The Pierre Auger Observatory

Physics and Detectors

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Cosmic Rays and Particle Physics

A long history in common:

Discovery of CR (Hess 1912)

Observation in cloud chamber (Skobelzyn 1927)

Discovery of positron (Anderson 1932)

Discovery of muon (Neddermeyer & Anderson, 1937)

Discovery of π,K,Λ,.. (various up to ~1953)

Astroparticle

Bringing together theory and techniques from

Cosmology, Astrophysics and Particle Physics

The Universe is a Lab

Very large energies
Unusual objects
Big Bang memories

This talk

- Focus on highest energy cosmic rays
- Tantalizing experimental results
- (Apparently) clear theoretical picture
- Is there any *real* conflict?
- To address the issue: *Better data!*
- The Auger project

The highest energy CR's

[aka ***U****(ltra)****H****(igh)****E****(nergy)****CR****'s*]

- By rather simple and safe arguments

  They should not be there

- Different experiments give

  Contradictory results

Time for new data

A general argument - I

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

(Greisen, 1965)

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

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

To get accelerated: *synchrotron loss < energy gain*

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

A general argument - II

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

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

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

$\rightarrow$ easy to detect!

No deflection @ high E

Little deflection from extragalactic mag field

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

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

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

$\rightarrow$*negligible deflection*

Most interesting observables

The energy spectrum

Shape

Composition

Anisotropy

The Spectrum - I

Shape: *Power law*

Energy: *12 decades+*

Flux *31 decades+*

Very interesting anomalies

Knee, Ankle, Endpoint

Spectrum shape

$I_N(E) \approx 1.8\ E^{-\alpha}$ nucleons / cm^2 - s - sr - GeV

α = 2.7, from several GeV to beyond 100 TeV,

(galactic origin)

α = 3.0,

10^{16} eV < E < 10^{18} eV

(from "knee" to "ankle")

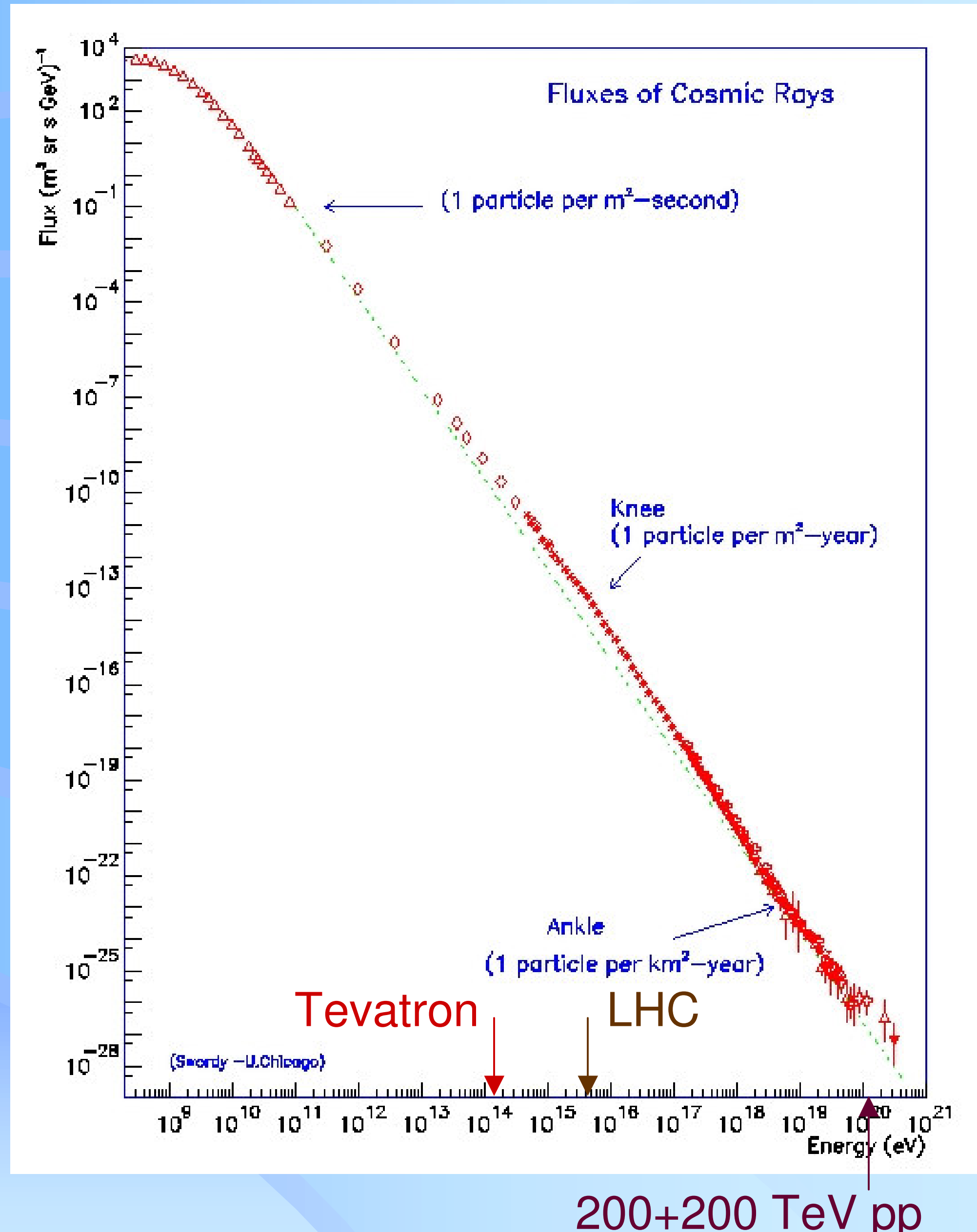
(galactic origin)

α = 2.8,

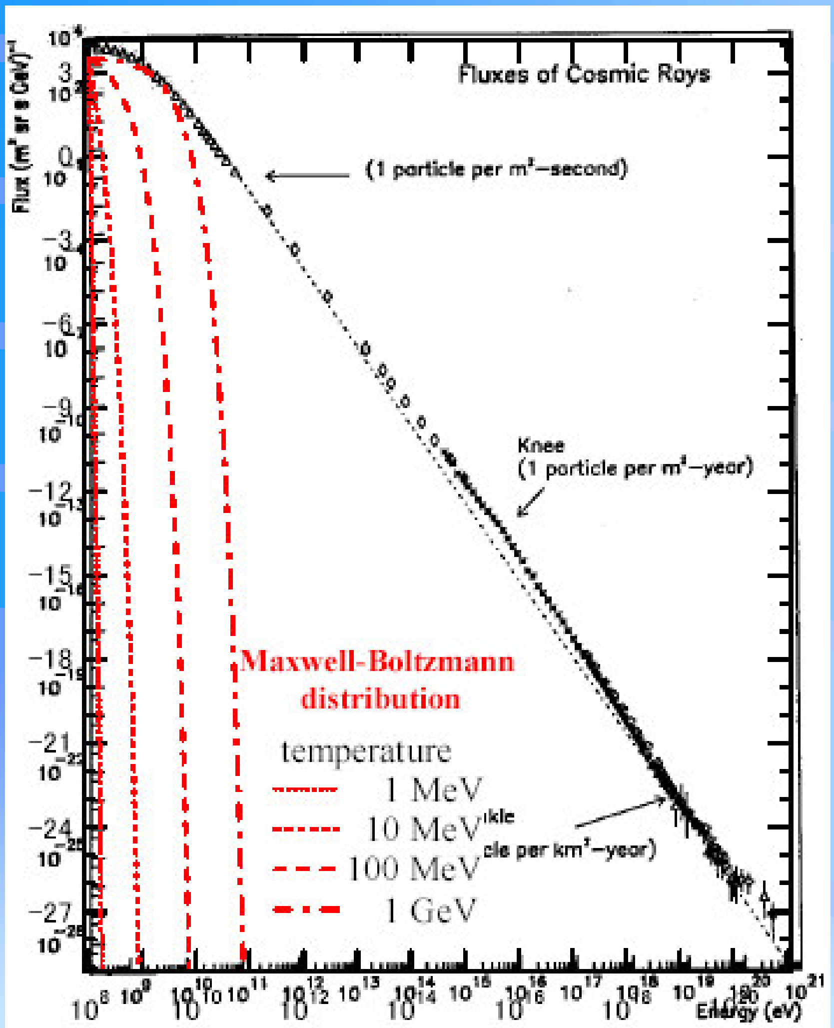
10^{18} eV < E (above "ankle")

(extragalactic origin)

100 TeV = 10^{14} eV



Thermal vs. Power law



(Terasawa, 2001)

No doubt CR's are *not* thermal!

Huge difference at high energy

The Spectrum - II

Composition

~79% of nucleons are protons

~14% of nucleons are within helium nuclei

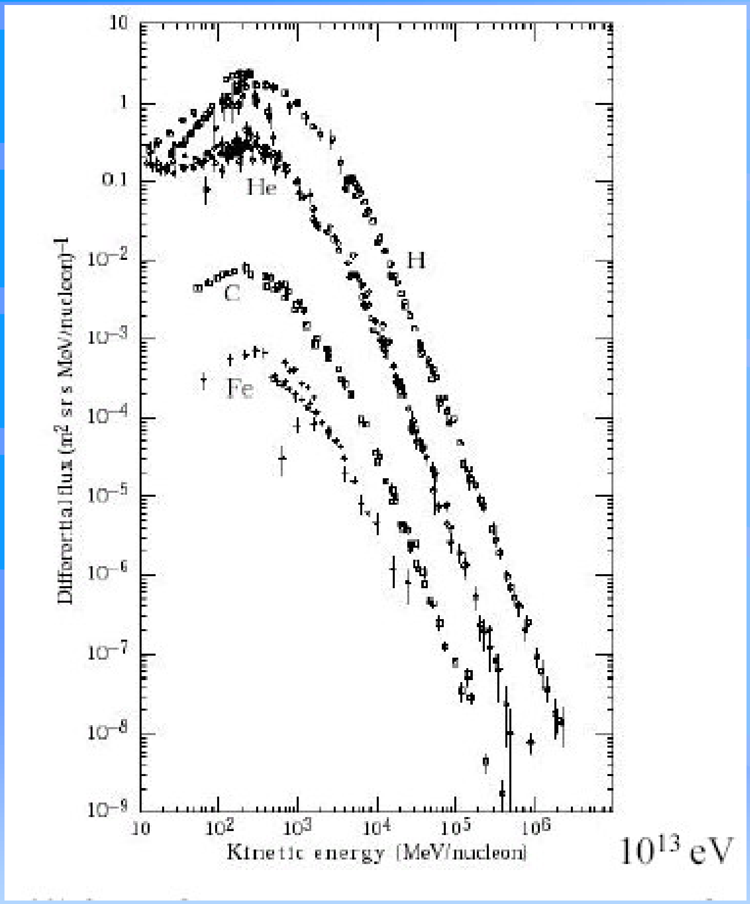
Z	element	abundance
1	H	485
2	He	26
3-5	Li-B	0.40
6-8	C-O	2.20
9-10	F-Ne	0.30
11-12	Na-Mg	0.22

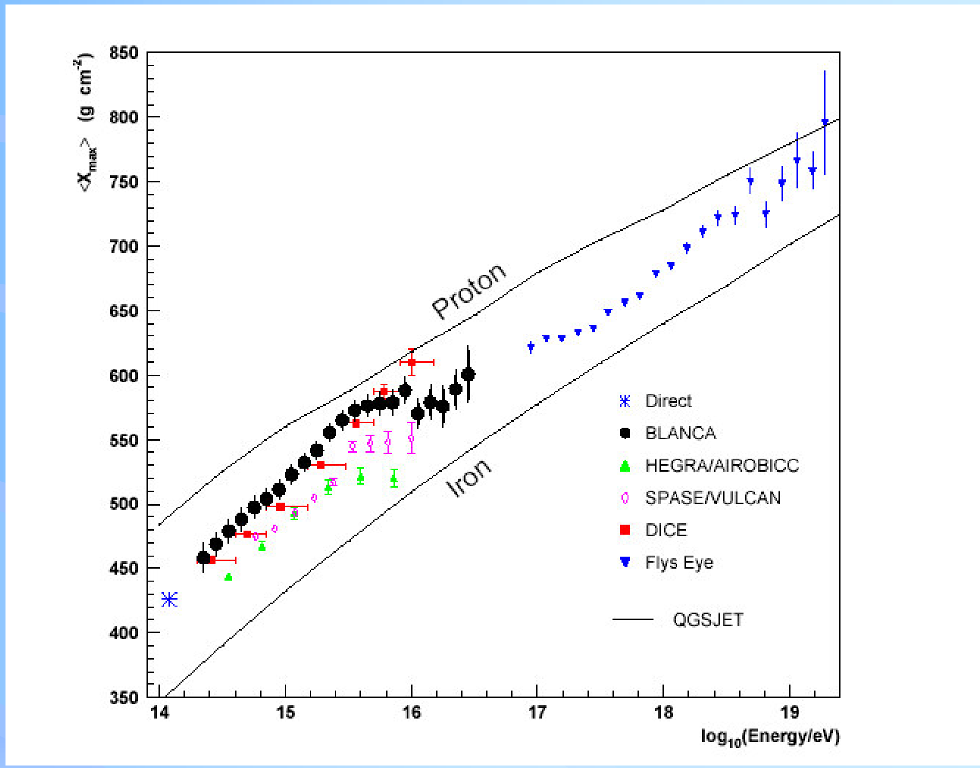
Z	element	abundance
13-14	Al-Si	0.19
15-16	P-S	0.03
17-18	Al-Ar	0.01
19-20	K-Ca	0.02
21-25	Sc-Mn	0.05
26-28	Fe-Ni	0.12

