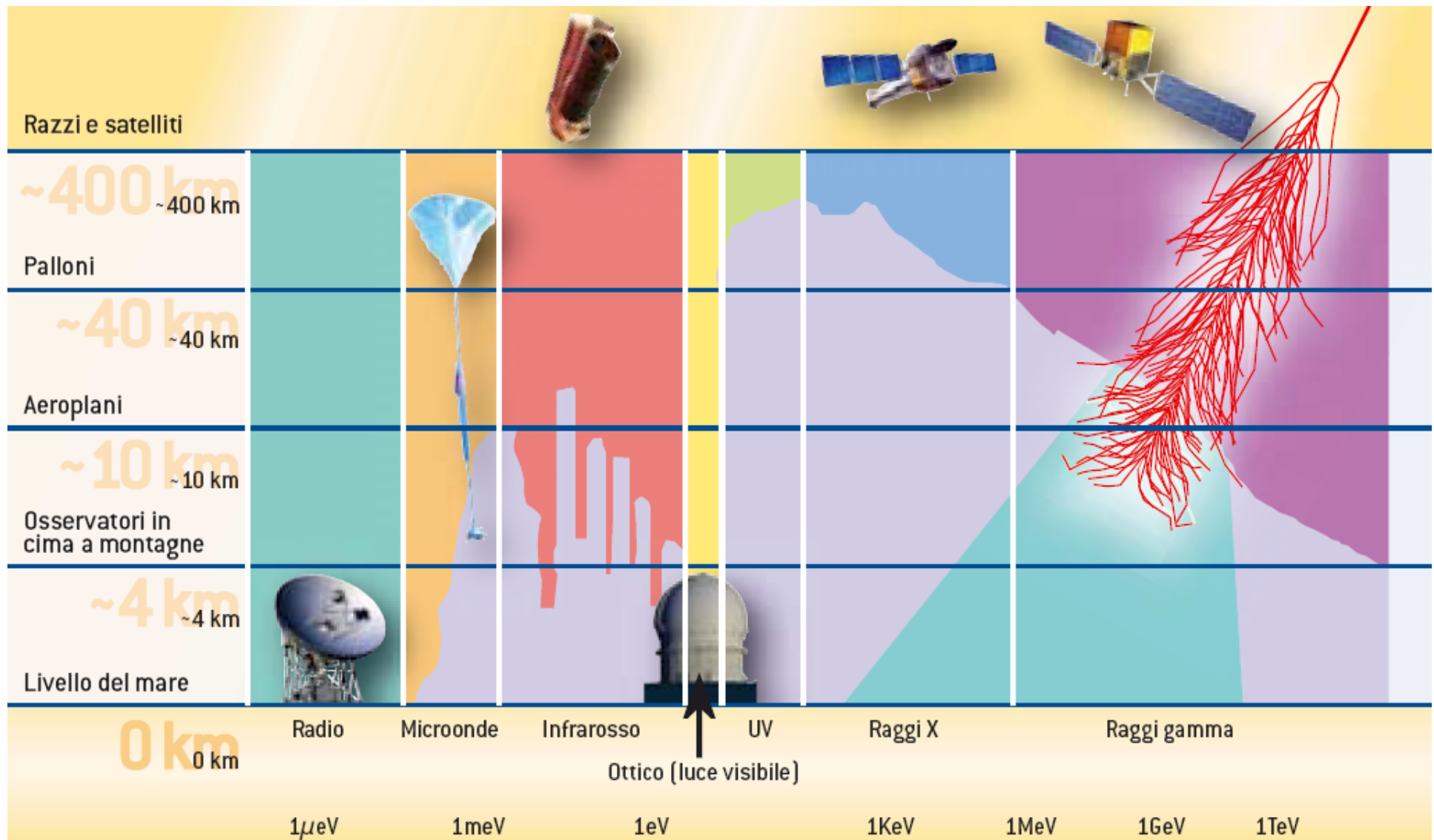


Astrofisica Nucleare e Subnucleare

TeV Astrophysics

The opacity of the atmosphere

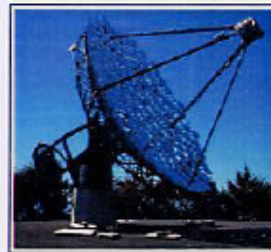


TeV detectors

The gamma ray spectrum



Satellites

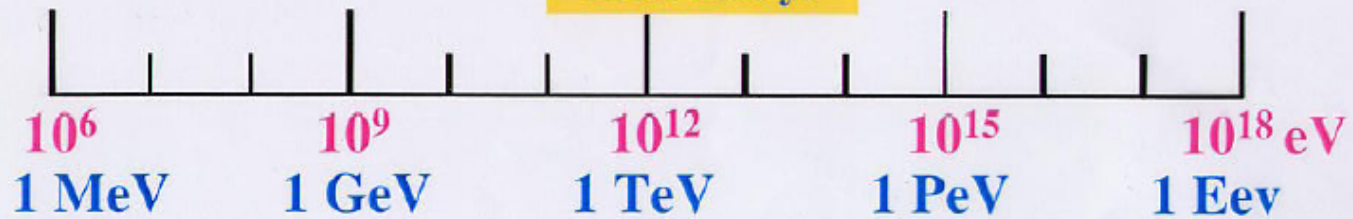


**Cerenkov
Telescopes**



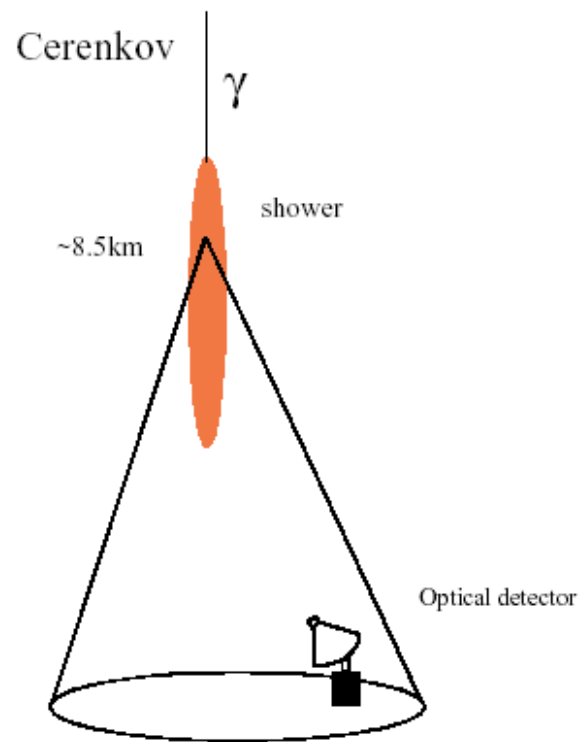
EAS arrays

