

**PIERRE  
AUGER**  
OBSERVATORY

# Rivelazione di UHECR

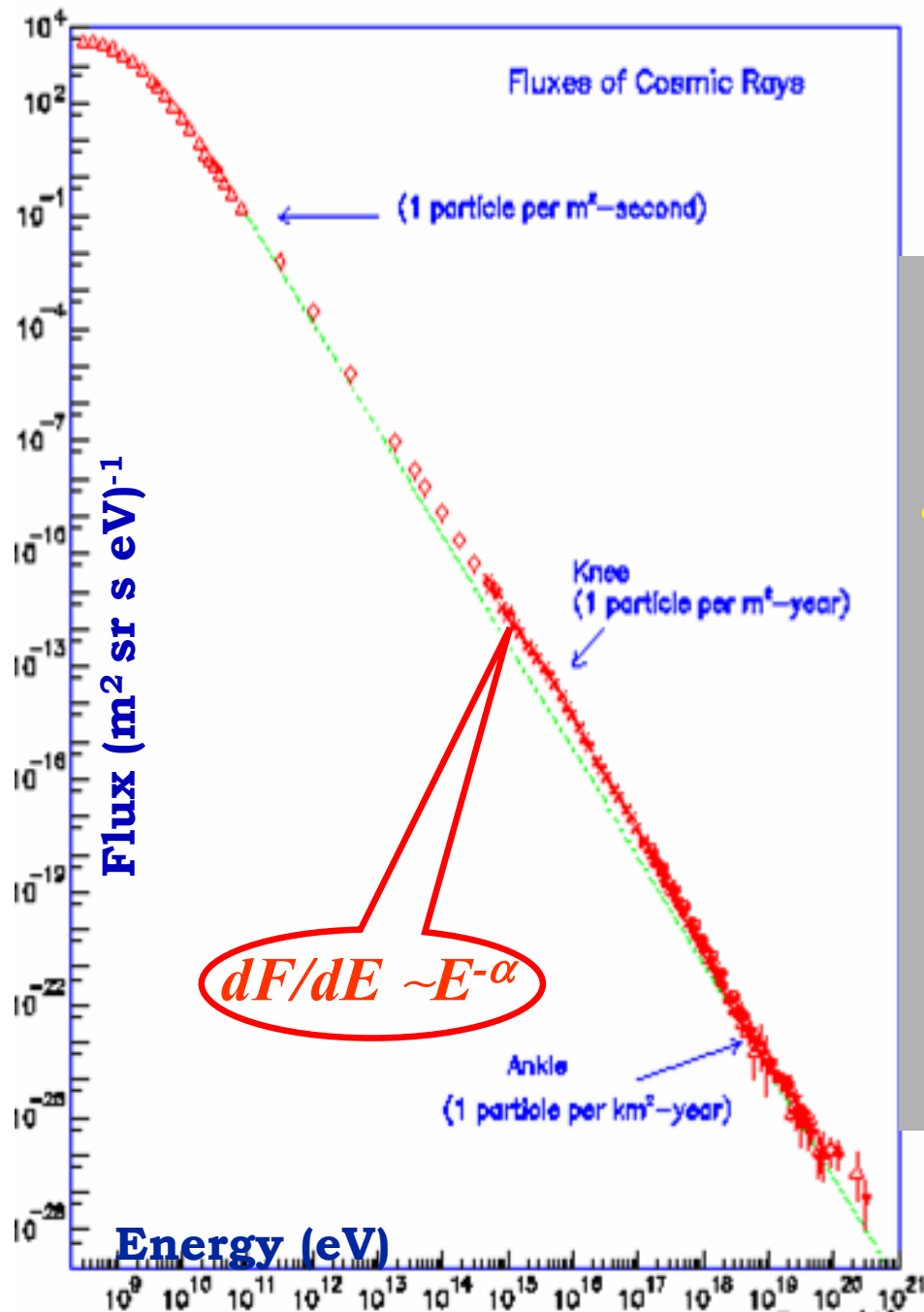
Carla Aramo

INFN, Sezione di Napoli  
Catania, 31 Marzo - 2005

# Contenuto

- Gli UHECR
- Richiami storici
- Tecniche di rivelazione
- Esperimenti passati
- Situazione attuale
- P. Auger Observatory
- Futuro

# Spettro energetico

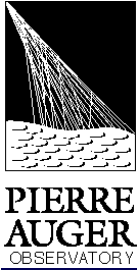


UHECR: 1 particle/ $km^2$ -century!

- $10^9 \text{ eV} < E < 10^{15} \text{ eV}$  origine galattica: diffusive shock acceleration process (first order Fermi) in the expansion shell of recent SN  $\longrightarrow E_{\text{max}} < \beta Z L B$

- $10^{15} \text{ eV} < E < 10^{19} \text{ eV}$   
Altri potenziali acceleratori con campi magnetici più alti o con L più grandi: (pulsar, sistemi binari ...)

- $E > 10^{19} \text{ eV}$  (UHECR):
- Origine extra-galattica. Sorgenti???

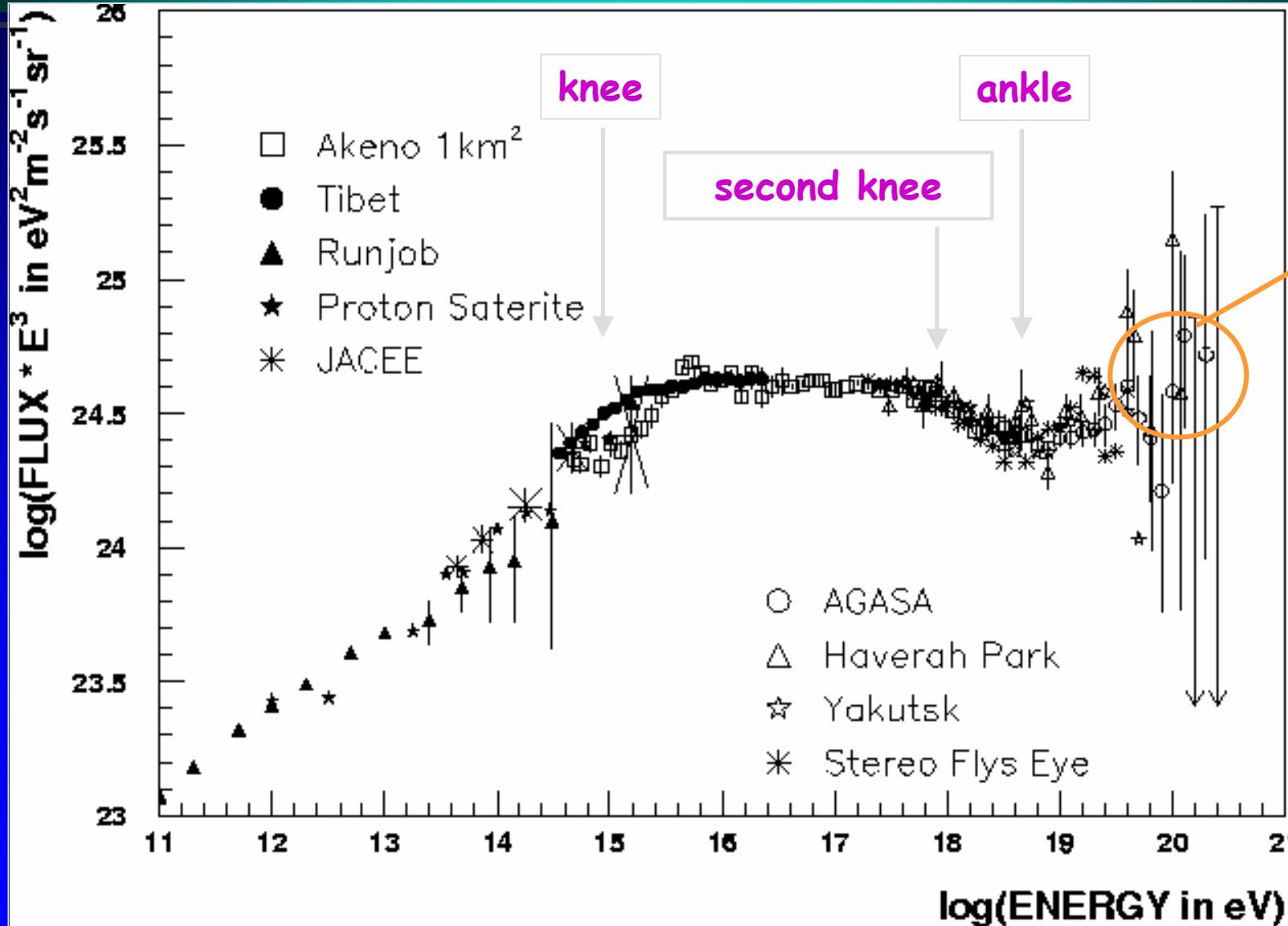


# La struttura dello spettro

supernova remnants

pulsars, galactic wind

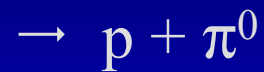
AGN, top-down ??



GZK

# Interazione di UHECR con la radiazione di fondo

Interazione per i protoni:



**Dominante:**

$$\lambda \sim 6 \text{ Mpc} / E_{th} \sim 10^{19.6} \text{ eV}$$

$$\Delta E \sim 20\% \text{ per interazione}$$

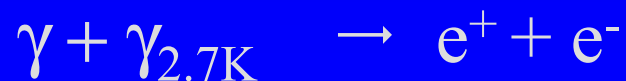
Interazione per nuclei:



**Dominante**

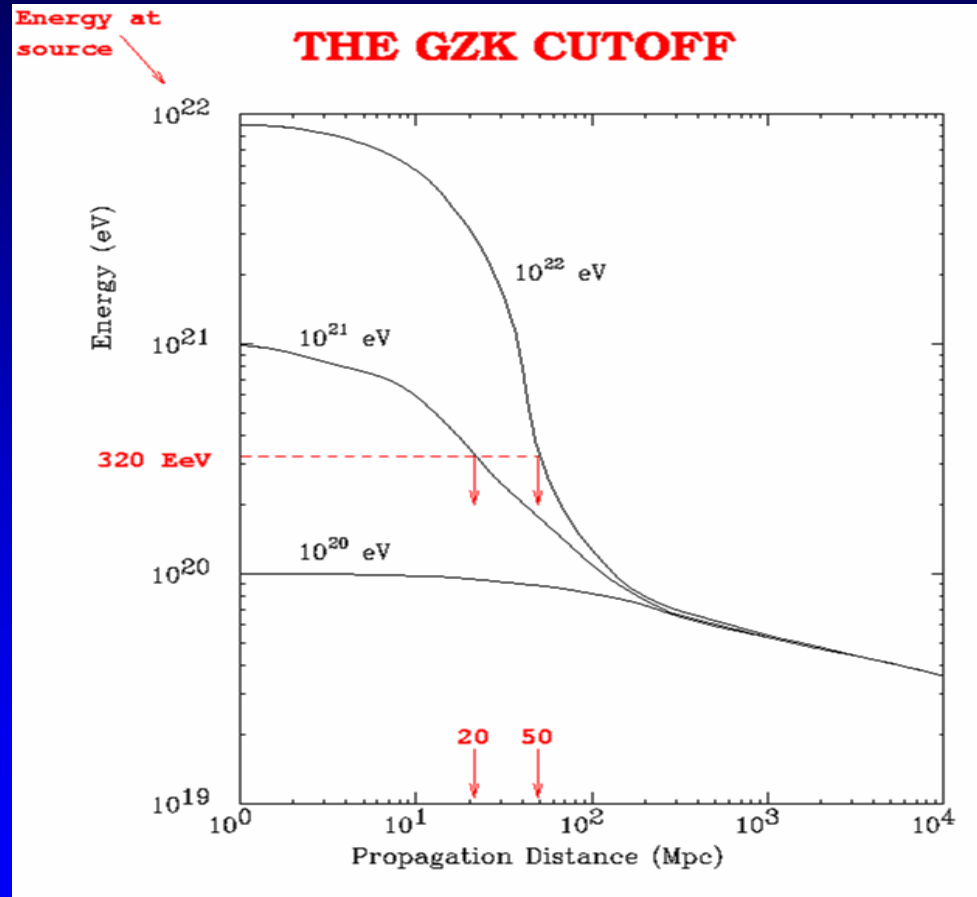
$$E_{th} > 5 * 10^{18} \text{ eV}/N$$

Interazione per i gamma:



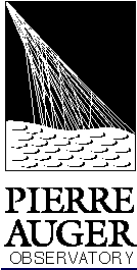
$$E_{th} > 4 * 10^{14} \text{ eV}$$

# Greisen-Zatsepin-Kuzmin cutoff

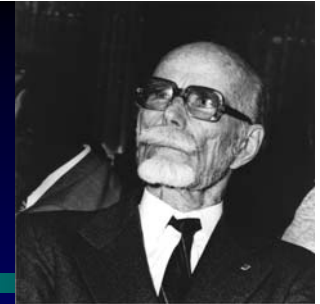


Effetti:

- per  $E > 5 \times 10^{19}$  eV le sorgenti ad una distanza  $\sim 50$  Mpc!
- le direzioni dei RC dovrebbero puntare alle sorgenti: astronomia UHECR!



# Un po' di storia



- 1938: Pierre Auger rivela per la prima volta gli EAS;
- 1962: John Linsley : il primo raggio cosmico con  $E > 10^{20}$  eV nell'esperimento Volcano Ranch. Negli ultimi 40 anni sono stati rivelati circa 14 eventi con  $E > 10^{20}$  eV in diversi esperimenti:
- Volcano Ranch: (New Mexico, 1962)
- Haverah Park: (UK, 1970 -1980)
- Yakutsk: (Siberia, 1989)
- Fly's Eye: (Utah, 1991 )
- AGASA: (Japan, 1993-2004).

• 1991: Fly's Eye  
(luce di fluorescenza)

Misura il profilo longitudinale della componente e.m. e l'evento con la più alta energia:  $3.2 \times 10^{20}$  eV;

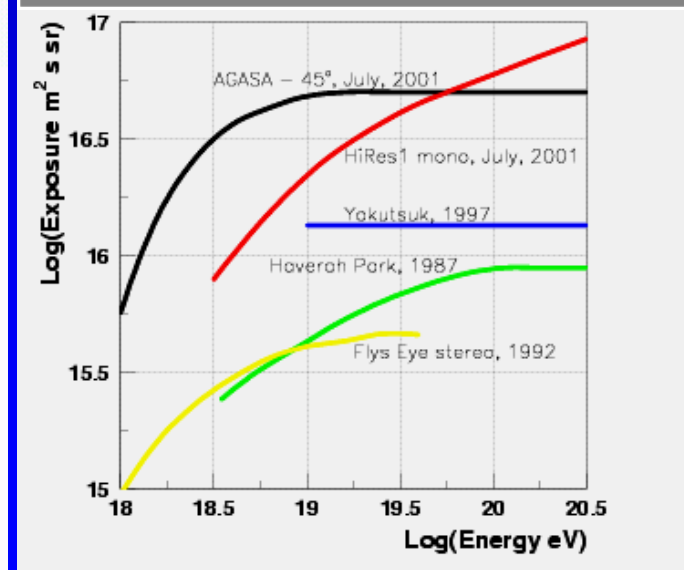
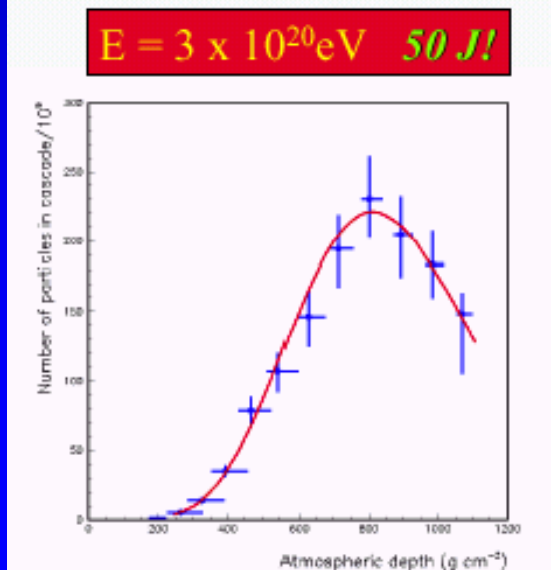
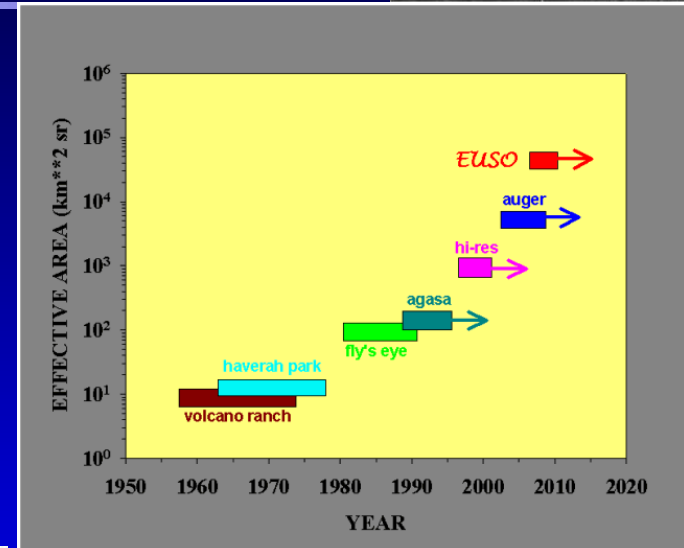
• 1993: l'array AGASA  
(array di superficie)

