Cosmic Rays at Extreme Energies
The Pierre Auger Observatory

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Lecture 1

Outline

- Lecture 1

  The High End of the Cosmic Ray Spectrum

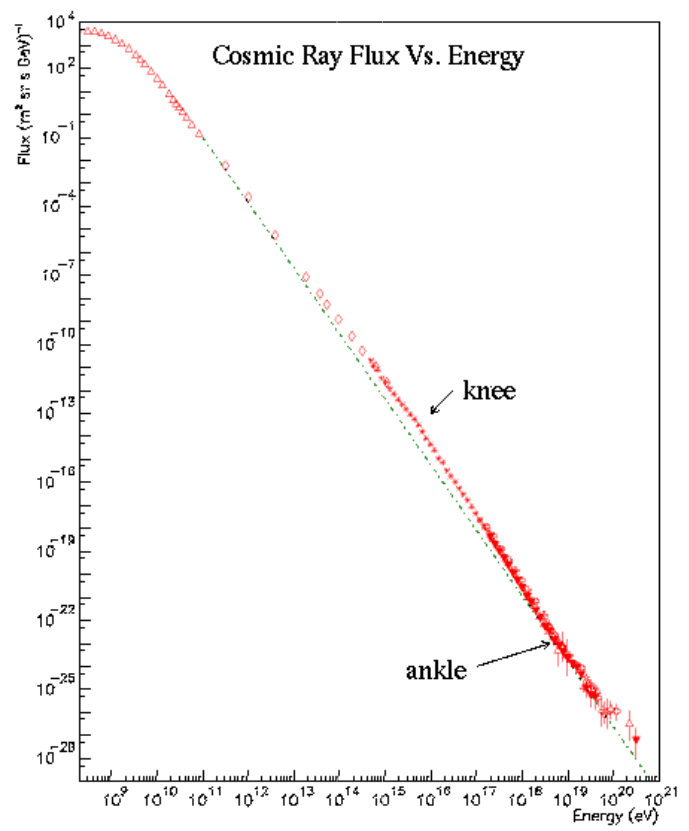
- Lecture 2

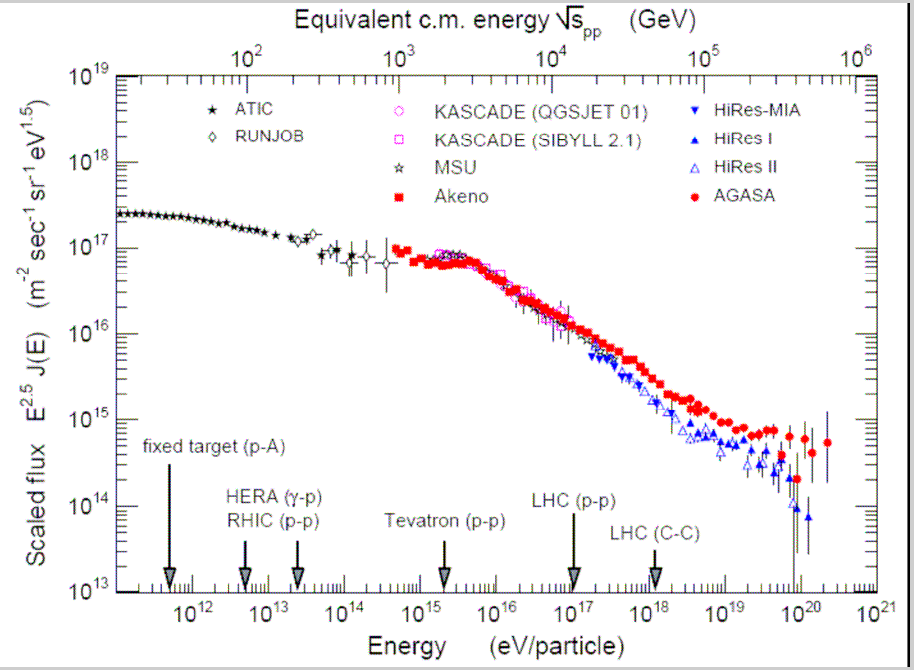
  Extended Air Showers Detection

- Lecture 3

  The Observatory and its First Results

The Cosmic Ray Spectrum





Outstanding Issues

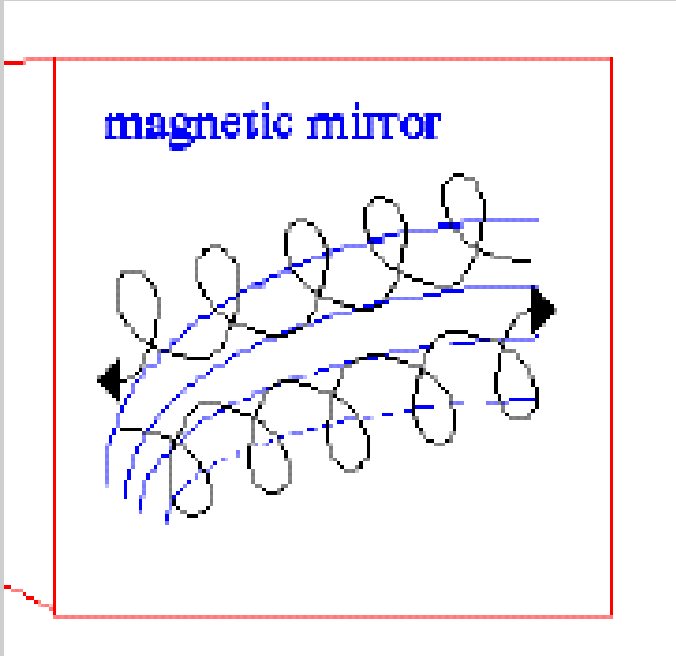
Acceleration Mechanism

GZK

Composition

Point Sources

The Magnetic Mirror

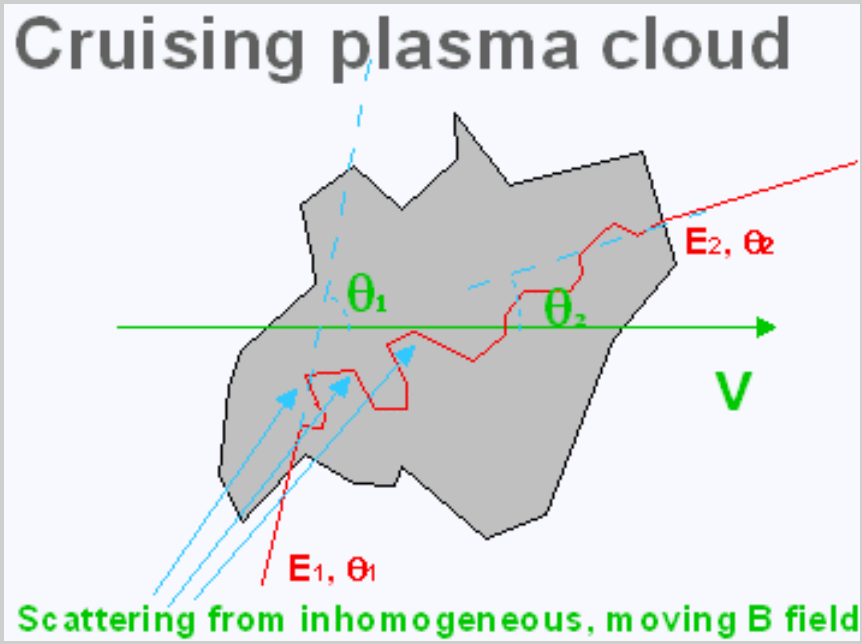


Energy exchange
Drift ↔ Revolution

$$v_{\parallel}^2(z) = v_{\parallel}^2(0) - v_{\perp}^2(0)\left[\frac{B(z)}{B(0)} - 1\right] .$$

Inhomogeneous B field
Spiral trajectories around field lines
High gradient regions acting like walls

Fermi Mechanism - 2nd Order



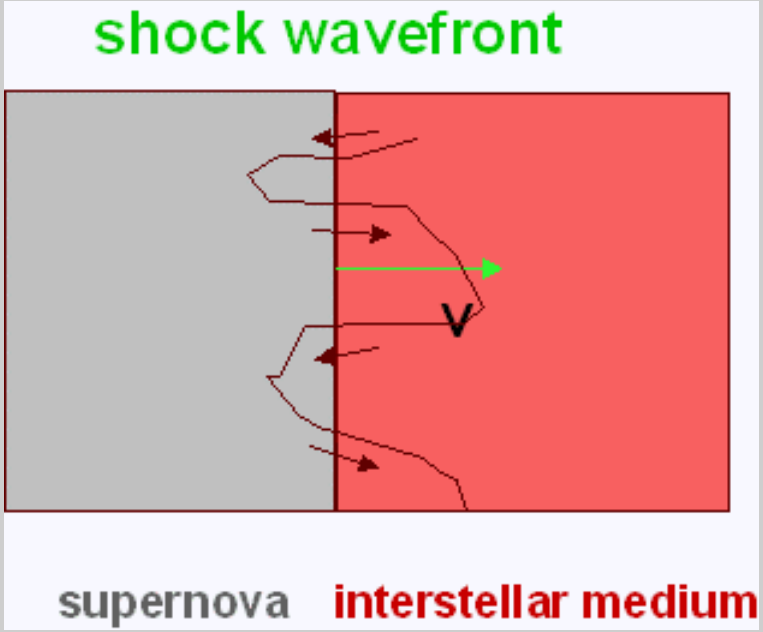
Scattering by ***B***-field
Stochastic process:

$$\Delta E \propto \beta^2 E$$

Expect:
Slow, inefficient

$$\left.\begin{aligned} E_1^{'} &= \gamma E_1 \left(1-\beta\cos\theta_1\right) \\ E_2 &= \gamma E_2^{'} \left(1+\beta\cos\theta_2\right) \end{aligned}\right\} \rightarrow \left\langle \frac{\Delta E}{E} \right\rangle_{\theta_1,\theta_2} \approx \frac{4}{3}\beta^2$$

Fermi Mechanism - 1st Order



$Speed = U_1 > Speed = U_2$

$$\left\langle \frac{\Delta E}{E} \right\rangle_{angles} \sim \frac{4}{3}\frac{R-1}{R}\beta$$

As before, scattering by ***B*** -field irregularities

Momentum gain:

$\delta p/p = +2U_1/c$ head-on acceleration

$\delta p/p = -2U_2/c$ tail-on deceleration

$\rightarrow \delta p/p = 2(U_1 - U_2)/c > 0$ net gain

Expect:

fast, efficient

Shock compression ratio

A General Argument - I

Just a couple of units:
1 pc = 3.2 light yr
1 EeV = 10^{18} eV = 0.16 J

To get accelerated: *No early escape from the source*

Source size > $$\left(\frac{R_{Larmor}}{kpc}\right) = \left(\frac{1}{Z}\right)\cdot\left(\frac{E}{1EeV}\right)\cdot\left(\frac{ZB}{\mu G}\right)$$

To get accelerated: *Synchrotron loss < energy gain*

$$dE/dt \propto B^2 \qquad dE/dt \propto B$$

(Greisen,1965)

A General Argument - II

$$\rightarrow W_B = \frac{B^2}{4\pi}\frac{4}{3}\pi R^3 \propto \gamma^5_{particle}$$

Ex. 10^{20} *eV* $\rightarrow W_B > 10^{57}$ *erg*

Such humongous source should be a strong radio emitter (like 10^{41} *erg* s^{-1}*)*

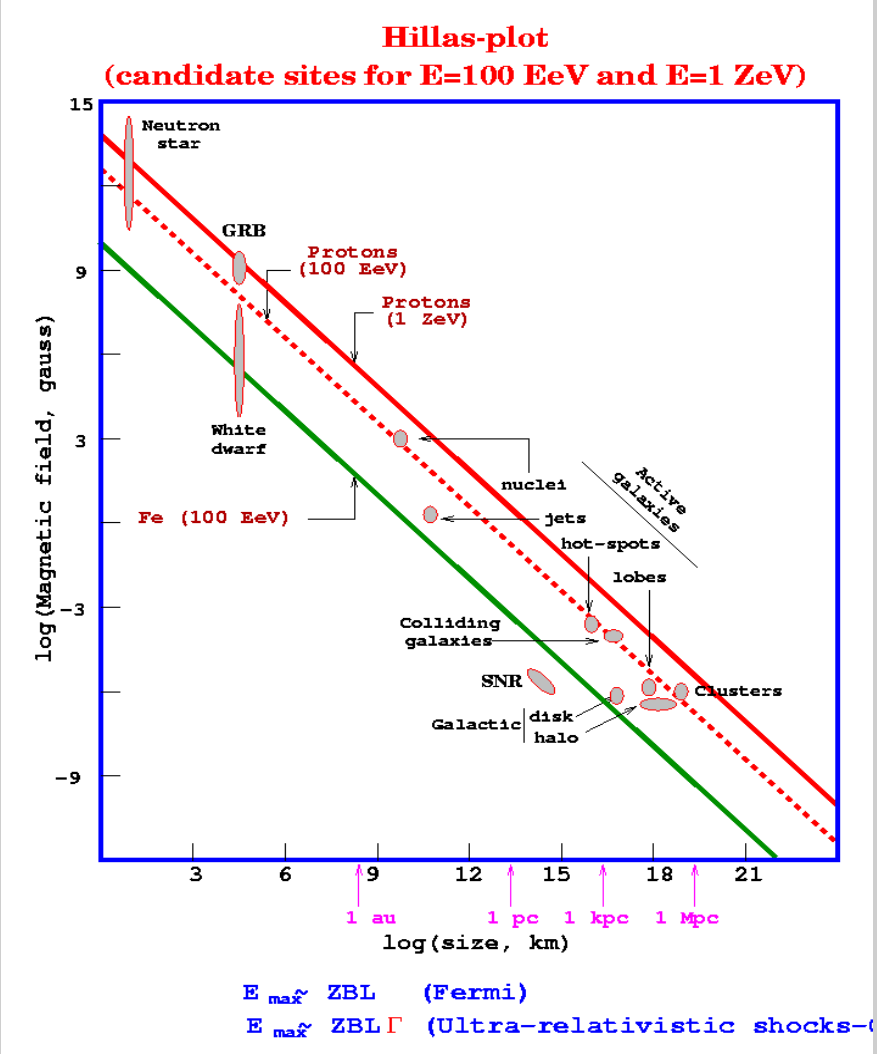
$\rightarrow$ *Easy to detect!*

Maximum Energy

Simple estimate of max. energy (Hillas):

$$E_{\max} = Ze\beta BL$$

β: *Plasma speed*
B: Mag field
L: Source size



Spectral Index, Time Constant

Power law spectrum

$$N(E) \propto E^{-x}$$

Fermi 2nd order:

$$x = 1 + \tau_{acc} / \tau_{esc} \gg 1$$

t_{acc}>10^8 yr! KO

Fermi 1st order:

$$x = \frac{R+2}{R-1} \sim 2$$

t_{acc}~1 month! OK

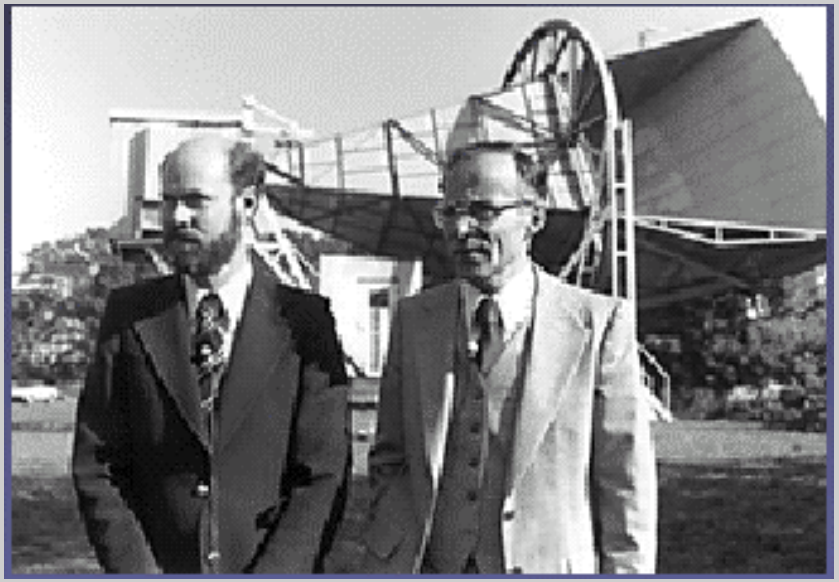
Compact sources

Just meaning: *Non* electromagnetic acceleration

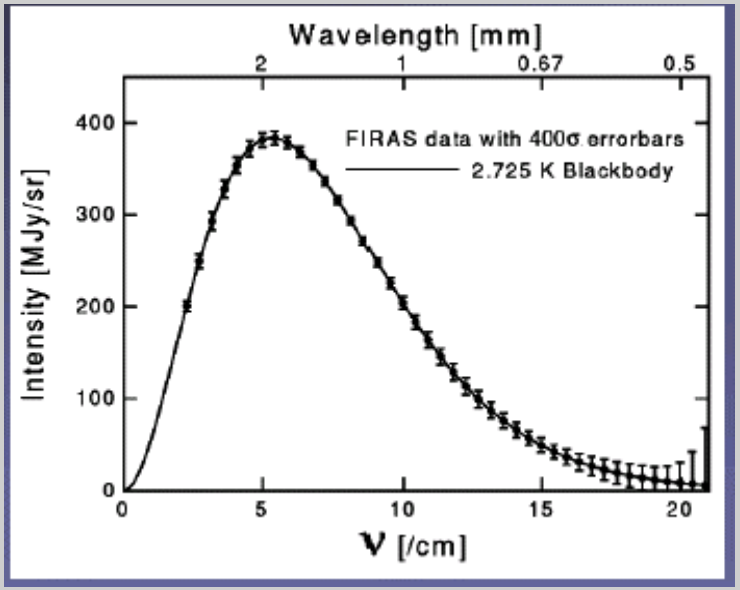
Various mechanisms proposed:

Black hole accretion disks
Gamma ray bursts
Topological defects (monopoles, cosmic strings, ..)
UHE ν's from decays of high mass particles

*C*osmic *M*icrowave *B*ackground



Penzias, Wilson
& the Antenna

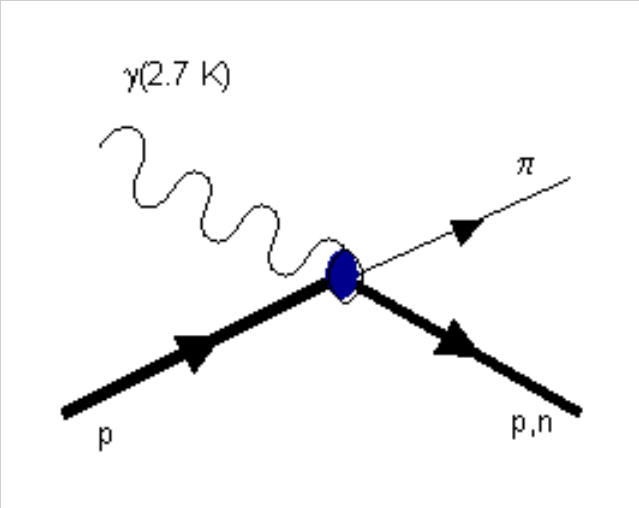


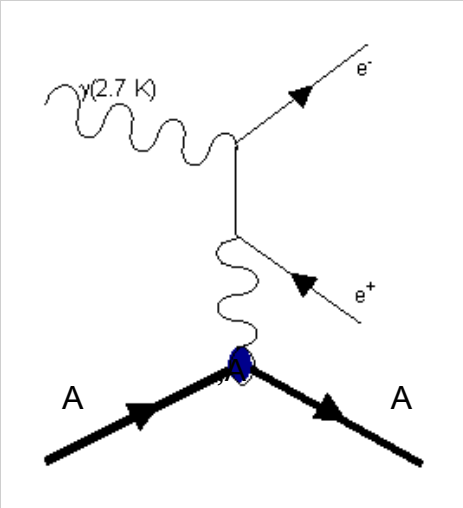
The CMB spectrum
(by FIRAS)

CMB Photons

Peak energy ~ $k_B T = 0.6\ meV$
Density ~ $400\ cm^{-3}$

Possible CR interactions:





