

Astrofisica e particelle elementari

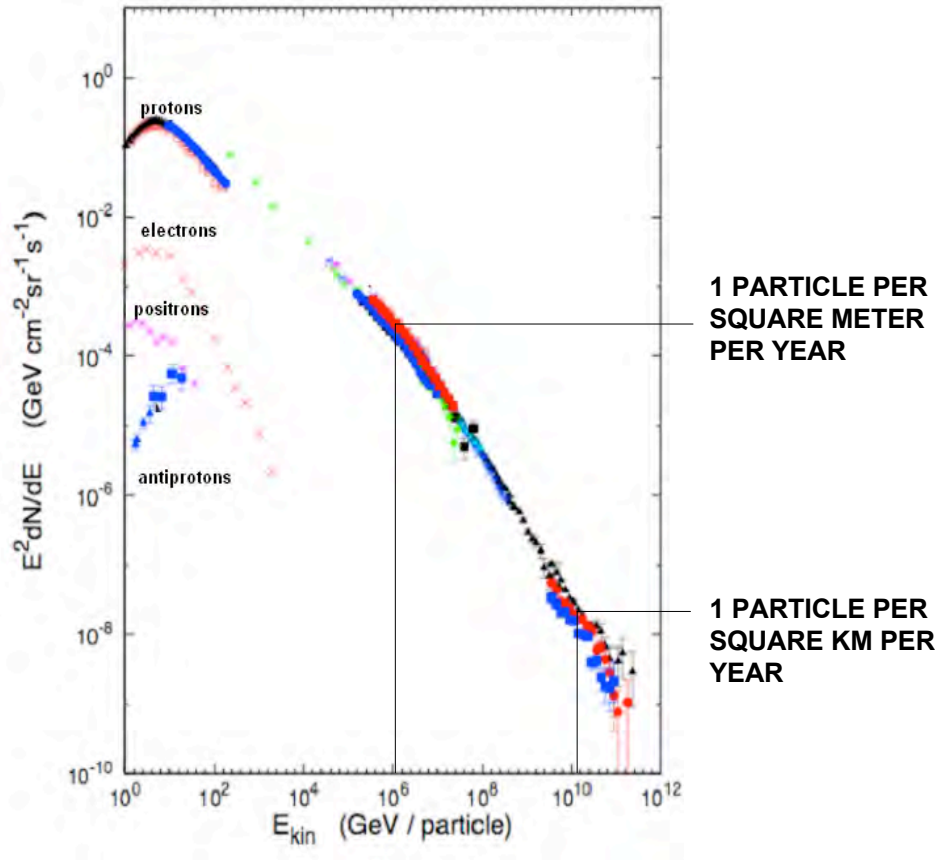
aa 2010-11

Lezione 4

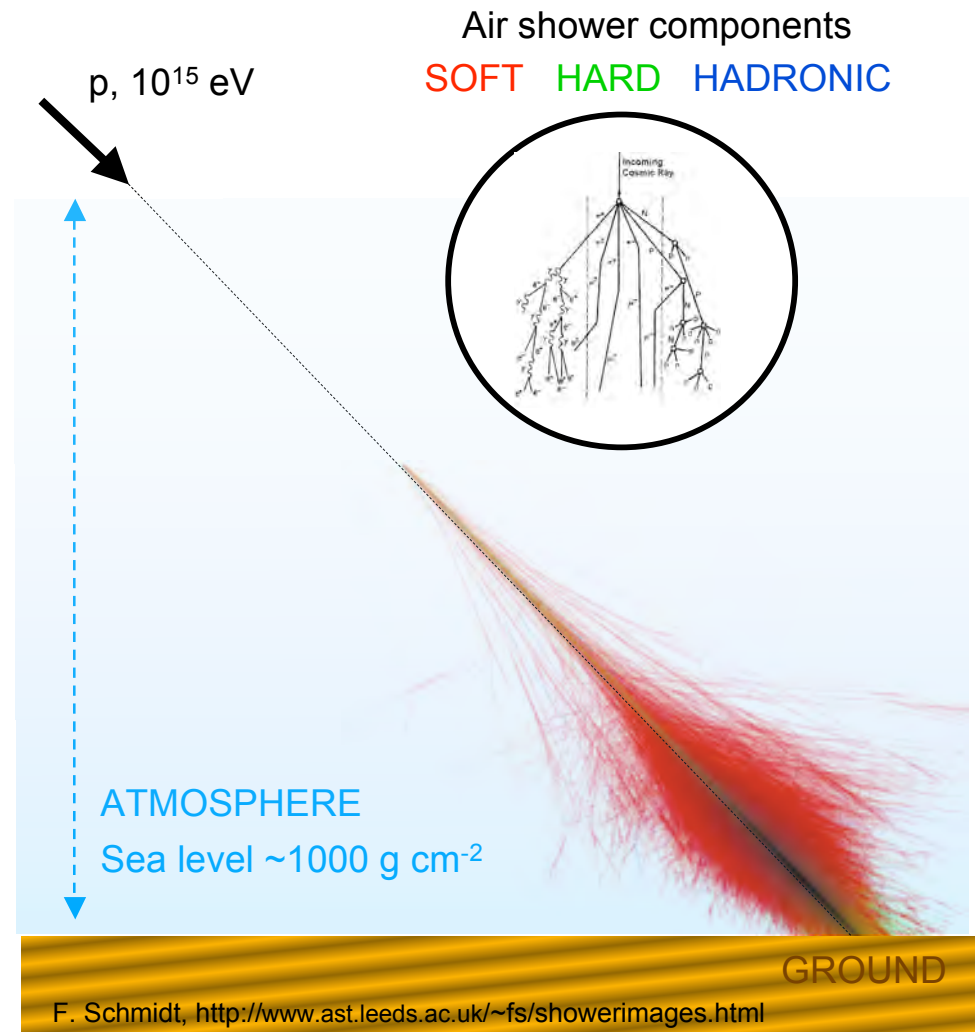
- UHECR/EAS
- Effetto GZK
- ARGO
- KASCADE
- HI RES
- AUGER
- Sommario

Bruno Borgia

Misure indirette dei RC



- large detection areas for significant statistics
- ground based detectors:
→ Extensive Air Showers



La fisica dei raggi cosmici UHE

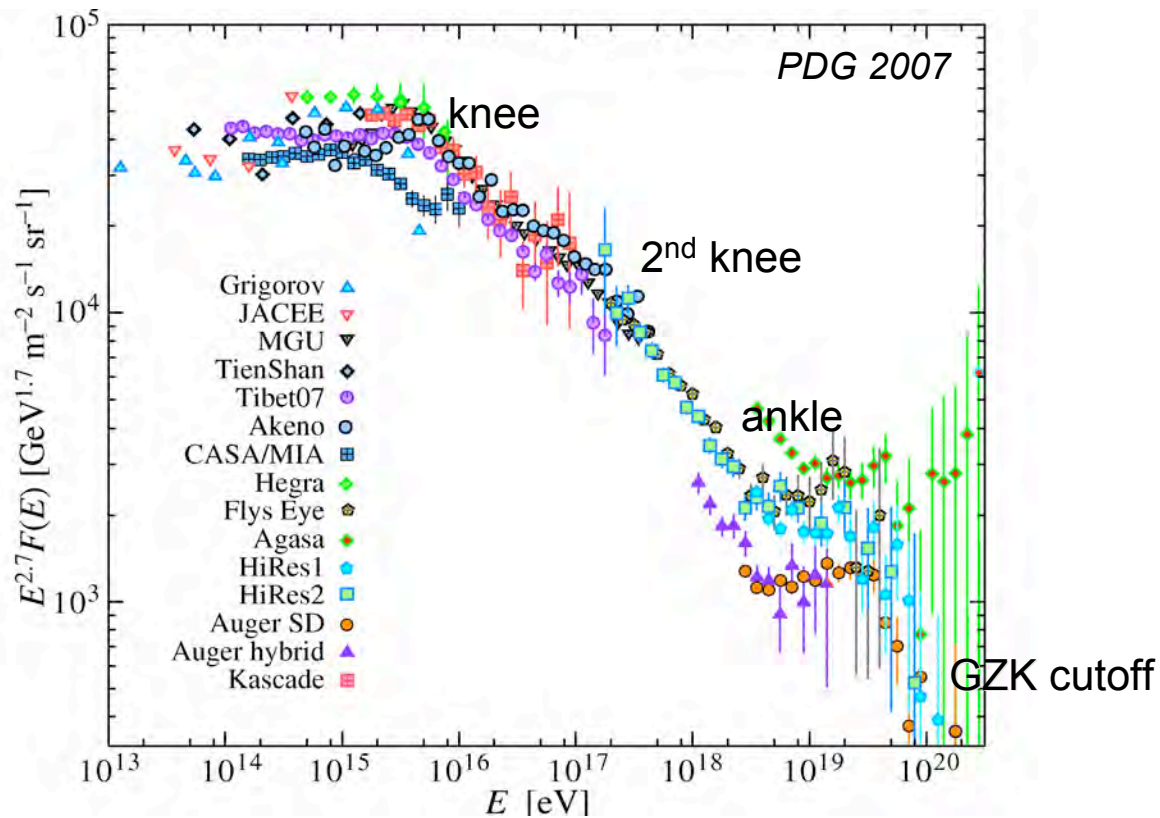
ASTRO -

- quali sono le sorgenti?
- quanto distanti e come distribuite?
- meccanismi di accelerazione?
- propagazione?



- PARTICLE

- interazioni di particelle ad energie superiori delle macchine acceleratrici?



Misure:

- distribuzione di energia
- composizione chimica
- direzione di arrivo
- verifica modelli di interazione ad alta energia

EAS

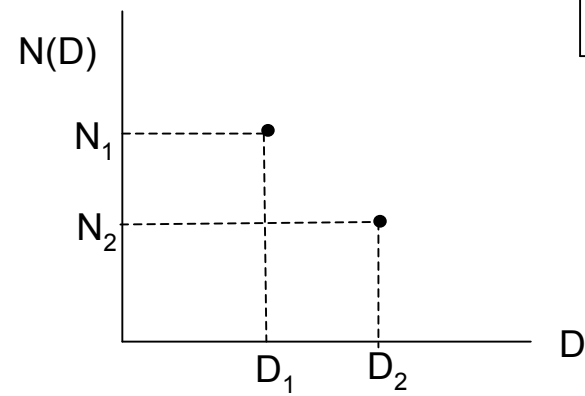
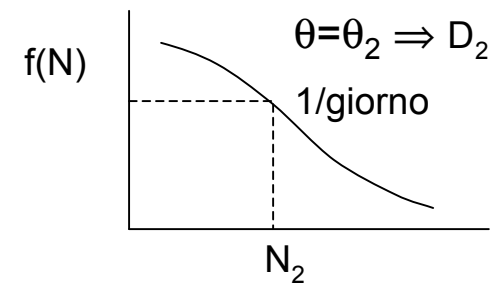
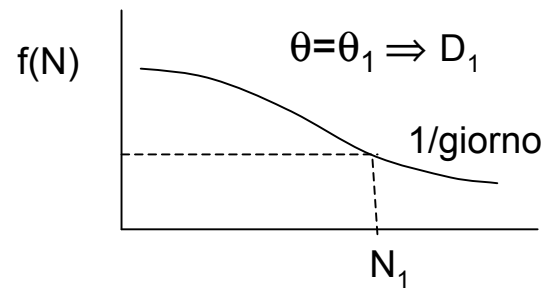
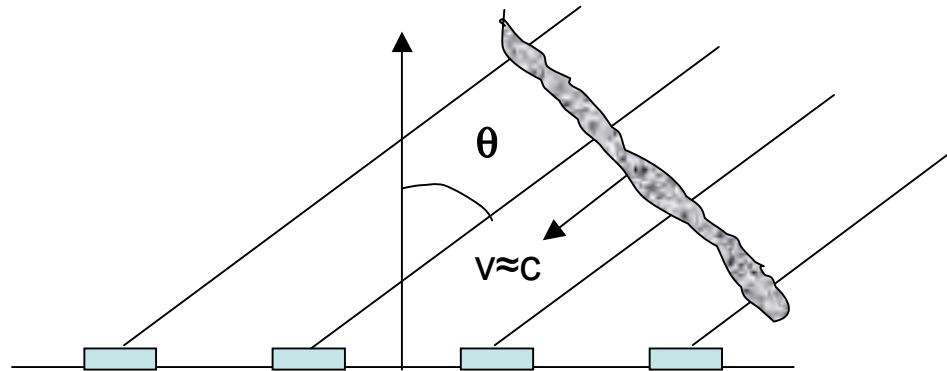
Extensive Air Shower

Le particelle cariche dello sciame possono provocare anche la fluorescenza dell'azoto atmosferico, generando circa 5000 fotoni per km di traccia, nella regione del blu. La luce di fluorescenza è emessa isotropicamente.

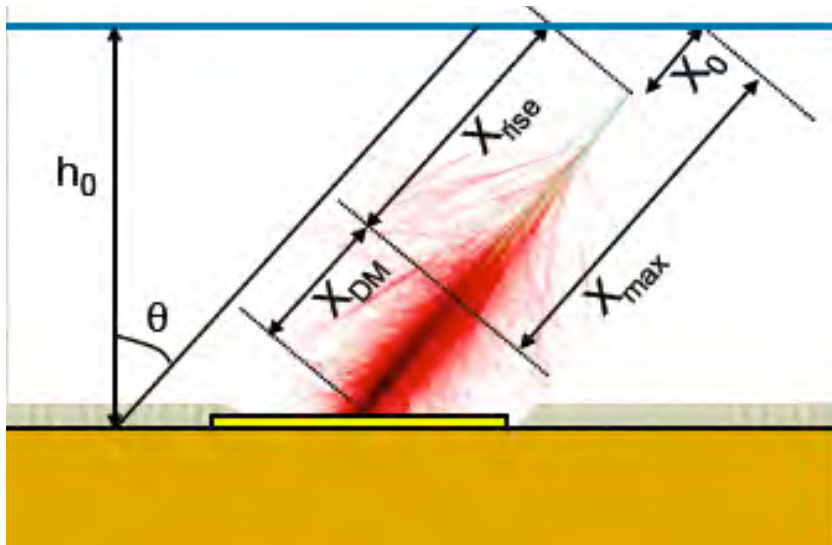
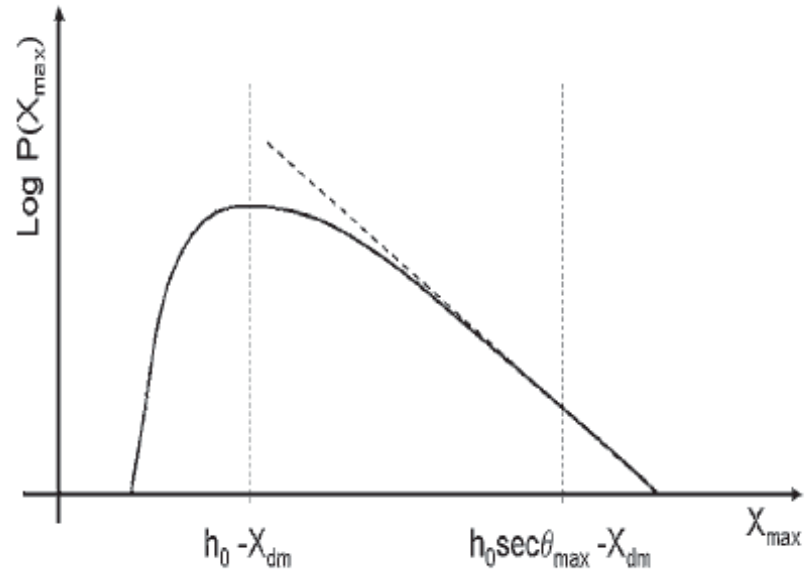
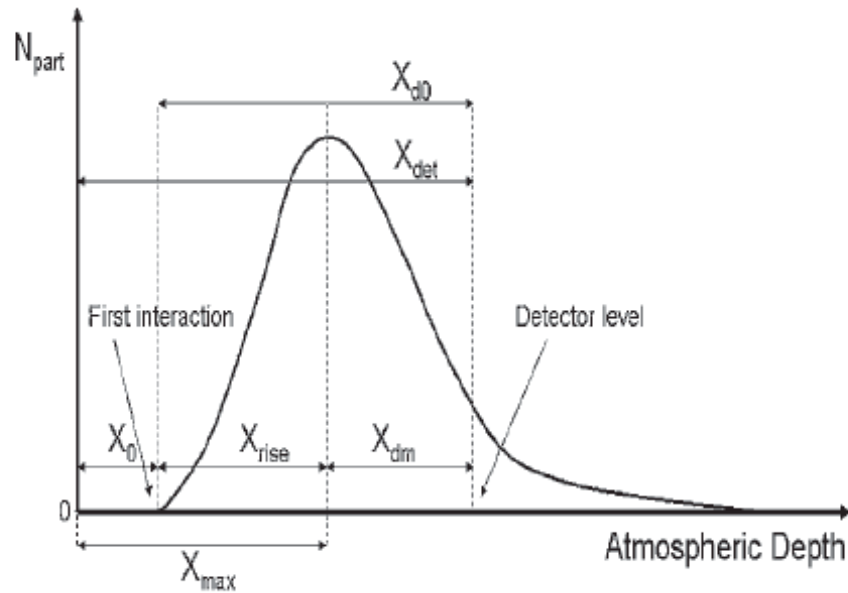
Particelle secondarie generate negli sciame iniziati da protoni o nuclei di alta energia possono arrivare a terra senza perdere tutta la loro energia nell'atmosfera. Per rivelare tali sciame si impiegano rivelatori di dimensioni limitate ma in gran numero distribuiti su una grande superficie. Il solo fatto di osservare a terra 10^6 o più particelle relativistiche ci dice che il primario deve aver avuto una energia molto grande. Per stimare l'energia si modella lo sviluppo di sciame adronici per mezzo di montecarli confrontando i risultati con le misure eseguite da una collaborazione US-Giappone sul Monte Chacaltaya in Bolivia a 5200 m di quota. A questa altezza la densità atmosferica sopra il rivelatore è circa la metà essendo 520 g/cm^2 . Si misura quindi il numero di particelle in funzione dell'angolo zenitale θ e quindi si studia lo sviluppo dello sciame per profondità variabili. L'angolo θ si ottiene dai tempi di arrivo delle particelle nei vari rivelatori, tenendo conto che lo spessore delle particelle che arrivano è dell'ordine di qualche metro. Inoltre si assume che sciame che arrivano da angoli diversi ma che hanno la stessa frequenza siano iniziati da primari della stessa energia. In definitiva si può quindi ottenere una distribuzione di numero di particelle per spessori variabili dell'atmosfera a energia fissata.