Above 10 GeV, 10^{-4} antiprotons/proton

No evidence for primary component of antiprotons

Composition





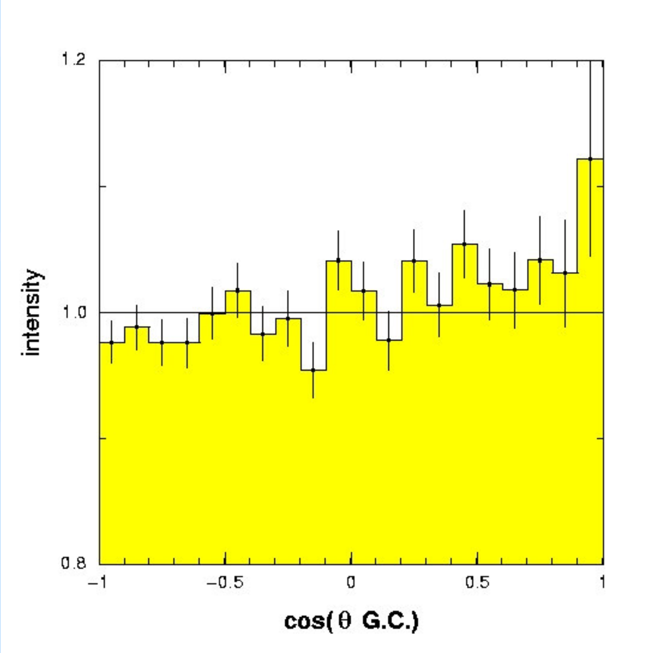
The Spectrum III - Anisotropy

2 kind of analysis

Harmonic Analysis

Aiming to find angular modulations

Smaller E, high statistics



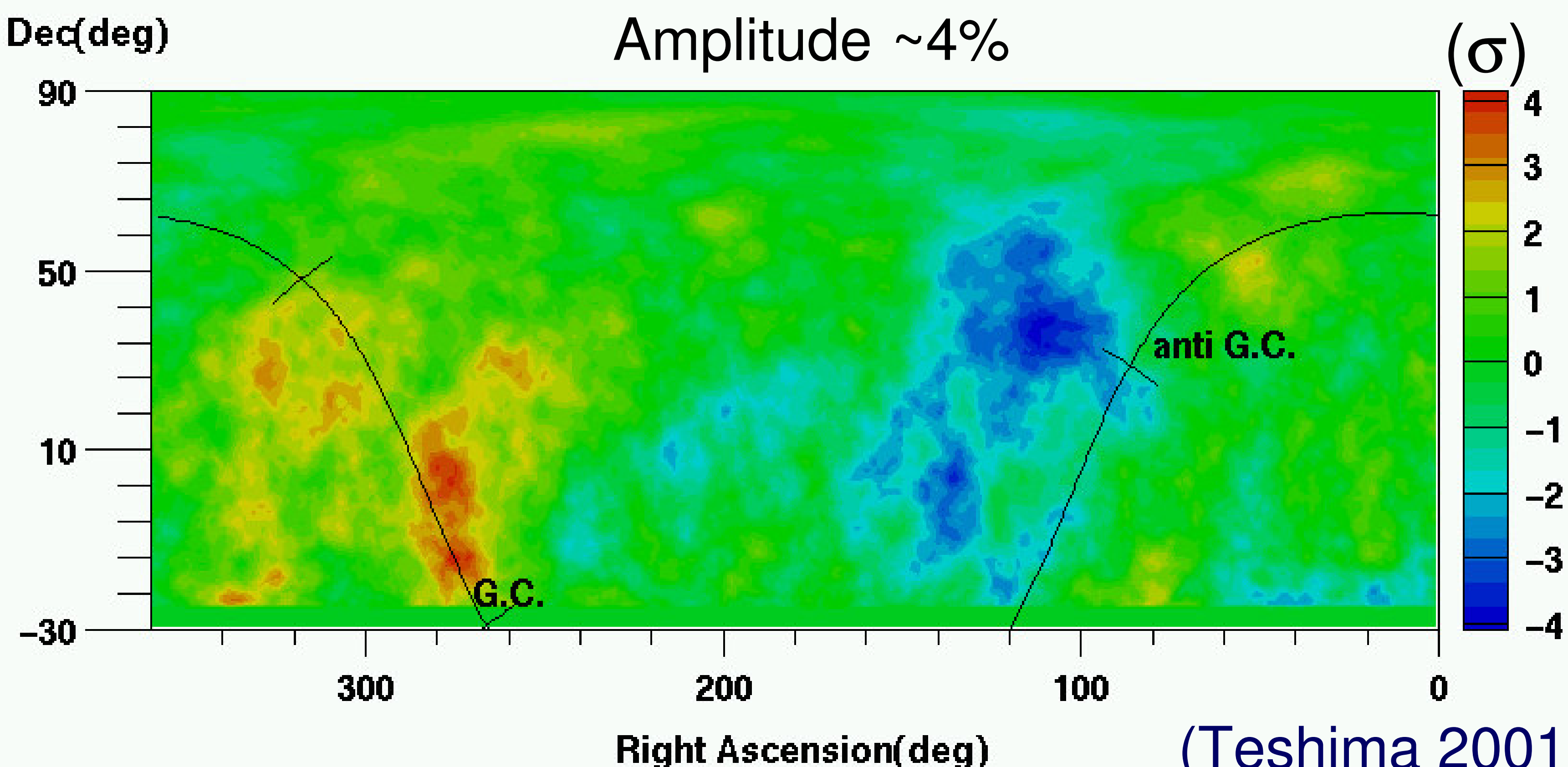
Point Sources

Doublets, triplets, …

Larger E, small statistics

H.A. - AGASA

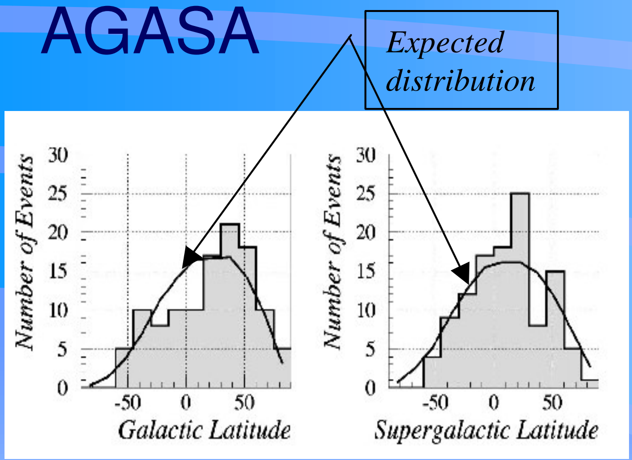
AGASA - 15 years - 284000 events E≤10^{18} eV

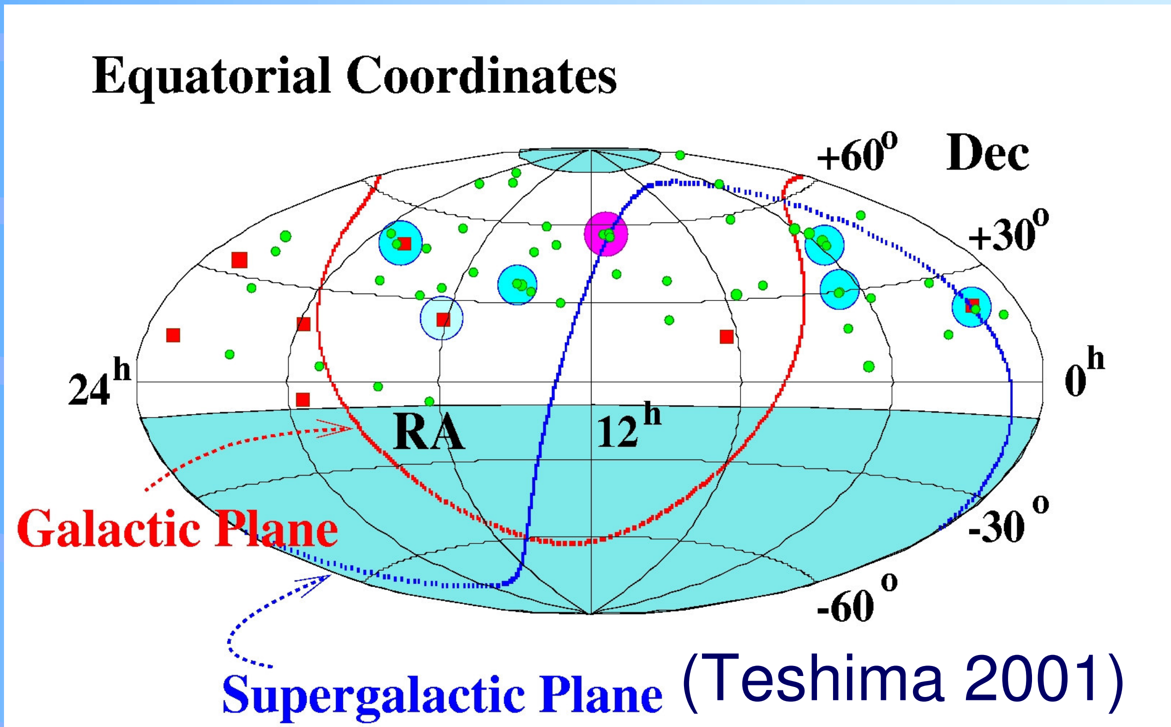


(Teshima 2001)

Point sources - AGASA

Arrival directions of 59 events > 4 x10^{19}eV observed by AGASA





(Teshima 2001)

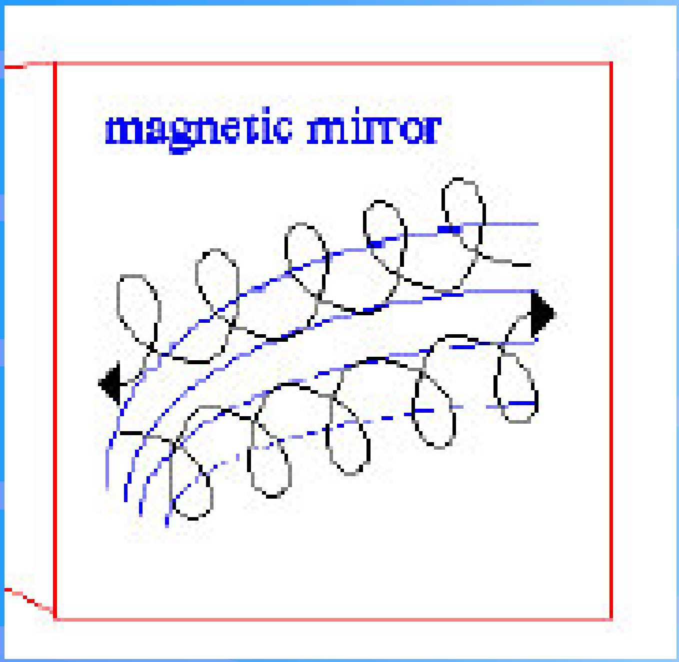
No Large Scale Anisotropy.
Event Clusters: 1Triplet and 6 doublets P(chance) ~ 0.07%.
Interacting Galaxy VV141 in the direction of triplet at 100Mpc.

Clusters < 4^0

Cluster	Exp.	Date	log *E*	R.A.	Dec.	*l*	*b*	S.G.Lng.	S.G.Lat.
Triplet #1	HP	810105	19.99	20.00	20.00	132.70	−41.70	318.10	−0.79
	AG	931203	20.33	18.91	21.07	130.48	−41.44	318.11	0.89
	AG	951029	19.71	18.53	20.03	130.18	−42.51	317.02	0.93
Triplet #2	AG	920801	19.74	172.30	57.14	143.20	56.65	56.82	2.04
	AG	950126	19.89	168.65	57.58	145.53	55.10	55.51	0.51
	AG	980404	19.73	168.44	55.99	147.51	56.23	56.84	−0.37
Doublet #1	AG	910420	19.64	284.90	47.79	77.88	18.45	24.95	57.83
	AG	940706	20.03	281.36	48.32	77.58	20.86	29.35	57.26
Doublet #2	AG	860105	19.74	69.03	30.15	170.08	−11.50	350.38	−33.33
	AG	951115	19.69	70.39	29.85	171.09	−10.79	351.23	−34.31
Doublet #3	HP	860315	19.71	267.00	77.00	108.50	30.10	30.83	27.99
	AG	960513	19.68	269.05	74.12	105.11	29.79	31.09	30.94
Doublet #4	HP	720525	19.65	239.00	79.00	113.30	34.60	35.05	23.27
	YK	911201	19.62	235.40	79.80	114.60	34.60	34.88	22.22
Doublet #5	VR	610319	19.73	154.10	66.70	143.00	44.30	44.59	0.35
	HP	850313	19.62	157.00	65.00	143.60	46.30	46.63	0.24
Doublet #6	HP	661008	19.67	164.00	50.00	159.00	58.80	61.08	−5.53
	YK	750317	19.67	163.70	52.90	154.90	56.80	58.45	−4.16
Doublet #7	HP	740228	19.86	264.00	58.00	86.36	32.52	41.02	45.22
	AG	980330	19.84	259.16	56.32	84.39	35.17	45.44	45.35
Doublet #8	HP	760206	19.62	165.00	64.00	140.98	49.43	49.49	2.41
	HP	850313	19.62	157.00	65.00	143.60	46.30	46.63	0.24

(Uchihori et al., 2000)

The magnetic mirror

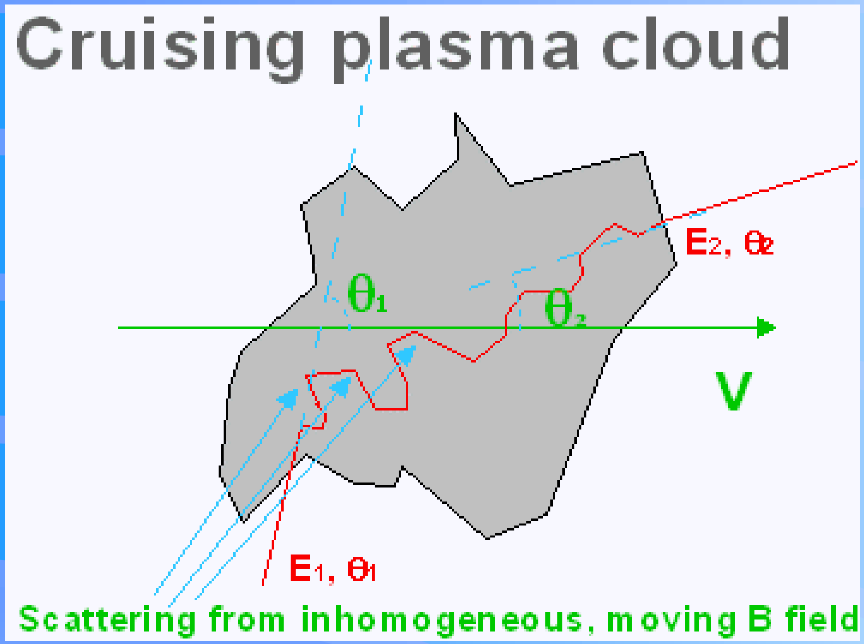


Energy exchange
drift→revolution

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

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

Fermi mechanism - 2nd order



Scattering by B-field

Stochastic process

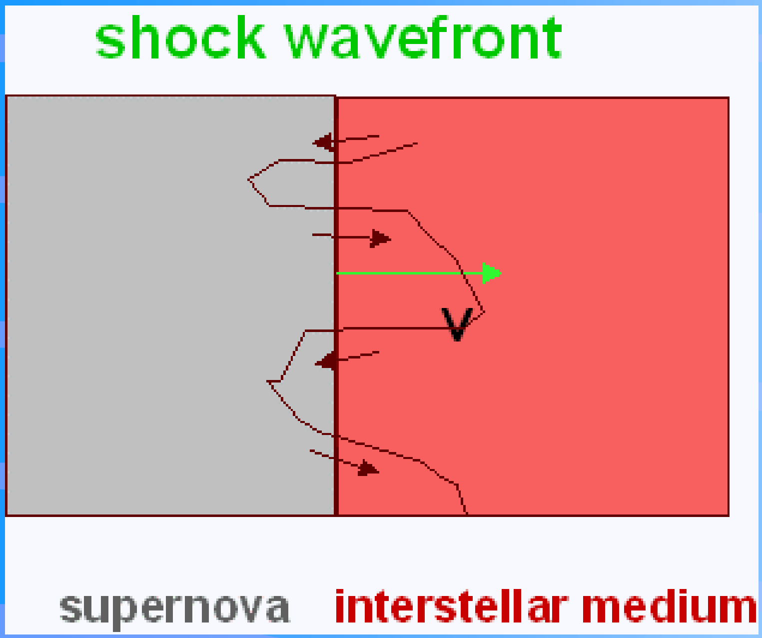
$$\Delta E \propto \beta^2 E$$

Expect:

