Present and future ground based gamma-ray experiments

VHE TECHNIQUES FOR GROUND BASED GAMMA RAY ASTRONOMY DETECTORS: PRINCIPLES, RUNNING EXPERIMENTS, FUTURE PROJECTS

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outline

- Photon interaction with matter & Photon detection
- Techniques vs photon energy
- The case of VHE energy
- The atmosphere as a detector
    - Atmospheric e-m and hadronic shower

- Imaging Cherenkov light technique in detail
    - Gamma / hadron separation
    - Trigger and effective area
    - Angular resolution
    - Energy resolution

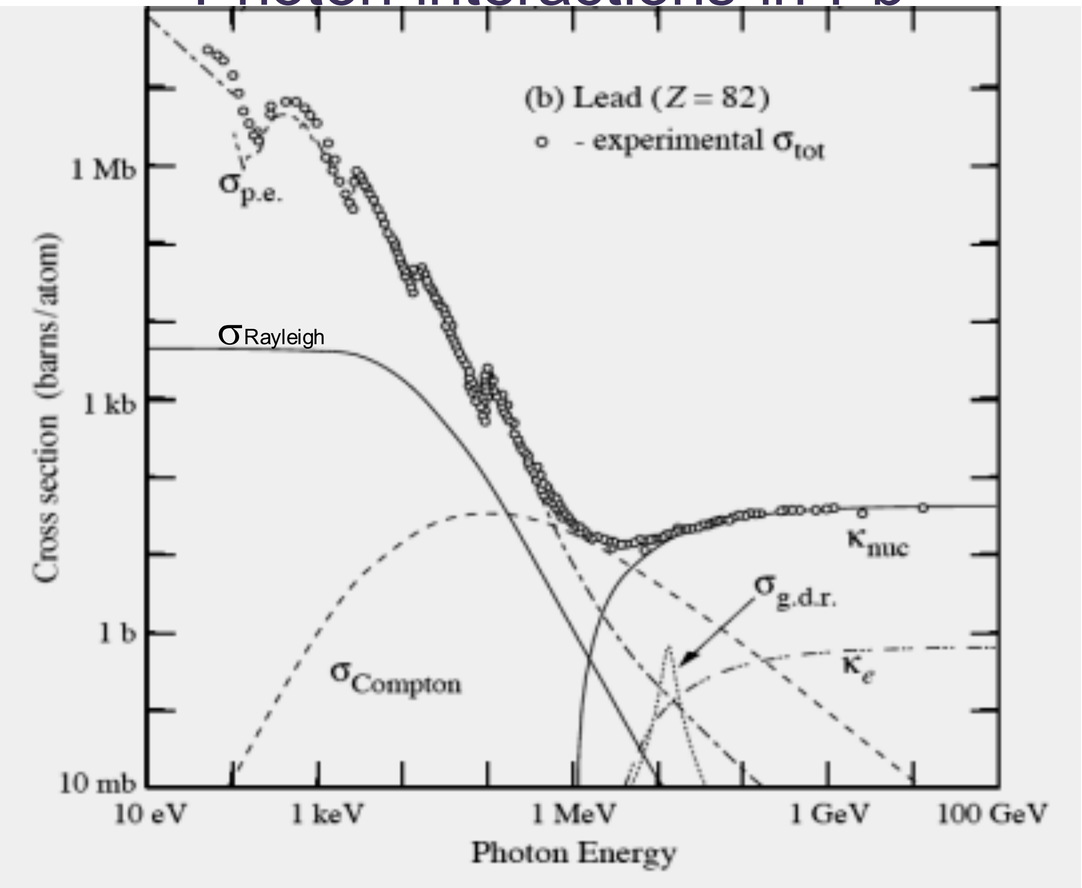
- Shower front particle detectors in detail
    - Gamma / hadron separation
    - Trigger and effective area
    - Angular resolution
    - Energy resolution

Photon interaction with matter

Detection of gamma rays takes place through the production of secondary electrons

The dominant interaction depends on the energy of the gamma ray

Photon interactions in Pb



From X-ray to Gamma-ray astronomy

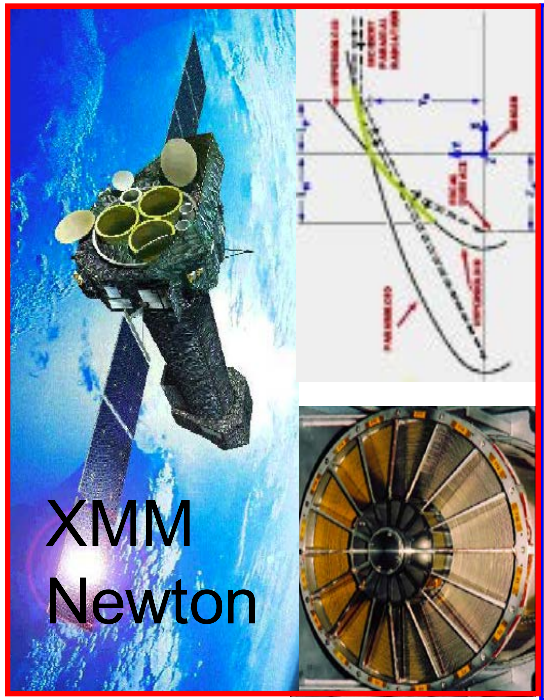
keV MeV GeV

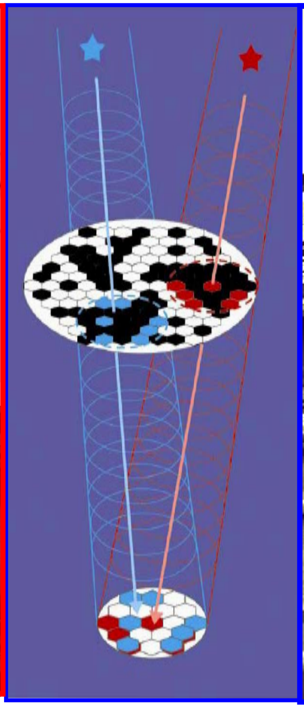
Focusing instruments

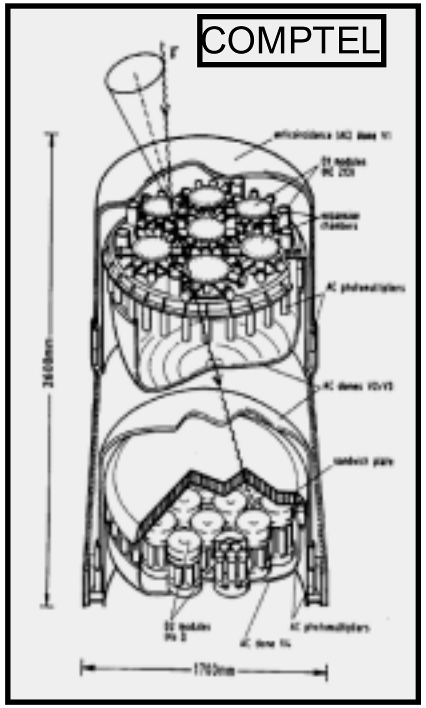
Coded masks, collimators
(i.e. INTEGRAL)

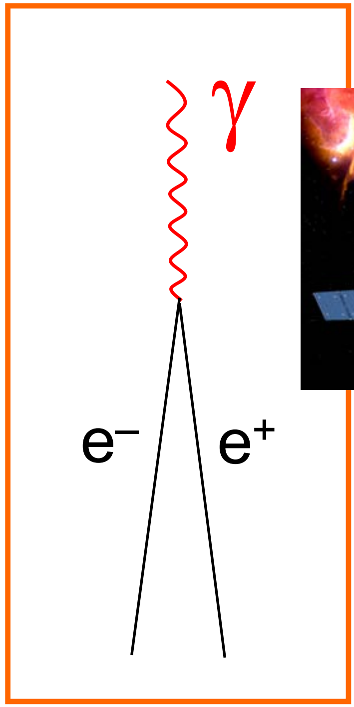
Compton telescopes

Pair conversion telescopes
(until ~300 GeV)

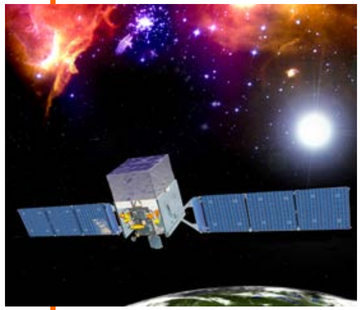








FERMI



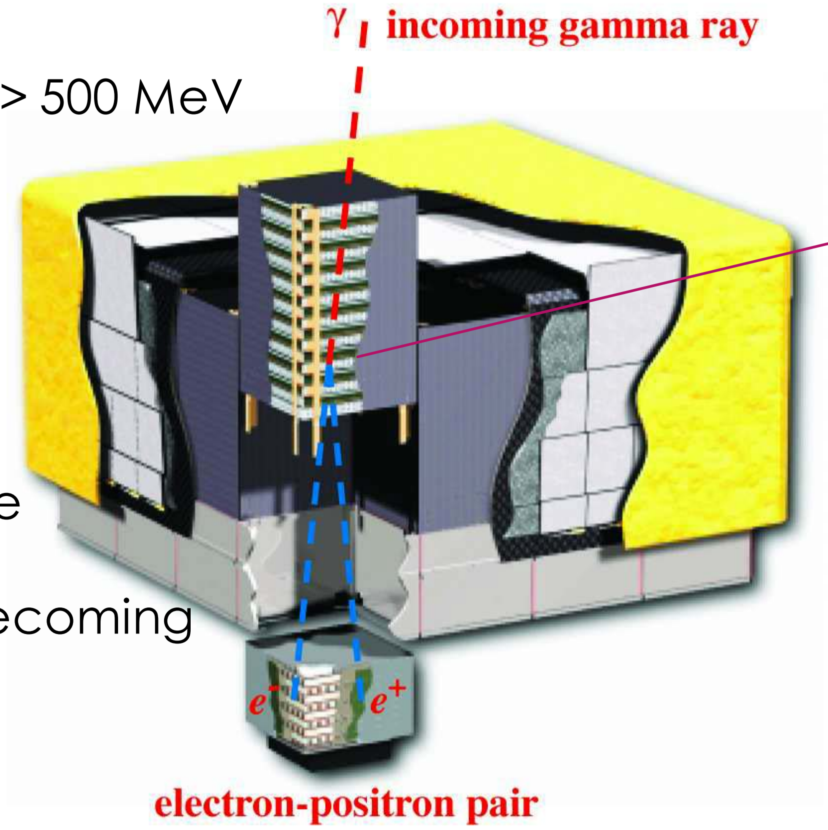
Direct detection of HE gamma ray

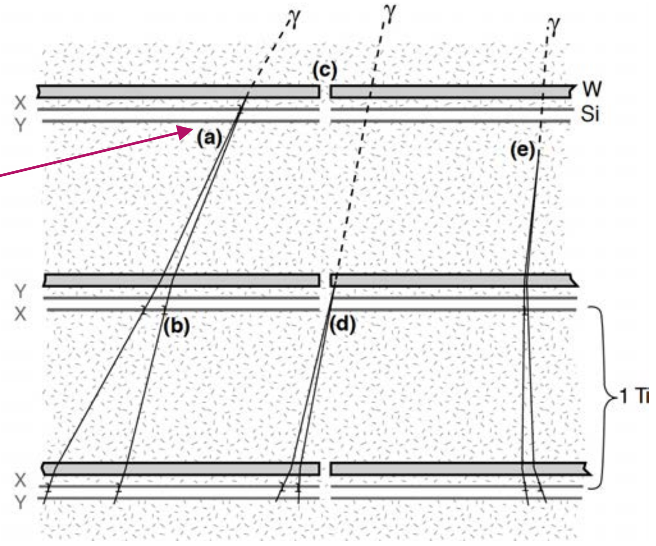
Direct detection of gamma ray
In the "pair production" regime With E> 500 MeV
Typical of satellite borne detectors

For VHE energy (>100 GeV) the direct detection is limited by 2 main effects

1) For E> 500 GeV the calorimeters does not contains the shower anymore

2) The Gamma ray event statistic is becoming poor



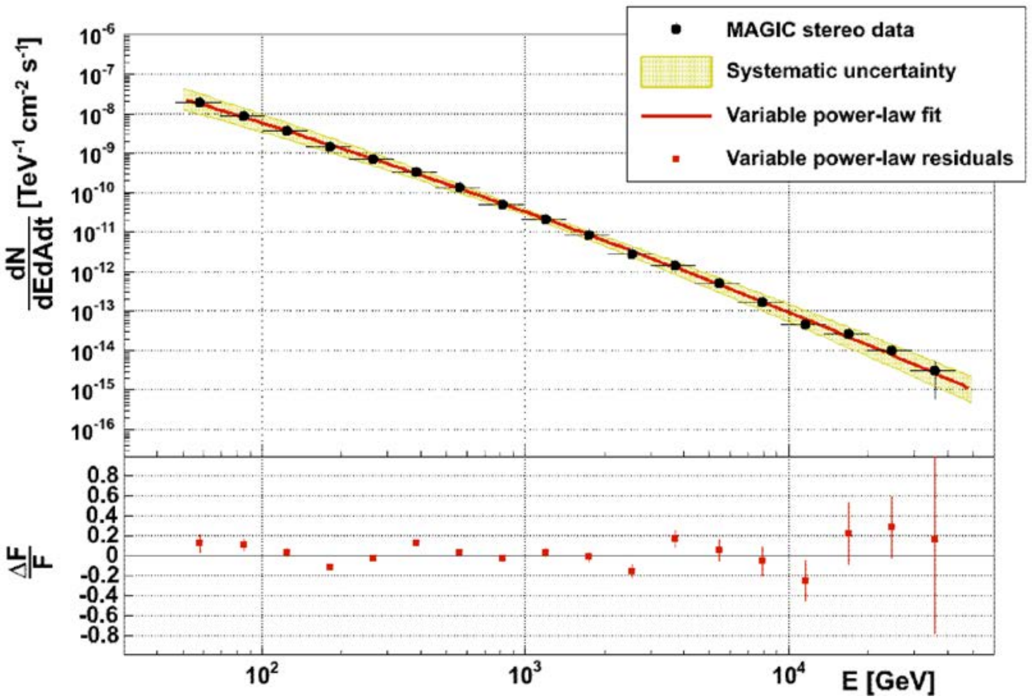


Gamma ray flux at High energy

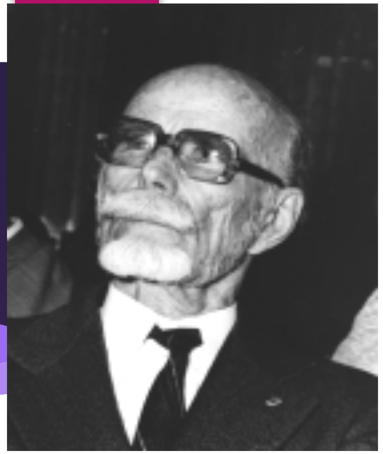
The gamma ray flux decreases rapidly with the energy

To have an Idea for CRAB nebula

Threshold	evt/h m^2
1 GeV	45
10 GeV	1
100 GeV	0.02
1 TeV	$6\ 10^{-4}$
10 TeV	$1.5\ 10^{-5}$

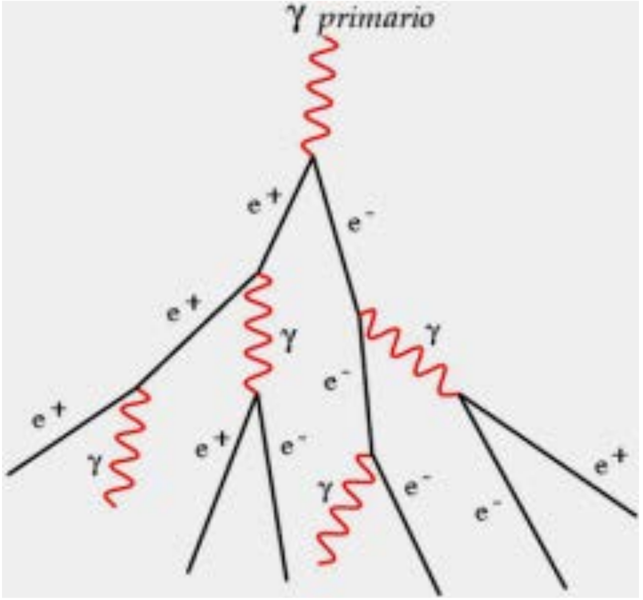


The Atmosphere as a Detector: Extensive Air Shower (EAS)

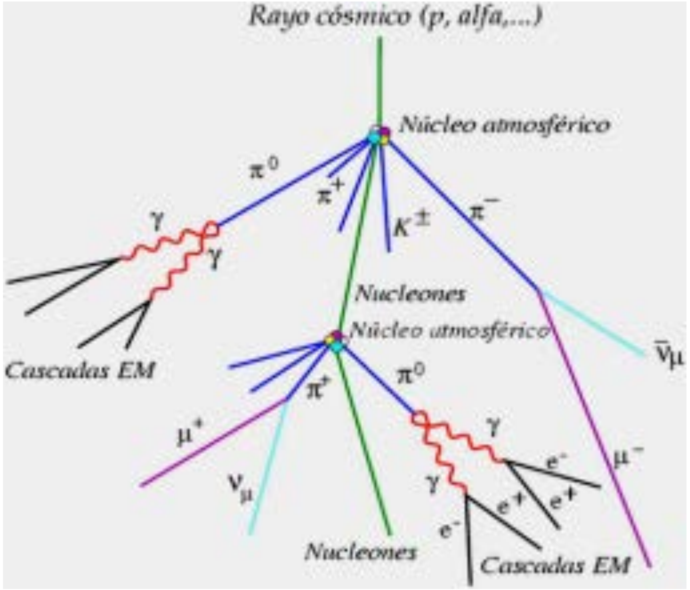


Discovered in 1938 by Pierre Auger

- **Electromagnetic showers:**
  - o $\gamma \longrightarrow e^+ e^-$ (pair production)
  - o $e^\pm \longrightarrow \gamma$ (*bremsstrahlung*)



- **Hadronic showers:**
  - o CR + atm. nucleus $\longrightarrow \pi^\circ, \pi^\pm + N^*$
  - o $\pi^\pm \longrightarrow \mu^\pm + \nu$
  - o $\pi^\circ \longrightarrow \gamma\,\gamma \longrightarrow$ e.m. showers



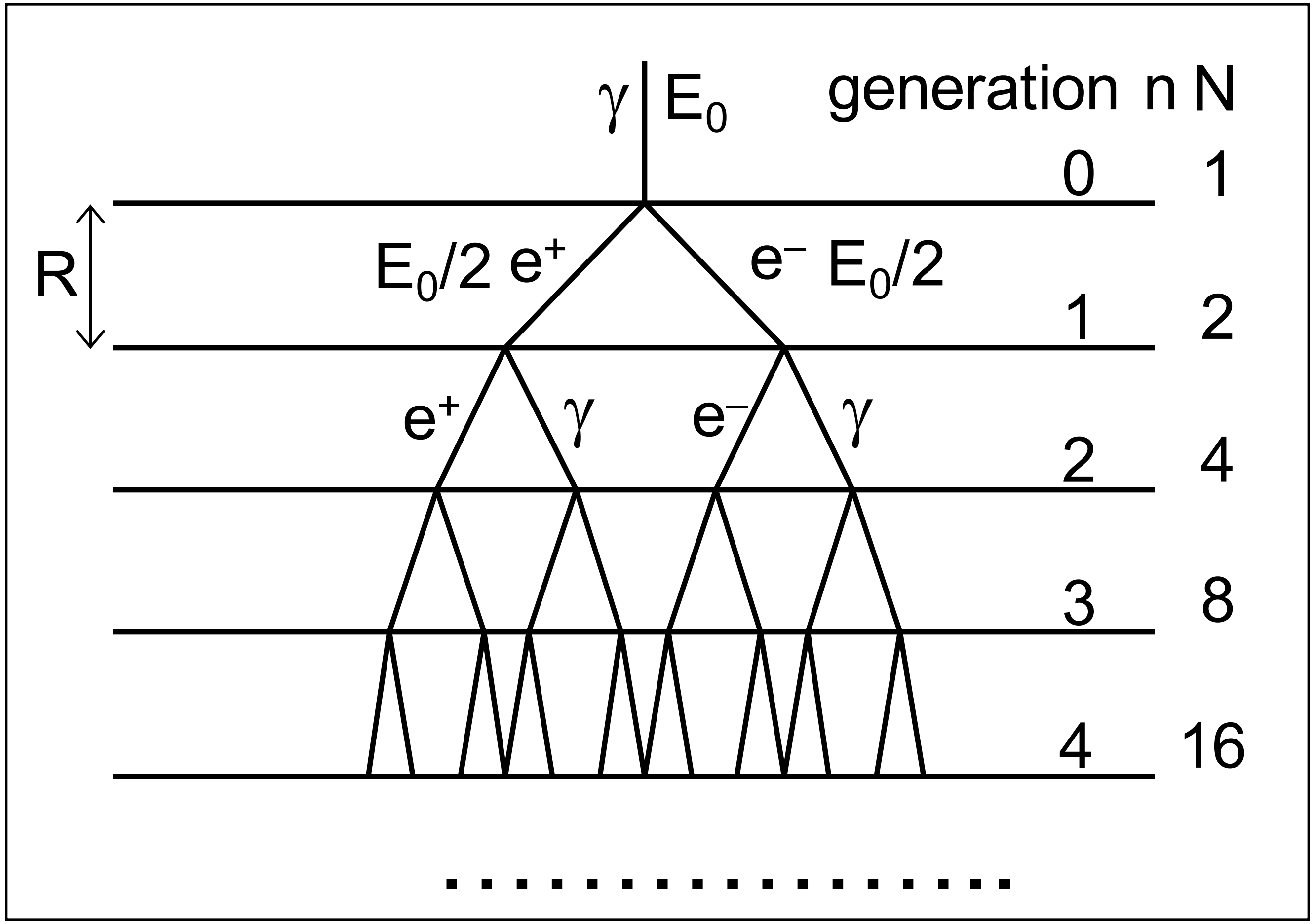
Heitler model for an electromagnetic shower

- Radiation length X_0: average distance traversed by an electron in a medium in the time in which its energy drops by a factor e. That is: $E = E_0 e^{-x/x_0}$
- For air, $X_0 = 36.7$ g/cm^2 (about 300 m at sea level)
- For ultra-relativistic electrons, X_0 roughly equals the **mean free path of gammas** of similar energy (m.f.p. ≈ 9/7 X_0)
- Heitler model assumptions:
  - Interaction probability for $e^{\pm}$ and γ is the same, and it is 1/2 after traveling a distance $R = X_0 \ln(2)$.
  - Further simplification: one interaction exactly every R
  - Energy is equally shared between the products of each interaction

Heitler model for an electromagnetic shower

- E_C : "critical energy" ($\cong$ 80 MeV in air) below which ionization dominates over bremsstrahlung in the energy loss of $e^{\pm}$.
- Multiplication of the number of $e^{\pm}$, N_e, goes on until $\langle E \rangle < E_C \Rightarrow N_{max} \propto E_0$ (shower maximum)
- After that, multiplication comes to an end: shower particles gradually lose their energy until the shower extinguishes.