Esistono altri metodi per calibrare gli sciame estesi.

EAS



σ (p - aria)



$P(X_{MAX})$: distribuzione probabilità di X_{MAX} in funzione dell'angolo θ

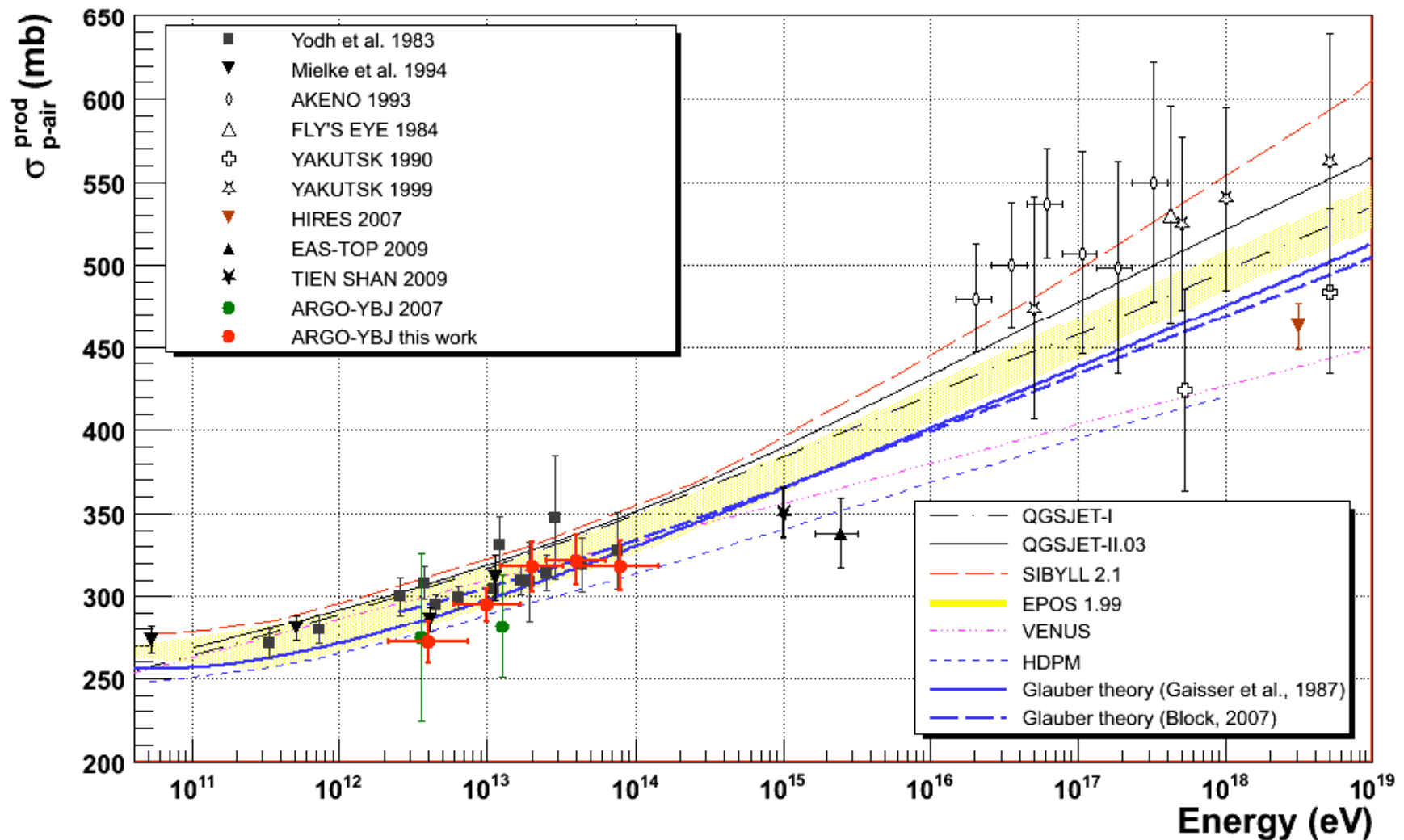
Distribuzione angolare sciami con X_{DM} fissato

$$R(\theta) \sim \exp \left[\frac{h_0}{k \lambda_{p-atm}} (\sec \theta - 1) \right]$$

$$\lambda_{p-atm} = 2.41 \cdot 10^4 / \sigma_{p-atm} \quad (\text{g/cm}^2)$$

k è un fattore di correzione che dipende dalla particella primaria
 X_{DM} distanza rivelatore X_{MAX}

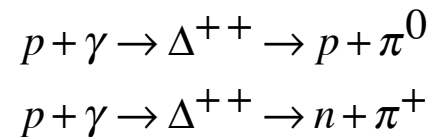
SEZIONE D'URTO P-ARIA



UHE e EHE CR

Lo spettro dei RC si estende fino a 10^{20} eV e i dati provengono da esperimenti con rivelatori distribuiti su grandi superfici. AGASA in Giappone ha un'estensione di 100 km^2 . Auger si estende su 3000 km^2 e può misurare ≈ 50 eventi/anno con $E \approx 10^{20}$ eV.

Greisen, Zatsepin e Kuzmin mostrarono che a quelle energie l'universo diventa opaco a causa della fotoproduzione di pioni alla risonanza Δ^{++} nell'urto di protoni contro i fotoni della radiazione cosmica di fondo:



La sezione d'urto per questa reazione al di là della risonanza è $\sigma \approx 2 \cdot 10^{-28} \text{ cm}^2 = 200 \text{ } \mu\text{barn}$ ($1 \text{ barn} = 10^{-24} \text{ cm}^2$)

La densità della radiazione di fondo è $\rho = 400 \text{ fotoni/cm}^3$

Il cammino libero medio è quindi $\lambda = 1/\rho\sigma \approx 10^{25} \text{ cm} = 5 \text{ Mpc}$ (dimensione di un cluster di galassie)

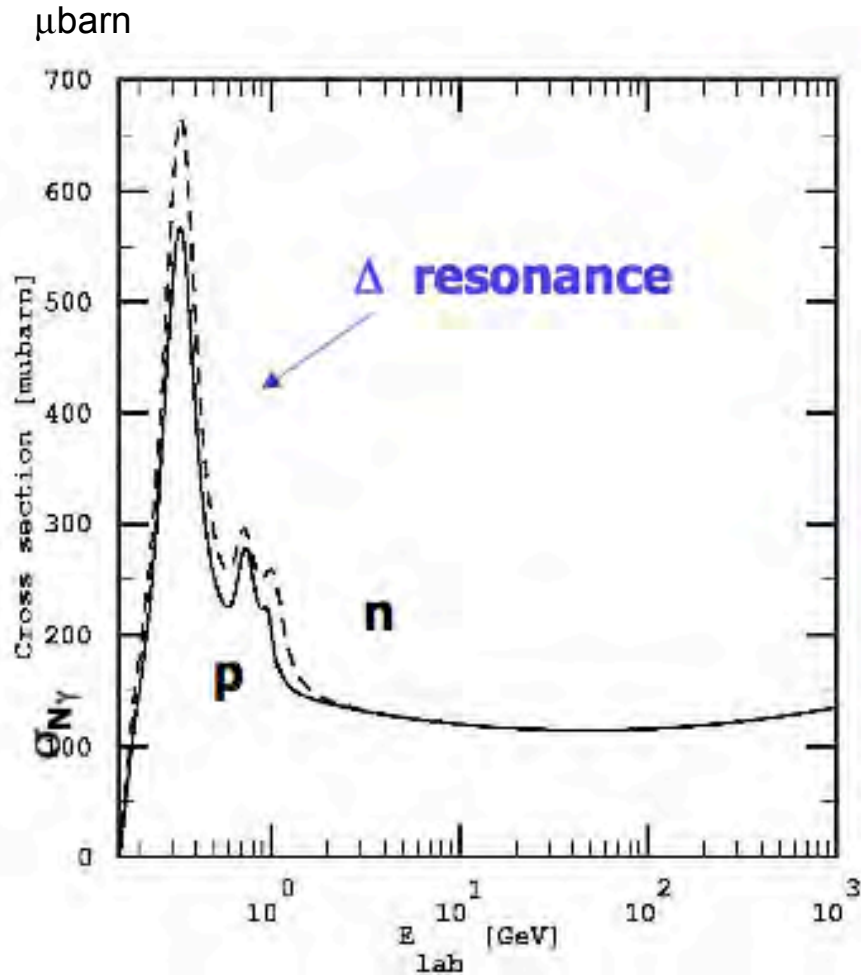
I protoni con energia $E_p \approx 10^{19}$ eV sono sopra soglia per la produzione di Δ^{++} .

Questo limite è noto come limite GZK.

A queste energie i protoni non sono confinati nella nostra Galassia.

{calcolare il raggio di curvatura nel campo magnetico galattico}

LIMITE GZK



protone : (\vec{p}, E) ; fotone_{CMB} : (\vec{q}, qc)

$$s = E_{cm}^2 = (E + q)^2 - (\vec{p} + \vec{q})^2 = M^2 + 2q(E - |\vec{p}| \cos \theta)$$

s iniziale > s a soglia

$$M^2 + 2q(E - |\vec{p}| \cos \theta) > M^2 + m_\pi^2 + 2Mm_\pi$$

protone relativistico

$$E \approx p$$

$$2qE(1 - \cos \theta) > m_\pi^2 + 2Mm_\pi$$

urto centrale

$$(1 - \cos \theta) = 2$$

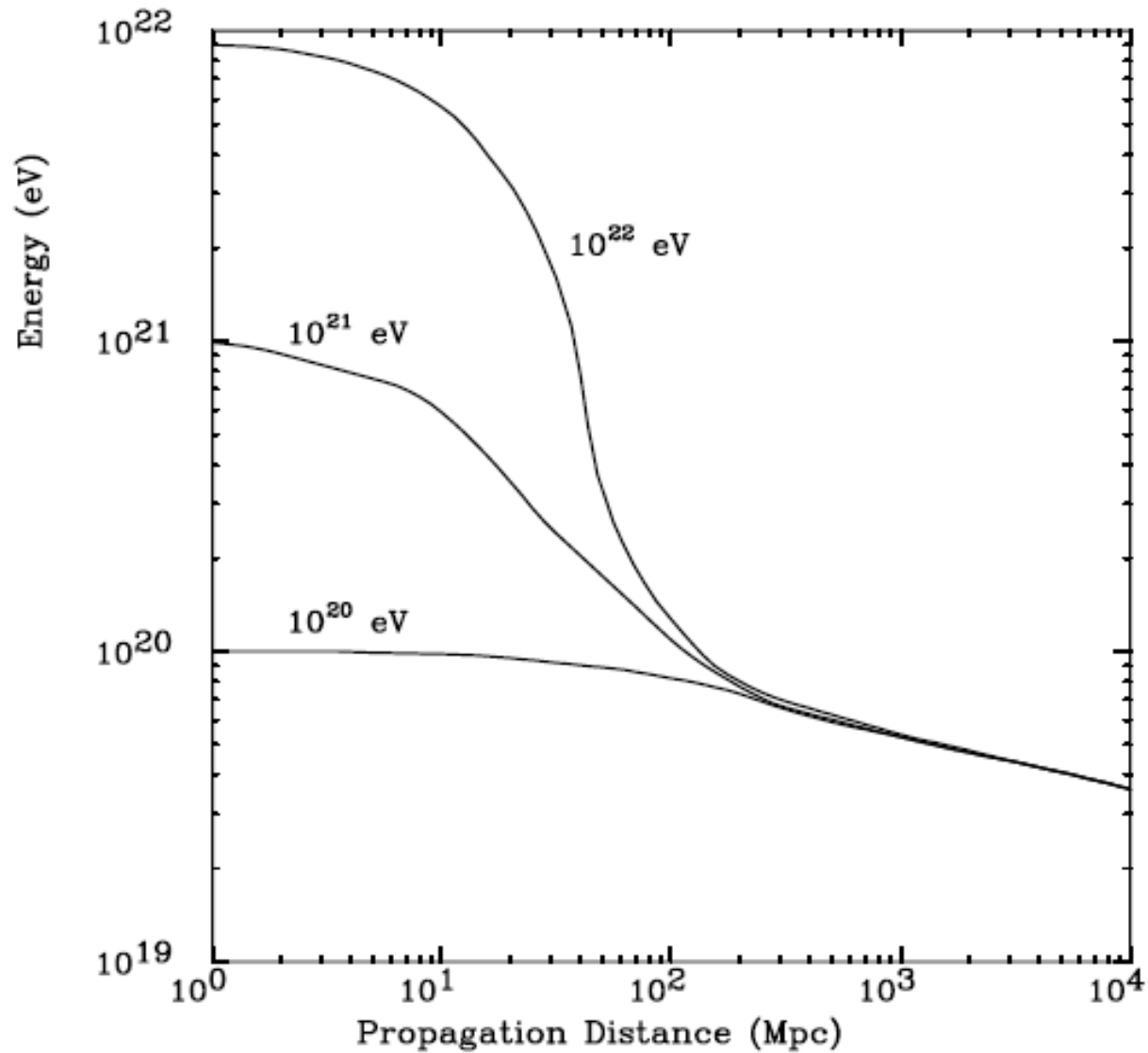
$$E_{soglia} = m_\pi \frac{M + m_\pi / 2}{2q}$$

fotoni CMB : T = 2.74K; qc = kT = 2.35 × 10⁻⁴ eV

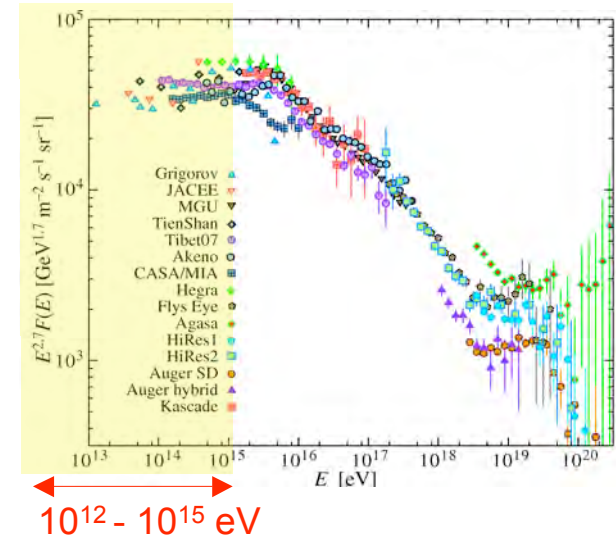
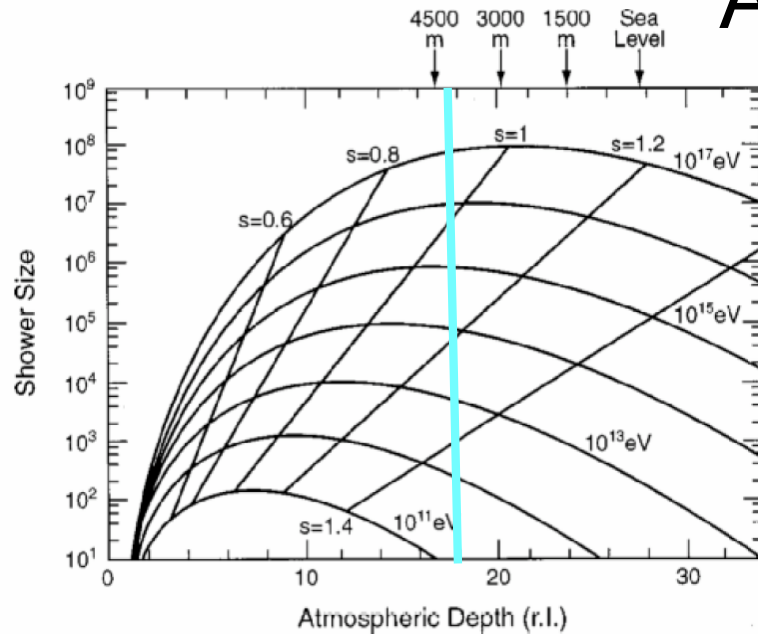
$$E_{soglia} = (4.3 / y) \times 10^{20} \text{ eV} \quad \text{con } qc = ykT$$

dove y da la coda dello spettro

Propagazione protoni nel CMB

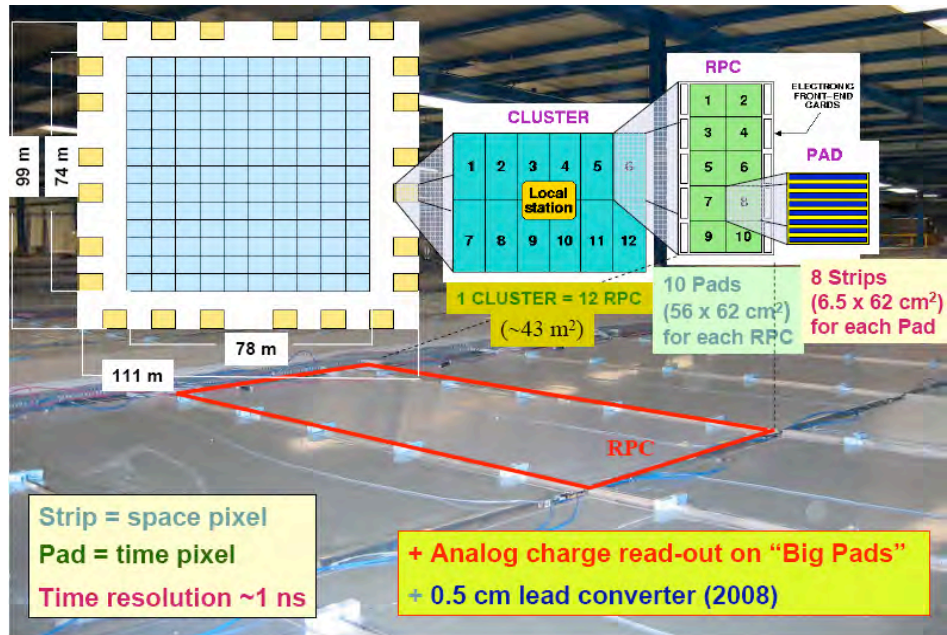


ARGO-YBJ



To lower the energy threshold:

- go to high altitude!
- reduce the spacing between particle detectors



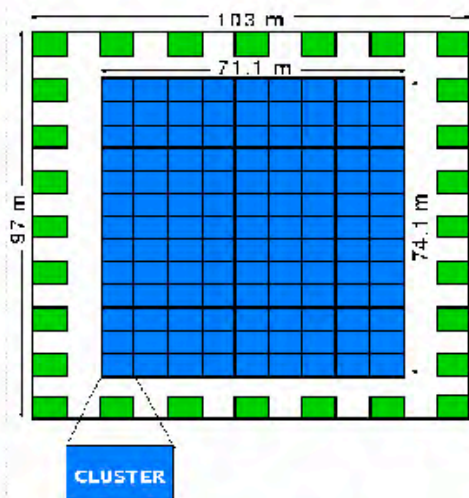
4300 m a.s.l. (~660 g cm⁻²)
Full coverage



ARGO

ARGO

Area 5.200 m² (full coverage)
(10.000 m² with guard ring)
Field of view ~ 1 sr
E = 50 GeV - 50 TeV
Location: Tibet 4300m alt.
Scheduled 2002 (final conf.)

