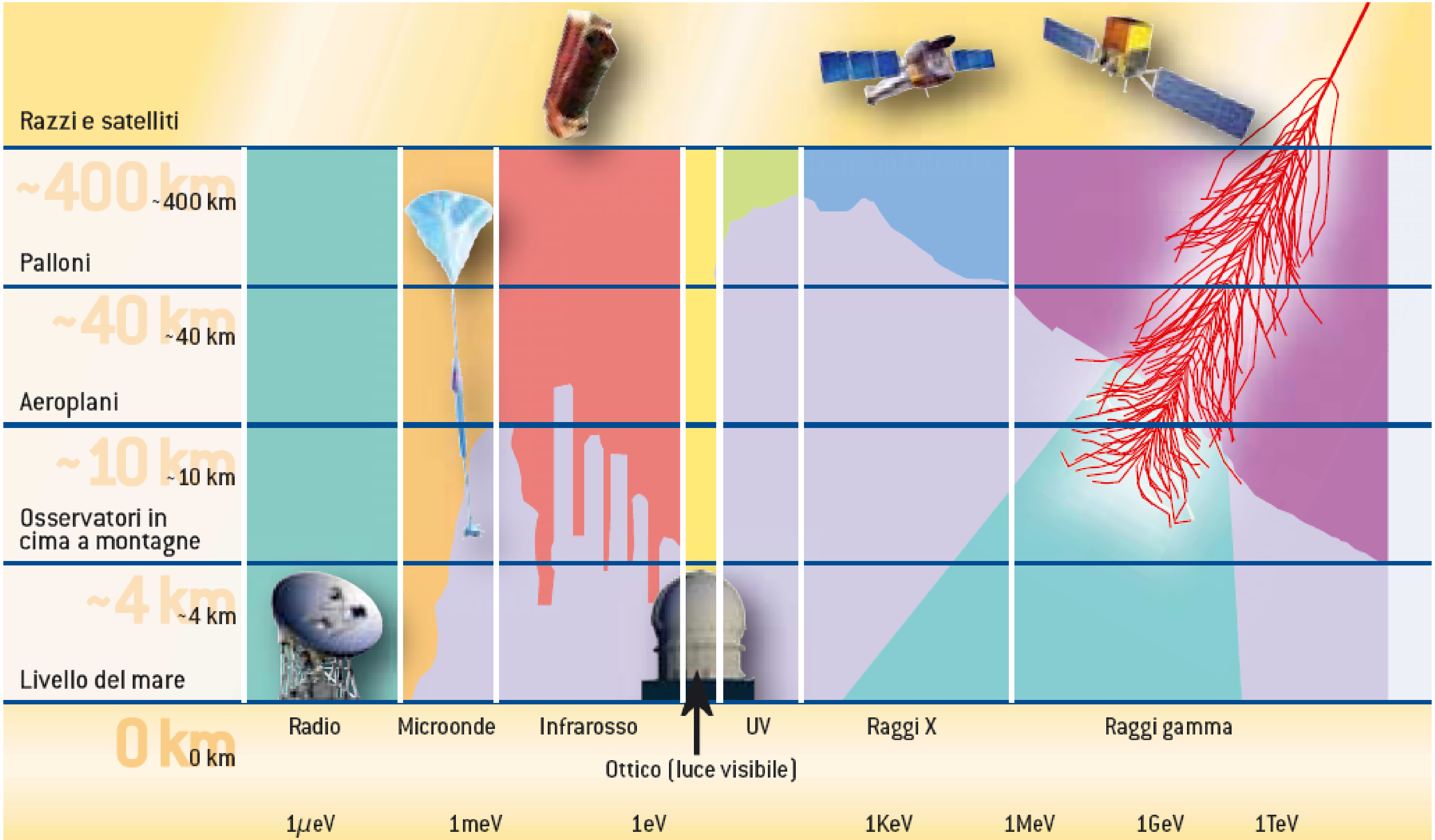
# Astrofisica Nucleare e Subnucleare

## TeV Astrophysics

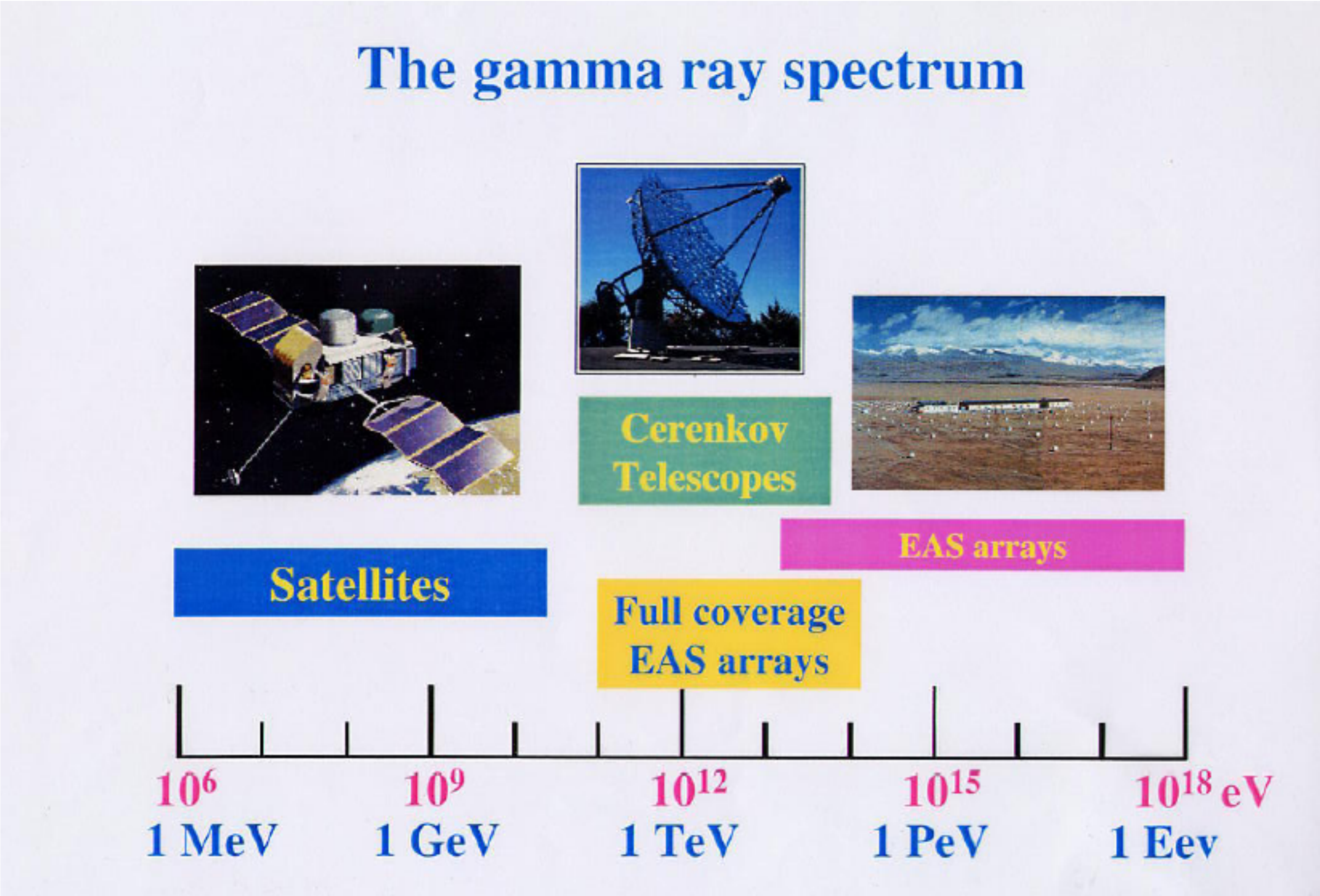
# Exercise #6

- Find the information about the 3 major currently operating IACT telescopes
- Visit the web site of CTA