,A

G(reisen),***Z***(atepsin),***K***(uz'min)

$$\left.\begin{array}{l} p+\gamma(2.7K)\rightarrow n+\pi^{+} \\ p+\gamma(2.7K)\rightarrow p+\pi^{0} \end{array}\right\}$$

(G, Z&K - 1965)

$E_{thresh} \sim 6\ 10^{19}$ eV En.loss $\sim 20\%$ /int

$$p+\gamma(2.7K)\rightarrow p+e^{+}+e^{-}$$

$E_{thresh} \sim 1\ 10^{18}$ eV En.loss $\sim 0.1\%$ /int

The moral:

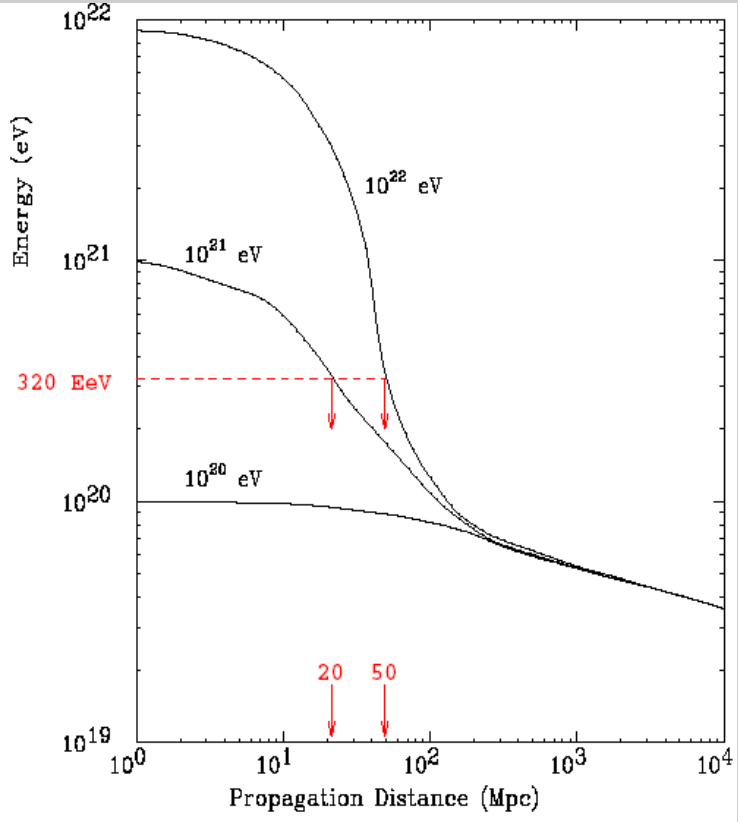
CR's above threshold bound to lose energy

The GZK Cutoff

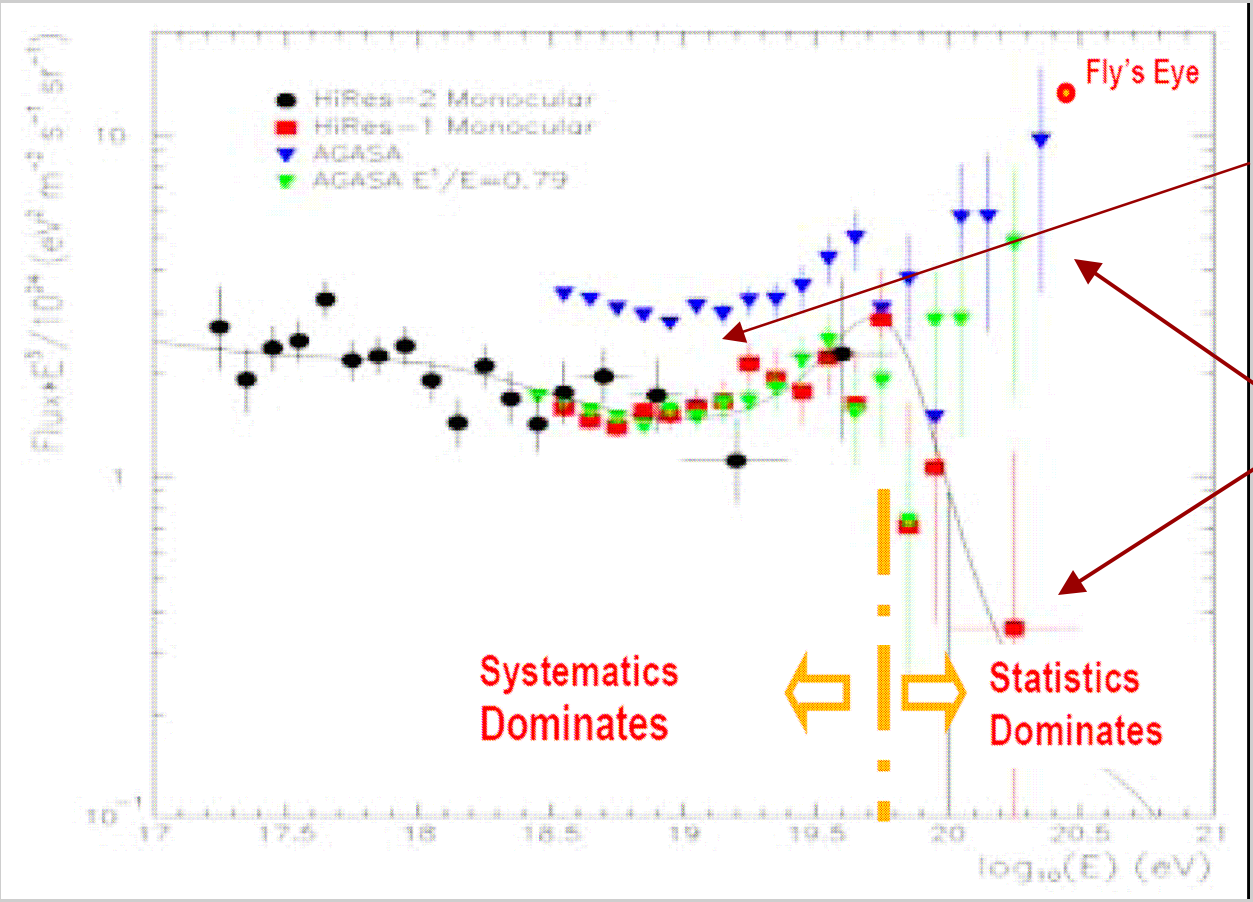
So UHECR's just can't propagate beyond, say, 50 Mpc!

Then we should find a suitable source just 'round the corner'.

But where?



The High End of the CR spectrum

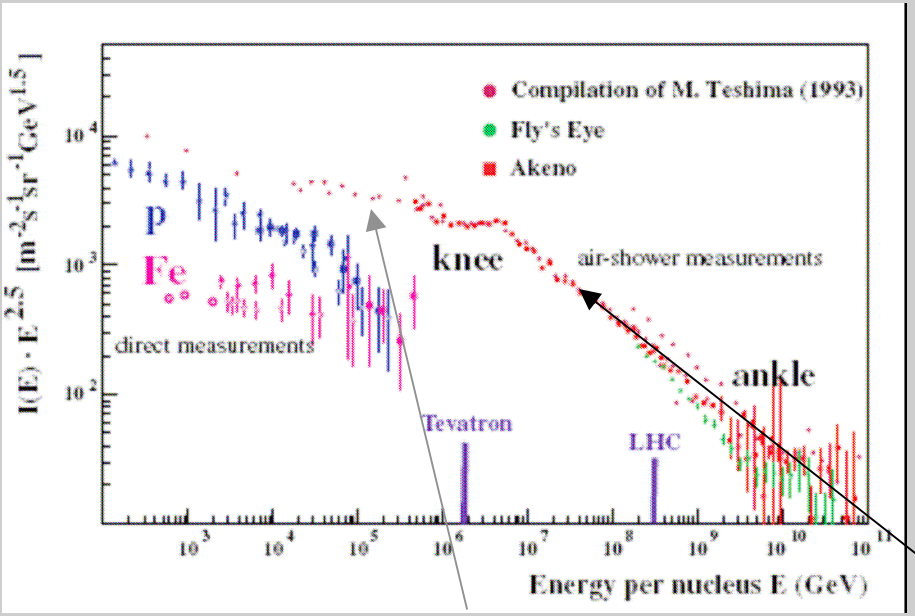


~ x 2 effect

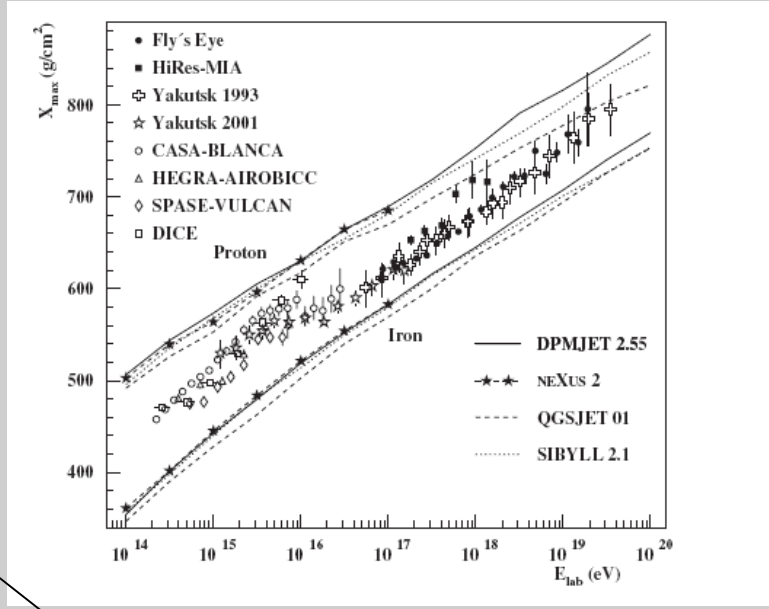
~ 2-3 σ issue..