Slow, inefficient

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

Fermi mechanism - 1st order



As before, scattering by B-field irregularities
Momentum gain:

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

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

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

$$\text{Speed=U}_1 > \text{Speed=U}_2$$

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

Expect:
fast, efficient

Shock compression ratio (R)

Spectral index, time constant

Power law spectrum

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

Fermi 2nd order:

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

τ_{acc}>10^8 yr! KO

Fermi 1st order:

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

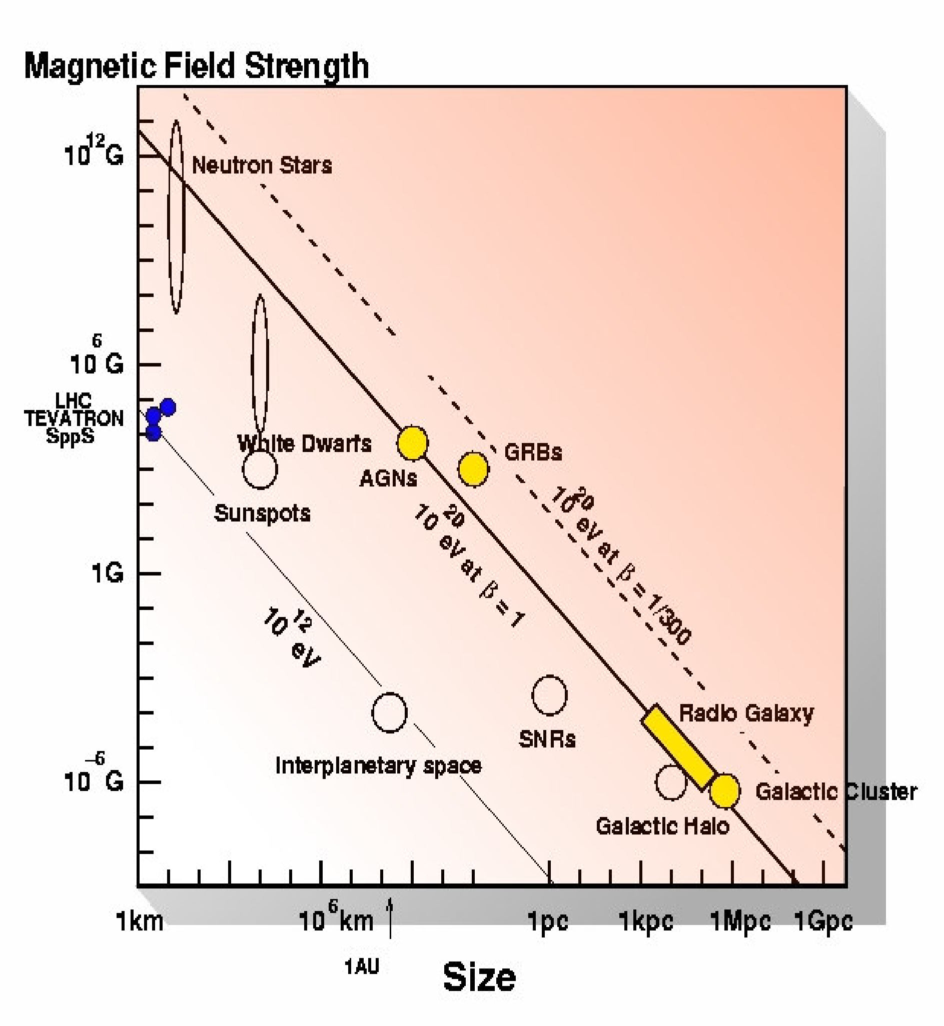
τ_{acc}~1 month! OK

Maximum energy

Simple estimate of max. energy (Hillas):

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

β: plasma speed
B: mag field
L: source size



Bounds

By plugging typical supernova numbers
$E_{max}<1\ 10^{15}\ eV$

By assuming multiple shock acceleration
$E_{max}<1\ 10^{18}\ eV$

$\rightarrow$*Very difficult to account for* $E>10^{20}\ eV$

Compact sources

Just meaning: *non* electromagnetic acceleration

Various mechanisms proposed:

Black hole accretion disks

Gamma ray bursts

Topological defects (monopoles, cosmic strings, ..)

UHE ν's from decays of high mass particles

Summary of predictions

CR's of E> 10^{15} eV are not easy to explain

CR's of E>10^{19} eV are *difficult* to explain

Require

either

Large source size

and/or

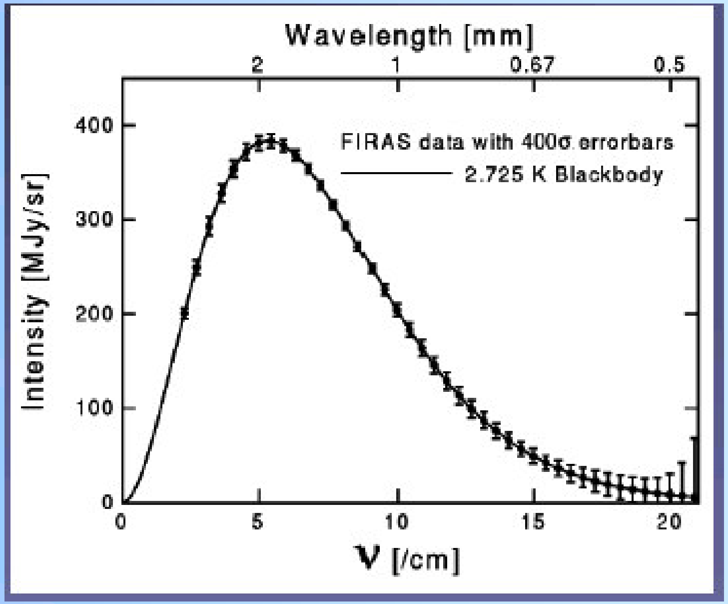
Strong B-field

or

Exotics

Neither easily available …

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



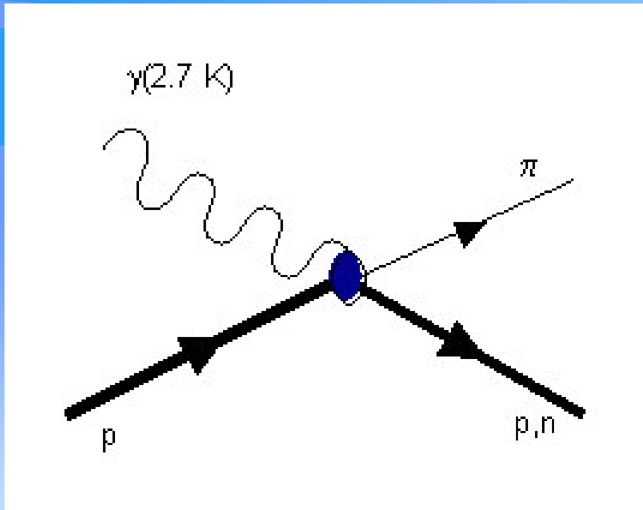
Penzias, Wilson
&
the Antenna

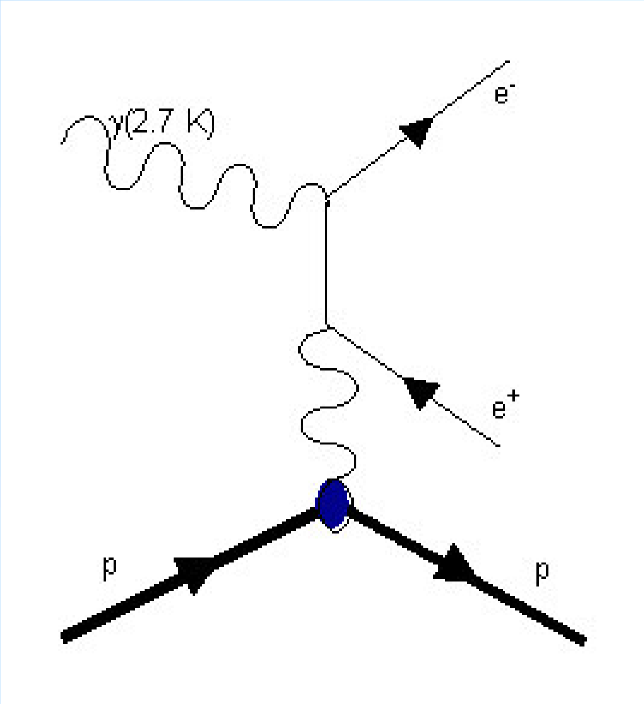
The CMB spectrum
(by FIRAS)

CMB photons

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

Possible CR interactions





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

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

(G, Z&K - 1965)

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

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

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

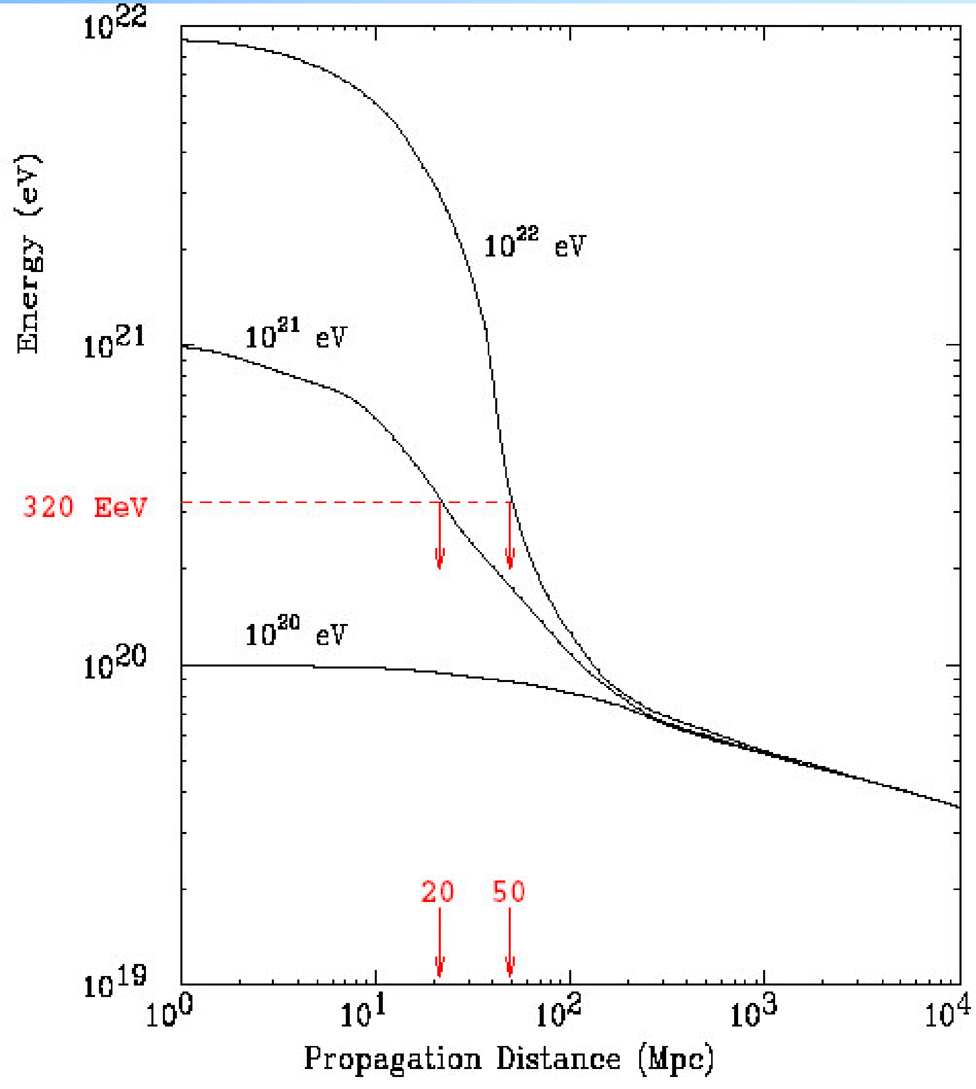
The moral:

CR's above threshold bound to lose energy

The GZK cutoff

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

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



Cosmic Rays Detection

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

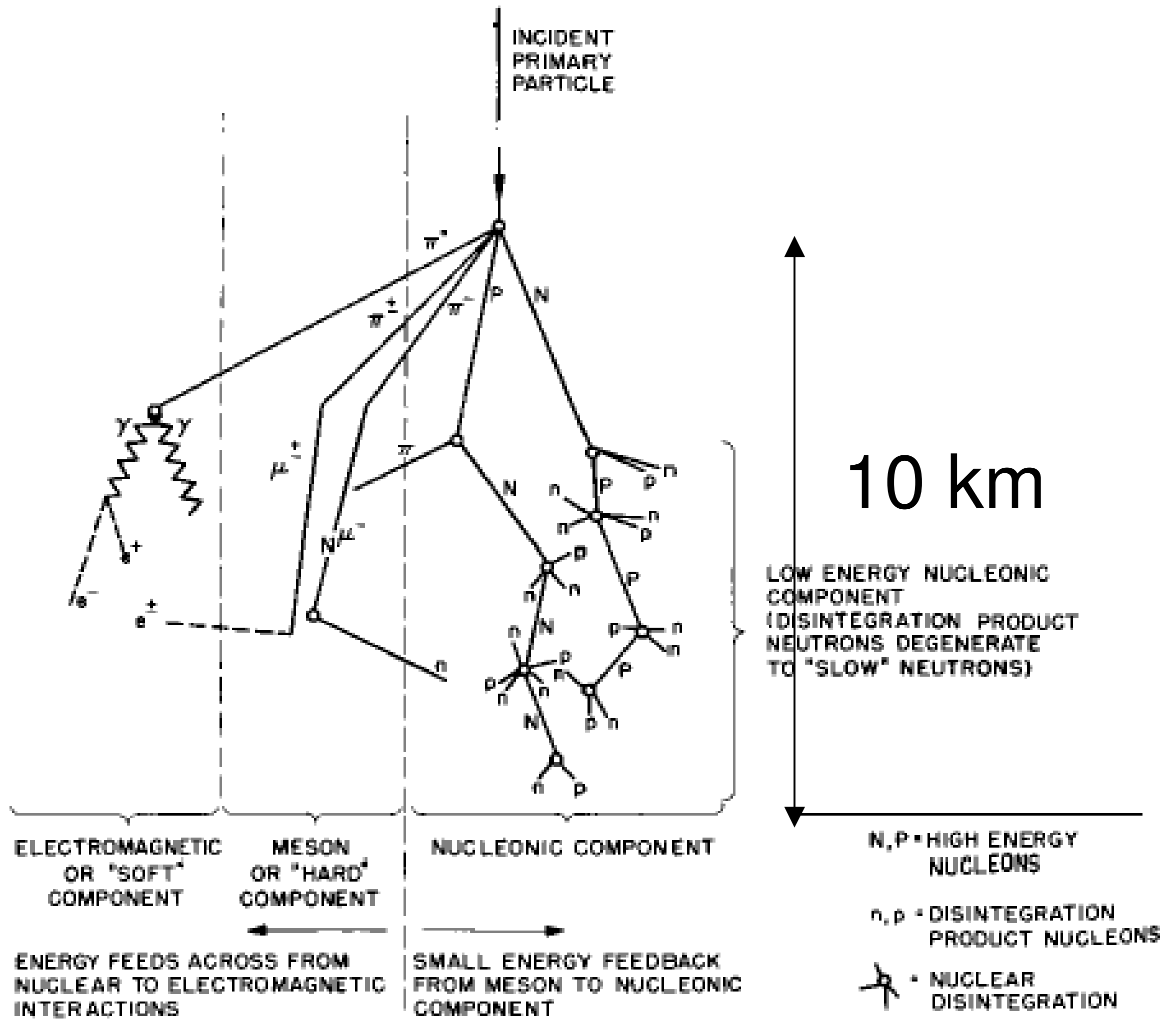
Not suitable to deal with small fluxes

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

Different techniques:

