The Status of Theoretical and Observational Work on Ultra High Energy Cosmic Rays

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Interest in studying UHECR

- A primary interest is in establishing the existence, or otherwise, of the Greisen-Zatsepin-Kuzmin cut-off

$$p + \gamma_{2.7k} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

$$n + \pi^{+}$$

If particles are observed > 5 x 10^{19} eV, then they must be local (**GZK cut-off**)

Local depends on energy:

>4 x 10^{19} eV   50% from within 130 Mpc

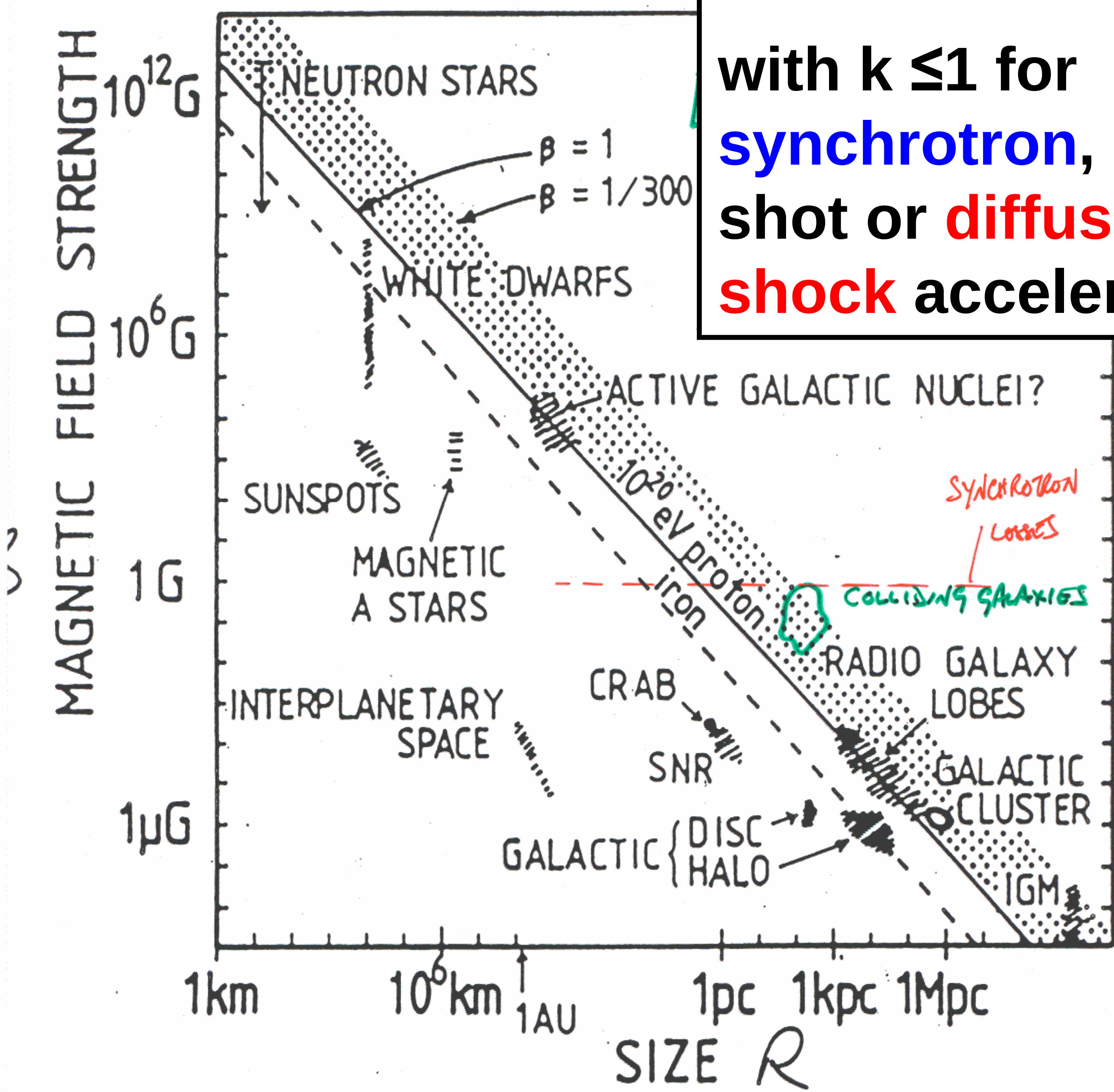
>10^{20} eV   50% from within 20 Mpc

So **ANISOTROPIES** expected from **nearby sources**

No steepening and no anisotropy would be an enigma

$E_{max} = kZeBR\beta c$

with k ≤1 for **synchrotron**, single shot or **diffusive shock** acceleration



Hillas 1984 ARA&A B vs R

Primary Goals of UHECR Research

To measure the properties of the highest energy cosmic rays

- **Energy Spectrum**
- **Arrival Direction Distribution**
- **Mass Composition:**

  Baryonic Masses
  Photons
  Neutrinos

Top Down Mechanisms

Developed under assumption that protons dominate at highest energies and consequently acceleration is difficult.

• Topological defects:

Cosmic strings and necklaces

Decay of monopoles

• Manifestations of Super-heavy relic particles decaying

Present Status of the Field

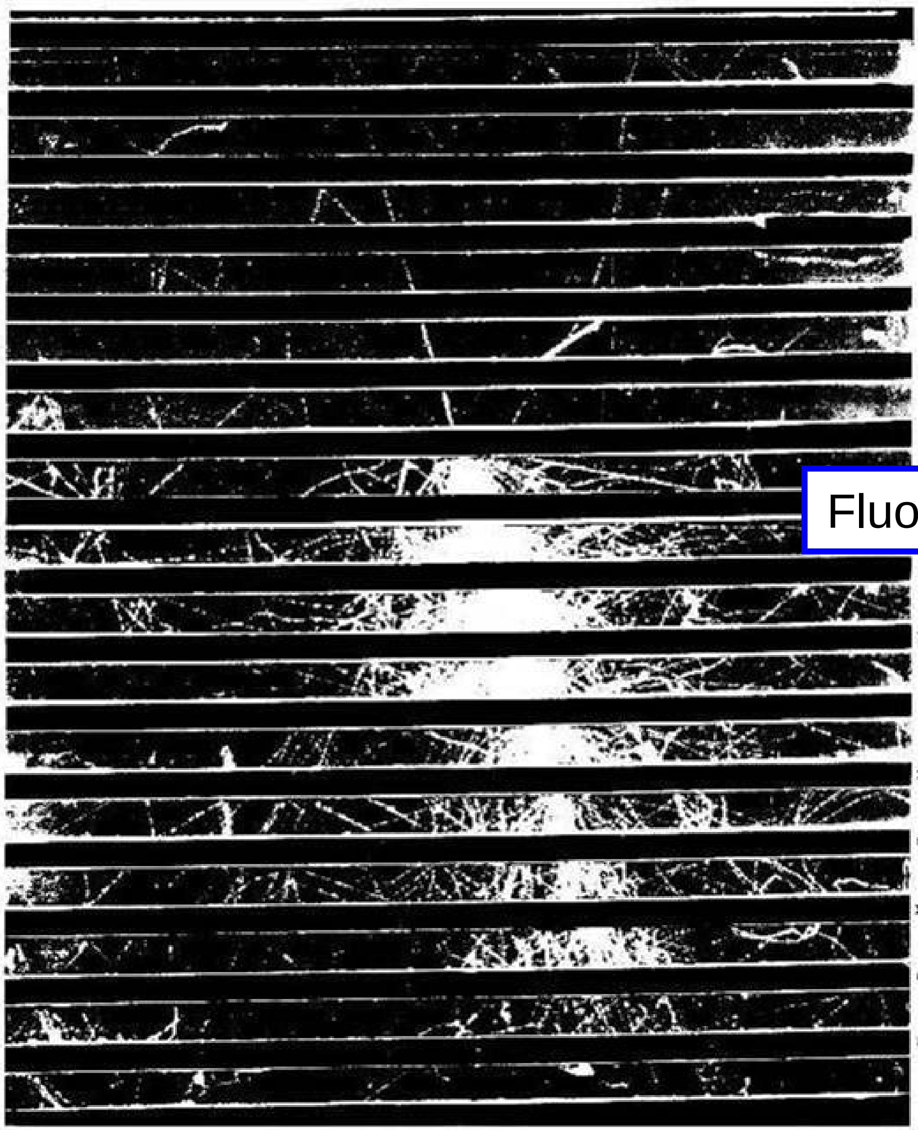
- **AGASA instrument closed down in early January 2004**
  approximately 1600 km^2 sr years

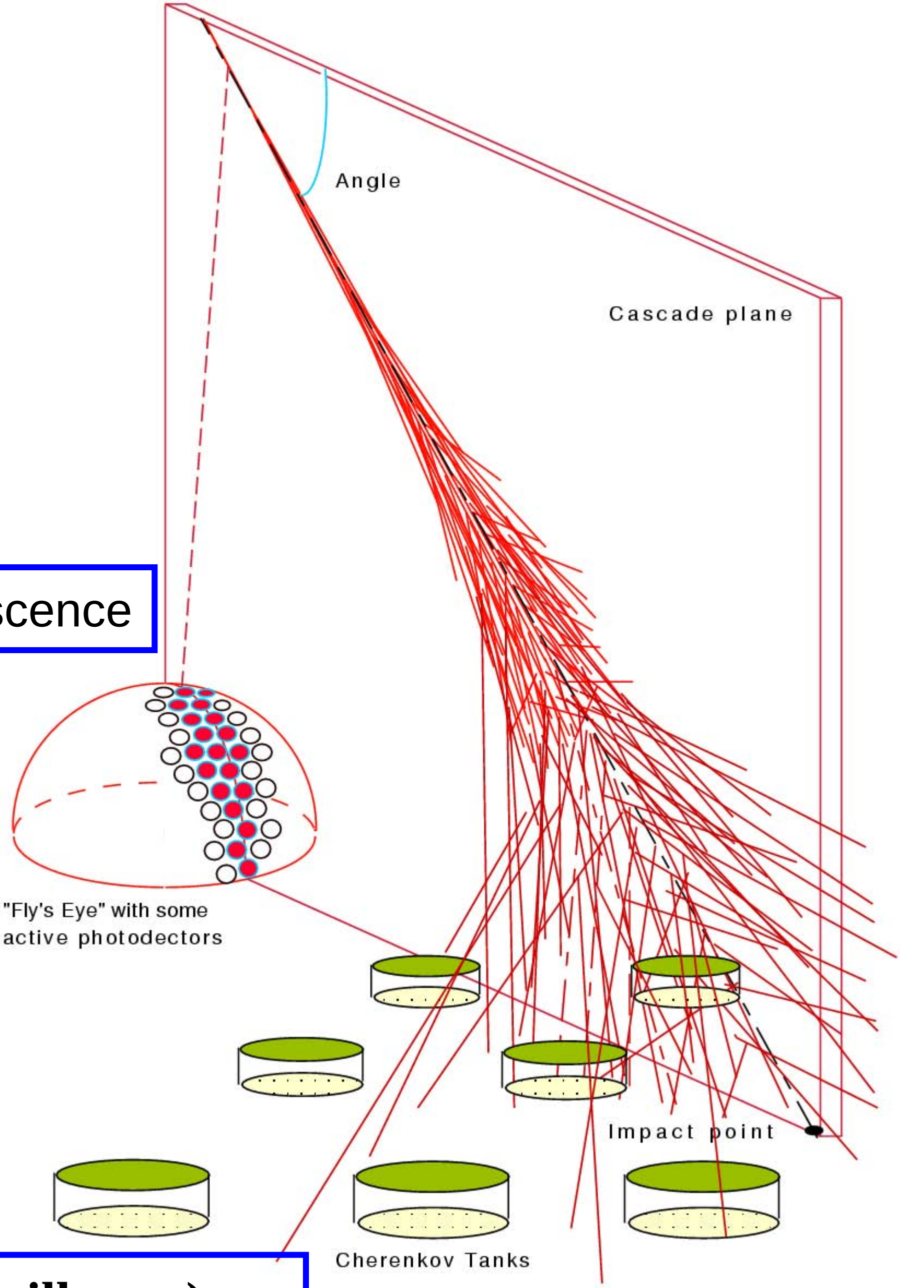
  Spectrum
  Arrival Directions
  Mass Composition

- **HiRes now operating in stereo mode**

  Spectrum from HiRes I and HiRes II
  Statement on Mass at energy lower than AGASA
  Data on arrival directions

