WHAT DO WE KNOW ABOUT SOURCES OF ULTRA HIGH ENERGY COSMIC RAYS?

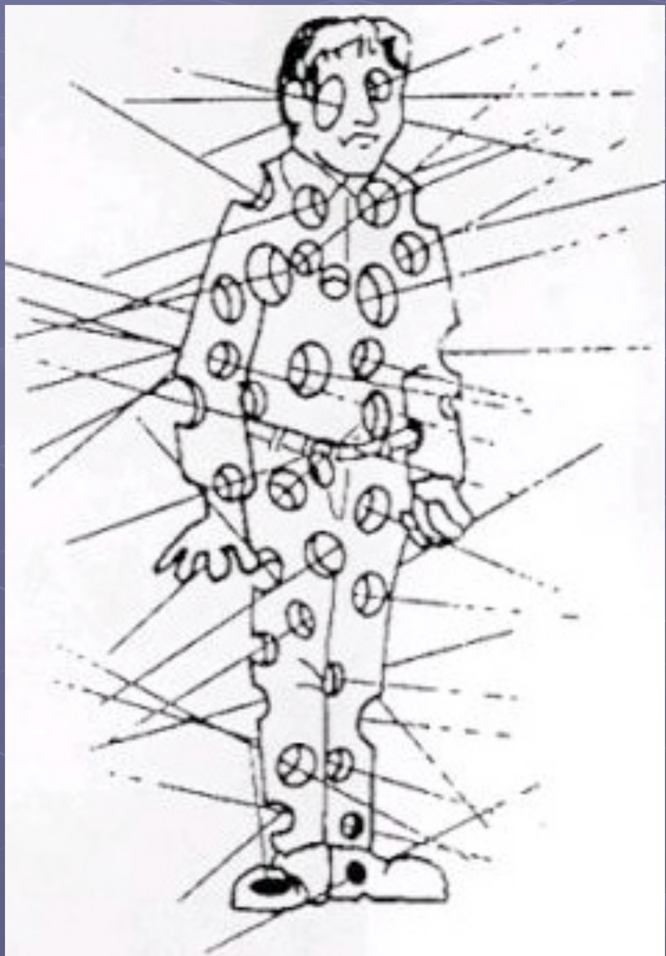
Danilo Zavrtanik
Pierre Auger Collaboration
University of Nova Gorica
Slovenia

7th International Summer School
LET'S FACE CHAOS THROUGH NONLINEAR DYNAMICS
Public evening lecture
July 7, 2008

OUTLINE

- Brief overview of UHECR
- P. Auger Observatory
    - Experimental method
    - Results
        - Spectrum
        - Arrival directions
- Conclusions

WARNING



During this lecture more than100.000 cosmic rays will hit each of your bodies!

HISTORY

Hess discovered CR **1912**

1927 CR seen in cloud chambers

Anderson discovered antimatter **1932**

1937 Discovery of muon

Auger discovered air showers **1938**

1946 First air shower experiments

Fermi's theory of CR **1949**

1962 First 10^{20} eV CR detected

Proposal of GZK cutoff **1966**

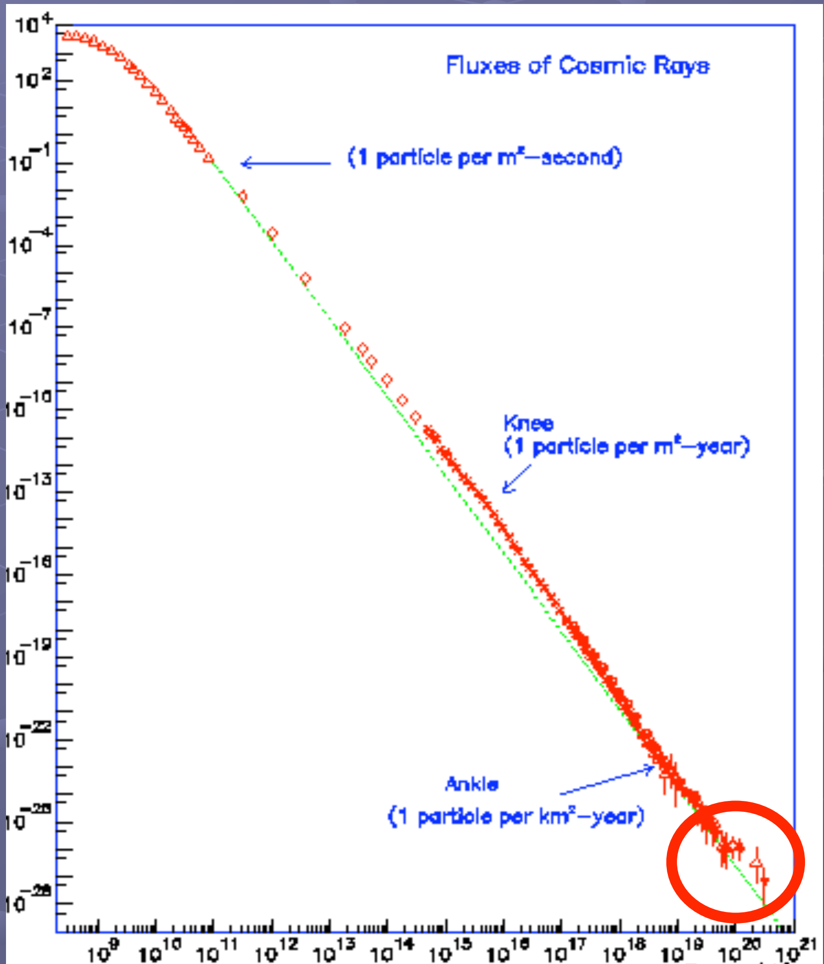
1991 Fly's Eye detected $3x10^{20}$ eV CR

AGASA high-energy event **1994**

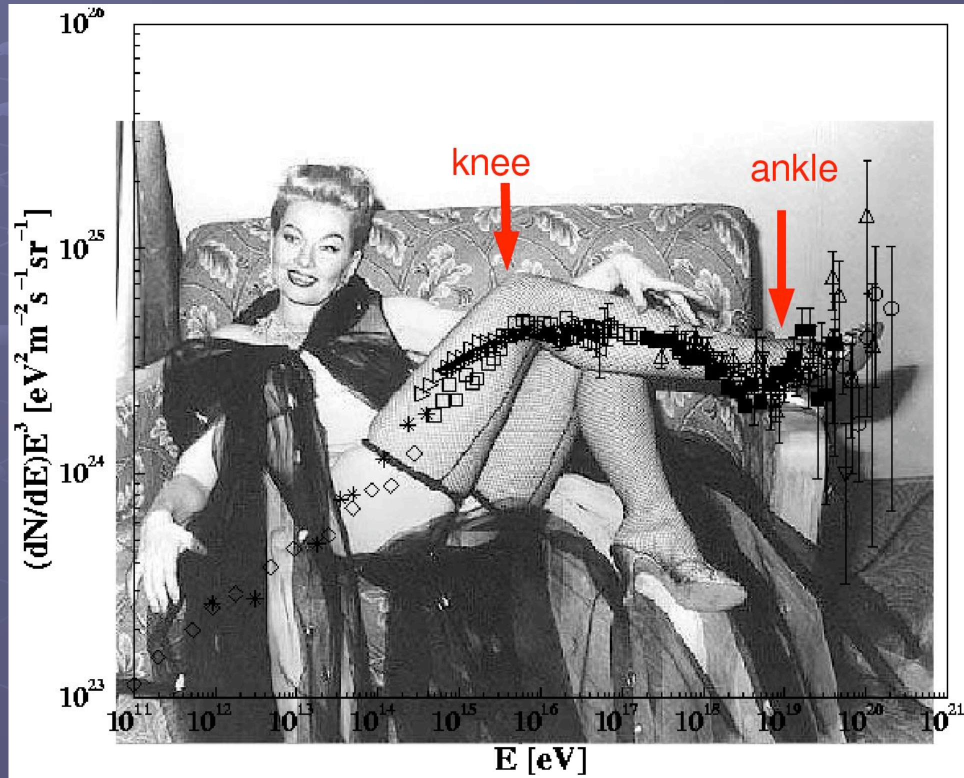
1995 Pierre Auger Project

SPECTRUM

Flux $(m^2\ sr\ s\ eV)^{-1}$



Energy (eV)



