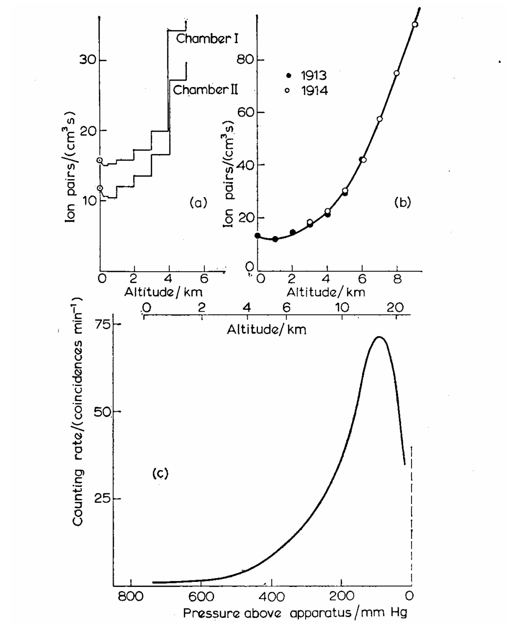
The Pierre Auger Observatory

Hunting the Highest Energy Cosmic Rays

I – High Energy Cosmic Rays and Extensive Air Showers

Discovery of Cosmic Rays

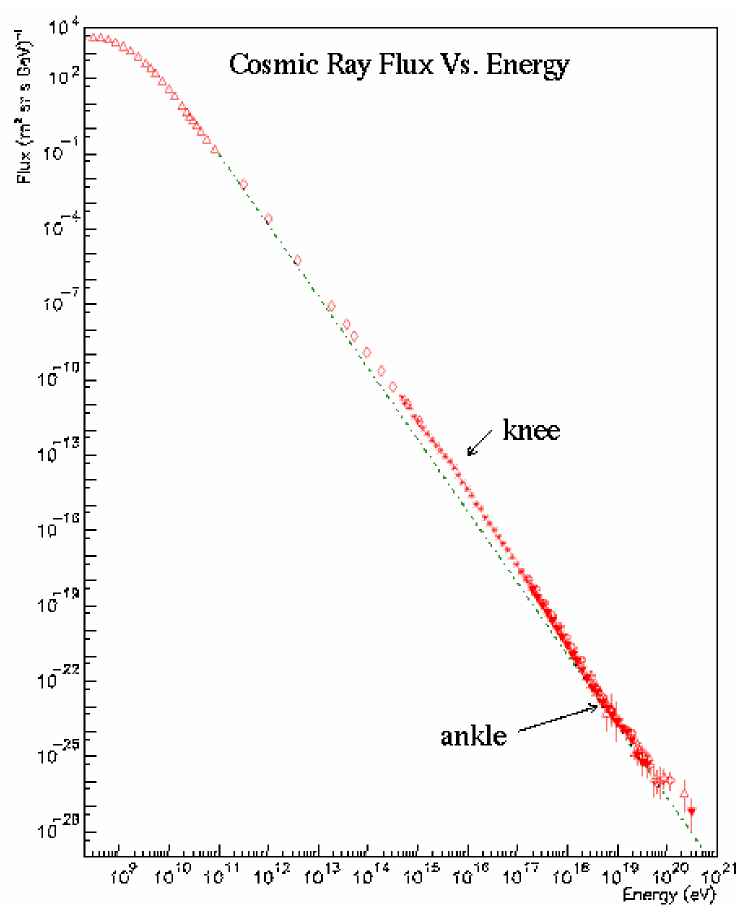
Hess bei Ballonlandung (1912).

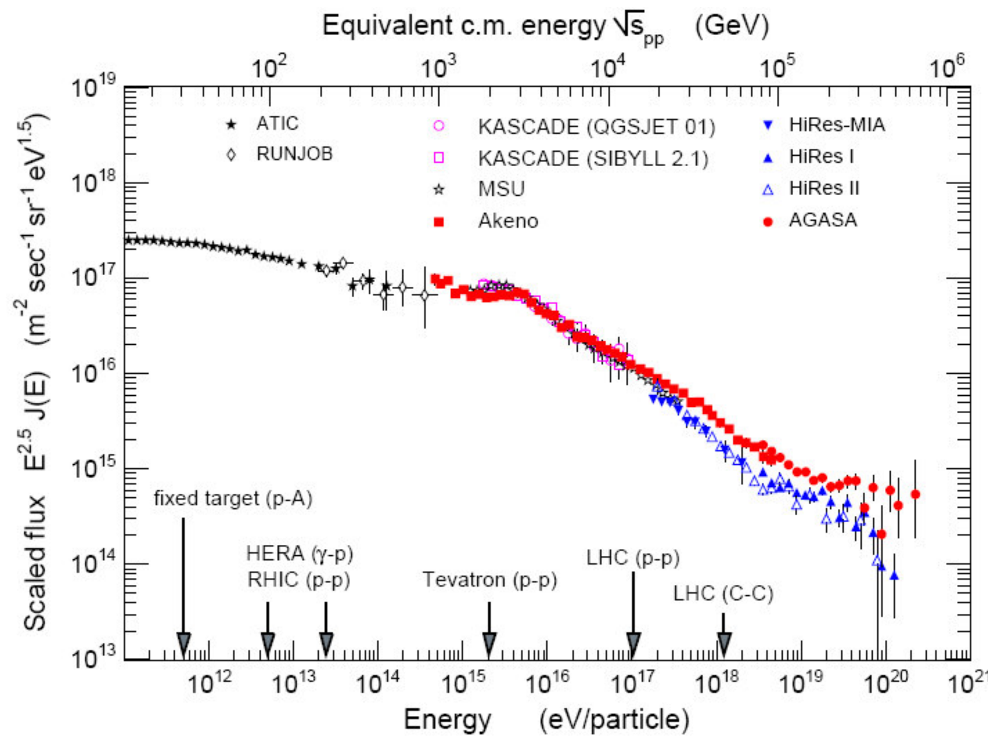


1. Altitude variation of ionization. (*a*) Balloon ascent by Hess (1912) carrying two ion chambers. (*b*) Ascents by Kolhörster (1913, 1914) using ion chambers. (*c*) Coincidence counter telescope flown by Pfotzer (1936).

Altitude variation of ionisation detected by Hess and Kohlhoster and Pfotzer

The Cosmic Ray Spectrum





Outstanding Issues

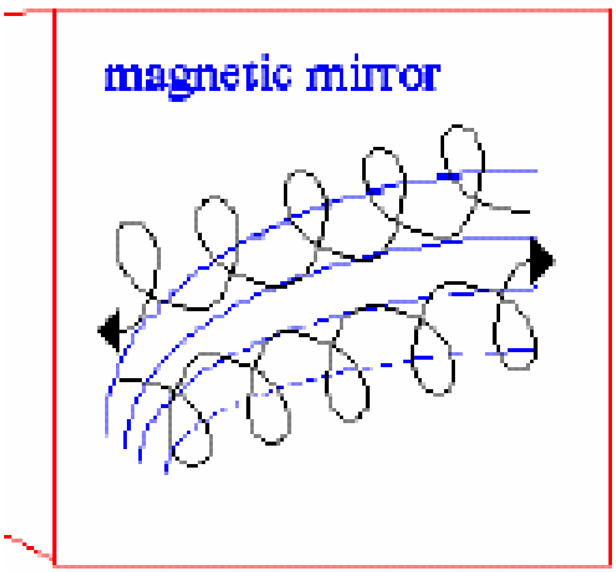
Acceleration Mechanism

GZK

Composition

Point Sources

The Magnetic Mirror

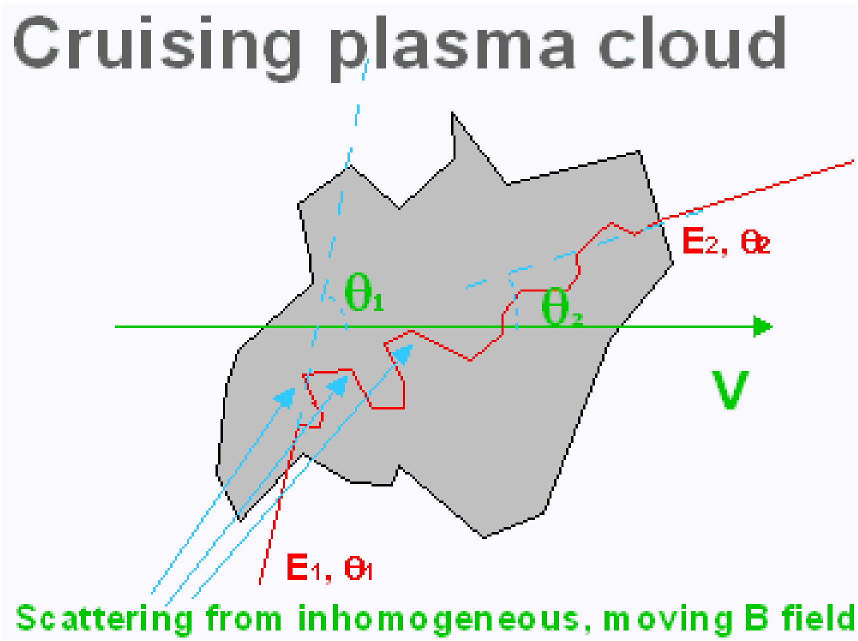


Energy exchange
Drift $\leftrightarrow$ Revolution

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

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

Fermi Mechanism - 2nd Order



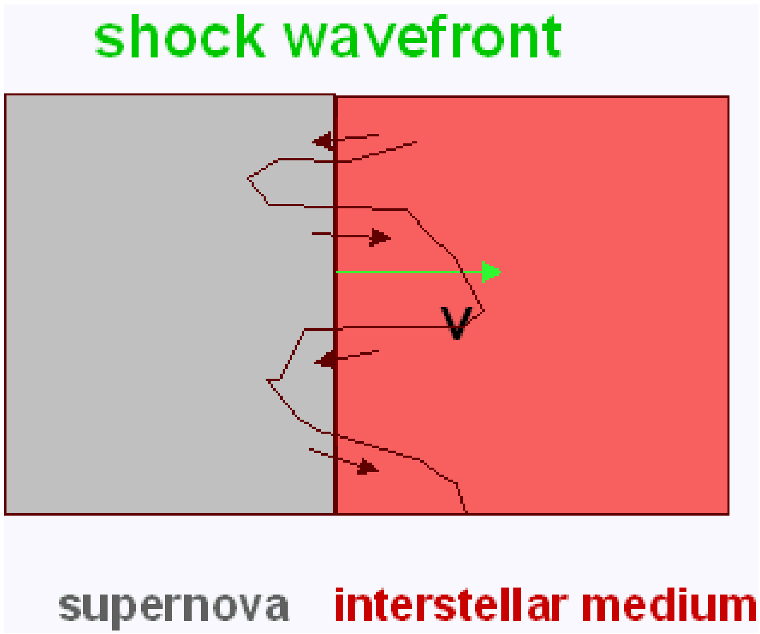
Scattering by ***B***-field
Stochastic process:

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

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:

$$\delta p/p = +2U_1/c \quad \text{head-on acceleration}$$

$$\delta p/p = -2U_2/c \quad \text{tail-on deceleration}$$

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

Expect:

fast, efficient

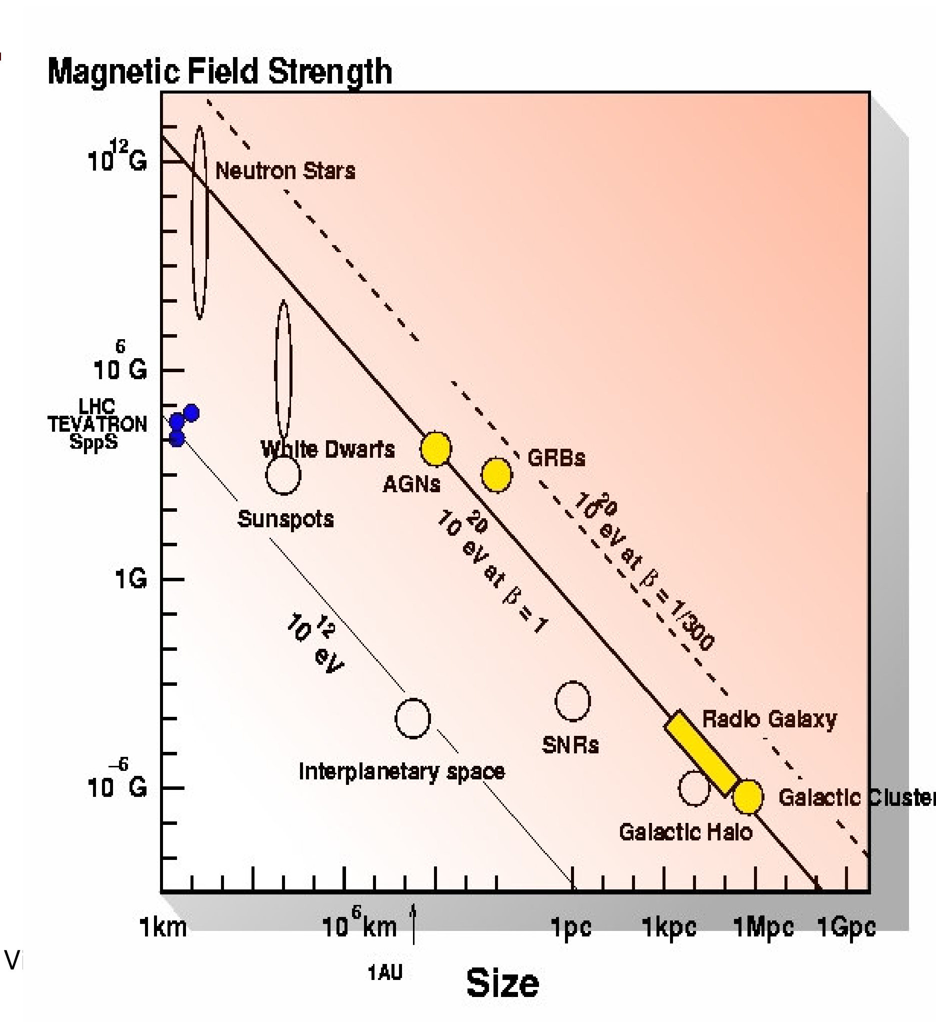
Shock compression ratio

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

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

Fermi 2nd order:

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

τ_{acc}>10^{8} yr! KO

Fermi 1st order:

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

τ_{acc}~1 month! OK

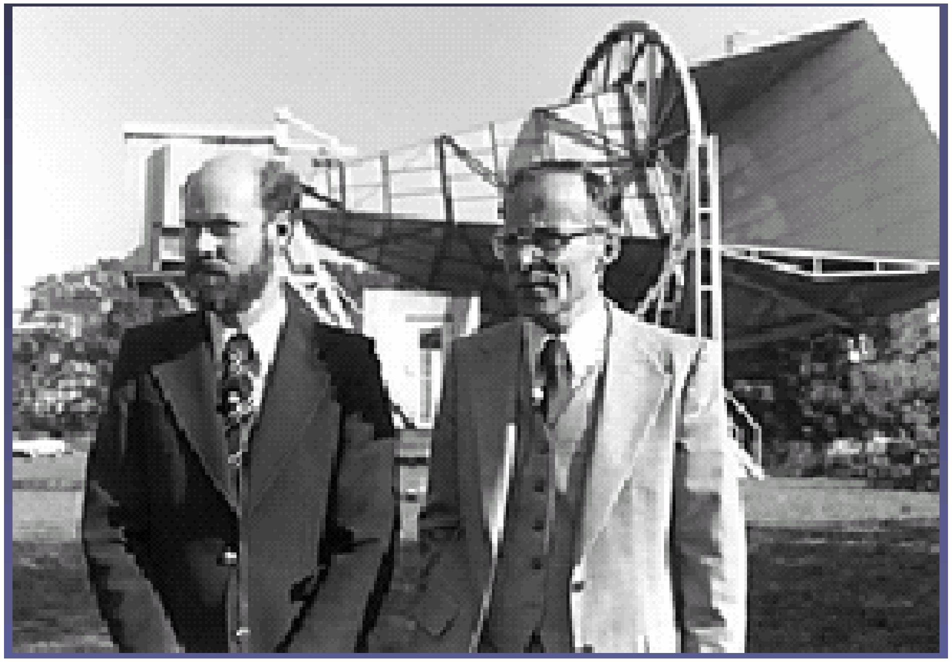
Compact sources

Just meaning: *non* electromagnetic acceleration

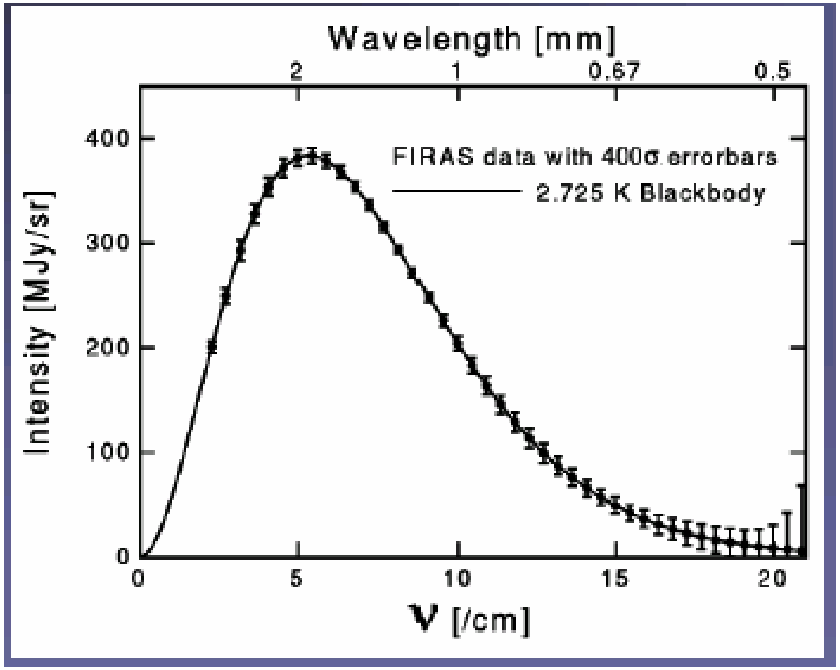
Various mechanisms proposed:

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

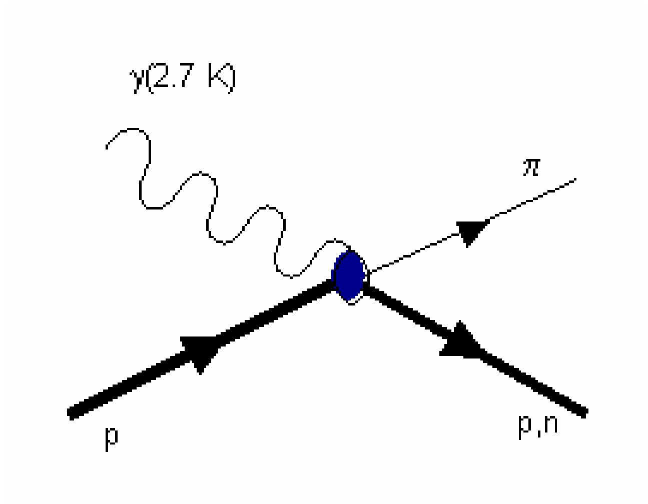


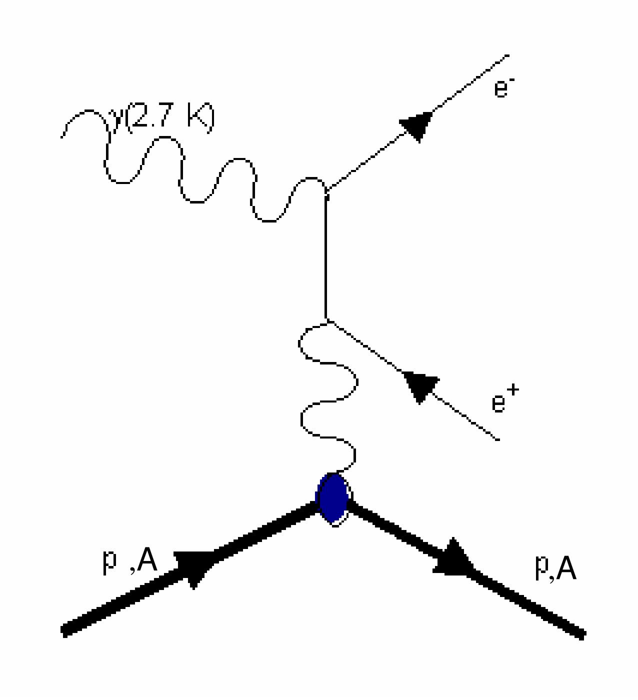
The CMB spectrum
(by FIRAS)

