Rivelazione da terra di fotoni di alta energia

con tecnica Imaging Atmospheric Cherenkov

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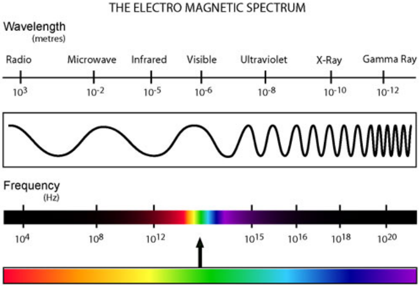
The γ–ray region of the Electromagnetic Spectrum

The electromagnetic spectrum can be split into bands.
The edges of the bands are loosely defined, and mostly driven by a mix of historical reasons and differences in detection techniques.



Gamma–rays: $h\nu \geq \; m_e c^2 \simeq 0.5$ MeV

HE band: $h\nu \leq$30 GeV VHE band: 30 GeV $\leq h\nu \leq$ 30 TeV

Everything begins when ....

Early after the discovery of natural radioactivity (Becquerel 1896, Nobel Prize in 1903) investigation on it's causes began.

In 1912, Victor Hess with a series of balloon–borne experiments, revealed that the level of natural radioactivity increased with height in atmosphere.

He inferred that some highly penetrating, unknown radiation of high energy coming from the space was the origin of this.

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Cosmic–rays

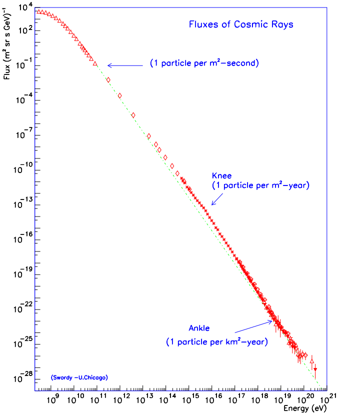
The Earth is bombarded by high energy particles originated in the space.

The composition of this particle flux is largely dominated by protons and heavier nuclei (~ 98 %), while electrons and photons together account for ~ 2 %.

The spectrum is clearly non thermal, but follows a power law

$$F(E) \propto E^{-\alpha} \quad , \quad \alpha \sim 2.7 \tag{1}$$

The spectrum spans more than 10 decades, from 10^{-1} GeV to 10^{11} GeV, and the power index is slightly changing with energy.



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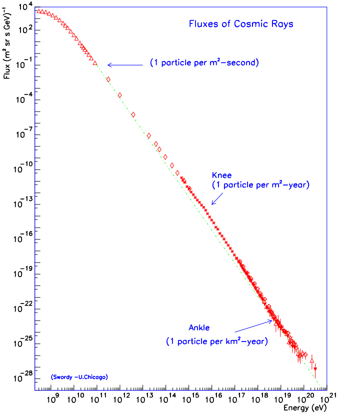

Questions

- Where do cosmic–rays originate?

Already Hess could exclude that the Sun played a major role as source of cosmic–rays, as he performed again his experiment during a solar eclypse without noticeable effect on the results.

- How do cosmic–rays originate?

Some mechanism for producing high energy particles is at work, possibly involving plasmas, magnetic fields .... a dare to astrophysics, plasma physics... with many feedbacks also on fundamental physics.

What we know now, is that many different sources (GRB, AGN, SNR, pulsars) produce high energy particles, and other can be speculated (Huge/dense environments, Dark Matter)

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High–Energy Astronomy with High–Energy Photons

The neutral photons travel across space without being deflected in the magnetic fields that permeate it

$$\longrightarrow$$

Determination of their arrival direction allows localization of the source

$$\longrightarrow$$

- A γ–ray map of the sky can be built
- Single sources can be studied in detail

This poses the problem of discriminating the neutral photons from the dominating charged component, here considered as an undesired, and strong background.

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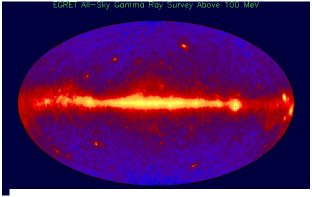
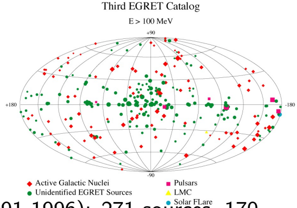
CGRO/EGRET ant it's view of the HE γ–ray sky

- Spark Chamber Tracker + Calorimeter + Anticoincidence
- Effective Area: 1000 cm^2 between 100 MeV and 3 GeV
- Energy Range: 20 MeV–30 GeV
- Energy Resolution: $\sim$20–25%
- FOV: Opening angle 45°
- Angular resolution: 0.5° at 5 GeV, 5.5° at 100 MeV on axis; worse above 30°
- Position accuracy: 10' for bright s.
- Timing accuracy: 50 μs

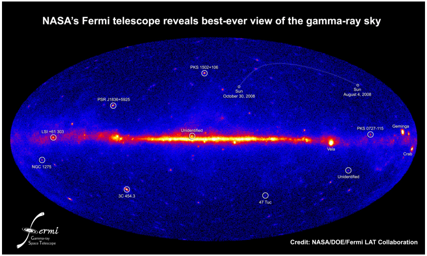




3EG (1991-1996): 271 sources, 170 unident. 5 Pulsar, 66(+27) blazars, CenA(RG), LMC, 1 Solar Flare

FERMI–LAT and it's view of the HE γ–ray sky

- Launched in June 2008
- Tungsten conversion foils, silicon strips for tracking
- FOV: 120° wide: ∼20% of the sky
- Full sky coverage every 3 hours
- Energy range: 20 MeV – 300 GeV
- PSF (68% cont. radius): ∼3° at 100 MeV, 0.04° at 100 GeV
- Effective area: 7000 cm^2 at 1 GeV
- ∼ 30 times better sensitivity than EGRET


NASA's Fermi telescope reveals best-ever view of the gamma-ray sky

Credit: NASA/DOE/Fermi LAT Collaboration

After 11 months 1FGL: 1451 sources.