Heitler model for an electromagnetic shower



- In the n^{th} generation, 2^n particles ($e^{\pm}$ and γ) of energy $E_0 / 2^n$
- Shower maximum reached when E_c is reached, hence $E_0 / 2^{n_{max}} = E_c$
- Number of generations until shower maximum: $n_{max} = \ln (E_0 / E_c) / \ln(2)$
- Atmospheric depth of shower maximum:

$$X_{max} \cong n_{max} \cdot R = X_0 \ln (E_0 / E_c)$$

(depends logarithmically on E_0)

The Rossi Greisen approximation

(Rev. Mod. Physics 13 (1941))

- Considers Bremsstrahlung and pair production
- Neglects Compton effect, photon-nucleus interactions

Number of $e^{\pm}$ vs. t (atmospheric depth):

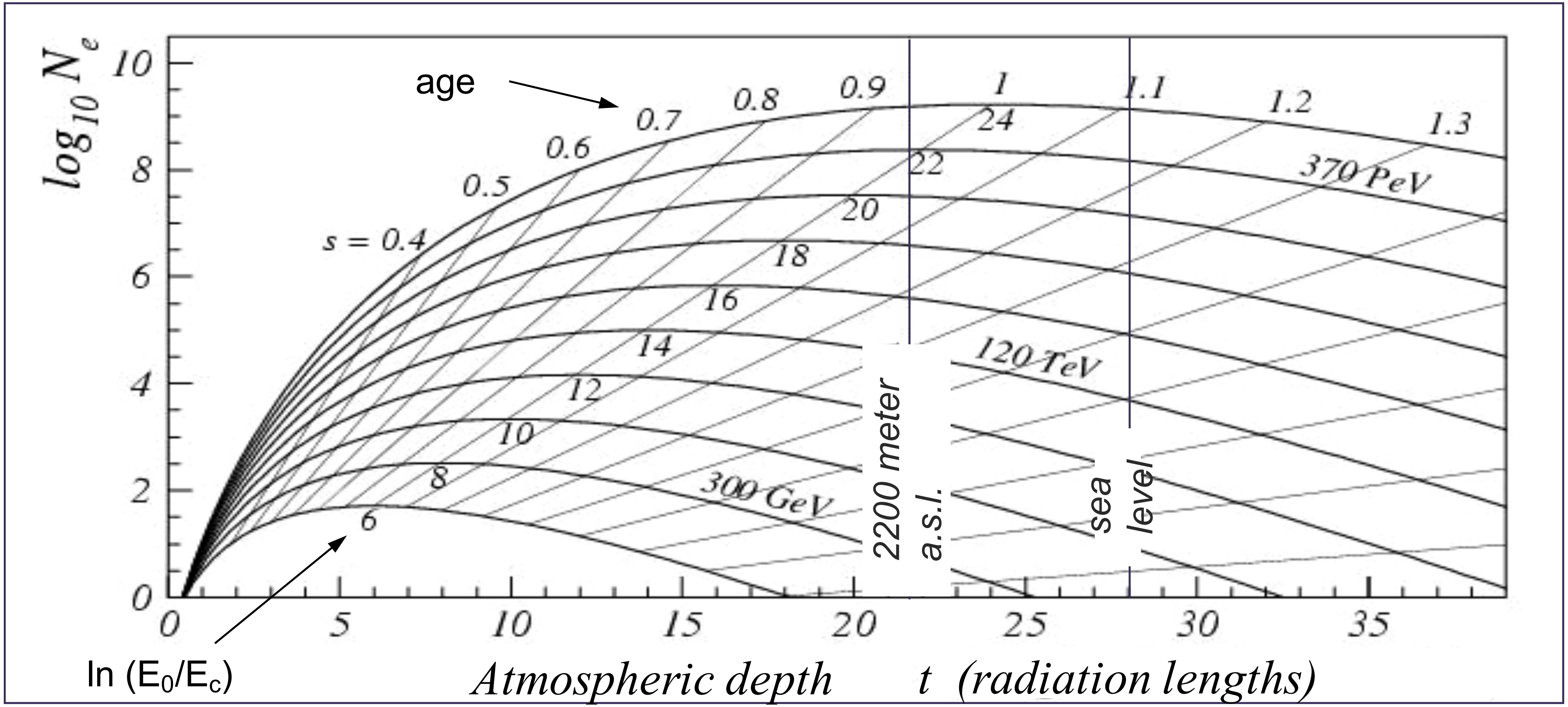
$$N_e(t) = \frac{0.31}{\sqrt{\ln(E_0/E_c)}} \cdot \exp[t \cdot (1 - 1.5 \ln s)]$$

$$s = \frac{3\,t}{t + 2\ln(E_0/E_c)}$$

"age" of the shower

s = 0 at first interaction, 1 at maximum, 2 when $N_e < 1$

Longitudinal EM shower development



Lateral distribution in an EM shower

- Many small-angle Coulomb scatters of $e^{\pm}$ on nuclei $\Rightarrow$ lateral spread of the shower
- Theory of Molière of multiple scattering: angular distribution of charged particles after traversing a thickness x of material is roughly gaussian for small deflection angles (and then has a long tail):

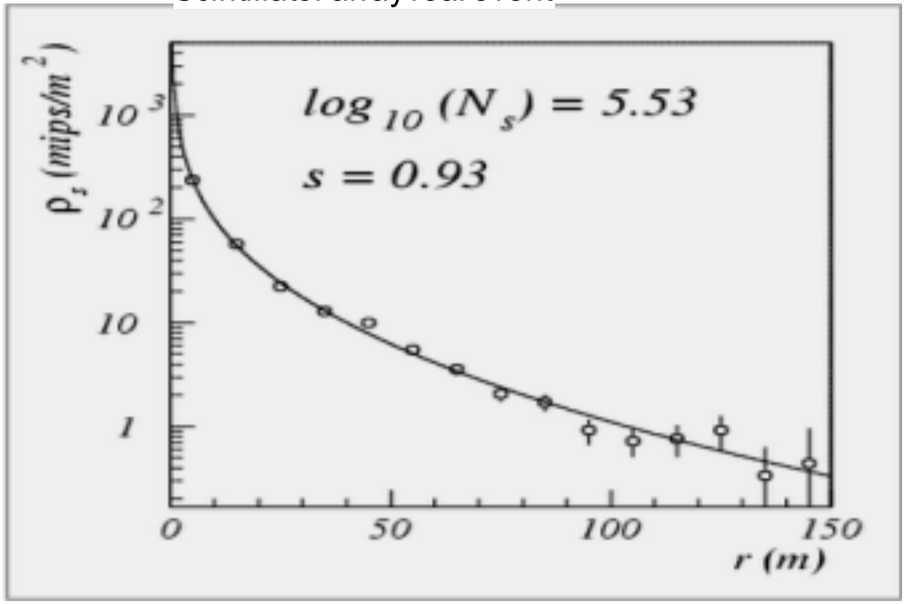
$$dN / d\Omega = \frac{1}{2\pi\,\theta_0^2} \exp\left(-\frac{\theta_{\text{space}}^2}{2\theta_0^2}\right) \quad \text{for small } \theta$$

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

z : charge number of the particle; β, p: velocity, momentum

Lateral distribution in an EM shower:
NGK semi-empirical formula (Nishimura Kamata Greisen)

HEGRA
Scintillator array real event



r_M: Molière radius

Lateral distribution in different materials scales with r_M:

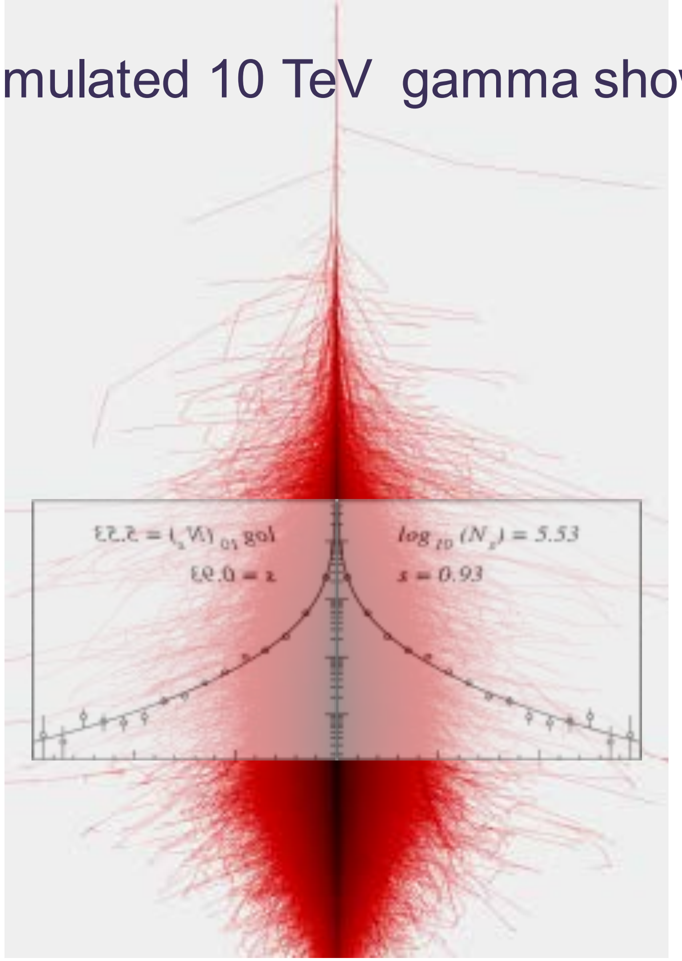
$r_M = X_0\, E_s/E_C$ (≈80 m for air at sea level)

$E_s = \sqrt{4\pi/\alpha}\; m_e c^2$
(scale energy, 21.2052 MeV)

$$\rho_e(r) = \frac{N_e}{r_M^2} \cdot \left(\frac{r}{r_M}\right)^{s-2} \cdot \left(1 + \frac{r}{r_M}\right)^{s-4.5} \cdot \frac{\Gamma(4.5-s)}{2\pi \cdot \Gamma(s) \cdot \Gamma(4.5-2s)}$$

Lateral distribution in an EM shower:
fully simulated EM shower

Simulated 10 TeV gamma shower



Lateral distribution: NKG formula

Hadron initiate showers

After the first interaction, the nucleonic component of the showers goes on interacting until

$\langle E/A \rangle < E_c = 1$ GeV (pion production threshold)

Simple model: “superposition” ⇒ nucleus behaves as A nucleons of energy E_0 / A :

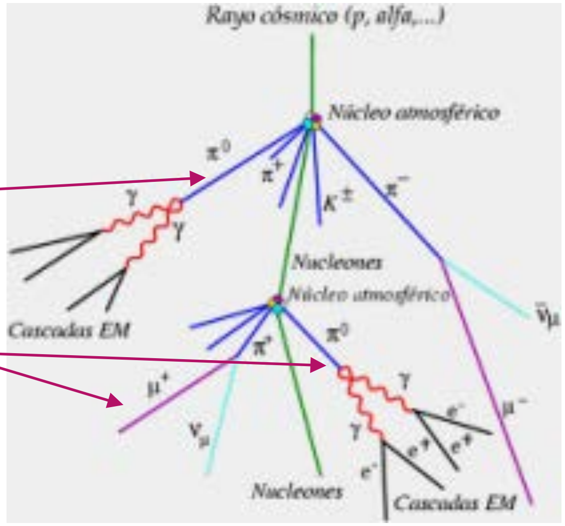
$X_{max} \propto \ln [E_0 / (A E_c)]$: given E_0, showers initiated by heavy nuclei develop higher in the atmosphere

Hadron initiate showers

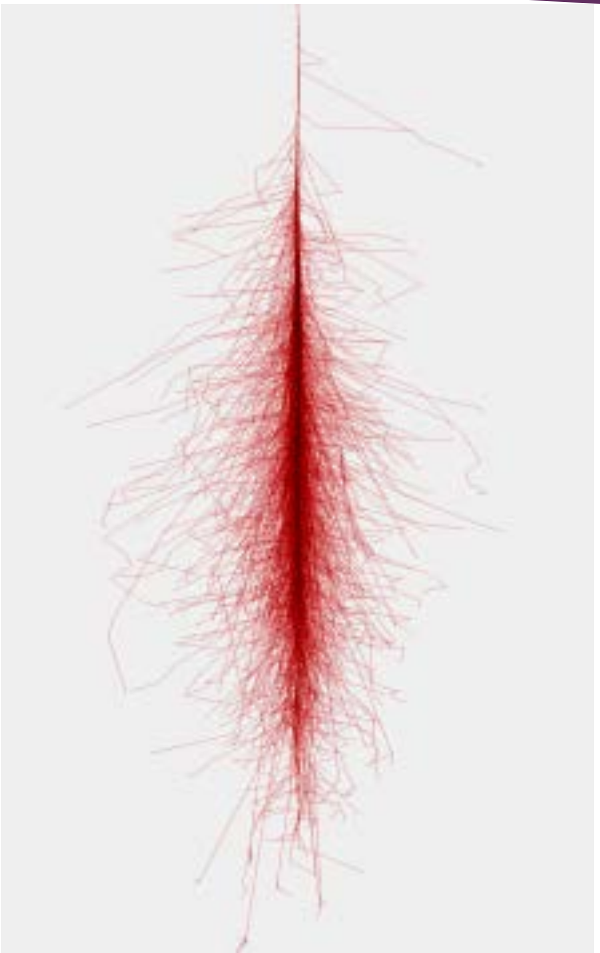
- Muons, resulting mainly from charged pions, have a half-life of 2.2 μs in their own reference frame $\Rightarrow$ many arrive at the ground before decaying (and account for 75% of all secondary CR detected at sea level)

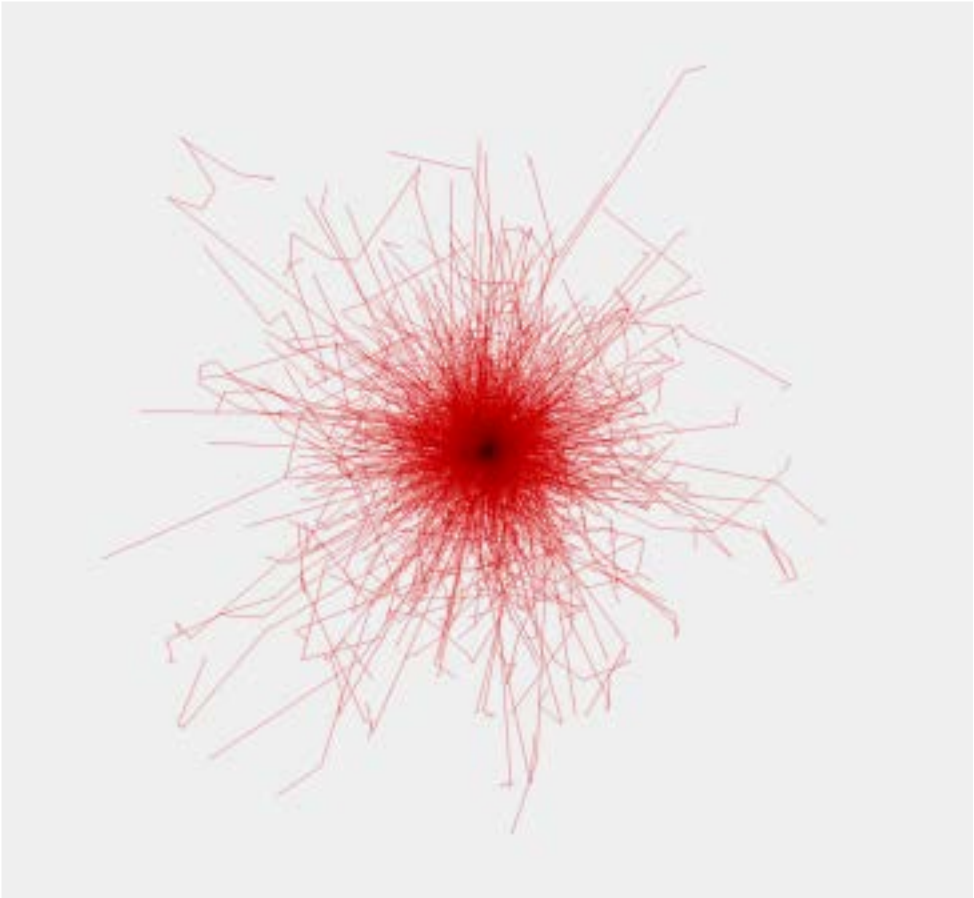
- Neutral pions decay (most often) in 2 γ, resulting in EM sub-showers at some angle w.r.t. the shower axis

- Detailed study requires a full Monte Carlo simulation

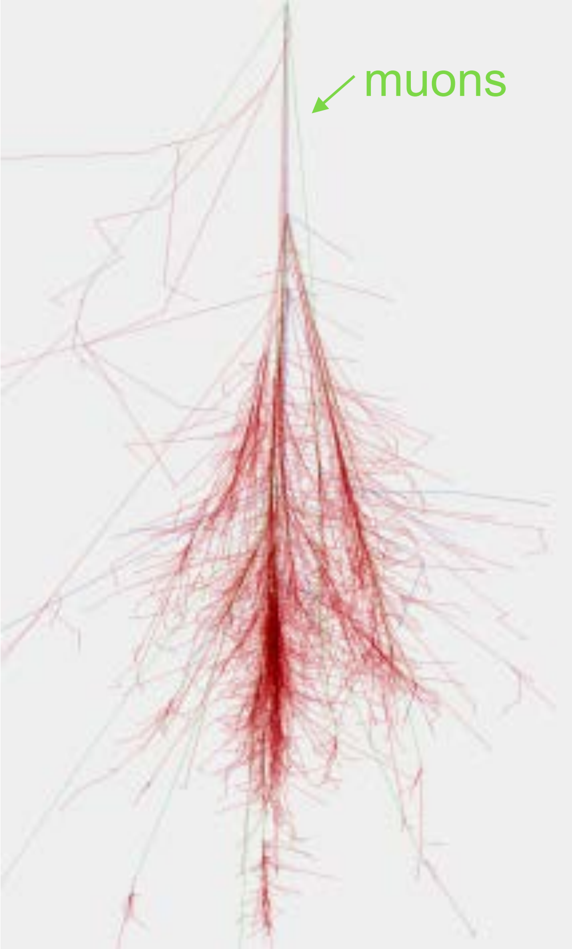


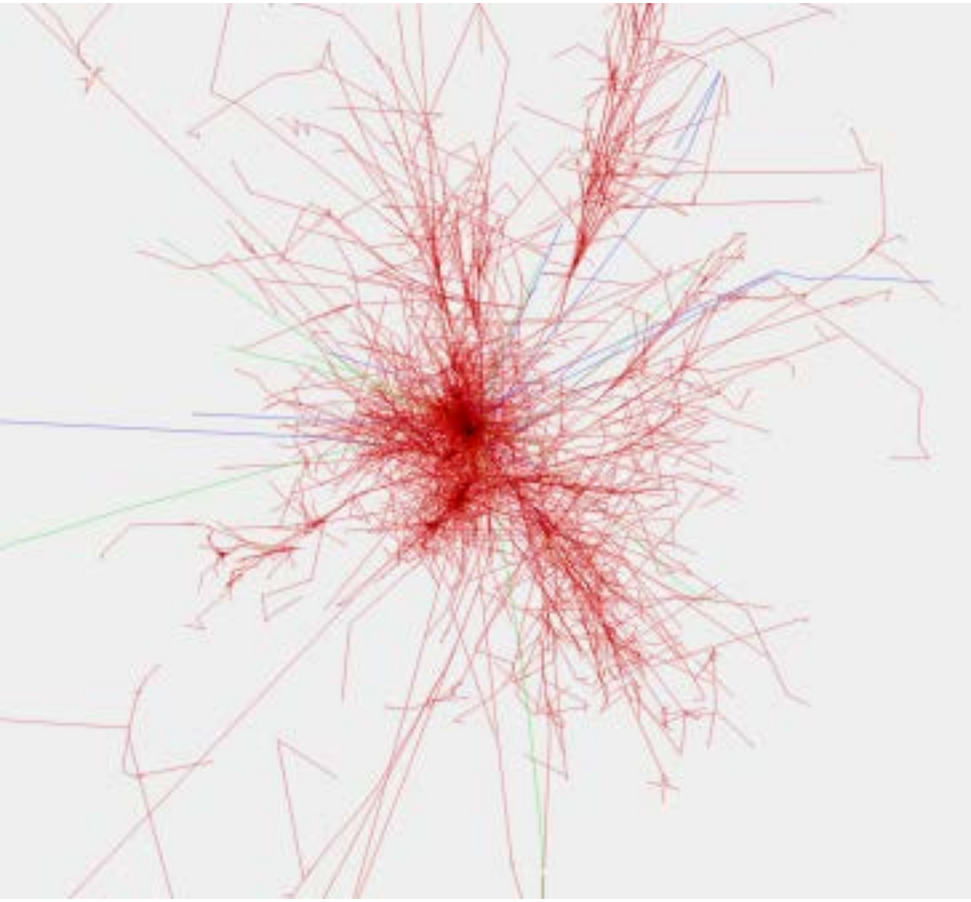
Simulated 50 GeV EM shower



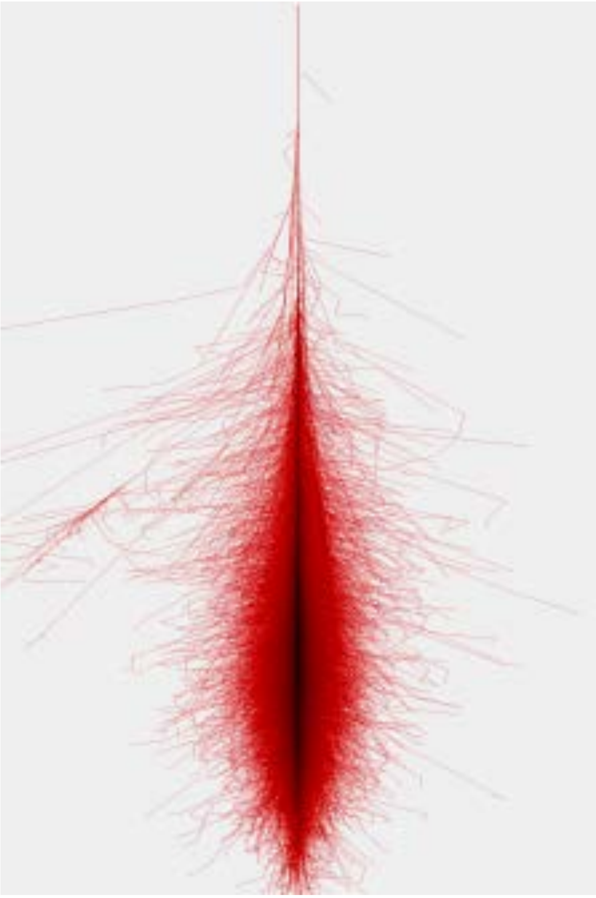


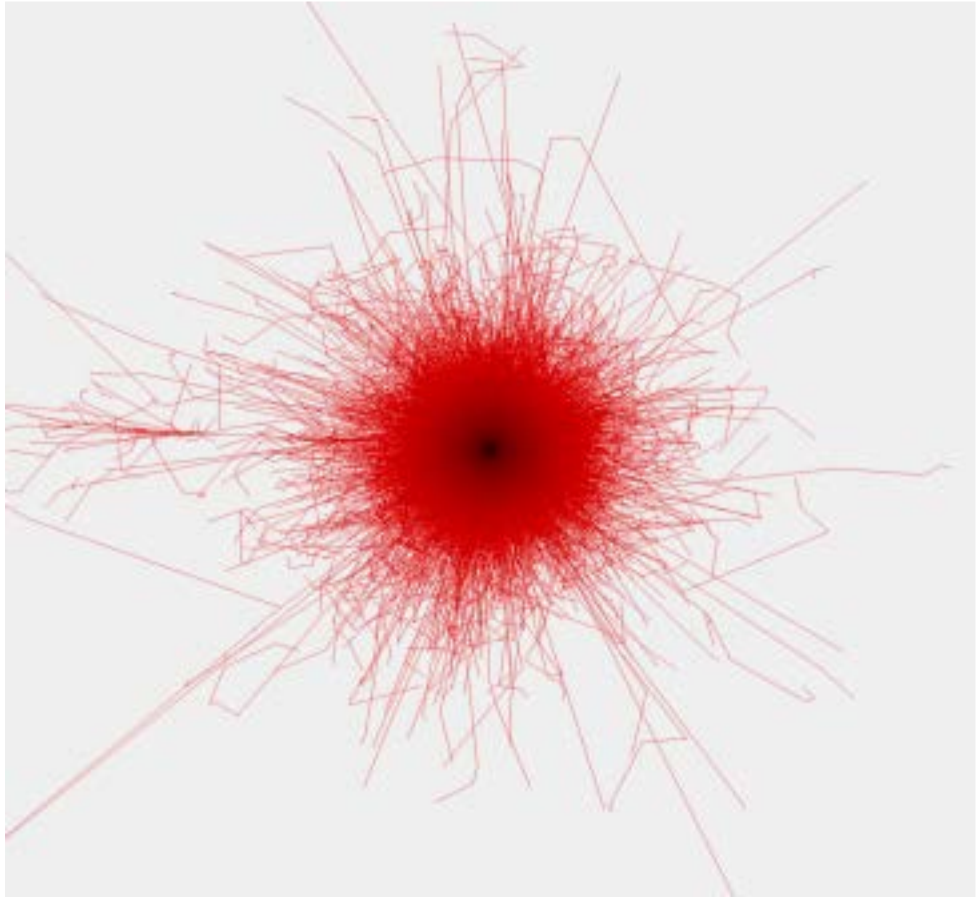
Simulated 100 GeV HA shower





Simulated 1 TeV EM shower





Ground based gamma ray detectors

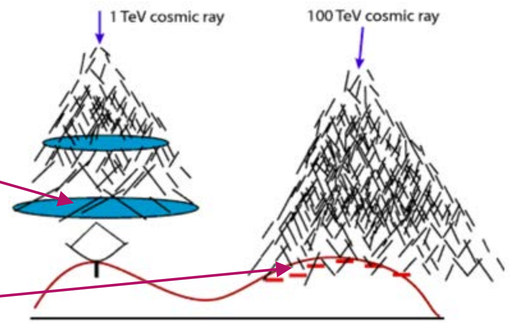
Once a VHE gamma ray enter in the atmosphere an **EAS shower** develop

Ground based experiments have to **detect** and **reconstruct** the **atmospheric shower**

There are 2 main way to detect a shower

- detect the **Cherenkov light** produced from relativistic (β>1/n n= refraction index)

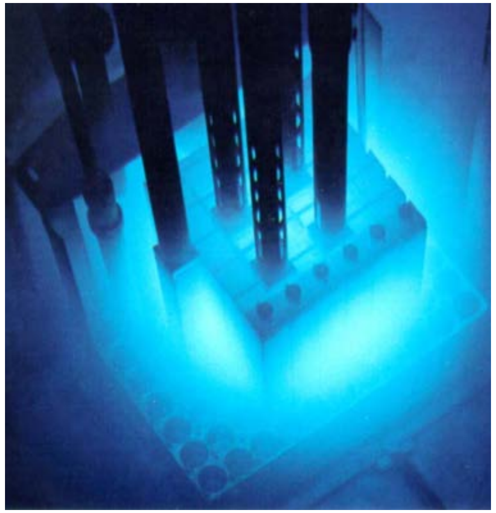
- detect the **particle from the shower front**

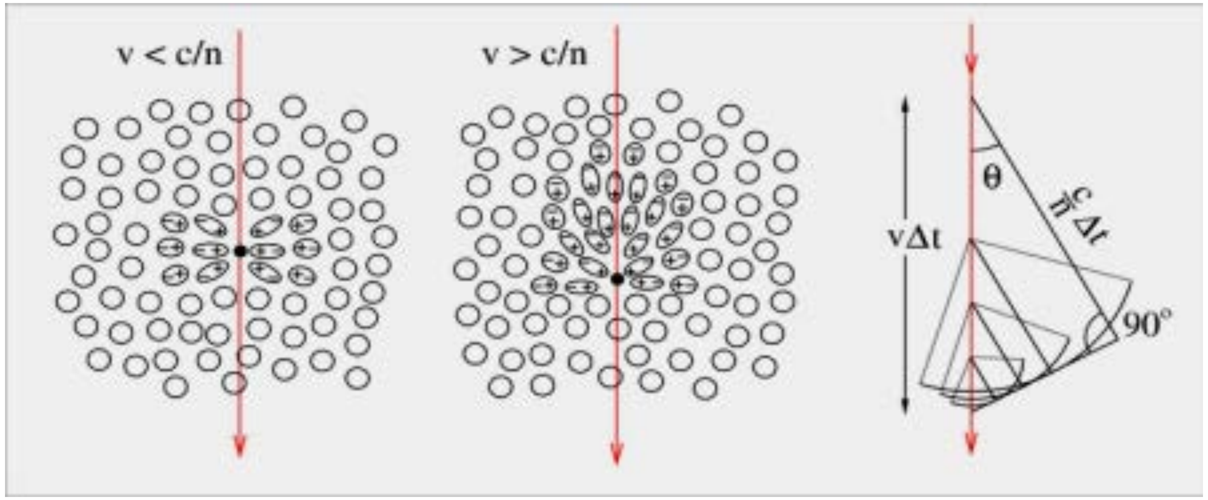


The observation of an extensive air shower particle cascade using by collecting Cherenkov radiation (left) and observing the shower particles at ground level (right). From the Milagro collaboration (copyright © 2002, University of California).

