

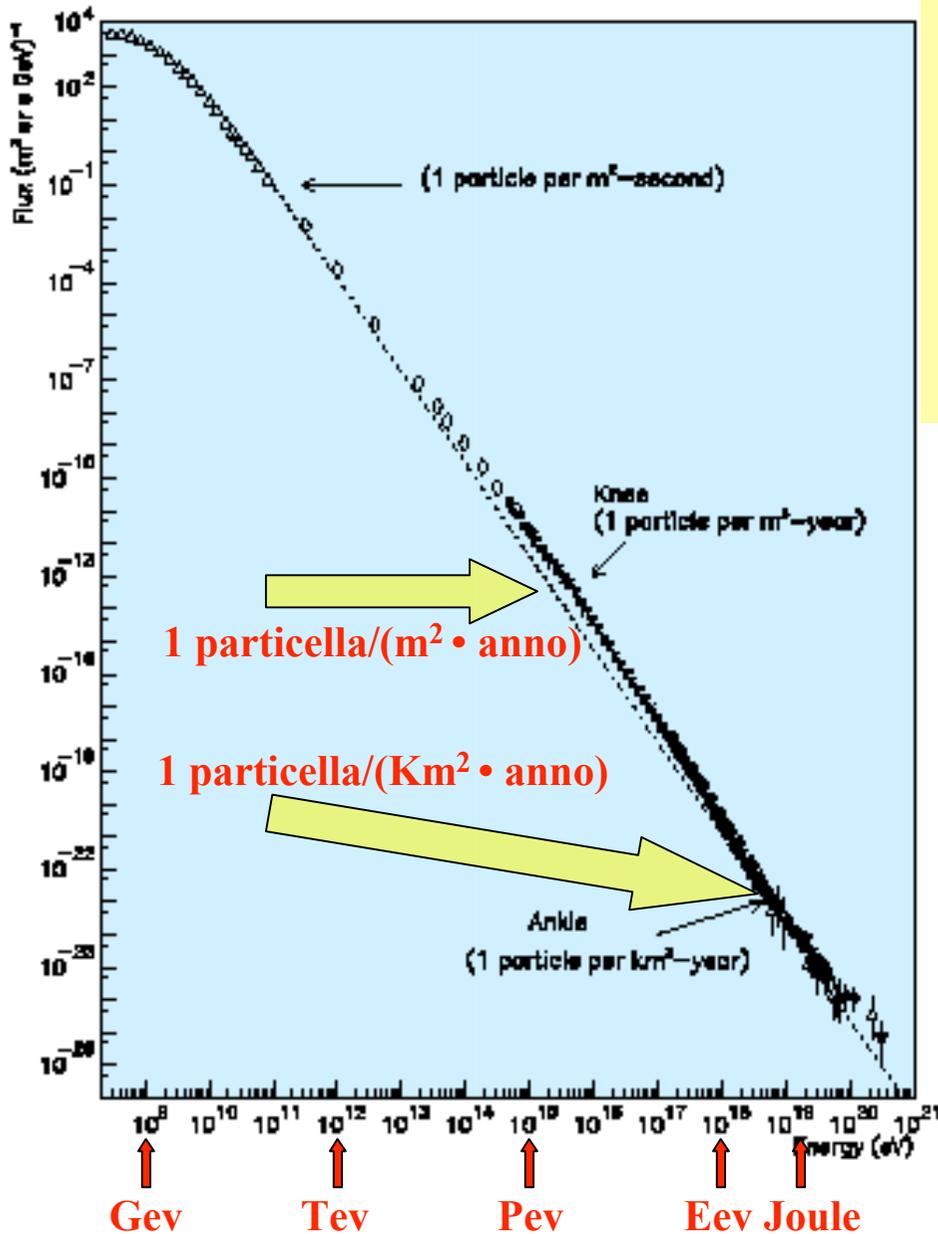
Fisica Nucleare e Subnucleare II

Lezioni n. 43 e 44

– Rivelazione di raggi cosmici con $E > 10^{18}$ eV

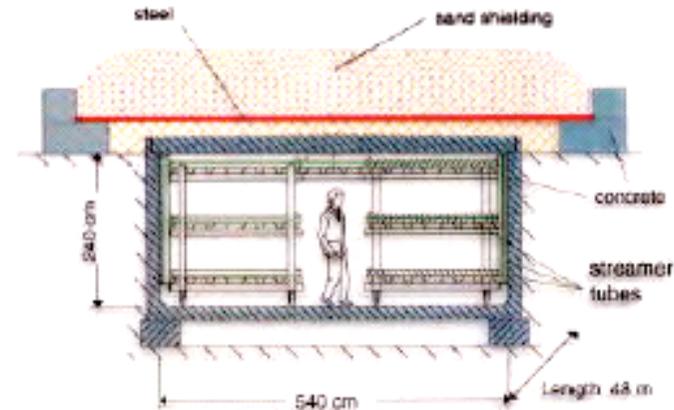
- misure di R.C. con energia maggiore di circa 100 TeV
- misure della natura, energia e direzione dei RC primari
- misure con apparati per la rivelazione di sciame estesi (KASKADE).
- Generalità sullo sviluppo di sciame adronici e sciame elettromagnetici.
- Effetto GZK
- Misure con apparati per la rivelazione di sciame estesi (AGASA)
- con apparati tipo fly's eyes (HI-RES) per misure di fluorescenza
- con apparati complessi, "ibridi" (AUGER).

Rivelazione di raggi cosmici di altissima energia ($E \sim 100\text{TeV}$)



Lo studio di raggi cosmici con $E \geq 100\text{TeV}$ richiede:

- ⇒ apparati di grandi dimensioni (apparati a scintillatore, per luce Cherenkov, traccianti, ..)
- ⇒ sulla superficie terrestre
- ⇒ si studiano i "risultati" delle interazioni dei raggi cosmici primari con l'atmosfera
- ⇒ si risale poi a E, direzione, natura dei "primari"

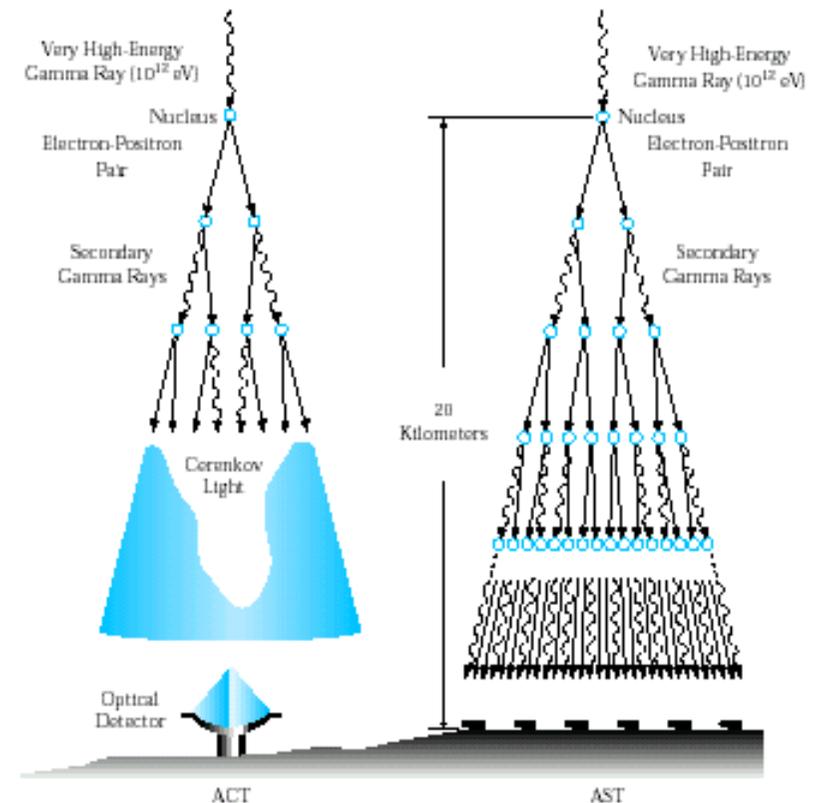


Ad esempio l'apparato KASCADE

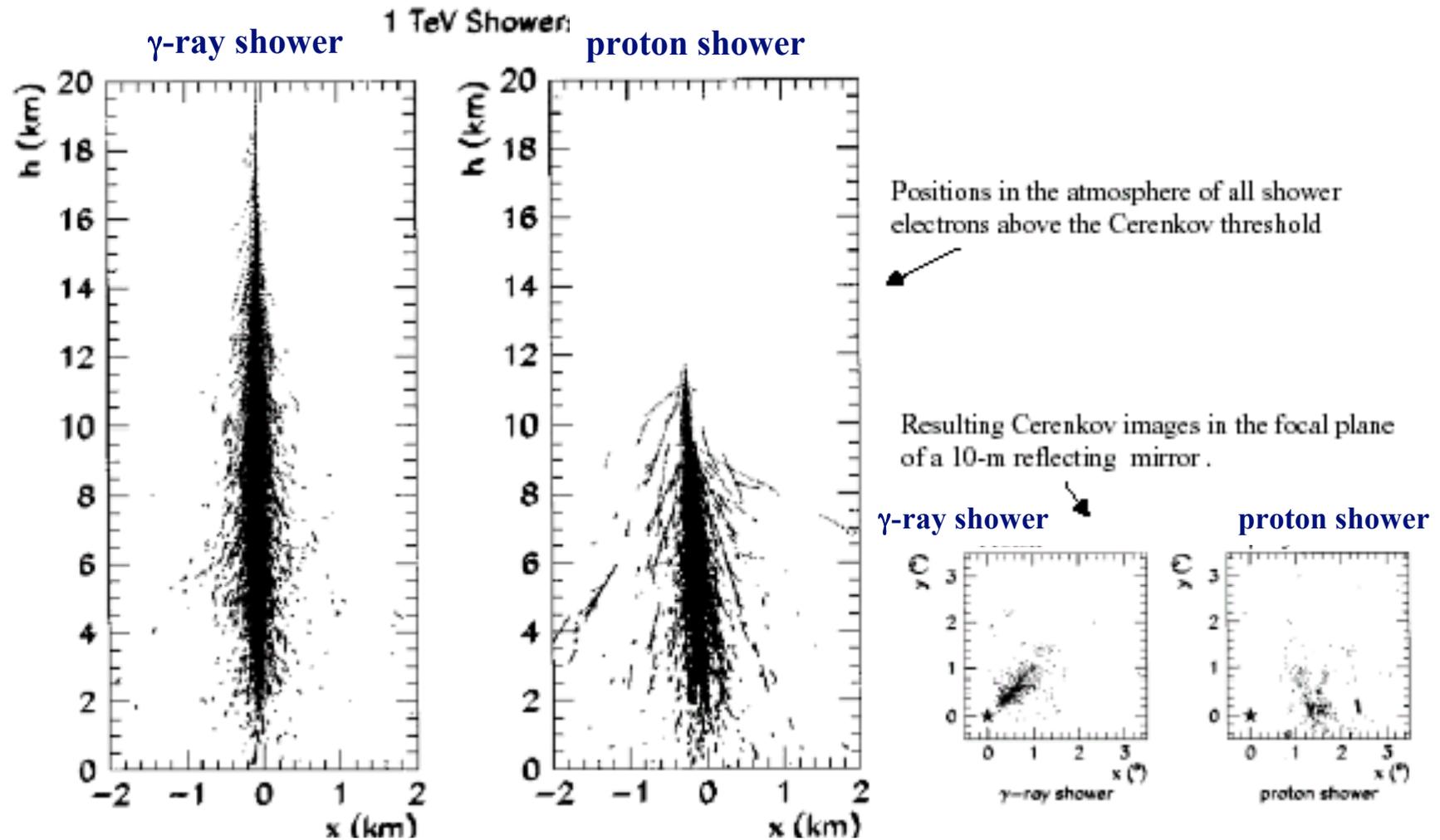


Esperimenti per rivelazione di sciame in aria

- $E_0 \sim 1 \text{ TeV}$ (Very High Energy) la rivelazione di sciame in aria può essere effettuata con telescopi “ottici” capaci di rivelare la luce Cherenkov prodotta da particelle cariche relativistiche nell’alta atmosfera (la massima quantità di luce dove lo sviluppo dello sciame e’ massimo) - **Air Cherenkov experiments**
- $E_0 \sim 100 \text{ TeV}$ (Ultra High Energy) un rivelatore disposto in montagna realizzato con apparati di grande superficie e’ attraversato da un numero sufficiente di particelle per essere “triggerato” - **Classic Air shower experiments**
- $E_0 > 1000 \text{ TeV}$ (Extreme UHE) anche un rivelatore a livello del mare può essere sensibile a sciame estesi. - **Fly’s Eye experiments**



Sviluppo di sciami verticali in aria originati da γ o p da 1 TeV



Interazione di p e di γ nell'alta atmosfera: a che quota ?

Atmospheric Thickness:

1035 g/cm²

$\approx 11 \lambda_I$ (hadr. interact. lengths)

$\approx 27 X_0$ (radiation lengths)

$\sigma_{p-Air} \sim 300$ mb per $E_p \sim 1$ TeV

Some basics...

$$\lambda_I = \frac{1}{n \cdot \sigma} \cong 90 \text{ g/cm}^2 \text{ (p-Air)}$$

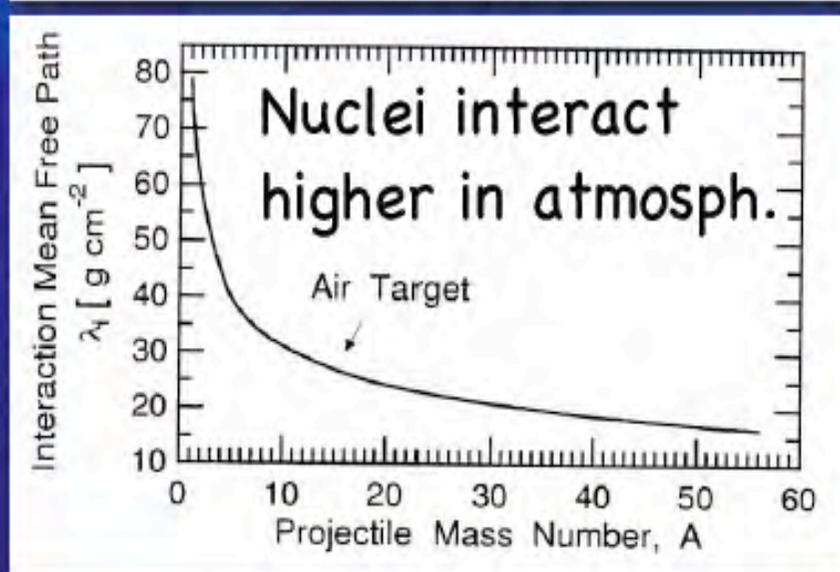
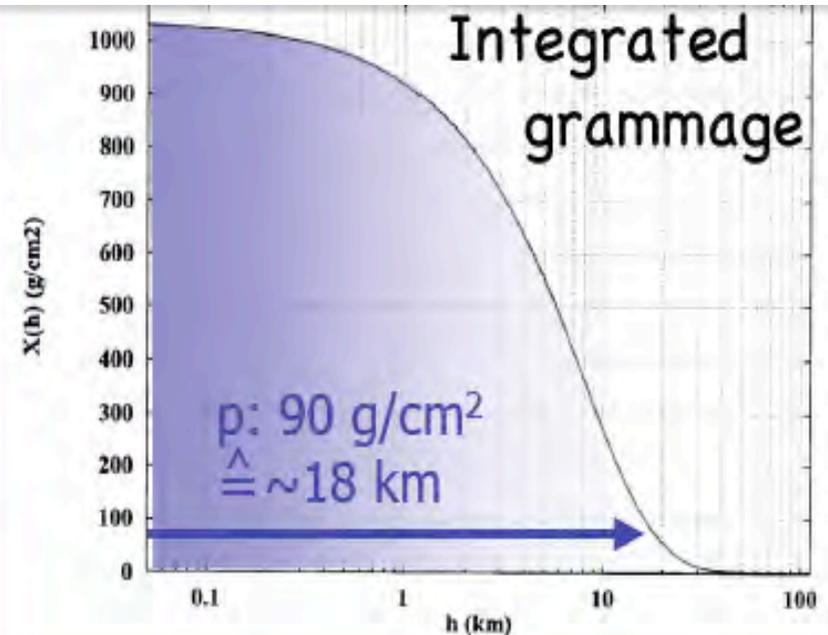
(n : density of absorber nuclei;

σ : total inelastic X -section)

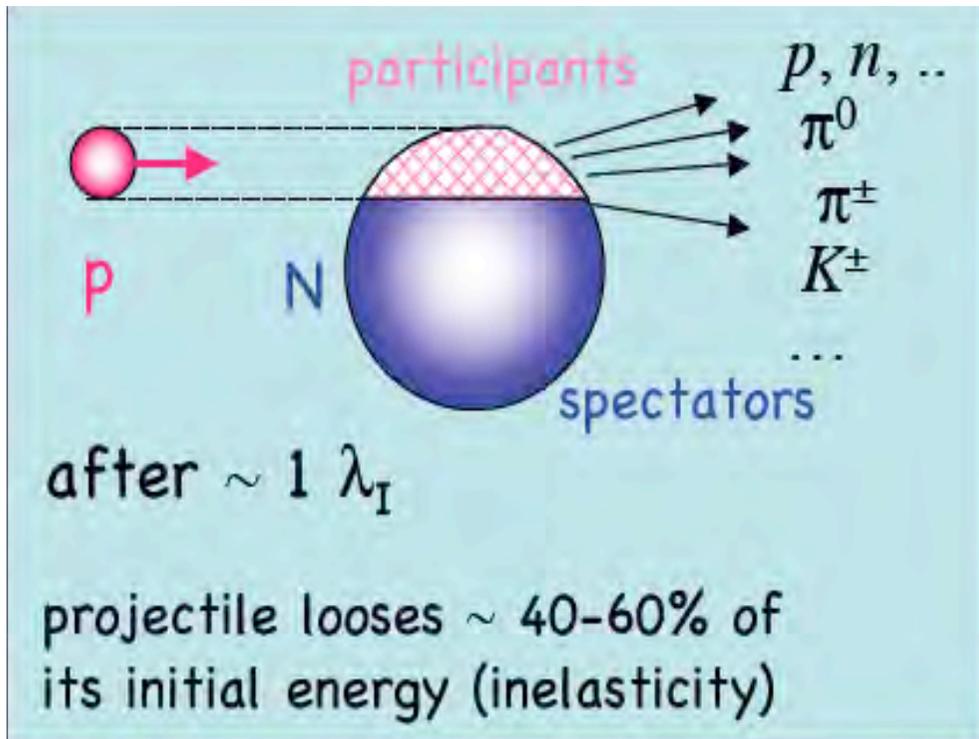
X_0 defined by energy loss of high-energy electrons in media:

$$\langle E_e \rangle \propto e^{-\frac{X}{X_0}}$$

In air: $X_0 = 36.66$ g/cm²



Interazione di p nell'alta atmosfera: i secondari delle interazioni



Consequences:

pions are the most abundant hadrons in showers;
 μ 's are integrative; decay into e^\pm of no relevance

$$\pi^0 \rightarrow \gamma\gamma \quad (\tau_0 = 0.8 \cdot 10^{-16} \text{ s})$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \quad (\tau_0 = 26 \text{ ns})$$

decay of π^\pm :

$$R_\pi = \gamma \cdot v \cdot \tau_0 \simeq \frac{E_\pi^{tot}}{m_0 c^2} \cdot c \cdot \tau_0$$

