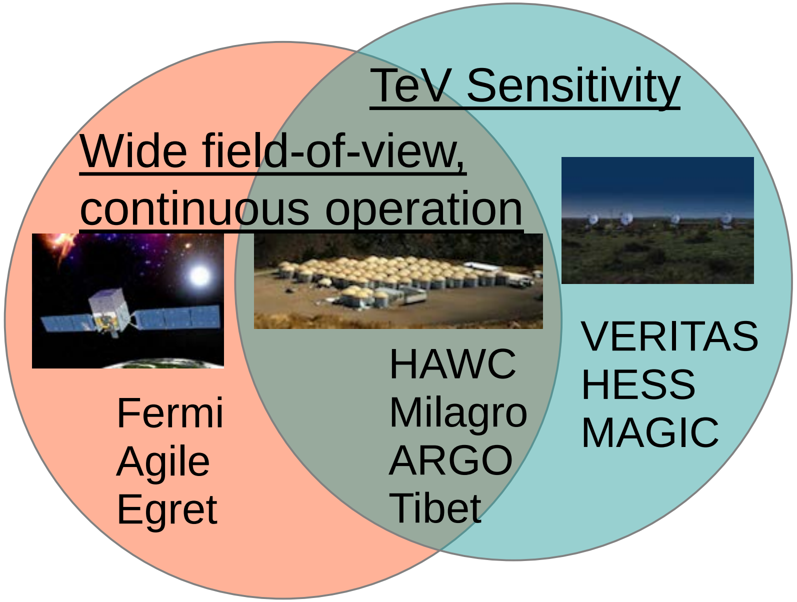


# Extensive Air Shower (EAS) Arrays

- **Observe the Cherenkov radiation from charged air shower particles traveling through water (or scintillator) at ground level**
- **Properties:**
  - Effective area: ~$10^4$ - $10^5$ $m^2$ ✓
  - Energy resolution: ~30 - 100% ✗
  - Angular Resolution: ~0.1°-1° ✓
  - Field-of-view: ~ ~2 sr instantaneous (2/3 sky each day) ✓
  - Duty cycle: ~ ~100% ✓
- **Excellent survey instruments**

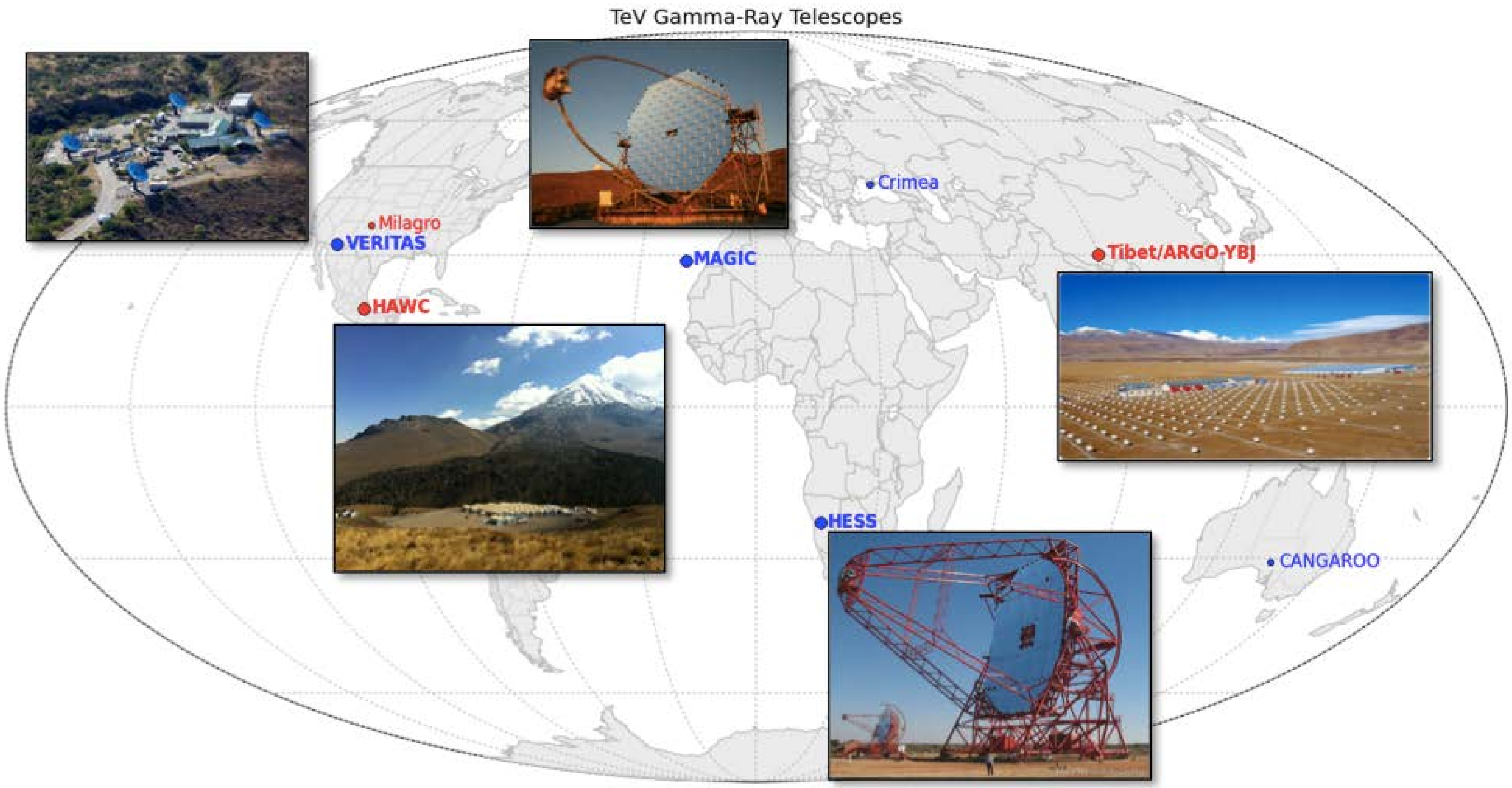
# EAS Arrays - Science

- **EAS Arrays are Survey Instruments**
- **Key niches:**
  - Transients
  - New sources
  - Hard spectrum sources
  - Source spectrum cutoffs
  - Extended sources