Composition Issues

Spectrum



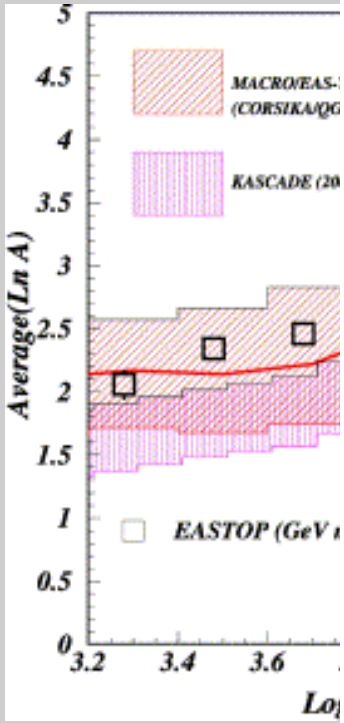
Depth of Shower Maximum in Air vs. E

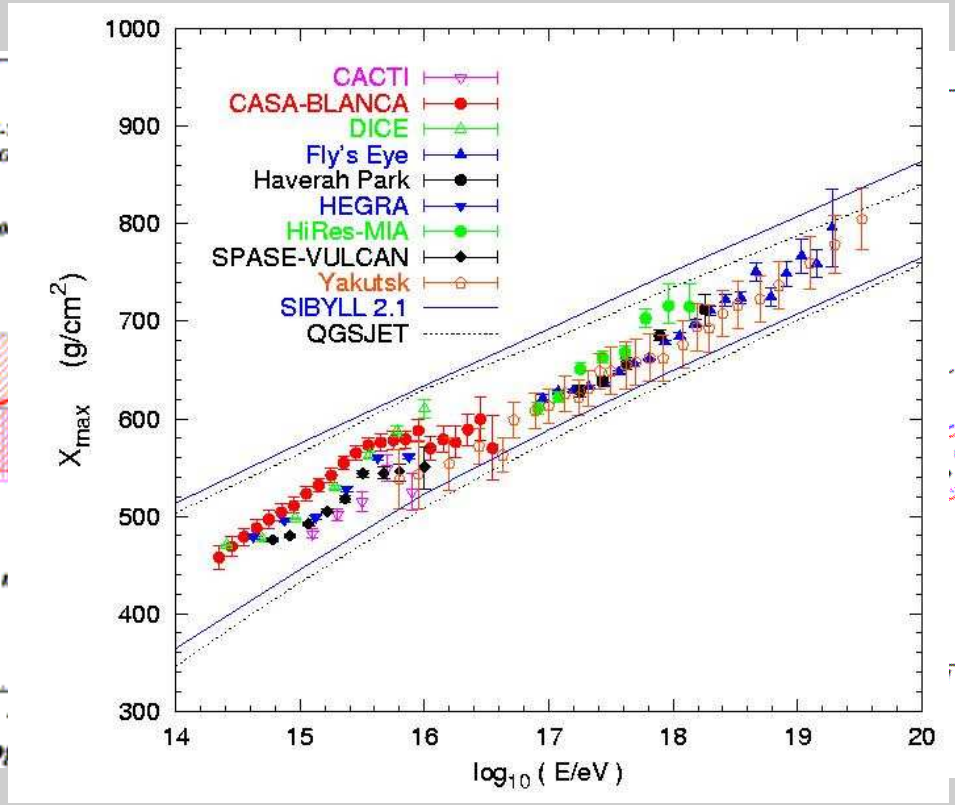


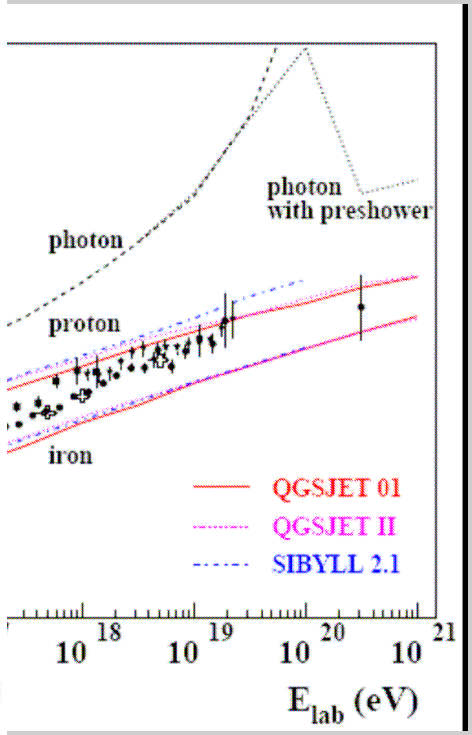
Galactic?

Extra-Galactic

More on Composition





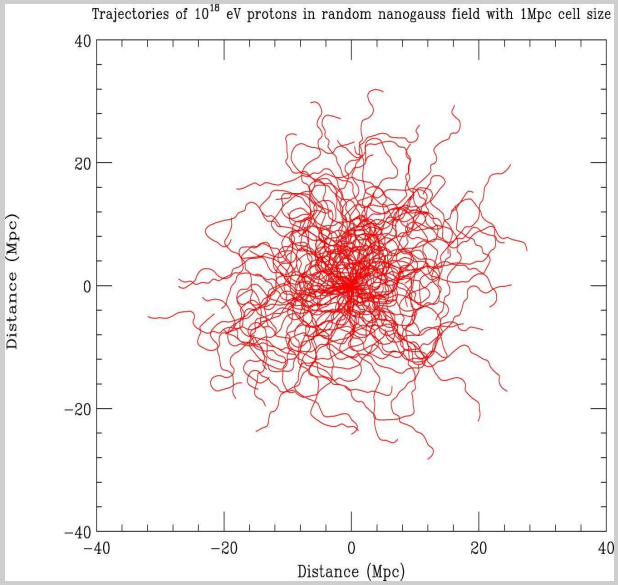


Proton/Iron Discrimination tied to Intra/Extra-Galactic origin

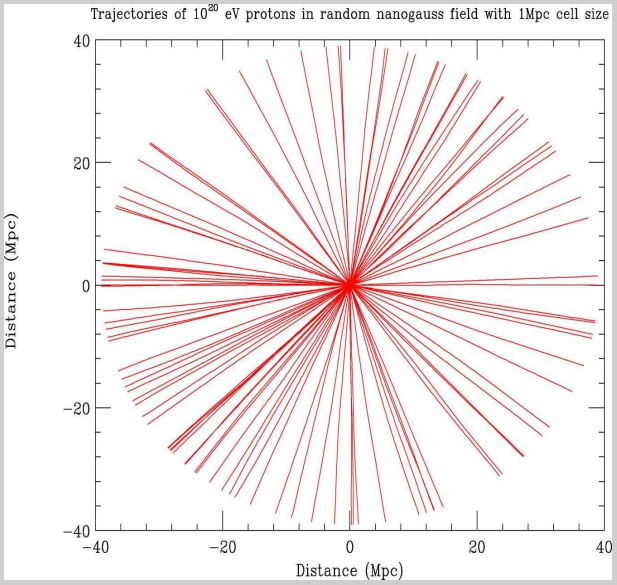
Opening a New Window?

Effect of Extra-Galactic Magnetic Field on CR trajectories Simulation

$E = 10^{18}$ eV



$E = 10^{20}$ eV



Clearly, around 10^{20} eV a new astronomy is feasible…
…if Cosmic Rays of that energy are actually observed

No deflection @ High E

Little deflection from extragalactic mag field

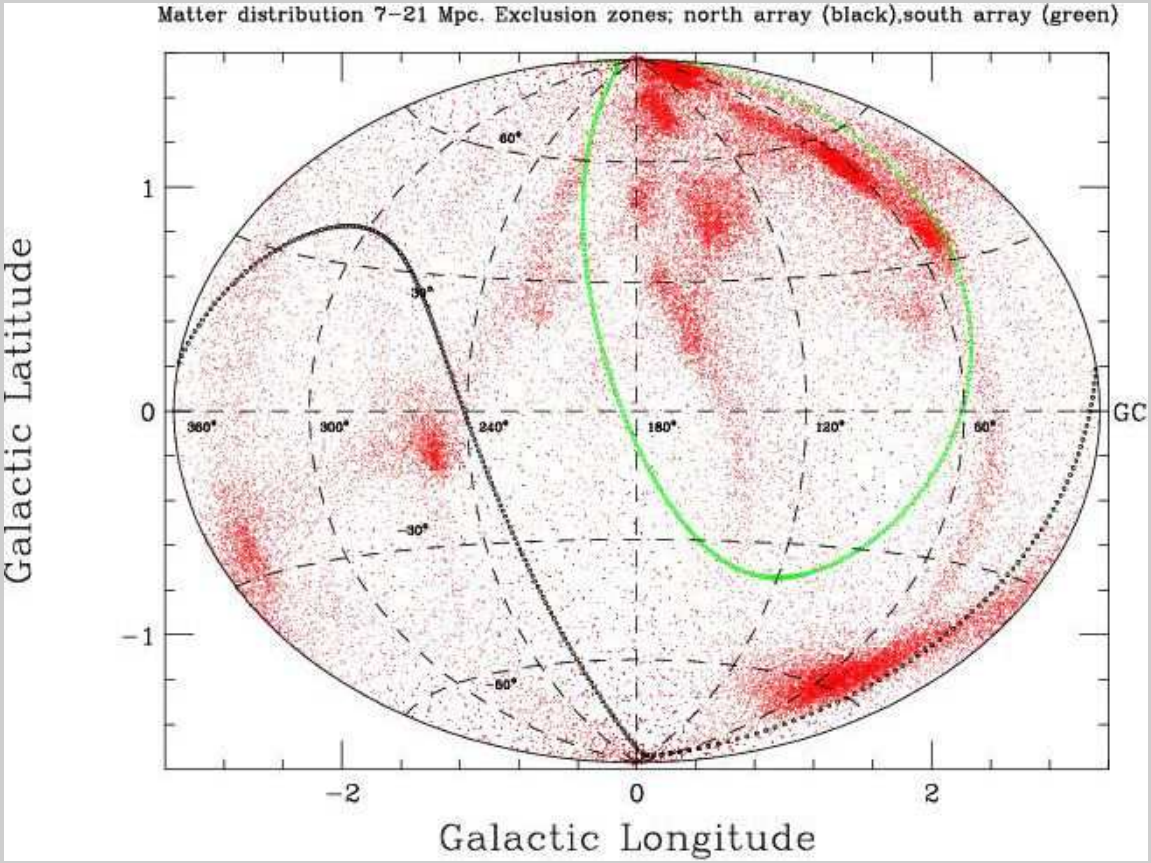
B not well known $\leq 10^{-9}$ *G*
Constant field region: *B*, size *l*, $var[defl]=\sigma^2$
Assuming random walk through *N* regions

$$\theta(E) \simeq 0.04 mrad \left(\frac{d}{\lambda}\right)^{1/2} \frac{1}{\lambda BE}$$