$\approx 7.8 \text{ m}$

e.g.: $E_\pi = 14 \text{ GeV} \rightarrow R_\pi = 780 \text{ m}$
 $\approx 1 \lambda_I$ at 5 km height

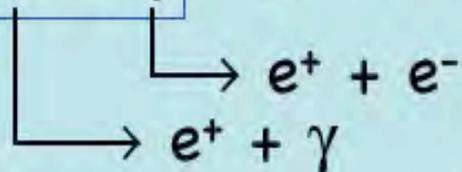
consequence:

in early shower, the hadronic interaction of π^\pm is more probable than decay into μ and vice versa in late showers

Interazione di γ nell'alta atmosfera: sviluppo dello sciame



γ either directly from space
or from $\pi^0 \rightarrow \gamma\gamma$ decay

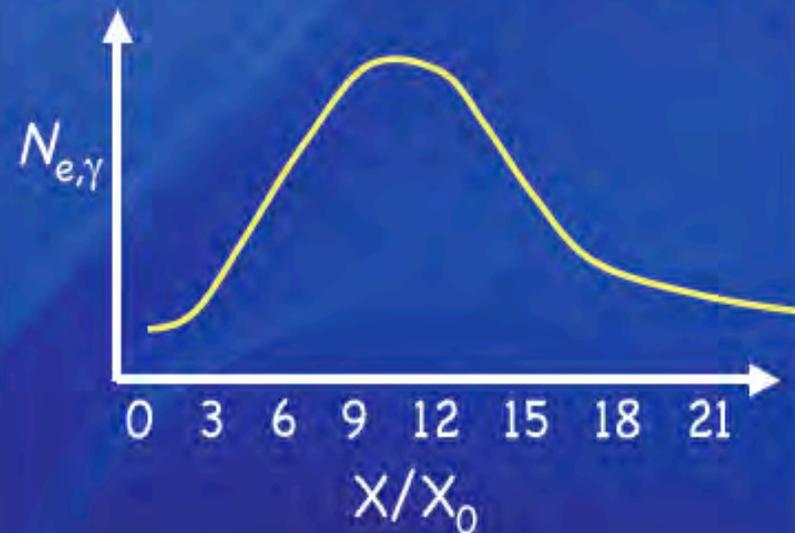


processes repeat every $\sim X_0$,

stops when $\left(\frac{dE}{dx}\right)_{\text{ionis}} > \left(\frac{dE}{dx}\right)_{\text{brems}}$

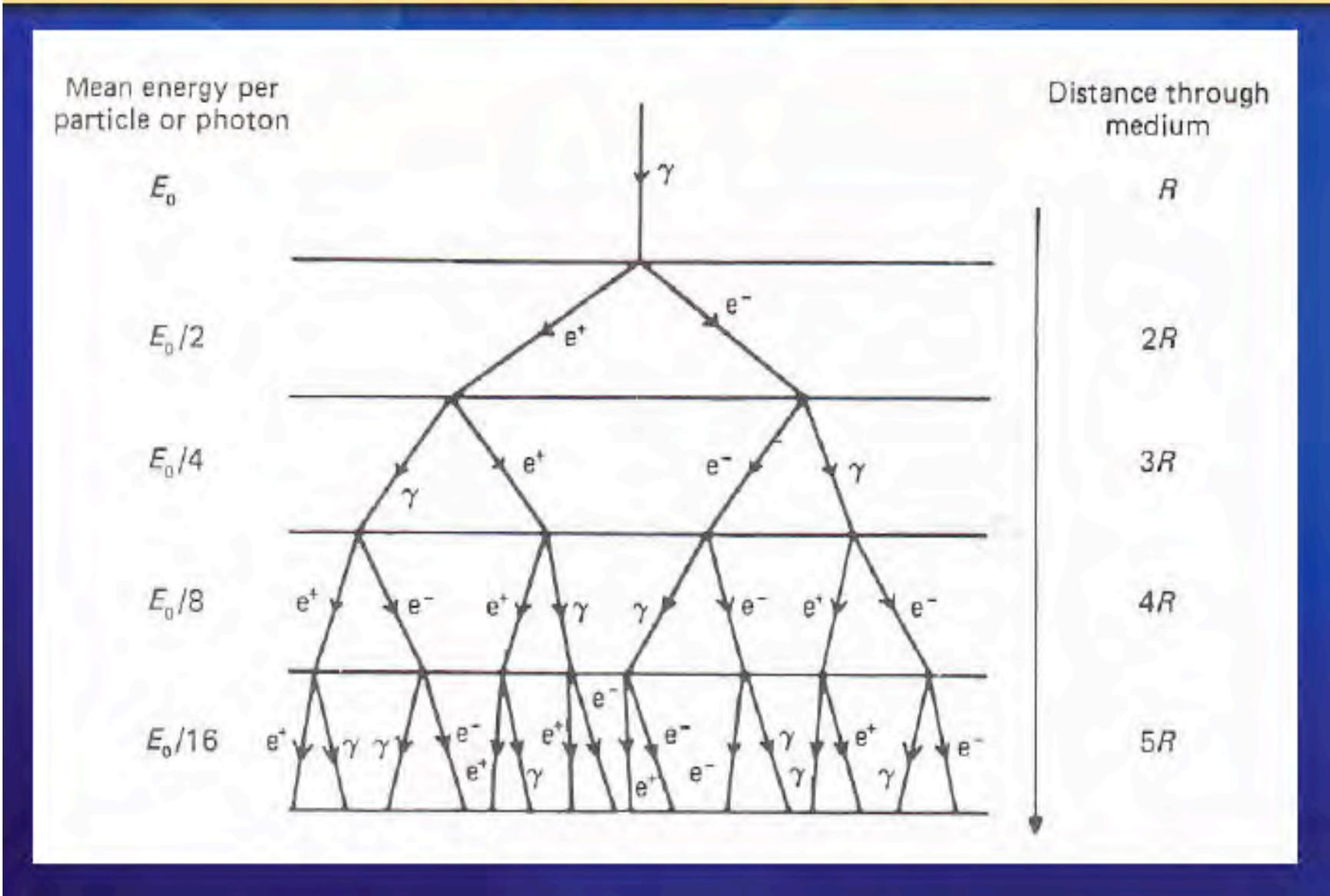
i.e. at $E < E_{\text{crit}}$

Number of electrons
(photons) doubled every X_0



Toy-model dello sviluppo di uno sciame e.m. nell'alta atmosfera

- electromagnetic component -



Sviluppo di sciame: parametrizzazioni

Cascata e.m.

Modello semplificato:

@ Δx_i ; X_0

$e \rightarrow e^+e^-$

$$E^+ = E^- = E/2$$

$\gamma \rightarrow e^+e^-$

il processo di moltiplicazione si arresta @ $E < E_c$

assorbimento di particelle dopo la moltiplicazione

$$E(t) \propto e^{-\beta t}$$

n. particelle dopo $x = t X_0$:

$$N(t) = 2^t$$

$$E(t) = \frac{E_0}{2^t}$$

$$\text{@ } t_{\max}: \frac{E_0}{2^{t_{\max}}} = E_c$$

$$\Rightarrow t_{\max} = \frac{1}{\ln 2} \ln \left(\frac{E_0}{E_c} \right)$$

$$N_{\text{tot}} = \sum_{t=0}^{t_{\max}} 2^t = 2^{t_{\max}+1} - 1 = 2 \frac{E_0}{E_c} - 1$$

Parametrizzazioni

- distribuzione longitudinale

$$\frac{dE}{dt} \propto t^\alpha e^{-\beta t}$$

- massimo dello sciame:

$$t_{\max} = 1.4 \ln \frac{E_0}{E_c}$$

- contenimento longitudinale

$$t_{95\%} = t_{\max} + 0.08Z + 9.6$$

- contenimento laterale dominato dallo scattering multiplo (+ propagazione dei fotoni)

$$\langle \theta_M \rangle = \frac{21}{p\beta} \sqrt{t}$$

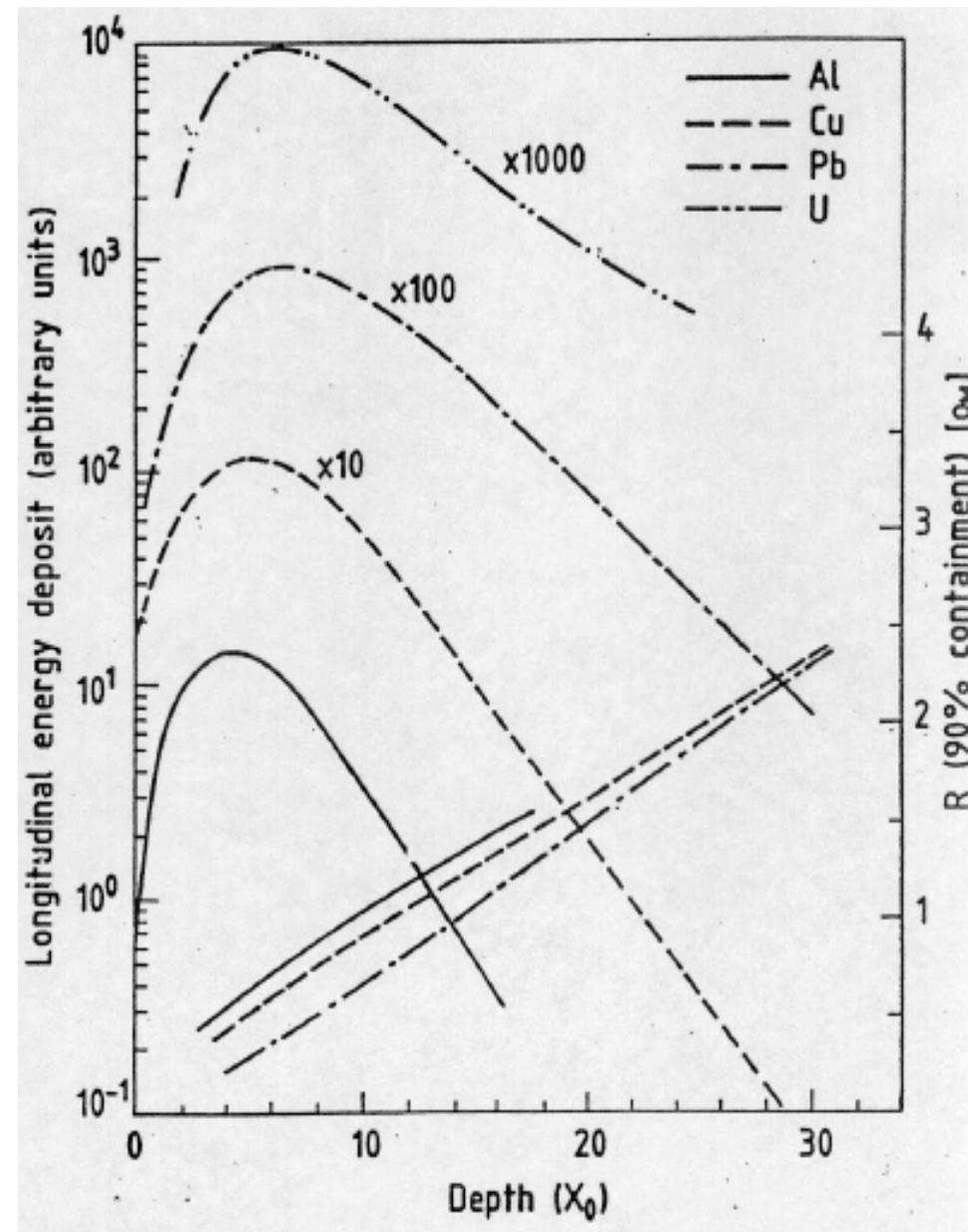
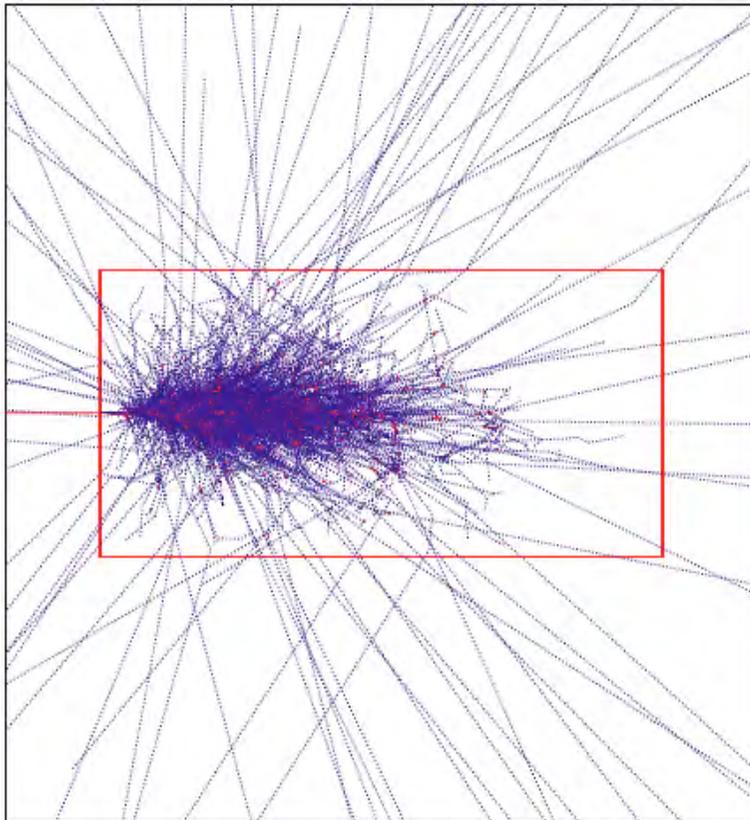
$$r_{95\%} = 2R_M$$

$$R_M = \frac{21 \text{ MeV}}{E_c} X_0 \quad \text{g/cm}^2 \text{ raggio di Molière}$$

$$R_M \propto \frac{X_0}{E_c} \propto \frac{A}{Z} \text{ per } Z \gg 1$$

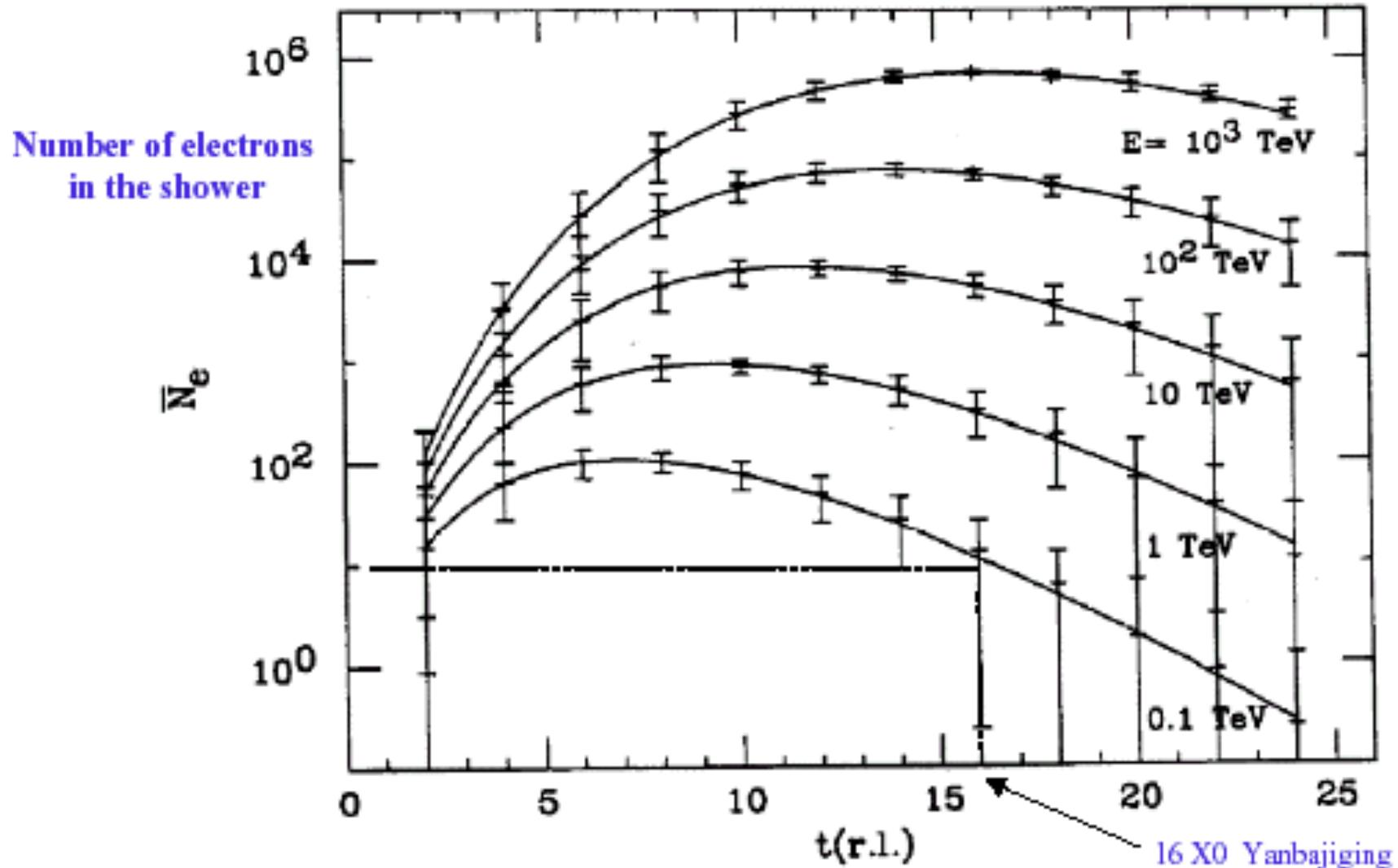
Sviluppo longitudinale e laterale di uno sciame e.m.

Risultato della simulazione, con tecniche di Montecarlo, dello sviluppo di uno sciame



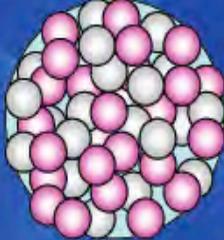
Numero medio di elettroni in uno sciame da γ verso il "numero di lunghezze di radiazione" di atmosfera attraversata

Longitudinal development of the electron component of photon initiated shower (with electron threshold energy of 5 MeV and fluctuations superimposed)



Sciame iniziati da p o da nuclei pesanti si sviluppano diversamente:
 uno sciame iniziato da un nucleo di ^{56}Fe di energia E_0 si può
 rappresentare come 56 sciame iniziati da p con energia $E_0/56$

p vs Fe induced EAS at the same total energy

$Fe =$

 $\left\{ \begin{array}{l} 30 \times \text{ } n \\ 26 \times \text{ } p \end{array} \right.$

$Fe\text{-Nucleus with Energy } E \approx 56 \text{ nucleon showers with } E/56$ (simple superposition model)

Fe-Showers:

larger χ -section $\rightarrow X_{max}$ develops higher in atmosphere

\rightarrow fewer electrons at ground, flatter $\rho(r)$

56 nucleons with $E/56 \rightarrow$ lower energy secondaries (π, K, \dots)

\rightarrow probability of π, K -decay favoured over interaction

& $n_\pi \sim 56 \cdot \log(E/56)$

\rightarrow more muons at ground

& smaller fluctuations than p-showers

Sviluppo di sciame dovuti a nuclei pesanti nell'atmosfera: misura di A

Un rivelatore per sciame estesi in aria si realizza con un apparato, di solito composto di diverse parti, capace di misurare con buona risoluzione i tempi di arrivo delle particelle incidenti, in cui sia possibile definire la “coincidenza” temporale fra i segnali su diverse parti dell'apparato stesso.