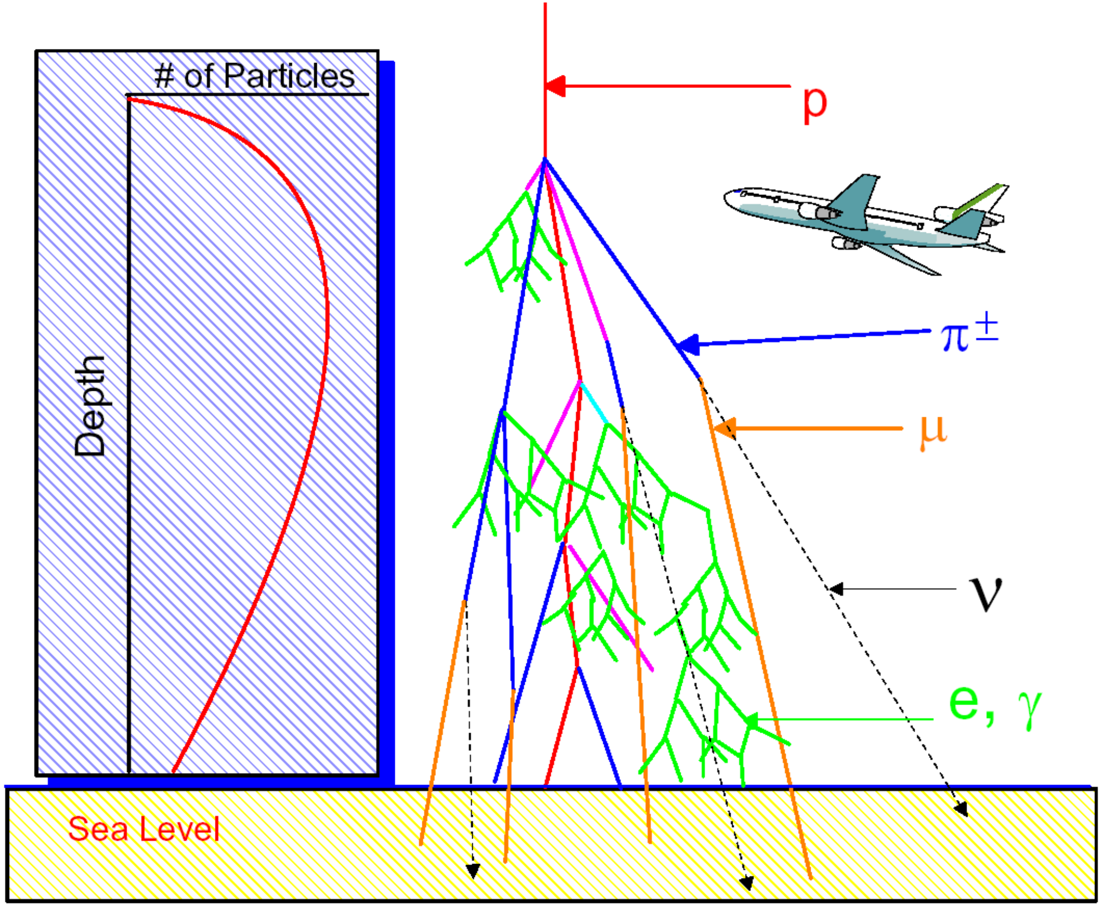


# TeV Observatories

Extensive Air Shower Array Observatories    Imaging Air Cherenkov Telescopes

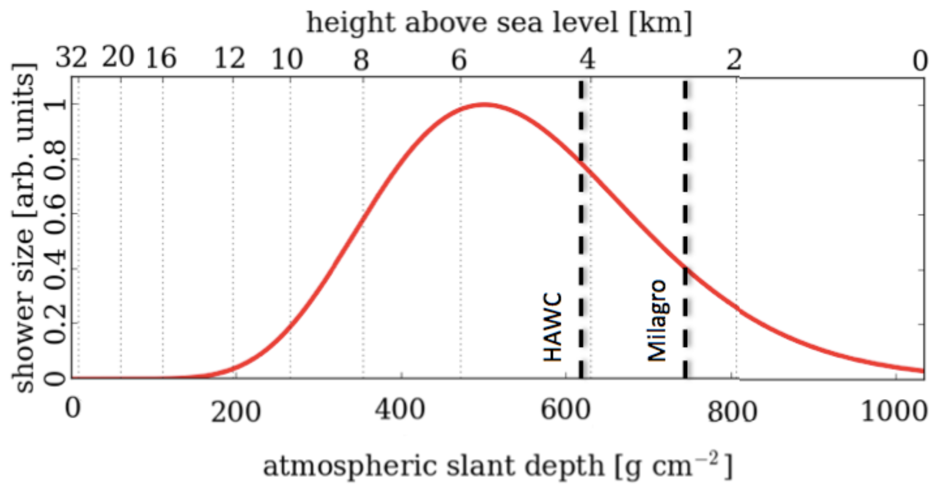


# Extensive Air Shower Development



# Get Thee to High Altitude!

- **The higher altitude the EAS array is, the more air shower particles are observed**
- **At low energy, observations are limited by the number of particles observed**
  - Higher altitude means sensitivity to lower energy primaries
  - Below shower maximum, many of the lowest-energy shower particles have "ranged out" and stopped propagating



## Lateral shower profile:

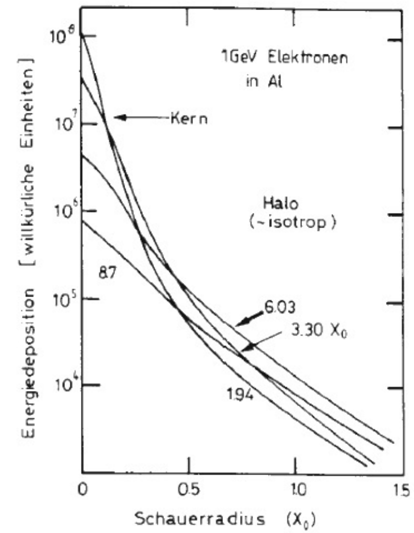
- The lateral shower profile is dominated by two processes:
  - multiple Coulomb scattering
  - relatively long free path length of low energy photons