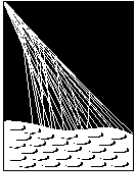
riporta 6 eventi con  $E > 10^{20}$  eV

J. Linsley, PRL 10 (1963) 146

NAGANO-WATSON

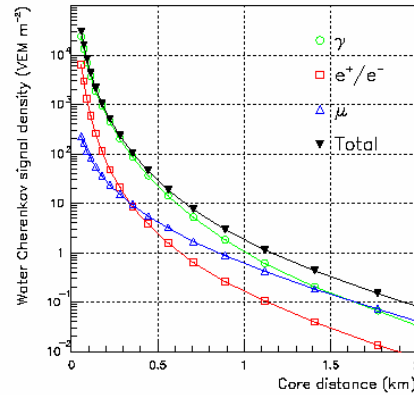
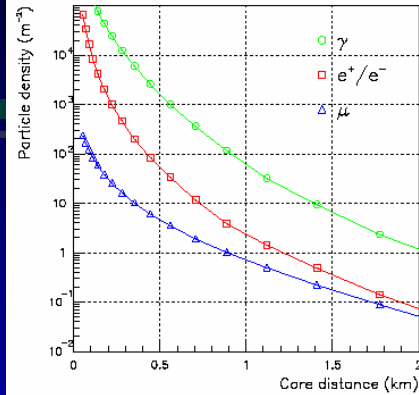
Rev.Mod.Phys. 72,689 (2000)





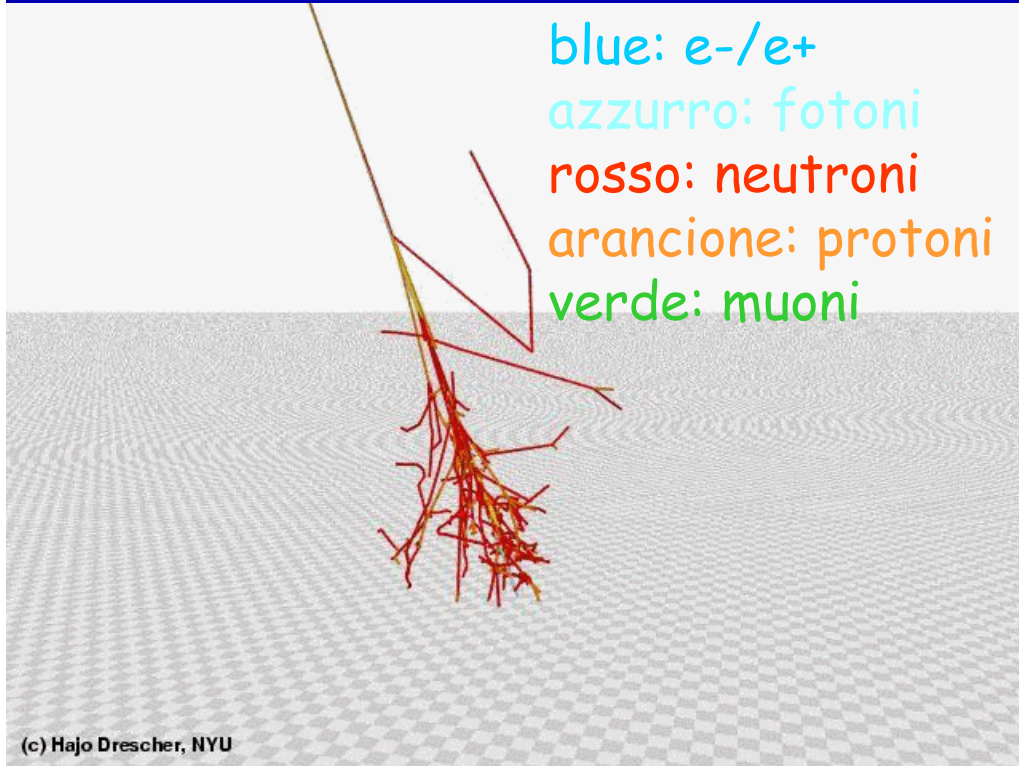
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# Array di superficie

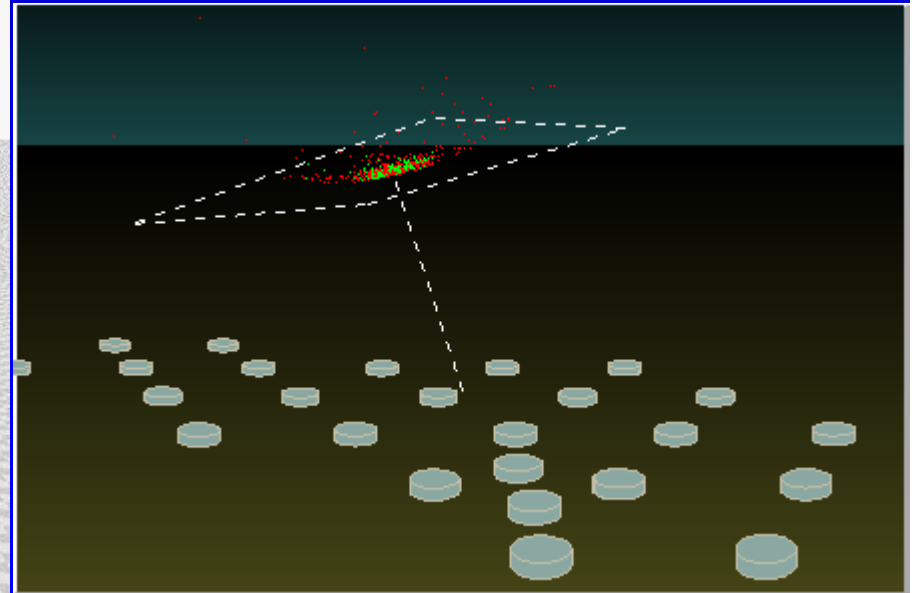
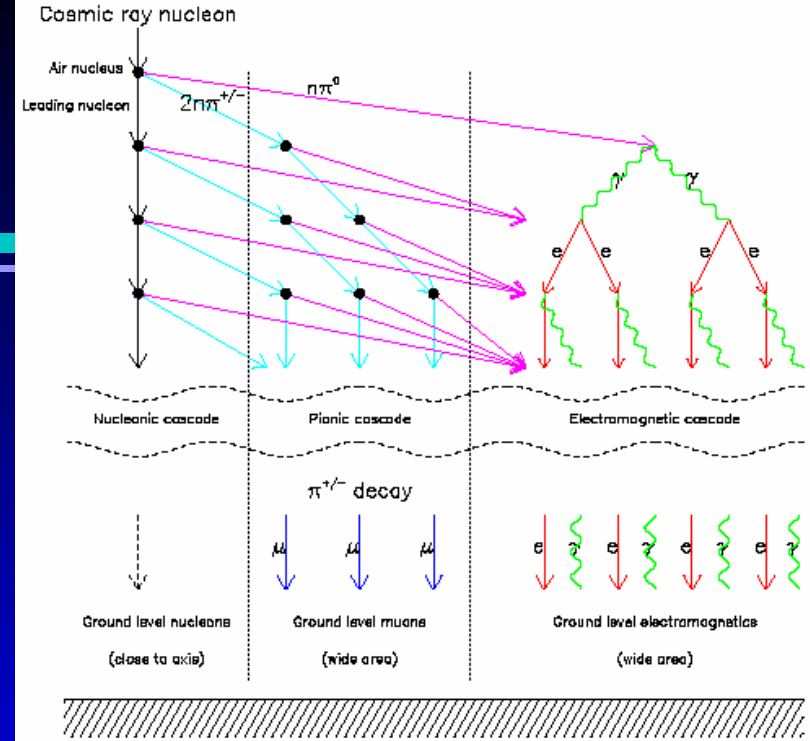


$$\rho(r) \propto k \cdot r^{-[\eta+f(r)]}$$

blue: e-/e+  
azzurro: fotoni  
rosso: neutroni  
arancione: protoni  
verde: muoni

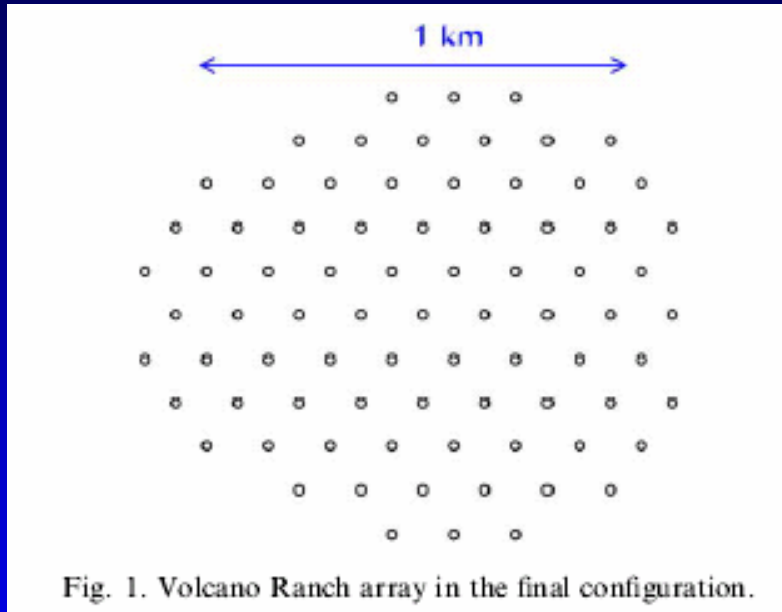


(c) Hajo Drescher, NYU





# Volcano Ranch



Configurazione finale: 80 rivelatori di  $0.815 \text{ m}^2$  ciascuno con spessore di  $9.032 \text{ g/cm}^2$  disposti su una griglia esagonale con una separazione di 147 m

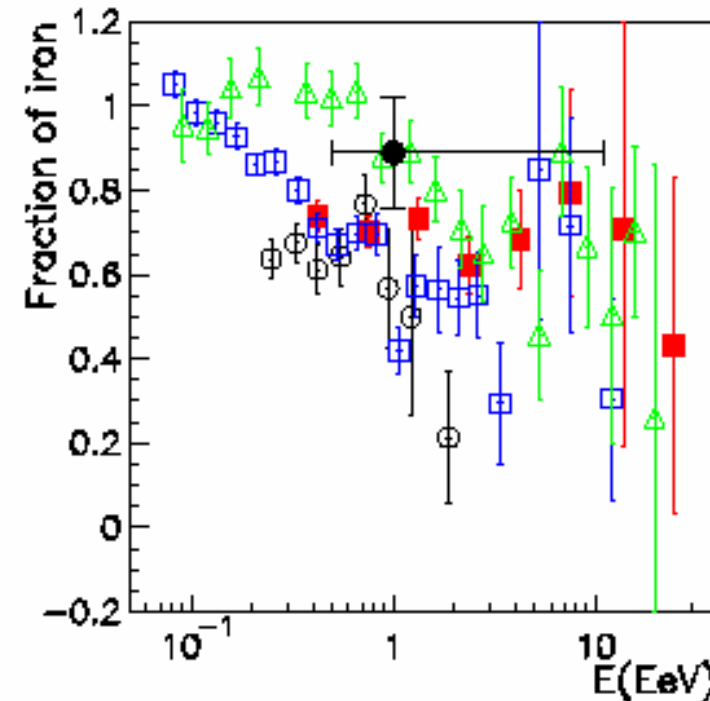
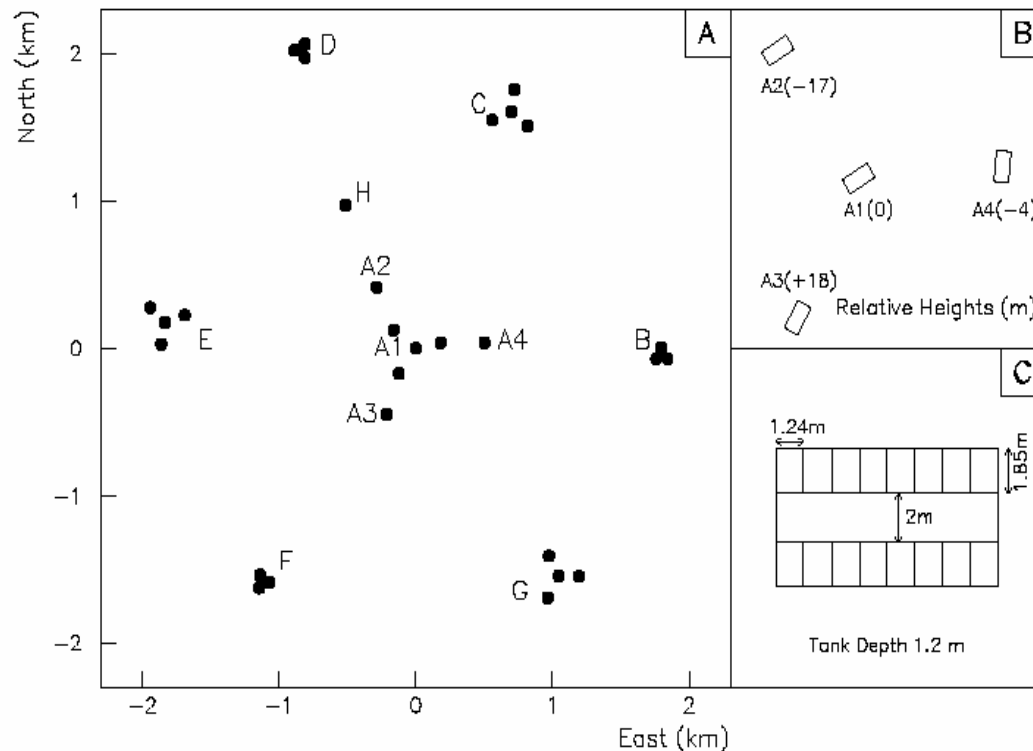


Fig. 8. Fe fraction from various experiments: Fly's Eye ( $\Delta$ ), AGASA A100 ( $\blacksquare$ ), AGASA A1 ( $\square$ ) using SIBYLL1.5 ([6] and references therein) and Haverah Park [1], using QGSJET98 ( $\circ$ ). The mass composition determined in this paper from Volcano Ranch data, using QGSJET98 ( $\bullet$ ), is shown, together with an estimate of the error and energy range.

# Haverah Park



**Fig. 1.** Layout of the HP array. A) The whole array. B) The orientations of the detector huts A1-A4. C) The arrangement of water tanks within an A-site detector hut.

3 L'array di Haverah Park era situato a Leeds, UK, a 220 m asl.

Le particelle venivano rivelate tramite rivelatori Cherenkov ad acqua di circa  $2.29 \text{ m}^2$  di area e 1.2 m di altezza, tramite PMT.

Il numero di fotoni Cherenkov prodotti nella tanica è proporzionale all'energia depositata dallo sciame nell'acqua.

# Nuova analisi dei dati di Haverah Park

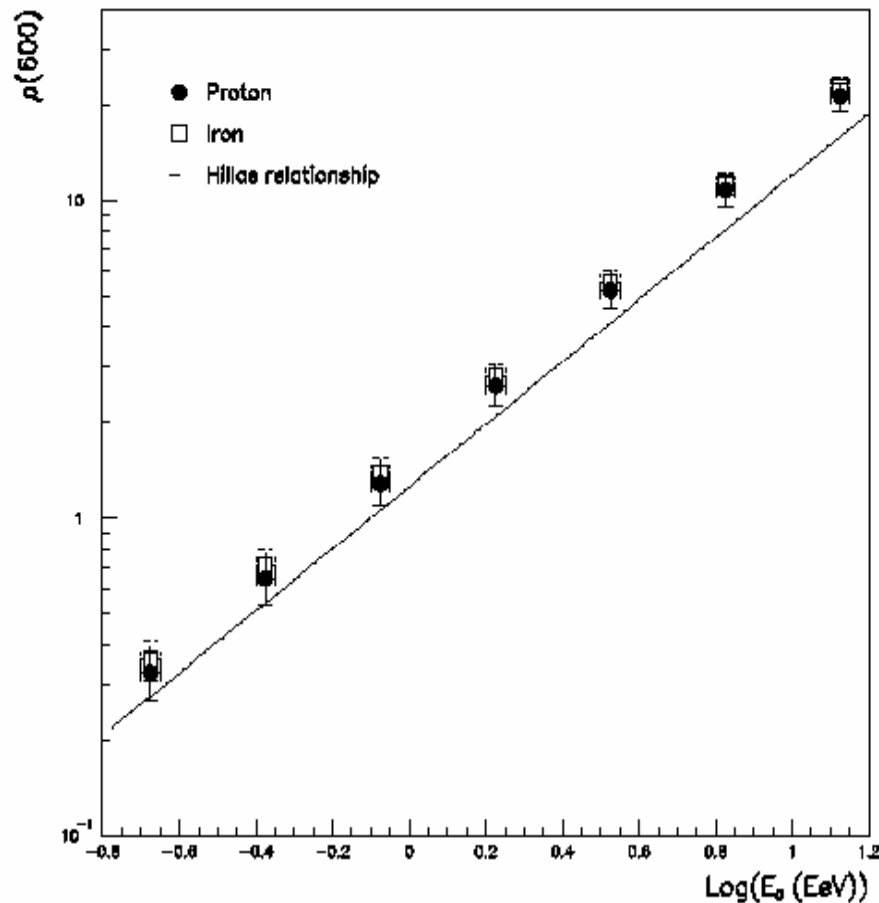


Fig. 2.  $\rho(600)$  as function of  $E_0$  for proton and iron showers at  $\theta = 26^\circ$ , from CORSIKA/QGSJET simulations. Simulation results by Hillas et al. (1971) are plotted as solid line.