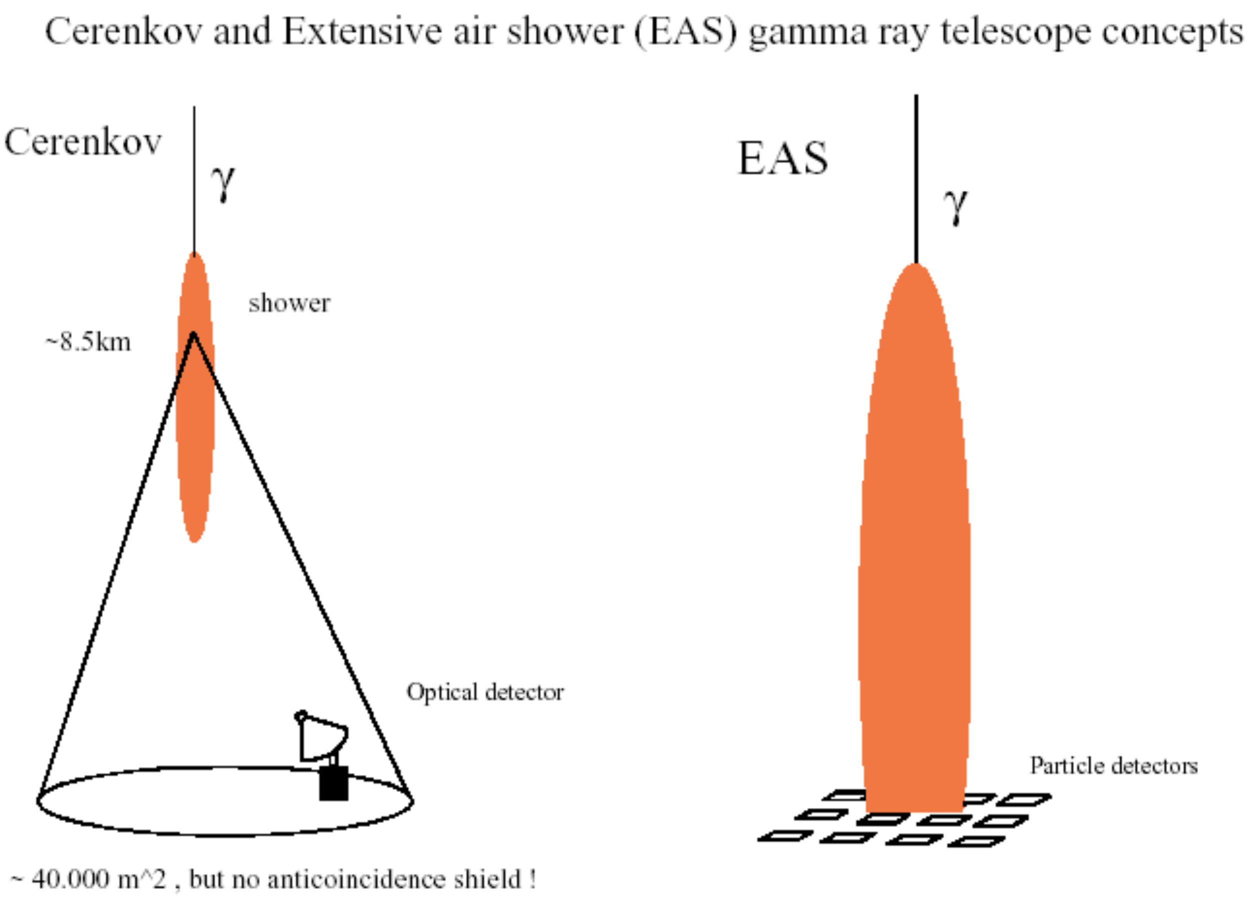
# The opacity of the atmosphere



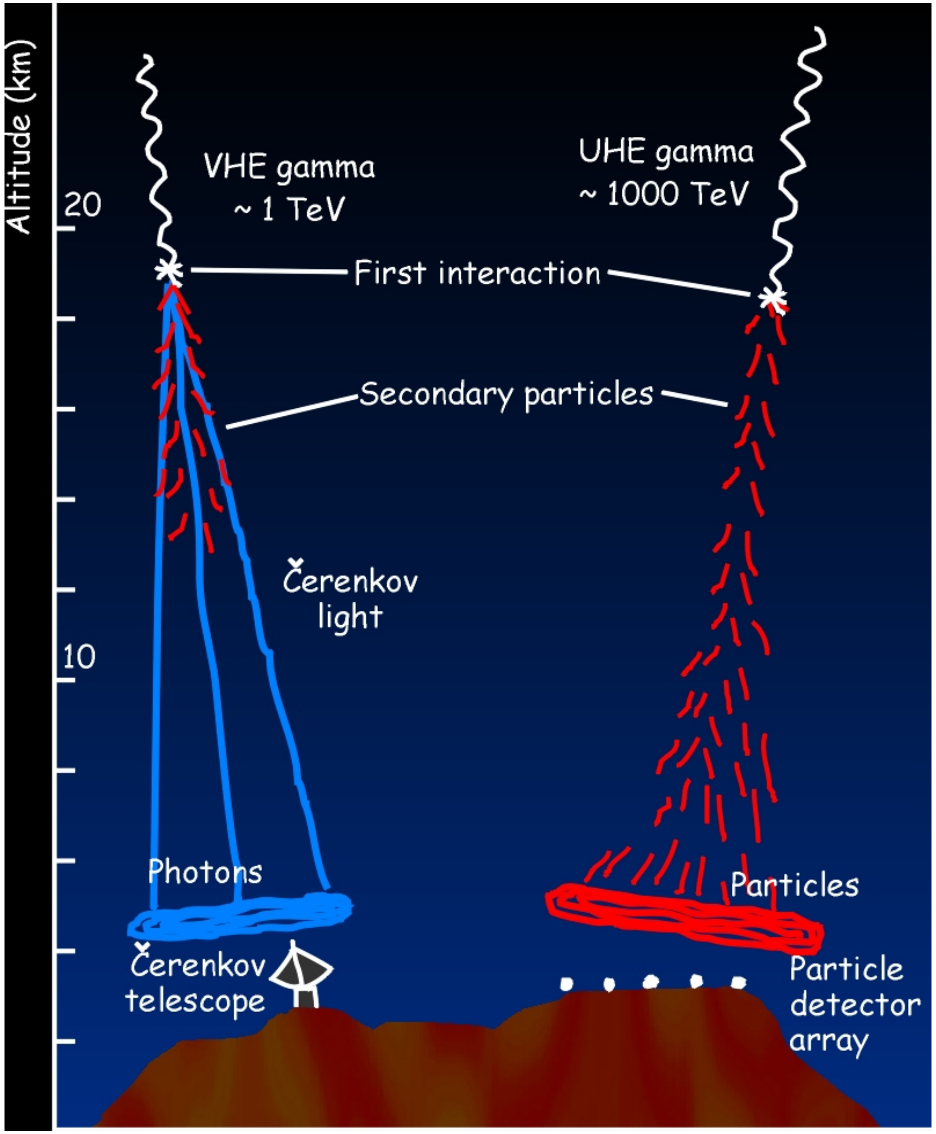
# TeV detectors



# TeV detectors



# IACT & EAS experiments




- Cherenkov experiments consist of almost-optical telescopes devoted to detect Cherenkov light.
- EAS (Extensive Air Shower) experiments are huge arrays or carpets of particle detectors.
- Cherenkov experiments have lower energy thresholds, but also a lower duty-cycle as well as a smaller field of view.

# Complementary Capabilities

| Parameter | Ground-based | | Space-based |
|---|---|---|---|
| | **ACT** | **EAS** | **Pair** |
| **angular resolution** | good | fair | good |
| **duty cycle** | low | high | high |
| **area** | large | large | small |
| **field of view** | small | large | large & can repoint |
| **energy resolution** | good | fair | good w/ smaller systematic uncertainties |

**The next generation of ground-based and space-based facilities are well matched!**

# EM Air Showers

## Air shower development

- Pair production $I = I_0 e^{-x/\lambda}$

  $\lambda$ = mean free path

- Bremsstrahlung $E = E_0 e^{-x/\chi_0}$

  $\chi_0$ = radiation length

In the ultra-relativistic limit $\lambda \sim \chi_0 = 36.5 \text{ g/cm}^2$ in air

$R = \chi_0 \ln 2$ $\Rightarrow$ After a distance $nR$ :

$N_{e,\gamma} = 2^n$ $E_{e,\gamma} \sim E_{pr} / 2^n$

# EM Air Showers

The process continues until the electrons energy is $E > E_c$

$E_c$= critical energy = 83 MeV in air

Number of particles at the shower maximum:

$N_{max} = 2^n = E_{pr} / E_c$

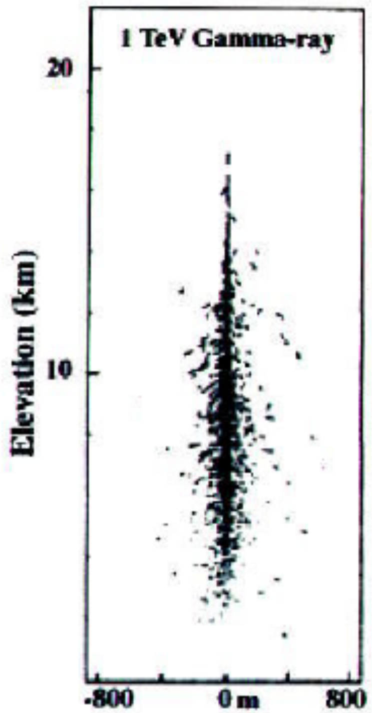
Depth of the maximum:

$n_{max} = \ln (E_{pr} / E_c) / \ln 2$

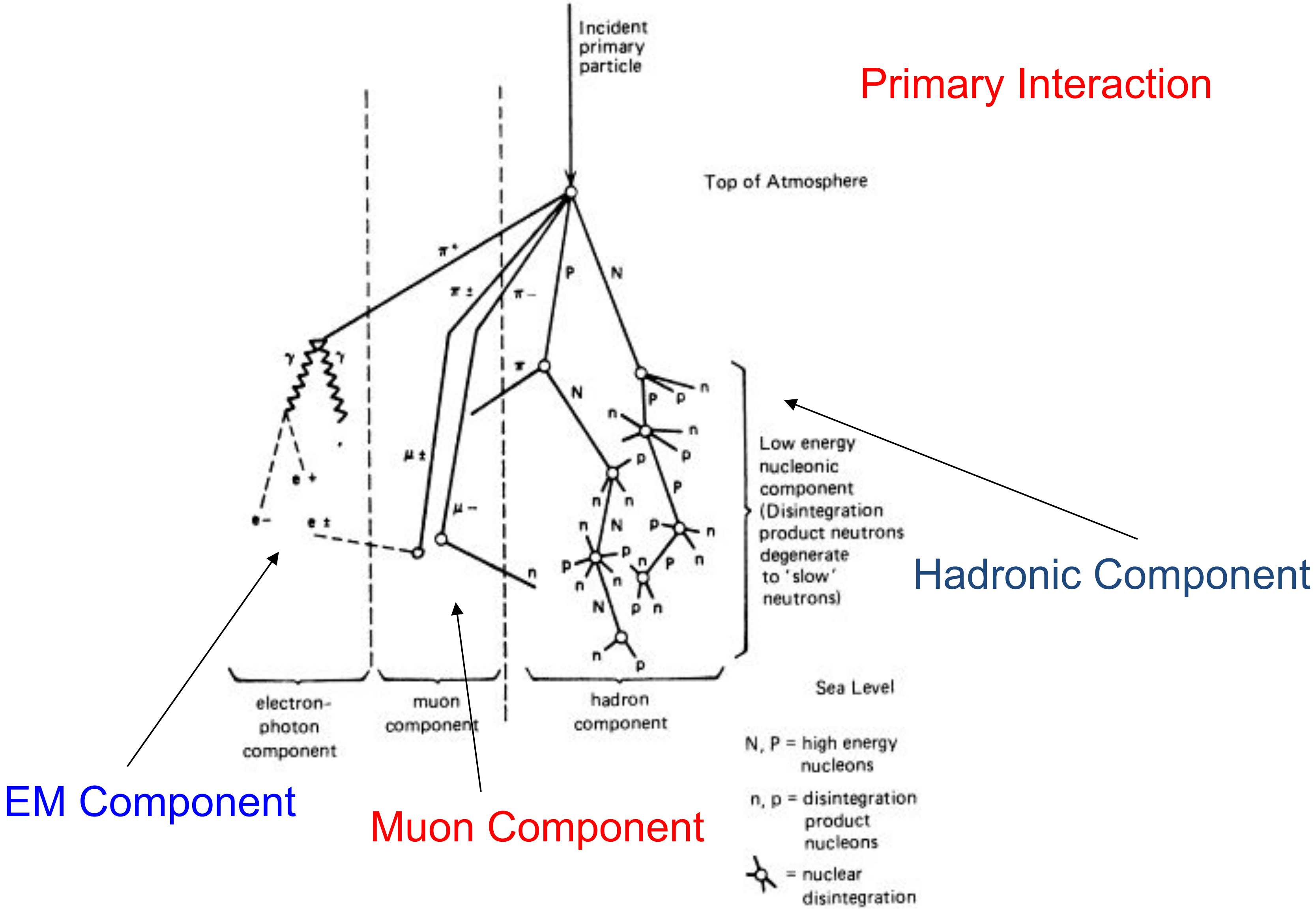
$\Rightarrow X_{max} = n R = n \chi_0 \ln 2 = \chi_0 \ln (E_{pr} / E_c)$

