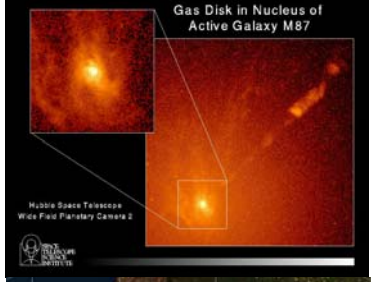
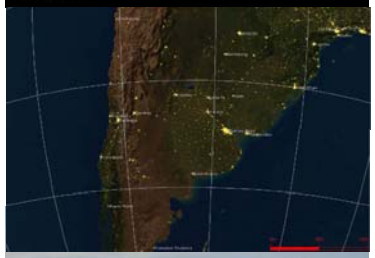
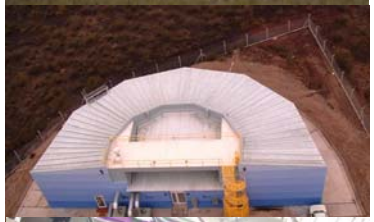






The Pierre Auger Project: Status and Recent Results

PIERRE AUGER OBSERVATORY

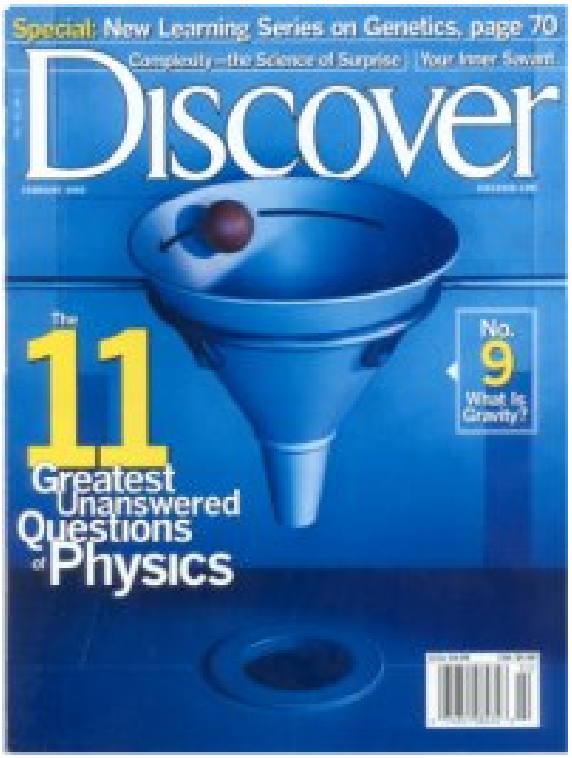
Markus Roth
Forschungszentrum Karlsruhe
Markus.Roth@ik.fzk.de

- **Astrophysical motivation**
- Pierre Auger Project
  - **Experimental concept**
  - **Status**
  - **Results**
- **Summary and outlook**

bmb+f
Großgeräte der physikalischen Grundlagenforschung

Report: Connecting Quarks with the Cosmos

The Discover cover story is based on the 105-page National Research Council Committee on Physics of the Universe *report Connecting Quarks with the Cosmos:*
11 Science Questions for the New Century.



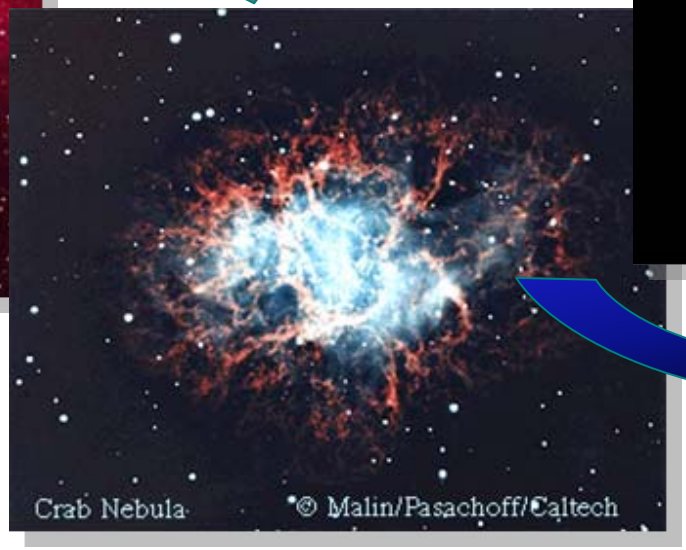
(Discover Magazine's Cover Story For February 2002)

1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from iron to uranium made?
4. Do neutrinos have mass?
5. **Where do ultra-energy particles come from?**
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
7. Are there new states of matter at ultrahigh temperatures and densities?
8. Are protons stable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the universe begin?

Cosmic Rays

Source → **Acceleration** → **Transport**

Injection



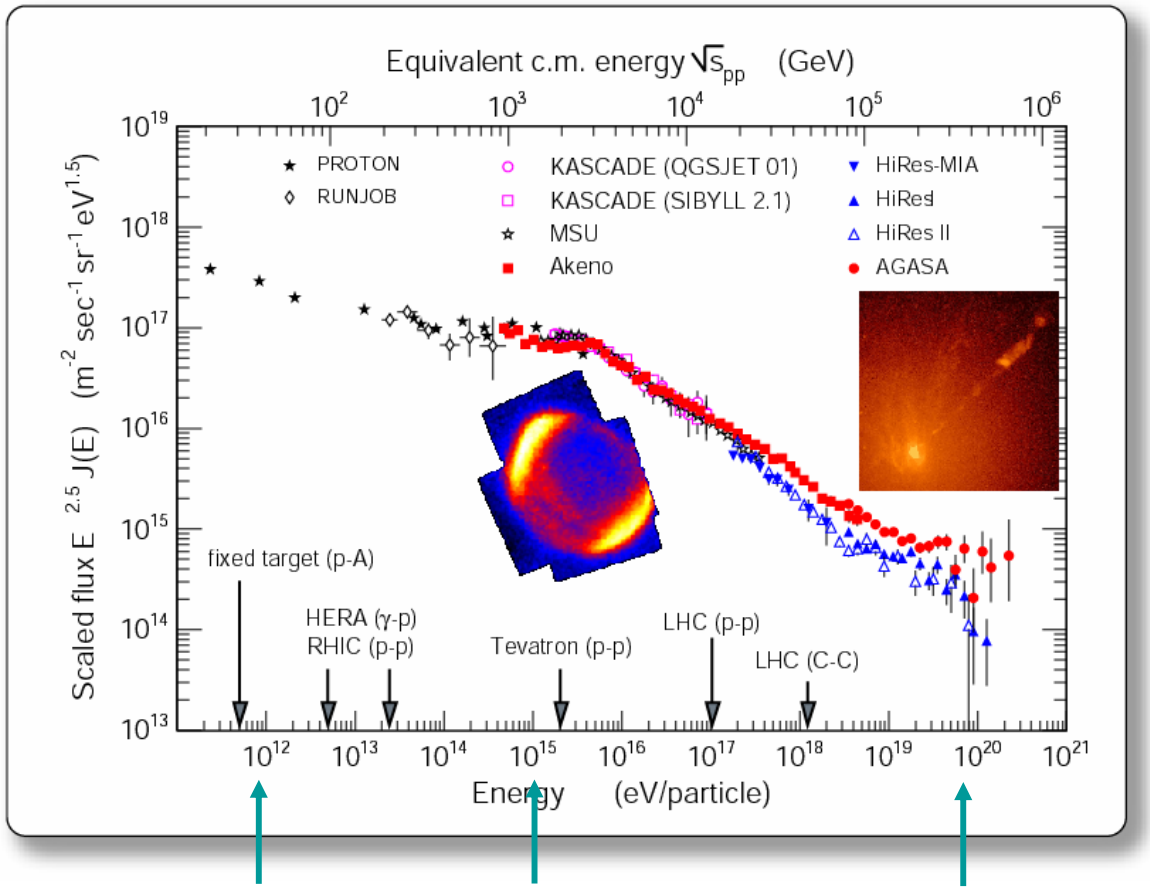
Spallation, Decays, Interactions

Stellar Matter

Supernovae, AGN‘s, etc.

Experiments

Cosmic Ray Spectrum



1 particle per m^2 and second

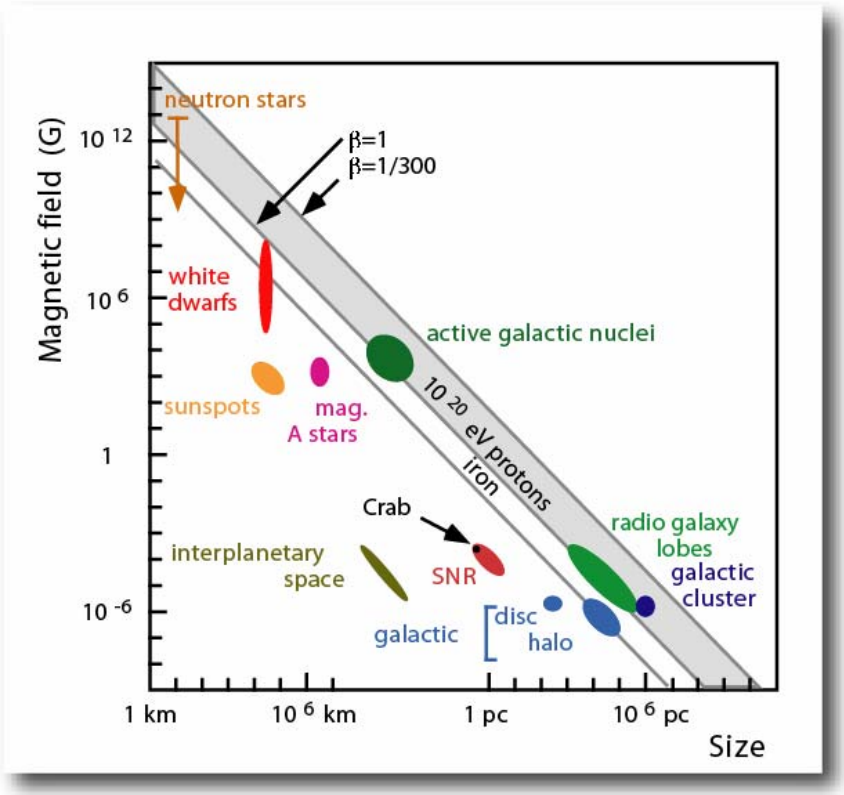
1 particle per km^2 and year

1 particle per km^2 and century

Problems of UHECRs

Hillas-Diagram:

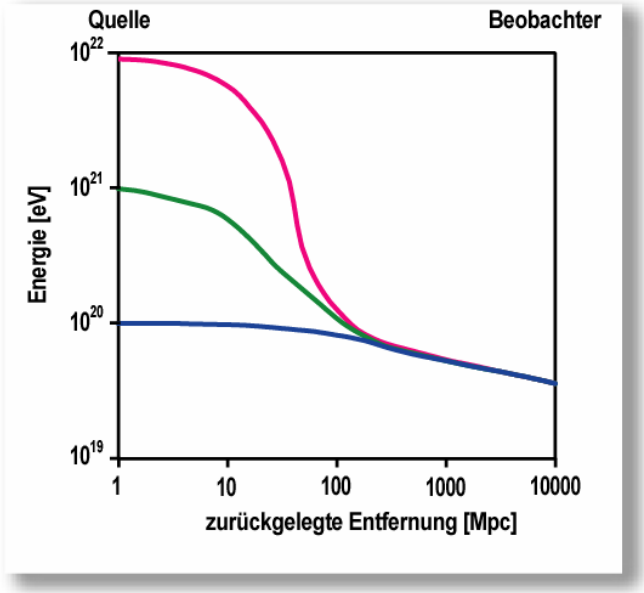
$$E_{EeV}^{max} \sim \beta_s \, Z \, R_{kpc} \, B_{\mu G}$$



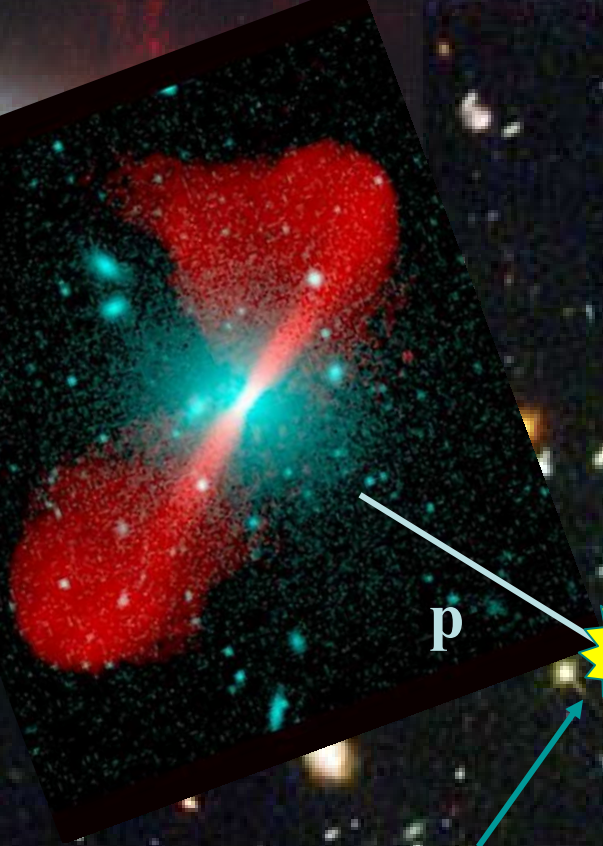
„GZK Cut-Off“:

„Greisen Zatepin Kutzmin cut-off“

$$p + \gamma_{2.7K} \rightarrow \Delta^{+}(1232) \rightarrow p + \pi^{0} \rightarrow p\gamma\gamma$$
$$\rightarrow n + \pi^{+} \rightarrow pe^{+}\nu$$



GZK Cut-Off



$E > 5 \cdot 10^{19}$eV

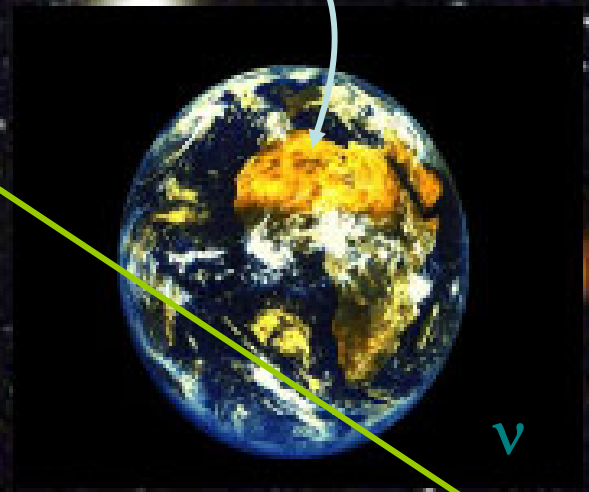
$$p+\gamma \longrightarrow p+\pi^0 \longrightarrow p + \gamma\gamma$$
$$\longrightarrow n+\pi^+ \longrightarrow n + e^+ + \nu$$

p

p

γ_{3K} (400 cm $^{-3}$)

ν,γ



ν

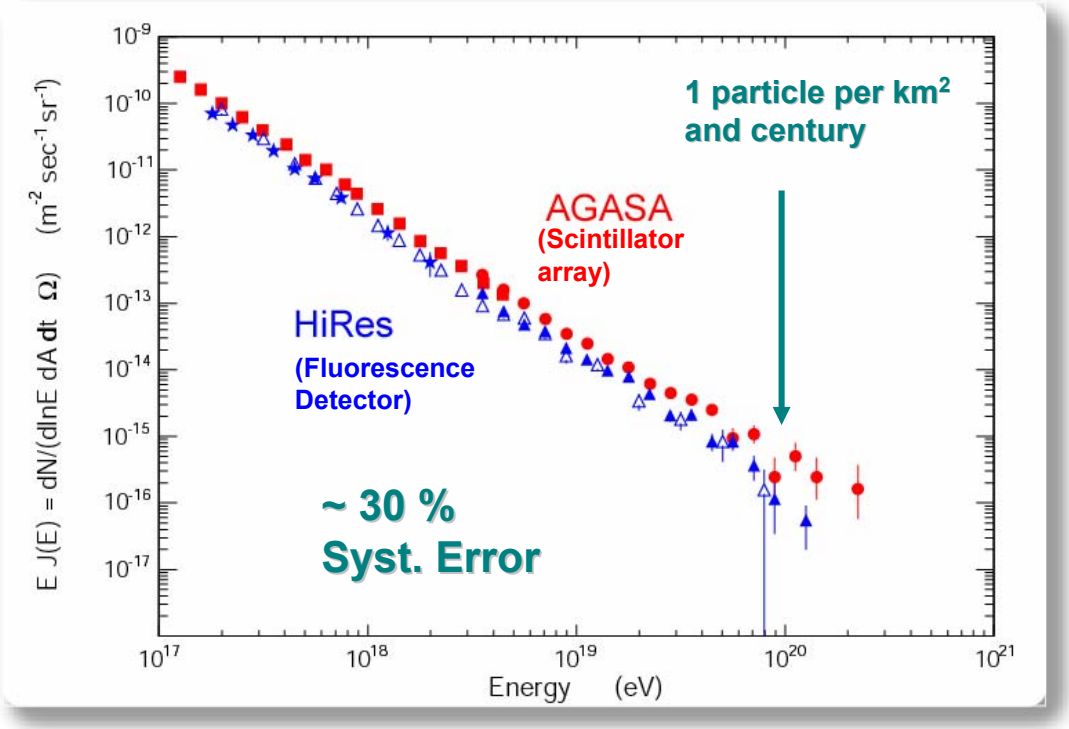
Problem:
Acceleration mechanism unknown
(strong extragalactic processes
needed, must be rather close (20Mpc)