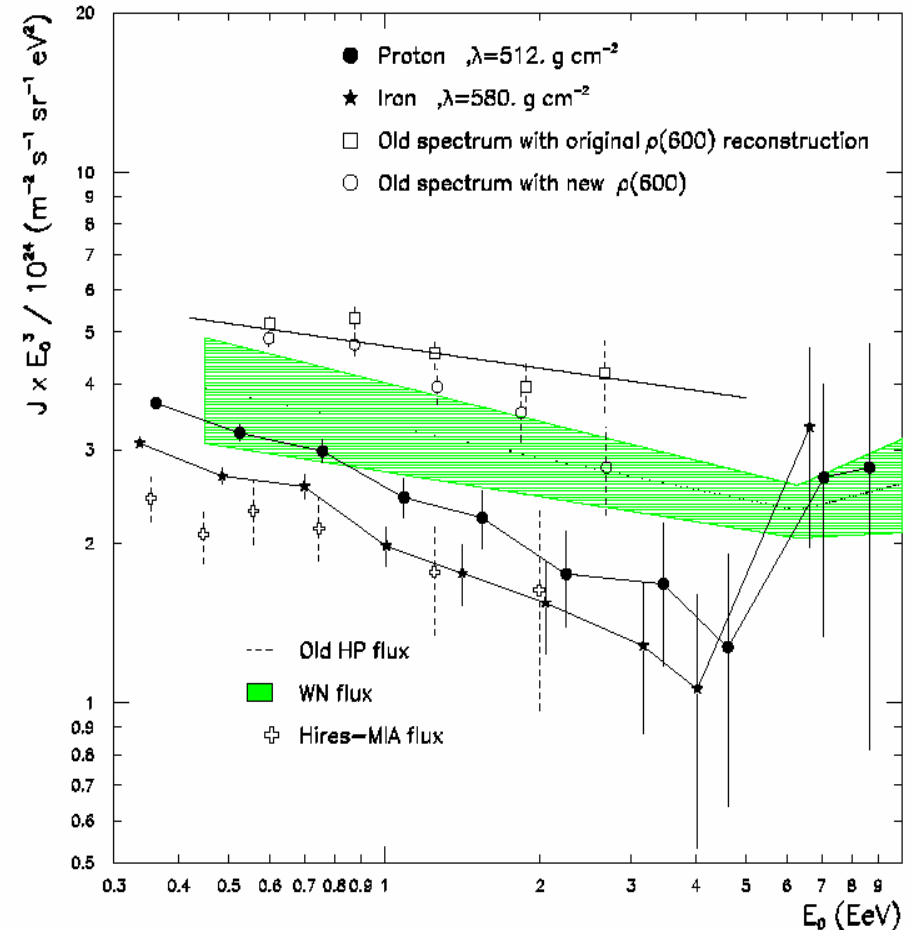
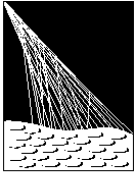


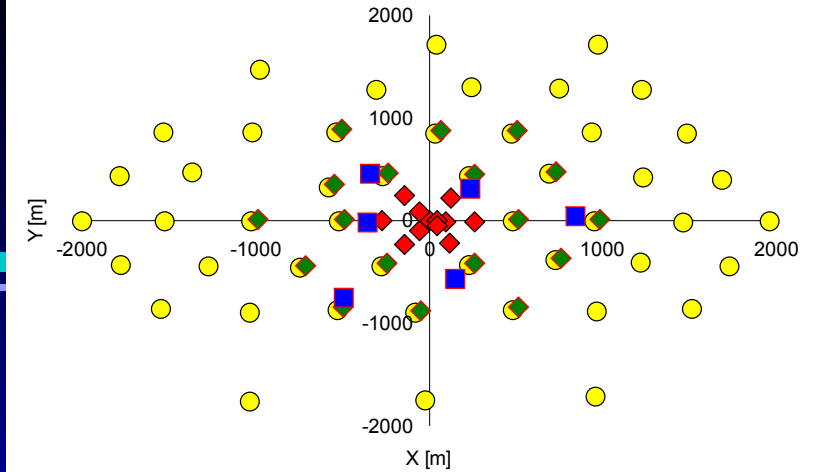
Fig. 4. Energy spectrum obtained from HP data compared with other spectra. The shaded area give the flux as compiled by Nagano and Watson (2000).



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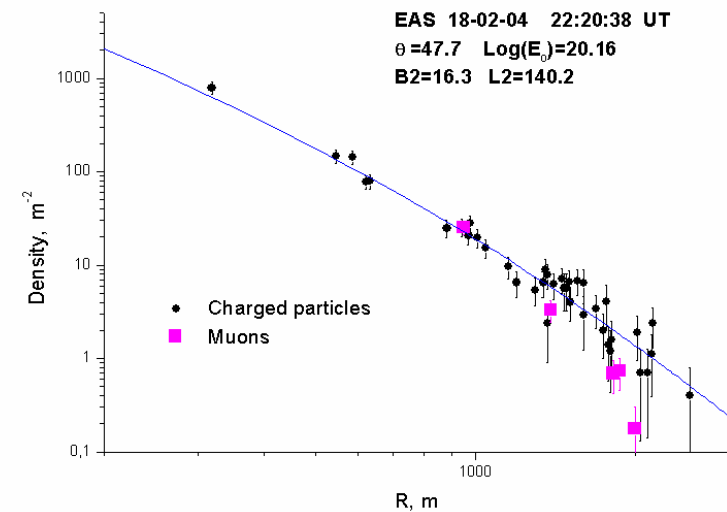
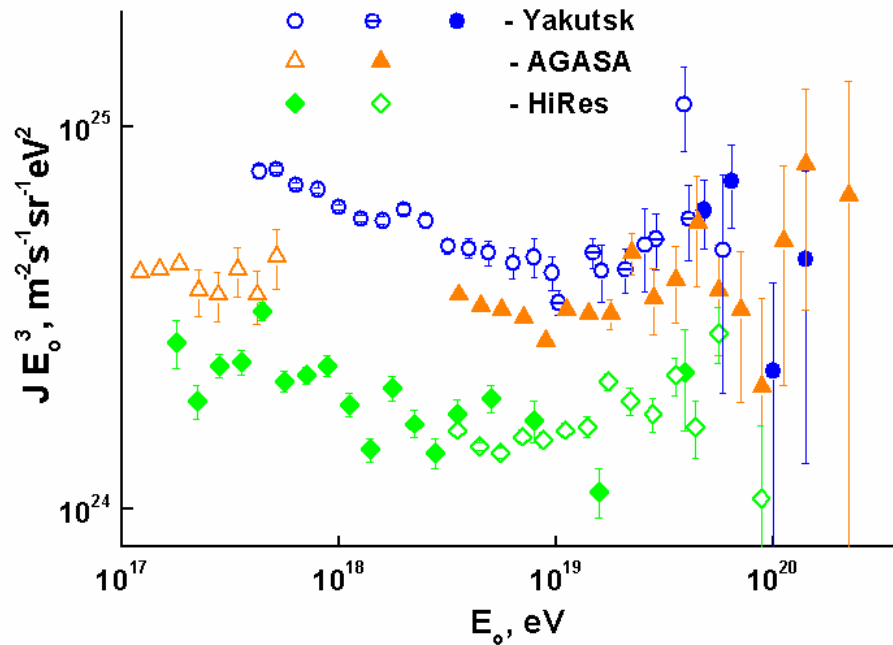
# Yakutsk array

N	Date	Time	$\theta^\circ$	$\text{Log}(E_0)$	Error $E_0$ %	Galactic latitude	Galactic longitude
1	18-02-04	22:20:38	47.7	20.16	42	16.3	140.2
2	07-05-89	22:03:00	58.7	20.14	46	2.7	161.6
3	21-12-77	18:45:00	46.0	20.01	40	50.0	220.6
4	15-02-78	03:35:00	9.6	19.99	32	15.5	102.0



## Configurazione attuale:

- 58 scintillatori
- 39 rivelatori Cherenkov
- 5 rivelatori di muoni
- 1 rivelatore di muoni di grande area (90 scintillatori di 2 m<sup>2</sup>)

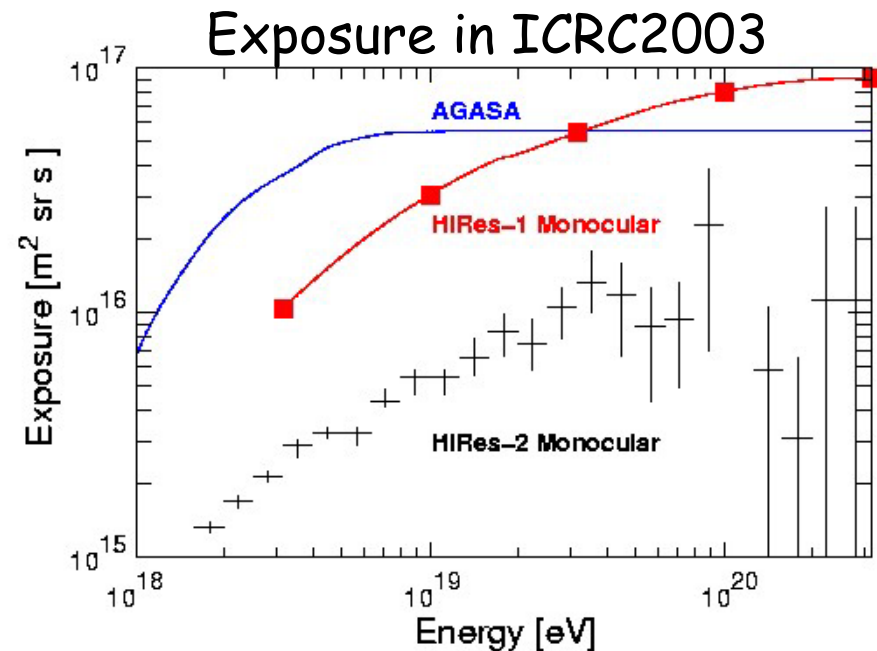
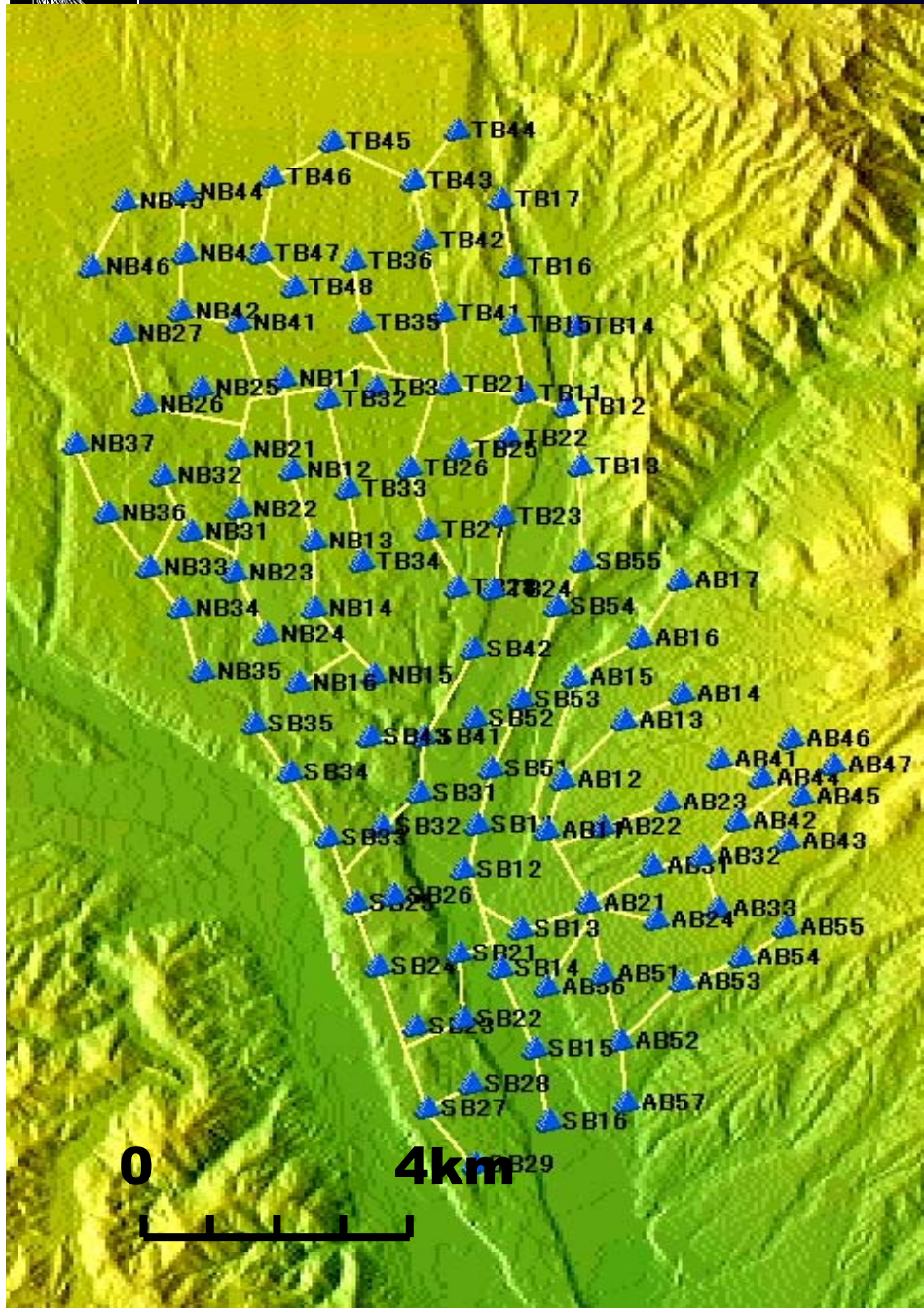


# AGASA

## Akeno Giant Air Shower Array

AGASA copre un'area di circa  $100 \text{ km}^2$  e consiste di 111 rivelatori a scintillazione posti a terra (surface detectors) e 27 rivelatori sotto un assorbitore (muon detectors).

Ogni rivelatore di superficie è posto a circa  $1 \text{ km}$  dal primo vicino e i rivelatori sono connessi tramite fibre ottiche.



# AGASA array

$$E = 2 \times 10^{20} \text{ eV}, E_{\min} = 1.6 \times 10^{20} \text{ eV}$$

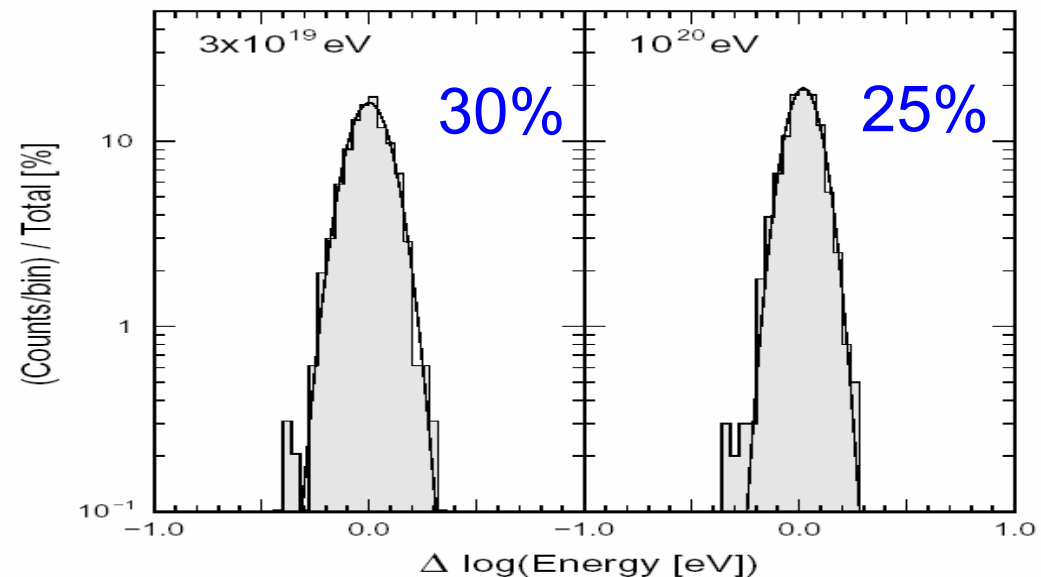
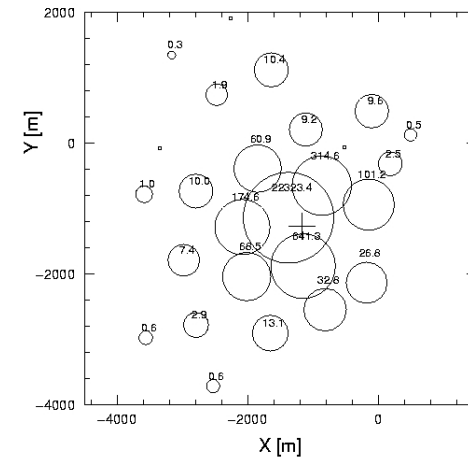
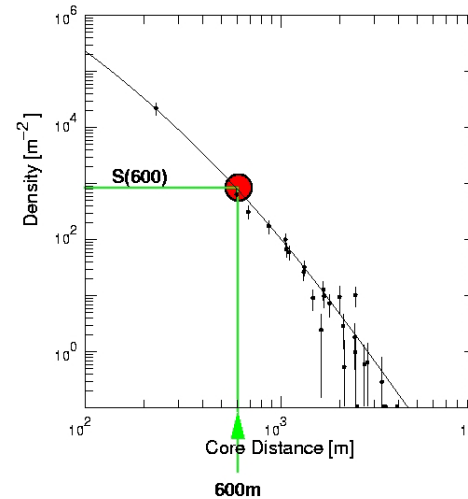
$$S(r) = C \left( \frac{r}{r_M} \right)^{-\alpha} \left( 1 + \frac{r}{r_M} \right)^{-\eta+\alpha} \left[ 1 + \left( \frac{r}{1 \text{ km}} \right)^2 \right]^{-\delta}$$

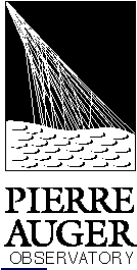
$$\eta = 3.97 - 1.79 (\sec \theta - 1.0)$$

$$E = 2.0 \times 10^{17} S_0(600) \text{ eV}$$

dove:  $r_M$  raggio di Molière  
(91.6 m per AGASA)  
 $C$  fattore di normalizzazione  
 $\alpha = 1.2$ ,  $\delta = 0.6$   
 $S_0(600)$  è la densità di  
particelle cariche in  $1/\text{m}^2$  a  
600 m dal core per sciami  
verticali

