Ecole de GIF 2013

Principes et méthodes de détection : Particules chargées au sol (I)

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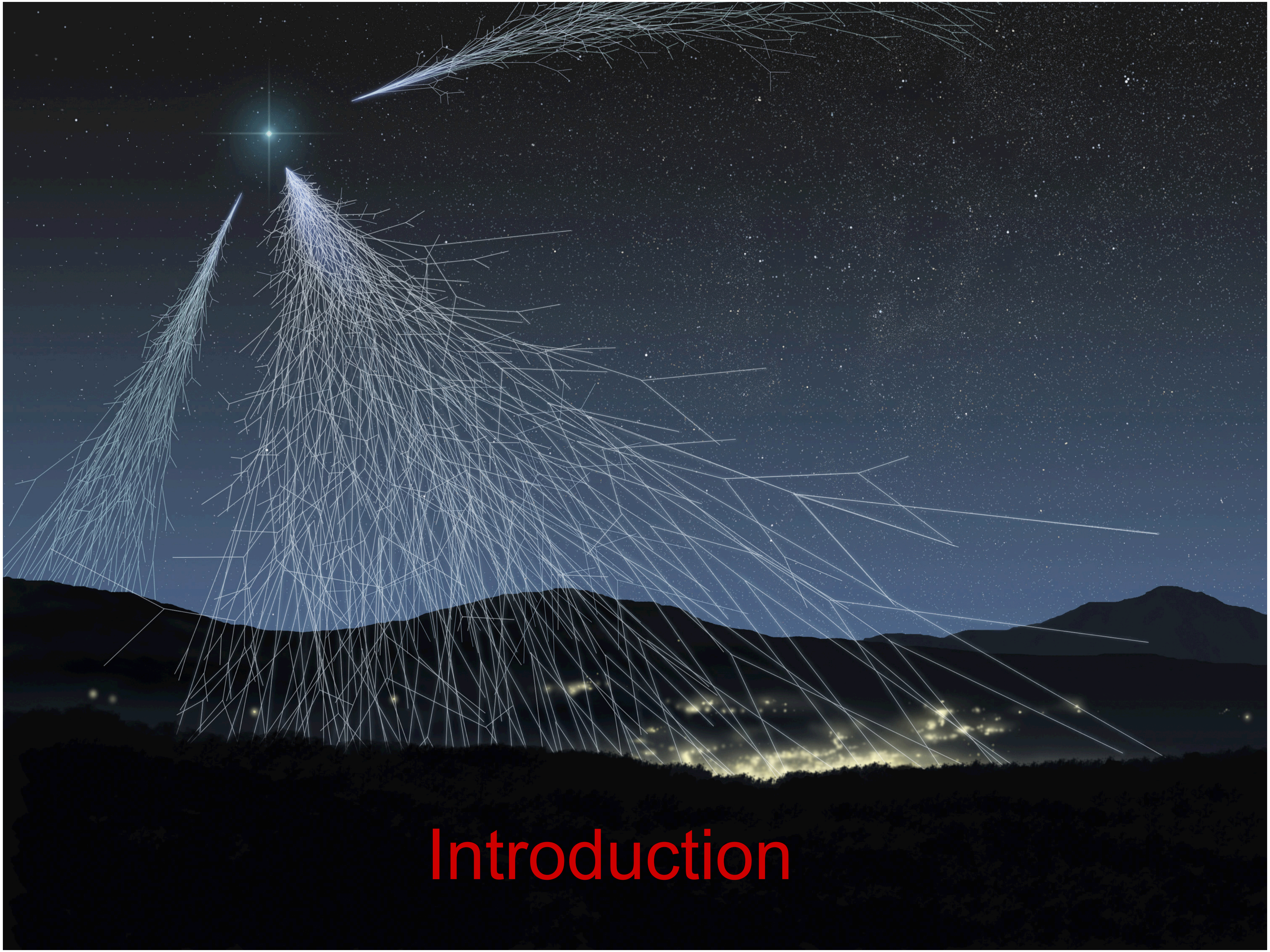


Introduction

Why to study cosmic rays?

Cosmic rays span over an enormous range of energies, up to 10^{20} eV: a unique feature in Physics.

They serve an important role in the energy balance of the Galaxy. Their energy density 1 $eVcm^{-3}$ is comparable to that contained in the galactic magnetic field or in the CMB.

They can be evidence of powerful astrophysical accelerators (supernovae, active galactic nuclei…) and can be used to study these accelerators.

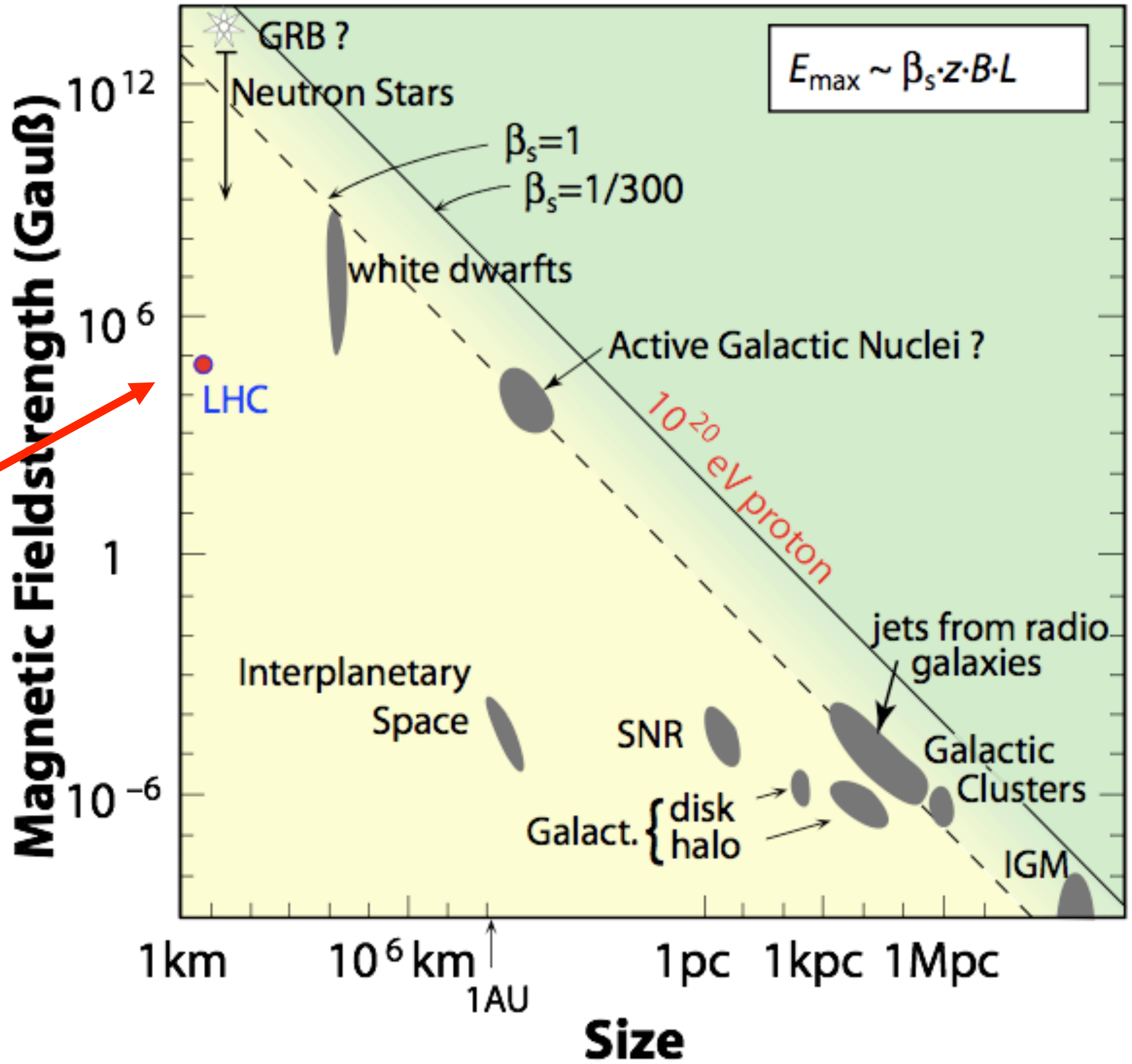
They propagate through universe and can give information on properties of cosmic environment (magnetic fields, matter densities…).

Their chemical composition, modulated by propagation, reflects the nucleosynthetic processes occurring at their origin.

They can also be messengers of yet unknown particles.

Power of cosmic accelerators

SPIRAL2?



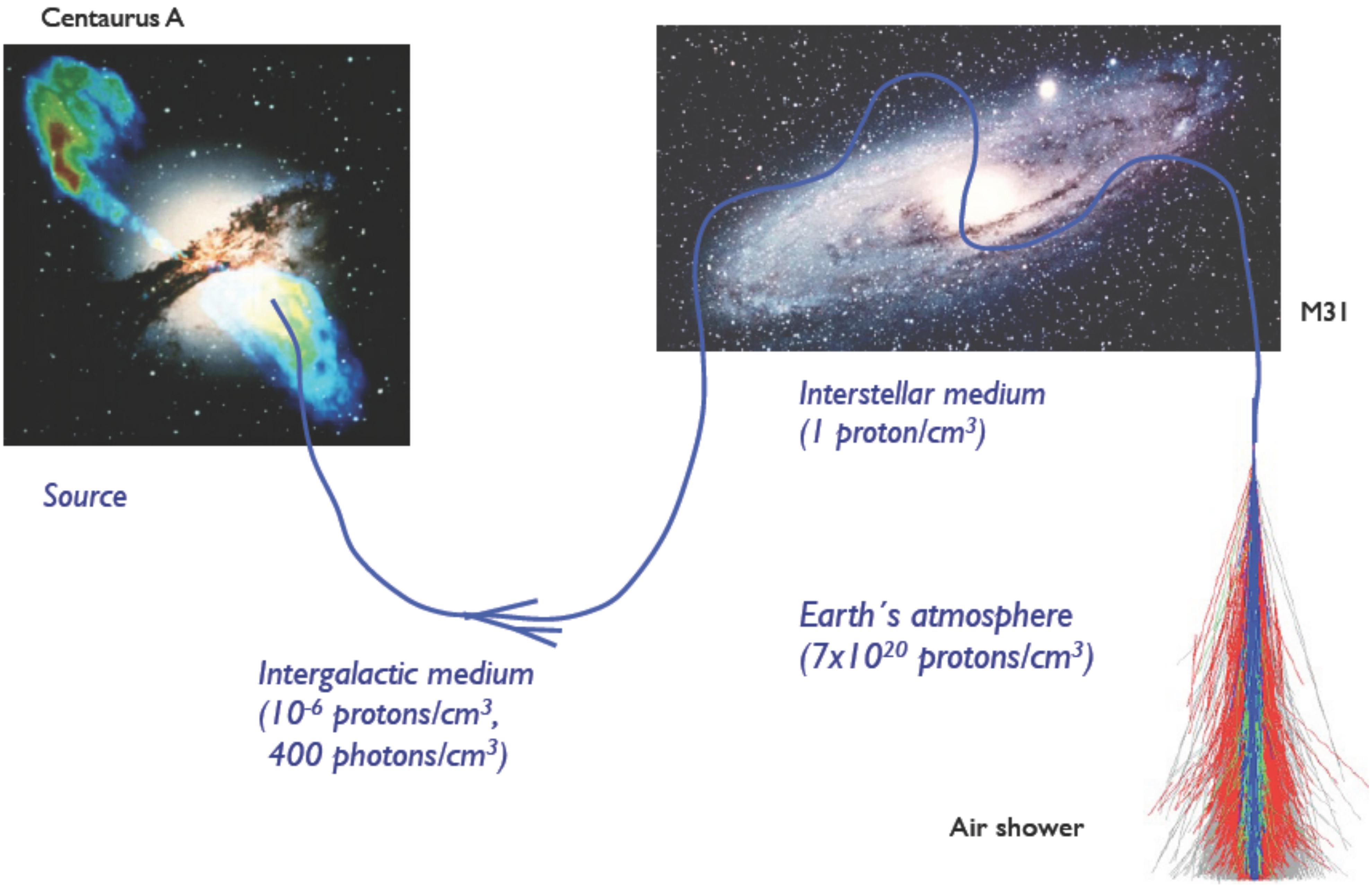
Acceleration in magnetic turbulences (Fermi acceleration)

Maximum energy is obtained when particles are confined in the acceleration site => large dimension necessary (1 Mpc), weak radiation around the site required : the jets of the radiogalaxies ?

Electrostatic acceleration in magnetized, rapidly rotating objects

Young neutron starts ?

Propagation of cosmic rays



Propagation: B and CMB

Cosmic rays <10^{18} eV are confined by the magnetic field to our Galaxy for about 10^7 years !

Lamor radii at **10^{20} eV** compared to Milky-Way

Ultra-high energy cosmic rays can point to sources.
They are not confined to our Galaxy: extra-galactic visibility.

Pion production with CMB

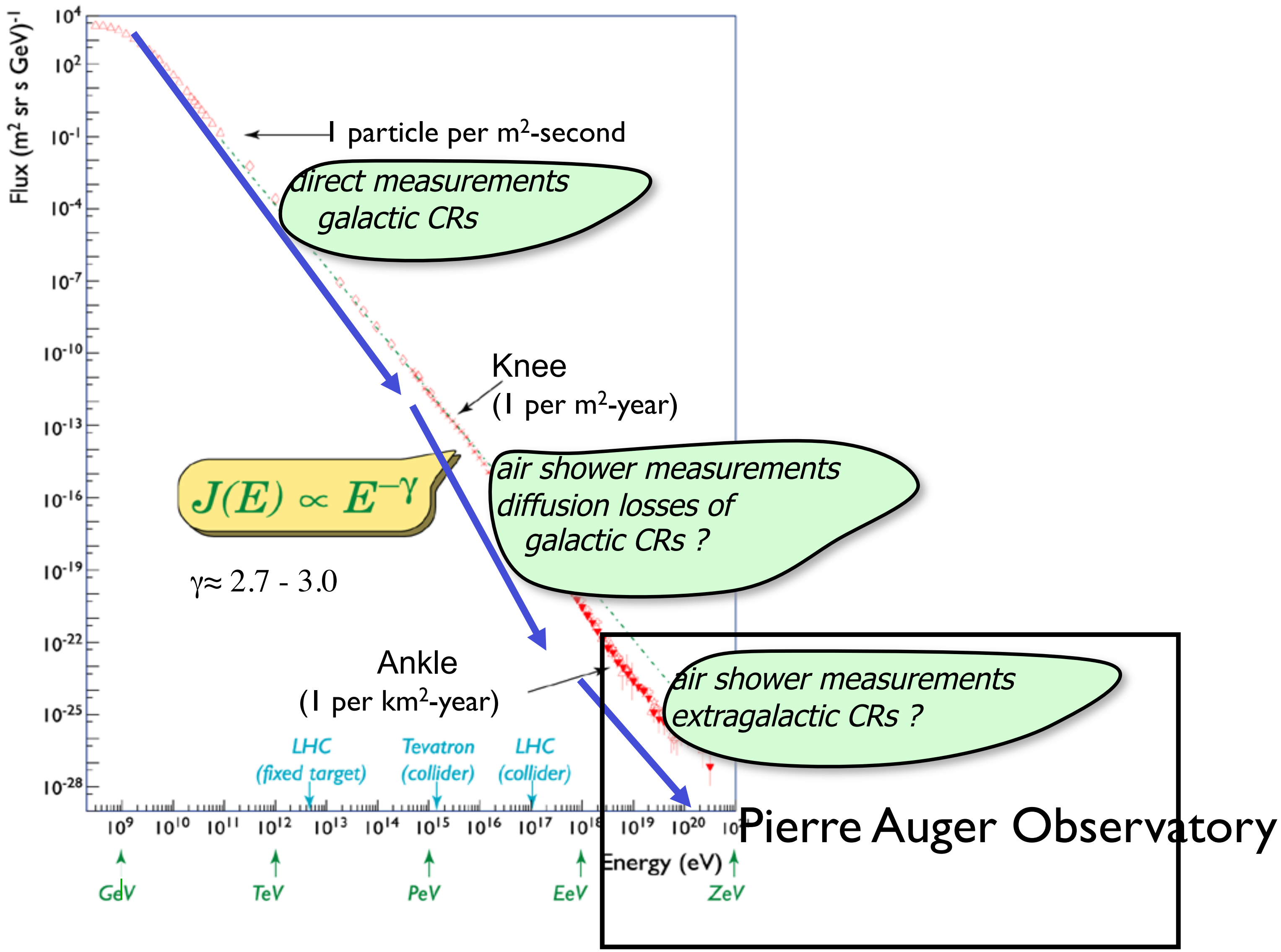
$$p + \gamma_{3K} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}\ ;\ n + \pi^{+}$$