Example: $E_{pr} = 1$ TeV

$\Rightarrow X_{max} = 340$ g / cm² ~ 8 Km



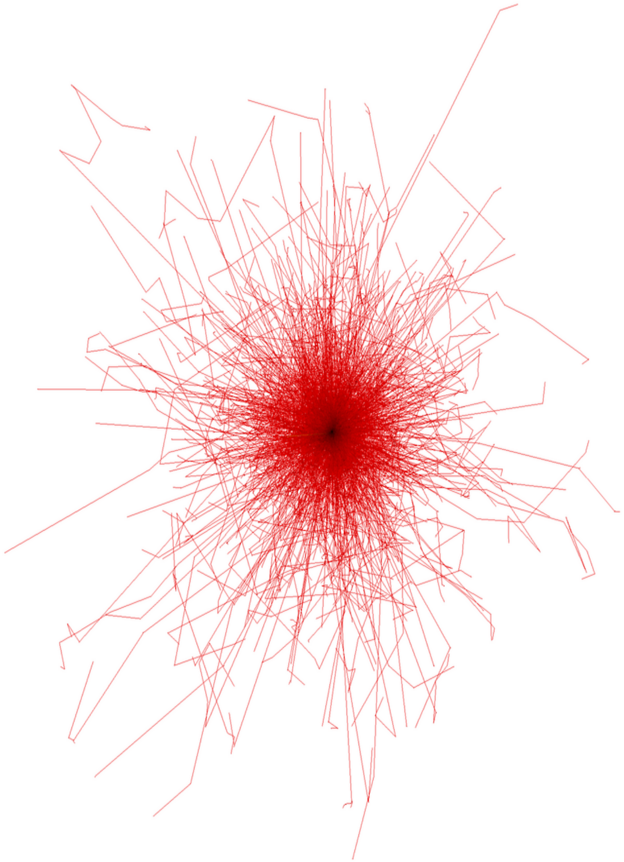
# CR interactions

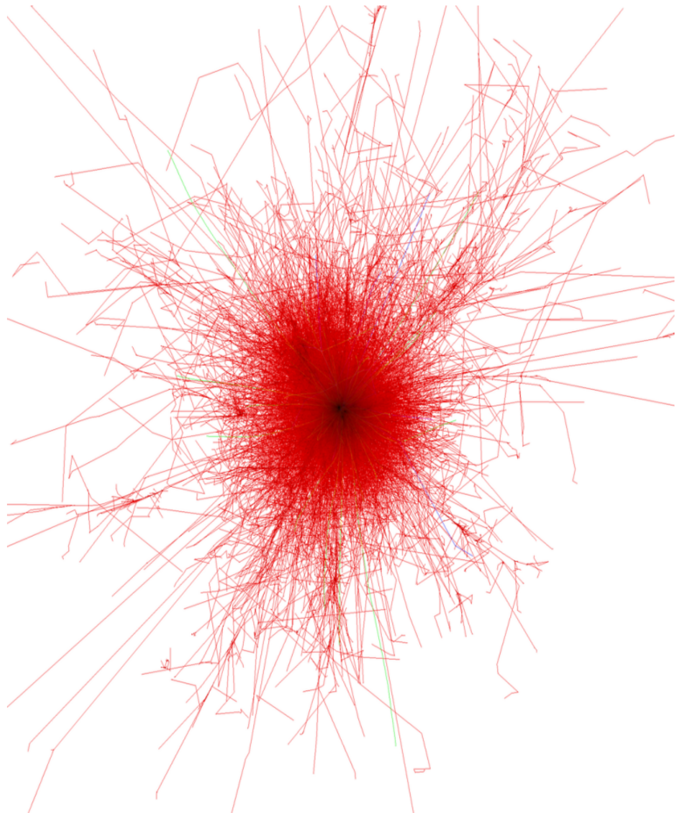


# The importance of MC

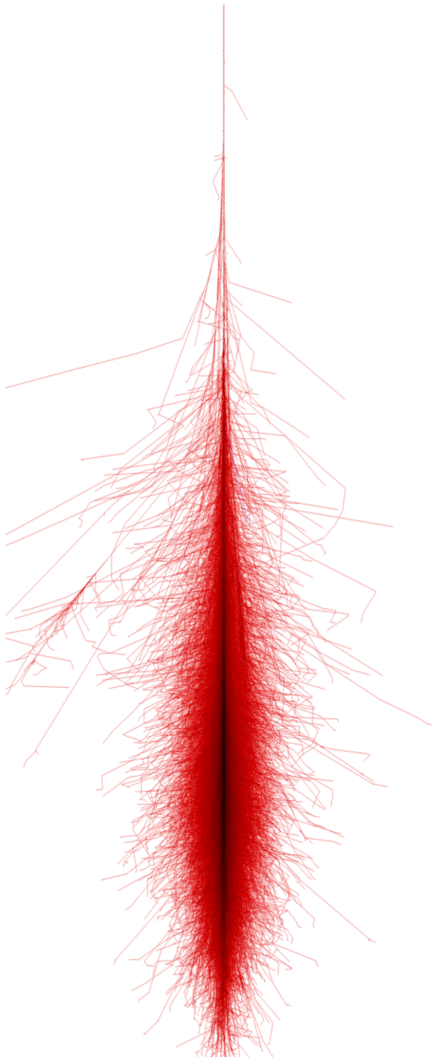
- CORSIKA (COsmic Ray SImulations for KAscade) is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. Protons, light nuclei up to iron, photons, and many other particles may be treated as primaries.
- The particles are tracked through the atmosphere until they undergo reactions with the air nuclei or - in the case of instable secondaries - decay.
- The hadronic interactions at high energies may be described by six reaction models alternatively: The VENUS, QGSJET, and DPMJET models are based on the Gribov-Regge theory, while SIBYLL is a minijet model. HDPM is inspired by findings of the Dual Parton Model and tries to reproduce relevant kinematical distributions being measured at colliders. The neXus model extends far above a simple combination of QGSJET and VENUS routines.
- Hadronic interactions at lower energies are described either by the GHEISHA interaction routines, by a link to FLUKA, or by the UrQMD model.
- In particle decays all decay branches down to the 1 % level are taken into account.
- For electromagnetic interactions a taylor made version of the shower program EGS4 or the analytical NKG formulas may be used.
- Options for the generation of Cherenkov radiation and neutrinos exist.
- CORSIKA may be used up to and beyond the highest energies of 100 EeV.
- http://www-ik.fzk.de/corsika/ → https://www.iap.kit.edu/corsika/