← 1 particle/km^2/century or a few particles/km^2/millenium

ENERGY SCALE

Proton mass

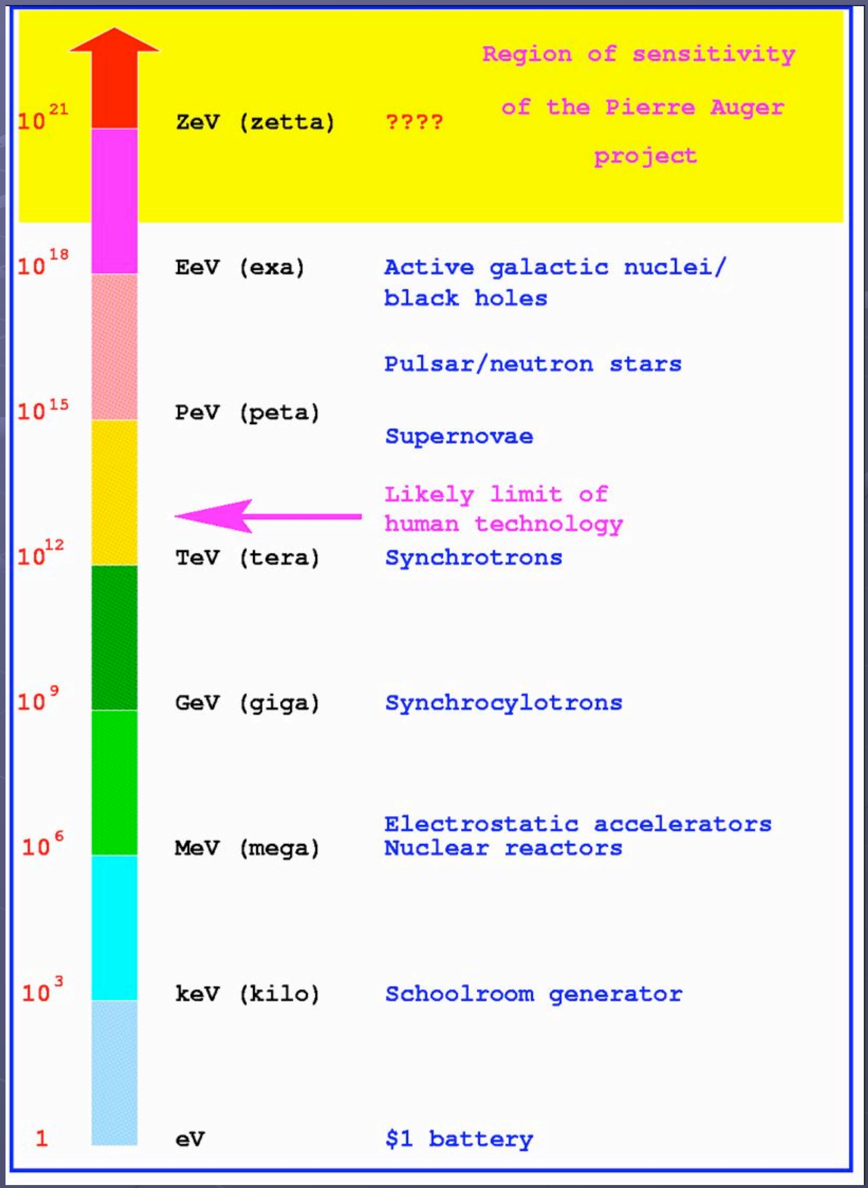
→

m = 1,7 x 10^{-27} kg = 938 MeV

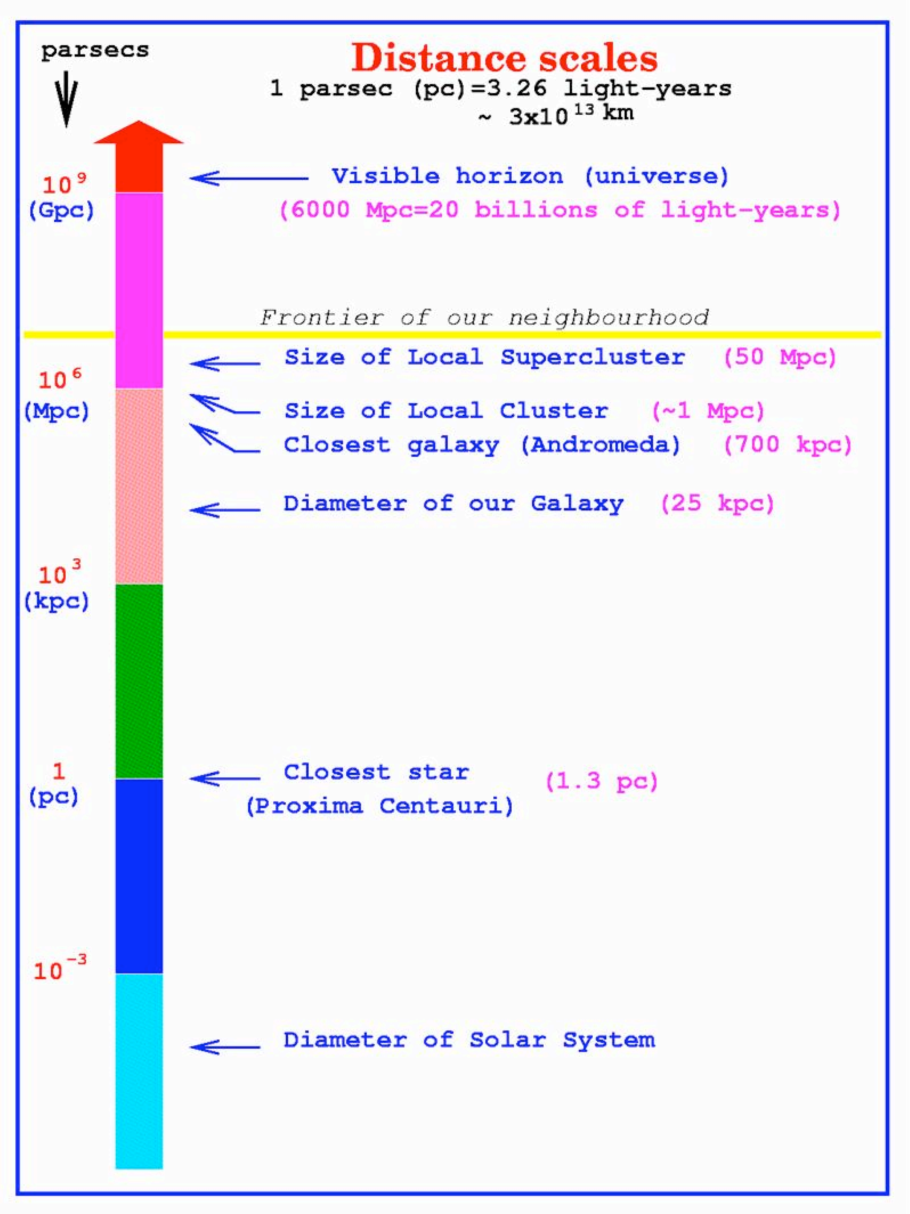
Electron mass

→

m = 9,1 x 10^{-31} kg = 511KeV



DISTANCES



parsecs
Distance scales
1 parsec (pc)=3.26 light-years
~ 3x10 13 km
10 9
(Gpc)
Visible horizon (universe)
(6000 Mpc=20 billions of light-years)
Frontier of our neighbourhood
Size of Local Supercluster (50 Mpc)
10 6
(Mpc)
Size of Local Cluster (~1 Mpc)
Closest galaxy (Andromeda) (700 kpc)
Diameter of our Galaxy (25 kpc)
10 3
(kpc)
1
(pc)
Closest star
(Proxima Centauri)
(1.3 pc)
10 -3
Diameter of Solar System

QUESTIONS

- **What do we know about UHERCs?**
  - They exist!
- **What we don't know about UHERCs?**
  - Their production mechanism
  - Their origin
  - Their nature

POSSIBLE SOURCES

Top - Down Models

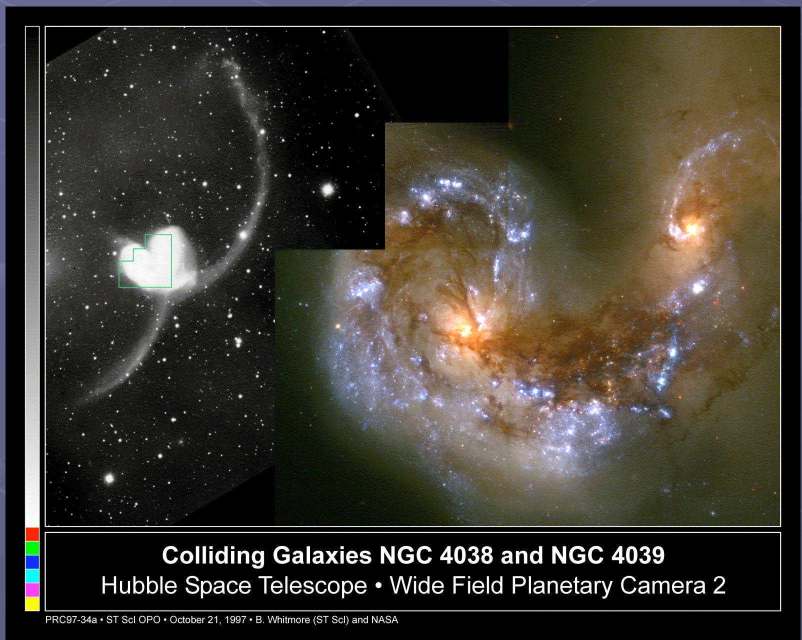
- Exotic Mechanisms
  - Decay of topological deffects
  - Relic monopoles
  - Etc.
- New Physics
  - Supersymmetric particles
  - Strongly interacting neutrinos
  - Decay of massive new long lived particles
  - Violation of LI
  - Etc.

Models do not reproduce the measured flux which is too high !

POSSIBLE SOURCES

Bottom – Up (Astrophysical Acceleration Mechanisms)

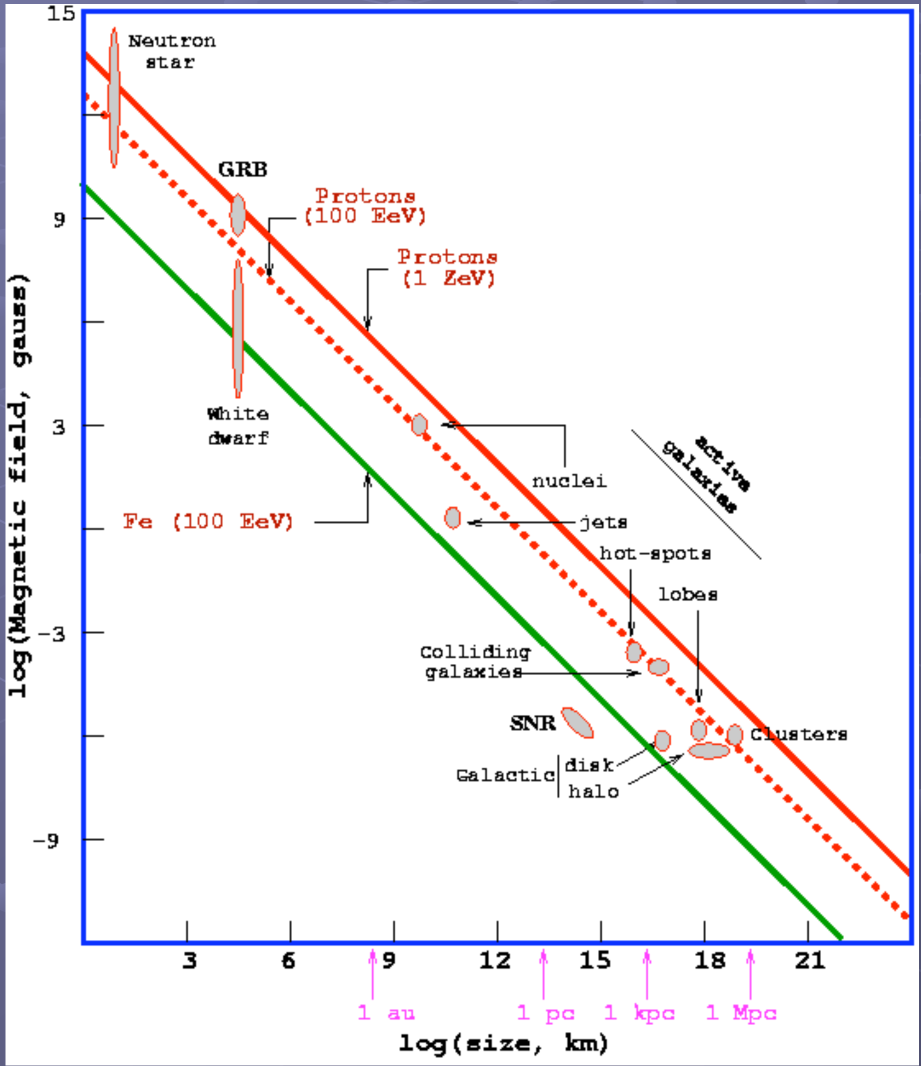
- Diffusive shock acceleration in extended objects (Fermi shock acceleration)
- Acceleration in strong fields associated with accretion disks and compact rotating galaxies



Collision of galaxies NGC4038 and NGC4039 as seen by Hubble Space Telescope

LIMITS TO ACCELERATION

Hillas plot

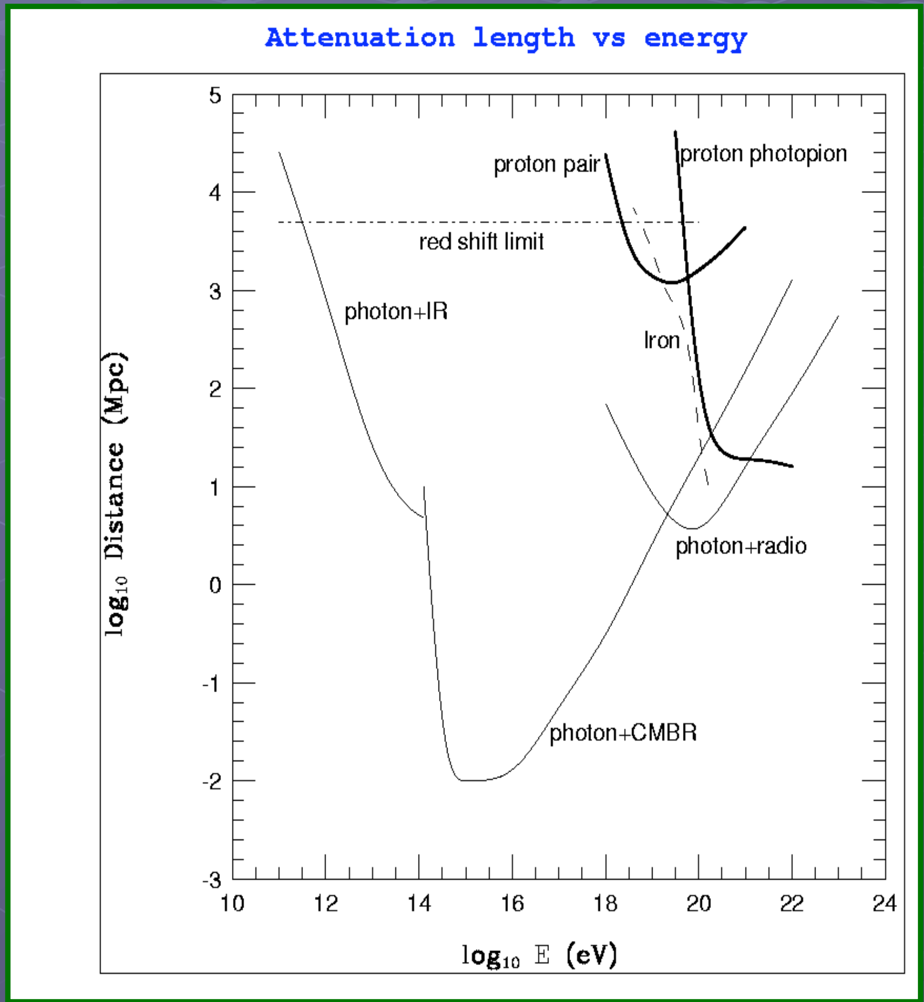


Maximal energy $E_{max} \sim \beta ZBL$

No good candidates for ZeV accelerators in the known Universe!