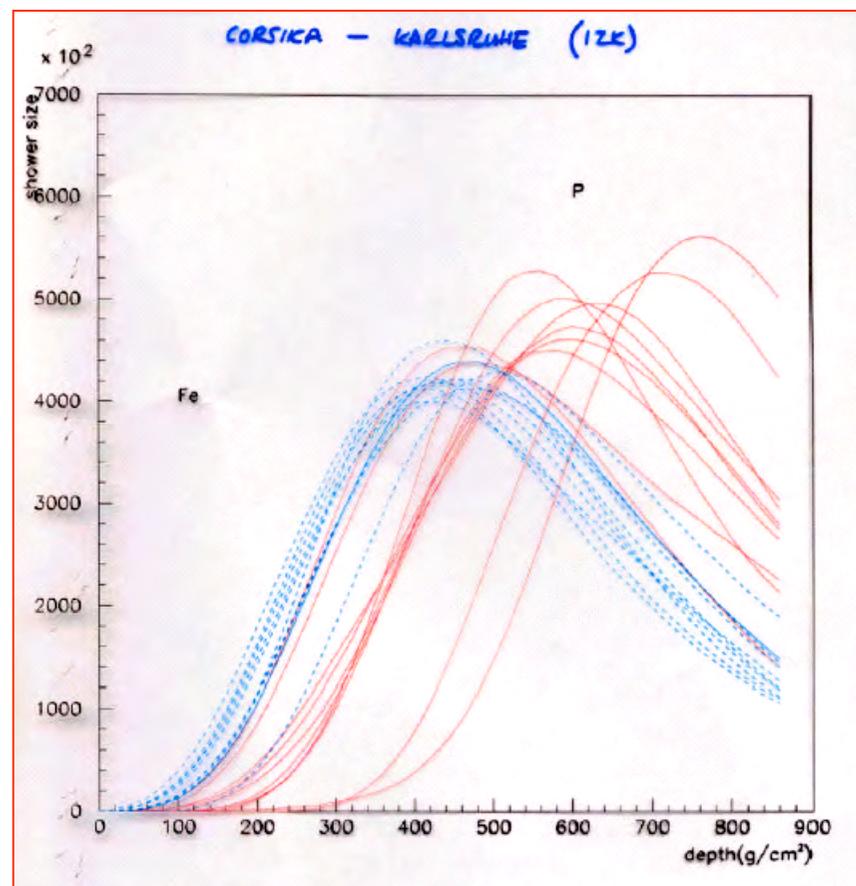
Un nucleo di massa A ed energia totale E_0 può essere trattato come un insieme di A nucleoni ognuno con energia $E = E_0/A$

Lo sciame indotto da un nucleo con massa A ed energia E simile ad A sciame indotti da protoni con energia E/A ma:

- per protoni $x_{\max} \sim \lambda \cdot \ln (E/E_C)/\ln(2)$

- per nuclei A $x_{\max} \sim \lambda \cdot \ln (E/AE_C)/\ln(2)$

→
$$\text{Log}A \approx \text{Log} \frac{E}{E_C} - \frac{X_{\max}}{\lambda}$$



L'esperimento KASCADE-GRANDE



KASCADE-Grande is an extensive air shower experiment array to study the cosmic ray primary composition and the hadronic interactions in the energy range $E_0=10^{16}$ - 10^{18} eV.

L'esperimento KASCADE-GRANDE (2)

The KASCADE-Grande Experiment

A scintillator [array](#) measures the electrons, photons and muons outside the core region of extensive air showers in 252 detector stations on a rectangular grid of 13 m spacing, hence forming an array of 200 x 200 m².

The key component of the [central detector](#) is a finely segmented [hadron calorimeter](#).

A 20 x 16 m² iron stack arranged in 9 horizontal layers of 11 nuclear interaction length is equipped with 10808 ionisation chambers filled with Tetramethylsilane (TMS) or Tetramethylpentane (TMP) respectively working at room temperature. Each chamber has 4 readout electrodes, thus the energy release of hadrons is measured in more than 43000 electronic channels. Below 30 radiation length of absorber the central calorimeter contains a layer of 456 scintillation detectors acting as [trigger](#) for the calorimeter and measuring the arrival time of hadrons. Underneath the calorimeter two layers of [multiwire proportional chambers](#) measure muon tracks above an energy of 2 GeV with about 1.0 ° angular accuracy.

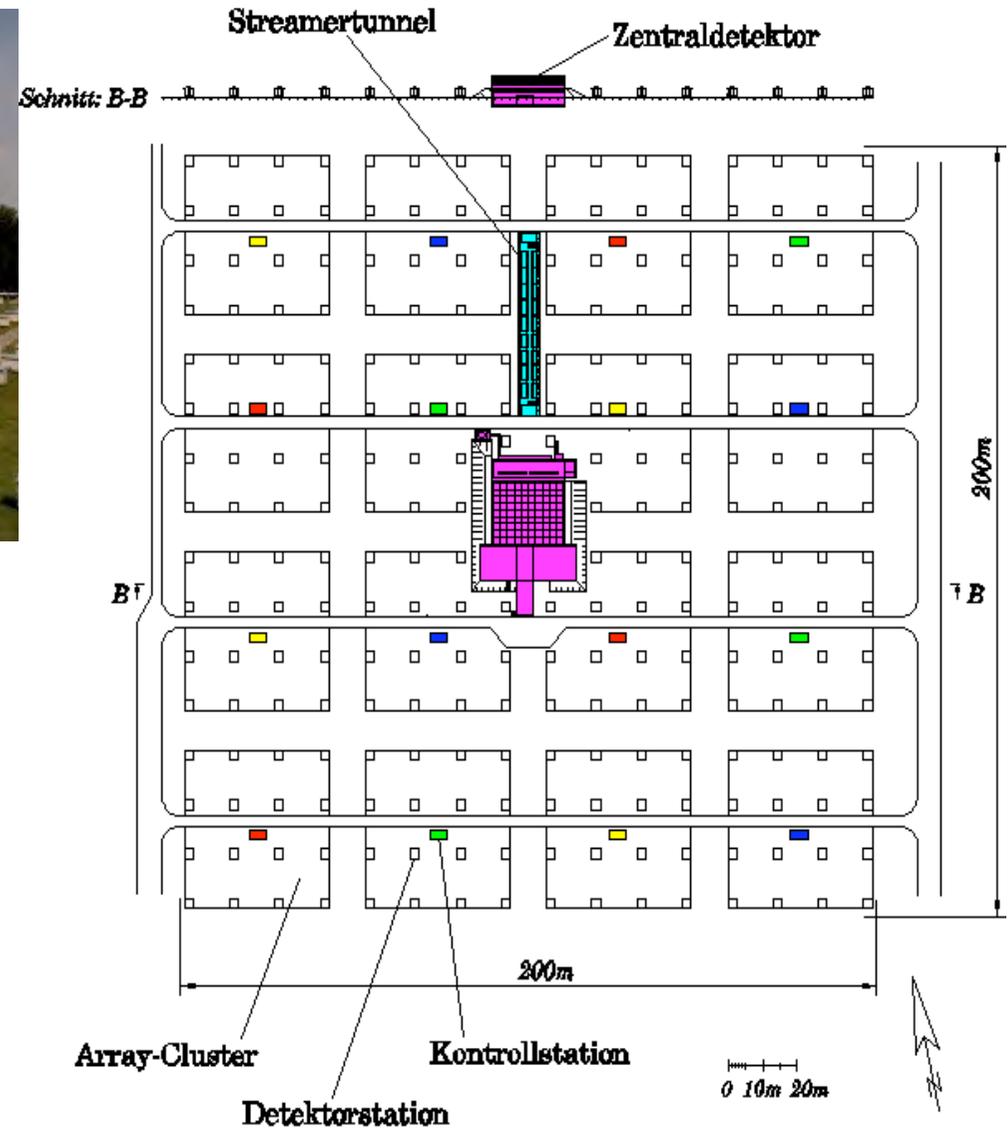
A [muon tracking detector](#) is located north of the KASCADE-Grande central detector. In a 50 m long tunnel muons above an energy threshold of 0.8 GeV are measured with [streamer tubes](#). On an active area of 128 m² muons are tracked with an accuracy of 0.5°.

The [KASCADE-Grande detector array](#) has been realized by means of 37 stations at a mutual distance of about 130 m covering an area of 0.5 km² next to the KASCADE site in order to operate jointly with the KASCADE detector components. Each KASCADE-Grande array station is equipped with 10 m² of scintillation counters and the electronic components to generate a trigger signal and for calibration purposes. A central data acquisition station (DAQ) collects the data from all stations and generates a valid experiment trigger.

The [KASCADE-piccolo trigger array](#) consists of an array of 8 stations equipped with 10m² of plastic scintillator each and is placed towards the center of the Grande array. The main aim of piccolo is to provide an external trigger to Grande and to KASCADE for coincidence events.



The field array (200m x 200m) consists of 252 detector stations arranged on a rectangular grid with a distance of 13 meters to each other. 16 of the stations form a so-called cluster with an electronics container in the center and which act as an independent shower experiment. In the middle of the array one can see the building with the KASCADE central detector.



KASCADE

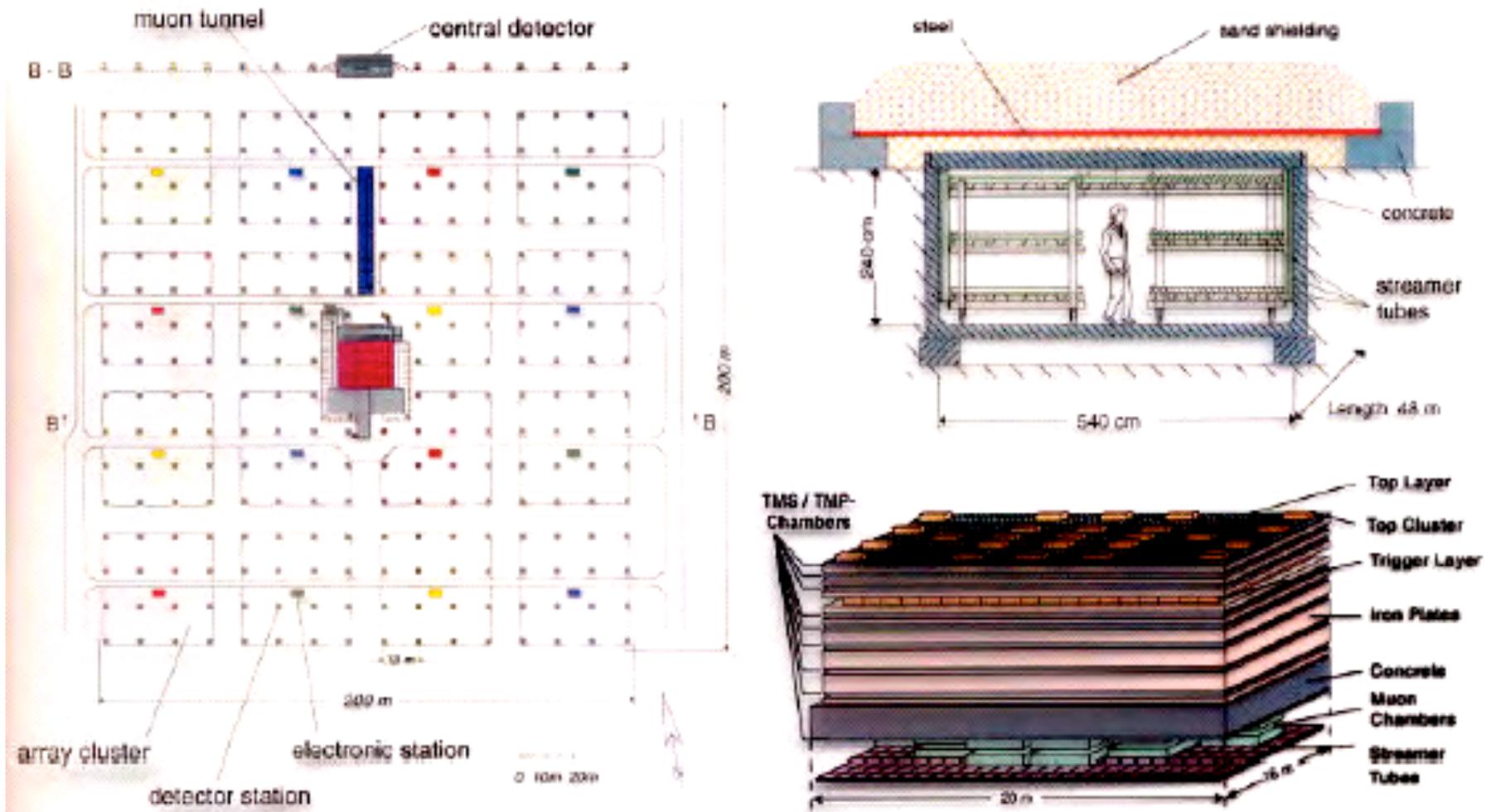
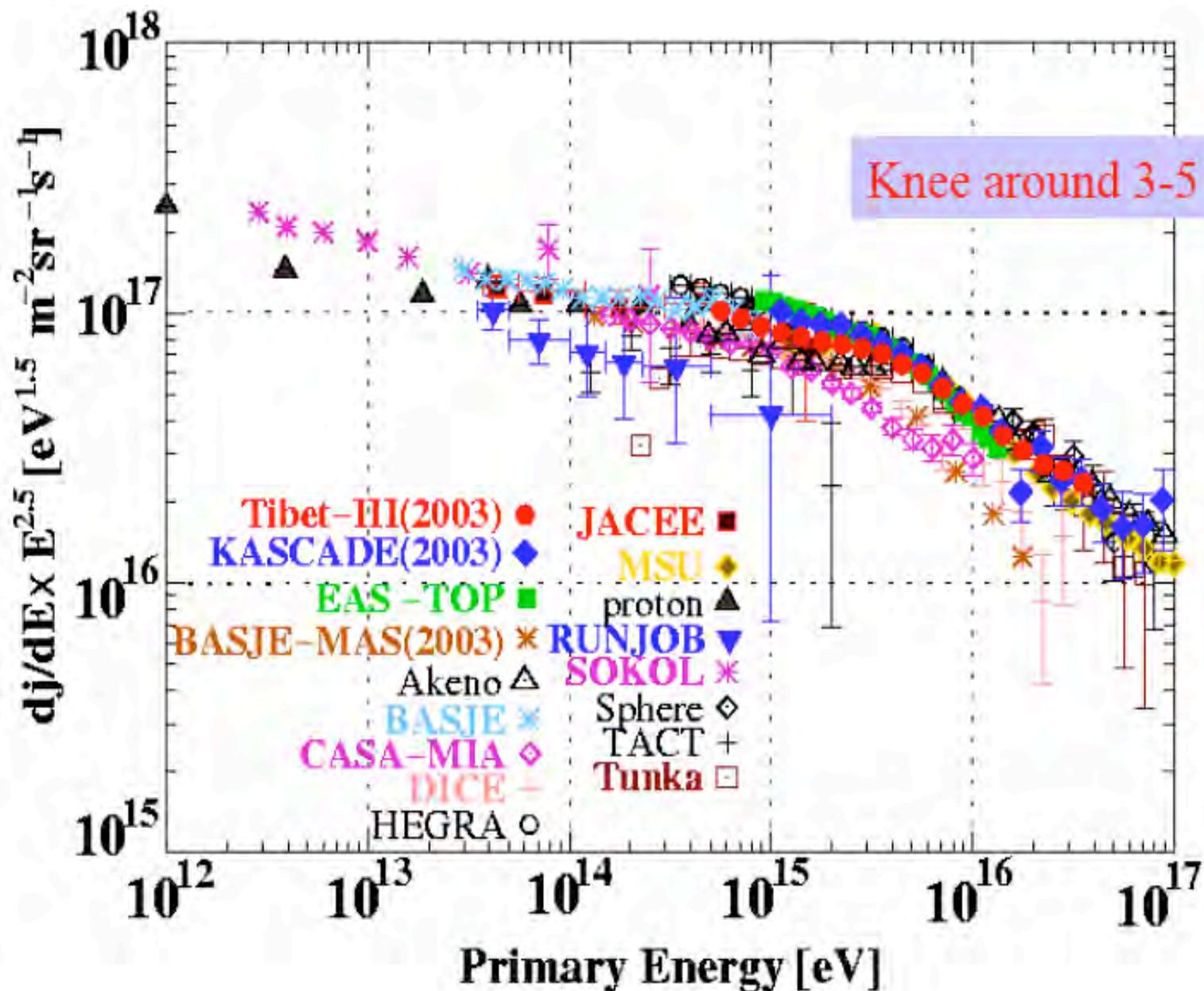


Fig. 1. Schematic layout of the KASCADE experiment (left), with its streamer tube tracking system (top right) and central detector (bottom right).

