Observations of Ultra-High Energy Cosmic Rays

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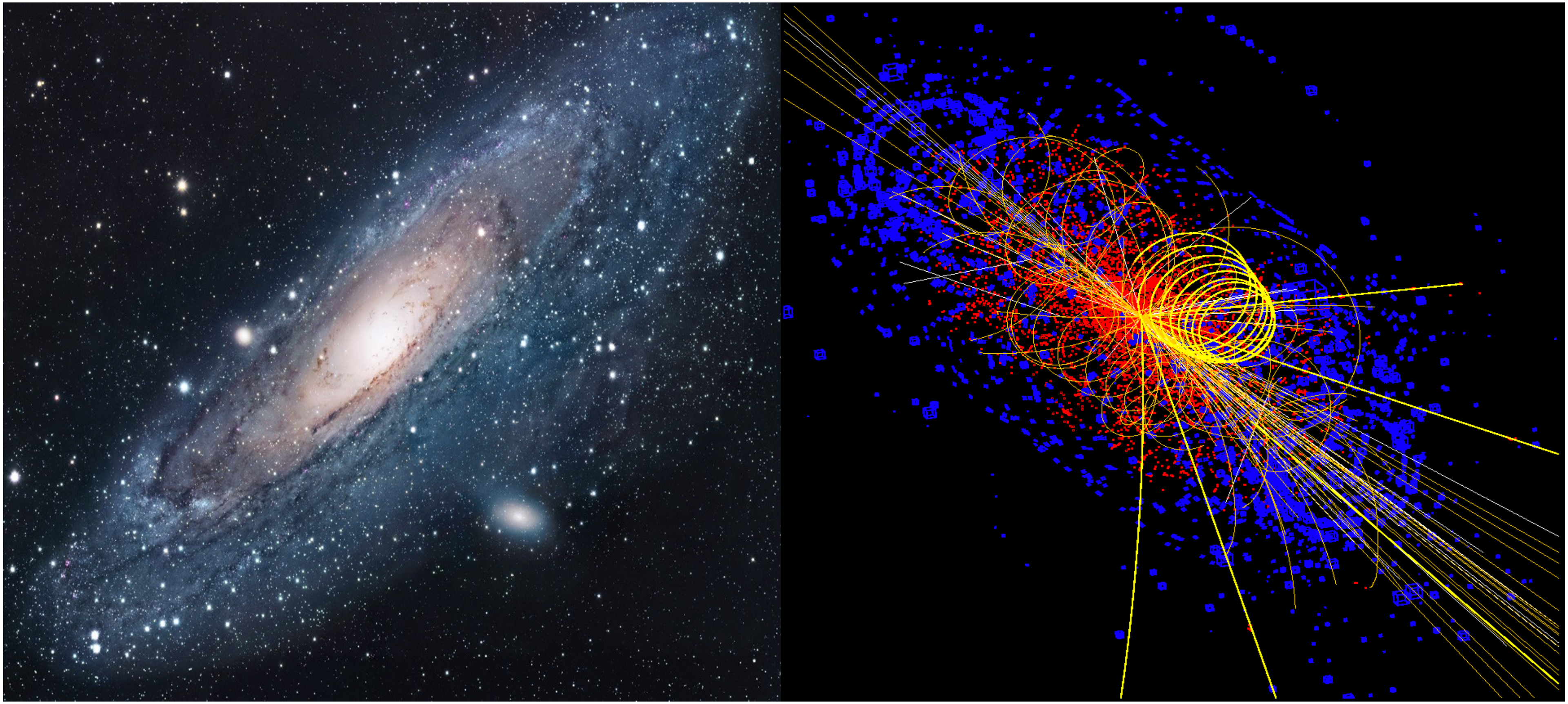
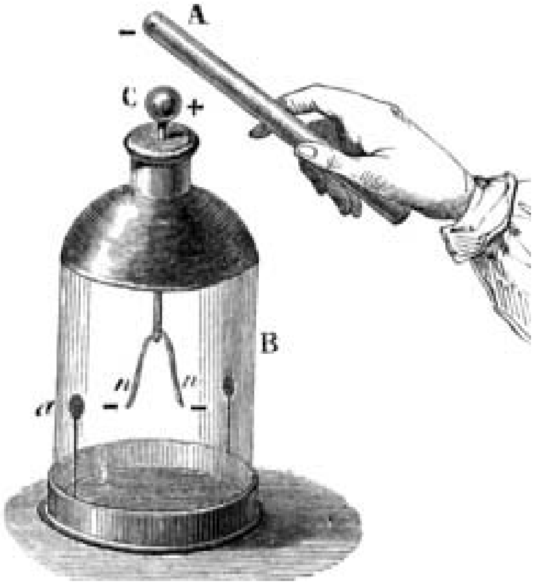
Astroparticle Physics

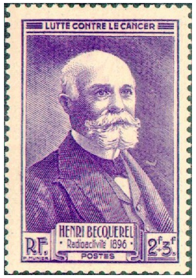


History of Cosmic Rays

- Searching for source of *air ionization*
- Air in electroscopes (detectors of electric charges) became electrically charged (ionized), even if they were shielded



- Radioactivity from Earth's crust (discovered by H. Becquerel in 1896)

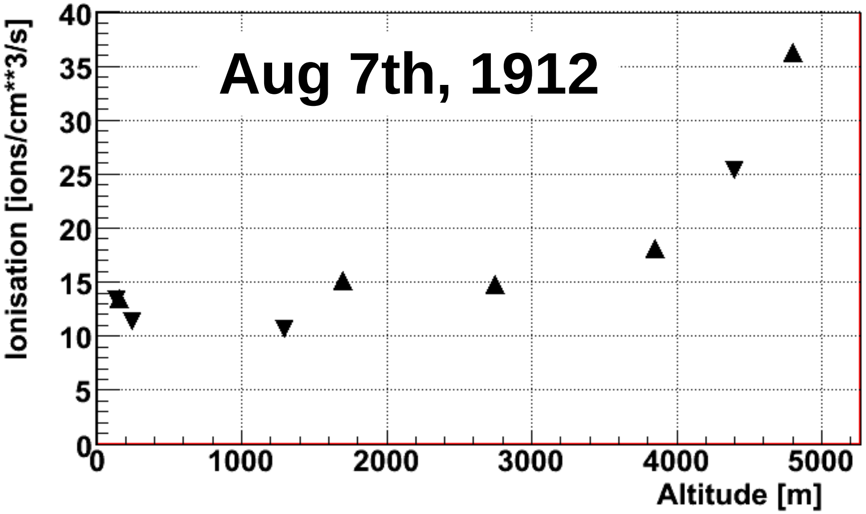


- But too low attenuation of intensity with height (1909 T. Wulf on Eiffel Tower)

Victor F. Hess

- Balloon flights

- Steep increase of radiation with altitude



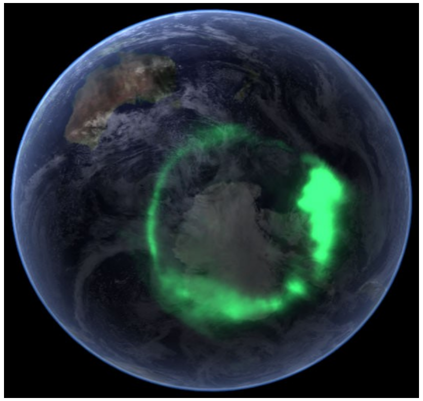
- Sun could not be the main source (flights at night, during solar eclipse)
- Radiation comes from *outer space*

End of Speculations

- Hess's theory about rays from outer space did not receive general acceptance
- Research after 1st WW supported it
- Finally Robert A. Millikan (1925) measured radiation tens meters deep in water

- 10 m of water
= 1 atmosphere
- *Cosmic radiation*

Charged Particles



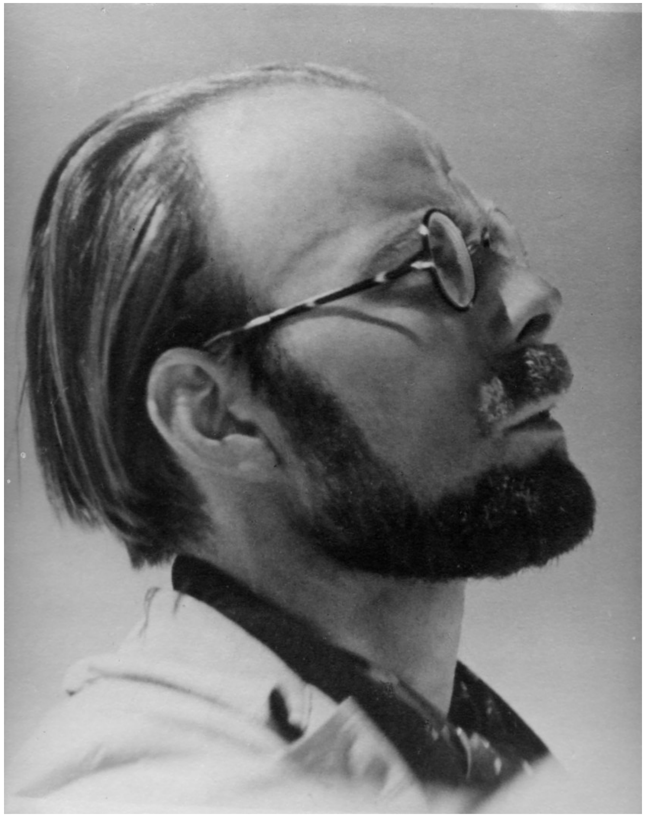
- Carl Störmer (1930) calculated trajectory of charged particles in geomagnetic field (aurora)

- Arthur H. Compton (1933): latitude dependence of CR intensity (increase towards magnetic poles)

- Asymmetry in longitude: more CR arrive from west (i. e. positively charged)

- *Do not point towards their sources !*

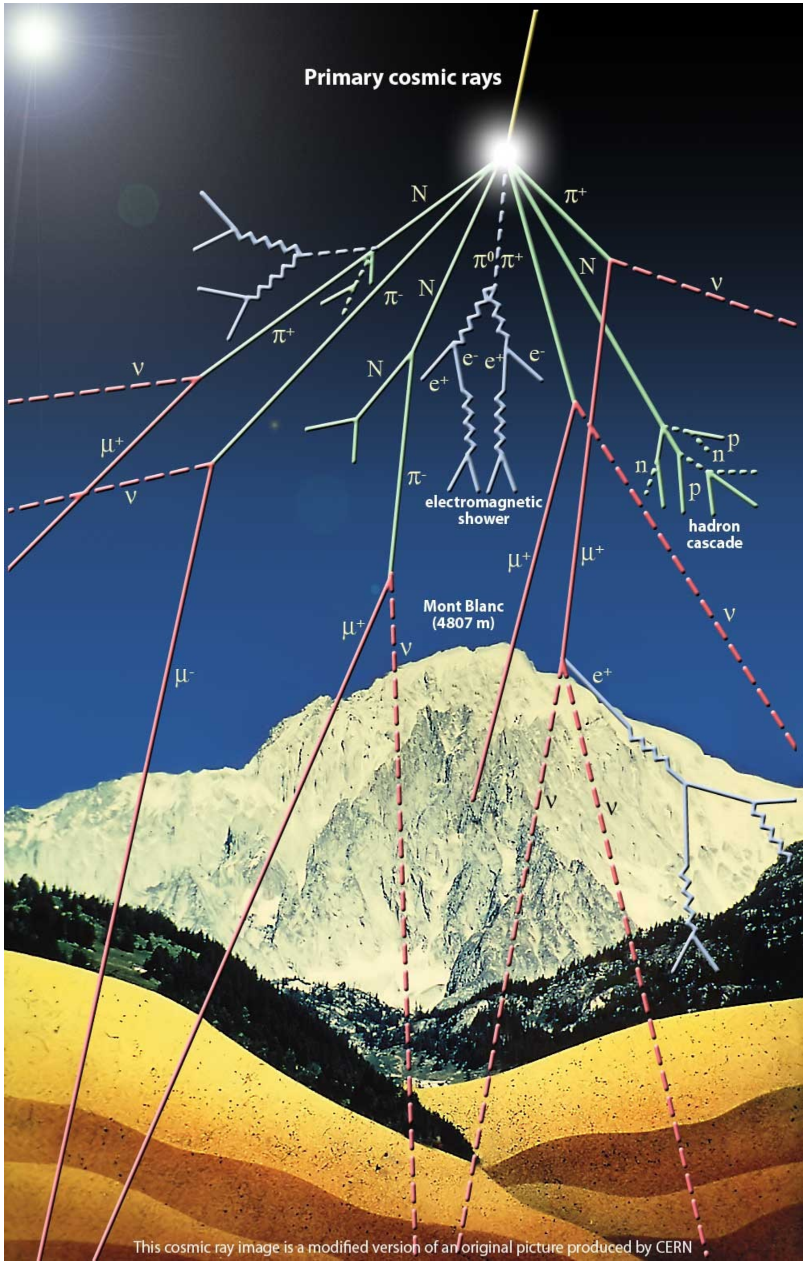
Pierre V. Auger



- 1938-39
- Coincidence detection at very large distances (hundreds of meters)
- Millions of particles arrive at same time