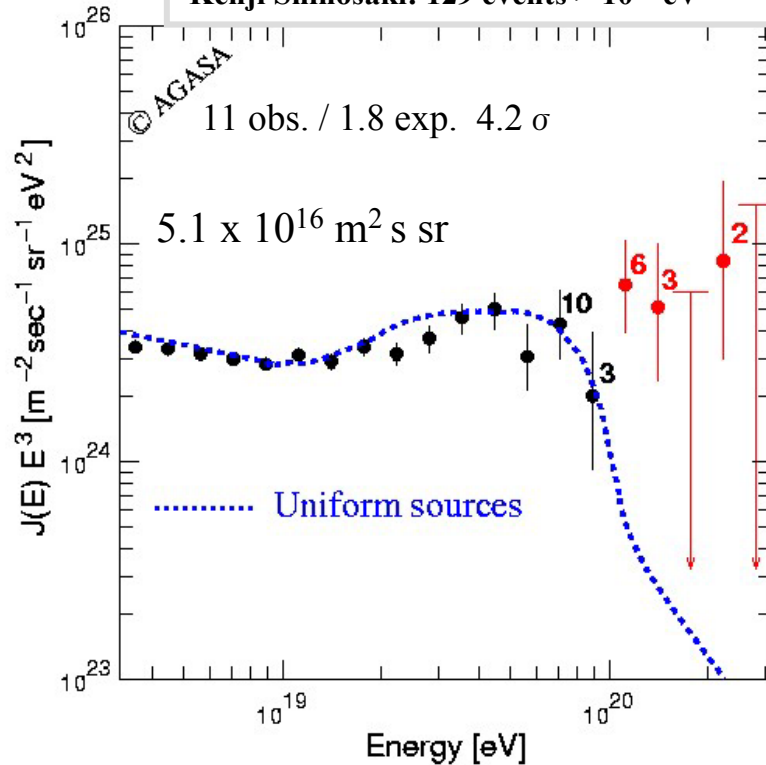
astro-ph/0209422





# Spettro, direzioni di arrivo e composizione

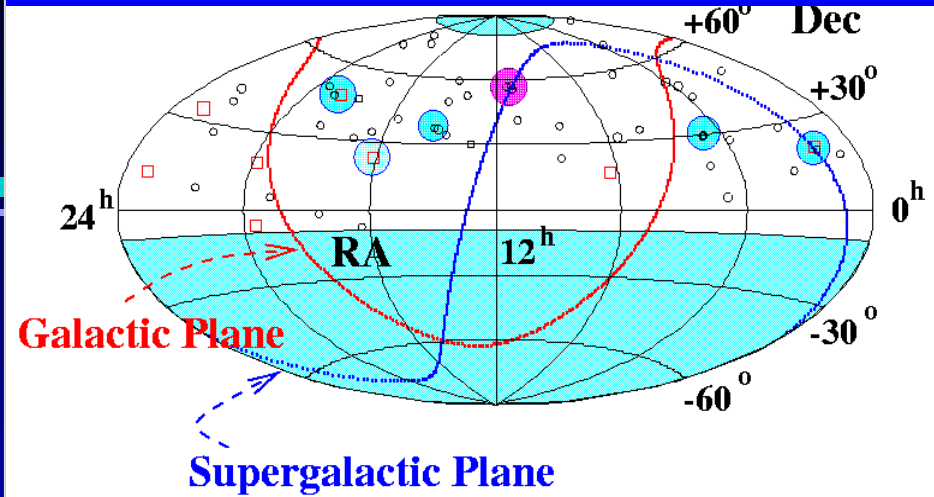
Kenji Shinosaki: 129 events  $> 10^{19}$  eV



**Claim: Consistent with proton dominant component**

$> 10^{19}$  eV (AGASA)  
Fe frac.:  $< 40\%$   
(@90% CL)

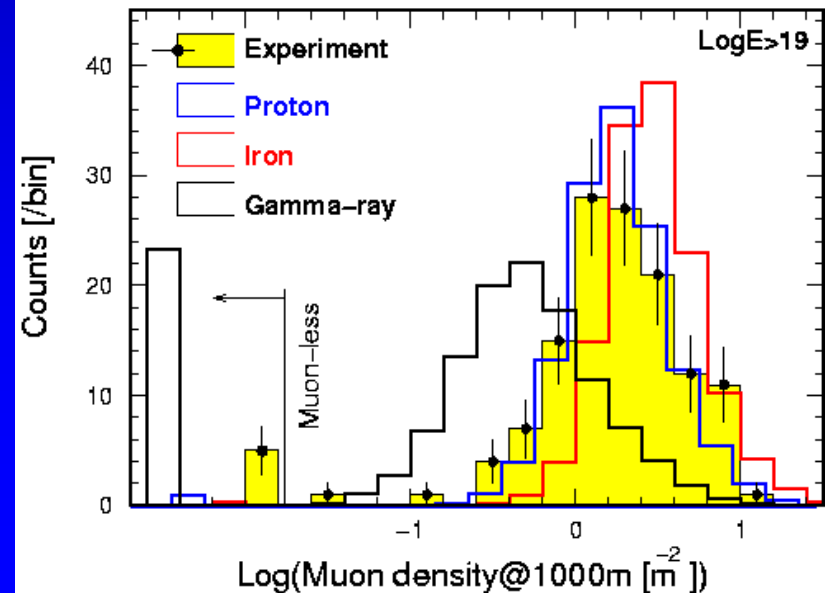
Direzioni di arrivo  $> 4 \times 10^{19}$  eV  
zenith  $< 50$  deg.

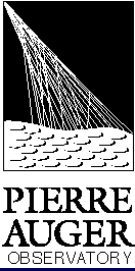


Isotropia su larga scala  $\rightarrow$  RC Extra-Galattici

Cluster su piccola scala ( $\Delta\theta < 2.5$  deg)

1 tripletto e 6 doppietti (2.0 doppietti si aspettano random): nessuna associazione chiara con sorgenti note

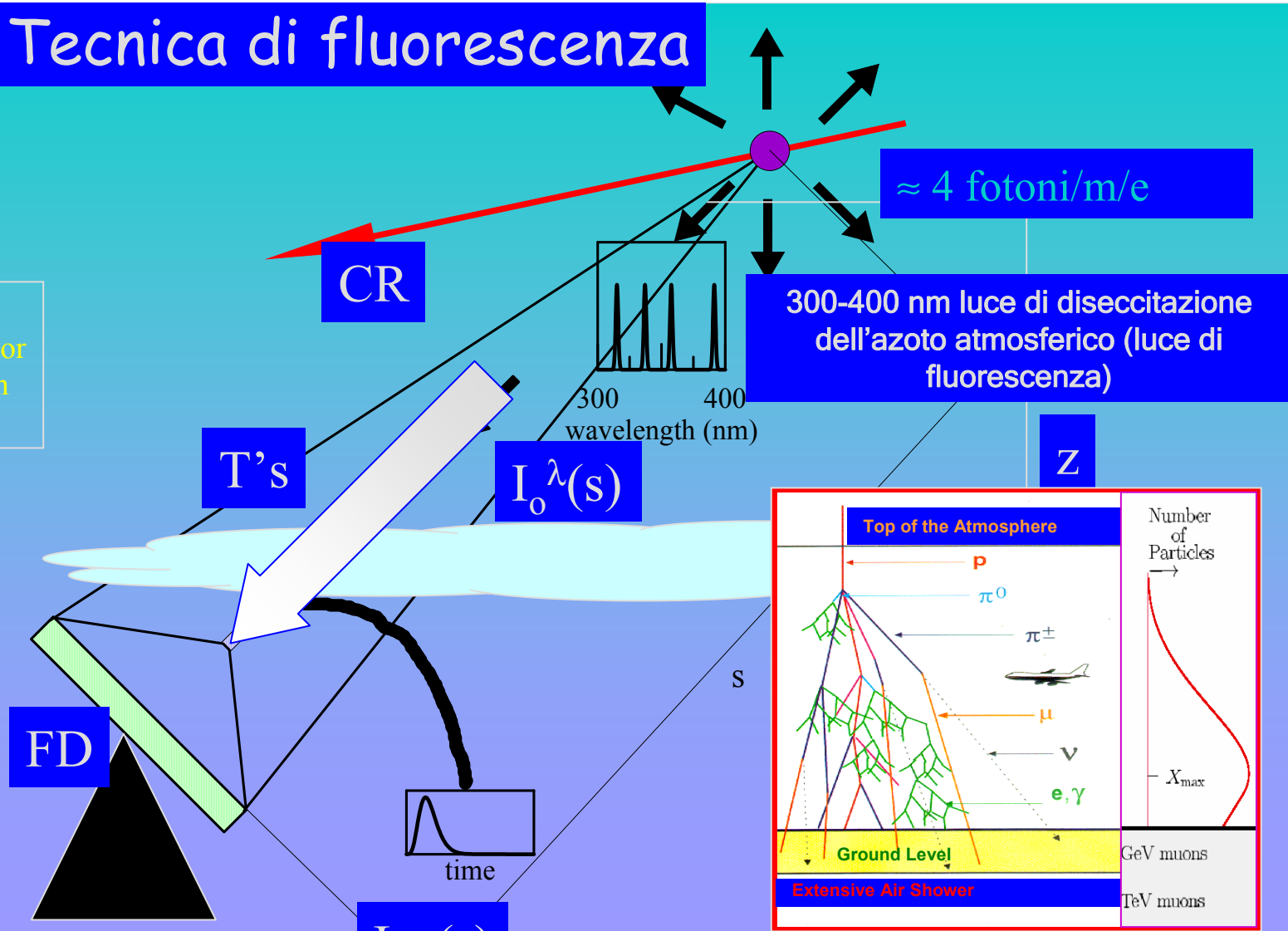




# Tecnica di fluorescenza

CR cosmic ray  
 FD fluorescence detector  
 T transmission function  
 z altitude

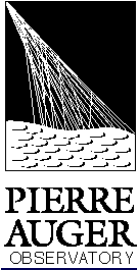
• 10-15 % duty cycle:  
 Notti chiare e senza luna



$$N_{p.e.} = \sum_{\lambda} N_e(\lambda) \times Y \times T(\lambda) \times \frac{A}{4\pi R_i^2} \times \epsilon(\lambda)$$

**Y** = fluorescence yield in air  
**A** = FD acceptance  
**T** = atmospheric transmission function  
 $\epsilon$  =  $\gamma$ -p.e conversion efficiency  
**R** = distance along sight line





# HiRes



4.2 m<sup>2</sup> spherical mirror

16 × 16 array of phototubes,

.96 degree pixels.



HiRes è un esperimento di fluorescenza per lo studio dei UHECRs.

Mono: range di energia ( $10^{17.4} < E < 10^{20.5}$  eV), alta statistica

Stereo: migliore ricostruzione su un range ristretto  
 $10^{18.5} < E < 10^{20.5}$  eV.

In questo range energetico si aspetta di vedere:

**Transizione da sorgenti galattiche ad extra-galattiche**  
**→ transizione da composizione pesante a leggera.**

HiRes1: Five Mile Hill

21 specchi, 1 anello (3° < altitude < 17 degrees).

Semplice elettronica (altezza dell'impulso e tempo di trigger).

HiRes2: Camel's Back Ridge

12.6 km Sud-Ovest di HiRes1.

42 specchi, 2 anelli (3° < altitude < 31 degrees).

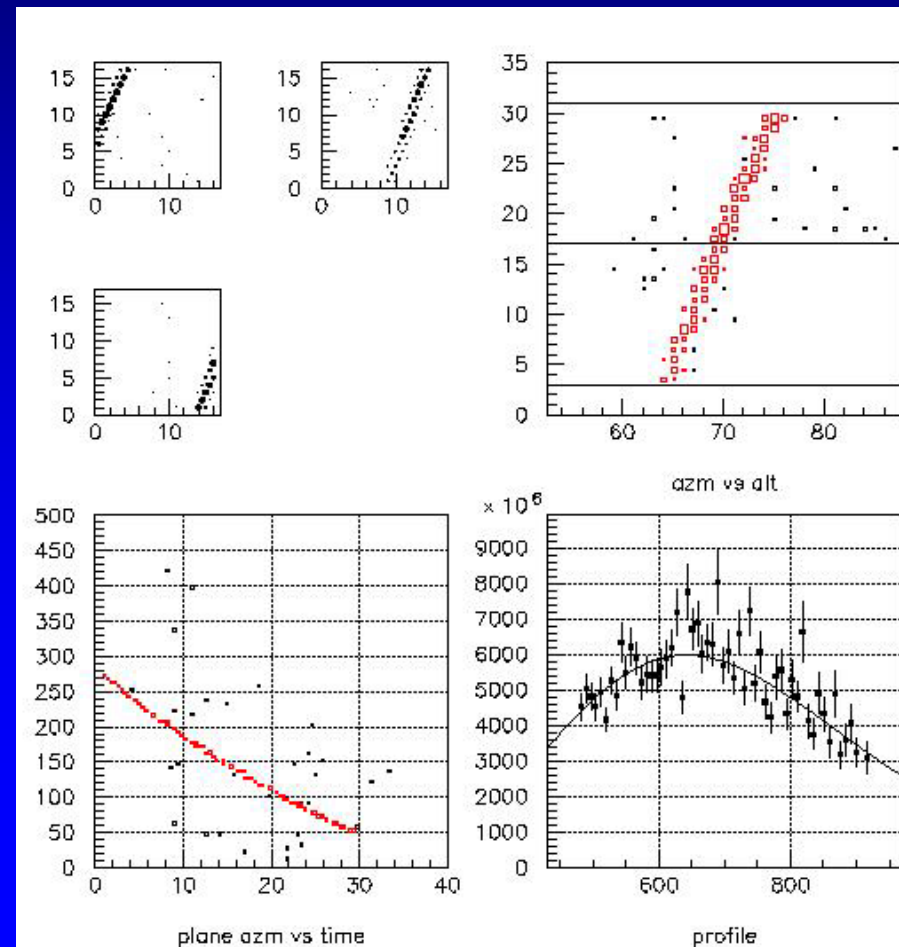
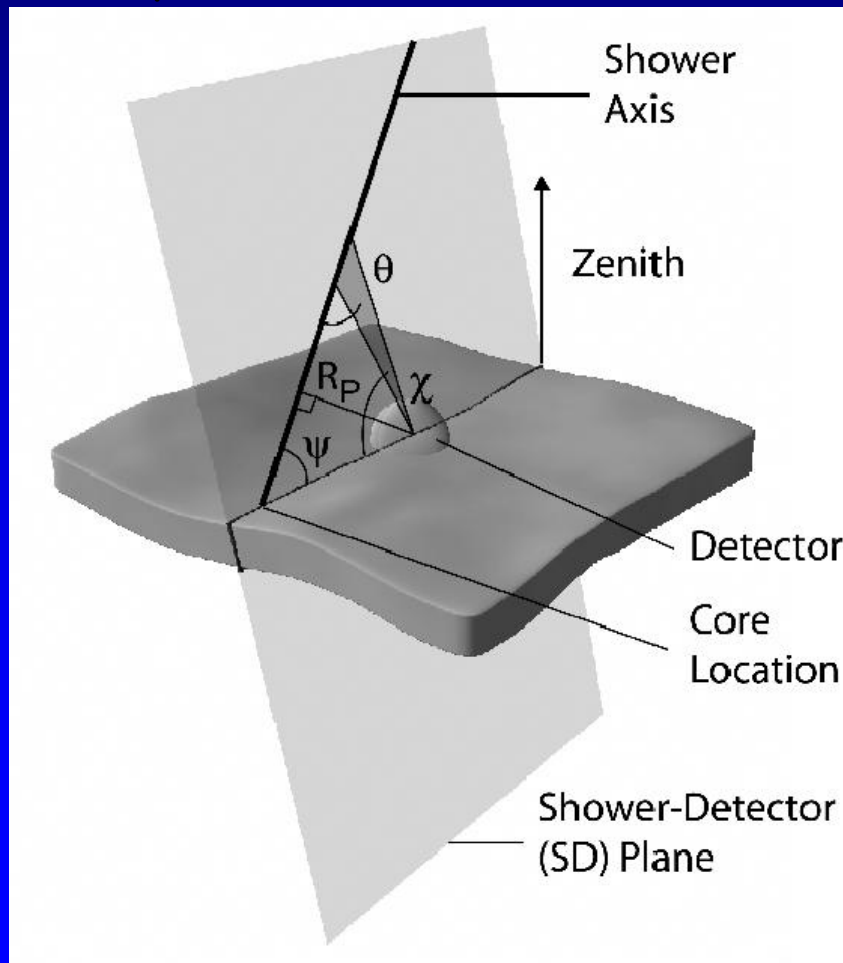
FADC elettronica (100 ns).



Astro-ph/ 0501317

# Analisi dei dati Mono

Pattern recognition. Fit SDP. Time fit (HiRes2), 5° resolution.  
Profile plot. Gaisser-Hillas fit. Profile-constrained fit (HiRes1), 7° resolution.



# Analisi Stereo e risoluzioni

L'intersezione dei piani SDP mono determina la geometria con  $0.6^\circ$  di risoluzione.

Due misure di energia e  $X_{max}$ .