PROPAGATION

All known particles except neutrinos undergo interactions with Cosmic Microwave Background

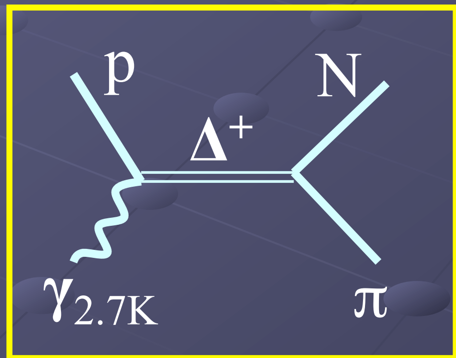


Example:

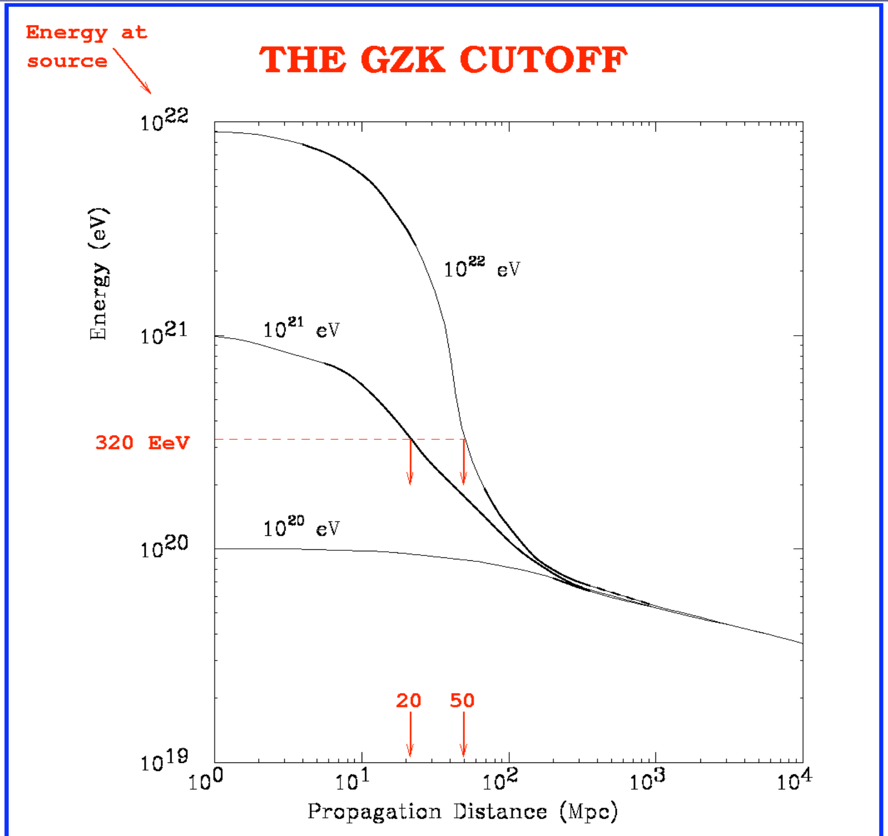
$p + \gamma_{2.7K} \rightarrow p + \pi^0$

$\rightarrow n + \pi^+$

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

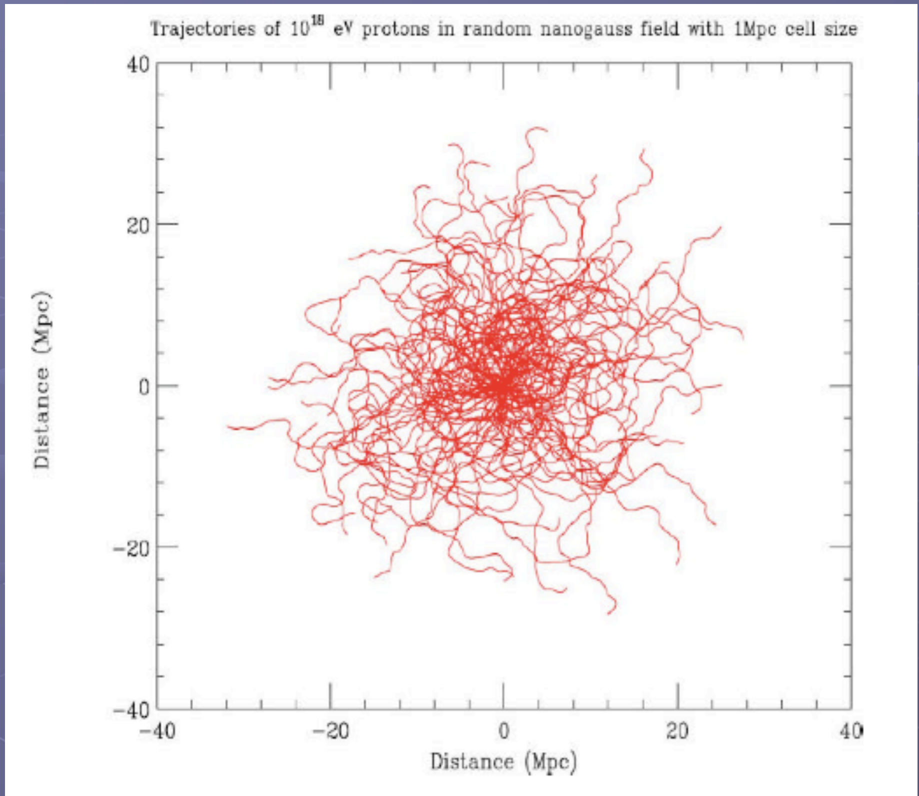
Greisen-Zatsepin-Kuzmin Cut-off

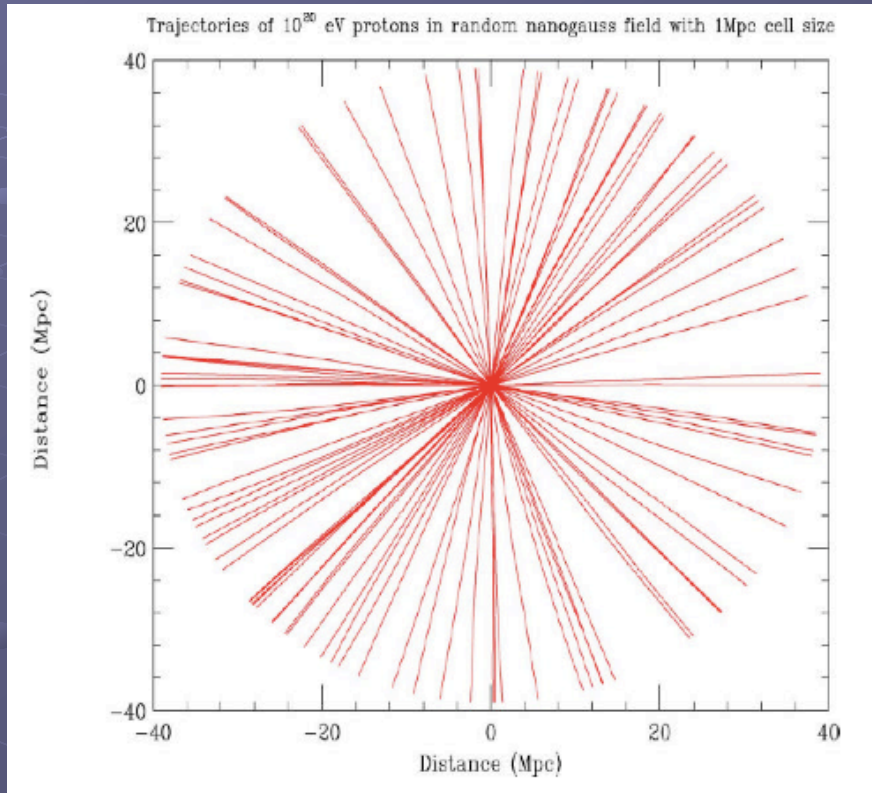
(Greisen '66, Zatsepin & Kuzmin '66)

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 $\Delta\phi < 2^0$ - larger than experimental resolution!

A window to CR astronomy

EXPERIMENTS

PAST

- **Volcano Ranch, USA**
  - Scintillators
- **Haverah Park, UK**
  - Water Čerenkov
- **SUGAR, Australia**
  - Scintillators
- **Fly's Eye, USA**
  - Atmospheric Fluorescence
- **AGASA, Japan**
  - Scintillators, muon detectors

PRESENT

- **Yakutsk, Russia**
  - Scintillators, Atmospheric Čerenkov
- **HiRes, USA**
  - Atmospheric Fluorescence
- **P. Auger, Argentina**
  - Hybrid: Atmospheric Fluorescence, Water Čerenkov

FUTURE

- **Telescope Array**
  - Atmospheric Fluorescence, Scintillator Array
- **AirWatch: OWL – EUSO - TUS**
  - Atmospheric Fluorescence

PIERRE AUGER OBSERVATORY

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

Colorado, USA
(design and proposal in preparation)

Mendoza, Argentina
(observatory fully operational)

P. AUGER COLLABORATION

Argentina Australia Bolivia Brazil Czech Republic

France Germany Italy Mexico Netherlands

Poland Portugal Slovenia Spain UK

USA Vietnam

~ 450 physicist from 104 institutions

17 countries

P. AUGER OBSERVATORY

Science Objectives

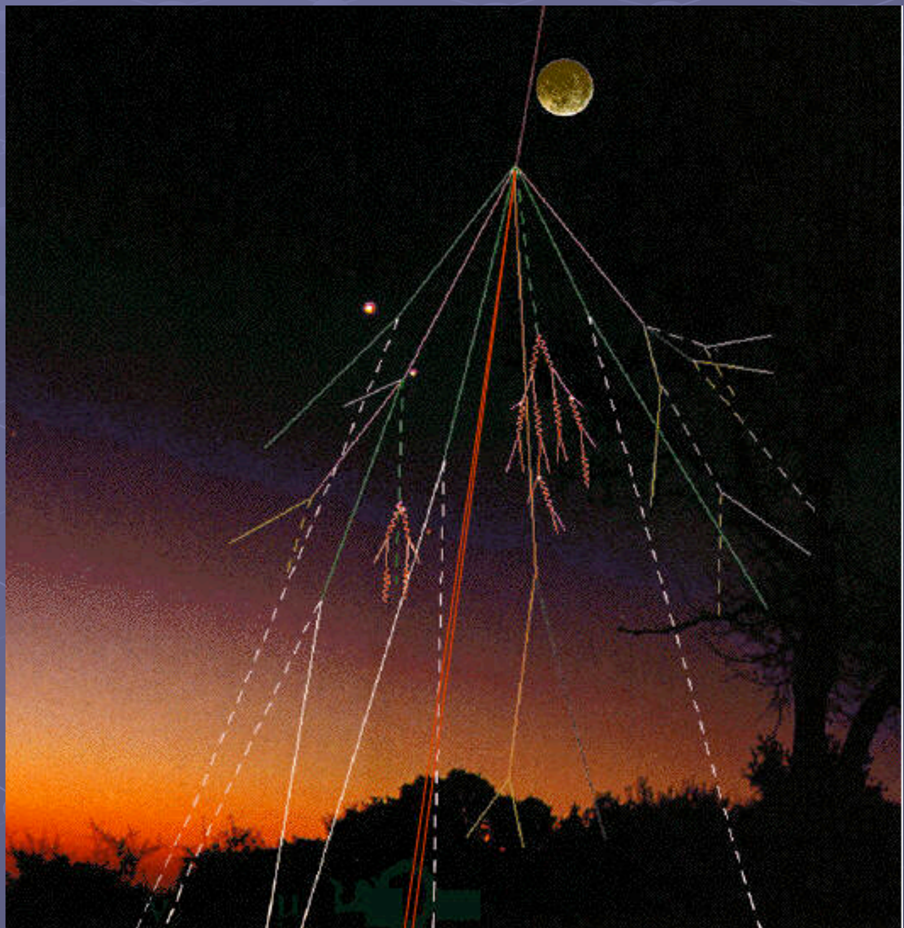
- Cosmic ray spectrum above 10^{19} eV
  - Shape of the spectrum in the region of the GZK feature
- Arrival direction distribution
  - Search for departure from isotropy - point sources
- Composition
  - Light or heavy nuclei, protons, photons, neutrinos or exotics