**Full coverage
EAS arrays**

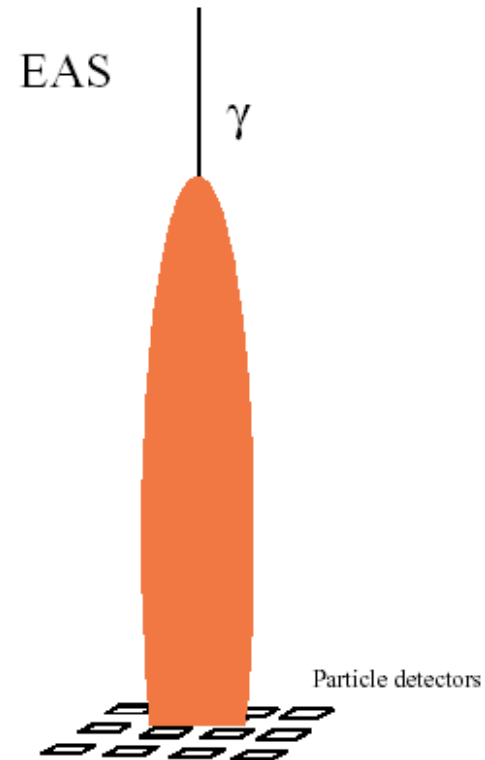


TeV detectors

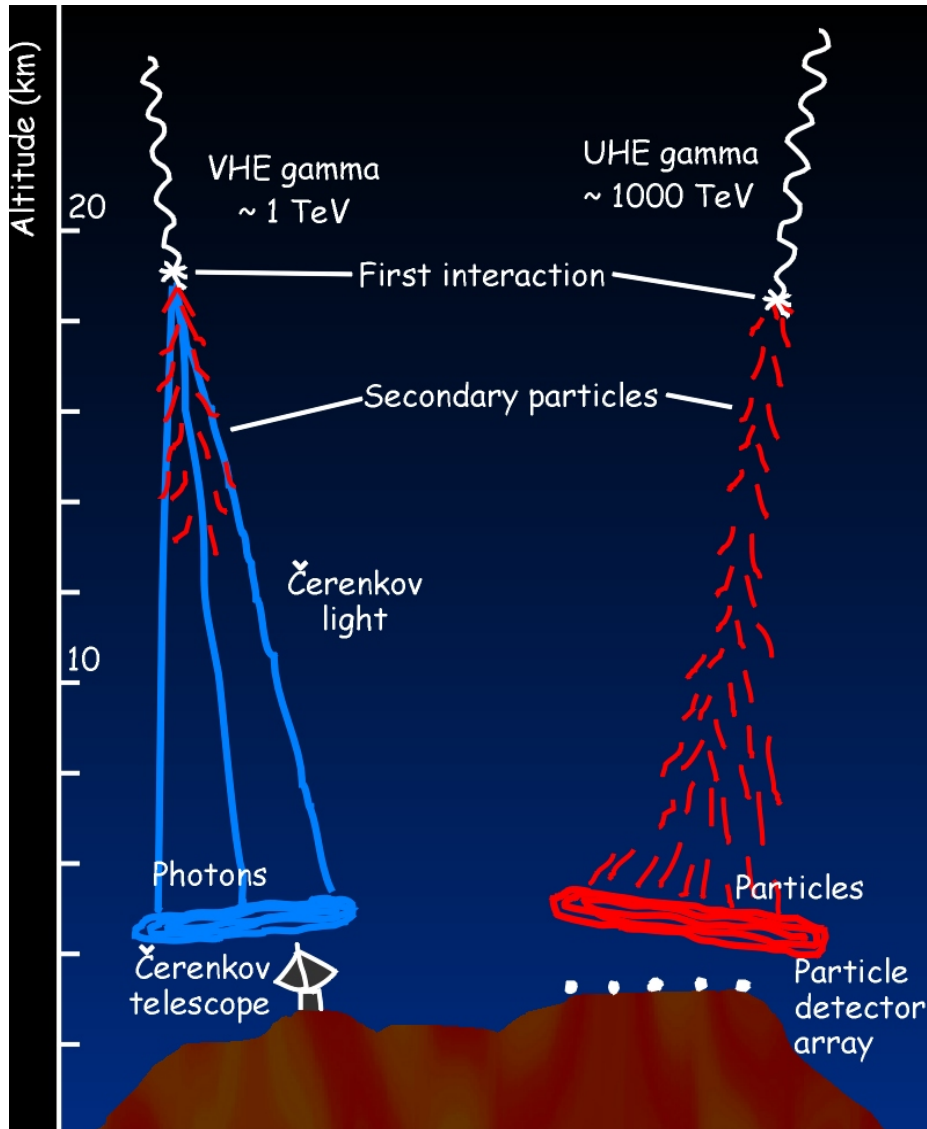
Cerenkov and Extensive air shower (EAS) gamma ray telescope concepts



~ 40.000 m² , but no anticoincidence shield !



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 $I = I_0 e^{-x/\lambda}$
 $\lambda = \text{mean free path}$

▪ Bremsstrahlung $E = E_0 e^{-x/\chi_0}$
 $\chi_0 = \text{radiation length}$

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 $n R$:

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

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:

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

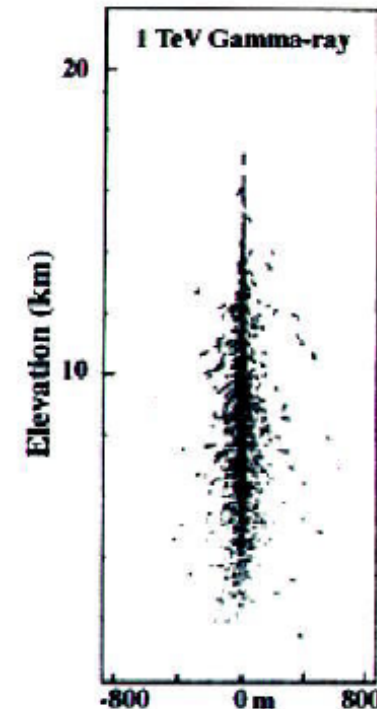
Depth of the maximum:

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

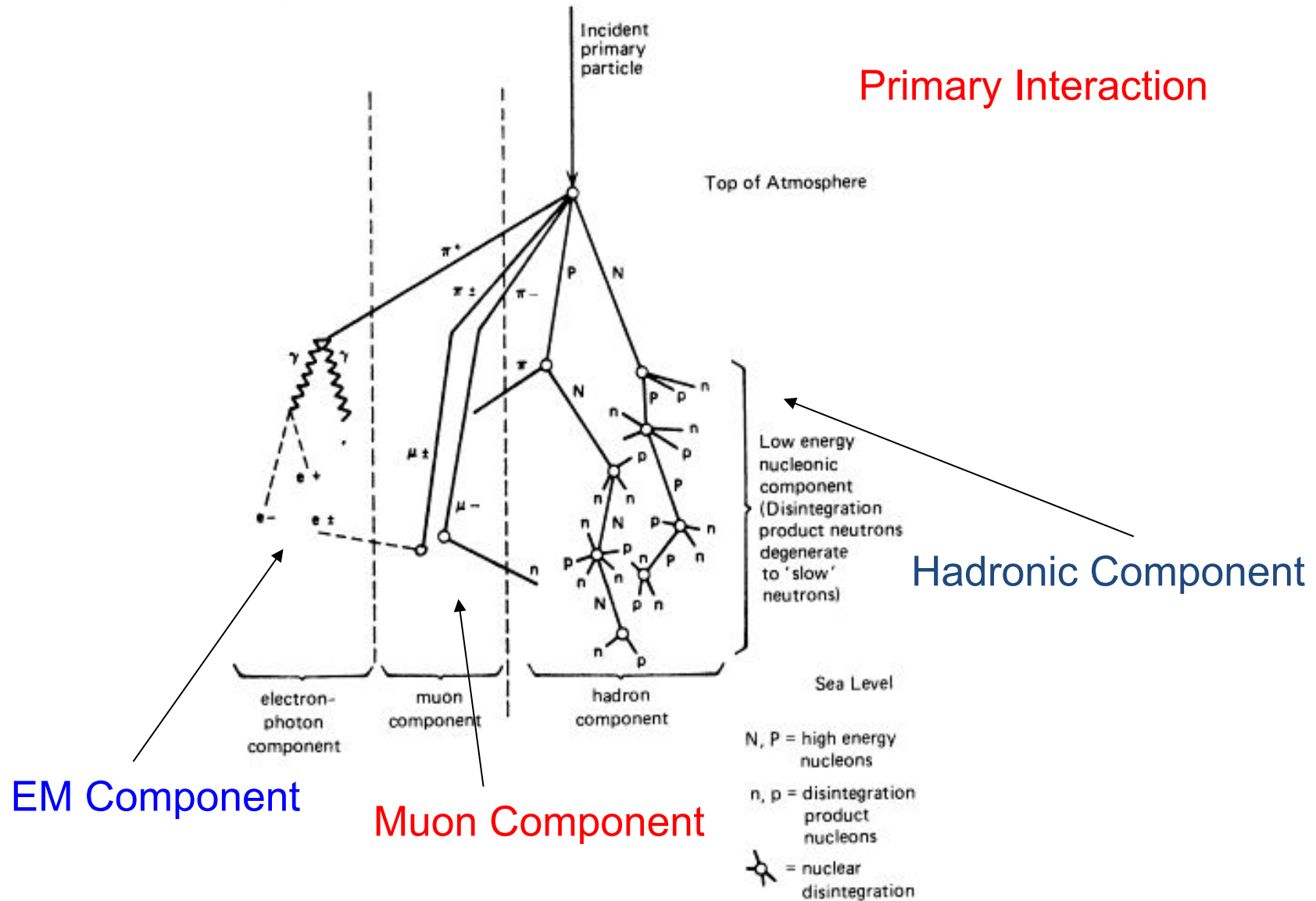
$$\Rightarrow X_{\max} = n R = n \chi_0 \ln 2 = \chi_0 \ln(E_{\text{pr}} / E_c)$$