Phototube calibration: 10%

Fluorescence yield: 10%

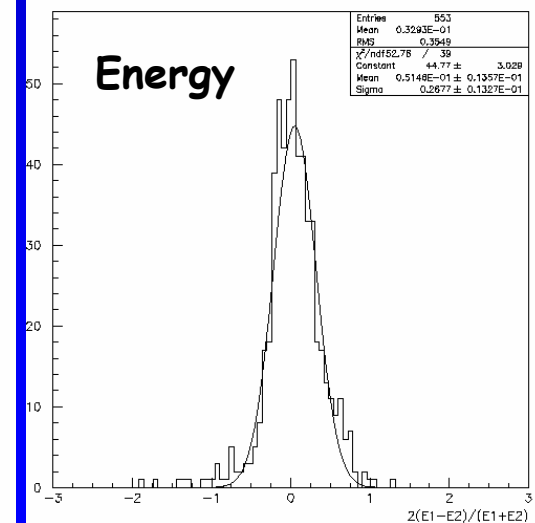
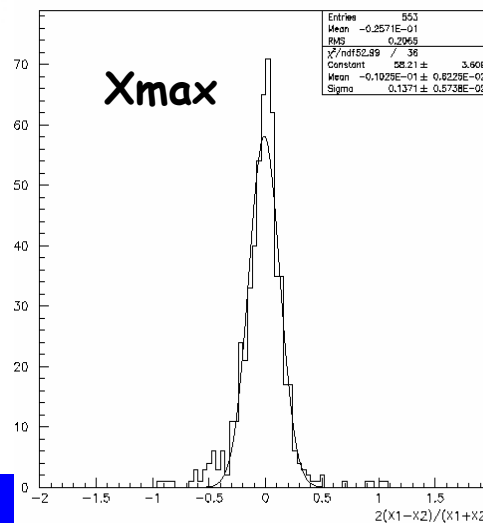
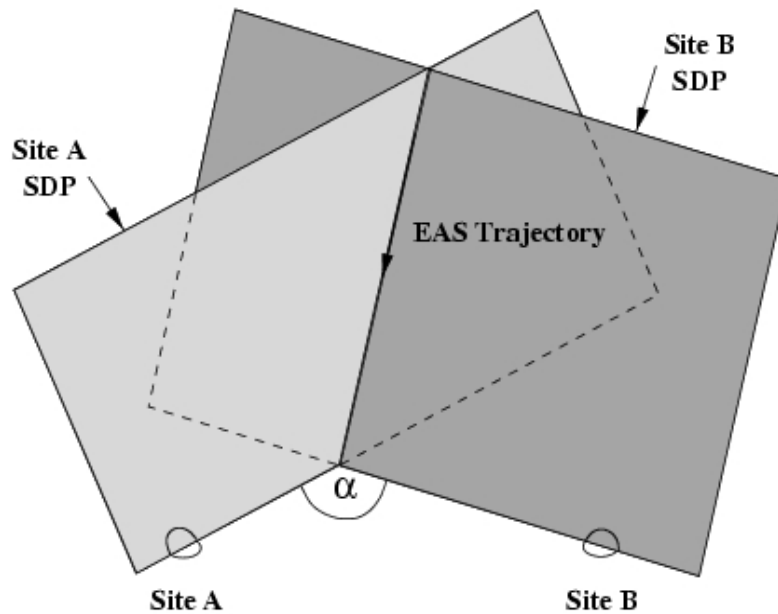
Unobserved energy in shower: 5%

Modeling of the atmosphere: 15%

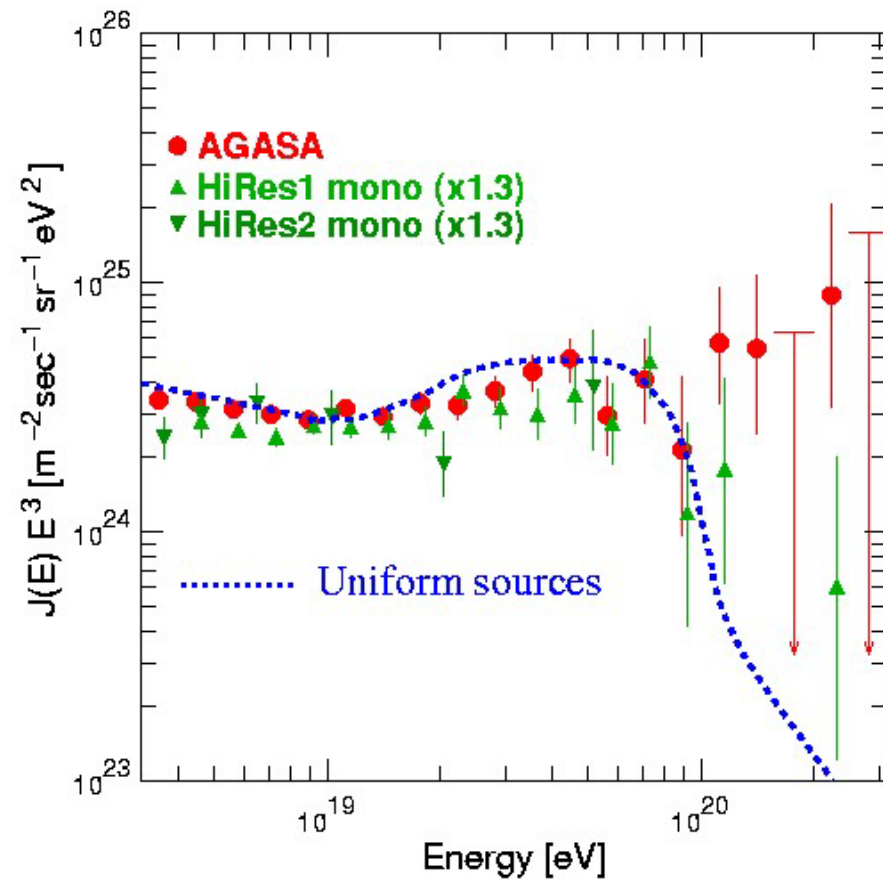
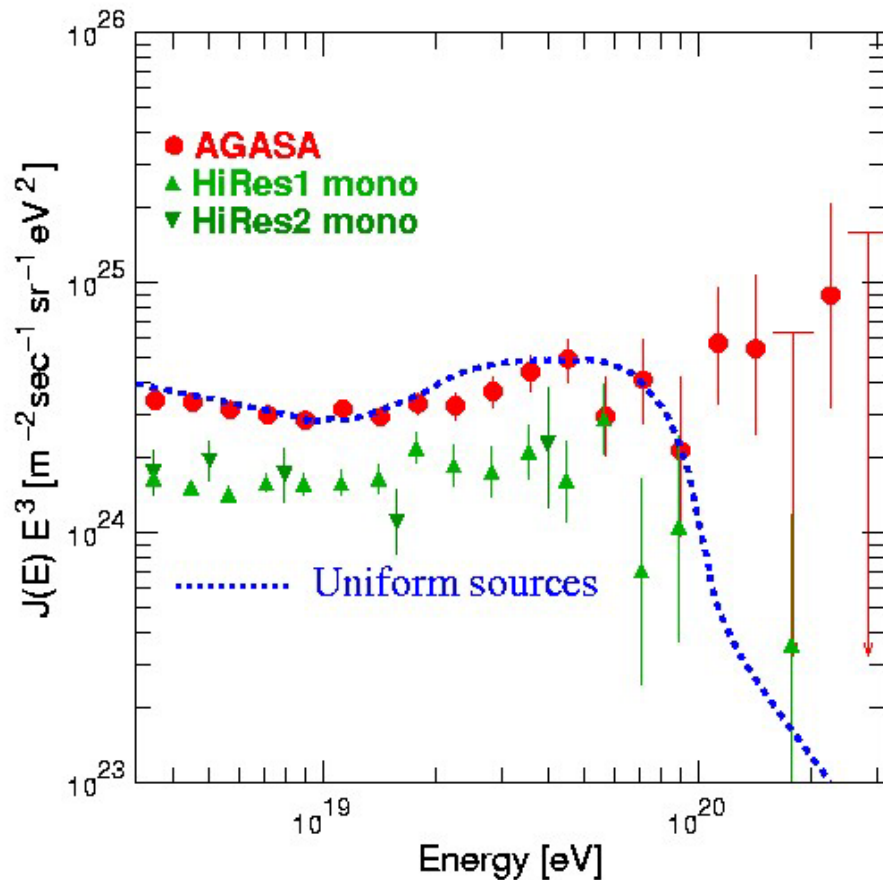
Energy scale: 21%

Flux: 31%

Le distribuzioni sia in energia che in  $X_{max}$  sono centrate  
Risoluzione: 20% in E e 15 g/cm<sup>2</sup> in  $X_{max}$ .

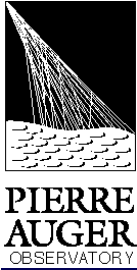


# Spettro energetico (AGASA vs. HiRes@ICRC2003)



~2.5 sigma di discrepanza tra AGASA & HiRes  
differenza in energia del 25%

Articolo: Energy determination  
in AGASA (astroph/0209422)  
Catania - IFAE 2005



# Composizione HiRes

Misure stereo di  $X_{\max}$  vs.  
energia

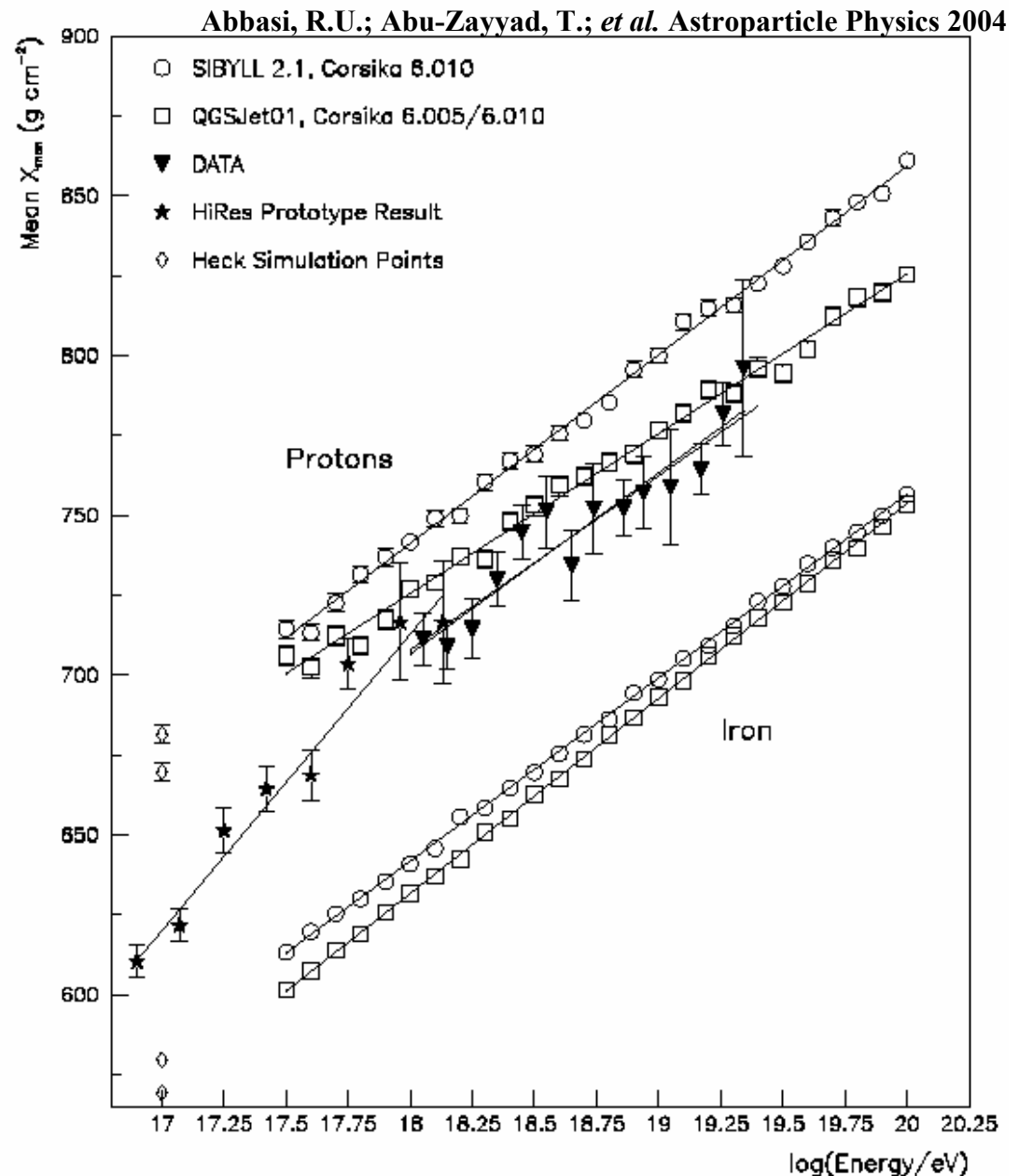
L'elongation rate cambia  
da  $\sim 90$  a  $\sim 50$  g/cm<sup>2</sup>/decade a  
 $10^{18.0}$  eV.

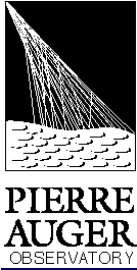
Transizione da sorgenti  
galattiche a extragalattiche

$$X_{\max} = (1 - B)X_0 \left( \ln \frac{E}{\epsilon} - \langle \ln A \rangle \right)$$

$$D_e = \frac{\delta X_{\max}}{\delta \ln E} = (1 - B)X_0 \left( 1 - \frac{\delta \langle \ln A \rangle}{\delta \ln E} \right)$$

where  $X_0$  is the radiation length in air ( $37.1 \text{ g cm}^{-2}$ ) and  $\epsilon$  is the critical energy in air (81 MeV). Here  $B$  is 0 for a pure electromagnetic cascade and less than 1.0 by an amount that depends on the hadronic interaction model.





# L'esperimento Pierre Auger

>250 ricercatori di 30 istituzioni e 19 Paesi:

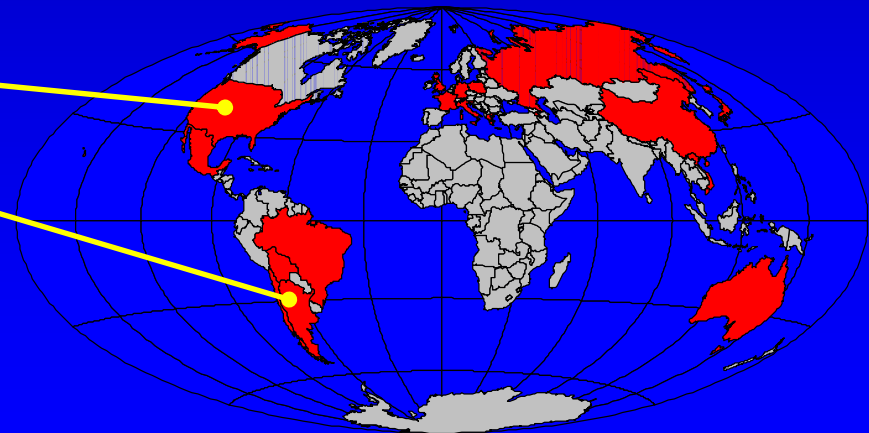
Argentina, Armenia, Australia, Bolivia, Brazil, Chile, China, Czech Republic, France, Germany, Greece, Italy, Japan, Mexico, Poland, Russia, Slovenia, U.K., U.S.A., Vietnam

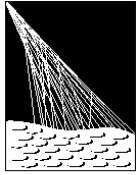
**Gruppo italiano:**

Catania, L'Aquila, Lecce, Milano, Napoli, Roma, Torino

**Studio degli UHECR:**  
spettro energetico, anisotropia,  
composizione in massa

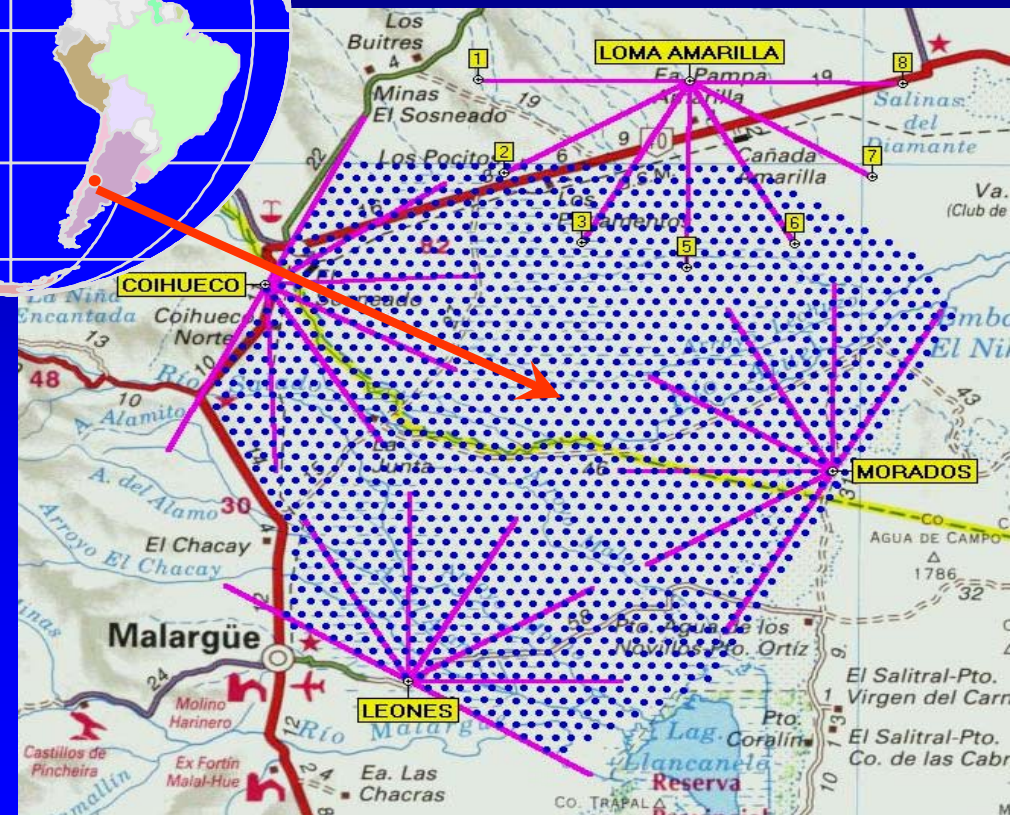
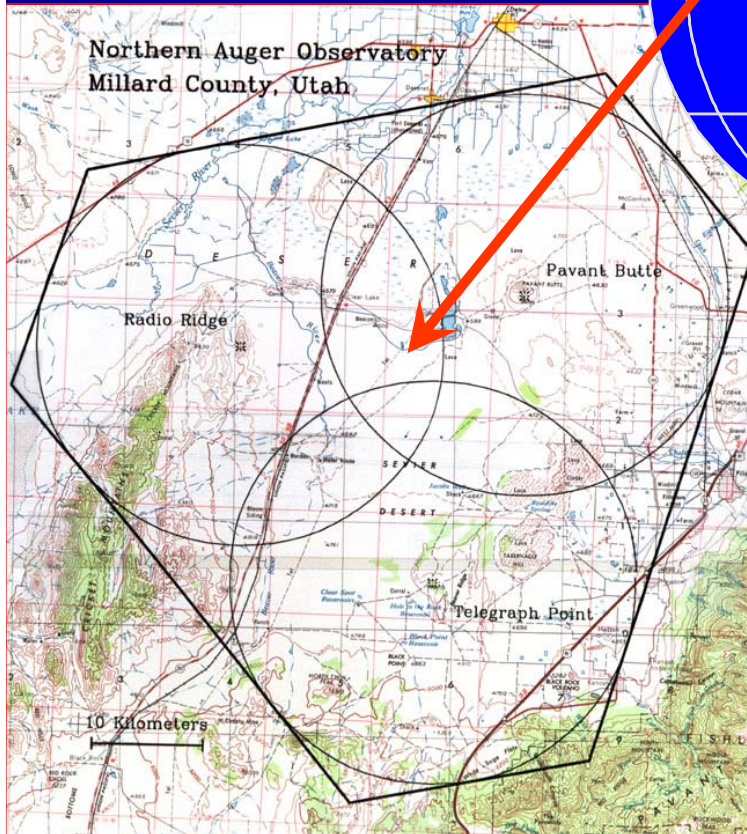
- Copertura totale del cielo:
- Emisfero Nord → USA
- Emisfero Sud → Argentina
- Rivelatore ibrido:
  - array di superficie
  - telescopi di fluorescenza
- Alta statistica, lunga durata
- Acquisizione durante l'installazione
- Buona risoluzione geometrica ed energetica