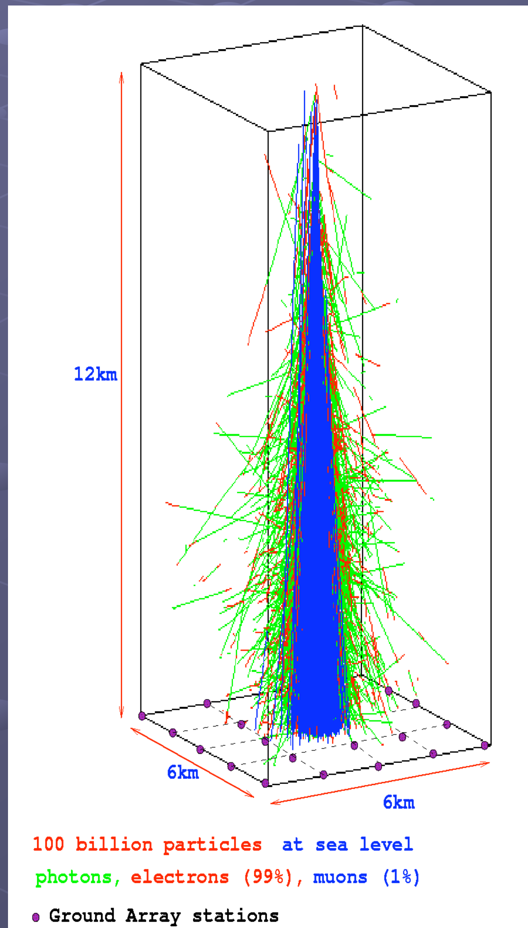
Design Features

- 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

EXPERIMENTAL TECHNIQUE

Measurement of extensive air showers



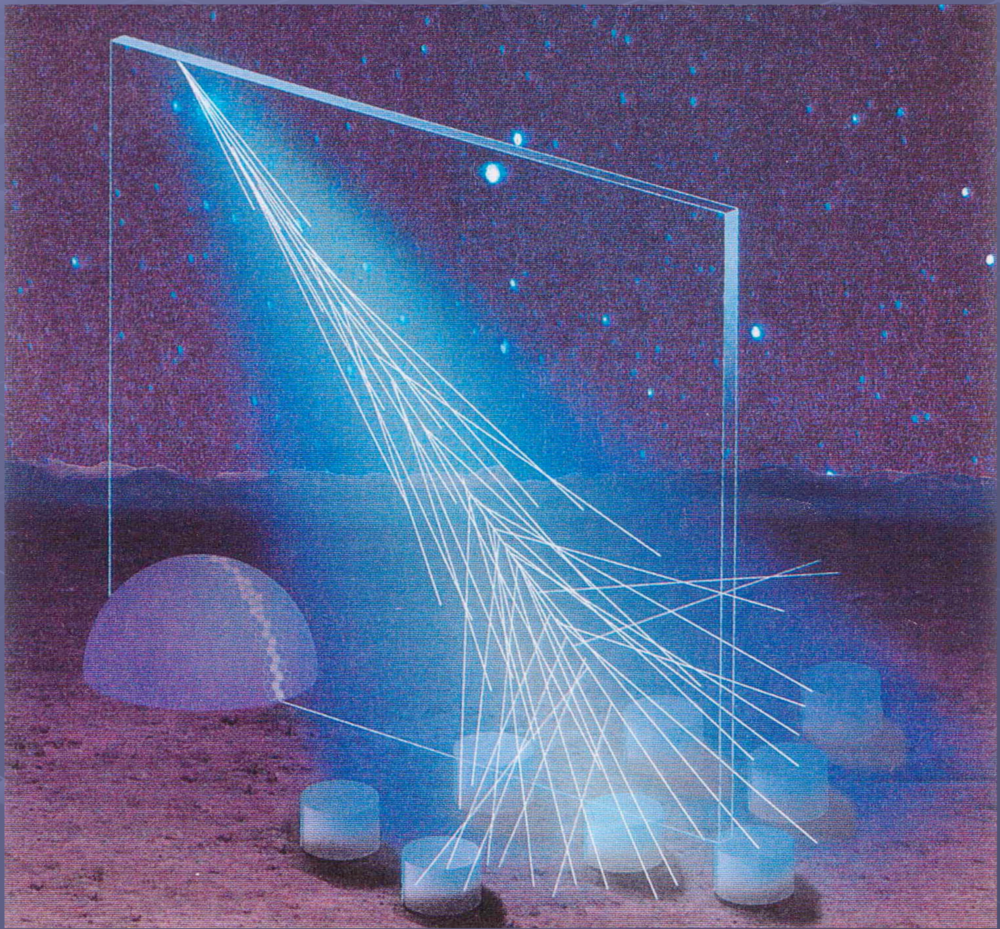


E=10^{19} eV

P. AUGER OBSERVATORY

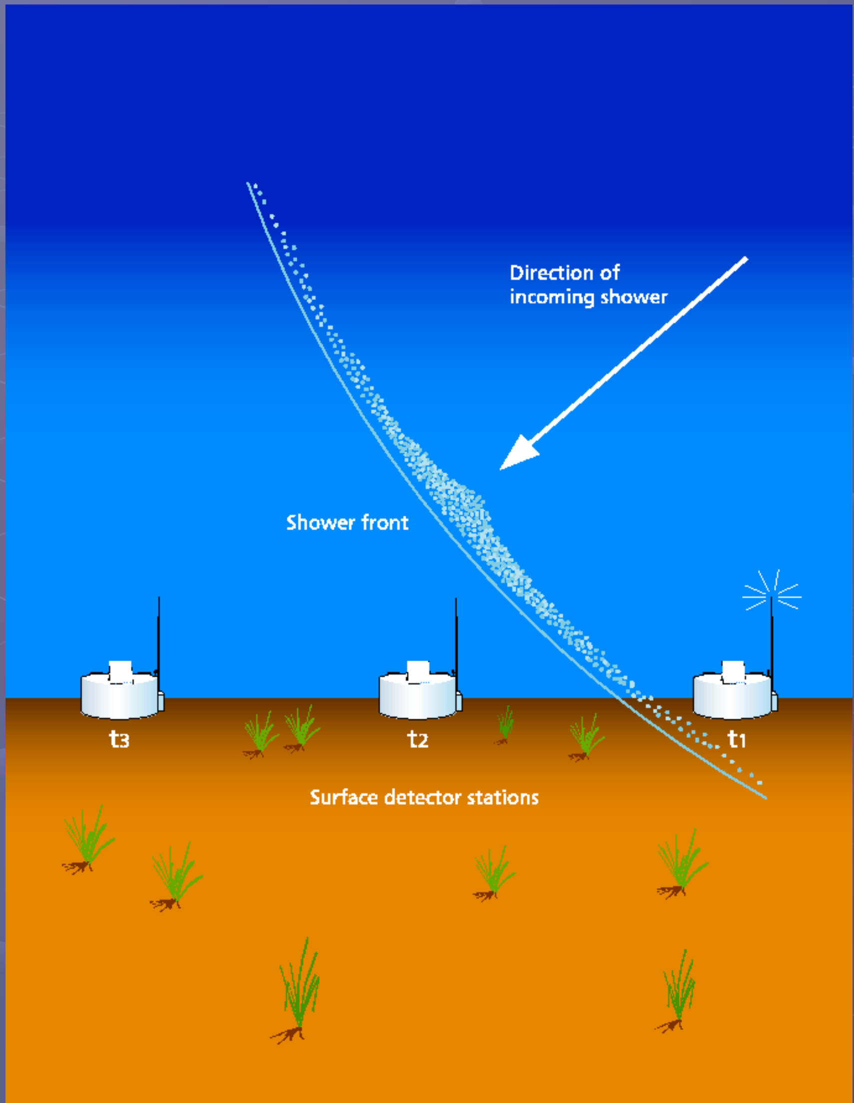
The Hybrid Design

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.