Cherenkov radiation

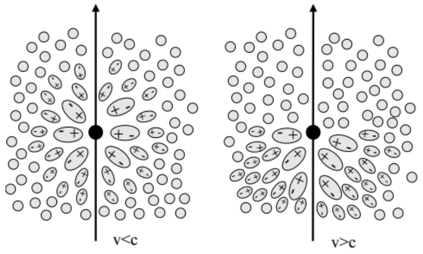
- Emitted whenever a charged particle traverses a medium at a speed larger than that of light in the medium
- The radiation results from the reorientation of electric dipoles induced by the charge in the medium. When v > c/n the contributions from different points of the trajectory arrive in phase at the observer as a narrow light pulse

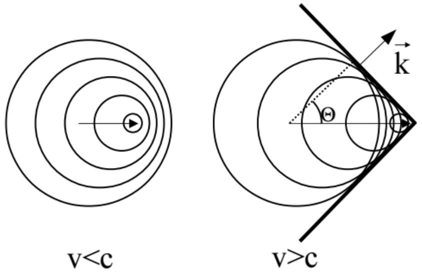




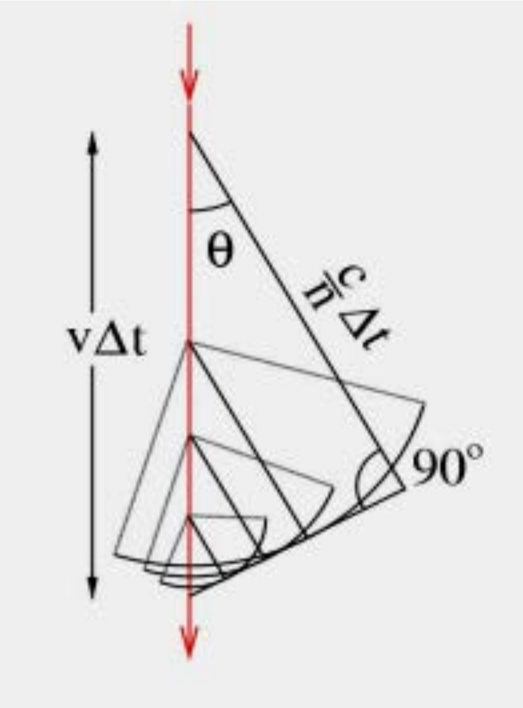
Cherenkov radiation

Analogous to "sonic bang"





$$\frac{d^2N}{d\lambda dx} = 2\pi\alpha\frac{\sin^2\theta}{\lambda^2}$$

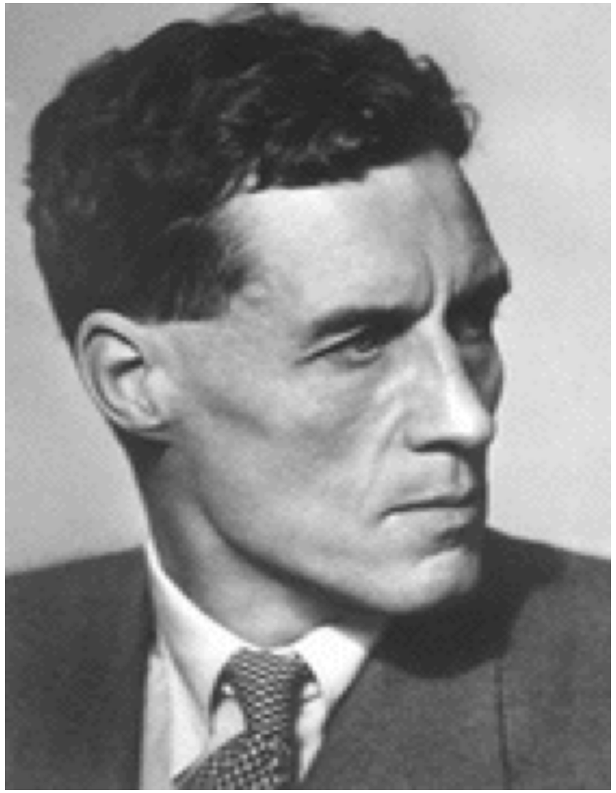


$\cos\theta = 1 / (\beta n)$

Setting β=1 =>

$\theta_{max} = \cos^{-1}(1/n)$

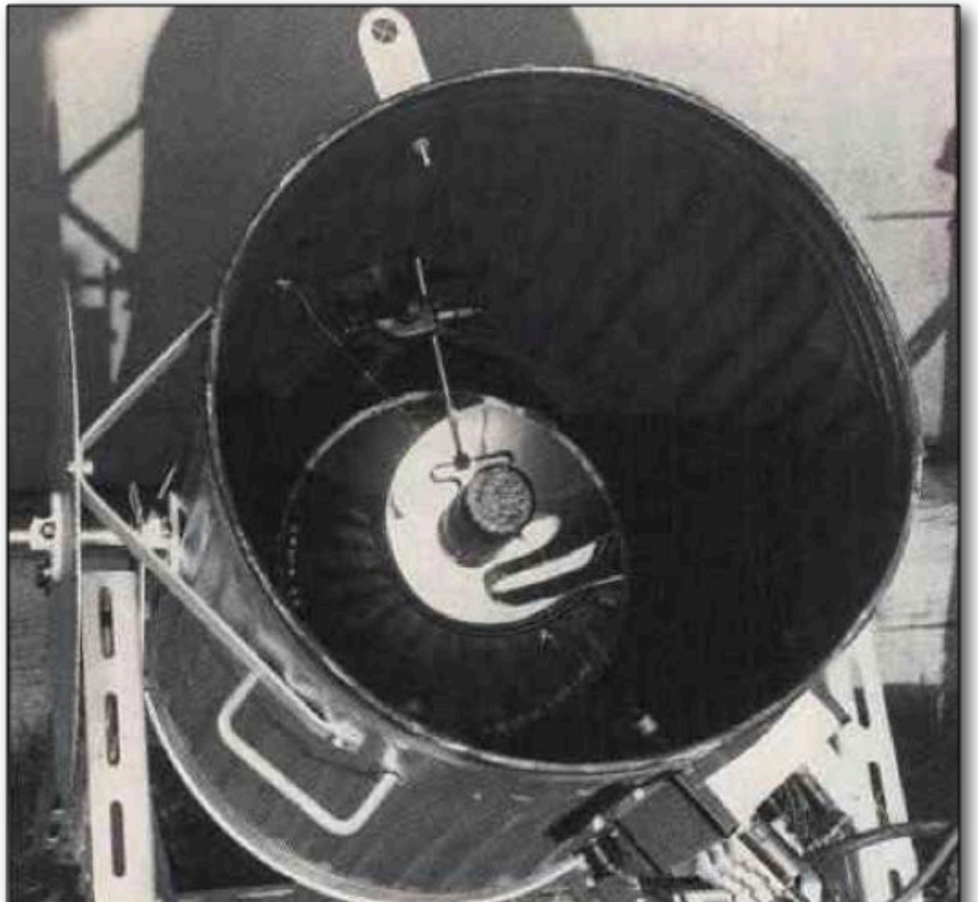
Cherenkov radiation in atmosphere



In 1948, Blackett suggested that secondary CR's should produce Cherenkov radiation which would account for a fraction 10^{-4} of the total night sky light

Pulses of Cherenkov light from air showers were first recorded by Galbraith and Jelley in 1953

The Very Beginning of the Atmospheric Air Cherenkov Telescope Technique....



1953 By using a garbage can, a 60 cm diameter mirror in it and a PMT in its focus Galbraith and Jelly had discovered the Cherenkov light pulses from the extensive air showers.

Cherenkov radiation in atmosphere

Air density: $$\rho(h) = \rho_0 \cdot e^{-\frac{h}{h_0}}$$ h_0 = 7.8 km

Refractive index: $$n = 1 + \eta_h = 1 + \eta_0 \cdot e^{-\frac{h}{h_0}}$$, with $\eta_0 = 2.9 \cdot 10^{-4}$

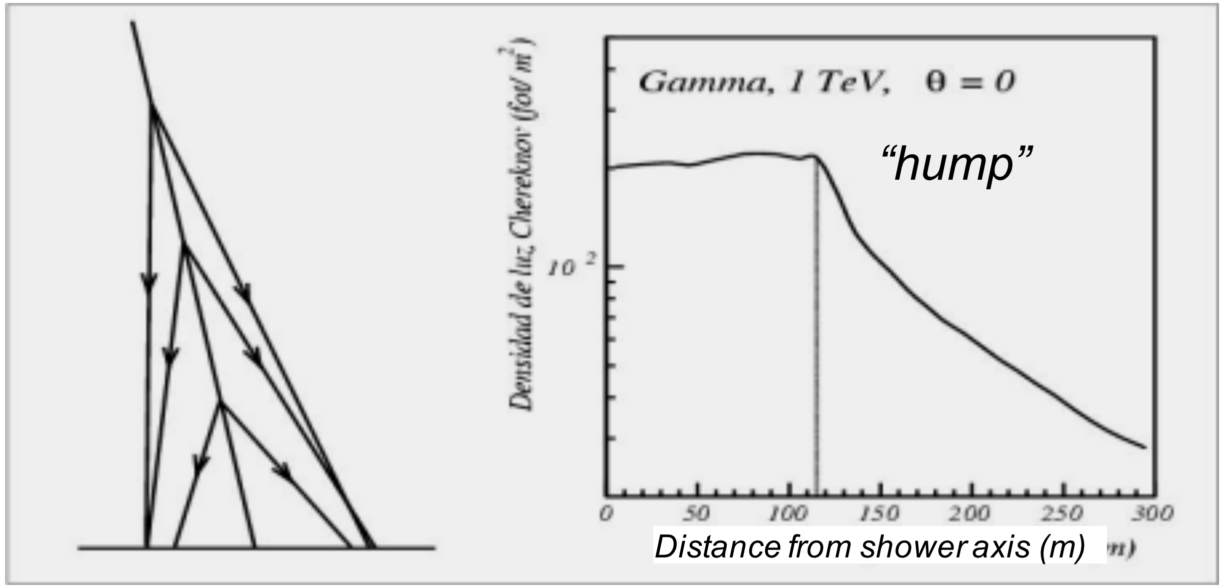
Threshold for Cherenkov emission: $$E_{min} = \frac{m_e c^2}{\sqrt{1-\beta_{min}^2}} = \frac{m_e c^2}{\sqrt{1-n^{-2}}} \simeq \frac{0.511\ MeV}{\sqrt{2\ \eta_h}}$$ (≈ 21 MeV at sea level, for electron)

Cherenkov angle for $\beta = 1$: $$\cos\theta_{max} = \frac{1}{n} = \frac{1}{1+\eta_h} \simeq 1 - \eta_h$$ ~1 deg at sea level

Cherenkov radiation in the atmosphere

R_c: Distance from shower trajectory at which the C-photons hit the ground

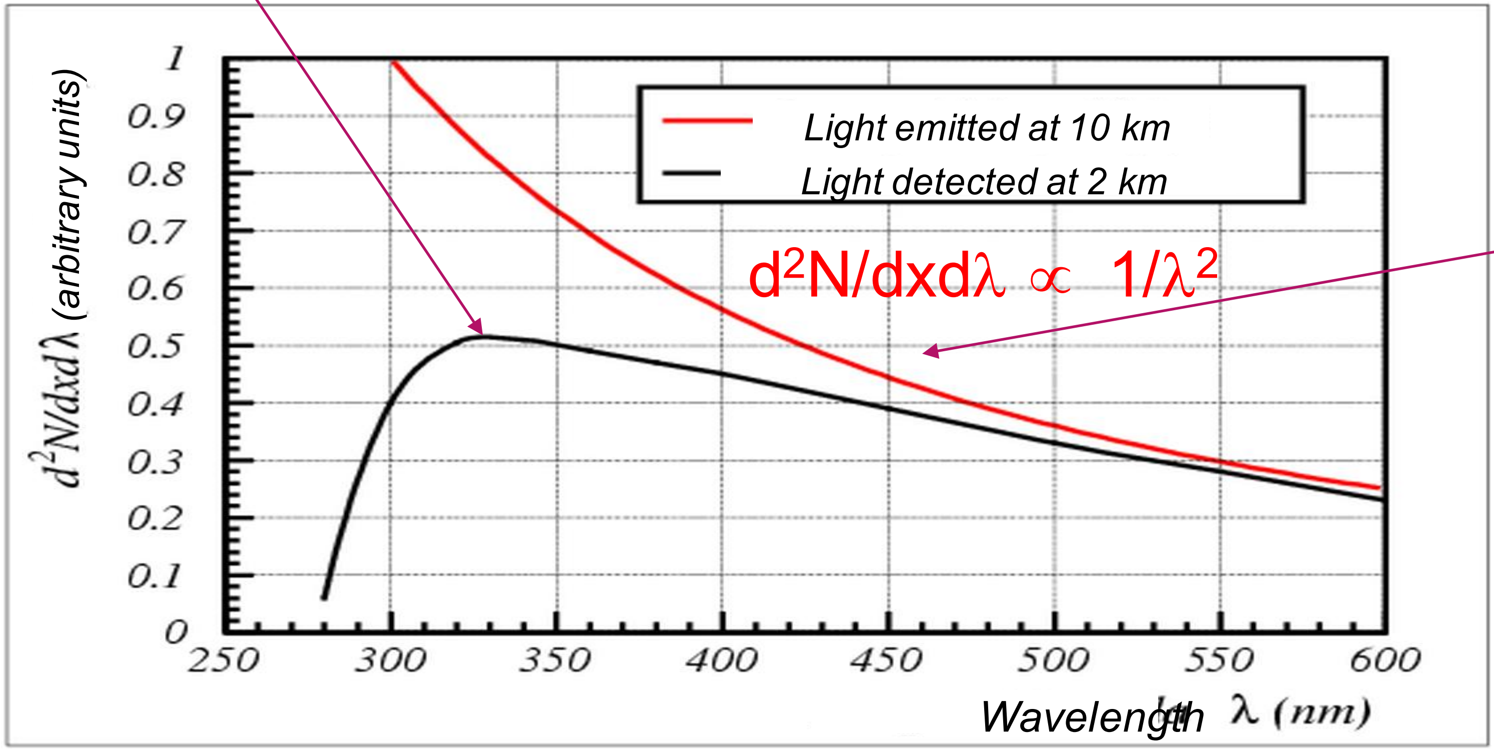
$$R_c \equiv (h - h_{obs}) \cdot \tan \theta_{max}$$ for $\beta = 1$



Hump position depends on observation altitude (but not on E_0)

Cherenkov observed spectrum

Transparency of the atmosphere absorption effect



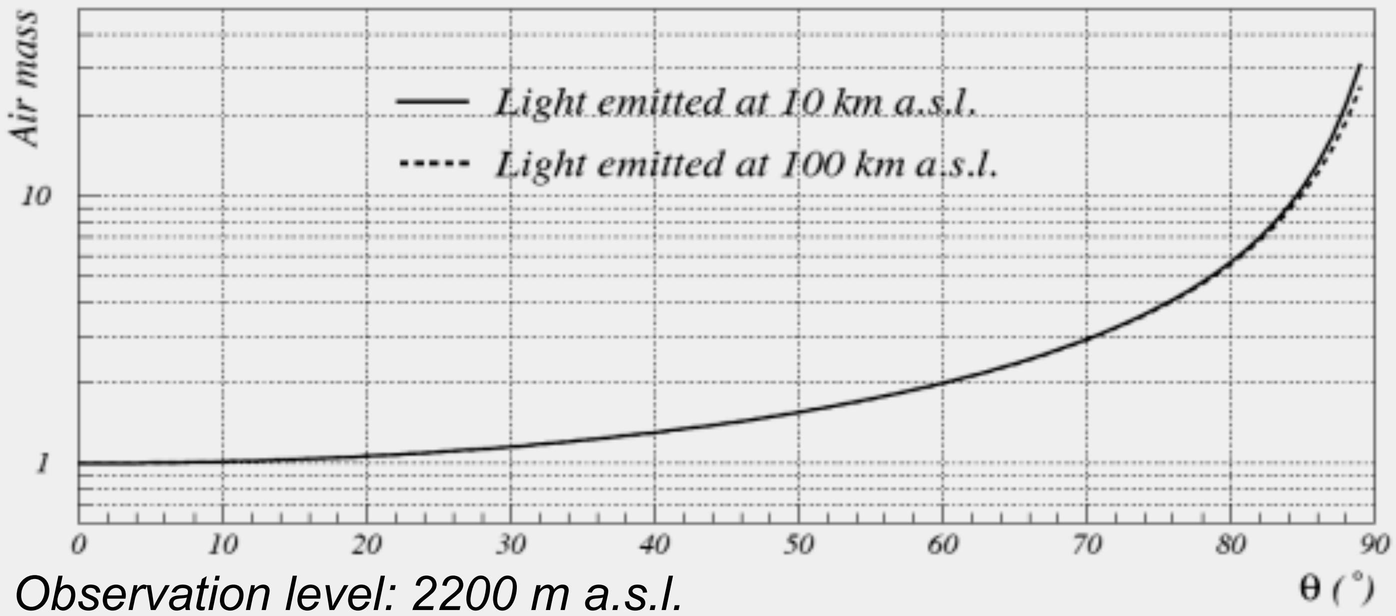
$$\frac{d^2N}{d\lambda dx} = 2\pi\alpha\frac{\sin^2\theta}{\lambda^2}$$

Three relevant processes of absorption:

- Mie scattering (by dust particles)
- Rayleigh scattering (by air molecules)
- Absorption by Ozone (but EAS develops mostly below O_3 layer)

Cherenkov observed spectrum

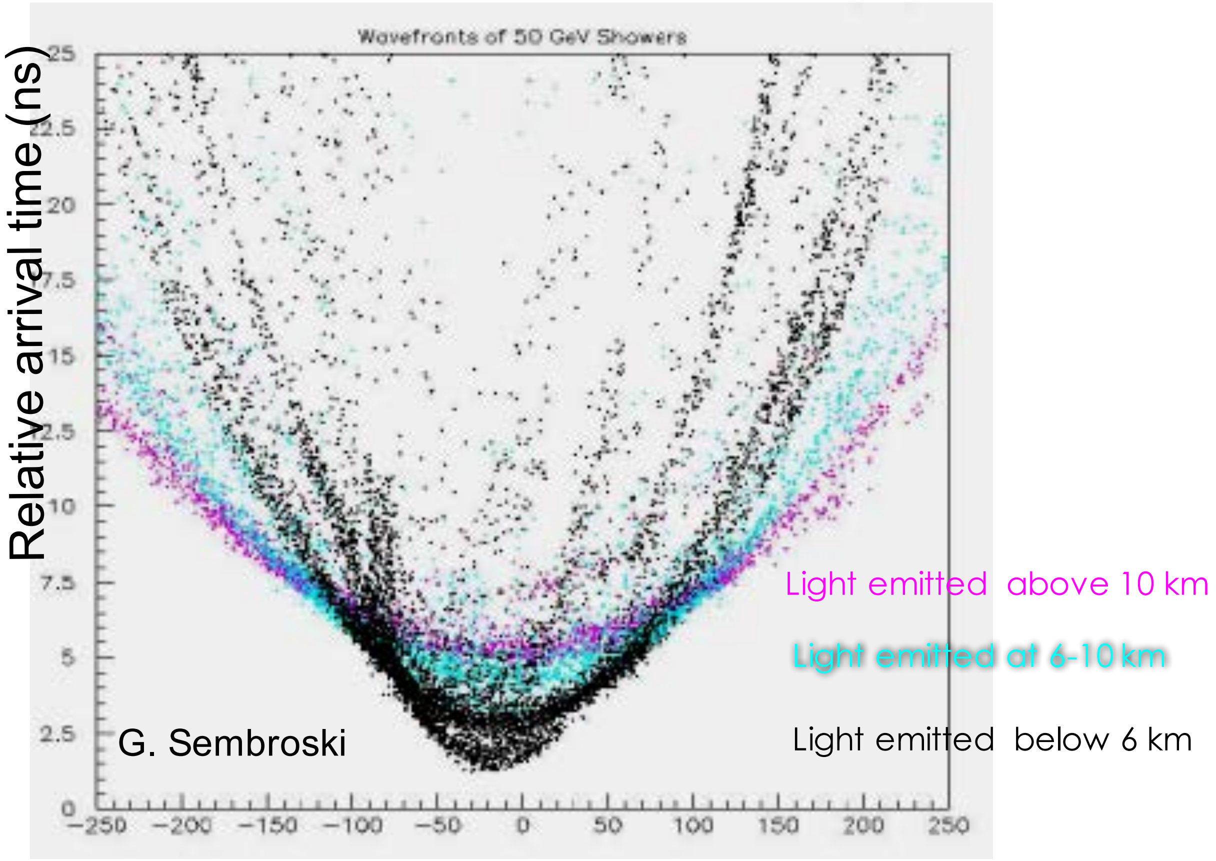
Attenuation gets more severe at larger zenith angles, as the optical path through the atmosphere increases:



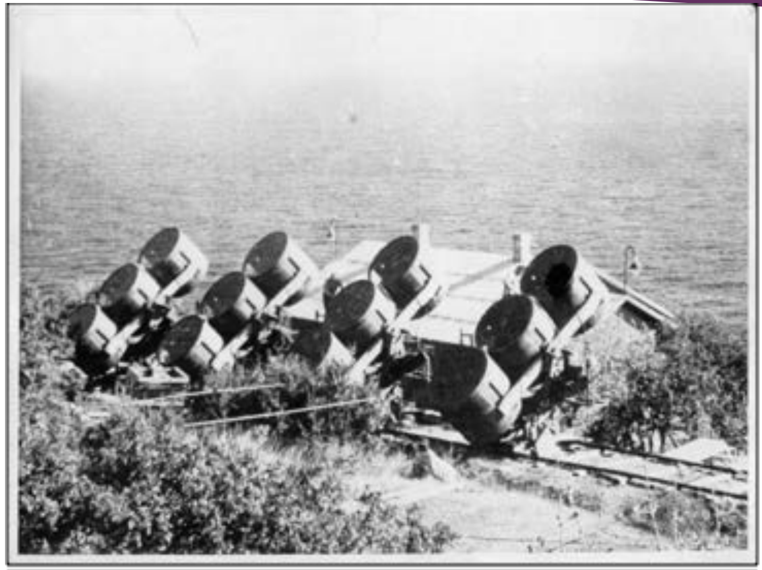
Observation level: 2200 m a.s.l.