CMB Photons

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

Possible CR interactions:





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)

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

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

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

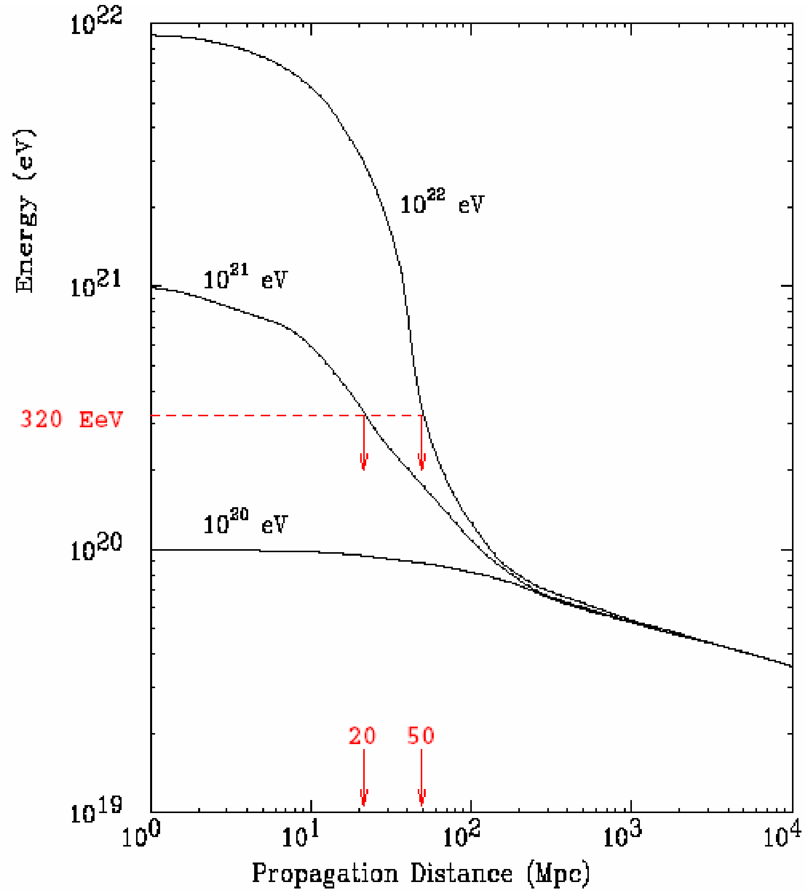
The moral:

CR's above threshold bound to lose energy

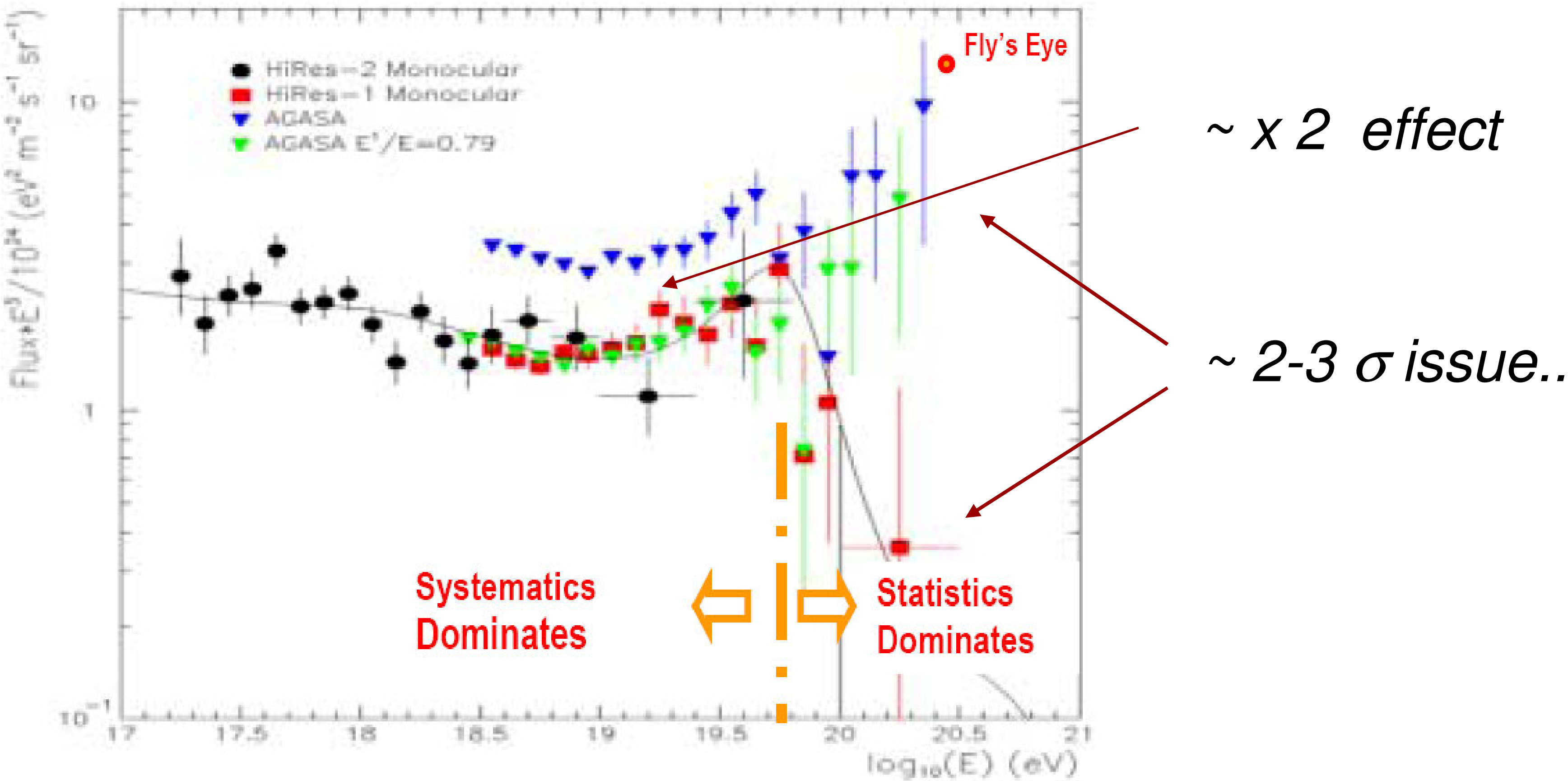
The GZK Cutoff

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

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

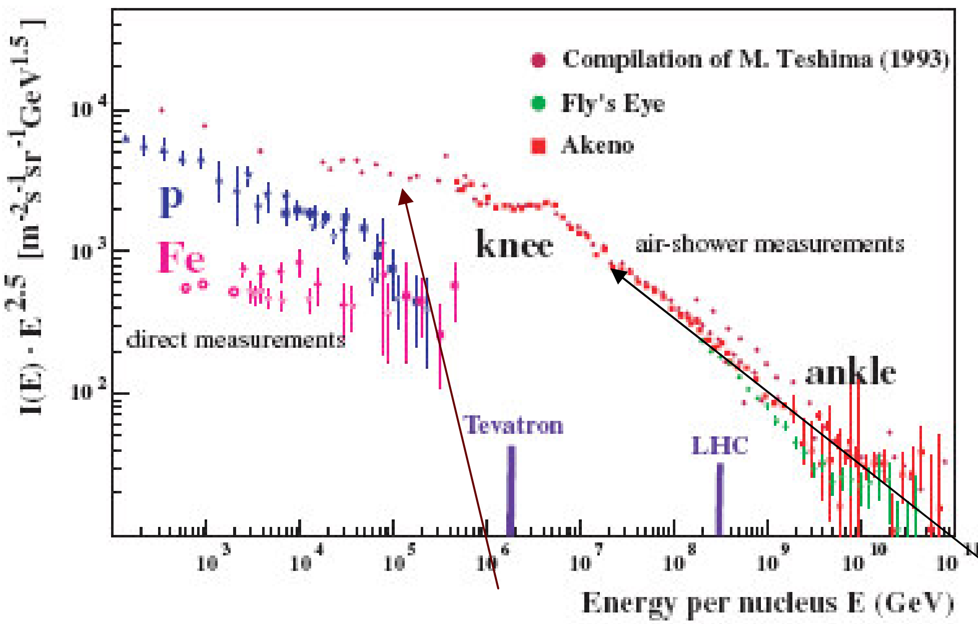


The High End of the CR spectrum

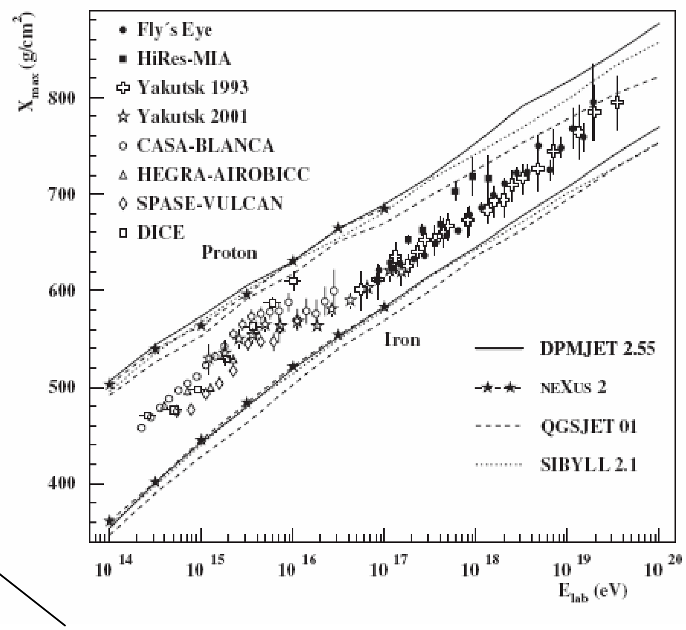


Composition Issues

Spectrum



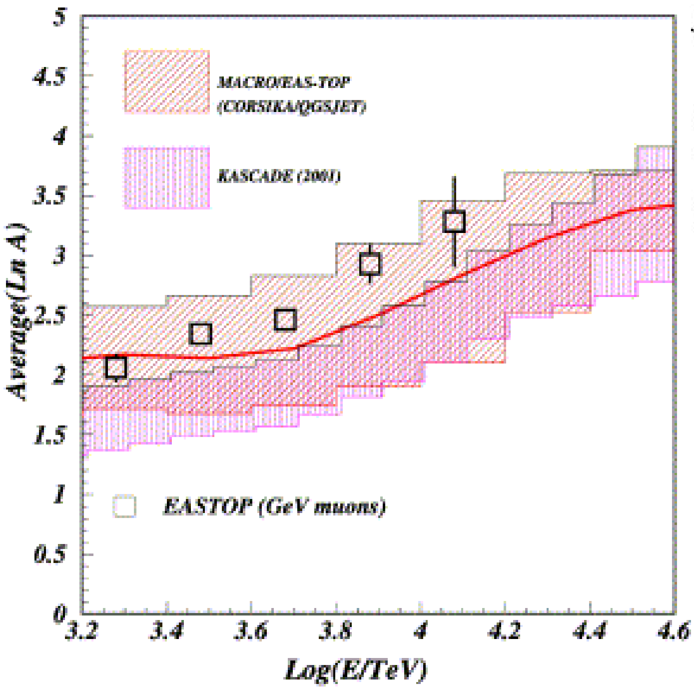
Depth of Shower Maximum in Air vs. E

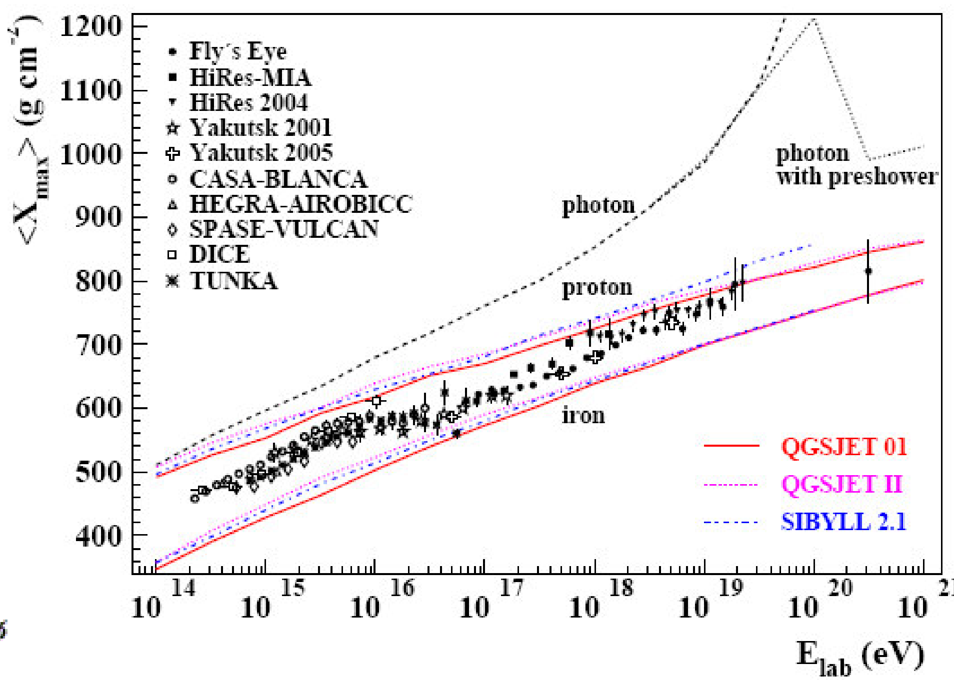


Galactic?

Extra-Galactic?

More on Composition



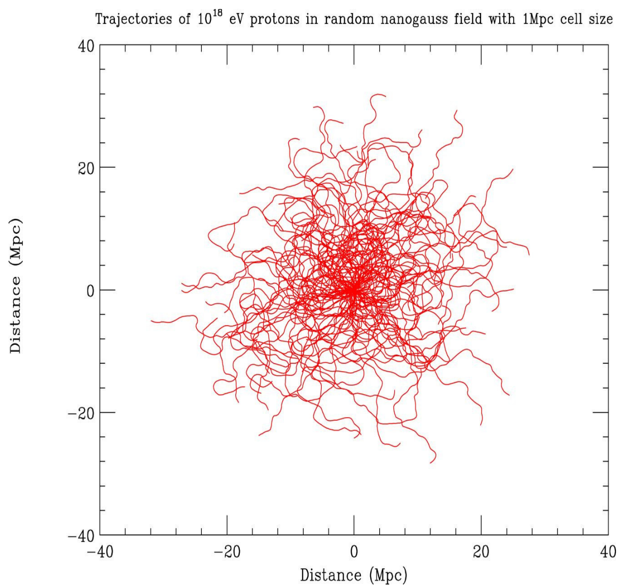


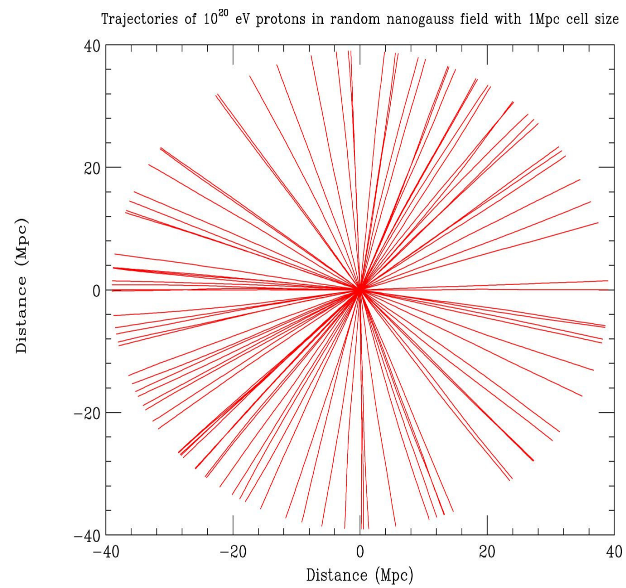
Proton/Iron Discrimination tied to Intra/Extra-Galactic origin

Opening a New Window?