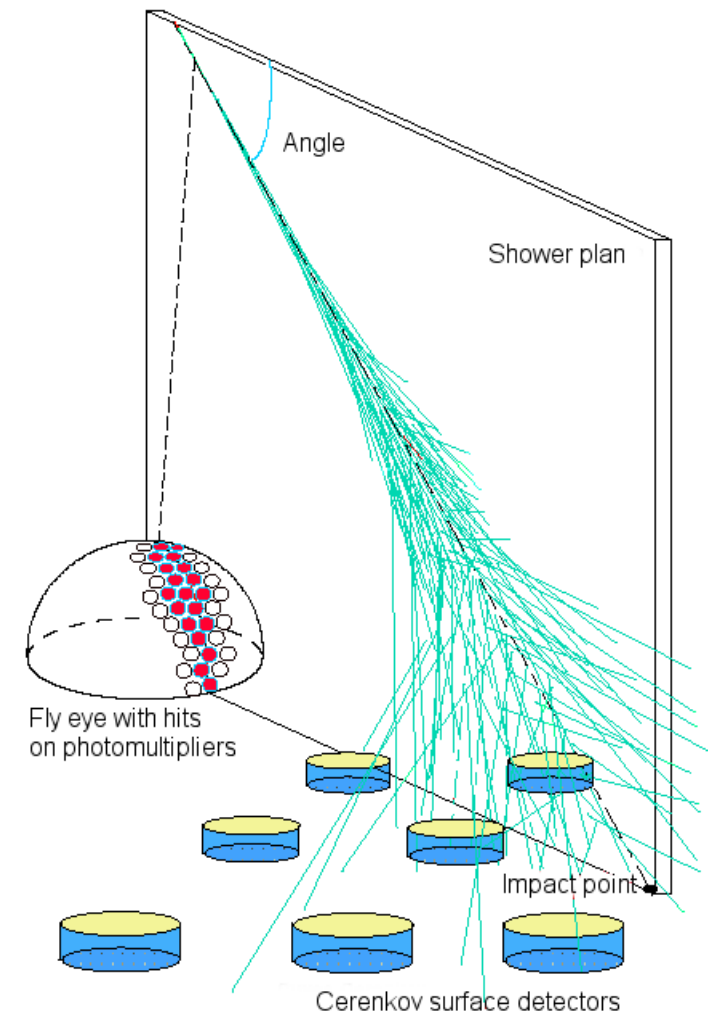
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# I siti Nord e Sud



# Rivelatore ibrido

- Array di superficie di 1600 rivelatori cilindrici Cerenkov ad acqua di  $10 \text{ m}^2$  di area e 1.2 m di altezza disposti su una griglia esagonale di 1.5 km di passo per un totale di circa  $3000 \text{ km}^2$ , per misurare la distribuzione laterale e quella spaziale dello sciame a livello di osservazione.
- Rivelatore di fluorescenza composto da 4 occhi (6 telescopi ciascuno con apertura angolare di  $30^\circ$ ) alla periferia dell'array per ricostruire lo sviluppo longitudinale dello sciame e  $X_{\text{max}}$
- L'unione delle due tecniche sperimentali permette l'intercalibrazione e la minimizzazione degli errori sistematici in modo da ottenere una accuratezza mai raggiunta fino ad ora

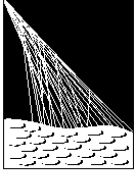


<http://www.auger.org>

Pierre Auger Collaboration: "Properties and Performances of the Prototype I Instrument for the Pierre Auger Observatory" NIM A523 (2004)

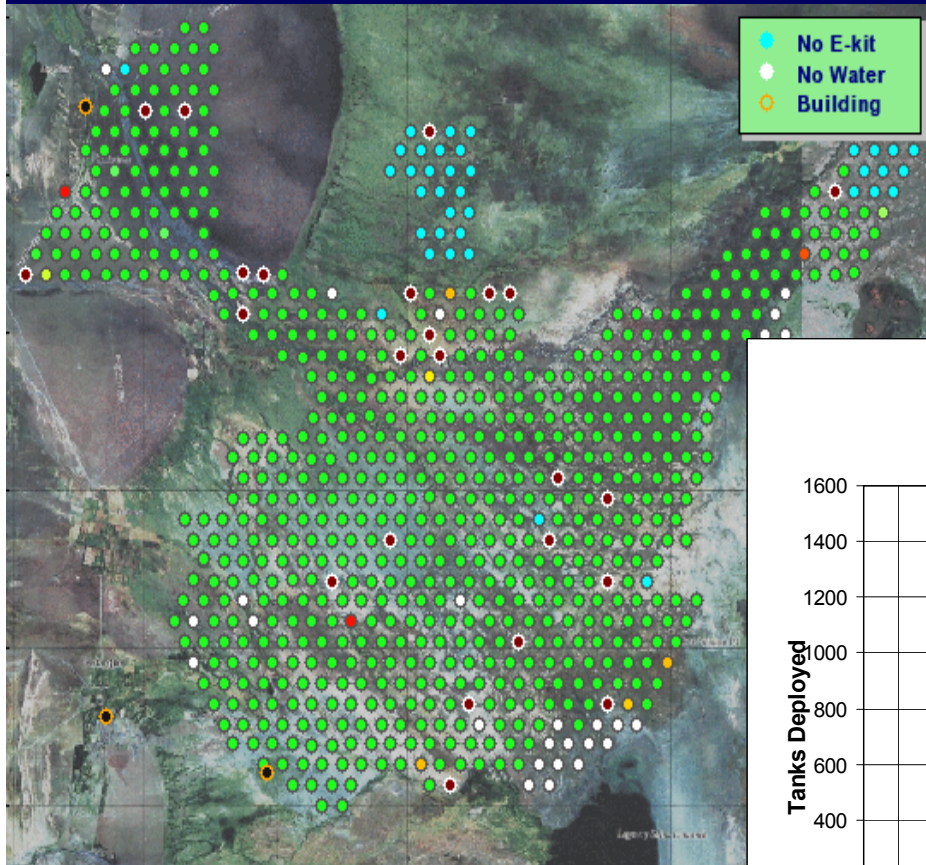
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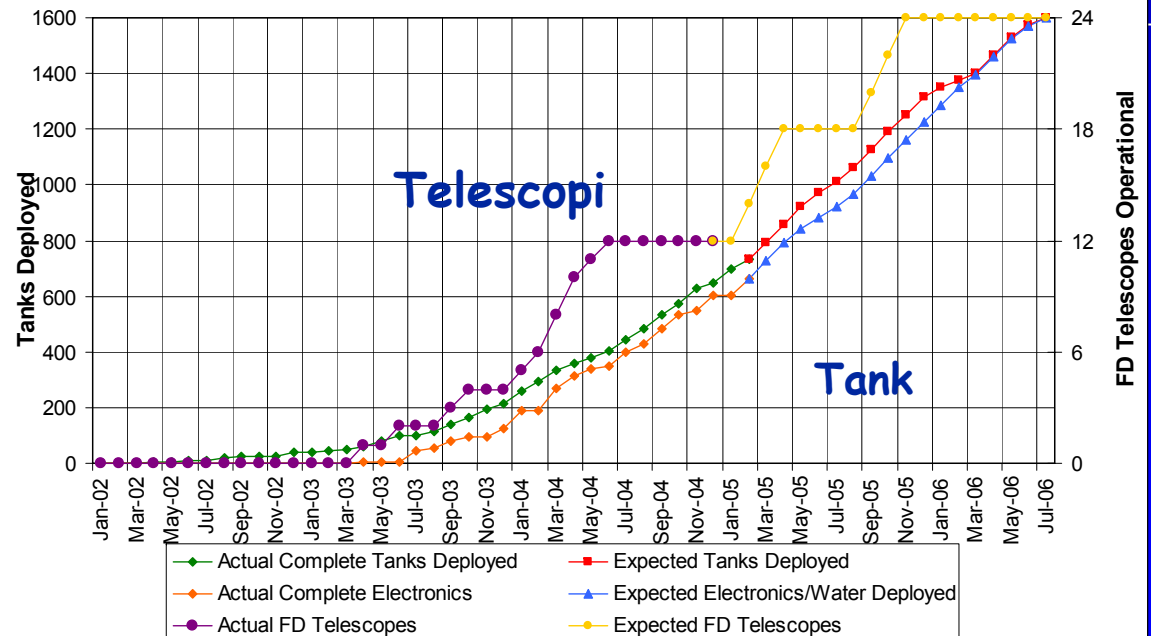
# Stato apparato Auger



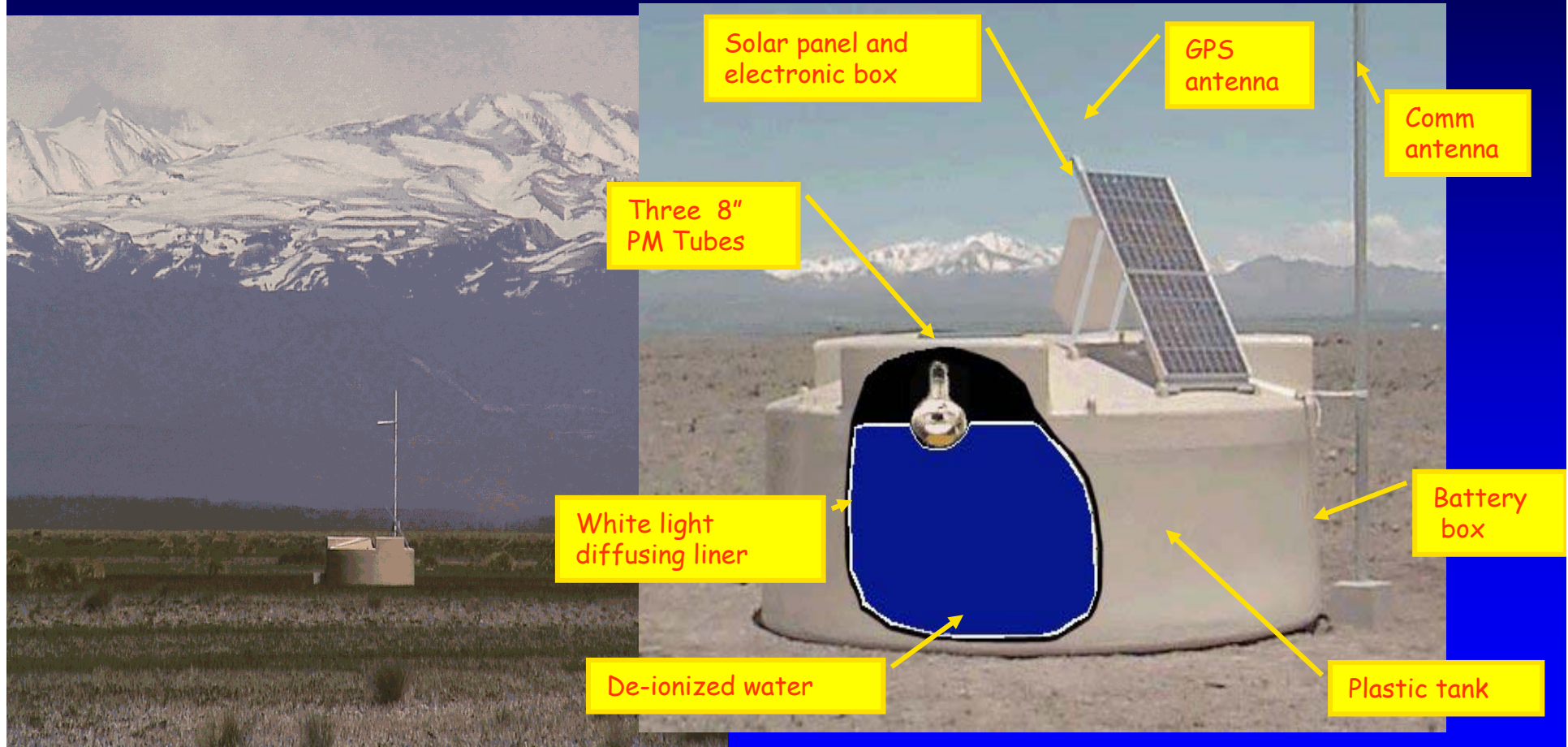
Stato delle Tank: 890 sul sito a Malargüe  
Più di 700 in acquisizione

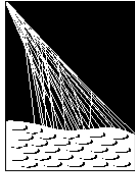
Stato dei telescopi FD  
2 occhi completi (Los Leones e  
Coiuheco)  
12 telescopi