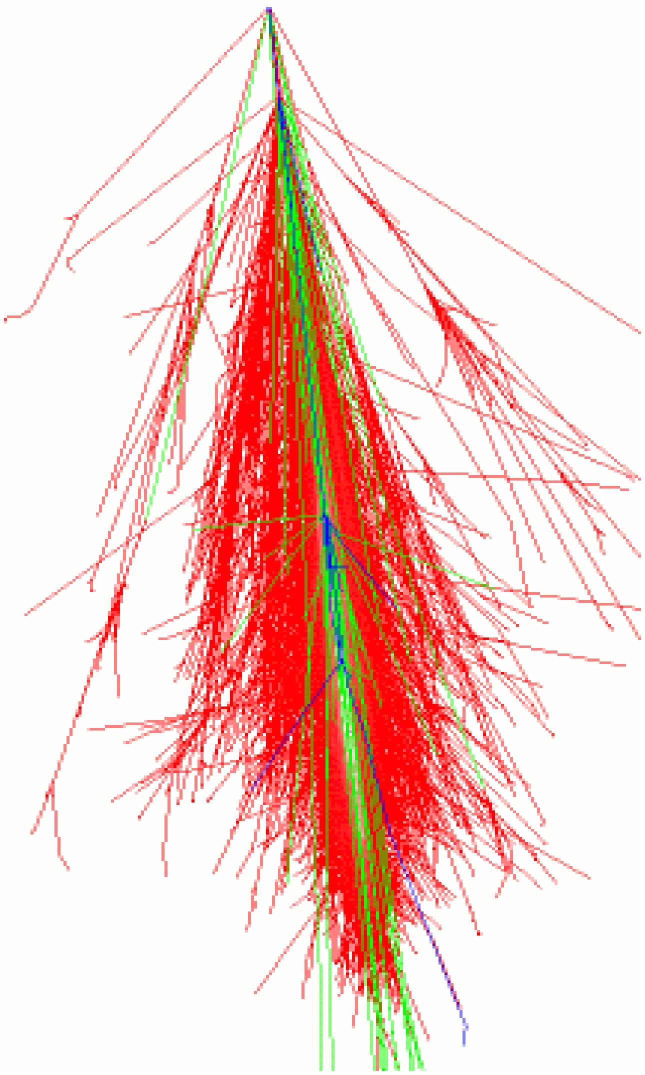
- Extensive air shower causes primary particle with energy of millions GeV!
  (For comparison accelerators ~ 10 MeV)

Extensive Air Showers



- Very energetic primary particle
- 1st interaction at height 10-30 km
- Subsequent collisions with air molecules
- Fast developing shower of relativistic secondary particles

Secondary Particles

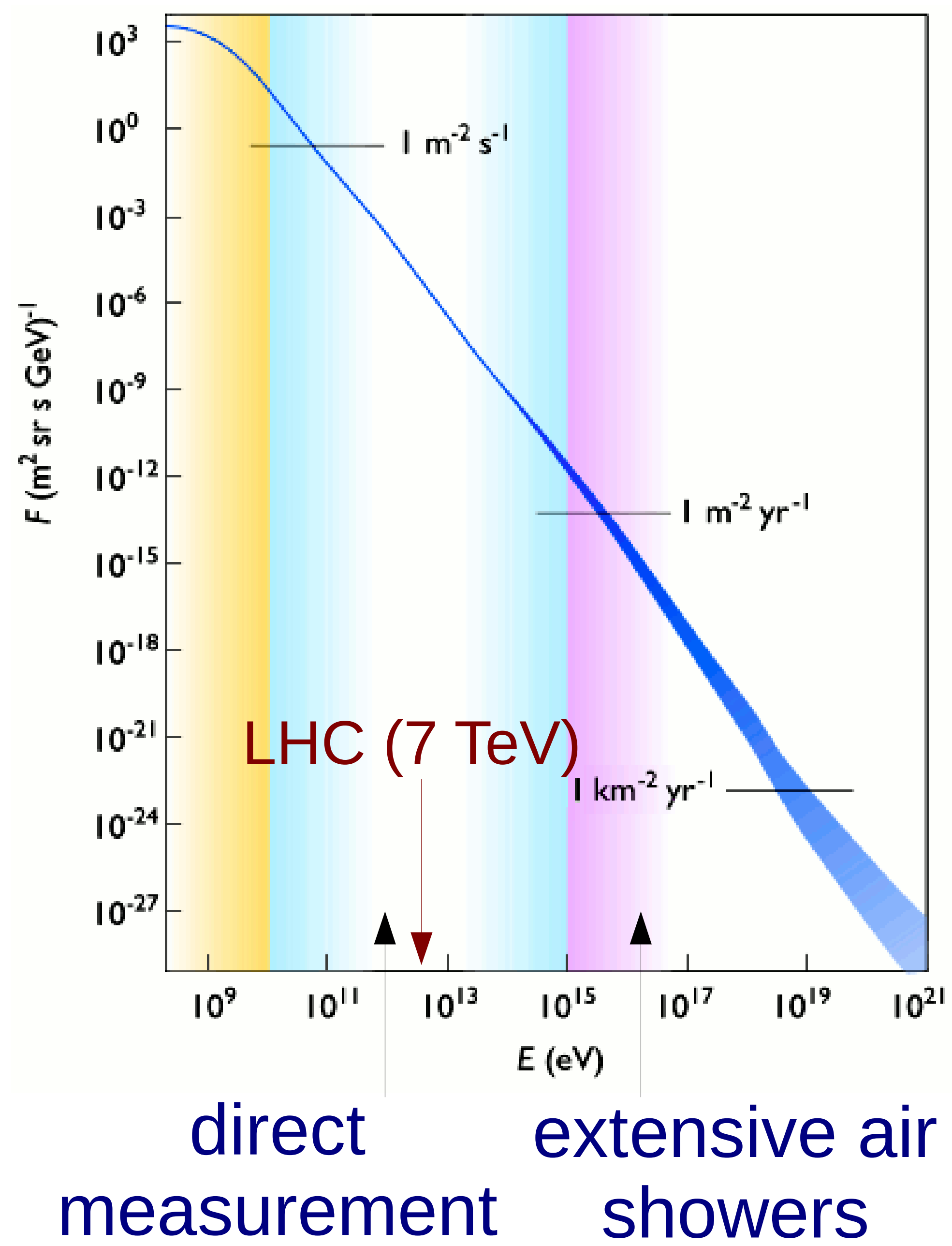


1) Electromagnetic component (red): electrons, positrons, γ

2) Hadronic core (blue): protons, neutrons, pions,...

3) Highly penetrating muons (green) and atmospheric neutrinos

Cosmic Ray Spectra



- For primary particles
- Modulation by Sun (E < 10 GeV)
- Power law shape $(dN / dE) \sim E^{-\alpha}$
- Steeply falling
- Over many ranges of energy ($\alpha \sim 3$)
- End of spectra?

Observation Techniques

1) Direct (primary particle)

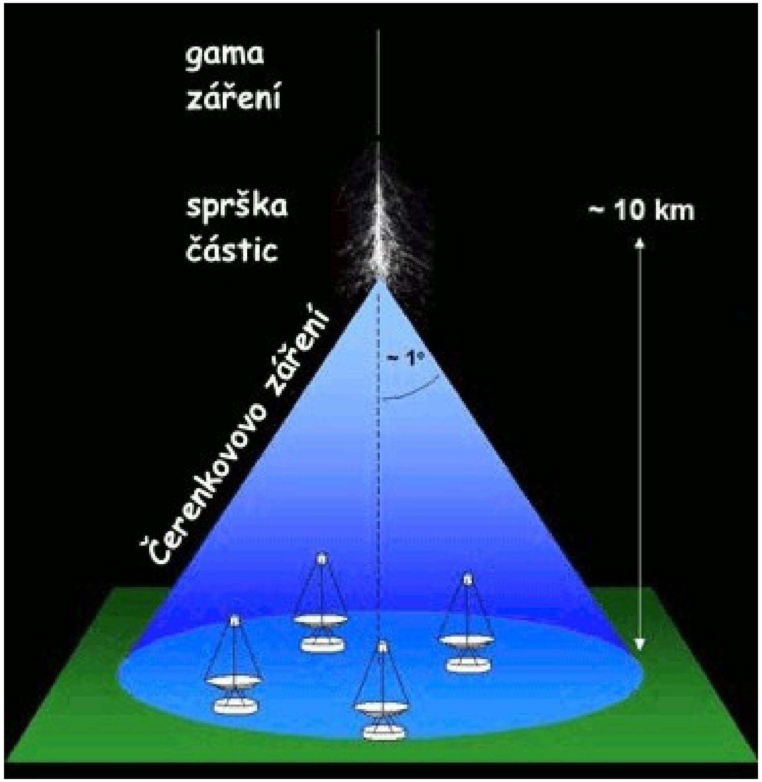
- only well above troposphere
- detector area limitations
- satellites, stratospheric balloons
- very precise: isotopes, antimatter

2) Indirect (air showers)

- atmosphere is part of detector
- Čerenkov radiation ($v > c_{air}$)
- fluorescence light (deexcitation N_2)
- secondary particles at/below ground

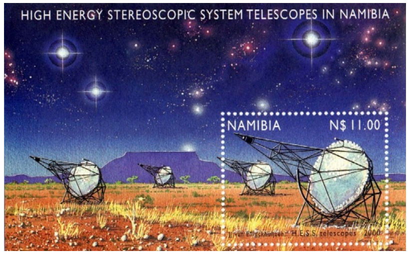
Čerenkov Telescopes

- Electromagnetic showers initiated by γ particles
- Only 1 from 1000 is γ

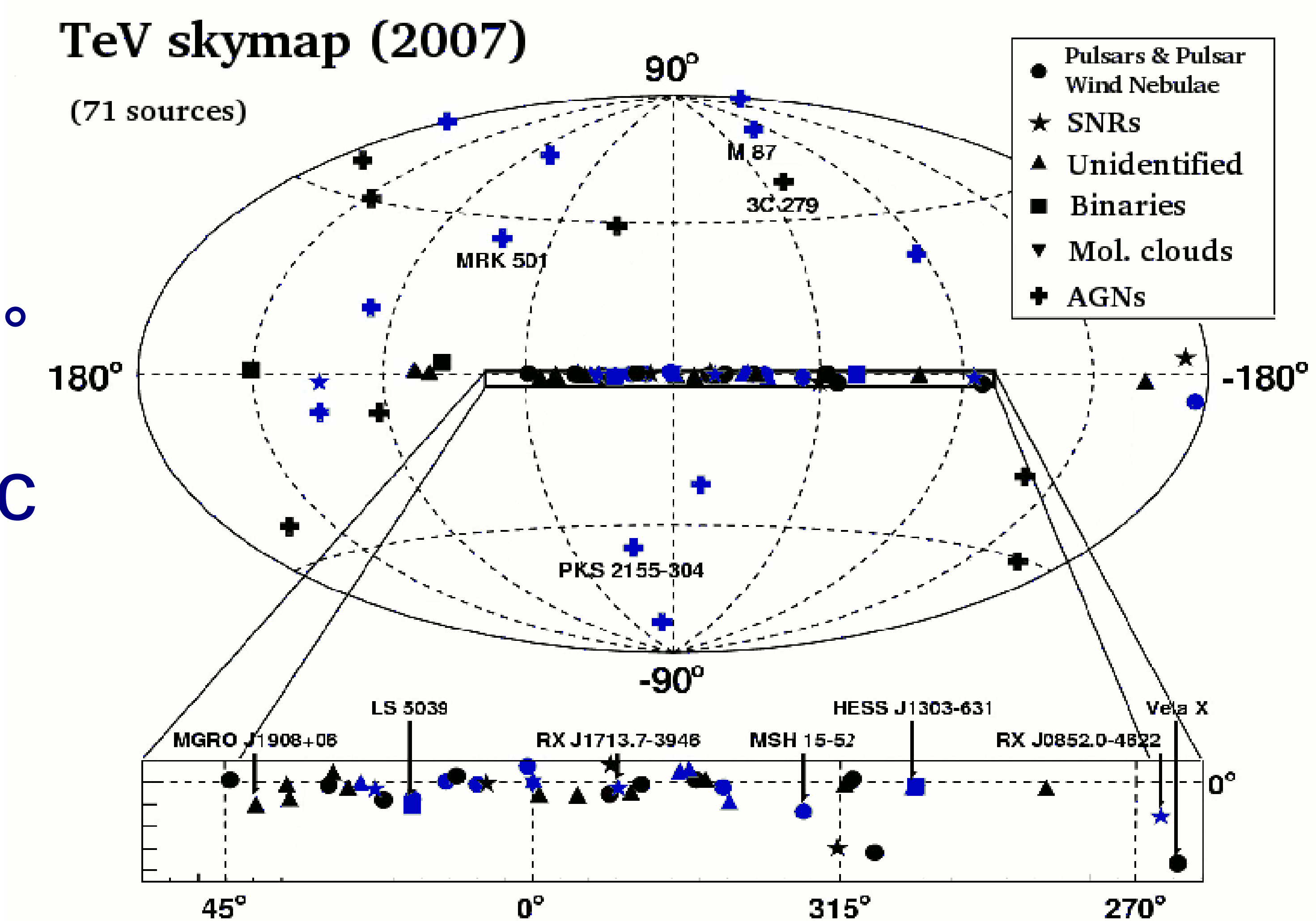


- 3rd generation (HESS, Magic, Whipple,...)