Effect of Extra-Galactic Magnetic Field on CR trajectories –Simulation

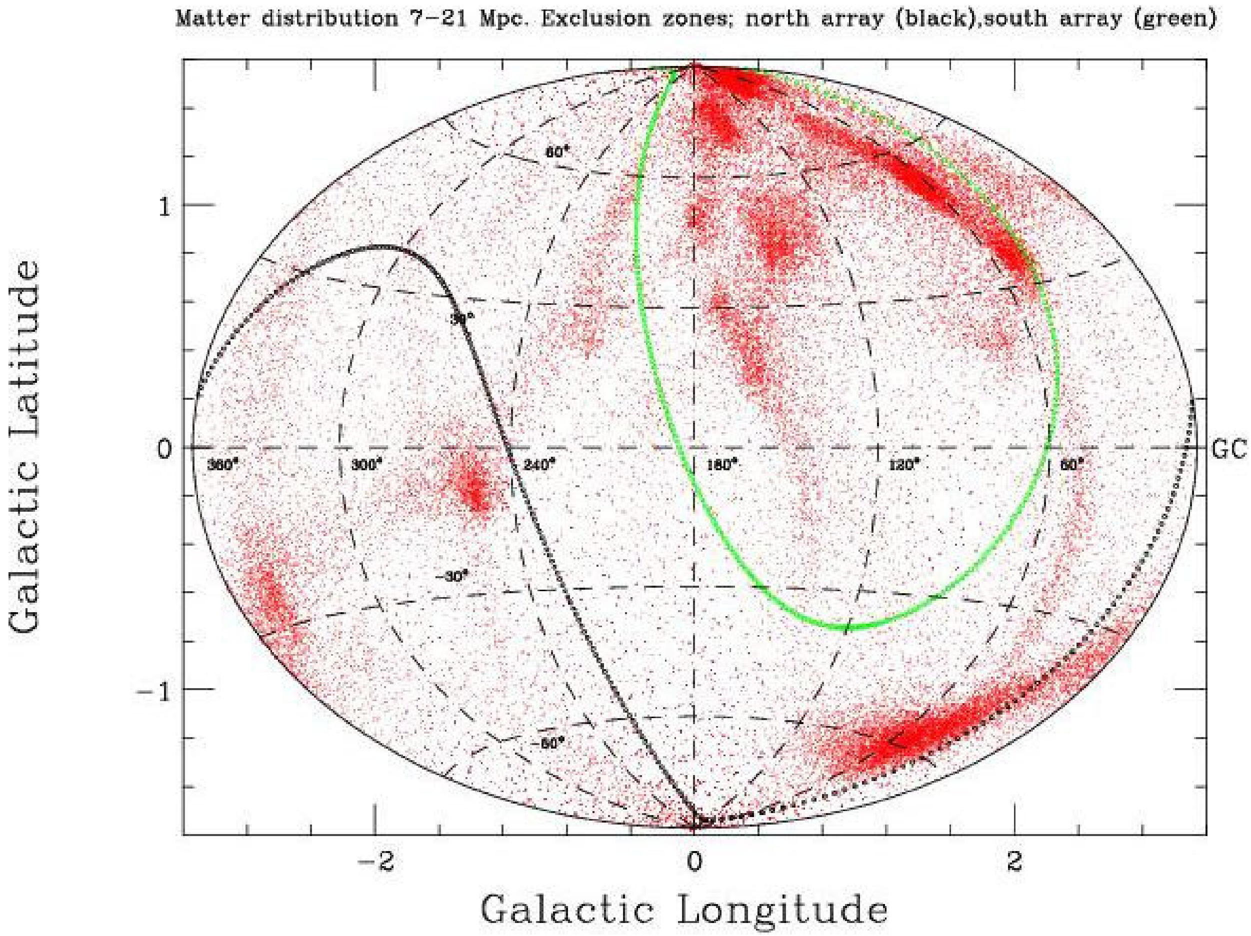
E = 10^{18} eV ***E = 10^{20} eV***



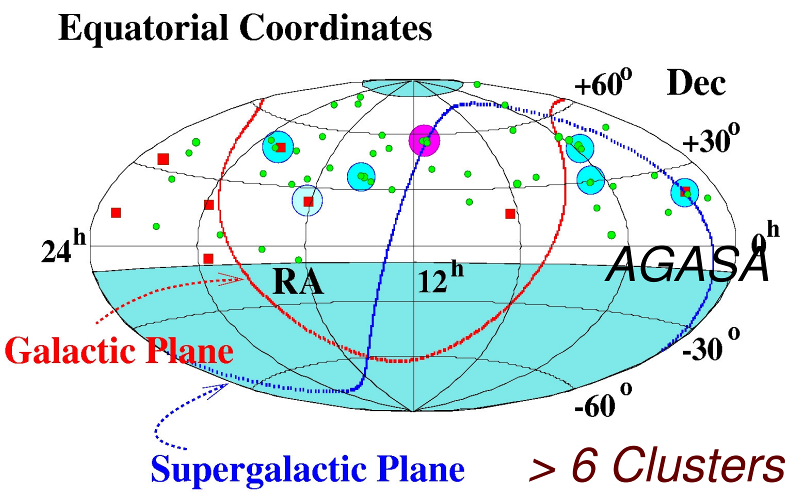


Clearly, around 10^{20} eV a new astronomy is feasible…
…if Cosmic Rays of that energy are actually observed

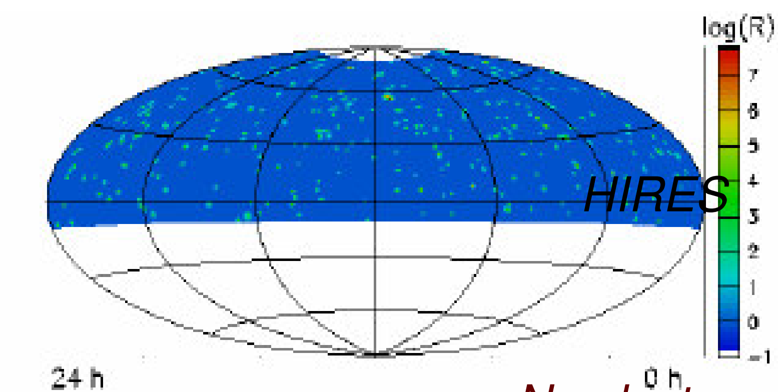
The Known Matter (< 21 Mpc)



Anisotropies, Point Sources?



> 6 Clusters observed



No cluster

Controversial results…
Issues at stake:

Detection Technique
Angular Resolution
Statistics!

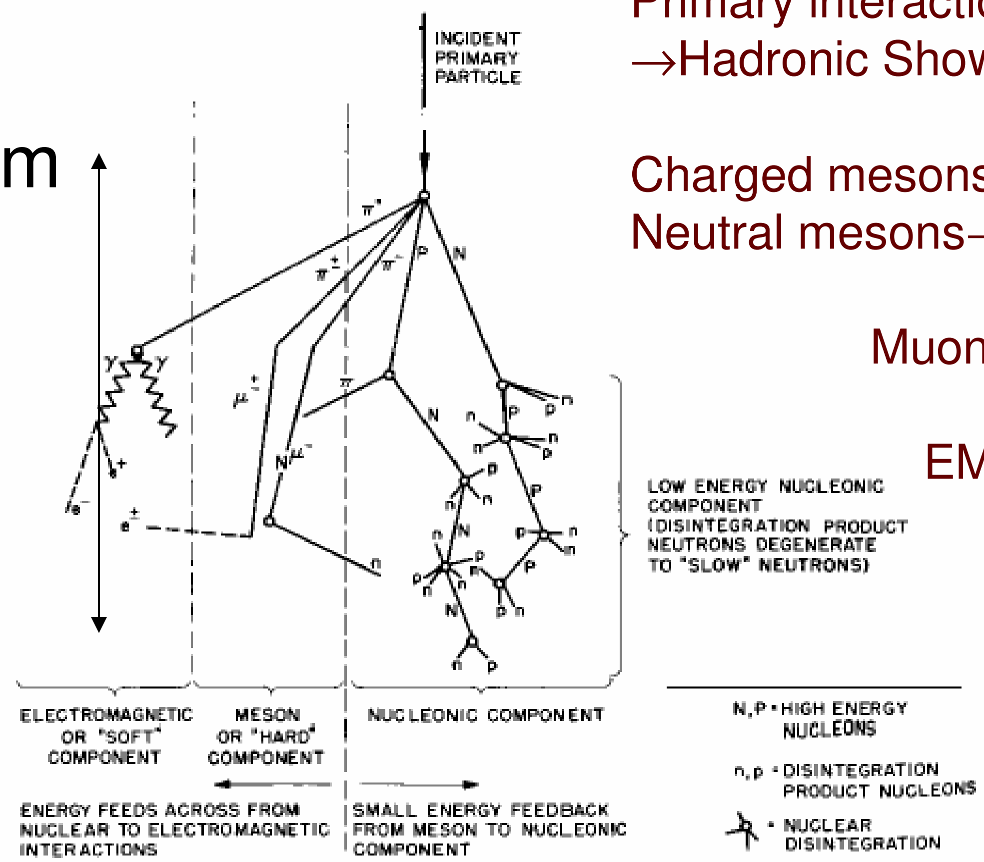
Cosmic Rays Detection

- Direct detection - Up to 10^{14} eV
  - Main limitation: Flux
  - Usually performed by balloons, satellites, …

- Extensive Air Showers – Above 10^{14} eV
  - Primary particle interaction in upper atmosphere
  - Developing shower detected by different techniques

EAS Development

~10 km

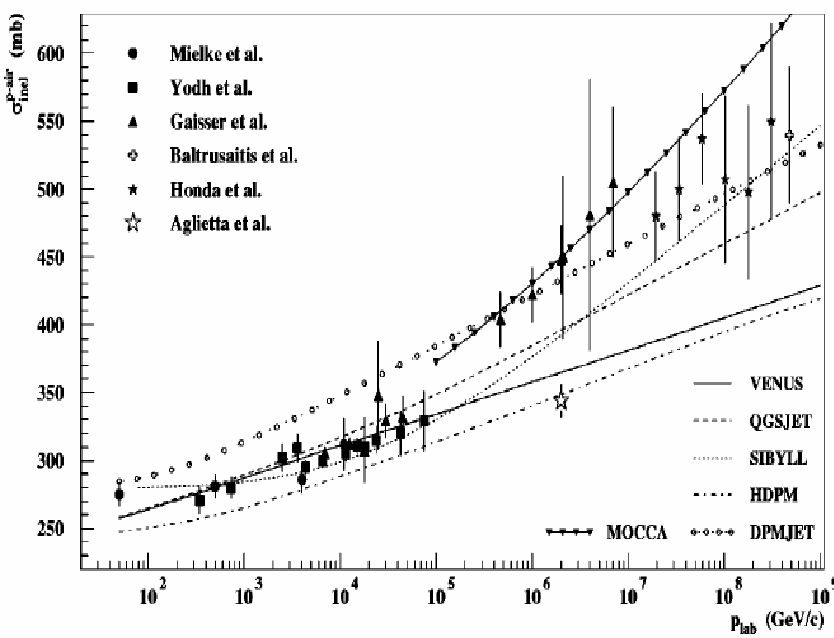


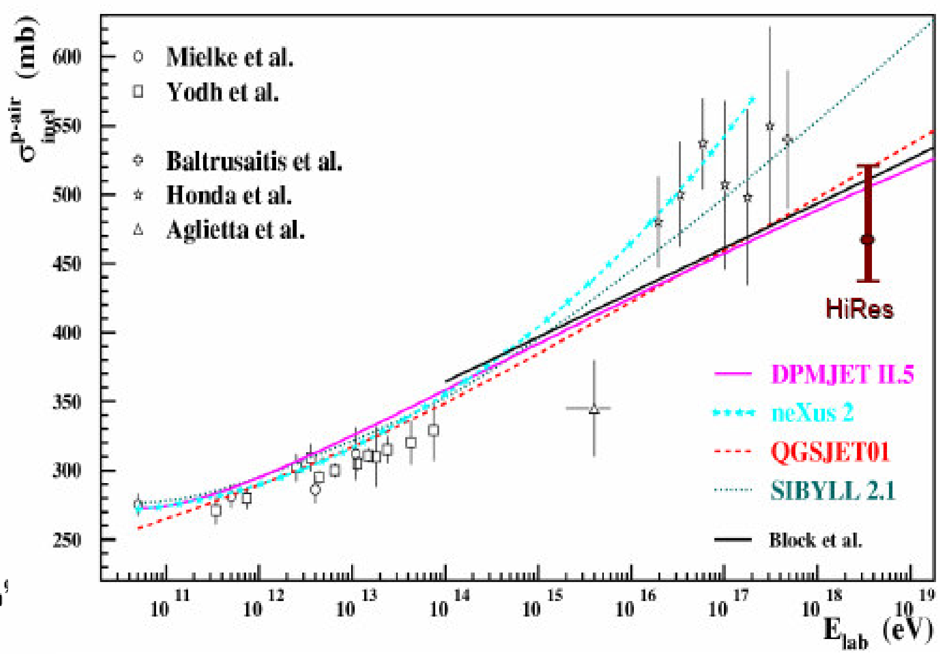
Primary interaction in the high atmosphere
→Hadronic Shower