- **Pierre Auger data run started on 1 January 2004**

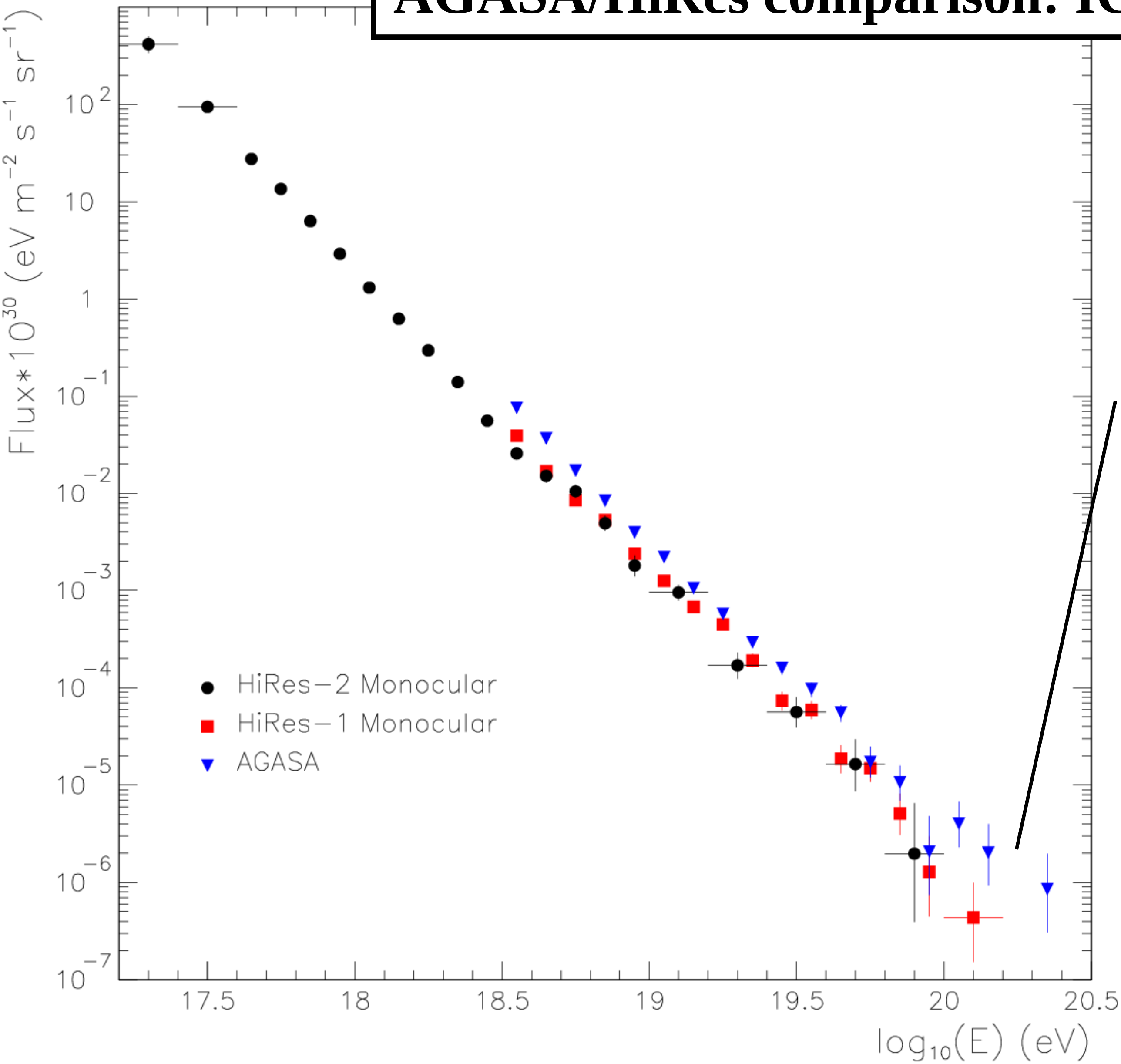




Fluorescence

Array of Detectors (Cherenkov or scintillators)

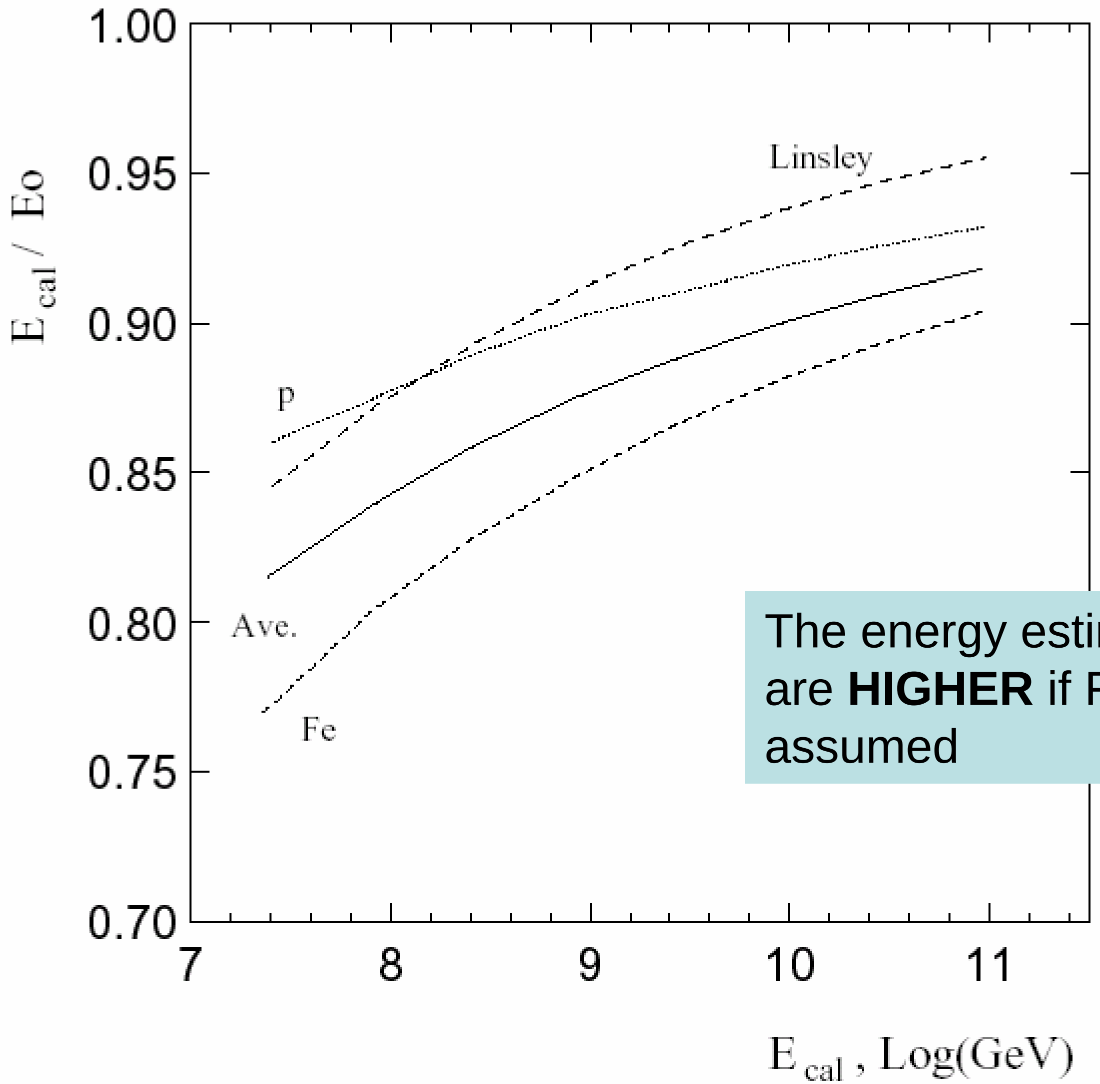
AGASA/HiRes comparison: ICRC2003



HiRes mono-aperture?
Energy estimates?

Thanks to D. Bergman: Rutgers

Corrections necessary to determine energy from fluorescence



~ 5%

The energy estimates are **HIGHER** if Fe is assumed

Song et al Astroparticle Physics 2000

For AGASA, the energy estimates are **LOWER** if iron is assumed

Table 1
Energy conversion from $S(600)$. The column "Single Particle" describes the definition of "a single particle" used in the evaluation of $S(600)$. Each formula is evaluated at the altitude given in the column "Altitude".

Simulation Code	Single Particle	Altitude	Interaction Model	Primary Composition	$E = a \times 10^{17} \cdot S_0(600)^b$ a	b		Citation
COSMOS	"electrons"	900m	QCDJET	p	2.03	1.02		[15]
CORSIKA	PH^0_{peak}	900m	QGSJET98	p	2.07	1.03	**1.04**	[20]
(v5.623)				Fe	2.24	1.00		
			SIBYLL1.6	p	2.30	1.03	**1.13**	
				Fe	2.19	1.01		
AIRES	PW^{θ}_{peak}	667m	QGSJET98	p	2.17	1.03	**1.09**	[21]
(v2.2.1)				Fe	2.15	1.01		
			SIBYLL1.6	p	2.34	1.04	**1.13**	
				Fe	2.24	1.02		

$S_0 = 50$ vem

From Takeda et al Astroparticle Physics 2003

1 triplet + 6 doublets
(2 triplets + 6 doublets with looser cut)

Clustering for E ~10^{19} eV and ~5 x 10^{19} eV,

Ratio of Cluster/All increases with E up to 5 x 10^{19} eV

Above GZK energy (5x10^{19} eV) statistics too small

p~ 0.003

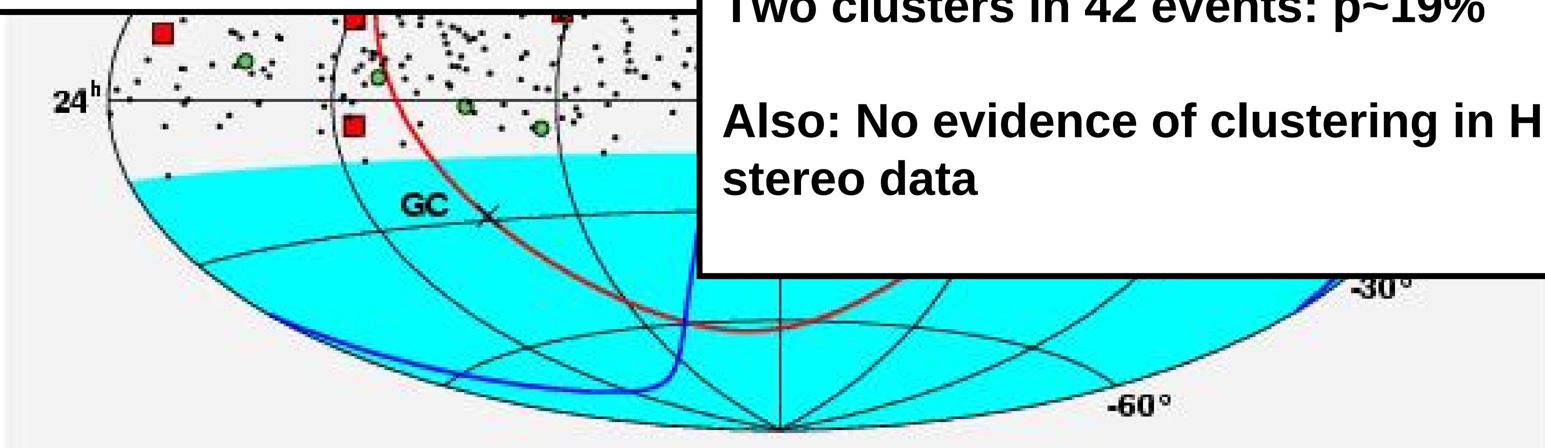
ll Scale Clustering

Important paper:astro-ph/0309159

Finley and Westerhoff: divided data into two sets - before and after first claim
30 (prior) + 42 (post)

Two clusters in 42 events: p~19%

Also: No evidence of clustering in HiRes stereo data



Mass Composition: muon content

$N_\mu(>1\ \mathrm{GeV}) = AB(E/A\varepsilon_\pi)^p$ (depends on mass/nucleon)

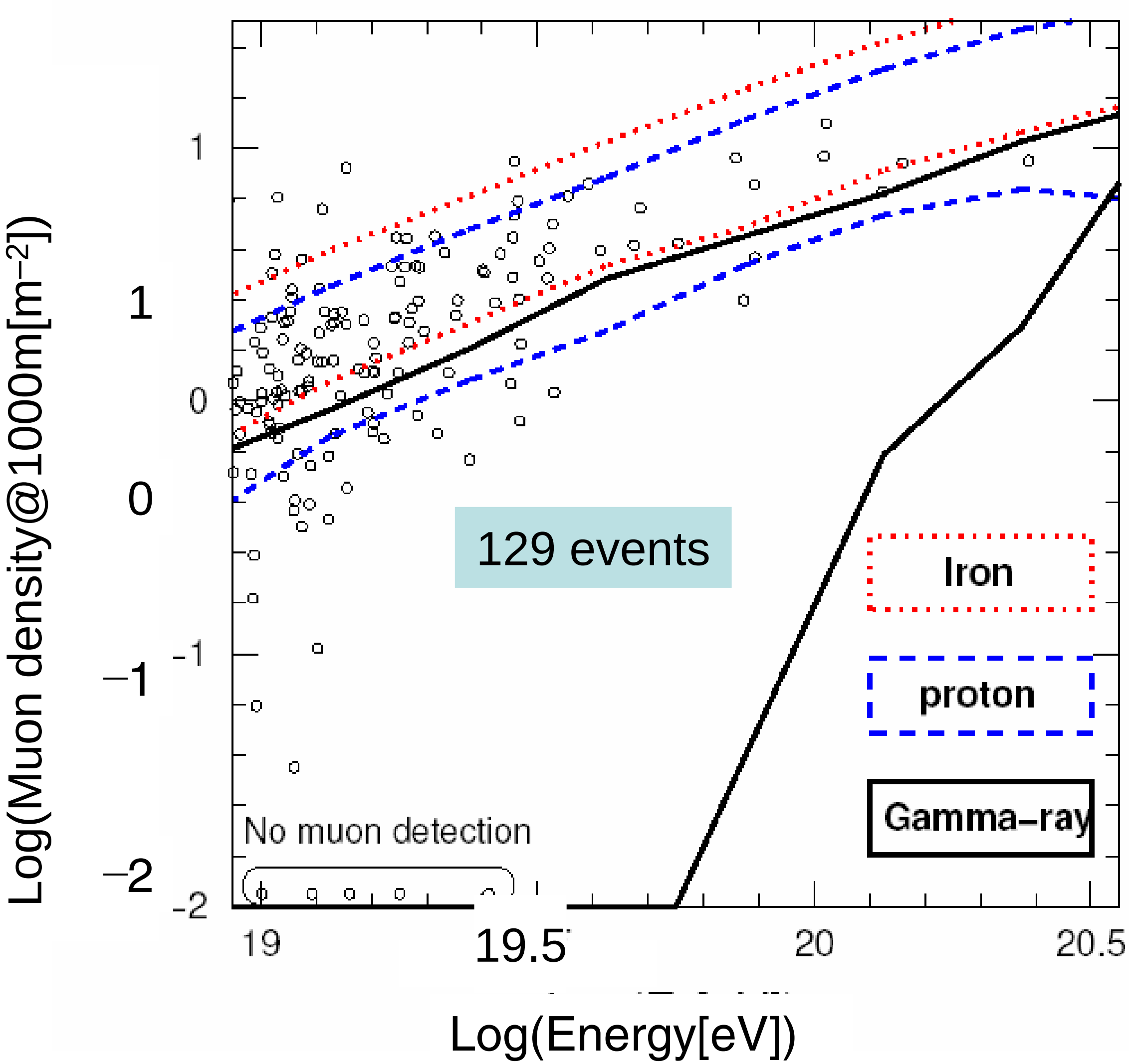
$N_\mu(>1\ \mathrm{GeV}) = 2.8A(E/A\varepsilon_\pi)^{0.86} \sim A^{0.14}$