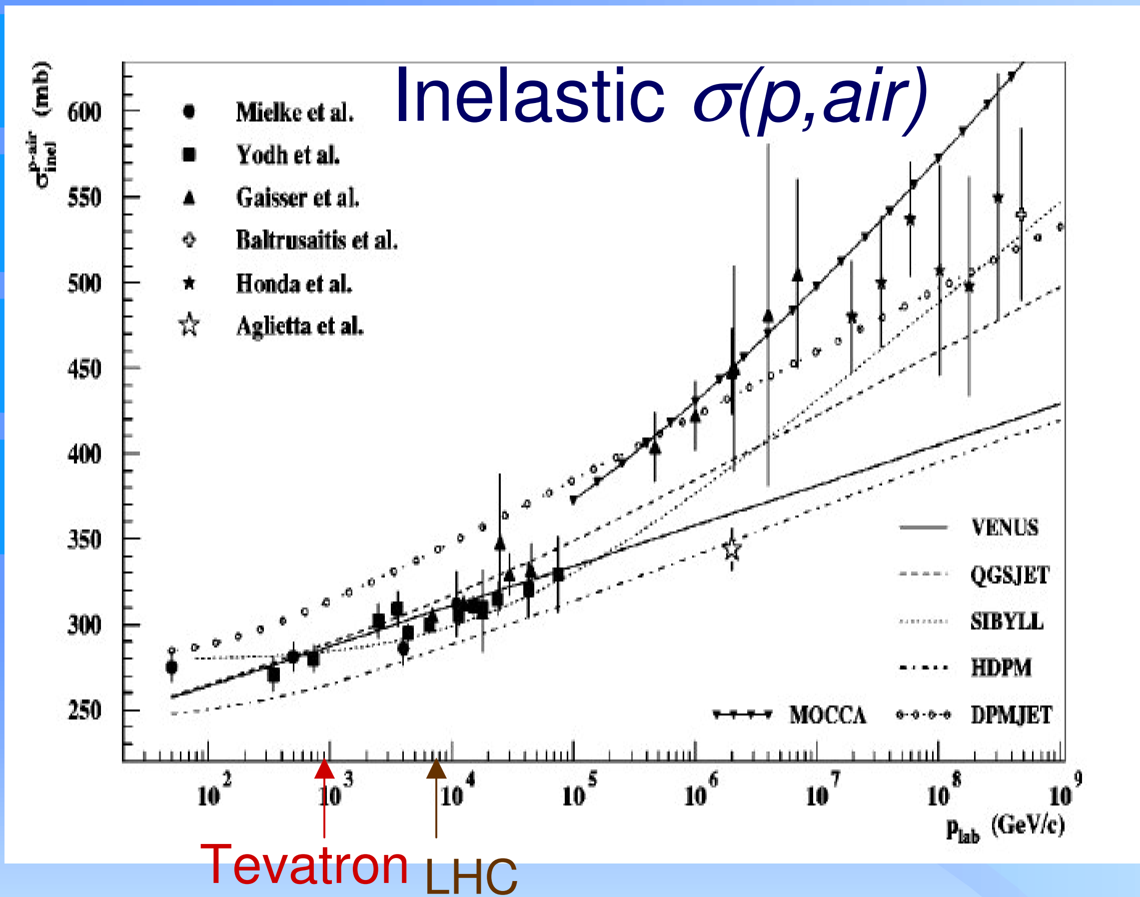
- *Ground arrays (scintillators, water Cherenkov)*
- *Air Cherenkov telescopes*
- *Fluorescence detectors*

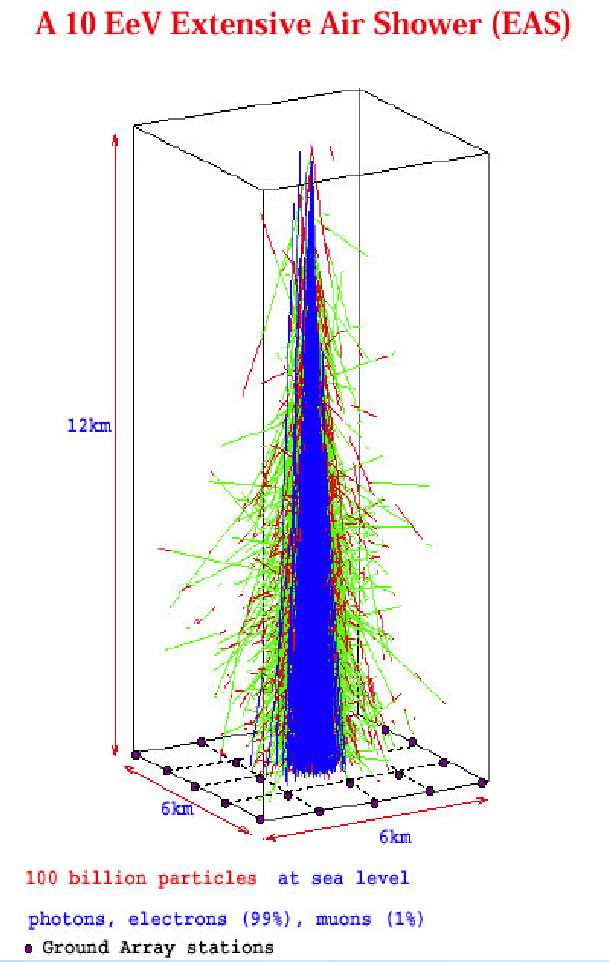
EAS's - I


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

EAS's - II

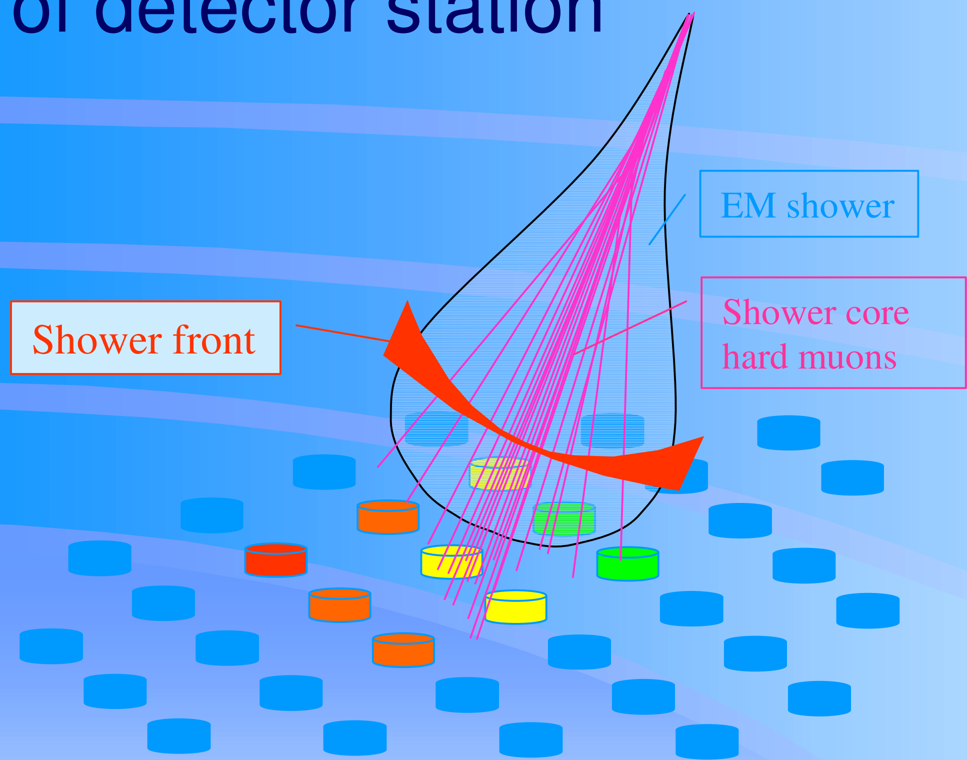
Data & MCarlo

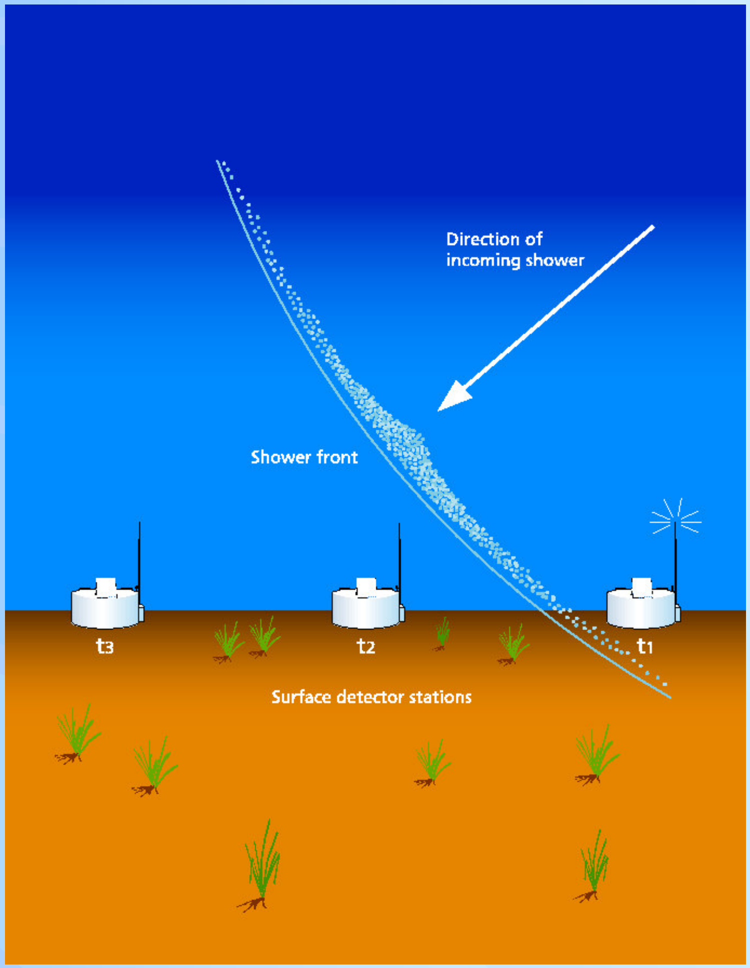




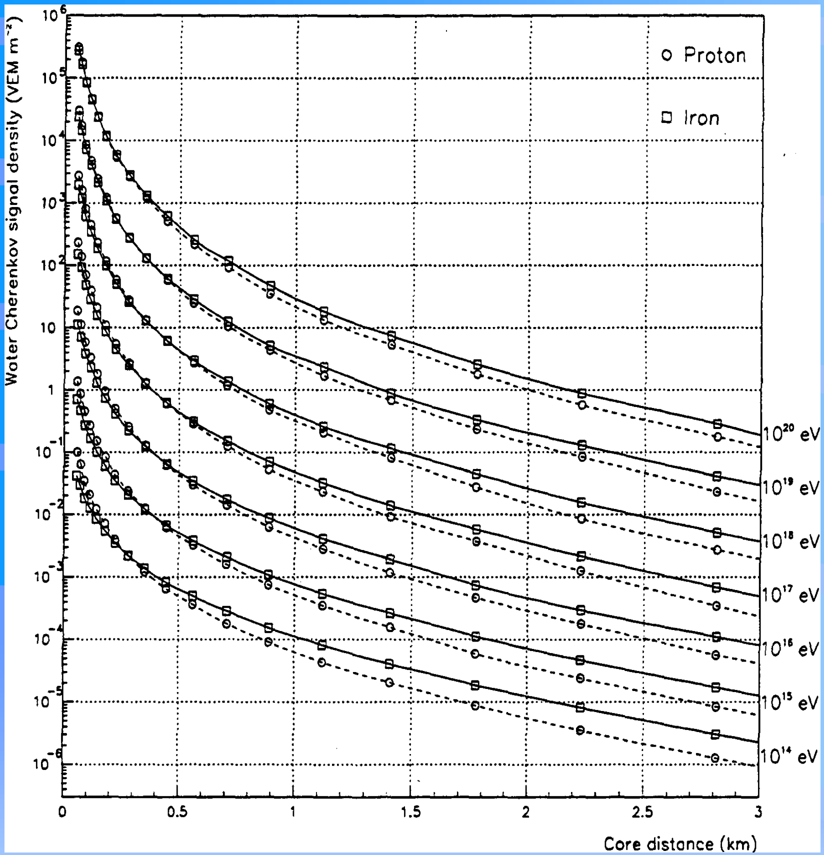
Ground Array

EAS sampled by a number of detector station





Ground Array - Direction



Time + Transverse shape

Resolution vs. energy:

$$\Delta\theta \sim 2^\circ \text{ at } 10^{19}\text{eV} \rightarrow 1^\circ \text{ at } 10^{20}\text{eV}$$

$$\Delta x, y \sim 80\text{m at } 10^{19}\text{eV} \rightarrow 40\text{m at } 10^{20}\text{eV}$$

Ground Array - Energy

- Measured density extrapolated to a reference point
  - *Typ. ρ(600m) to ρ(1000m) to minimize fluctuations*
- Compare to Monte Carlo simulation
- Good linearity with $E_{primary}$
- Results somewhat depending on :
  - *Primary interaction (physics)*
  - *Composition (p vs. Iron)*
- E range fixed by detector spacing