Charged mesons→ Muons
Neutral mesons→ Photons

Muon component
+
EM Shower

EAS – Cross Section



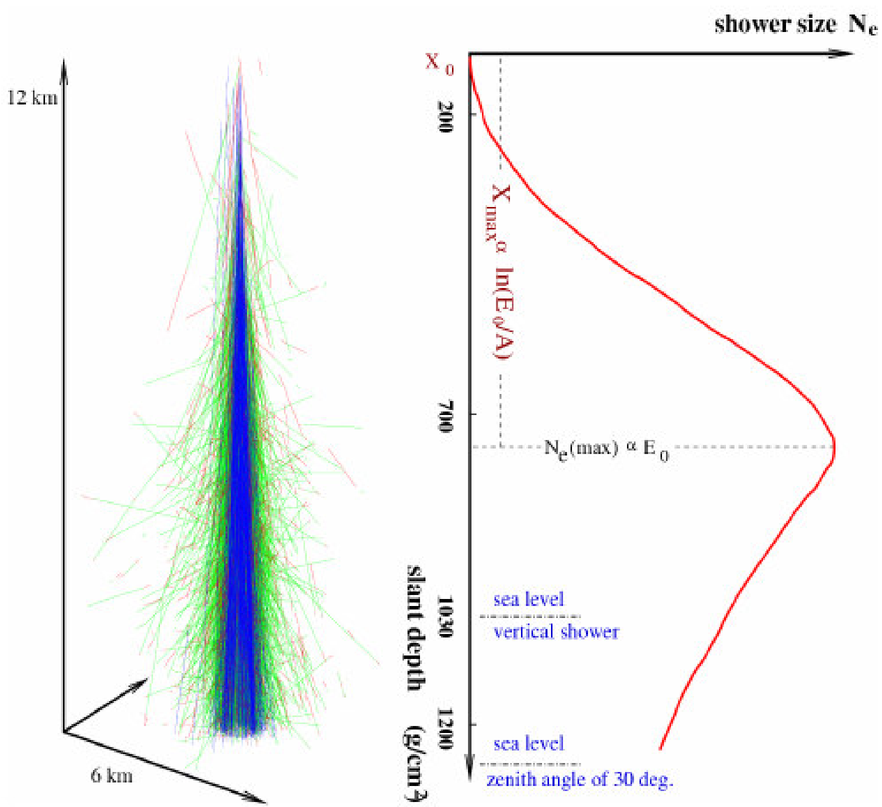


EAS – EAS development

Next ~6 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



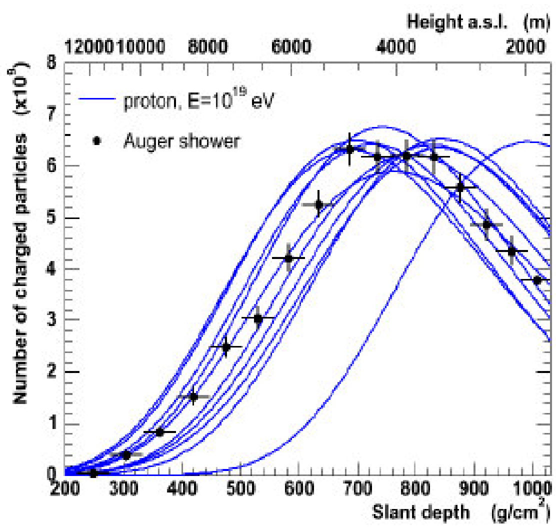
Atmospheric depth:

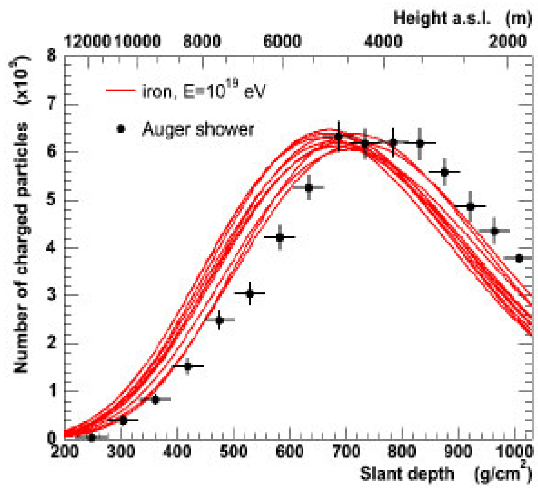
$$\int_h^{\infty} \rho(l)\, dl = X(h)$$

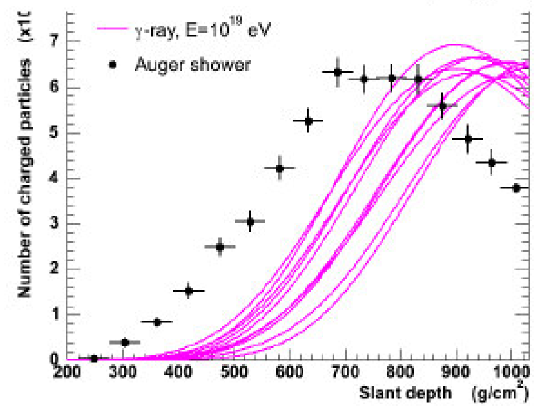
- Shower particles: mainly $e^{\pm}, \gamma$
- 80 – 95% of primary energy converted to ionization energy
- Up to 10^{11} charged particles