Cherenkov light in the atmosphere:
Time structure of the C-light front

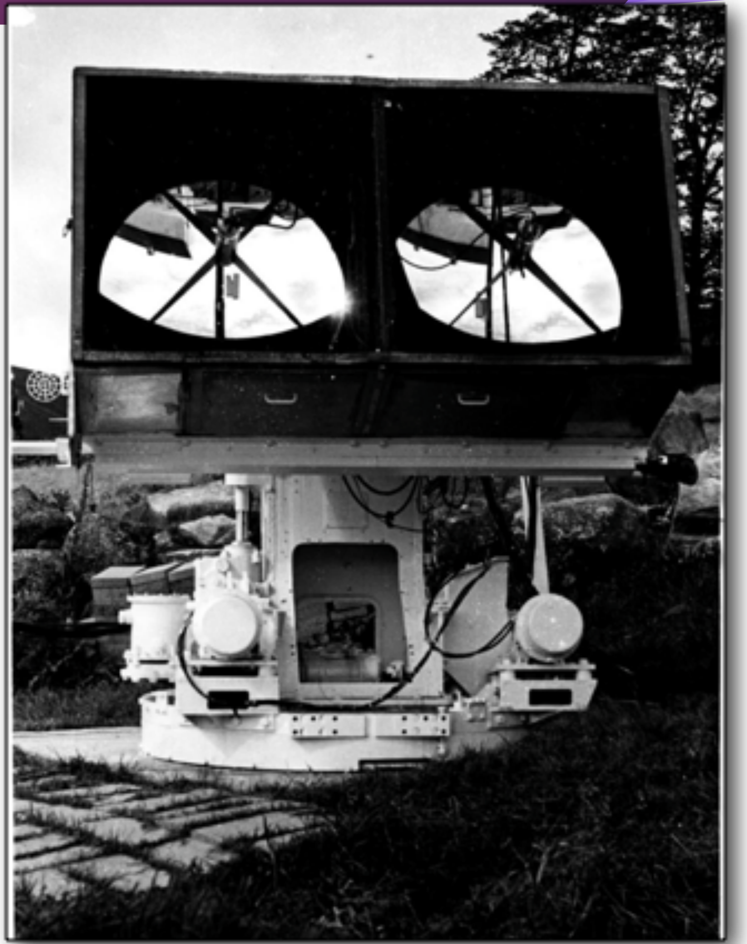
C-light front is shaped as a rather flat, narrow cone, sharper than the charged particles front



The Very Beginning of the Atmospheric Air Cherenkov Telescope Technique



Crimea Experiment 1959-1965, Chudakov, et al., (SNR, radio galaxies)



Telescope Glencullen, Ireland ~1962-66University College, Dublin group led by Neil Porter(in collaboration with J.V.Jelley)

The first Imaging Atmospheric Telescope: IACT era

Wipple observatory: the first ever sucesful ground based experiment

30h for 20 sigma signal from crab

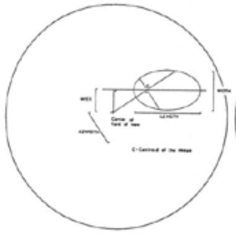


Fig. 2. Definition of image parameters.

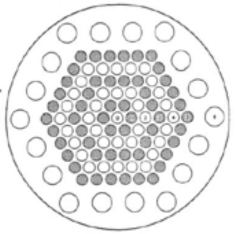


Fig. 3. The layout of the photomultipliers in the focal plane of the reflector. The inner pixel spacing is 0.25°. The numbers refer to the zones, the convention used to designate the position of the images relative to the center of the camera.

Observations of TeV Photons at the Whipple Observatory

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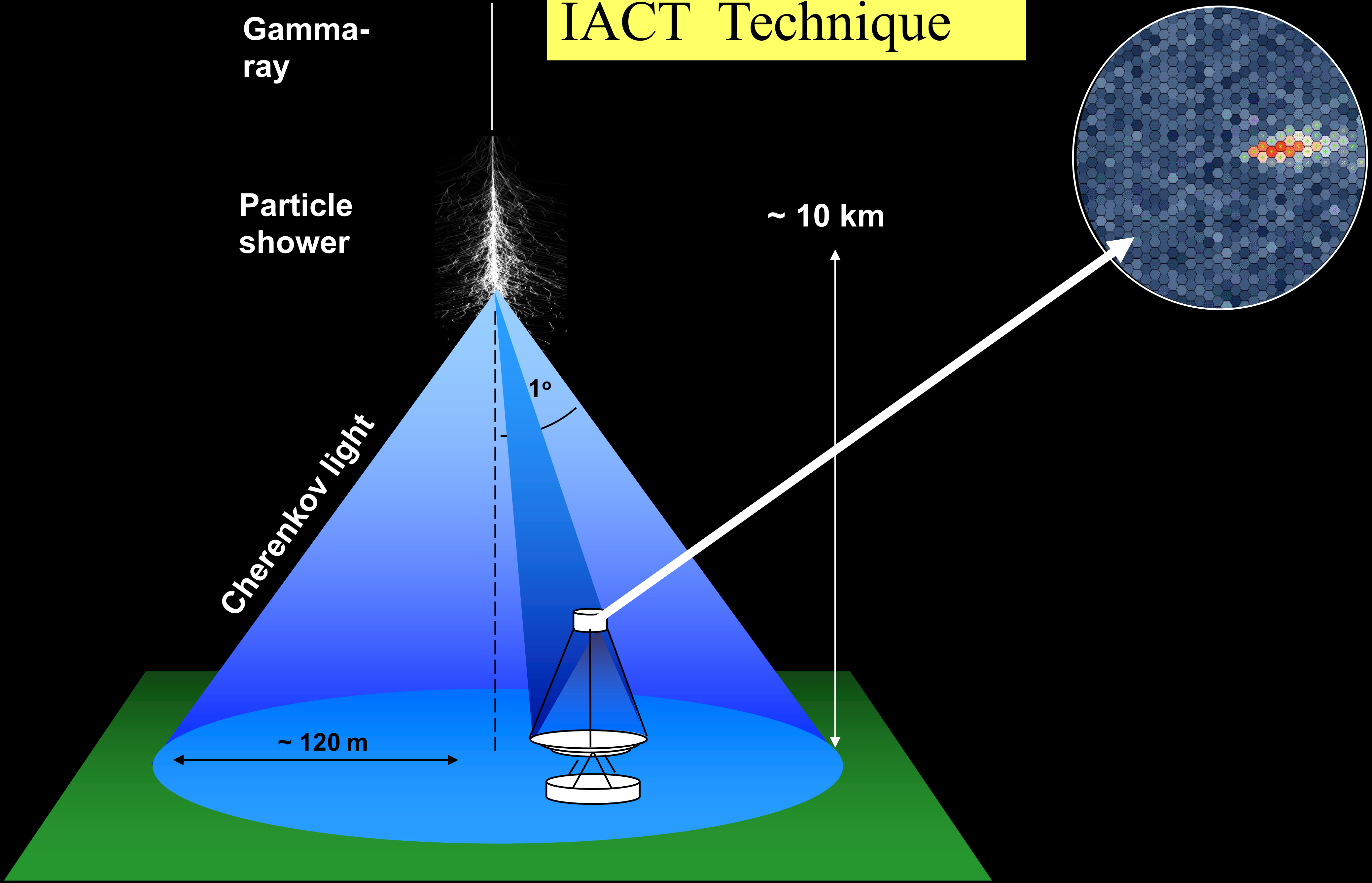
Abstract

The Whipple Observatory 10 m gamma-ray telescope has been used to search for TeV gamma-ray emission from a number of objects. This paper reports observations of six galactic and three extragalactic objects using the Cherenkov image technique. With the introduction of a high-resolution camera (1/4° pixel) in 1988, the Crab Nebula was detected at a significance level of 20 σ in 30 hours of on-source observation. Upper limits at a fraction of the Crab flux are set for most of the other objects, based on the absence of any significant dc excess or periodic effect when an *a priori* Monte Carlo determined imaging selection criterion (the "azwidth cut") is employed. There are weak indications that one source, Hercules X-1, may be an episodic emitter. The Whipple detection system will be improved shortly with the addition of a second reflector 11 m in diameter (GRANITE) for stereoscopic viewing of showers. The combination of the two-reflector system should have a signal-to-noise advantage of 10^3 over a simple nonimaging Cherenkov receiver.

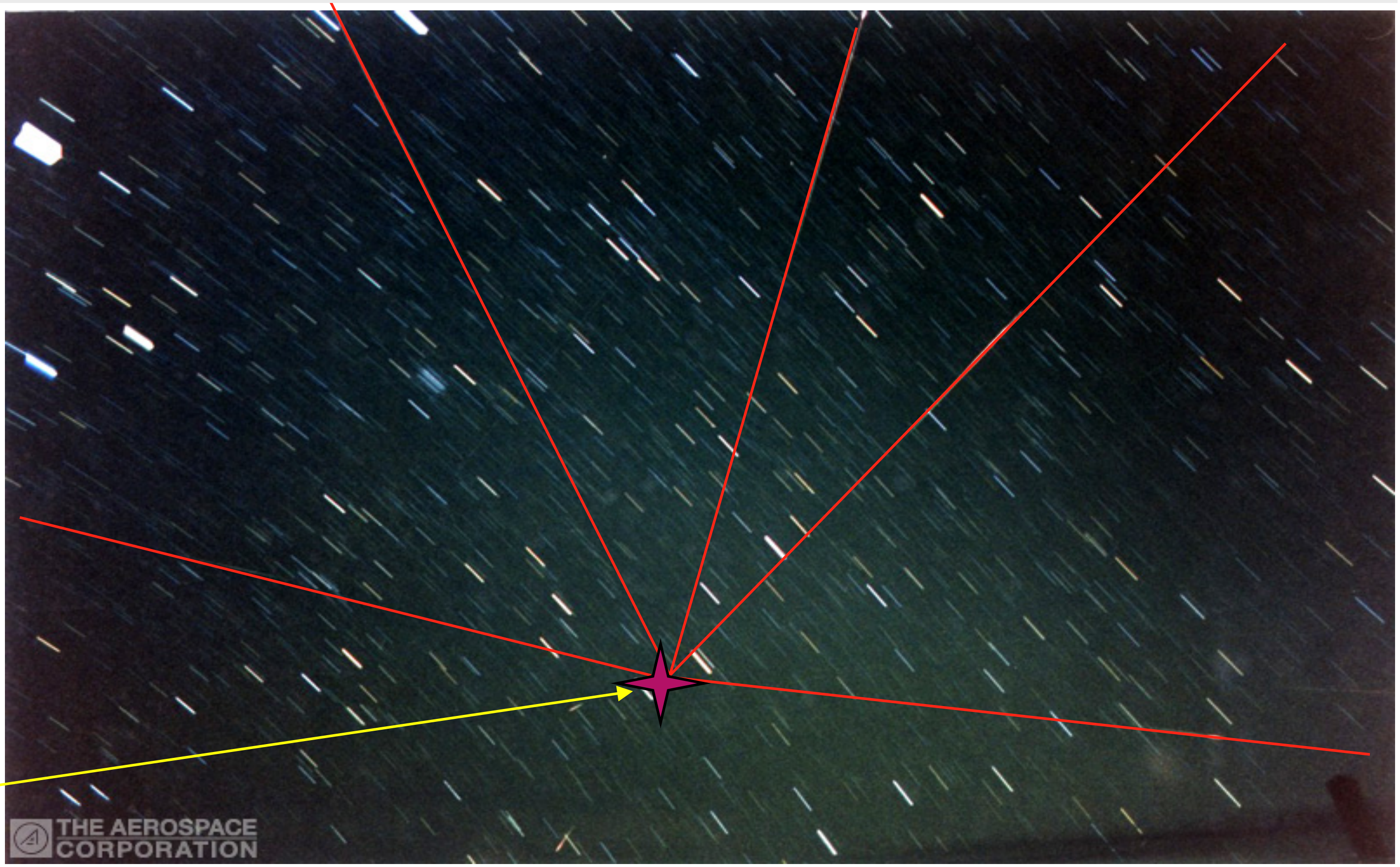
IACT Technique



Gamma showers from a point source

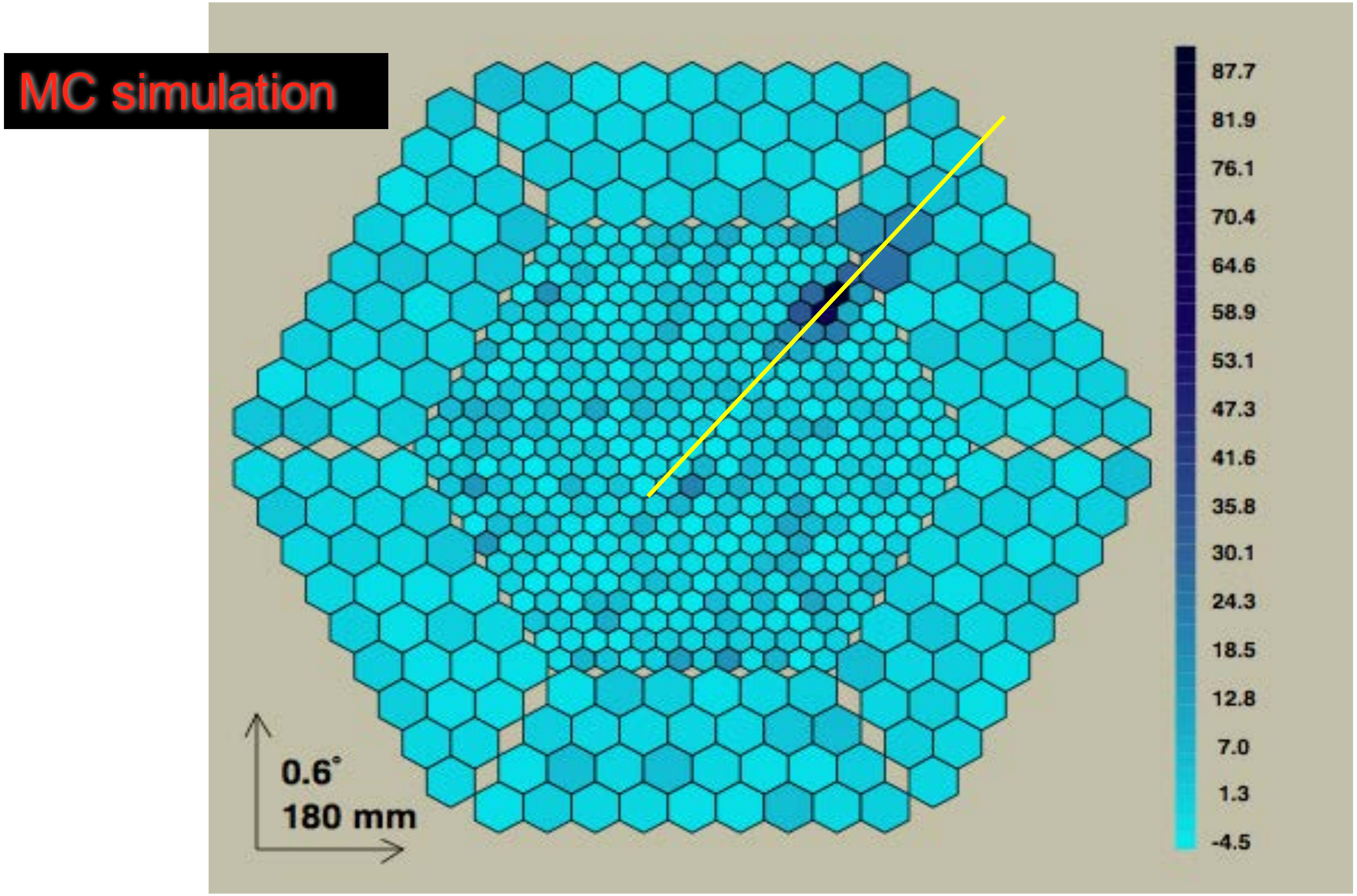
Imaging Air Cherenkov Telescopes are detecting a gamma source finding superimpositions on many shower axes of Cherenkov images

Like in some meteor showers, the apparent movement direction of the Earth can be seen as the radial point of meteor axis