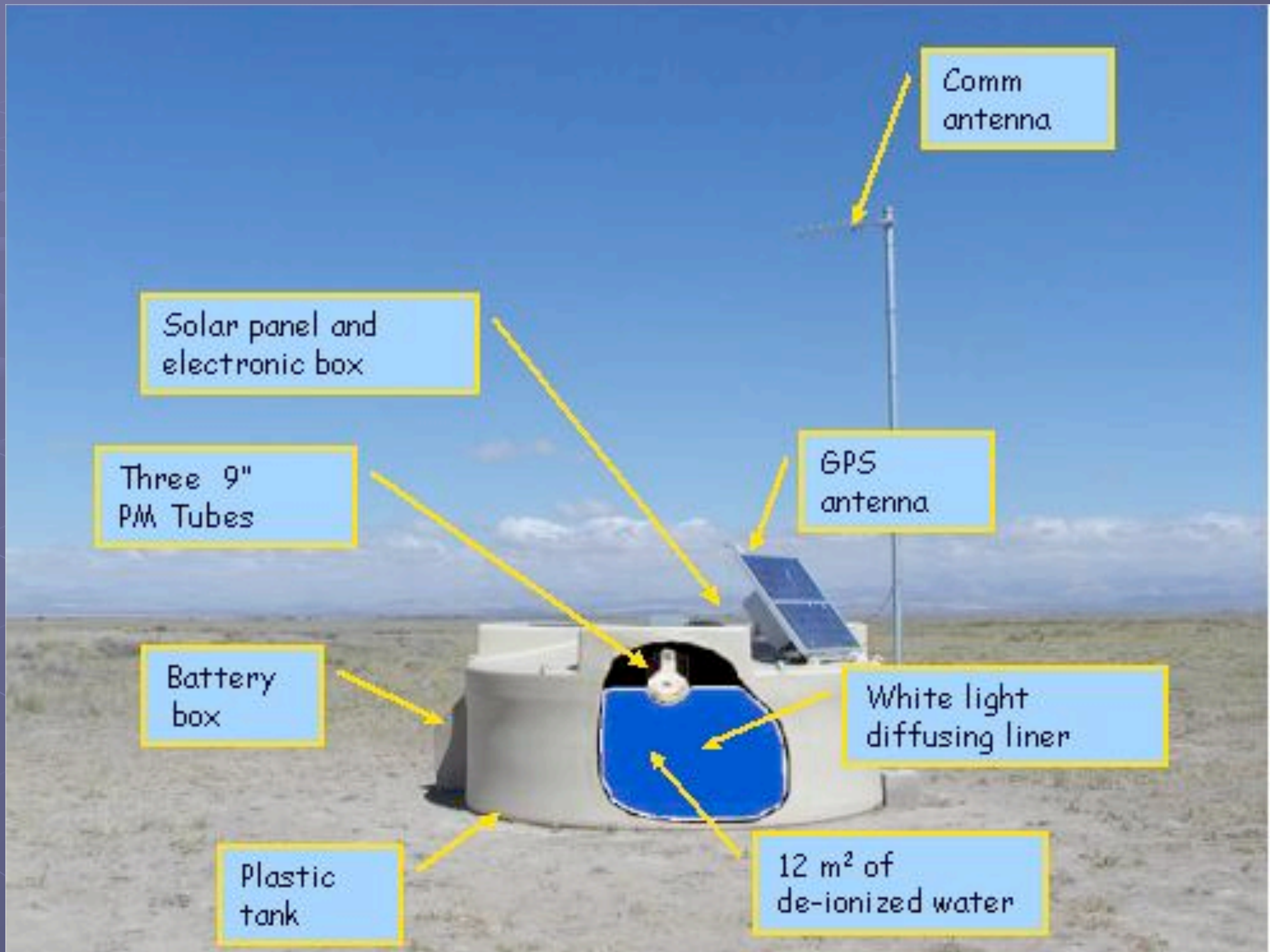
SURFACE DETECTOR ARRAY



Event timing and direction determination

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

WATER ČERENKOV DETECTOR



WATER ČERENKOV DETECTOR

Cows

Black widow

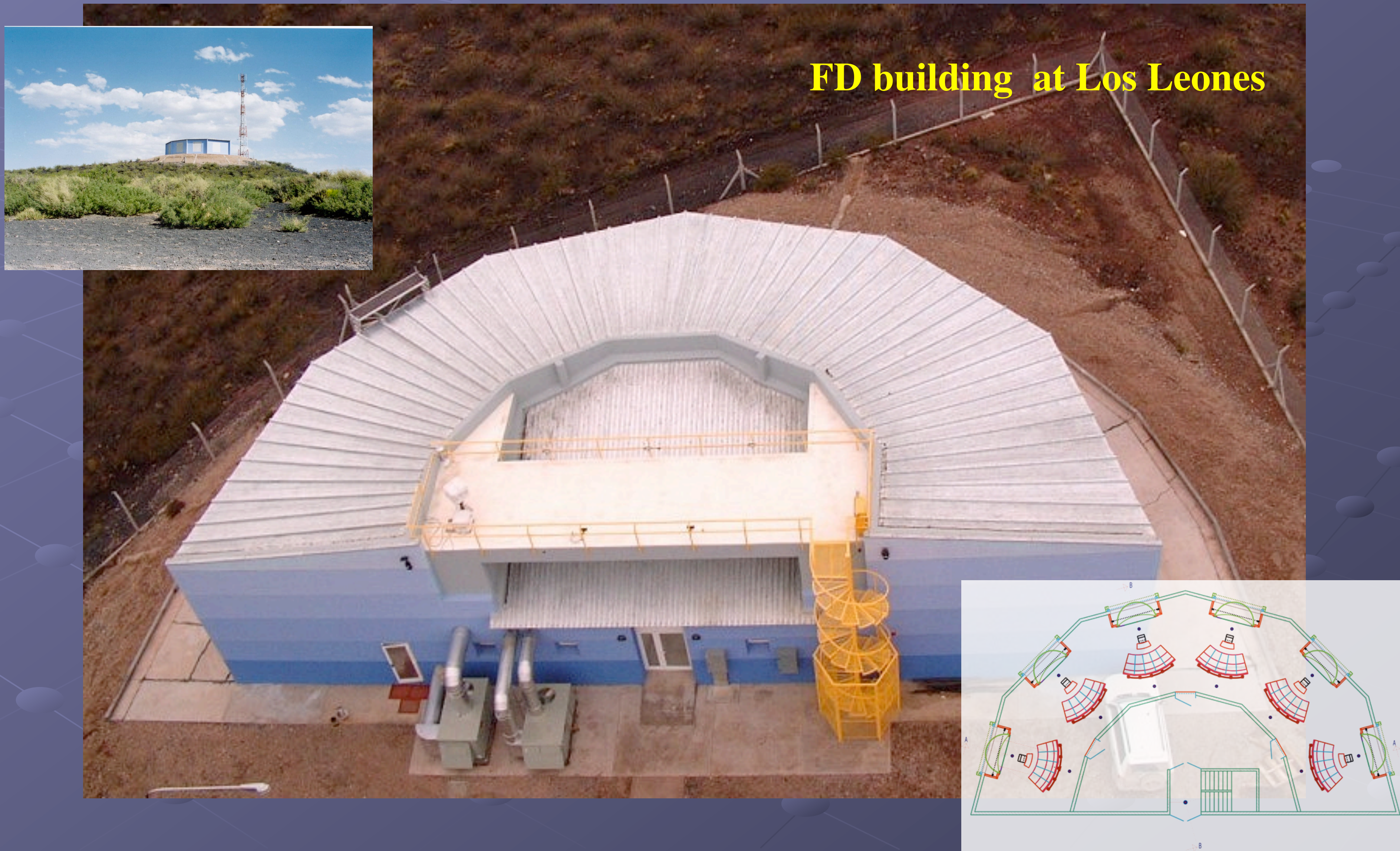
FLUORESCENCE DETECTOR

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

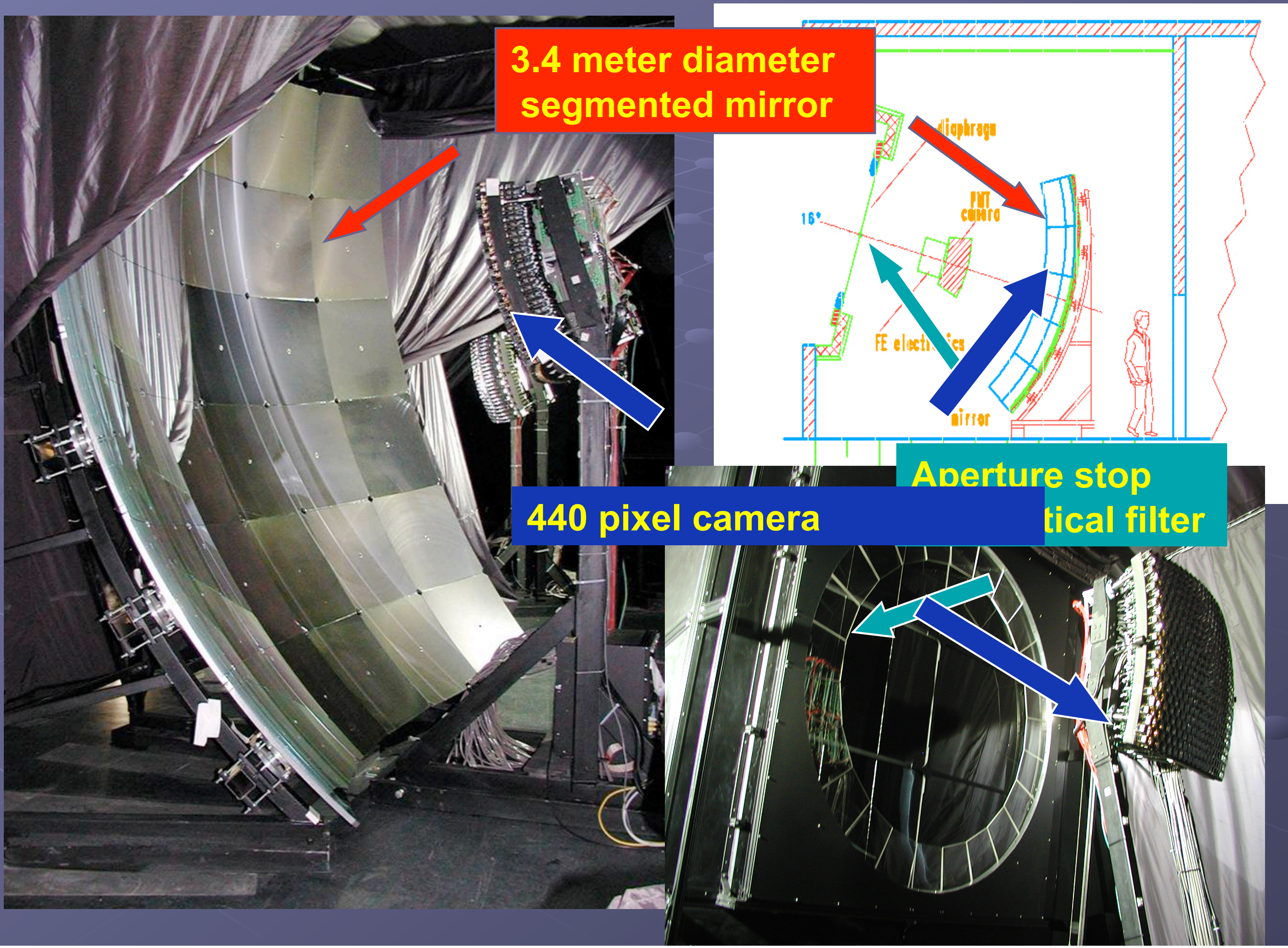
⇓

- Calorimetric energy measurement
- Measure of shower development

FLUORESCENCE DETECTOR

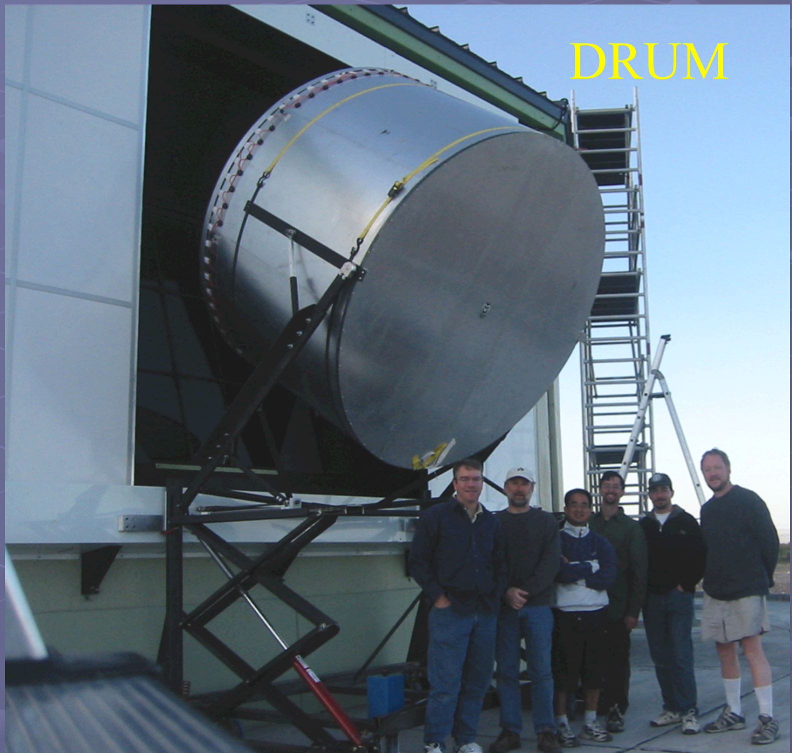


FLUORESCENCE DETECTOR



ATMOSPHERIC MONITORING AND CALIBRATION

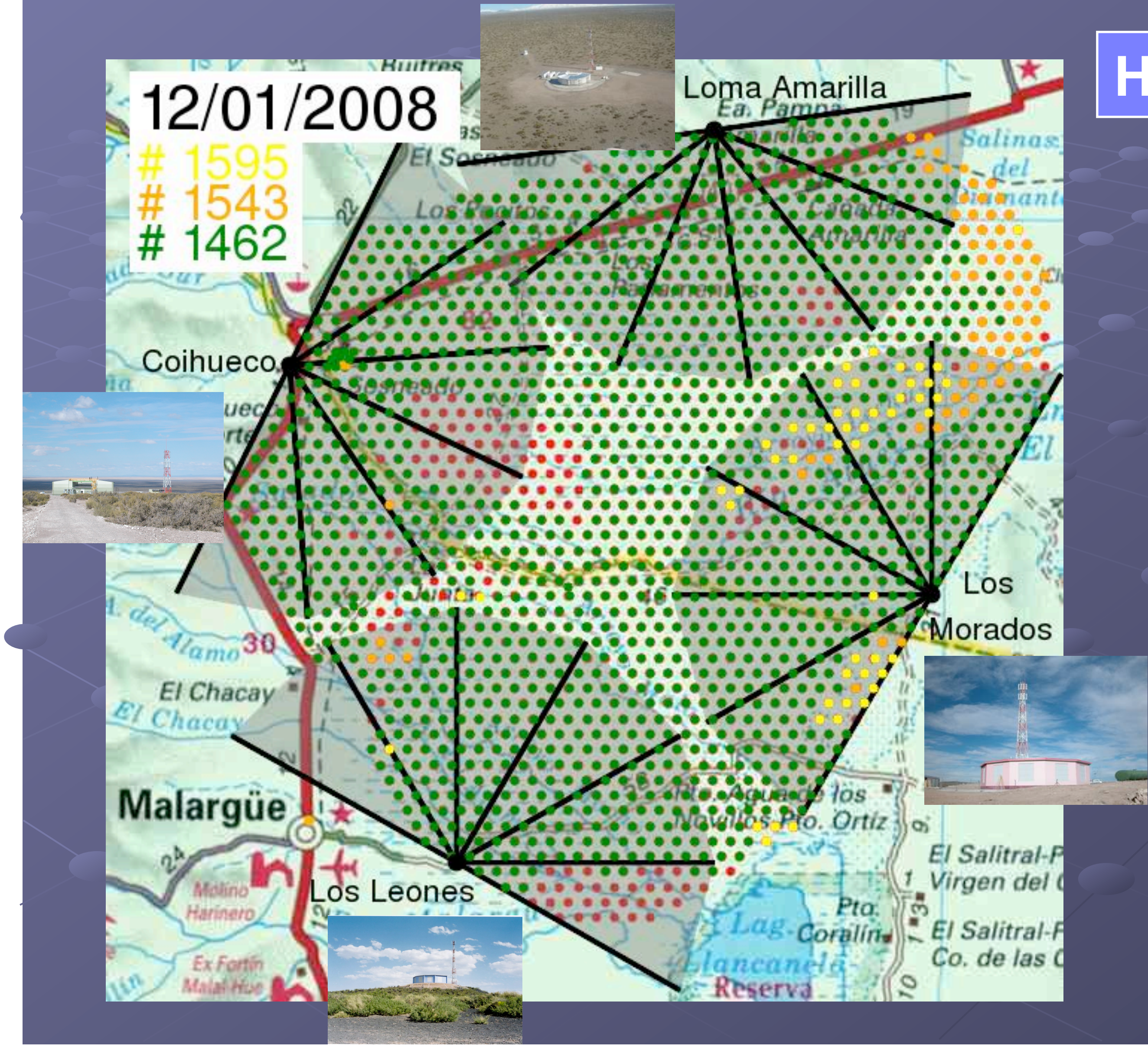
Absolute Calibration



Monitoring

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

