COSMIC RAYS AT EXTREME ENERGIES: STATUS AND RECENT RESULTS OF THE PIERRE AUGER OBSERVATORY

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Pierre Auger Collaboration

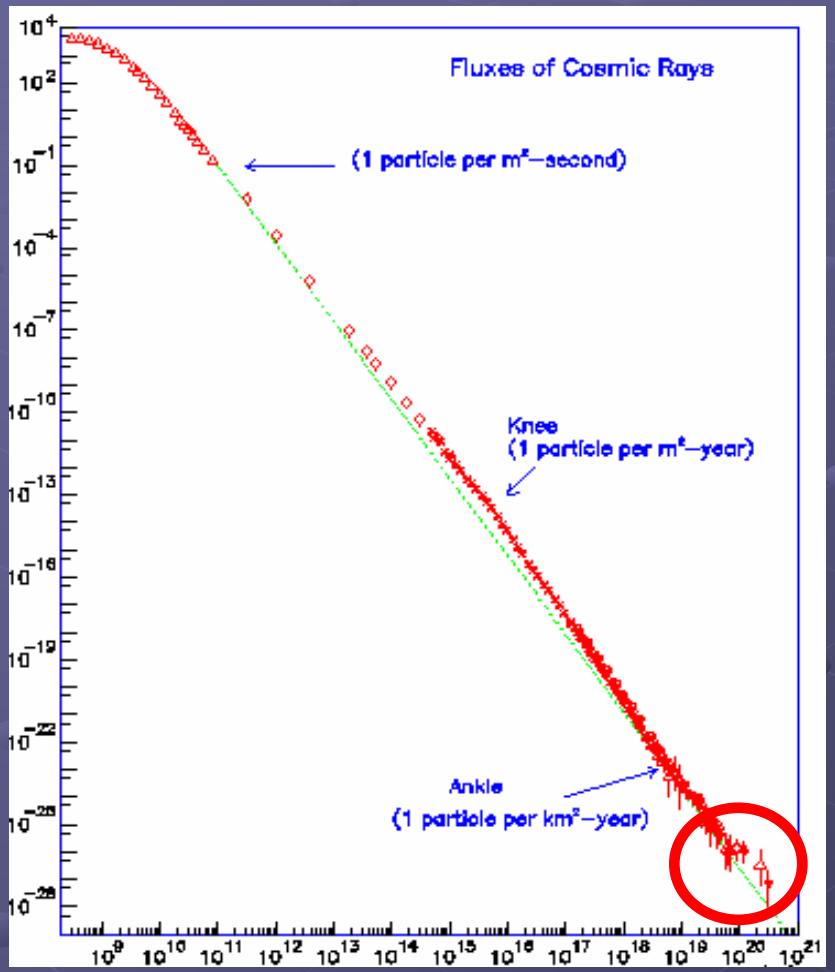
University of Nova Gorica

Slovenia

2006 LHC days in Split, Croatia

October 2 - 7, 2006

SPECTRUM



- **Highest energy event:**
  3.2 x 10^{20} eV
  Fly's Eye in Utah in 1991

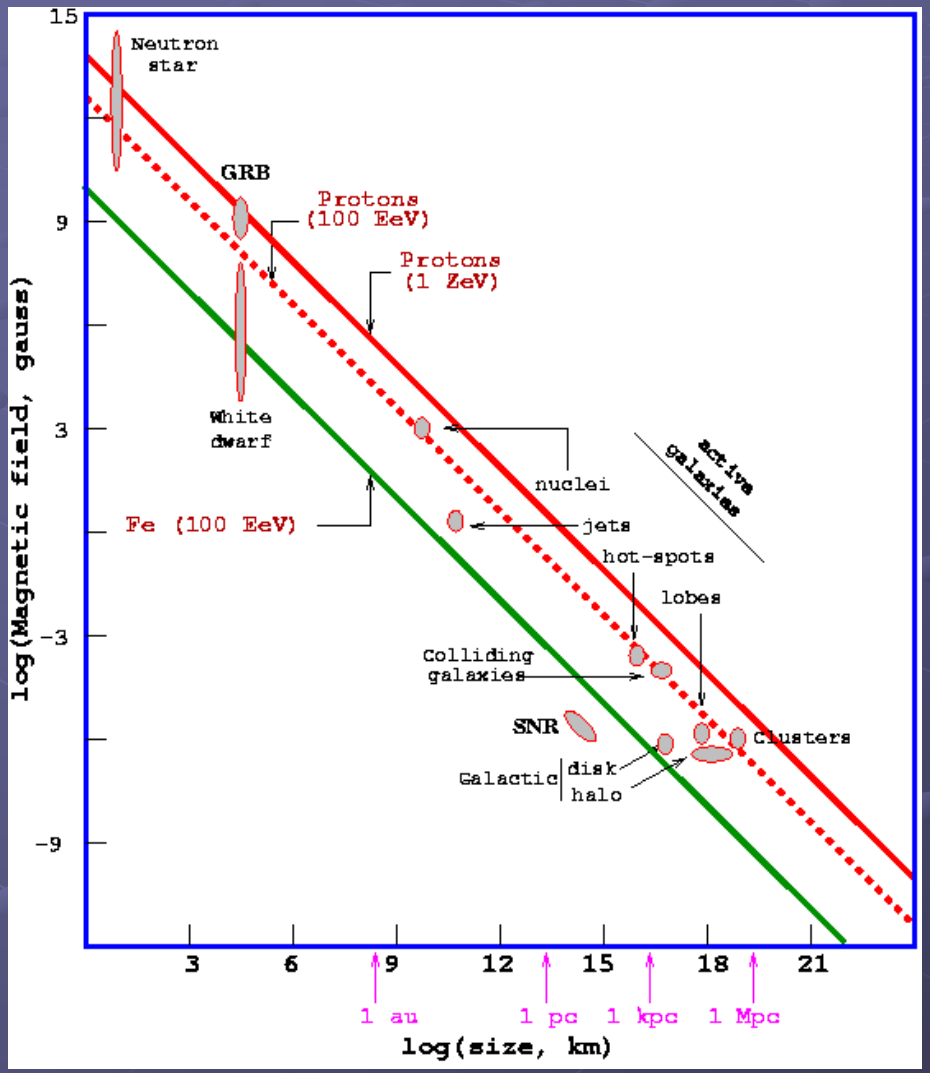
	LHC	Cosmos
E	7x10^{12} eV	~ 10^{20} eV
S	1.4x10^{13} eV	~ 5x10^{14} eV

- **Low flux - large areas**
- **No known astrophysical sources seem able to produce such enormous energies**

← 1 particle/km²/century

LIMITS TO ACCELERATION

Hillas plot

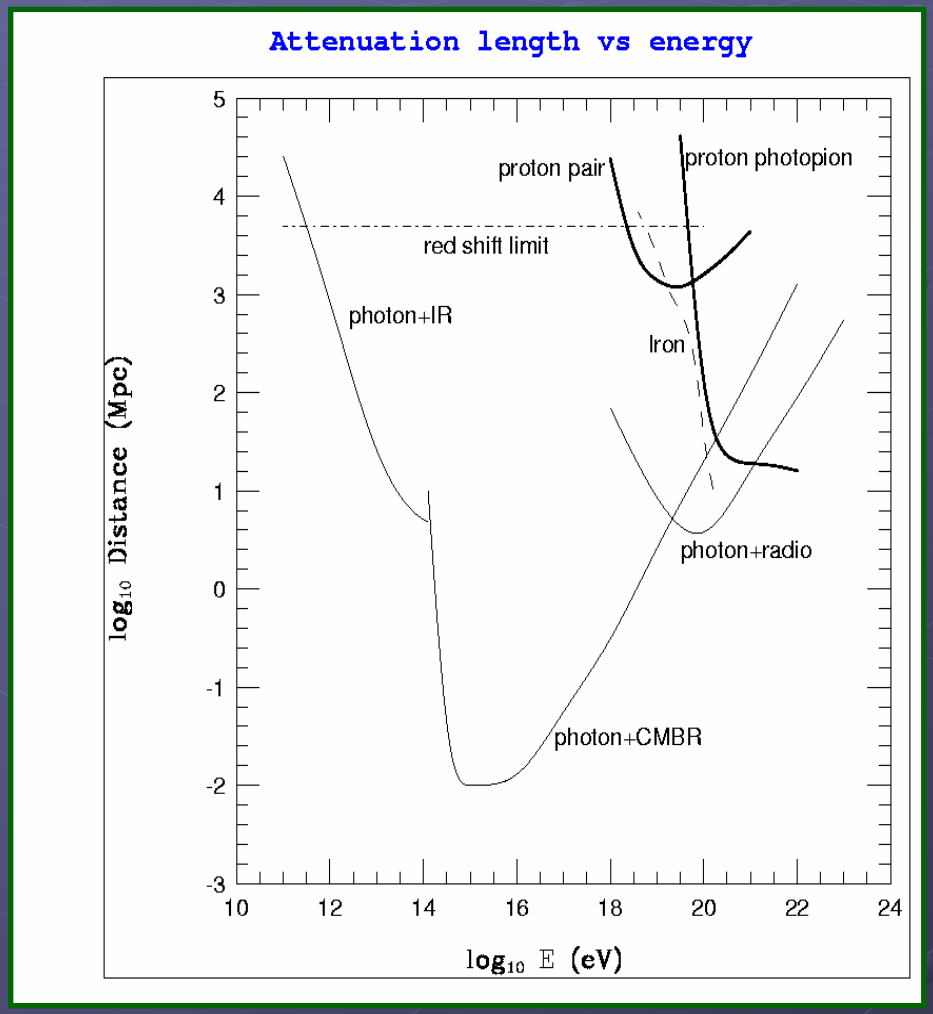


Maximal energy $E_{max} \sim \beta ZBL$

No good candidates for ZeV accelerators in the known Universe!

PROPAGATION

All known particles except neutrinos undergo interactions with Cosmic Microwave Background

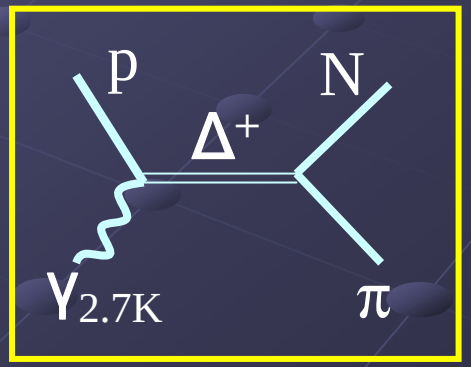


Example:

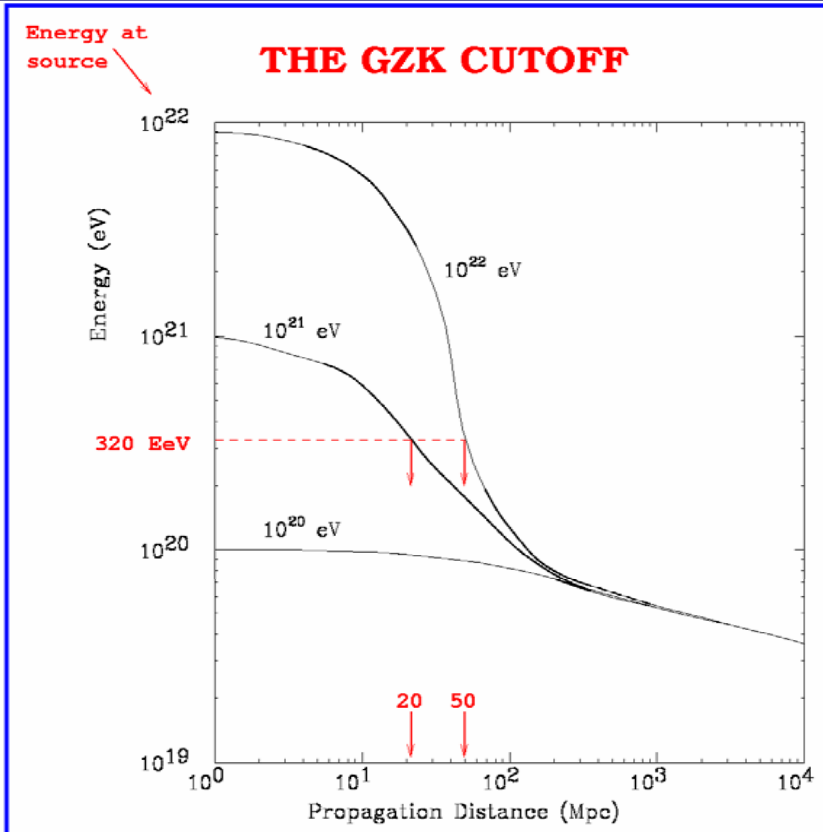
$p + \gamma_{2.7K} \rightarrow p + \pi^0$

$\rightarrow n + \pi^+$

For energy > 5 x 10^{19}



PROPAGATION



Energy attenuation of protons

Protons: photopion threshold @ ~50 EeV

Photons: pair production threshold @ ~200 TeV

Nuclei: photodisintegration above 50 EeV

Neutrinos: no problem!