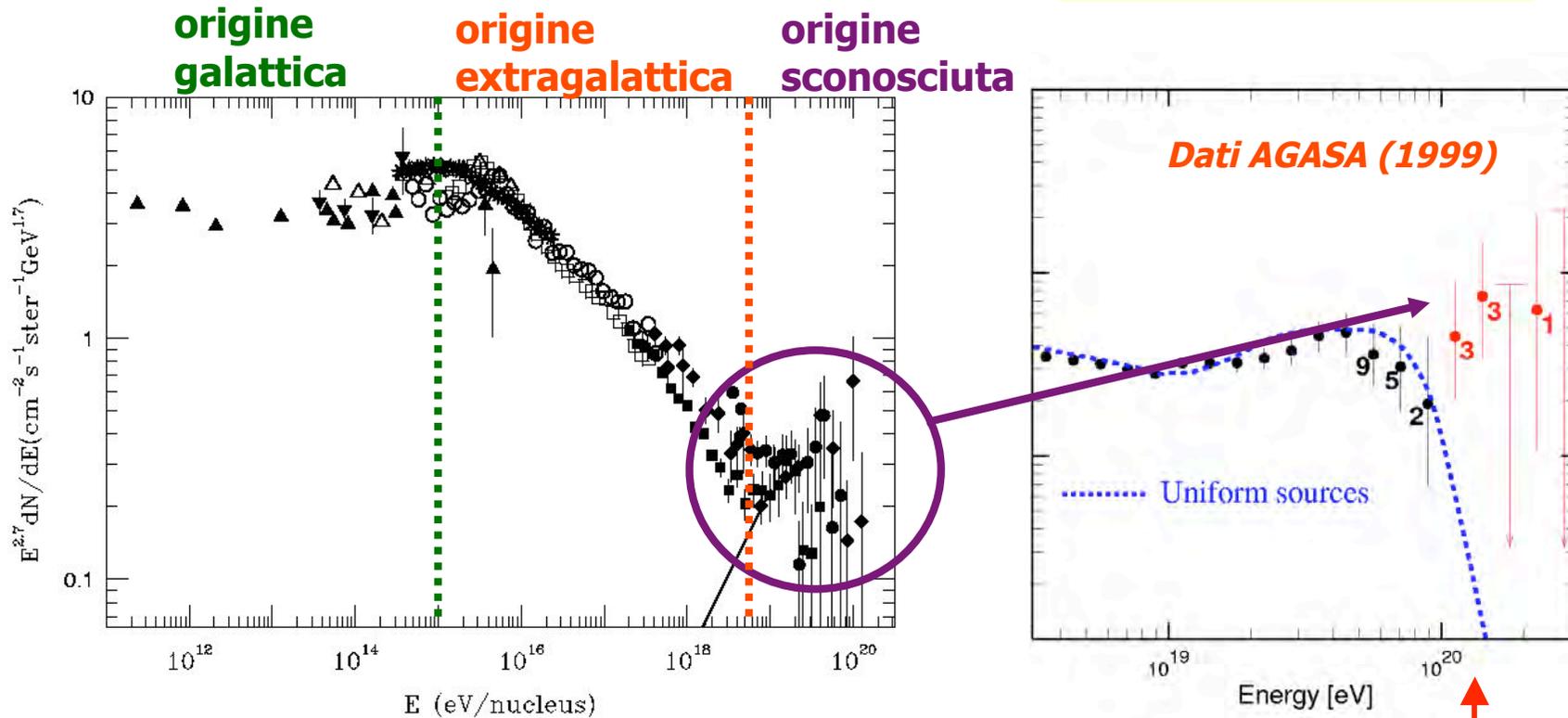
La distribuzione $Flusso \cdot E^{2.5}$ per Raggi Cosmici primari carichi



... osservati raggi cosmici di altissima energia

- protoni e gamma di altissima energia
- Gamma Ray Burst

10^{20} eV \approx 17 Joules



Raggi cosmici: protoni, altre particelle cariche, radiazione elettromagnetica, neutrini

Cut-off atteso dovuto all'effetto GZK

Greisen Zatsepin Kuzmin effect

Particles lose energy on background particles

- protons

$$p + \gamma_{3K} \rightarrow \Delta \rightarrow \pi + N \quad E_p > 3 \cdot 10^{19} \text{ eV}$$

- photons

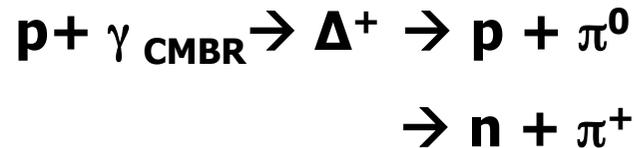
$$\gamma + \gamma_{3K} \rightarrow e^- + e^+ \quad E_\gamma > 10^{15} \text{ eV}$$

- neutrinos

$$\nu + \nu_{2K} \rightarrow W/Z + X \quad E_\nu > 4 \cdot 10^{22} \text{ eV}$$

The Greisen – Zatsepin - K'uzmin (GZK) cutoff (1)

Nucleons propagation in the Universe:

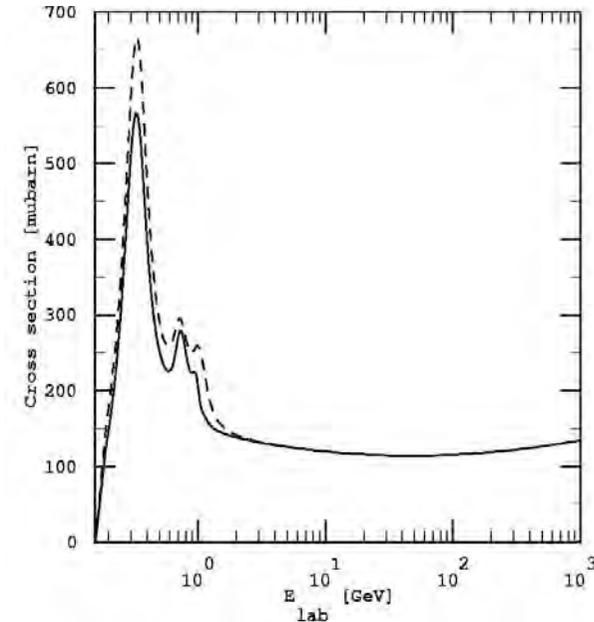


Per $T = 2.725 \text{ K}$ (present day CMBR temperature)

$\langle E_{\text{CMBR}} \rangle \approx 6.62 \cdot 10^{-4} \text{ eV}$, invece di prendere $\langle E_{\text{CMBR}} \rangle$

consideriamo fotoni CMBR piu' energetici :

$$E_{\gamma} \sim 1.4 \cdot 10^{-3} \text{ eV}$$



$$s_{out} = (m_p + m_{\pi})^2$$

$$s_{in} = (E_p + E_{\text{CMBR}})^2 - (\vec{p}_p + \vec{q}_{\text{CMBR}})^2 = E_p^2 + E_{\text{CMBR}}^2 + 2E_p E_{\text{CMBR}} - p_p^2 - q_{\text{CMBR}}^2 - 2|\vec{p}_p| \cdot |\vec{q}_{\text{CMBR}}| \cos(\theta)$$

$$s_{in} = E_p^2 - p_p^2 + 2E_p E_{\text{CMBR}} - 2|\vec{p}_p| \cdot |\vec{q}_{\text{CMBR}}| \cos(\theta) \approx m_p^2 + 2E_p E_{\text{CMBR}} (1 - \cos(\theta))$$

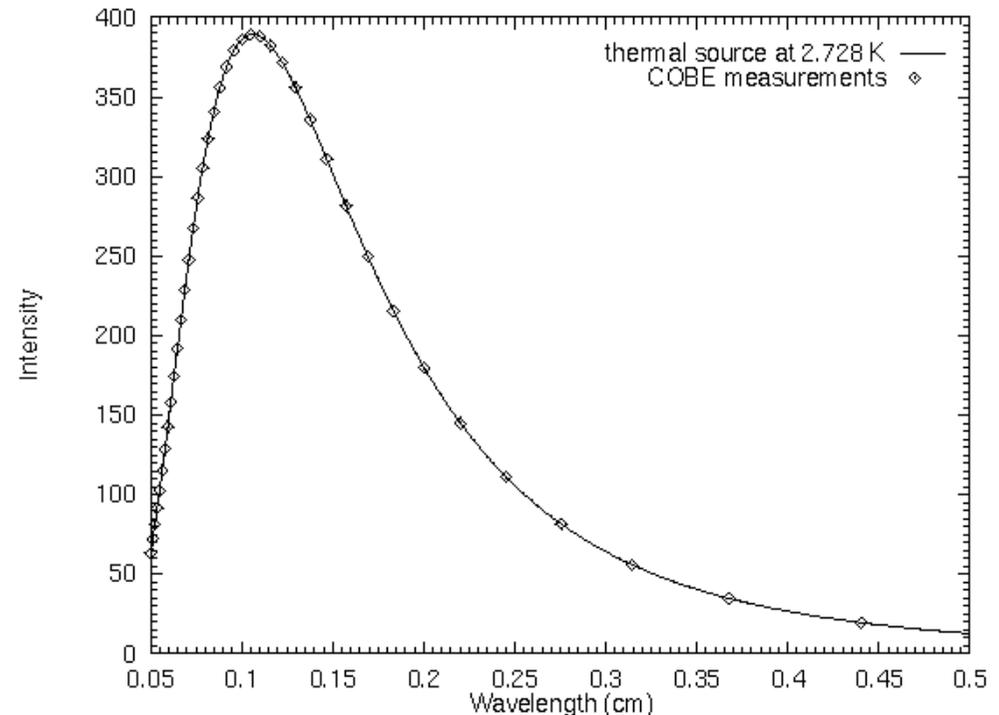
la condizione di produzione della risonanza Δ^+ richiede $s_{in} \geq (m_p + m_{\pi})^2$

$$m_p^2 + 2E_p E_{\text{CMBR}} (1 - \cos(\theta)) \geq m_p^2 + m_{\pi}^2 + 2m_p m_{\pi} \quad \text{per } \theta = \pi \Rightarrow 1 - \cos(\theta) = 2$$

$$E_p \geq \frac{2m_p m_{\pi} + m_{\pi}^2}{4E_{\text{CMBR}}} = \frac{2 \cdot 938 \cdot 10^6 \cdot 140 \cdot 10^6 + (140 \cdot 10^6)^2}{4 \cdot 1.4 \cdot 10^{-3}} \approx 5.0 \cdot 10^{19} \text{ eV} = 50 \text{ EeV} \sim 8J$$

General Properties of the CMBR

- * The radiation has very low temperature:
 $T \sim 2.7$ Kelvins.
- * The spectrum of the radiation is well-described by a blackbody spectrum.
- * The radiation is isotropic, i.e., it is very close to the same temperature all across the sky -- temperature differences of $< 0.004\%$ on angular scales of 7 degrees (excluding a well-known 0.12% variation known as the dipole anisotropy).
- * The temperature over the sky, although very smooth does exhibit structure.



Per $T = 2.725$ K (l'attuale temperatura della Cosmic Microwave Background Radiation (CMBR))

$$kT = (8.617 \cdot 10^{-5} \text{ eV/K}) \cdot 2.725 \text{ K} = 2.35 \cdot 10^{-4} \text{ eV}$$

$$\text{ma: } E_{\text{peak}} = 2.70 \cdot k \cdot 2.725 = 6.34 \cdot 10^{-4} \text{ eV}$$

$$E_{\text{mean}} = 2.82 \cdot k \cdot 2.725 = 6.62 \cdot 10^{-4} \text{ eV}$$

Assumiamo per i fotoni piú energetici $E_{\gamma} \sim 1.4 \cdot 10^{-3} \text{ eV}$

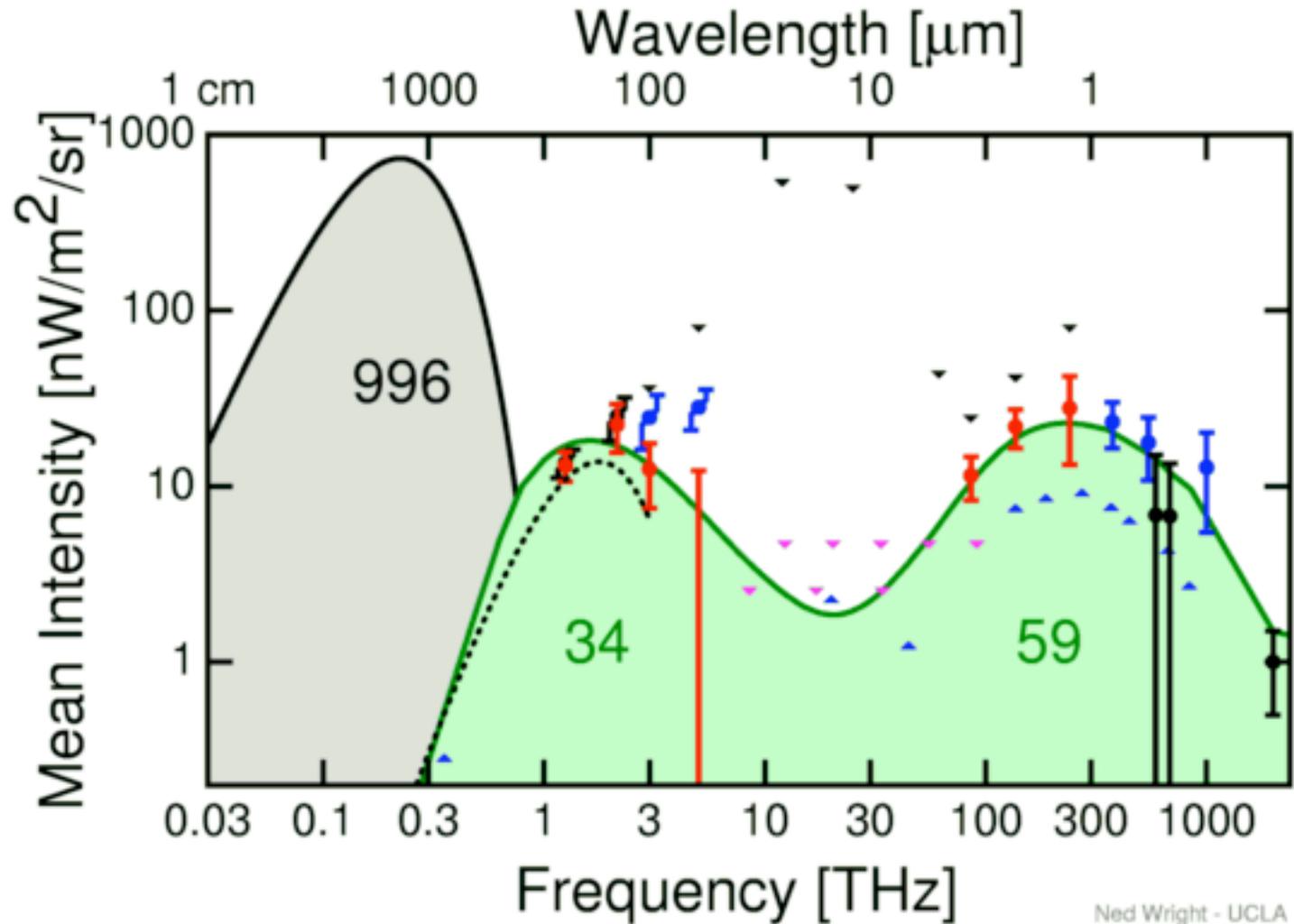
Anche i fotoni hanno un percorso limitato ...

Interagendo sia con la radiazione CMBR che con la radiazione "Infrarossa"

Photons : pair production $\gamma_{HighEnergy} \gamma_{CMBR} \Rightarrow e^+ e^-$

$$E_{\gamma} \geq \frac{m_e^2}{E_{CMBR}} \approx \frac{10^{12} eV^2}{1.4 \cdot 10^{-3}} \approx 0.7 \cdot 10^{15} eV$$

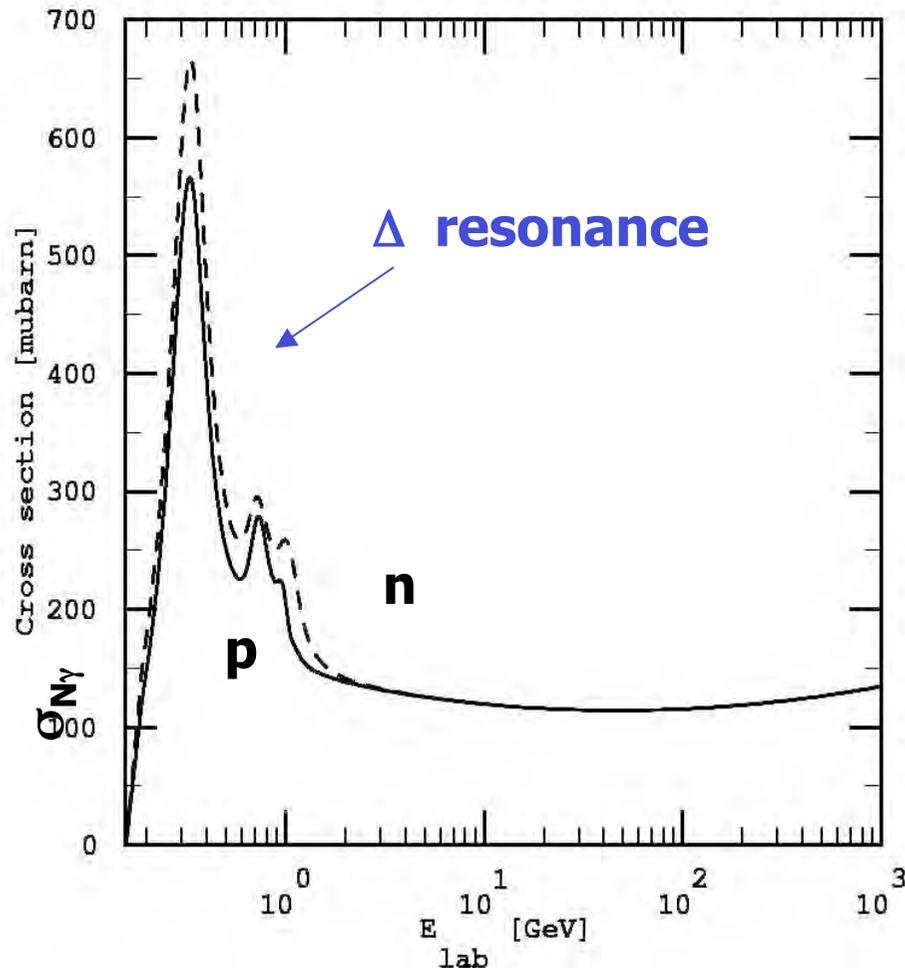
La radiazione "infrarossa" cosmica



↑
 $\sim 4 * 10^{-3} \text{ eV}$

↑
Ned Wright - UCLA
 $\sim 4 \text{ eV}$

L'effetto della produzione risonante della Δ (GZK cutoff) pone un limite alla propagazione dei p nello spazio cosmico

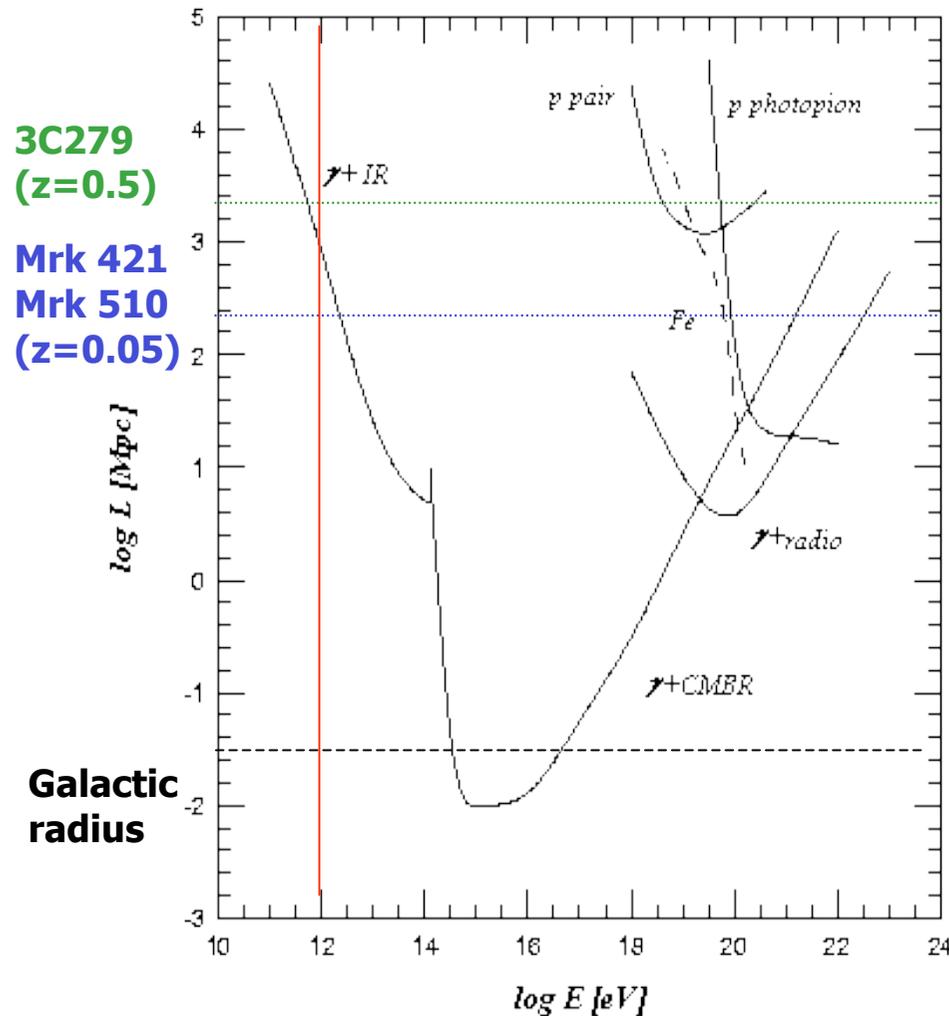


Possiamo calcolare la "Lunghezza di attenuazione" dei p conoscendo la densità dei fotoni CMBR e la sezione d'urto dell'interazione $p\gamma \rightarrow \Delta$

$$L = \left(\sigma_{N\gamma} \rho_{\text{CMBR}} \right)^{-1}$$

$$\approx \left(130 \mu\text{b} \cdot 410 \text{cm}^{-3} \right)^{-1} \approx 6 \text{Mpc}$$