Ground Array - Composition

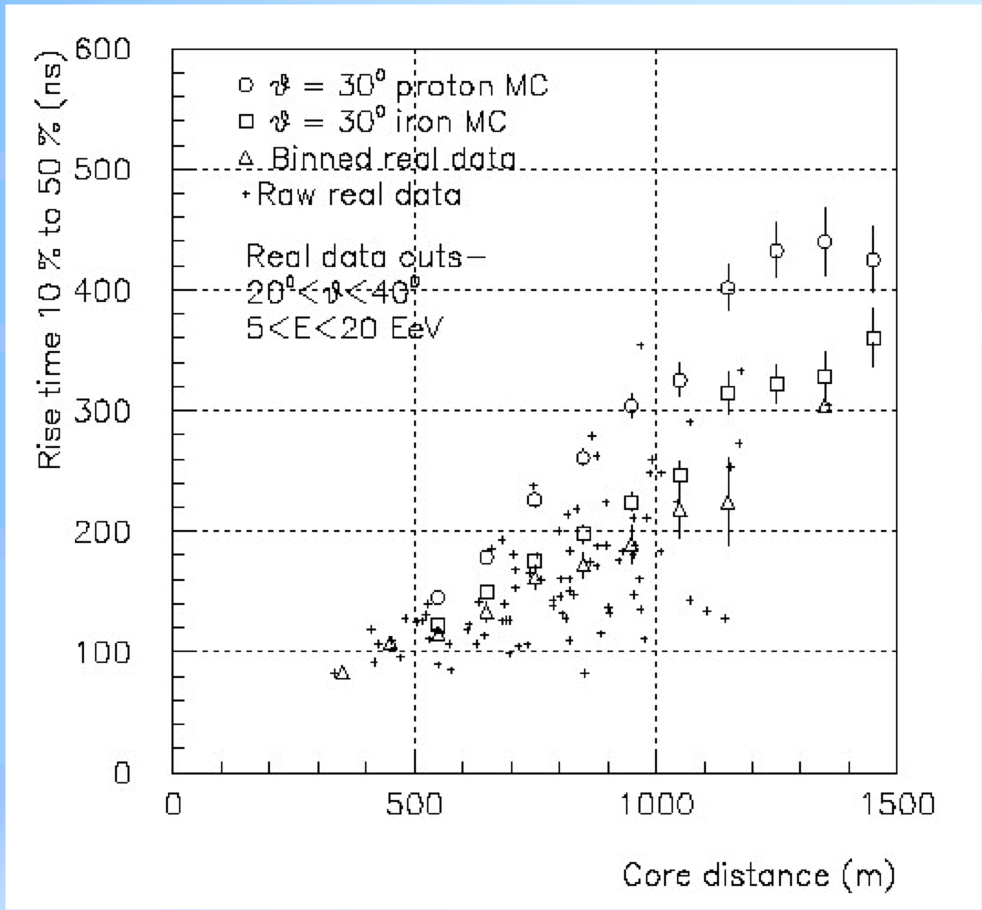
Iron nucleus:

less cascade steps before reaching ε_π

$\Rightarrow$ *more μ's*.

$\Rightarrow$ *less EM energy*

$\Rightarrow$ *smaller muon rise time*



Fluorescence detector

EAS: *90 % electrons*

Think of atmosphere like a giant calorimeter
Air molecules excited by fast electrons
Lots of fluorescence light available from N_2
Put large mirrors + PMs watching the sky

But:
Need dark, clear nights + clean environment
$\rightarrow$ *~ Desert*
$\rightarrow$ *Low duty cycle ~ 10%*

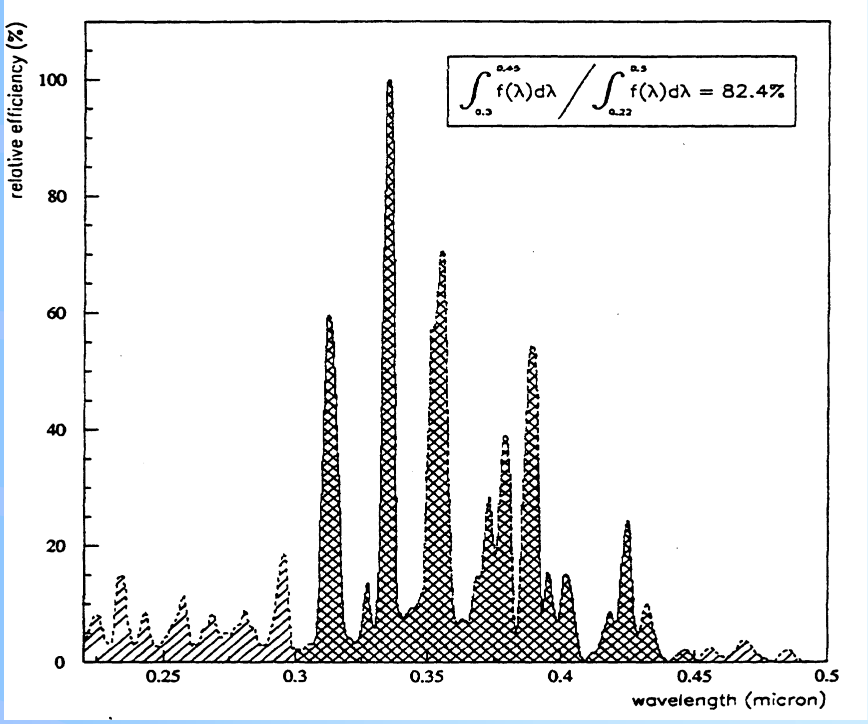
Fluorescence detector - I

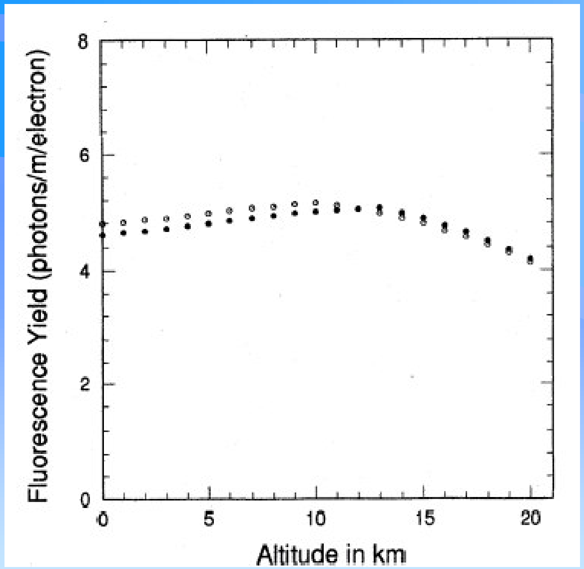
Nitrogen spectrum

Near UV

Narrow band 300-440 nm

→*Optical filtering*





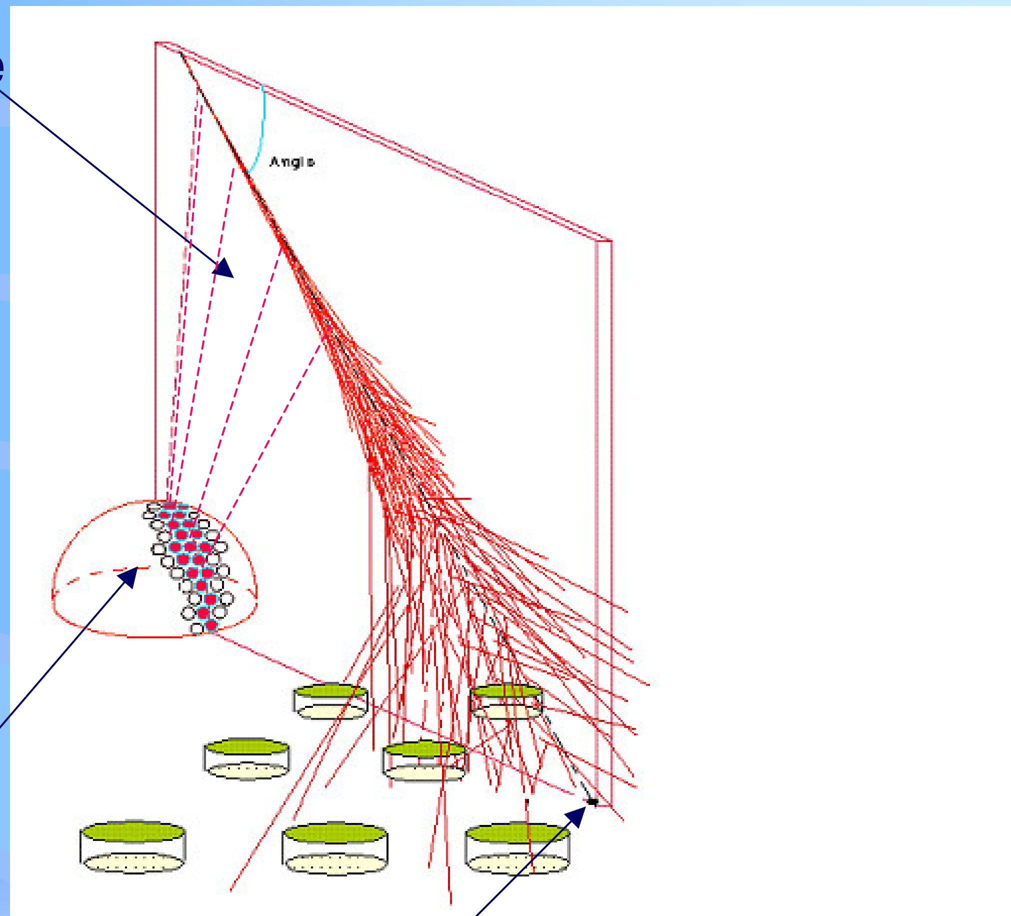
Light yield

~ 4 γ/m*electron

Fluorescence detector - II

Each PM sees one segment of the shower

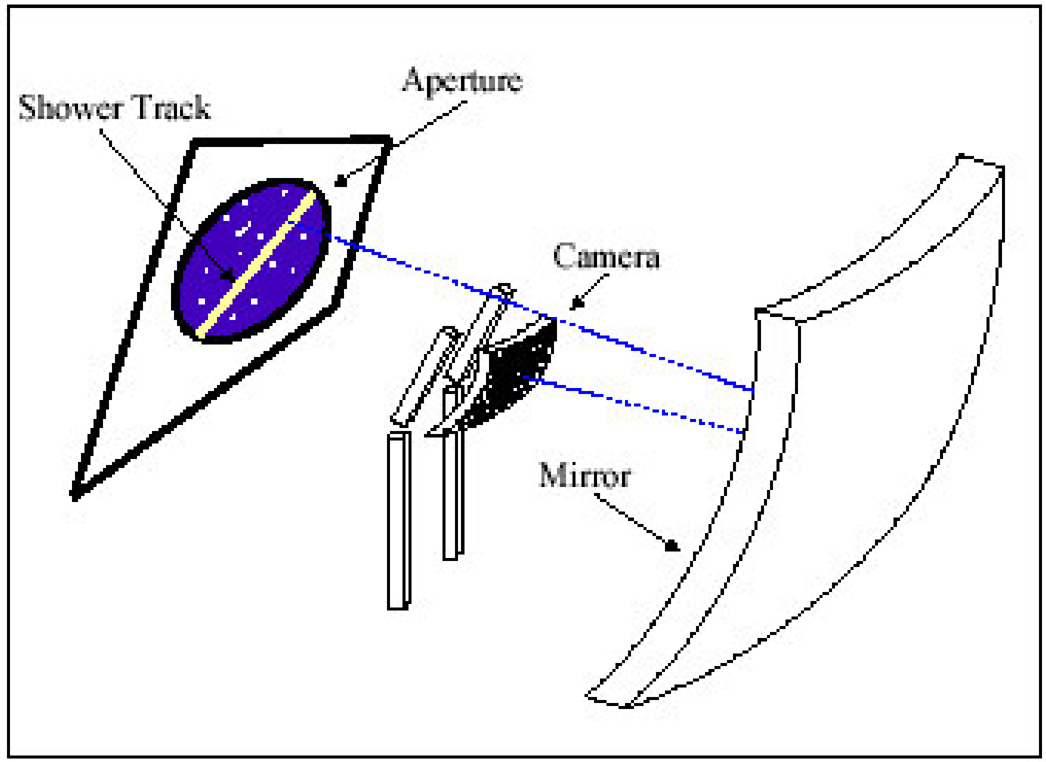
→Sequence of fast pulses by adjacent PMs



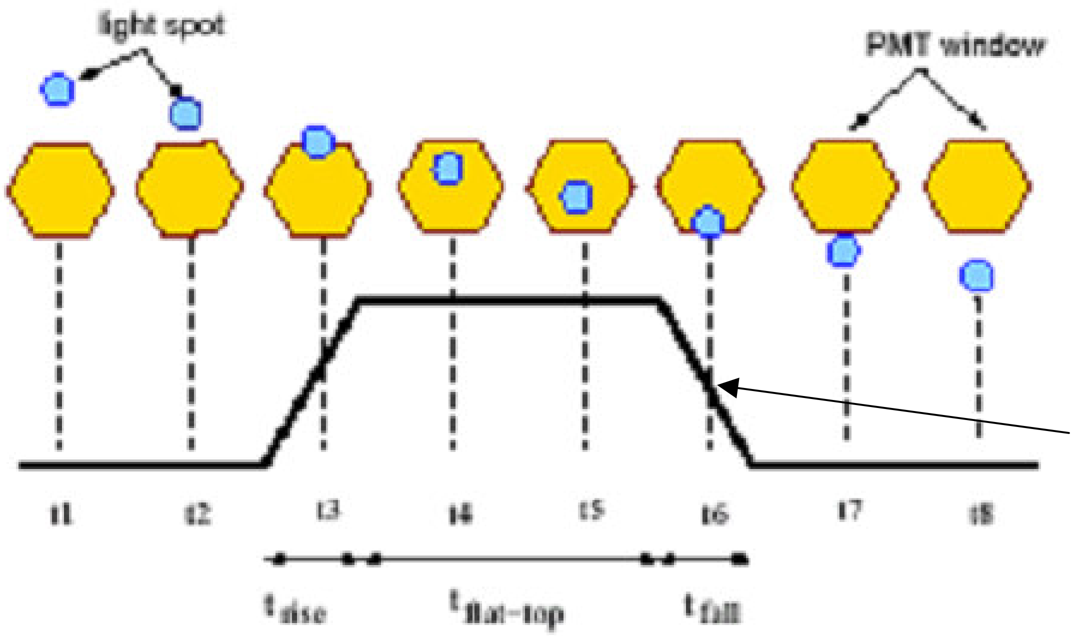
Fluorescence detector - III

Light collection
(AUGER)