TeV Astronomy

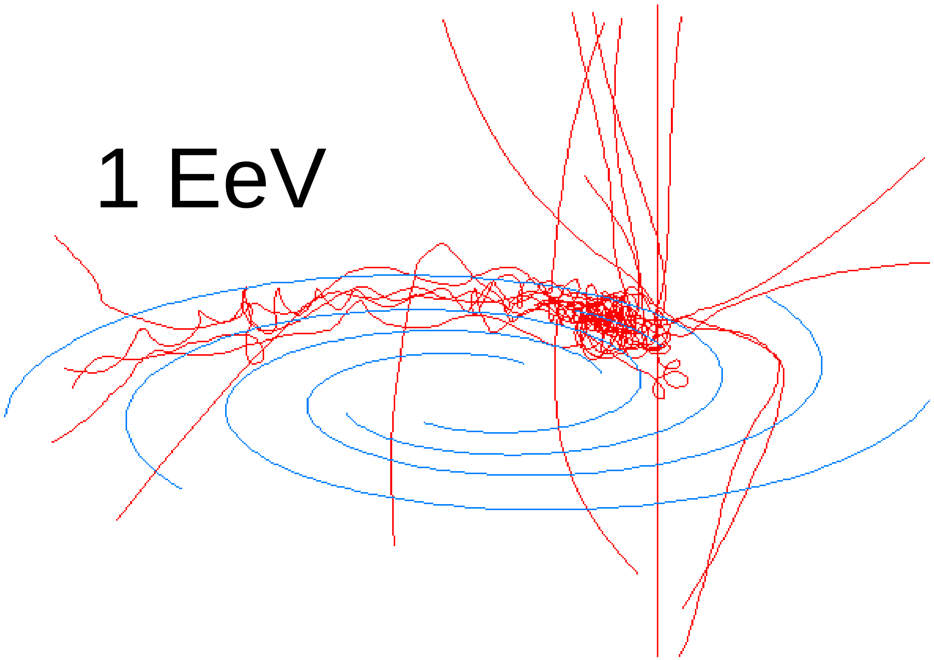


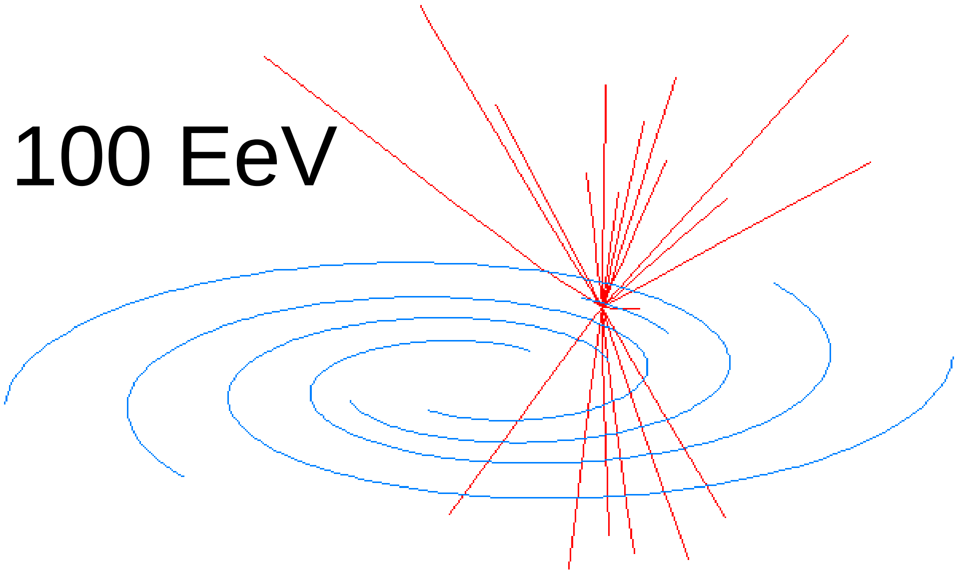
- Neutral γ points back to sources
- Angular resolution ~ 0.1°
- FOV 3°- 5°
- 51 galactic sources



Motion of Charged Particles

- Mainly protons and nuclei
- Galactic and extragalactic magnetic fields
- Curved trajectories
- ***Astroparticle astronomy*** > 50 EeV





John Linsley (1963)

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

Analysis of a cosmic-ray air shower recorded at the MIT Volcano Ranch station in February 1962 indicates that the total number of particles in the shower (Serial No. 2-4834) was 5×10^{10}. The total energy of the primary particle which produced the shower was 1.0×10^{20} eV. The shower was about twice the size of the largest we had reported previously (No. 1-15832, recorded in March 1961).[1]

The existence of cosmic-ray particles having such a great energy is of importance to astrophysics because such particles (believed to be atomic nuclei) have very great magnetic rigidity. It is believed that the region in which such a particle originates must be large enough and possess a strong enough magnetic field so that $RH \gg (1/300) \times (E/Z)$, where R is the radius of the region (cm) and H is the intensity of the magnetic field (gauss). E is the total energy of the particle (eV) and Z is its charge. Recent evidence favors the choice $Z=1$ (proton primaries) for the region of highest cosmic-ray energies.[2] For the present event one obtains the condition $RH \gg 3\times10^{17}$. This condition is not satisfied by our galaxy (for which $RH \approx 5\times10^{17}$, halo included) or known objects within it, such as supernovae.

The technique we use has been described elsewhere.[1] An array of scintillation detectors is used to find the direction (from pulse times) and size (from pulse amplitudes) of shower events which satisfy a triggering requirement. In the present case, the direction of the shower was nearly vertical (zenith angle $10\pm5°$). The values of shower density registered at the various points of the array are shown in Fig. 1. It can be verified by close inspection of the figure that the core of the shower must have struck near the point marked "A," assuming only (1) that shower particles are distributed symmetrically about an axis (the "core"), and (2) that the density of particles decreases monotonically with increasing distance from the axis. The observed densities

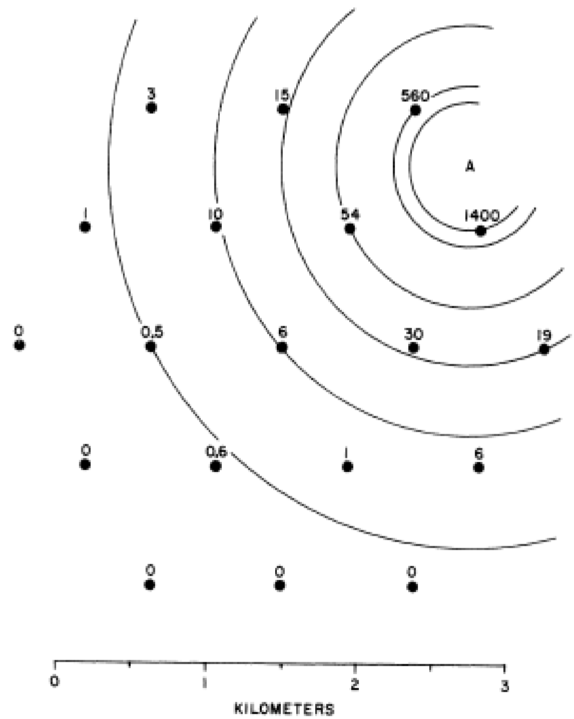
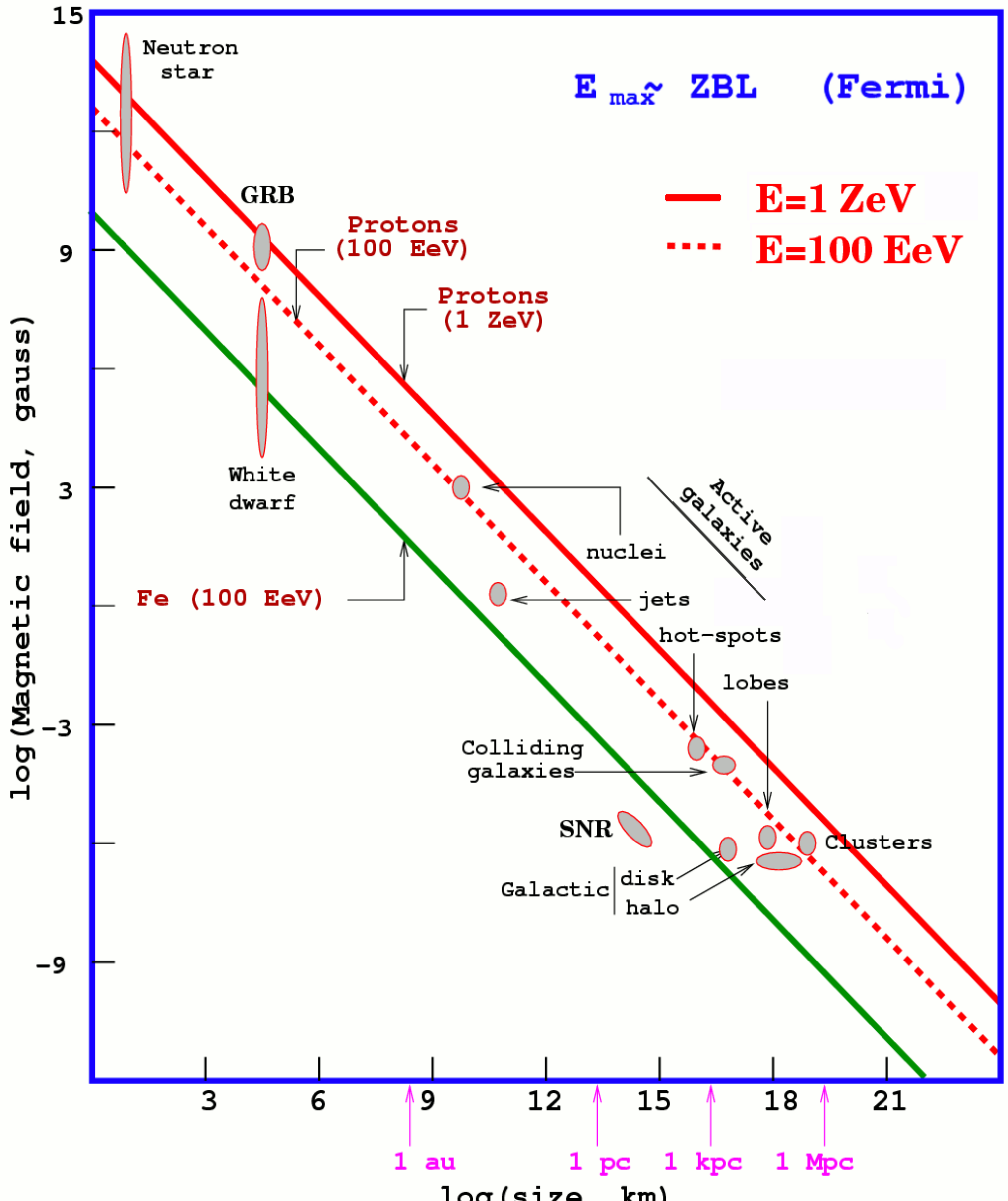


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m^2 scintillation detectors. The numbers near the circles are the shower densities (particles/m^2) registered in this event, No. 2-4834. Point "A" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

Sites of Origin

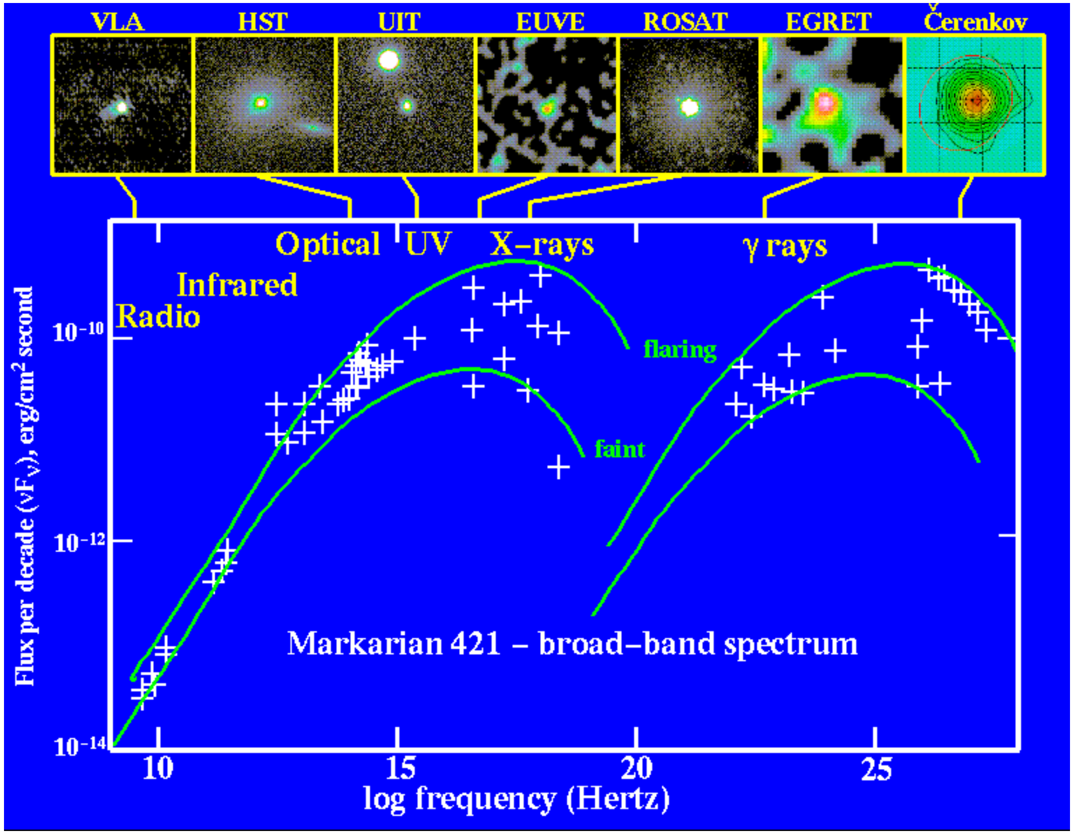
- Gyroradius < size
- Very few objects
- Compact or extended objects
- Acceleration up to 100 EeV is difficult
- Energy losses must be included (non-thermal radiation)