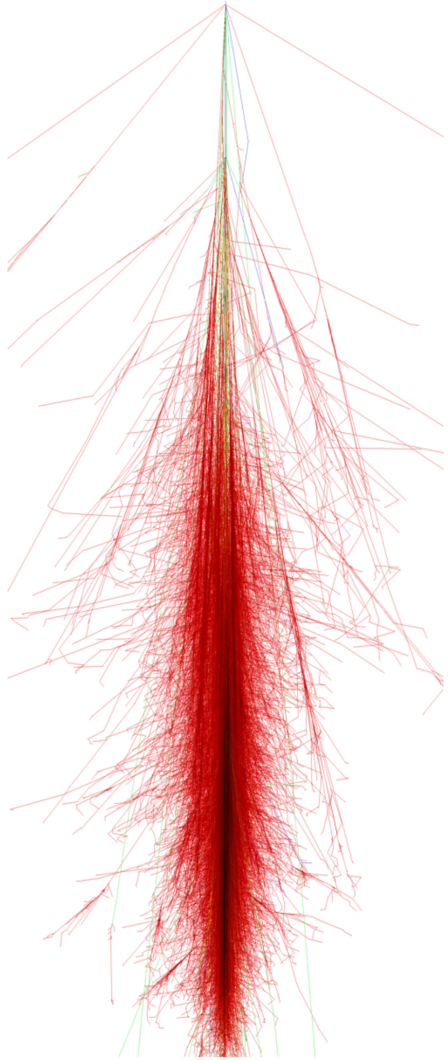
# Shower Images



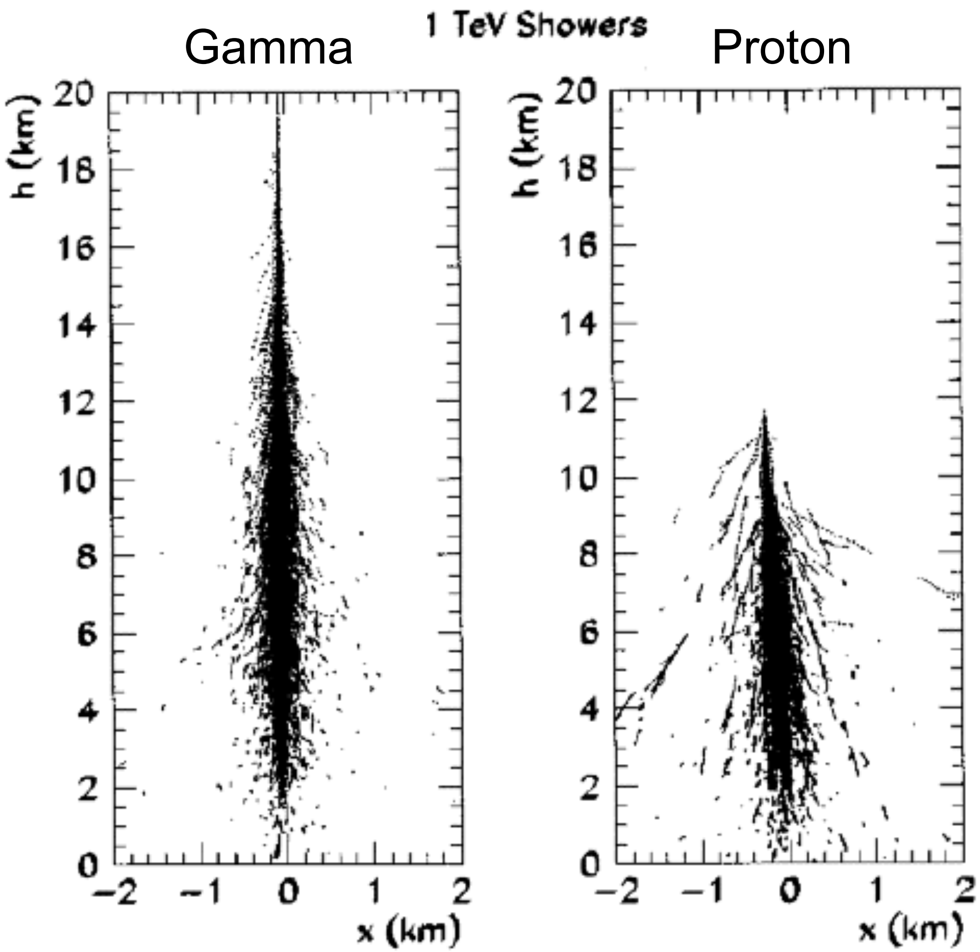


# Shower Images



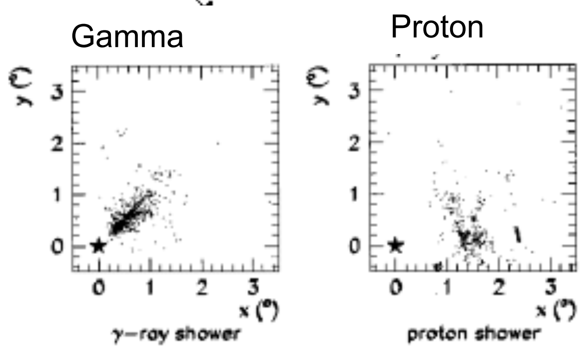


# Development of vertical 1-TeV proton and γ-ray shower

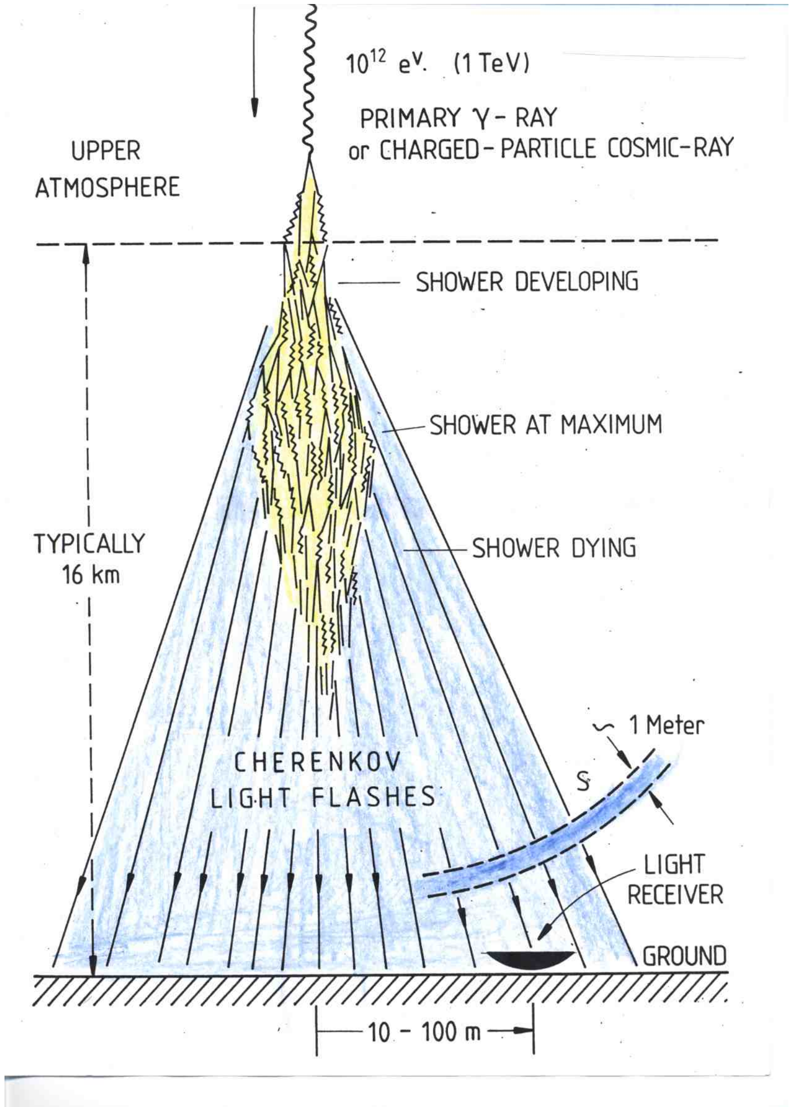


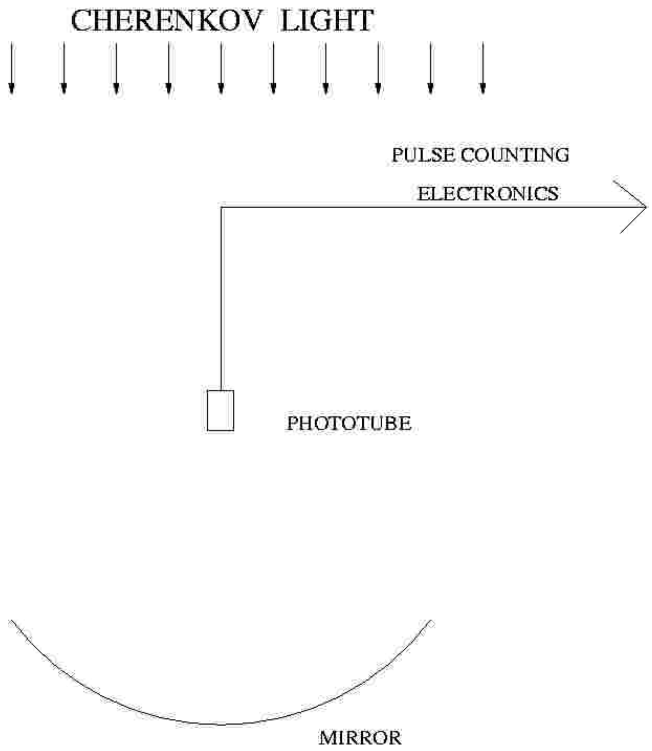

Positions in the atmosphere of all shower electrons above the Cerenkov threshold

Resulting Cerenkov images in the focal plane of a 10-m reflecting mirror .