Mirror size
$3 \times 3\ m^2$
Focal length:
340 cm
Camera size:
22x20 PMs



Fluorescence detector - IV

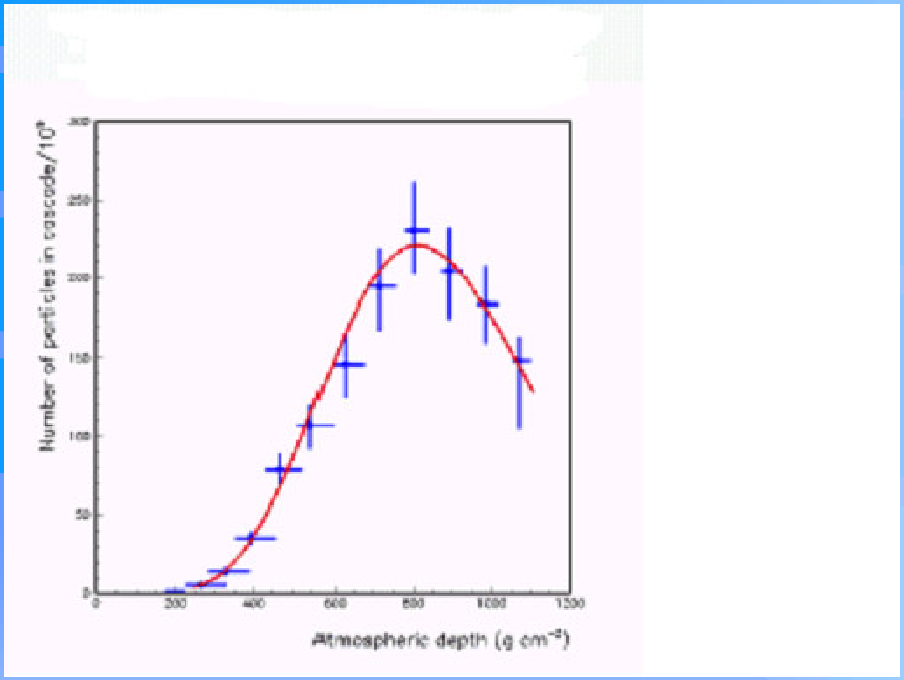


PM current

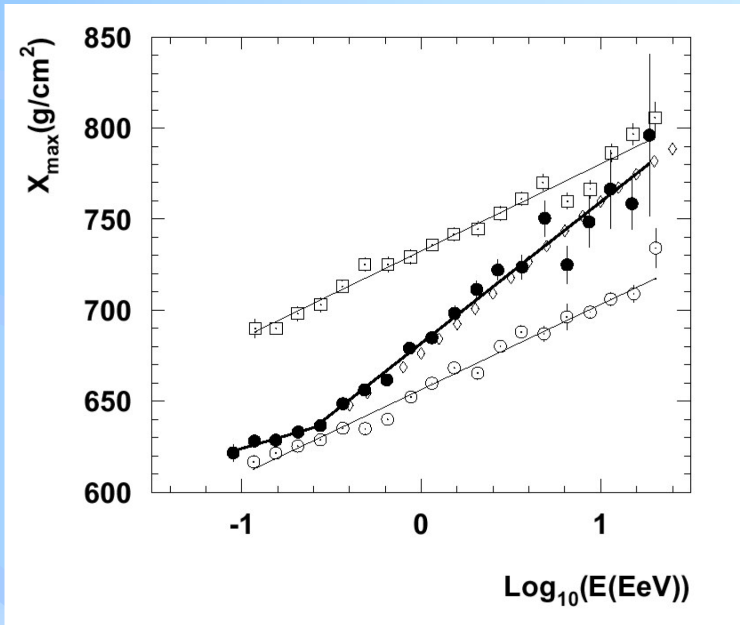
Signal formation:
one PM, sequence of time slices

Fluorescence detector - V

Unique FD capability: *longitudinal profile*



E=3.2 10^{20} eV (Fly's Eye)



Composition (Fly's Eye)

Comparison: GA vs. FD

GA

- Sampling detector
- 100% duty cycle
- Large number of simple,modular elements
- Shower parameters from x-section
- Need reliable MCarlo simulation

FD

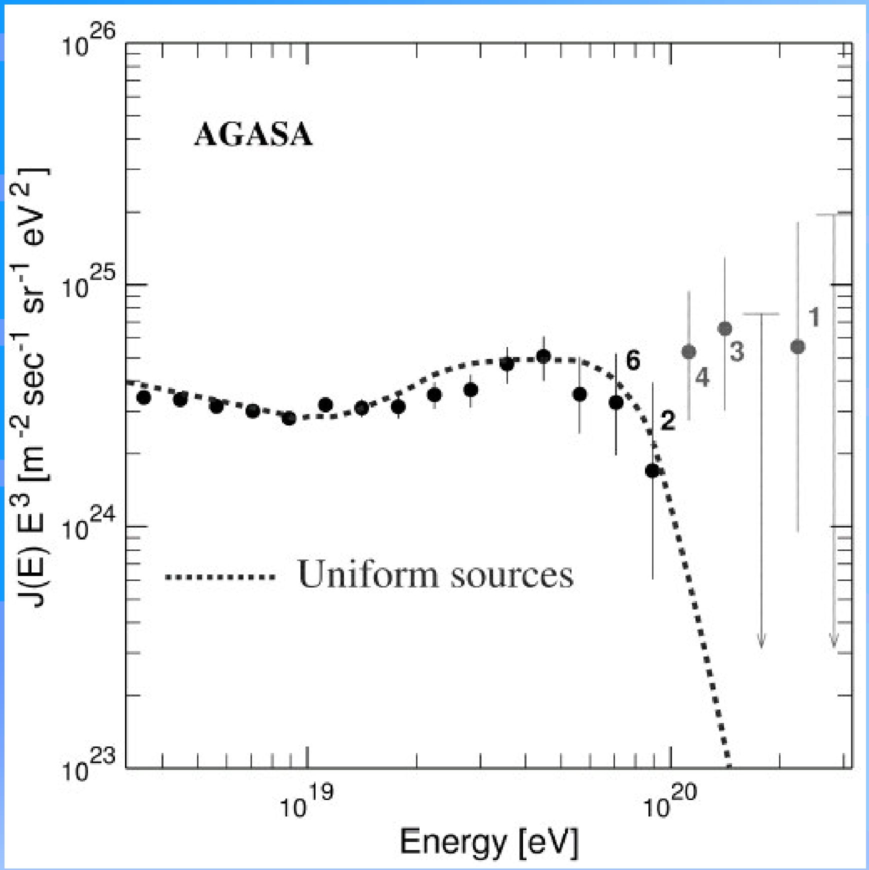
- Integral calorimeter
- 10% duty cycle
- Small number of complex stations
- Shower parameters from full shower track
- Need good atmospheric monitoring+calibration

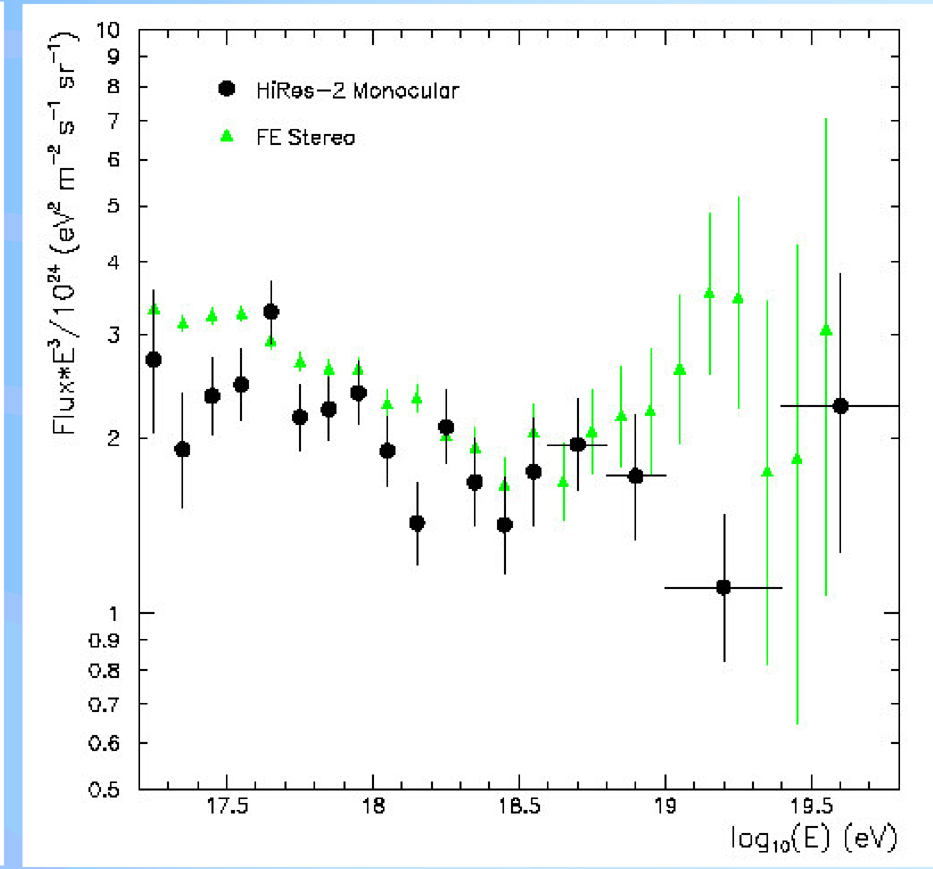
Data above 100 EeV

Existing experiments sensitive >10^{20} eV

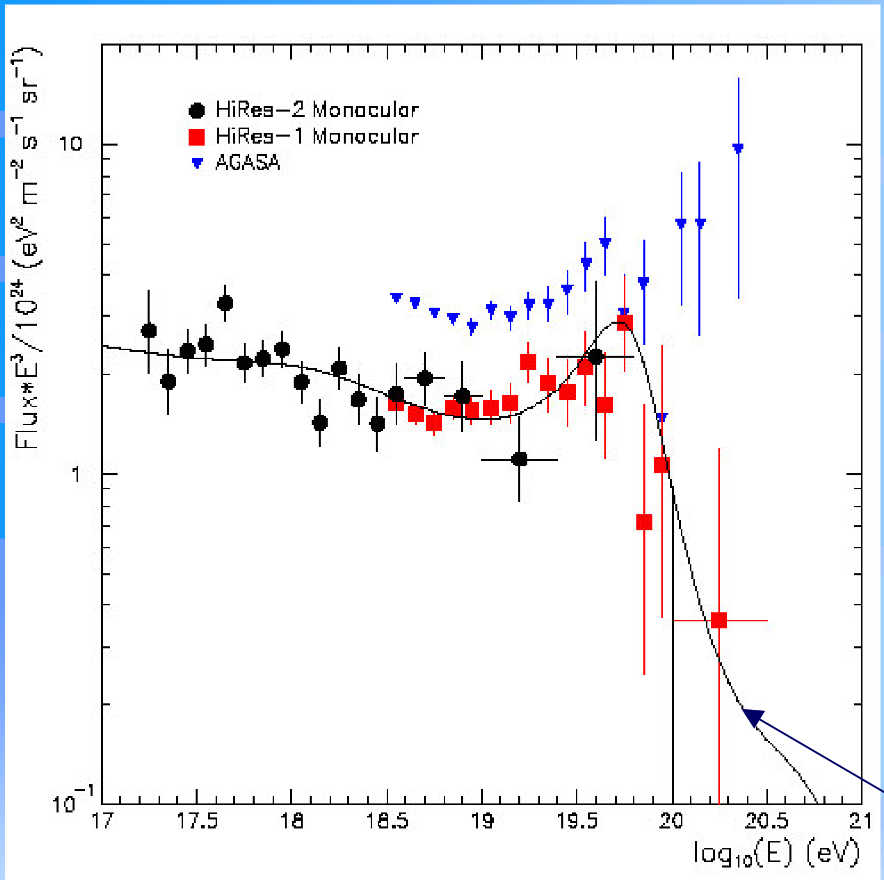
Experiment	Type	Exposure	Surface
Volcano Ranch	**GA**	***63 km²·sr·yr***	***8 km²***
SUGAR	**GA**		***60 km²***
Haverah Park	**GA**	***275 km²·sr·yr***	***12 km²***
Yakutsk	**GA**	***428 km²·sr·yr***	***58 km²***
AGASA	**GA**	***1268 km²·sr·yr***	***111 km²***
Fly's Eye (mono)	**FD**	***825 km²·sr·yr***	
Fly's Eye (stereo)	**FD**	***145 km²·sr·yr***	
HiRes1 mono	**FD**	***1090 km²·sr·yr***	

Data from AGASA, HiRes





Comparison



Flux systematics

+

Clear inconsistency above 5 10^{19}

E-scale?

Other?

GZK-compliant, model fit

Auger: GA + FD

The concept of a *large hybrid* detector

- **Cross calibration**

  Independent measurements of E_{prim}, direction and composition
- **Better control of systematic**
- **Much better identification**

  3 parameter correlation ρ_{μ}/ρ_{em}, $T_{10\%-50\%}$, $X_{max.}$
- **Stronger constraints on models**

  ρ_{μ} and ρ_{em} combined to shower profile measurement.

- **100 % duty cycle**

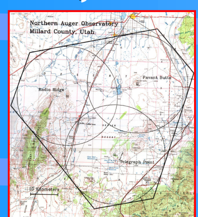
  Ground array is 100% efficient all time (versus 10% FD stereo detectors)
- **Reduced cost**

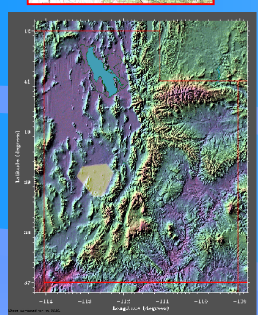
  Cost per >10^{19}eV event reduced with hybrid techniques than with FD stereo detectors,

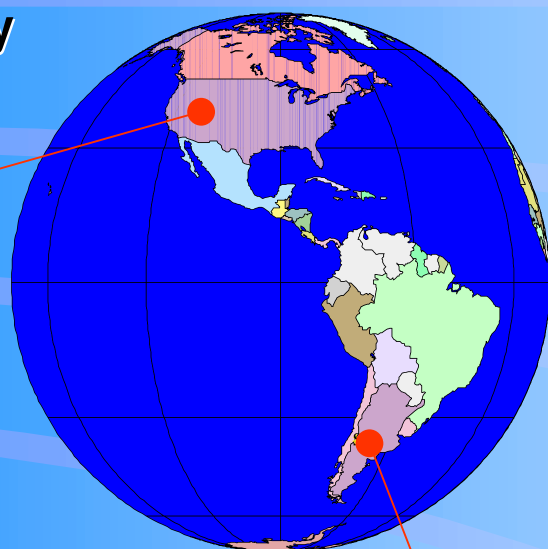
  Reduced requirements on fluorescence eyes (lower range and less pixels),