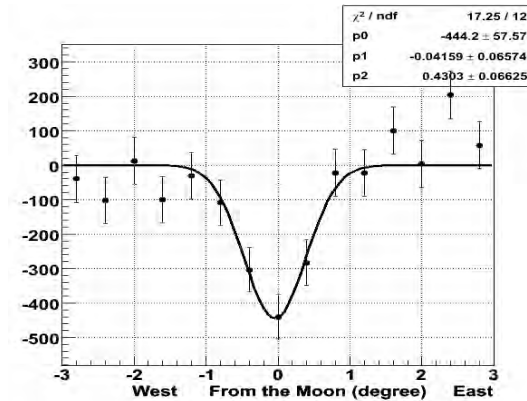
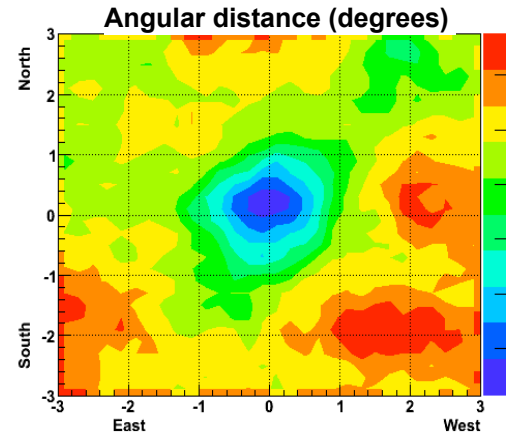
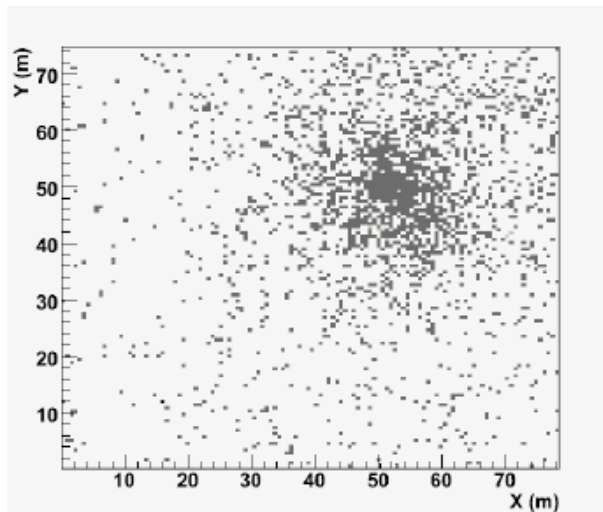
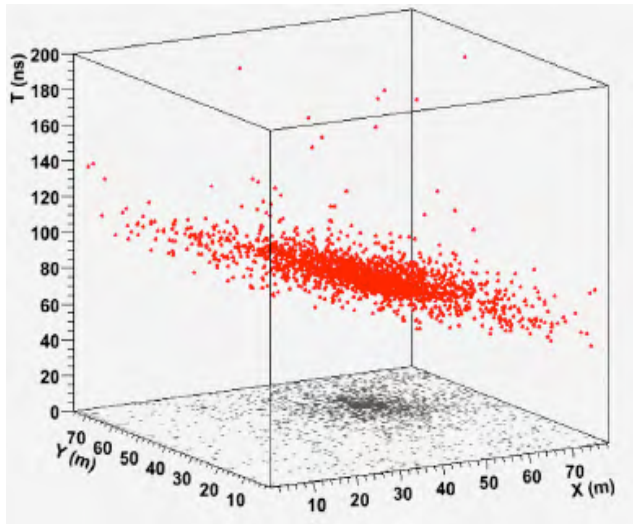


17400 Pads 56 by 60 cm² each of Resistive Plate Chamber (RPC).
Each pad subdivided in pick-up strips 6 cm wide for the space pattern inside the pad.
The CLUSTER is made of 12 RPCs Pads

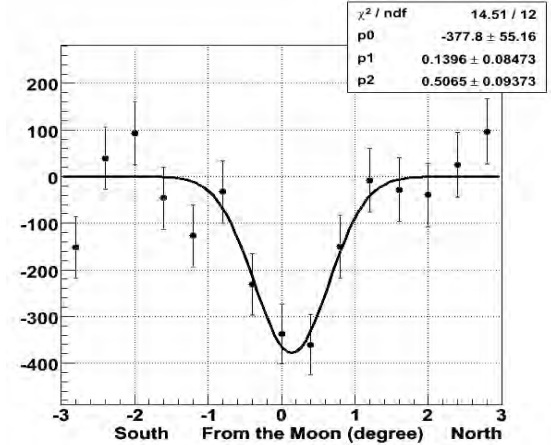


Risultati ARGO-YBJ (I)

High space-time granularity



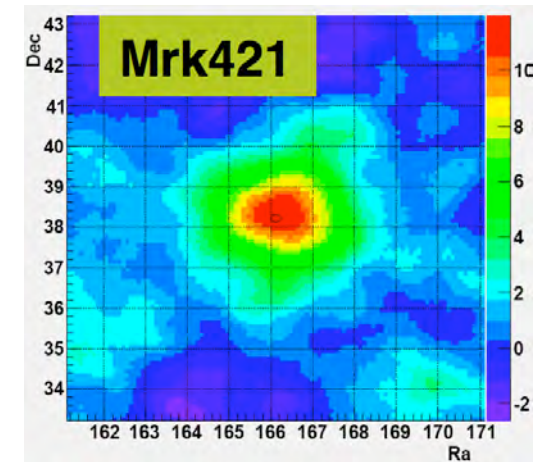
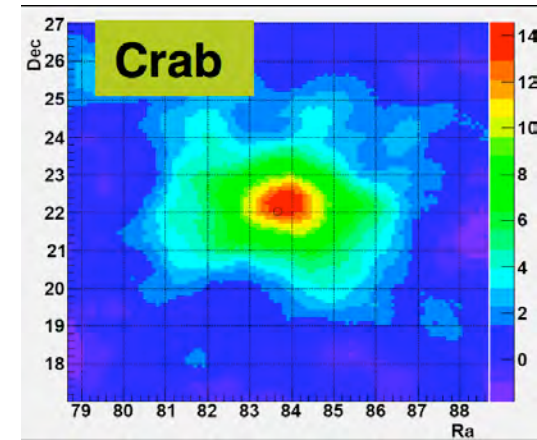
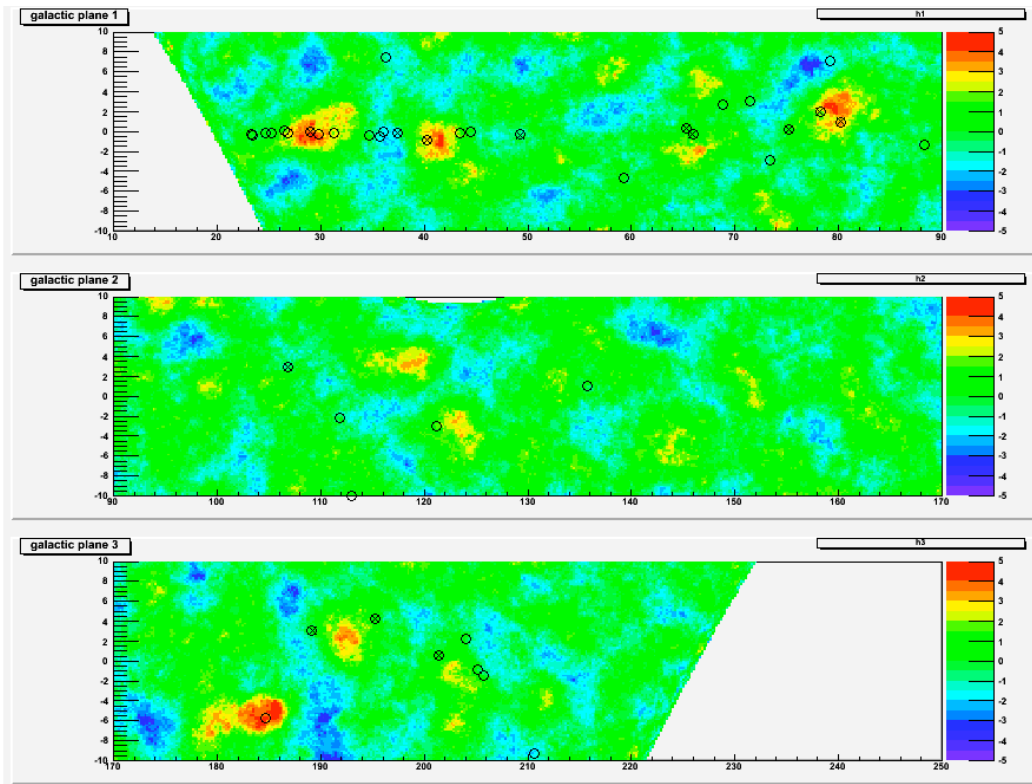
Moon Shadow



- 560 h of Moon observation with $\vartheta < 45^\circ$
- $N_{\text{pad}} > 500$ (median energy ~ 5 TeV)
- only events with core reconstructed inside the array

Deficit significance $\sim 10 \sigma$
 Angular shift with respect to the Moon position :
 0.04° westward
 0.14° northward

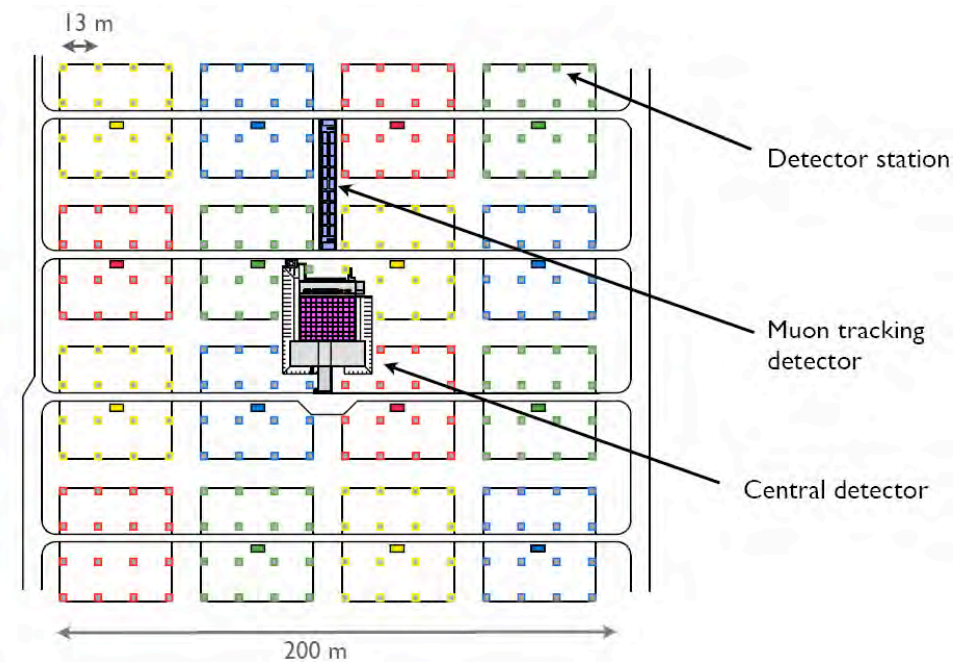
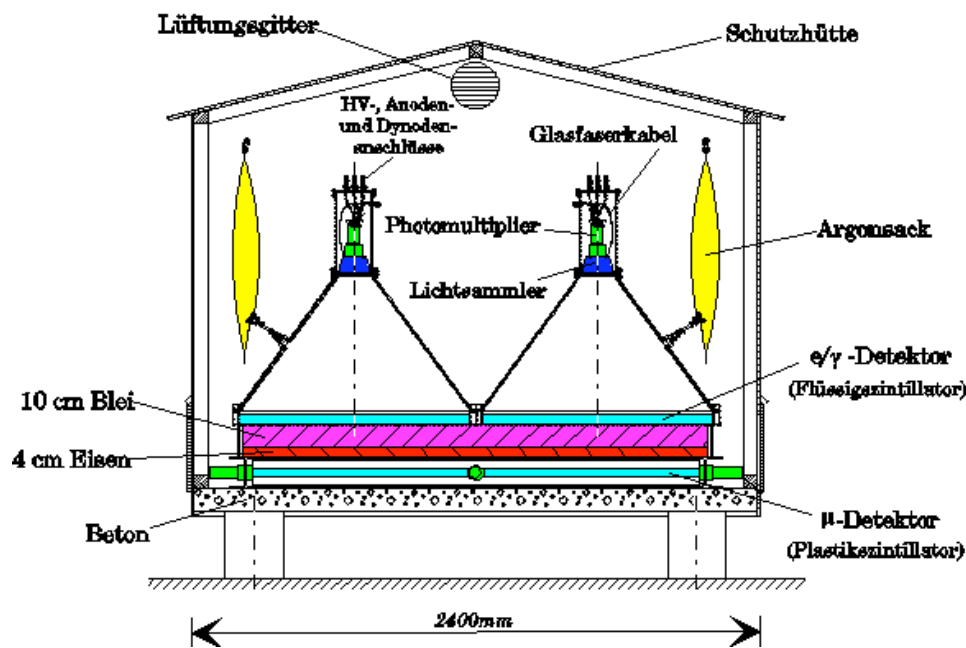
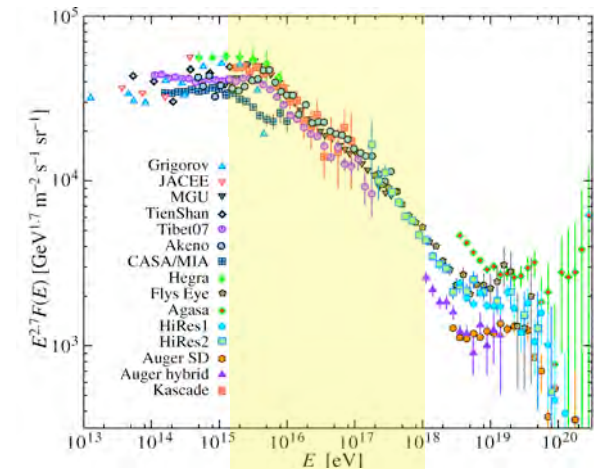
Sorgenti osservate da Argo



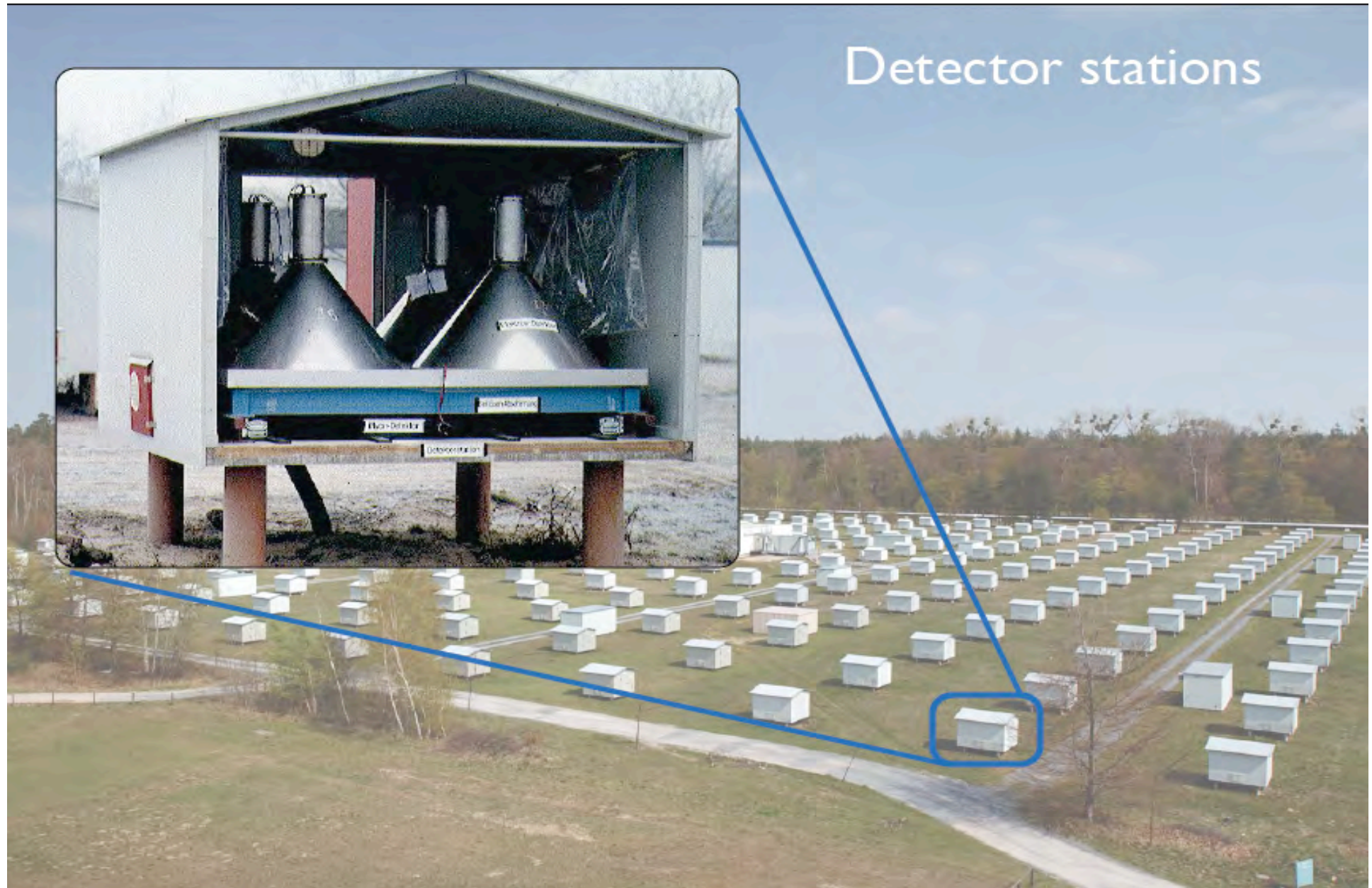
Karlsruhe Shower Core Array DEtector

Simultaneous measurement of the shower components:

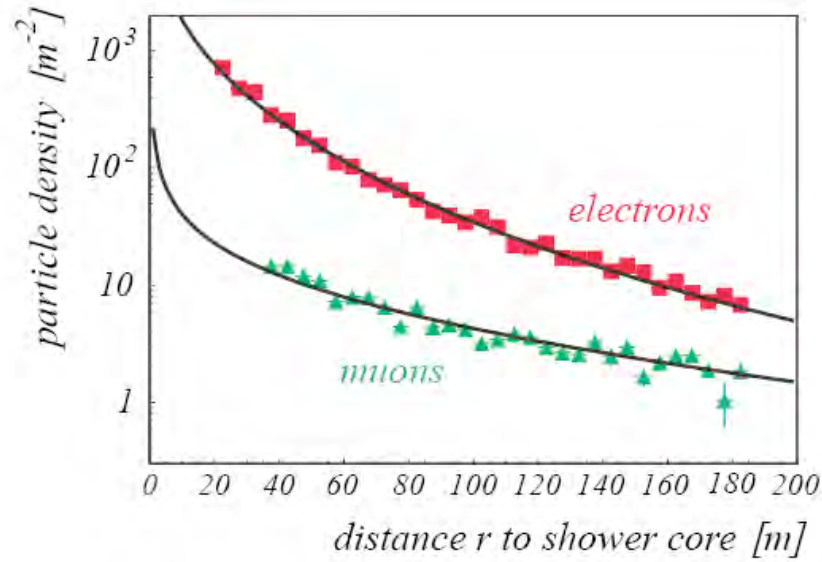
- electromagnetic
- muonic
- hadronic



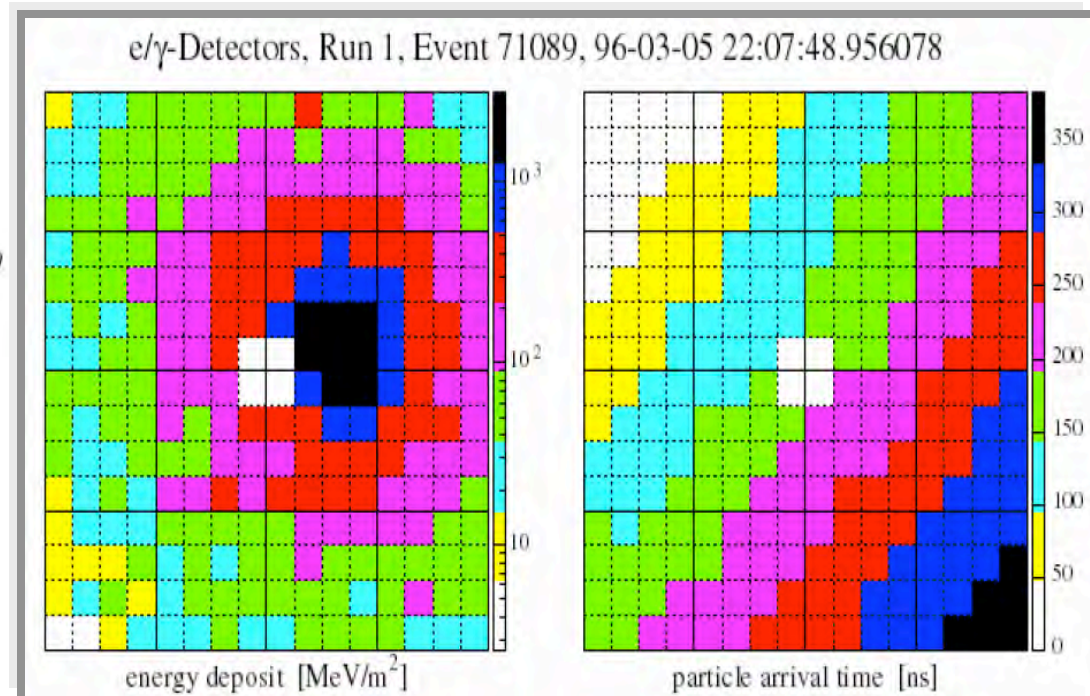
KASCADE e/ γ and muon detector



KASCADE



shower core	$\Delta r = 2.5 - 5.5 \text{ m}$
shower direction	$\Delta\alpha = 0.5^\circ - 1.2^\circ$
shower size	$\Delta N_e/N_e = 6 - 12 \%$



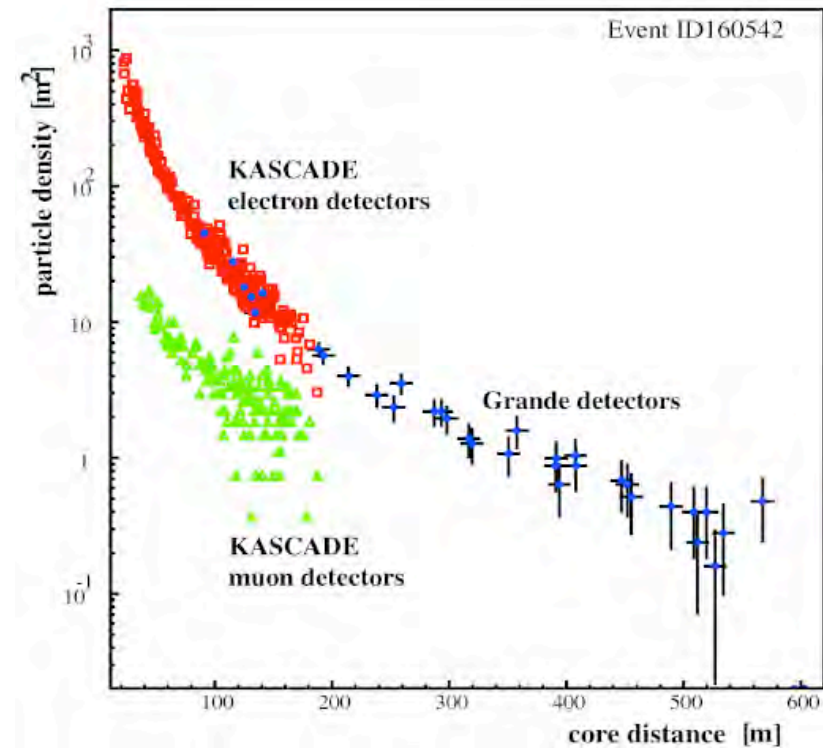
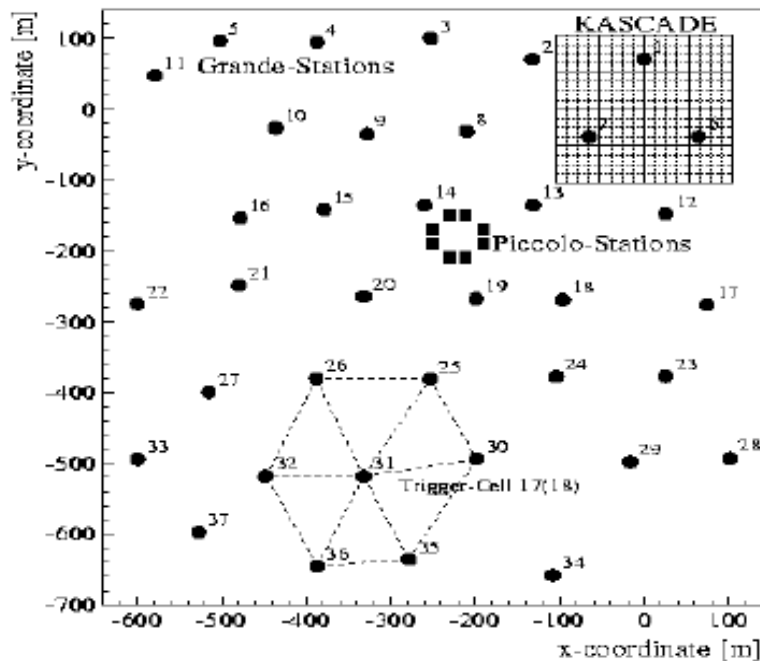
KASCADE-Grande



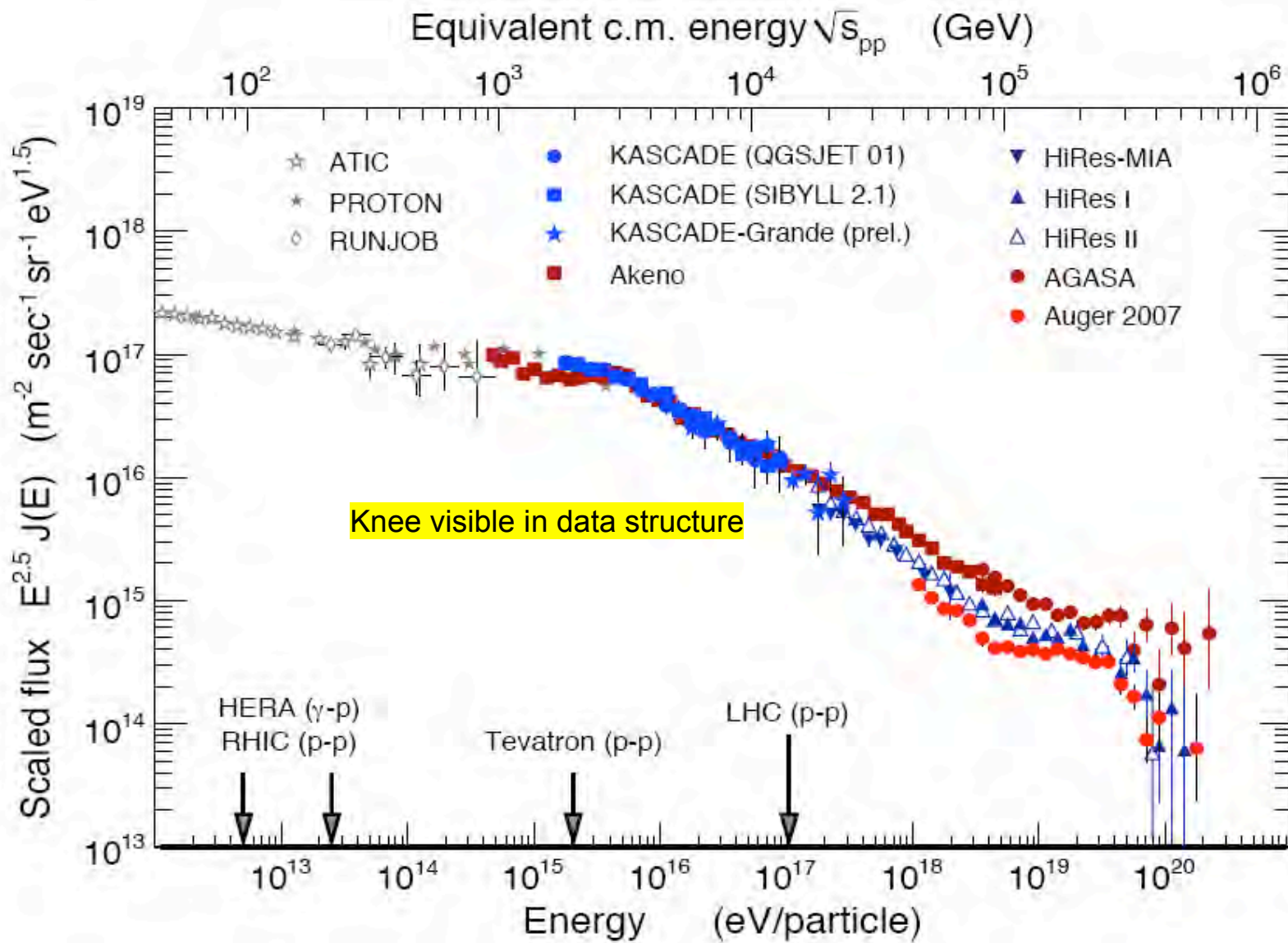
Using scintillators from EAS-TOP, the Instrumented area is increased of more than a factor 10:

$$0.04 \rightarrow 0.5 \text{ km}^2$$

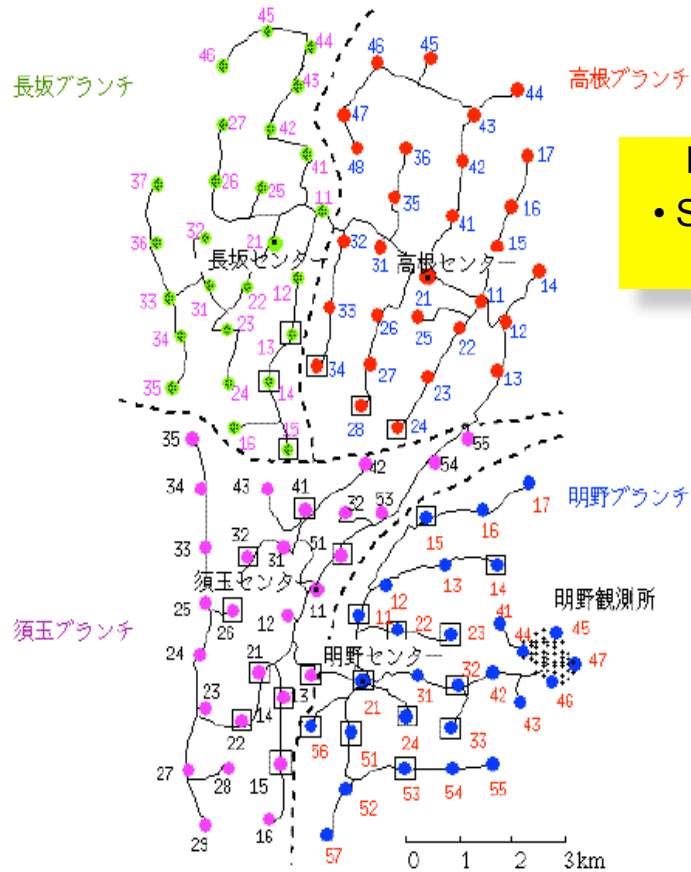
Energy range extended to 1 EeV



KASCADE all-particle spectrum



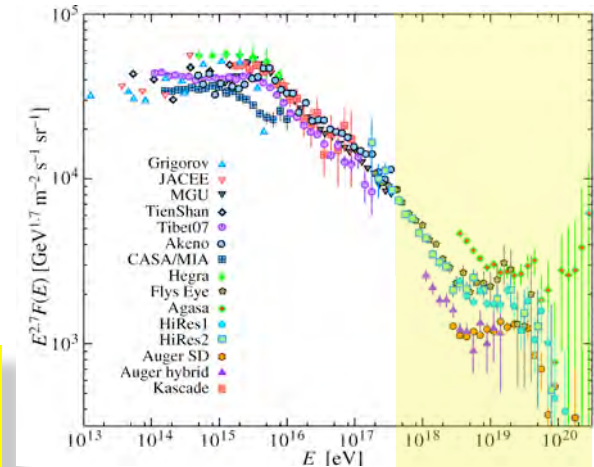
La regione delle alte energie



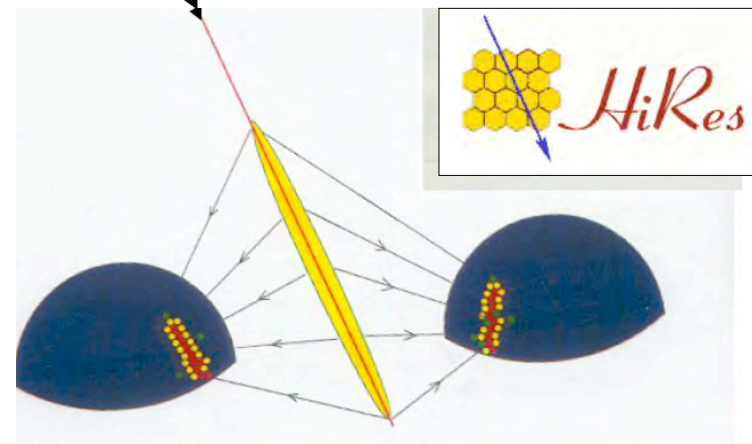
AGASA (Akeno, Japan)
 100 km² array
 1990-2003

Due tecniche di rivelazione:

- Surface particle detector array
- Fluorescence telescopes

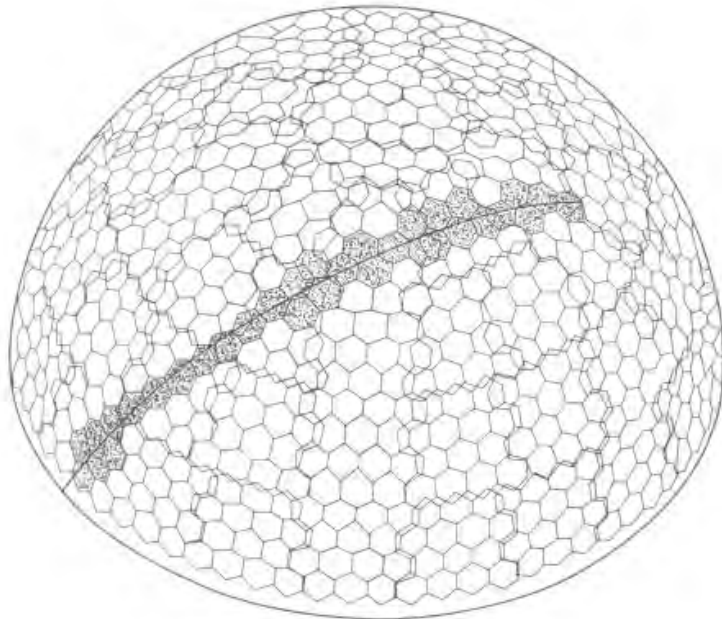


Utah
 Stereo FD
 1997-2006



- Fluorescence UV photons imaged with a pixel detector
- Track the longitudinal profile