Example: $E_{\text{pr}} = 1 \text{ TeV}$

$$\Rightarrow X_{\max} = 340 \text{ g / cm}^2 \sim 8 \text{ Km}$$



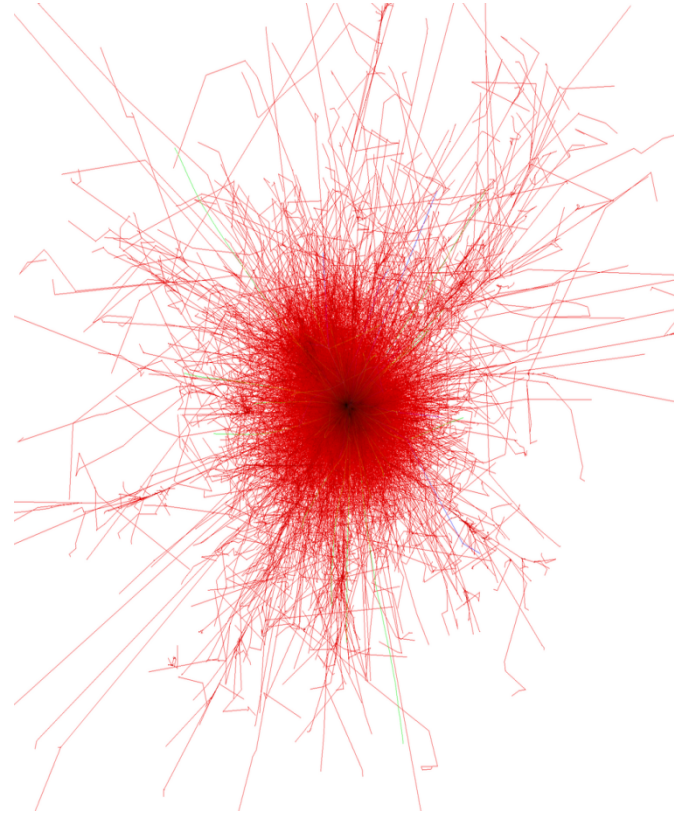
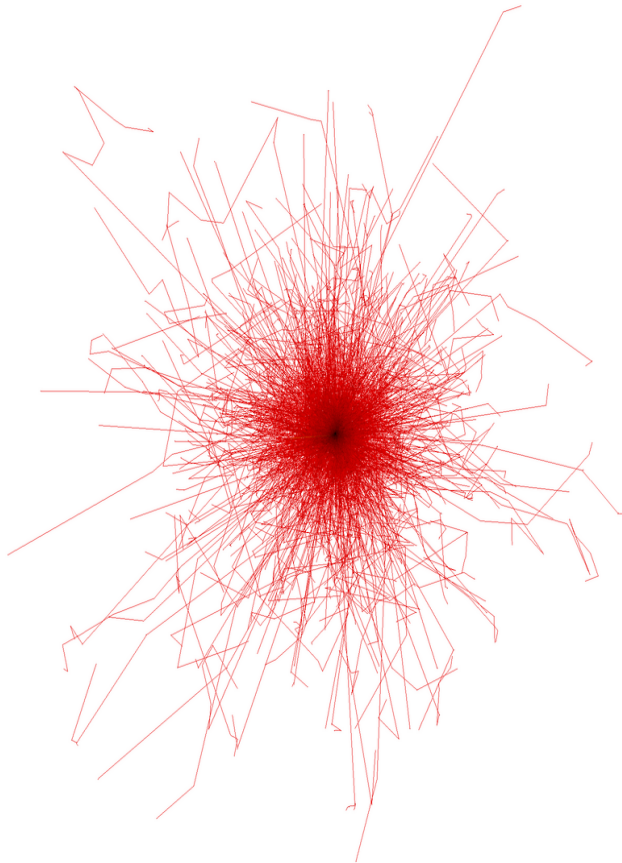
CR interactions