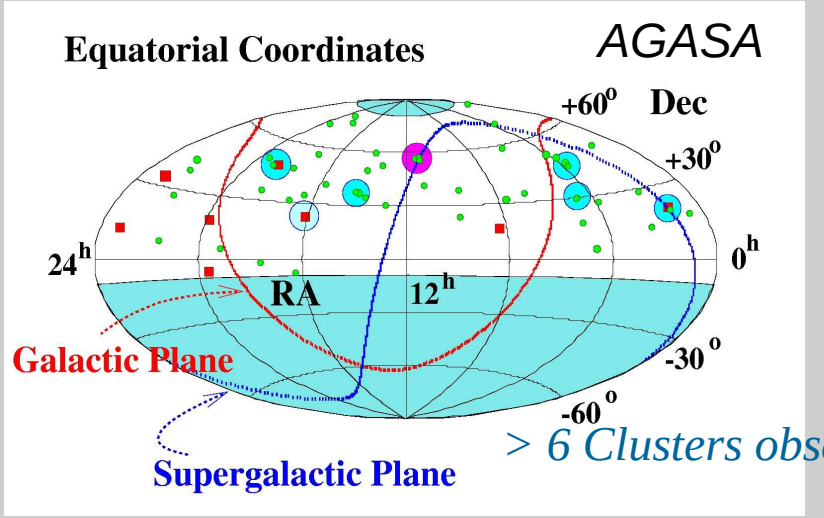
$$\lambda : Mpc, \quad B : nG, \quad E : 10^{20} eV$$

→*Negligible deflection*

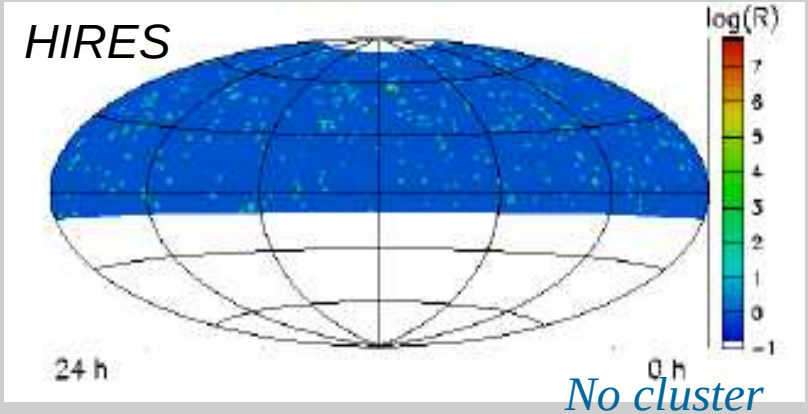
The Known Matter (< 21 Mpc)



Anisotropies, Point Sources?



> 6 Clusters observed



No cluster

Controversial results…
Issues at stake:

Detection Technique
Angular Resolution
Statistics!

Cosmic Rays Detection

Airborne conventional detectors: $E<10^{14}$ *eV*

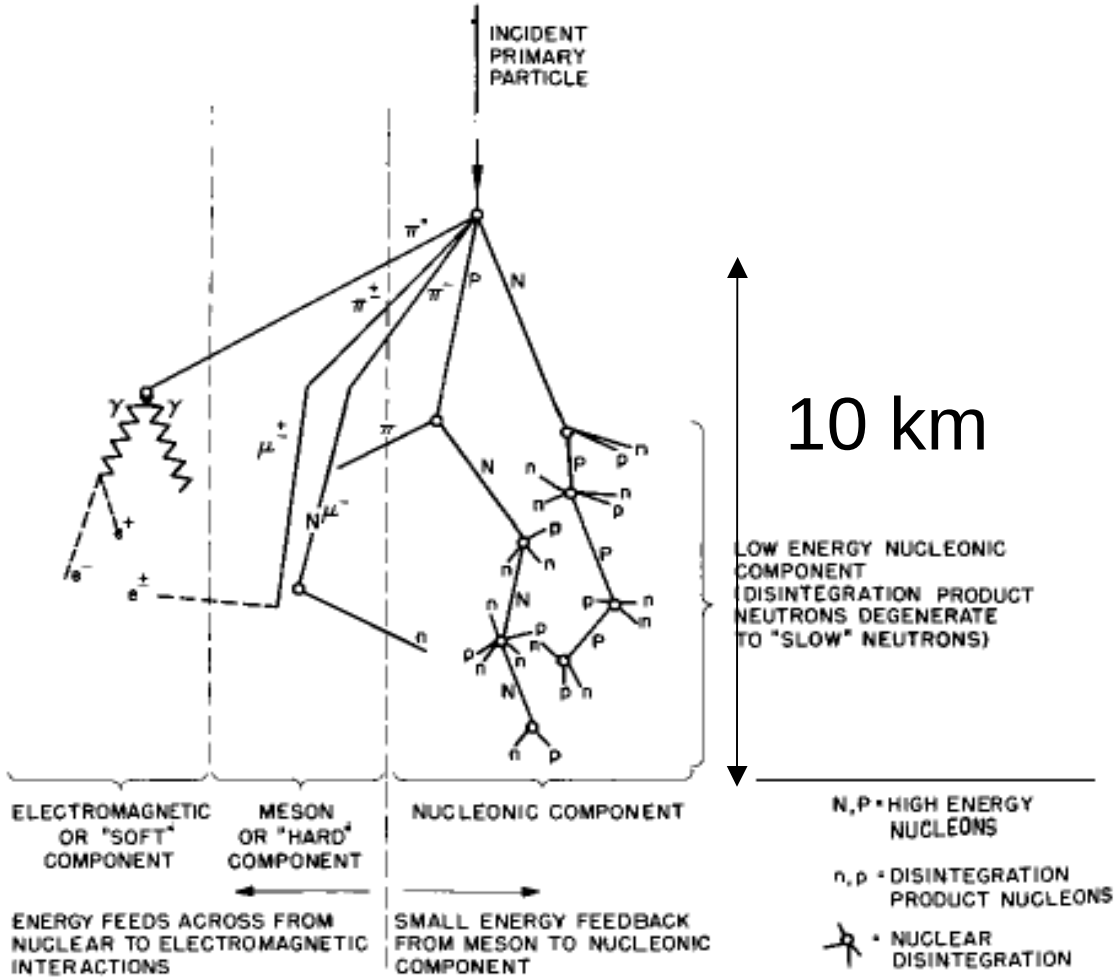
Not suitable to deal with small fluxes

E> 10^{14} eV : ***E***(xtensive) ***A***(ir) ***S***(showers)

Different techniques:

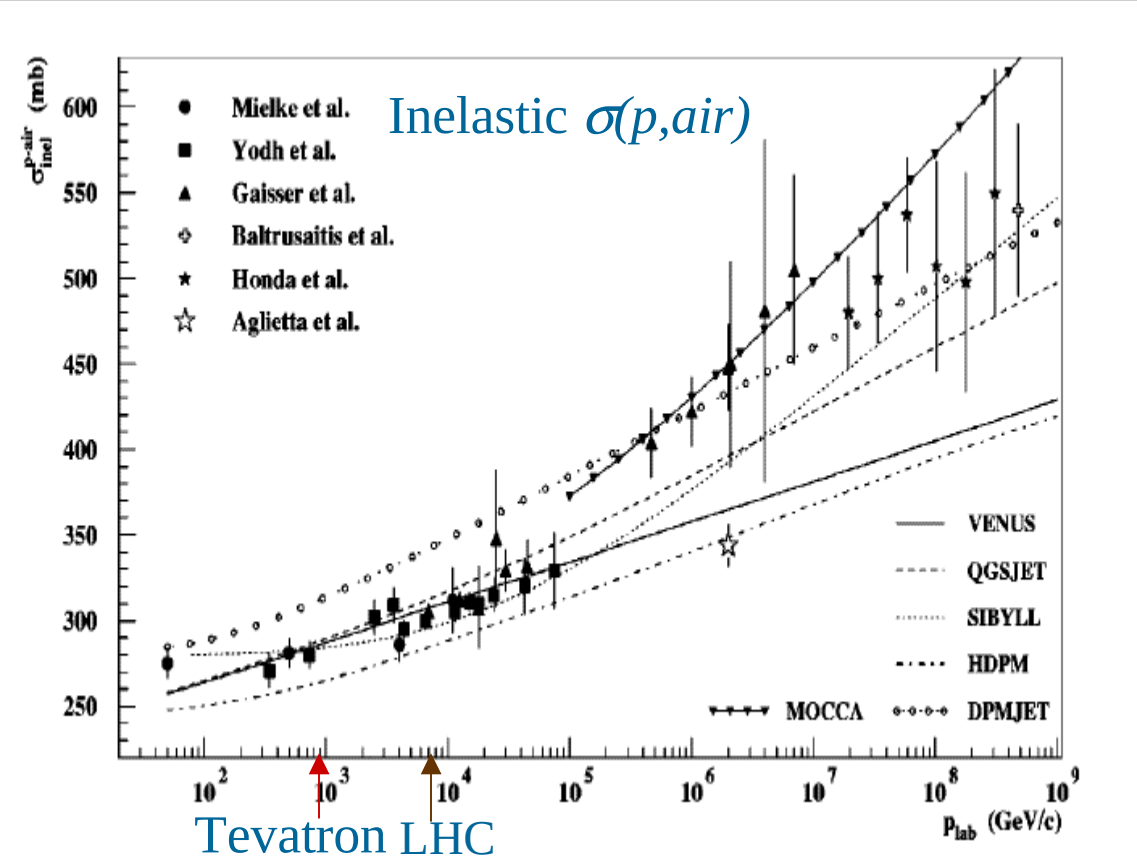
- *Ground arrays (scintillators, water Cherenkov)*
- *Air Cherenkov telescopes*
- *Fluorescence detectors*