After 2 years 2FGL: 1888 entries.

Pros & Cons of space–borne Gamma–ray instruments

Pros	**Cons**
Detect γs directly	Highly expensive
Not prone to metereology	Cannot be repaired
Can operate 24h/day	Small Effective Area

So, how can γ–rays be observed fron the ground.... if the atmosphere is opaque at wavelenghts below $\sim 3500\ \mathring{A}$?

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Atmosphere: density and total path lenght

Assuming idrostatic pressure and isothermal atmosphere the *barometric* formula can be derived:

(ρ_0, $x_0 \equiv$ at sea level)

$$\rho = \rho_0 exp(-x/x_0) \tag{2}$$

with

$$\rho_0 = 1.35 \text{ kg m}^{-3} \quad x_0 \simeq 7.25 \text{ km} \tag{3}$$

Total path lenght in atmosphere:

$$l_x = \int_\infty^x \rho dx = \int_\infty^x \rho_0 \exp(-\frac{x}{x_0}) dx \tag{4}$$

$$= \rho_0 x_0 \exp(-\frac{x}{x_0}) = 10000 \exp(-\frac{x}{x_0}) \text{ kg m}^{-2} \rightarrow l_0 = 10000 \text{ kg m}^{-2} \tag{5}$$

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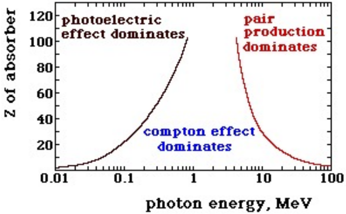
Interaction of High Energy Photons

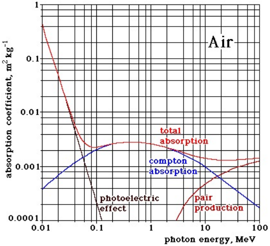
Photons interact in three ways with matter:

- photoelectric absorption
- Compton scattering
- pair production (h$\nu > 2m_ec^2$)

The dominant one at higher energy (our range of interest) is the latter.



(Hillier 1984)



Electromagnetic shower in atmosphere: developement

$$\gamma + \gamma' \rightarrow e^+ + e^-$$

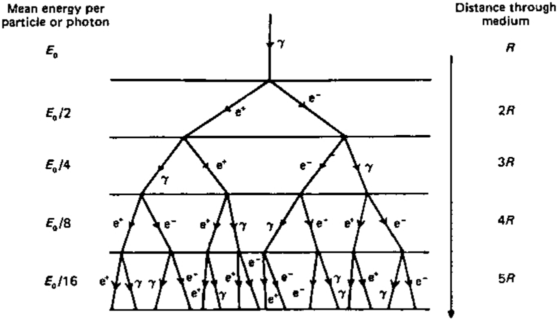
and in turn leptons radiate by bremsstrahlung

$$e^\pm + \gamma^* \rightarrow e^\pm + \gamma$$

In the ultrarelativistic limit

$$\xi_{pair} \approx \xi_{brems} \tag{6}$$

Moreover, we assume that the energy is halved at each branching
This process is purely electromagnetic: no nuclear interactions at play



After n radiation lenghts, 2^n particles with $E = E_0/2^n$
Roughly e^+, e^- and γ are equally represented

Developement of showers

- Maximum developement, around critical energy E_c (83 MeV in air)
- This happens after $n = ln(E_0/E_c)$ radiation lenghts.

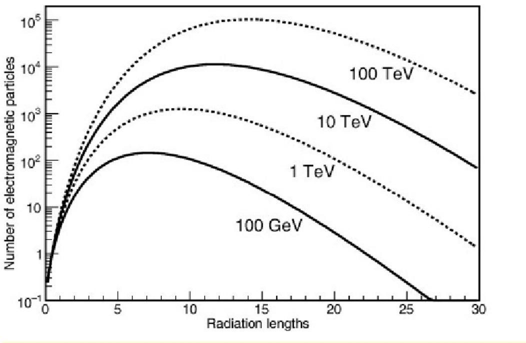
$$\xi_0 \equiv \rho \cdot R_0$$

$$\xi_0 = 365 \text{ kg m}^{-2} \quad \text{in air}$$

  At sea level $R_0^{brems} = 280$ m
- Products are now $N \simeq E_0/E_c$

After the maximum:

- Leptons start to ionize atoms, rather than radiate
- Photons give up producing pairs: photoelectric, Compton



(Adapted from Rossi & Greisen 1941)