- So, more muons in Fe showers
- Muons are about 10% of total number of particles
- Used successfully at lower energies (KASCADE)
- VERY expensive - especially at high energies

– ONLY AGASA DATA: muon density at 1000 m

Results from the AGASA array

"Consistent with proton dominant component"



Sibyll 1.7: Sibyll 2.1: QGSjet98

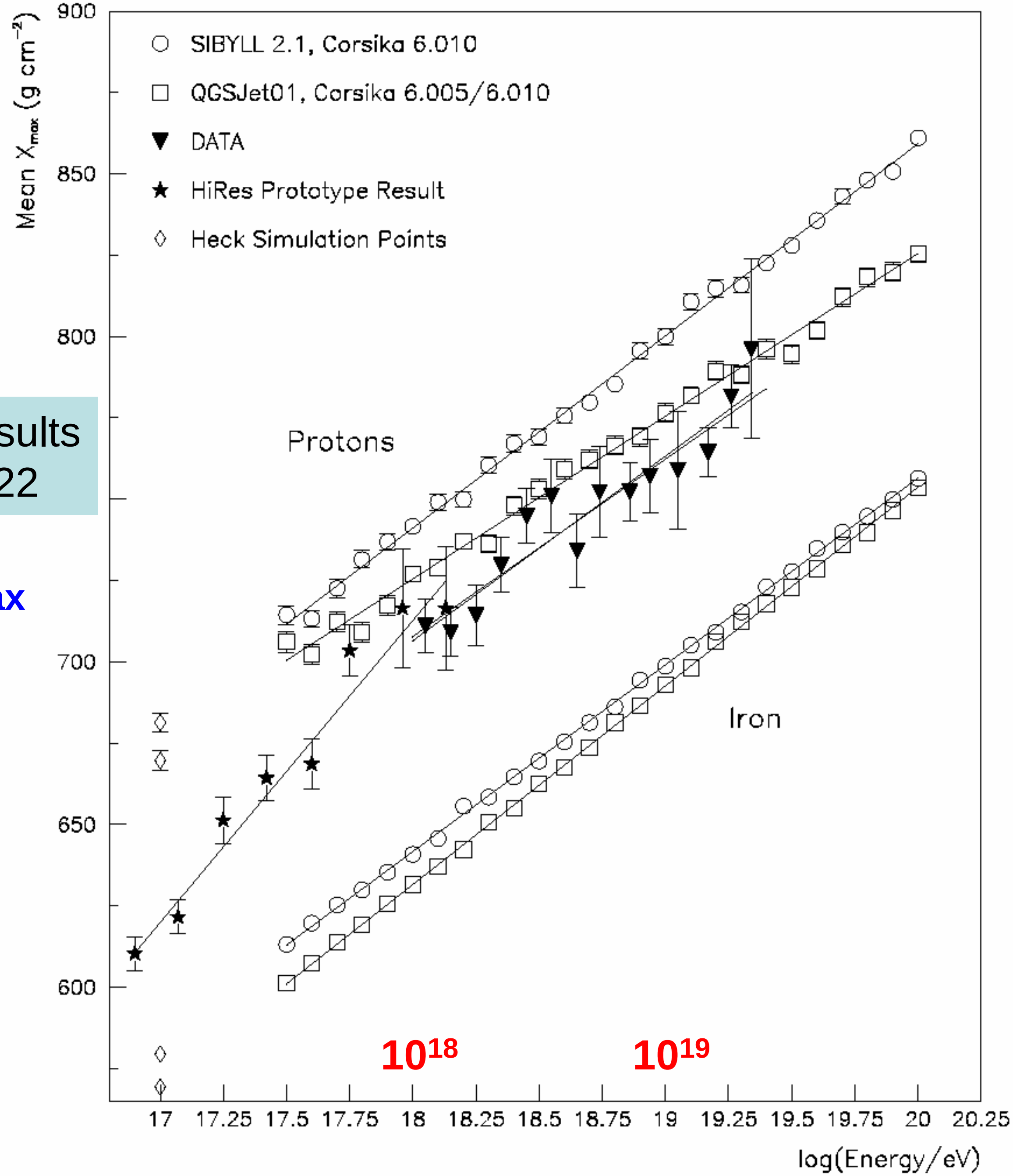
muon numbers 1: 1.17:1:45

Forthcoming QGS jet model will contain fewer muons – so mass estimates will be HIGHER

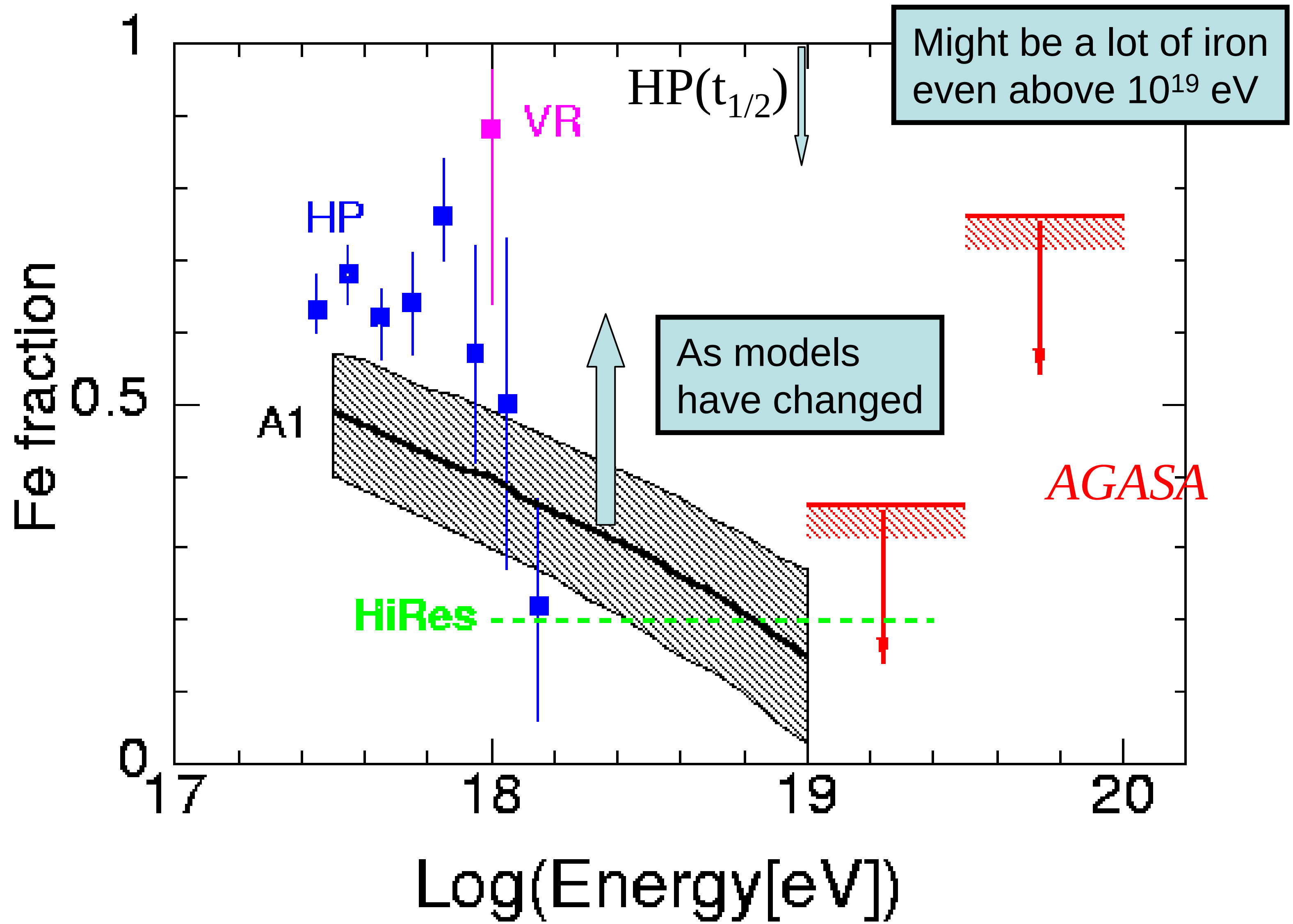
LHC CMS energy corresponds to ~ 10^{17} eV

Latest HiRes results
Astro-ph/0407622

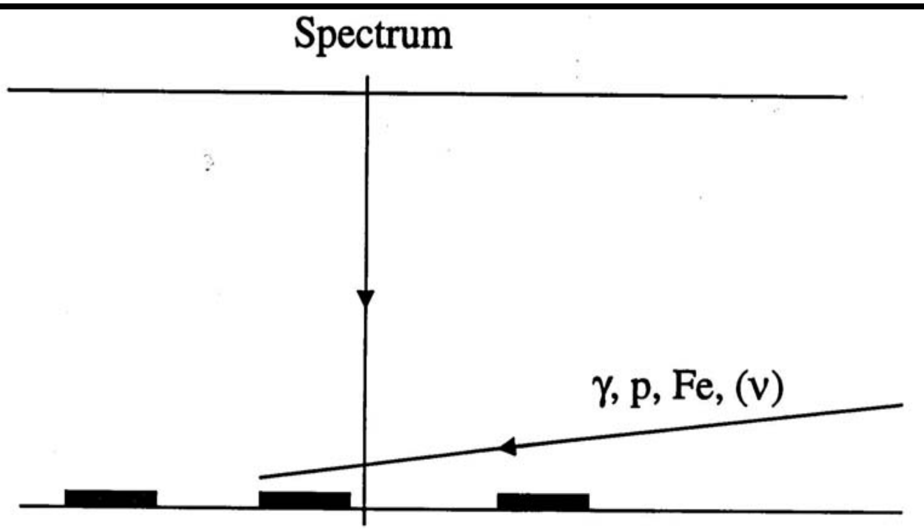
X_{max}



Summary of baryonic mass composition claims



Mass information from study of Inclined Showers



INPUT: Spectrum (mass-independent) e.g. FLUORESCENCE
Assumptions about mass

OUTPUT: Predicted Spectrum

COMPARISON: Measured Rate

Example: Photon limit at 10^{19} eV
(Ave et al. Phys Rev Lett 2000)

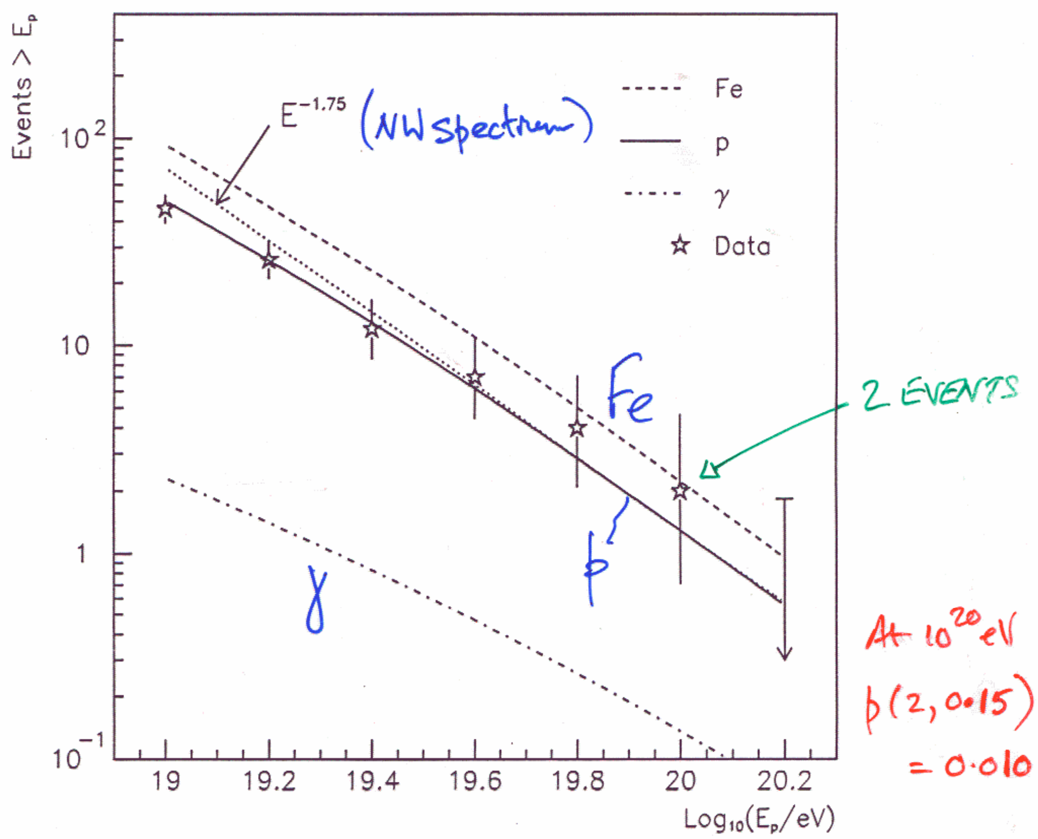
Haverah Park:
Photon limit at 10^{19} eV
< 40%
(@95% CL)