For E>100 EeV, the source must be within ~50 Mpc

Greisen-Zatsepin-Kuzmin Cut-off

(Greisen '66, Zatsepin & Kuzmin '66)

Particles > 5 x 10^{19} eV
must be < 50 Mpc away

Size of the observable Universe
~ 4.000 MPc

MAGNETIC FIELD DEFLECTION

Above 100 EeV $\Delta\phi < 2^0$ - of the order of experimental resolution!

A window to CR astronomy

PIERRE AUGER PROJECT

A cosmic ray observatory designed for a high statistics study of

The Highest Energy Cosmic Rays (10^{19} - 10^{21} eV)

using

Two Large Air Shower Detectors

Mendoza, Argentina
(construction underway)

Colorado, USA
(in planning)

P. AUGER COLLABORATION


Argentina


Australia


Bolivia


Brazil


Czech Republic


France


Germany


Italy


Mexico


Netherlands


Poland


Portugal


Slovenia


Spain


UK


USA


Vietnam

~ 360 physicist from 63 institutions

17 countries

P. AUGER OBSERVATORY

Science Objectives

- Cosmic ray spectrum above 10^{19} eV
  - Shape of the spectrum in the region of the GZK feature
- Arrival direction distribution
  - Search for departure from isotropy - point sources
- Composition
  - Light or heavy nuclei, protons, photons, neutrinos or exotics

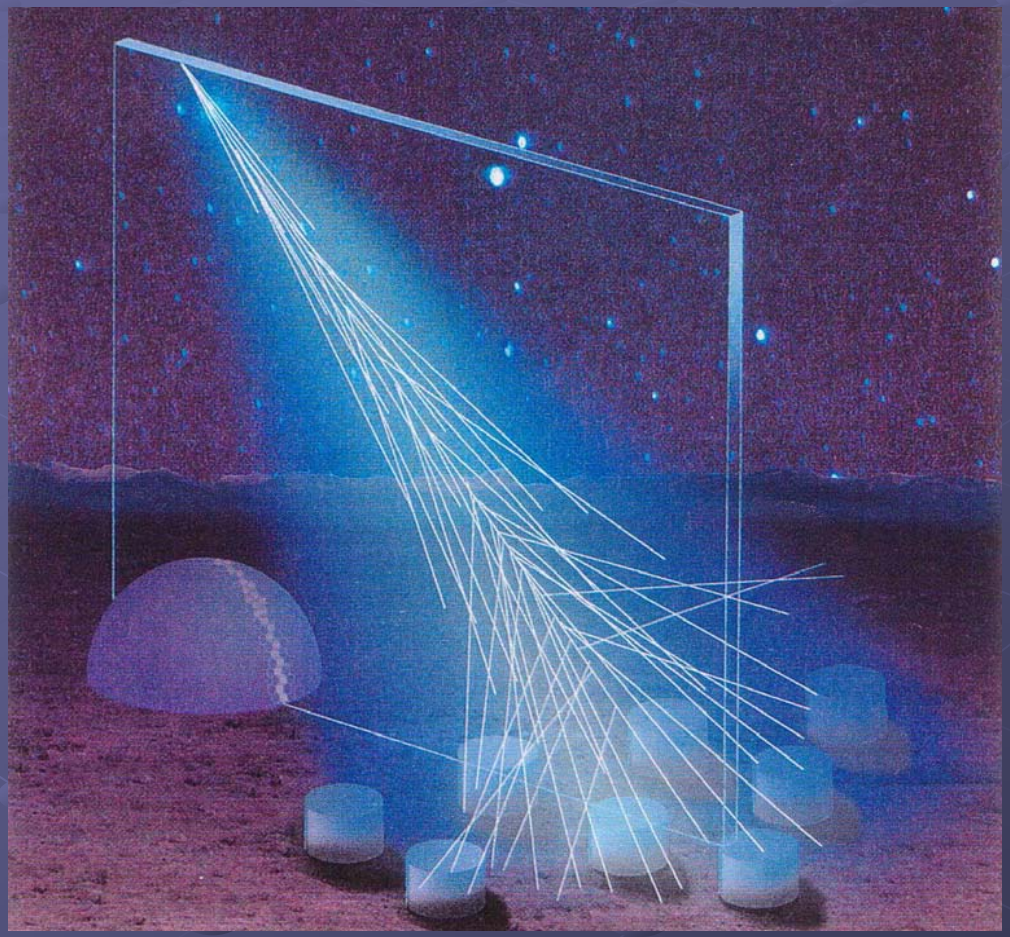
Design Features

- High statistics (aperture > 7.000 km^2 sr above 10^{19} eV in each hemisphere)
- Full sky coverage with uniform exposure
- Hybrid configuration surface array with fluorescence detector coverage

P. AUGER OBSERVATORY

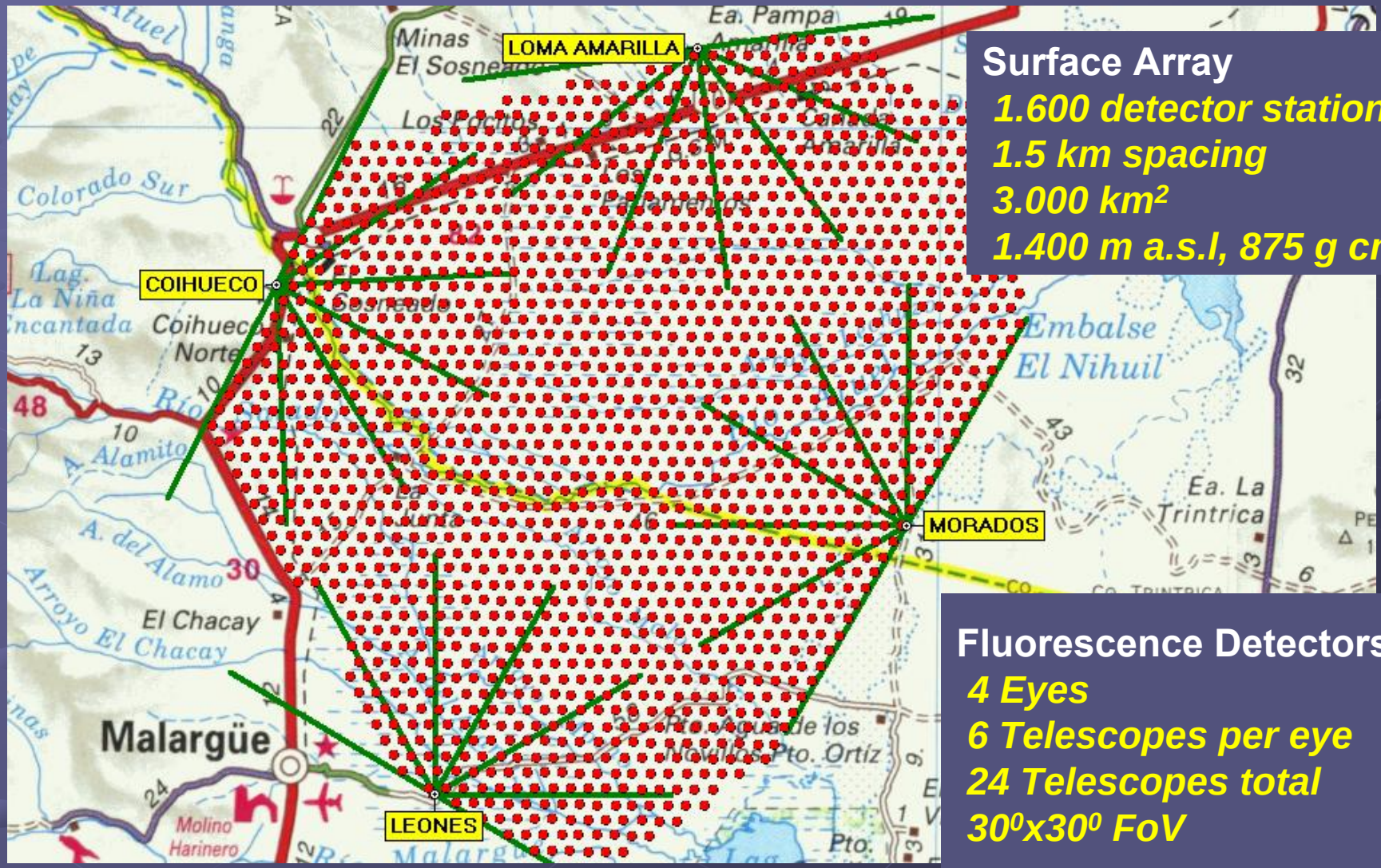
The Hybrid Design

Surface detector array + Air fluorescence detectors



- Nearly calorimetric energy calibration of the fluorescence detector transferred to the event gathering power of the surface array.
- A complementary set of mass sensitive shower parameters.
- Different measurement techniques force understanding of systematic uncertainties.
- Determination of the angular and core position resolutions.

SOUTHERN OBSERVATORY - PLAN



Surface Array

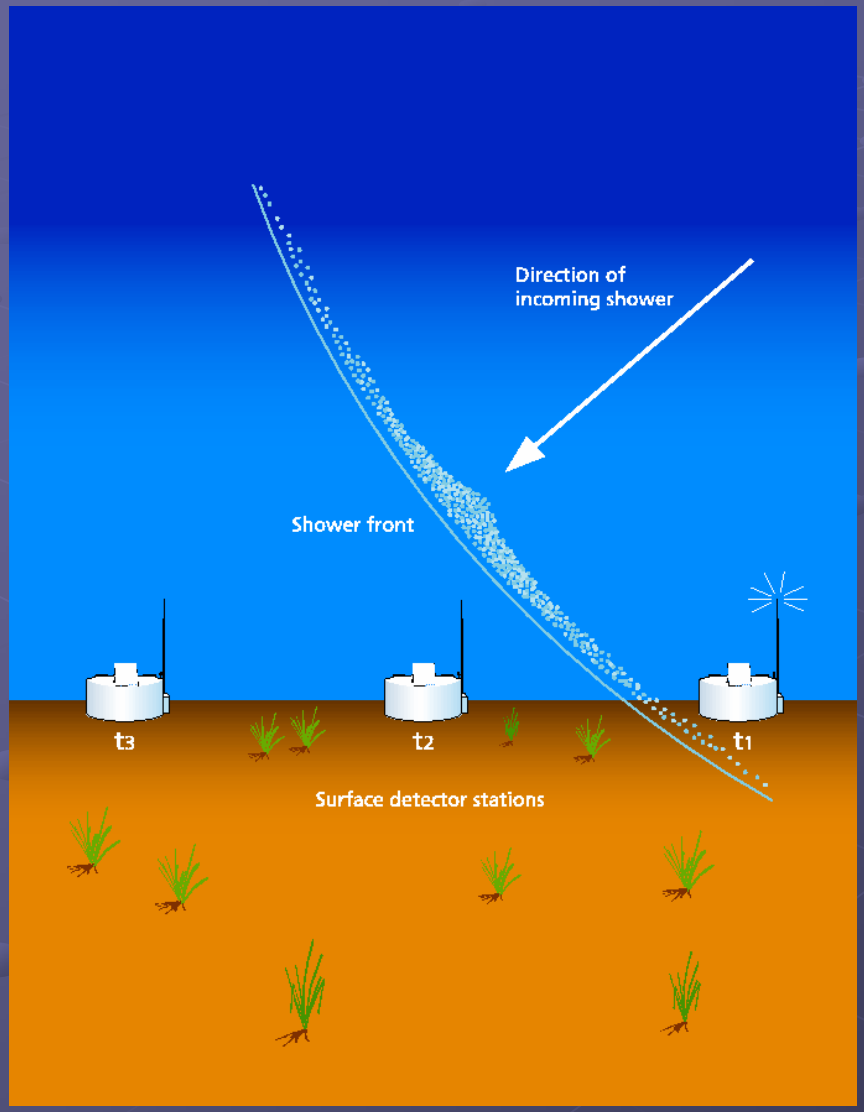
1.600 detector stations
1.5 km spacing
3.000 km²
1.400 m a.s.l, 875 g cm⁻²