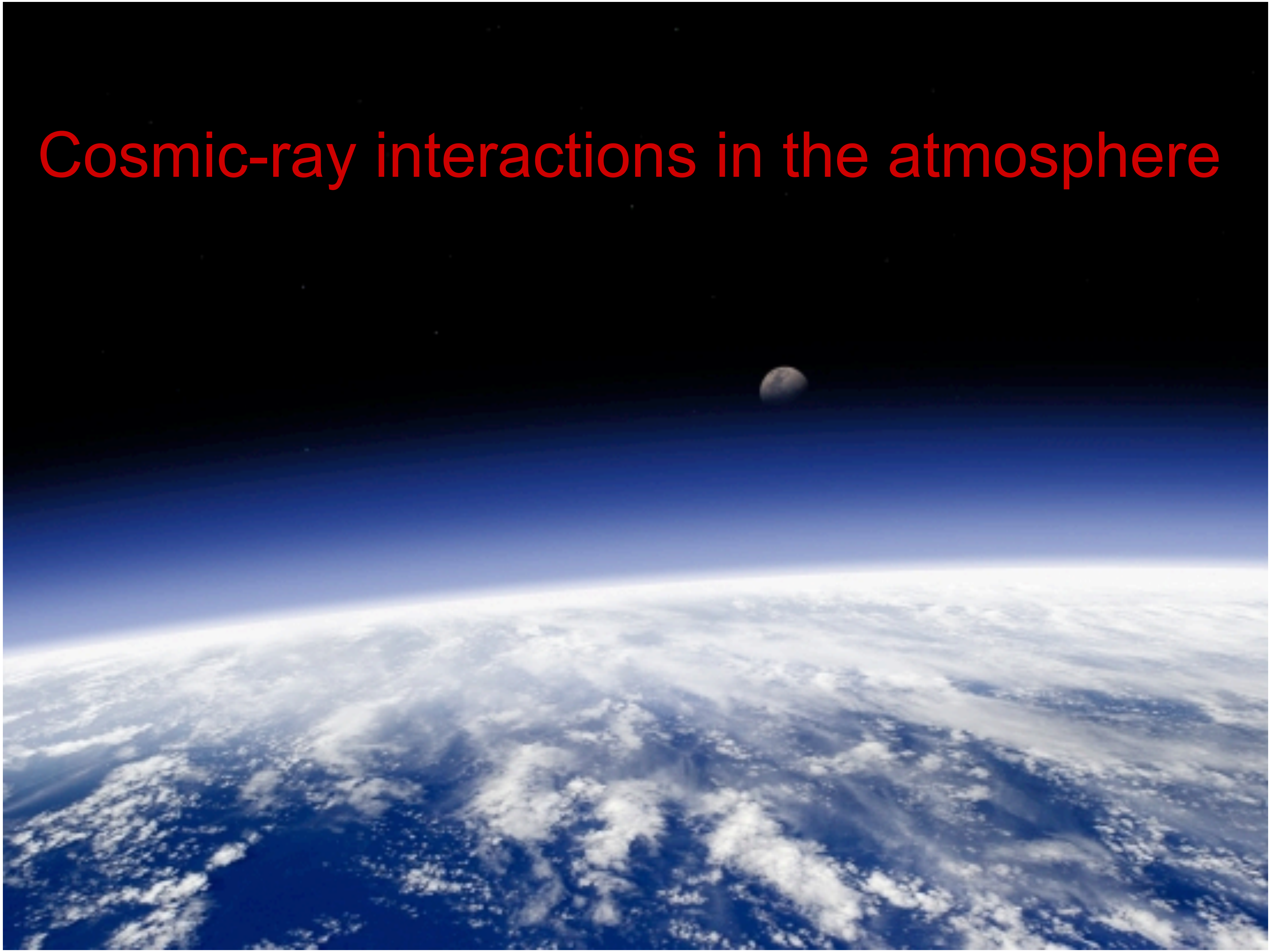
$$\text{threshold: } E_p E_\gamma > (m_\Delta^2 - m_p^2)$$
$$\Rightarrow E_{GZK} \approx 6 \cdot 10^{19}\ \text{eV}$$

Heavy nuclei: GDR excitation with CMB (GDR cross sections are important!)

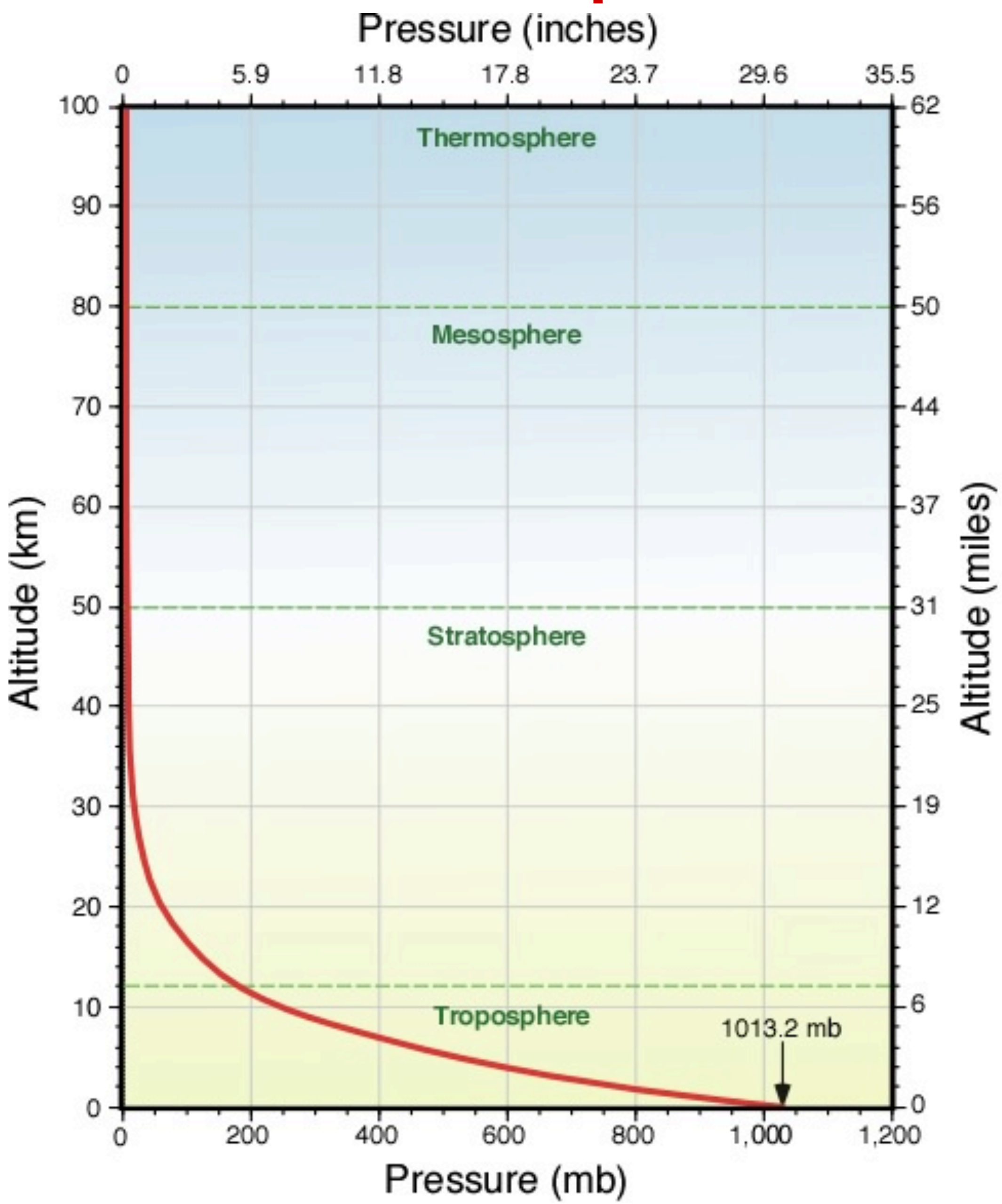
Propagation effects limit the horizon to about 100 Mpc.

All-particle CR energy spectrum




Cosmic-ray interactions in the atmosphere

Atmosphere



N_2 79.0 %

O_2 20.9 %

CO_2 0.03 %

Atmospheric structure

Altitude (km)	Vertical depth (g/cm^2)	Local density (10^{-3} g/cm^3)	Molière unit (m)	Electron Cherenkov threshold (MeV)	Cherenkov angle (°)
40	3	3.8×10^{-3}	2.4×10^4	386	0.076
30	11.8	1.8×10^{-2}	5.1×10^3	176	0.17
20	55.8	8.8×10^{-2}	1.0×10^3	80	0.36
15	123	0.19	478	54	0.54
10	269	0.42	223	37	0.79
5	550	0.74	126	28	1.05
3	715	0.91	102	25	1.17
1.5	862	1.06	88	23	1.26
0.5	974	1.17	79	22	1.33
0	1,032	1.23	76	21	1.36

US standard atmosphere

Atmospheric depth

$$\int \rho_{\text{air}}\, dl = X$$

X = atmospheric depth = amount of matter above any atmospheric layer

Typical values

$$\lambda_\pi \approx \lambda_K \approx 120\,\mathrm{g/cm^2}$$

$$\lambda_p \approx 90\,\mathrm{g/cm^2}$$

$$\lambda_{Fe} \approx 5\,\mathrm{g/cm^2}$$

Interaction length

$$\lambda_{\text{int}} = \frac{\langle m_{\text{air}} \rangle}{\sigma_{\text{int}}} = \frac{24160\,\mathrm{mb\;g/cm^2}}{\sigma_{\text{int}}}$$

$$\frac{dP}{dX_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}}$$

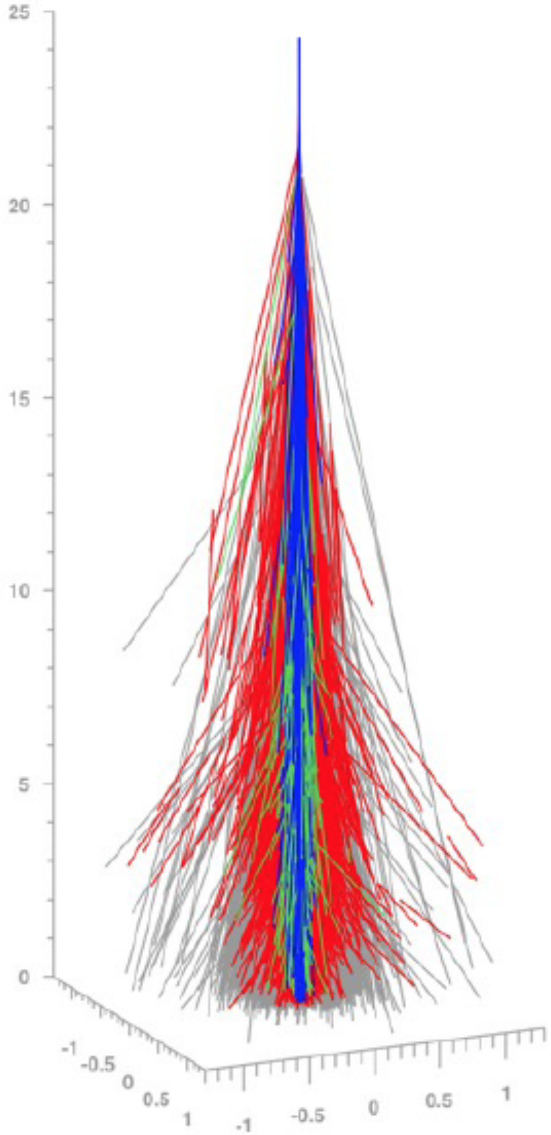
Moliere Radius

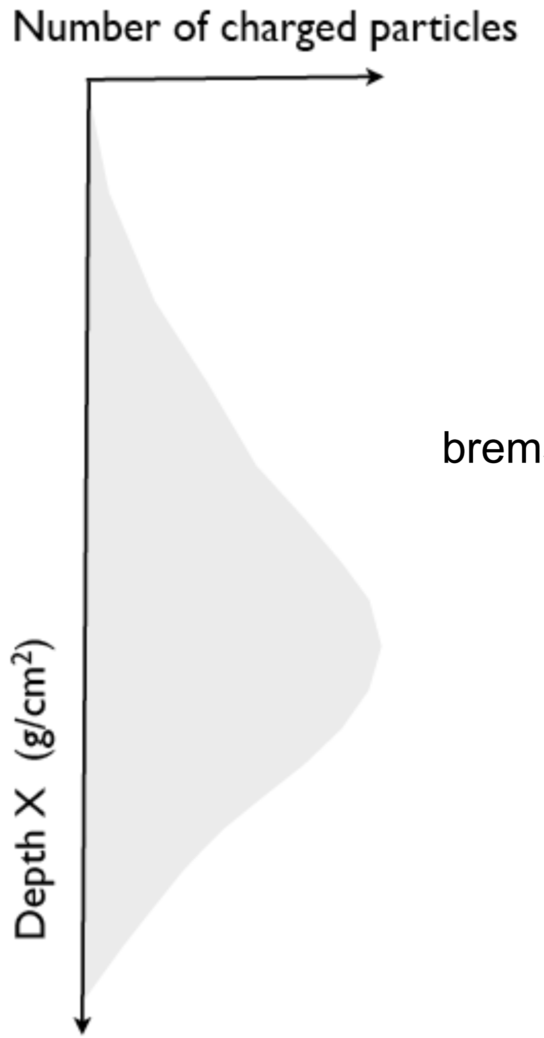
$R_M = 0.0265 X_o (Z+1.2)$

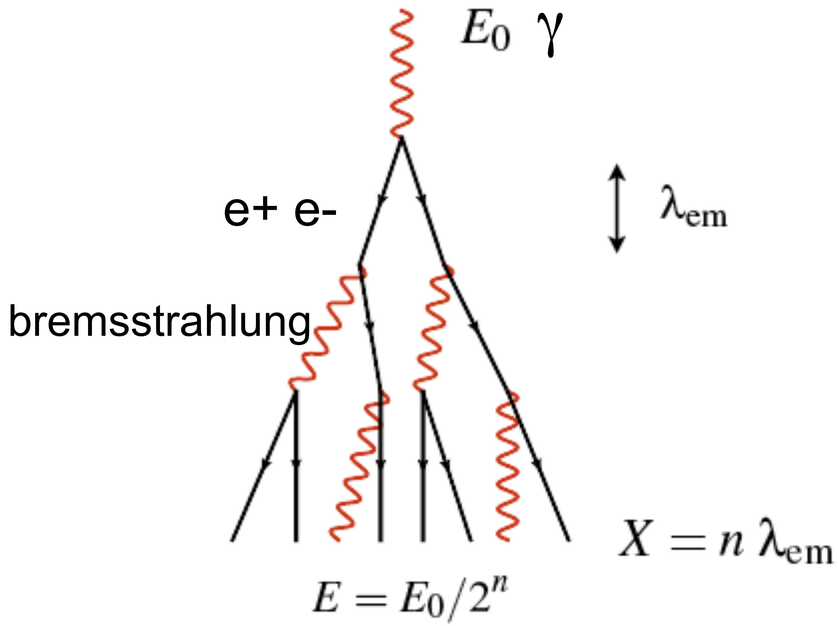
X_o = Radiation Length

Describes the transverse dimension of e/m showers.