A. M. Hillas (1984)

Non-thermal Radiation

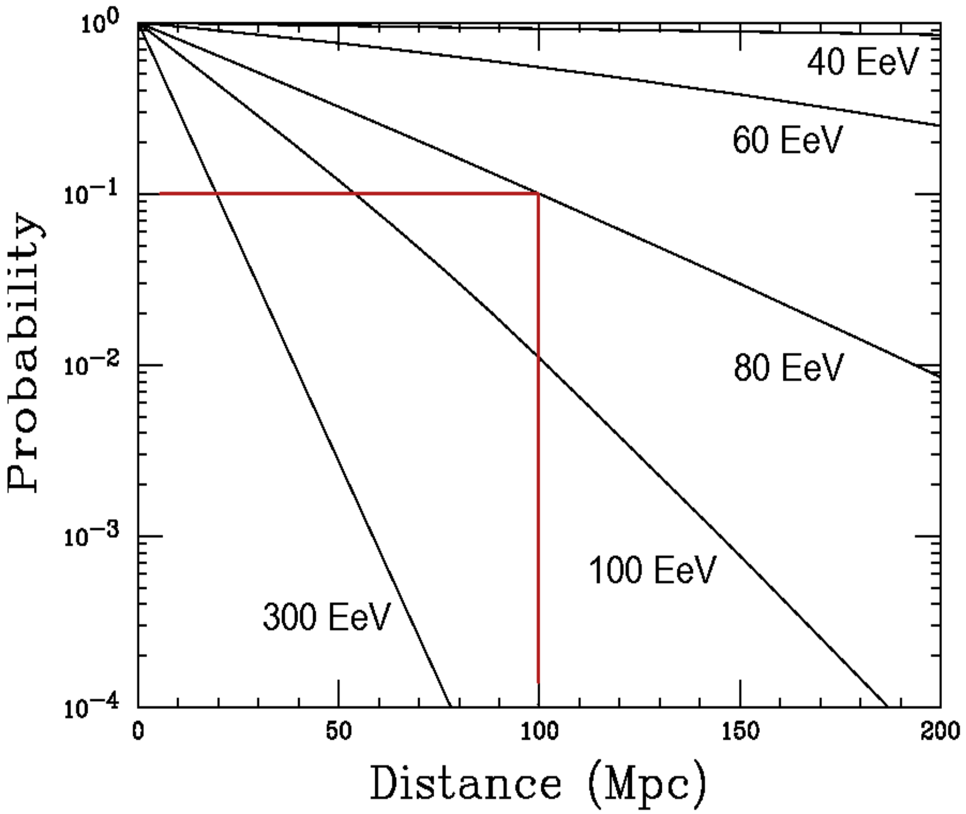
- Does not follow Planck's law
- Radiation losses (bremsstrahlung, synchrotron, inverse Compton)



- Interactions with ambient matter and pair creation (γ rays are produced)
- *Multiwavelength observation is important*

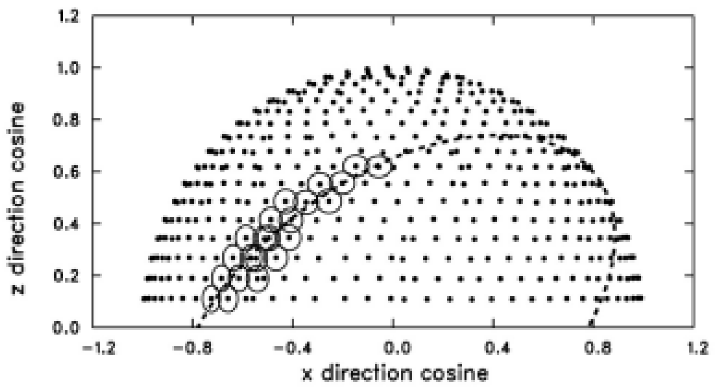
GZK Cutoff

- Cosmic Microwave Background (1965)
- Greisen, Zatsepin & Kuzmin (1966)
- Energy losses due to interaction with CMB (2.7 K)

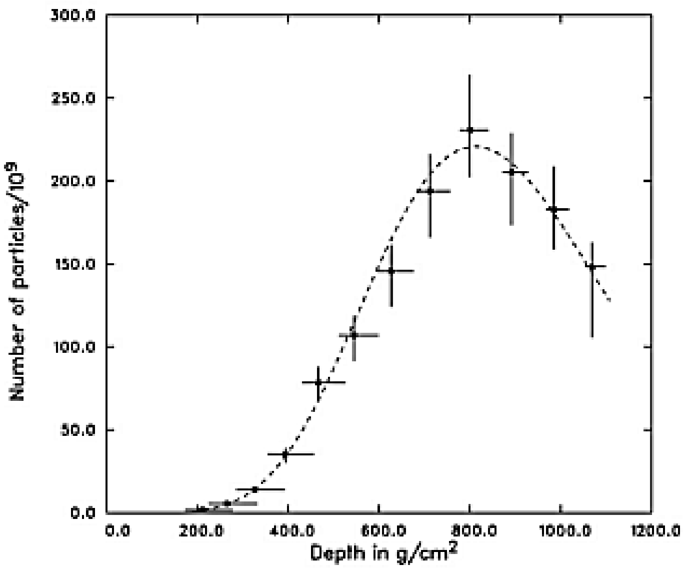


- *Significant for energies above 40 EeV*
- Distance to sources less than 100 Mpc

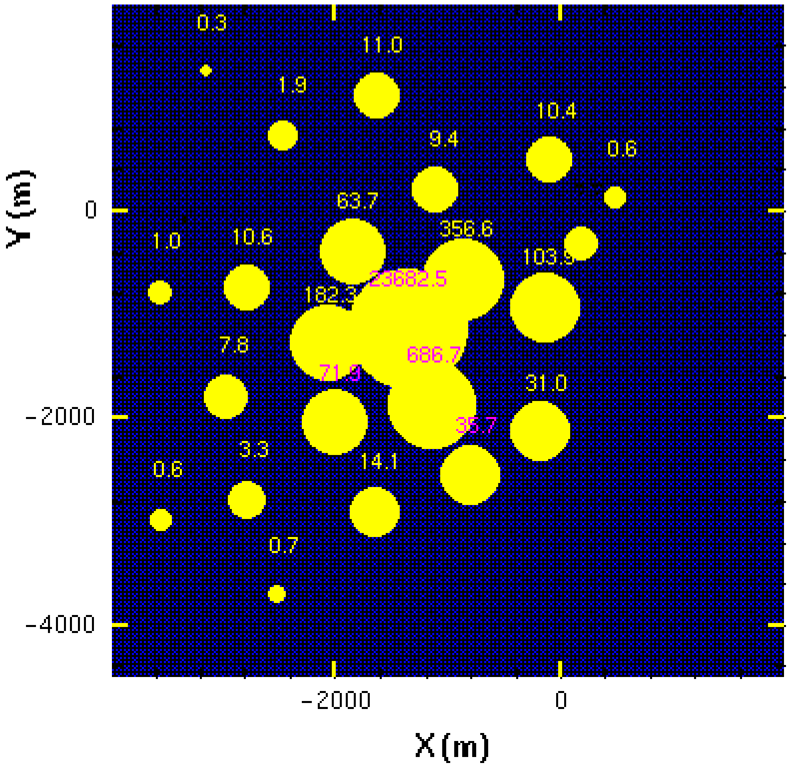
Highest Energies



Fly's Eye
(Oct 15th 1991)
320 EeV (8 x GZK)



AGASA
(Dec 3rd 1993)
213 EeV



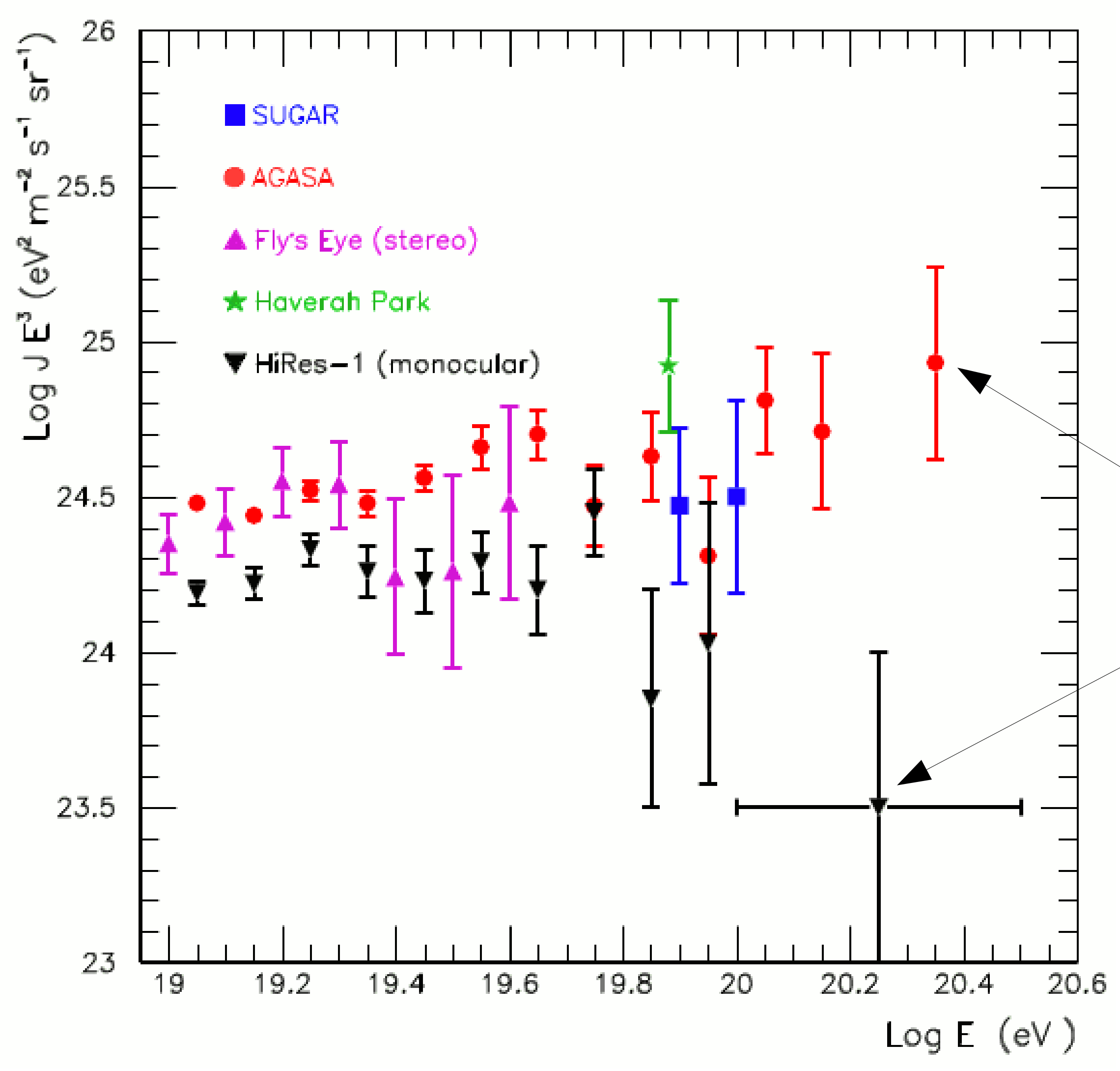
20th Century Experiments

Table 1.1: Sites of UHECR detectors operated in 20th century and approximate event numbers.

Experiment	Operation	Latitude	Longitude	Altitude [m]	Depth [g/cm^2]	Area [km^2]	Detection	# Events > 10 (> 50) EeV
Volcano Ranch	1959-63	35.1° N	106.8° W	1770	834	8	SC	44 (5)
SUGAR	1968-79	30.5° S	149.6° E	250	1015	60	SC	423 (47)
Haverah Park	1968-87	54.0° N	1.6° W	200	1016	12	WČ	106 (10)
Yakutsk	1974-	61.7° N	129.4° E	105	1020	18/10	SC/AČ	171 (6)
Fly's Eye	1981-93	40.3° N	112.8° W	1597	860		F	?
AGASA	1990-2004	35.8° N	138.5° E	900	920	100	SC	886 (46)
HiRes I	1997-2006	40.2° N	112.8° W	1597	860		F	561 (31)
HiRes II	1999-2006			1553			F	179 (12)
HiRes stereo							F	270 (11)

- Problems with energy reconstruction
- Low statistic for anisotropy studies
- Disagreements between their results

Discrepancy in Spectra



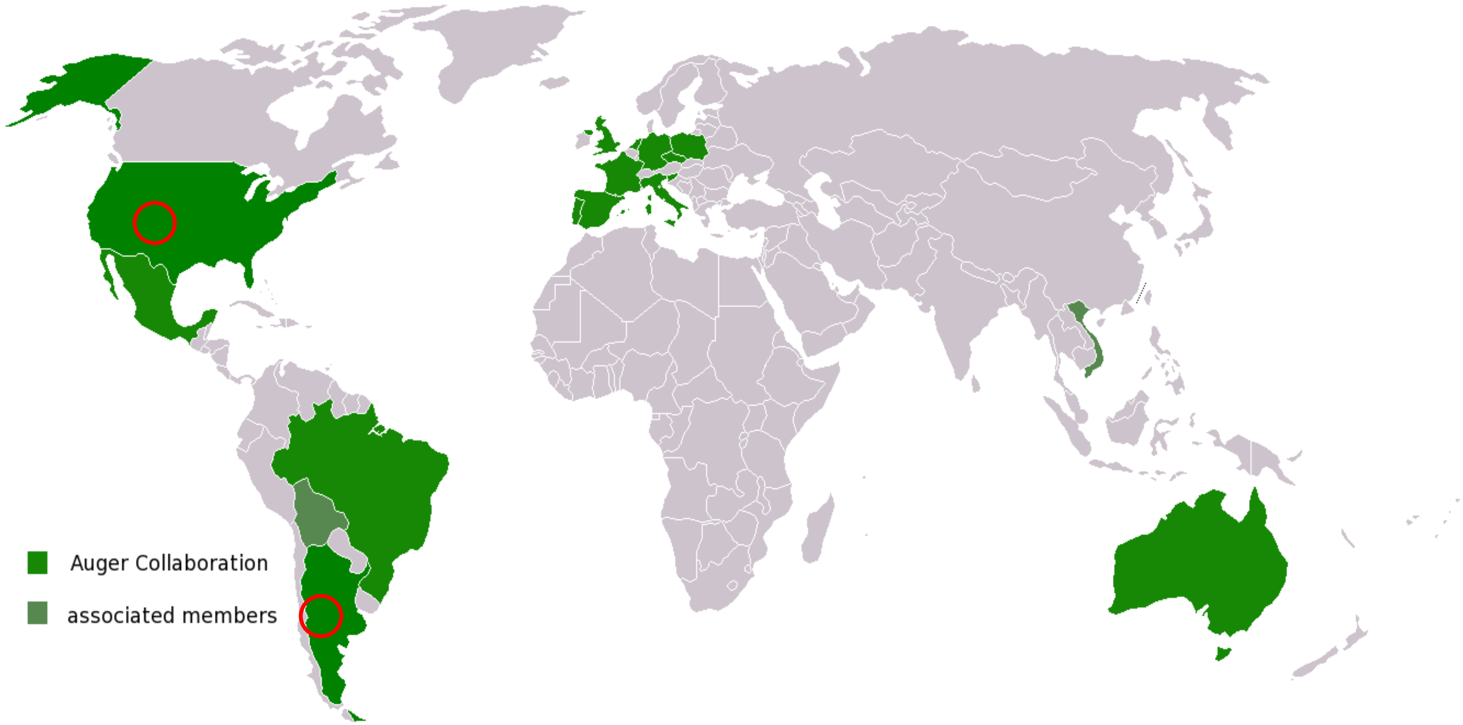
Is there any cutoff?