- It is characterized by the so-called Molière radius $\rho_M$

$$\rho_M = \frac{21\text{MeV}}{E_C} X_0 \approx 7 \frac{A}{Z} \left[\frac{g}{cm^2}\right]$$

- About 95% of the shower energy are contained within a cylinder with radius r = 2 $\rho_M$

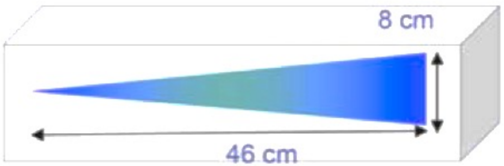
in general well collimated !



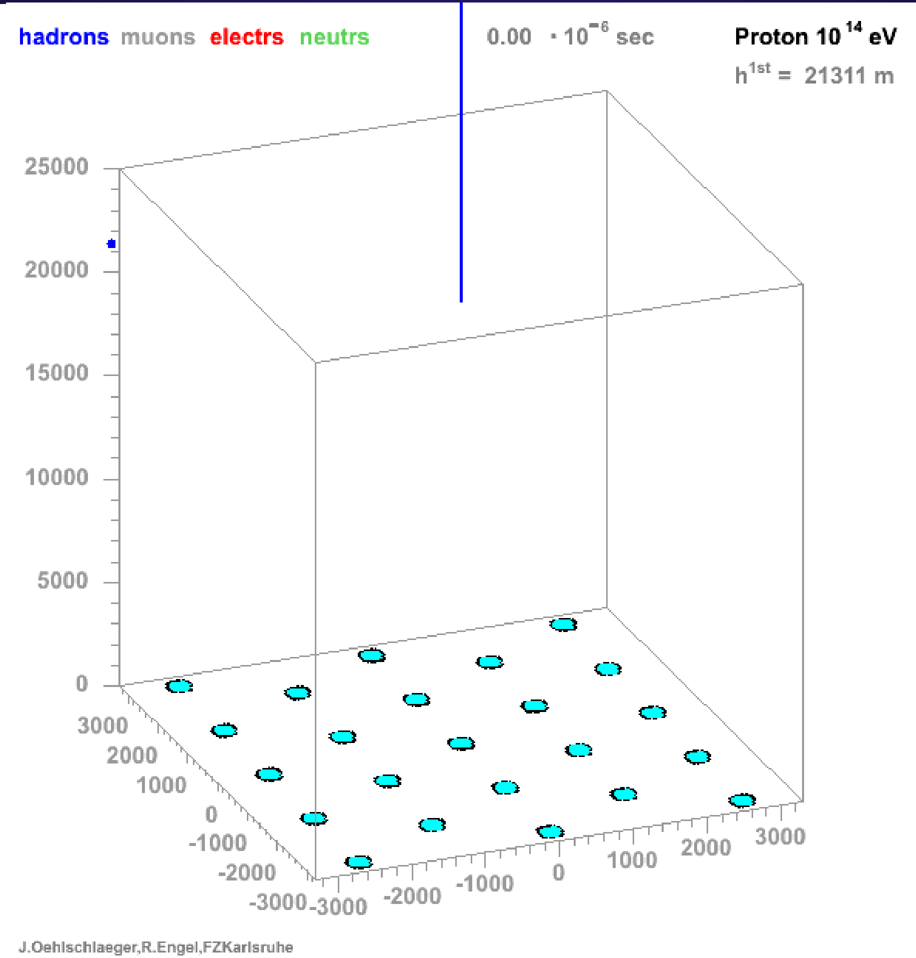

Example: $E_0$ = 100 GeV in lead glass

$E_c$=11.8 MeV → $t_{max}$ ≈ 13, $t_{95\%}$ ≈ 23

$X_0$ ≈ 2 cm, $R_M$ = 1.8·$X_0$ ≈ 3.6 cm