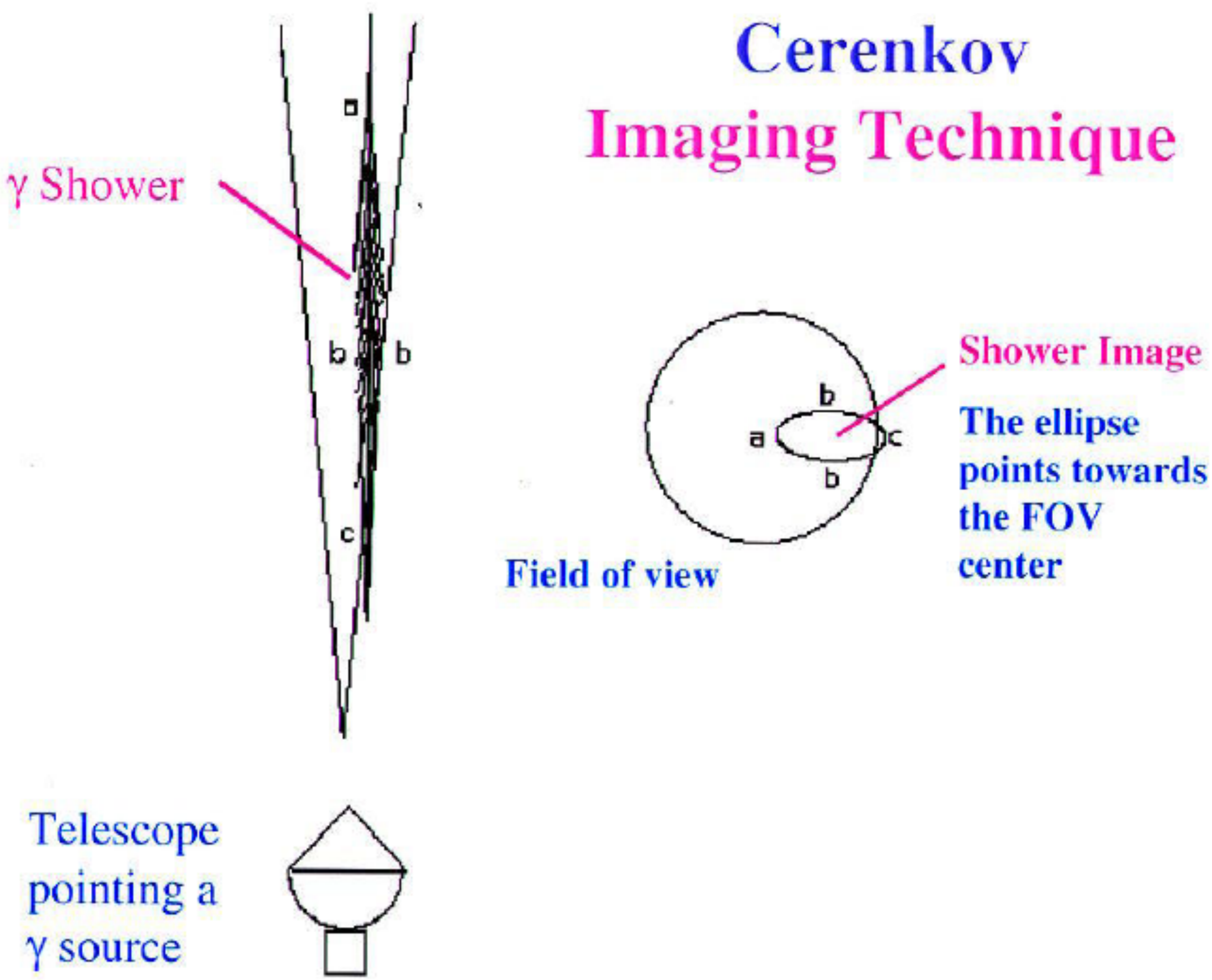
# TeV detectors



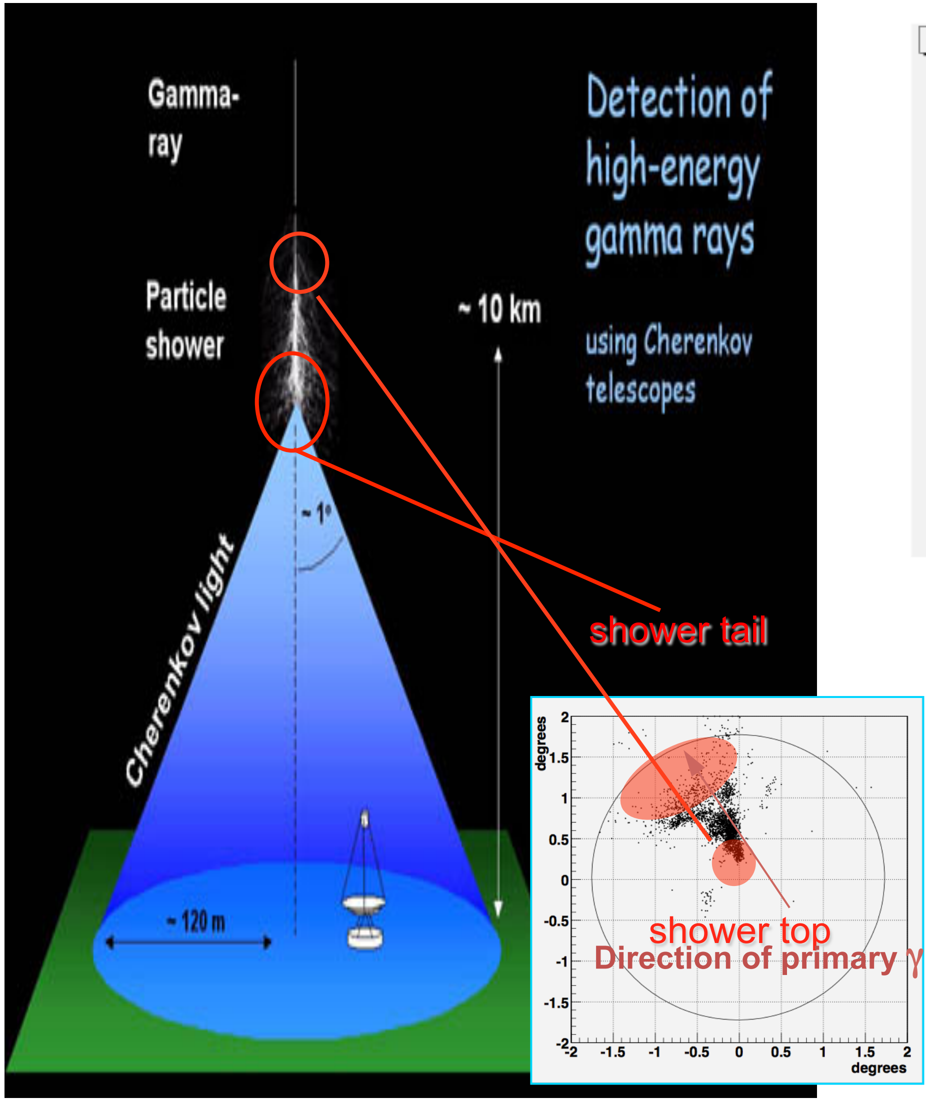



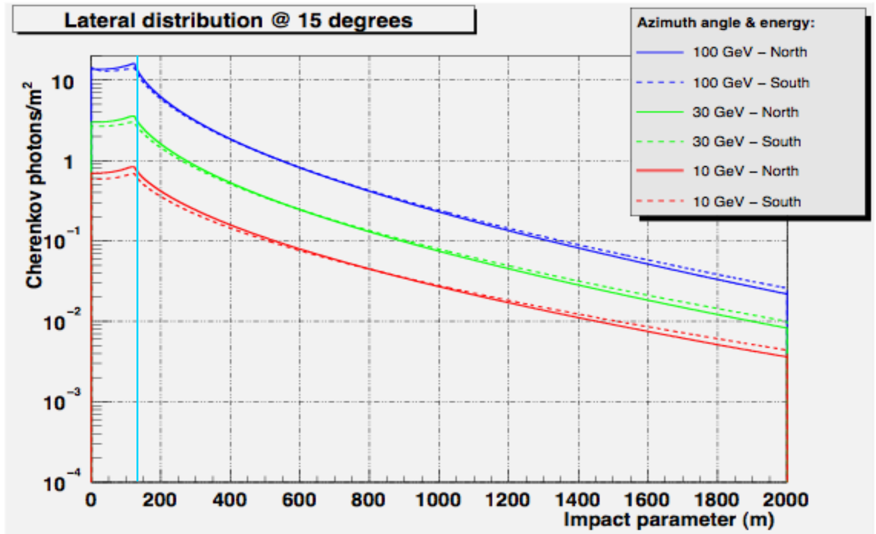

**Direction ~ → arc-min**
**Energy Resolution ~ →10%**
**Background ~ →0**

# TeV detectors



## Imaging Atmospheric Cherenkov Telescopes

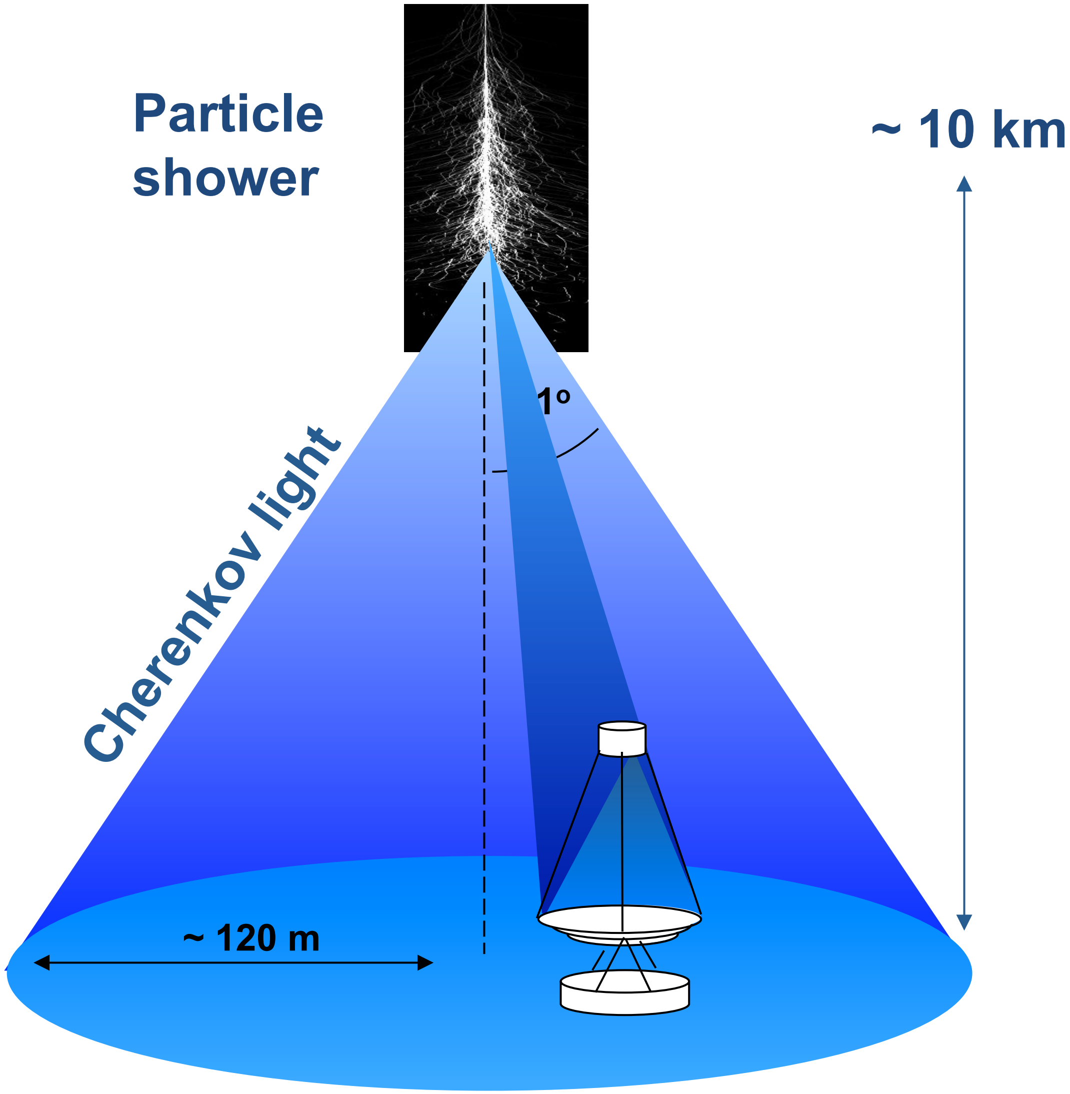



# The principle:

A telescope placed inside the (huge) Cherenkov light pool can obtain an image of the development of the shower above the bkg fluctuations