The Pierre Auger Observatory

Nothern site
Millard County
Utah, USA

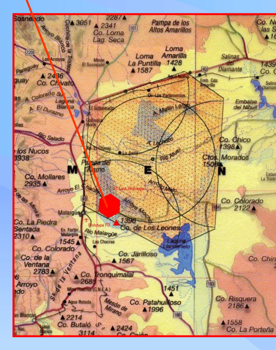




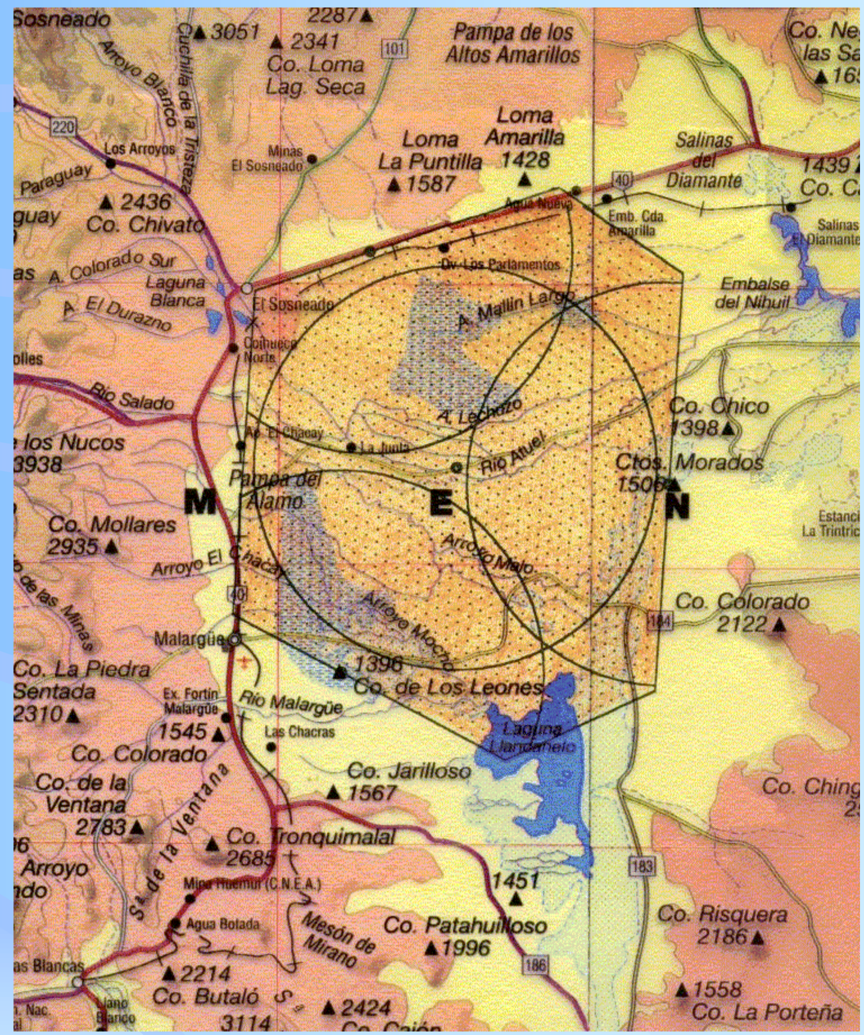


Total of
3000+3000 Km^2

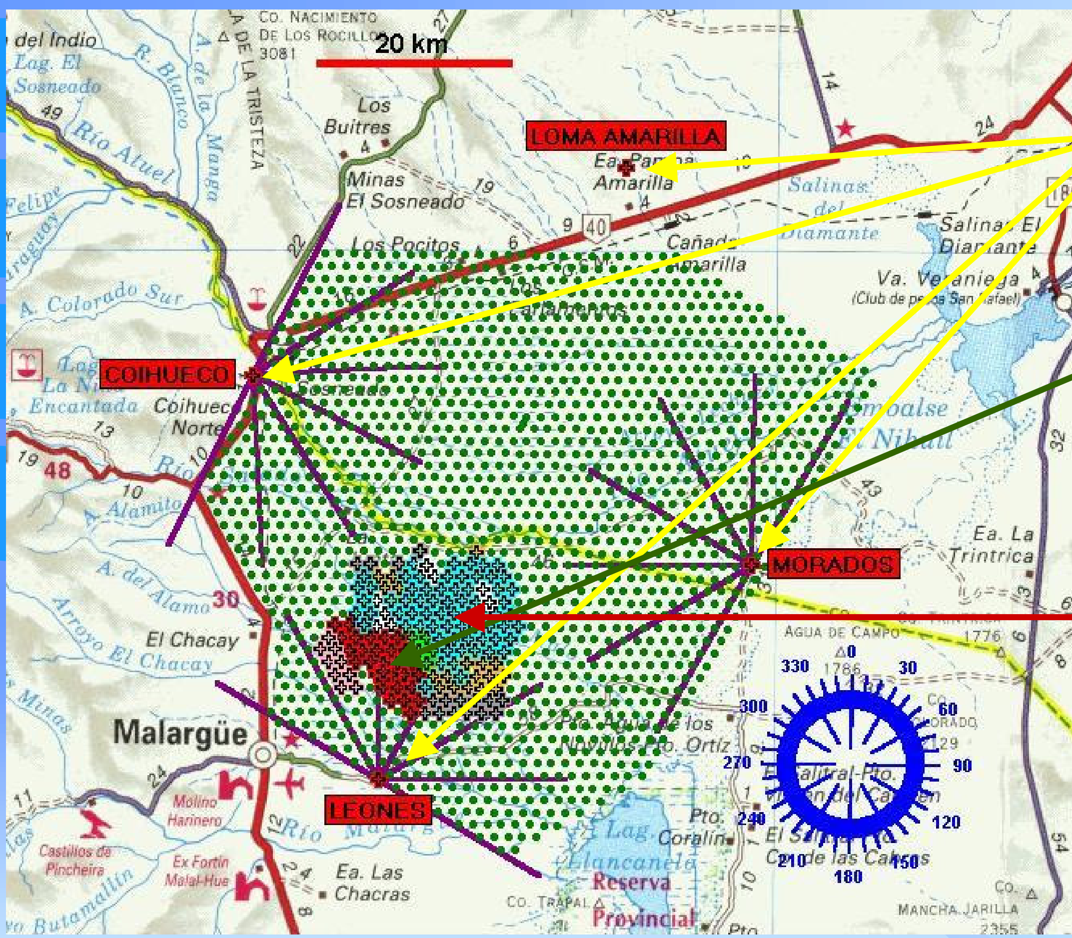
Southern site
Malargüe
Provincia de Mendoza, Argentina



Some geography



The PAO Southern Site



FD half-eyes

38 tanks prototype Engineering Array

200 tanks array Pre-Production

PAO Performance - I

Expected flux:

Integral flux > 10 EeV (>10^{19} eV) = 0.5/(km^2.sr.yr)

> 100EeV(>10^{20} eV) ~ 0.01 /(km^2.sr.yr)

1 year of AUGER, each site

E > 10 EeV	3000 events	(1281)
E > 40 EeV	300 events	(126)
E > 100 EeV	25-45 events	(15)

PAO Performance - II

Each site:

1600 SD (surface detectors); distance 1.5 km; 7000 km^2 sr

4 FD stations (fluorescence detectors); range 25 km

Duty Cycle:

SD: 100%

FD: 10%

Energy resolution (efficiency *> 90% above 10 EeV*) :

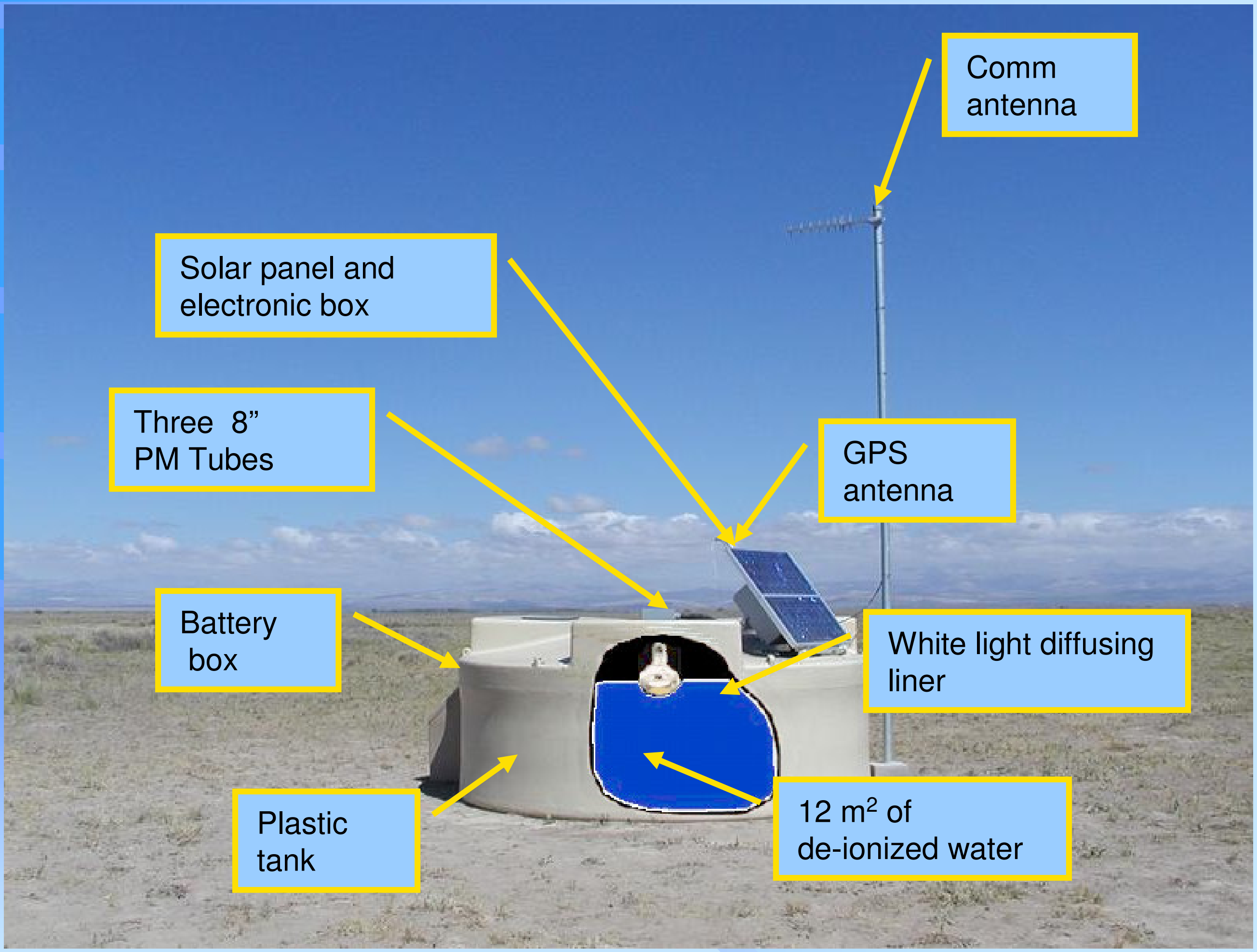
	SD	SD+FD
100 EeV	15%	10%
10 EeV	30%	20%

Angular resolution:

	SD	SD+FD
100 EeV	0.5°	0.20°
10 EeV	1.0°	0.35°

Much improved primary identification with hybrid mode

The SD tank

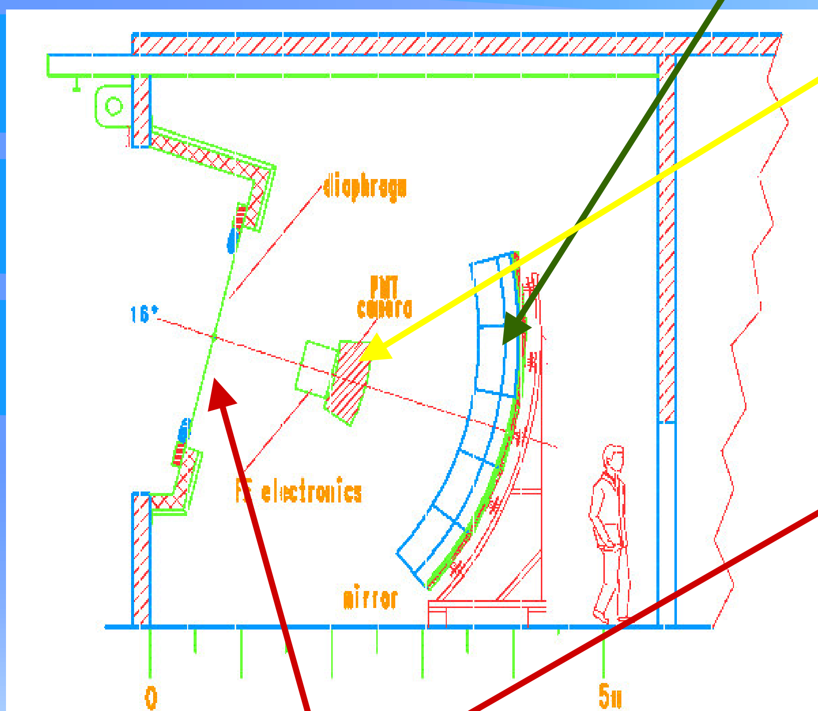

Comm
antenna
Solar panel and
electronic box
Three 8”
PM Tubes
GPS
antenna
Battery
box
White light diffusing
liner
Plastic
tank
12 m2 of
de-ionized water