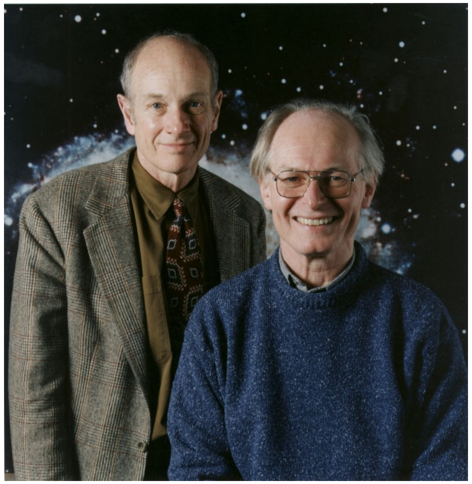
Exotic sources, violation of Lorentz invariance?

Motivations for Observatory

- Existence of GZK cutoff
- Anisotropy (small-, large-scale)
- Signal from Galactic center
- Correlations with extragalactic objects
- CR composition
- Fraction of photons and neutrinos

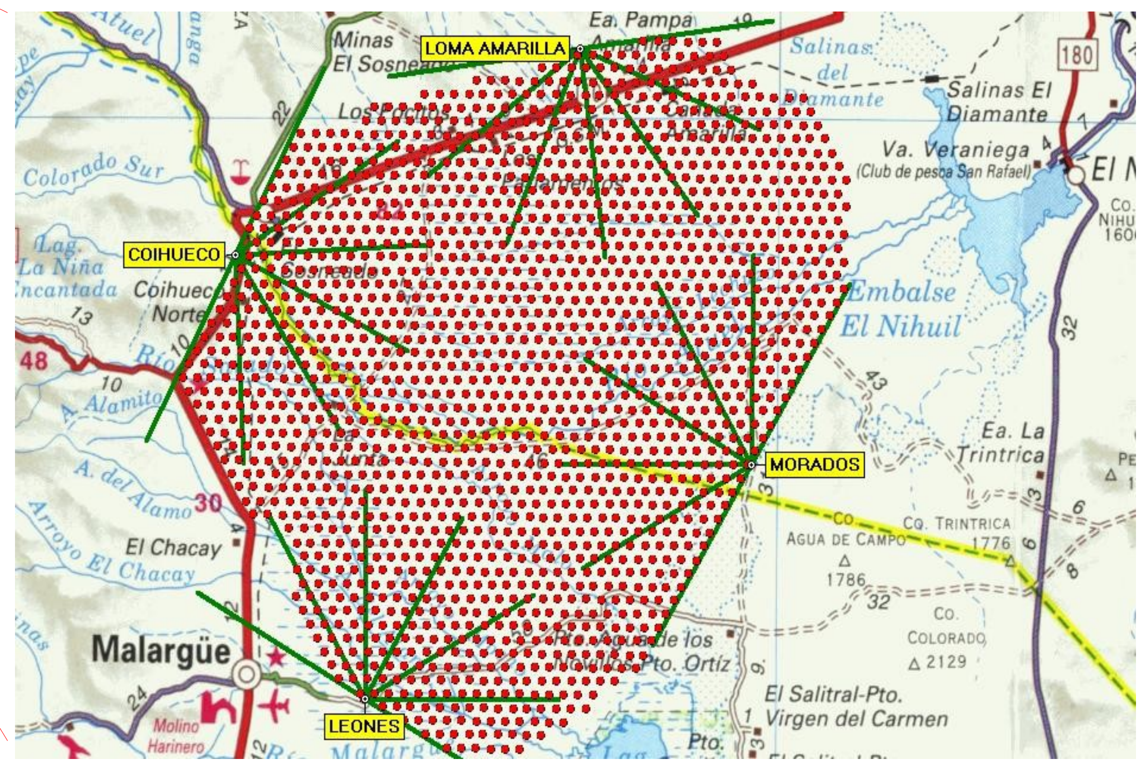
Pierre AUGER Observatory





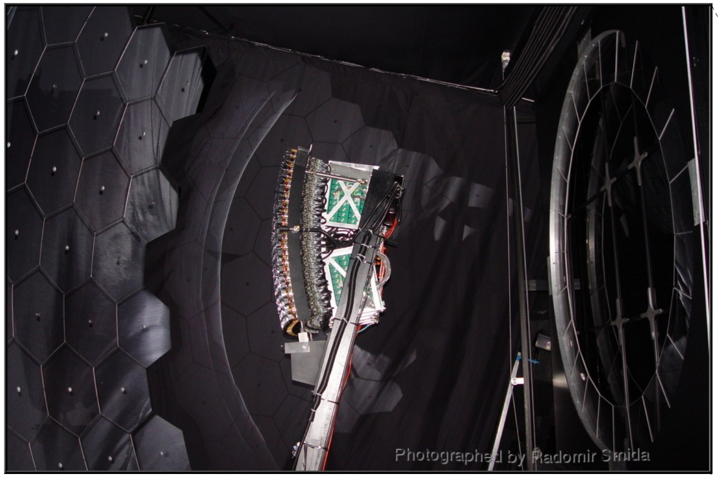
Southern Site

- western Argentina
- 3000 km^2
- 1400 m a.s.l.



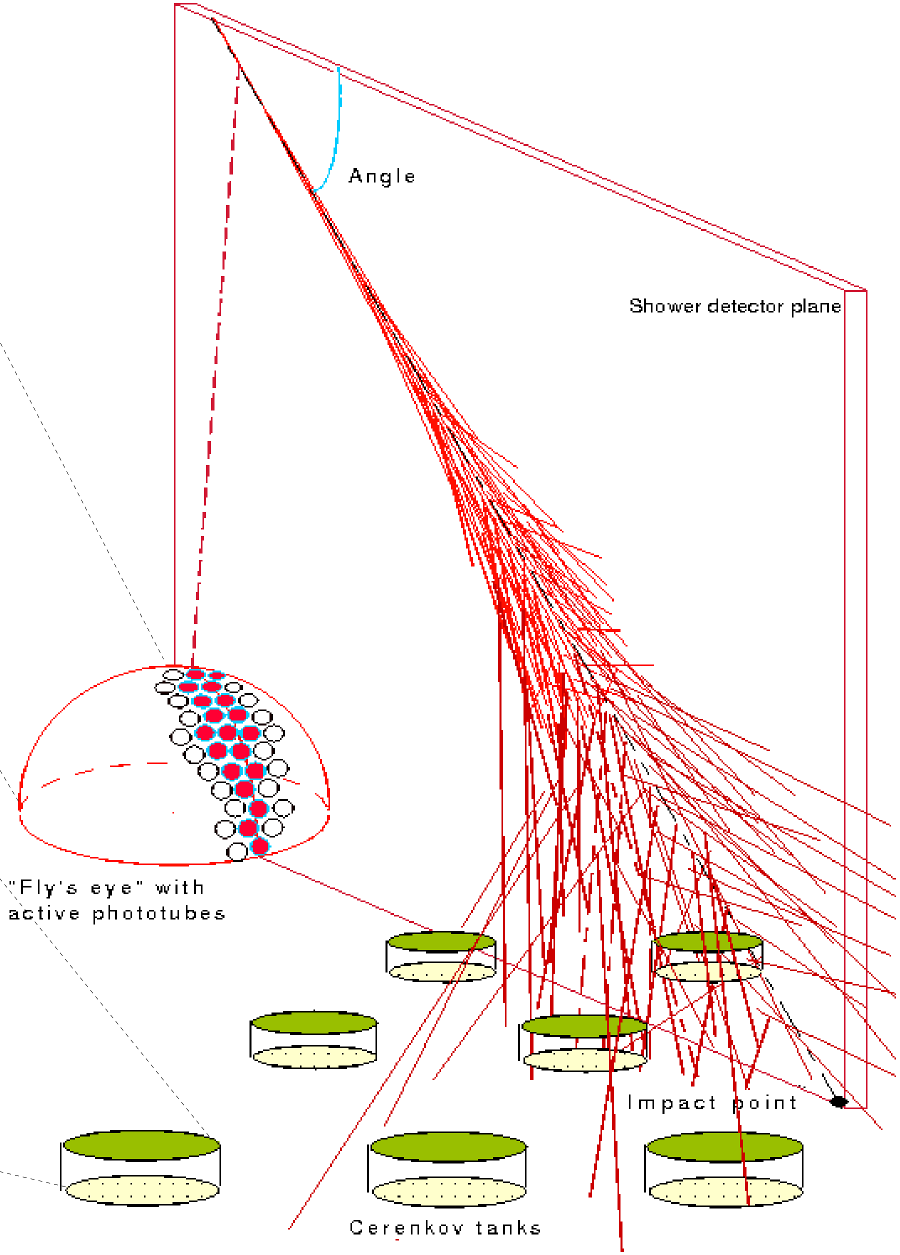
- 1600 tanks
- 4x6 telescopes

Hybrid Detector



fluorescence telescope

surface detector



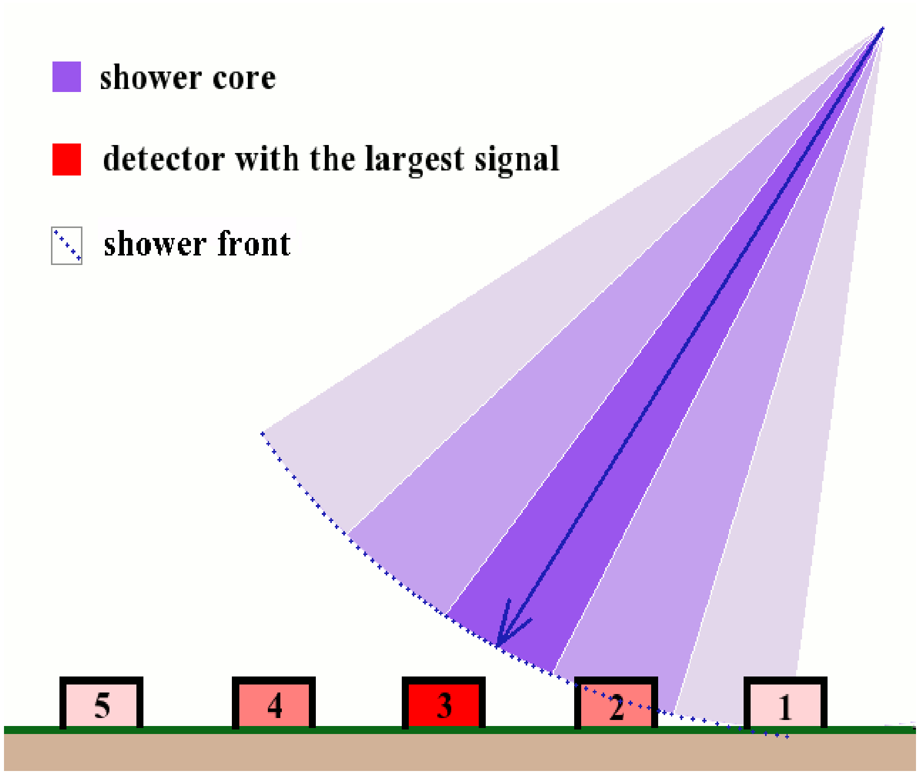
Advantages

Technique	Hybrid	SD-only	FD-only mono (stereo: low N)
Angular Resolution	~ 0.2°	~ 1 - 2°	~ 3 - 5°
Aperture	Flat with energy, mass (A) and model (M) *FREE*		E, A, spectral slope and M dependent
Energy	A and M *FREE*	A and M dependent	A and M *FREE*

SD surface, FD fluorescence detector

Surface Detector

- 1600 water tanks on ground
- Self-sufficient
- Measure 24 h
- Lateral distribution of secondary particles
- Time of arrival, signal
- E reconstruction is model dependent
- Analytical calculation of exposure