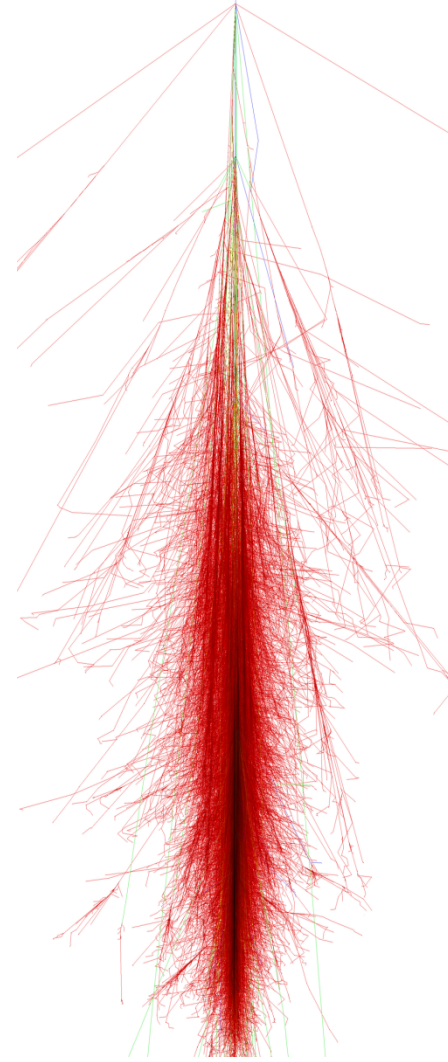
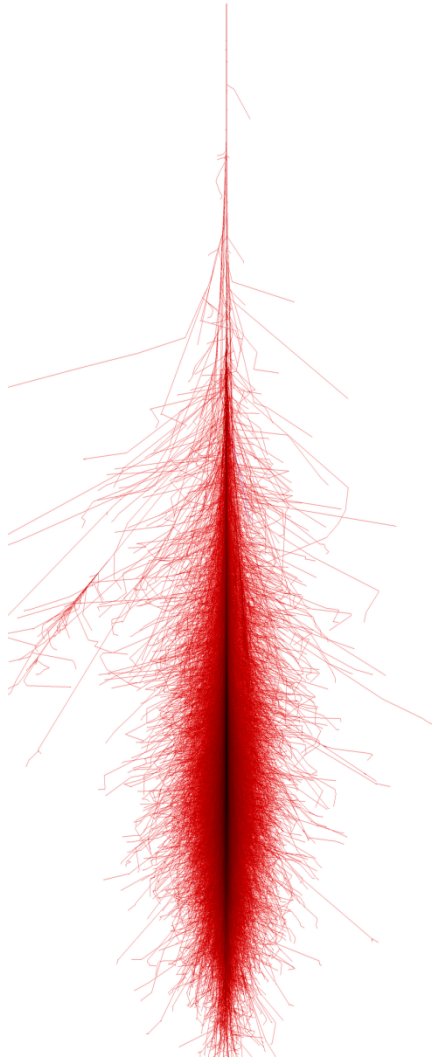
The importance of MC