Fluorescence Detectors

4 Eyes
6 Telescopes per eye
24 Telescopes total
30⁰x30⁰ FoV

← 65 km →

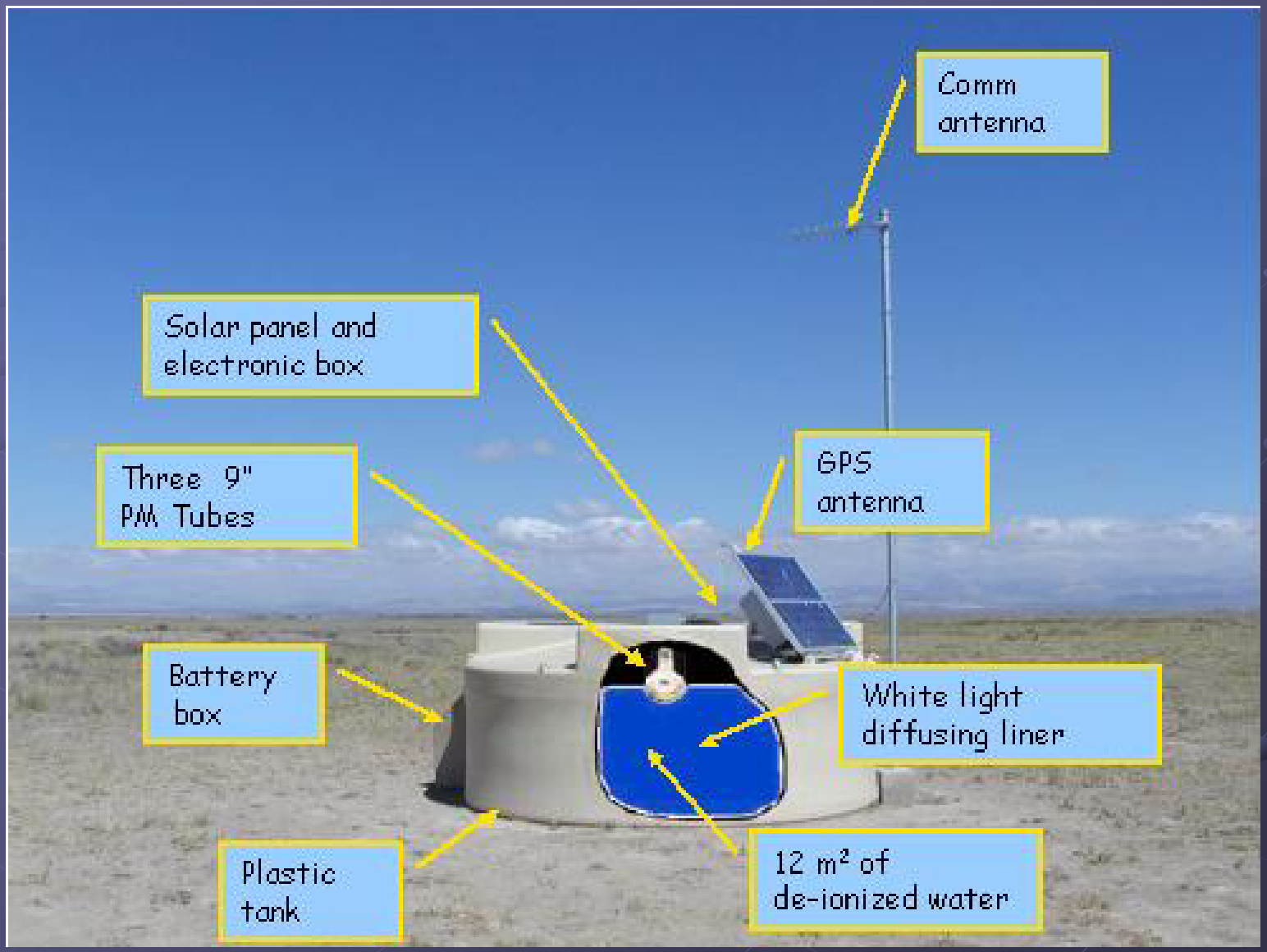
SURFACE DETECTOR ARRAY



Event timing and direction determination

- Shower timing → Shower angle
- Particle density → Shower energy
- Pulse rise time → Measure of primary mass

WATER ČERENKOV DETECTOR



SURFACE DETECTOR ARRAY

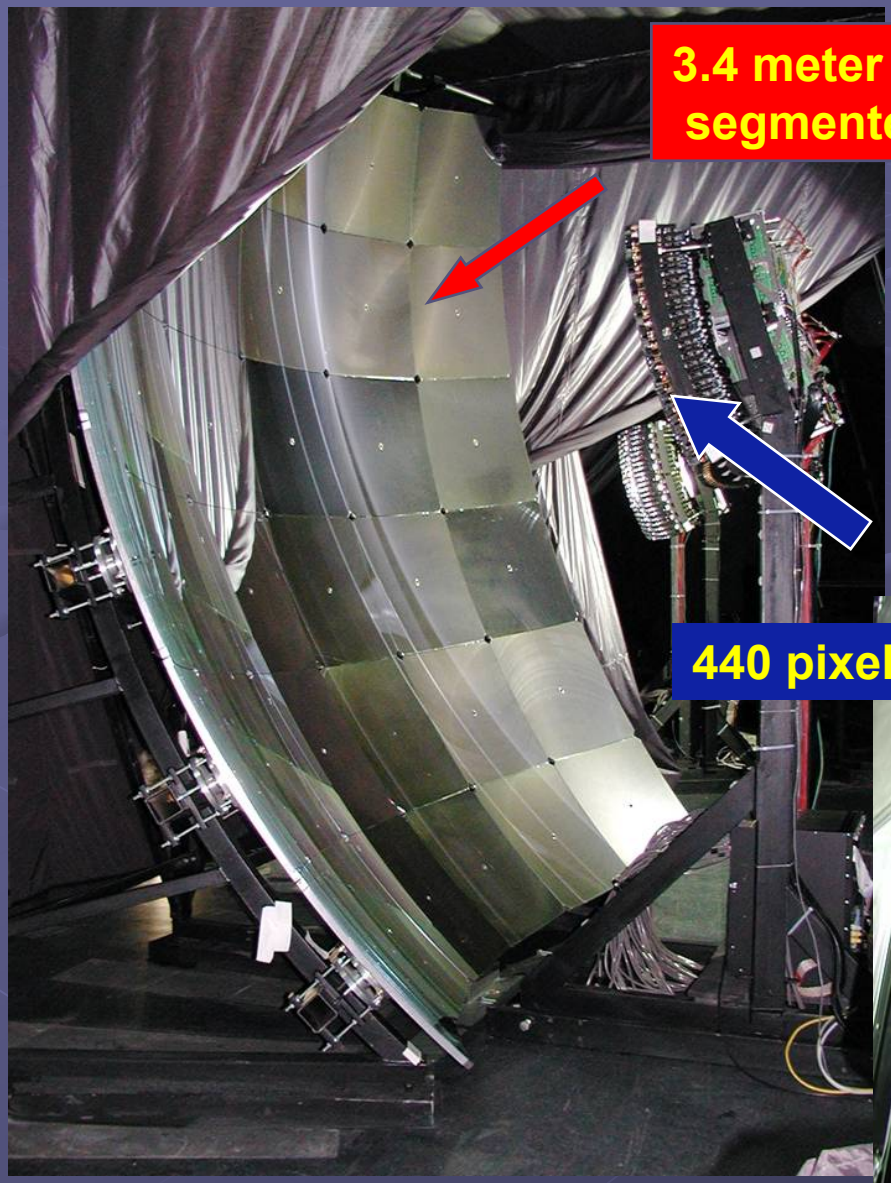
FLUORESCENCE DETECTOR

- Shower ~ 90% electromagnetic
- Ionization of nitrogen measured directly

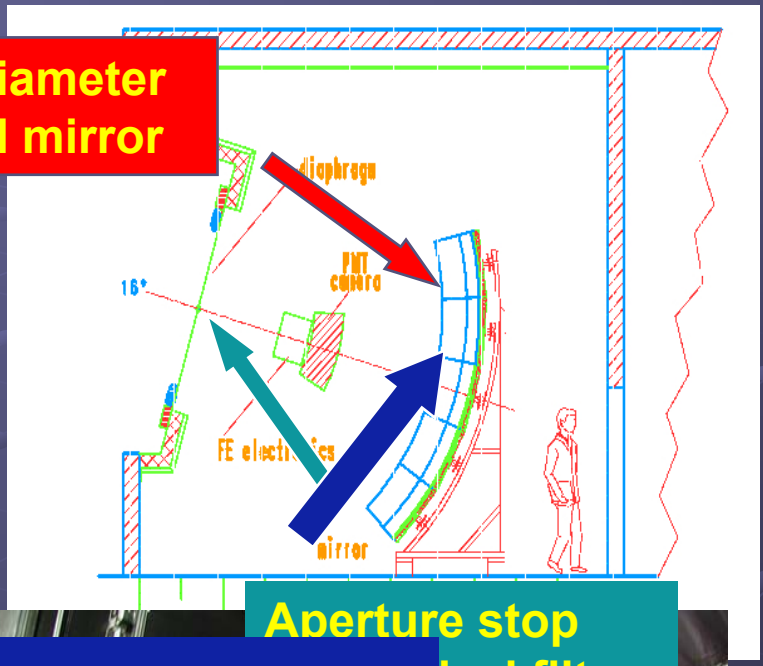
- Calorimetric energy measurement
- Measure of shower development