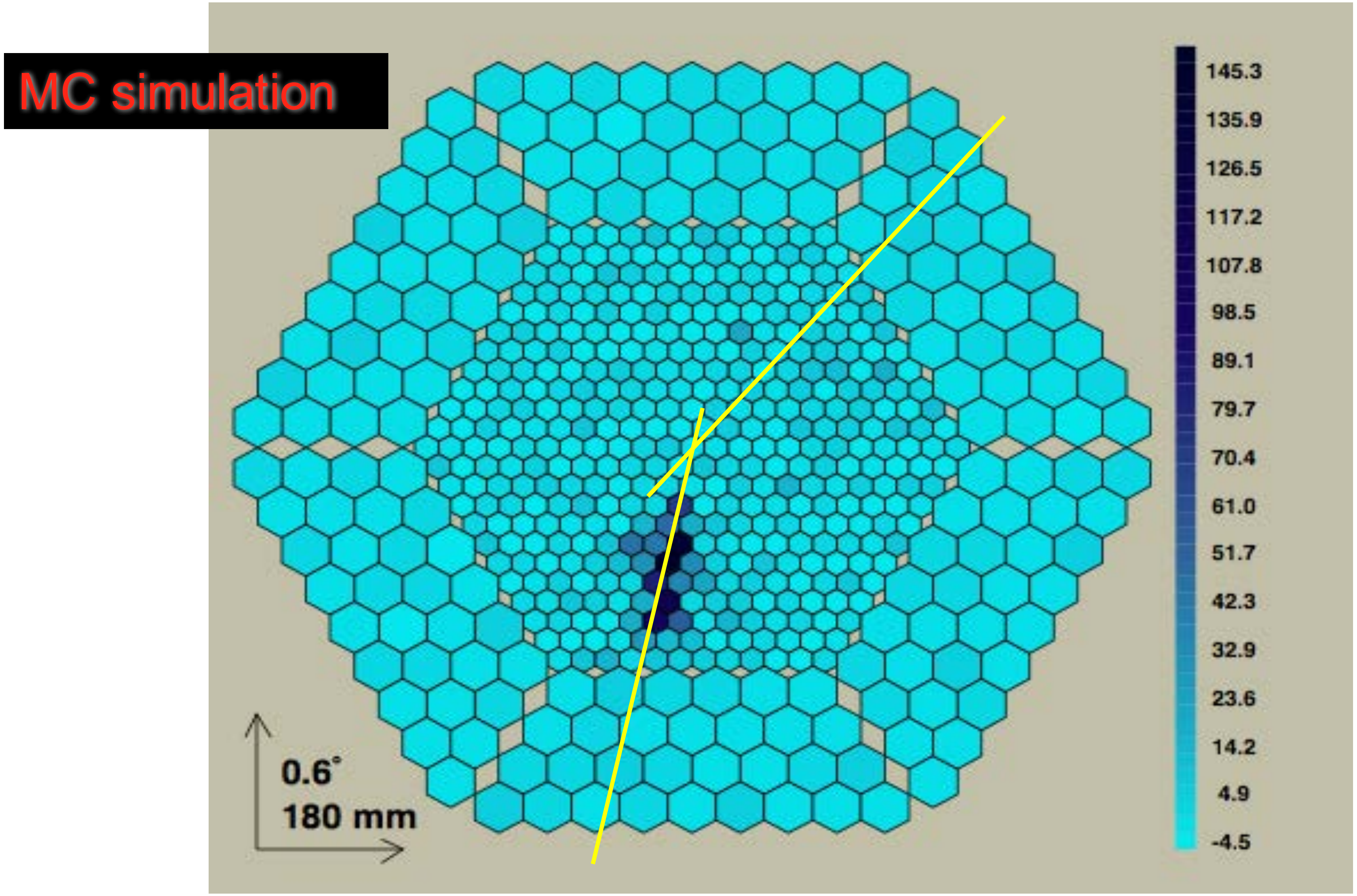


Source direction

E = 38 GeV, b = 130 m

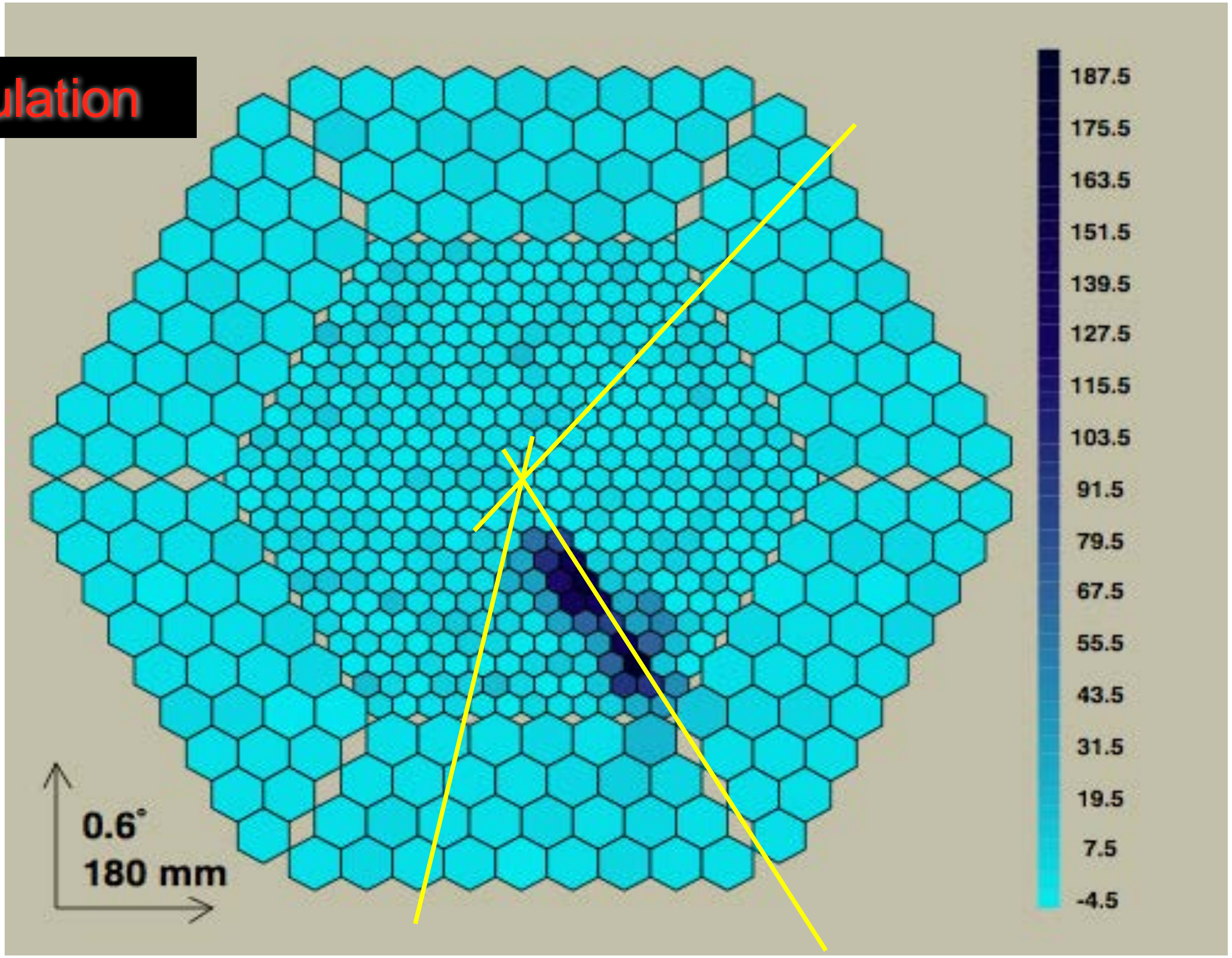


E = 76 GeV, b = 100 m



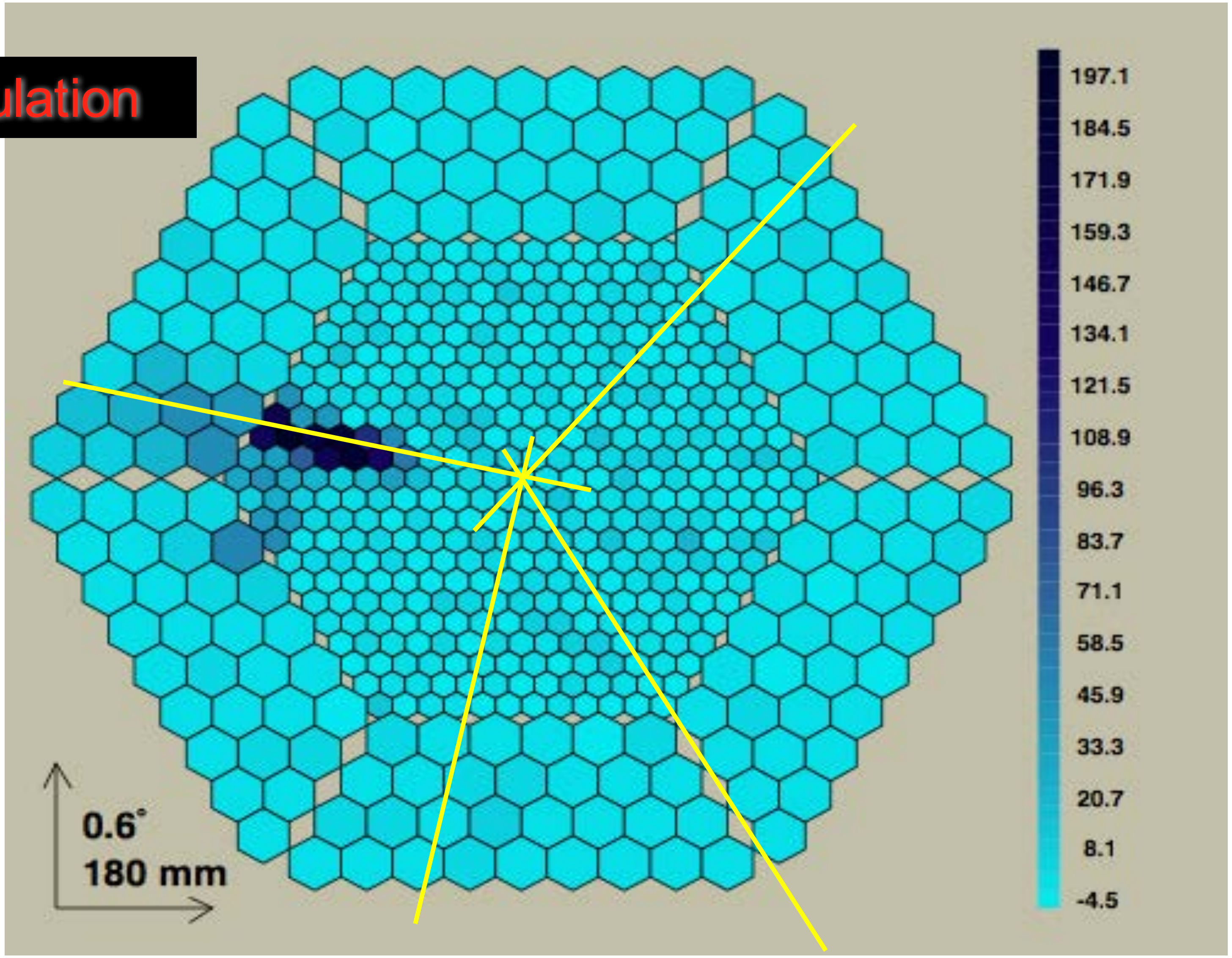
E =120 GeV, b = 107 m

MC simulation

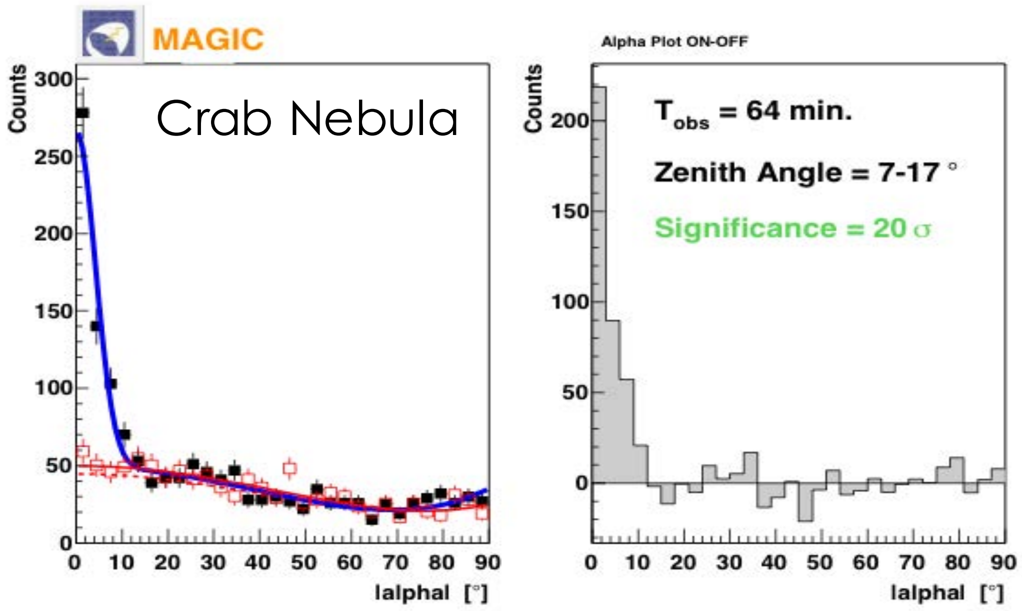


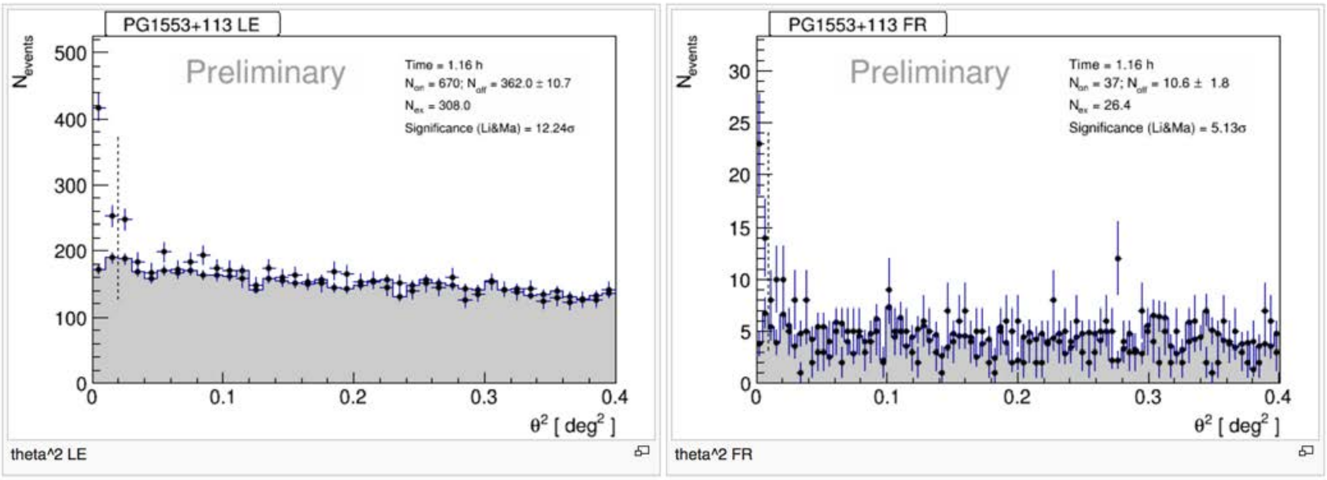
E =286 GeV, b = 119 m

MC simulation

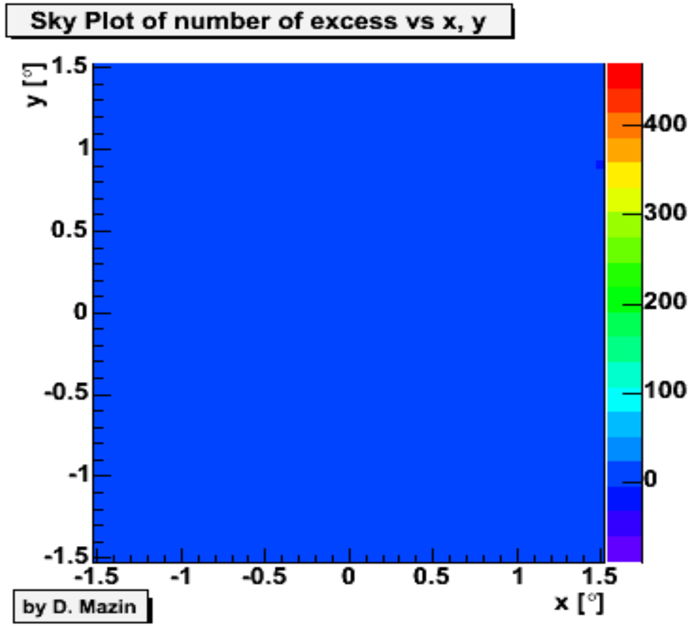


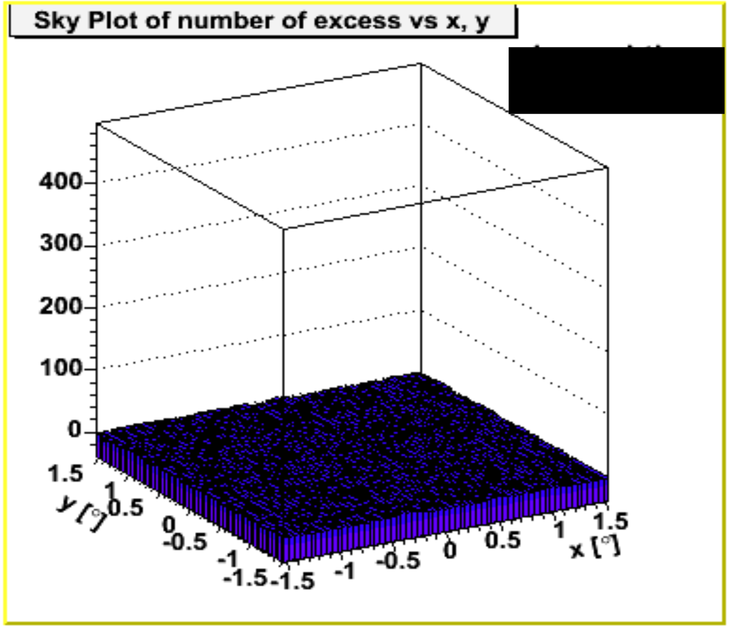
Alfa plot MONO (1D)



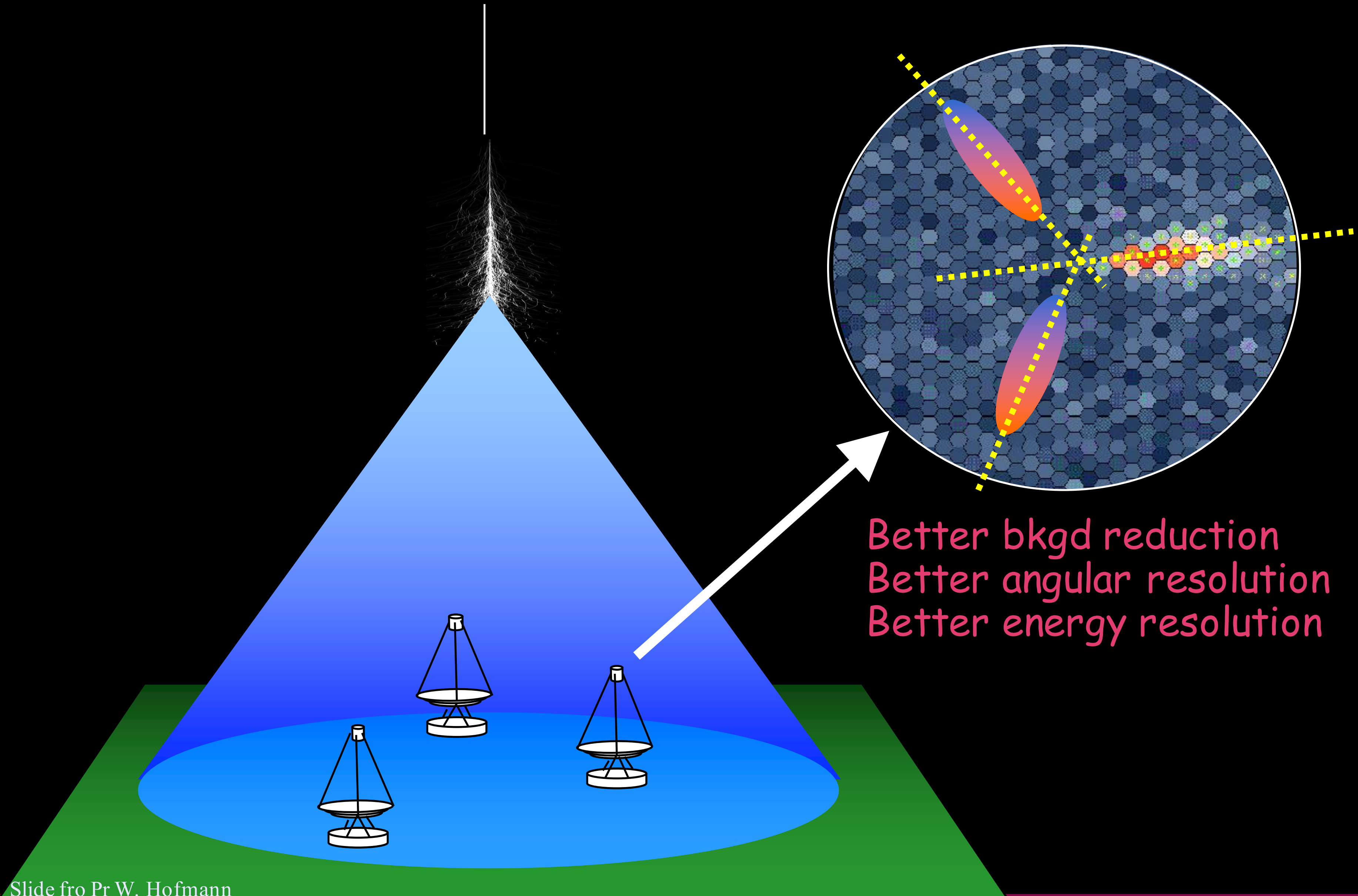


Theta square plot stereo (2D)





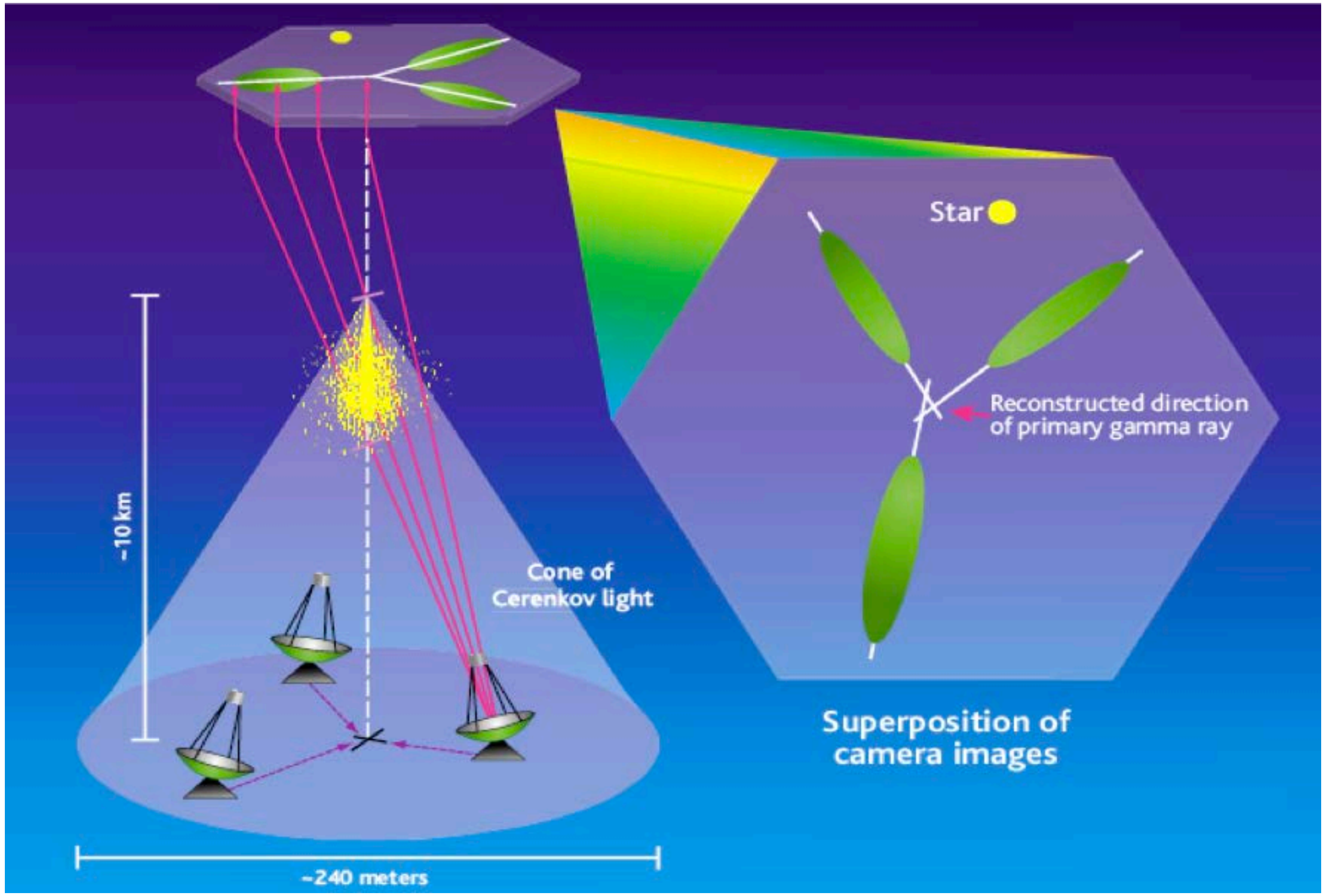
Using a system of telescope, in the same event with the stereoscopic vision the shower reconstruction is much better !



Better bkgd reduction
Better angular resolution
Better energy resolution

Slide fro Pr W. Hofmann

The stereoscopic concept



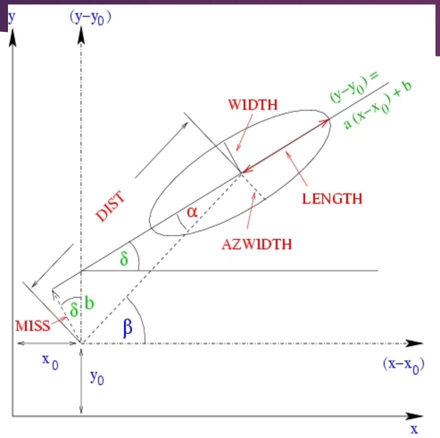
IACT data analysis:
from shower images to photon flux and spectrum reconstruction

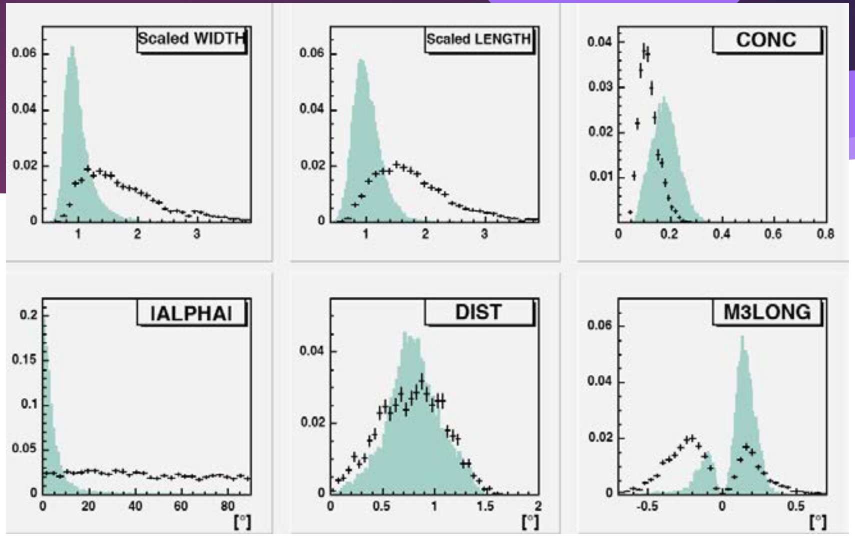
Data analysis steps:

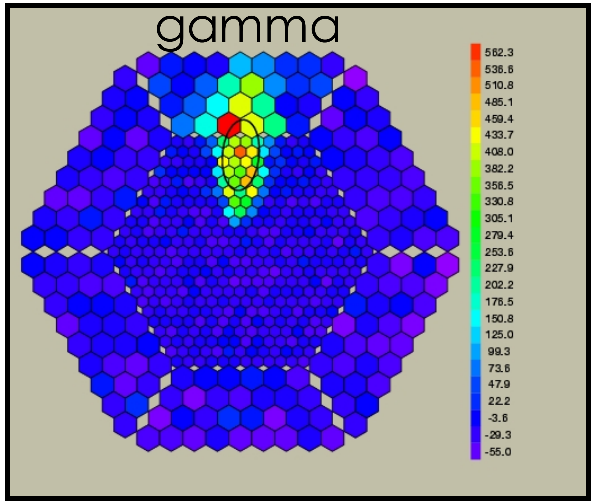
1. Signal extraction and image analysis
2. Gamma hadron separation
3. Energy reconstruction
4. Photon (shower) direction
5. Photon flux detection
6. Spectrum reconstruction

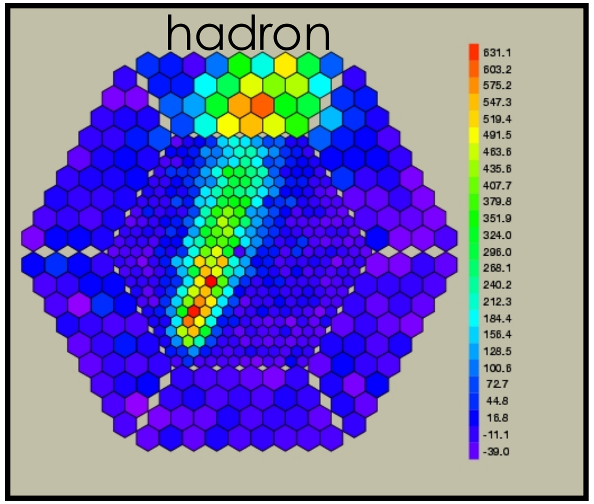
Image analysis

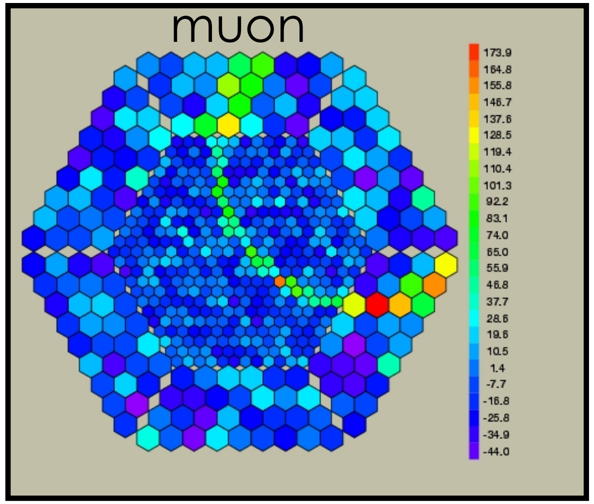
Hillas image parameters









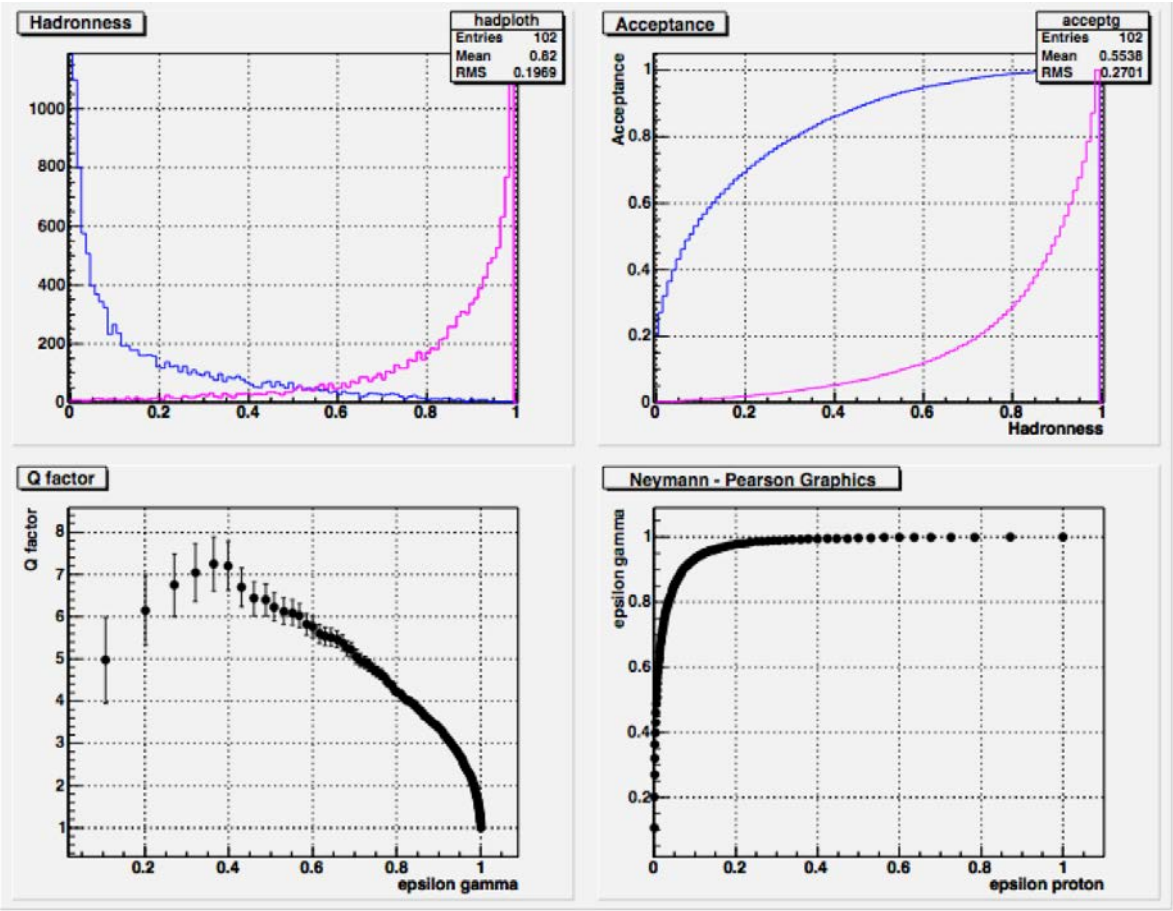


Gamma/Hadron separation

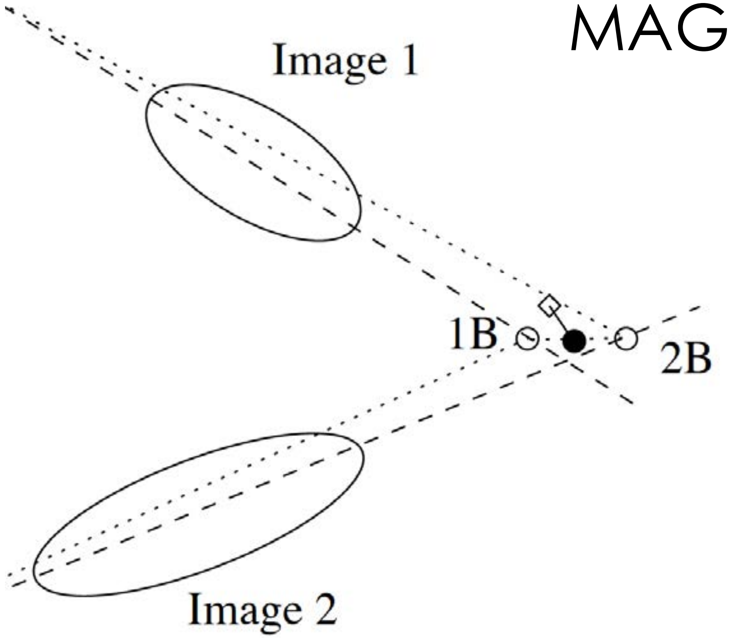
Random forest classification method

- Classification algorithm:
- No a priori parameterization
- Using "decision trees", constructed through training samples of known typology events
- It can combine multiple parameters taking into account any correlations between them
- Label each event with a "coefficient of adronnes"