# 100 TeV Proton



# High Altitude Water Cherenkov Observatory

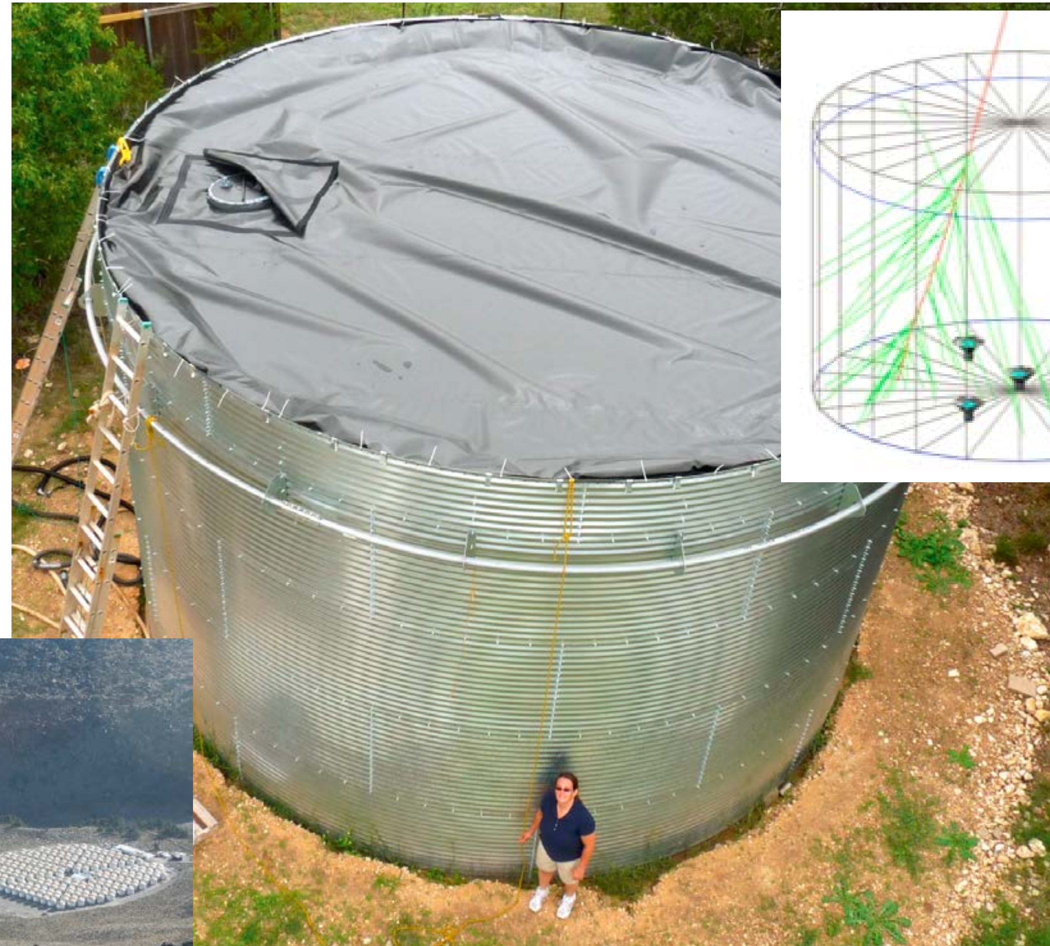

Altitude: 4100 m (13000 ft)        Latitude: 19° N

# HAWC Location

# Water Cherenkov Detectors

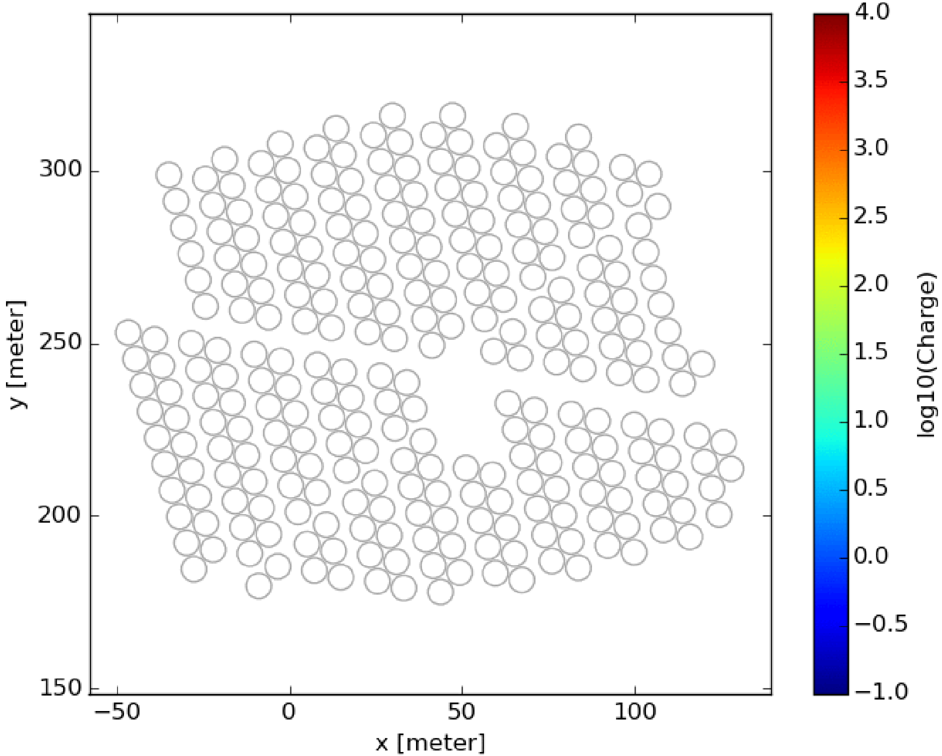
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

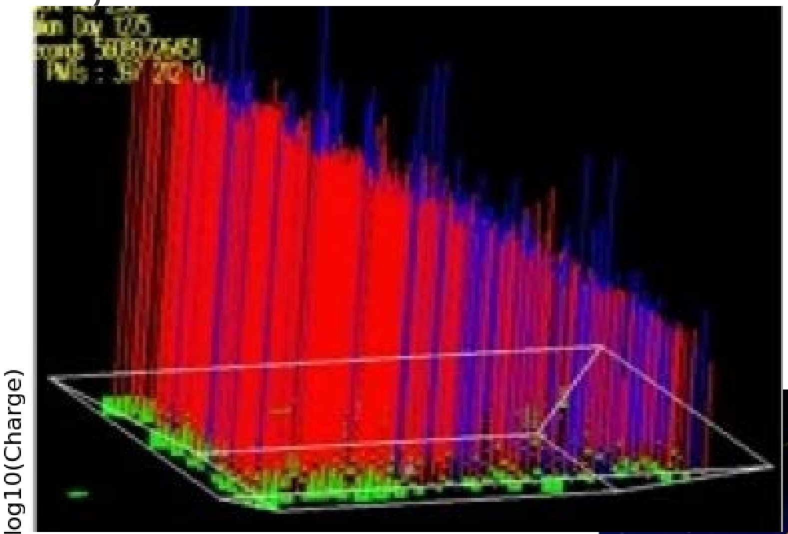
- 300 tanks
- 5 m x 7.3 m tanks
- 200,000 L of water
- 4 PMTs
  - 3 8” R5912
  - 1 10” R7081 HQE

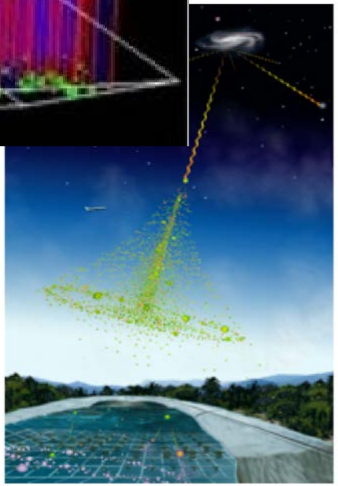


# Direction

- **As the shower sweeps across the WCDs, we can reconstruct the direction it's sweeping from**