HI RES

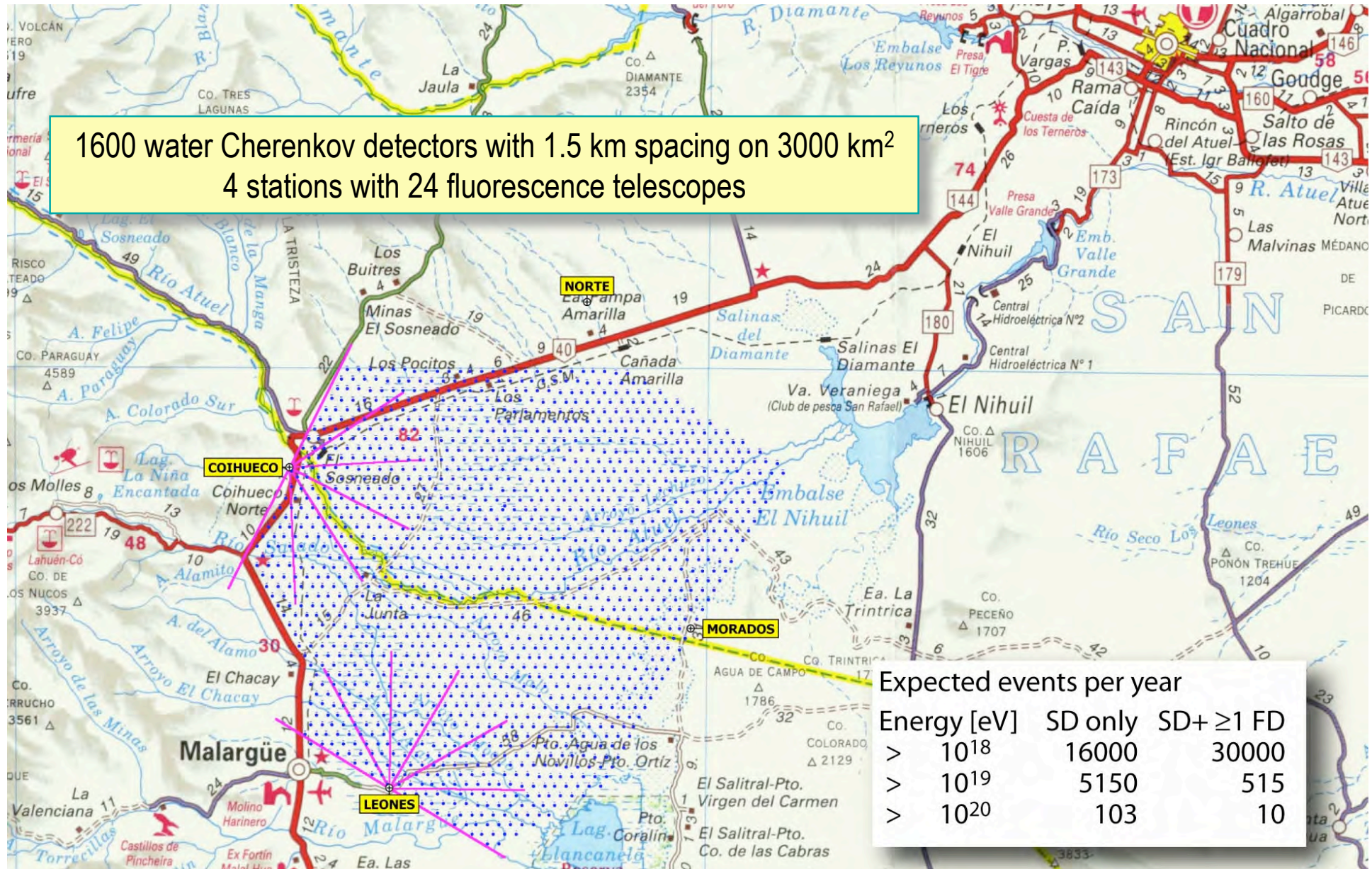


Fly's Eye Detector Parameters

Number of mirrors	67
Diameter of mirrors	1.575 m
Focal Length	1.500 m
Number of PMT (and Winston cones)	880
Mirror Obscuration by PMT cluster	13%
Mirror-cone efficiency product	~0.7
PMT type	EMI 9861 B
Peak PMT quantum efficiency at 360 nm	0.21
Angular Aperture per PMT	91.5 mr
Solid Angle per PMT	6.57 msr
Number of electronic channels	2640
Charge dynamic range	10 ⁵ linear

AUGER

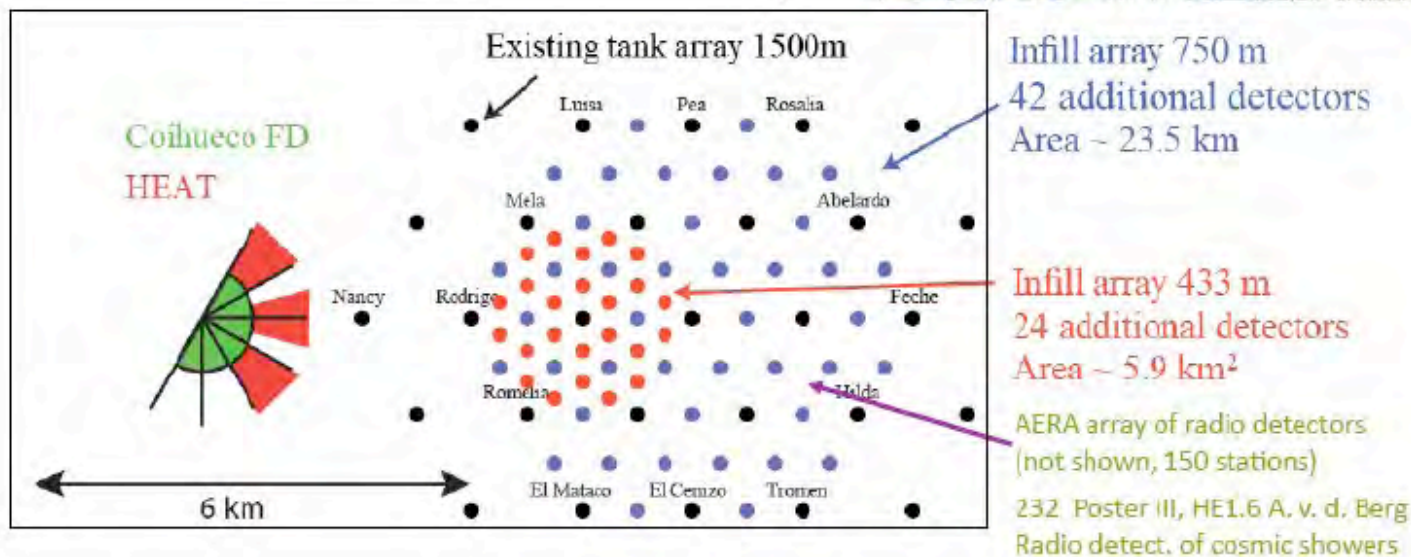
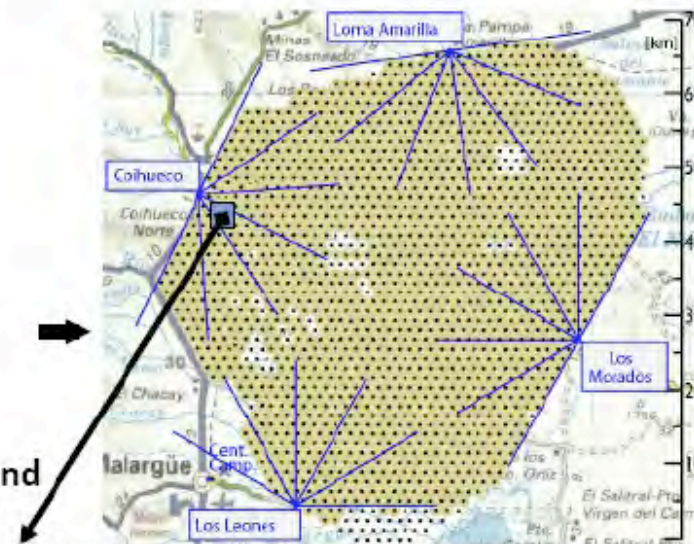
1600 water Cherenkov detectors with 1.5 km spacing on 3000 km²
 4 stations with 24 fluorescence telescopes



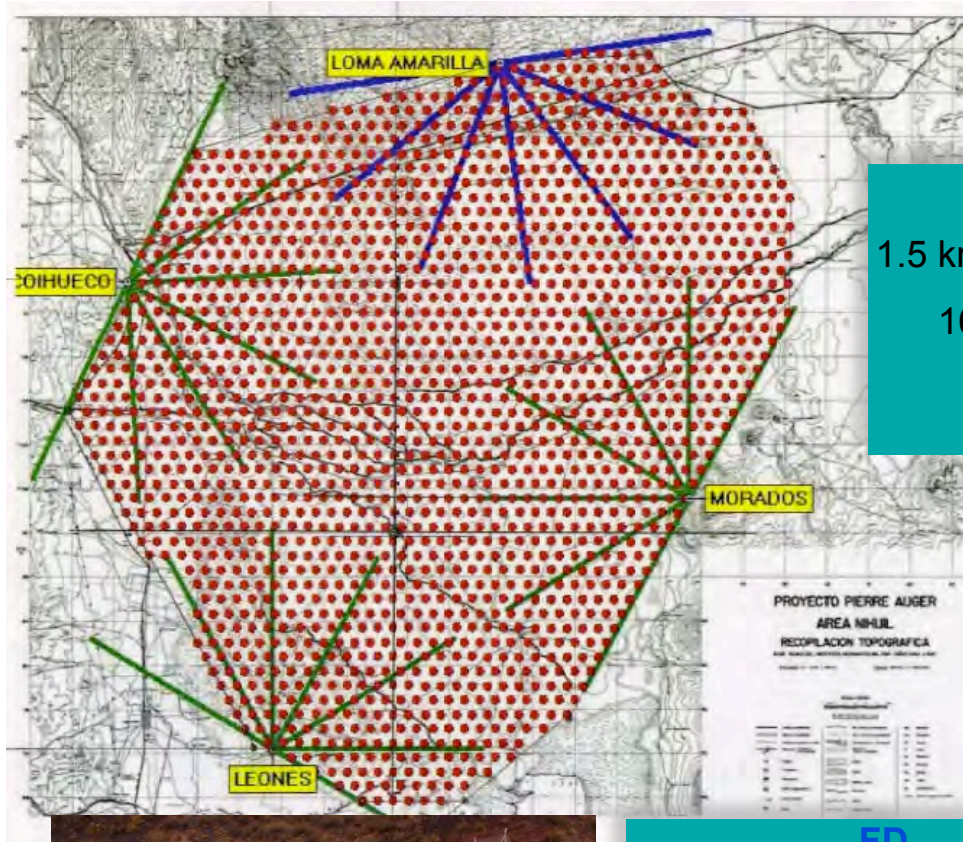
Auger 2010

- Costruzione terminata Apr. 2008
- Nuovi rivelatori per Low Energies:
 - HEAT** (High Elevation Auger Telescopes)
 - AMIGA** (Auger Muon and Infill Array)
 - + **AERA** array of radio detectors

from ...Matthias Kleifges, ICRC 2009, Lodz, Poland



The Pierre Auger Observatory Southern Site



SD
1.5 km spacing, triangular grid
1600 water Cherenkov stations
~ 3 000 km



**PIERRE
AUGER
OBSERVATORY**



FD
4 telescope enclosures
6 telescopes x 4 FD sites



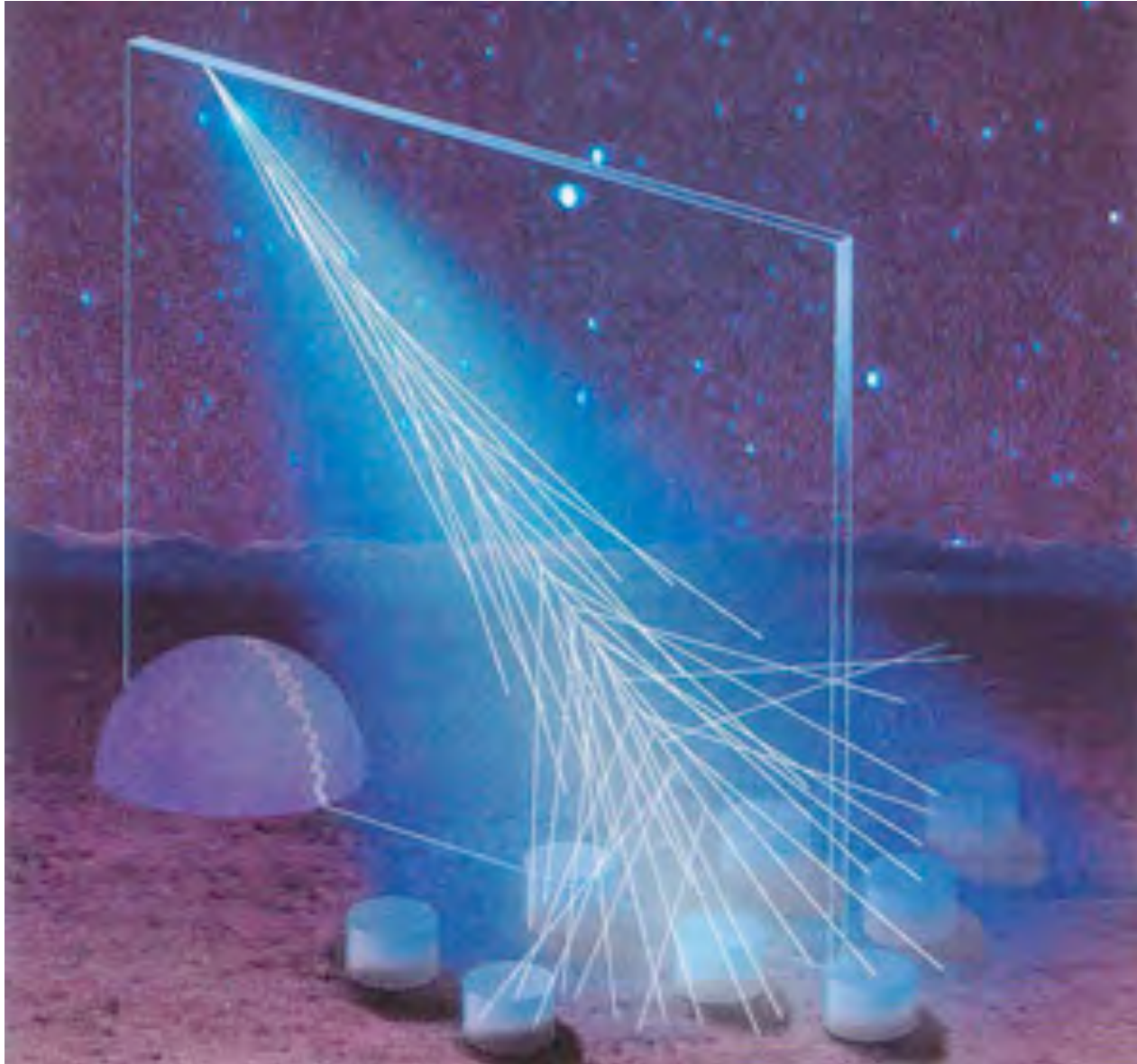
Pampa Amarilla, Argentina
35° S, 69° W
≈ 1400 m a.s.l
≈ 880 g/cm²

AUGER SEEN WITH GOOGLE

Los Leones



AUGER



AUGER: IL METODO IBRIDO

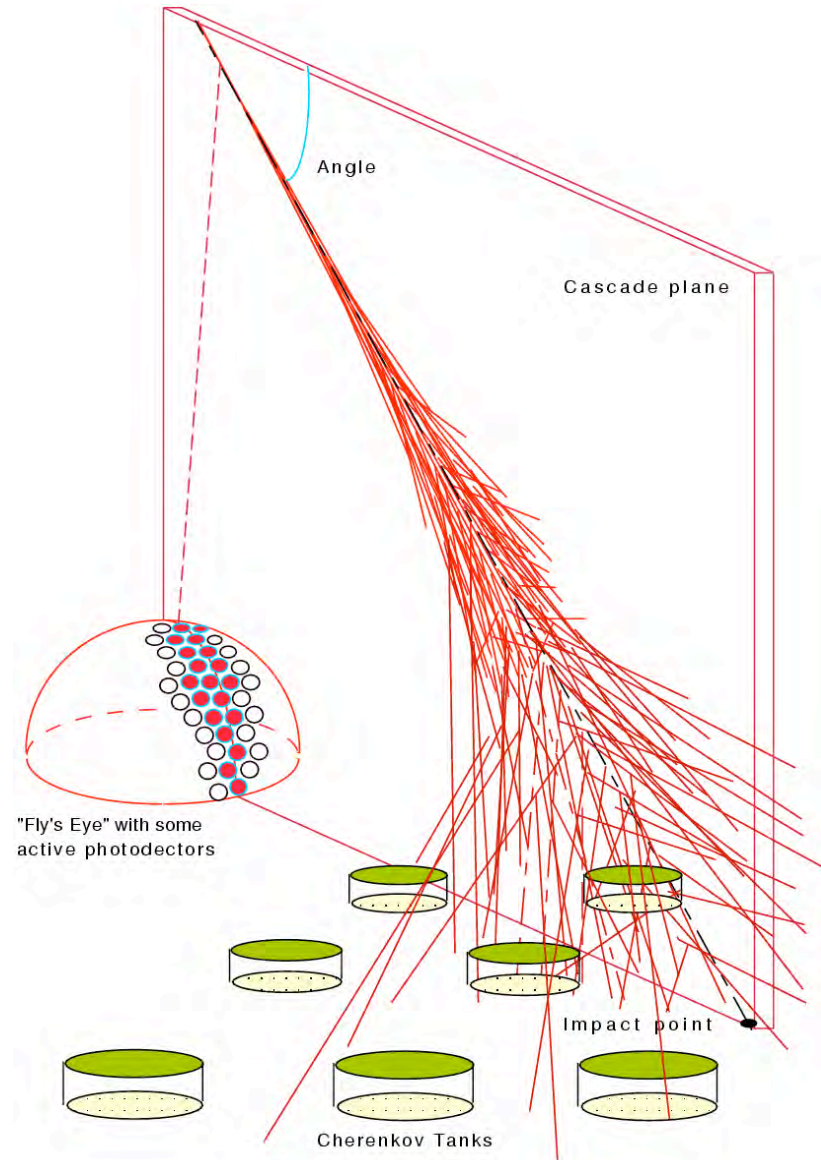
L'Osservatorio Pierre Auger combina le due tecniche