Every event is labeled with "hadronnes" Coefficient that is related with the probability do be background

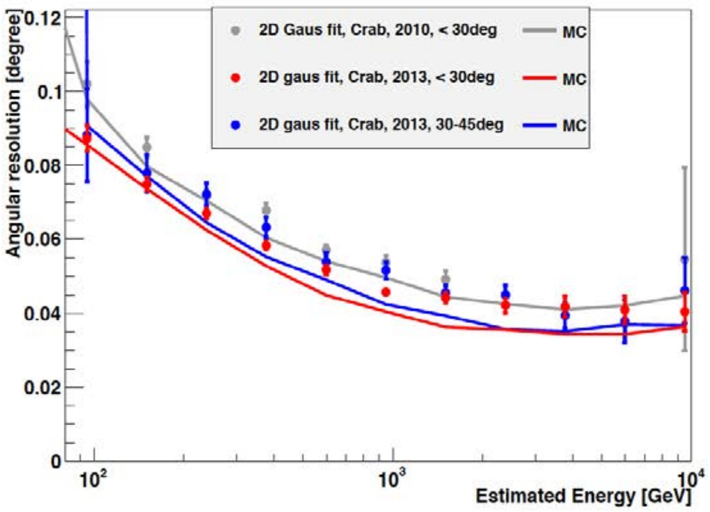


Direction and angular resolution

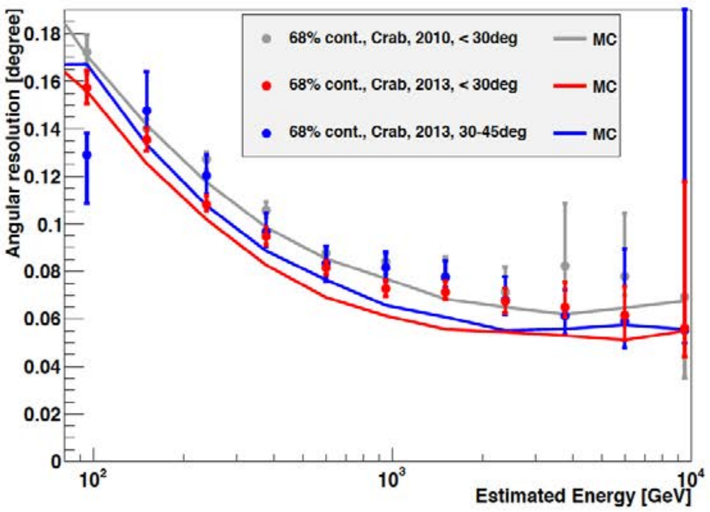


MAGIC performance as an example

stereo



mono

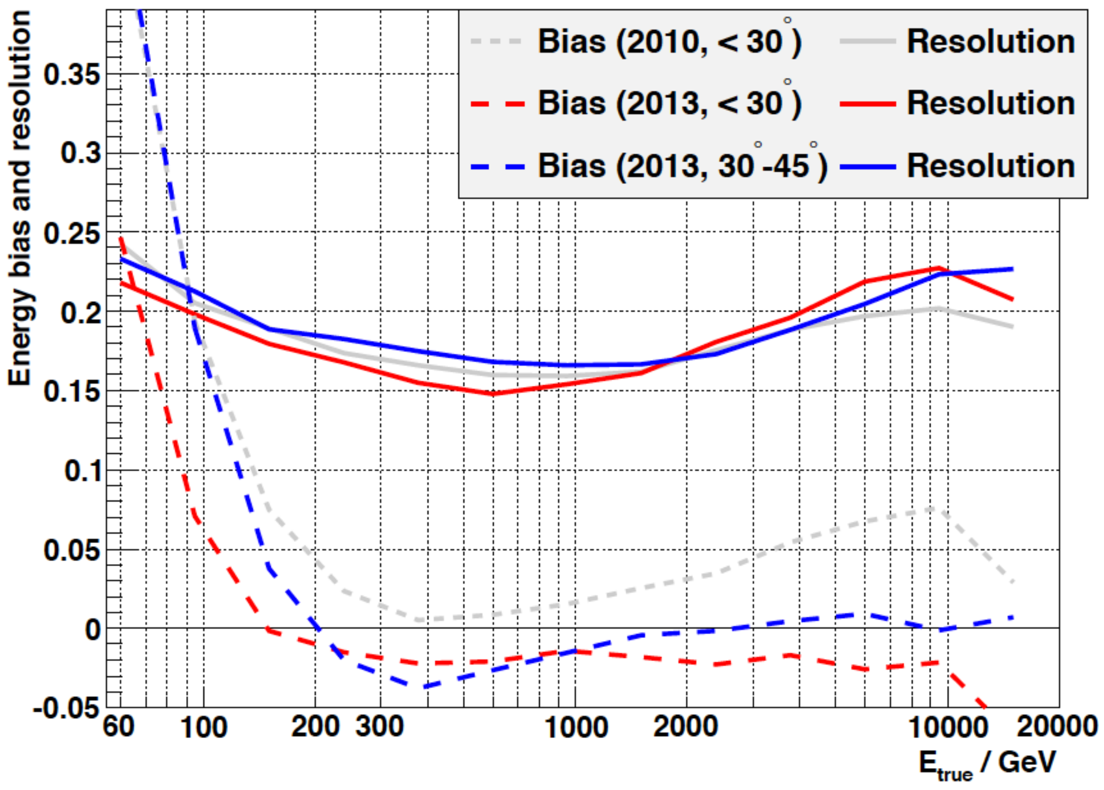


Energy resolution

Energy is very much related with the images intensity (we call it "size" of the event).
The primary energy estimation is calculated by comparing the collected light with the expected from simulation.

Many parameters like atmosphere transparency, mirror reflectivity, photosensor efficiency have to be taken into account

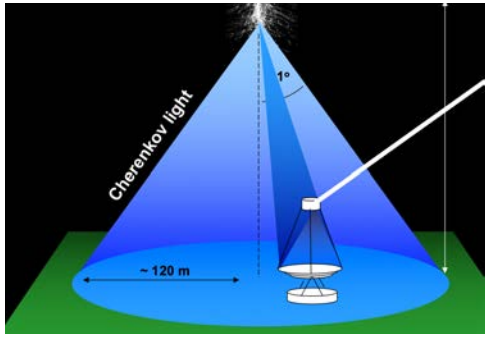
The calibration/simulation of the detector is a crucial element, and has to be updated frequently

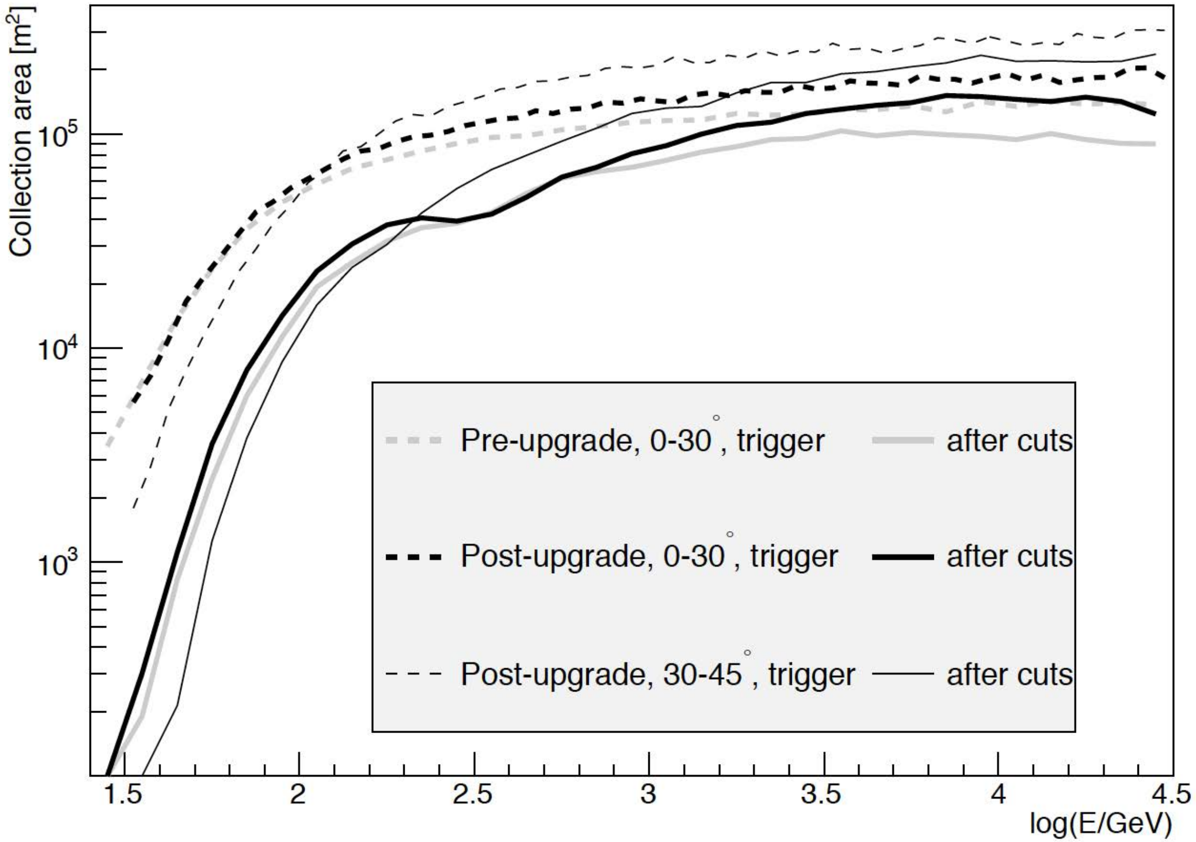


Effective area

The effective area is the **integral of the observation surface weighted** with the **probability** that a **shower** with a given **energy** can **trigger**, trigger and pass some given analysis cuts.

Note that effective area exceed by far the telescope surface!!





Sensitivity

Integral MAGIC sensitivity

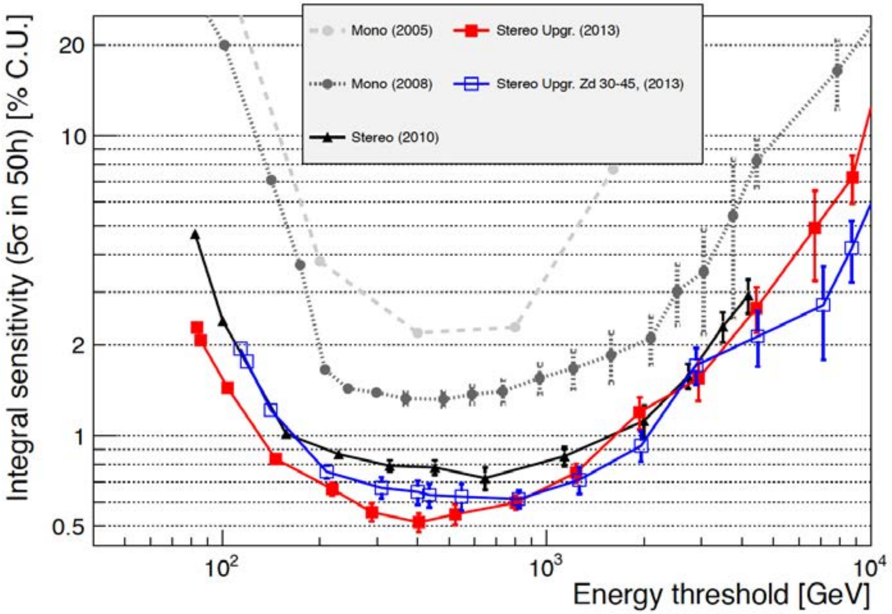


Figure 17: Evolution of integral sensitivity of the MAGIC telescopes, i.e. the integrated flux of a source above a given energy for which $N_{\mathrm{excess}}/\sqrt{N_{\mathrm{bkg}}} = 5$

Differential MAGIC sensitivity

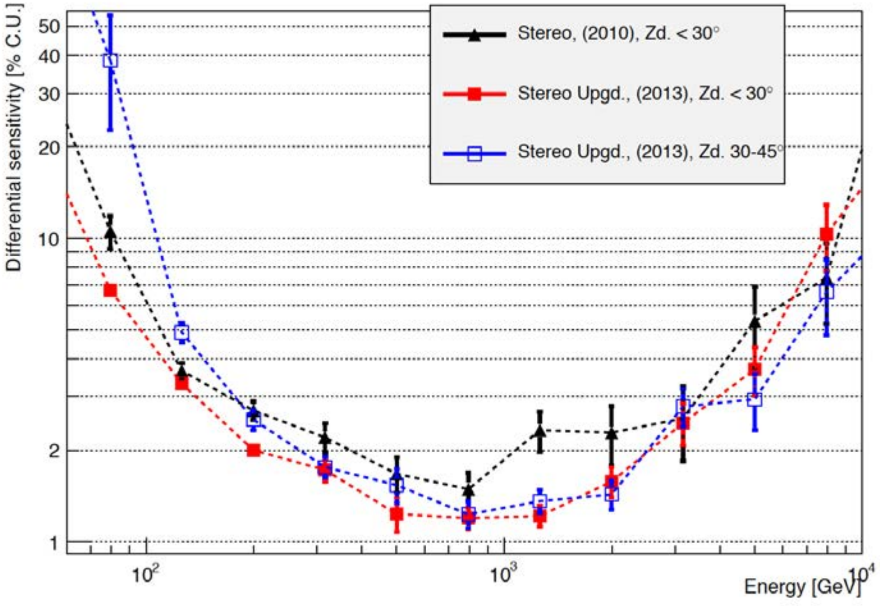
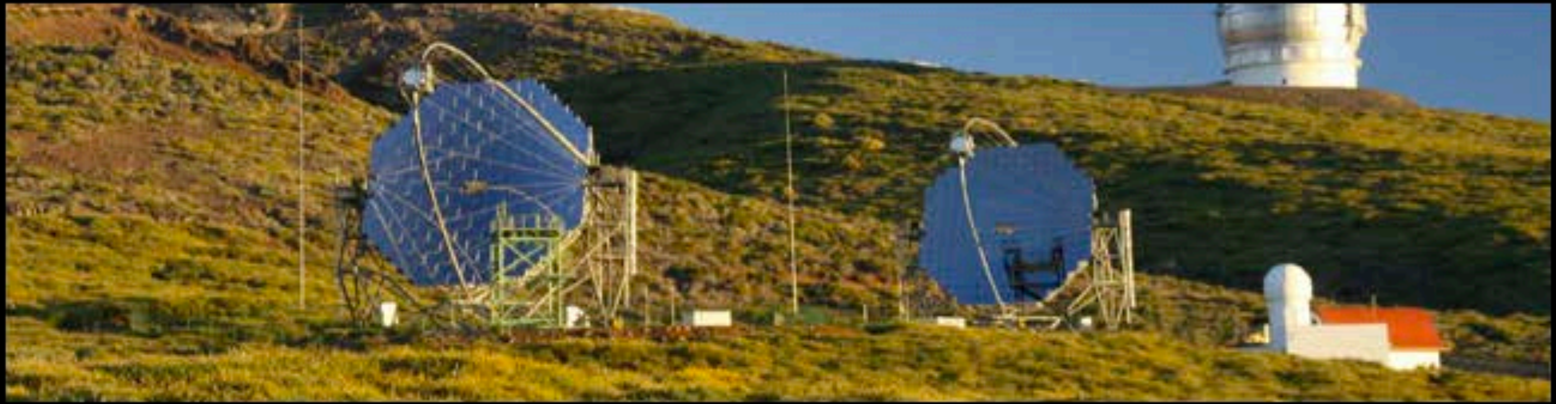


Figure 18: Differential (5 bins per decade in energy) sensitivity of the MAGIC Stereo system. We compute the flux of the source in a given energy range for which $N_{\mathrm{excess}}/\sqrt{N_{\mathrm{bkg}}} = 5$ with $N_{\mathrm{excess}} > 10$, $N_{\mathrm{excess}} > 0.05 N_{\mathrm{bkg}}$ after 50 h of effective time. For better visibility the data points are joined with broken dotted lines.

HESS I: Array 4 tel. of 12m
HESS II: 28m diameter (2013)
1800 m asl
> 2003



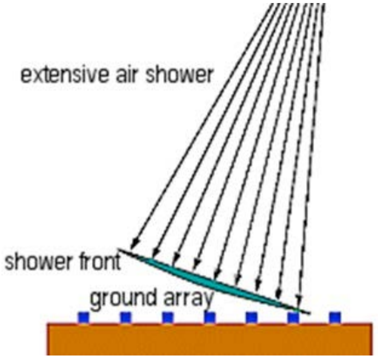
MAGIC:
Array 2 telescopes
17m diameters
2200 m asl
>2004

Array 4 telescopes of
12m diam.
Central mast mounting
1800 m asl
>2007

Evolution of sensitivity

Crab discovery Wipple	5 sigma crab in 2h
HEGRA, Wipple granite	5 sigma crab in 6 min
MAGIC, HESS, Veritas	5 sigma crab <20 s

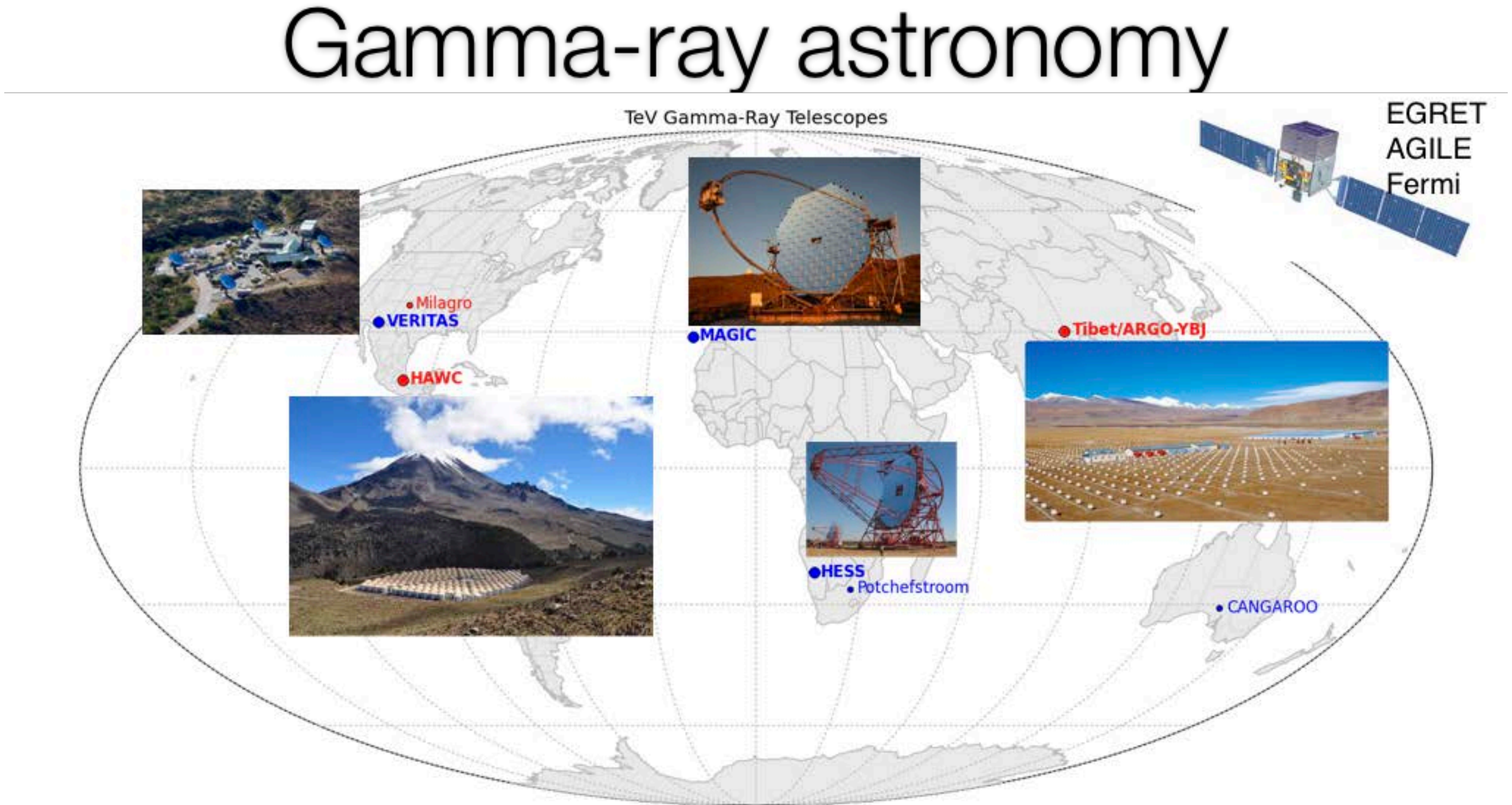
Shower front particle detectors



- Shower particles detectors are detecting **charged particles from the shower** front
- The detector should be in **HIGH altitude** to avoid the absorption of the cascade in the atmosphere
- The particle are detected via **ionization processes** (scintillators, gas chamber…) or via **Cherenkov light** emission in a **dense medium** (water, glass)
- The shower front particle detectors can work 24h/day every day, with a **wide field o view** (all the sky al ZA< 35 deg)
- By sampling only the shower front, the **angular** and **energy** resolution is **poor**

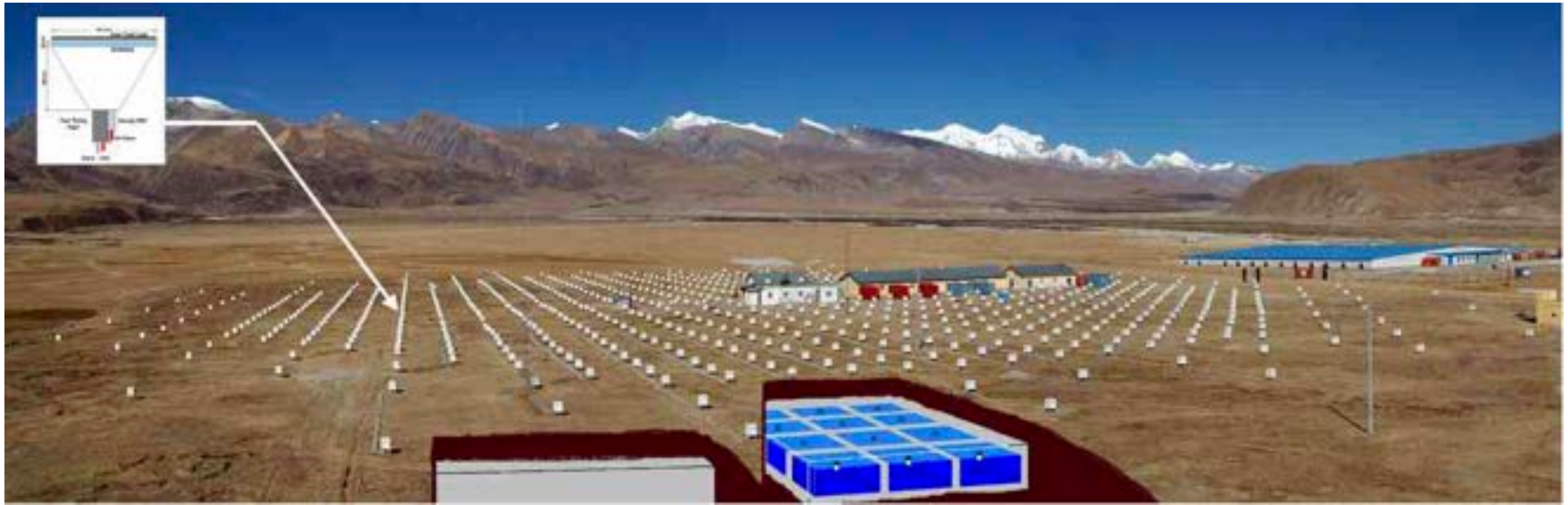
I will take the experiment HAWC as an example of ground based air shower detector

Shower front particle detectors



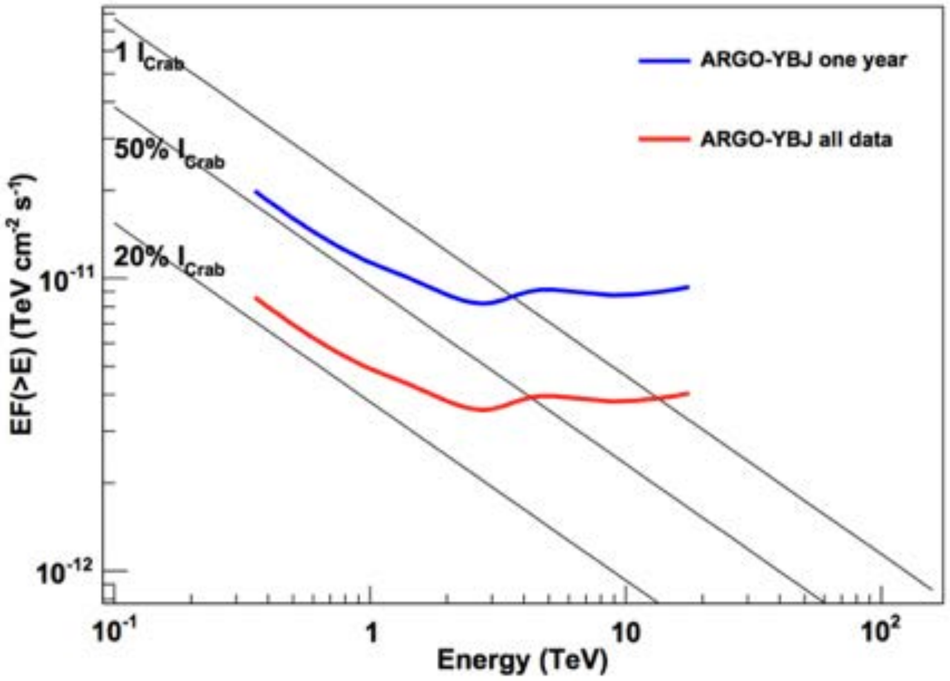
Tibet ASγ

- 761 fast-timing scintillation counters equipped with 2" PMTs
- 28 density counters equipped with 1.5" PMTs
- Area covered: 36900 m2
- Altitude: 4300 m
- Achievement: Crab at 6.9 σ with 6 years of data.