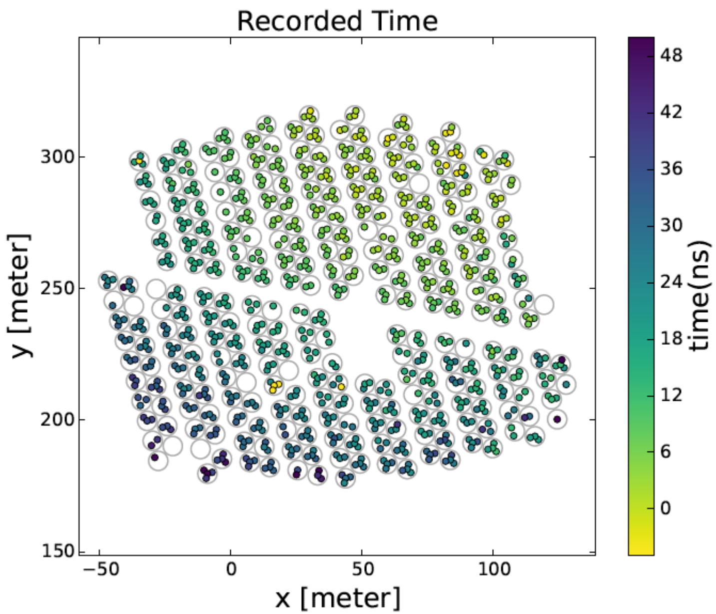


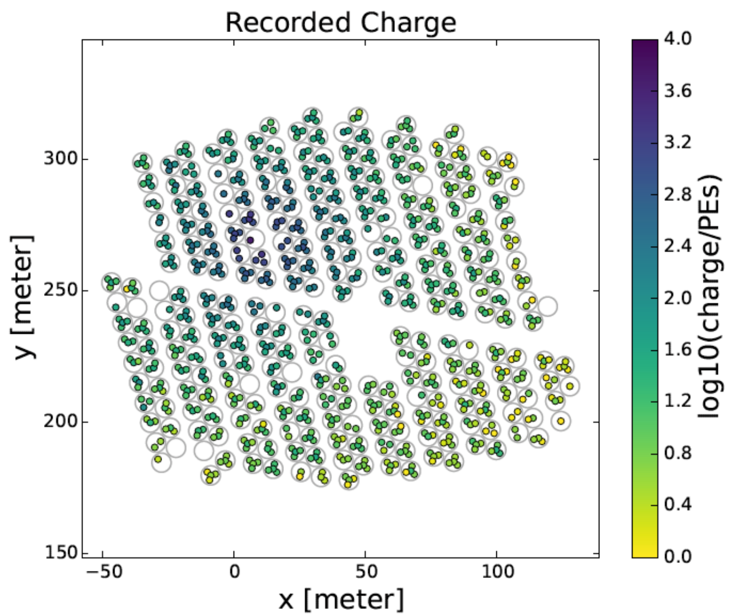





# Energy

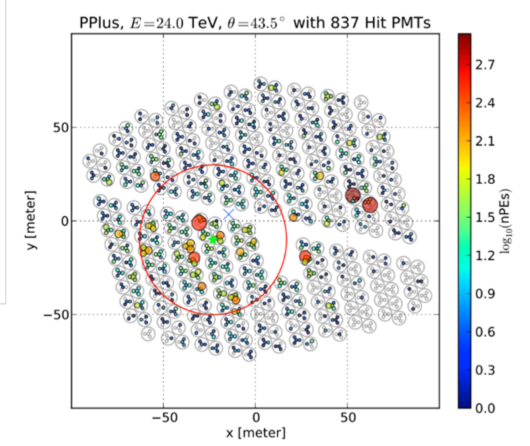
- The light level is each PMT and its LDF correlates with energy
- More PMTs hit, more light in PMTs → higher energy