Pierre Auger Project Schedule Chart  
Updated 10-Mar-05



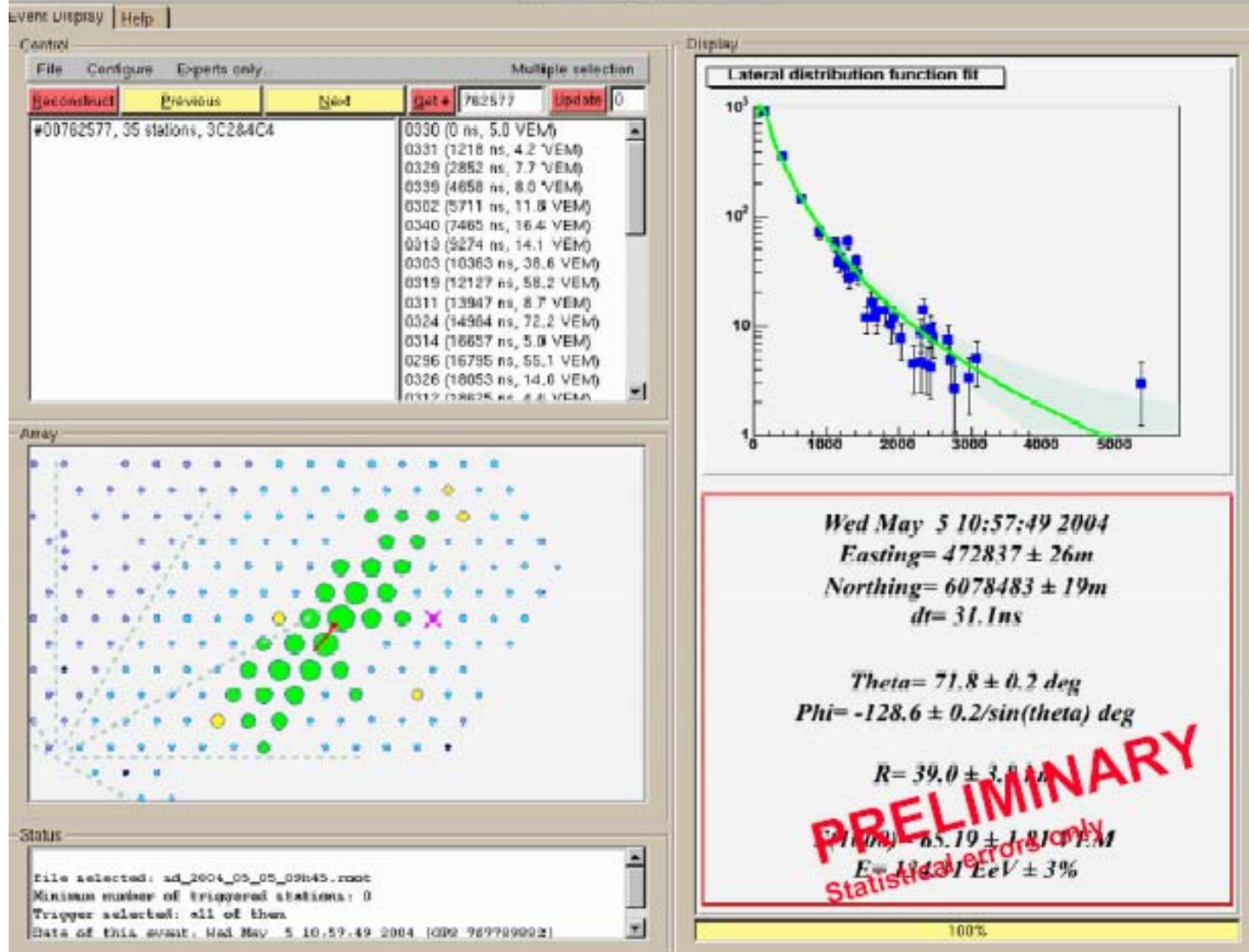
# I rivelatori Cerenkov



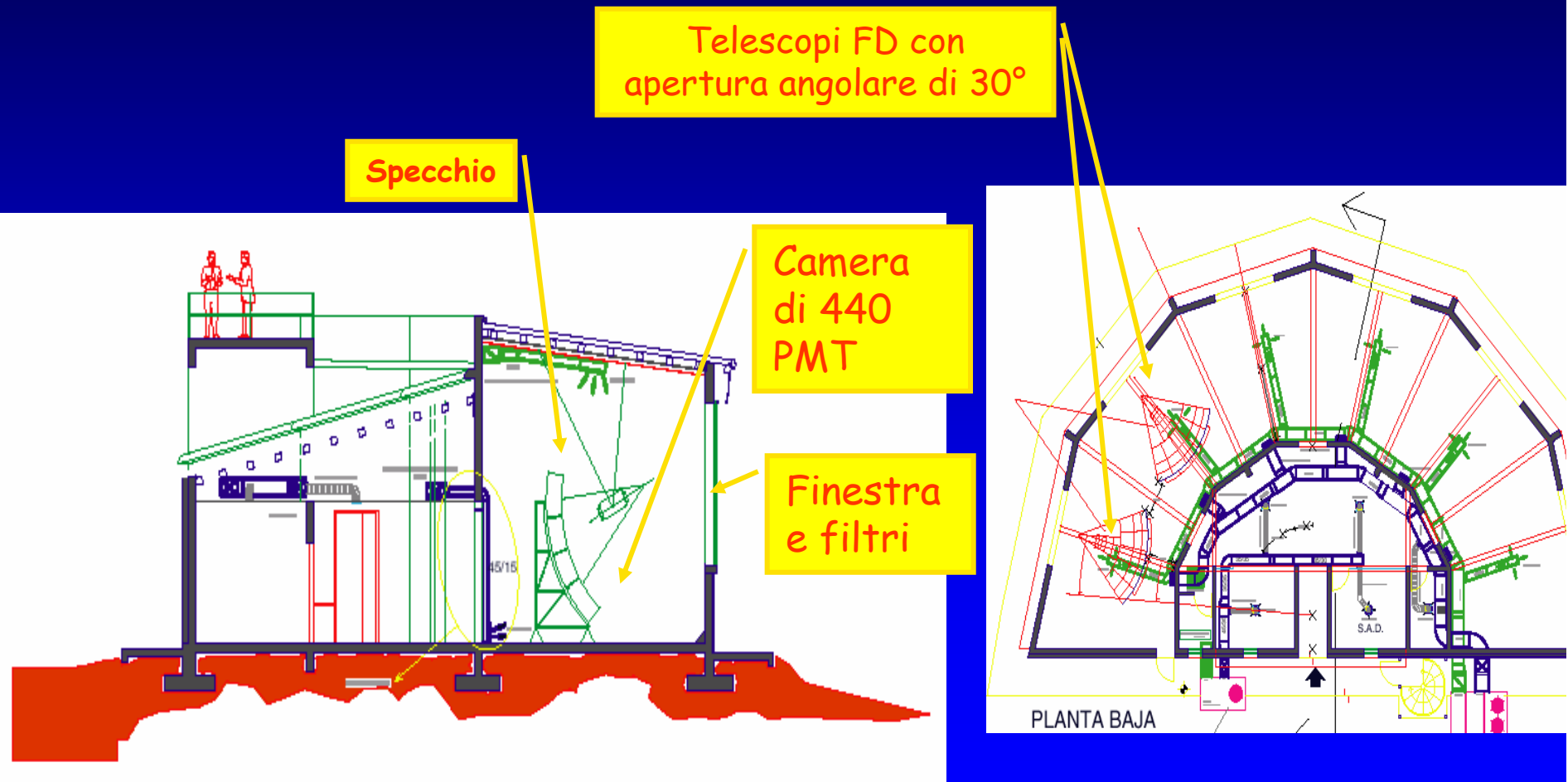


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# I dati del rivelatore di superficie



# Il rivelatore di fluorescenza

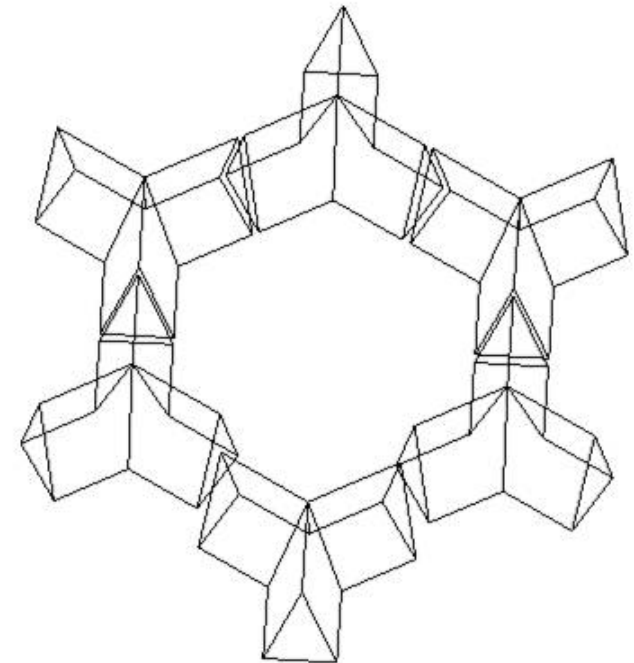


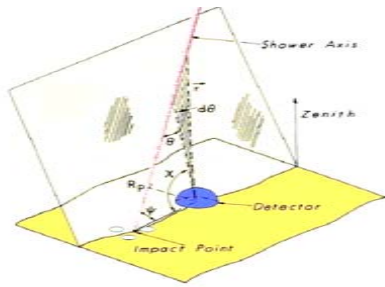
# Telescopio FD a Los Leones

Box di apertura e corrector ring

PMT  
Camera

Elettronica di Fron





# Grandezze rivelate dal rivelatore FD

Un evento registrato dall'apparato di fluorescenza e' identificato da una informazione spaziale e temporale

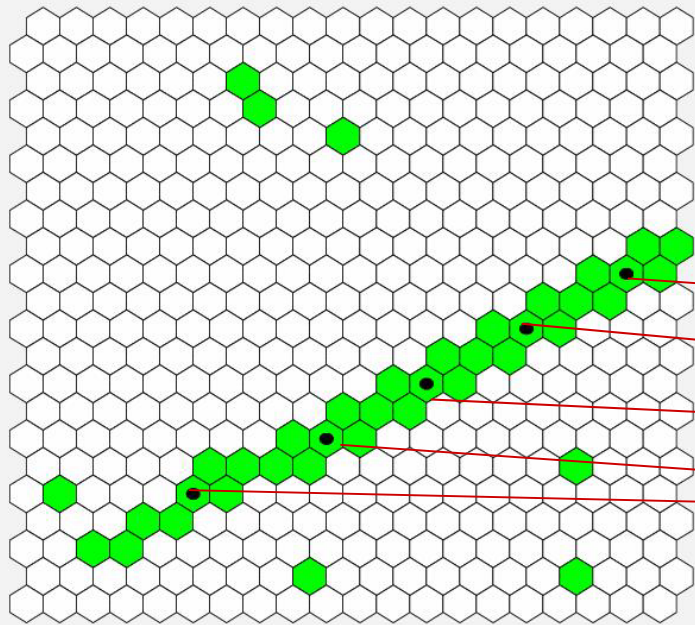
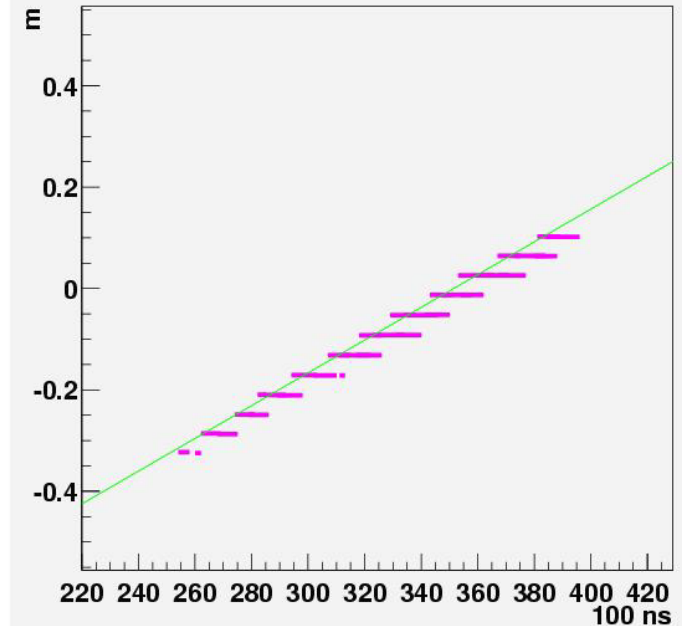
L'informazione spaziale permette

la ricostruzione dello Shower Detector Plane

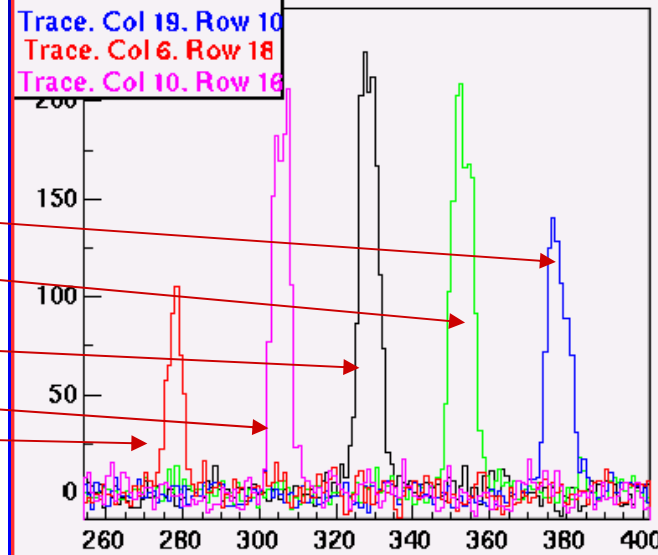
La successione dei tempi di arrivo sui PMT permette

la determinazione dell'asse dello sciame

Run 505 Event 544

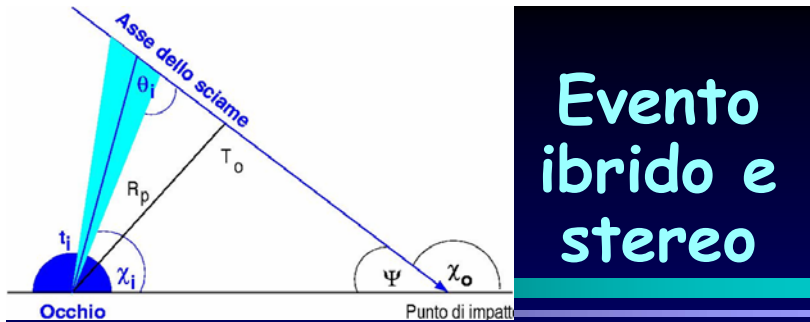


Trace. Col 13. Row 14  
Trace. Col 16. Row 12  
Trace. Col 19. Row 10  
Trace. Col 6. Row 18  
Trace. Col 10. Row 16



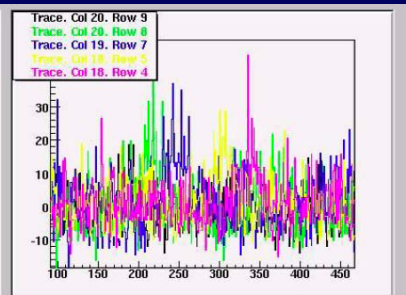
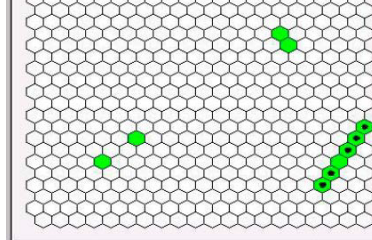
- rate of cosmic ray shower candidates ~few per hour
- PMT signals are 300 ns up to 1  $\mu$ s wide, and are small
- the signals show a characteristic time sequence when passing from one pixel to the next
- the tracks start from the bottom of the Camera and their total duration is 5-9  $\mu$ s.

Traccia dello sciame sulla camera Segnale sui singoli pixel (100 ns per bin)

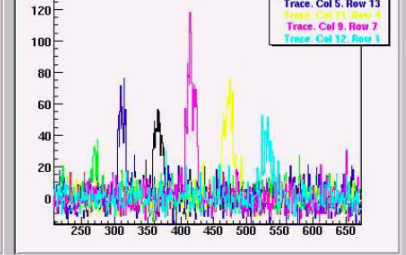
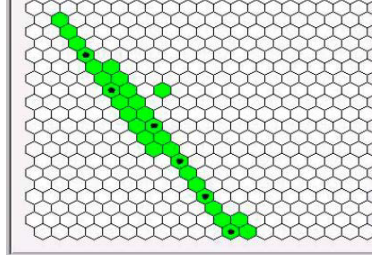


# Evento ibrido e stereo

**Coiheco (6 pixels)**



**Los Leones (29 pixels)**



**Event 673411**

Event Display, version v3r1

Control: File Configure Experts only... Multiple selection

Reconstruct Previous Next Get # 673411 Update 0

#00673411, 19 stations, FD	0162 (0 ns, 3.5 VEM)
	0166 (778 ns, 13.2 VEM)
	0174 (1458 ns, 4.7 VEM)
	0172 (2130 ns, 210.5 VEM)
	0157 (2542 ns, 3.3 VEM)
	0156 (3439 ns, 95.9 VEM)
	0171 (4218 ns, 14.2 VEM)
	0173 (5053 ns, 1092.8 VEM)
	0151 (6415 ns, 18.1 VEM)
	0131 (8408 ns, 19.6 VEM)
	0215, station deleted
	0132, station deleted
	0283, station deleted
	0036, station deleted
	0155, station deleted

Array

From Coiheco ->

From Los Leones ->

Status

file selected: sd\_2004\_02\_27\_00h20.root  
 Minimum number of triggered stations: 0  
 Trigger selected: all of them  
 Date of this event: Fri Feb 27 07:57:52 2004 (GPS 761903885)

*Fri Feb 27 07:57:52 2004*

*Easting= 465830 ± 11m*

*Northing= 6090308 ± 21m*

*dt= 52.8ns*

*Theta= 35.9 ± 0.4 deg*

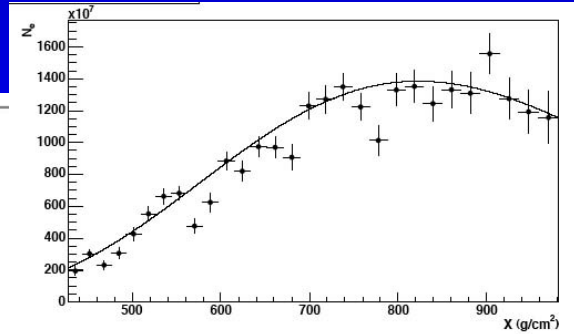
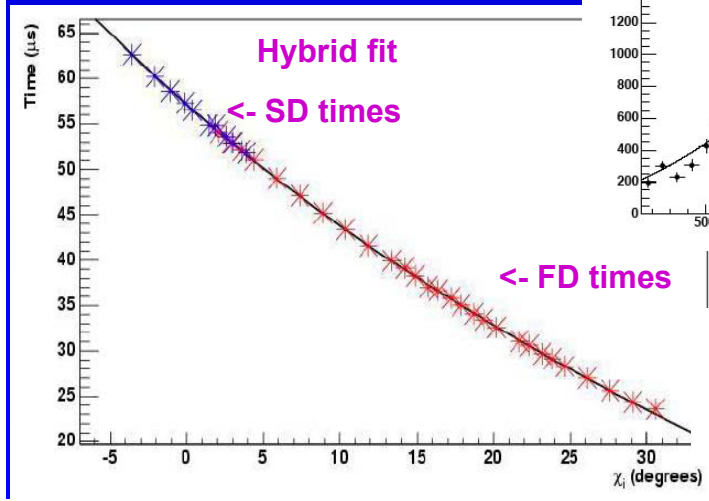
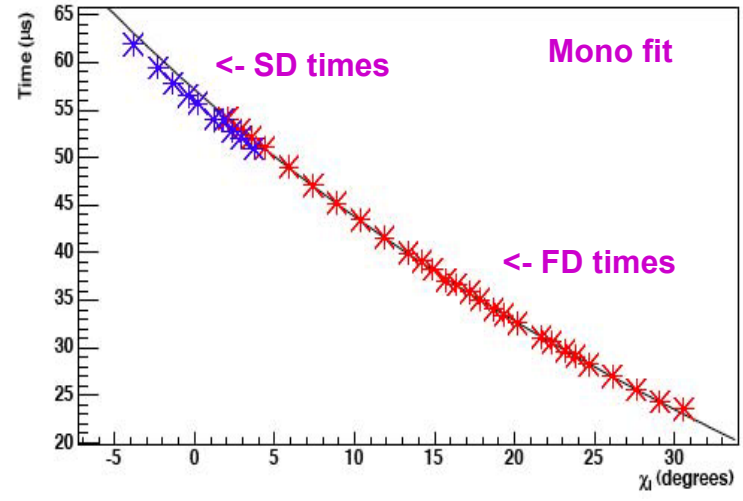
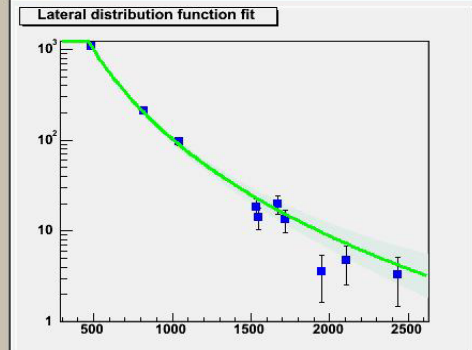
*Phi= -173.3 ± 0.3/sin(theta) deg*