Science Objectives

Fundamental problems

- Primaries of energies >10^{20}eV exist
  Standard astrophysical models cannot account for such energies
- Complication (d > 20 Mpc):
  GZK cut-off E>5•10^{19}eV
- If no GZK:
  - Nearby sources:
    GUT fossils (TD, DM, ...)
  - Propagation effects:
    violation of Lorentz invariance …
- Near sources should be identified by point source astronomy
  High magnetic rigidity of the primaries (charged particle astronomy)

Contradicting measurements



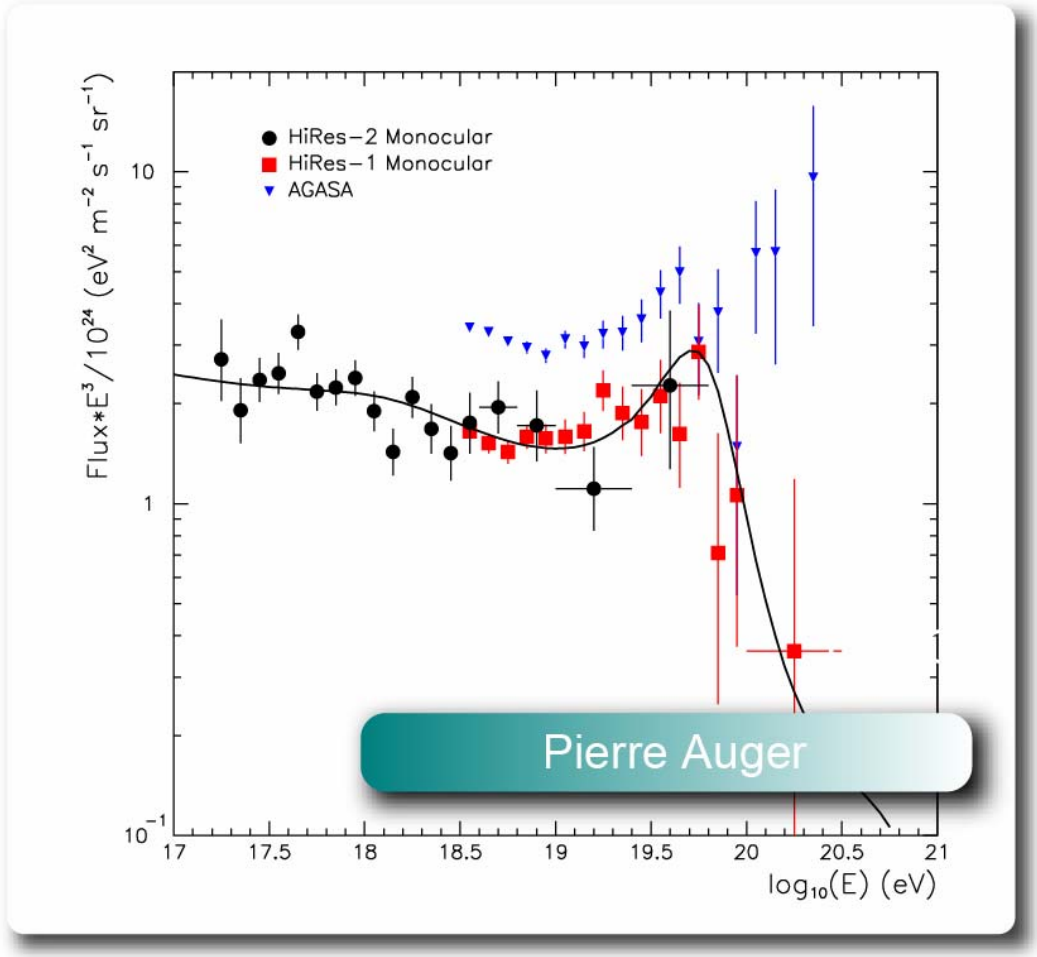
Newest HIRES stereo data give even more contradicting results (W. Springer et al.; ICRC05)

Experimental Approach

1. **Cosmic ray spectrum above 10^{19} eV:**
   Precisely measure the shape of the spectrum in the region of the GZK cut-off

2. **Arrival direction distribution:**
   Search for departure from isotropy, point sources

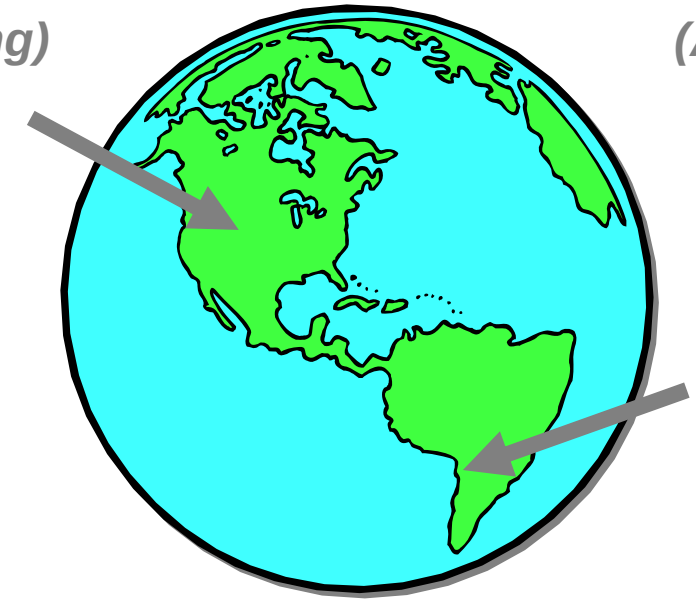
3. **Composition:**
   Light or heavy nuclei, photons, neutrinos, exotics(?)



The Pierre Auger Project

Two Large Air Shower Detectors

Colorado, USA
(in planning)



Mendoza, Argentina
(Auger South)

The Auger Collaboration

Participating Countries

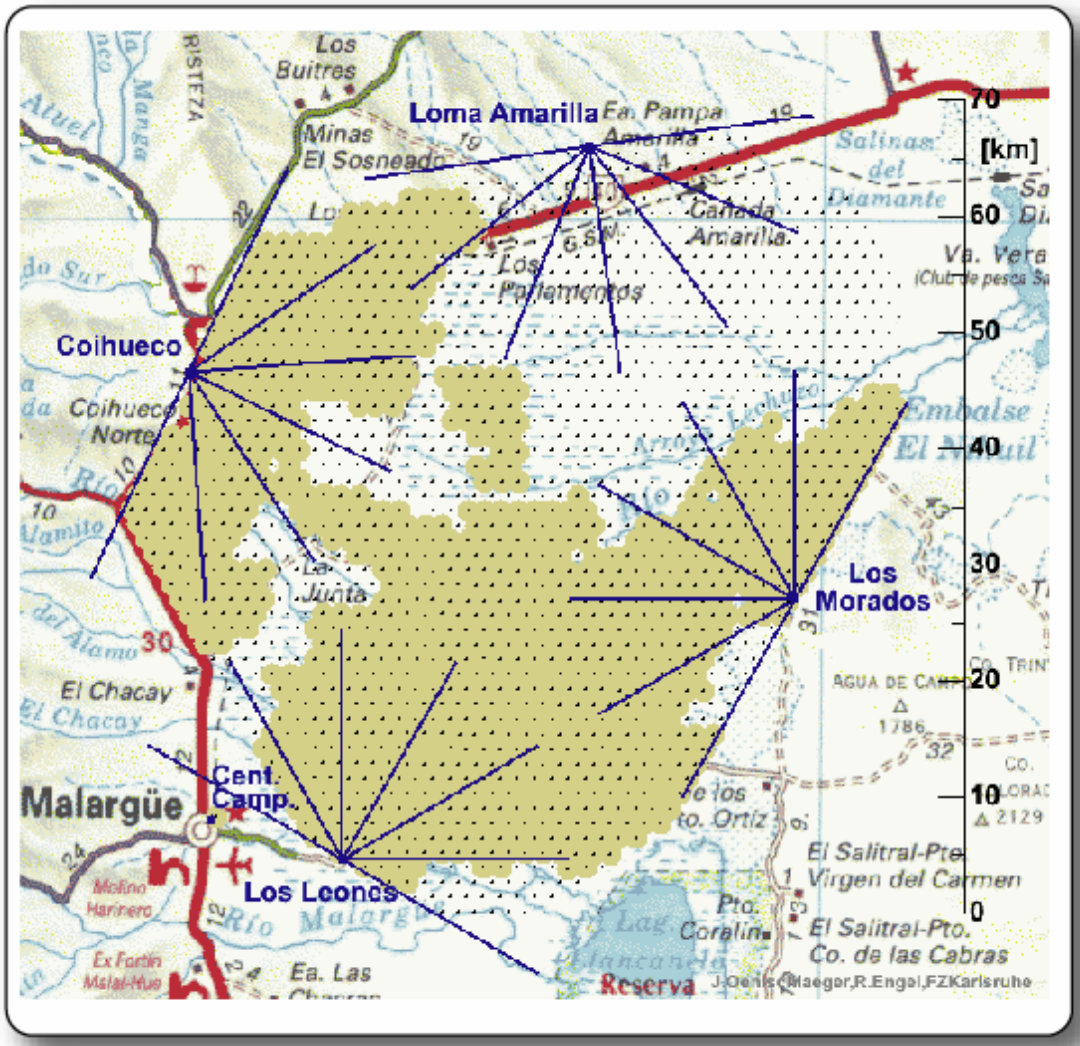
Argentina
Australia
Bolivia*
Brazil
Czech Republic
France
Germany
- **Aachen**
- **Bonn**
- **Karlsruhe**
- **Siegen**
- **Wuppertal**

Mexico
Netherlands
Poland
Slovenia
Spain
United Kingdom
USA
Vietnam*
Italy

****Associate***

63 Institutions, 369 Collaborators

Hybrid Design



Surface Array

- *1600 water Cherenkov detector stations (995)*
- *1.5 km spacing*
- *3000 km²*

Fluorescence Detectors

- *4 Telescope enclosures (3)*
- *6 Telescopes per enclosure*
- *24 Telescopes total (18)*

Design Features

1. High statistics
   (aperture >7000 km^2 sr above 10^{19}eV in each hemisphere)

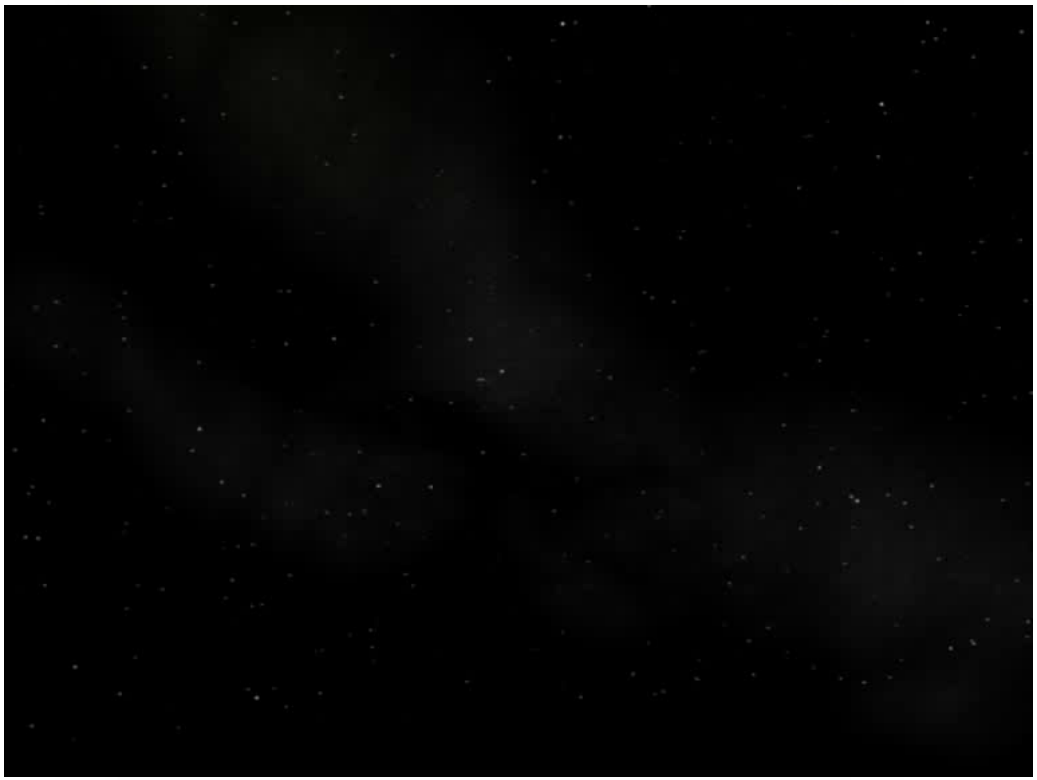
2. Full sky coverage (S&N)
   with uniform exposure

3. Hybrid configuration
   surface array with fluorescence detector coverage

The Hybrid Design

Surface detector array + Air fluorescence detectors

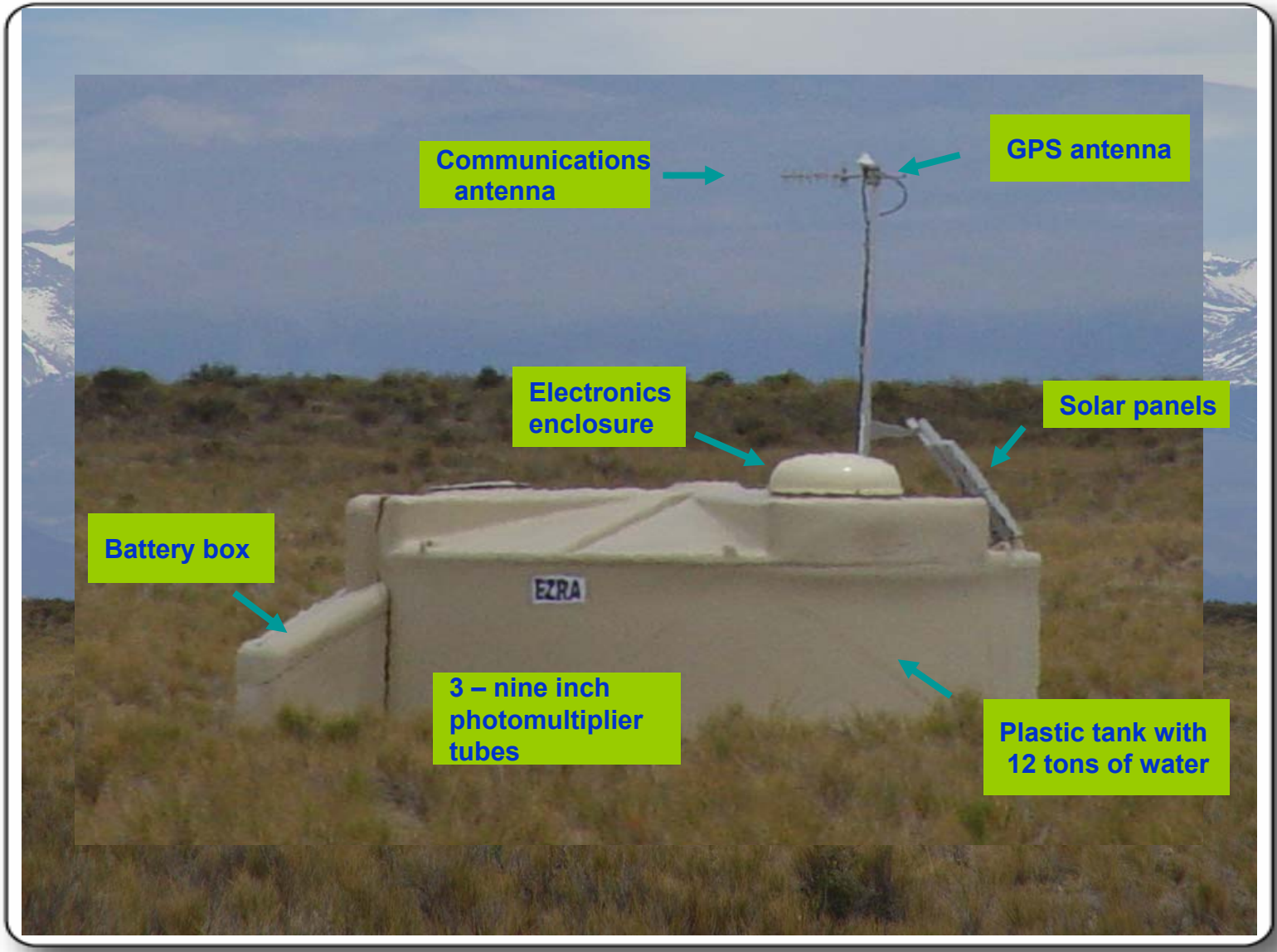
A unique and powerful design



- **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
- (Xmax, risetime, radius of curvature, …).
- **Different measurement techniques help** understanding of systematic **uncertainties**
- Improve **of the angular and core position** resolutions