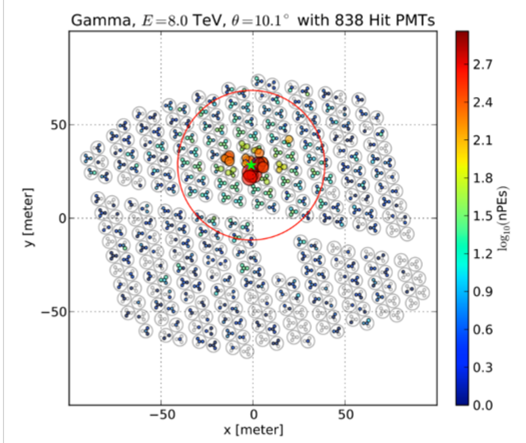



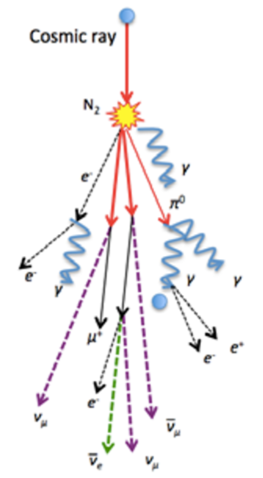
# Particle Type

Proton

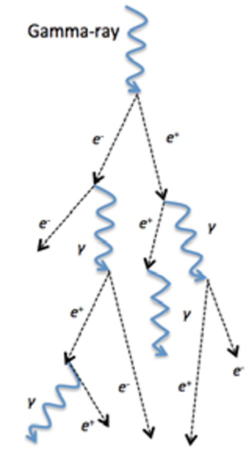



Gamma

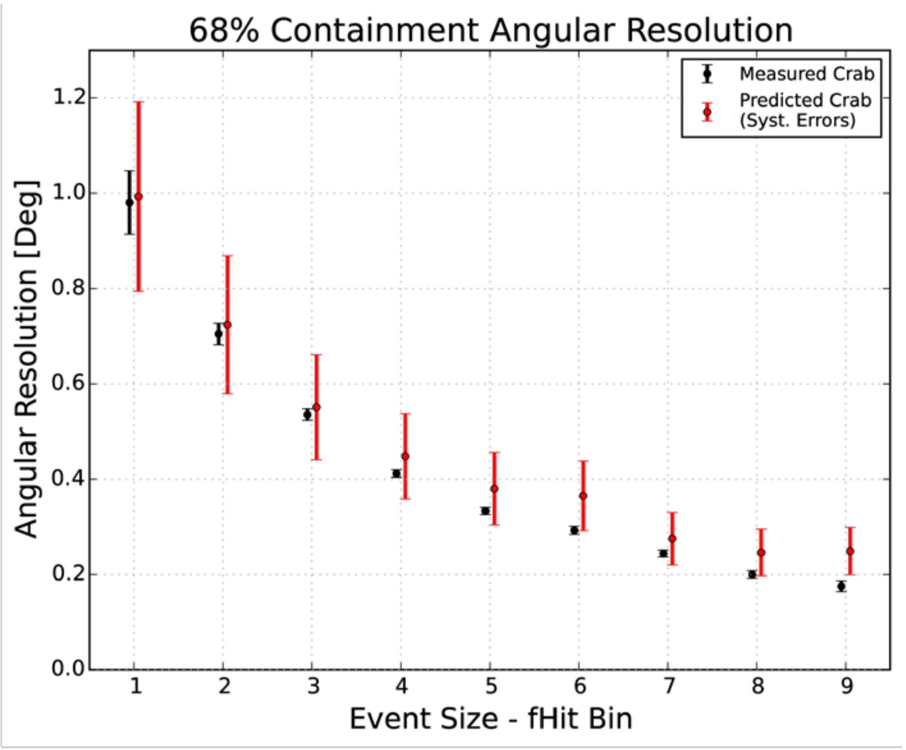


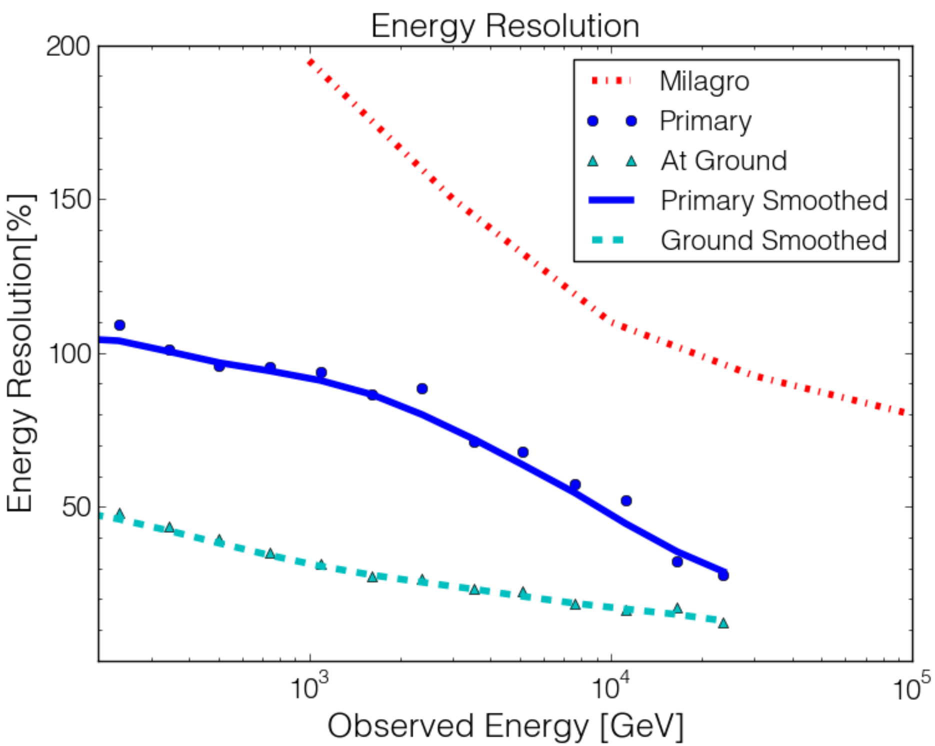




- Hadron-induced showers produce subshowers with a lot of transverse momentum and muons, so their distributions tend to clump in several regions on the array
- Gamma-ray showers produce a smoother, more peaked distribution on the array
- Looking for the sub-showers on the array and the larger spread of the hadronic showers, we can distinguish gammas from hadrons