With increasing energy, the maximum grows and digs into atmosphere

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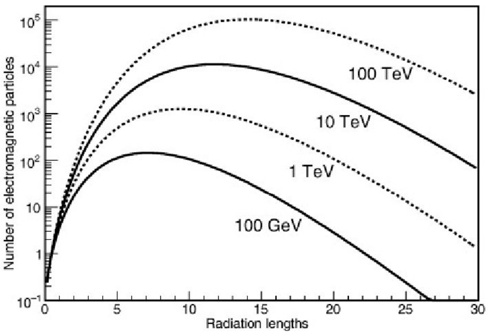

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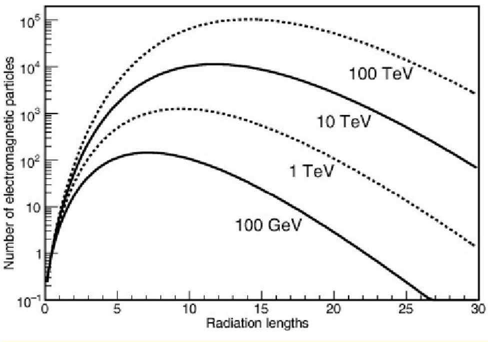

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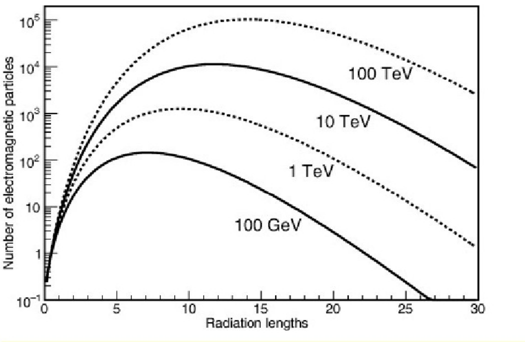

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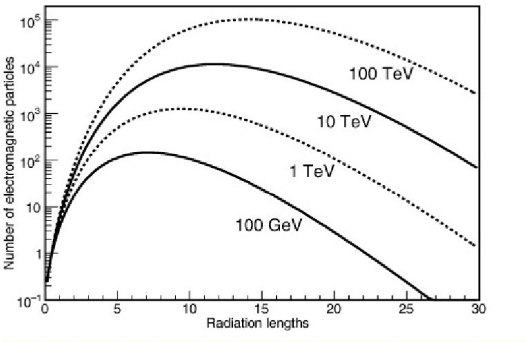

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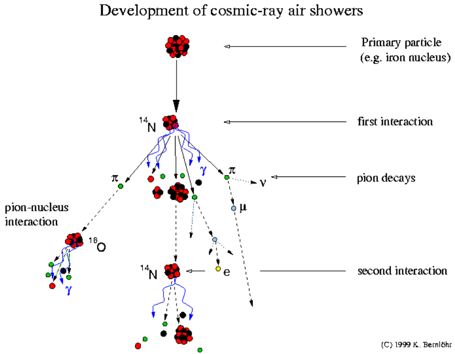
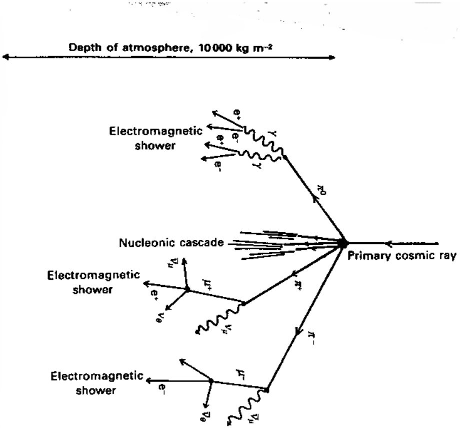
Nuclear interaction of high energy protons and heavier nuclei

- Interact with nucleons, producing mainly $\pi^{\pm}$, π^{0}; but strange particles or antinucleons as well
- nucleons and pions emerge with high energy
- Pions can emerge with relevant transverse momentum of the order $m_\pi c \approx$ 100–200 MeV c^{-1}
- Secondary particles can interact within the same nucleus (mini-cascade)
- 1–2 nucleons can be freed → nuclear decay → spallation fragments
- Above 1 GeV a proton of energy E (in GeV) produces $\sim E^{\frac{1}{4}}$ charged particles
- At small energy π^{+} are favoured products (charge conservation)



Nucleonic cascades in atmosphere

- Mean free path for interaction ~ 800 kg m^{-2}
- Scale lengh of decaying proton flux $\sim$ 1200 kg m^{-2} (they can survive interaction)
- Energetic secondary nucleons & $\pi^{\pm}$ $\rightarrow$ more generations until $\langle E \rangle \simeq 1$ GeV (no more multiple π prod.)
- Secondary protons lose energy by ionization; those at 1 GeV go at rest
- $\pi_0 \rightarrow 2\gamma$ rapidly ($\tau = 1.78 \times 10^{-16}$ s) $\rightarrow$ EM shower
- $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\tau = 2.551 \times 10^{-8}$ s



Muons

Muons:

- almost **do not** interact nuclearly;
- $m_\mu \sim 207 m_e \to$ bremsstrahlung inefficient;

$\to$

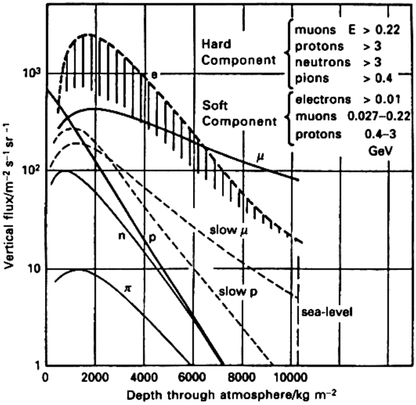
- ionization losses
- EM decay:

$\mu^+ \to e^+ + \nu_e + \bar{\nu_\mu}$, $\tau = 2.2 \times 10^{-6}$ s $\to$ secondary EM shower.