AGASA: muon poor events

Gamma-ray fraction upper limits (@90%CL)

34% (>10^{19}eV) (γ/p<0.45)

56% (>$10^{19.5}$eV) (γ/p<1.27)



60° < θ < 80°

Ave, Hinton, Vazquez, aaw, and Zas

PRL 85 244 2000

Pierre Auger Collaboration

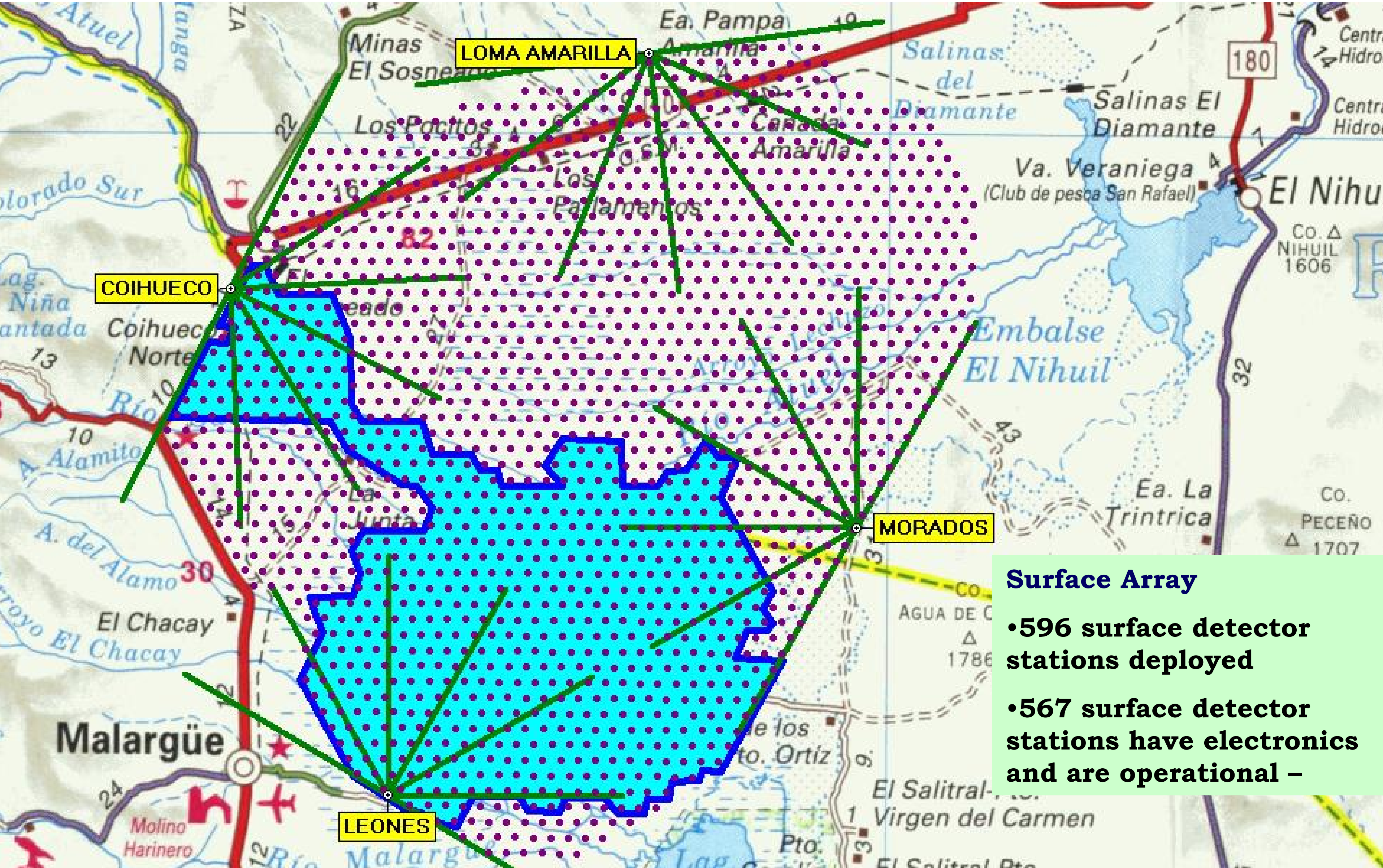
Czech Republic
France
Germany
Italy
Poland
Slovenia
Spain
United Kingdom

Argentina
Australia
Brasil
Bolivia*
Mexico
USA
Vietnam*

****Associate Countries***

~250 PhD scientists from 63 Institutions and 15 countries

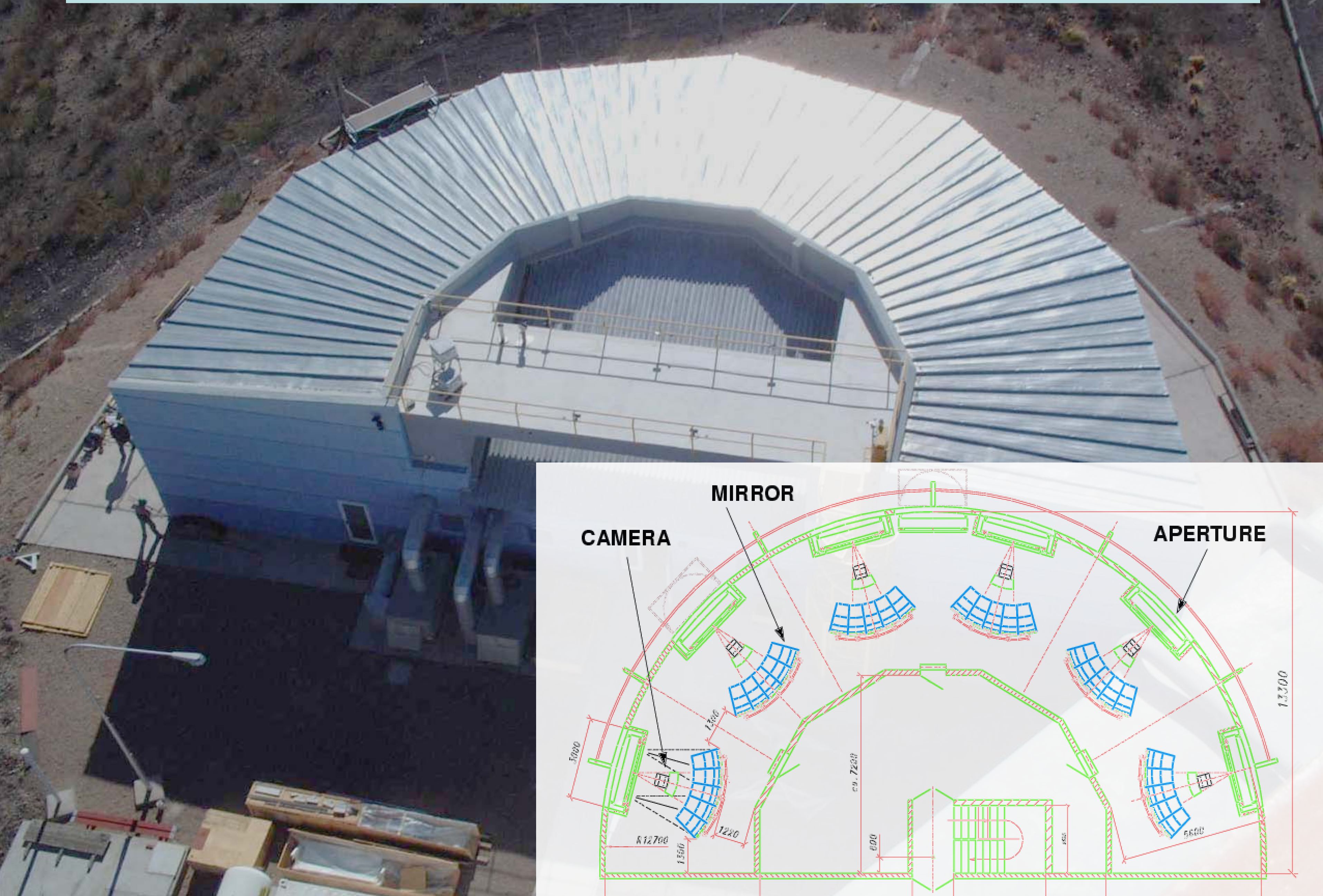
Pierre Auger Observatory: Status at December 2004