The Surface Array

Detector Station



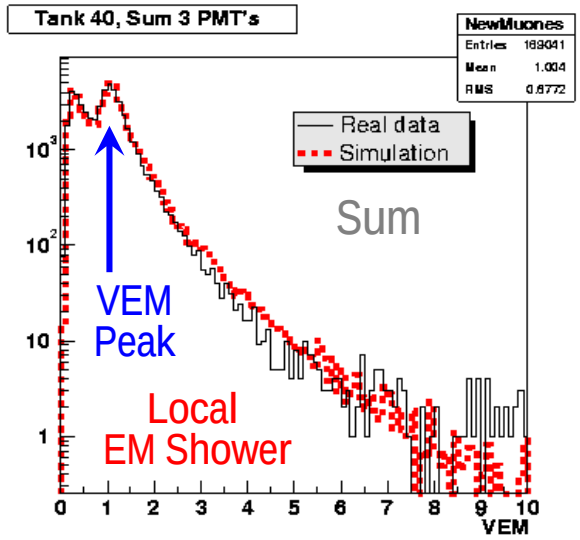
Surface Detector Deployment

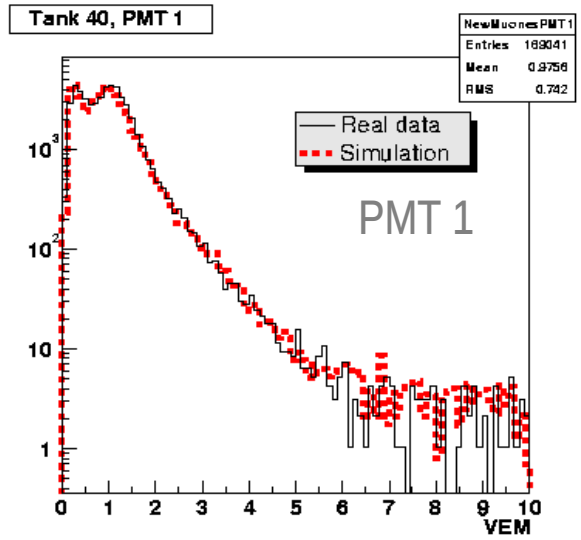
SD calibration by single muon triggers

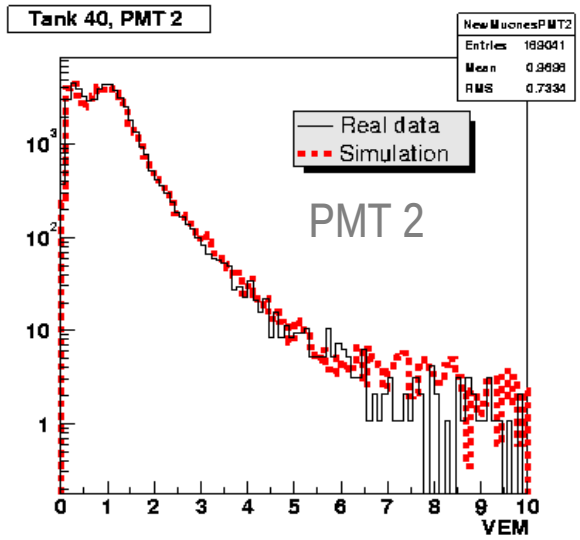
Agreement with GEANT4 simulation up to 10 × VEM (Vertical Equivalent Muons).

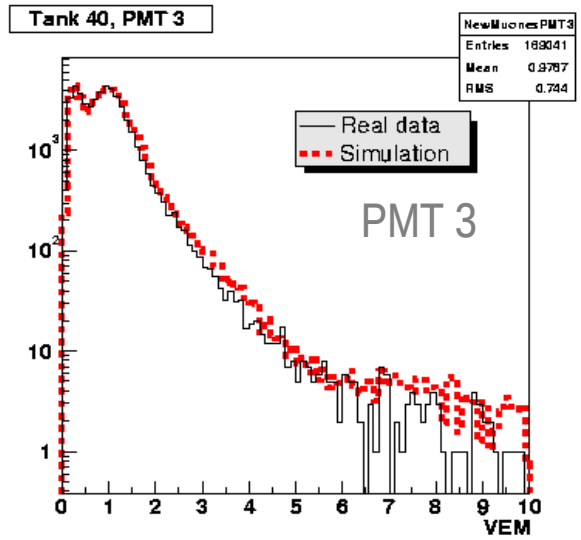
VEM ~ 100 PE /PMT

Huge Statistics!
Systematic error ~5%

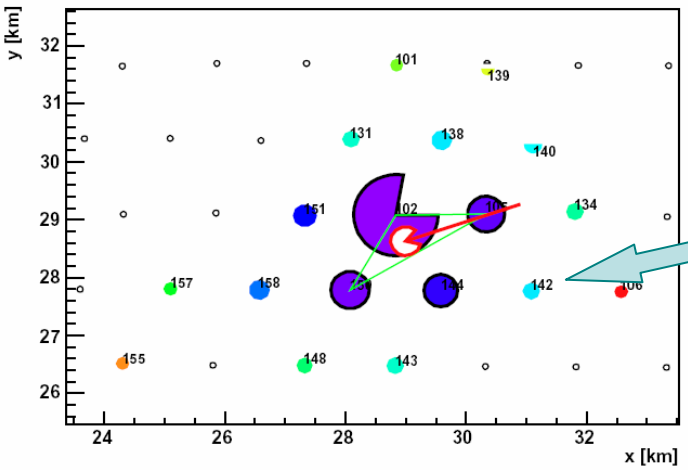


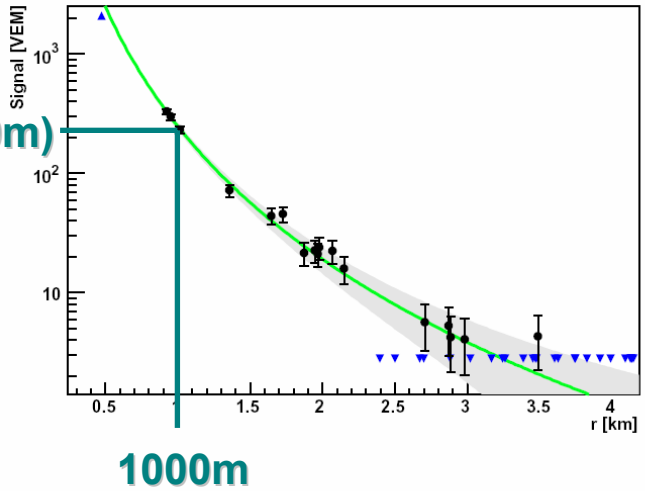


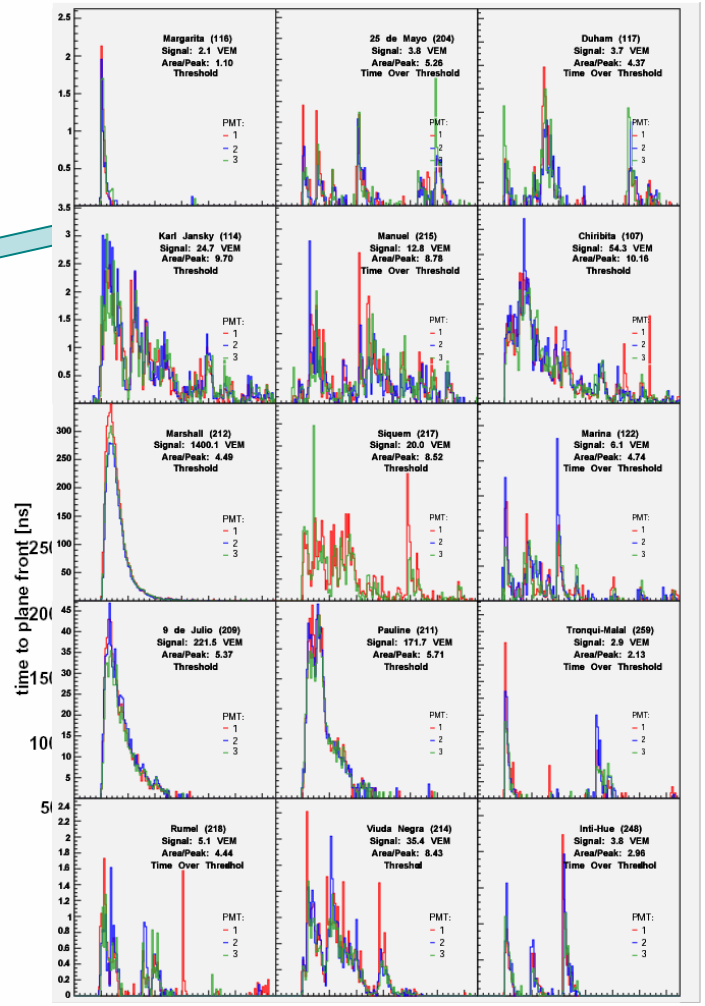




Example Event (48°, E~70 EeV)

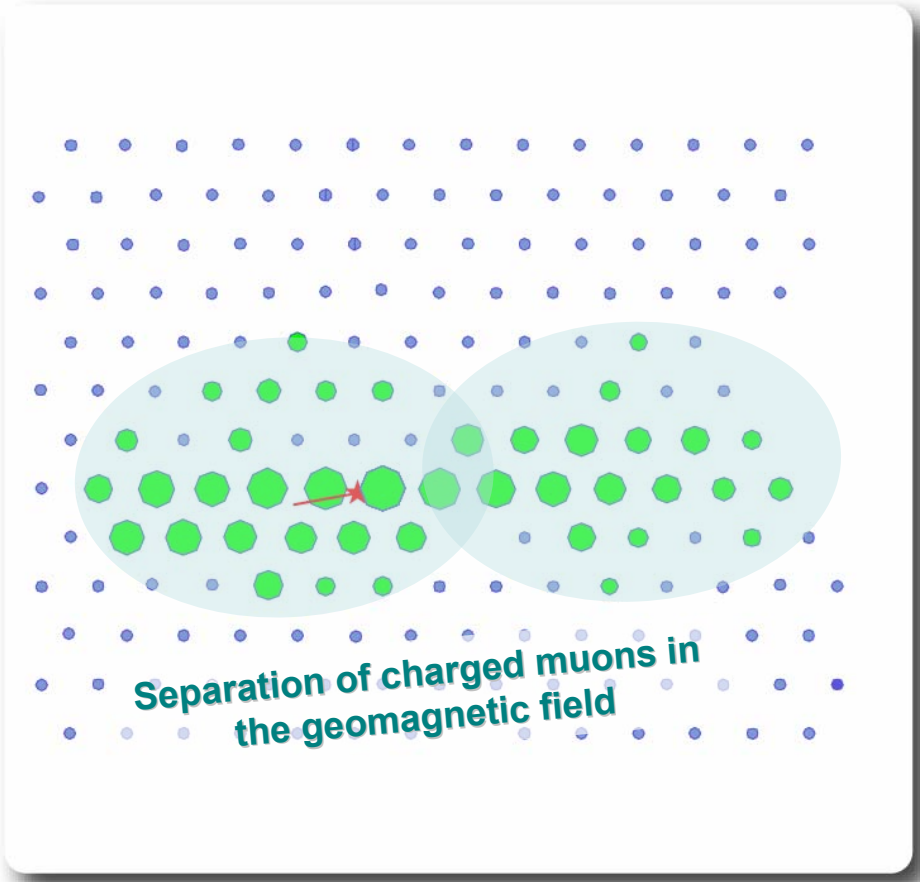


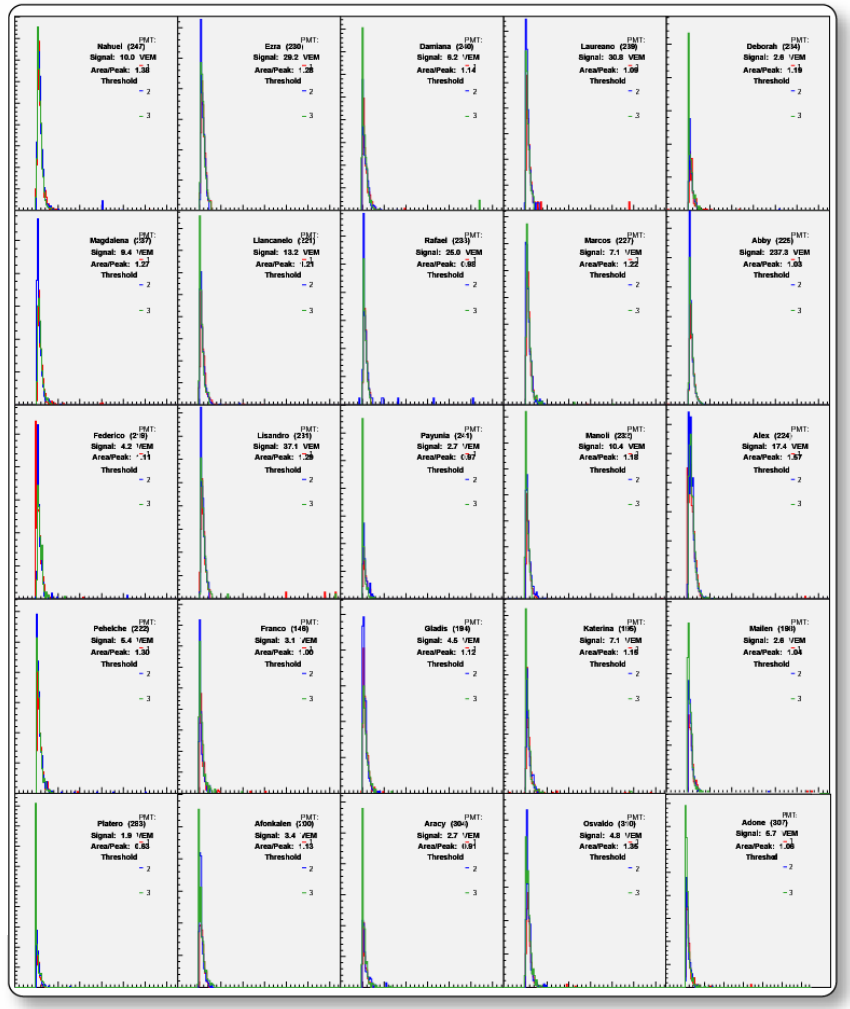




Horizontal Showers

$E \sim 5 \cdot 10^{19}$ eV $\theta = 82°$



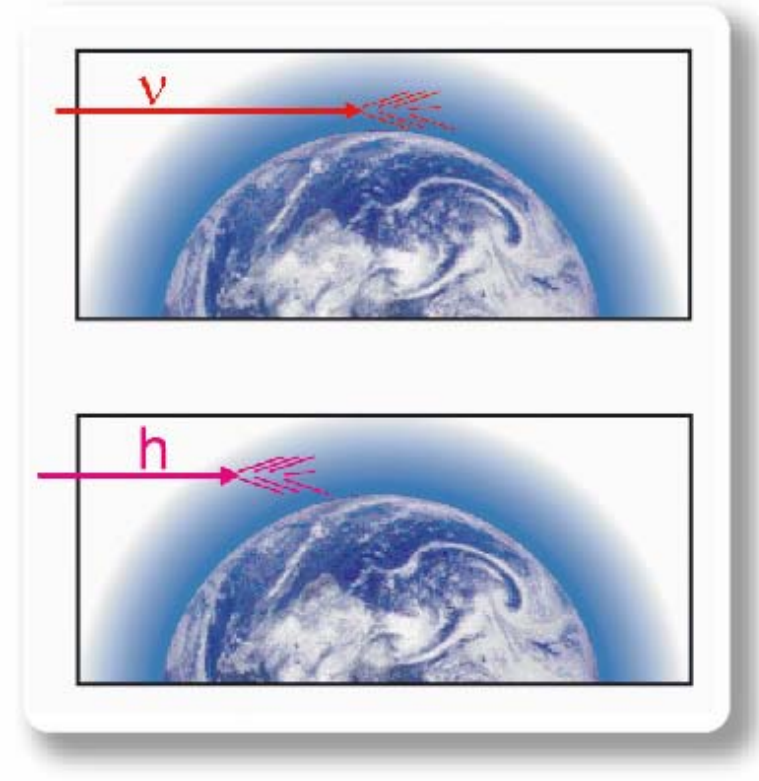


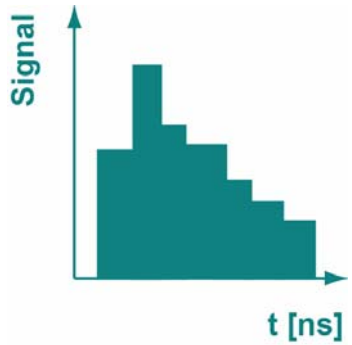
Electromagnetic component is attenuated;
Only "high" energetic muons survive