... quindi possiamo calcolare quanto p e γ possono propagarsi nello spazio cosmico (in funzione della loro energia) per effetto del "GZK cutoff" e per le altre interazioni possibili



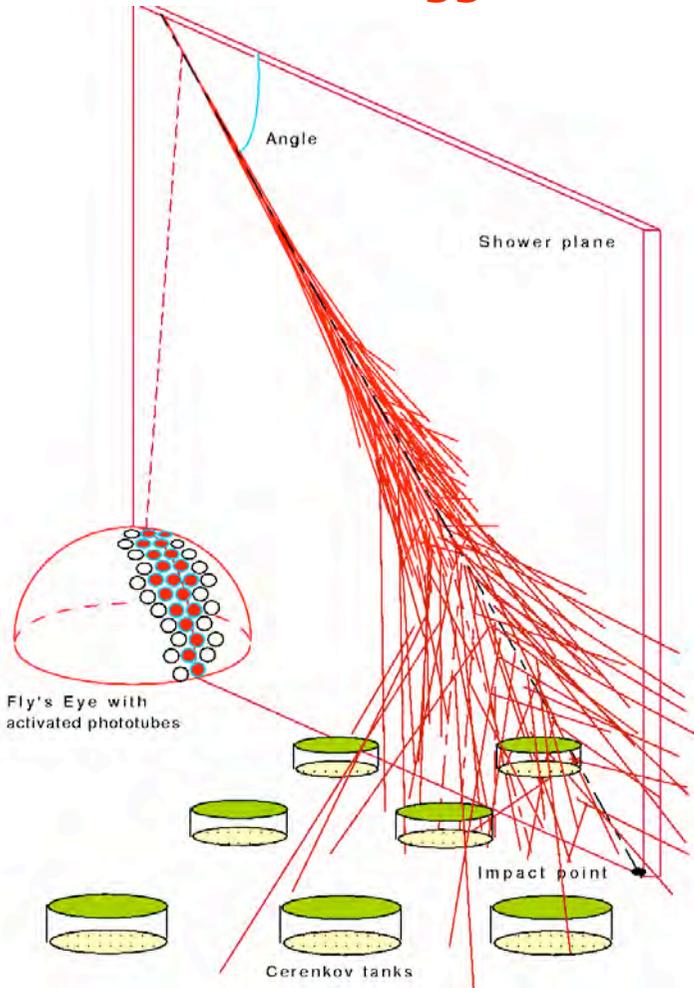
γ observed from extragalactic sources only up to TeV energies

UHE protons and gammas are strongly attenuated in the Universe

AGASA and Fly's Eye 10^{20} eV events analysis has not conducted to source identification.

Only UHE neutrinos could be detected from far Universe

Rivelazione di Raggi Cosmici di energia $\sim E_{\text{eV}}$: esperimenti a terra "ibridi"



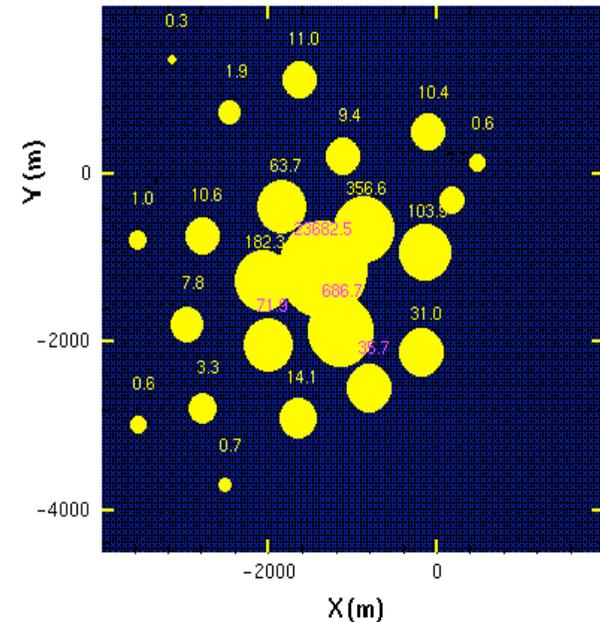
Raggi cosmici inducono "extensive air showers" (EAS) nella atmosfera. La maggior parte del R.C. iniziale va in energia persa, dE/dx , dalle particelle dello sciame nell'atmosfera. Di questa energia la frazione $\sim 5 \cdot 10^{-5}$ risulta visibile come luce di fluorescenza in aria nell'intervallo di lunghezze d'onda 300nm-420nm. ~ 4.8 fotoni/m/elettrone

- Esperimenti sensibili alla "fluorescenza" dell' N_2 indotta dagli sciame nell'atmosfera (Fly's Eye): osservano lo **sviluppo longitudinale** dello sciame

X_0, X_{max} (natura "chimica" del primario)

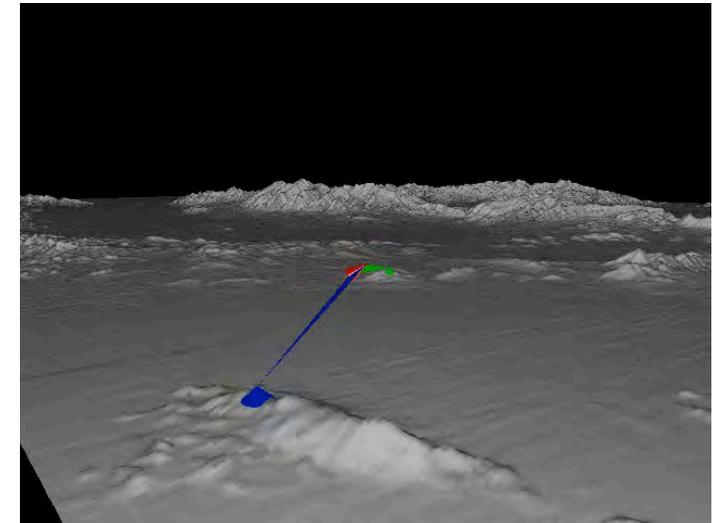
- Gli esperimenti con rivelatori a terra (AGASA) campionano lo **sviluppo laterale** degli sciame

Ottenendo così E_0



La rivelazione della radiazione di "fluorescenza" nell'atmosfera è stata adottata inizialmente dai rivelatori "Fly's Eye" ad HiRes

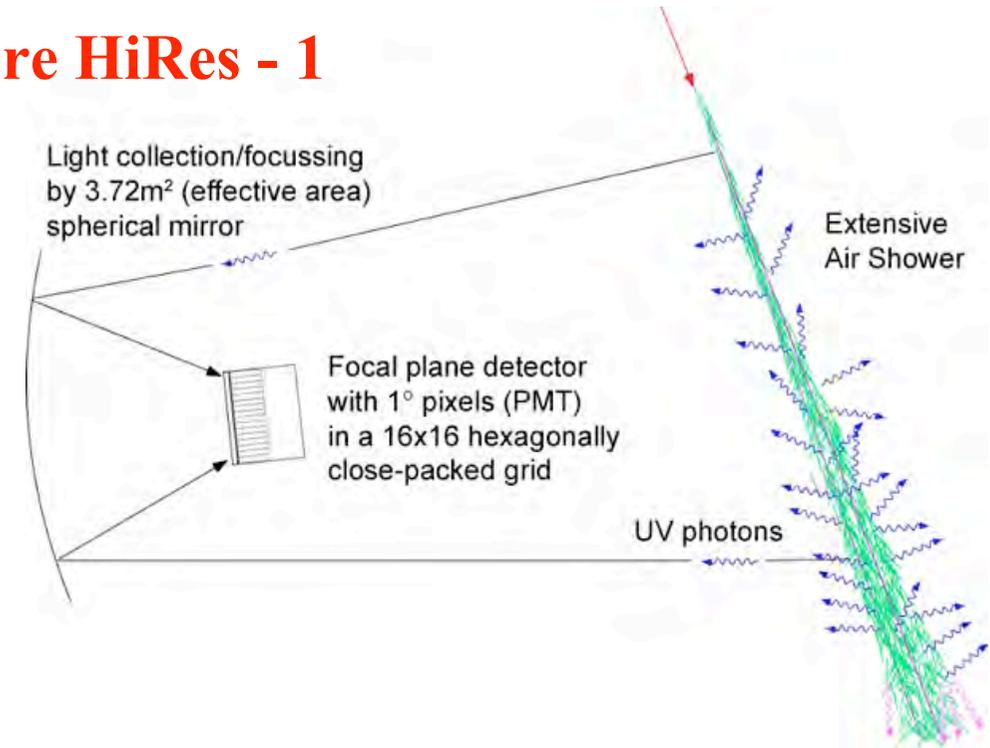
In 1976, Physicists from University of Utah were the first to detect fluorescence light from cosmic ray air showers. **Three prototype modules** were used in a test at Volcano Ranch near Albuquerque, New Mexico. **Each prototype module contained a 1.8 m diameter mirror for light collection, with 14 PMT's at the focal plane. Each PMT covers a solid angle about 0.008 steradians (~5 degrees by 5 degrees)** in the sky. **The large mirrors provided a 20-fold increase in the light collection area over that of the lenses used in them Cornell detector.** The clear desert air also provided much improved visibility over the Cornell experiment. The HiRes experiment is a new and significantly upgraded version of the original Fly's Eye experiment. Cosmic rays make extensive air showers in the atmosphere. Most of the initial energy becomes charged particle energy loss, dE/dx , in the atmosphere. Of that about 5×10^{-5} appears as air fluorescence light which is mainly in the wavelength interval 300nm to 420nm. Thus the air fluorescence signal provides a calorimetric measurement directly proportional to the initial cosmic ray energy. HiRes uses the resulting air fluorescence to measure the properties of the initial cosmic rays. Showers are observed by 2 fluorescence eyes, i.e. in stereo, to obtain a precision measurement. The fluorescence detectors require cloudless moonless nights with little aerosol light scattering. The optimal conditions are found in desert locations and have about a 10% duty factor.

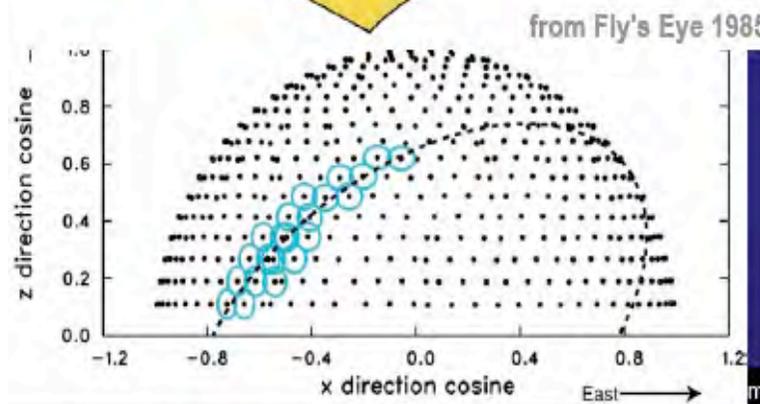
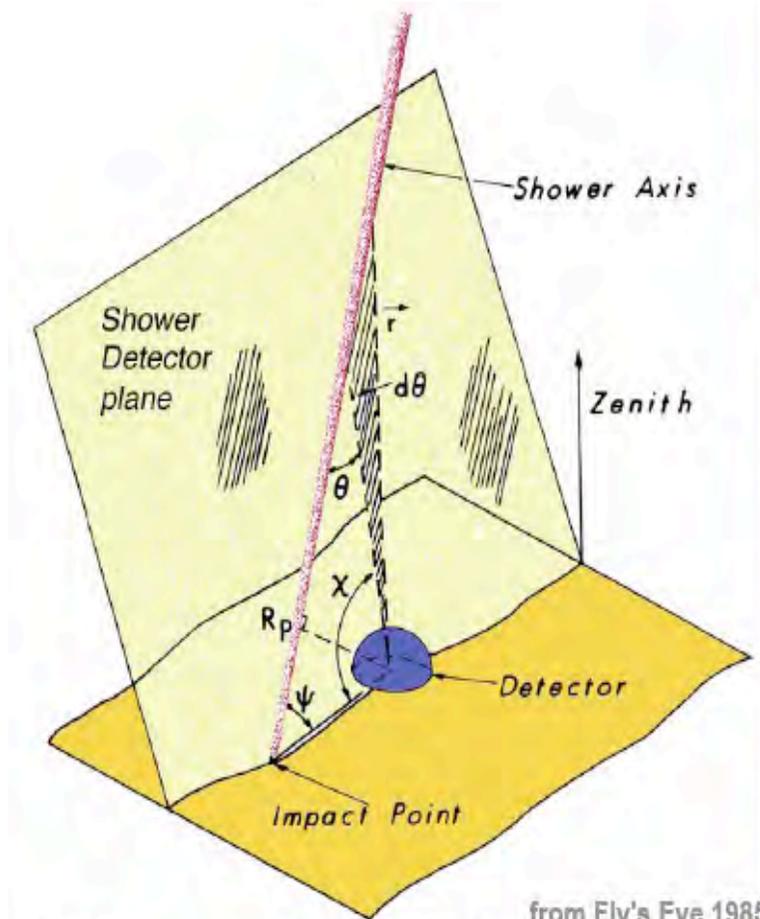


... attualmente è usata estensivamente dall'esperimento AUGER

Il rivelatore HiRes - 1

- Each HiRes detector unit (“*mirror*”) consists of:
 - spherical mirror w/ 3.72m^2 unobstructed collection area
 - 16×16 array (hexagonally close-packed) of PMT pixels each viewing 1° cone of sky



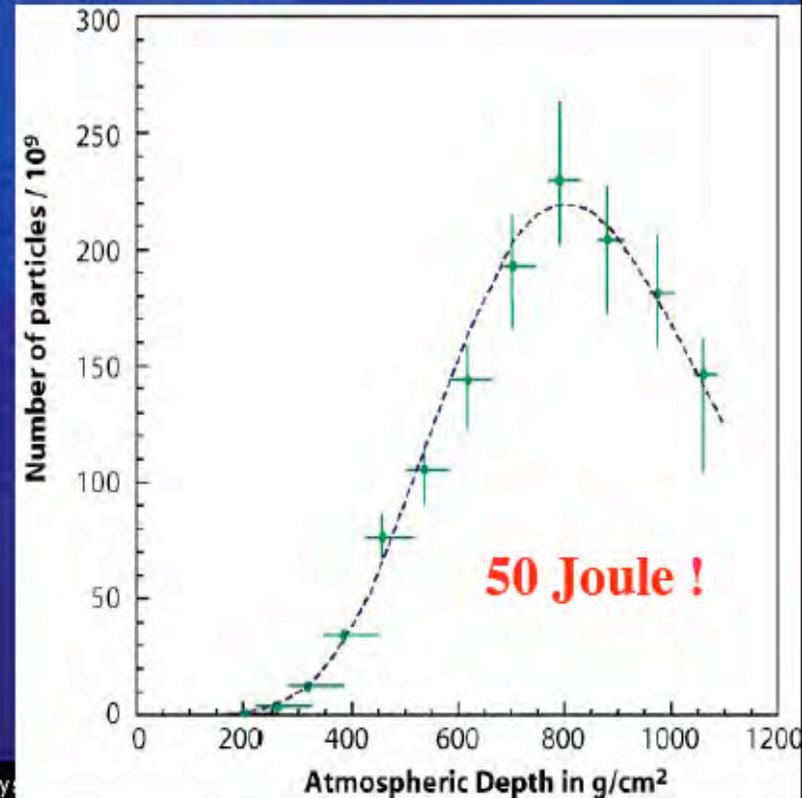


The most energetic event seen by Fly's Eye

seen by Fly's Eye

$$3.2^{+0.4}_{-0.5} \times 10^{20} \text{ eV}$$

(Astrophys. J. 1995)

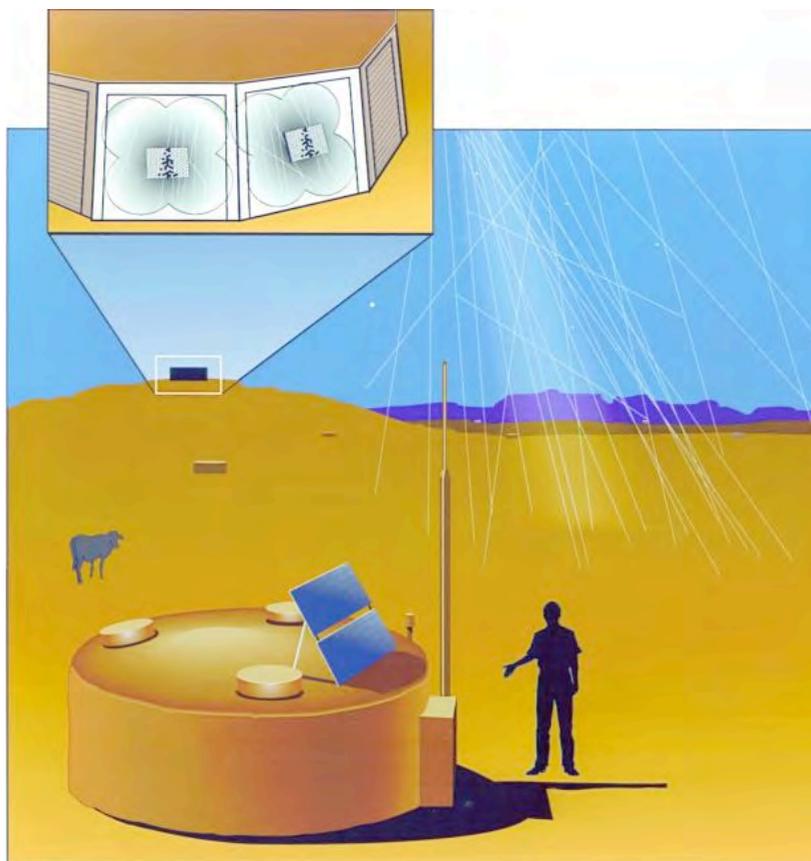


Pierre Auger: an hybrid experiment

Due giganteschi apparati da 3000 km² (Nord e Sud America) con 1600 contatori Cherenkov ad acqua e 4 rivelatori per fluorescenza per misurare l'energia, la direzione di arrivo delle particelle primarie e la loro composizione in massa nello intervallo di energie $> 10^{19}$ eV. Totale superficie sensibile ~ 3000 km².