If they are enough Lorentz–boosted ($\gamma \geq 20$) in the observer frame this gets longer than the travel time through atmosphere.

. The first pions in the high atmosphere, produce energetic $\mu^\pm$, that reach the ground.

$\to$ “muon Cherenkov rings”



(Hillas 1972)

The Cherenkov Effect

According to special relativity the speed of light *in vacuum* c is a universal constant for all the inertial observers.

c also the asymptotic speed limit for motion of any massive particle (except for OPERA ν_μ perhaps...).

In a dielectric of refractive index n, photons travel at $\frac{c}{n}$, and *superluminal* motions are possible.

EM perturbation induced by a *charged* particle polarizes the dielectric. Equilibrium is restored emitting photons, that are summed coherently if the perturbation travels across the medium faster than light.

This gives rise to *Cherenkov radiation*.

Although foreseen by Oliver Heaviside already in the late XIX century, it was first observed by Pavel Cherenkov (1934) and theoretically developed by Ilia Frank and Igor Tamm (1937).

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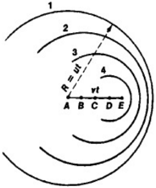
The Cherenkov threshold

$$v < \frac{c}{n}$$



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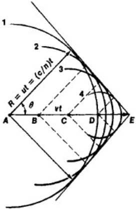


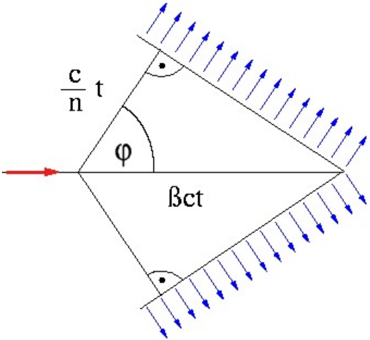
$$\beta_t \equiv \frac{v_t}{c} = \frac{1}{n}$$

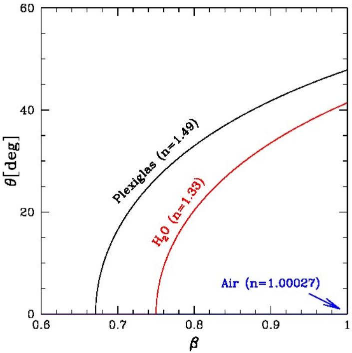
For instance:

- in plexiglas $n = 1.5 \rightarrow v_t = 0.67c$
- in water $n = 1.33 \rightarrow v_t = 0.75c$
- in air at sea level $n = 1 + 2.763 \cdot 10^{-4} \rightarrow v_t = 0.9997c$

This can be exploited for construction of threshold detectors.

Properties of the Cherenkov Cone: Aperture Angle





- Aperture angle:

$$\cos\theta = \frac{\frac{c}{n}t}{\beta ct} = \frac{1}{\beta n} \quad (7)$$

- Maximum angle:

$$\beta \simeq 1 \rightarrow cos(\theta_{max}) = 1/n \quad (8)$$

and in gases ($\theta \ll 1$; $n - 1 \ll 1$)

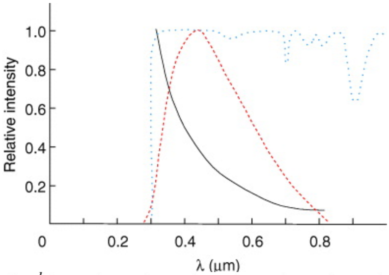
$$1 - \frac{(\theta_{max})^2}{2} = 1/n \rightarrow \theta_{max} = \sqrt{2(n-1)} \quad (9)$$

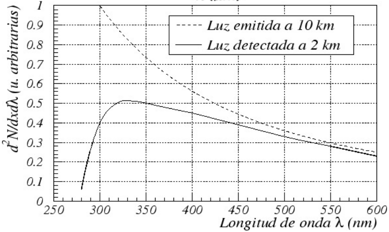
Properties of the Cherenkov Cone: Emitted Spectrum

- Intensity of emission per unit path lengh:

$$\frac{dU(\omega)}{dx} = \frac{\omega e^2}{4\pi\epsilon_0}(1 - \frac{c^2}{n^2 v^2})$$

(Frank & Tamm 1937)





Atmosphere: refractive index and energy threshold

At the Cherenkov threshold, $v/c = 1/n$

$$\gamma_t = (1 - \frac{v^2}{c^2})^{-1/2} = (1 - \frac{1}{n^2})^{-1/2} \approx 1/(2n))^{1/2}$$

$n_0 = 1 + 2.763 \times 10^{-4} \Rightarrow \gamma_t \simeq 40 \rightarrow E_t \approx 20 MeV$