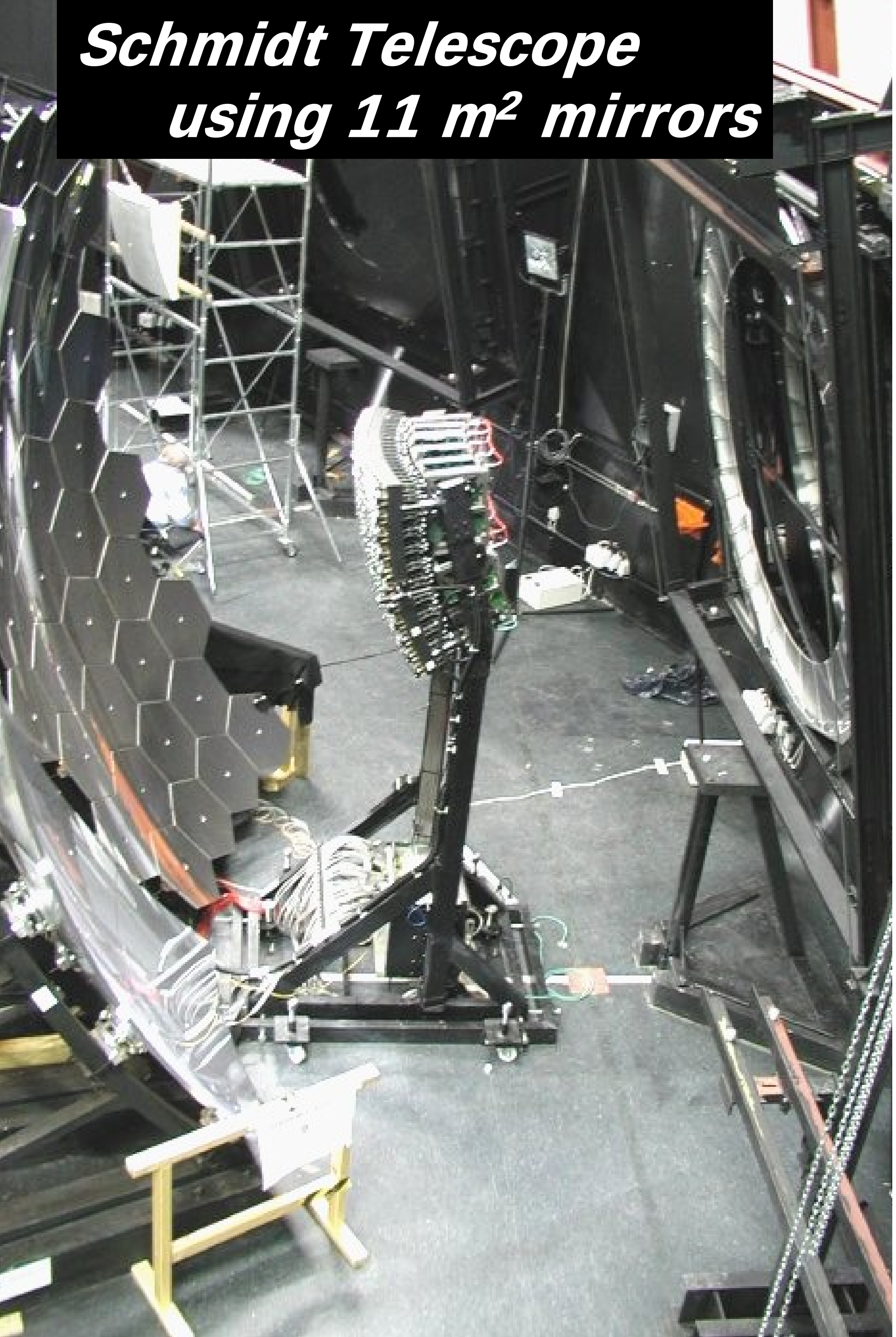


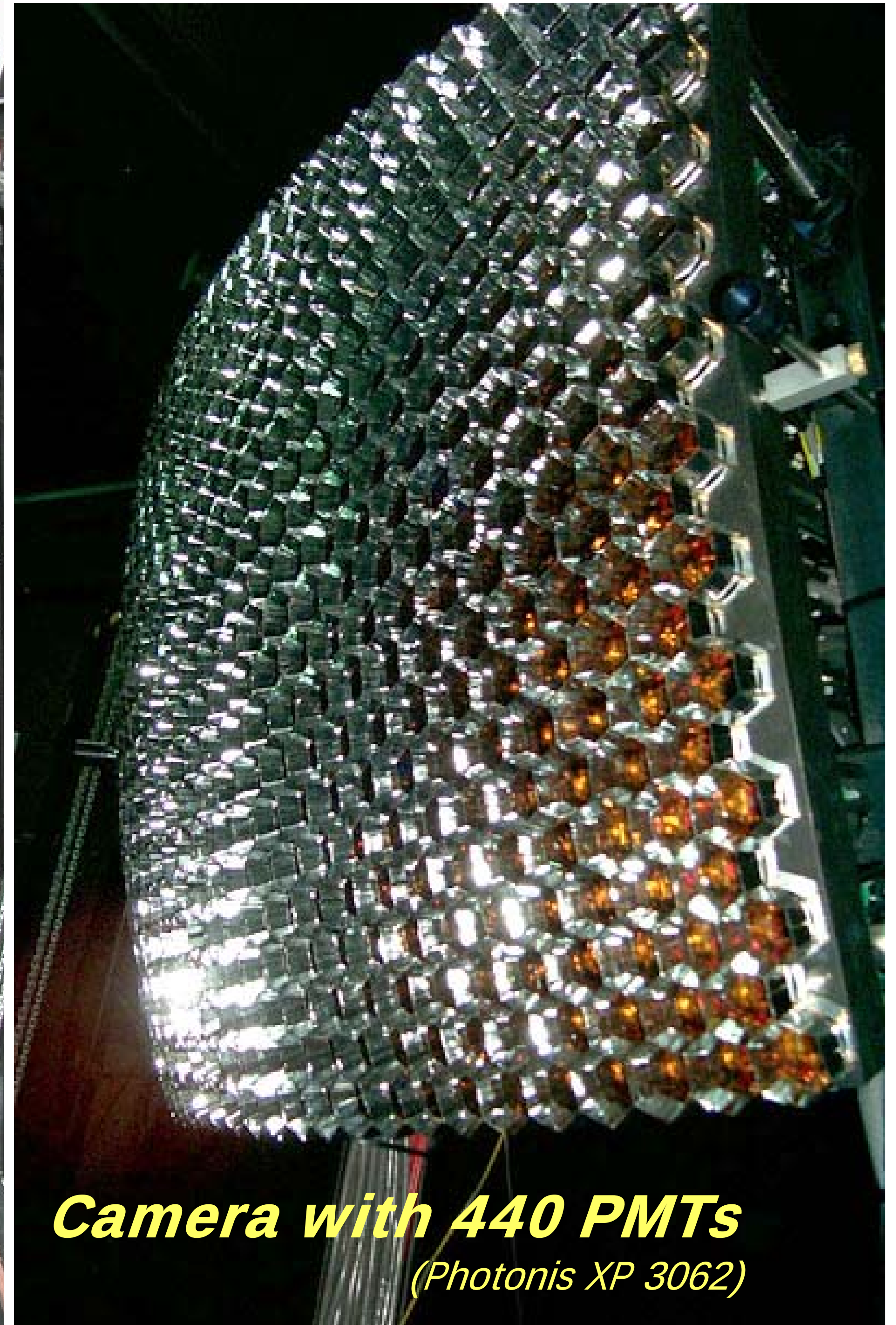
Surface Array

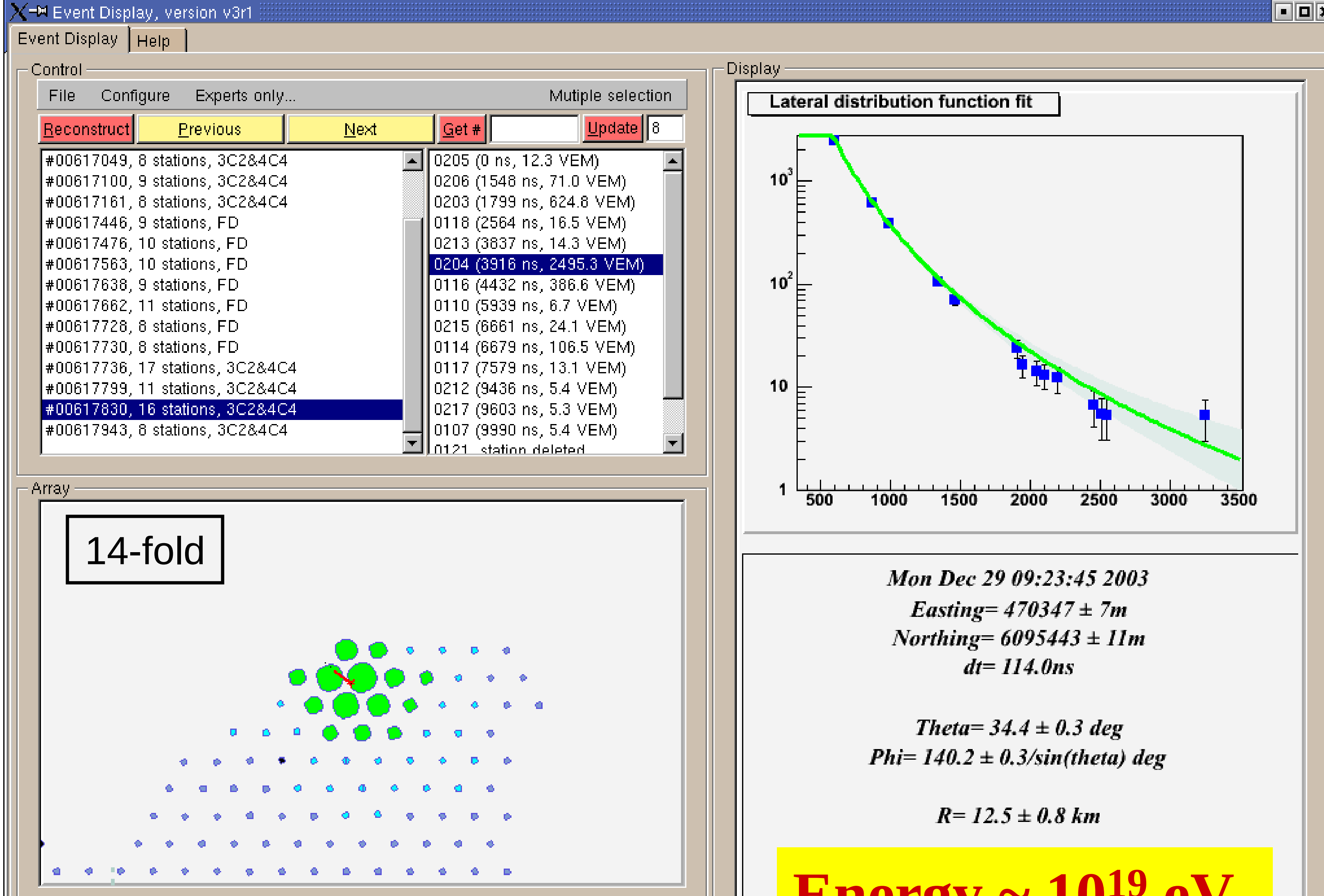
- **596 surface detector stations deployed**
- **567 surface detector stations have electronics and are operational –**

Six Telescopes viewing 30°x30° each




Schmidt Telescope
using 11 m² mirrors


Camera with 440 PMTs
(Photonis XP 3062)