# Observation tecnique




**Detection of TeV gamma rays**

using Cherenkov telescopes

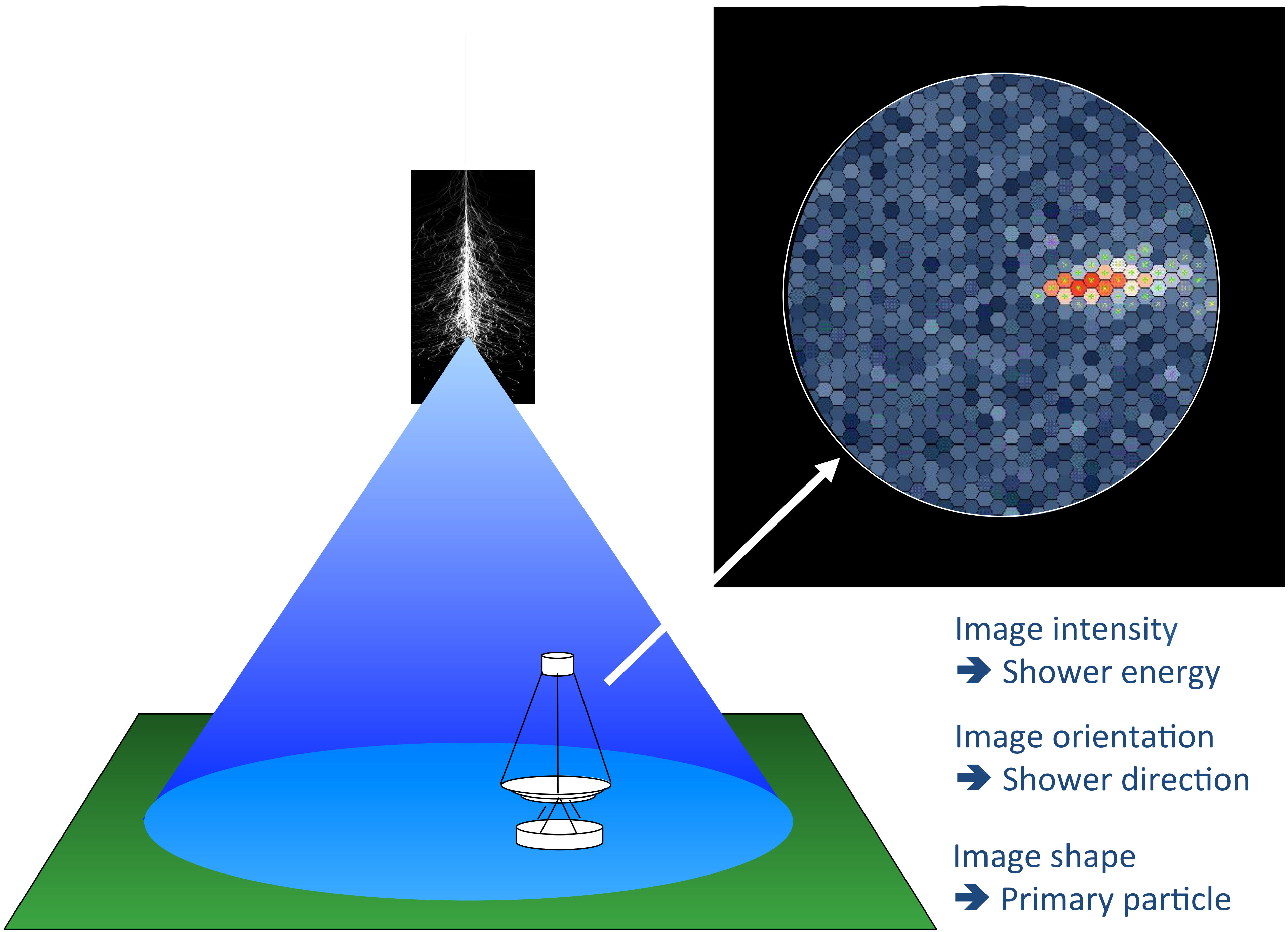
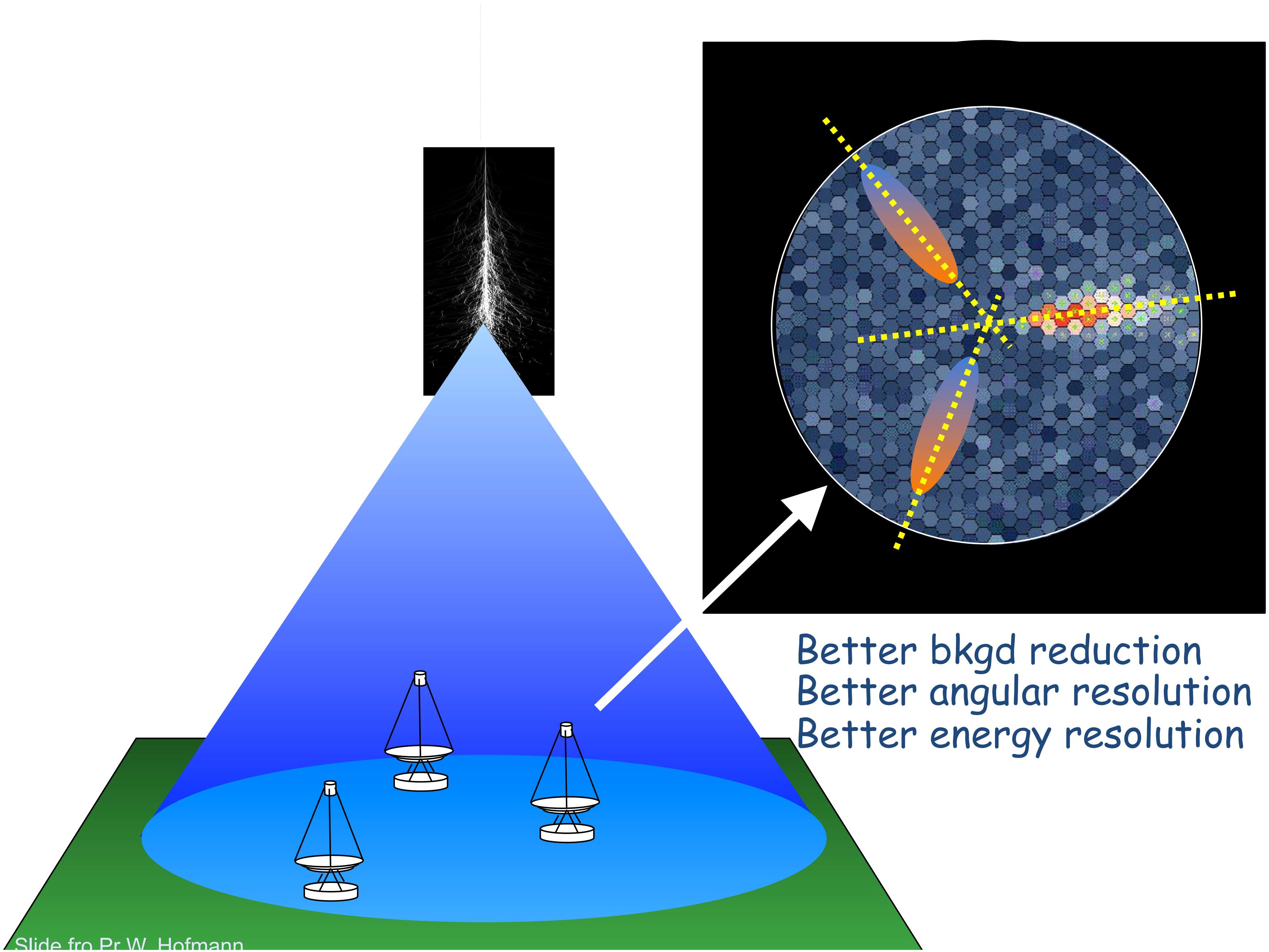
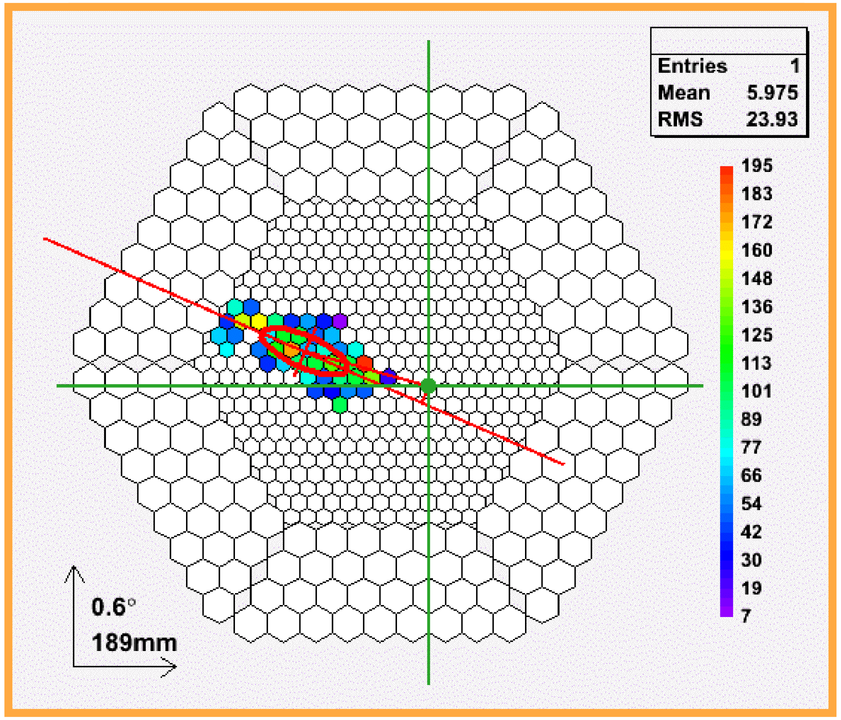