Electromagnetic air showers







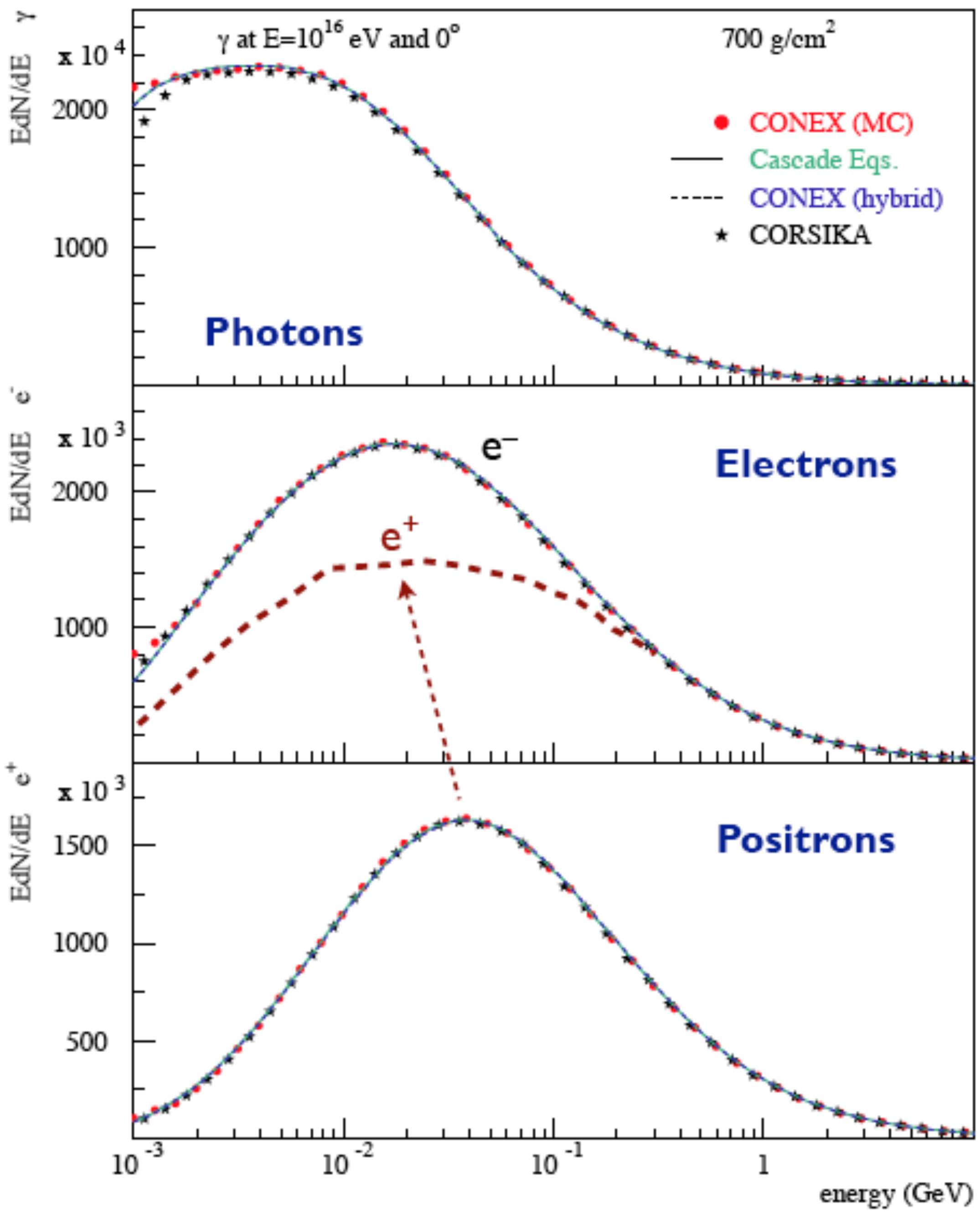
Shower maximum: $E = E_c$

E_c critical energy for bremstrahlung

$$N_{max} = E_0/E_c$$

$$X_{max} \sim \lambda_{em} \ln(E_0/E_c)$$

Energy spectra of secondary particles



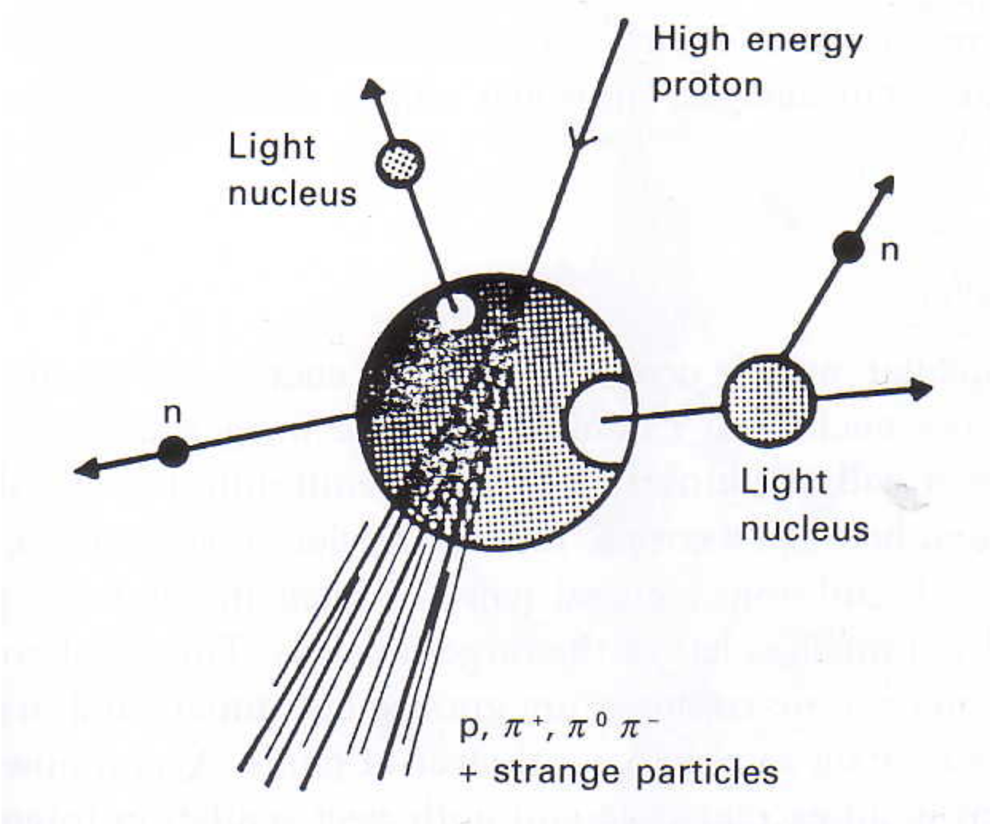
Number of photons divergent

- Typical energy of electrons and positrons $E_c \sim 80$ MeV
- Electron excess of 20 - 30%
- Pair production symmetric
- Excess of electrons in target

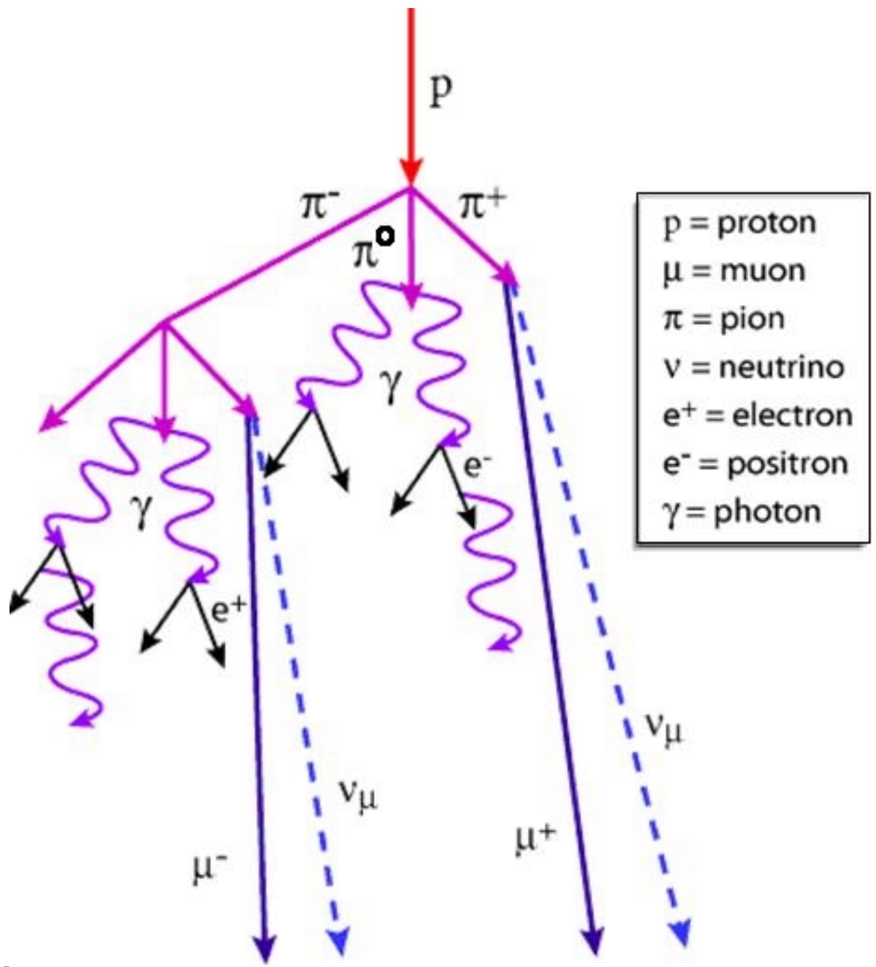
(Bergmann et al., *Astropart.Phys. 26 (2007) 420*)

Interactions of high-energy protons with matter

- Proton interacts with an individual nucleon in a nucleus
- Pions, π^+, π^-, and π^0 are produced together with some strange particles
- In the laboratory frame all products are very forward focused
- The remaining nucleus is left in a very highly excited, unstable state and several nuclear fragments can evaporate from the nucleus: **spallation** fragments



Main features of hadronic showers



$$\pi^0 \rightarrow 2\gamma$$

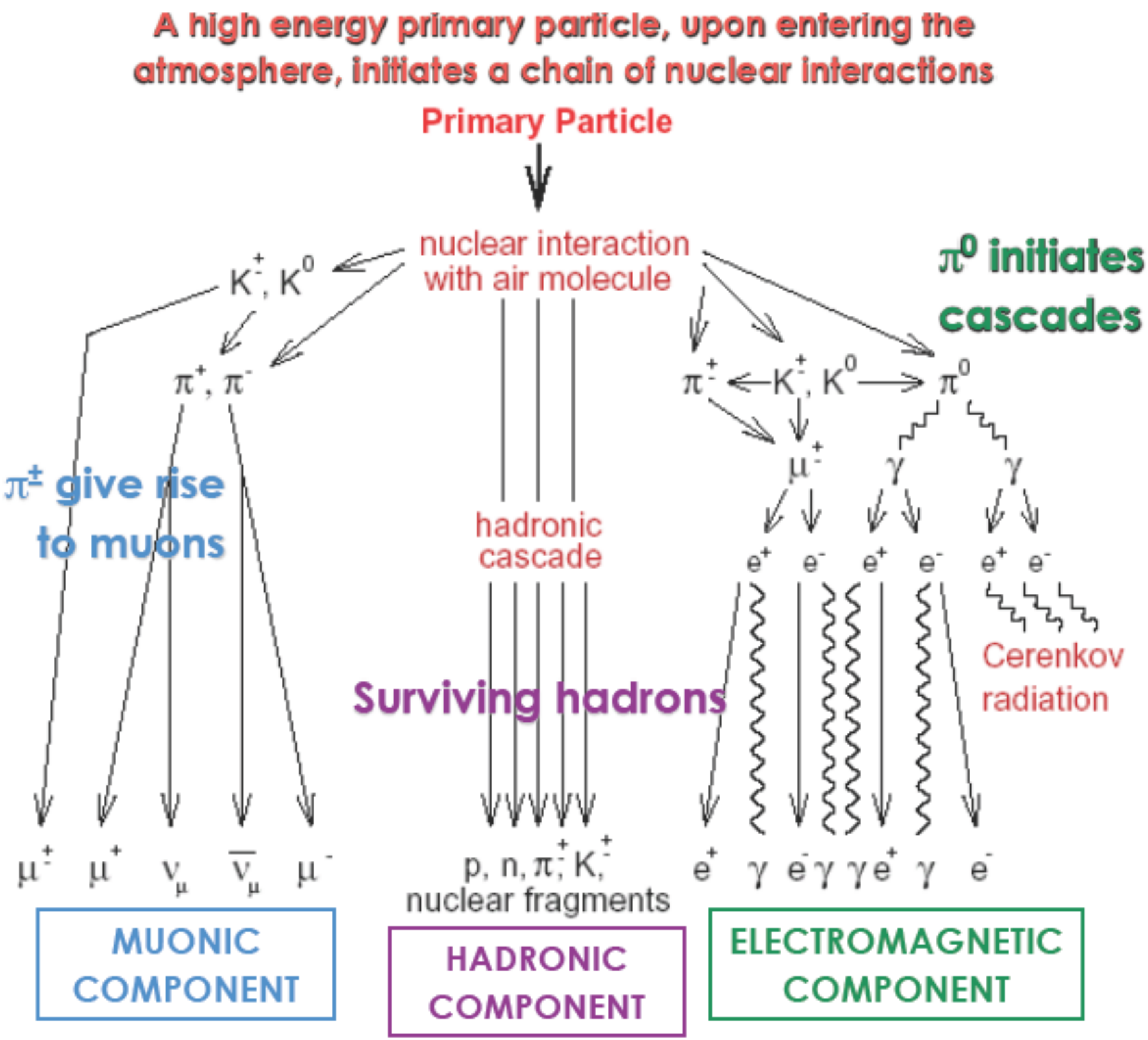
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Secondary nucleons and charged pions continue to multiply in successive nuclear collisions until the energy per particle drops below the energy necessary for pion production, about 1 Gev

High energy muons are produced in the upper layers of the atmosphere. They have virtually no nuclear interactions and penetrate far underground.

Extended Air Shower (EAS)



Superposition model

Proton-induced shower

$$N_{\max} = E_0/E_c$$

$$X_{\max} \sim \lambda_{\text{eff}} \ln(E_0)$$

$$N_\mu = \left(\frac{E_0}{E_{\text{dec}}}\right)^\alpha \qquad \alpha \approx 0.9$$

E_{dec} Muon decay energy

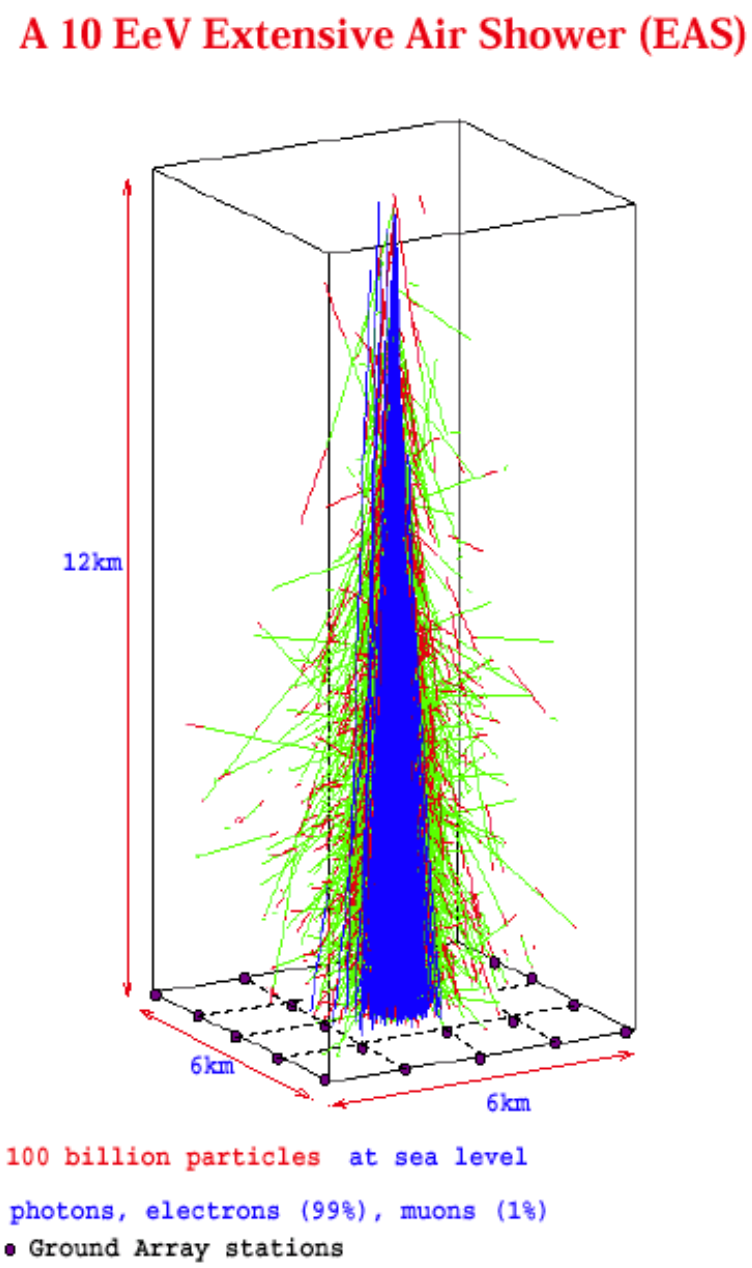
Assumption: nucleus of mass *A* and energy E_0 corresponds to *A* nucleons (protons) of energy $E_n = E_0/A$

$$N_{\max}^A = A\left(\frac{E_0}{AE_c}\right) = N_{\max}$$

$$X_{\max}^A \sim \lambda_{\text{eff}} \ln(E_0/A)$$

$$N_\mu^A = A\left(\frac{E_0}{AE_{\text{dec}}}\right)^\alpha = A^{1-\alpha} N_\mu$$

Atmosphere as a calorimeter



The energy loss of the shower along the cascade is essentially deposited through low energy charged particles.
Only a few percent of initial energy goes into neutrinos which are mainly produced in meson and muon decays.