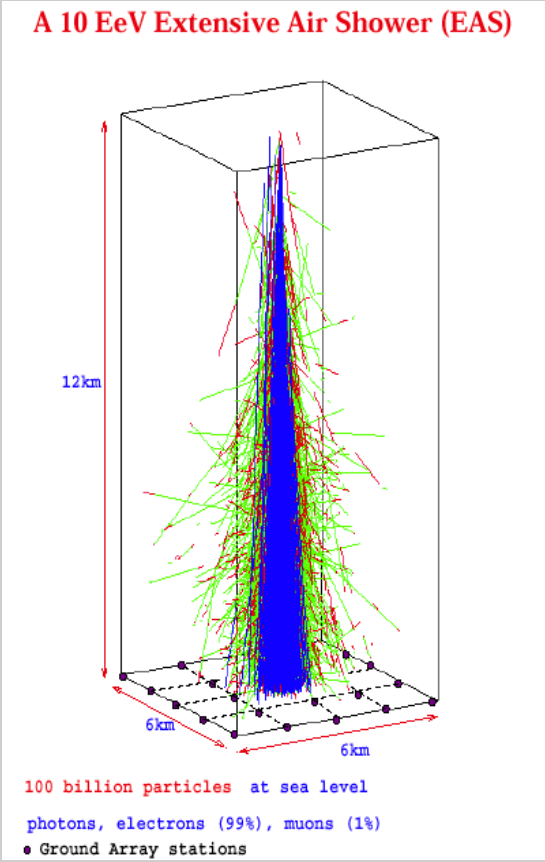
EAS - I


INCIDENT PRIMARY PARTICLE
10 km
LOW ENERGY NUCLEONIC COMPONENT (DISINTEGRATION PRODUCT NEUTRONS DEGENERATE TO "SLOW" NEUTRONS)
ELECTROMAGNETIC OR "SOFT" COMPONENT
MESON OR "HARD" COMPONENT
NUCLEONIC COMPONENT
N,P = HIGH ENERGY NUCLEONS
n,p = DISINTEGRATION PRODUCT NUCLEONS
= NUCLEAR DISINTEGRATION
ENERGY FEEDS ACROSS FROM NUCLEAR TO ELECTROMAGNETIC INTERACTIONS
SMALL ENERGY FEEDBACK FROM MESON TO NUCLEONIC COMPONENT

EAS - II

Data & MCarlo





EAS development

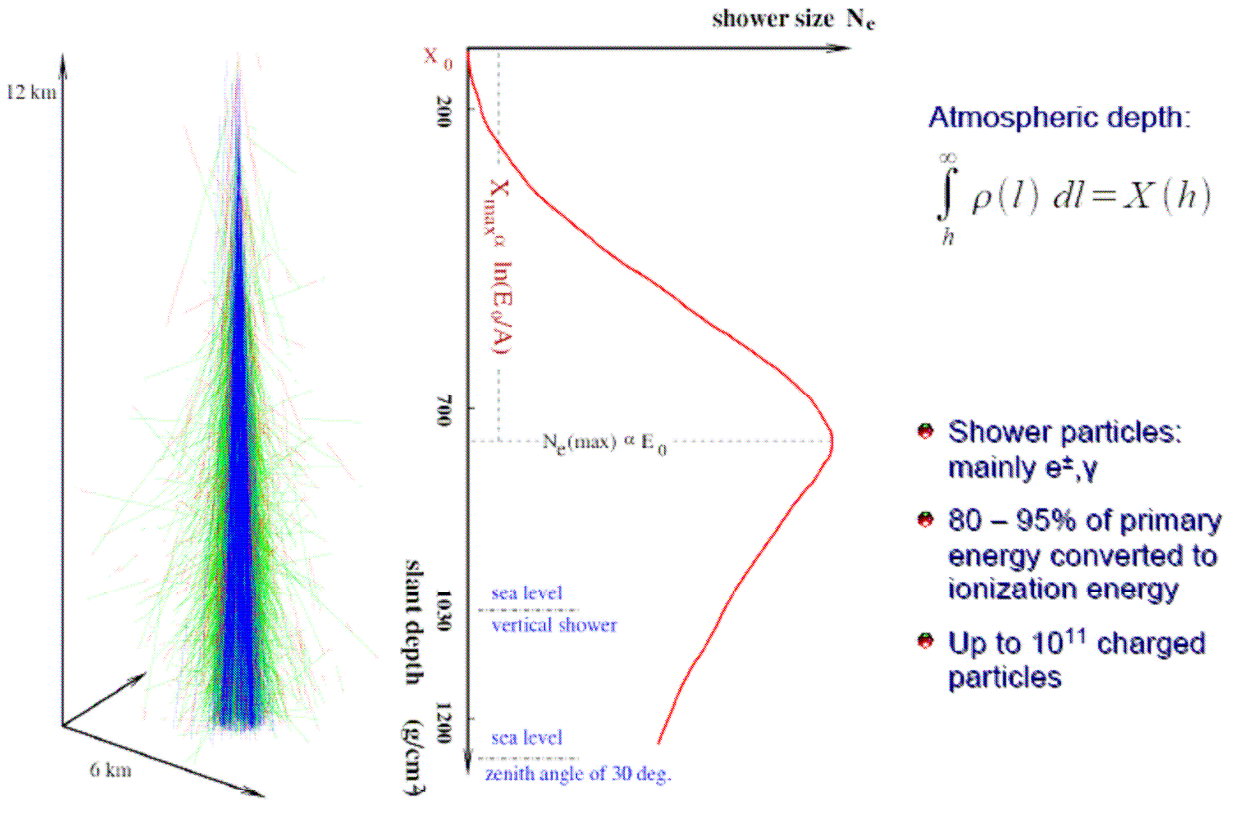
Next slides from R.Engel's simulations
See for example:

R.Engel

EAS

Lectures given at ISAPP 2005 Summer School
http://www.isapp2005.to.infn.it

EAS-I

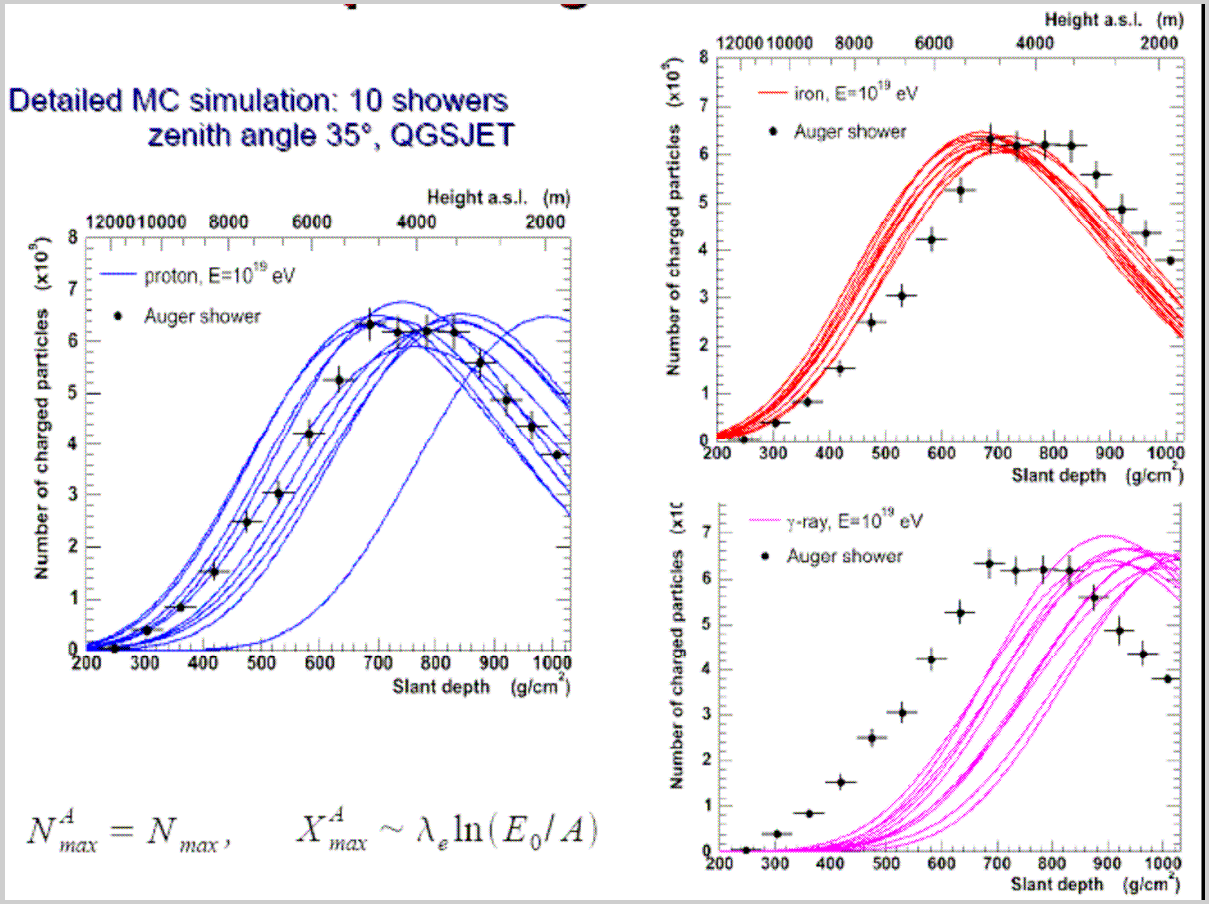


Atmospheric depth:

$$\int_h^\infty \rho(l)\, dl = X(h)$$

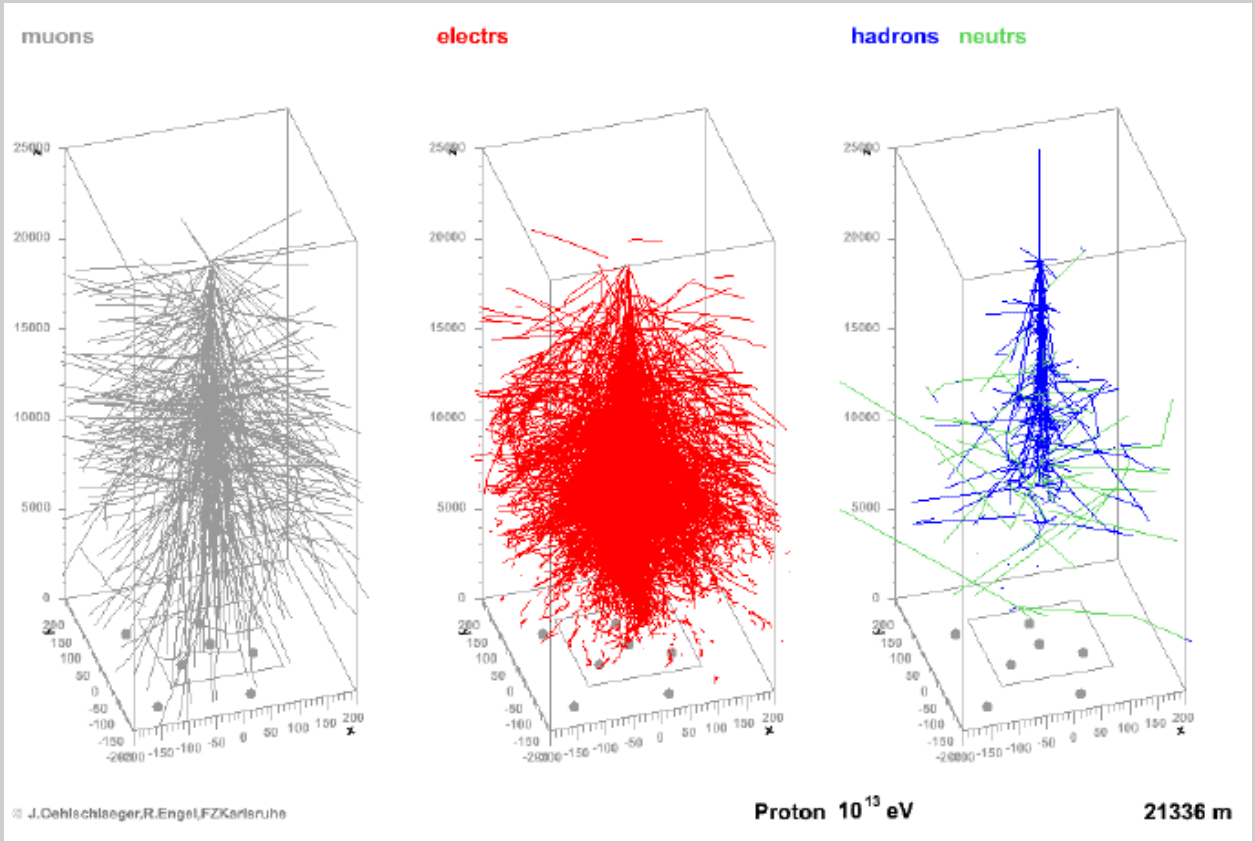
- Shower particles: mainly $e^{\pm}, \gamma$
- 80 – 95% of primary energy converted to ionization energy
- Up to 10^{11} charged particles

EAS-II

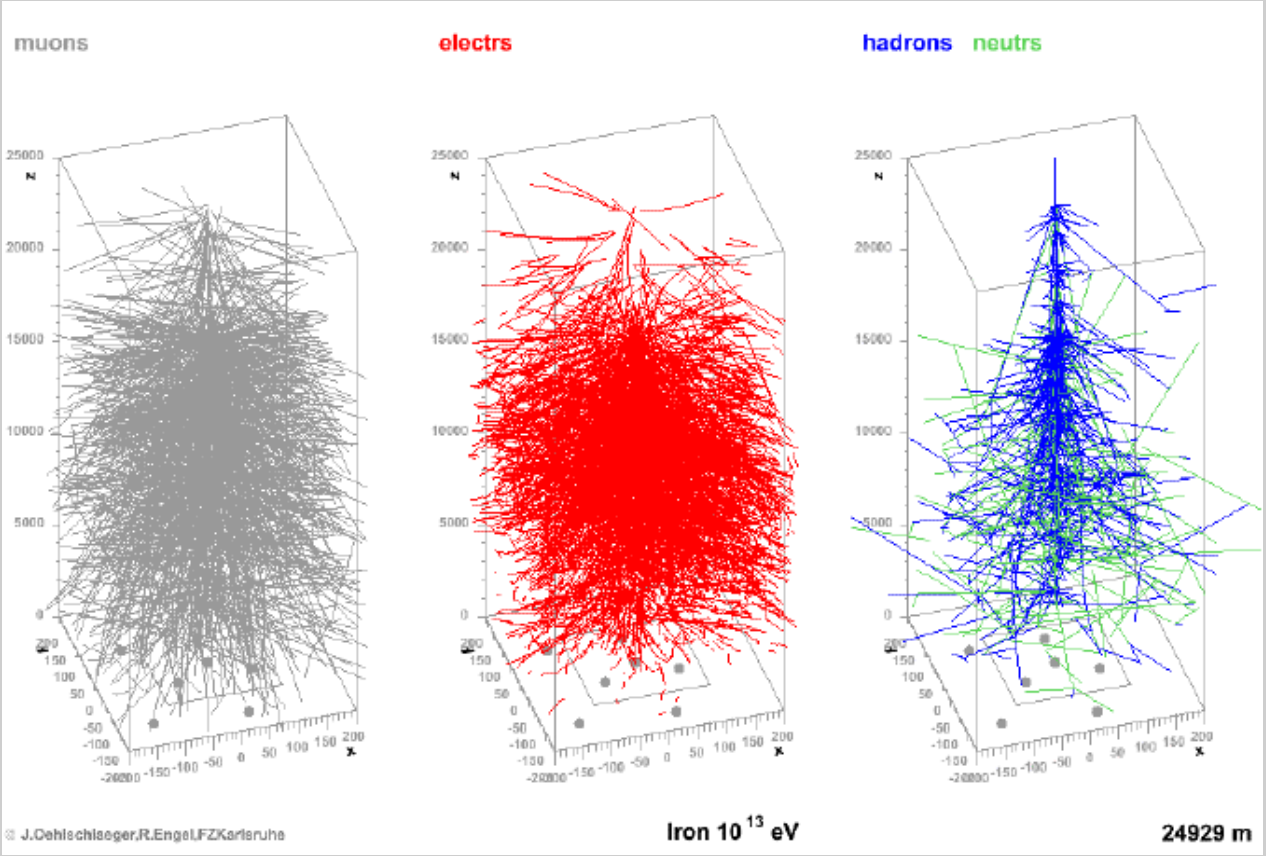


$$N^A_{max} = N_{max}, \qquad X^A_{max} \sim \lambda_e \ln(E_0/A)$$

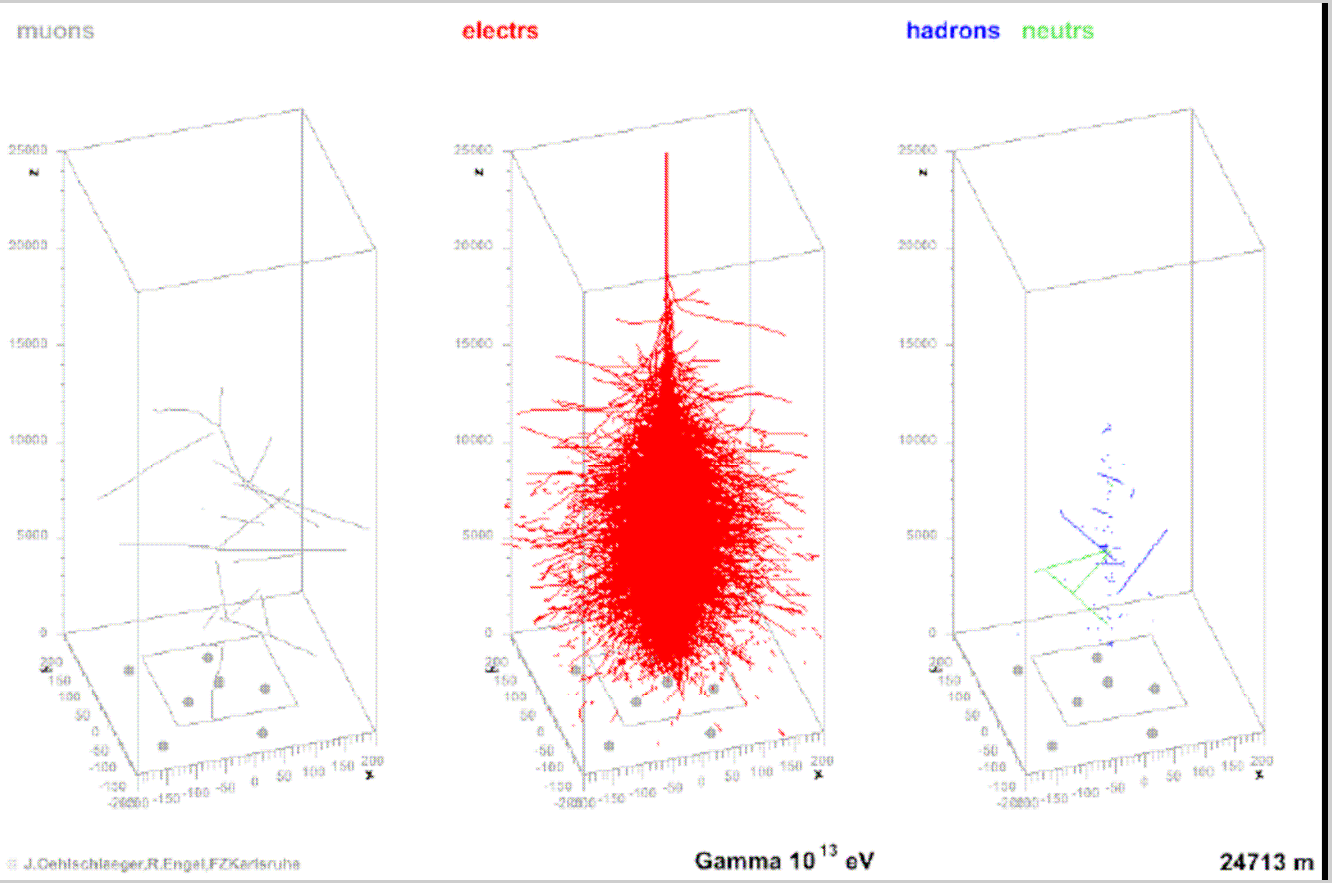
EAS-III


muons
electrs
hadrons
neutrs
J.Oehlschlaeger,R.Engel,FZKarlsruhe
Proton 10^{13} eV
21336 m