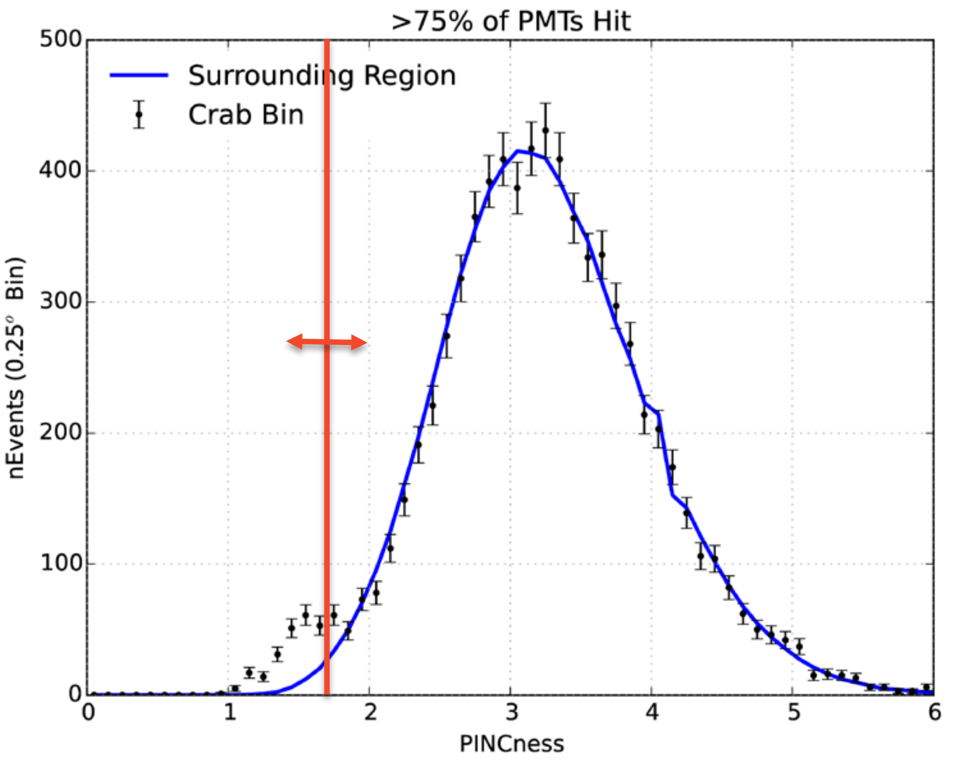


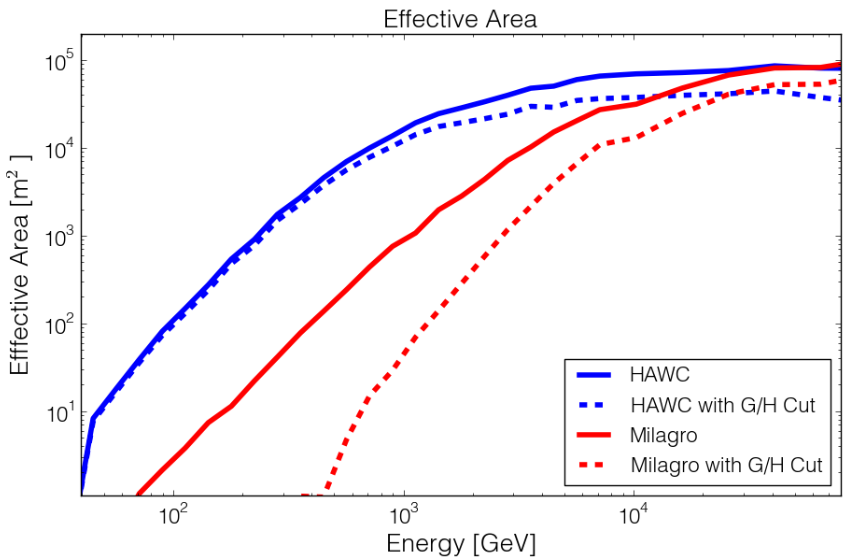
# HAWC Resolution



# HAWC Efficiency

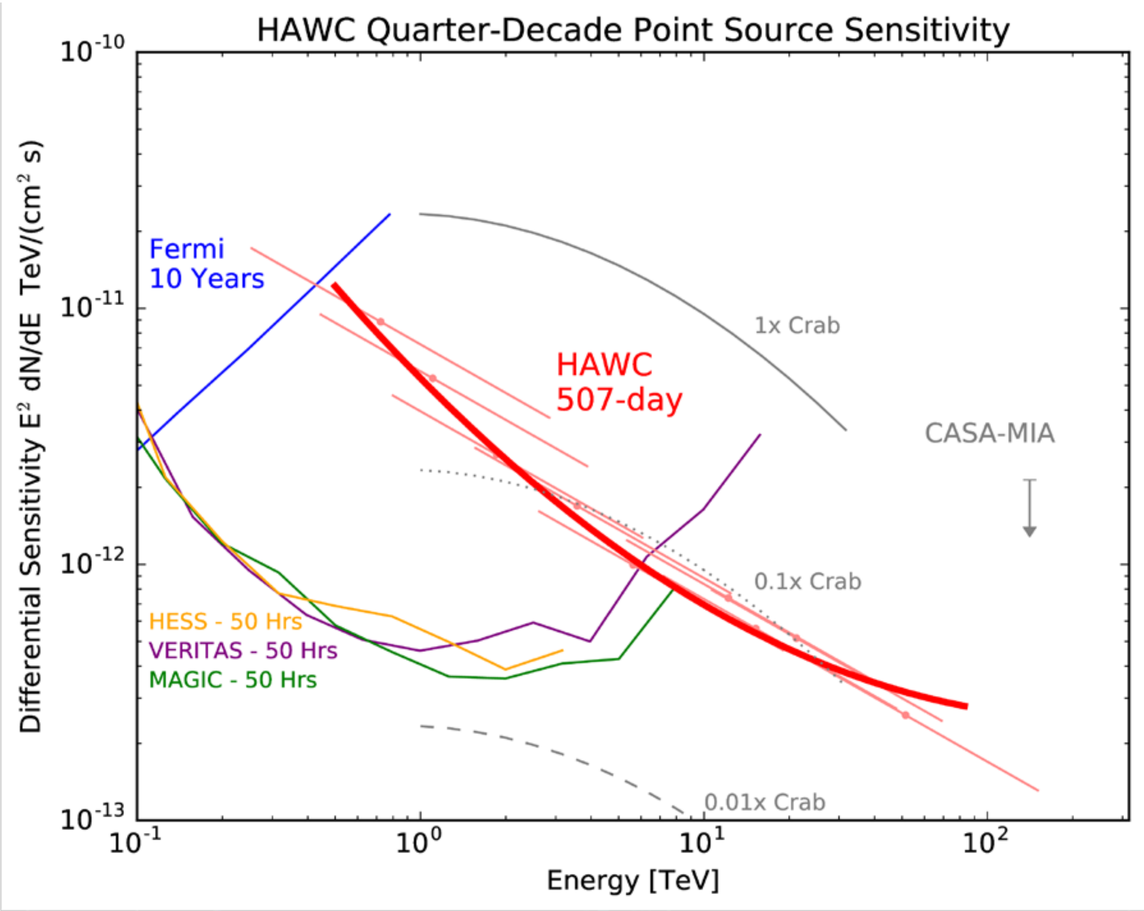


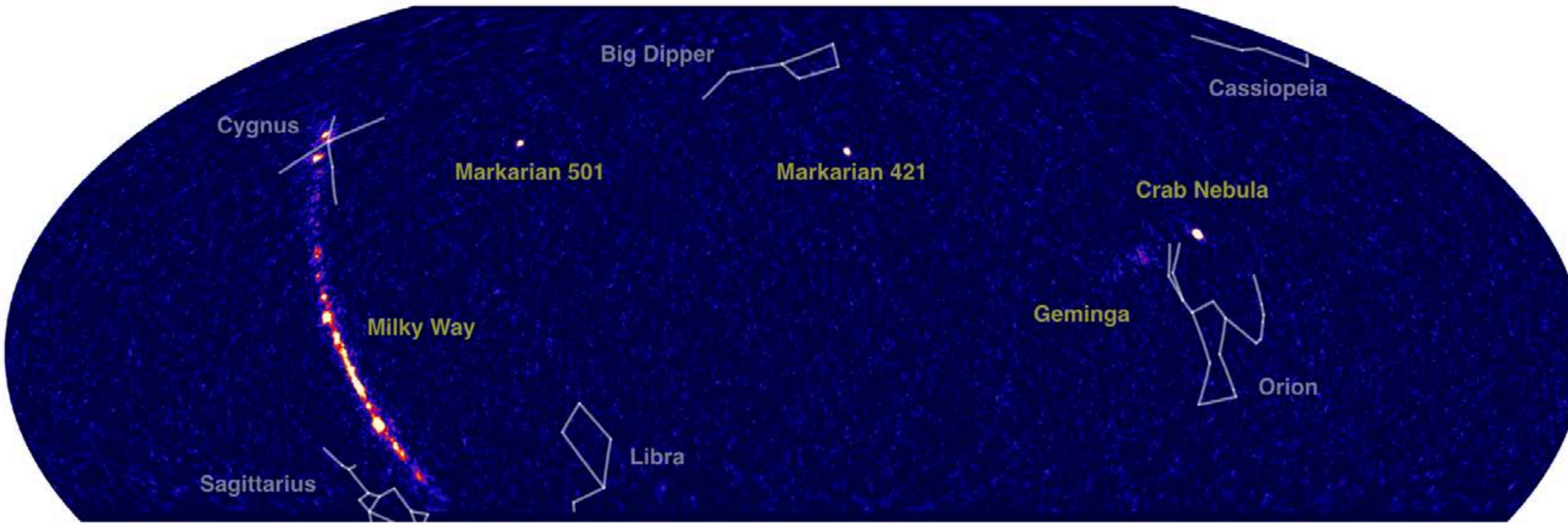

Effective Area = Area * Efficiency

Want to keep as many gammas and as few hadrons as possible