Image intensity
➔ Shower energy
Image orientation
➔ Shower direction
Image shape
➔ Primary particle

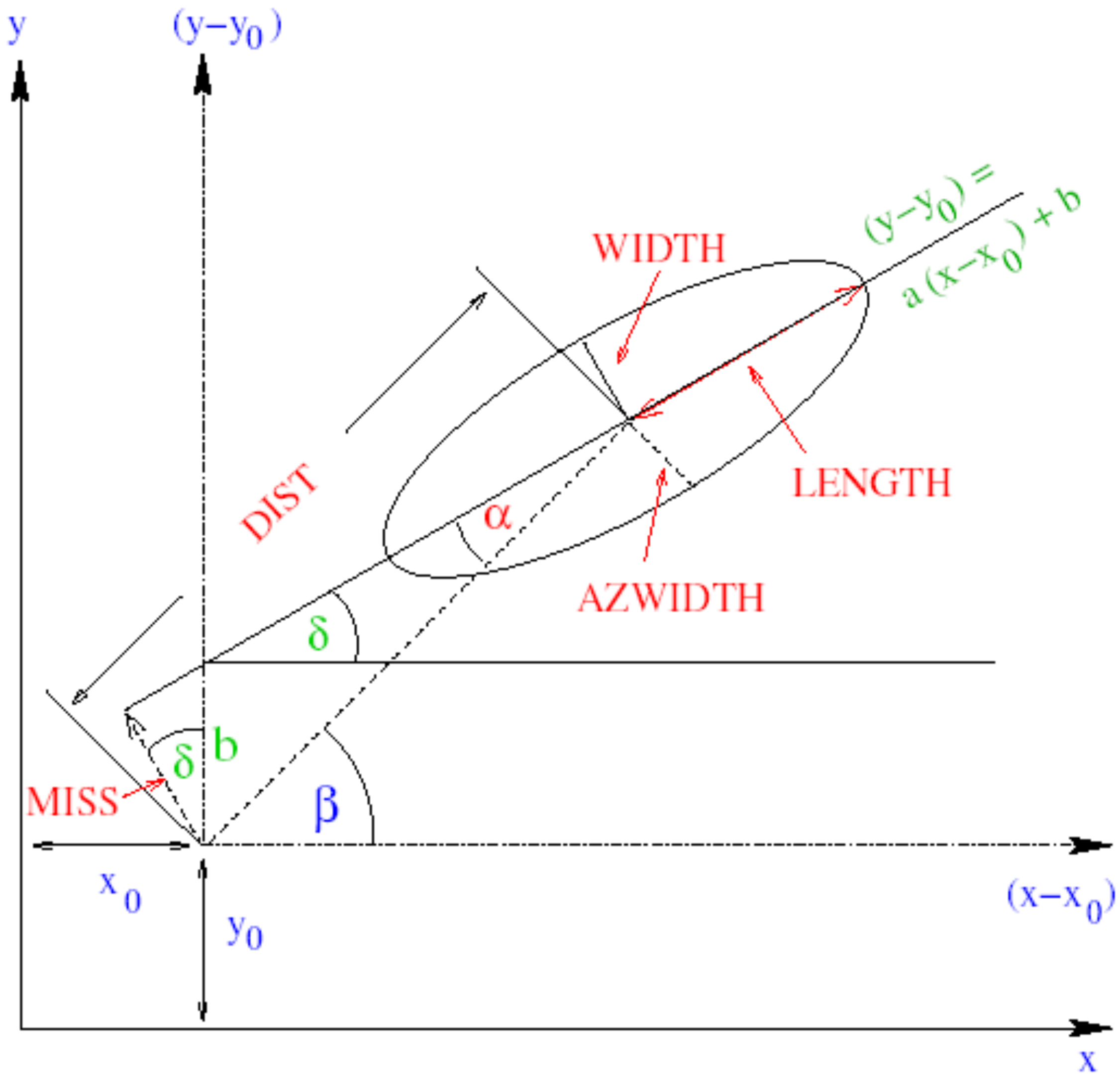

Better bkgd reduction
Better angular resolution
Better energy resolution
Slide fro Pr W. Hofmann

# IACT image reconstruction

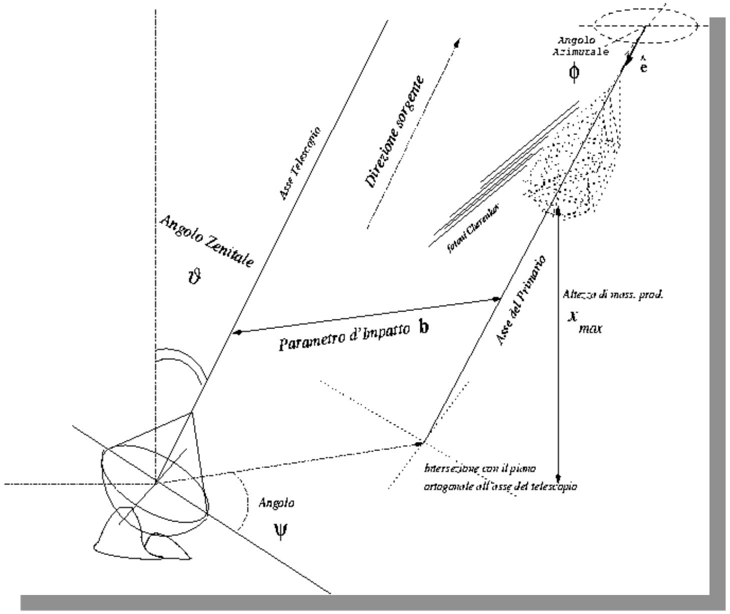
- Primary γ parameters reconstruction by particle shower image analysis
- Different primary particles give different image shapes
- Possible γ-hadron separation
- Reconstructed parameters of primary γ: energy, direction, arrival time
- Signal estimation
- Spectrum calculation
- Lightcurve