SOUTHERN OBSERVATORY



HYBRID DETECTOR

SA

- **~ 1600 surface detectors**

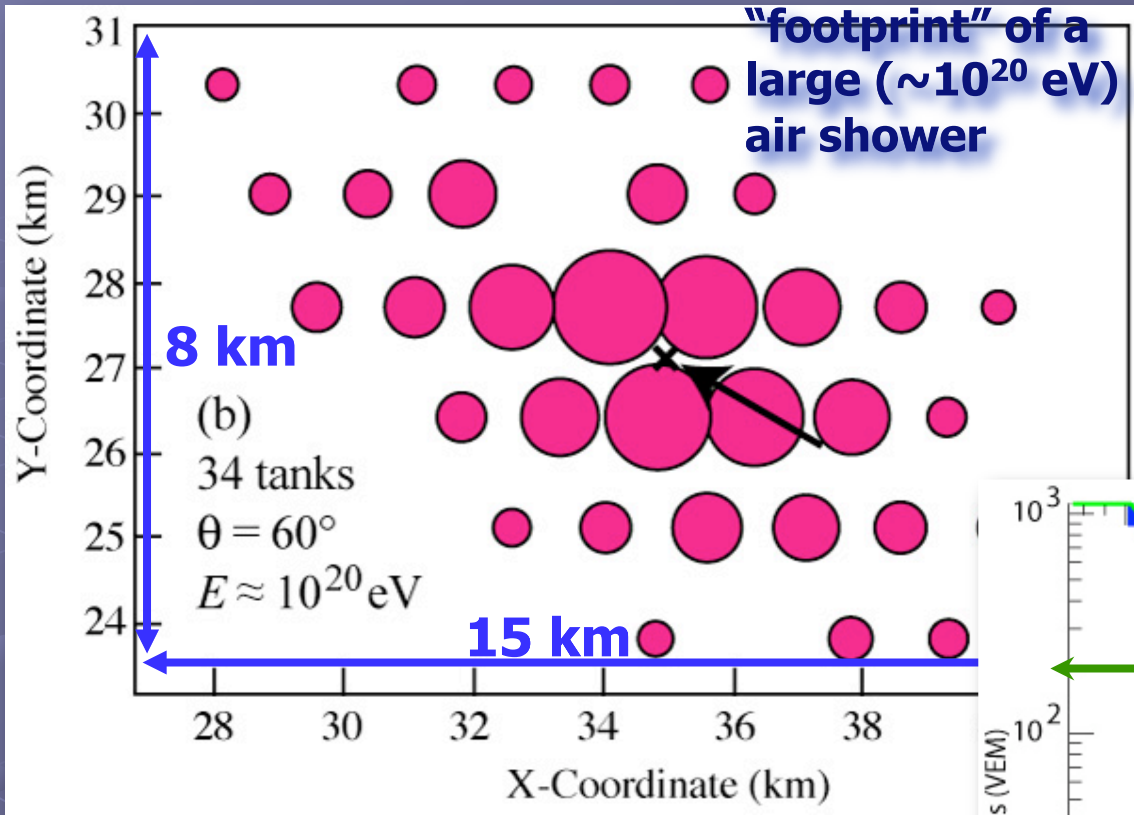
World largest array

FD

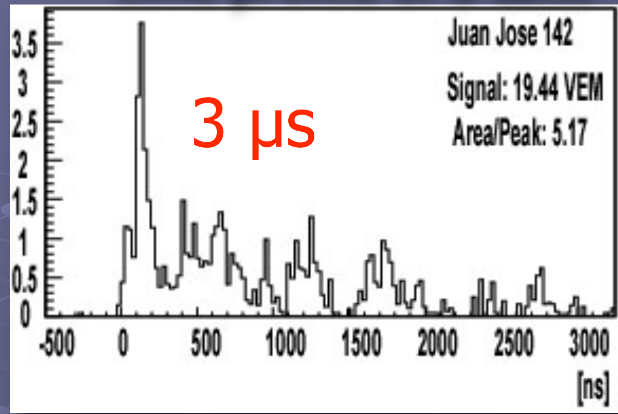
- **4 fluorescence buildings with 6 telescopes each**

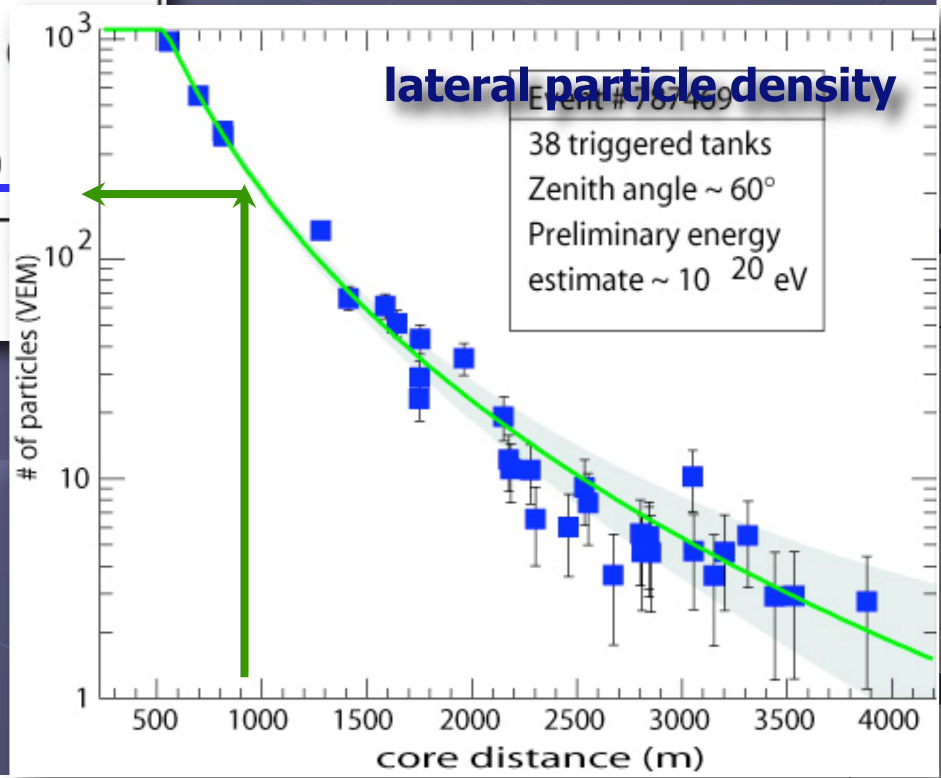
SOUTHERN OBSERVATORY

SD RECONSTRUCTION



time profile of a tank





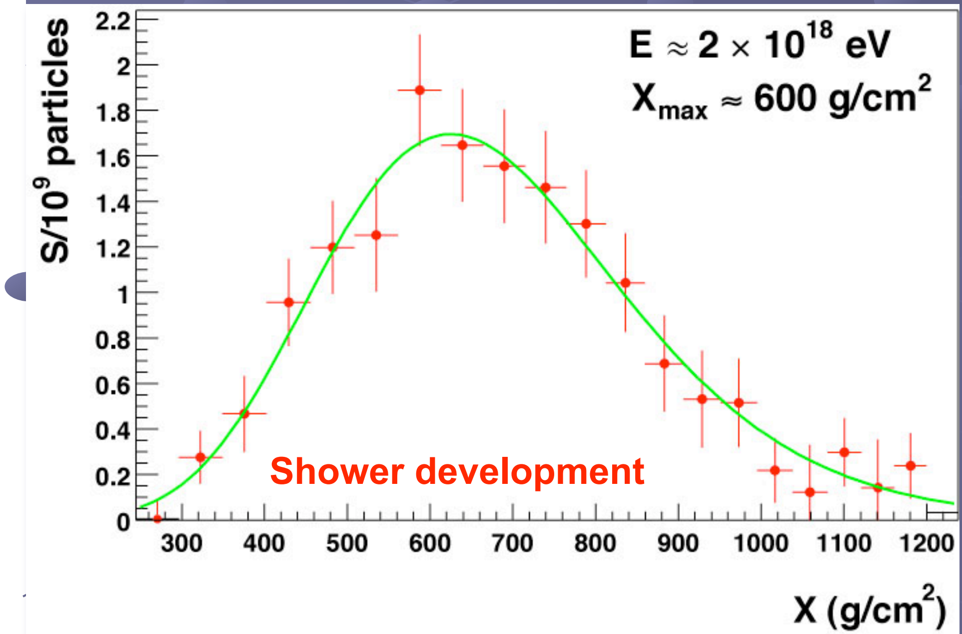
Simulations: particle density at 1000 m provides good estimate of primary energy

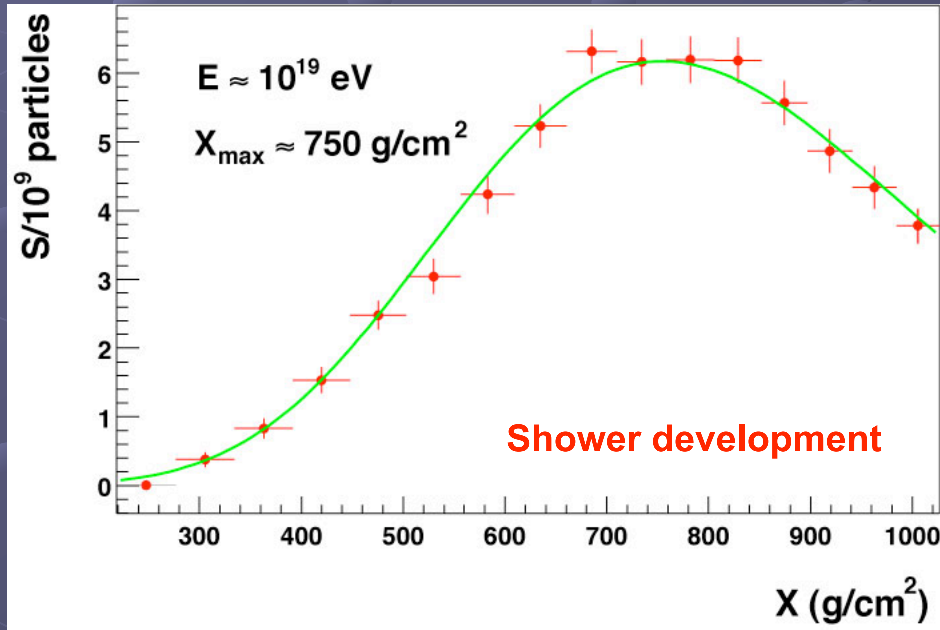
different models: ~20 syst. errors

FD RECONSTRUCTION

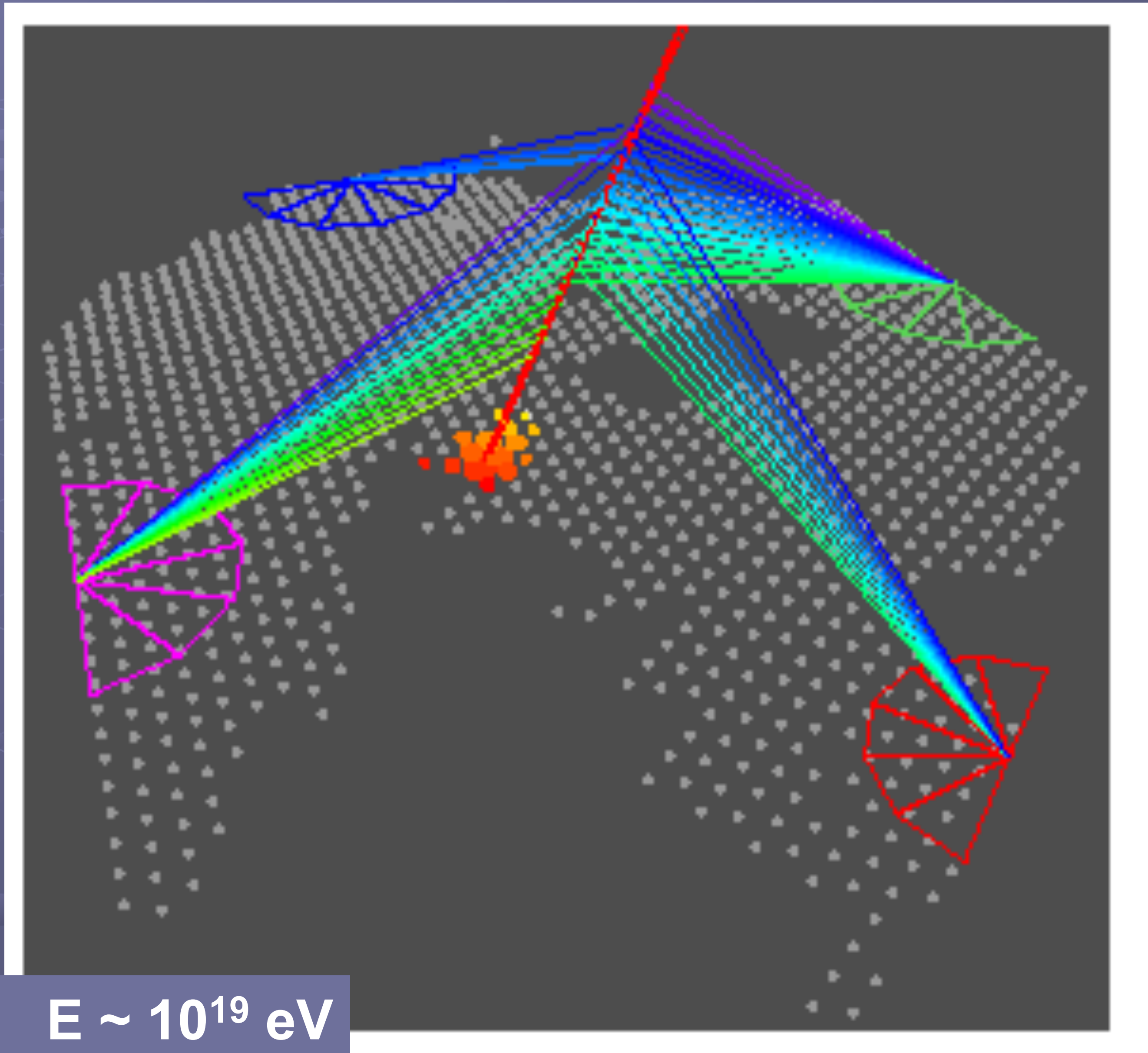
- **Fit with empirical formula of Gaisser-Hillas**

Calorimetric measurement of the energy.