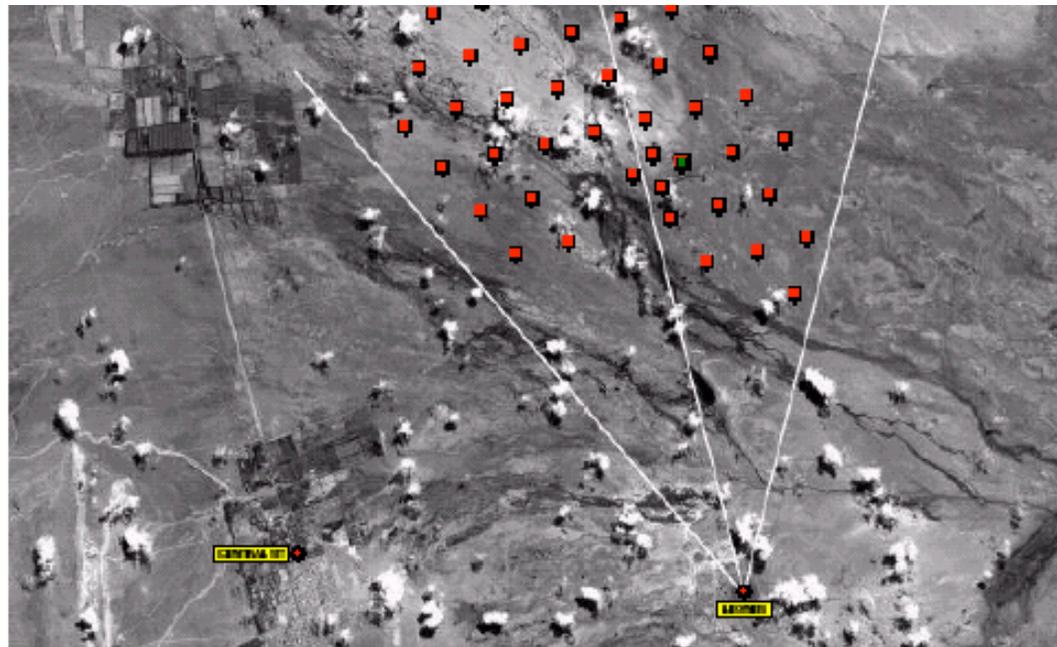
Flussi aspettati: $E > 10^{19}$ eV \rightarrow 1 R.C./(km²·anno) \rightarrow collezionati ~ 3000 eventi/anno
 $E > 10^{20}$ eV \rightarrow 1 R.C./(km²·secolo) \rightarrow collezionati ~ 30 eventi/anno
 $\sim 15\%$ di tali eventi saranno osservabili anche con i rivelatori di fluorescenza

I rivelatori Cherenkov sono realizzati con “serbatoi” contenenti 12 tons di acqua e fotobubi. I moduli utilizzano energia solare e trasmettono “via radio” le informazioni al Computer centrale per data acquisition.



Fisica Nucleare e Subnucleare II, A.A. 2009-10, Prof. A. Capone

Vista da satellite dell'apparato Sud (Argentina). Si notano le posizioni dei rivelatori di superficie (quadrati rossi, la distanza fra due rivelatori vicini ~ 1.5 km) Le linee rappresentano il “campo visivo”, circa 30°, dei primi due rivelatori a fluorescenza.

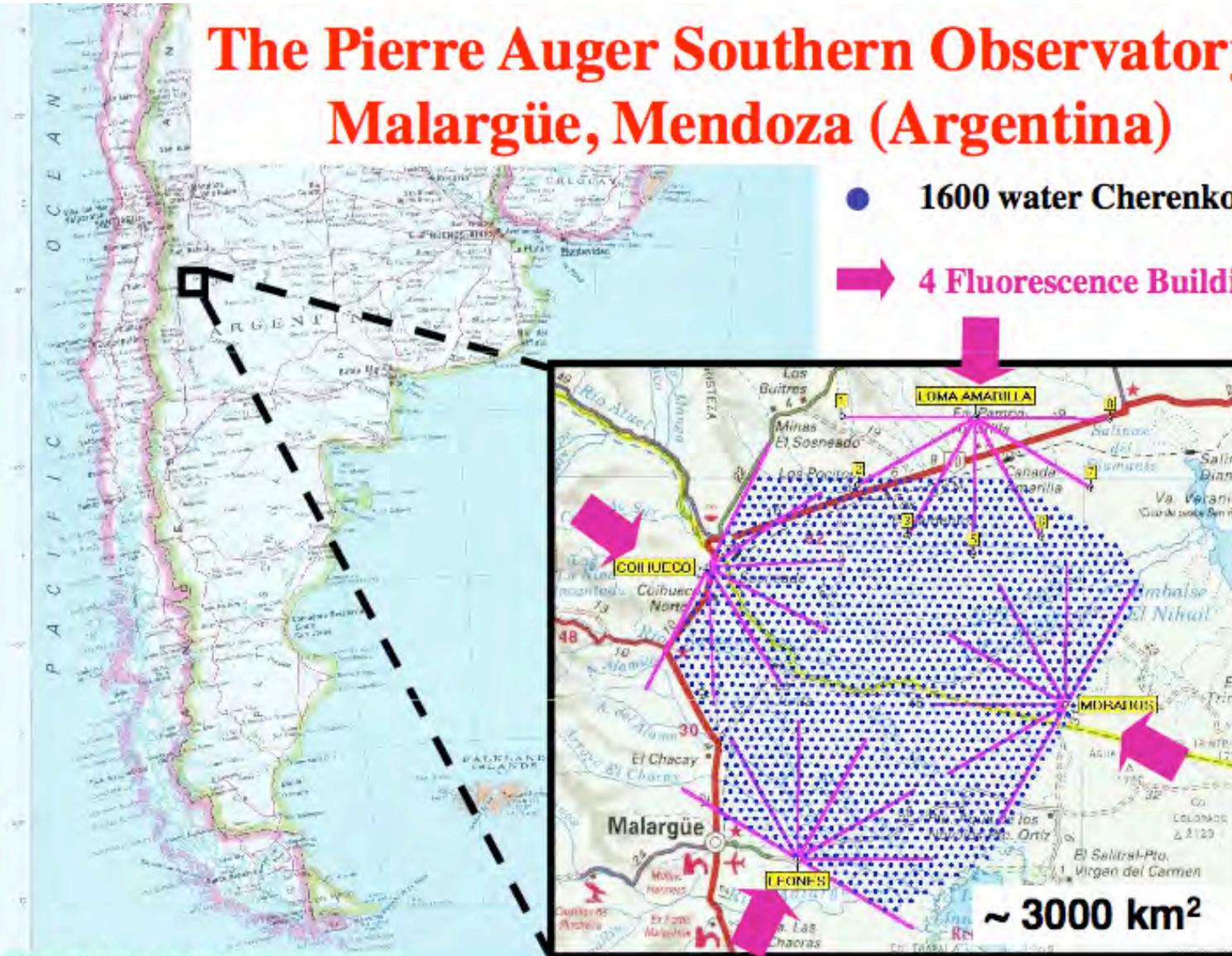


Lezioni 43-44

The Pierre Auger Southern Observatory: Malargüe, Mendoza (Argentina)

● 1600 water Cherenkov tanks

➔ 4 Fluorescence Buildings



35.5° S, 69.3° W
1400 m a.s.l. (880 g cm⁻²)

Objectives, aims, questions,...

Measure properties of UHECRs ($E > 10^{18}$ eV) with unprecedented statistics & accuracy

Energy spectrum:

Cutoff at the highest energies?

Ankle ?

Mass composition (nature of the UHECRs):

Is the UHECR flux proton-dominated ?, iron?, mixed composition ?

Are there any photons in the UHECR flux ?

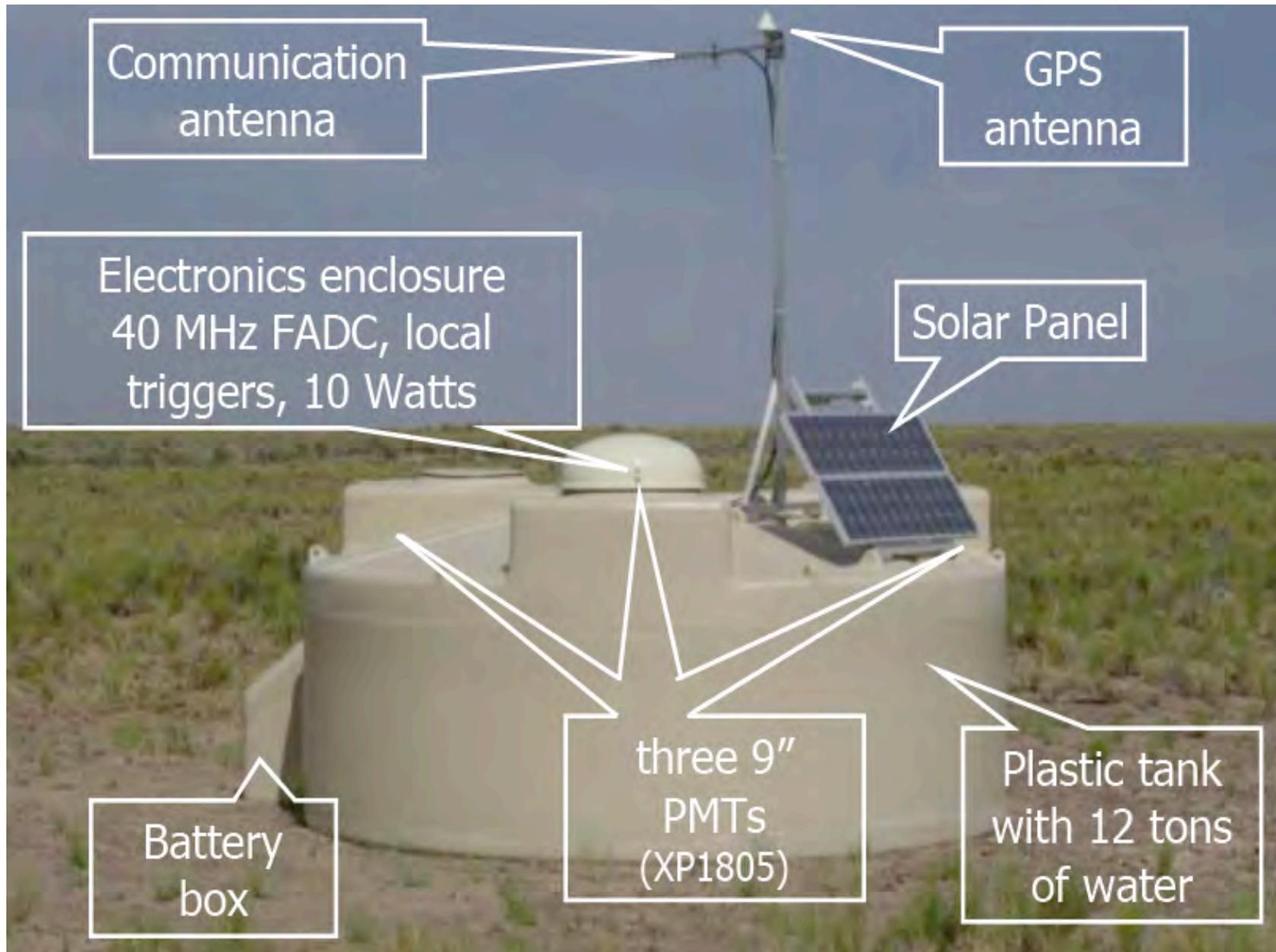
Are there any neutrinos ?

Establish arrival directions of UHECR:

Is the UHECR flux isotropic ?

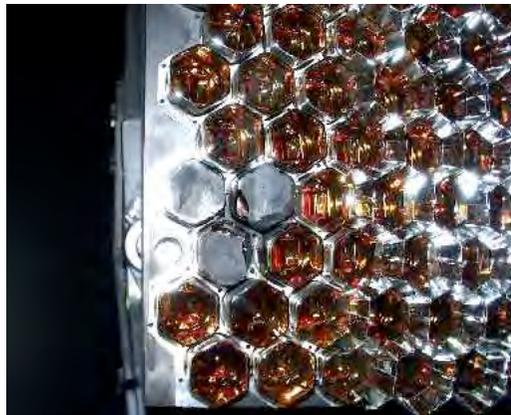
What are the sources of the UHECRs ?

Il rivelatore "Pierre Auger": i rivelatori "Cherenkov"

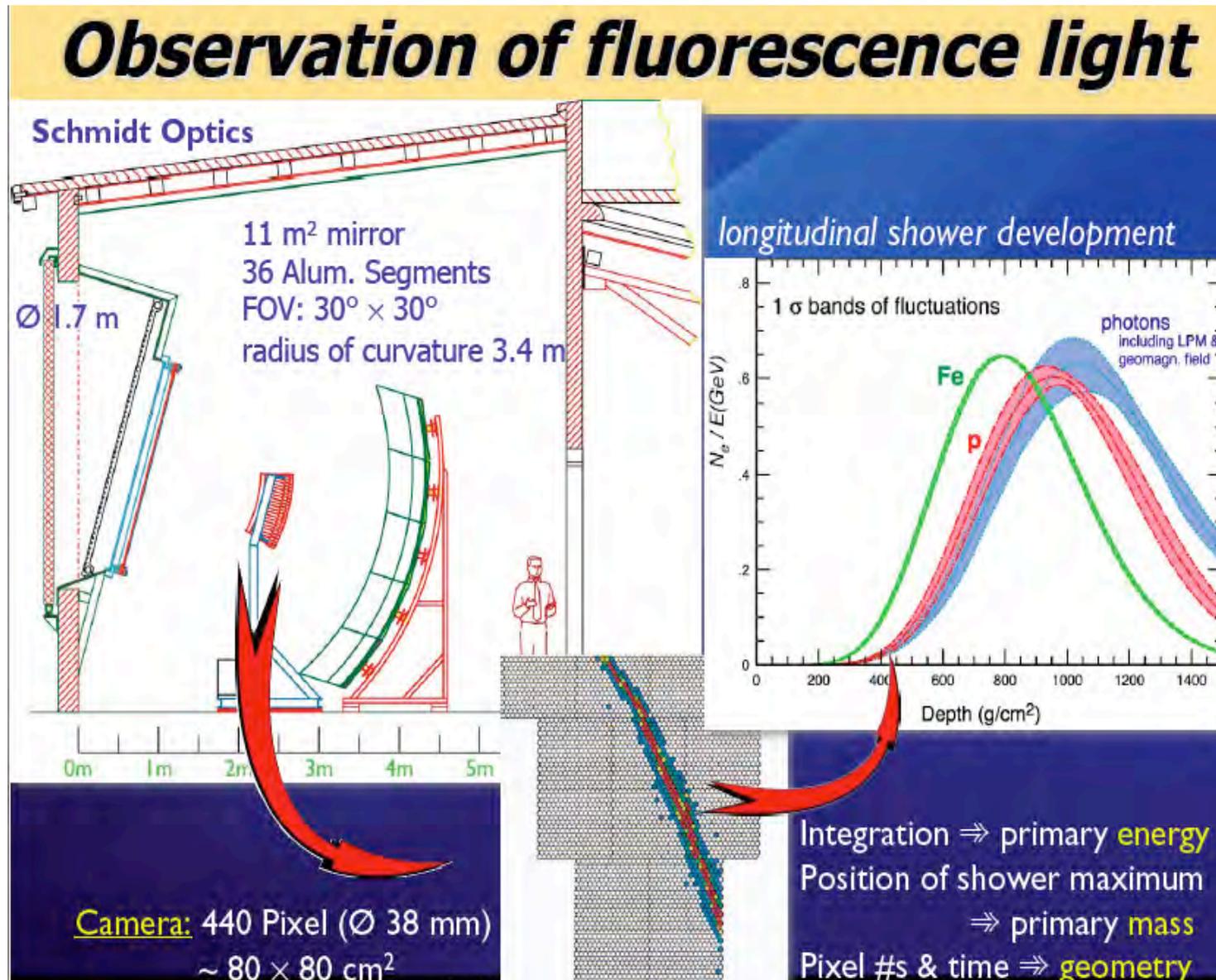


Il rivelatore "Pierre Auger": i telescopi per fluorescenza

Previsti 4 rivelatori di fluorescenza. Osserveranno l'atmosfera sovrastante il rivelatore: **3 posizionati sul perimetro** ed **il quarto all'interno** dell'area occupata detector. Il **campo visivo** di ognuno dei tre rivelatori esterni e' pari a **180° in azimuth** e di **~30° in elevazione**. Il rivelatore centrale ha una visuale, in azimuth, di 360°. La luce e' raccolta da 30 specchi con 3m di diametri e focalizzata su fotomoltiplicatori (in totale 13.000 PMTs, il cielo sara osservato con pixels di 1.5°). **Sciami con energia ~10¹⁹eV possono essere visti a ~ 30 km di distanza.**



Dalla misura di X_{max} , dell'energia e dello sviluppo dello sciame si può ottenere una misura di A : il numero di massa del Raggio Cosmico "primario"



The importance of being hybrid

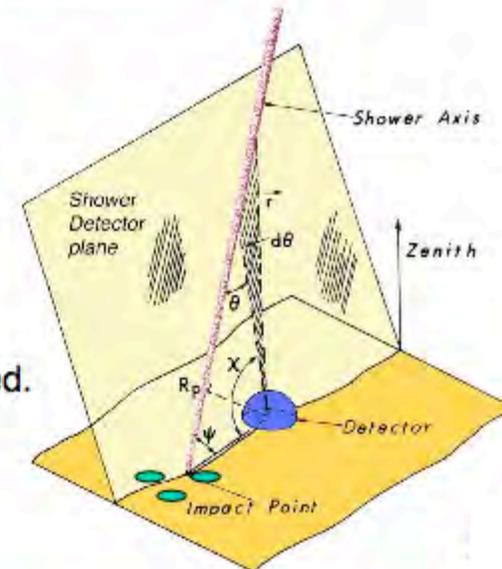
	hybrid	SD only	FD only
angular resolution	0.2°	1-2°	3-5°
aperture	independent of E, mass, models	independent of E, mass, models	dependent of E, mass, models and spectral slope
energy	~ independent of mass, models	dependent of mass, models	independent of mass, models

Most events are detected only with the SD (~ 100% duty cycle).

~ 10% of hybrid events (detected with both the SD and the FD).