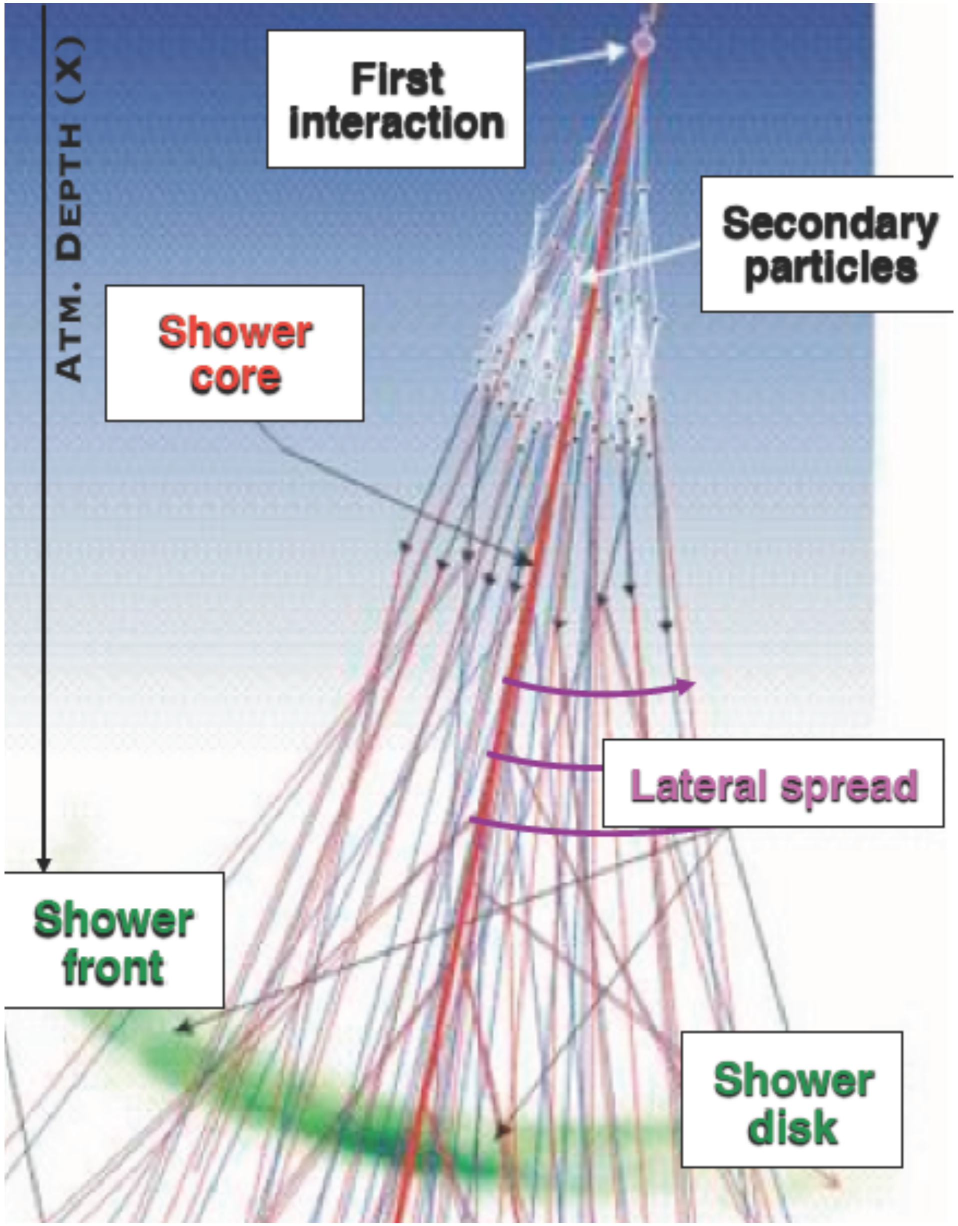
Atmosphere behaves as a giant calorimeter with good linearity !

Typical energies at ground level:
γ, e, (99%) μ (1%)

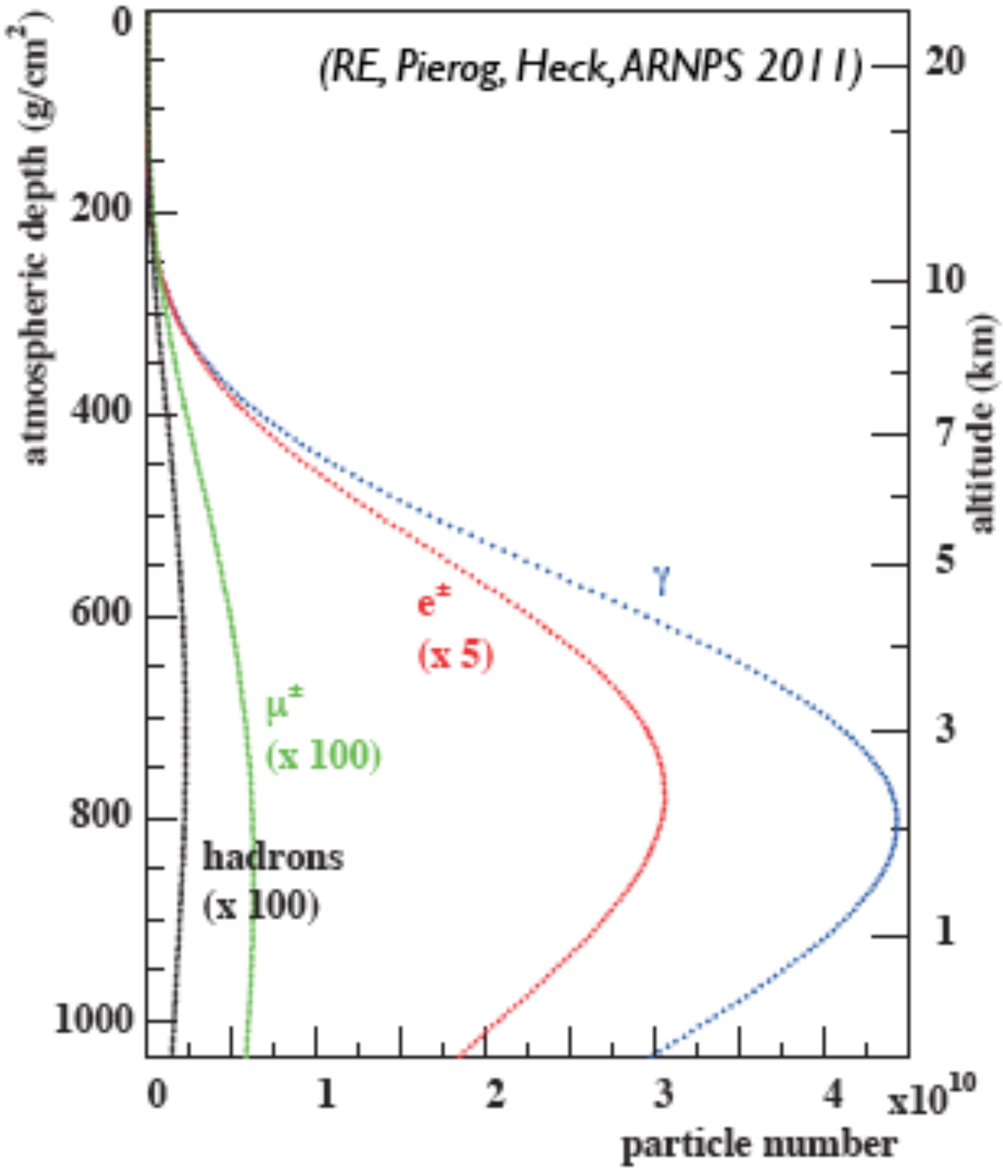
γ et e : Energy about a few MeV

μ : Energy about a few GeV

Shower parameters

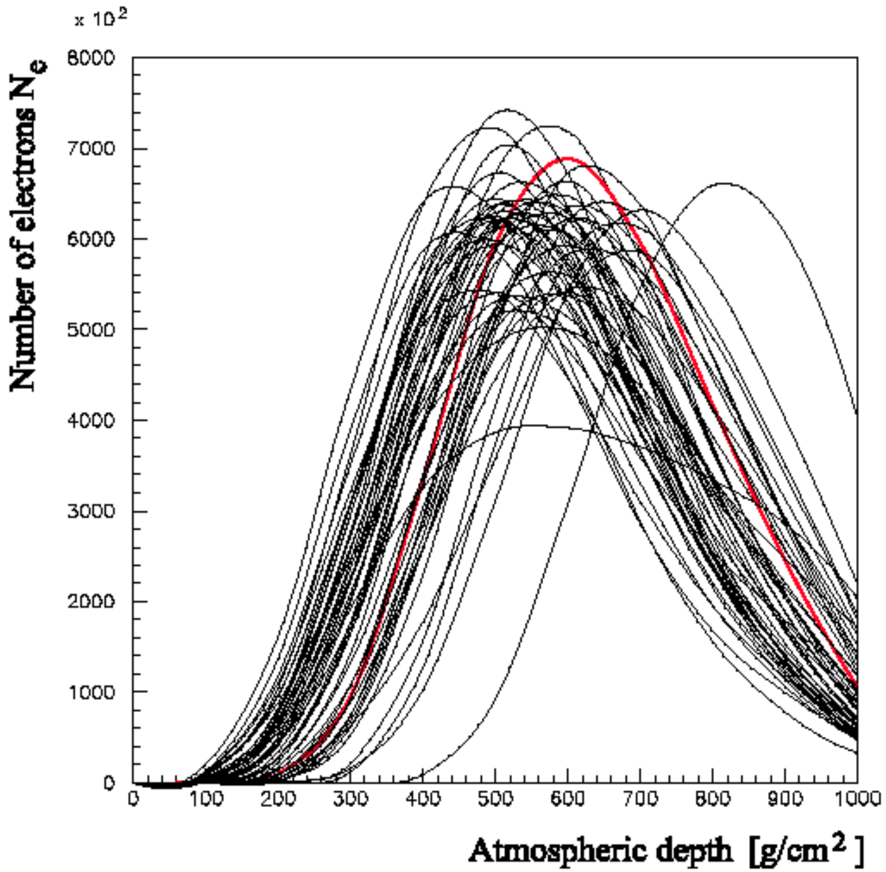


Longitudinal shower development



Fluctuations

Fluctuations originate mainly from the very first steps, and especially from the position X_0.

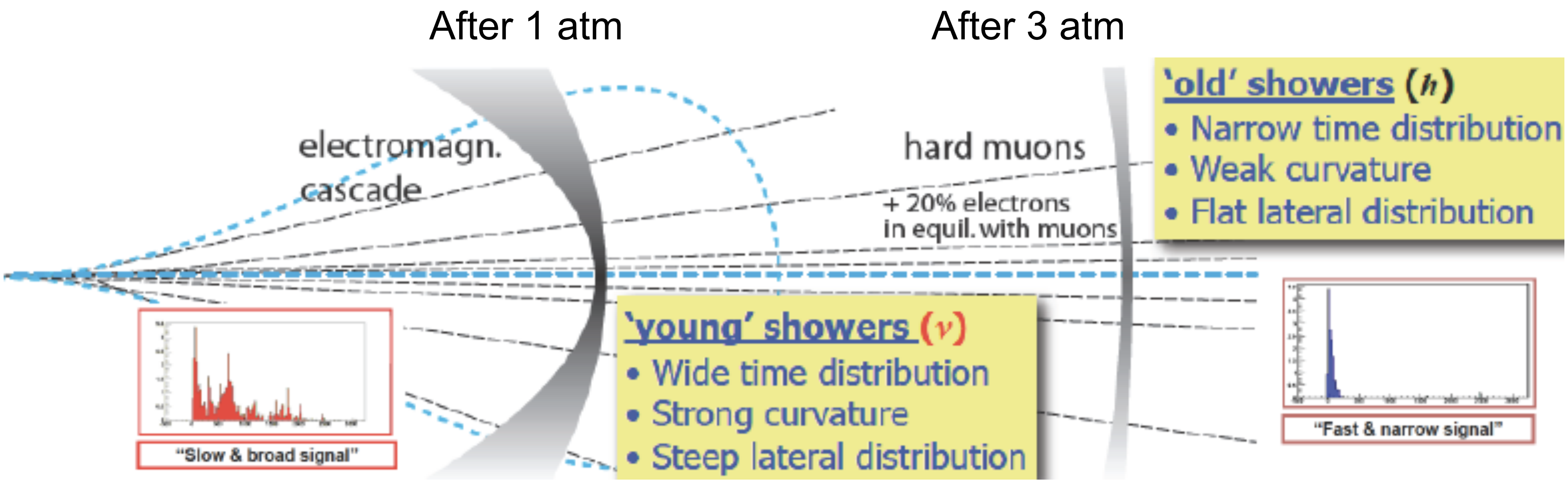


The position Xmax has a fluctuation of a few 10 g cm^{-2}.

The distribution of the ground particles (lateral distribution) depends on X and is also affected by the X_0 fluctuations.

Dispersion decreases as a function of primary mass. Sensitive to primary mass!

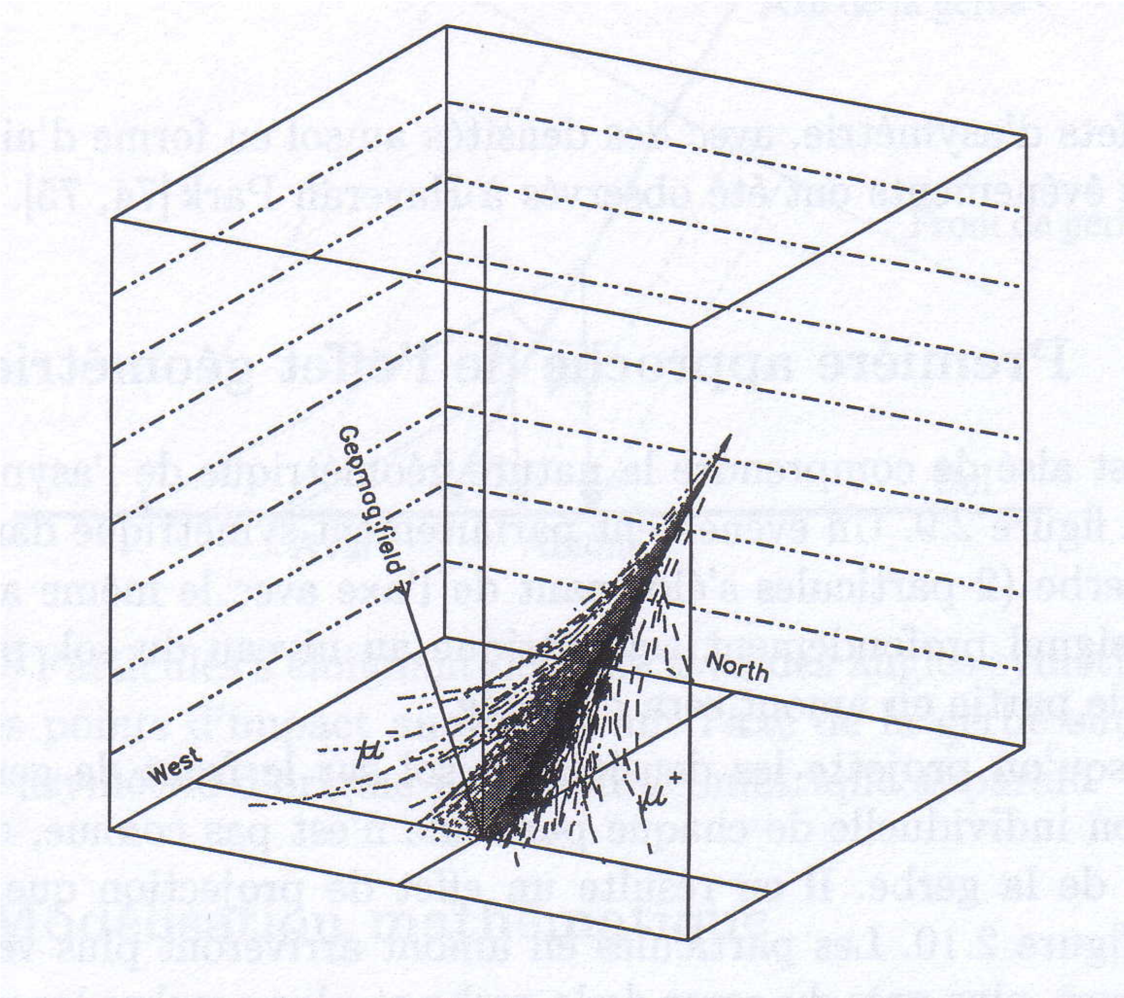
Space-time structure of showers



The muons and surviving pions are generally highly relativistic and very forward focused.
The muons are mostly concentrated in the front part of the shower cone.