STEREO HYBRID OBSERVATIONS



20 May 2007 E ~ 10^{19} eV

DATA SET

- Auger south : Lat -35.2º South, Long. 69.5º West, m.a.s.l. 1400 m
  - 154 surface array detectors and 2 FD sites in January 2004
  - 1388 surface array detectors and 4 FD sites in September 2007
- Over a million CR events recorded above about 0.2 EeV.
- Full acceptance above 3 EeV for zenith < 60º
- Data set : January 1st 2004 until August 31st 2007, 81 events
  - T5,
  - $E > 40$ EeV,
  - $\Theta < 60^\circ$
- Geometrical exposure α sin[θ] or rate α sin^2[θ]. Array growth modulation or atmospheric effects < 1%.

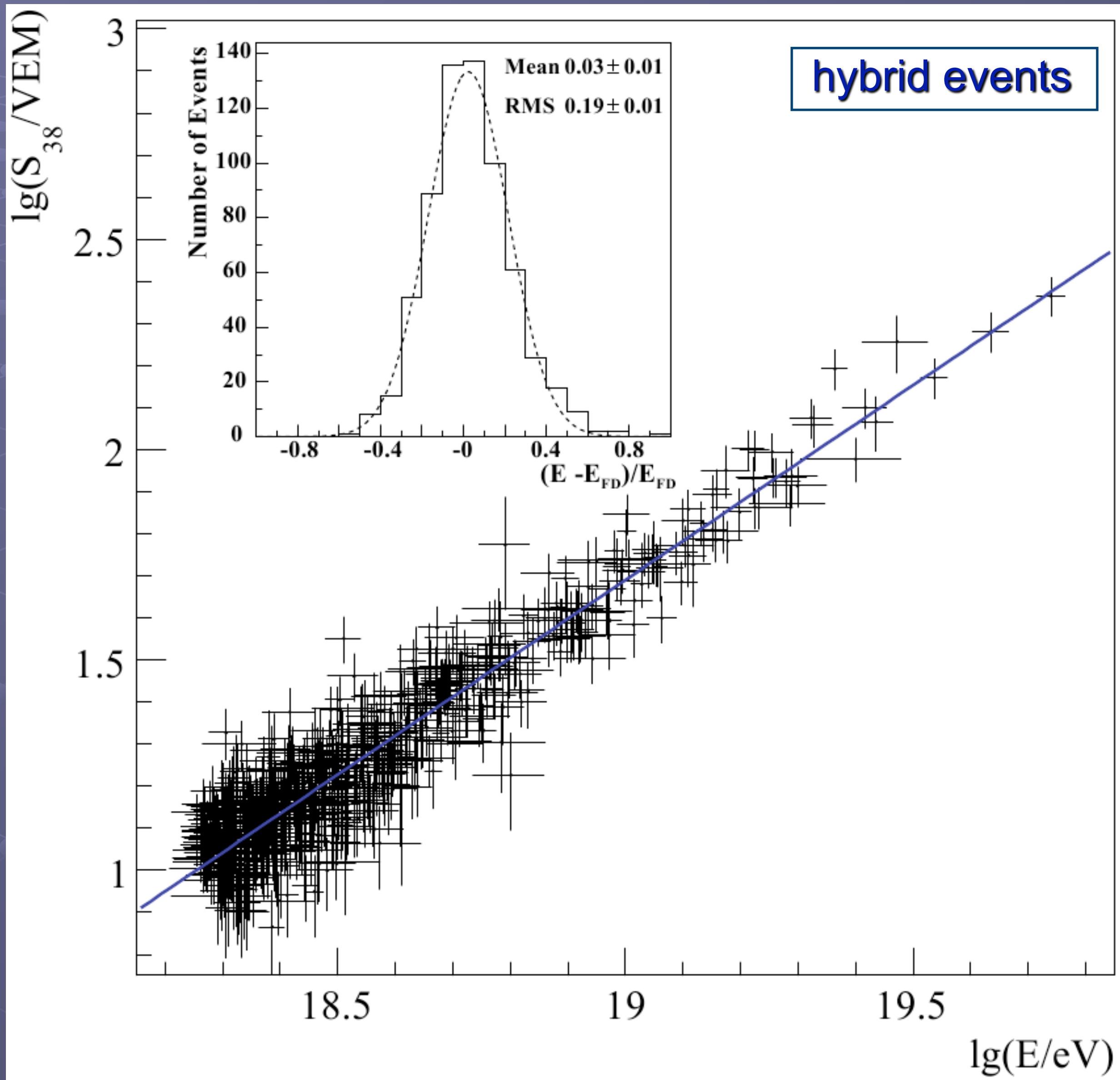
ENERGY DETERMINATION

The energy converter:

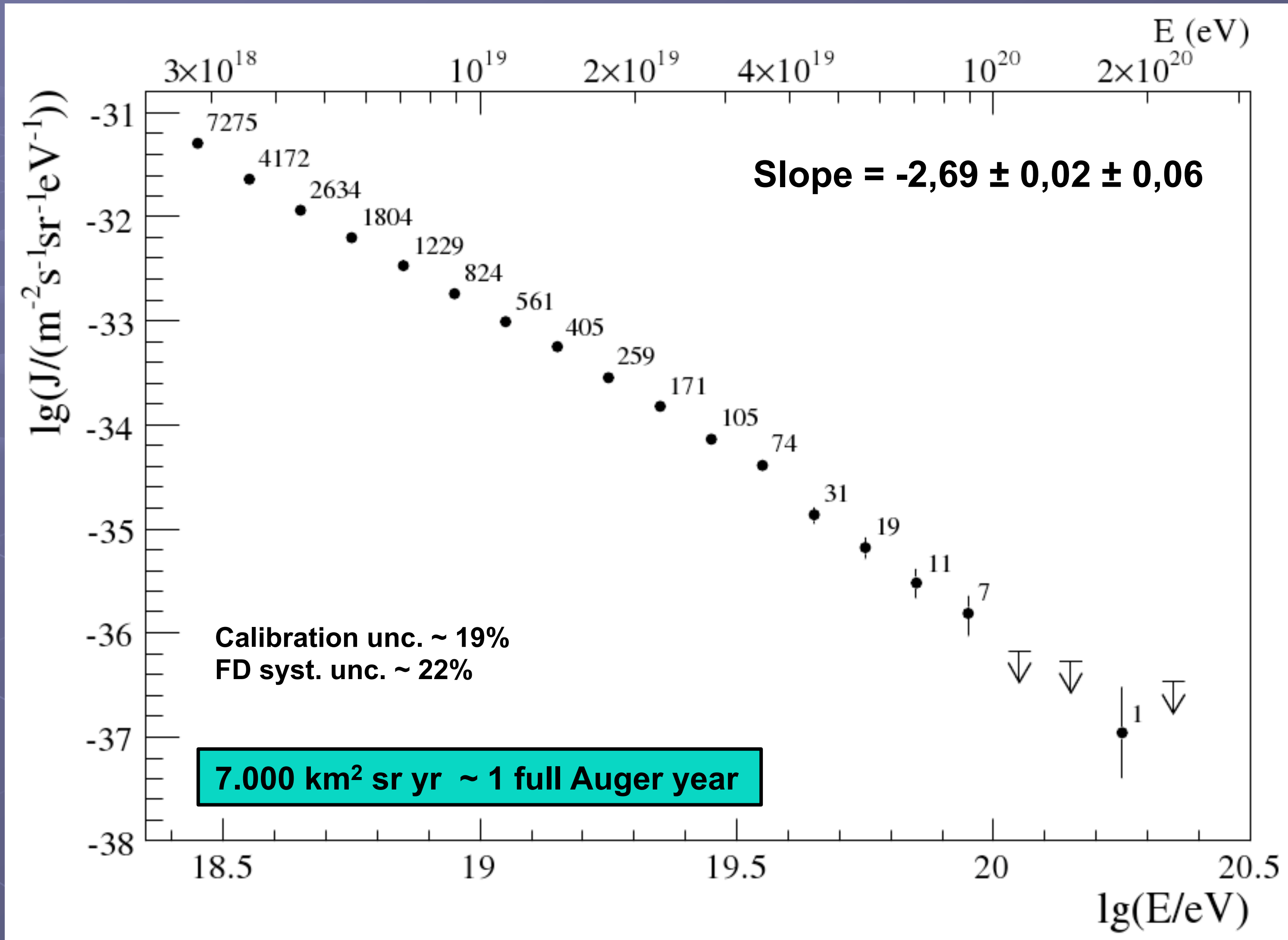
Compare ground parameter S_{38} with the fluorescence detector energy.

Transfer the energy converter to the surface array only events.

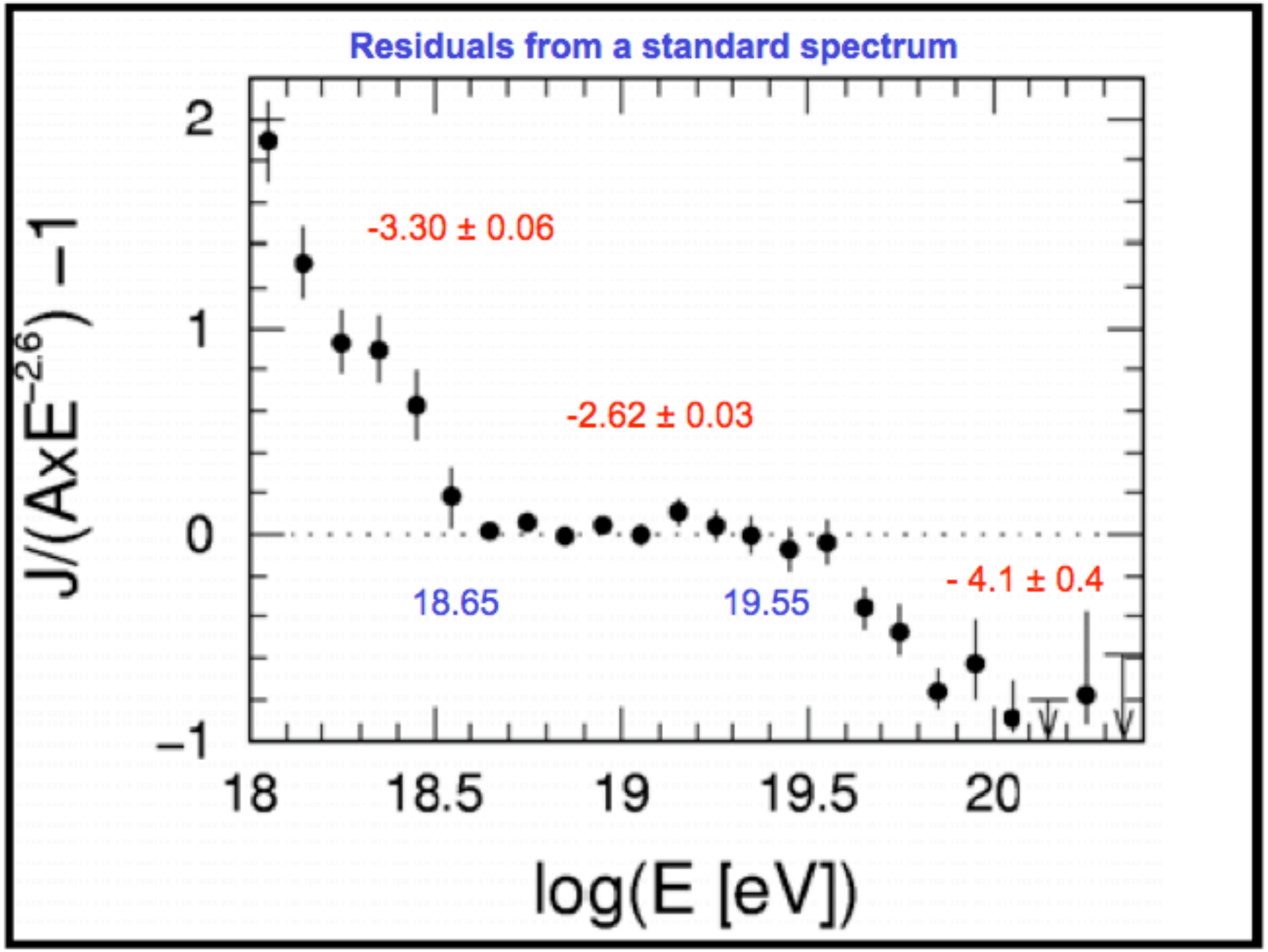
Simulation not needed.