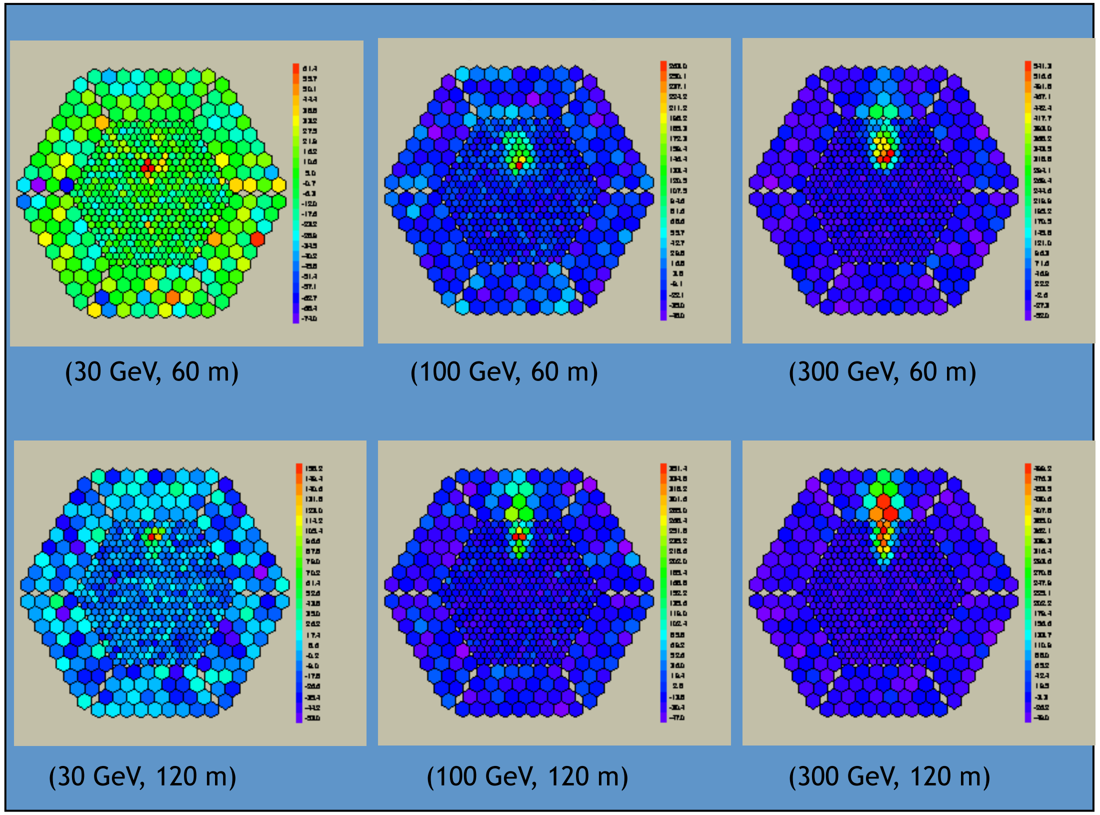
# Hillas parameters



# Imaging Atmospheric Cherenkov Telescopes

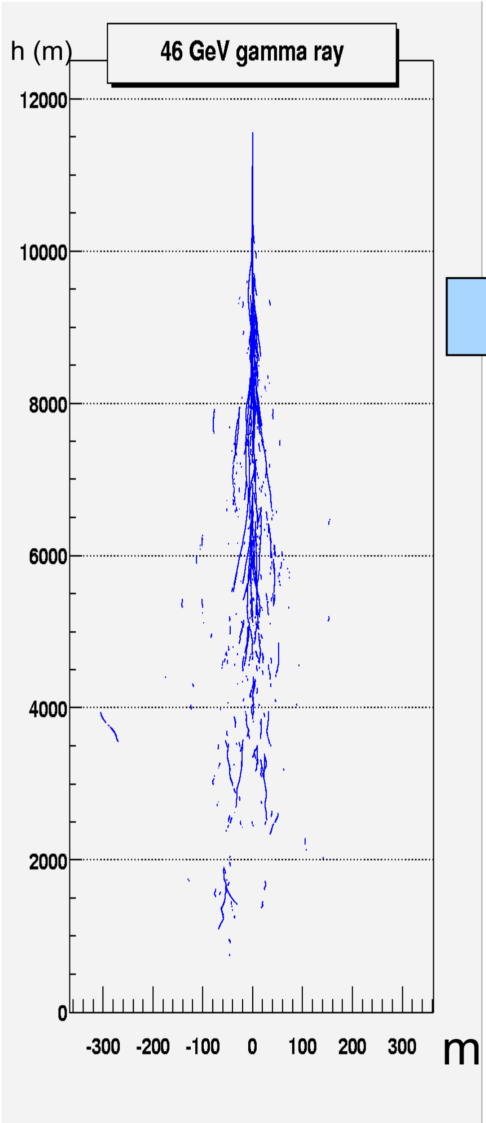


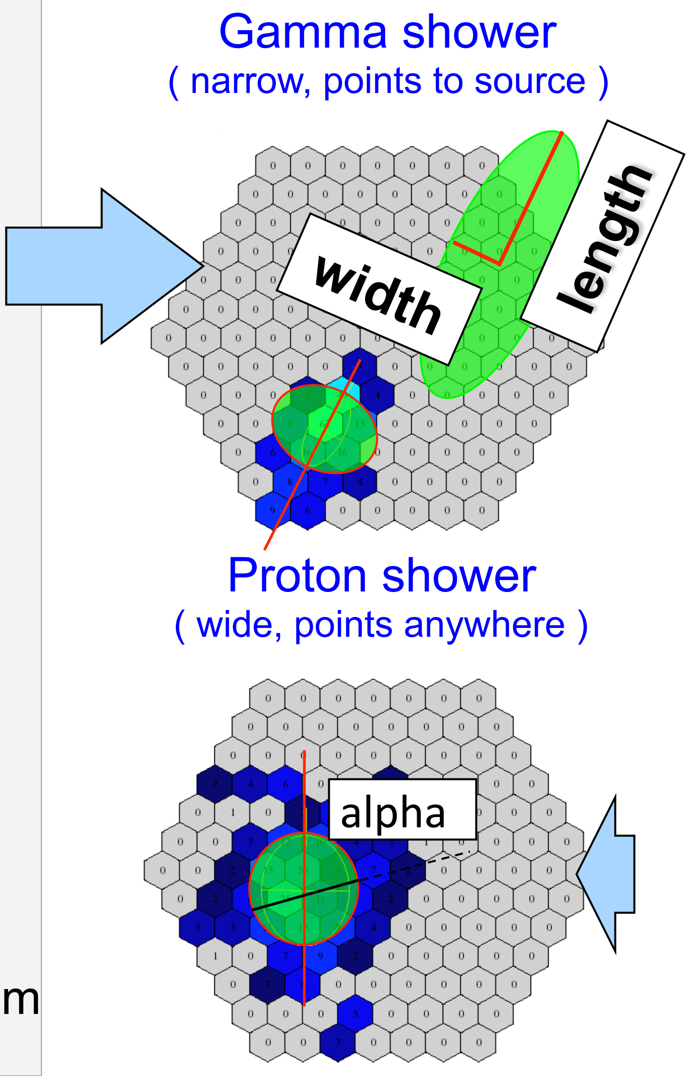

Typical γ shower images simulated with different energy and different impact parameter

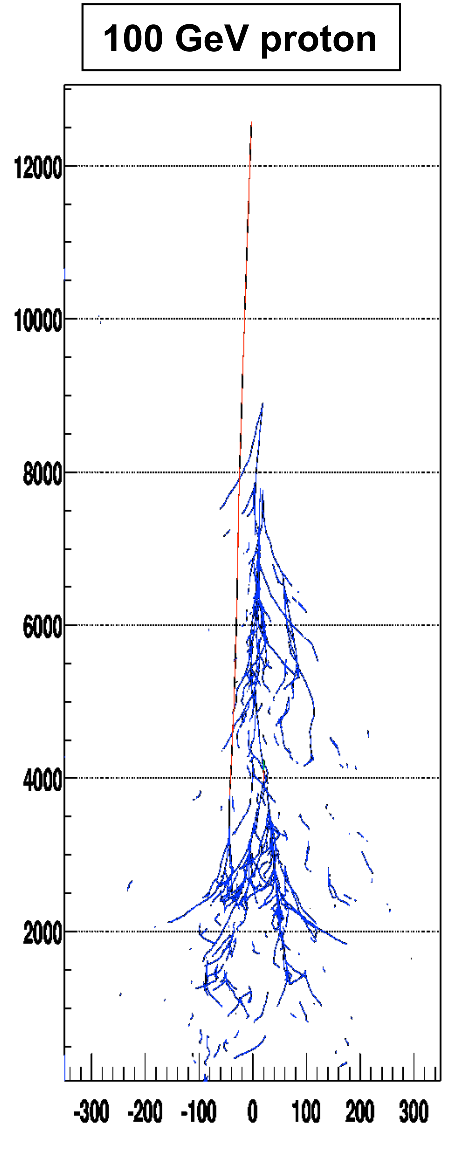



Geometric relations between a shower and the Cherenkov Telescope optics

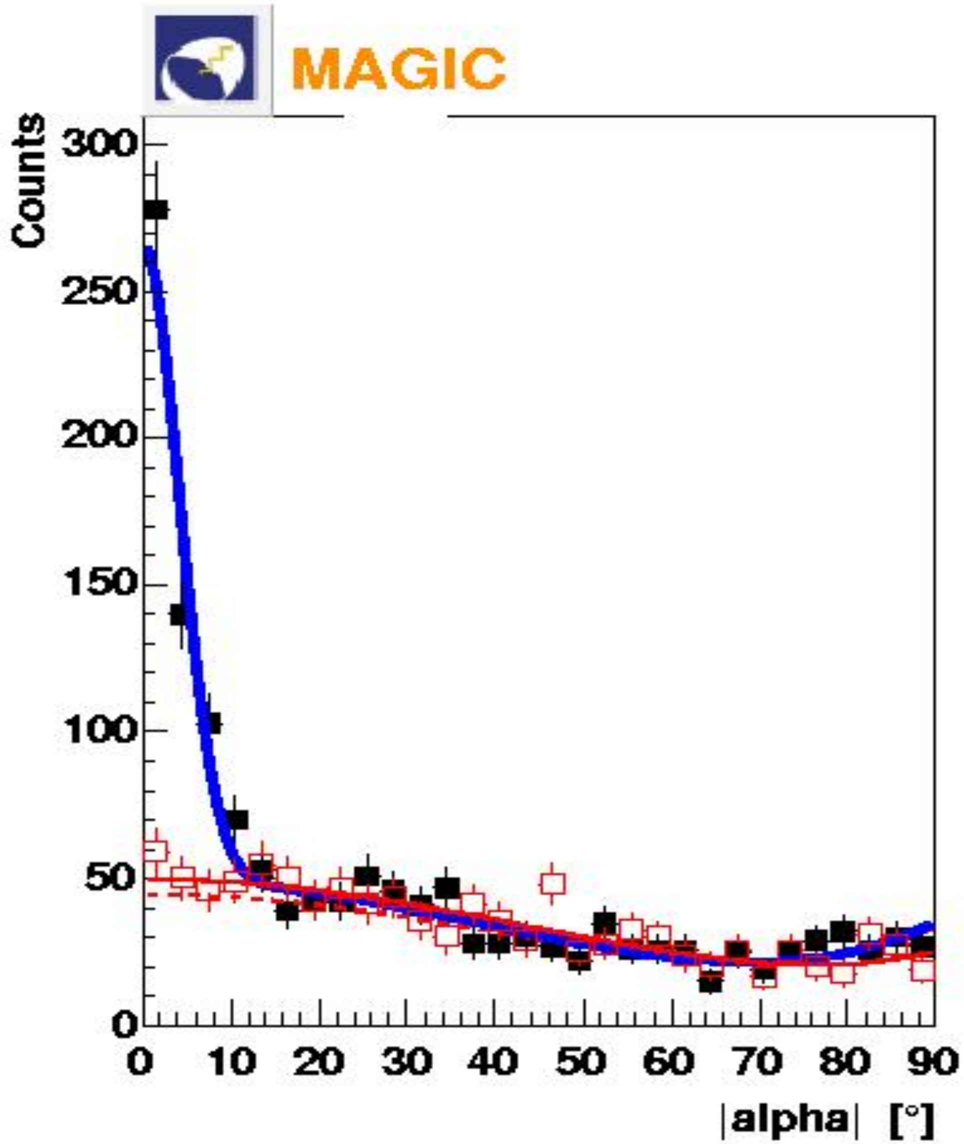
# Gamma / hadron separation



# γ /hadron separation




**Crab Nebula**