Electromagnetic component is a result of a diffusive process and has a larger spread.
Horizontal showers: electromagnetic component is absorbed by the atmosphere, mostly only muons are left.
Identification of neutrino induced showers!

Effect of the Earth's magnetic field



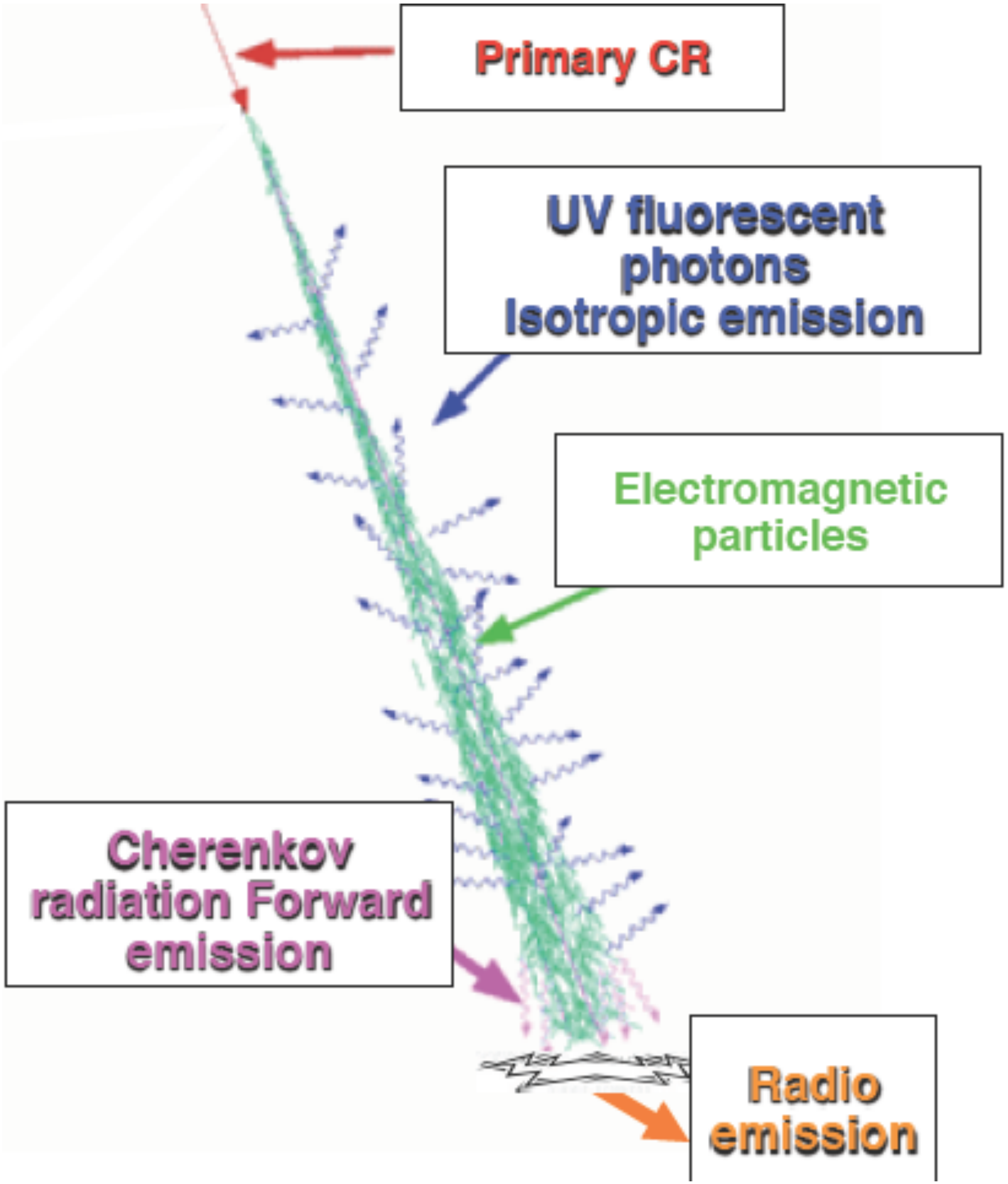
At large primary angles (> 60°), the distance traveled by muons is large enough to be affected by the Earth's magnetic field. A muon of 50 GeV traveling 10 km deviates about 200 m.

Electromagnetic cascade develops on shorter distances and is not affected by the magnetic field.

Must be taken into account in the case of horizontal showers !

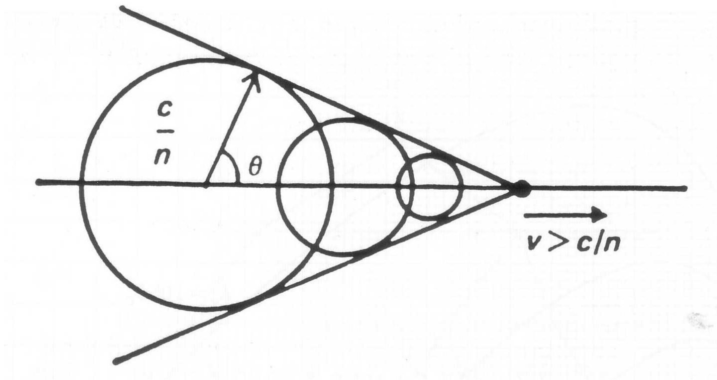
Radiations from shower development

Shower development



Cherenkov radiation

Particle moves through medium at a constant velocity which is greater than the velocity of light in that medium.



A shock wave is created behind the particle resulting in a energy loss

Atmospheric Cherenkov Telescopes to detect gamma rays ! Can also be used to detect charges cosmic rays.

Cherenkov wavelength around 400 nm

Atmosphere is transparent to light between 300 and 600 nm.
Most Cherenkov light reach ground.
Cherenkov photons are strongly beamed.
Cherenkov photon yield initiated by cosmic ray primaries (hadrons) is significantly smaller than for yield initiated by gamma rays.

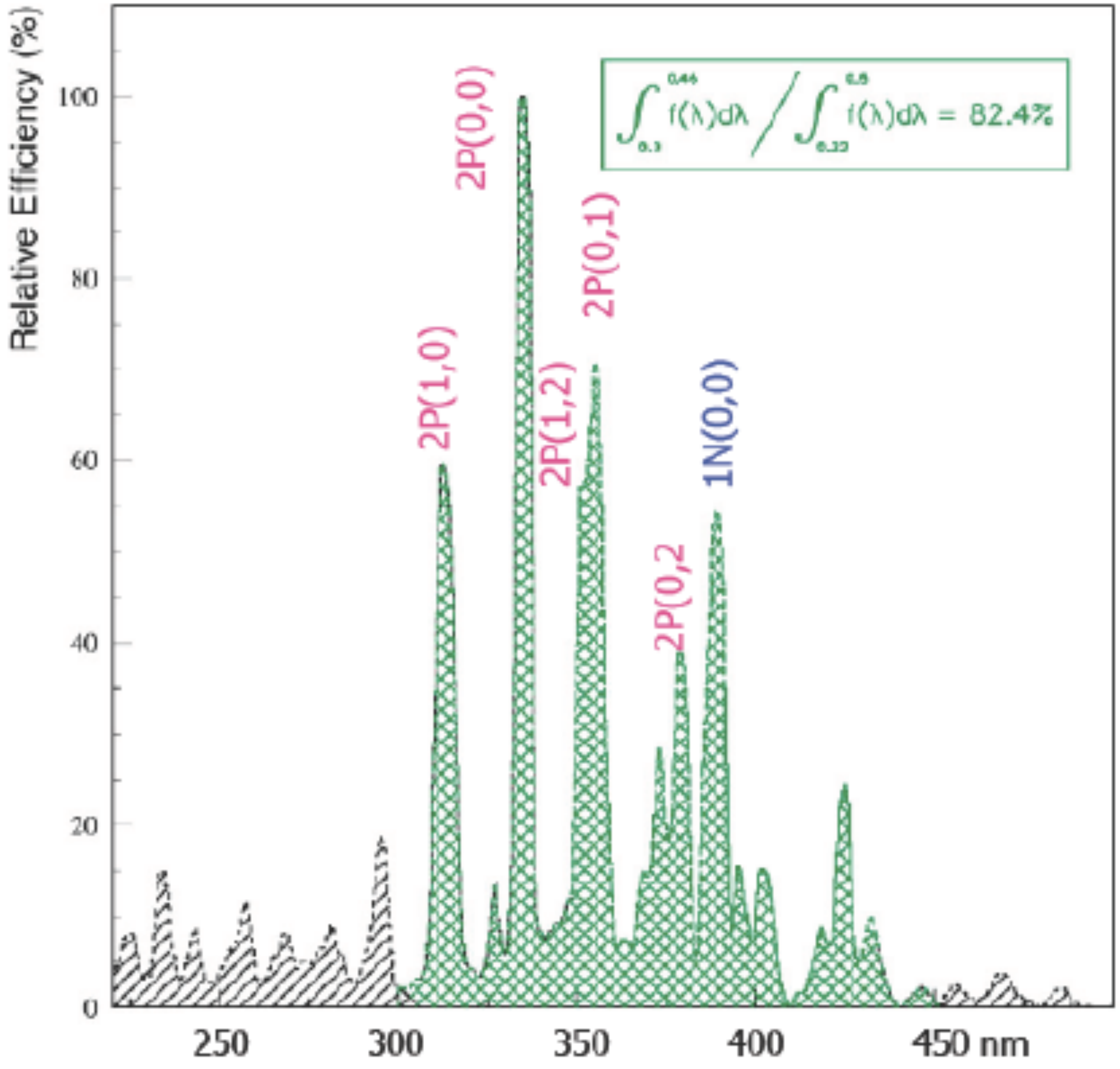
Fluorescence light emission

The nitrogen molecules are excited by charged particles (electrons and positrons).

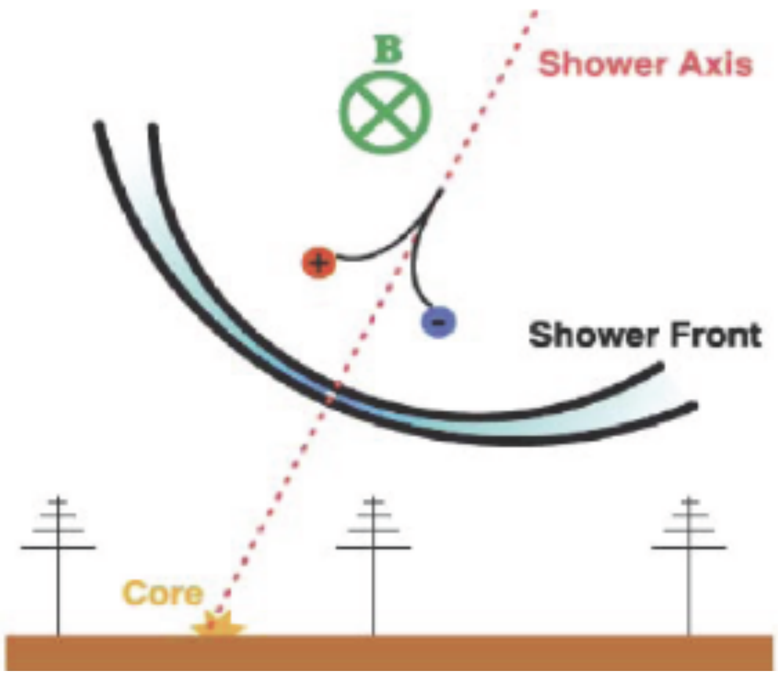
They decay emitting fluorescence light.
Emission is isotropique.

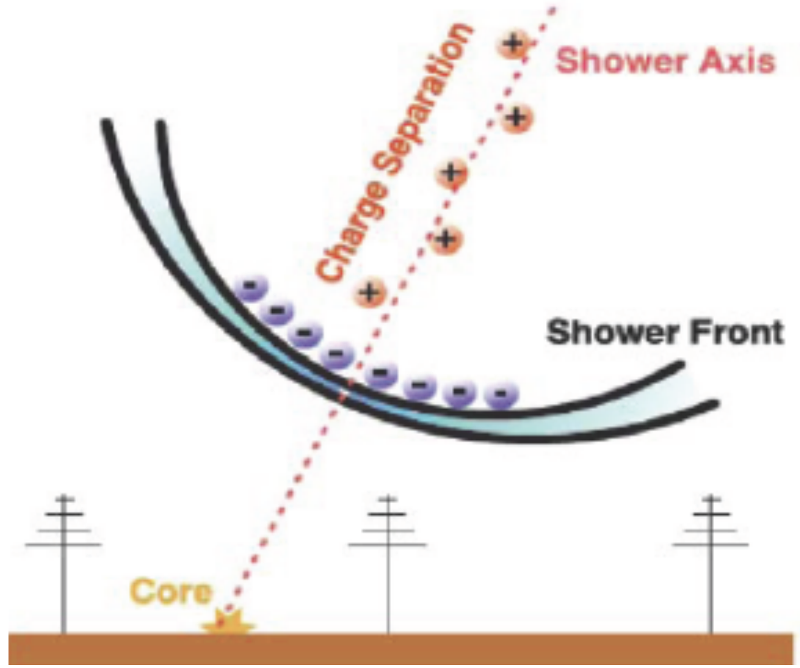
Fluorescence light can be detected at large distances, up to 40 km with current telescopes.

It gives the longitudinal profile of the shower.



Radioemission





Geomagnetic effect:
deflection of charged particles in Earth's magnetic field (B). Electric current develops when the plasma moves through B. Radiation emitted by time varying electric current

Askarian effect:
radio emission in the form of Cherenkov radiation. Due to the annihilation of positrons an excess of negative charge is created, producing radio emission.

Microwave emission

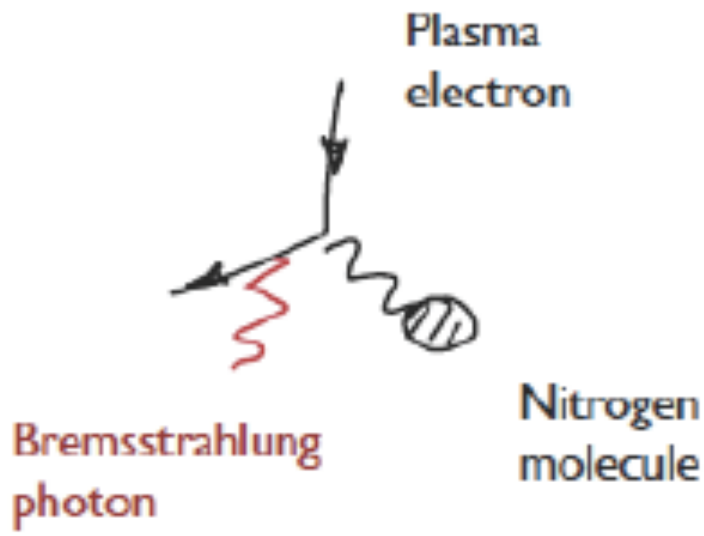
Molecular bremsstrahlung emission

Shower particles dissipate energy through ionization.

This produces a plasma with T(electrons) ~ 10^4-10^5K.

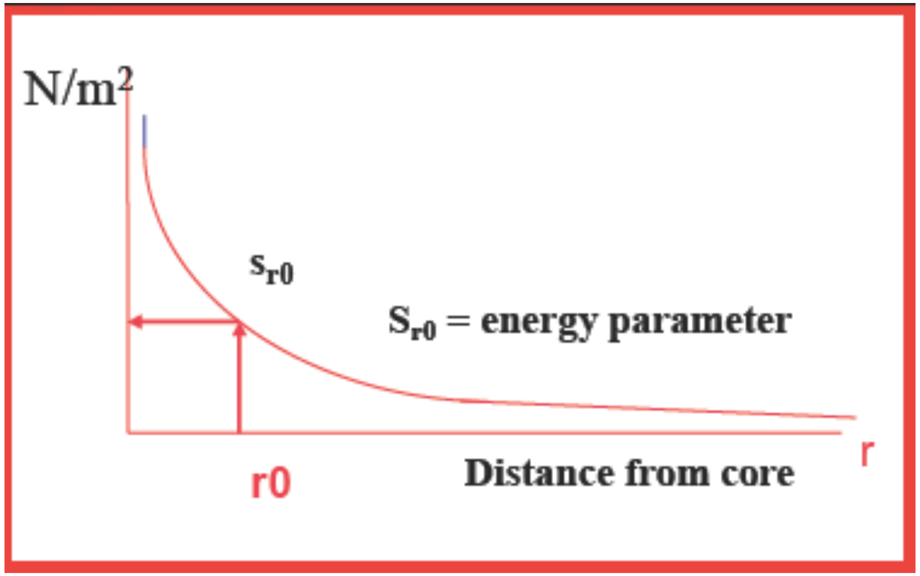
The low energy tail of free electrons produce Bremsstrahlung emission in microwave regime from scattering interactions with neutral air molecules.