FLUORESCENCE DETECTOR

FLUORESCENCE DETECTOR



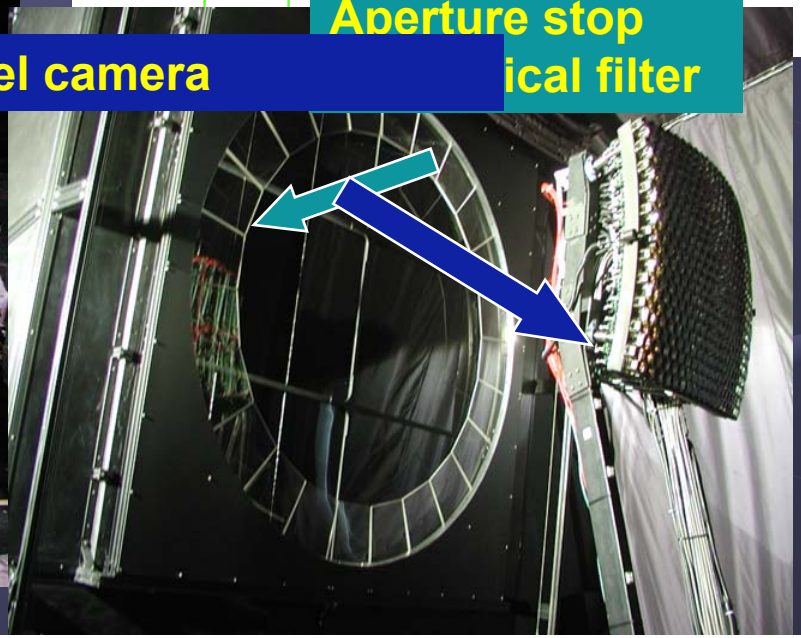
3.4 meter diameter segmented mirror



Aperture stop

440 pixel camera

ical filter



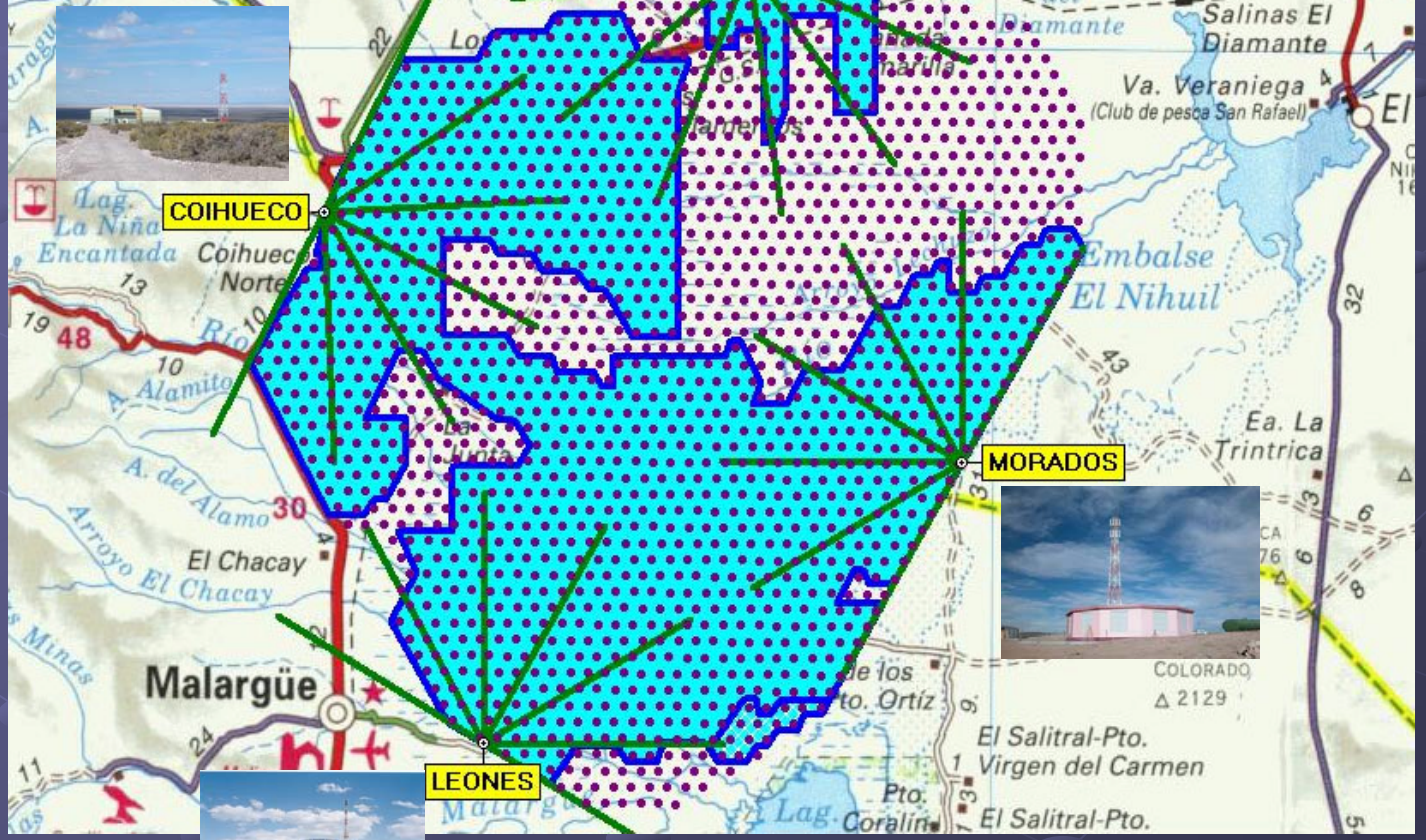
ATMOSPHERIC MONITORING AND CALIBRATION

Absolute Calibration

- Calibrated (movable) light sources
- Cloud monitors
- Balloon sondes

Monitoring

CURRENT STATUS



SA

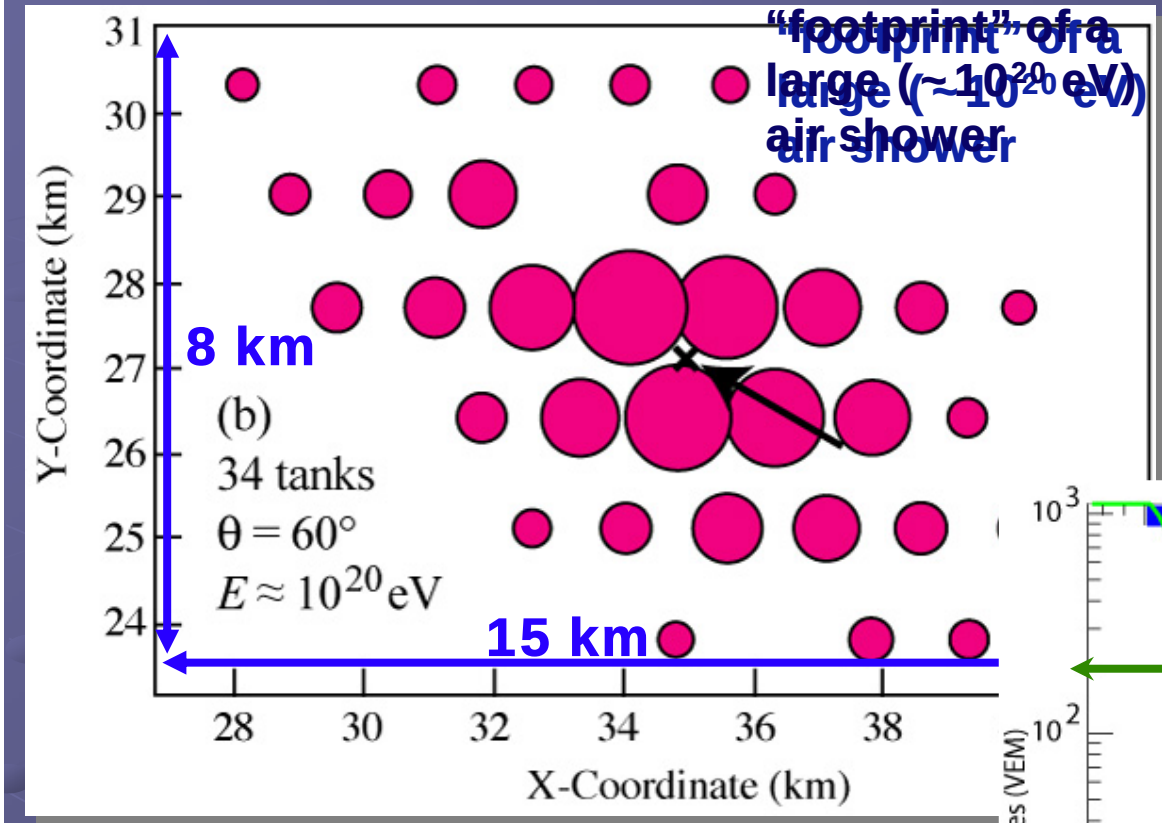
- **~ 1100 surface detector stations deployed**
- **~ 1000 surface detector stations have electronics and are operational**

World largest array

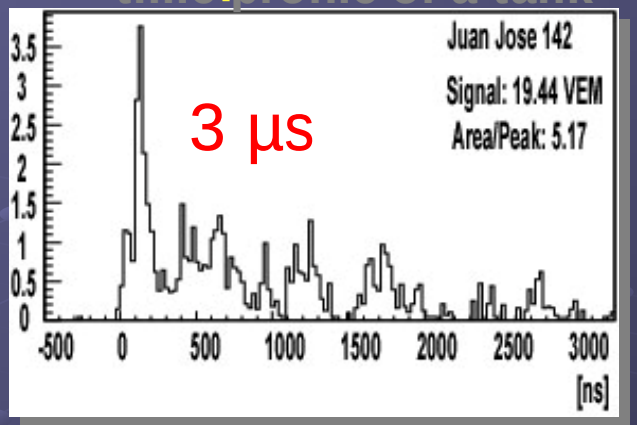
FD

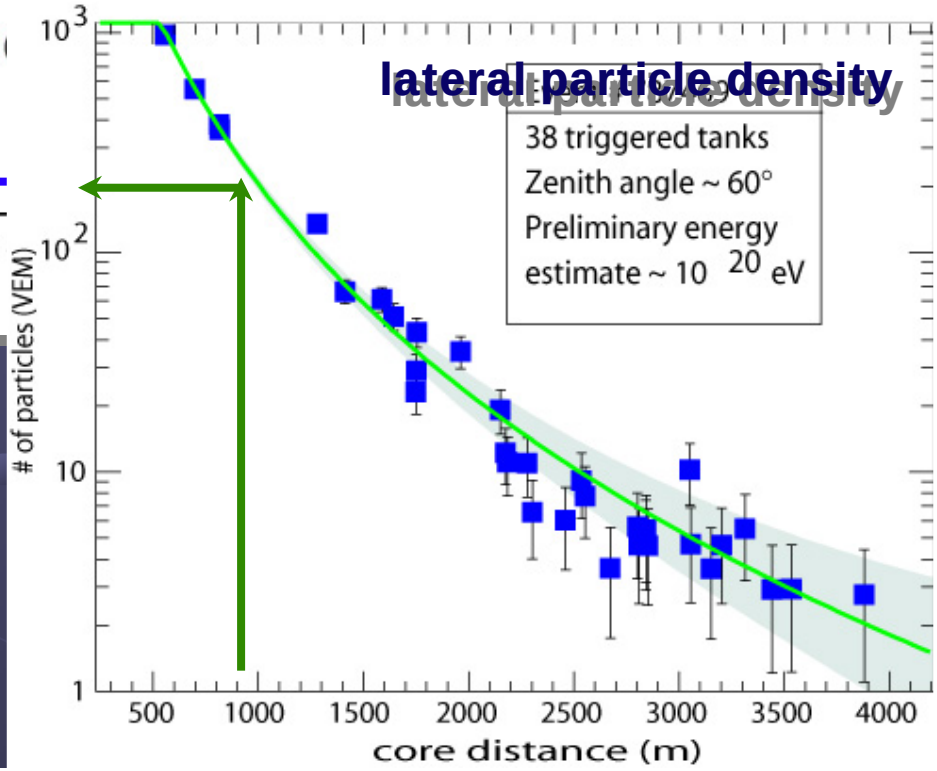
- **3 fluorescence buildings complete each with 6 telescopes (Los Leones, Coihueco, Los Morados)**
- **Fourth fluorescence building under construction (Loma Amarilla)**

SD RECONSTRUCTION



time profile of a tank



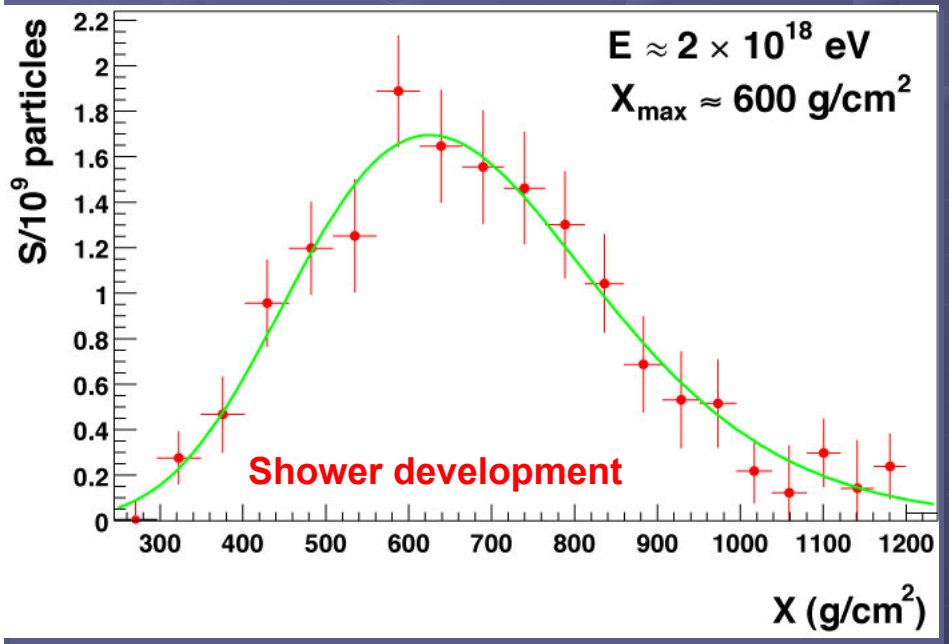


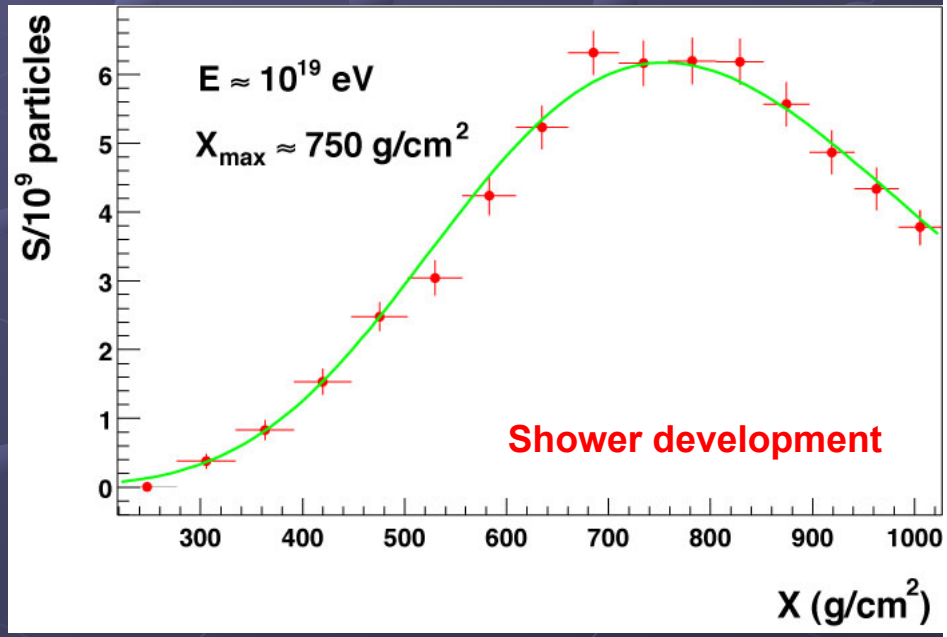
Simulations: particle density at 1000 m provides good estimate of primary energy