Water Tank

- Diameter 3.6 m
- Height 1.2 m
- Čerenkov radiation in water

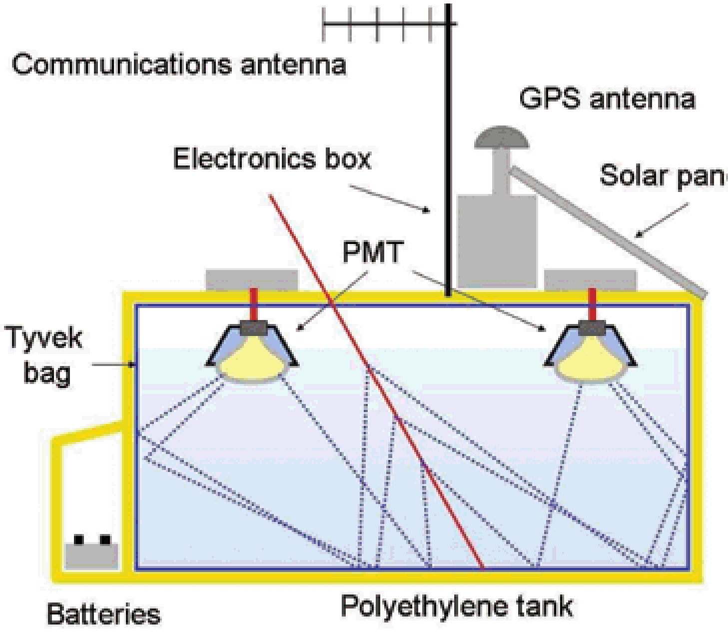
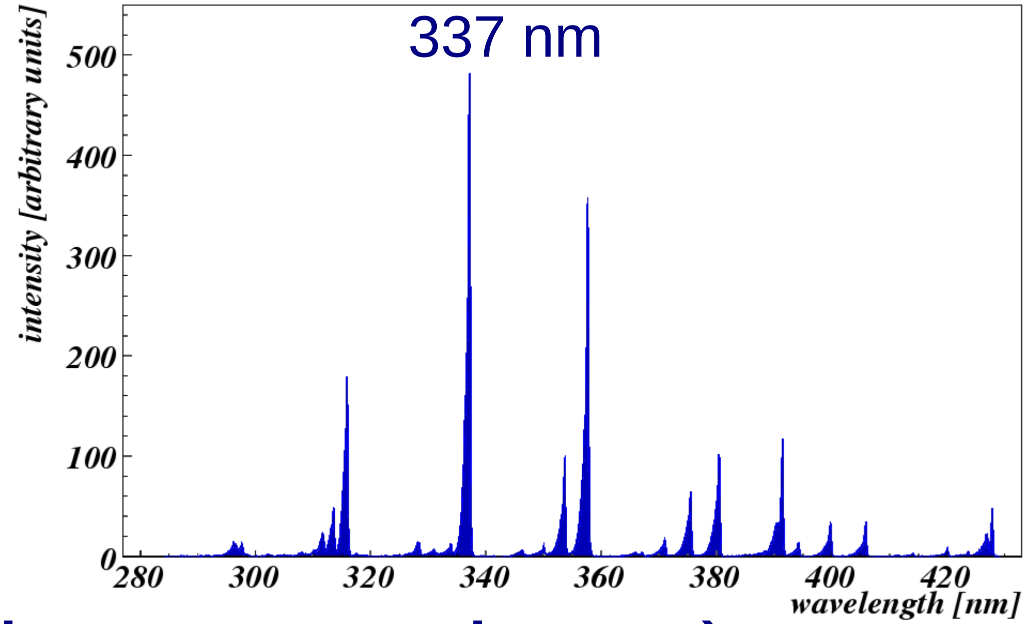


FIG. 2: A schematic view of the Cherenkov water tanks, with the components indicated in the figure.

- Monitored by 3 PMTs
- Spacing 1.5 km
- Regular grid

Fluorescence Detector

- Fluorescence light (300 - 400 nm)
- Calibration measur.
- FLY (p,T, humidity)
- 5% invisible energy
- See shower development (and shower maximum)



- Operated during clear moonless nights (about *12%* observational SD time)

Schmidt Telescopes

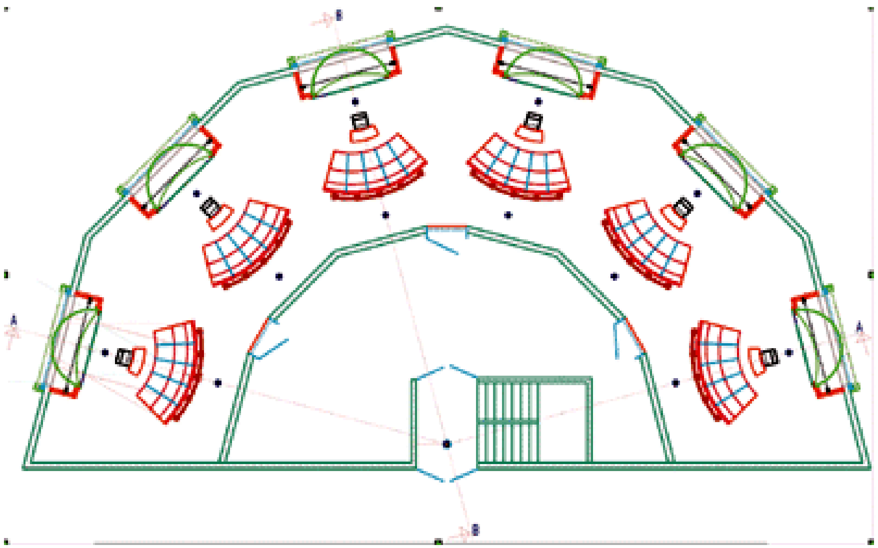
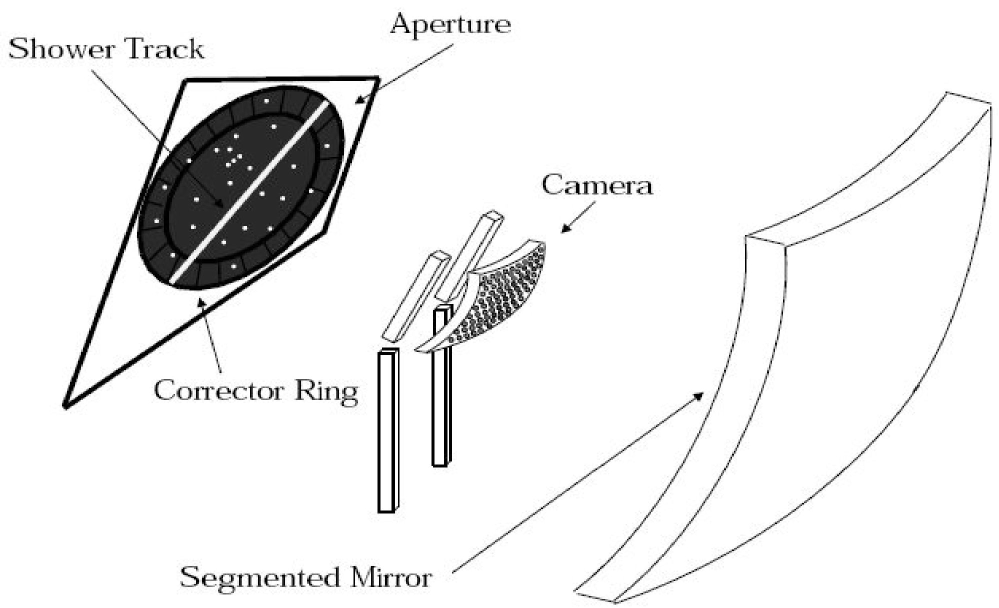


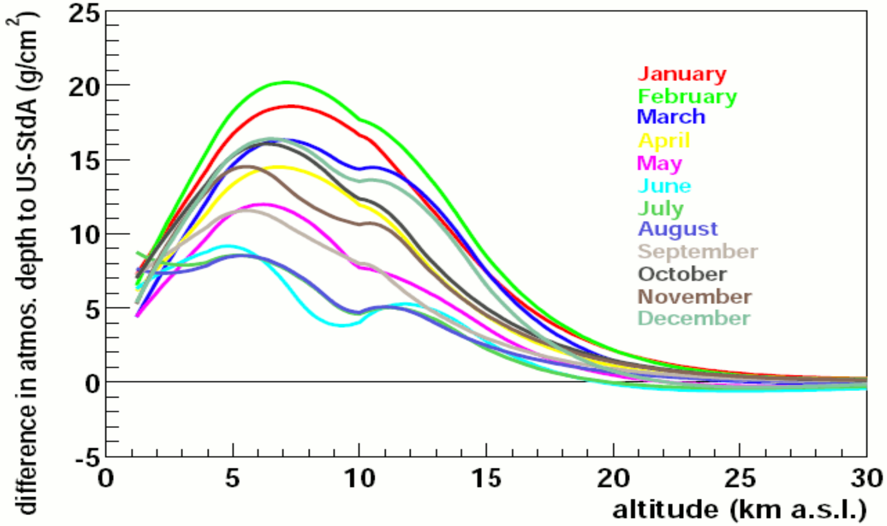
Figure 5. Upper view of a FD station.

- Segmented spherical mirror (radius 3.4 m)
- FOV 30º x 28.6º
- Aperture (2.2 m)



- UV filter (MUG 6)
- Camera with 440 photomultipliers

Atmospheric Monitoring



Profiles of atmospheric depth of the Malargüe Monthly Models in difference to the US-StdA.

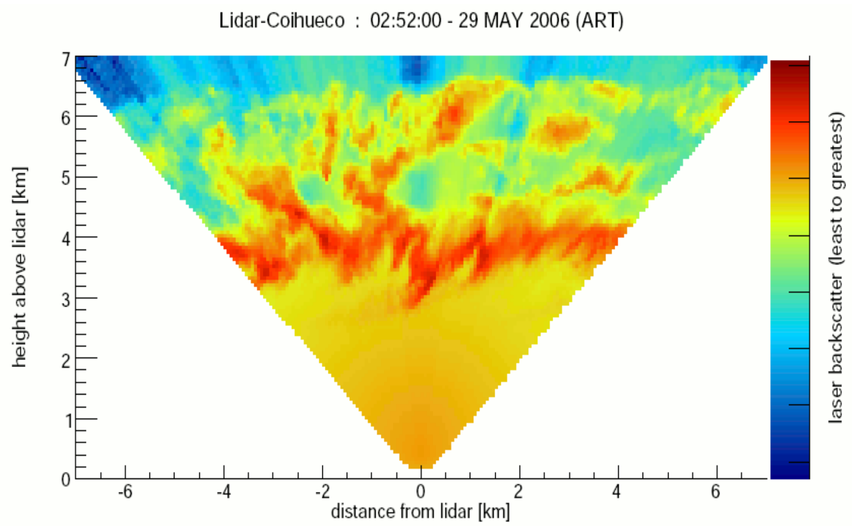


Fig. 8. *Result of a typical continuous lidar scan. Shown is the intensity of backscattered light as a function of height and horizontal distance to the lidar station at (0,0). A cloud layer around 3.5 km height is clearly visible in this scan.*

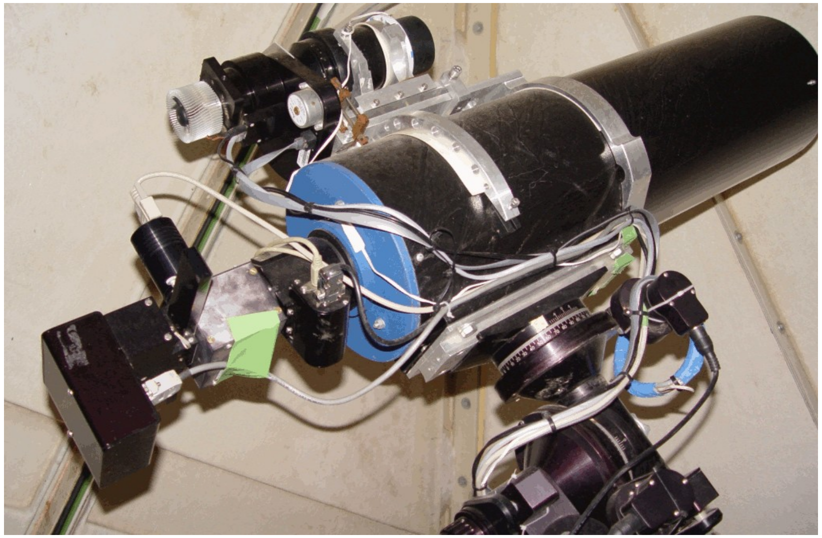
- FD calibrate SD energy !
- 10% error in the worst cases
- Regular measurement of temperature, humidity, density profile and aerosols

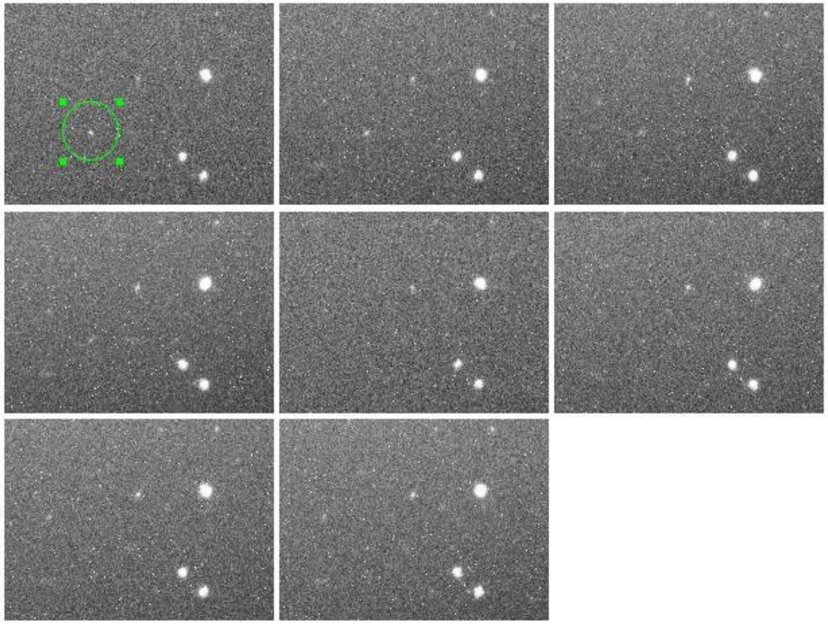
Robotic Telescope FRAM

- Measure wavelength dependence of extinction coefficient

- Cassegrain (20 cm)
- focal length 2970 mm
- photometer Optec SSP5
- Johnson filters + others
- 2 CCD cameras (WF, NF)