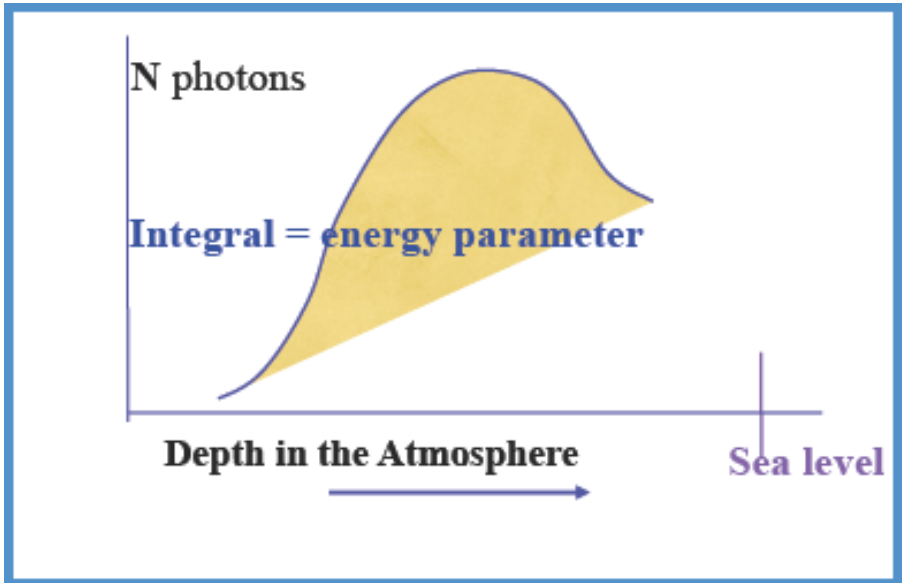
Observed in laboratory. First observation from showers too (2011)



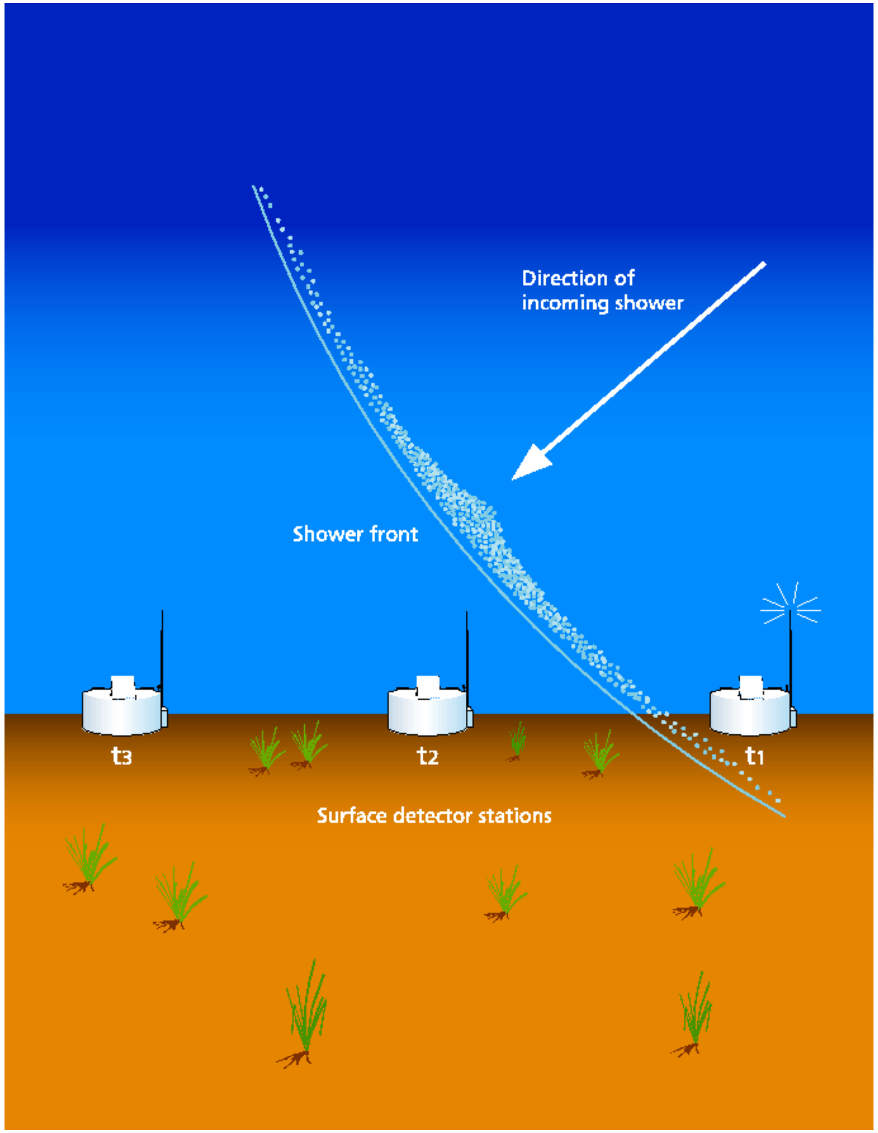
Estimation of energy

Number of electrons N_e: at shower maximum
N_e is proportional to primary energy (need of MC)
– **Lateral distribution of particles:** there is a distance, r_0, at which density fluctuations are minimal with respect to primary energy/mass: S (r_0) is the energy estimator (need of MC)
– **Number of muons N_μ : less absorbed,** "flatter" longitudinal development, less fluctuations. Less numerous than electrons, but ≈ independent of mass (need MC)
– **Cherenkov and fluorescence photons: direct measurement of shower** energy deposited in atmosphere (total number of Cherenkov photons; longitudinal shower profile). Model independent



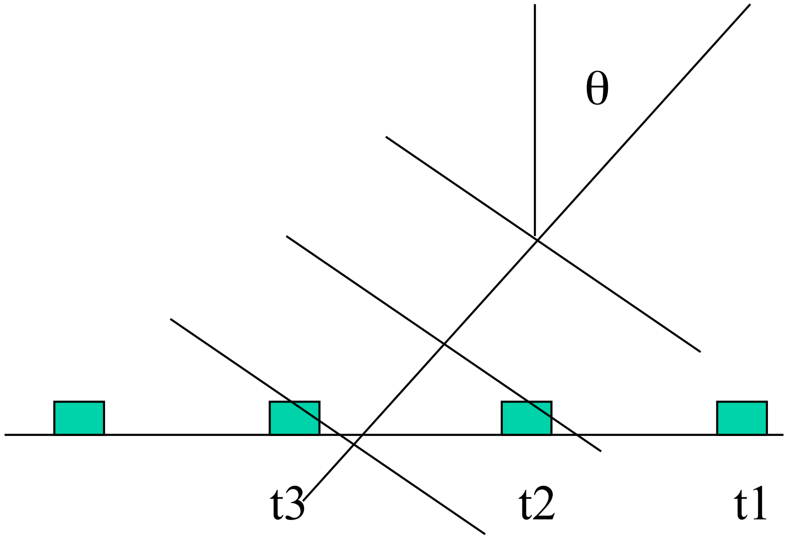


Reconstruction of primary angle



Surface detectors:

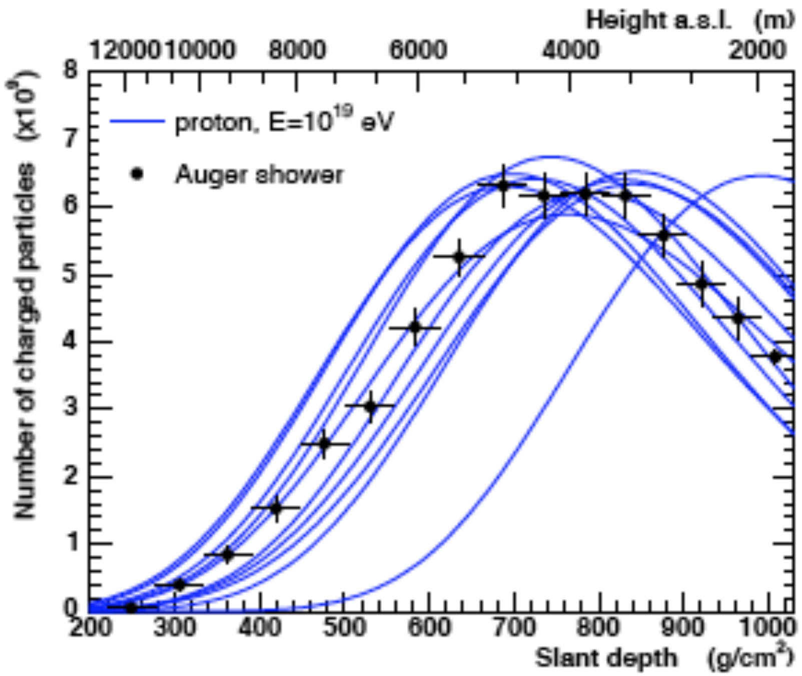
Primary angle obtained from arrival time of the shower front $c\Delta t = d\cos(\theta)$, d is the distance between detectors projected to the shower axis.

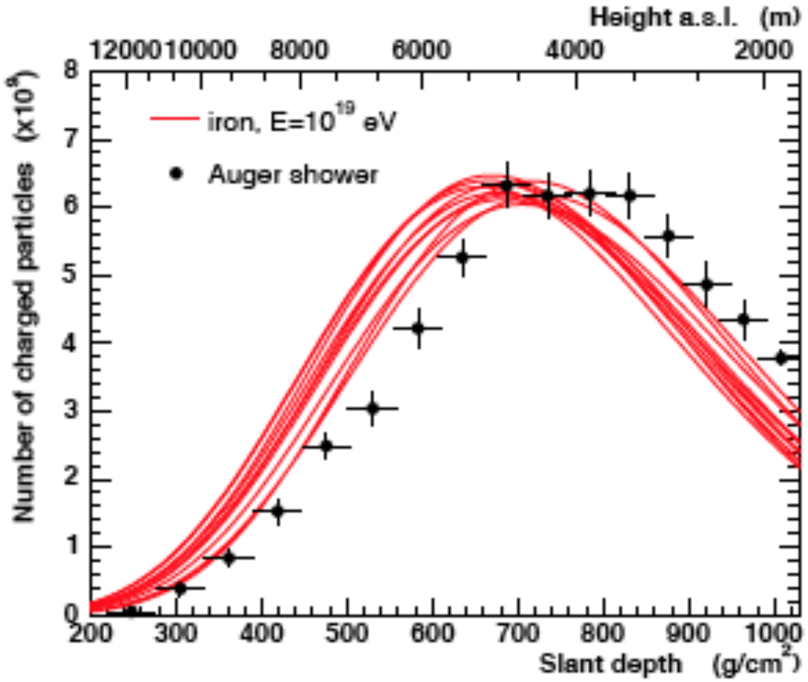


Fluorescence detectors:

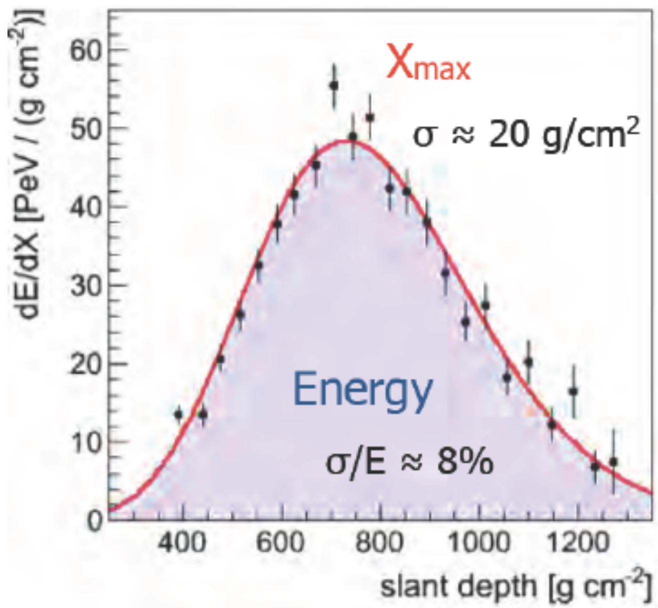
Primary angle obtained from shower core reconstruction.

Estimation of primary mass



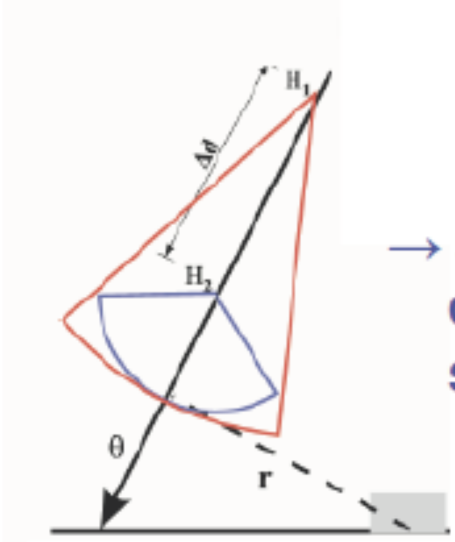


First interaction of heavy primaries is shallower and fluctuates less.
Measurement of longitudinal profile by measuring the fluorescence light.

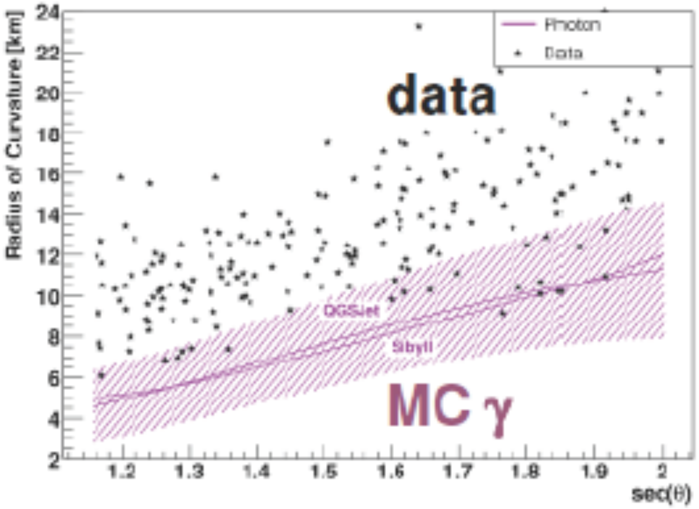


Identification of photon induced showers

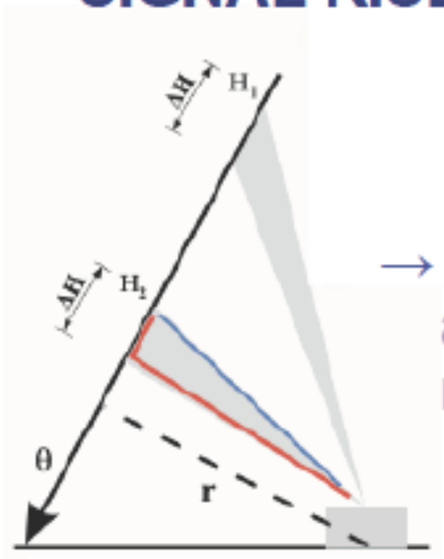
SHOWER FRONT CURVATURE



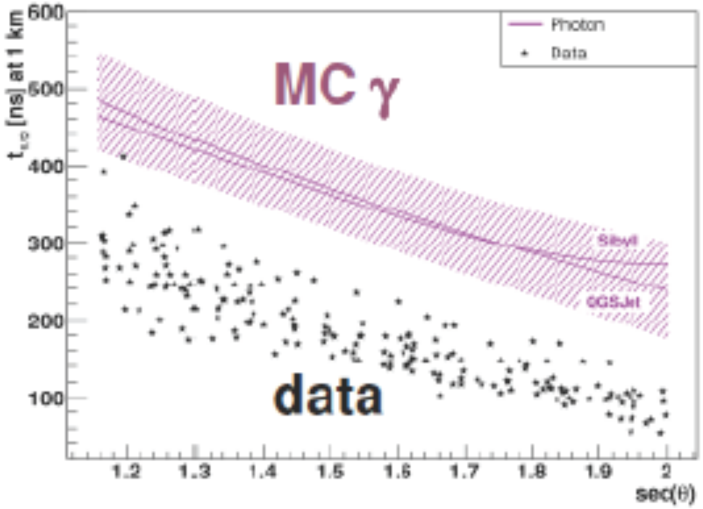
→ smaller radius of curvature of the shower front