*R= 10.0 ± 0.8 km*

*S(1000)= 102.94 ± 4.39 VEM*

*E= 21.03 EeV ± 4%*

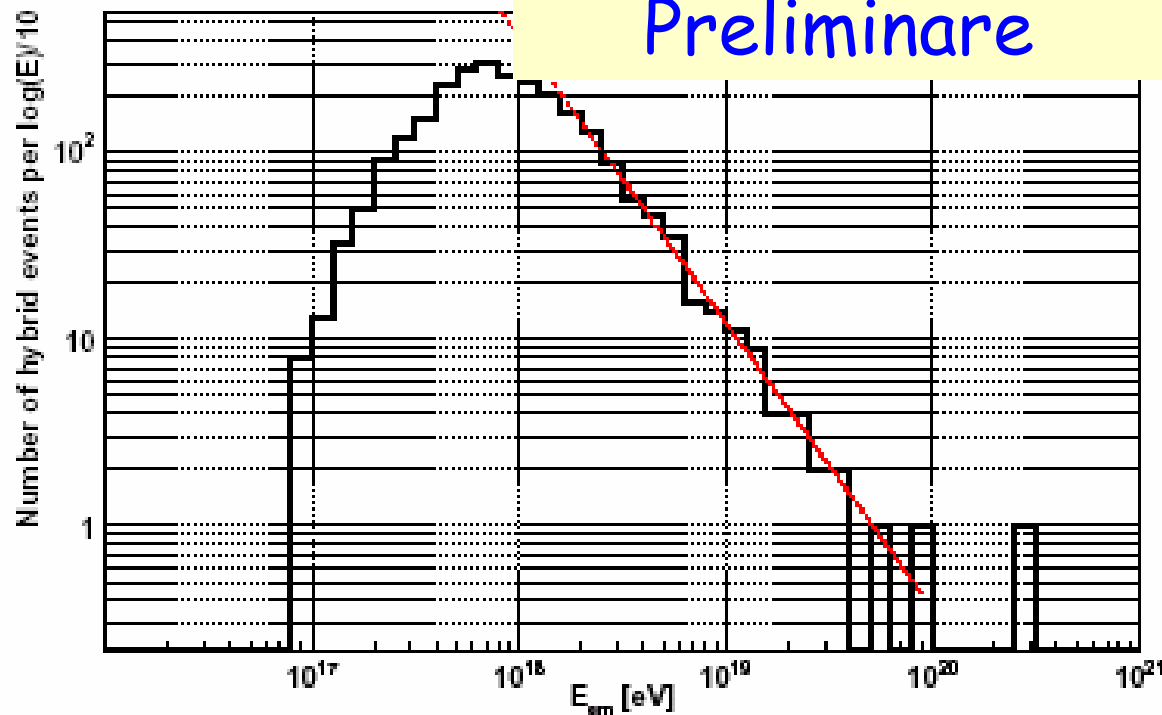
100%



**FD energy ~ 2x10<sup>19</sup> eV**

*(preliminary)*  
**SD energy = 2.1x10<sup>19</sup> eV**

# Distribuzione in energia degli eventi ibridi



Gennaio 2004 - Marzo 2005  
Solo SD



60649 events with  $E > 0.5 \text{ EeV}$   
32546 events with  $0.8 \text{ EeV} < E < 3 \text{ EeV}$   
24992 events with  $1 \text{ EeV} < E < 5 \text{ EeV}$   
1131 events with  $E > 5 \text{ EeV}$



# Auger Performance

On each site:

1600 SD (surface detectors)

4 FD eyes (fluorescence detectors)

Duty Cycle:

SD 100%

FD 10%

Efficiency:

>90% above 10 EeV

Energy resolution:

	SD alone
100 EeV	15%

10 EeV	30%
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Hybrid mode

10%

20%

Angular resolution:

	SD alone
100 EeV	0.5°

10 EeV	1.0°
--------	------

Hybrid mode

0.20°

0.35°

# The Fluorescence from space EUSO

**John Linsley, 1979 in Field Committee Report, "Call for Projects and Ideas in High Energy Astrophysics for the '1980s"**

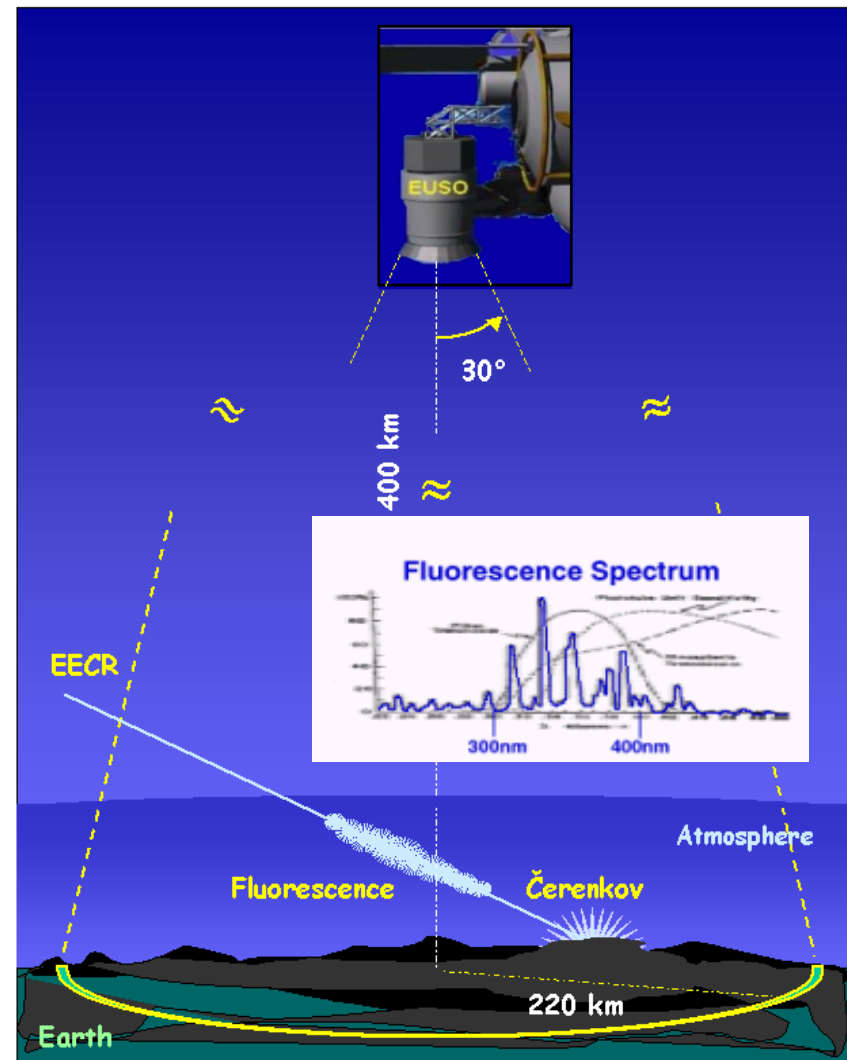
**The concept is to observe fluorescence light and the Cherenkov reflected bump produced by EAS from a space based telescope**

The collecting power of the night sky on the whole Earth is  $4 \times 10^8 \text{ km}^2 \text{sr}$ , the ultimate limit for space based observatories

**By comparison ground based observatories are reaching a practical limit of  $10^4 \text{ km}^2 \text{sr}$**

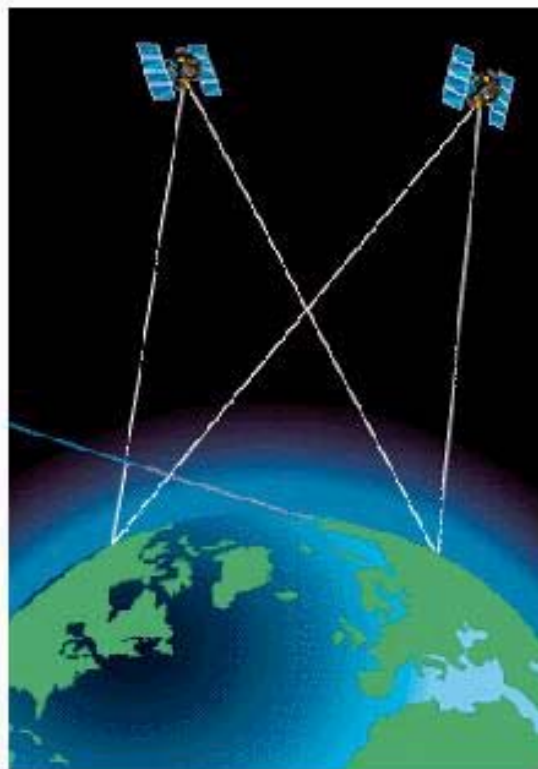
Ref.: "EUSO Instrument Red Book -

Report on Phase A Study", EUSO-PI-REP-005, 21 Apr2004; EUSO-PI-REP-002, 31 Aug 2003.



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# The OWL Concept



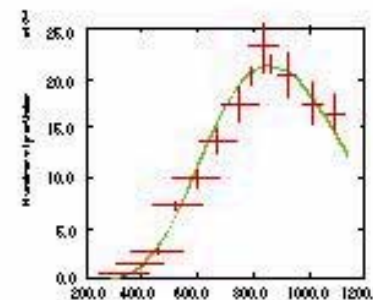
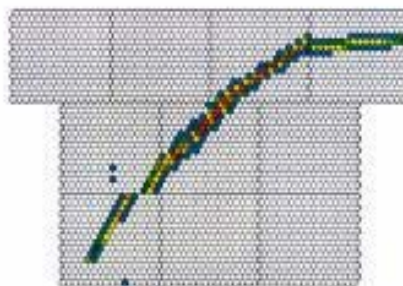
Use air fluorescence technique to image 300 → 400 nm photons in  $\sim 0.1^\circ$  pixels (with 10 ns →  $\mu$ s timing), from low Earth, equatorial orbit, airshowers induced by  $E \gtrsim 10^{19}$  eV cosmic rays

Wide angle ( $\sim 60^\circ$  full, FOV) optics at a 640 km orbit in a stereo configuration → an asymptotic, *instantaneous* aperture  $\sim 3 \times 10^6$  km<sup>2</sup>-ster

10% duty cycle → *effective* aperture  $\sim 3 \times 10^5$  km<sup>2</sup>-ster

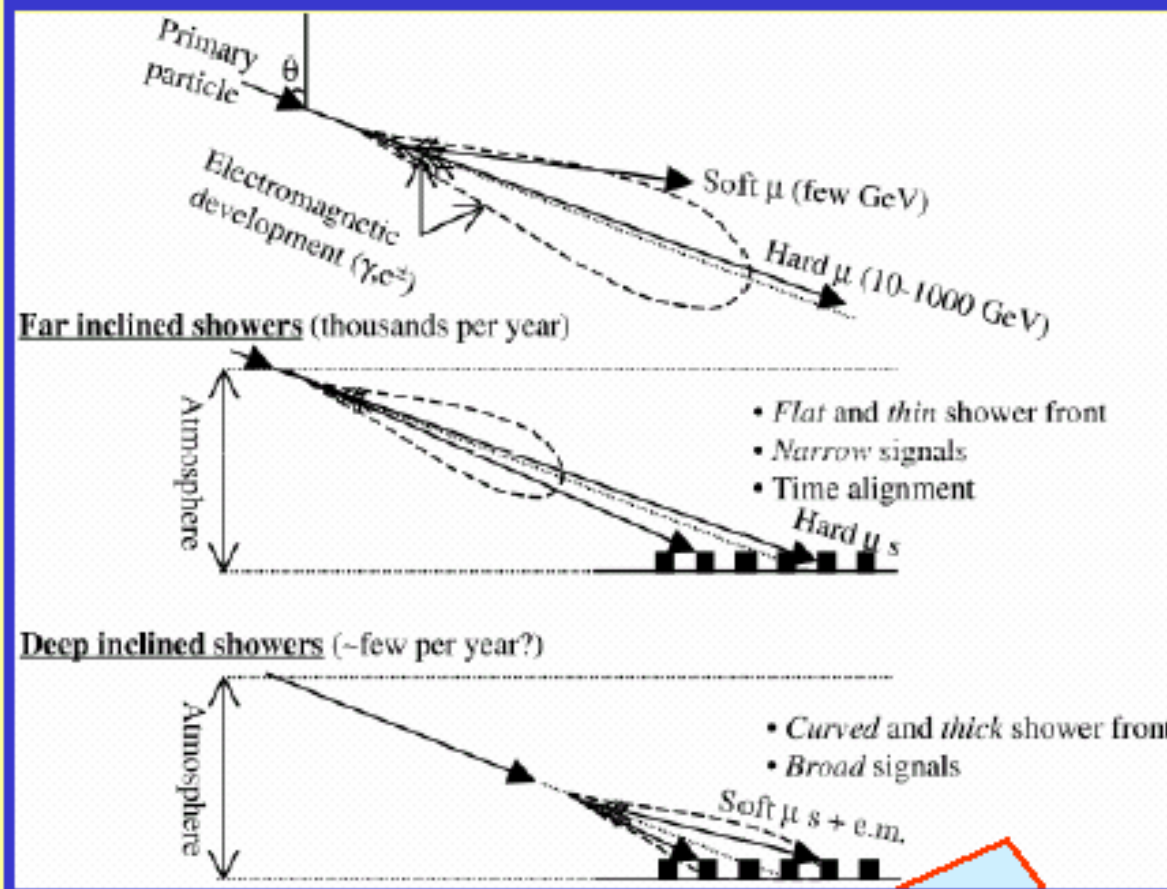
Assuming  $\Phi_{\text{CR}}(E) \sim E^{-2.75}$ , the asymptotic OWL stereo aperture leads to  $\sim 3000$  events/year with  $E \gtrsim 10^{20}$  eV

**OWL could be a stepping stone to viewing majority of night side atmosphere**

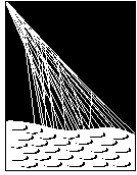


**OWL**

# Neutrino detection in AUGER

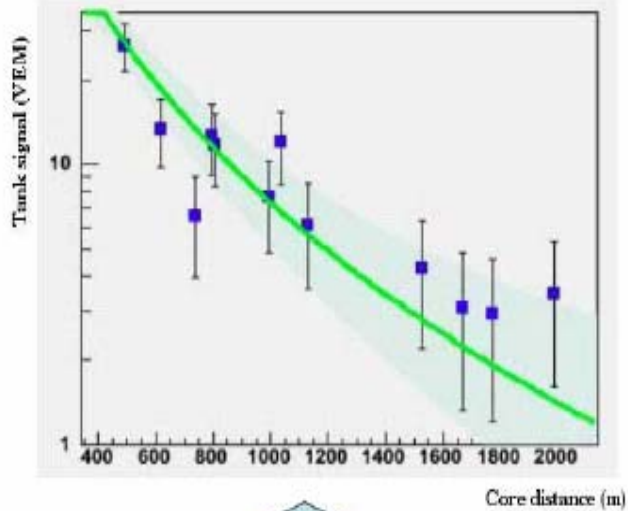


X. Bertou, P. Billoir, and S. Coutu



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# Sciame vecchio (71°)



Mon Feb 16 21:57:03 2004  
Easting= 477789 ± 120m  
Northing= 6083293 ± 173m  
dt= 49.1ns

Theta= 71.3 ± 0.4 deg  
Phi= 51.3 ± 0.3/sin(theta) deg

R= 30.3 ± 8.3 km

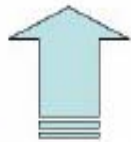
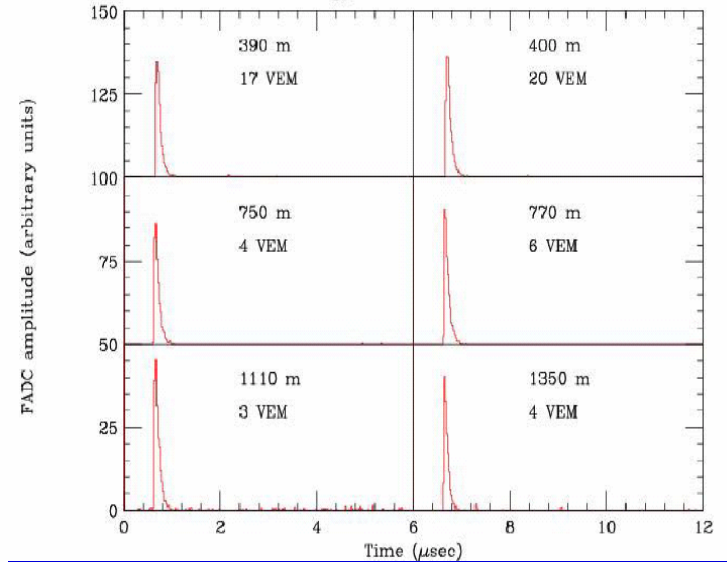
Energy estimate preliminary

$E = 1.3 \pm 0.7 \text{ EeV}$   
Statistical errors only

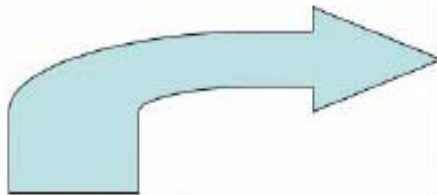
Error statistical only

**PRELIMINARY**

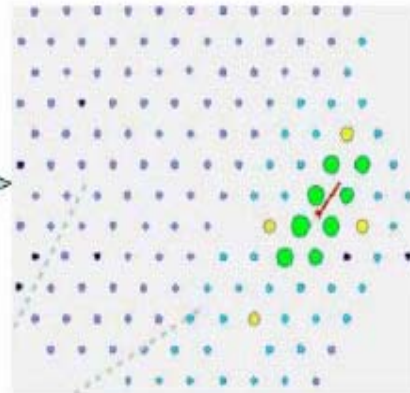
FADC traces, Energy =  $5.0 \times 10^{18}$  eV, zenith =  $76^\circ$



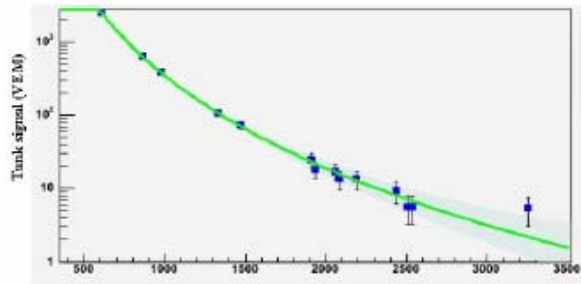
Lateral Distribution Function Fit



Surface Array view



# Sciame giovane (verticale)



Mon Dec 29 09:23:45 2003  
Easting =  $470343 \pm 21$  m  
Northing =  $6095432 \pm 25$  m  
 $dt = 126.8$  ns

$\Theta = 34.4 \pm 0.3$  deg  
 $\Phi = 140.1 \pm 0.3 \sin(\Theta)$  deg

$R = 12.5 \pm 0.8$  km

$S(1000) = 1.7 \pm 0.1$  VEM

$E = 1.6 \pm 0.3$  EeV  $\pm 3\%$

Core distance  
Statistical error only  
PRELIMINARY

Lateral Distribution Function Fit

Surface Array view



DC traces, Energy =  $1.2 \times 10^{19}$  eV, zenith =  $13^\circ$