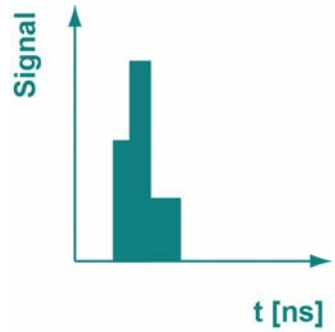
⇨ short prompt pulses

Horizontal Showers and Neutrinos

E > 10^{18} eV





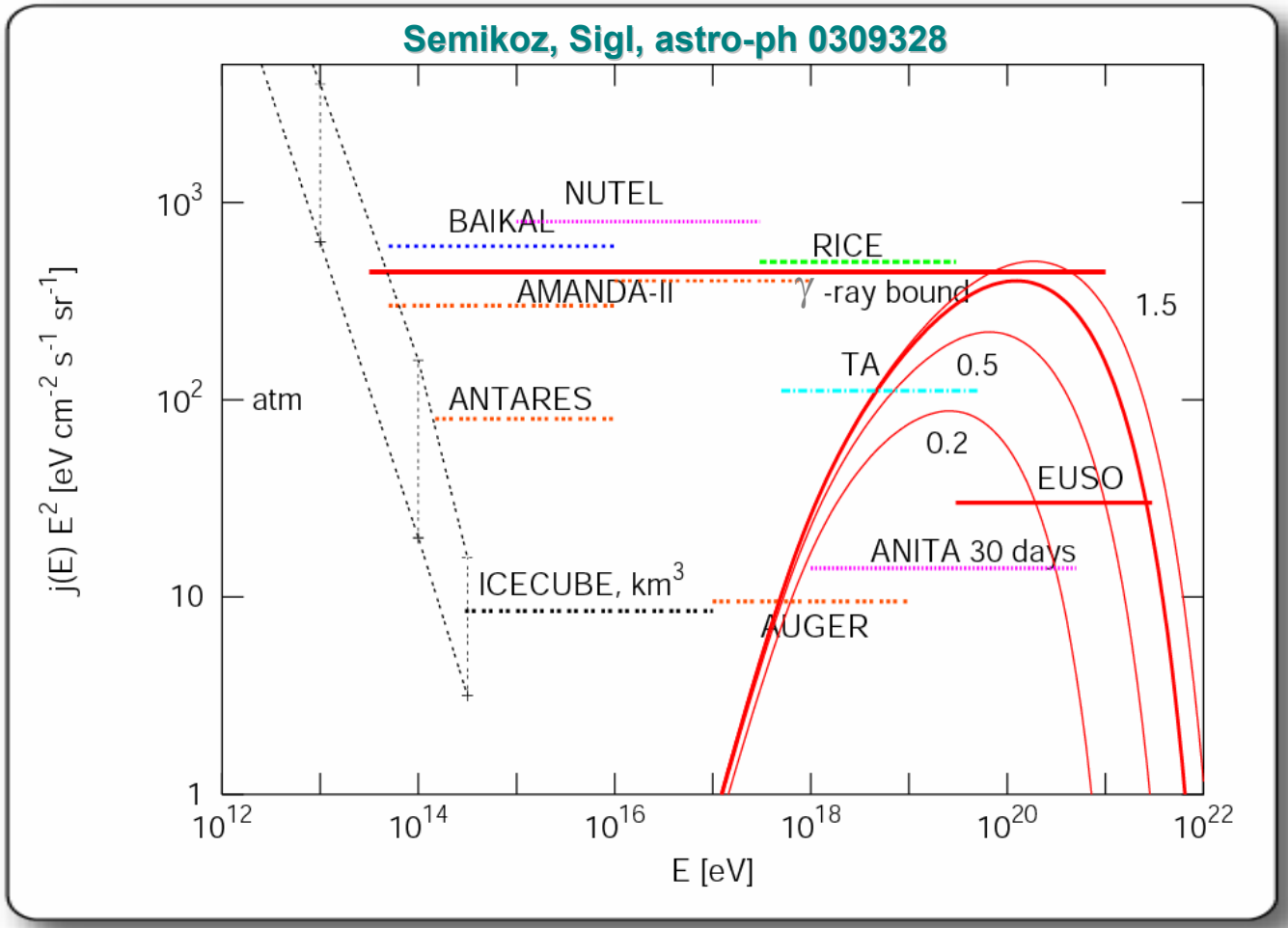


Only neutrinos can produce such signatures

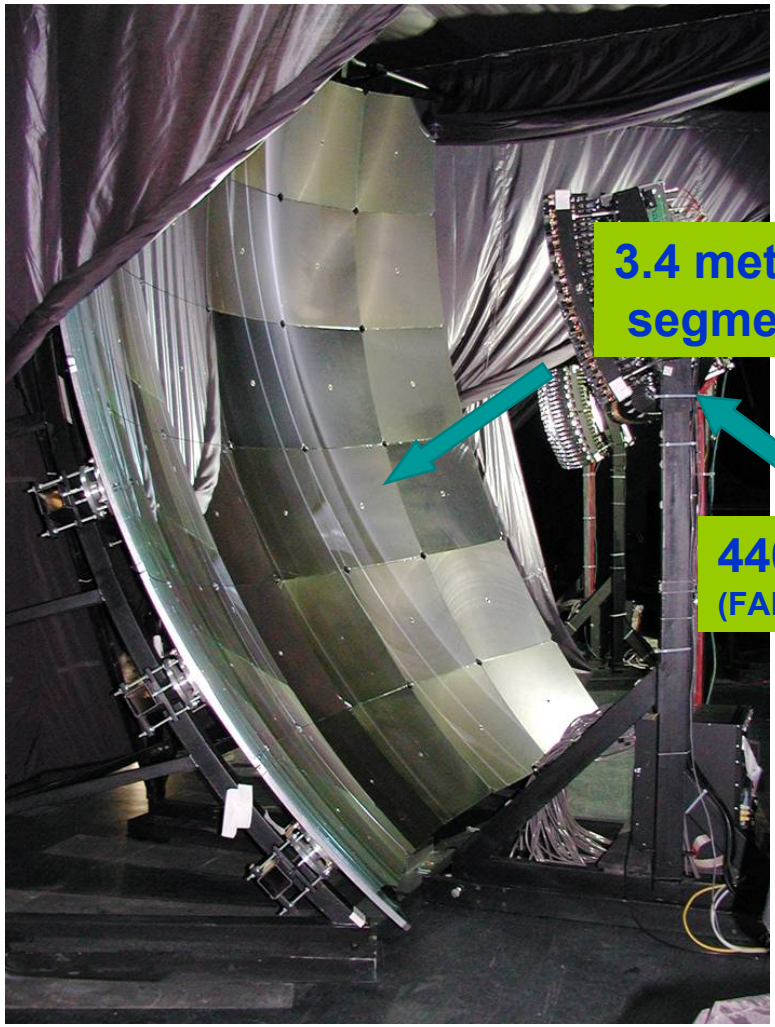
Neutrino rate ~ 0.5 - 1 particle / year

Depends strongly on the theoretical model

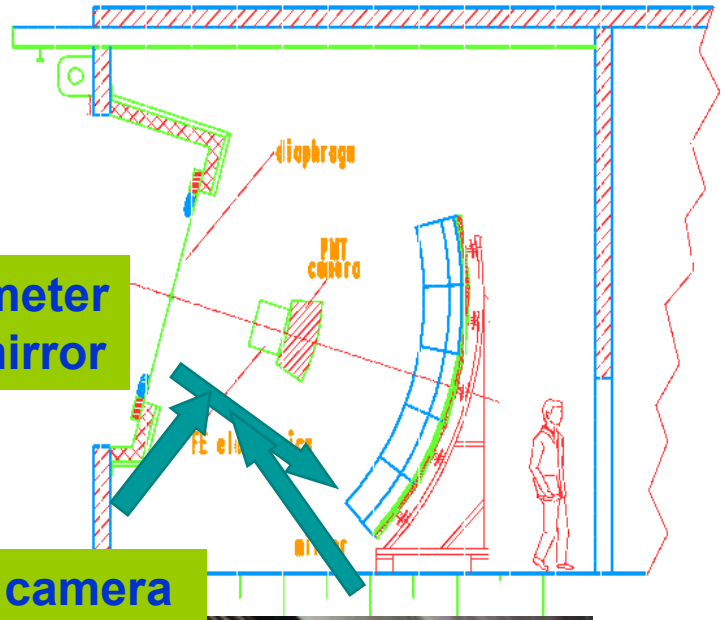
Cosmogenic Neutrino-Flux and Experimental Sensitivities



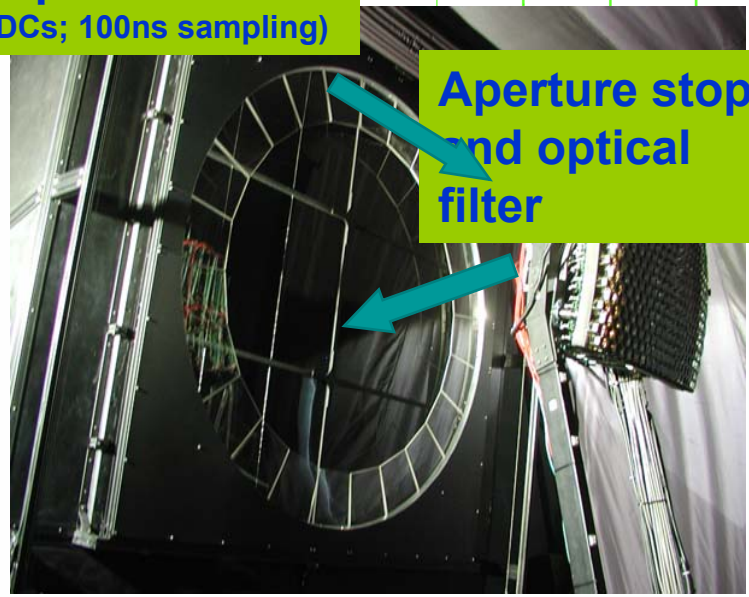
The Fluorescence Detector



3.4 meter diameter segmented mirror



440 pixel camera
(FADCs; 100ns sampling)



Aperture stop and optical filter

Duty cycle ~14%

The Fluorescence Detector Stations

K.-H. Kampert

Atmospheric Monitoring

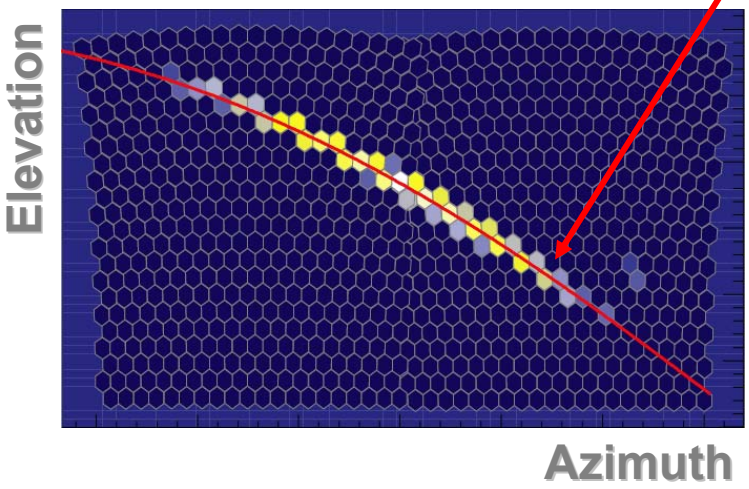
Central Laser Facility

Lidar at each fluorescence eye

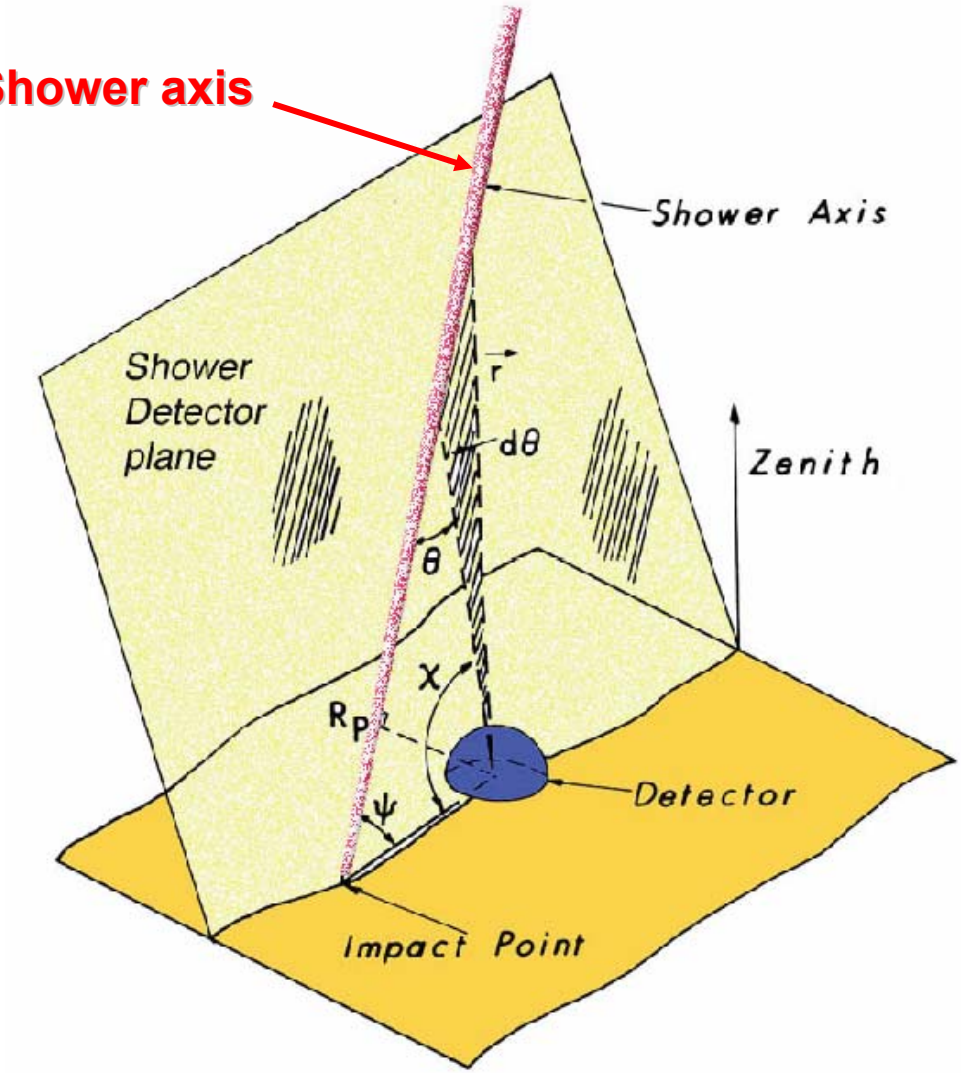
Atmospheric radio sounding measurements

FD-Reconstruction

Pixel camera:



Shower axis

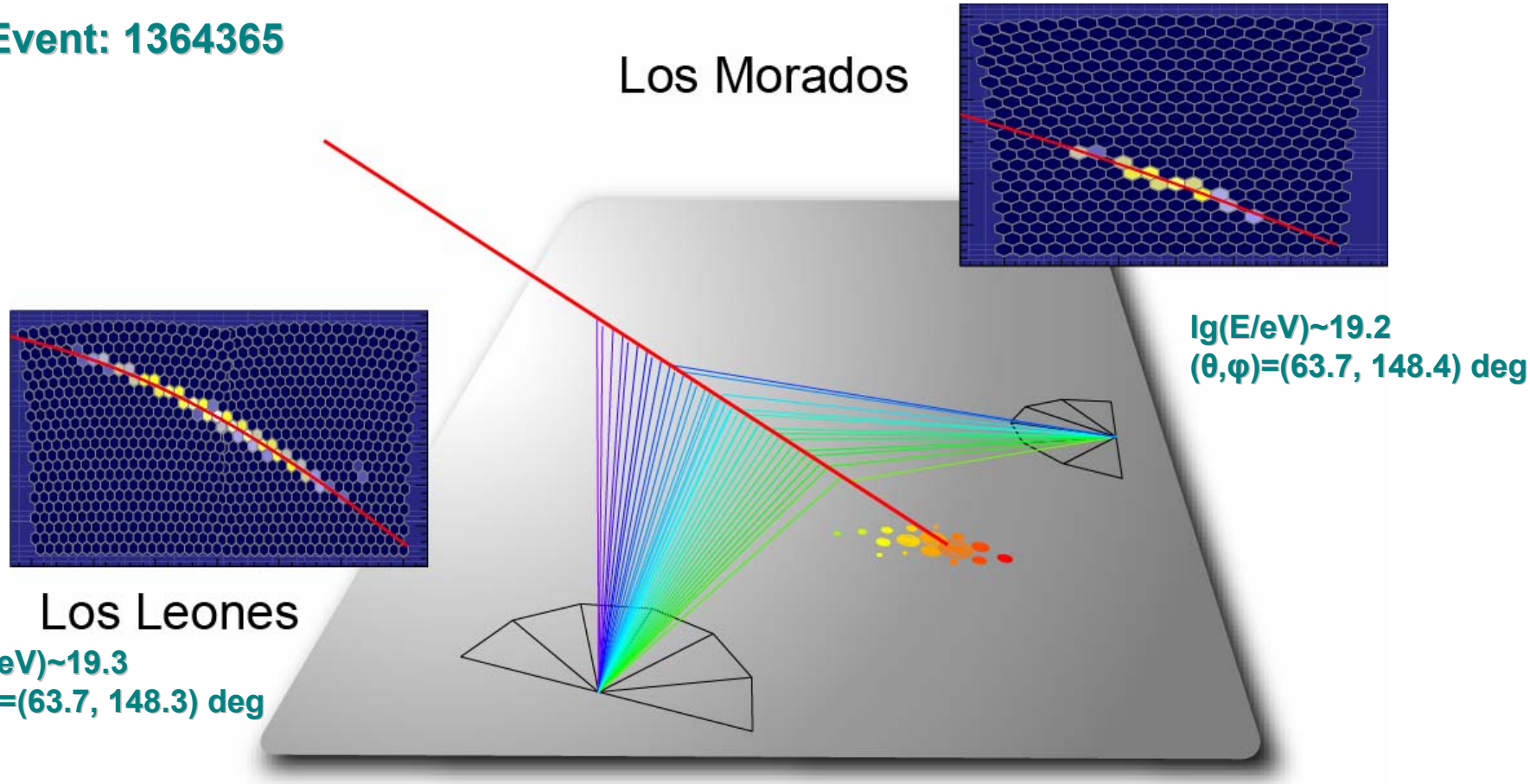


A stereo measurement gives intersecting planes

⇨ **much better core and angular reconstrection**

Stereo Hybrid Measurement

Event: 1364365

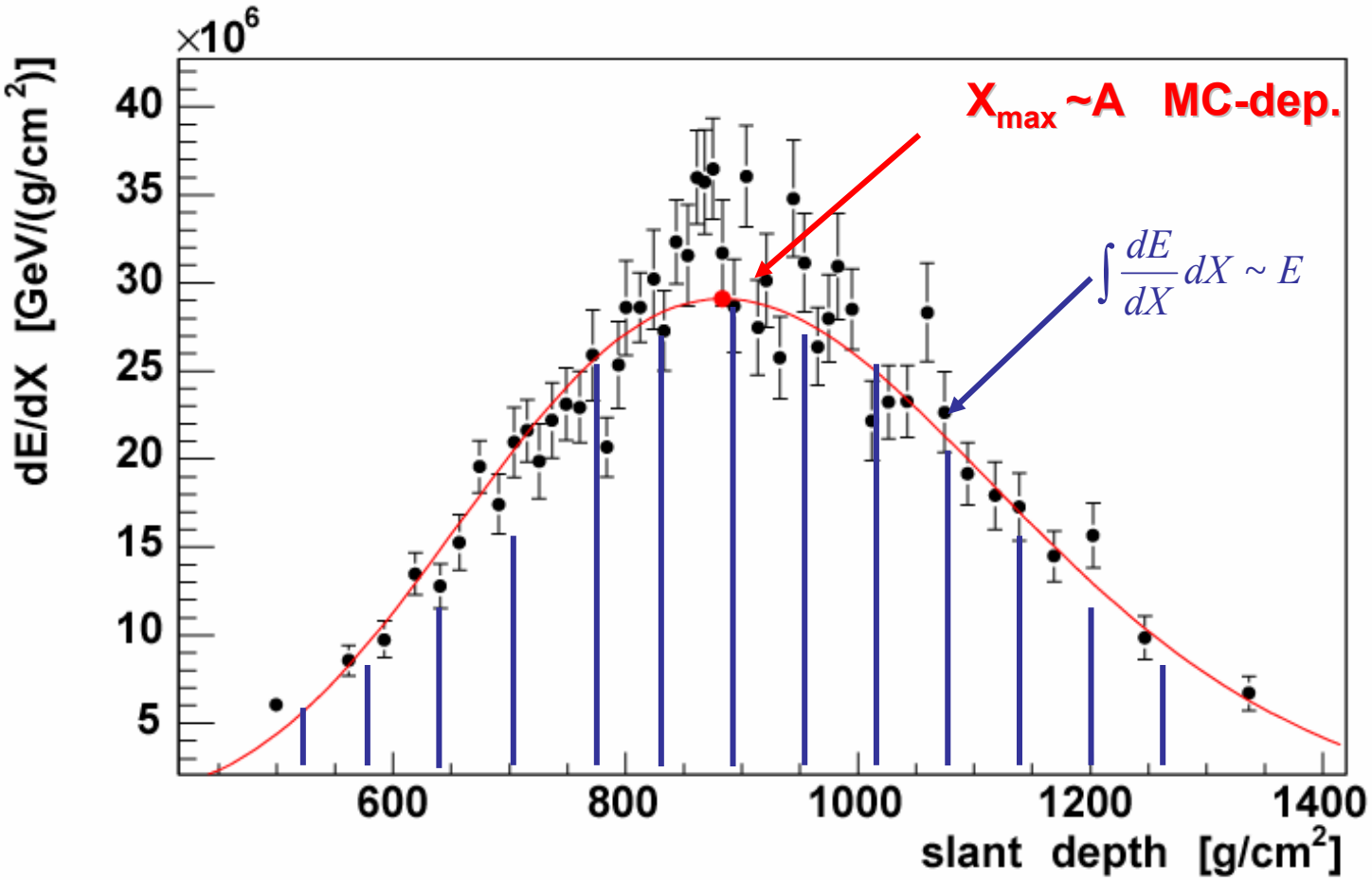


lg(E/eV)~19.2
(θ,φ)=(63.7, 148.4) deg

lg(E/eV)~19.3
(θ,φ)=(63.7, 148.3) deg

SD array: lg(E/eV)~19.1
(θ,φ)=(63.3, 148.9) deg

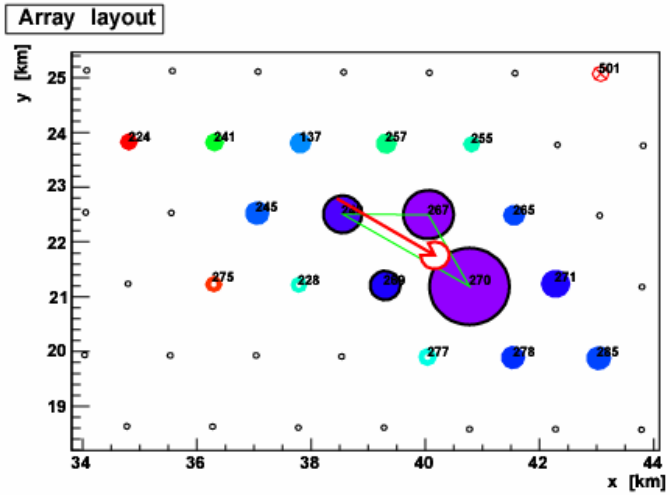
Stereo Hybrid Event: FD-Measurement

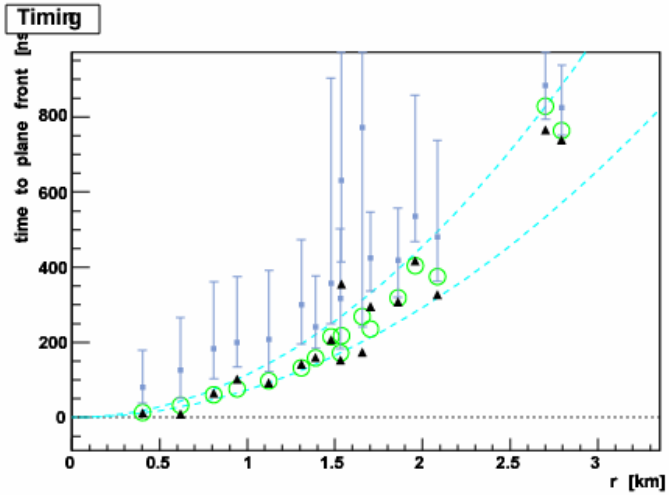


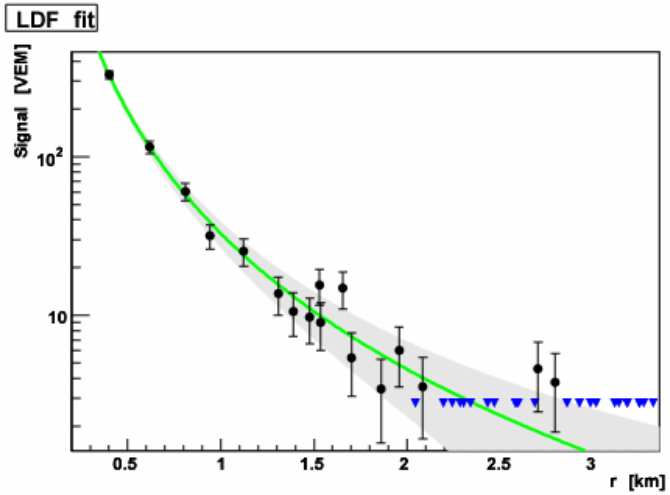
Event: 1364365

Stereo Hybrid Event: SD-Footprint

Event: 1364365

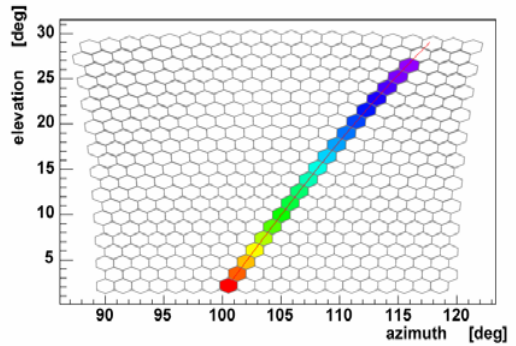


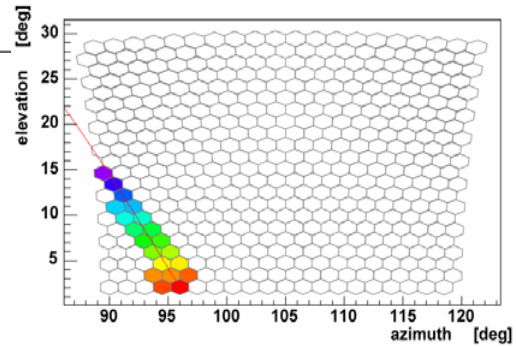


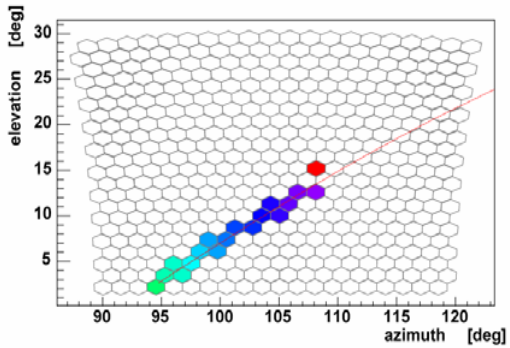


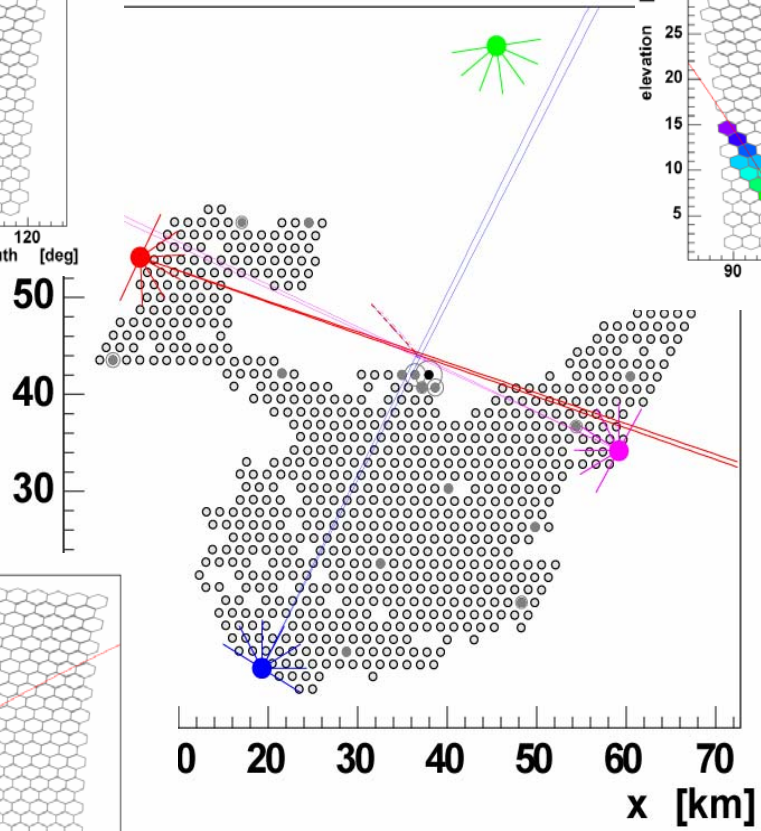
Event: 1364365
Time: 00:33:36 16 MAY 2005
GPS Time: 800238829 s, 347741000 ns
T4: FD+3TOT+4C1 T5: Yes
Reconstruction stage: 4.1
Easting: 479996. ± 35.7 [m]
Northing: 6082011. ± 13.5 [m]
θ: 63.3 ± 0.3 [°]
ϕ: 148.9± 0.3 [°]
R_c: 19.6 ± 0.05 [km]
S_{1000}: 32. ± 1.2 [VEM]
β: -1.71± 0.04