FLUORESCENCE DETECTOR (FD)

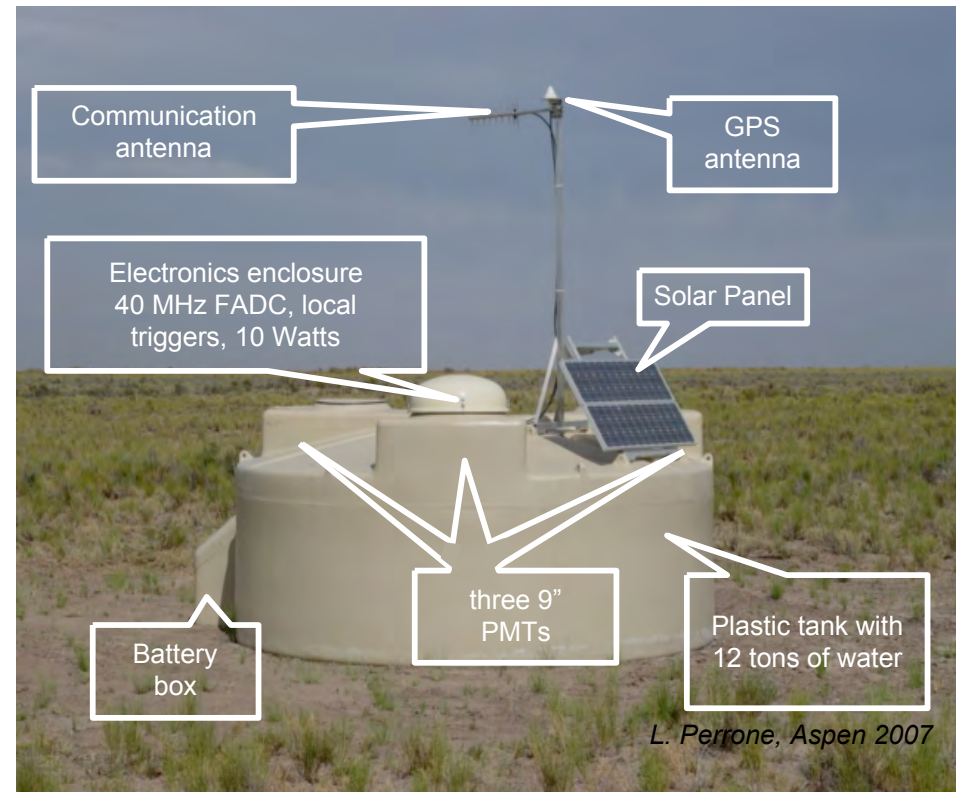
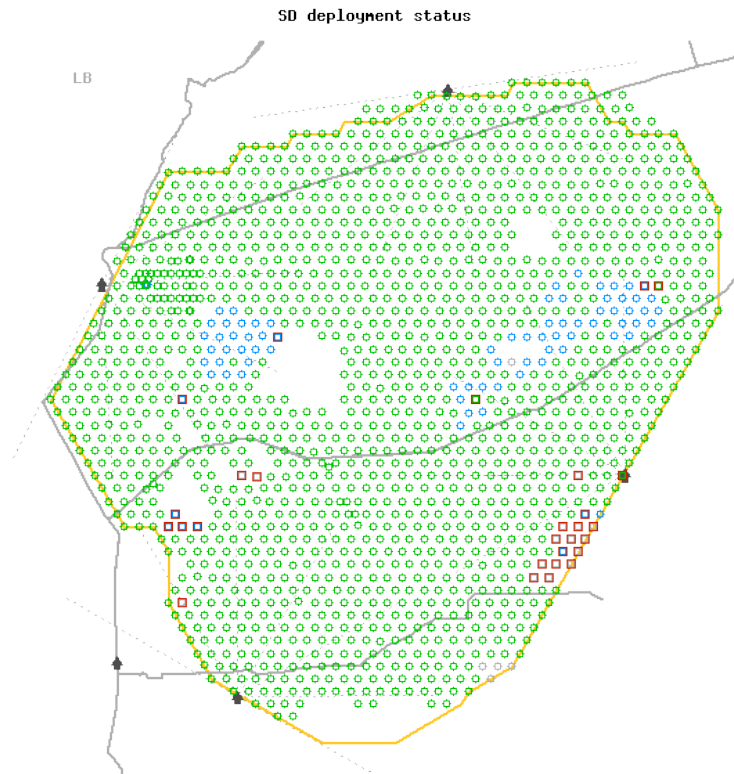
- calorimetric measurement of the energy

SURFACE DETECTOR (SD)

- large collection area, 100% duty cycle

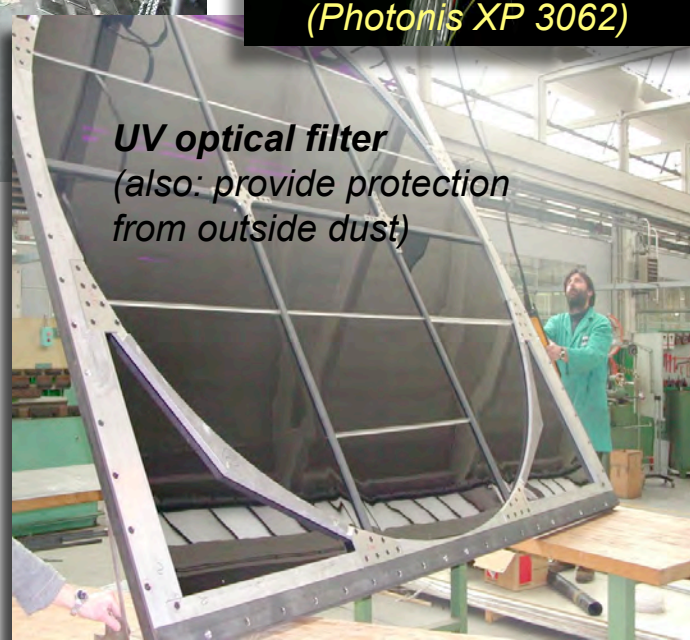
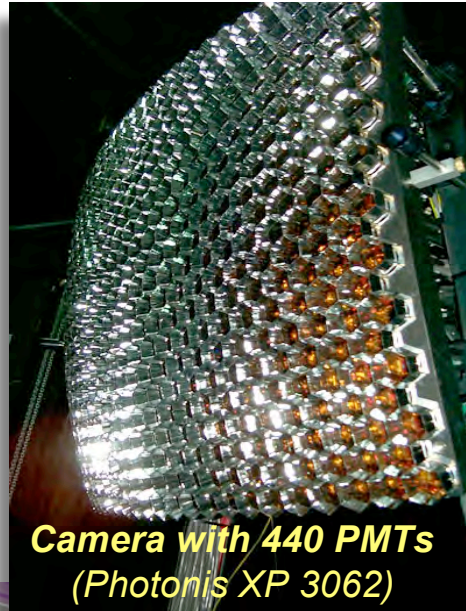
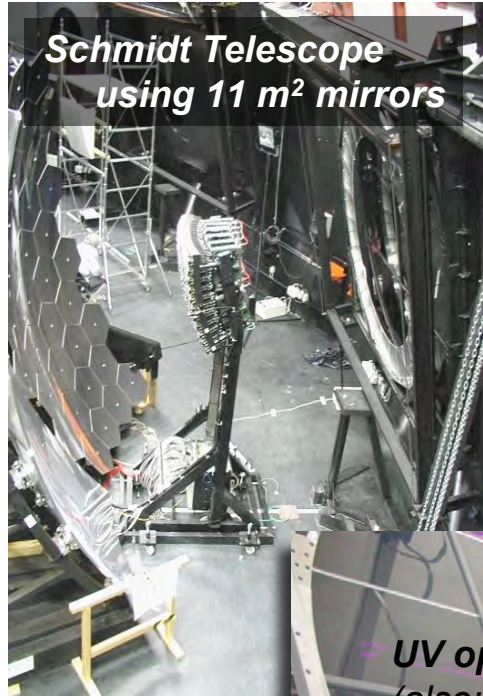


SURFACE DETECTOR (SD)

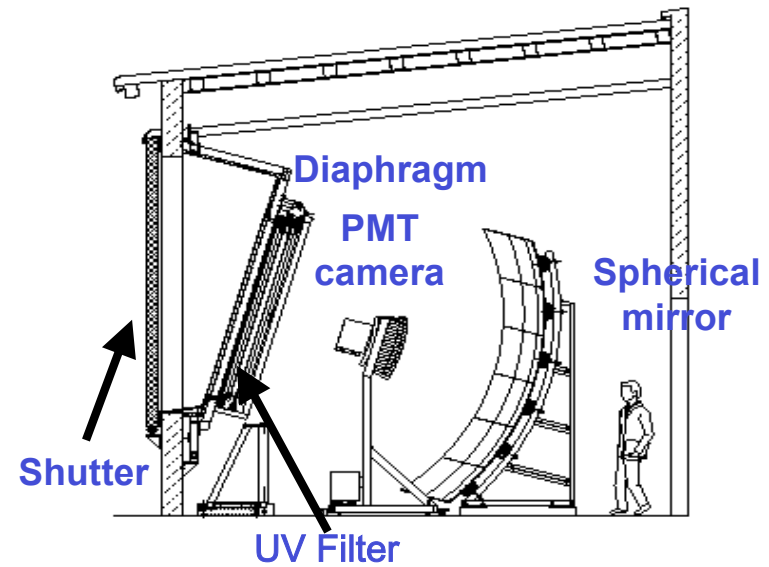
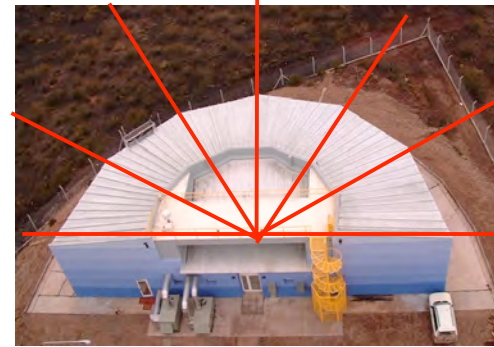


- Stable data taking started in January 2004
- Deployment status: completed!

FLUORESCENCE DETECTOR (FD)

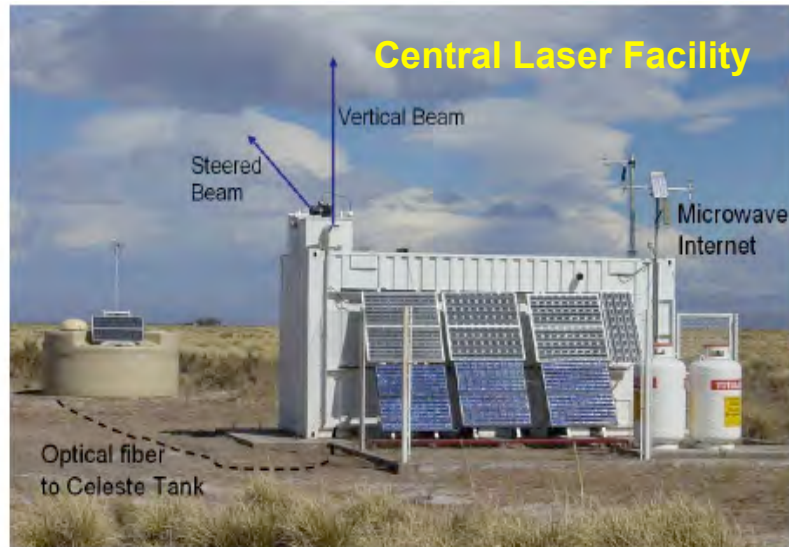


FD completed 2008

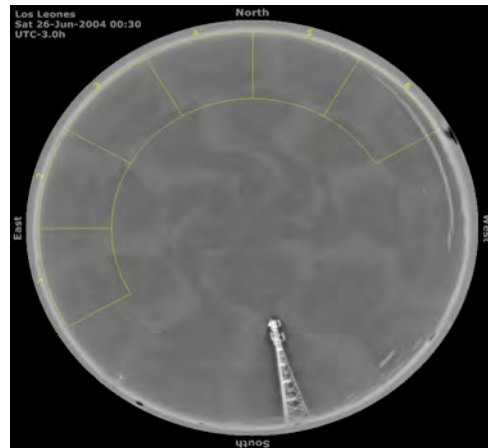


FOV : 30° x 30°

MONITOR ATMOSFERA

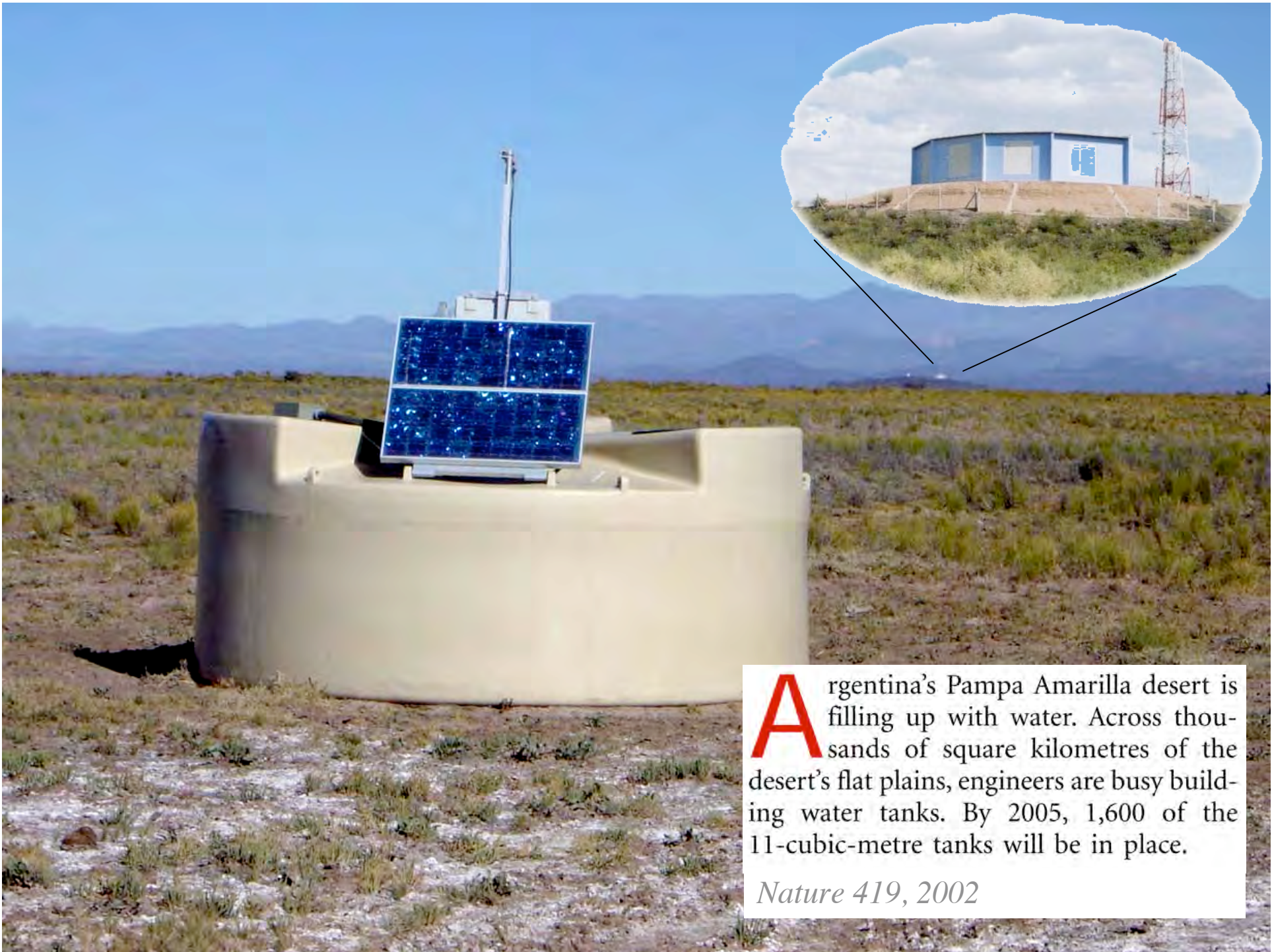


Radio Soundings with balloons equipped with T,P, wind, humidity sensors



Cloud Camera
(one per FD site)



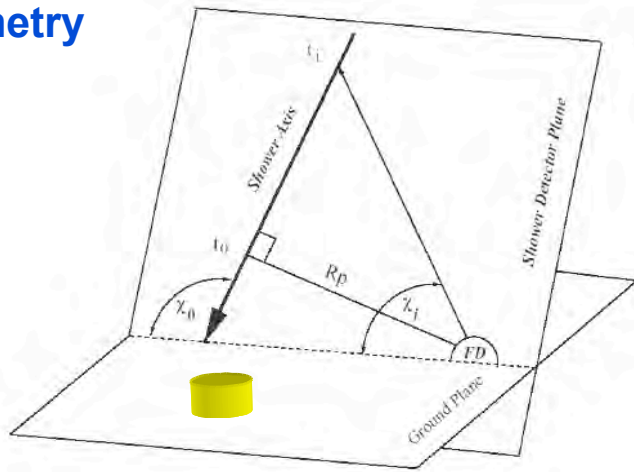


Argentina's Pampa Amarilla desert is filling up with water. Across thousands of square kilometres of the desert's flat plains, engineers are busy building water tanks. By 2005, 1,600 of the 11-cubic-metre tanks will be in place.