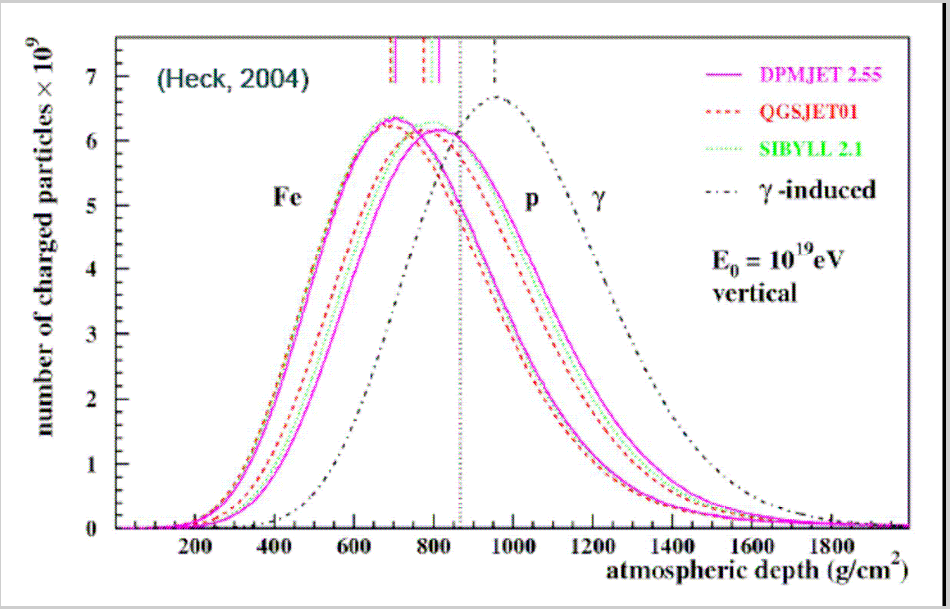
EAS-IV

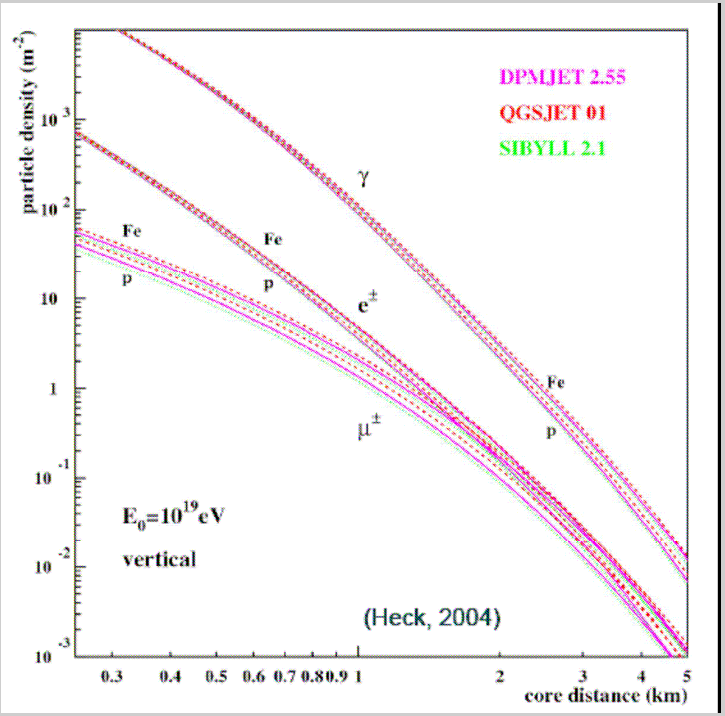

muons
electrs
hadrons
neutrs
J.Oehlschlaeger,R.Engel,FZKarlsruhe
Iron 10 13 eV
24929 m

EAS-V


muons
electrs
hadrons
neutrs
J.Oehlschlaeger,R.Engel,FZKarlsruhe
Gamma 10 13 eV
24713 m

EAS - Profiles

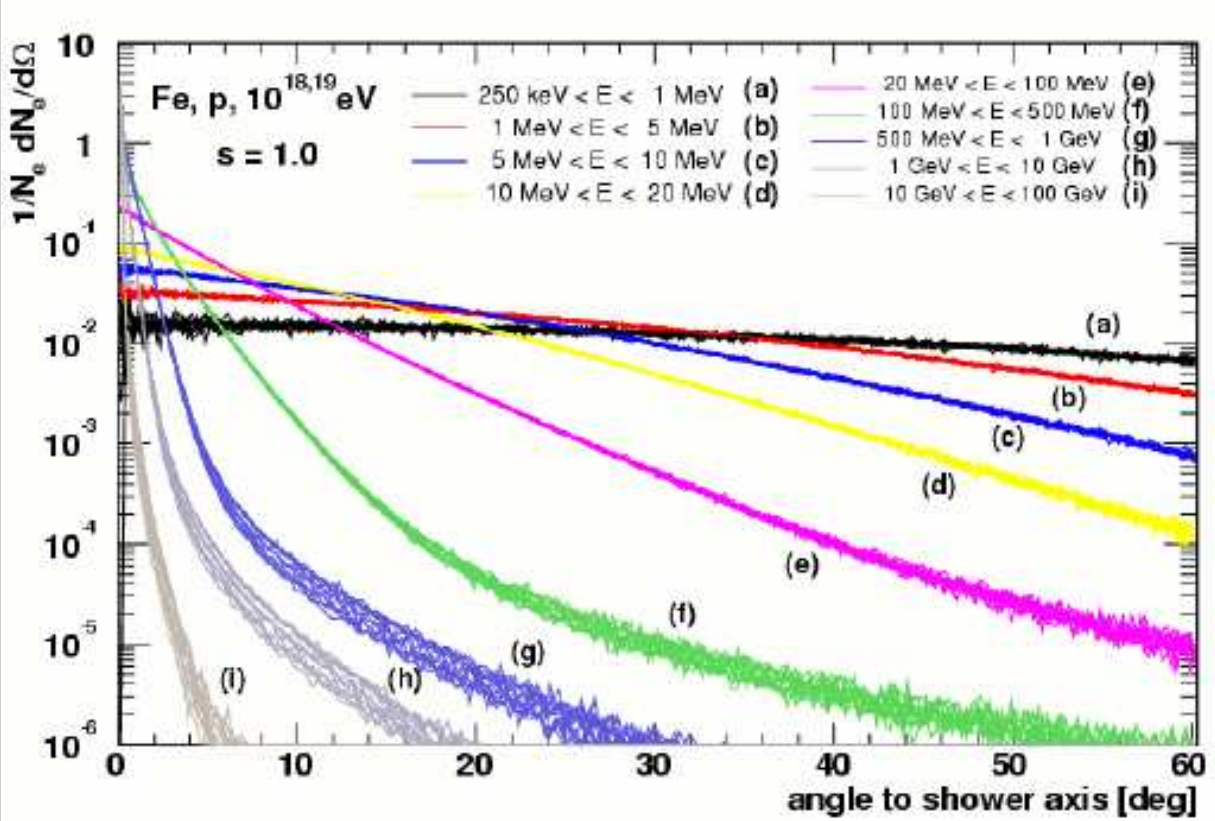




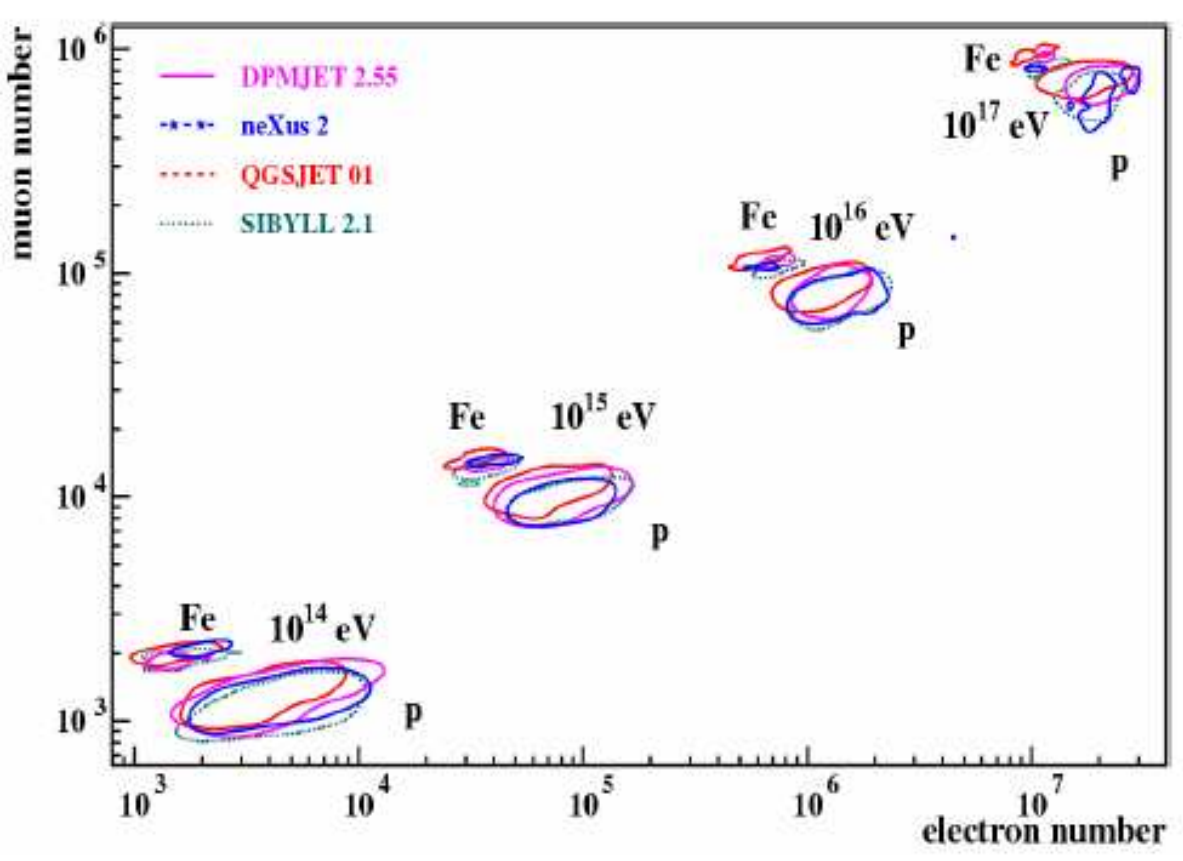
Longitudinal

Lateral

EAS - Electron Lateral Distribution



EAS - Muons vs Electrons



EAS – The Movie