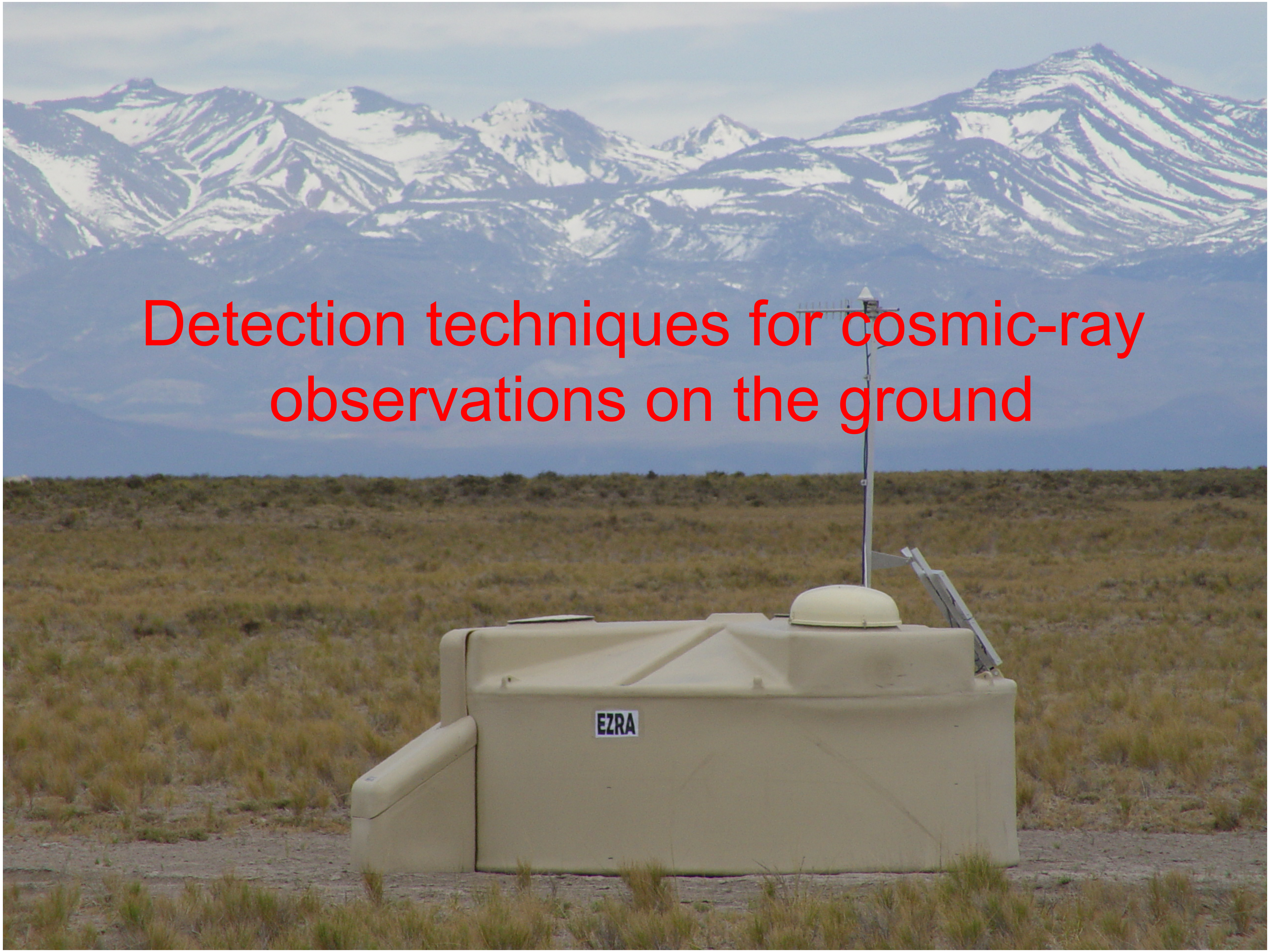
SIGNAL RISE TIME



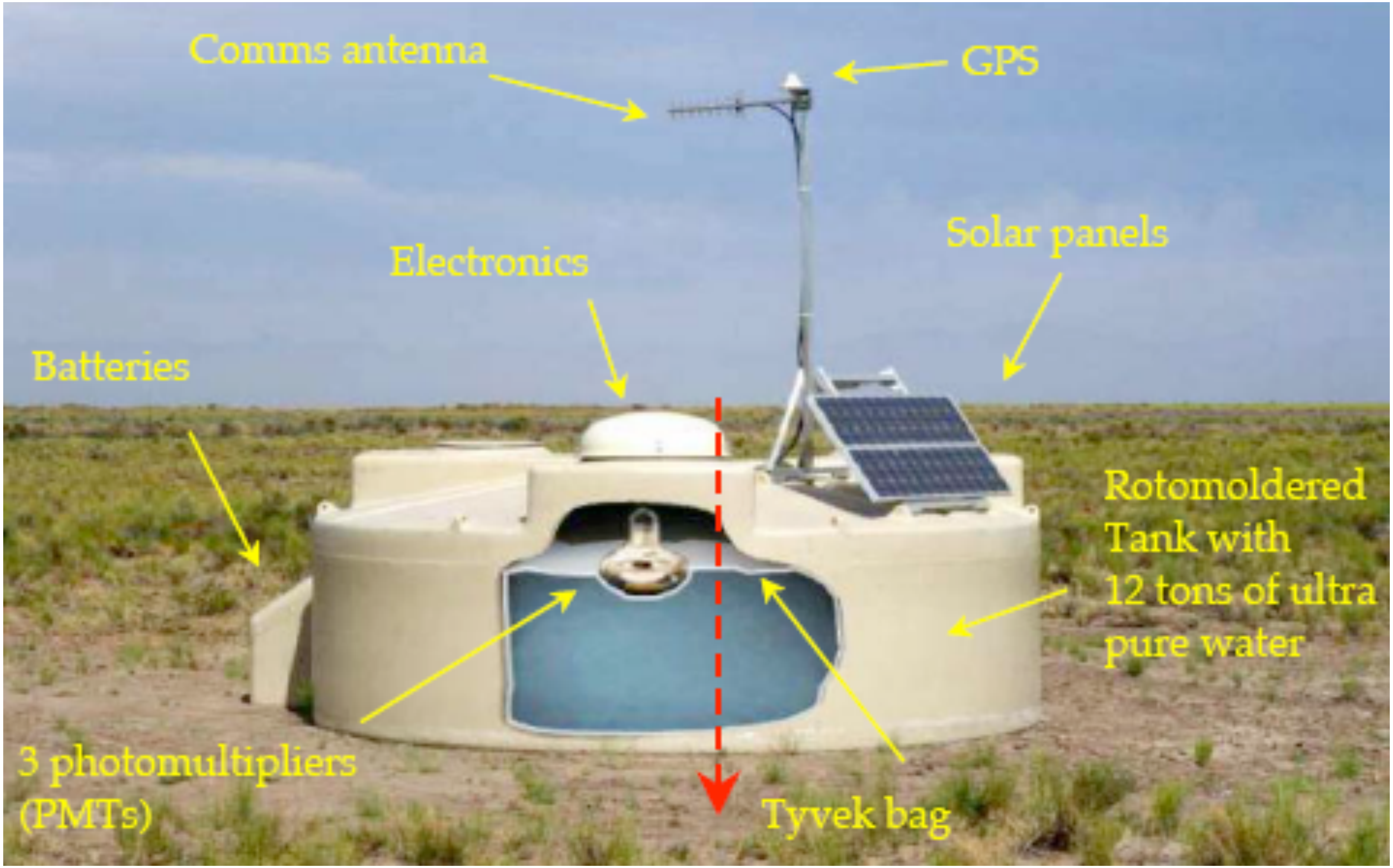
→ larger time spread and longer signal risetime



Detection techniques for cosmic-ray observations on the ground



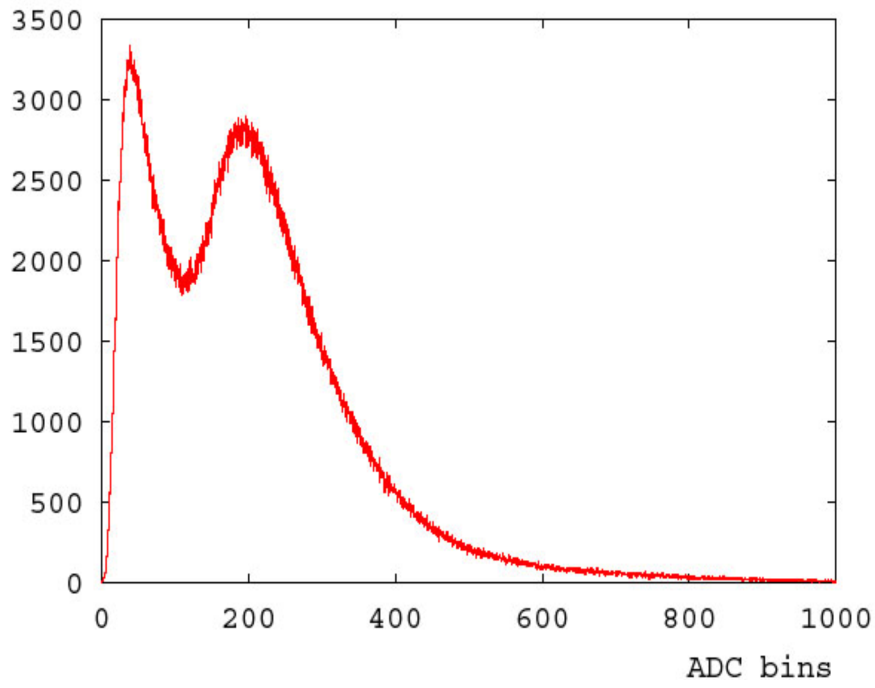
Water Cherenkov Detector (Auger)



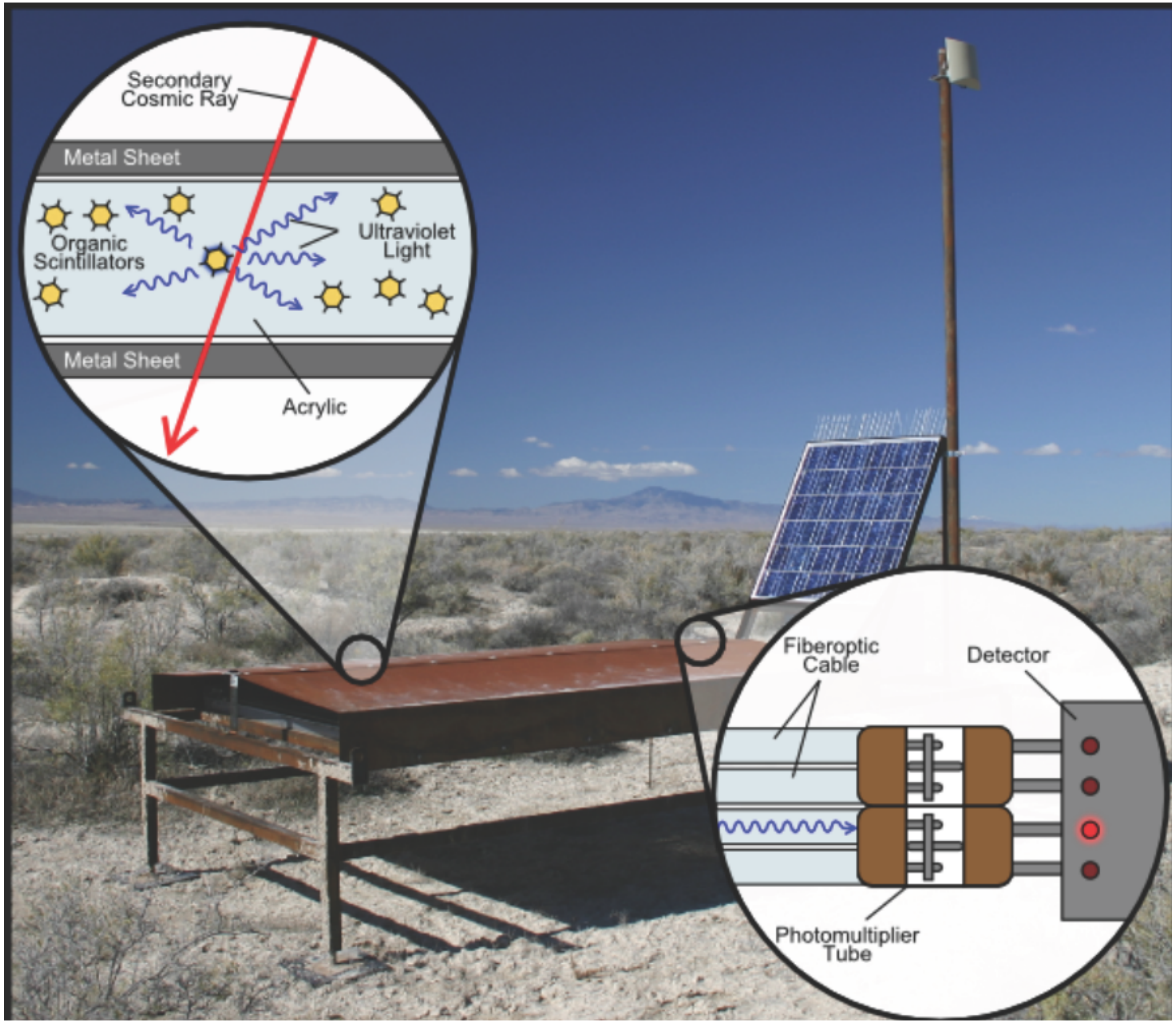
Detector response

Shower particles at the ground level are mainly gammas, electrons and muons with mean energies below 10 MeV for gammas and electrons and about 1 GeV for muons.
Electrons and gammas are completely converted while vertical muons deposit approximately 240 MeV of energy.
Electrons and muons emit Cherenkov radiation which is propagated in the purified water and uniformly reflected by the Tyvek liner.
Gammas are converted by Compton scattering and pair production into relativistic electrons emitting similarly Cherenkov radiation.

For the detector calibration, the chosen unit is the total charge deposited by the vertical muons crossing the center of the tank: VEM
Determination of the VEM unit (Q peak) with background muons
Conversion between the Q peak and the charge corresponding to vertical muons through test tank measurements and simulations



Scintillator (Telescope Array)

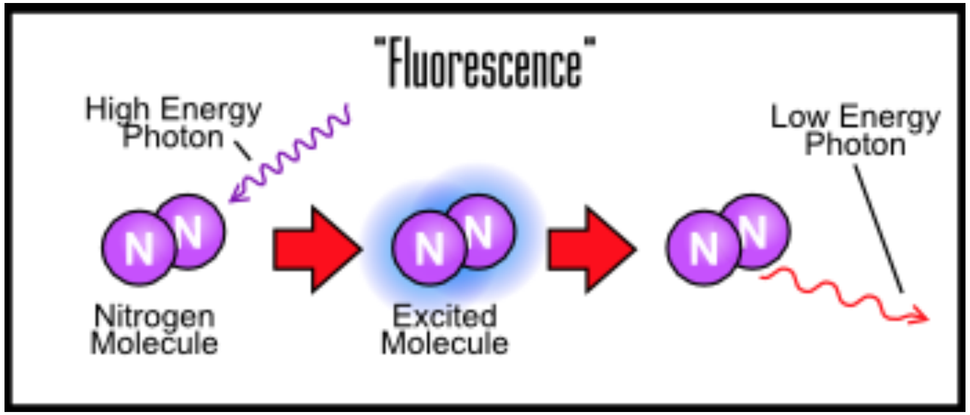


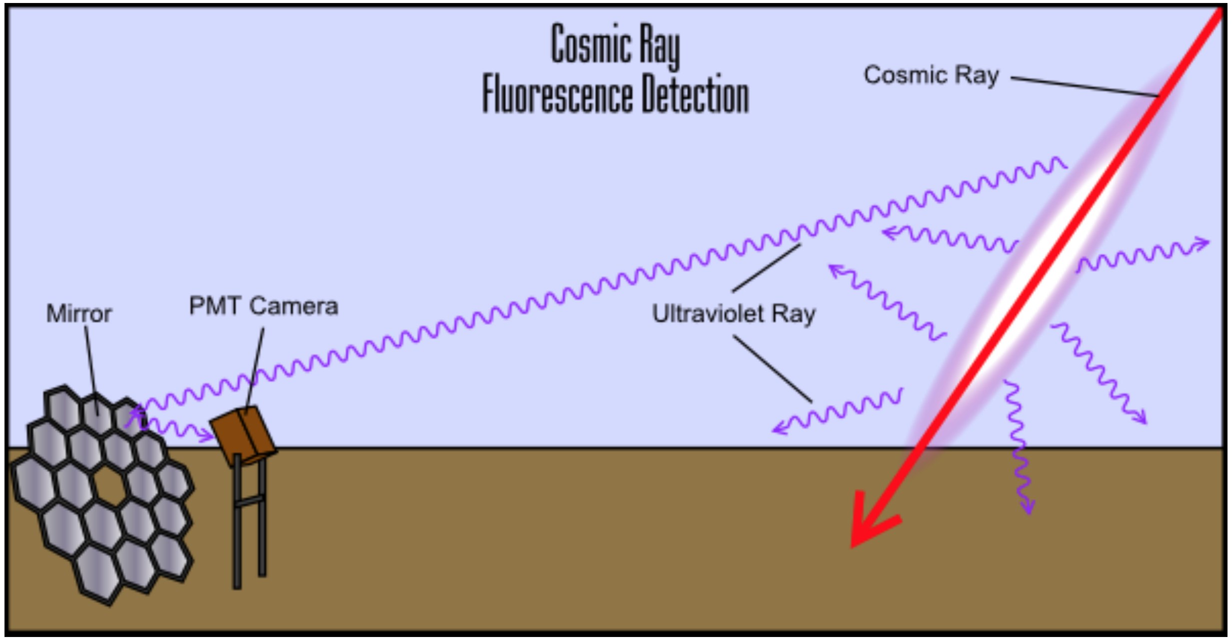
The detecting device consists of sheets of acrylic which have been infused with molecules designed to interact with charged particles.