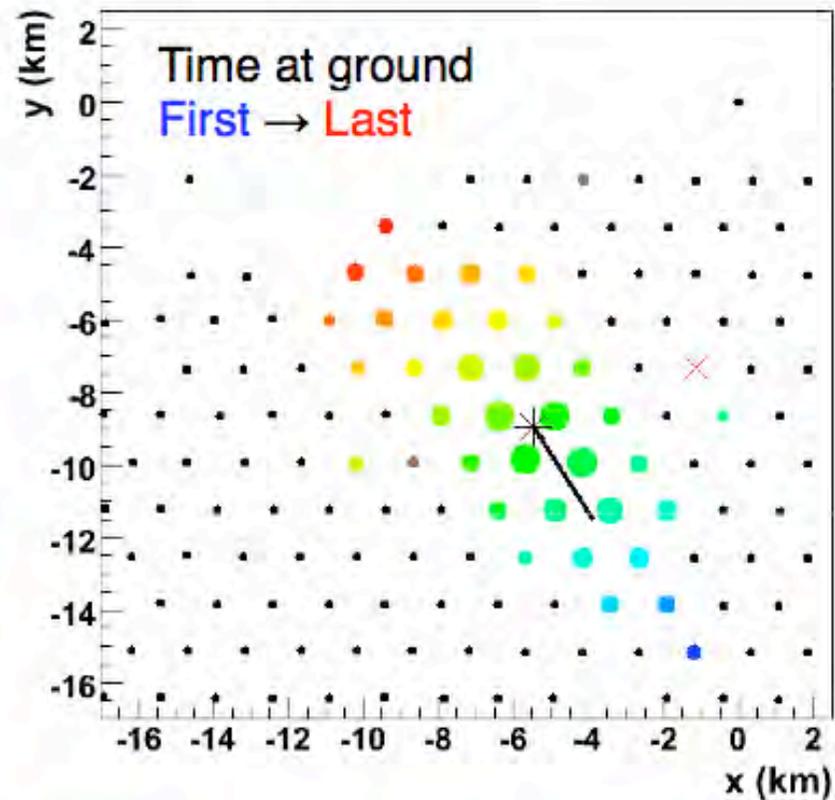
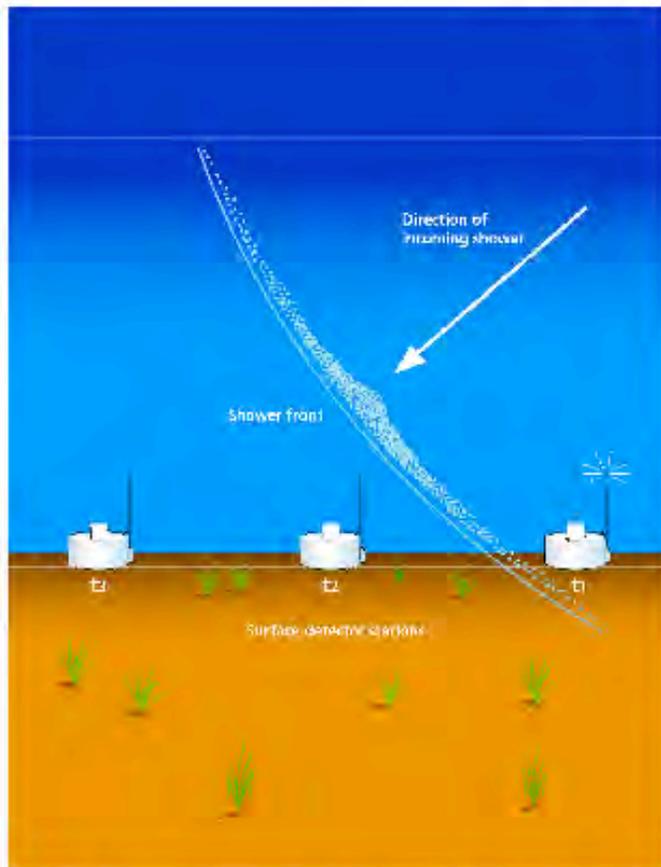
Using hybrid events:

- ✓ **Angular reconstruction** of SD-only events can be fine-tuned.
- ✓ **Energy** of SD-only can be calibrated with hybrid events.



Reconstruction of events: Arrival direction

Fit arrival times of shower front in tanks to a curved front propagating at the speed of light.

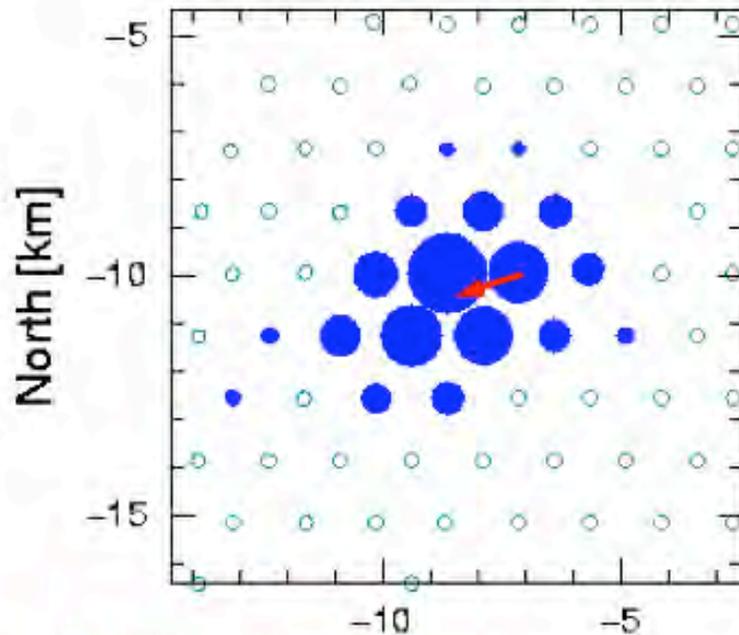


Angular reconstruction accuracy $< 1^\circ$ above 10^{19} eV

Reconstruction of “vertical” SD events $\theta < 60^\circ$

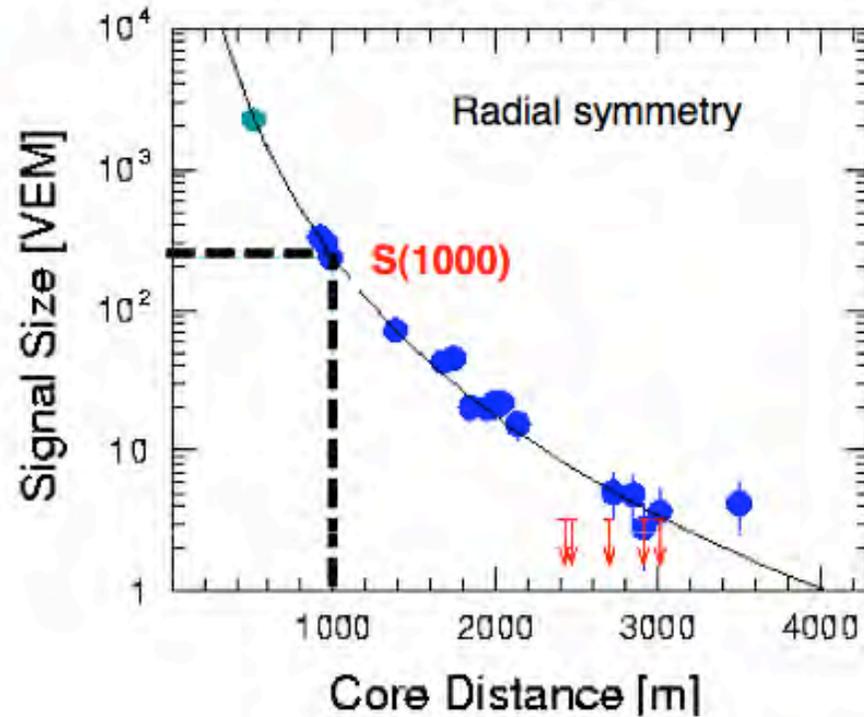
Footprint on the ground

ID 762238



Lateral density distribution

ID 762238



Energy estimator:

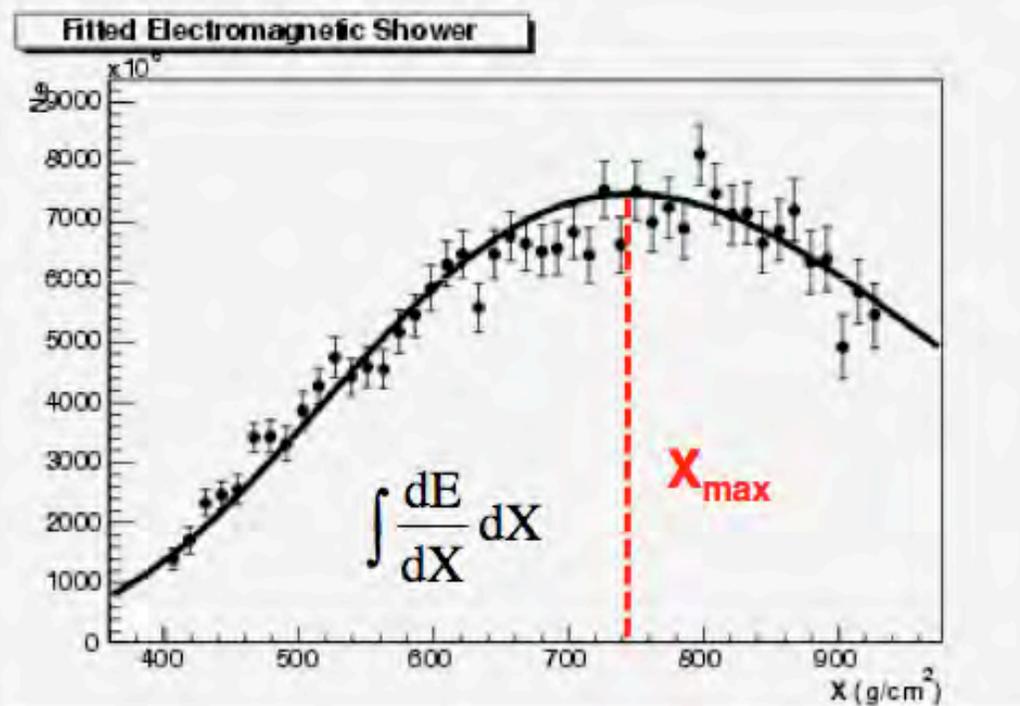
$S(1000)$ = signal at 1000 m from the core of the shower.

Event with $\theta \sim 48^\circ$ & $E \sim 70$ EeV

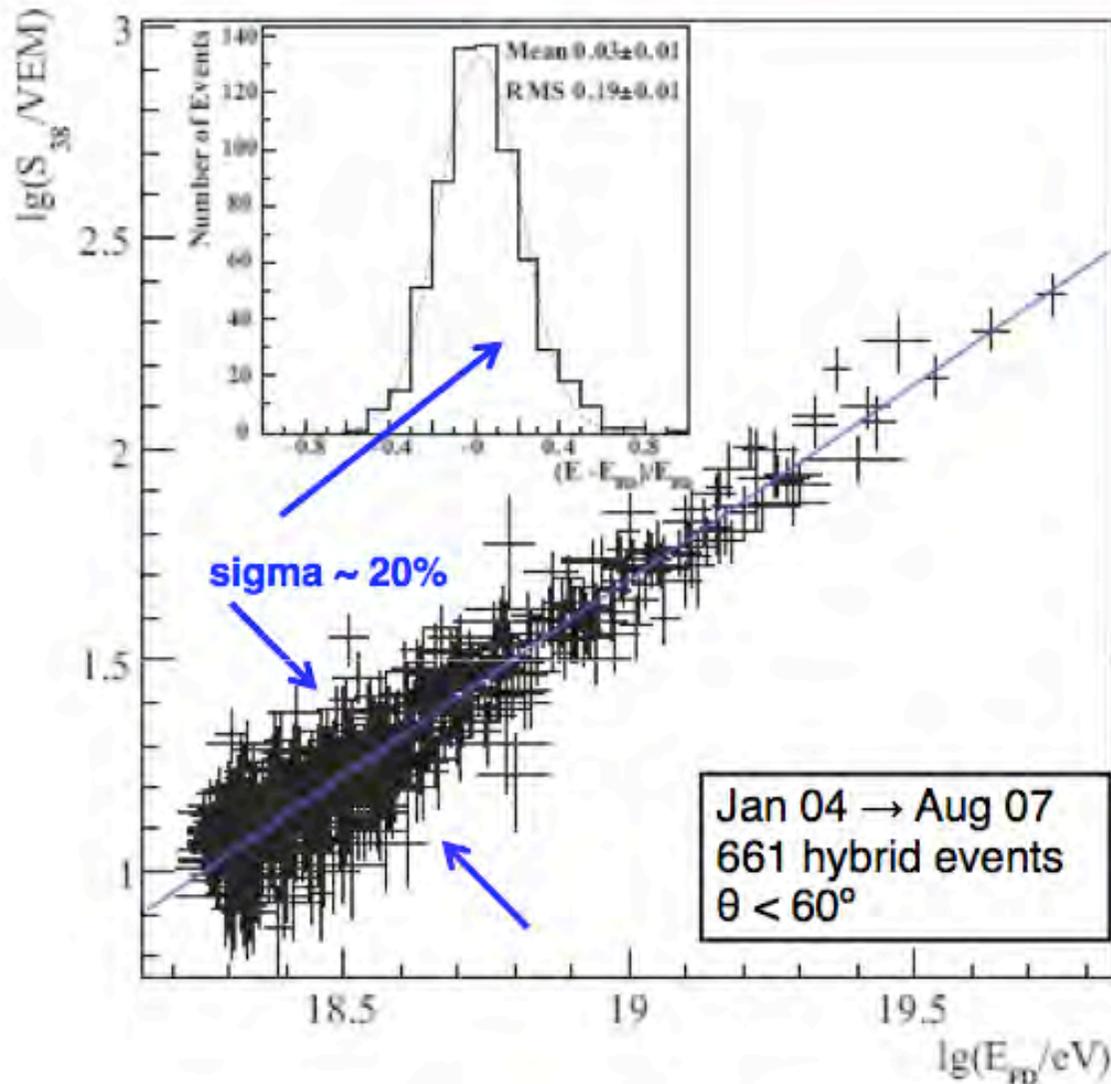
Energy calibration of S(1000): hybrid events

Energy reconstruction with the fluorescence detector

- Measured dE/dX vs X (shower longitudinal profile proportional to fluorescence light collected) fitted to a “Gaisser-Hillas” function.
- Shower $E \sim \int dX (dE/dX)$: nearly **calorimetric** measurement
weakly dependent on hadronic model & composition ($\sim 5\%$).



Energy calibration of S(1000)



**Linear correlation
between E_{FD} and S(1000)**

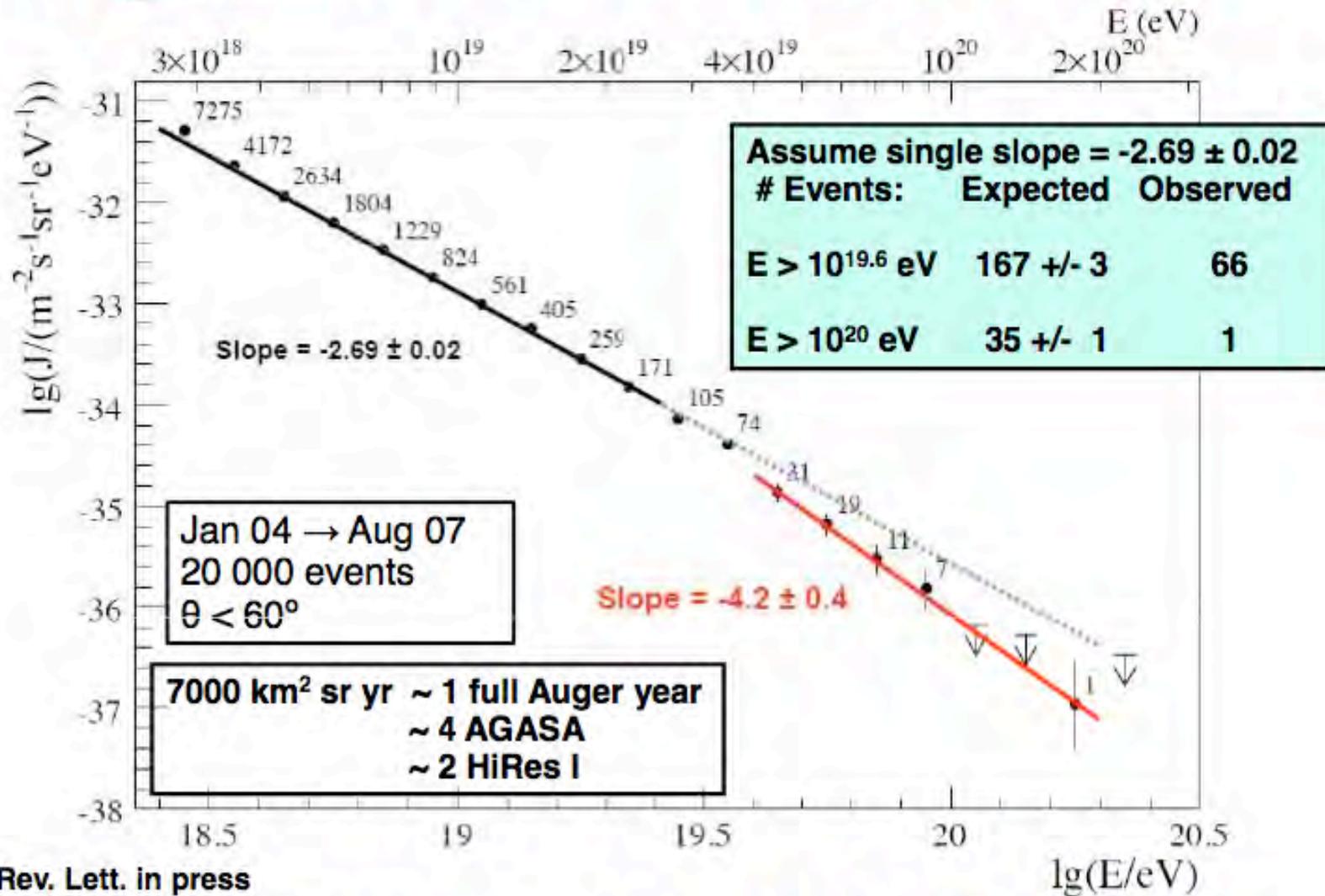
**Energy scale determined
with hybrid events:**

~ 20% E resolution.