# HAWC Sensitivity

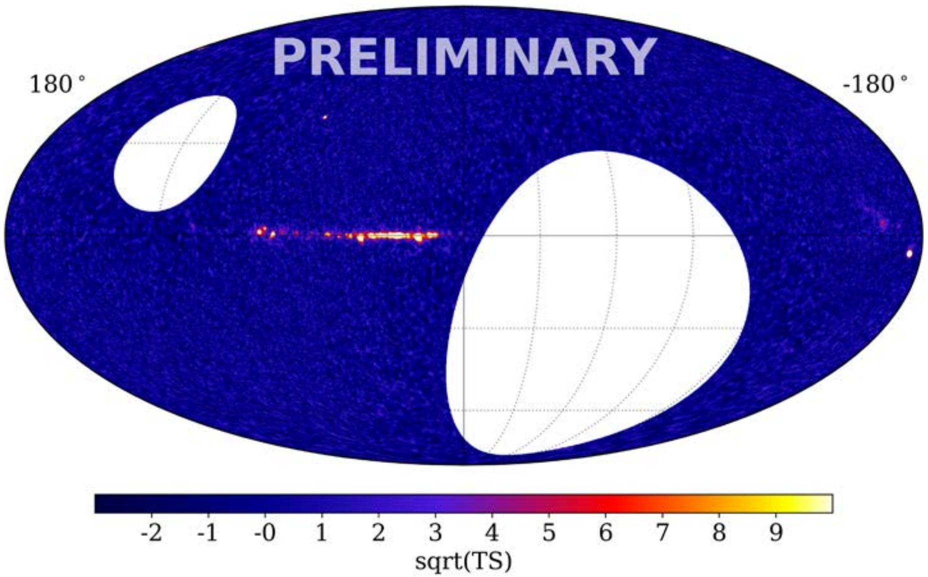


# Observable HAWC Sky

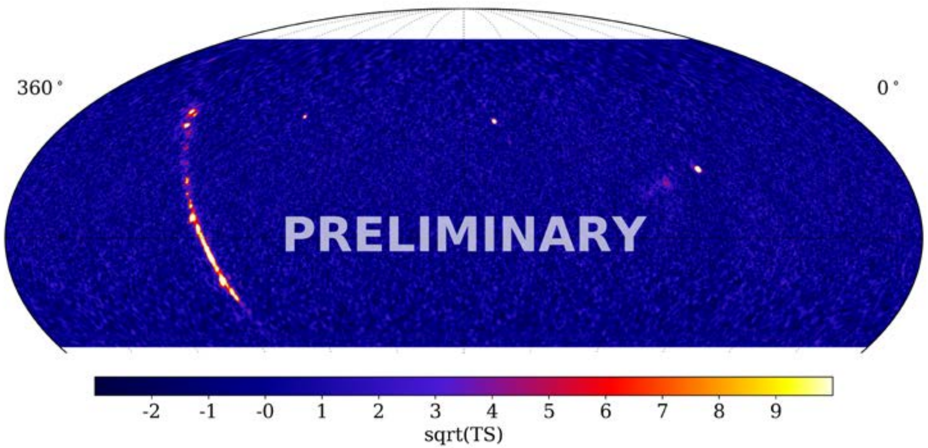


# Astrophysical Coordinate Systems

## Galactic Coordinates (l,b)




## Equatorial Coordinates (RA,dec)



## The Science of HAWC