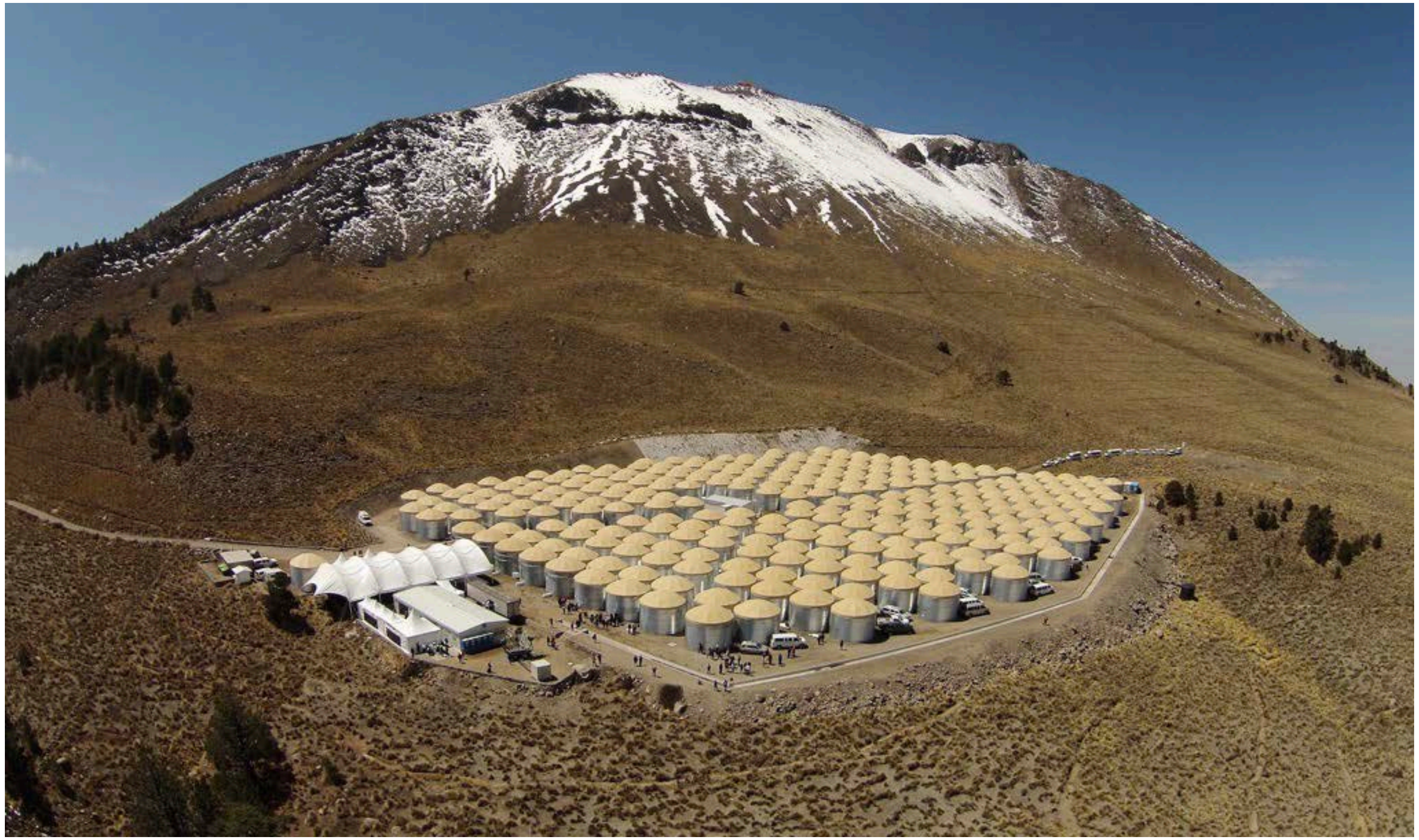
ARGO

- Located at Yangbajing Laboratory at 4300 m
- RPCs covering an area of 6700 m2
- Aim: Detect gamma rays down to energies of 100 GeV
- Achievement: 6 sources in 5 years of data.

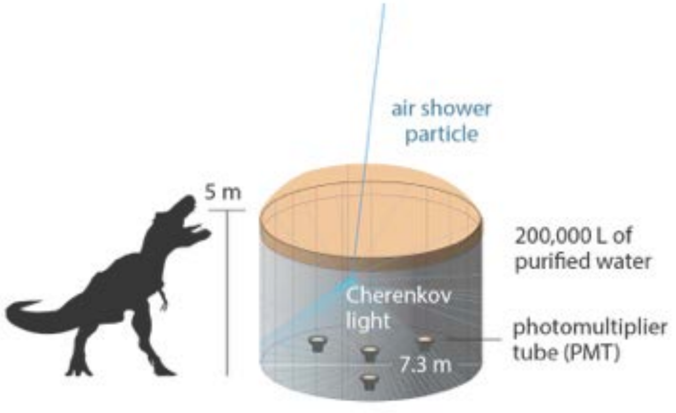


High Altitude Water Cherenkov (HAWC)

- Located in Sierra Negra (Mexico)
- 4100 m above sea level
- 300 tanks
- 200 kL water each
- 22 000 m2 area w. 57% coverage
- 15-20 kHz trigger rate
- FoV ~ 2 sr
- Energy range 0.1 - 100 TeV
- Angular resolution ~ 0.2°-1°
- Duty cycle > 95%



Detectors elements



- 300 water tanks
- 4.5 m deep
- 7.3 m diameter
- 4 PMTs each tank

- 1200 PMTs
- 300 10" diameter -> located at the center
- 900 8" diameter -> surrounding the 10"

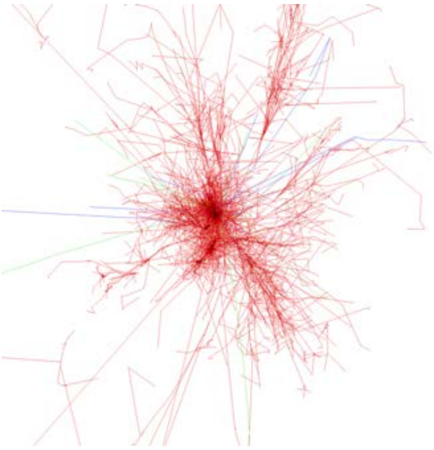
Gamma hadrons separation

Most of the events triggered by HAWC have hadronic origin -> it is important to properly identify them and separate from gammas

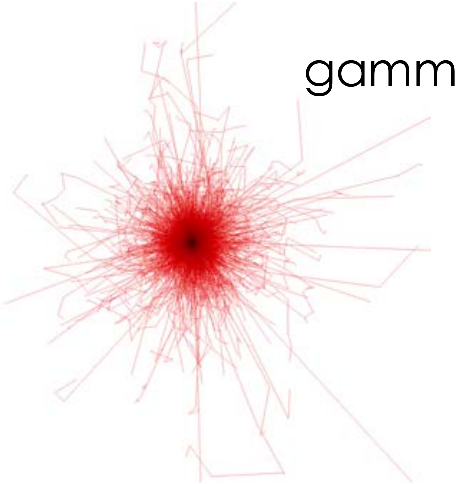
Hadrons have a **clumpy** lateral distribution.

Gammas have a **smooth** lateral distribution.

proton



gamma



Gamma hadrons separation

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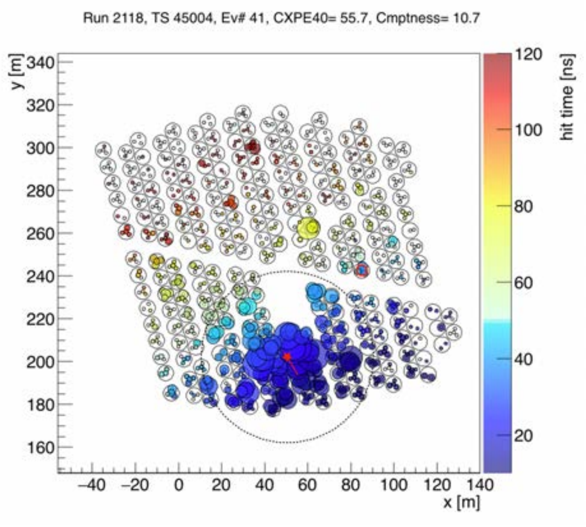
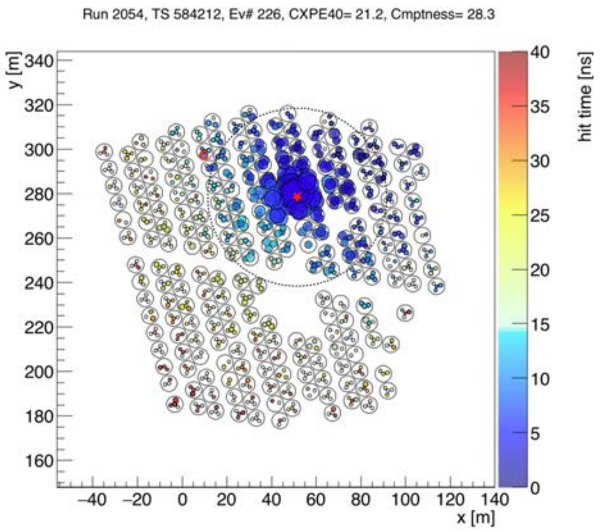
proton



gamma



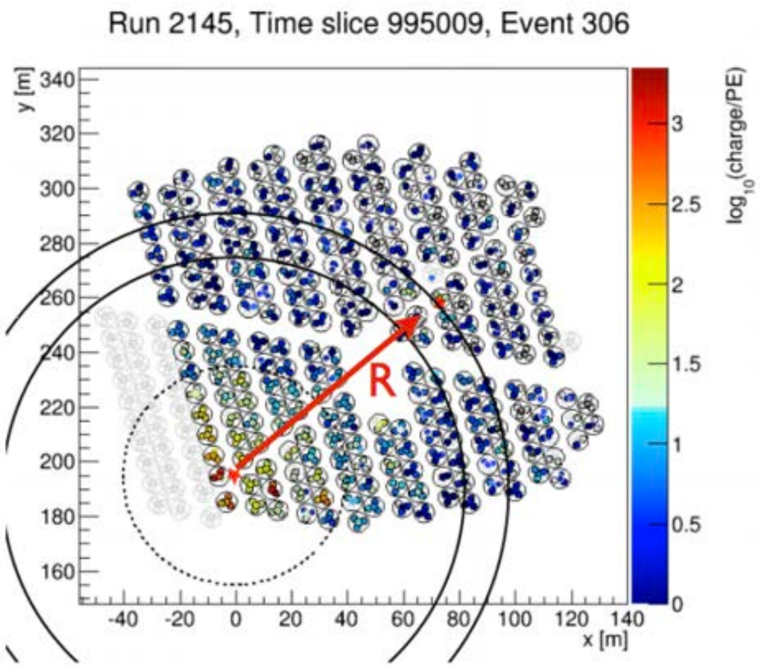
Gamma hadrons separation

Most of the events triggered by HAWC have hadronic origin -> it is important to properly identify them and separate from gammas

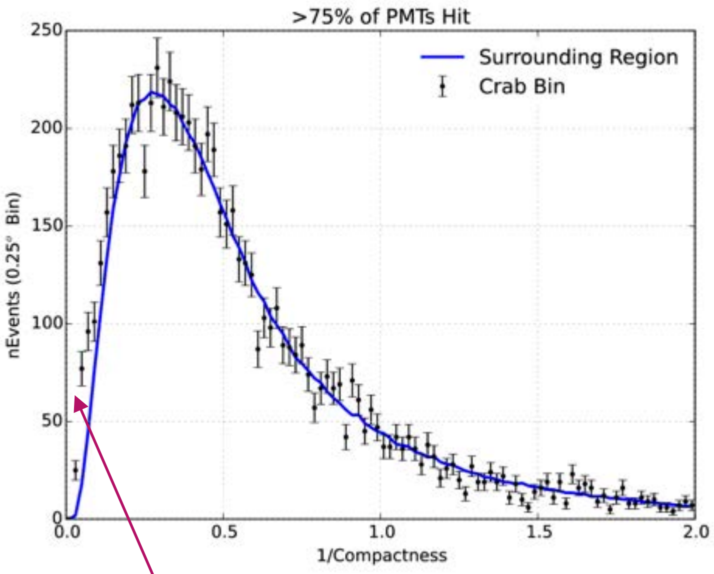
two values are currently used for separation:

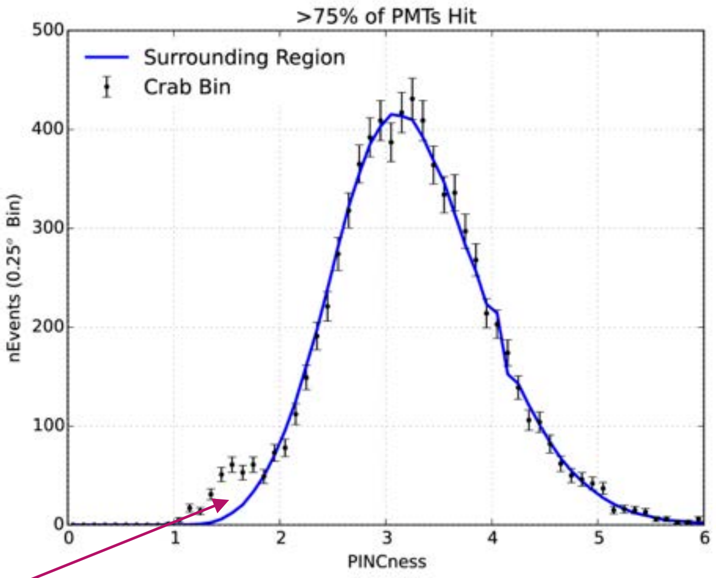
Compactness: Measures how compact the PMT hits at the detector are.

PINCness: The $\chi 2$ of the lateral distribution of all PMTs' measurements of PEs as compared to the average number of PEs in radial annuli for that shower.



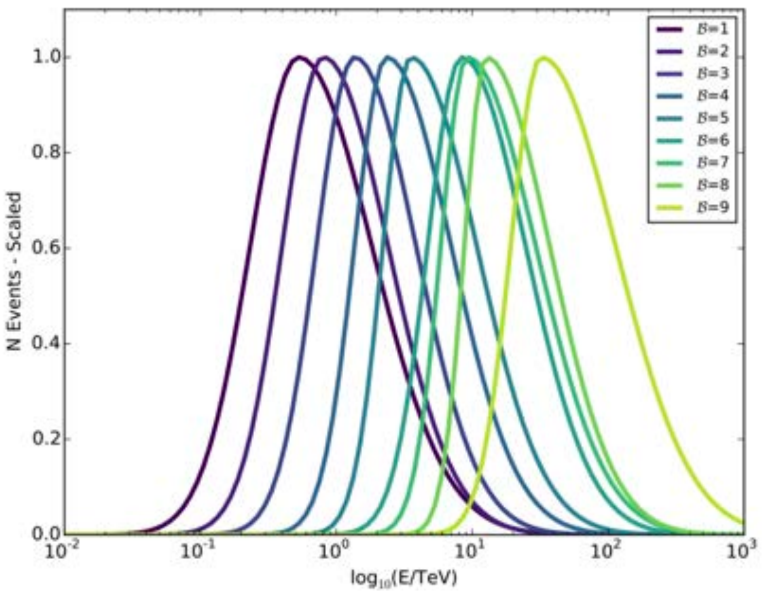
Gamma hadrons separation



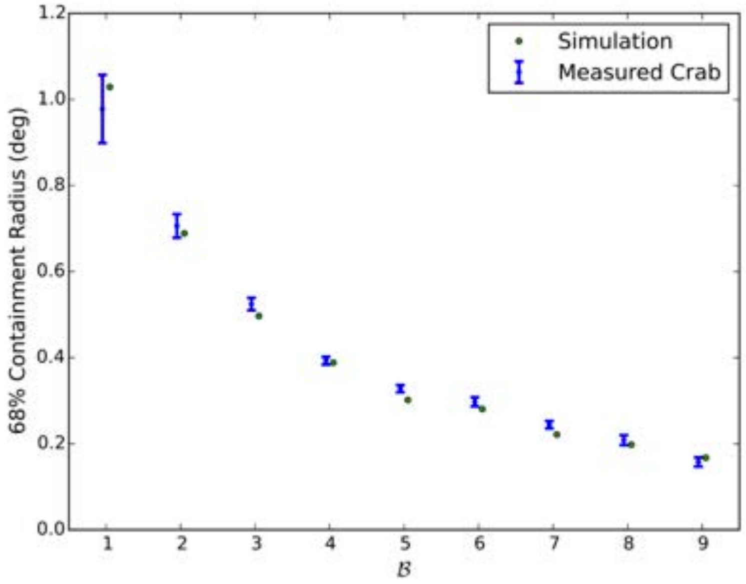


Regions with the presence of a gamma-ray source follow a different distribution of **Compactness** and **PINCness** than the background ones

Angular and energy resolution

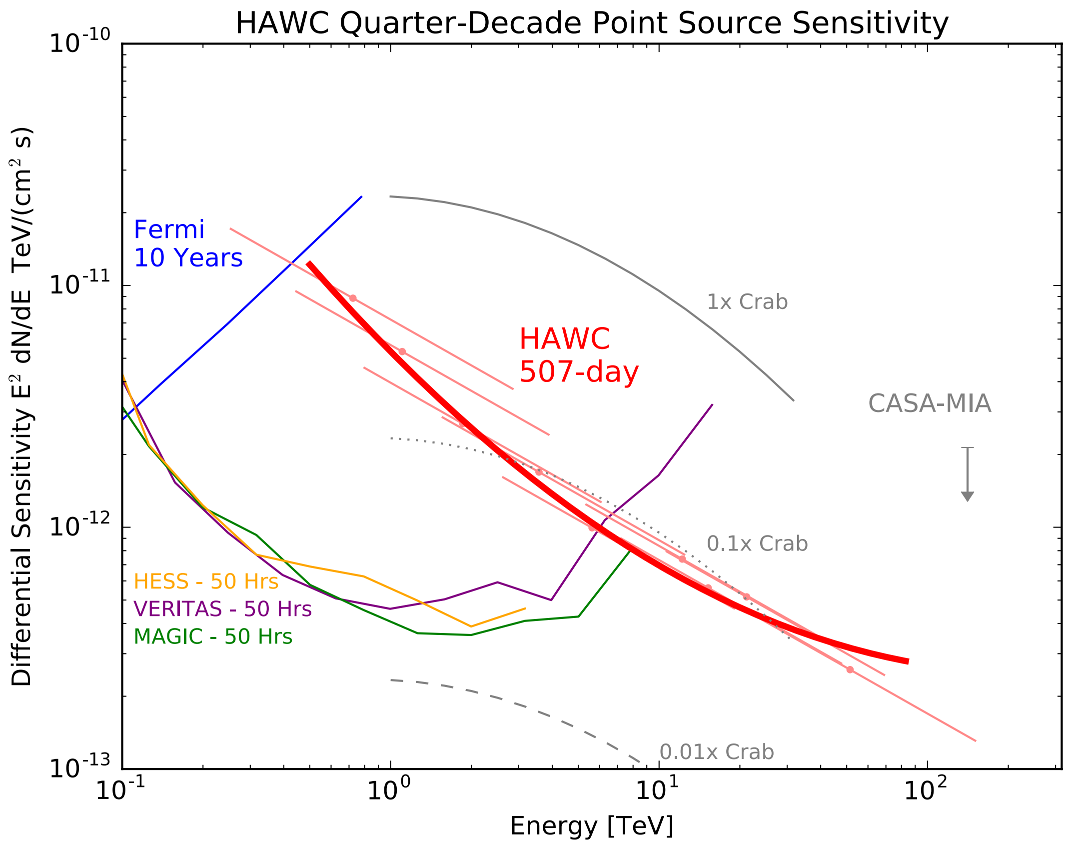


Bin energy resolution



Angular resolution for large events:68% containment ~ 0.2 degAchieving proposed resolution

Sensitivity



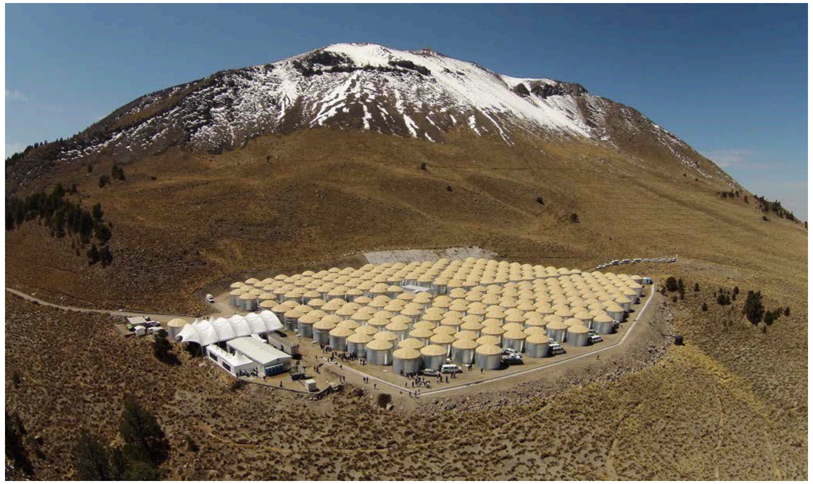
15x better sensitivity than Milagro (previous generation of water Cherenkov tanks)

Better sensitivity than current IACTs for point-like sources for E > 10 TeV for sources in 1 year.