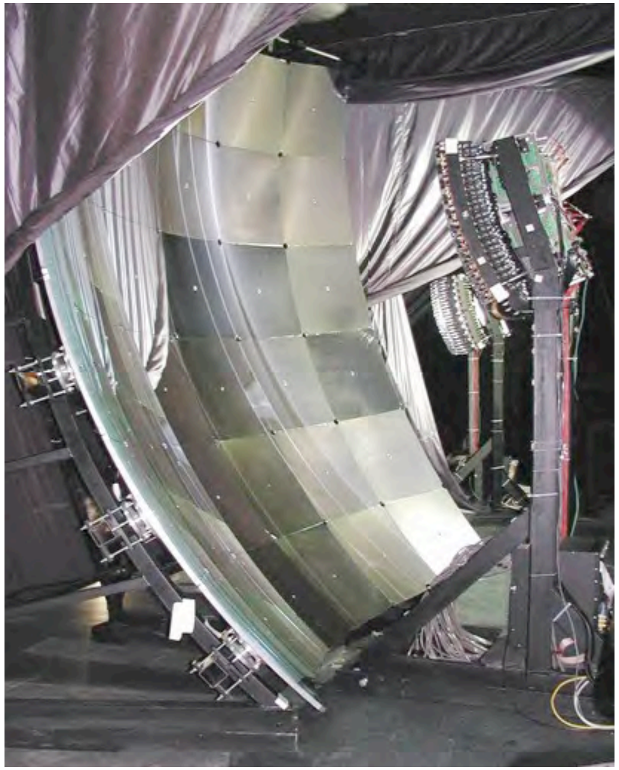
When a secondary air shower particle passes through this material, the scintillating molecules are excited and release ultraviolet light.

This light is gathered by optical fibers which direct the light onto a Photomultiplier Tube. Calibration is done with background muons.

Fluorescence telescopes (Auger)

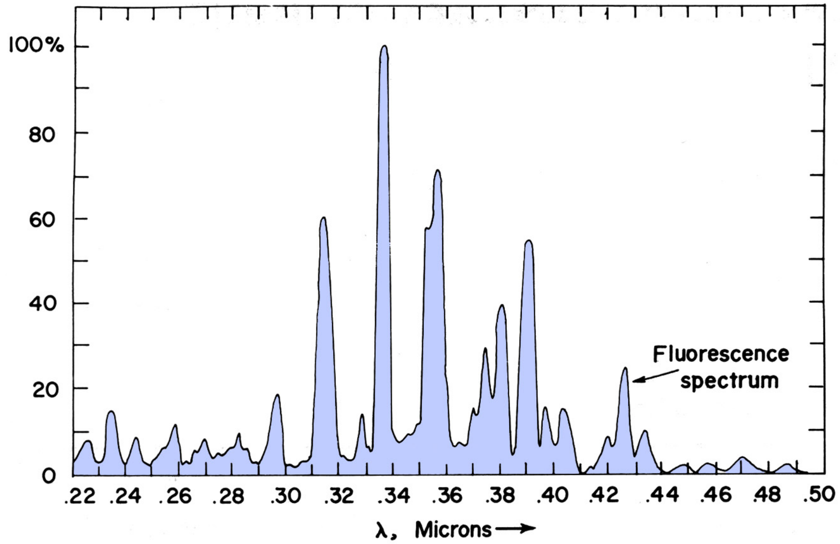


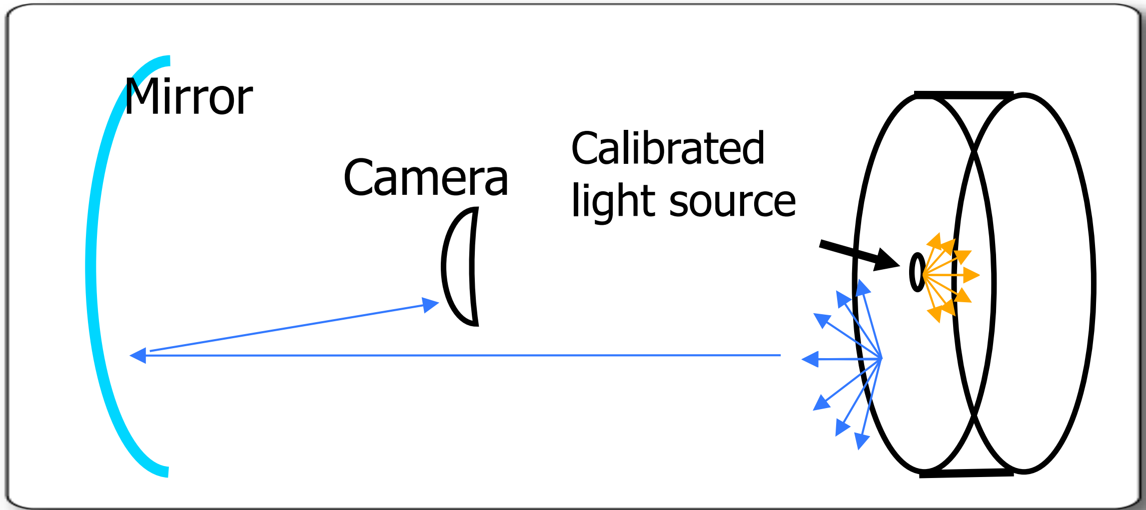




Isotropic light emission.
About 10-15% duty cycle.
Atmospheric monitoring is important!

Fluorescence yield and calibration





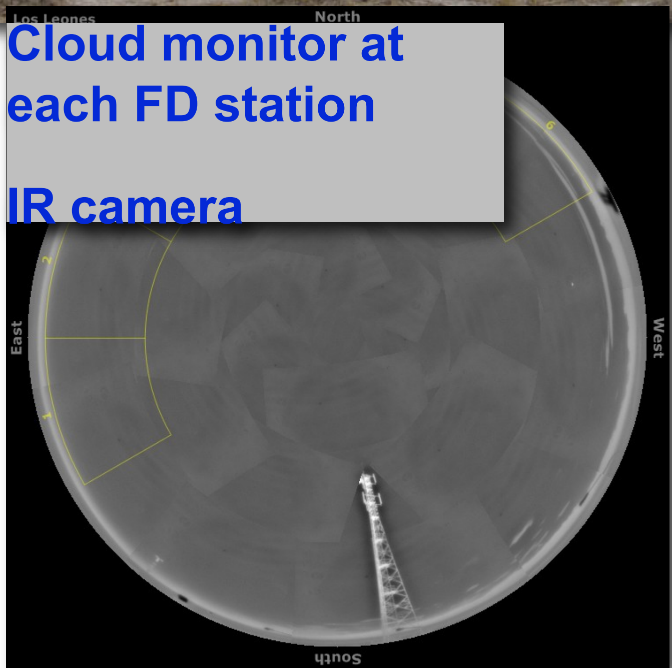
Diffuse Lightsource

Requires knowledge of fluorescence yield. Requires absolute calibration.

Atmospheric Monitoring

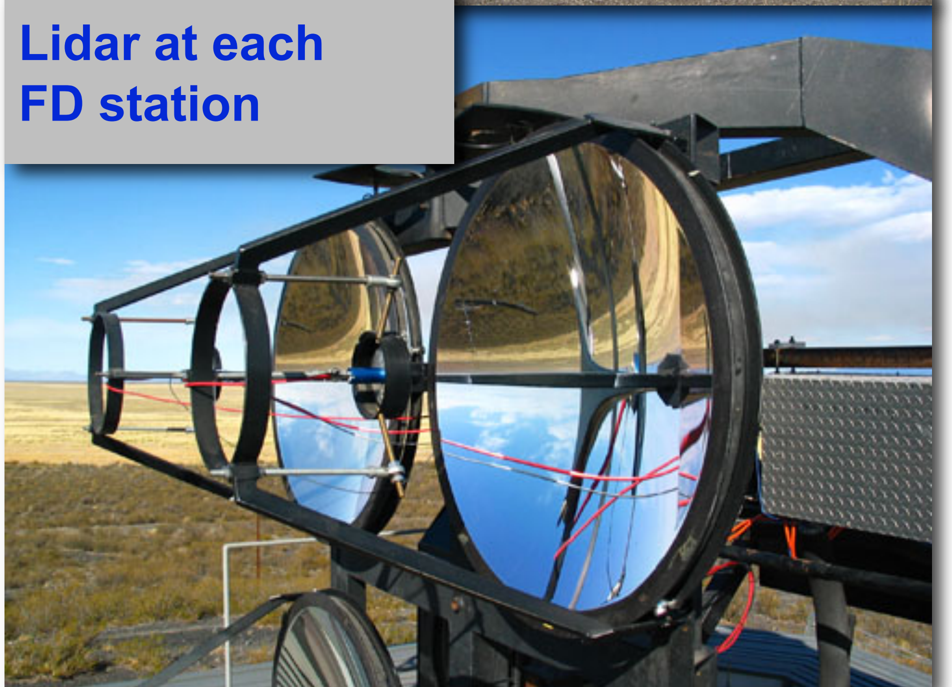
Central Laser Facility

Radiosounding of atmospheric profiles



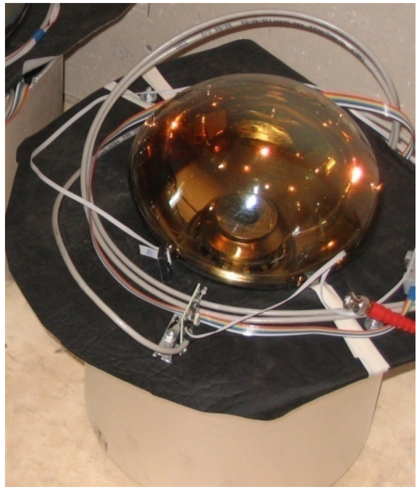
Cloud monitor at each FD station

IR camera



Lidar at each FD station

Cherenkov telescopes (Tunka array)

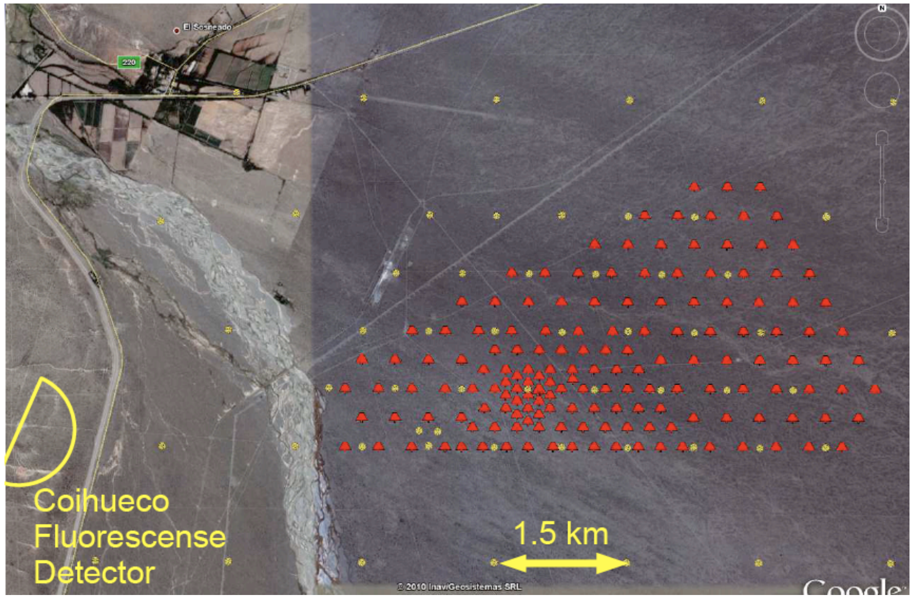


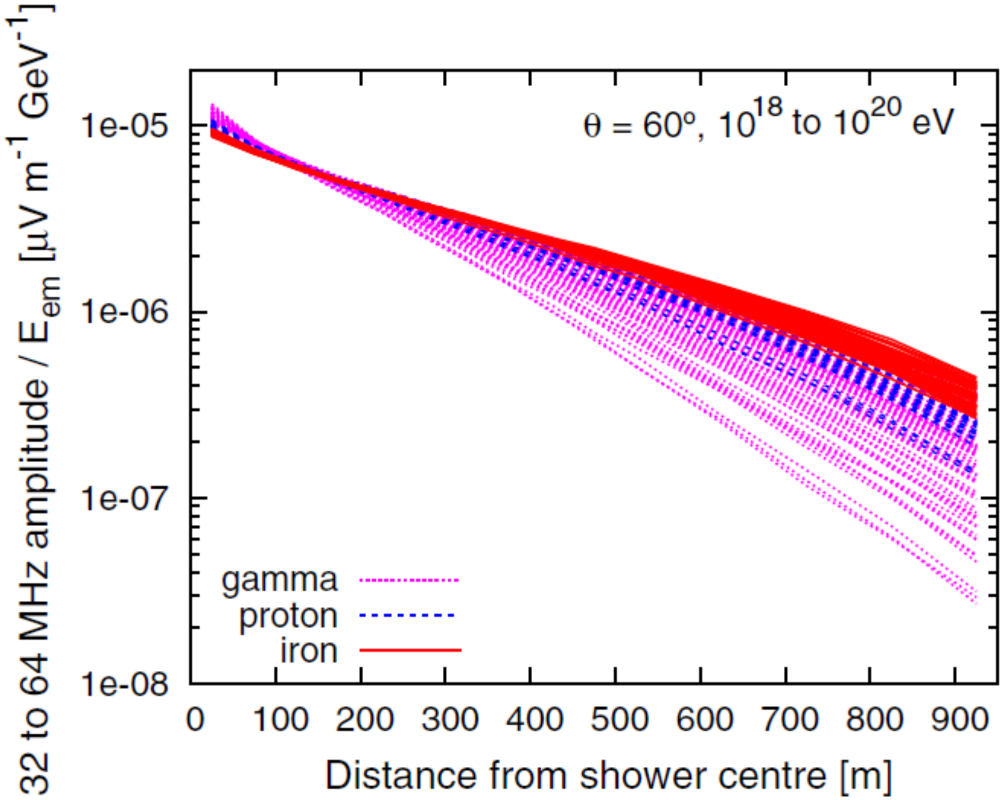
Radio arrays (AERA)

Auger Engineering Radio Array

- calorimetric energy measurement
- near 100% duty cycle (cf. 10% of optical fluorescence detectors)
- Xmax sensitivity
- Problem: Signal drops as a function of distance from the shower core.

AERA: 161 MHz radiodetector stations





GHz emission detection

- Emission 3.4-4.2 GHz
- R&D on Auger site
- Parabolique antennas with camera
- Antennas on Surface Detector tanks

MIDAS
Chicago/Rio/Bariloche/USC

Conclusions

Cosmic rays produces cosmic showers in the atmosphere.

From observation of these showers, characteristics of primary particle can be deduces.

These showers can be detected by

✓sampling ground particles

✓detecting fluorescence or Cherenkov light

✓Detecting radio or microwave emission (under development)

References

High Energy Astrphysics, Vol. 1 – 3, Malcolm S. Longhair,
Cambridge University Press