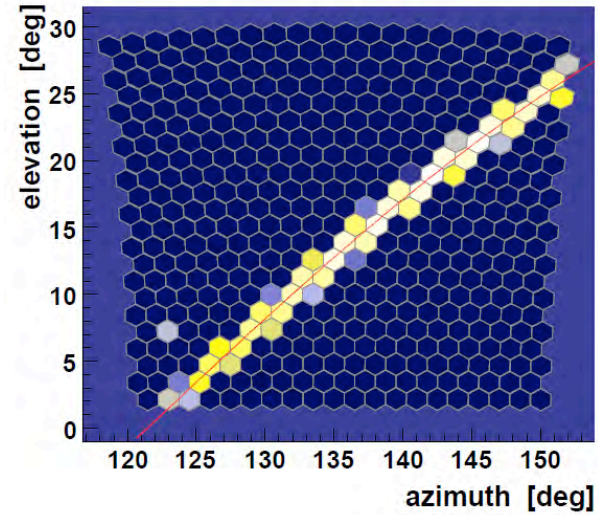
Nature 419, 2002

Ricostruzione con FD (hybrid)

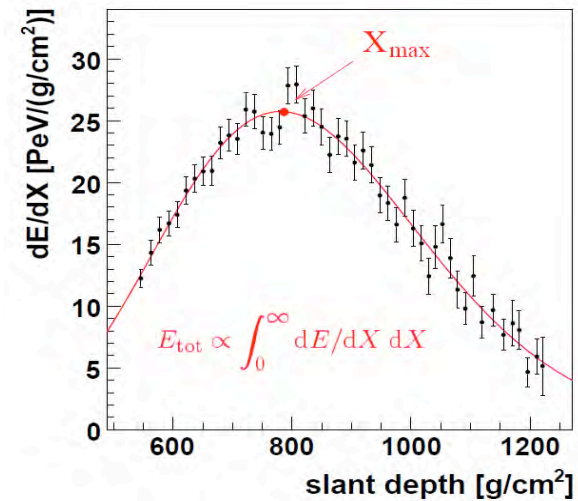
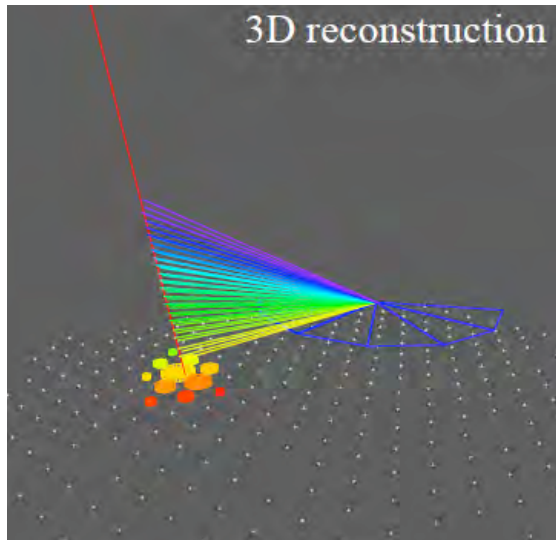
Geometry



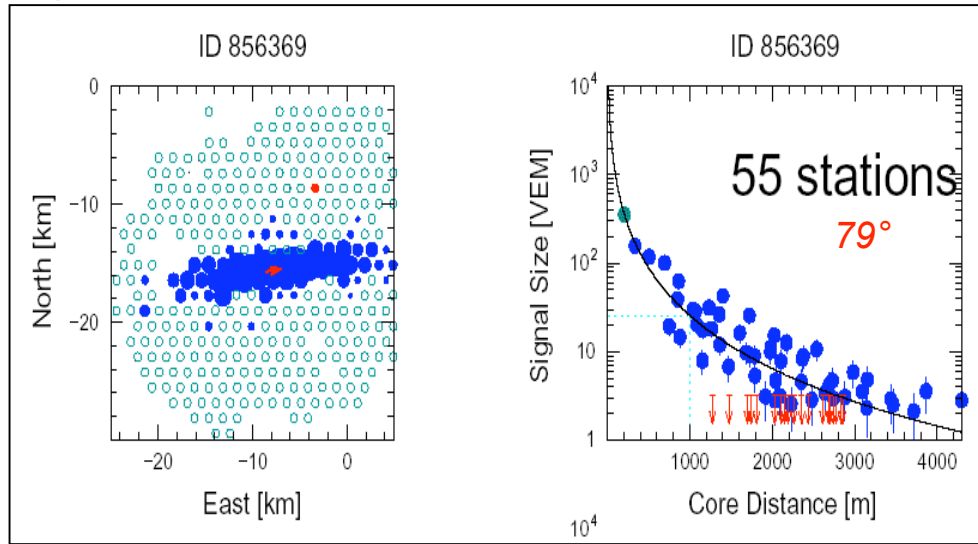
camera view



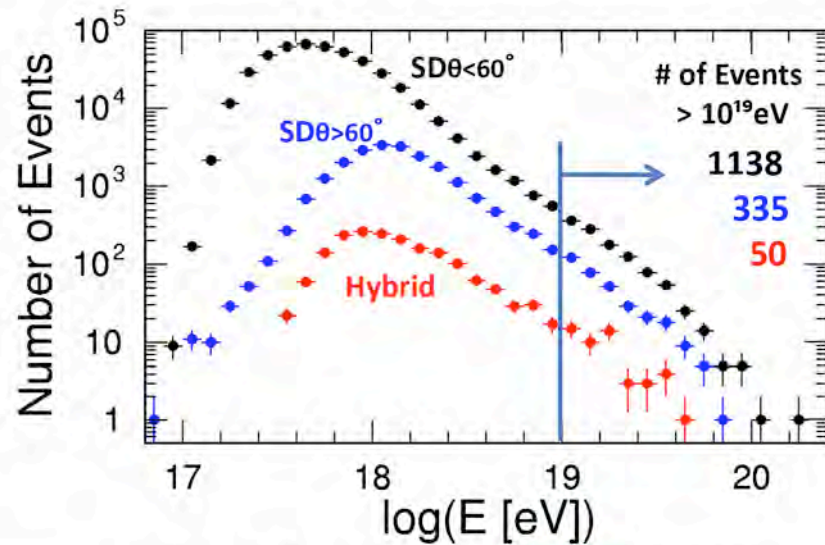
Energy and X_{\max}



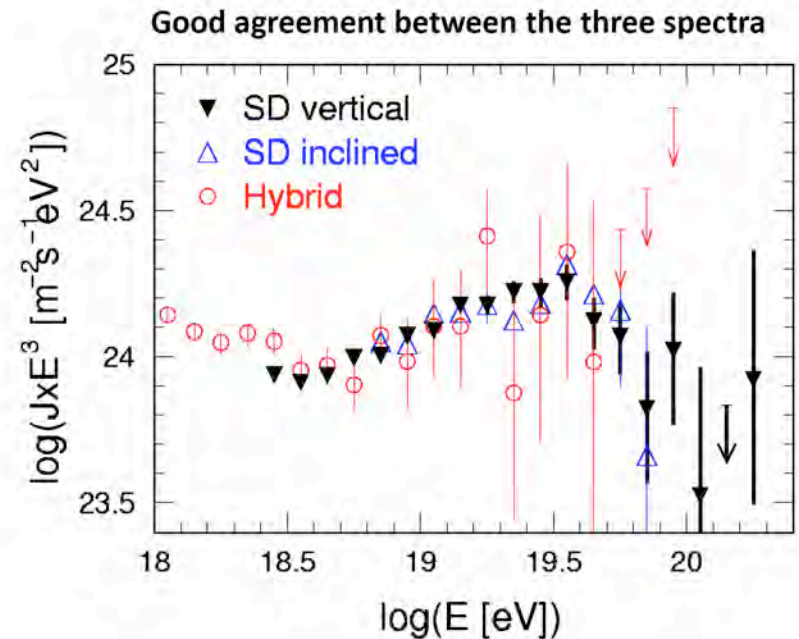
Auger spettro RC: SD, SD-inclined and hybrid



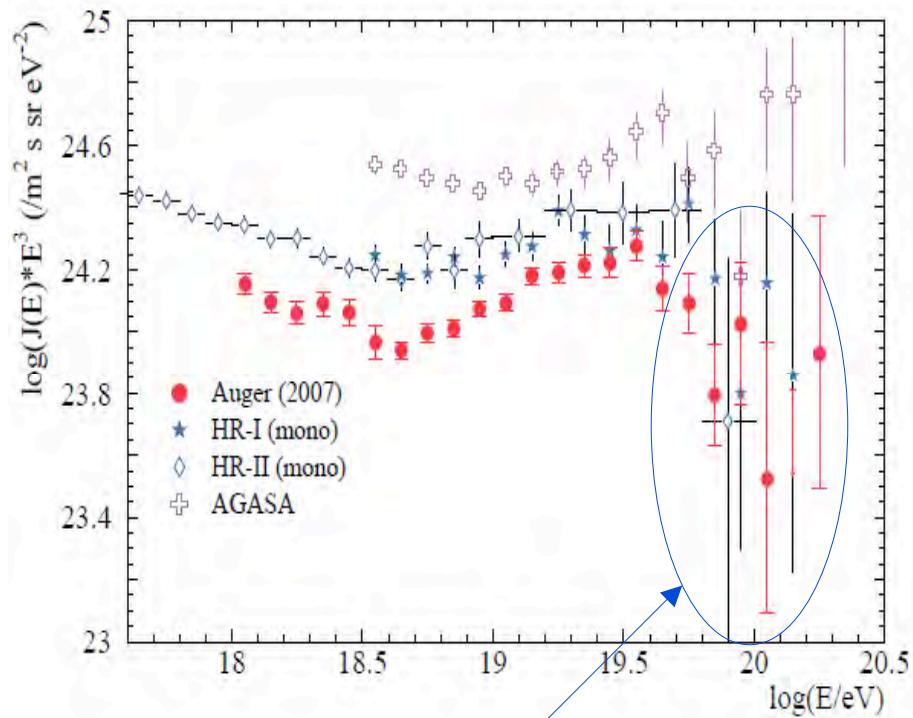
VEM: Vertical Equivalent Muon



Energy scale is measured with Hybrid Observation



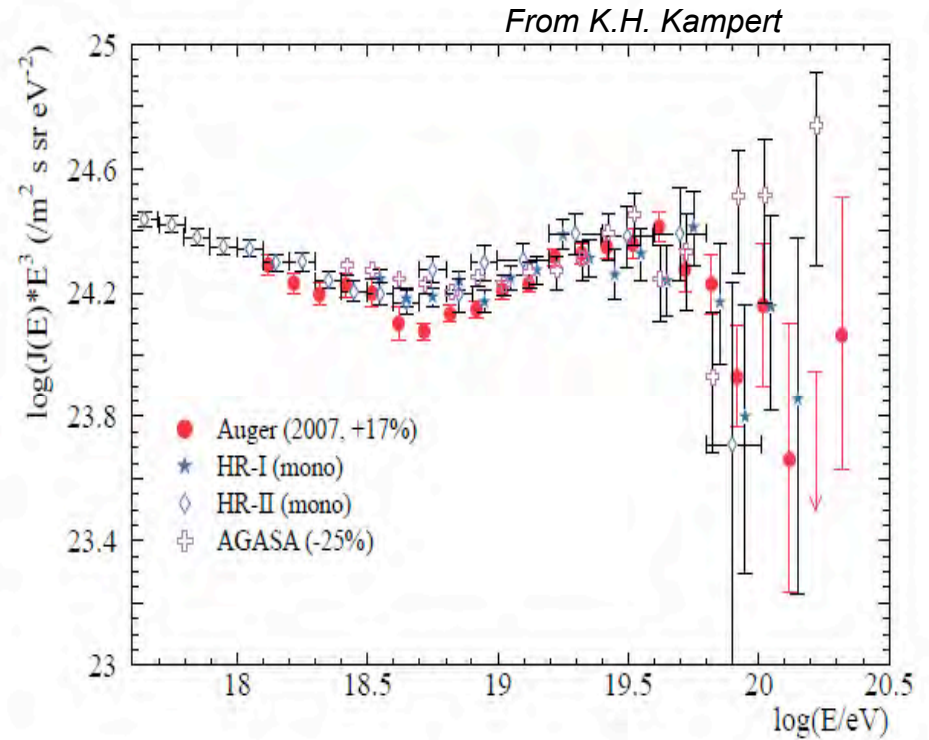
SPETTRO UHECR



GZK cutoff?

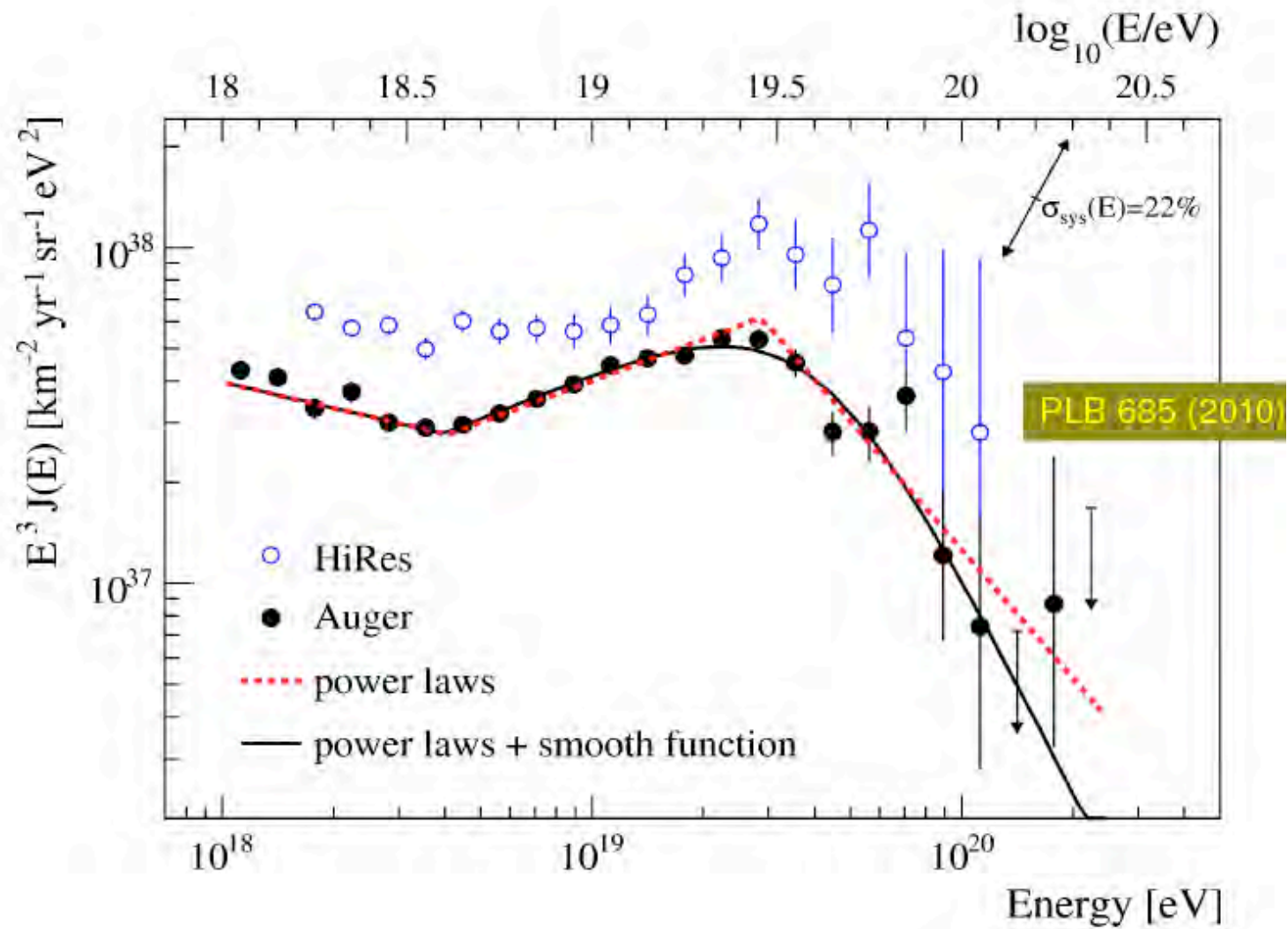
Acceleration limit?

Drop off of lighter elements?



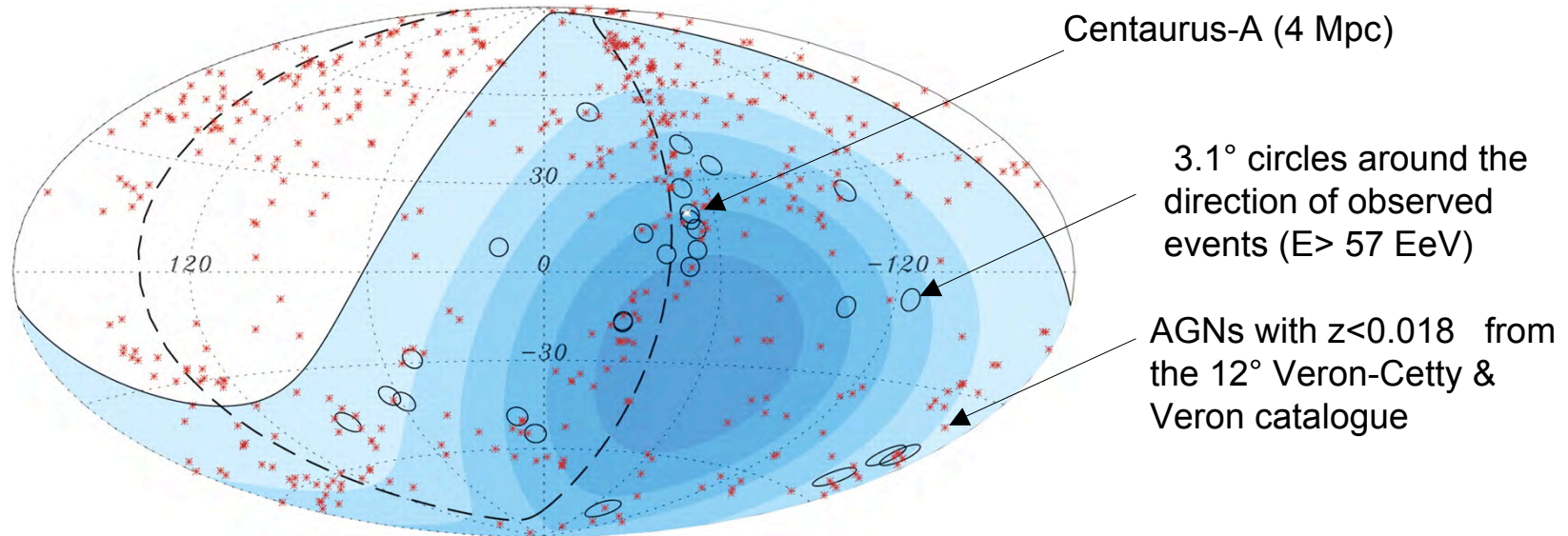
Energy scale problem !