In gases, $n - 1 \ll 1 \rightarrow n \approx 1 + \alpha\rho$

$$\rightarrow \gamma_t \propto \rho^{-1/2}$$

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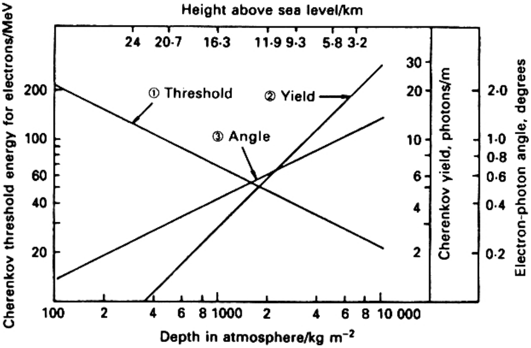
Depth–in–Atmosphere dependence of Cherenkov flash properties

- $\gamma_t \propto \rho^{-1/2}$
- $\cos\theta \approx 1 - \frac{\theta^2}{2} = c/vn \approx 1 - \alpha\rho \rightarrow \theta \propto l^{1/2}$
- $I(\omega) \propto (1 - \frac{c^2}{v^2 n^2}) \propto \rho \propto l$



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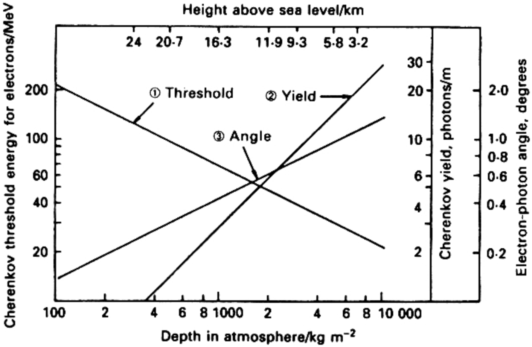

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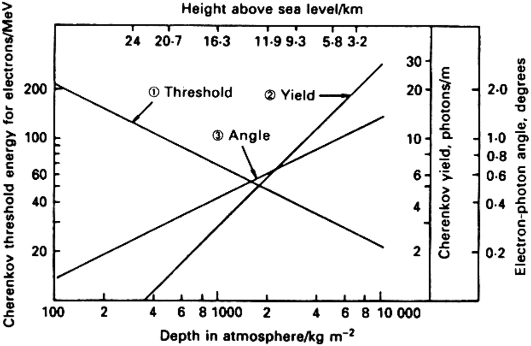

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Idea of the IACT detection tecnique

The critical energy E_c in air is 83 MeV

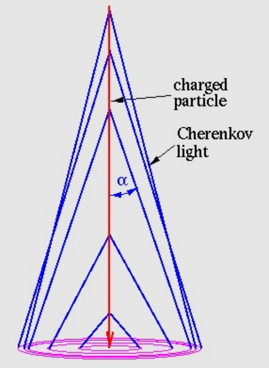
$E = 300$ GeV $\rightarrow E \approx 3.5 \times 10^3 E_c$ (particles in the shower)

Maximum developement after 7–8 radiation lenghts in atmosphere

$R \sim 365 \text{ kg m}^{-2} \rightarrow \approx 3000 \text{ kg m}^{-2}$

$\rightarrow 10\text{km}$ a. s. l.

Neither the primary nor the shower particles reach the troposphere, but the optical Cherenkov light does → can be detected by a ground–based telescope.



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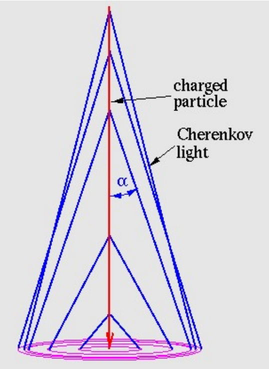

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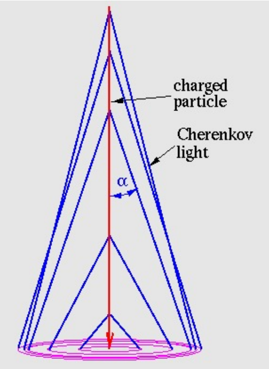

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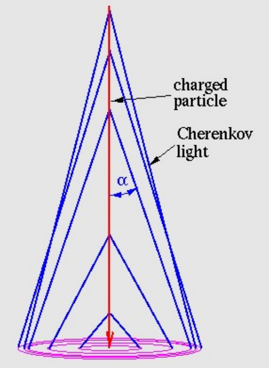

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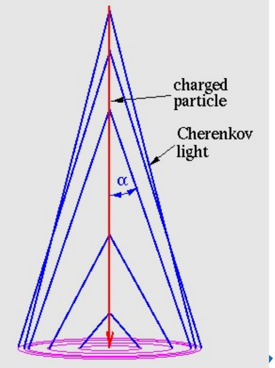

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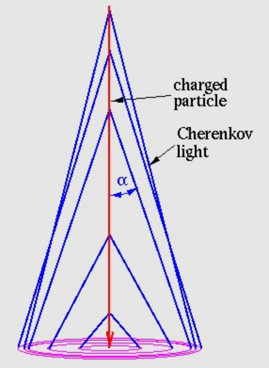

Space and time width of the Cherenkov flash

The aperture of the cone is $\sim$ 1-2° due to:

- Cherenkov angle at 10 km
- Coulomb scattering: leptons not perfectly parallel

The flash shines a wide area (R ~ 120 m) but for a very short time (few ns)

Millions of photons produced , but density $\sim$ 7 m^{-2}

Night Sky Background (stars, zodiacal light, pollution...) contributes $7 \times 10^{11}\mathrm{ph\ m^{-2}\ s^{-1}\ sr^{-1}}$

Blackett (1949): Cherenkov light emitted by cosmic rays and secondary particles contribute the 0.01 % of Night Sky Background (NSB)