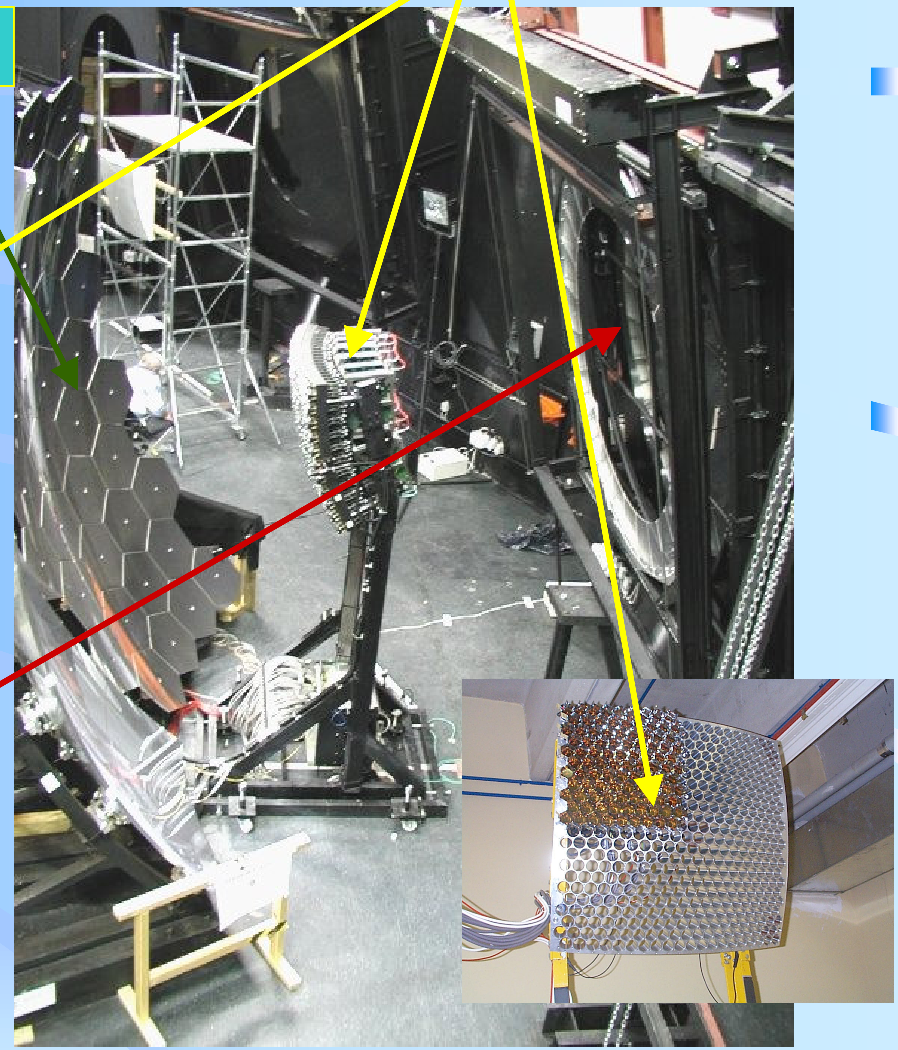
The FD telescope

4 half-eyes
24 telescopes
10560 PMs

Mirror system

PM camera



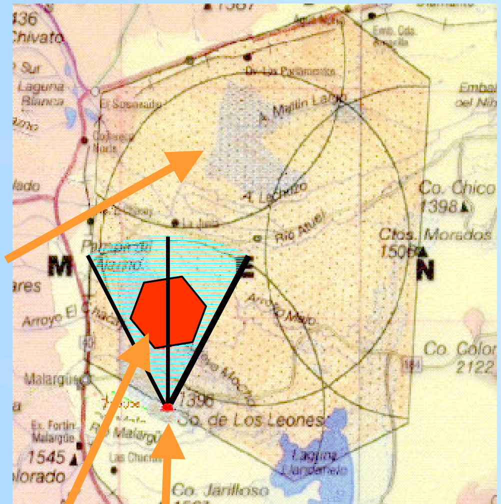


Aperture, shutter, filter,

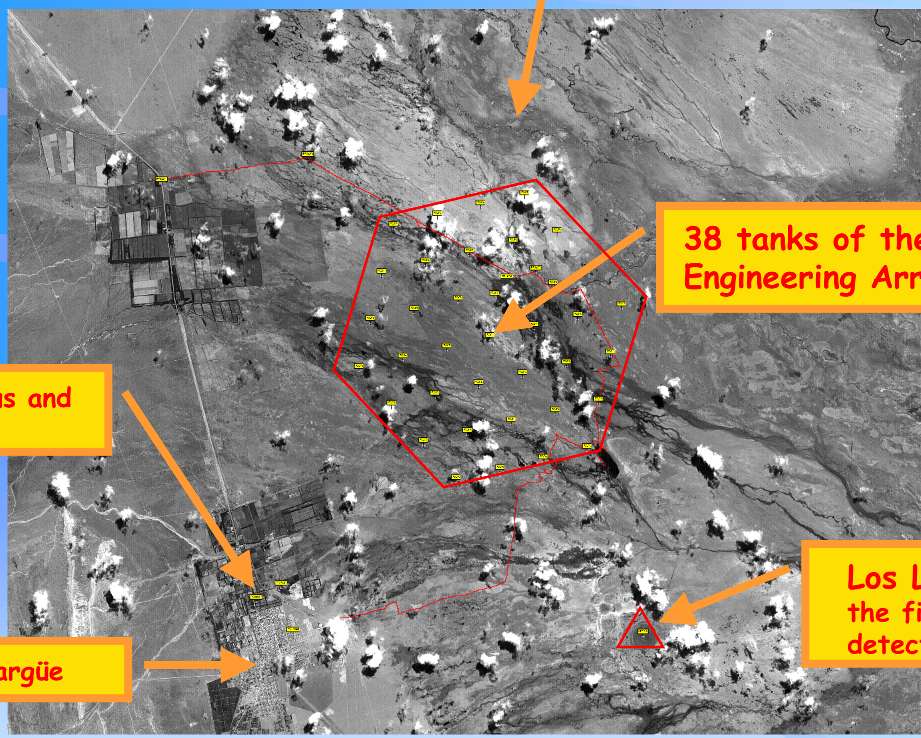
The Engineering Array

Engineering Array :
1/40 of the Surface Detector

38 tanks + 2 Fluorescence Telescopes



The pampa amarilla, 3000 km^2 of grassland



38 tanks of the Engineering Array

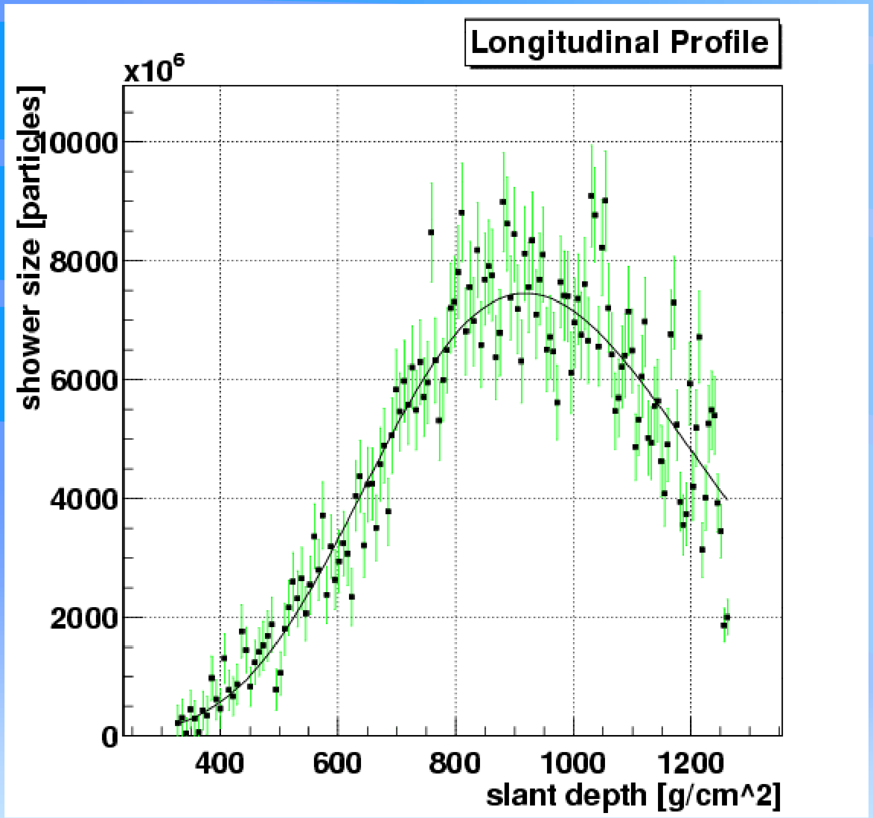
Central campus and Assembly Hall

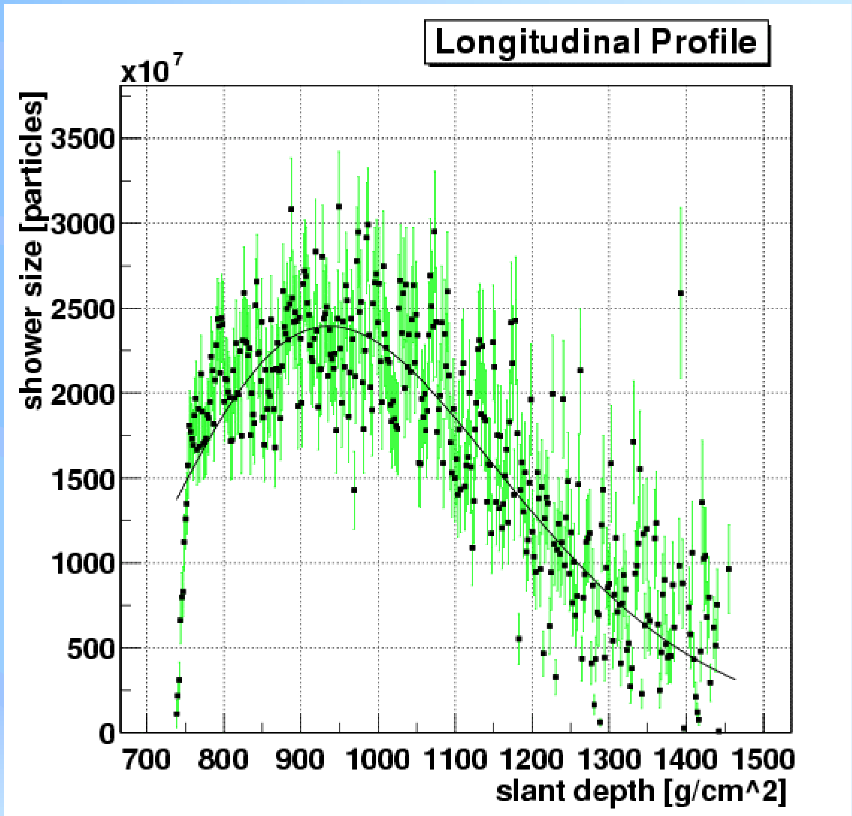
Town of Malargüe

Los Leones: the first 2 fluorescence detectors overlooking the EA

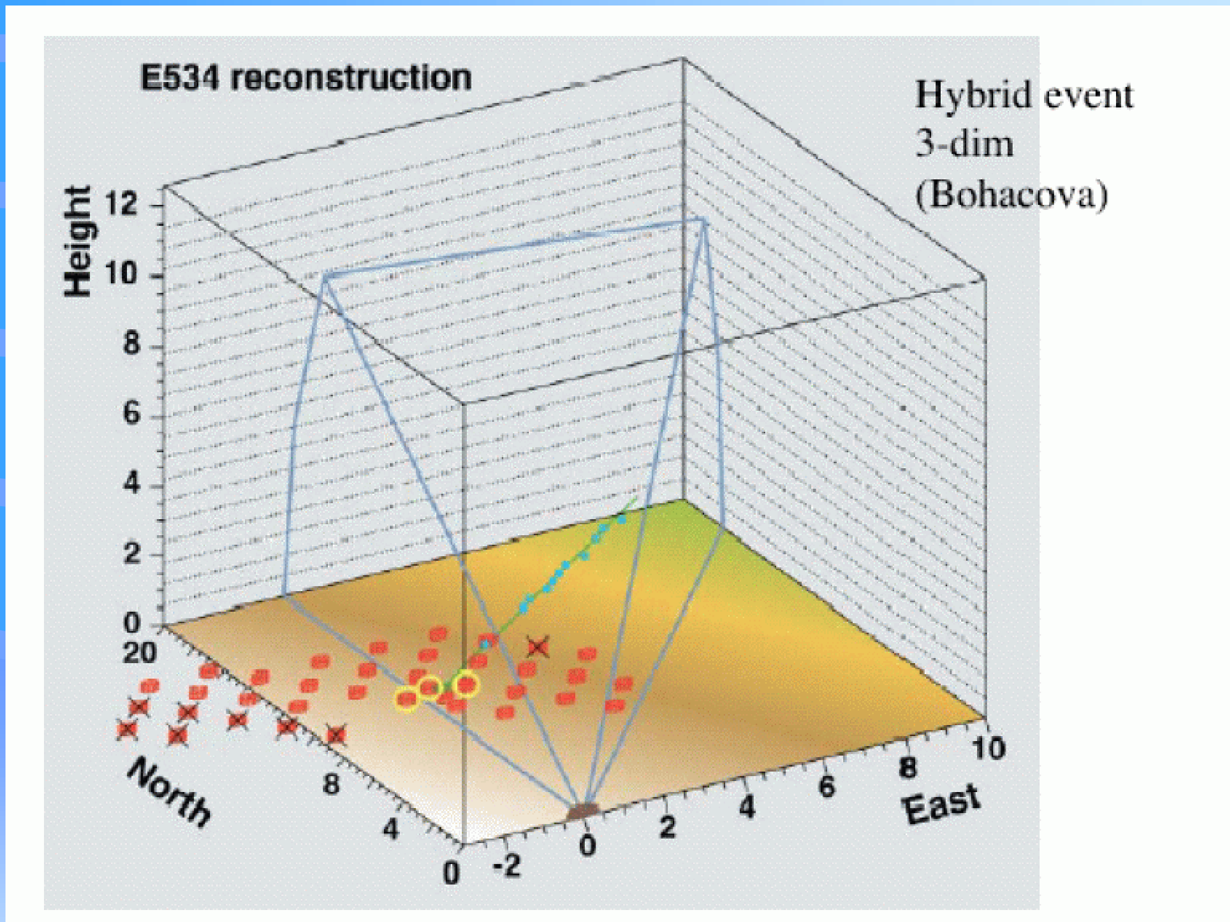
Longitudinal profiles

D=13.1 km E_{est}*= 1.3 10^{19} eV* *D=19.5 km* E_{est}*= 3.3 10^{19} eV*





Hybrid event



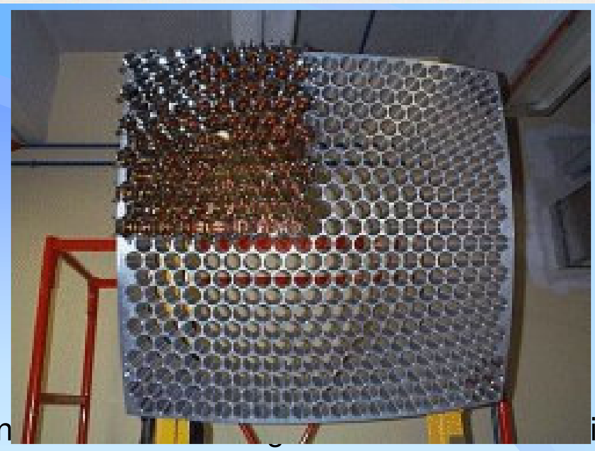
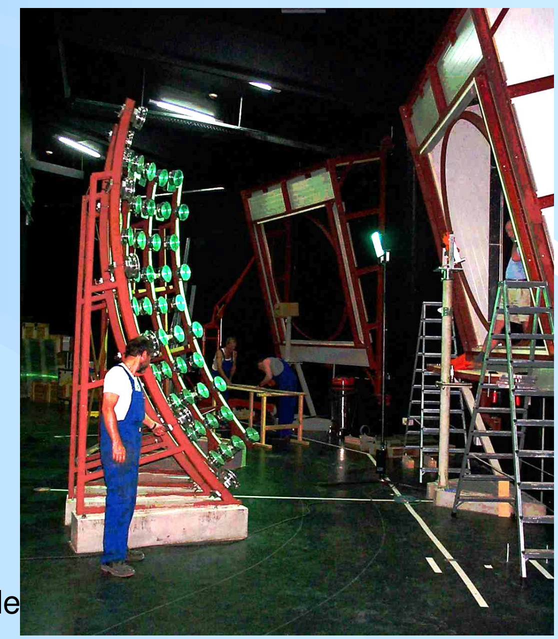
Postcard - SD

Postcard - FD







Conclusion

E>10^{20} eV particles exist

They must be produced or accelerated somewhere: GZK point to the 'neighborhood' of our Galaxy

Standard astrophysical mechanisms cannot easily account for *E>10*^{19} eV

At such extreme energies, source localization is feasible

Existing data are contradictory above *5 10*^{19} eV

Auger is coming!