- Optical counterpart of GRB060117 (124 s after SWIFT)



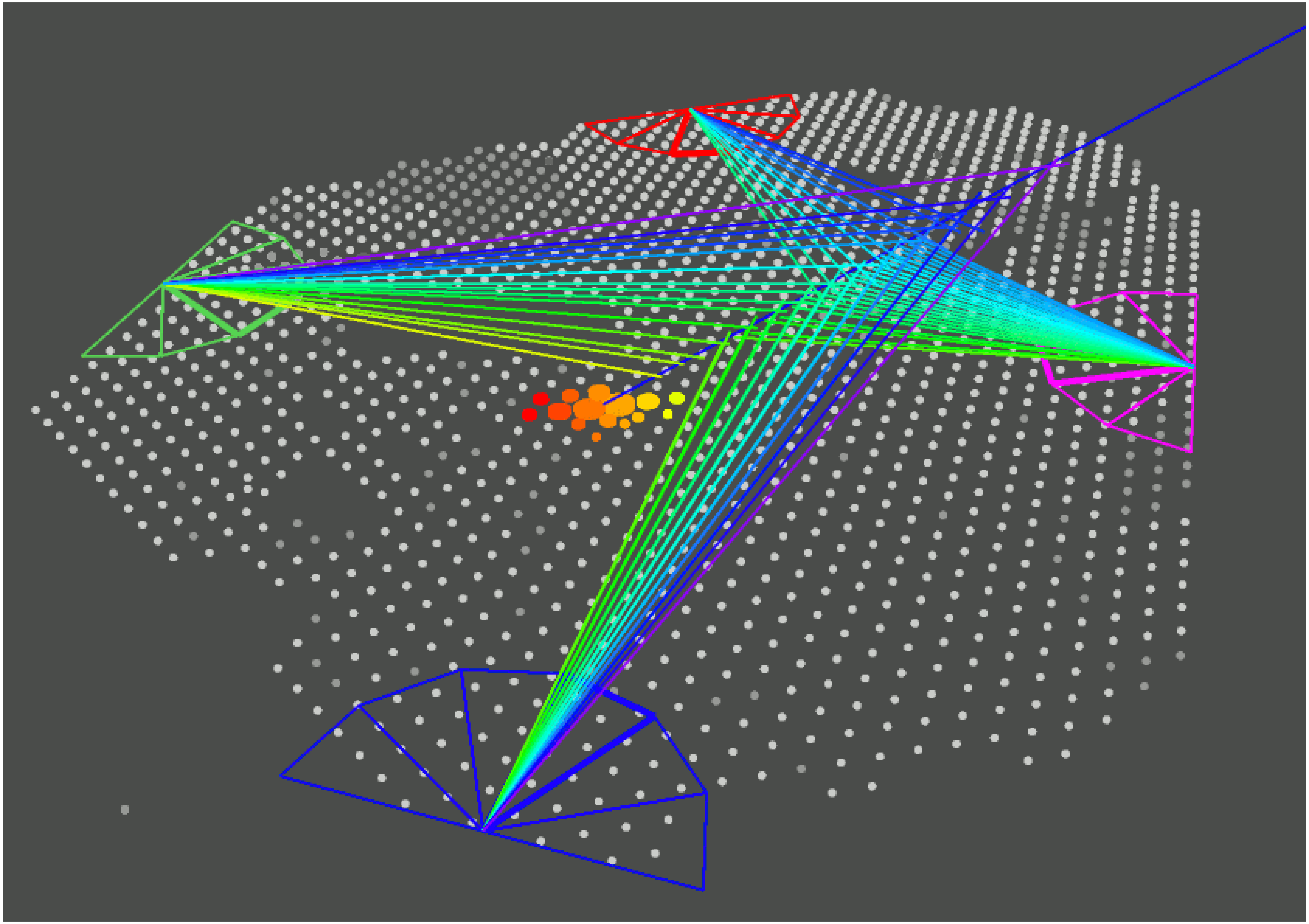


A&A 454, L119 (2006)

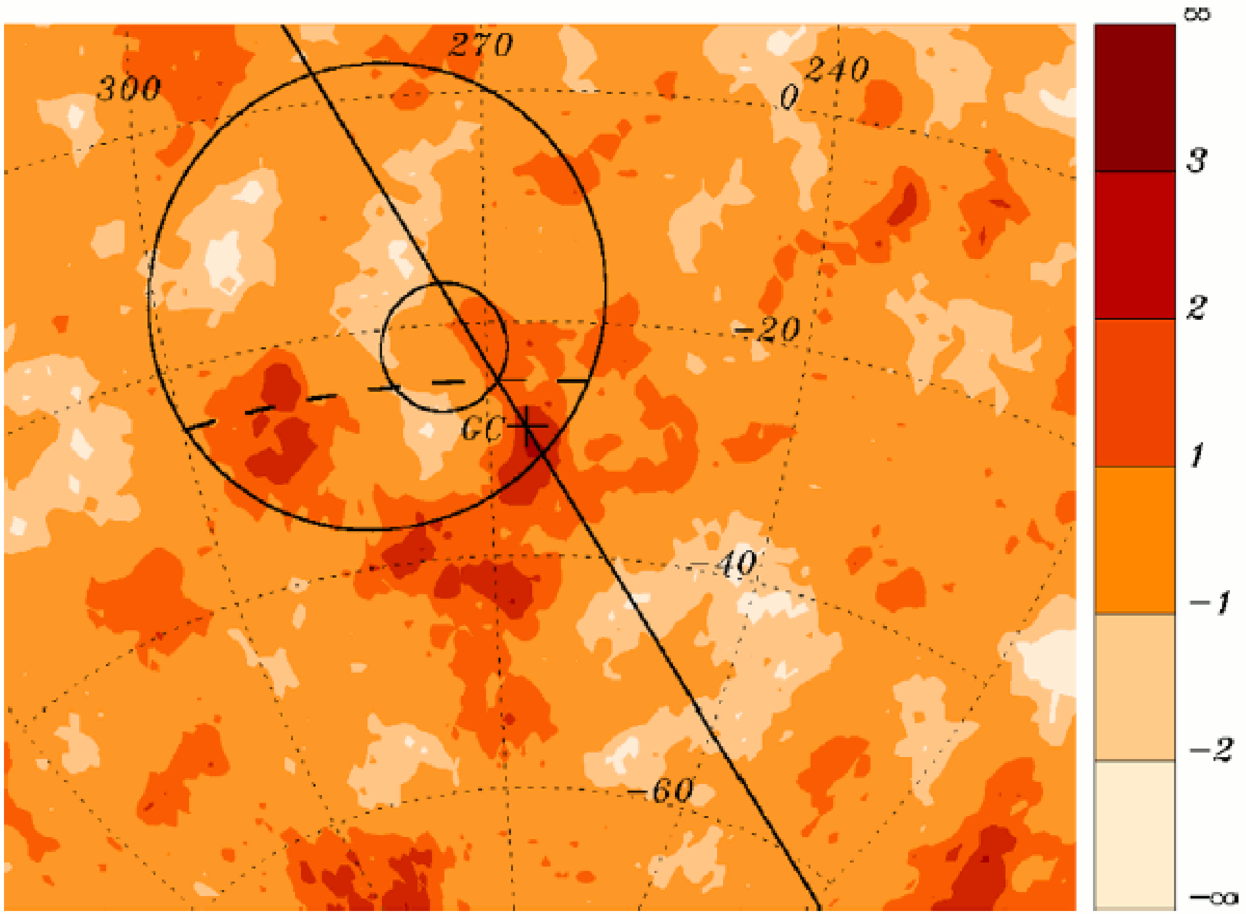
AUGER Results

sniffing armadillo in pampa

AUGER Quattro



Galactic Centre

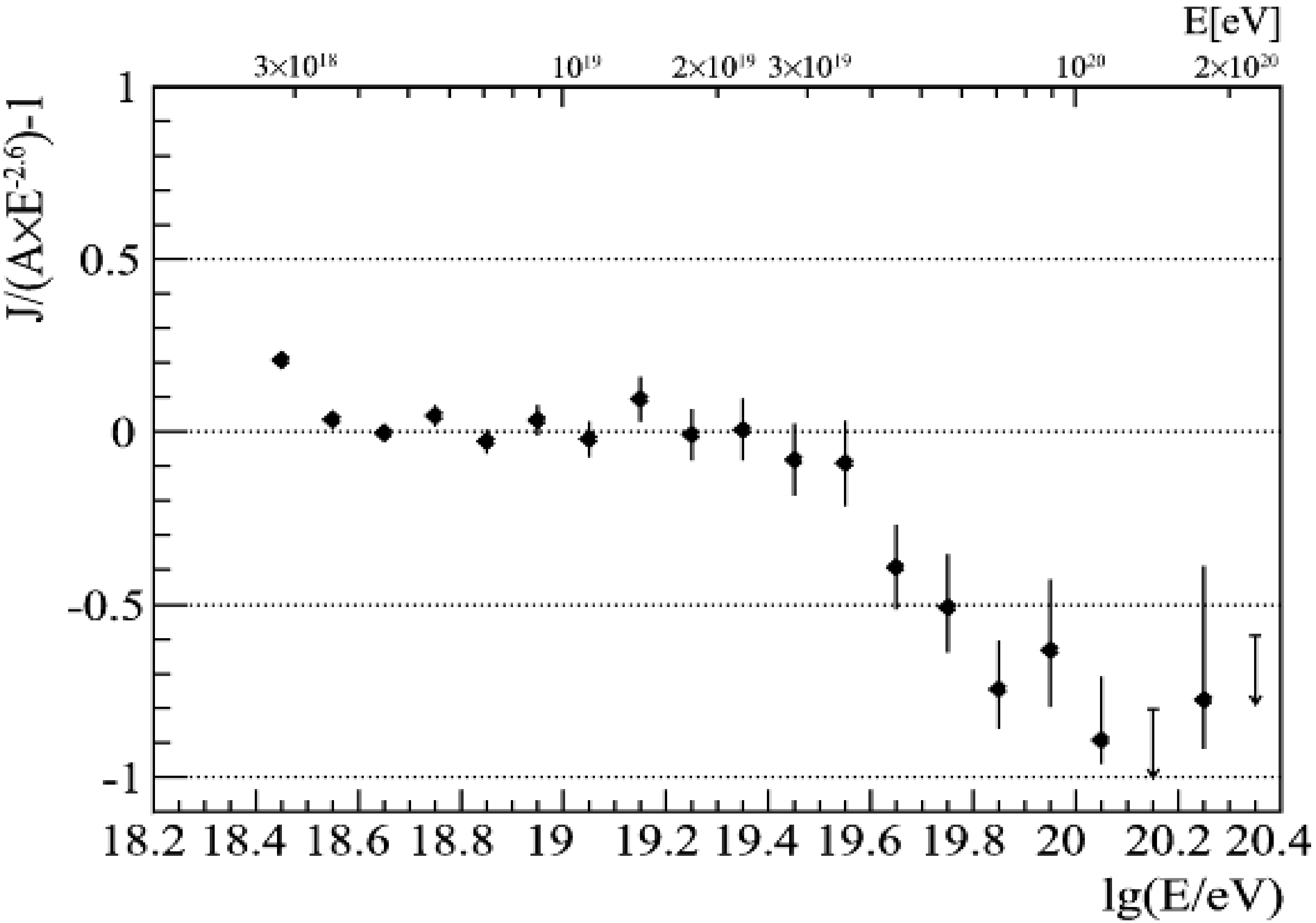


Map of CR overdensity significances near the GC region on top-hat windows of 5° radius. The GC location is indicated with a cross, lying along the galactic plane (solid line). Also the regions where the AGASA experiment found their largest excess as well as the region of the SUGAR excess are indicated.

No excess so far.

APh 27, 244 (2007)

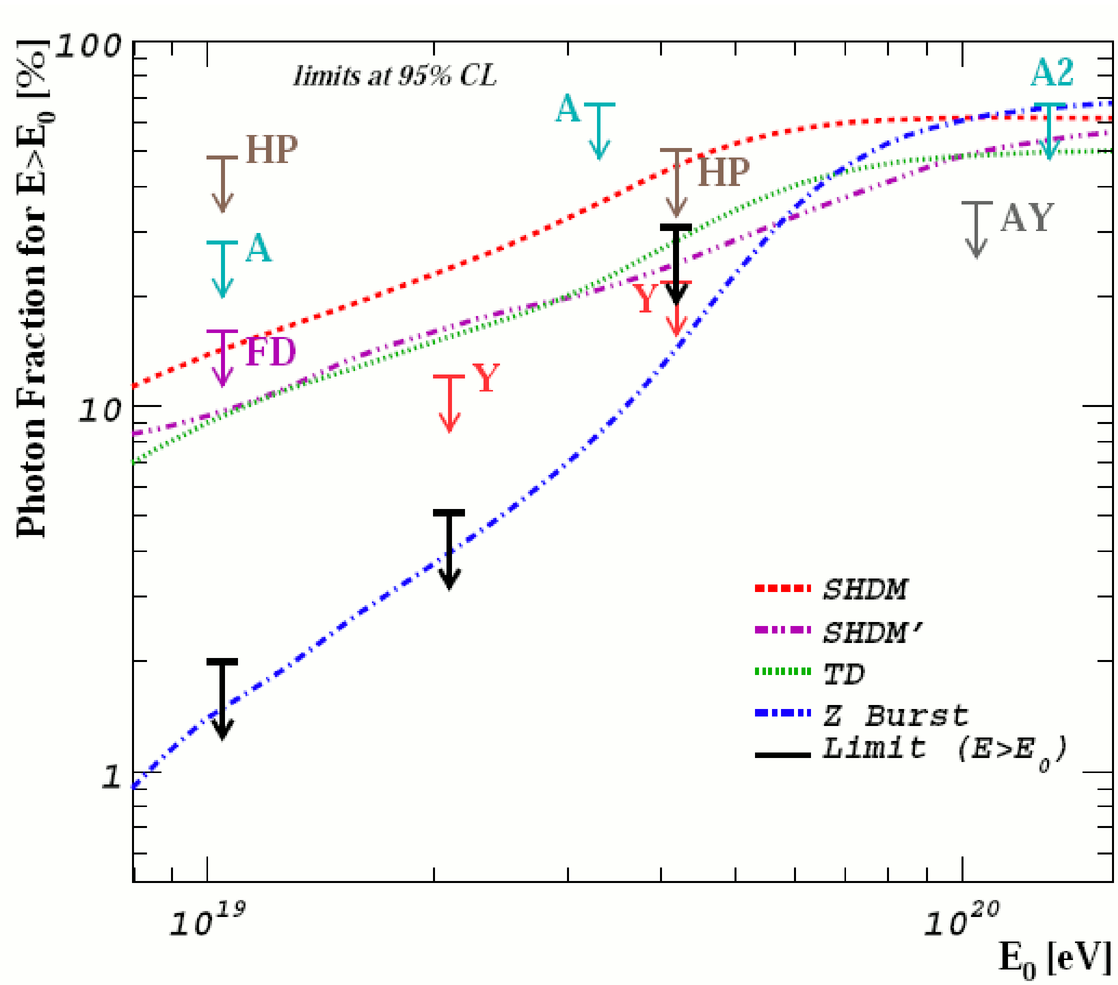
Cosmic Ray Spectra



Suppression of flux above 40 EeV.