Comparison of instruments and technique

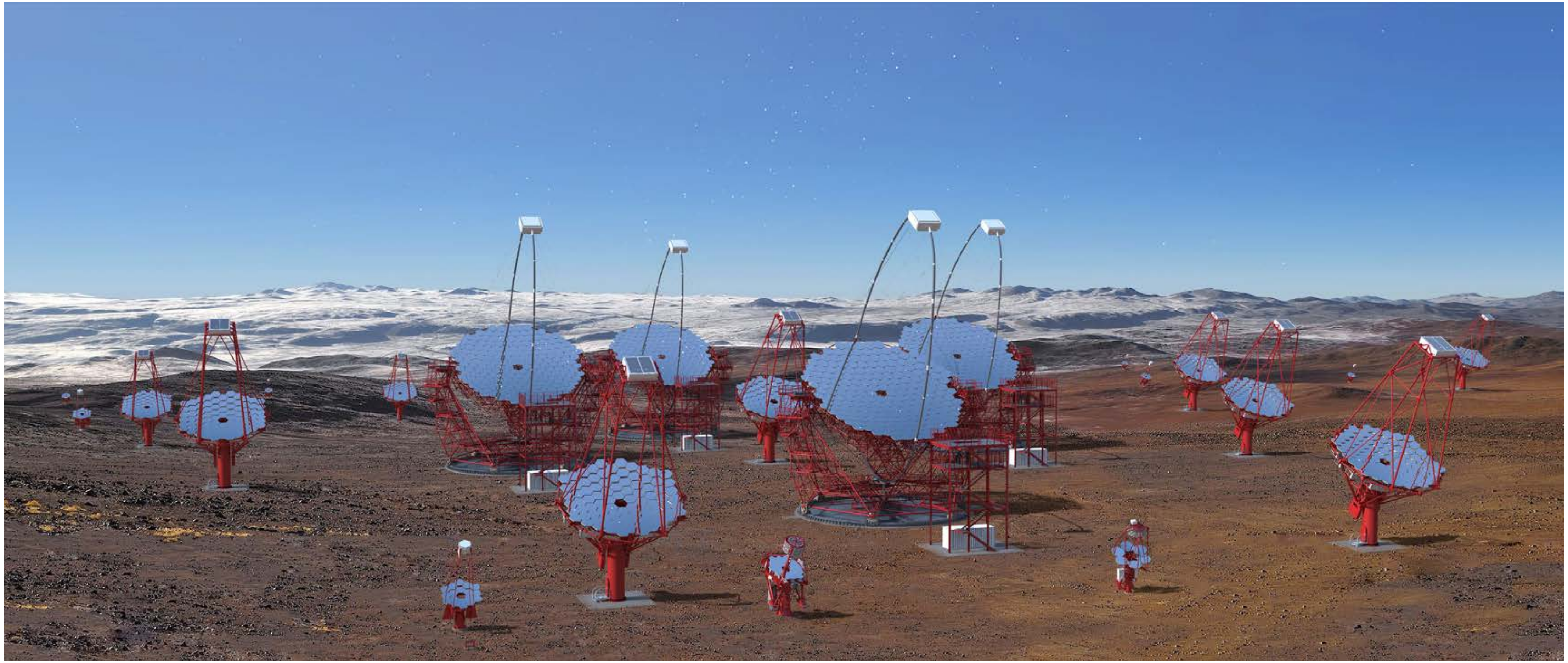
Energy Range 0.1-100 GeV
Area: 1 m^2
~ Background Free
Angular Resolution 0.1 - 0.3
Aperture 2.4 sr
Duty Cycle > 90%

Energy Range 20 GeV-50 TeV
Area > 10^5 m^2
Background Rejection > 99.8%
Angular Resolution 0.05°
Aperture 0.003 sr
Duty Cycle 10%

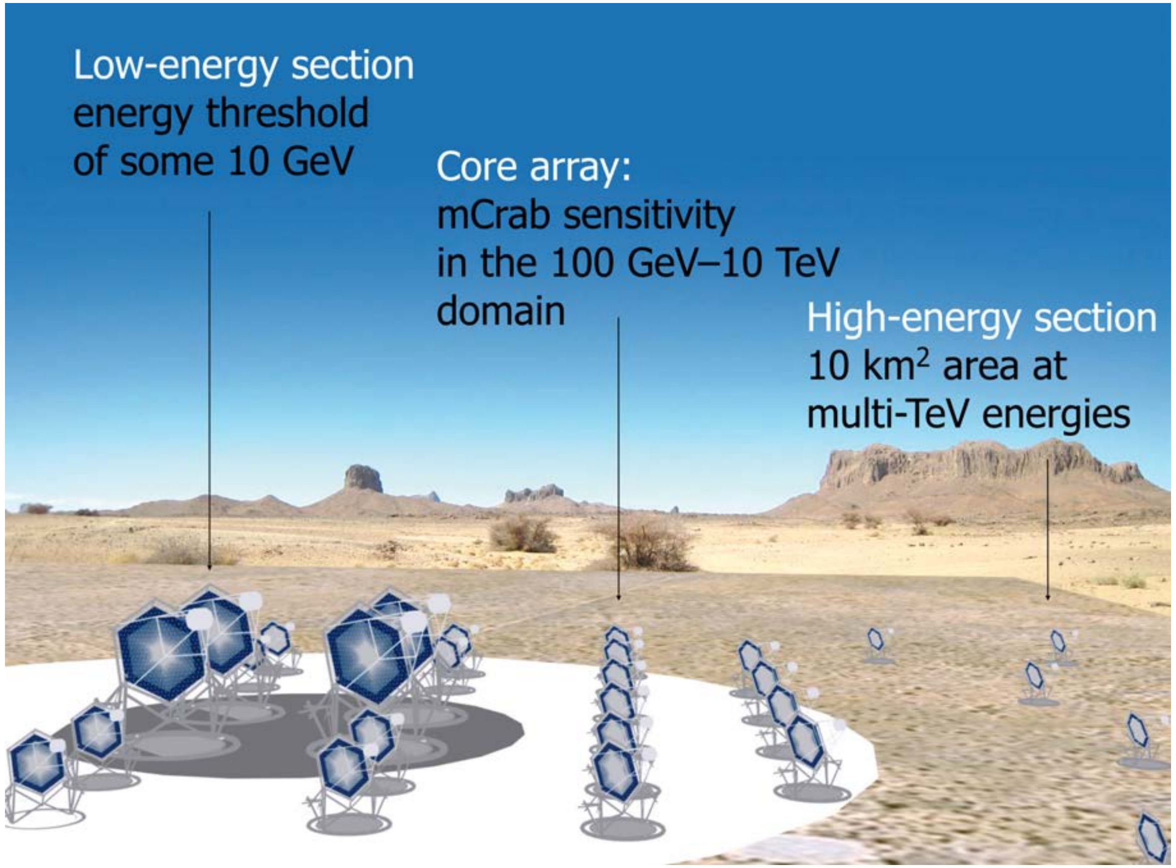


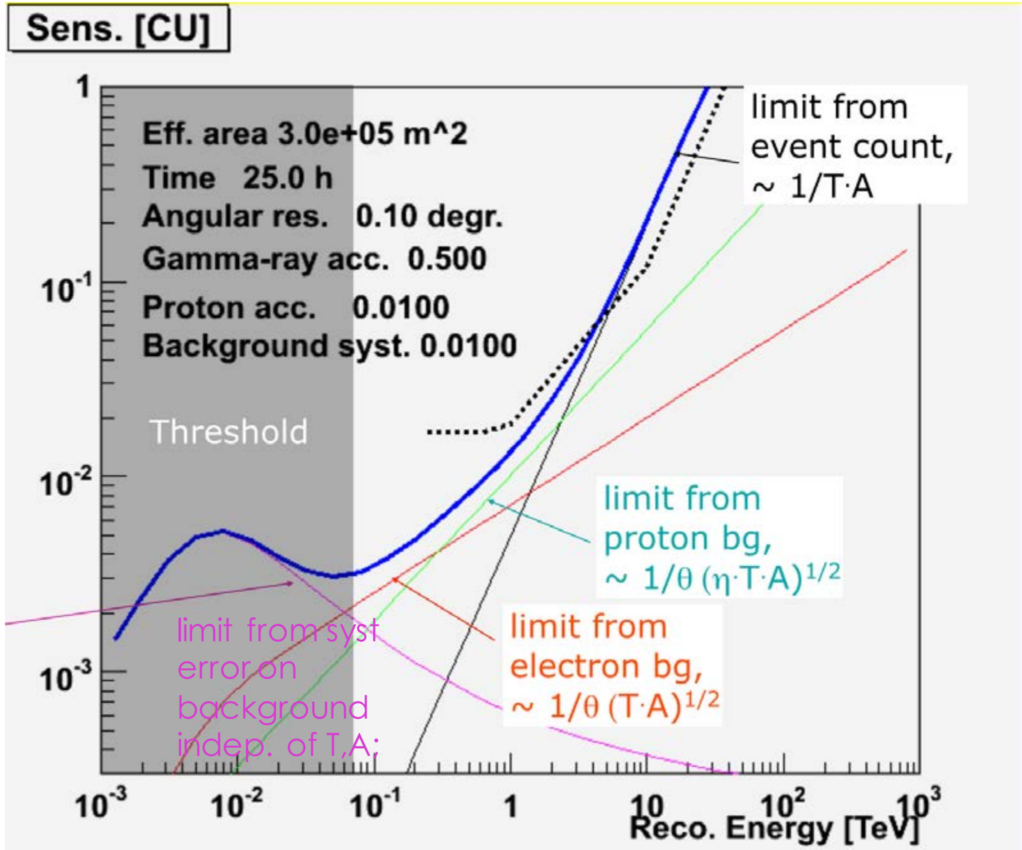
Energy Range 0.1-100 TeV
Area > 10^4 m^2
Background Rejection > 95%
Angular Resolution 0.3° - 0.7°
Aperture > 2 sr
Duty Cycle > 90%

Future of IACT: CTA

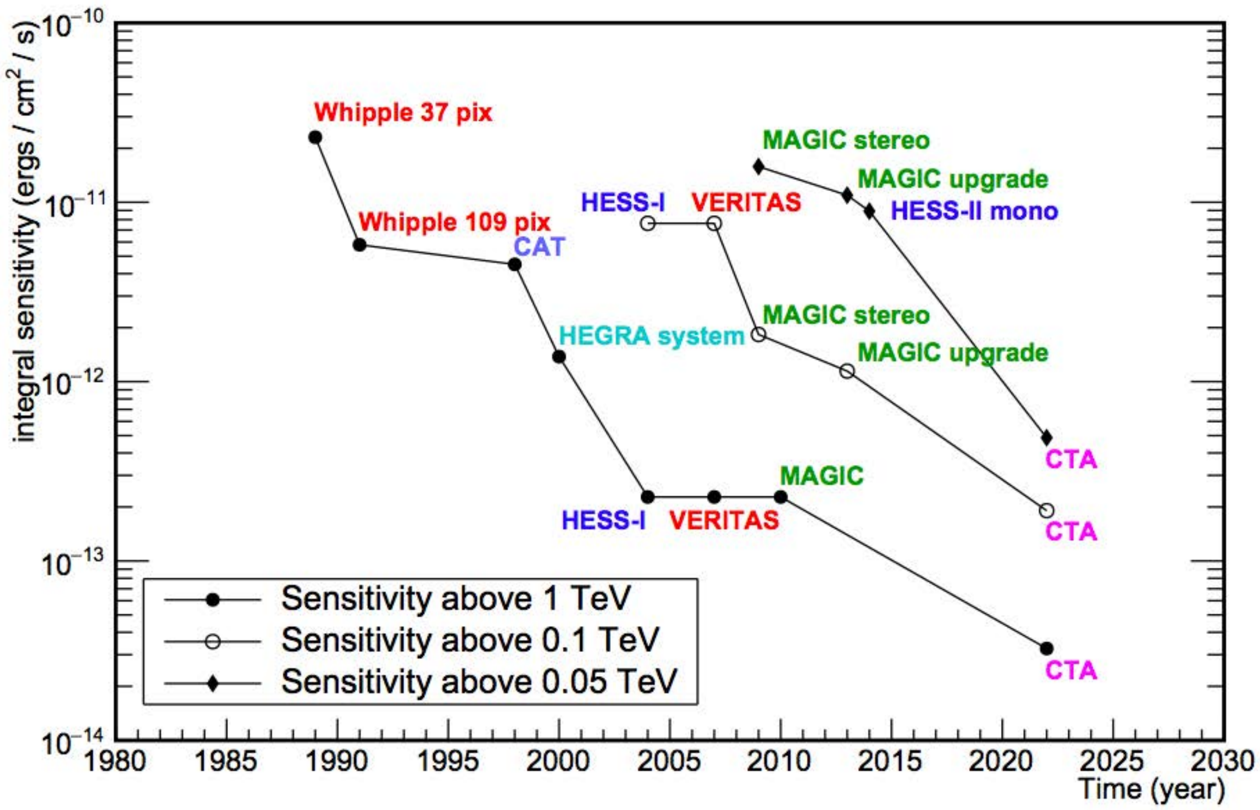


Future of IACT: CTA





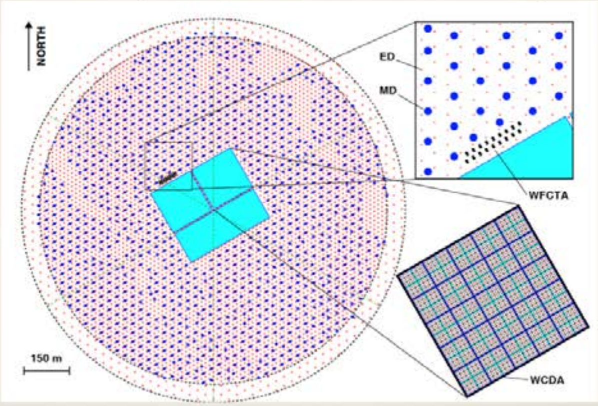
Future of IACT: CTA



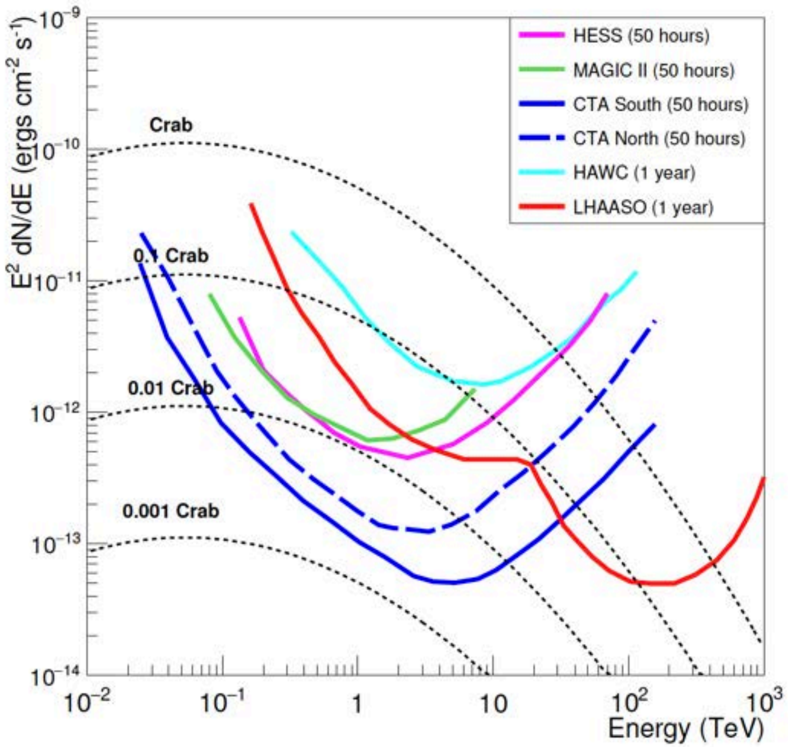
Future of shower front detector

LHAASO

- 1 km^2 array, including 4941 scintillator detectors 1 m^2 each, with 15 m spacing.
- An overlapping 1 km^2 array of 1146, underground water Cherenkov tanks 36 m^2 each, with 30 m spacing, for muon detection (total sensitive area ≈ 42,000 m^2).



- A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m^2.
- 18 wide field-of-view air Cherenkov (and fluorescence) telescopes (for CR studies).
- Total cost: ~ 100 M$



Future of shower front detector

Go South…

- With a wide FoV gamma-ray observatory on the Northern hemisphere, now the question of one at the Southern hemisphere is opened.
- There are several groups around the world proposing different techniques to be used in this kind of experiment.
- All of them coincide in the idea of going to an altitude of 5000 - 5500 m.

Future of shower front detector

HYBRID DETECTORS

LATTES

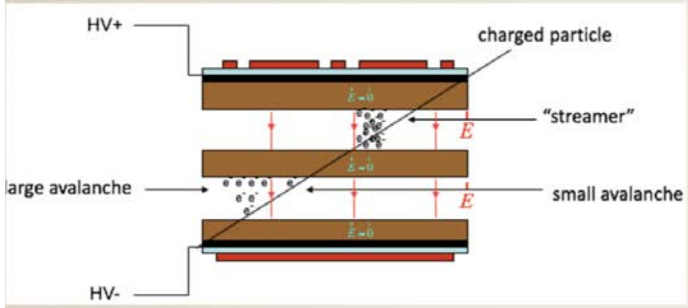
- Large Array Telescope to Tracking Energetic Sources.
- Portugal, Brasil, Italy.

- Expected coverage: 10 000 m^2

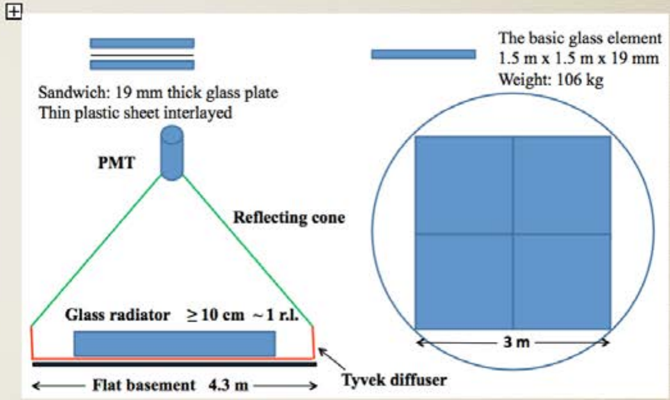
- Performance expectations:
  - Angular resolution:
    - 0.5 deg @ 1 TeV
    - 0.1 deg @ 10 TeV
  - Energy range: above 100 GeV

LATTES

RPC + Electromagnetic detector

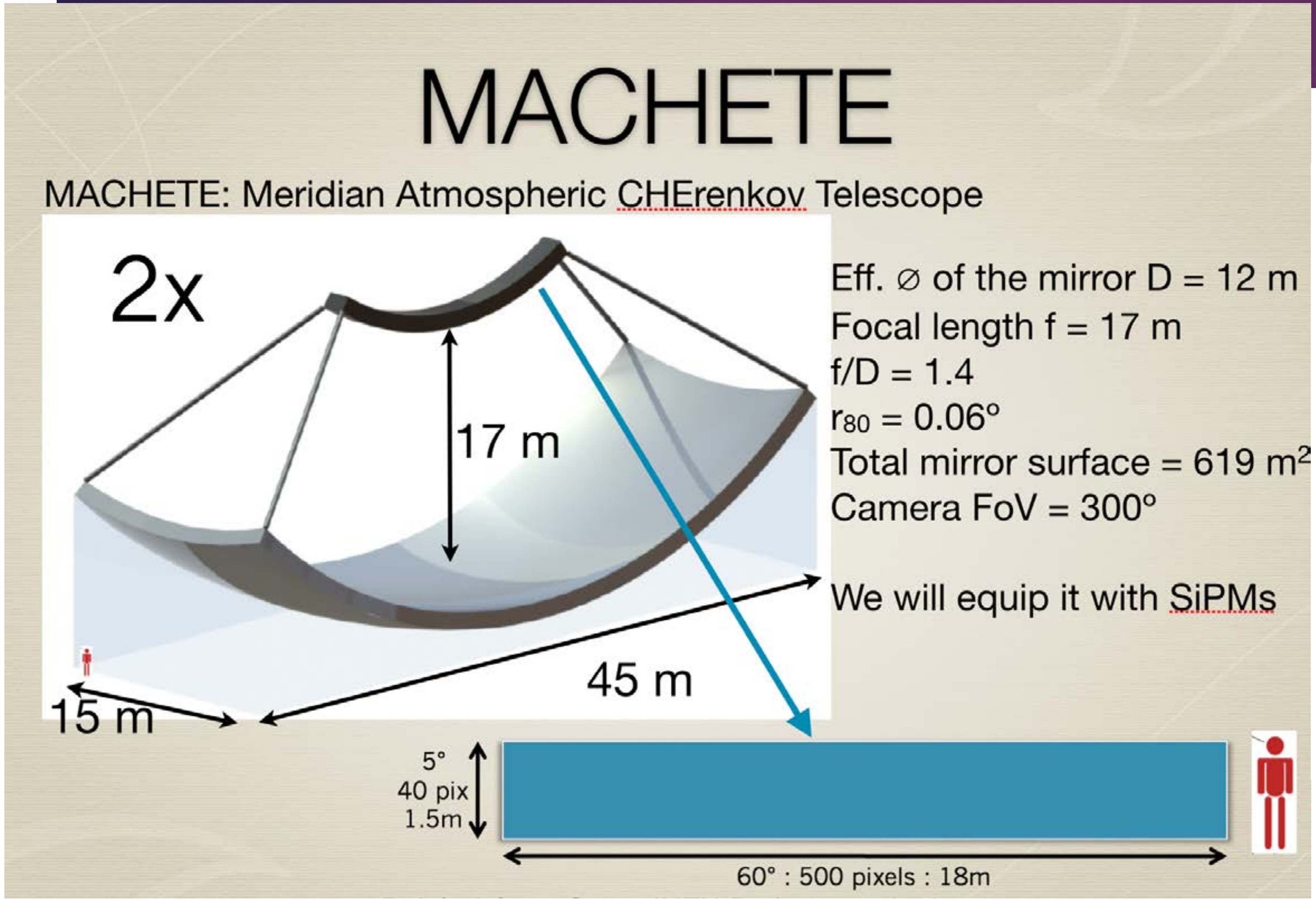


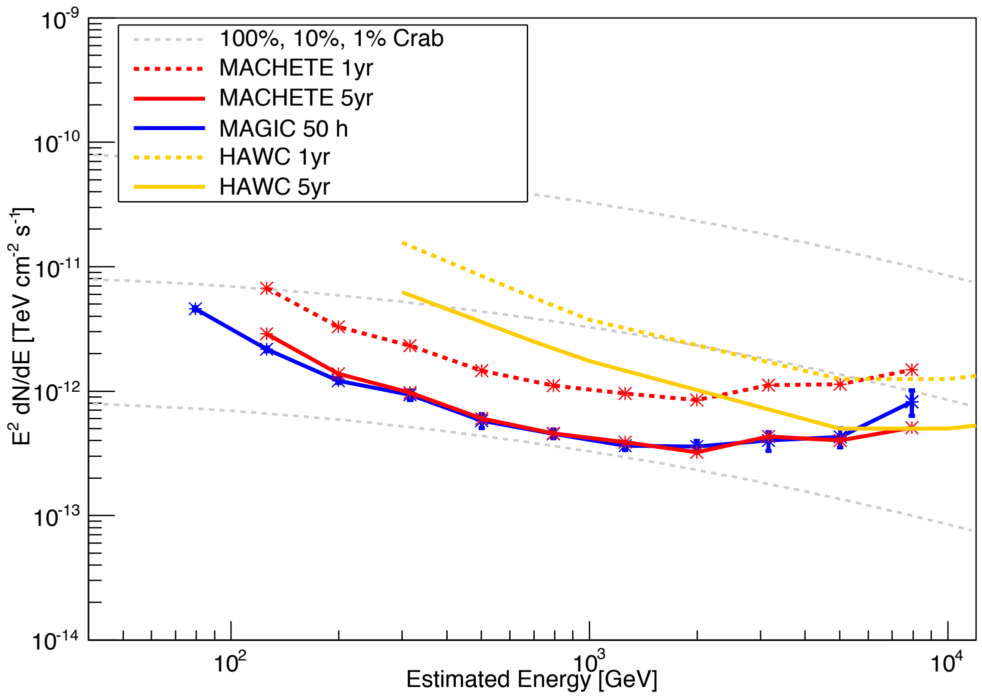
Particle counter already used in the Auger experiment



Using ultra-clear float glass as radiator (or water)

Novel ideas on IACT Wide FoV





Discussion

- Ground based gamma ray astronomy can profit of a **very large effective area** which is a fundamental parameter for the **HIGH energy** range.

- IACT have the **best angular and energy resolution**, **lower energy threshold** however **small field of view** that makes such technique (at present stage) not very suitable for survey or transient search (need to be guided/alerted)

- Shower front particle detectors have **wide field of view** and **great duty cycle**, however they suffer from **poor energy resolution and angular resolution**

- Novel Ideas of moderate wide FoV optical design IACT might be a good compromise very sensitive instrument for transient search and catalog of the VHE gamma ray sky.