Triocular Event





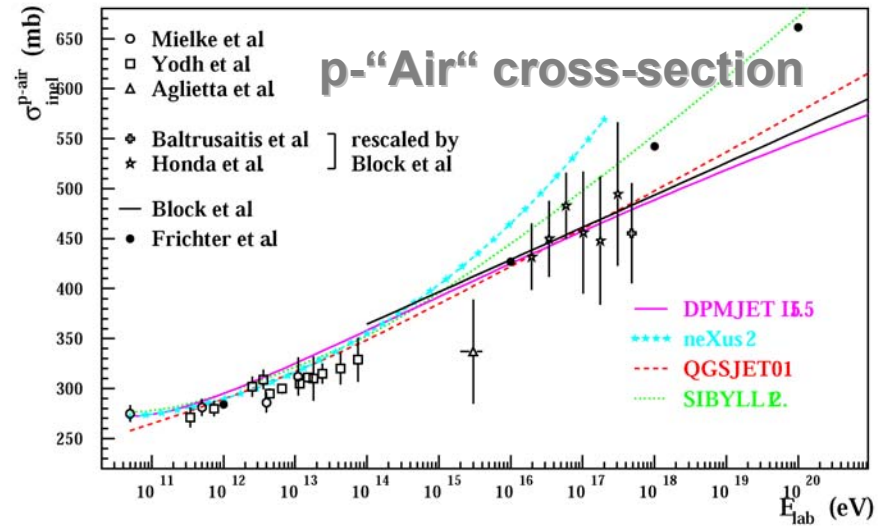


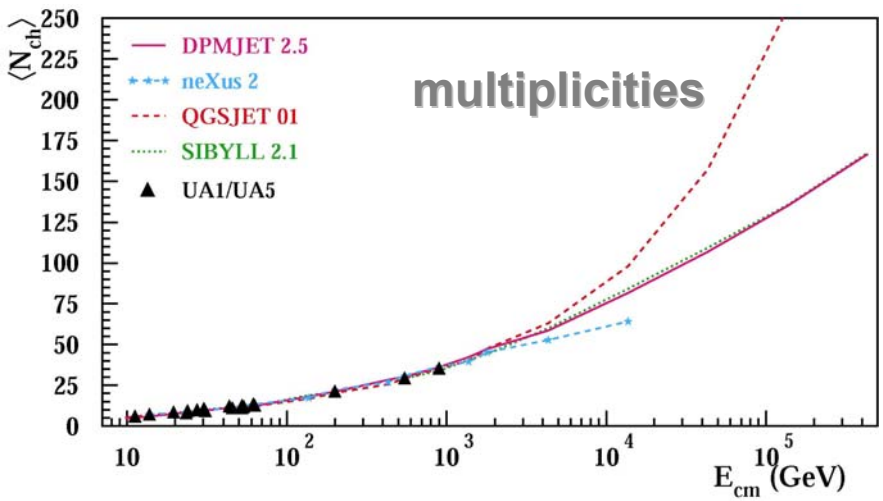


lg(E/eV)~19.7
θ=52°

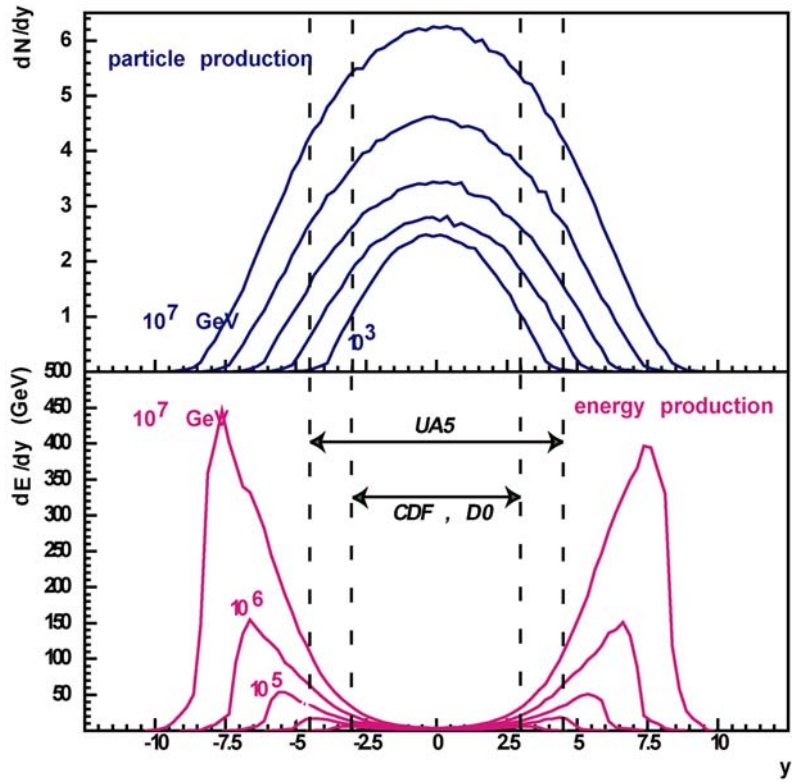
Hadronic Interactions

- Extrapolation of cross-sections to ultra-high energies
- Secondary particle multiplicity in high-energy interactions
- Extrapolation of kinematics to the extreme forward region (diffractive part of X-sections)



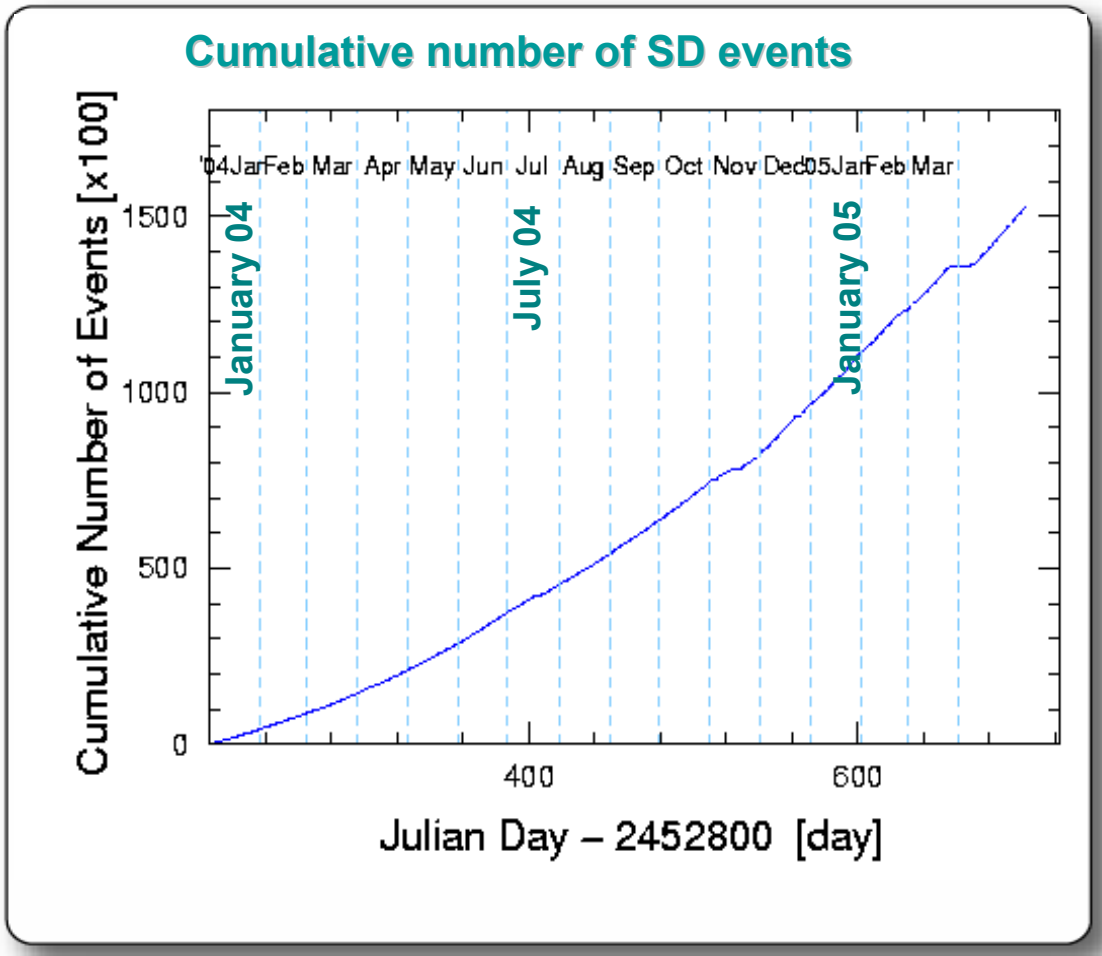


rapidity distribution



CORSIKA (Heck et al) FZKA report 6019

The First Data Set



Collection period:

1 January 2004 to 5 June 2005

Zenith angles:

0 - 60º

Total acceptance:

AUGER : ~1750 km² sr yr ~ AGASA

HIRES I : ~5000 km² sr yr (mono)

HIRES II: ~2500 km² sr yr (mono)

Surface array events (after quality cuts):

Current rate: ~18,000 / month

Total: ~180,000

Hybrid events (after quality cuts):

Current rate: ~1,800 / month

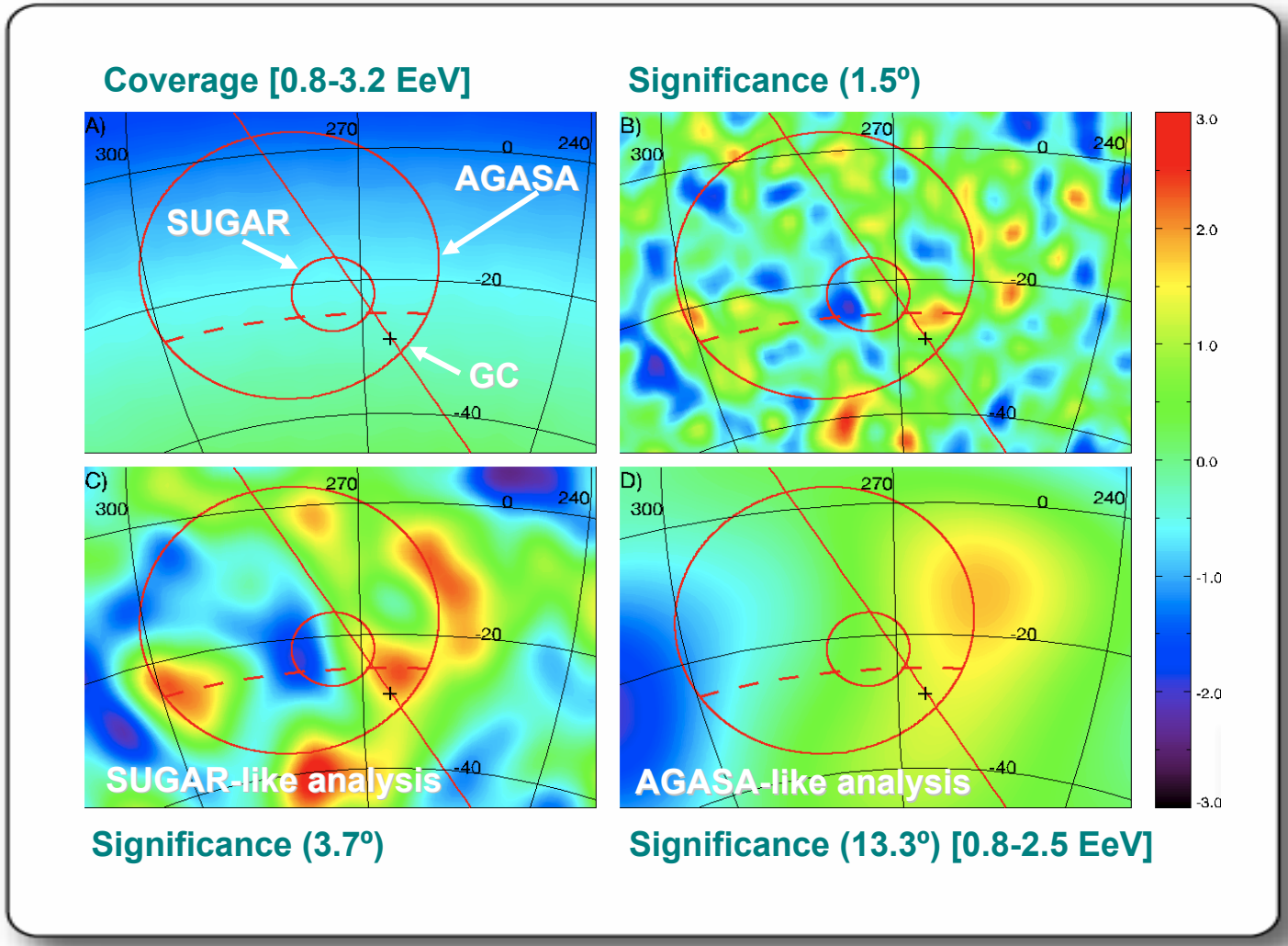
Total: ~18,000

Anisotropy: Galactic Center

excess flux
AGASA: 4.5 σ
Sugar: 2.9 σ

$\Phi_S < 10.6\ 10^{-15}\ m^{-2}\ s^{-1}$

excludes neutron source at the GC



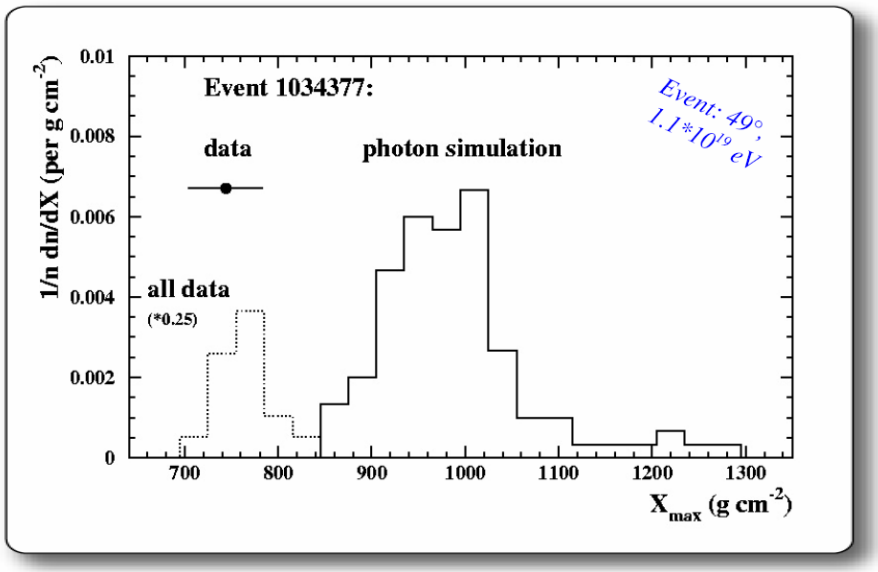
Photon Limit

Hybrid events: **improved geometry fit**

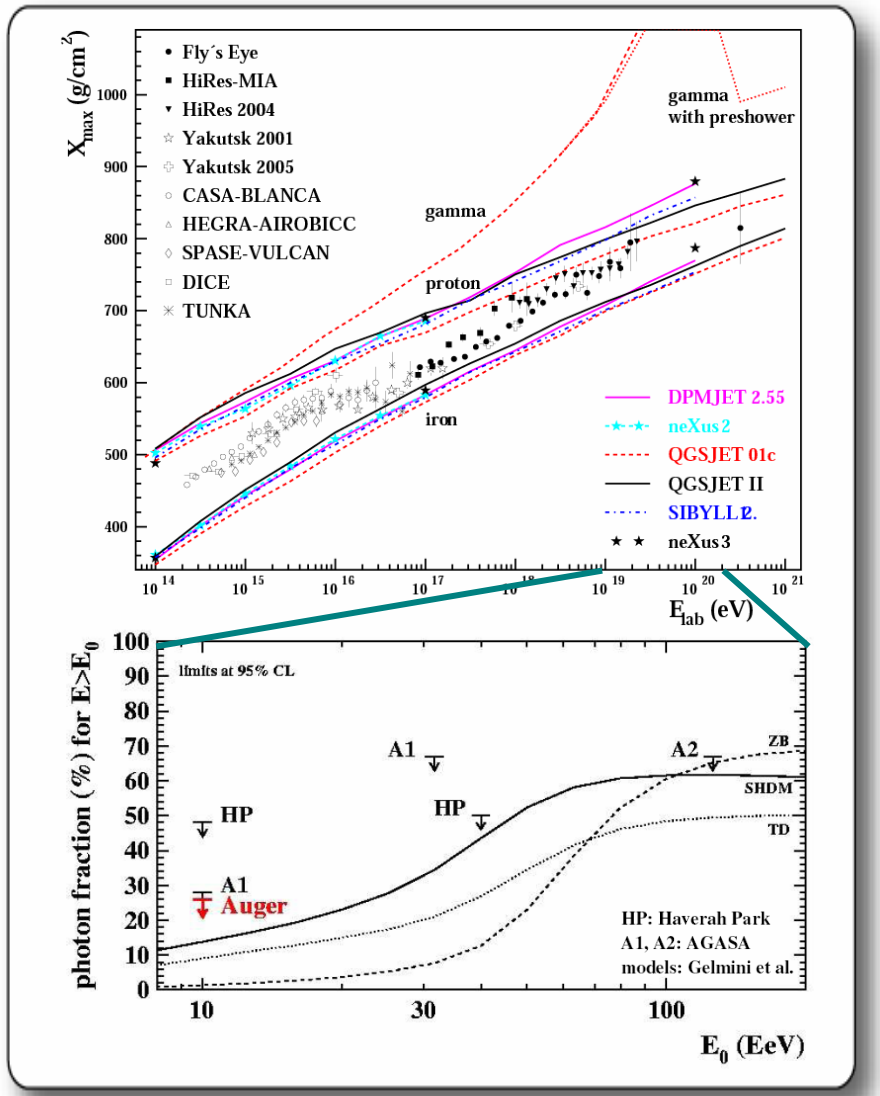
Selection criteria:

- **$E > 10^{19}$eV, $\theta > 35°$**
- **X_{max} observed, track length > 400 g/cm²**
- **Energy dependent distance cut**

16 Events after cuts



26% upper limit (95% CL) on CR photon fraction



Energy Determination (Conversion)

The energy converter:

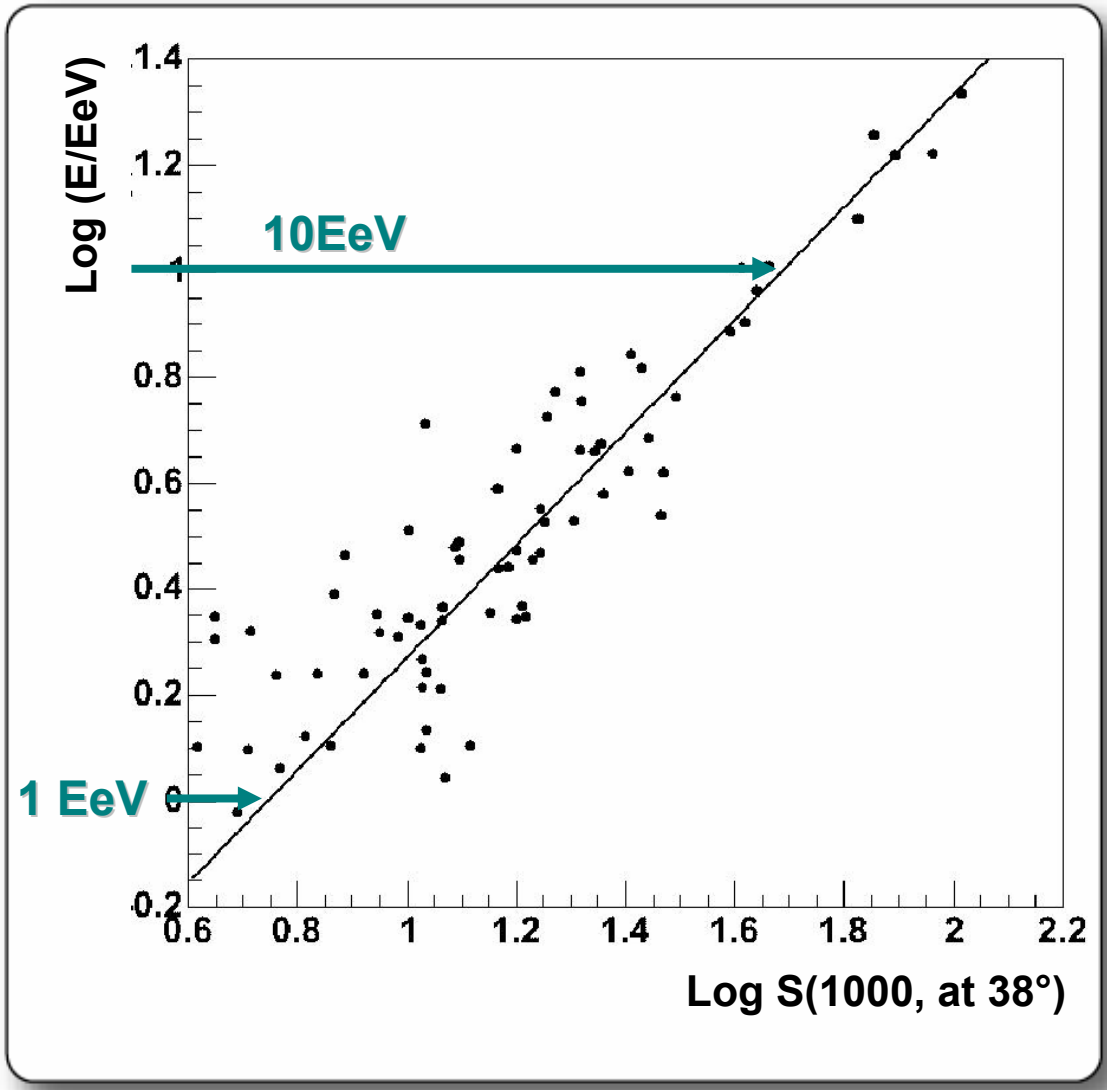
Compare ground parameter S(1000, at 38°) with the fluorescence detector energy (CIC method)

Transfer the energy converter to the surface array only events

$$\text{Log}(E) = -0.79 + 1.06\ \text{Log}(S_{38})$$

$$E = 0.16\ S_{38}^{1.06}$$

(E in EeV, S_{38} in VEM)



Auger Energy Spectrum

SD data calibrated by FD

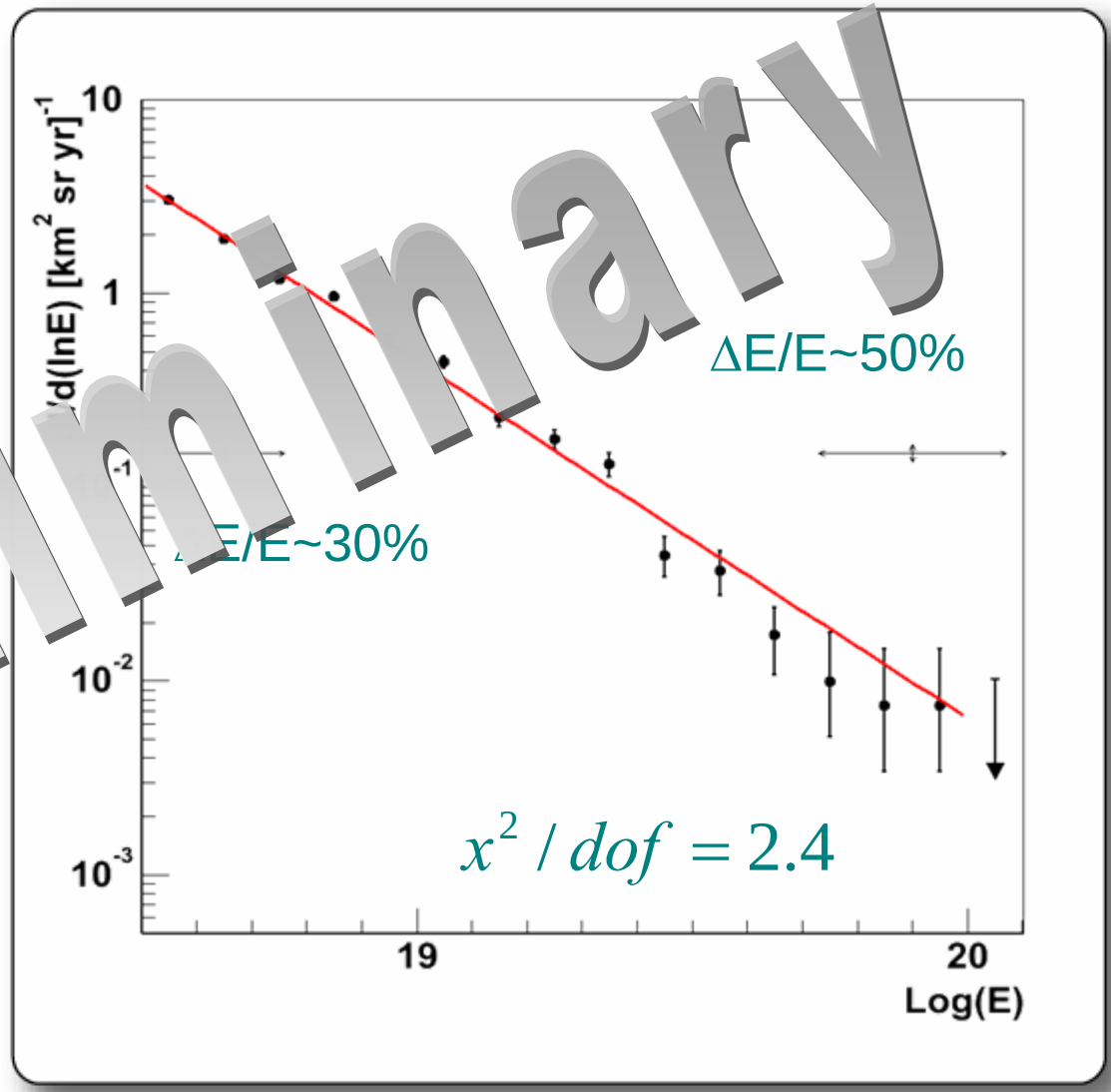
$$\frac{dI}{d\ln(E)} \equiv E\frac{dI}{dE}$$ vs. Lg(E)

Error bars on points indicate Poisson statistical uncertainty (or 95% CL upper limit) based on the number of events

Systematic uncertainty indicated by double arrows at two different energies

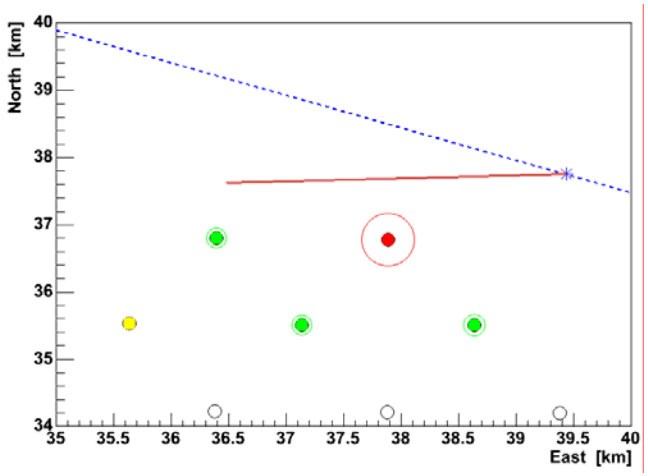
Horizontal: Systematic ΔE

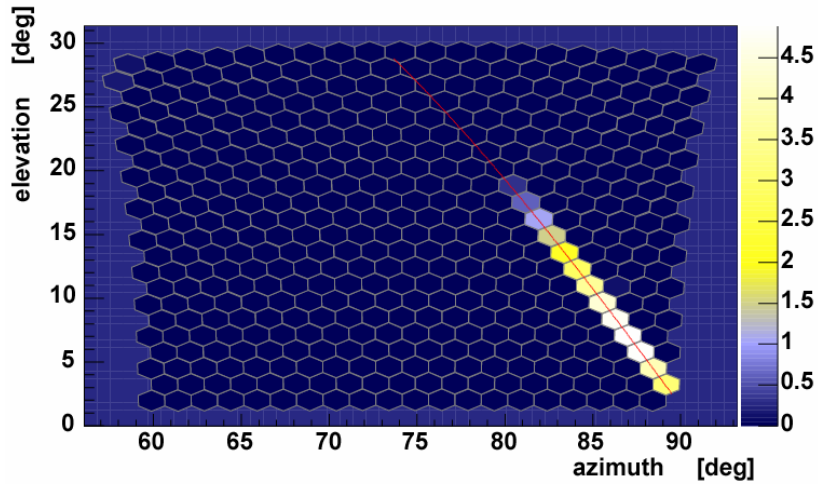
Vertical: Exposure uncertainty

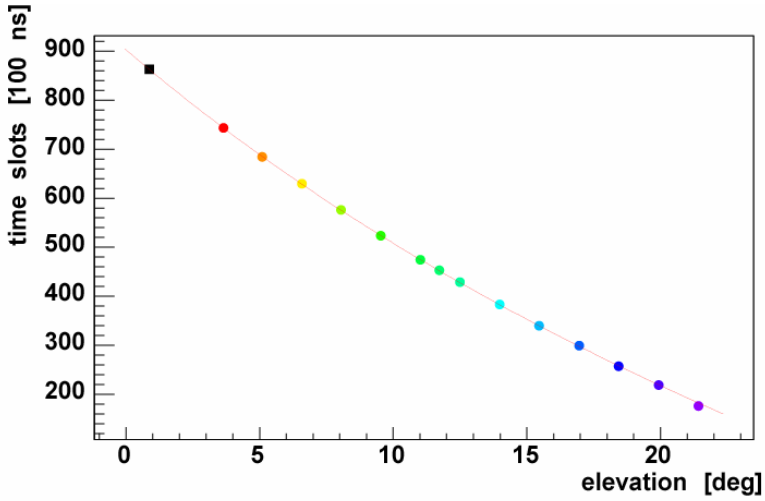


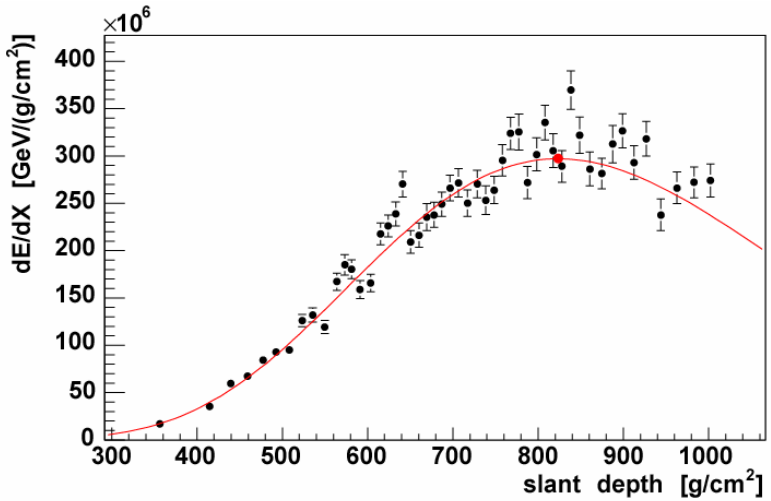
A Big Event - *One that got away!*

Energy estimate >140 EeV

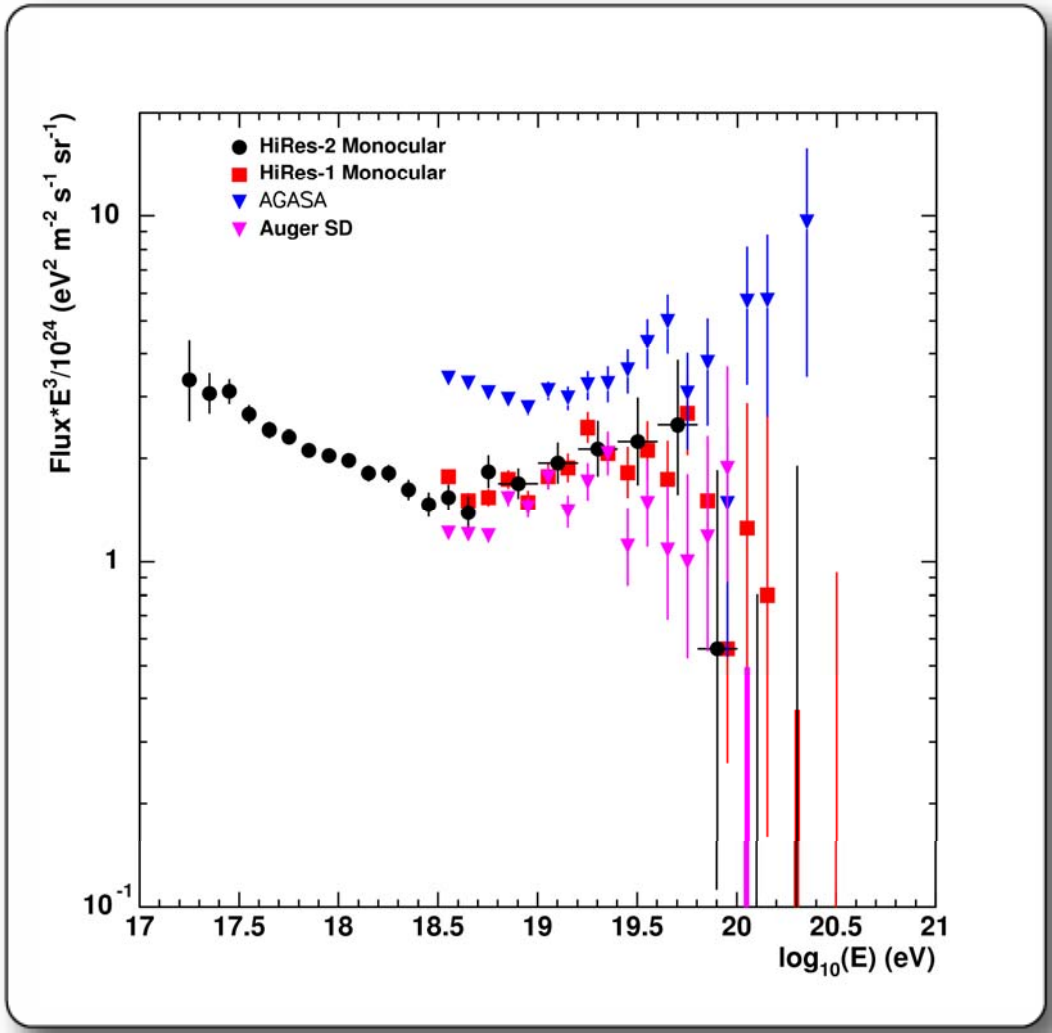








Comparison with HIRES, AGASA



AUGER: Energy scale uncertainty still large

~50 % at 100 EeV

Summary and Outlook: Pierre Auger Observatory

Status:

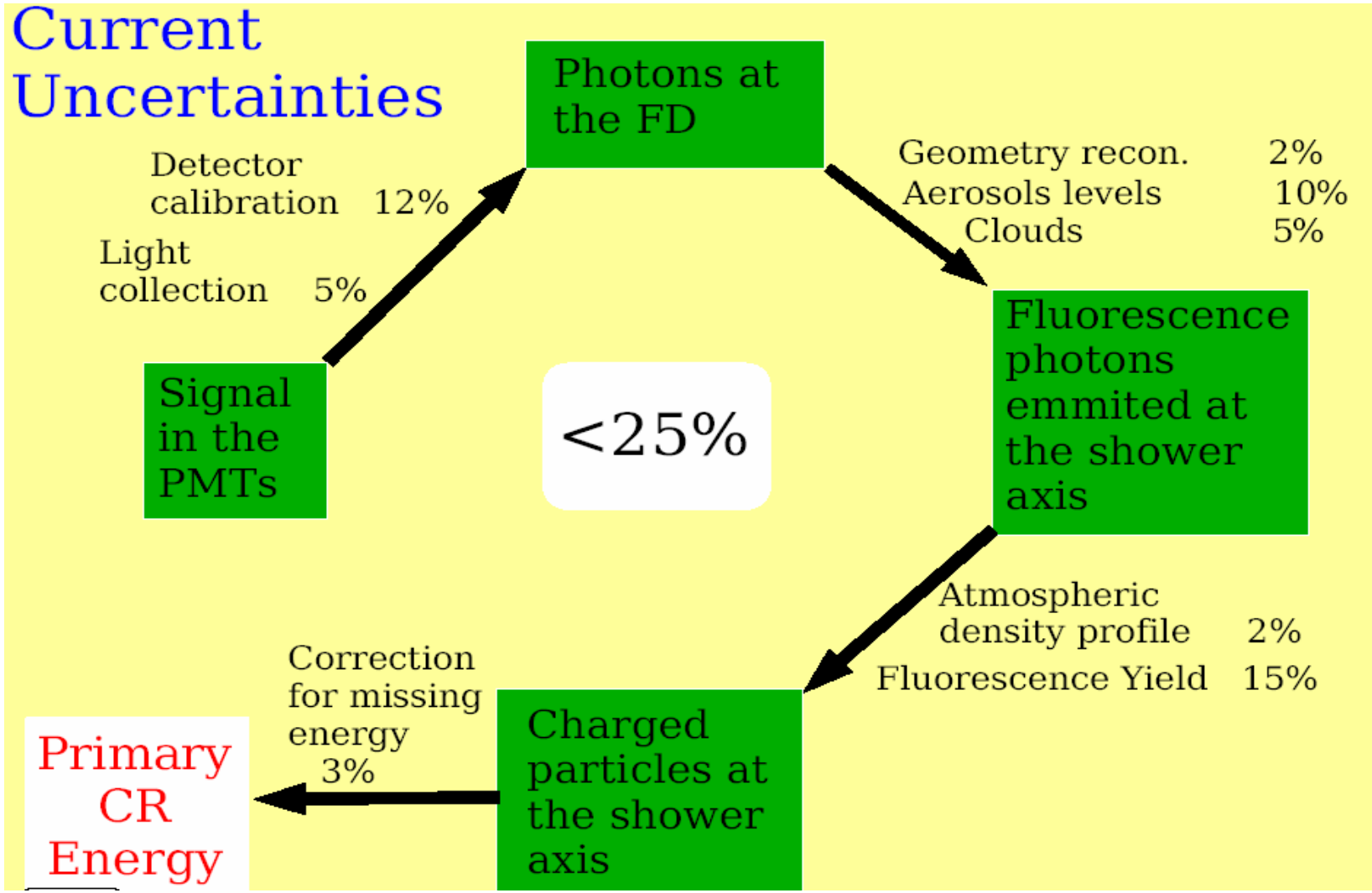
- Southern Observatory over half finished
- With 25% of a full Auger-year exposure, we have:
  - First estimate of an FD-calibrated spectrum
  - First studies of anisotropies in the sky
  - Limits on photon primaries

Future plans:

- Completion by mid 2006
- Full understanding of our instruments
- Usage of rapidly expanding data set (x7 in two years)
- Measure spectrum around 10^{20}eV with unprecedented precision
- Solve AGASA/HIRES dispute
- Composition studies with SD, FD and HYBRID
- Large/small scale anisotropies
- Search for neutrinos and exotics (horizontal showers)
- Begin working on Auger North
- R&D for radio, …

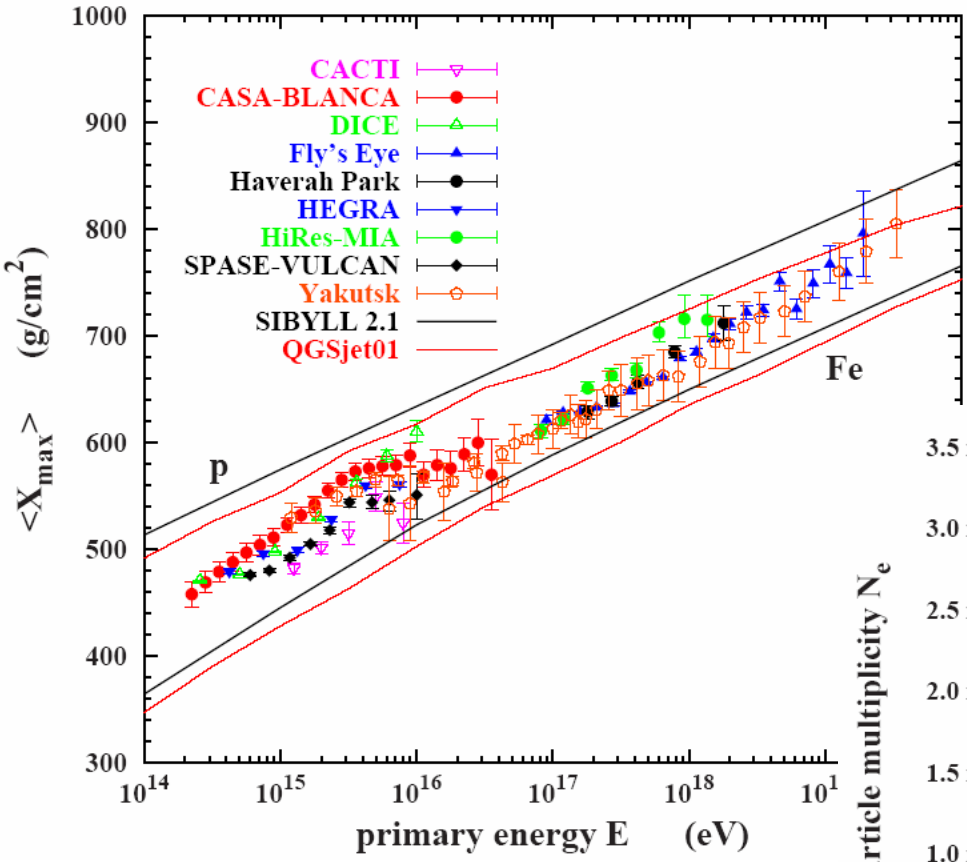
END

Systematic Errors in the FD (Hybrid) Energy Normalization

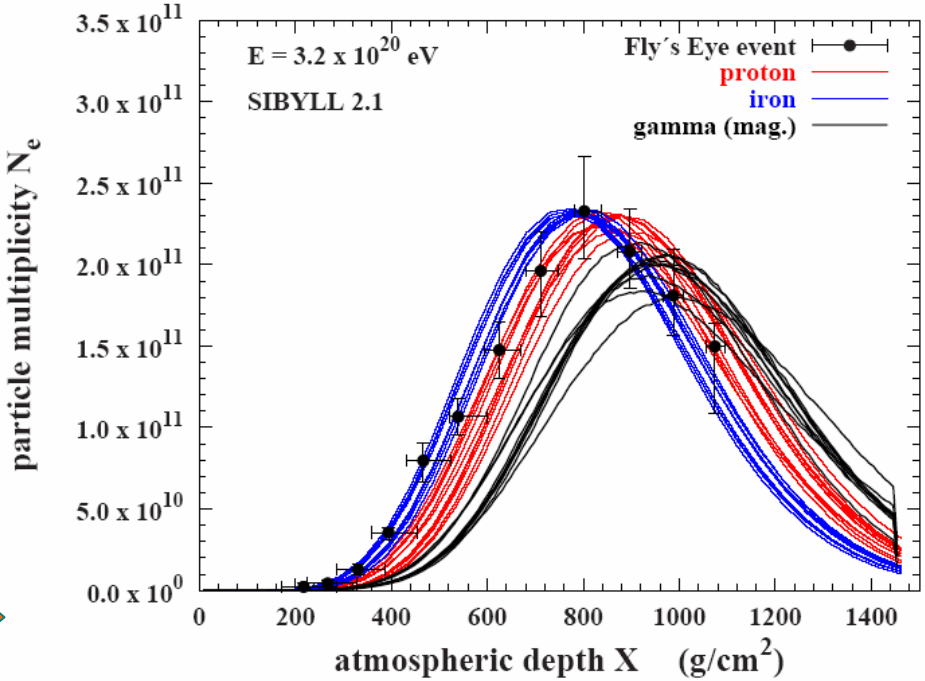


CORSIKA and Auger

Influence of hadronic interaction model on shower maximum:



measured X_{max} by Cherenkov and fluorescence telescopes compared with simulations

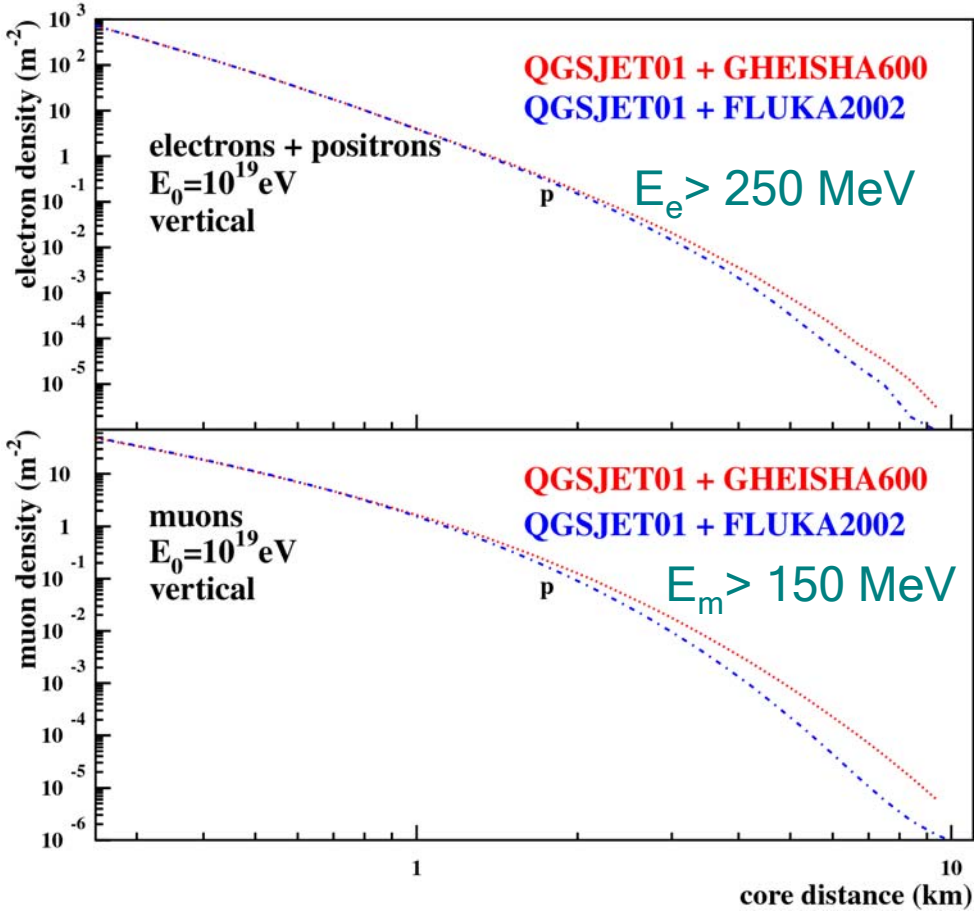


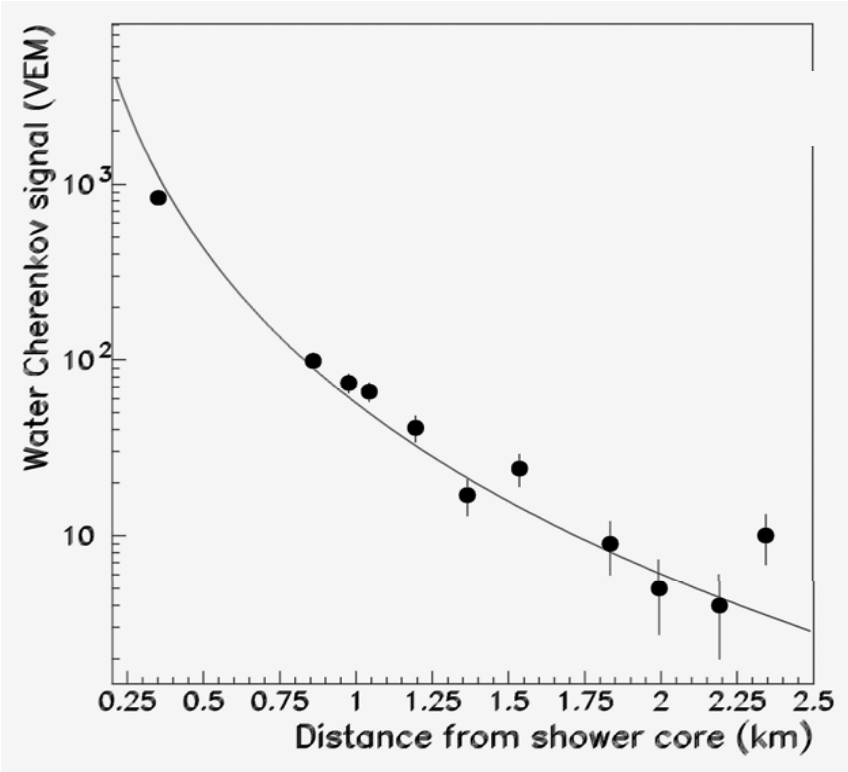
longitudinal development of the highest energy shower ever measured compared to simulations

CORSIKA and Auger

Influence of hadronic interaction model to lateral distributions:

simulations of high-energy lateral distributions for different models





measured Auger lateral distribution (11 tanks)