different models: ~20 syst. errors

FD RECONSTRUCTION

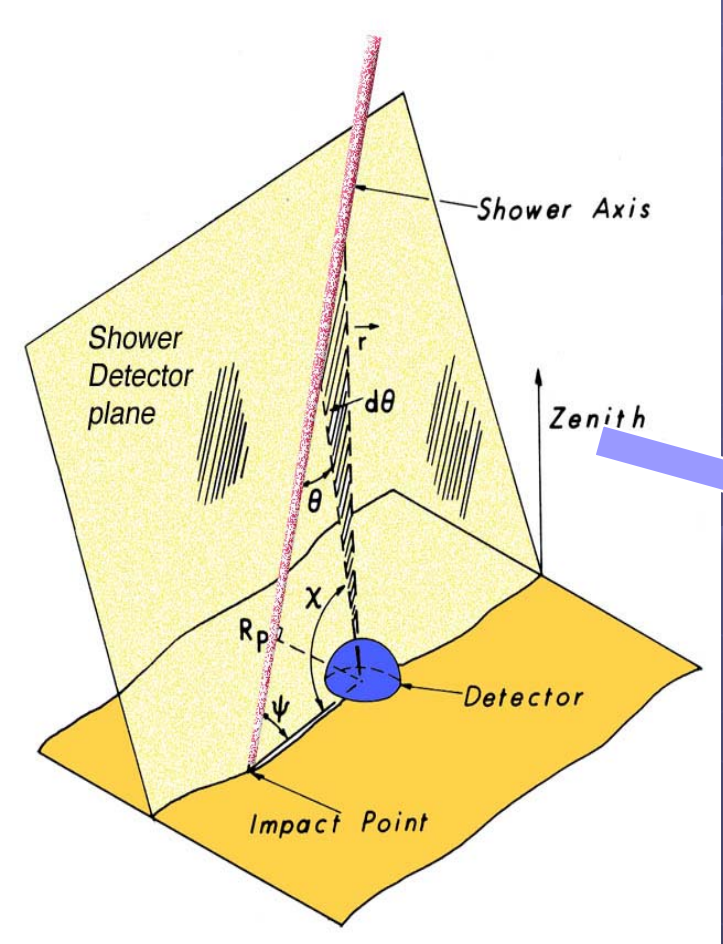
- Fit with empirical formula of Gaisser-Hillas
- Calorimetric measurement of the energy.