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Important Remarks on IACT

- the atmosphere is part of the detector and the telescope is the final end of a huge air calorimeter
- A light collector within 120 m from the shower axis is shined by the Cherenkov signal
- Effective area is different from the area of the pupil, much greater $\sim 10^9$cm^2
- Nevertheless, it's still an asset to have a large collector (and high QE detectors) as weak flashes are more likely detected above NSB.
- The time compactness of the flashes favors **fast** integration times ($\tan \sim 10^{-9}$ s) → CCDs are not viable → PMTs

Aims of an IACT

- Detect Cherenkov flashes, above NSB
- Discriminate γ–ray induced showers form the hadronic ones
- For each survived event,
    - Reconstruct the incoming direction (to locate the position of the source in the sky)
    - Reconstruct the primary energy (to derive spectra and fluxes)

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Basics of a Cherenkov telescope

- A big mirror, to collect photons in the camera
- A camera made of photomultipliers
- A trigger system
- An analysis method

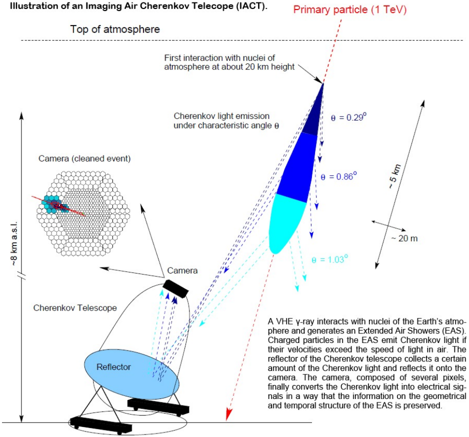

Illustration of an Imaging Air Cherenkov Telecope (IACT).

A VHE γ-ray interacts with nuclei of the Earth's atmosphere and generates an Extended Air Showers (EAS). Charged particles in the EAS emit Cherenkov light if their velocities exceed the speed of light in air. The reflector of the Cherenkov telescope collects a certain amount of the Cherenkov light and reflects it onto the camera. The camera, composed of several pixels, finally converts the Cherenkov light into electrical signals in a way that the information on the geometrical and temporal structure of the EAS is preserved.

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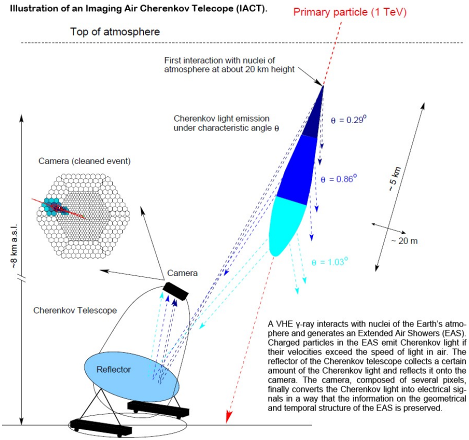

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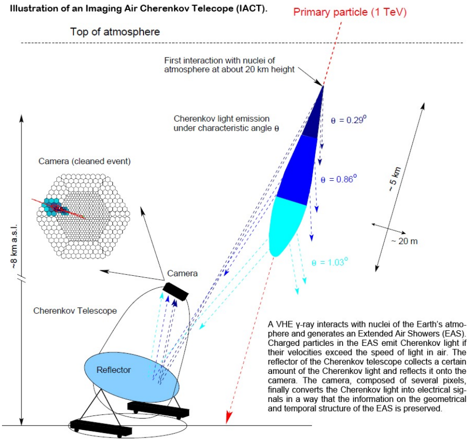

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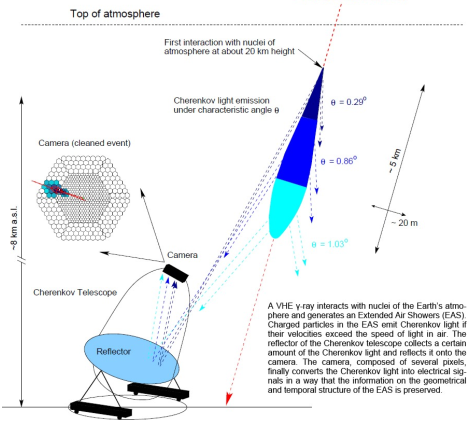

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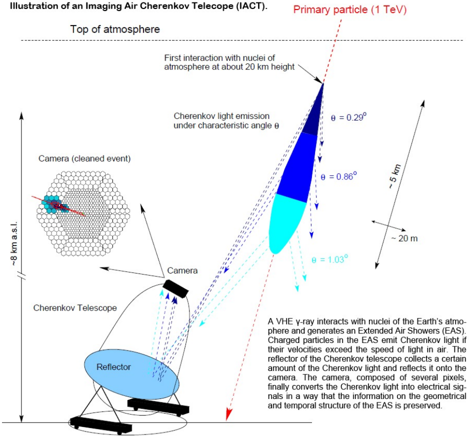
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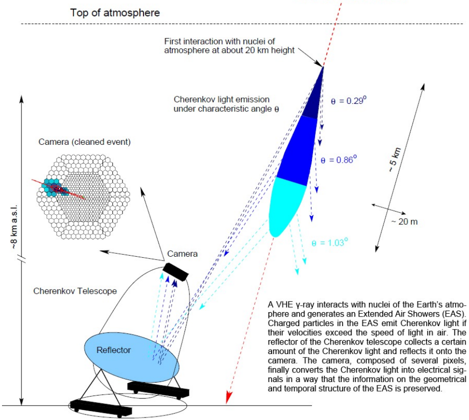
- An analysis method

Illustration of an Imaging Air Cherenkov Telecope (IACT).