**Extrapolate calibration to
events observed with the
Surface Detector only**

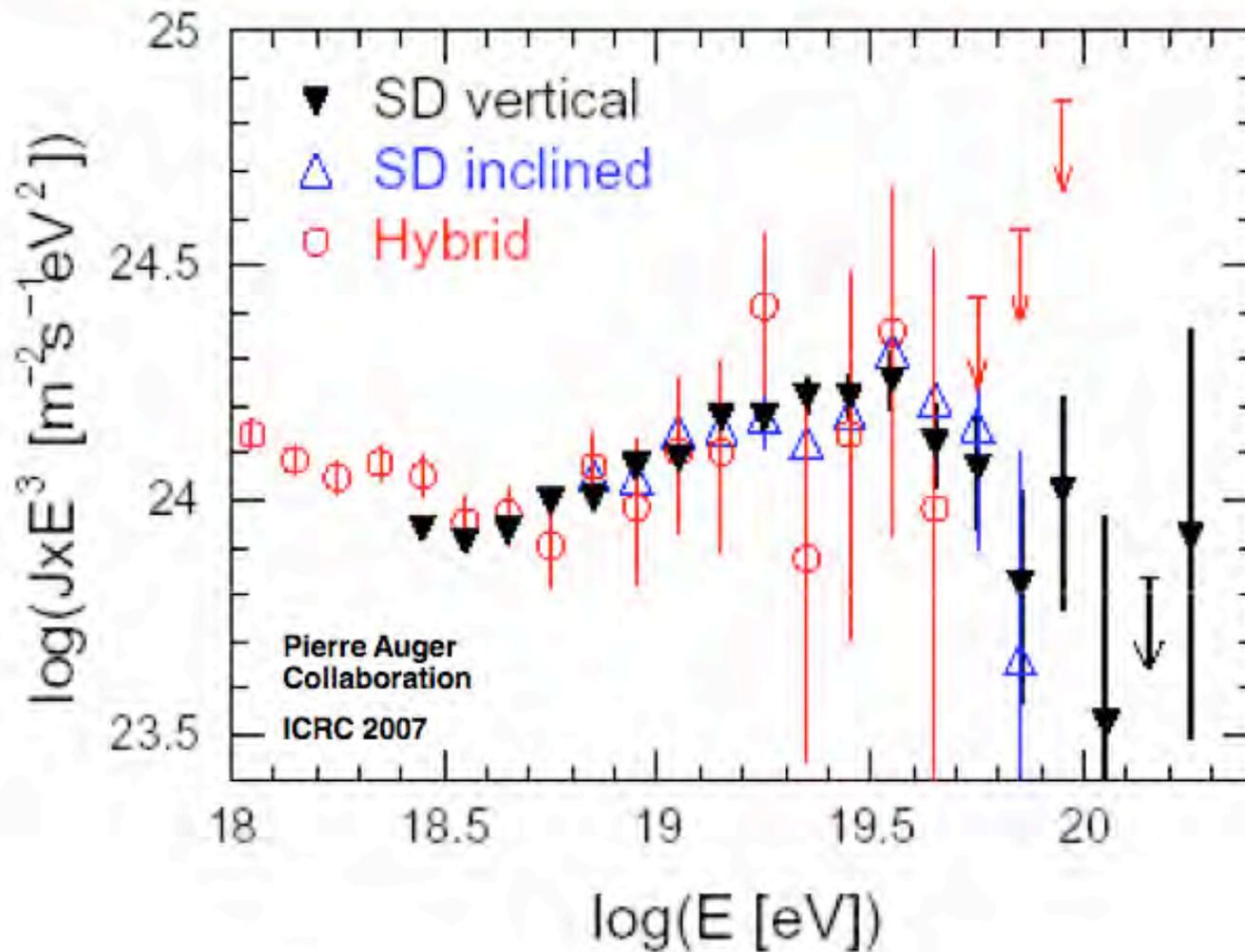
**Minimises Monte Carlo
and mass composition
dependence**

Energy spectrum SD events ($\theta < 60^\circ$)



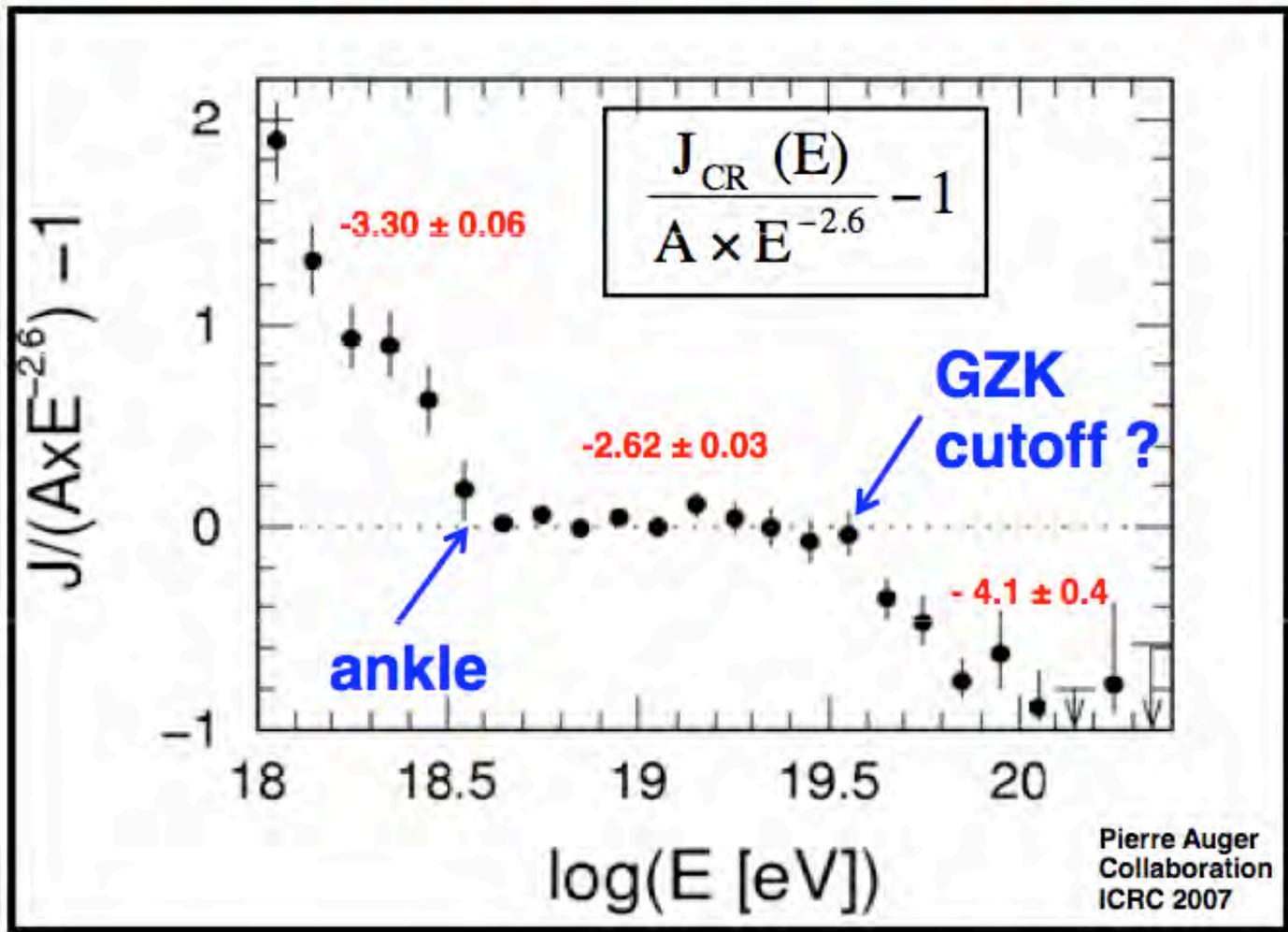
Suppression of the spectrum above $\sim 4 \times 10^{19} \text{ eV}$ @ 6σ : GZK?

Consistency between E spectra: vertical, inclined & hybrid events

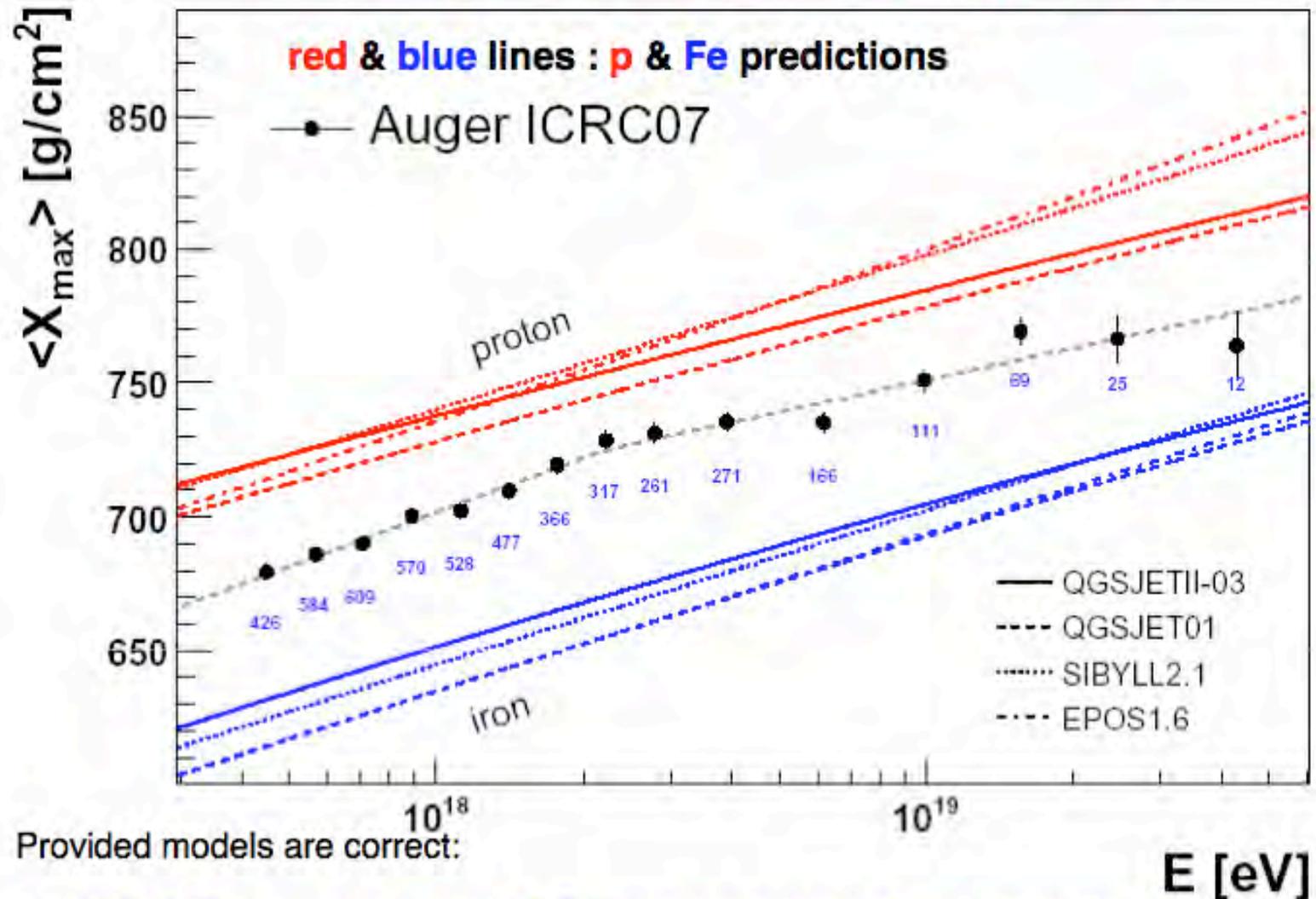


L'andamento dello spettro si giustifica bene con "l'effetto GZK"

Residuals w.r.t. a "standard" spectrum



Elongation Rate: X_{\max} vs E



Provided models are correct:

UHECR mass is NOT proton-dominated

(Fluctuations in X_{\max} yet to be exploited)

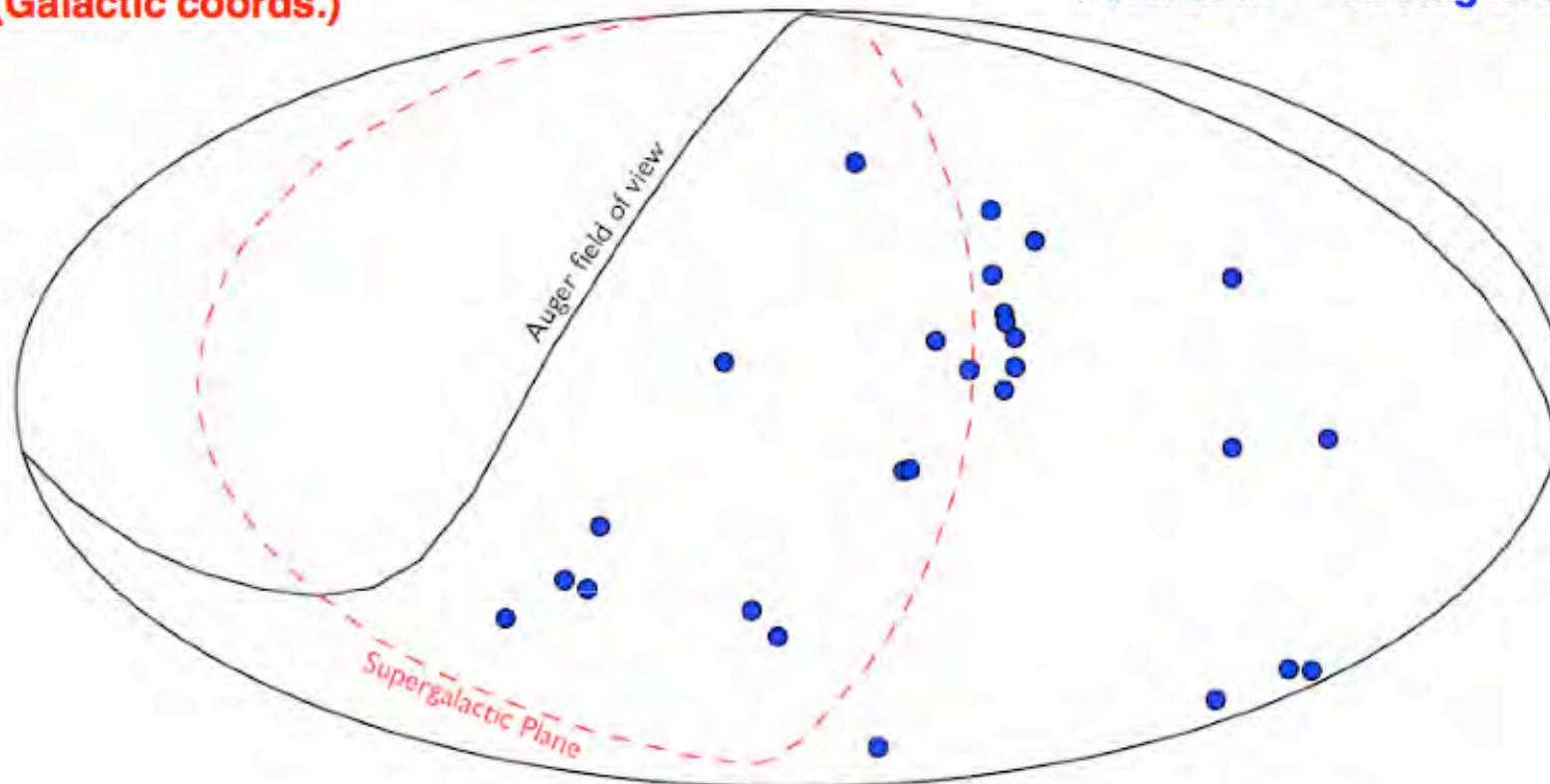
Arrival direction of UHE cosmic rays

Auger UHECR sky

27 events with $E > 56 \text{ EeV}$

1 Jan 2004 → 31 Aug 2007

(Galactic coords.)

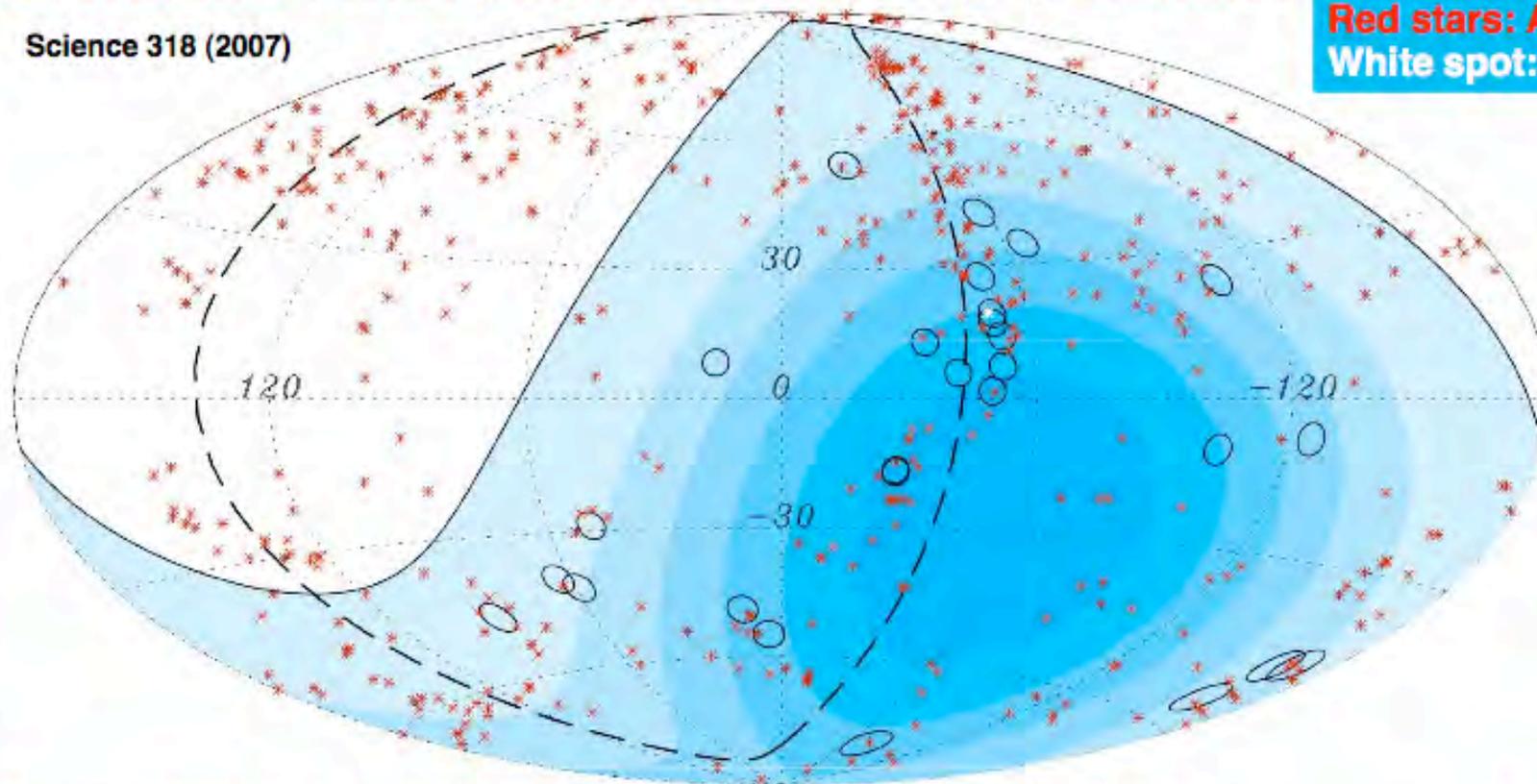


Is the UHECR sky isotropic?, how to quantify?

Correlation with potential source population?

Science 318 (2007)

Black circles: data
Red stars: AGNs
White spot: CenA



Demonstrate/refute isotropy hypothesis based on correlation w source catalog:

12th ed. Veron-Cetty catalog (694 AGNs, $D < 100$ Mpc)

Vary: Max. Angular distance to sources (ψ)
Max. distance to AGNs (D_{\max})
Min. CR Energy (E_{\min})

Find params. minimising the probability that an isotropic distr. of CR directions produces the same degree of correlation