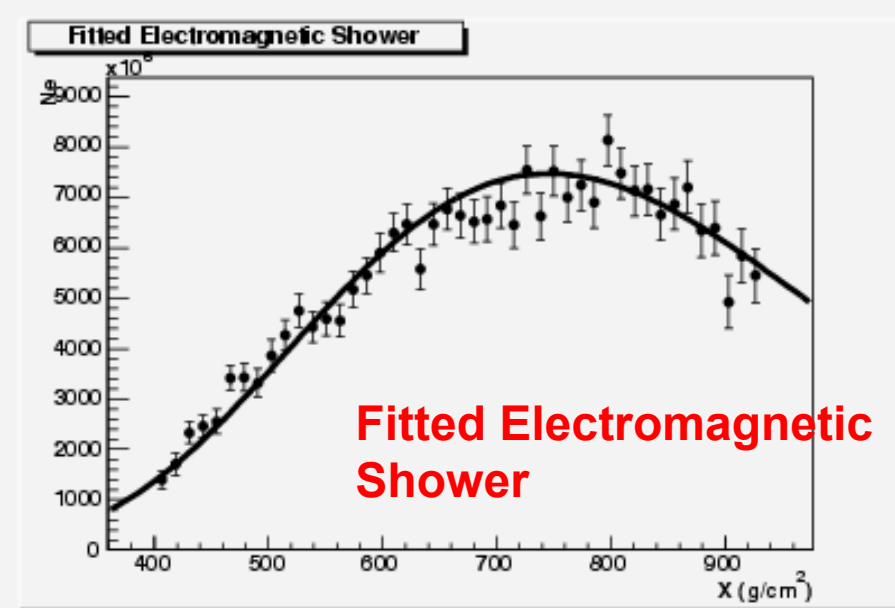


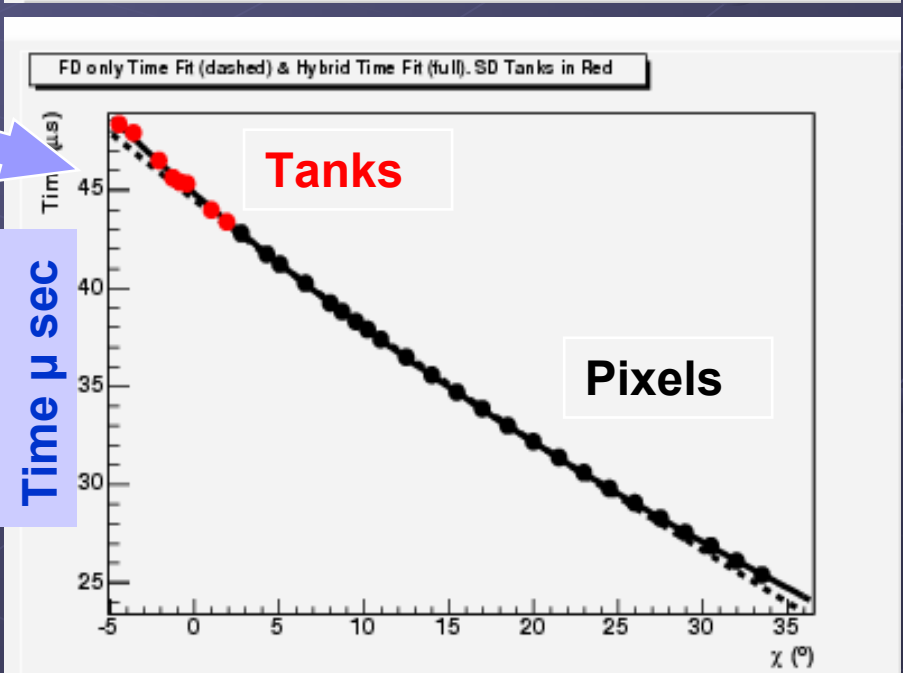


HYBRID DATA

Hybrid Event Θ~ 30º, ~ 8 EeV



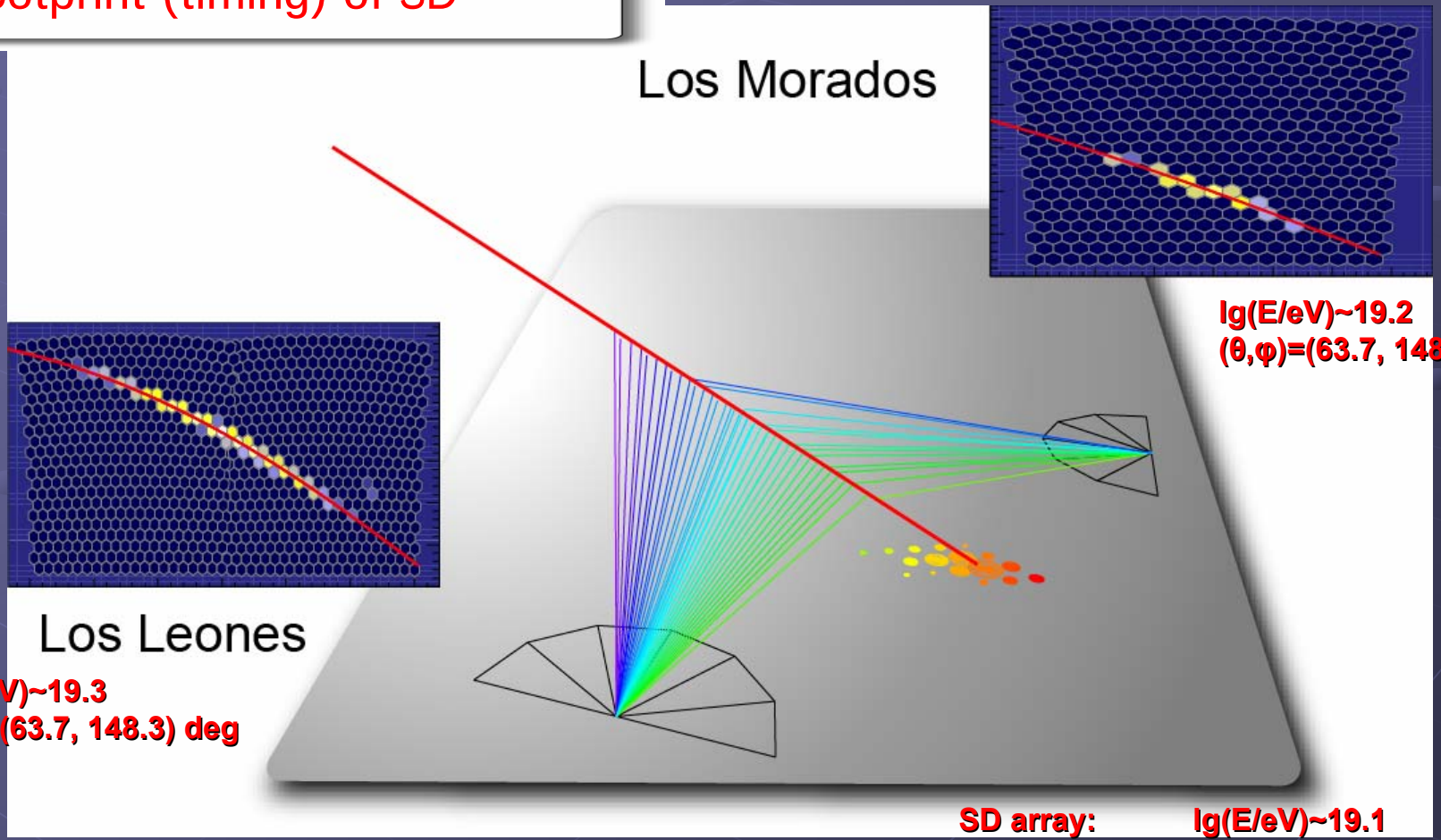




Angle χ in the shower-detector plane

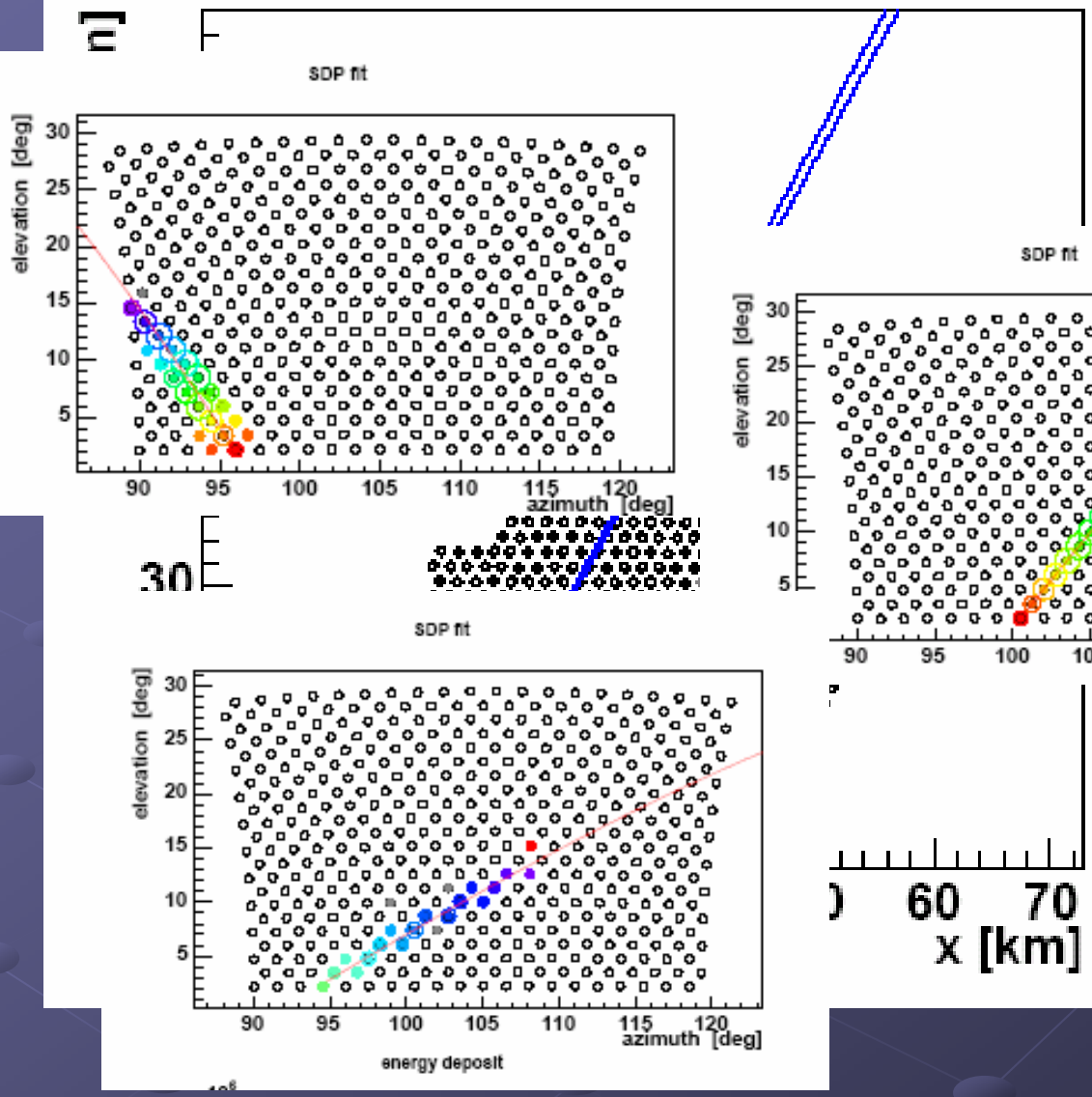
STEREO HYBRID OBSERVATIONS

Advantage of Hybrid:
Shower axis reconstr. improved
by footprint (timing) of SD

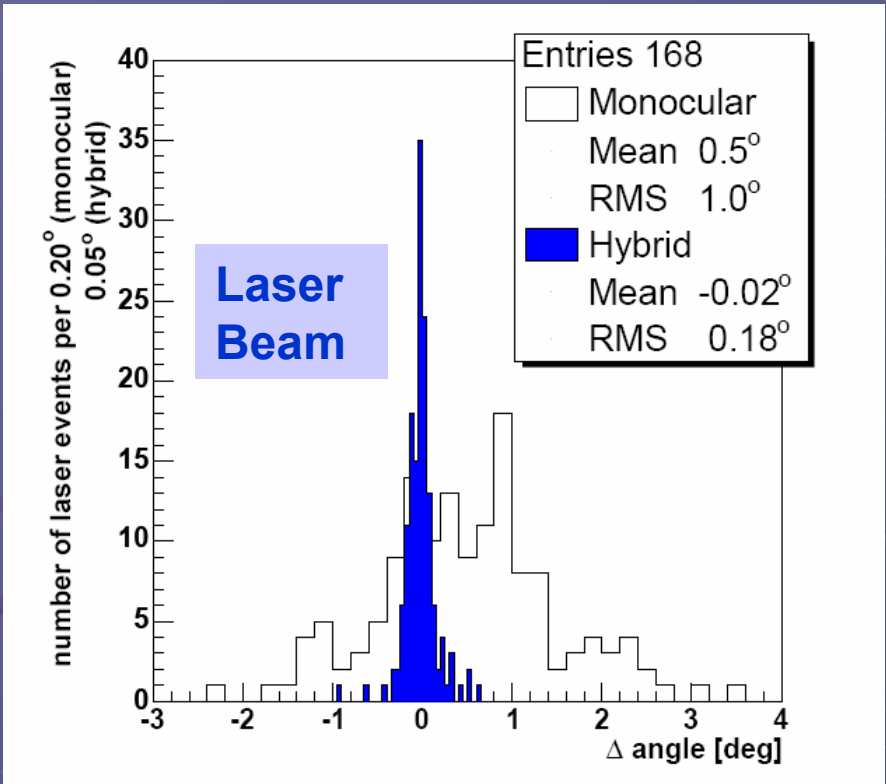


HYBRID RECONSTRUCTION

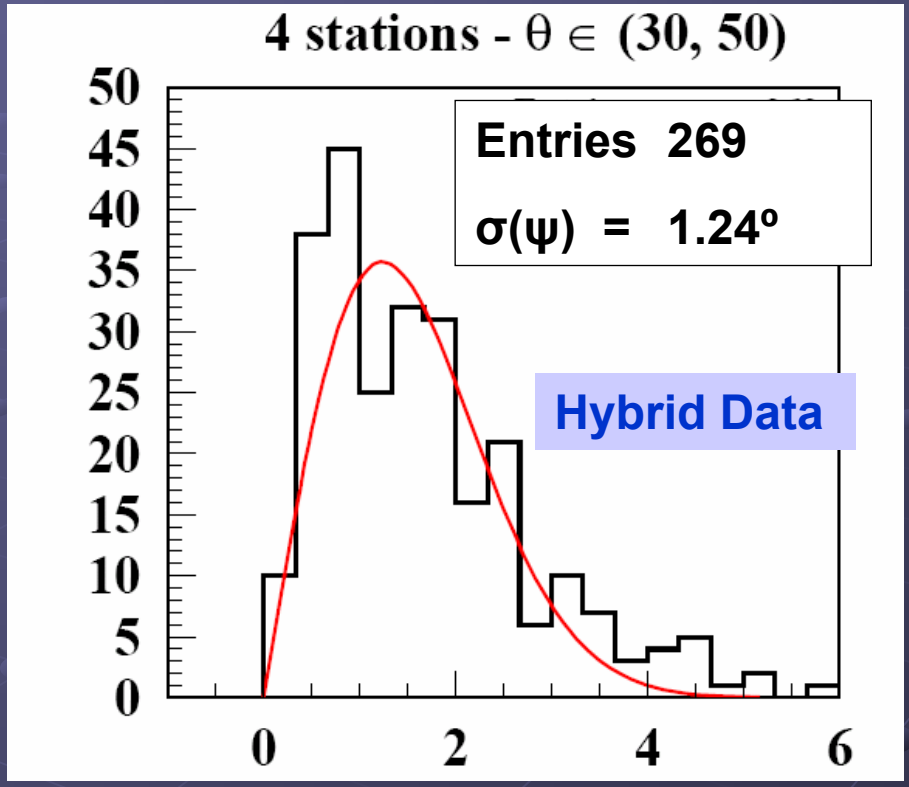
A Tri-ocular Event!
~20EeV



PERFORMANCE: *Angular Resolution*



Angle in laser beam /FD detector plane



Hybrid-SD only space angle difference

Hybrid angular resolution (68% CL)

0.6 degrees (mean)

Surface array angular resolution (68% CL)

< 2.2° for 3 station events (E< 3EeV, θ < 60°)

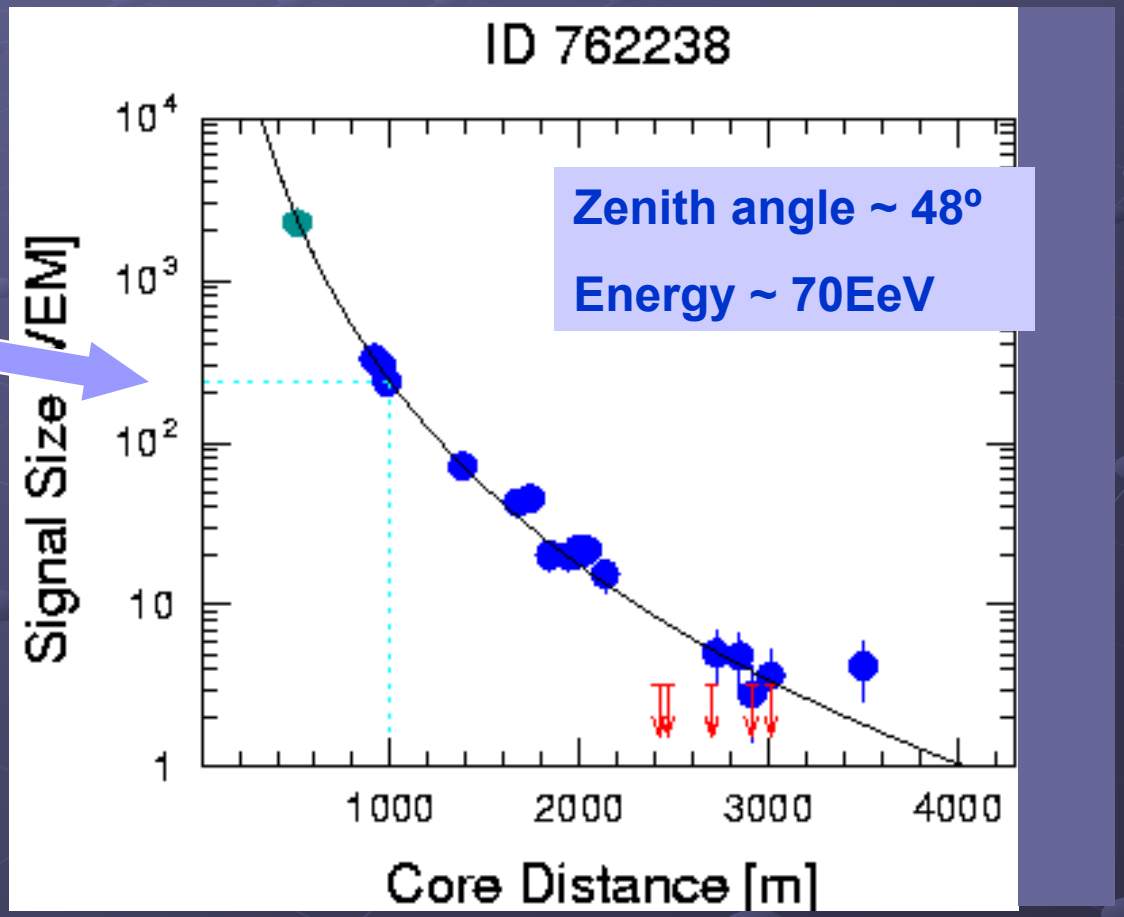
< 1.7° for 4 station events (3<E<10 EeV)

< 1.4° for 5 or more station events (E>10 EeV)

ENERGY DETERMINATION

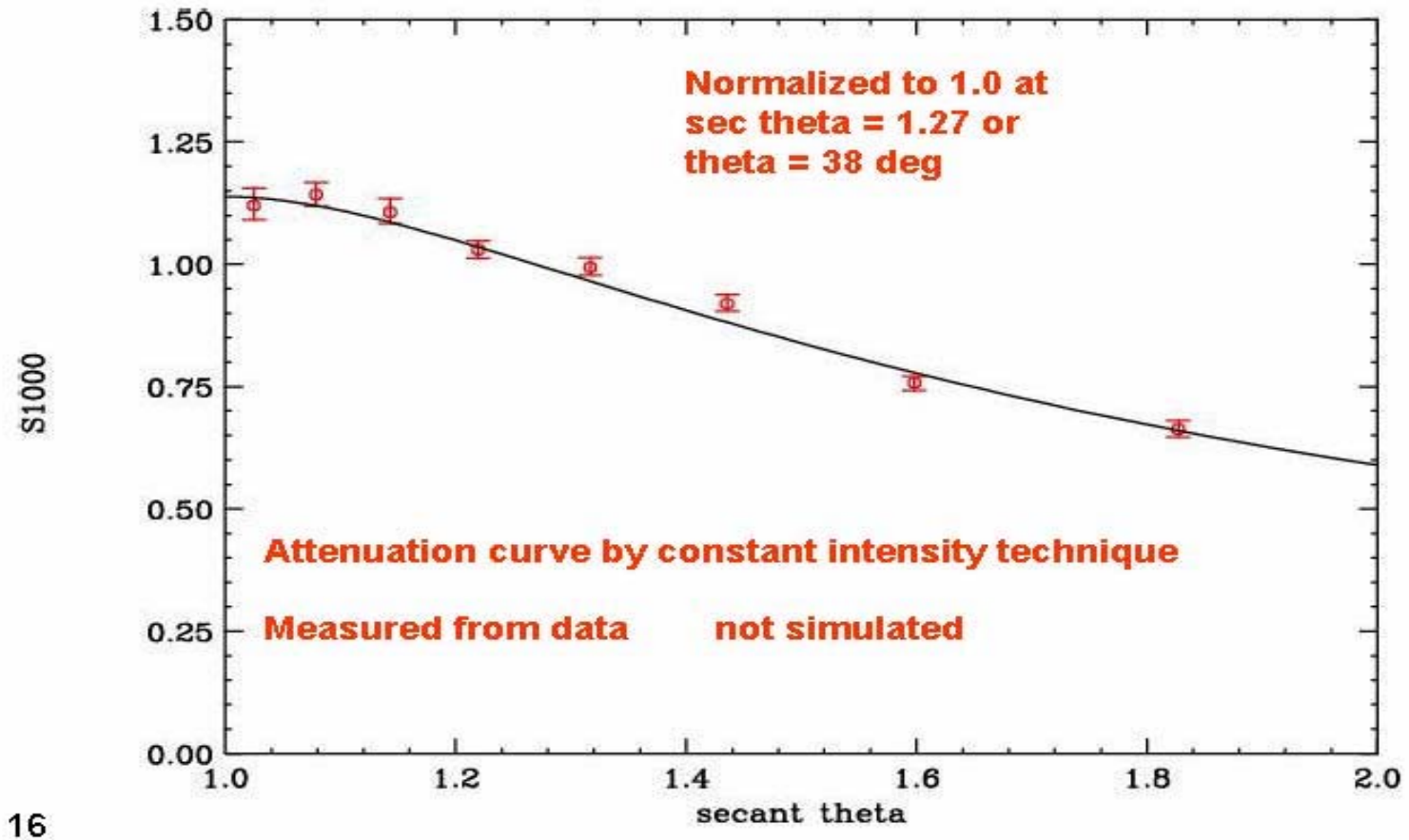
The energy scale is based on fluorescence measurements without reliance on a specific interaction model or assumptions about the composition.