A VHE γ-ray interacts with nuclei of the Earth's atmosphere and generates an Extended Air Showers (EAS). Charged particles in the EAS emit Cherenkov light if their velocities exceed the speed of light in air. The reflector of the Cherenkov telescope collects a certain amount of the Cherenkov light and reflects it onto the camera. The camera, composed of several pixels, finally converts the Cherenkov light into electrical signals in a way that the information on the geometrical and temporal structure of the EAS is preserved.

A key quantity: the energy threshold

A simple "rule of thumb" calculation can suggest what's important to go down with the energy threshold (Fegan 1997):

- N be the noise contributed by background fluctuations
- Ω be the solid angle subtended by the detector
- A the mirror area $\pi D^2/4$
- τ the electronic integration time
- η the QE of photon detectors
- ϕ the photon flux from NSB

Then: $N \propto (\Omega A \tau \phi \, \eta)^{1/2}$, $S \propto \eta A$

$$E_t \propto (S/N)^{-1} \rightarrow E_t \propto (\frac{\Omega \tau \phi}{A \eta})^{1/2}$$

Energy Threshold evolution with Zenith Angle

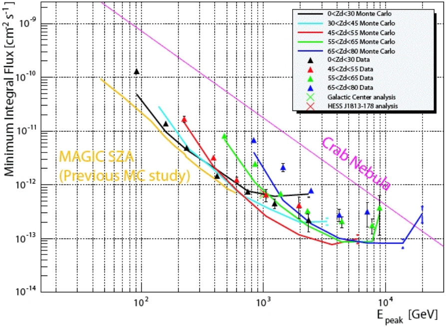
- As a rule of thumb, the energy threshold E_t increases with some power of the $\cos(\theta)$:

$$E_t \propto \cos(\theta)^{-\alpha} \qquad \alpha \simeq 2.5$$

- an exponent 2 comes from the geometrical dispersion of photons over a larger area, so that the surfacedensity is lowered
- another 0.5 comes from the increased extinction due to the longer path in atmosphere.
- Instead, again because of the increased travel in atmosphere, the collection area of the telescope is increased, thus improving the point source sensitivity

Therefore the sensitivity curves evolves with increasing zenith angle as such:

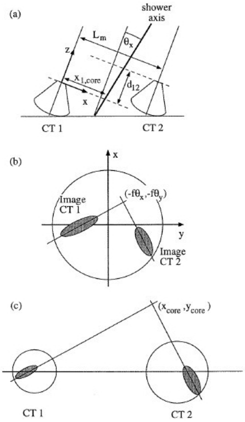
- the energy threshold increases,
- the sensitivity curve slides at lower fluxes,
- and extends to higher energies.



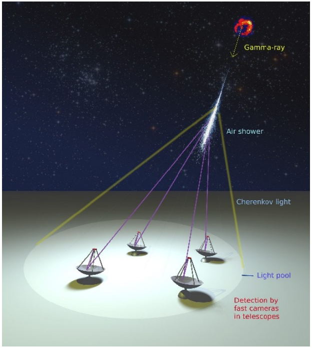
What if we use more than on telescope?

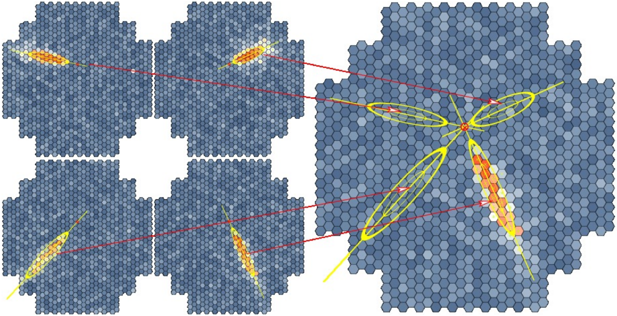
Many advantages:

- The incoming direction og the primary γ can be determined, as the crossing point of the image axes
- NSB triggers are highly depressed
- The background hadronic showers are more easily discriminated
- The production heigh of the shower is accessible, improving the energy reconstruction
- In the end the sensitivity increases significantly



Four telescopes are better than two...





(Völk & Bernlöhr, 2008)

A bit of history

Blackett (1949): Cherenkov light emitted by cosmic rays and secondary particles contribute the 0.01 % of Night Sky Background (NSB)

After this came:

- some primitive tries (a photomultiplier above a 25 cm mirror in a garbage can (Galbraith & Jelley 1953), able to detect short light pulses correlated to charged cosmic rays
- The Whipple 10 m telescope (1968) was the first large mirror reflector built for observations based on Cherenkov effect. No γ/nhadron discrimination was possible in the first implementations.
- The background of showers induced by cosmic rays is 10^3–10^4 times dominant over gamma–ray initiated showers: no TeV source could emerge over such a huge background, even if isotropically distributed.