- 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/>

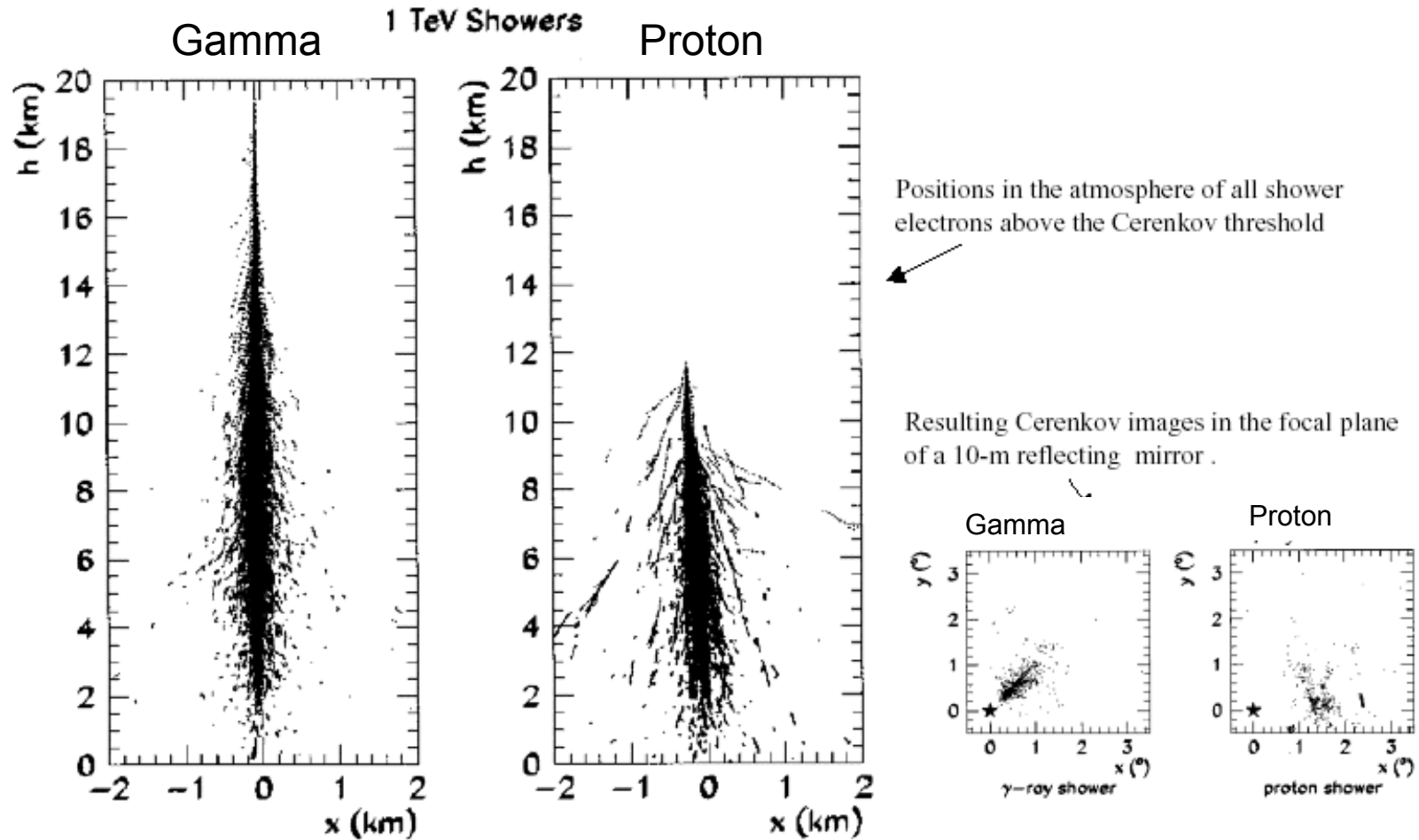
Shower Images



Shower Images

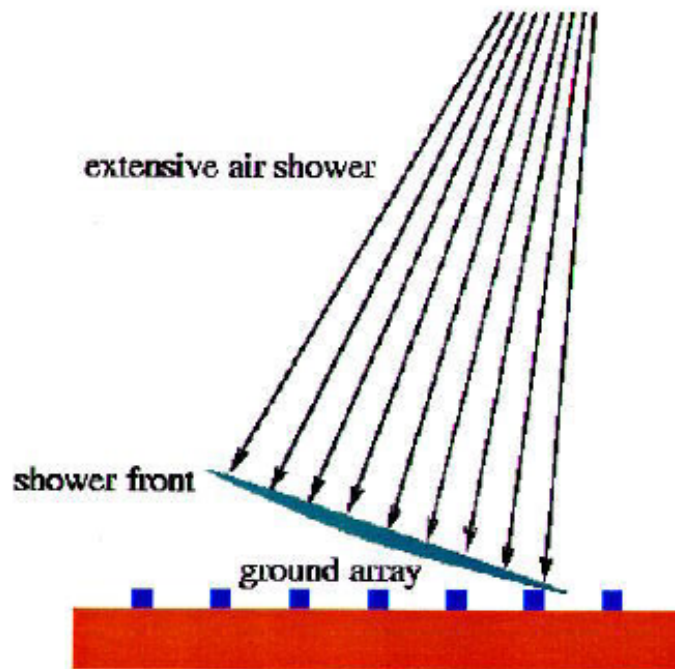


Development of vertical 1-TeV proton and γ -ray shower



TeV detectors

Air Shower Arrays



Reconstruction of the γ direction
with the particles arrival times

Large field of view: $\sim \pi$ sr

Duty cycle $\sim 100\%$

Gamma-hadrons discrimination:

μ -poor showers