SPECTRUM - SD < 60^0



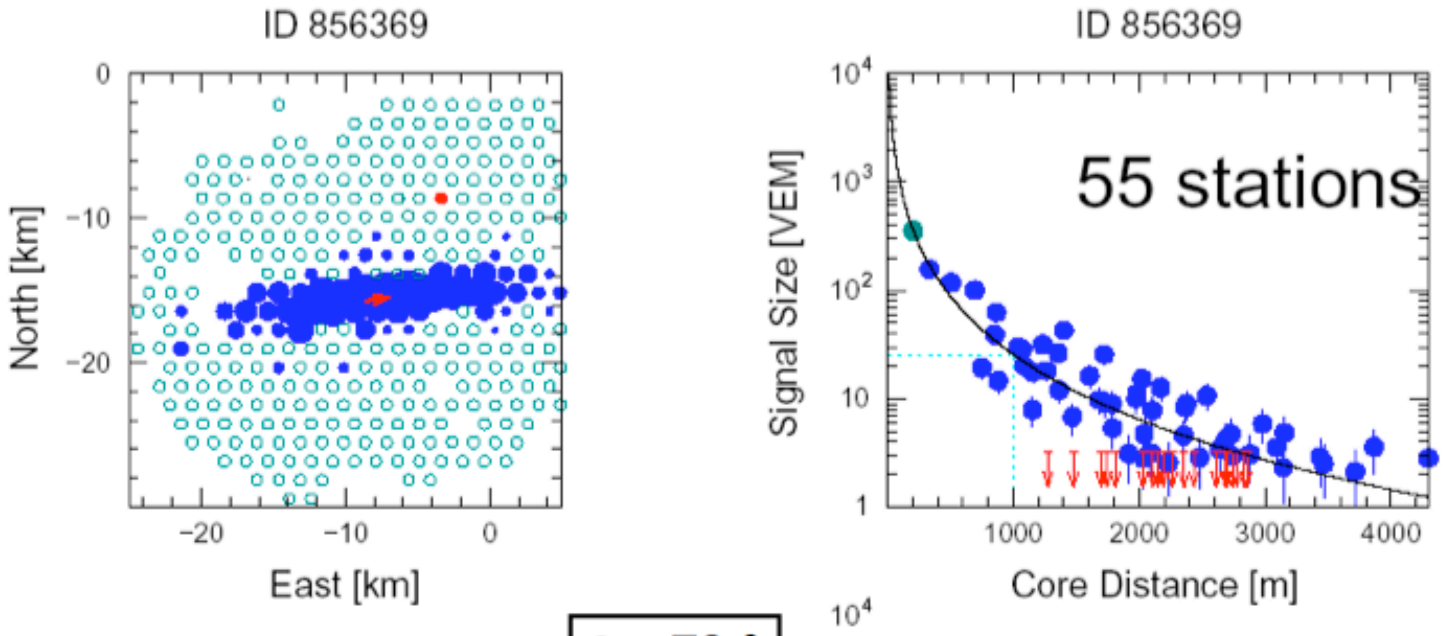
SPECTRUM



Subm. Phys. Rev. Lett.

INCLINED EVENT

Inclined Events offer additional aperture



$\theta = 79°$

ARRIVAL DIRECTIONS

Anisotropy search method

- Define a data set (adjusting minimum energy E)
- Define a tentative source catalog (adjusting catalog depth z)
- Count number of events k at less than angular distance ψ from a source (we call this a correlation)
- Calculate probability for such a number of correlations to occur by chance :

$$P(E,z,\psi) = \sum_{j=k}^{N(E)} \binom{N(E)}{j} p(z,\psi)^j (1-p(z,\psi))^{N(E)-j}$$

where P(E,z,ψ) is the cumulative binomial probability and p(z, ψ) is the probability for a random CR seen by Auger (exposure weighted) to fall within ψ^o of one of the sources in the catalog

- Look for the minimum of P(E,z,ψ) as a function of E, z and ψ.

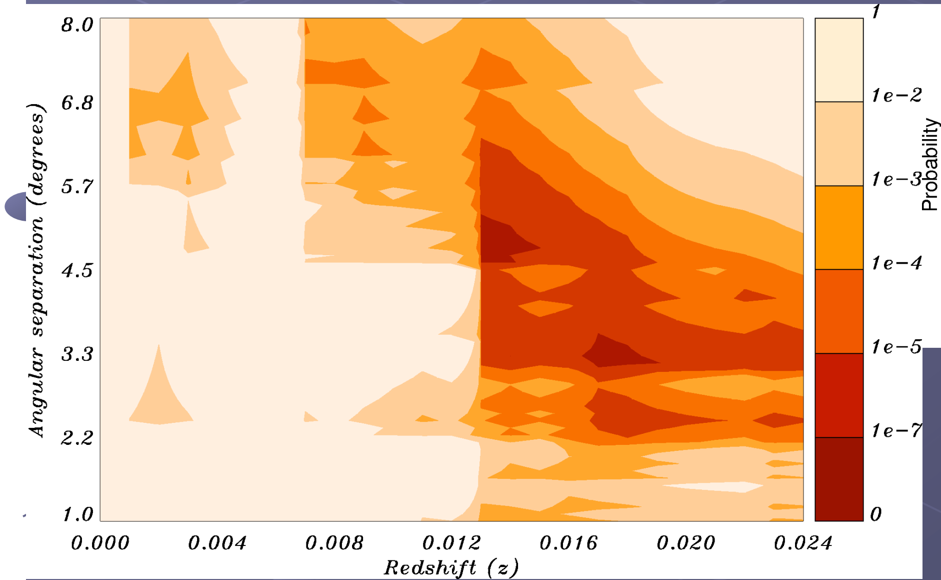
ARRIVAL DIRECTIONS

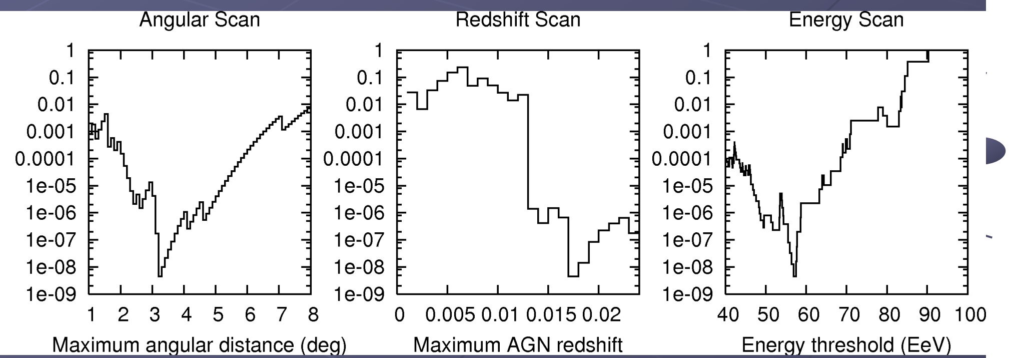
Full data set analysis (1.1.2004 – 31.8.2007)
81 events above 40 EeV

- Minimum :
  - E = 57 EeV
  - Z = 0.017
  - ψ = 3.2º

  20 out of the 27 events selected correlate, 5.6 expected. P = 5×10^{-9}
- After penalization P ~ 10^{-5} note that this is about:

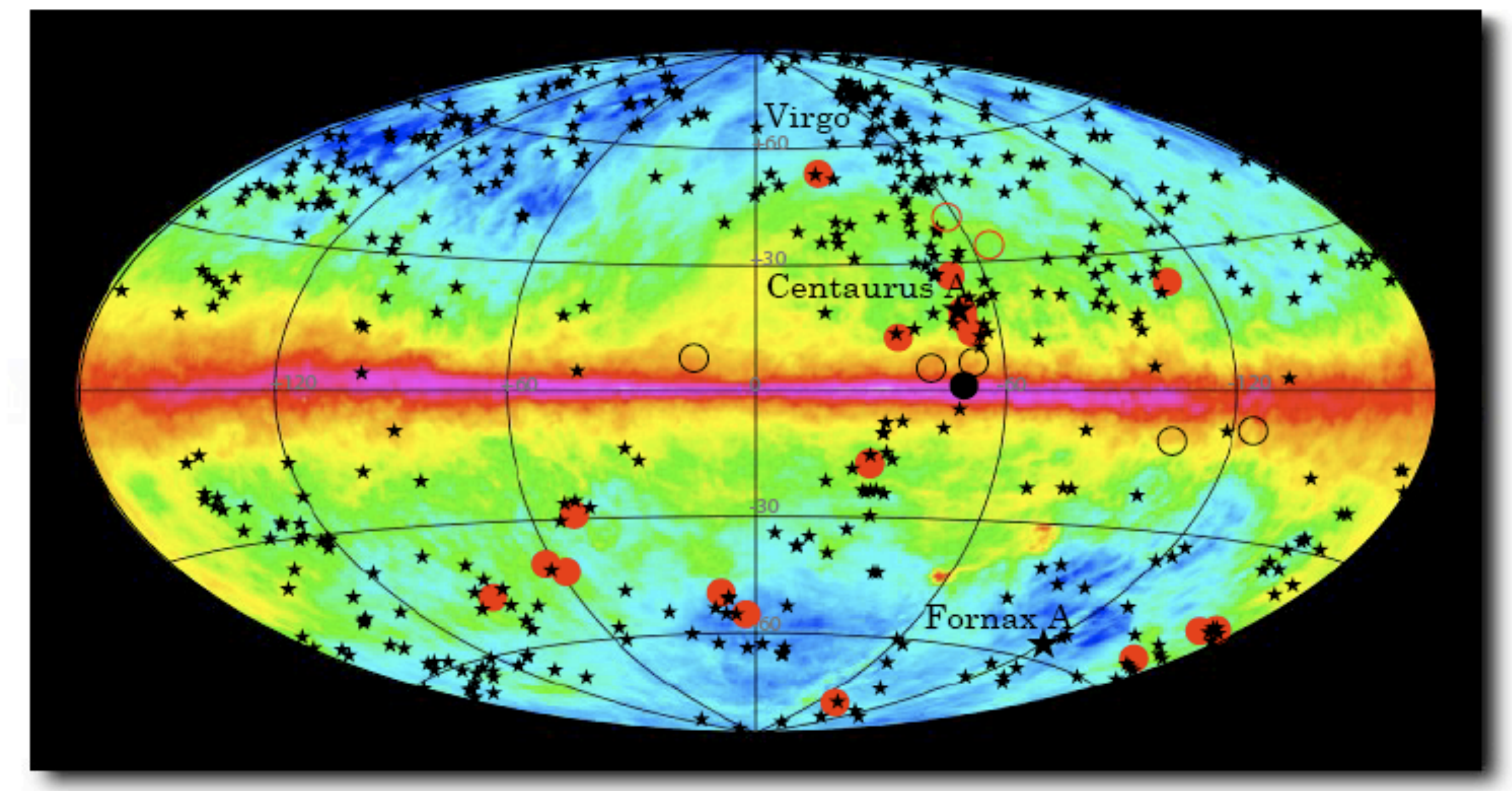
  10^{-3}(exploratory) x 10^{-2}(prescribed)





Similar minima in the region
E~60 EeV, z<=0.024, ψ <=6º

ARRIVAL DIRECTIONS



- The V-C catalog is likely to be incomplete near the Galactic plane also the Galactic magnetic field is stronger in the disk. Out of the 7 events out of the correlation, 5 are within 12º of the Galactic Plane.
- Cutting on the Galactic Plane (|b|<12º) the minimum reads :

  $P = 2 \times 10^{-10}$ at E=57 EeV, z=0.017 and ψ =3.2º,

  with 19 of of 21 events in correlation where 5 are expected

Short article published in Science **318** (2007) 938-943.

Long article published in Astroparticle physic 29 (2008) 188-204.

ARRIVAL DIRECTIONS

Acceleration sites

- Can we say something about the sources?
  - They are not in the Milky Way
  - They are likely bottom up (astrophysical)
  - AGN are plausible acceleration sites
- More data are needed to identify the sources and their characteristics

CONCLUSIONS

It is just the beginning….

- Anisotropy of UHECR has been established at > 99% CL for the parameters E~60 EeV, D~100 Mpc, ψ~4°
- Nature of the correlation and spectrum provides evidences for the 'GZK' effect and the hypothesis that the CR are dominantly protons from AGN within our 'GZK' horizon
- Sources could be other than AGN as long as they have similar spatial distributions
- Increased statistics (+Auger North) will allow source identification as well as measurements of MF along the line of sight and maybe some surprises….
- Recent results call for a much larger Auger North aperture (~ 20.000 km^2) – design and proposal in preparation !