EAS-II

Detailed MC simulation: 10 showers
zenith angle 35°, QGSJET

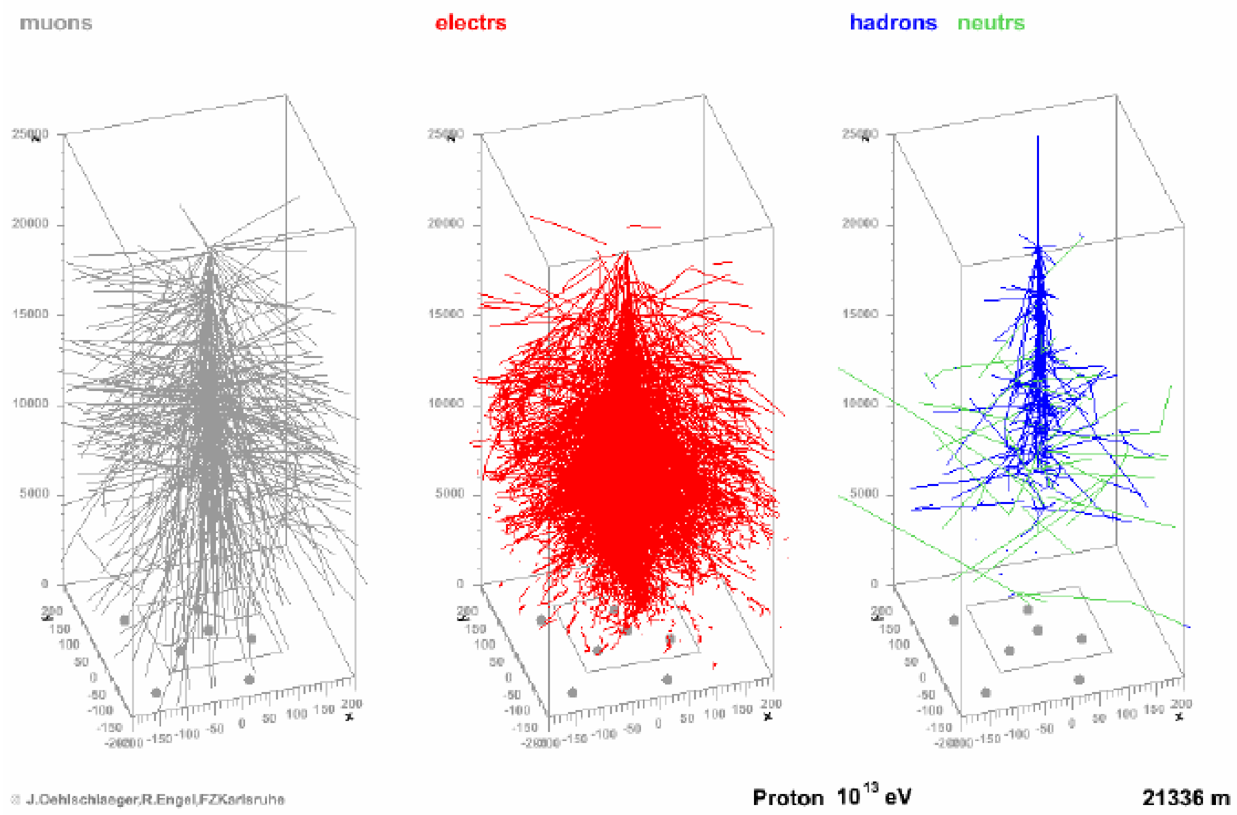




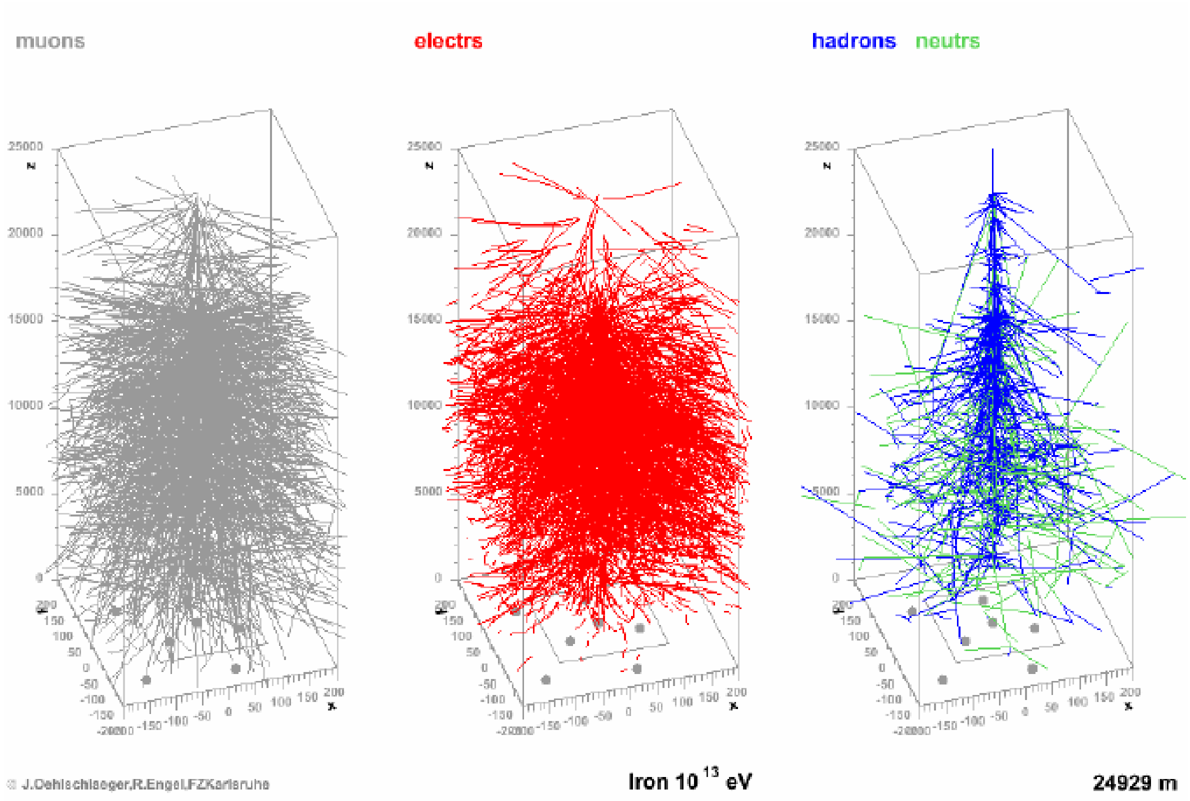


$$N^A_{max} = N_{max}, \qquad X^A_{max} \sim \lambda_e \ln(E_0/A)$$

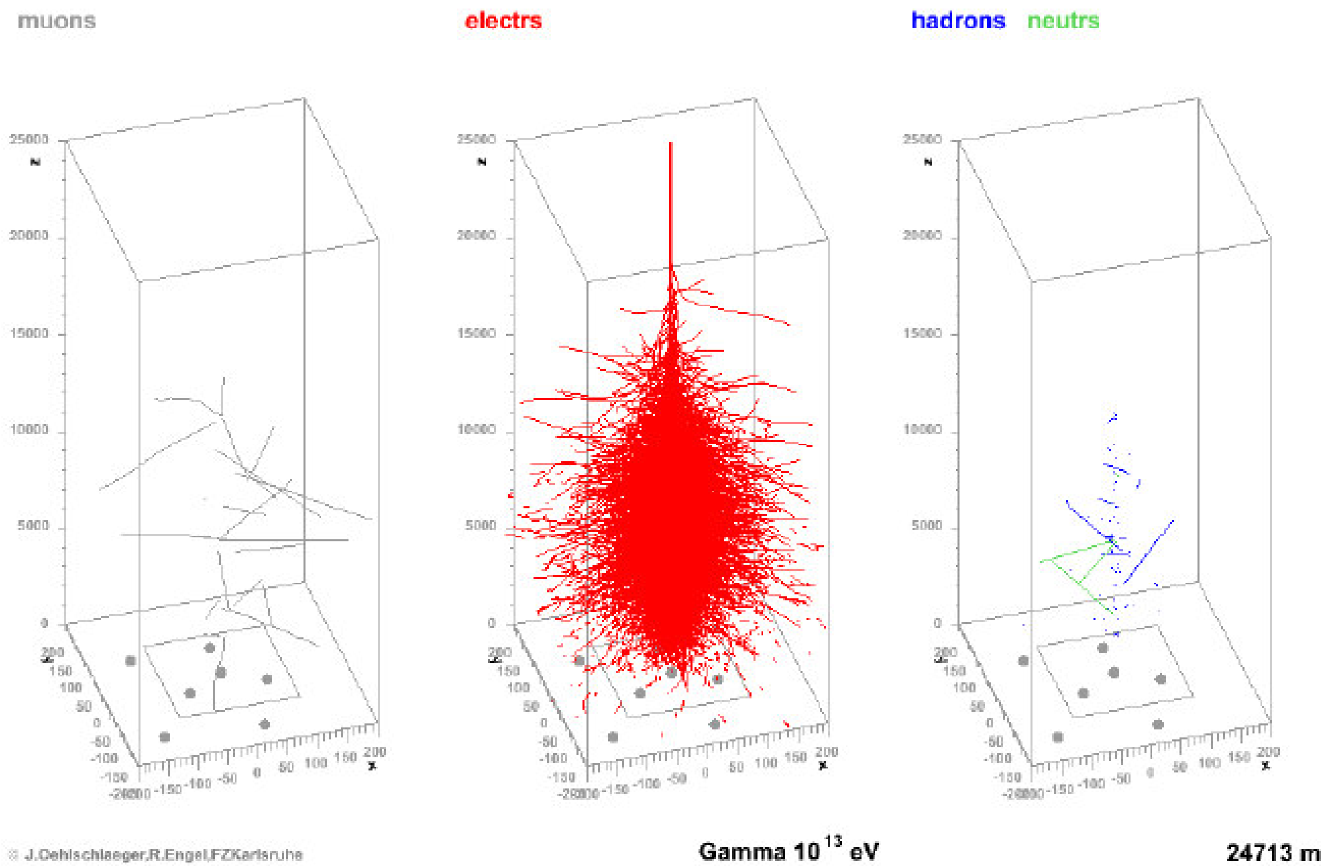
EAS-III


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

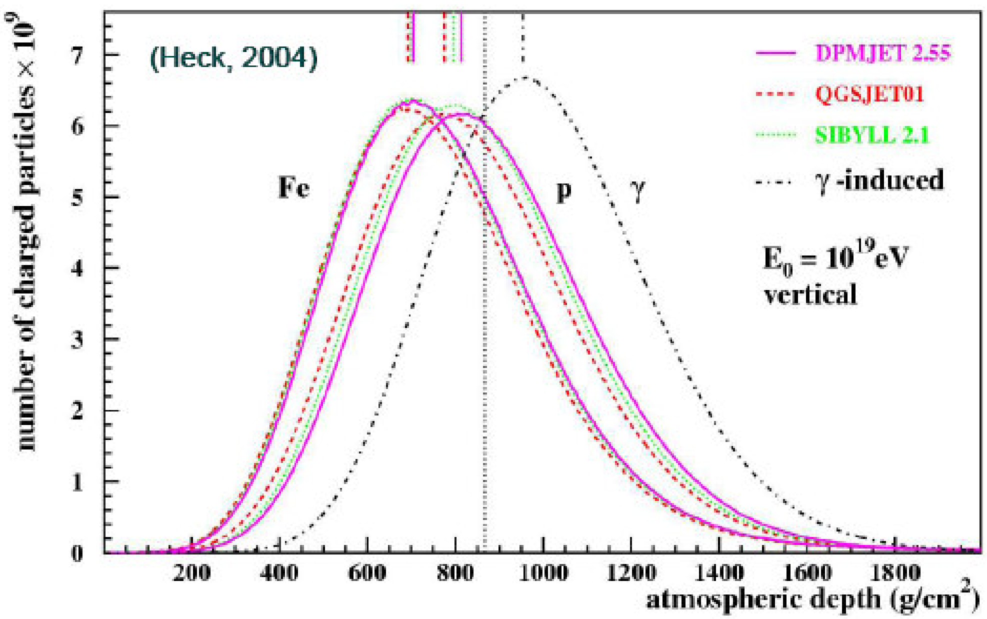
EAS-IV

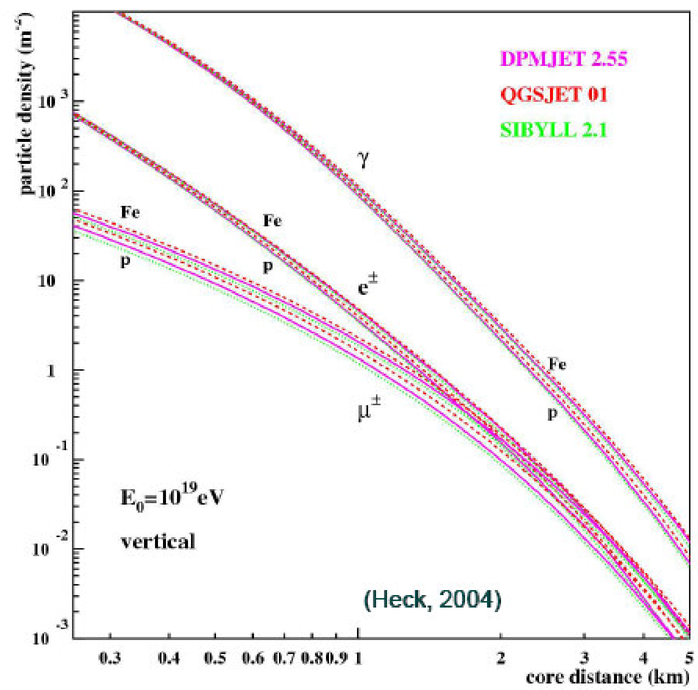

muons
electrs
hadrons
neutrs
© J.Oehlschlaeger,R.Engel,FZKarlsruhe
Iron 10^{13} eV
24929 m