AUGER



Correlation with nearby AGNs (I)

Pierre Auger Coll., 9 Nov 2007



Data set 1 Jan 2004 – 31 Aug 2007

20 of 27 events with $E > 57$ EeV are within 3.1 degrees of an AGN at a distance of less than ~ 75 Mpc

also *J. Abraham et al., Astroparticle Physics 29 (2008) 188-204*

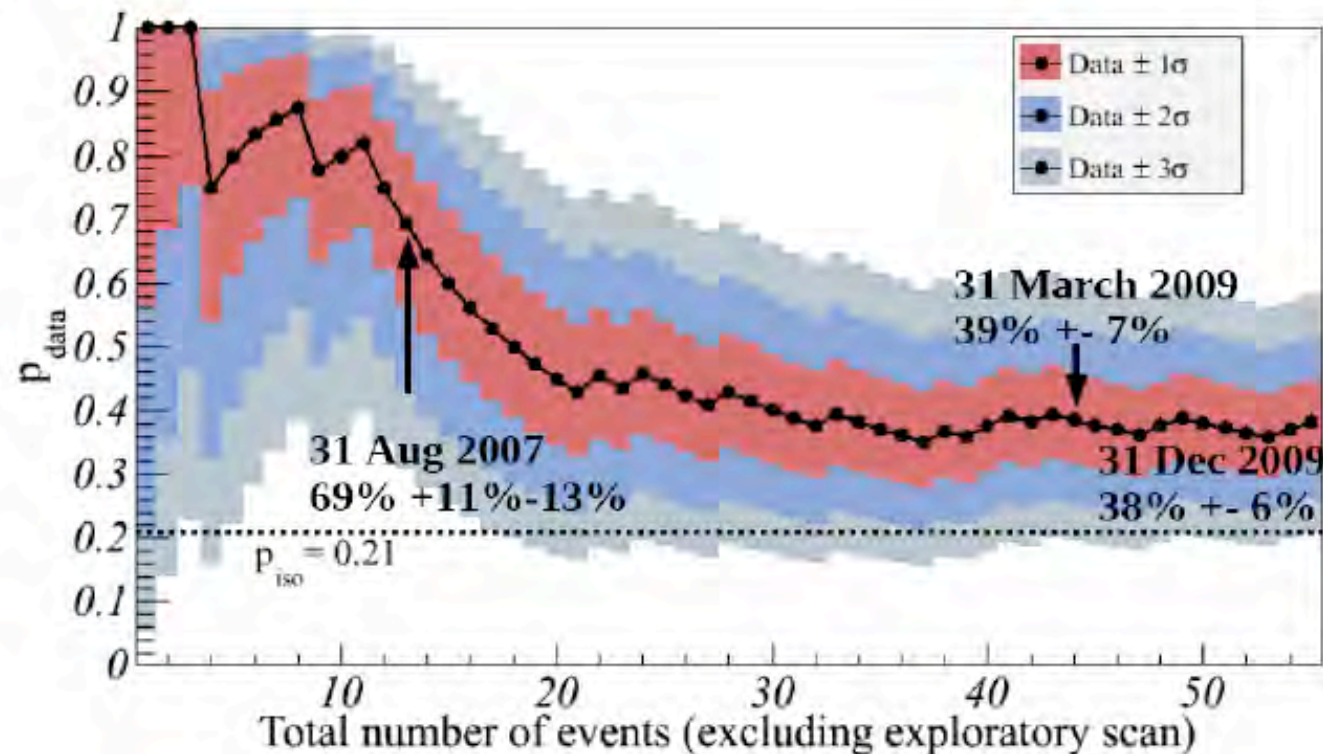
Correlazione attuale: 21/55 (38±6)%

attesa: 21%

Era 69%

CORRELAZIONE CON CATALOGO VCV

► Anisotropy



Status of the Prescribed Anisotropy Test (*correlation with VCV catalog of AGNs*)

38% (21/55) correlate (post exploration) vs. 21% expected from isotropy \Rightarrow 99% C.L.

Nuovo paper in preparazione: update prescrizione, cross-correlation con 2MASS, HIPASS, Swift-BAT, autocorrelazione, eccesso da CenA

X_{\max} , $\text{RMS}(X_{\max})$ vs A

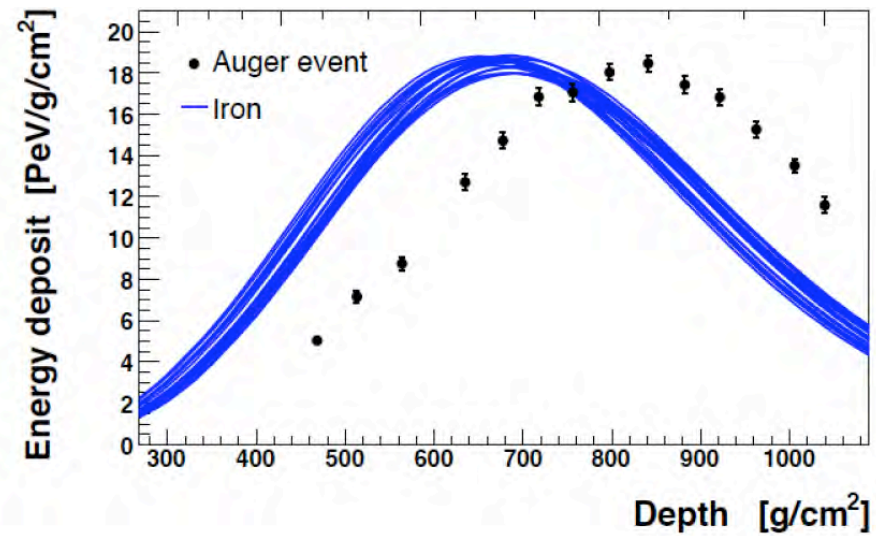
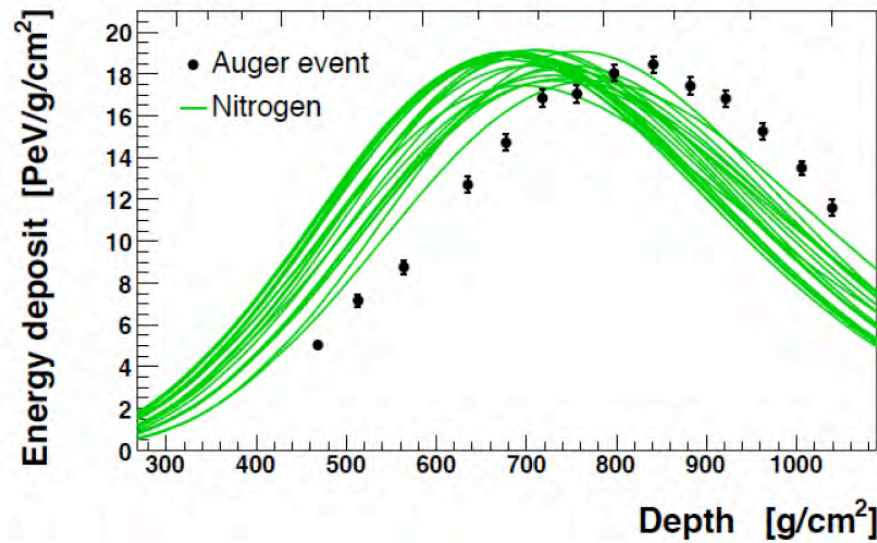
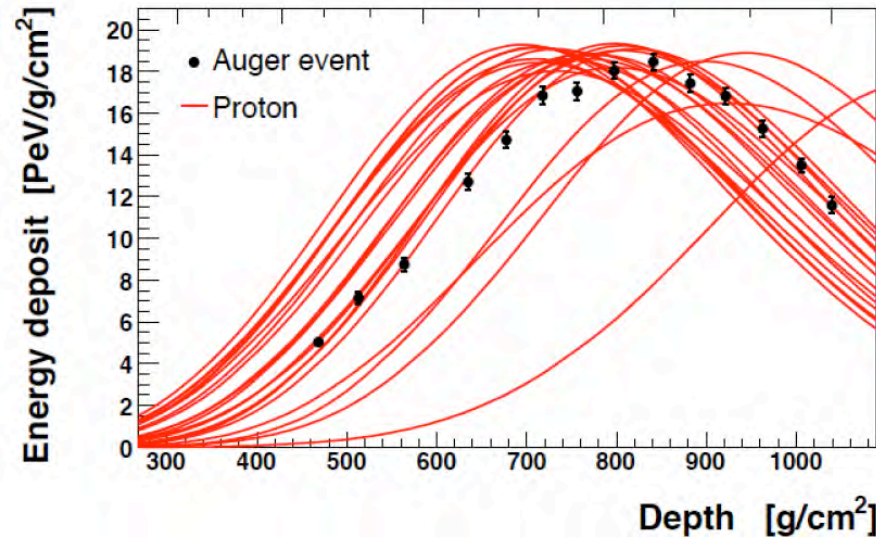
Modello empirico di sciame adronici:

$$\langle X_{\max} \rangle = \alpha(\ln E - \langle \ln A \rangle) + \beta$$

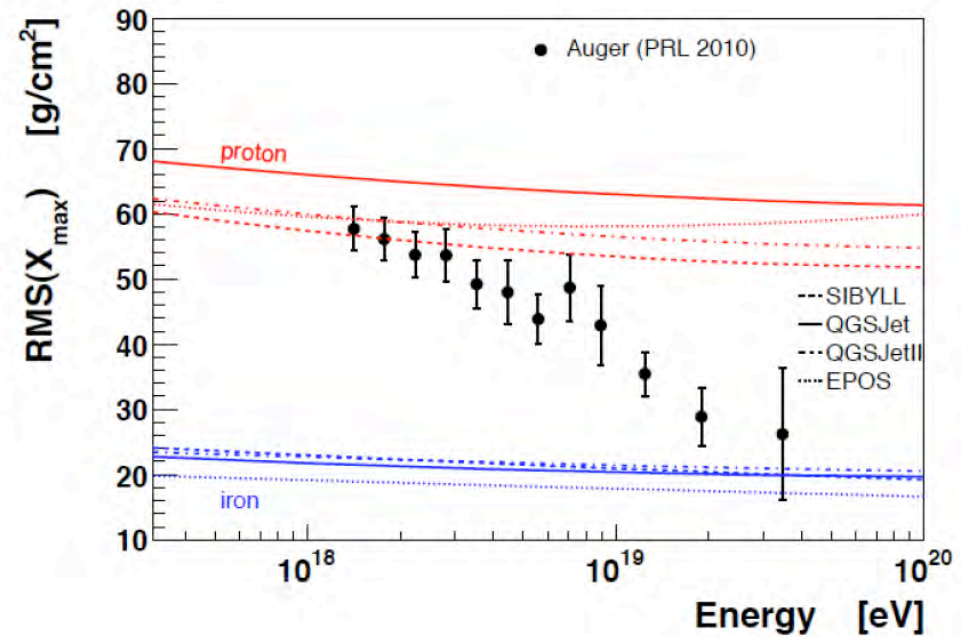
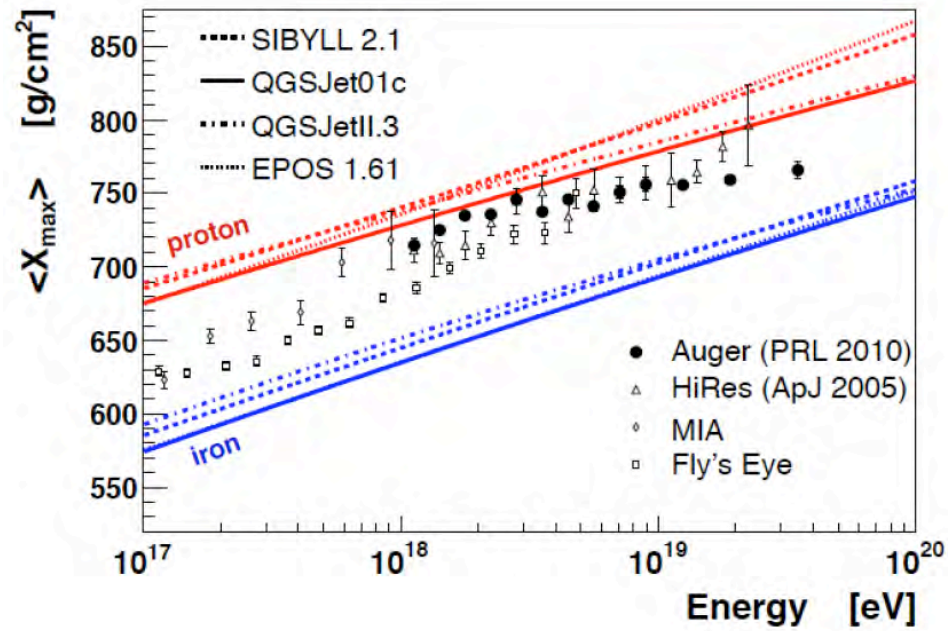
X_{\max} : profondità in atmosfera del massimo dello sciame

A : n. massa del primario

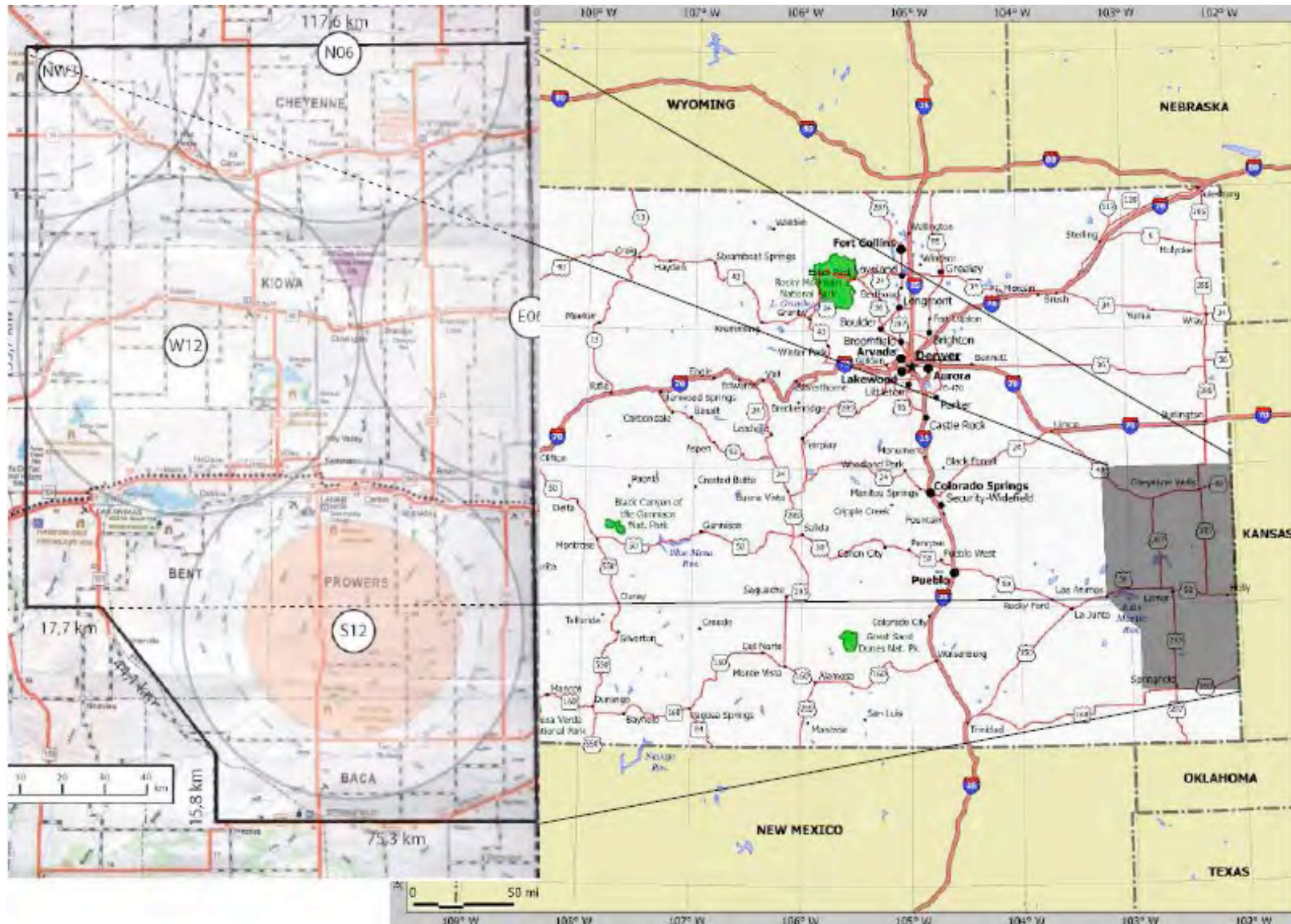
α , β : parametri indipendenti dall'energia



COMPOSIZIONE RC PRIMARI



AUGER NORD



	Auger South	Auger North
Location	35° S, 69° W	38° N, 102° W
Altitude	1,300 - 1,500 [m a.s.l.]	1,300 [m a.s.l.]
Area	3,000 km ²	20,000 km ²
Number of SD stations (infill)	1,600	4,000 (400)
SD spacing (infill)	1,500 m	2,300 m (1,600 m)
PMT sensors / SD station	3	1
Communications network	SD-tower radio	peer-to-peer
SD array 50% efficient at	0.7-1 EeV	8-10 EeV
SD array 100% efficient at	3 EeV	80 EeV
FD stations	4	5
FD telescopes	24 (4 × 6)	39 (2 × 12 + 2 × 6 + 1 × 3)
Begin construction	1999	2011
End construction	2008	2015

UHECR SOMMARIO

•SPECTRUM

- Hi-Res and Auger measure a flux suppression above $\sim 4 \cdot 10^{19}$ eV with 5 and 6 σ significance level (AGASA data are being reanalysed)
- GZK cutoff?

•ARRIVAL DIRECTION

- Auger sees a correlation of highest energy events with nearby AGNs, not confirmed by Hi-Res

•MASS COMPOSITION

- Xmax analysis suggests increasing heavier nuclei composition with energy