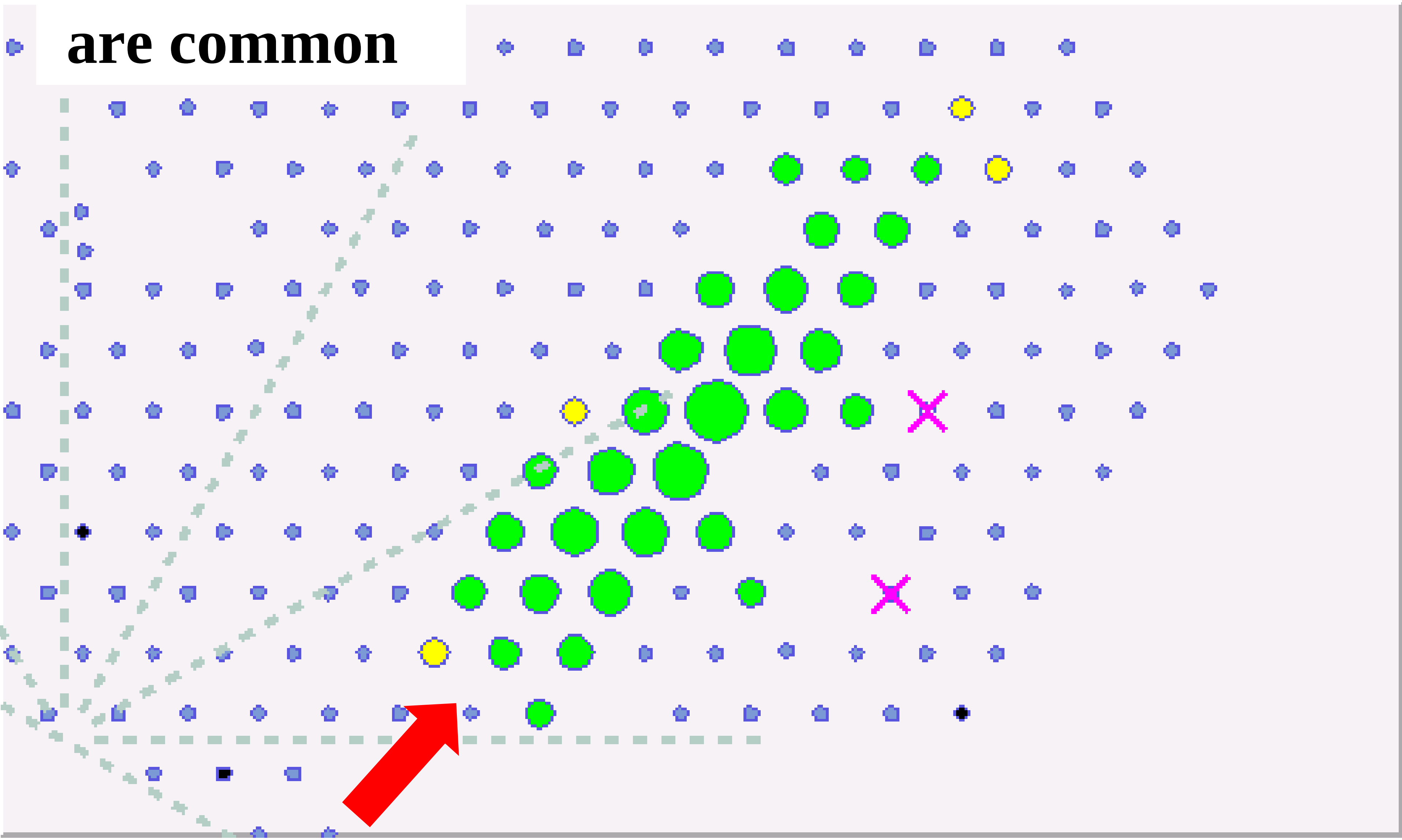


Energy ~ 10^{19} eV

Good Progress in Analysis

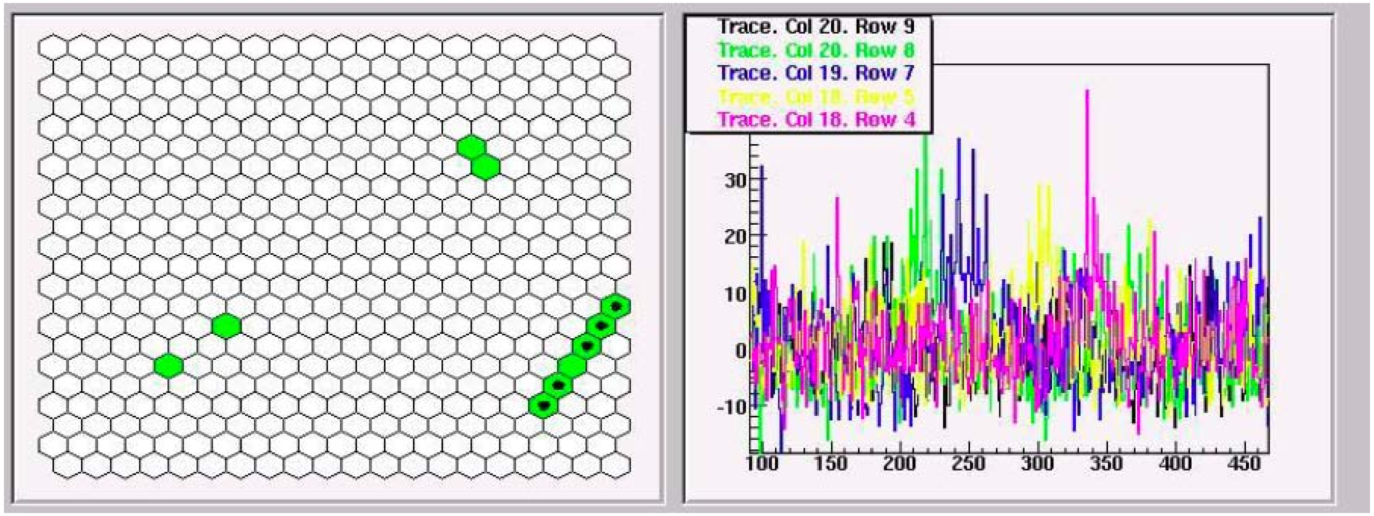
Detailed studies under way

Inclined events are common

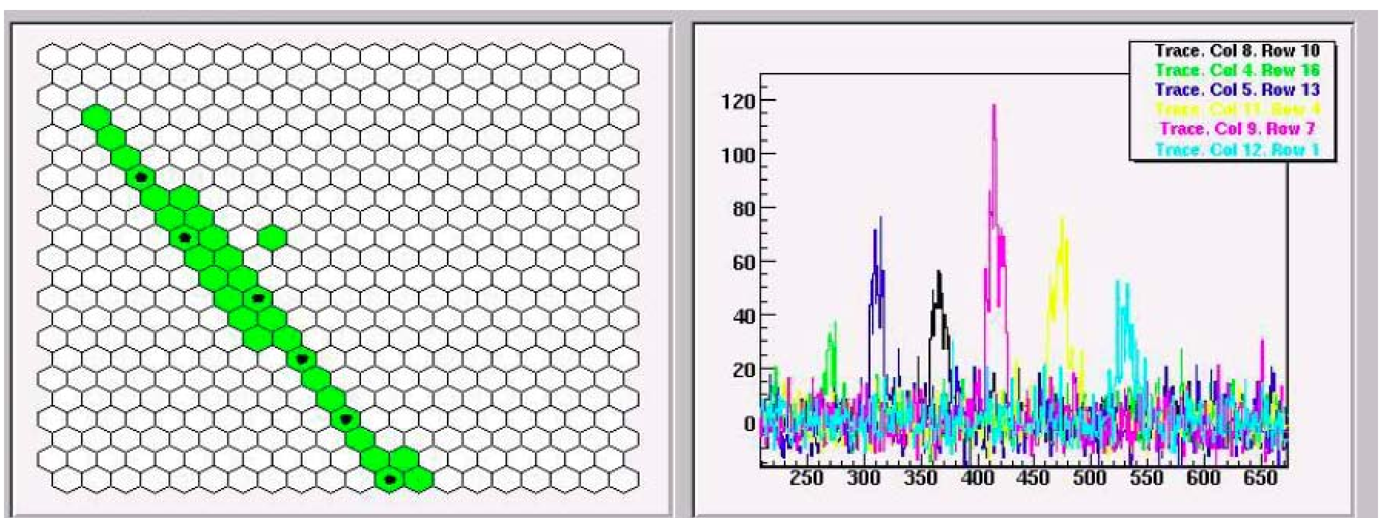


5 May 2004 33 tanks $\theta = 72^0$ R=37 km

Fluorescence Display

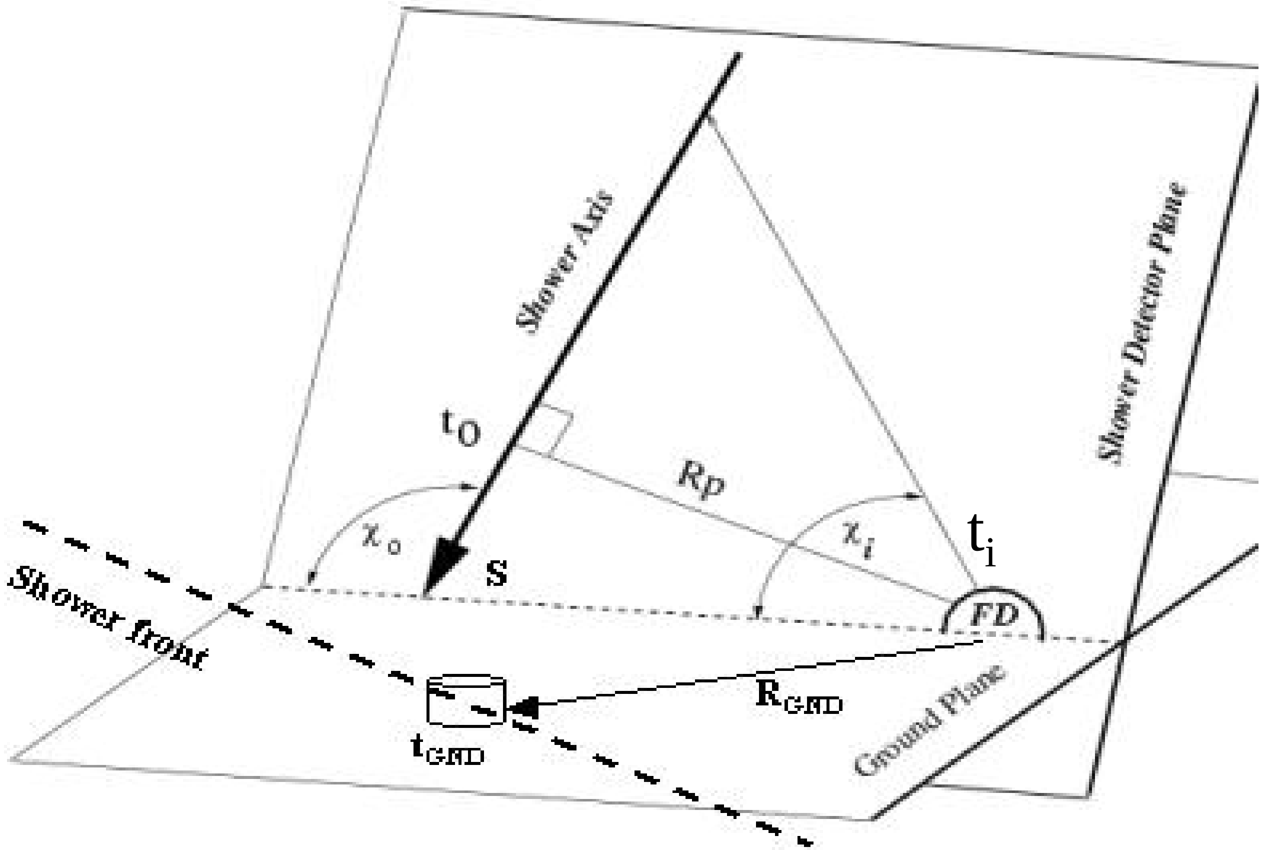


Coiheco (6 pixels)



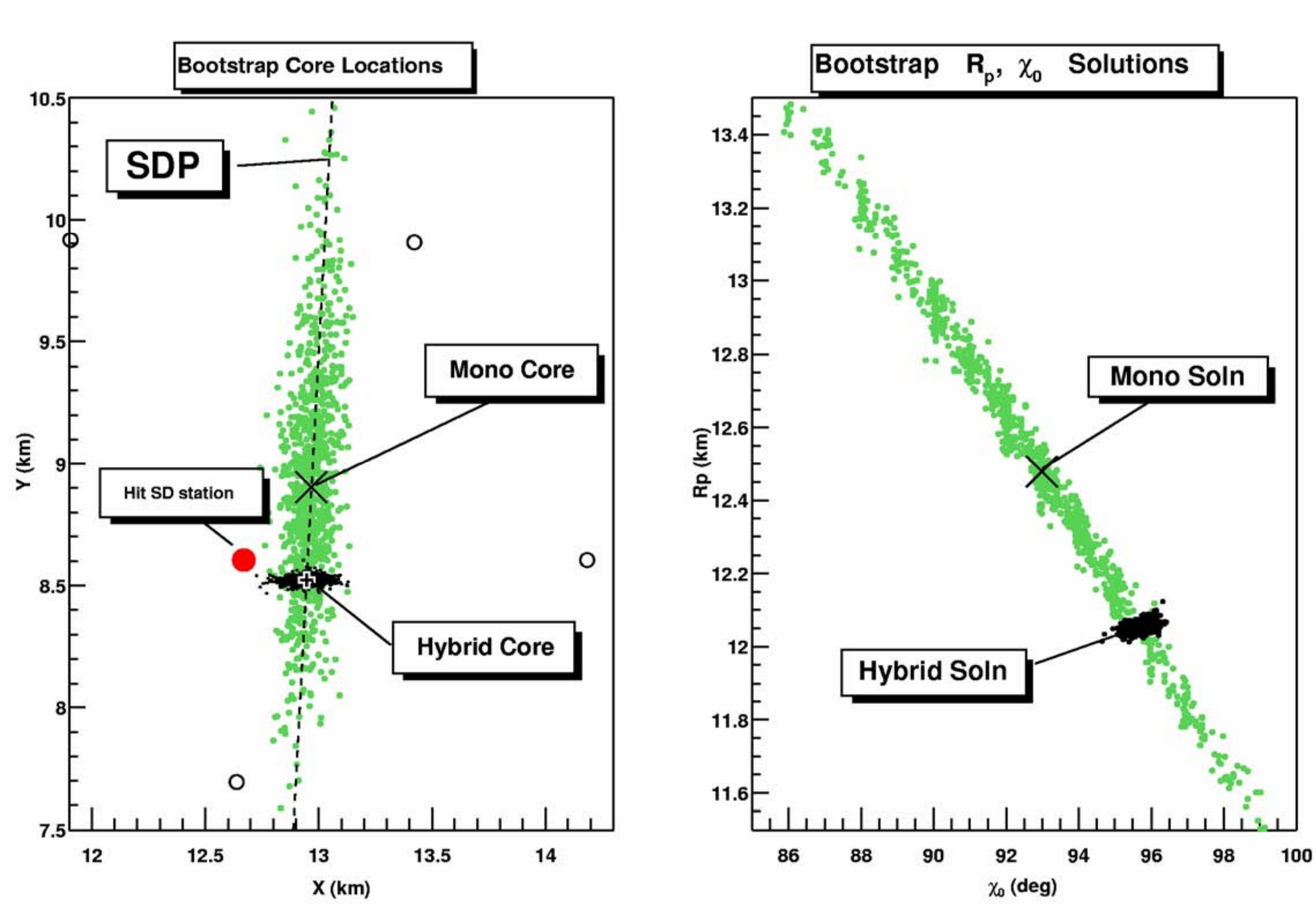
Los Leones (29 pixels)

The Power of Hybrid Geometry

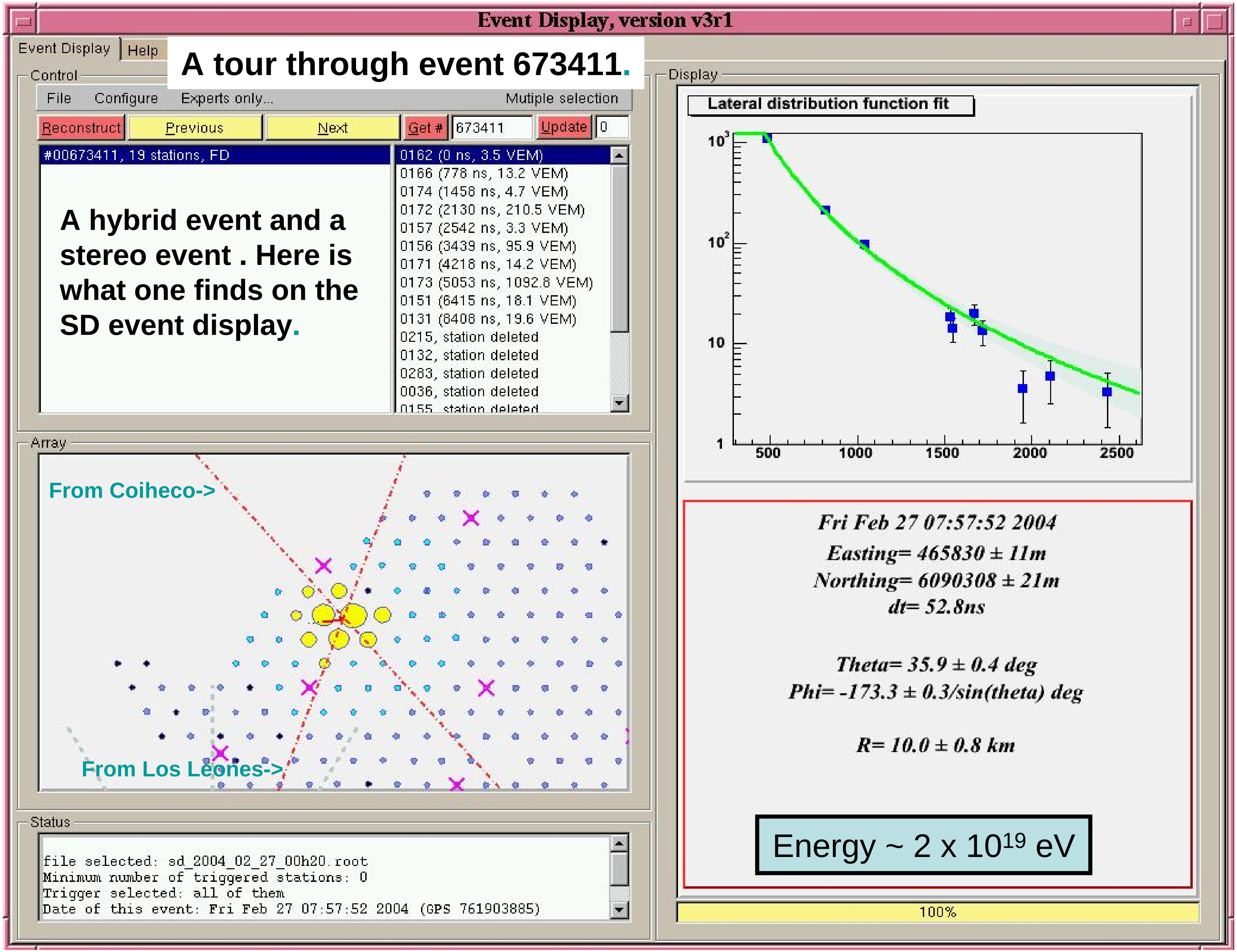


$$t_i = T_0 + \frac{R_p}{c} \cdot \tan\left(\frac{\chi_0 - \chi_i}{2}\right) \qquad t_{Tank} = T_0 - \frac{\hat{s} \cdot \vec{R}_T}{c}$$