The detector signal size at 1000 meters from the shower core - called the ground parameter or S(1000) - is determined for each surface detector event using the lateral density function. S(1000) is proportional to the primary energy.



ENERGY DETERMINATION

Zenith angle dependence of the energy estimator S(1000)



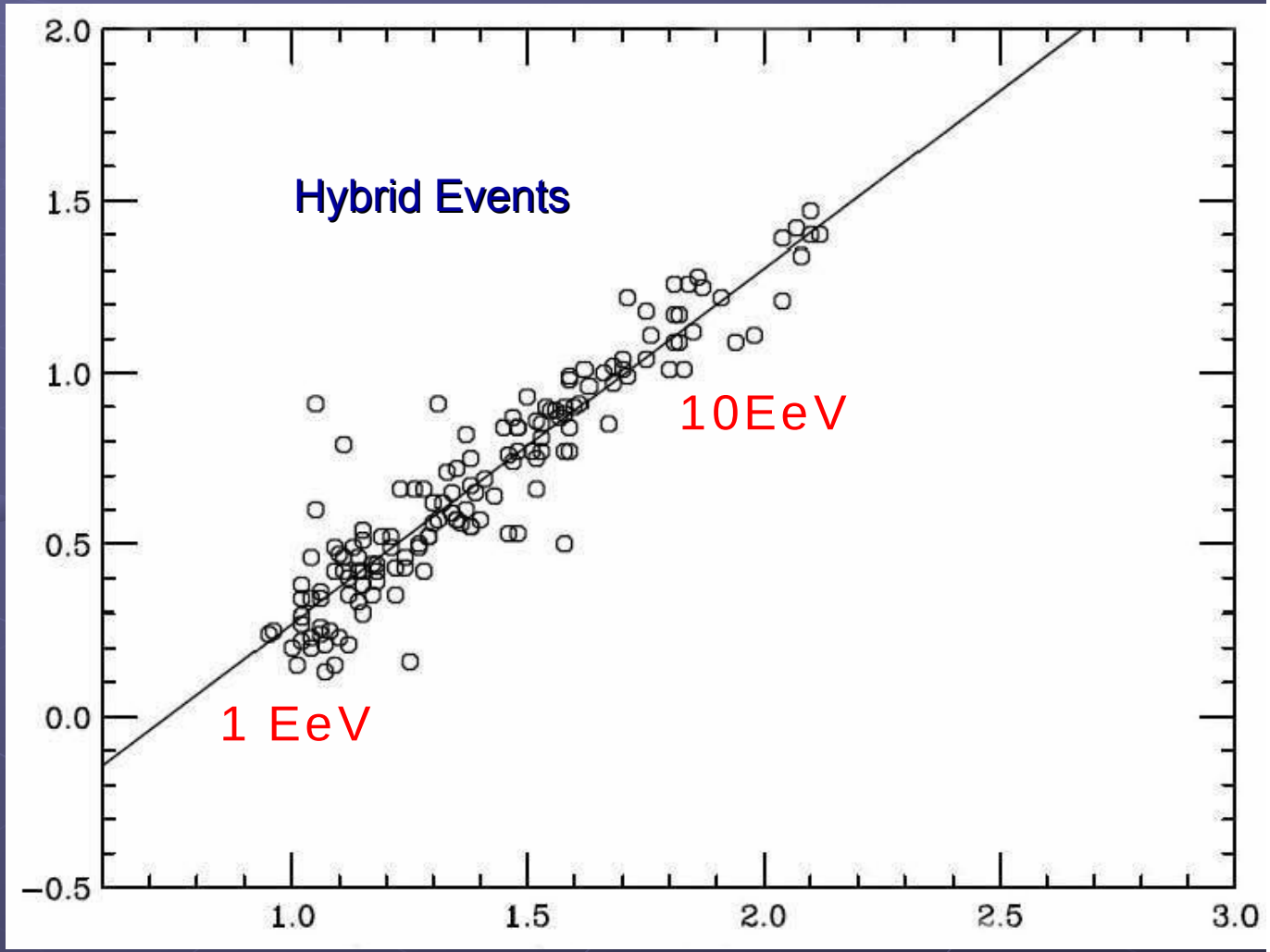
ENERGY DETERMINATION

The energy converter:

Compare ground parameter S(1000) with the fluorescence detector energy.

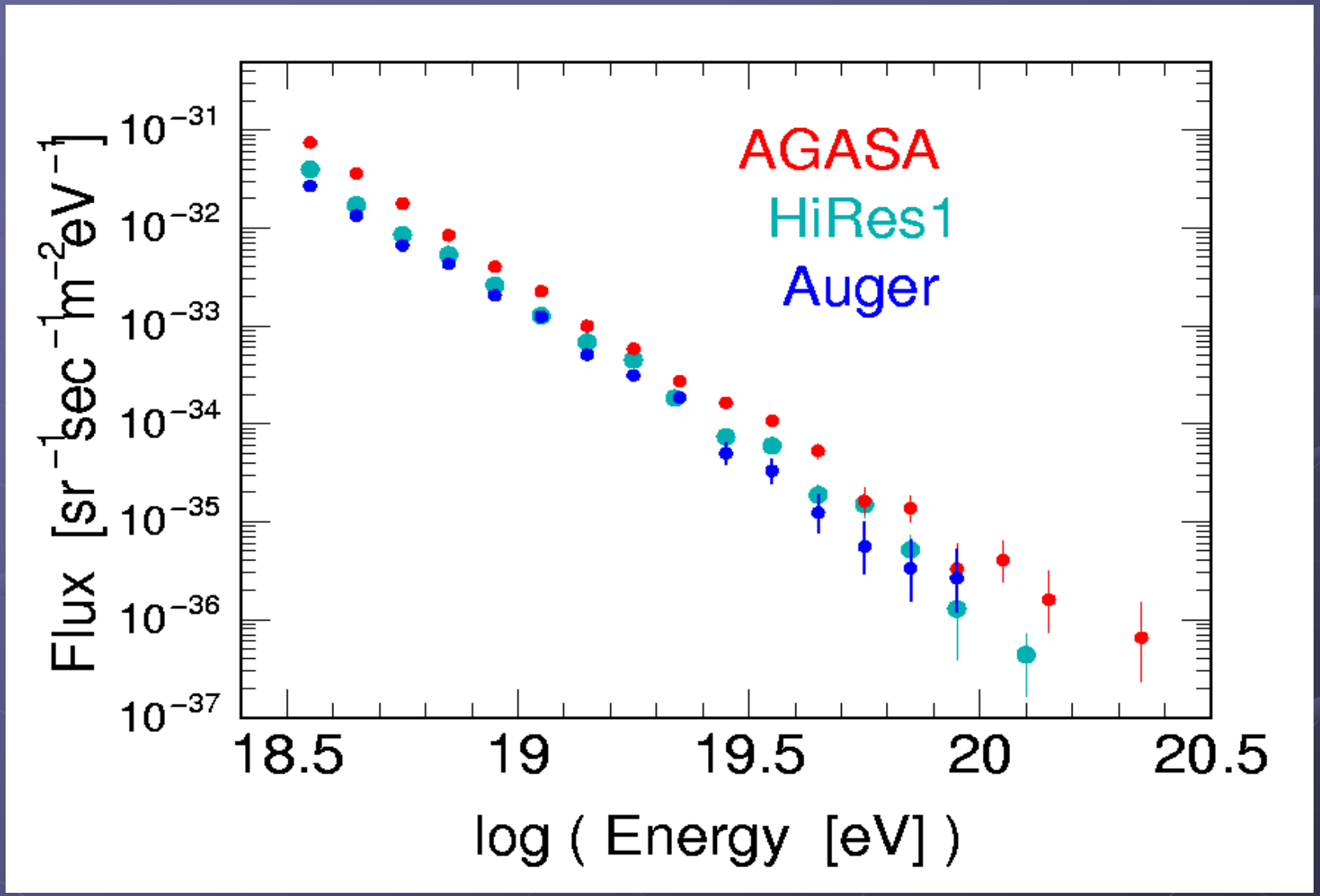
Transfer the energy converter to the surface array only events.

Simulation not needed.



SPECTRUM

Comparison with HiRes1, AGASA

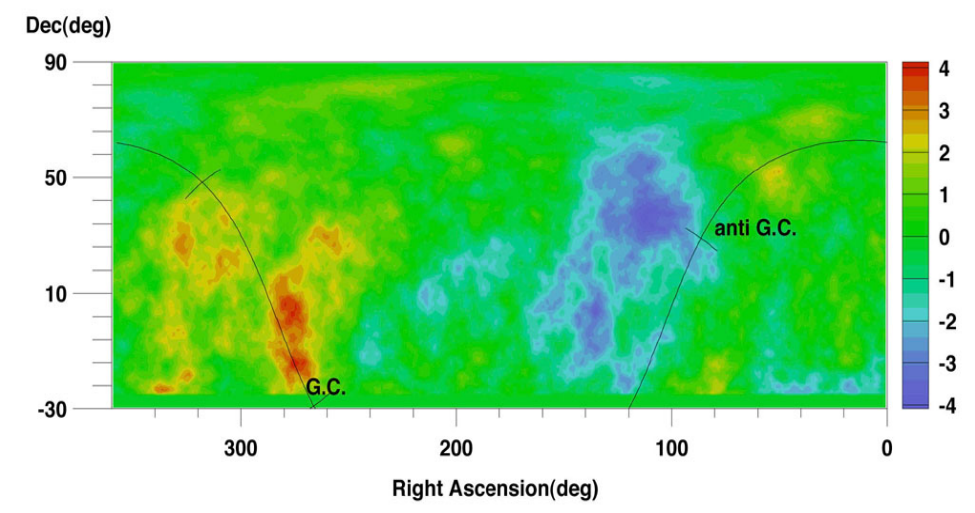


1) M. Takeda *et al.* Astroparticle Physics 19, 447 (2003)

2) R.U. Abbasi *et al.* Phys Lett B (to be published)