EAS-V


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

EAS - Profiles

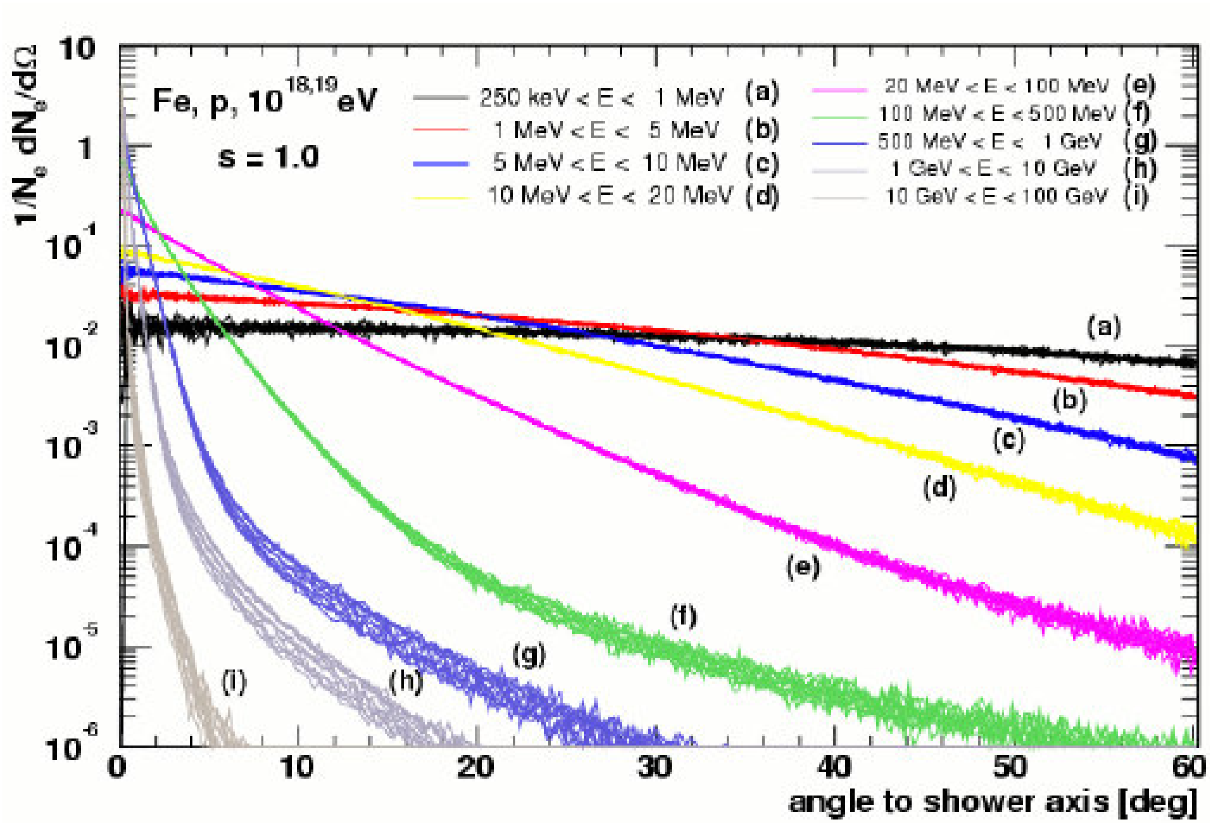




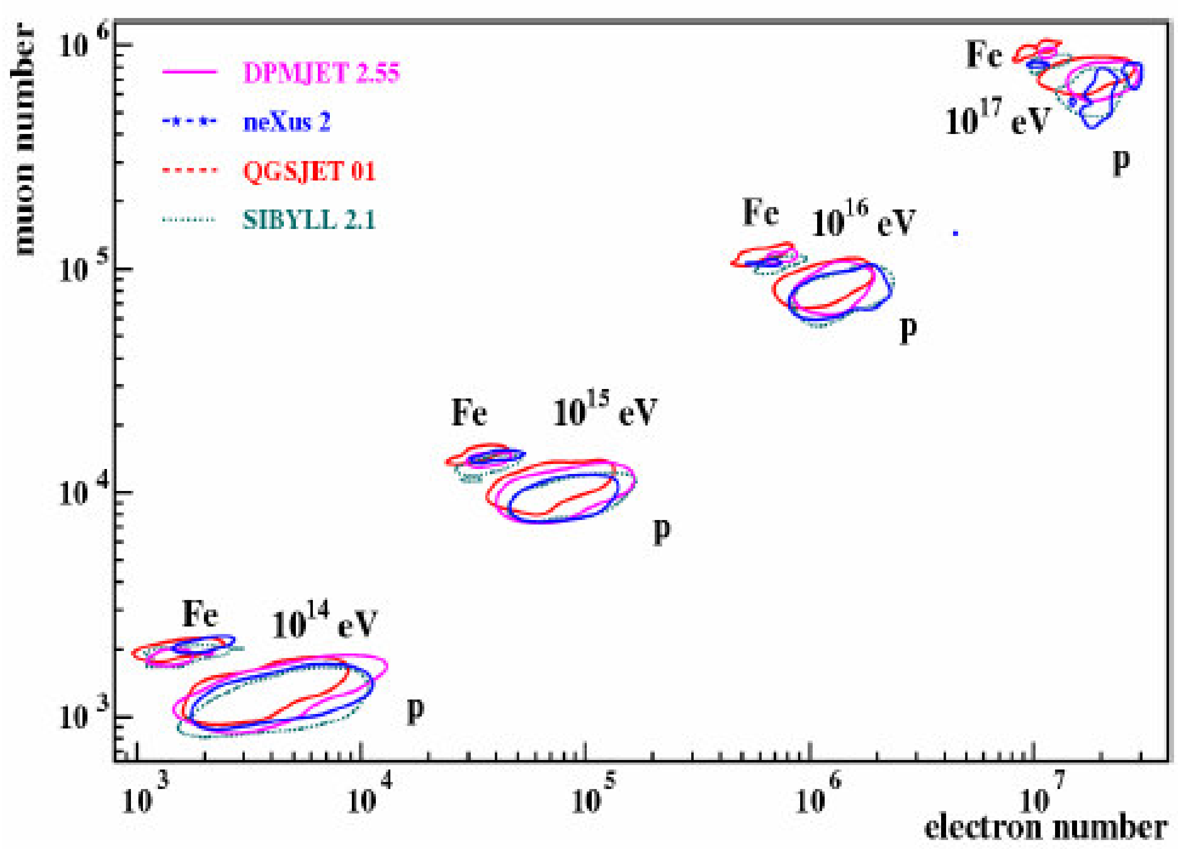
Longitudinal

Lateral

EAS - Electron Lateral Distribution



EAS - Muons vs Electrons



EAS- Elongation Rate

Elongation rate

$$D_e = \frac{\langle dX_{\max} \rangle}{d \ln E}$$

$$D_{10} = \frac{\langle dX_{\max} \rangle}{d \lg E} = \ln(10) D_e$$

Photon-induced shower

$$\langle X_{\max}^{\gamma} \rangle \sim X_0 \ln E$$

$$D_{10}^{\gamma} = \ln(10) X_0 \approx 84 \text{ g/cm}^2$$

Elongation rate theorem

Constraint on elongation rate of hadron-induced showers

$$D_{10}^{\text{had}} = D_{10}^{\gamma} (1 - B_n - B_\lambda)$$

$$B_n = \frac{d \ln \langle n(E) \rangle}{d \ln E} \qquad B_\lambda = \frac{-\lambda_{\text{int}}}{X_0} \frac{d \ln \lambda_{\text{int}}}{d \ln E}$$

(Linsley, Watson, PRL 46(1981)459)

EAS Detectors

Long history, dating back to the '60s

Volcano Ranch (USA) – Sampling
Haverah Park (UK) – Sampling
SUGAR (Australia) - Sampling
Yakutsk (Russia) - Sampling
Fly's Eye (USA) – Fluorescence
AGASA
HiRes

AGASA Akeno Giant Air Shower Array

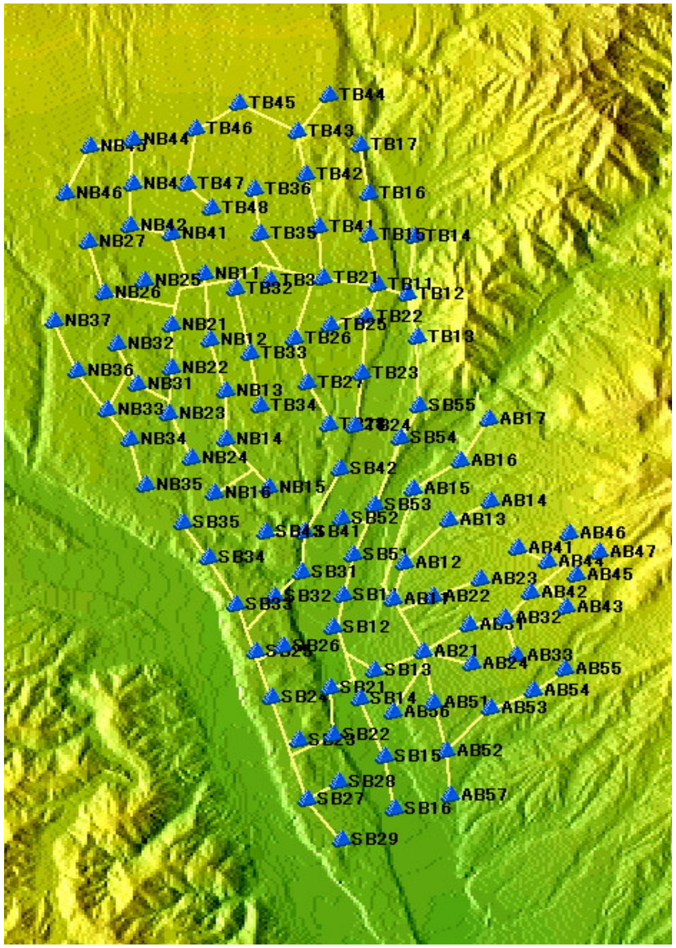
111 scintillators + 27 muon det.
Akeno, Japan

11 Super-GZK events

Small Scale Clustering

Constraints on Composition:

→ protons at UHEs.
(“Classical” analysis based on N_e vs N_μ)



HiRes High Resolution Fly's Eye

Pioneers of FluorescenceTechnique

Air fluorescence detectors
HiRes 1 - 21 mirrors
HiRes 2 - 42 mirrors
Dugway, Utah, USA

No Super-GZK flux
No Small Scale Clustering
Composition Change

EAS – The Movie