105573

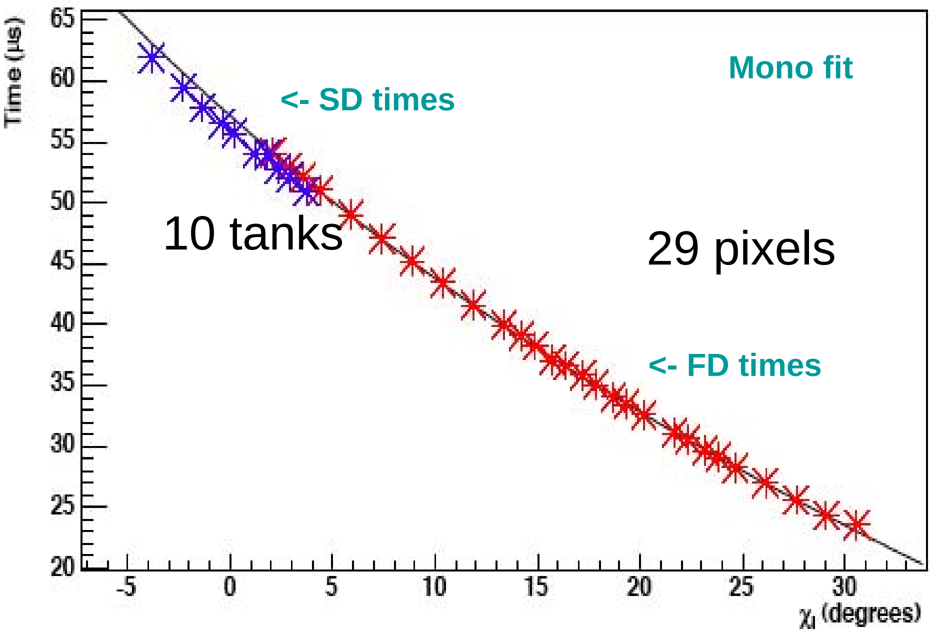


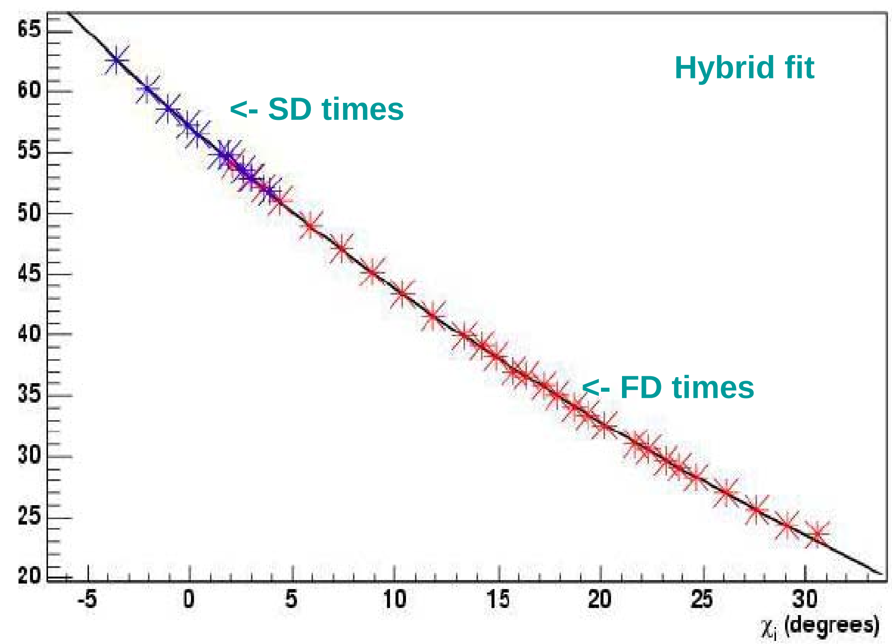
Hybrid events are equivalent to stereo events and superior to mono events


Event Display, version v3r1
A tour through event 673411.
Event Display
Help
Control
File
Configure
Experts only...
Mutiple 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
A hybrid event and a stereo event . Here is what one finds on the SD event display.
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)
Display
Lateral distribution function fit
10^3
10^2
10
1
500
1000
1500
2000
2500
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
Energy ~ 2 x 10^{19} eV
100%

Event 673411

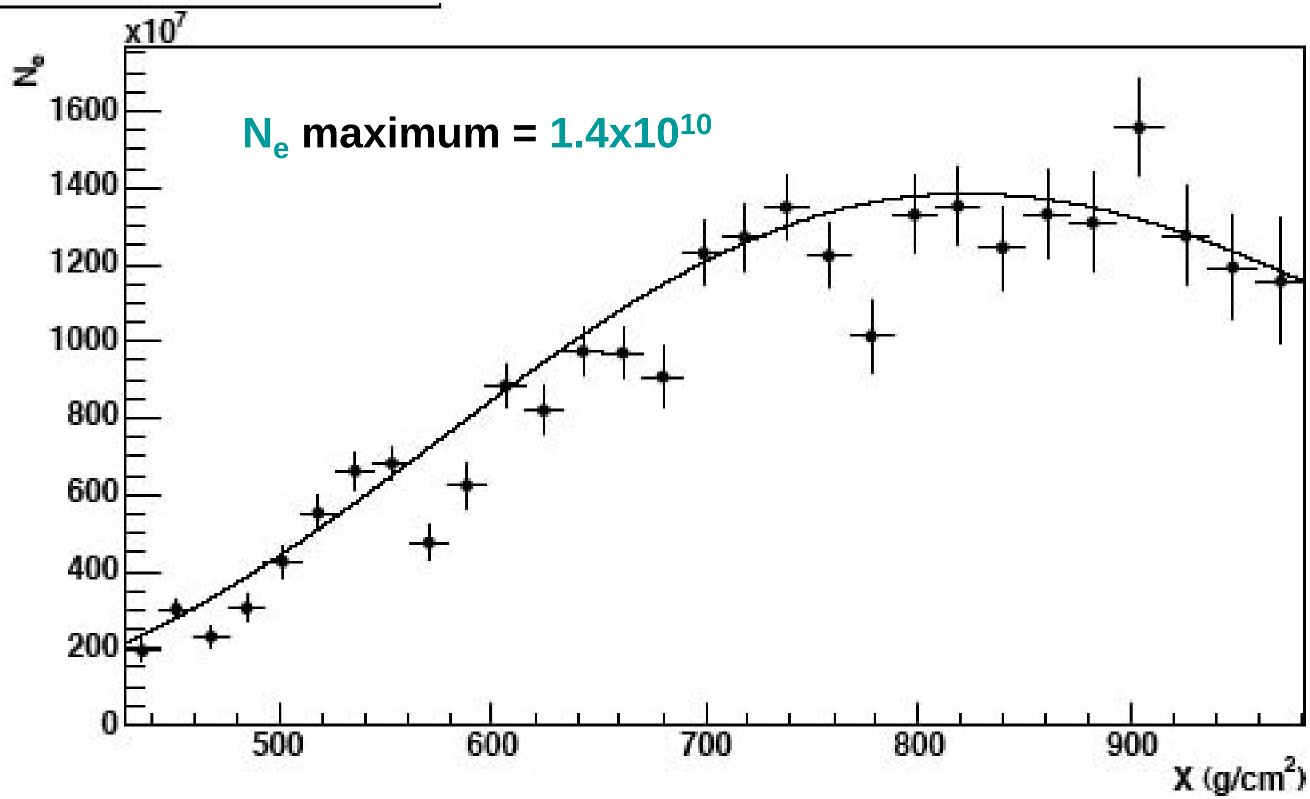
Hybrid Reconstruction





	Hybrid (Los Leones)	Surface	Difference
Easting	465960 ± 80	465830	130 m
Northing	6090234 ± 20	6090308	-74 m
Theta	36.7 deg	35.9 deg	0.8 deg
Phi	185.8 deg	186.7 deg	-0.9 deg

Event 673411



N_e maximum ~ $7x10^{10}$ for energy = 10^{20} eV

Fluorescence energy ~ $2x10^{19}$ eV

preliminary!

Surface detector energy ~ $2.1x10^{19}$ eV

Ideas to explain the Enigma
- if there turns out to be one

- Decay of super-heavy relics from early Universe (or top down mechanisms)

  Wimpzillas/Cryptons/Vortons

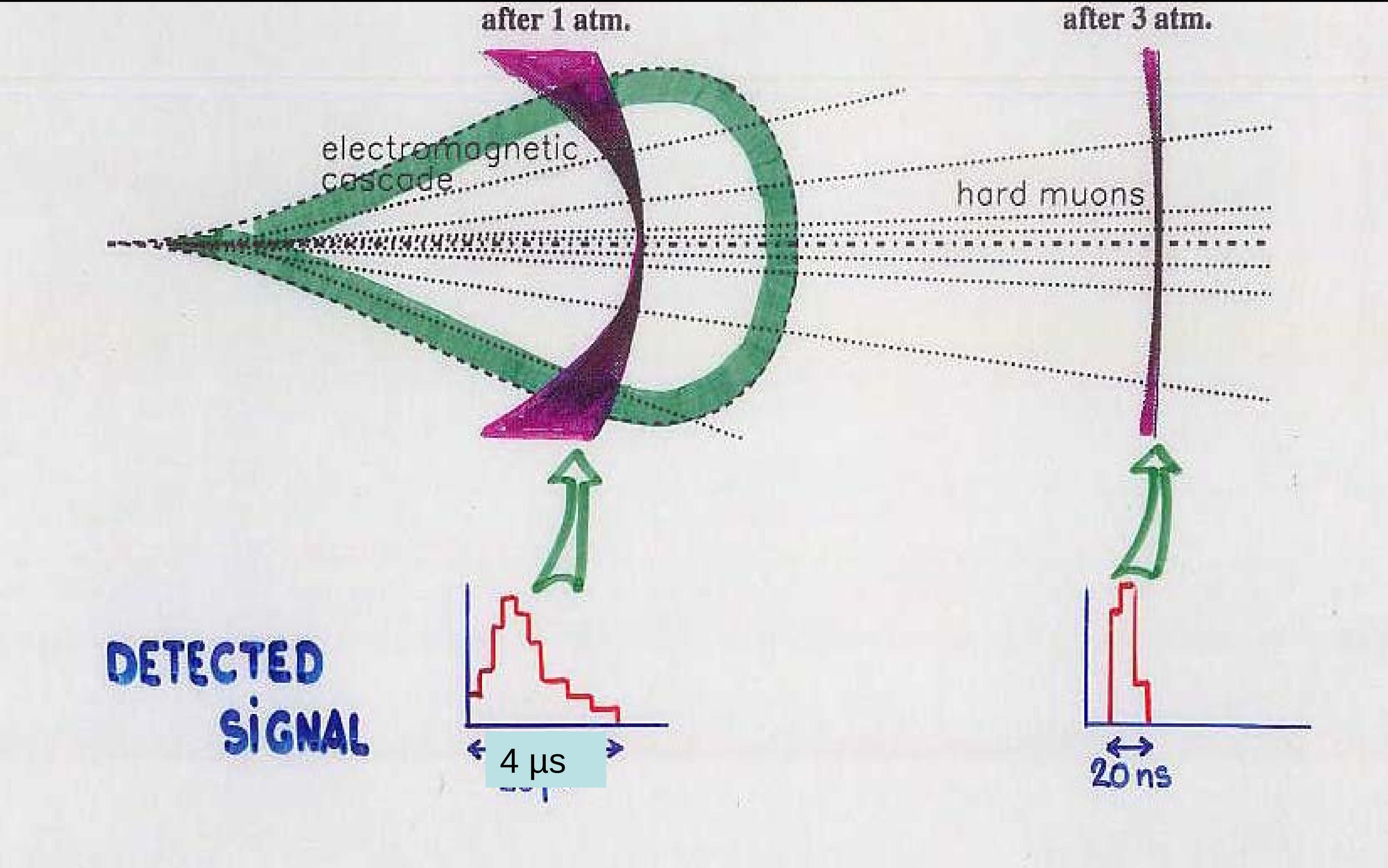
Predictions:

dominance of photons (?) and neutrinos

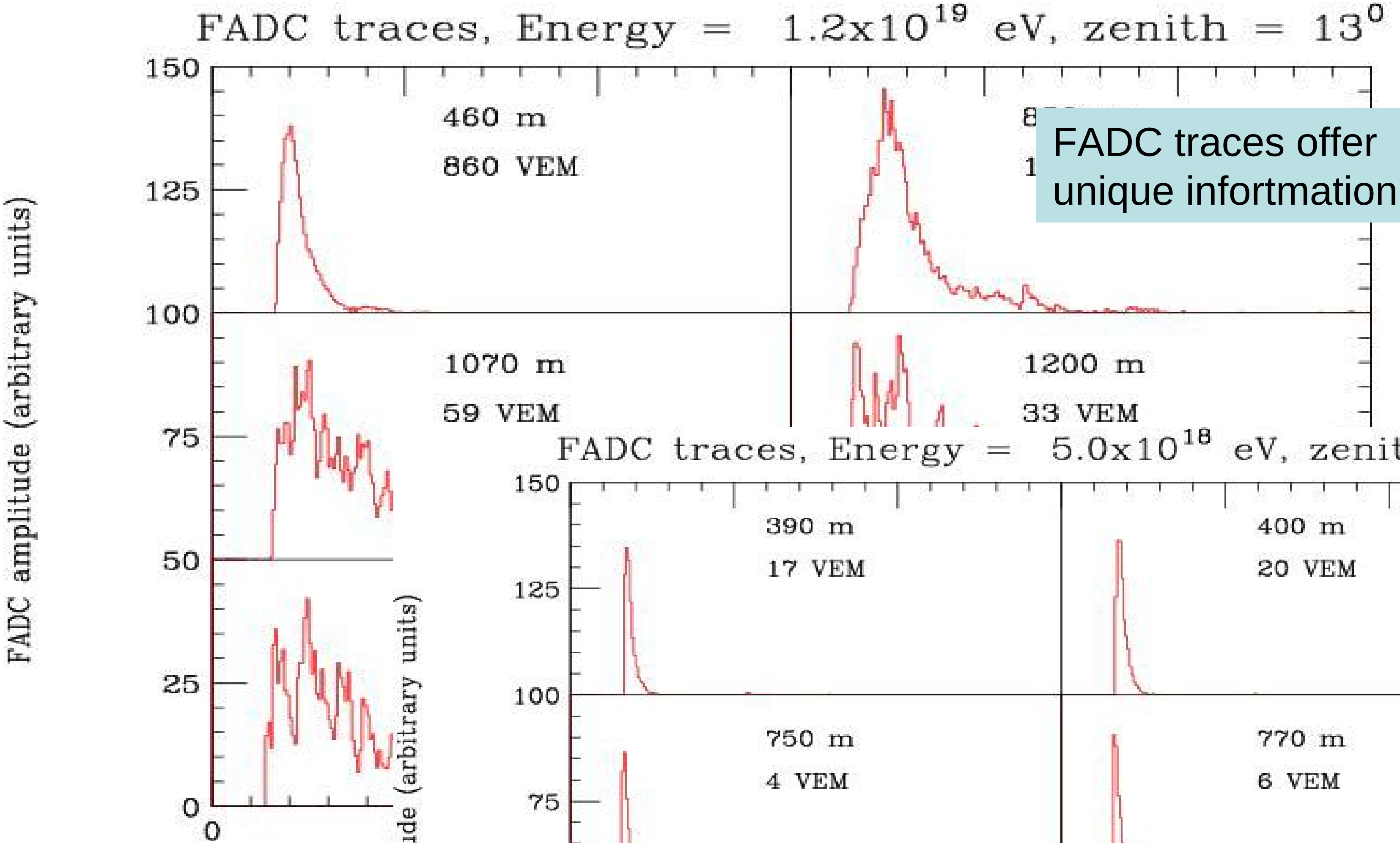
- New properties of old particles

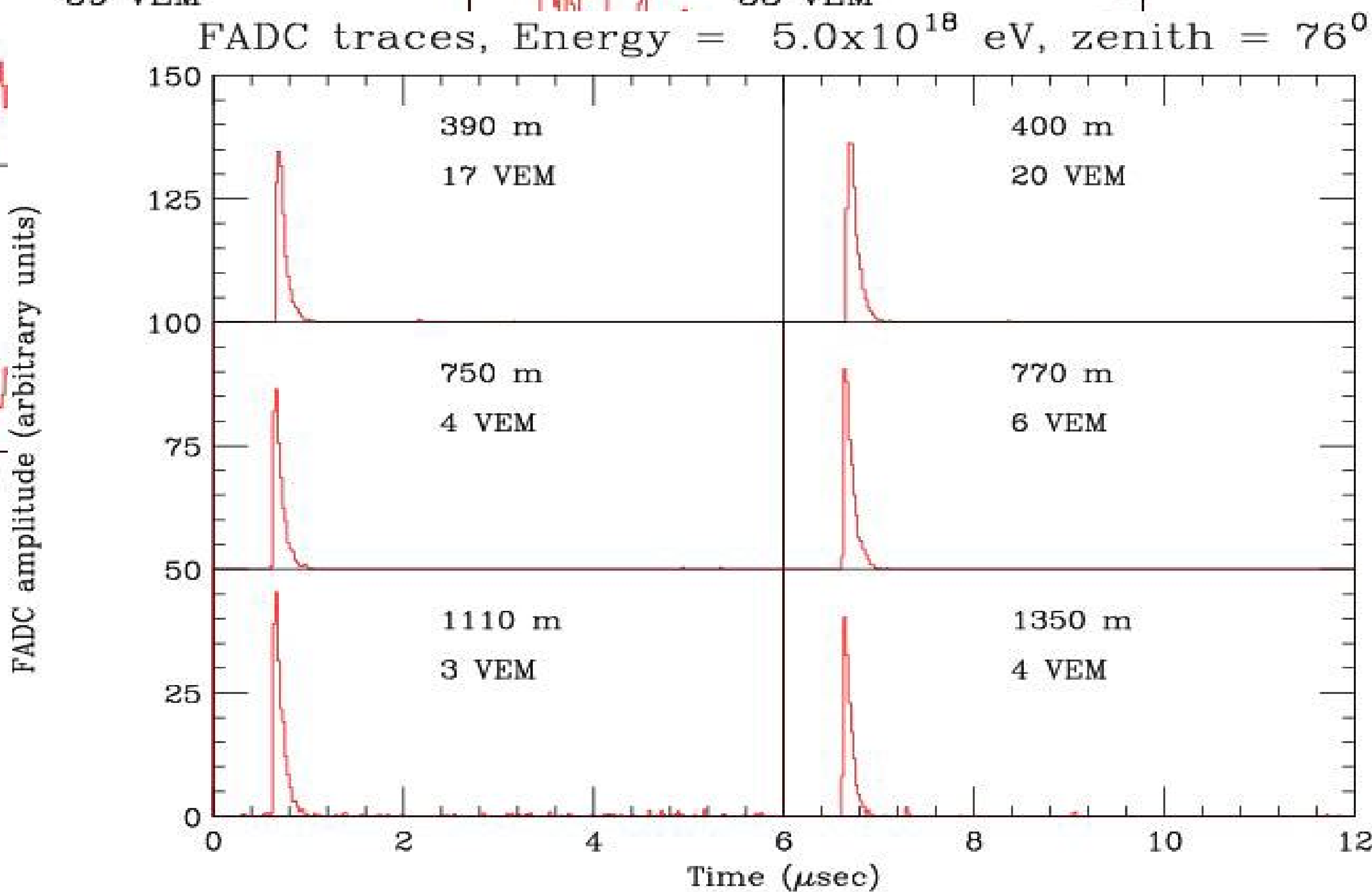
- Breakdown of Lorentz Invariance

Concept of neutrino detection : Berezinsky and Smirnov 1975, Capelle et al 1998



FADC traces offer unique informtation





Tau neutrino detection

PIERRE AUGER OBSERVATORY

- **Principle:**
  - **Interaction length in the earth ~ 300 km at 10^{18} eV**
  - **Tau time of flight ~ 50 km at 10^{18} eV**
  - **1° below horizon $\Rightarrow$ 200 km of rock**
  - **Shower maximum ~10 km after decay**

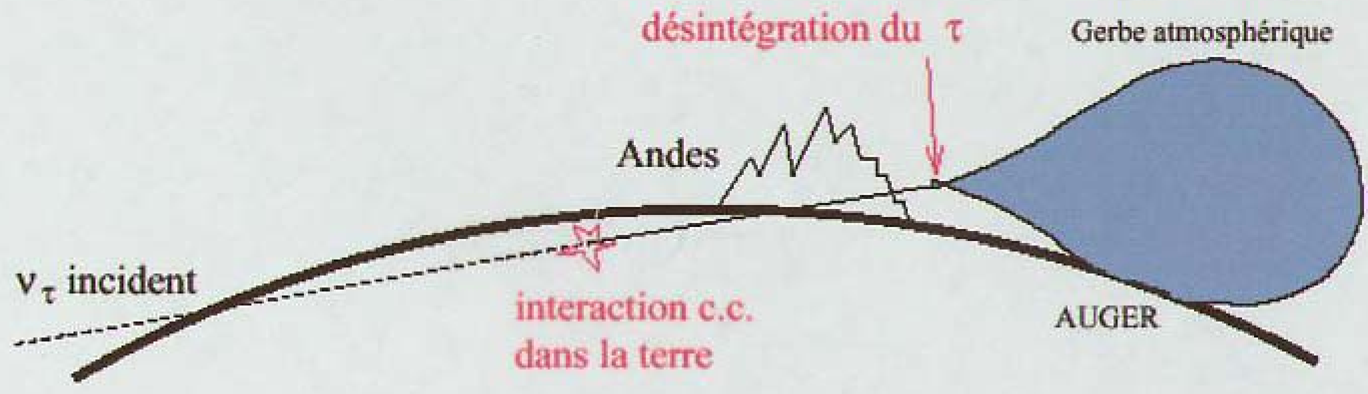
  In practice $85° < \theta_z < 95°$

  AUGER window: 10^{17} to 10^{20} eV

X.Bertou, P.Billoir, O.Deligny
A.Letessier-Selvon

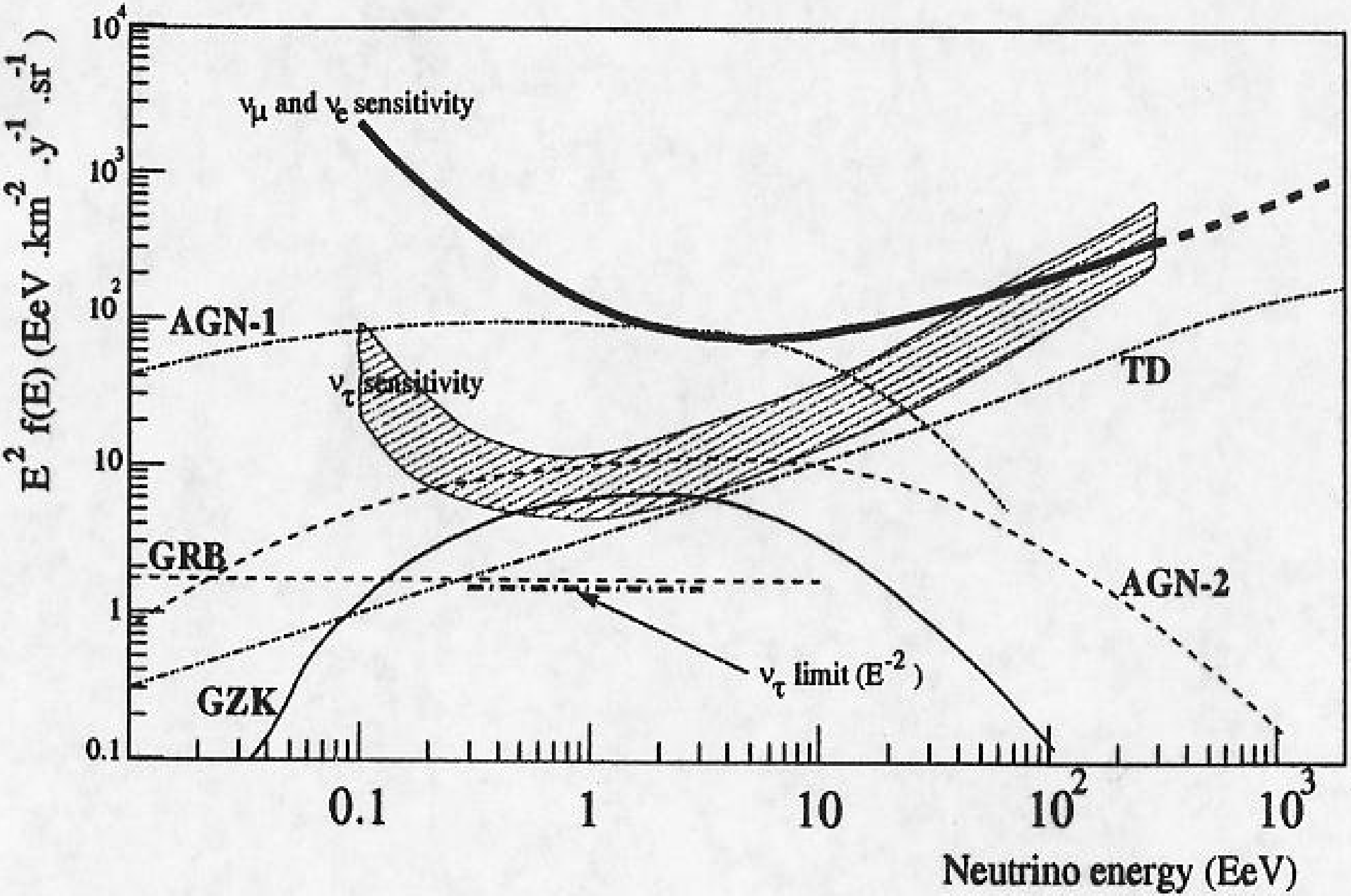
astro-ph/0104452v4
Accepted in Astropart. Phys.

ApP 17, 183, 2002



Paul Mantsch May 2002

Neutrino Sensitivity of Auger Observatory



Bertou et al. 2001

Potential of the Auger Observatory

- **Directions** ✓✓✓
- **Energy** ✓✓
- **Mass**
  - **photons** ✓✓ **X_{max}, shower front thickness, inclined events**
  - **neutrinos** ✓✓✓
  - **protons or iron?**

HARDER: will use X_{max}, LDF, FADC traces, inclined events, radius of curvature…

Conclusions

• **The Pierre Auger Observatory is now taking data**

• **By March 2005, the exposure with be similar to AGASA and we will rapidly overtake HiRes stereo.**
First results will be reported ~30 June 2005.

• **There are still some funding difficulties (~$1.4 M)**

• **Planning for the Northern Site is underway although, clearly, it will be influenced by what is seen in the South.**

• **We are looking forward to seeing our first point source and to understanding how far the spectrum extends beyond 10^{20} eV.**