The pioneer: Whipple

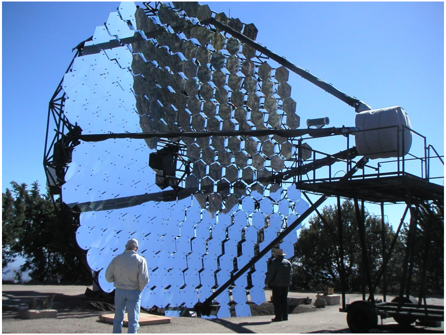
Located at F.L. Whipple Observatory
Mount Hopkins, USA

PMT Camera, with 37, then 109 pixels

First TeV Detection of Crab Nebula

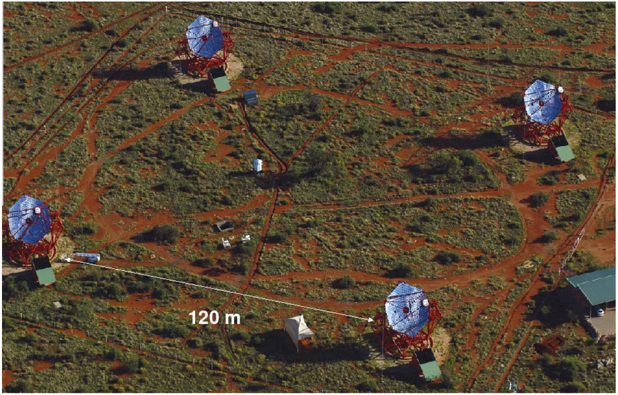
(Weekes, 1989)

Still in operation as monitoring instrument
for bright TeV emitters
(e.g. the AGN of HBL class Mrk421)



The present: HESS

- Located in Namibia (23° S)
- 1800 m a.s.l.
- 4 dishes 12 m each
- 5.0° FOV
- 960 pixels/camera
- Energy threshold ≈ 100 GeV



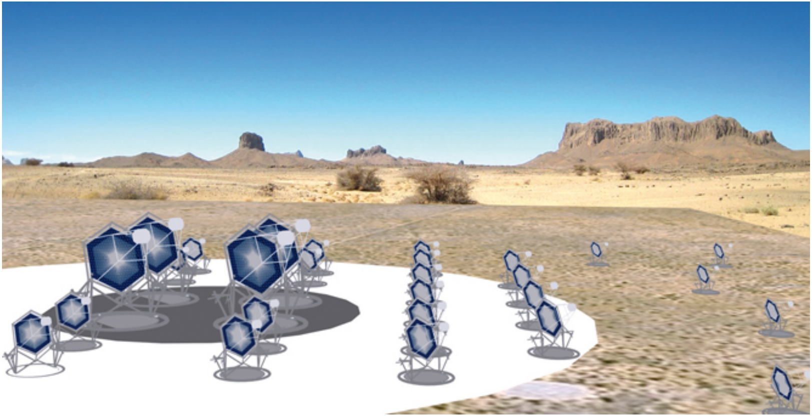
The present: VERITAS

- Located in Arizona, U.S,A (+31° N)
- 1300 m a.s.l.
- 4 dishes 12 m each
- 3.5° FOV
- 499 pixels/camera
- Energy threshold ≈ 100 GeV

The present: MAGIC II

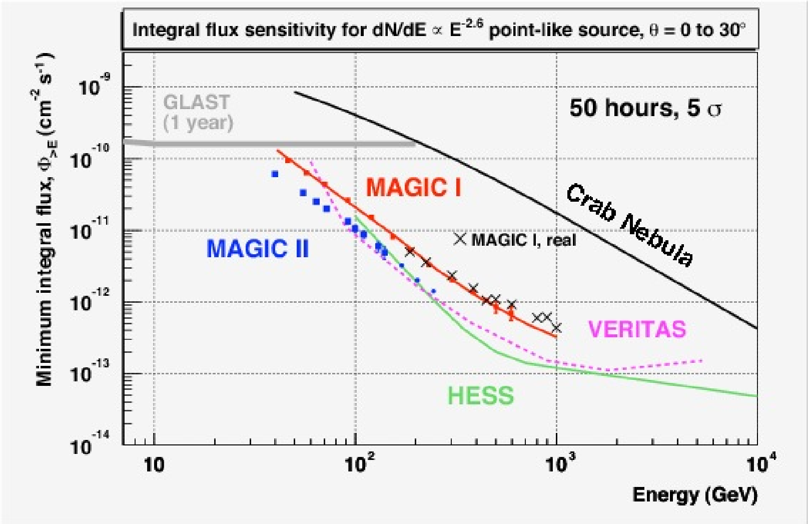
Stereo system at Canary Islands, ~ 80 m separation, camera $\sim$ 1000 pixels (upgrading M–I)

The future: Cherenkov Telescope Array (CTA)



Energy Band: 10 GeV – 100 TeV, 10 times better sens. w.r.t. present IACT, AR < 3 arcmin

Sensitivity for point sources



Crab Nebula: the VHE standard candle

- The Crab Nebula (Messier 1) is the Remnant of the 1054 A.D. SuperNova reported by Chinese astronomers.
- The remnant is a bright source of VHE photons, and the first detected , by WHIPPLE (Weekes et al. 1989)).
- It's believed to emit with the SSC mechanism
- Integral VHE Flux: $F_{E\,>\,200\mathrm{GeV}} \simeq 2 \times 10^{-10}\ \mathrm{ph/cm^2 s}$
- For MAGIC I, this "bright" flux level means $\sim 5\ \ \gamma/$ minute ...