ARRIVAL DIRECTIONS

GALACTIC CENTER

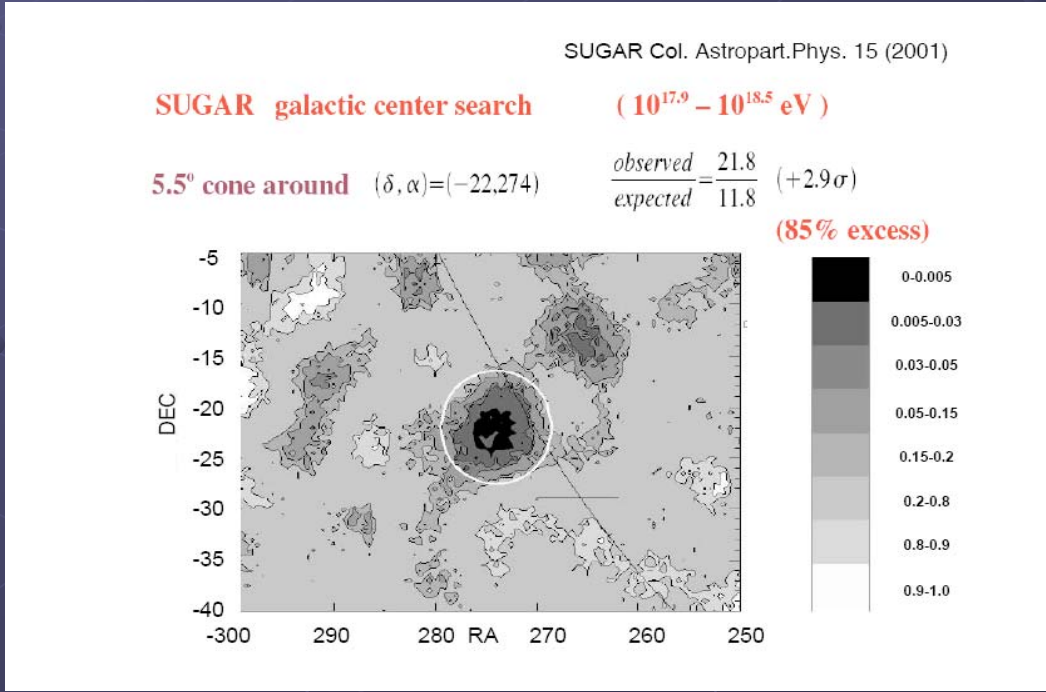


AGASA Collaboration

- $E=10^{18}$ - $10^{18.4}$ eV
- 4.5 sigma excess (~ 22 %) from direction of Galactic Centre
- Astropart. Phys. **10** (1999)

SUGAR Collaboration

- $E=10^{17.9}$ - $10^{18.5}$ eV
  - stronger excess
  - weaker significance
- Astropart. Phys. **15** (2001)



GALACTIC CENTER

AUGER Collaboration

Astro-ph/0607382

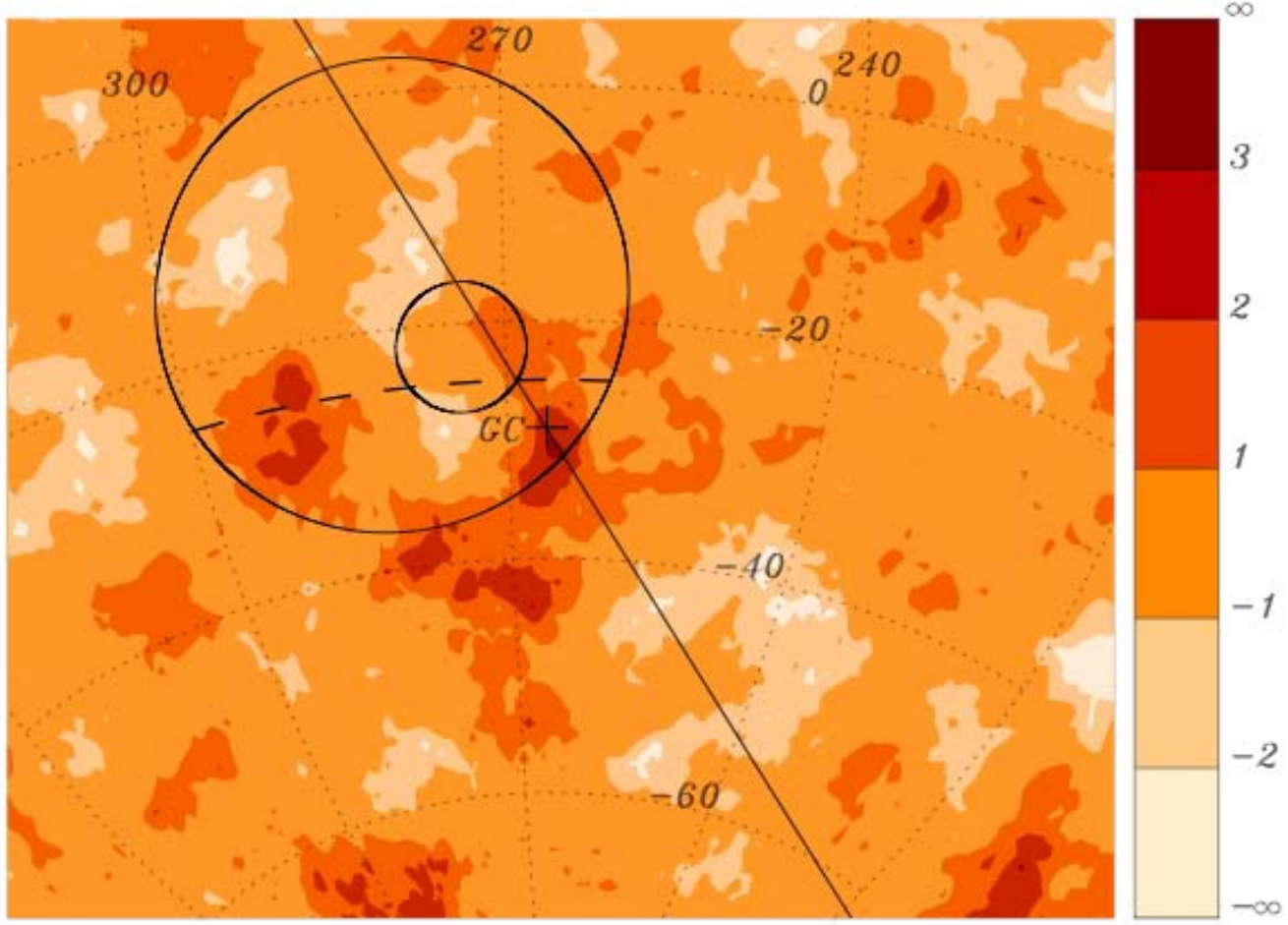


Figure 1: Map of CR overdensity significances near the GC region on angular scales of 5° radius. The GC location is indicated with a cross, lying along the galactic plane (solid line). Also the regions where the AGASA experiment found their largest excess as well as the region of the SUGAR excess are indicated.

GALACTIC CENTER

Comparison to AGASA

- **Energy interval (1.0 – 2.5 EeV)**
- **Angular scale 20°**

2116 / 2159.5 ratio = 0.98 ± 0.02 ±0.01

22% excess would give 2634 and a 10 σ excess

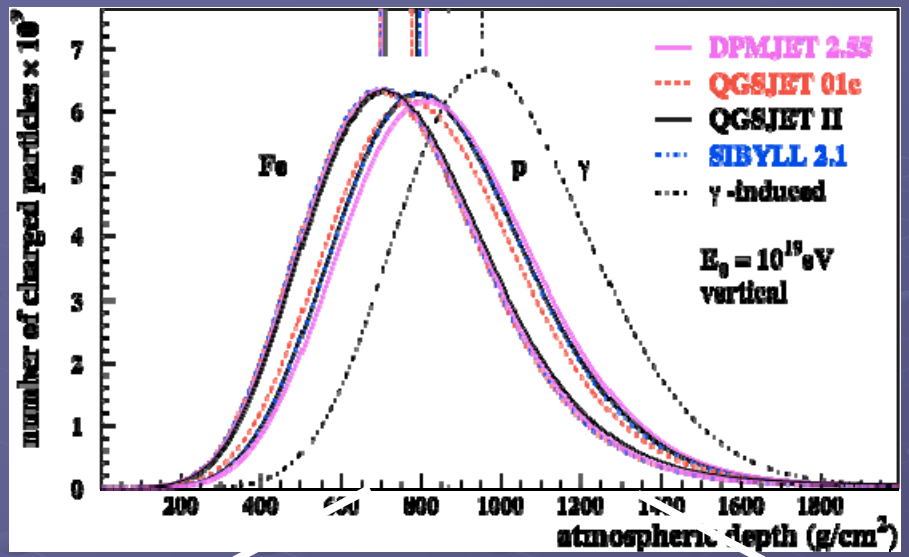
Comparison to SUGAR

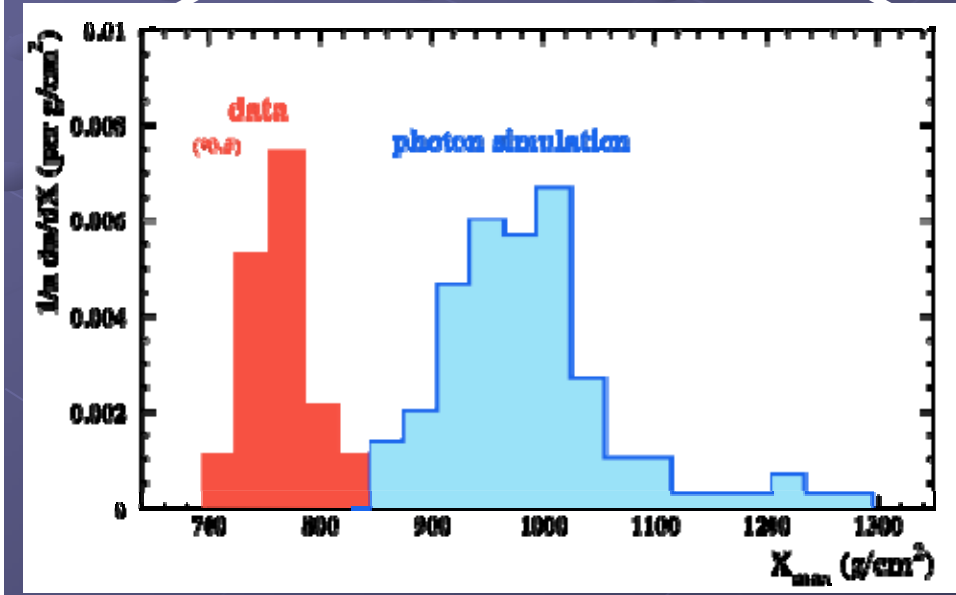
- **Energy interval (0.8 – 3.2 EeV)**
- **Angular scale 5°**

286 / 289.7 ratio = 0.98 ± 0.06 ± 0.0

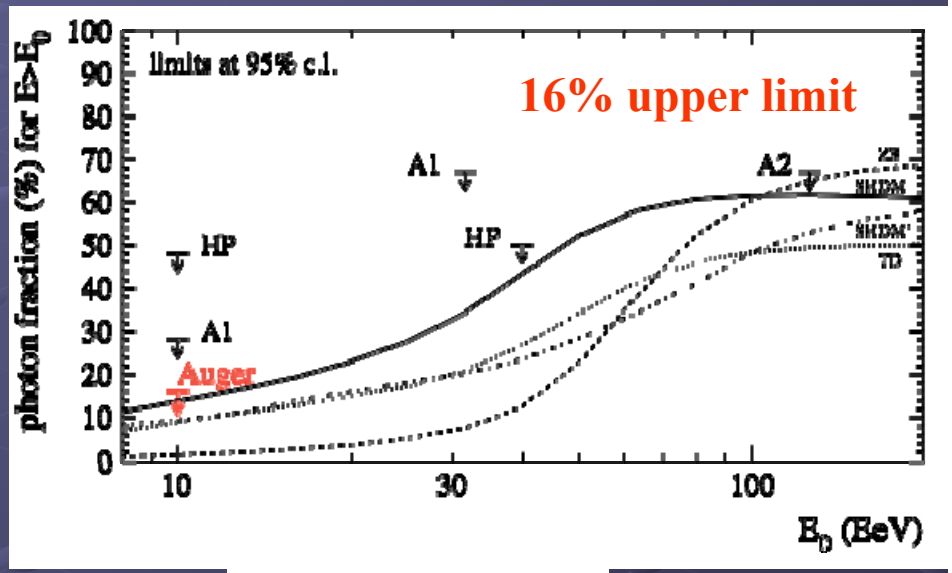
85% excess would give 536 and a 14.5 σ excess

PHOTON LIMIT





Position of shower maximum
⇔ primary mass



Astro-ph/0606619

- Constraint on top-down non-aceleration models
- End of 2009:
  - ~ 2% limit at 10 EeV
  - ~ 15% limit at 35 Eev

CONCLUSIONS

- The Observatory is now well over half finished.
- With data collected from January 2004, we have:
  - Defined our empirical spectrum analysis strategy and produced our first model-independent spectrum
  - Performed first studies of anisotropies in the sky
  - Set limits on photon primaries

CONCLUSIONS

Future Plans

- Complete Auger South by mid 2007
- Fully understand our instruments.
- Use rapidly expanding data set (x7 in two years) to enable
  - Improvement in the energy assignment
  - High statistics study of the spectrum in the GZK region
  - Anisotropy studies and point source searches.
  - Composition studies
- Reduce systematic uncertainties.
- Exploit events beyond a zenith angle of 60º
  - search for neutrinos and exotics
- Begin work on Auger North