Will be sent into PRL

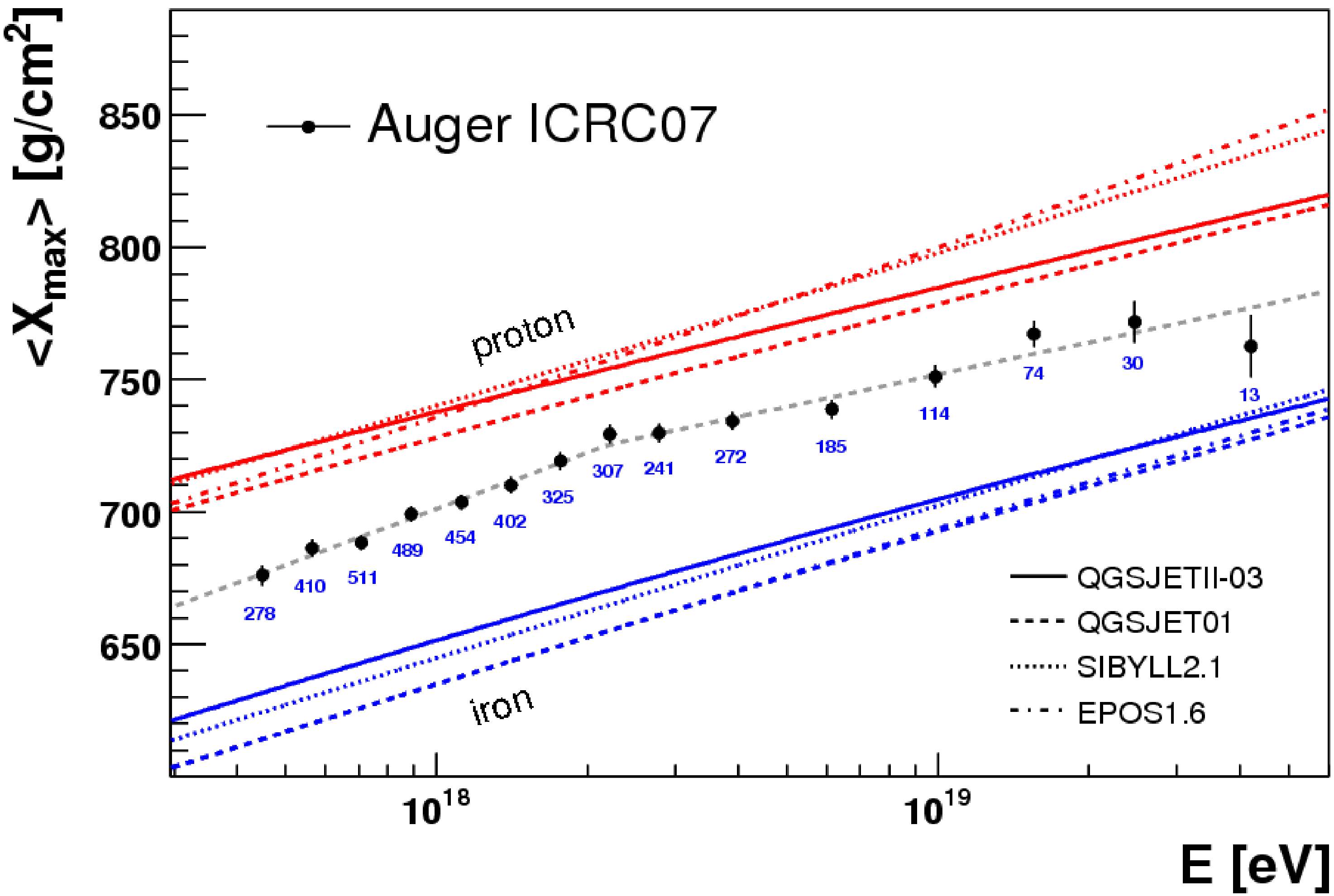
Photon Limit



Upper limits on flux of photons.

Accepted in APh

Chemical Composition



Indication of change in composition.

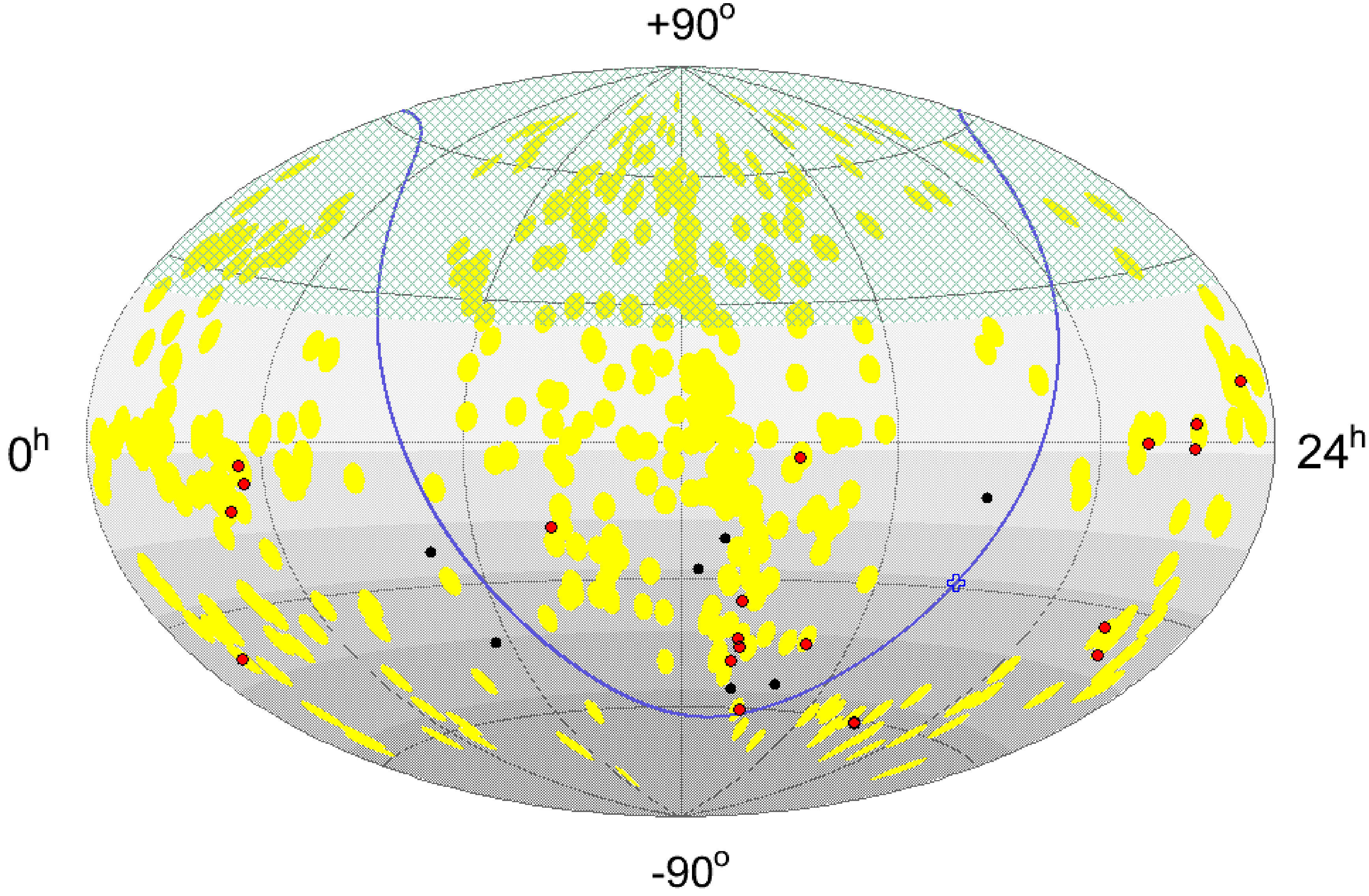
ICRC 2007

Test of Isotropy

- Based on signal found in data
- Arrival directions above 57 EeV
- Positions of AGN from 12th Veron-Cetty & Veron catalogue (maximum redshift 0.018, i.e. 75 Mpc)
- Hypothesis of isotropic distribution of CR with E > 57 EeV was rejected with at least 99% confidence level from prescribed a priori test *using independent data set*.

Science 318, 938 (2007) & APh 29, 188 (2008)

Arrival Directions



3.1° radius areas around AGN positions cover 21% of visible sky, together 20 from 27 CR lie on them.

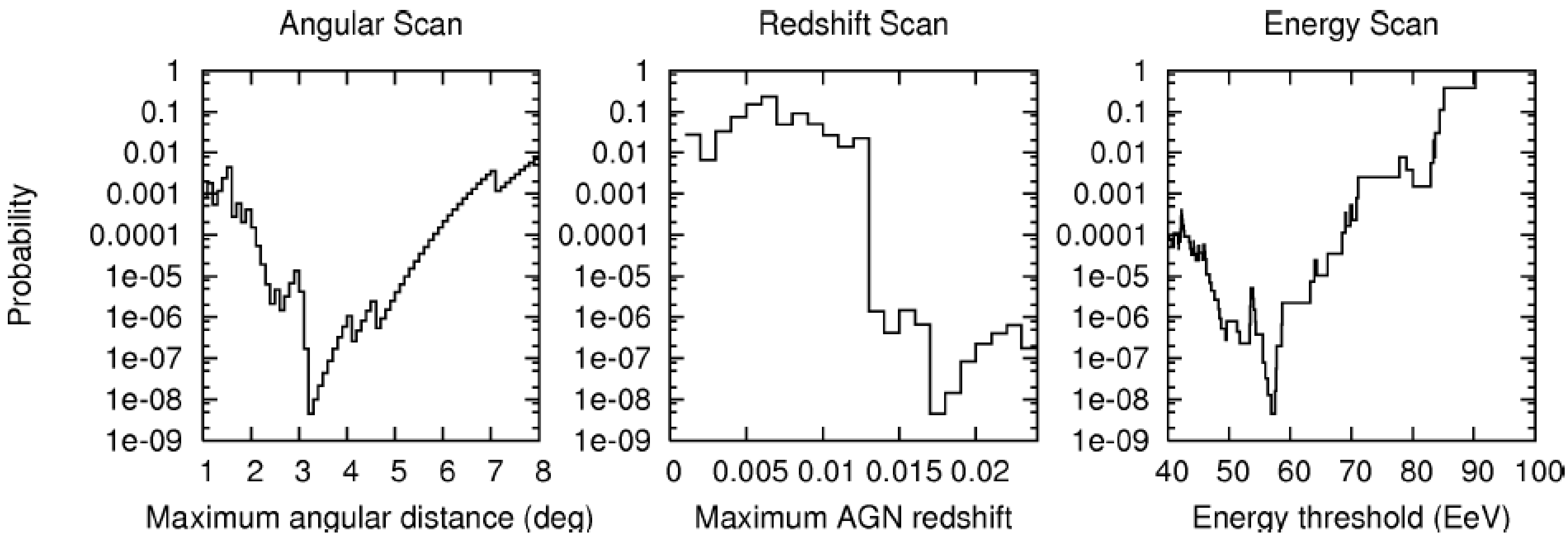
AUGER Statements

- Anisotropy at CL of more than 99%
- **Data do not identify AGN as the sources**
- Observation is compatible with GZK cutoff
- A few degrees angular scale correlation suggests predominantly proton composition
- Our results ruled out:
  a) Galactic sources, sources in halo
  b) top-down models (decay of superheavy particles and topological defects)

AUGER on Stamp

Backup Slides

Exploratory Scan



Probability for the null hypothesis (isotropic distribution) vs. maximum angular distance ψ (left), maximum AGN redshift $z_{\max}$ (centre), and threshold cosmic-ray energy E_{th} (right). In each case the other two parameters are held fixed at the values that lead to the absolute minimum probability. $\psi = 3.1^\circ$, $z_{\max} = 0.018 \rightarrow p = 0.21$, $E_{\text{th}} = 56$ EeV $\rightarrow N/k = 15/12$

$$P = \sum_{i=k}^{N} \binom{N}{i} p^i (1-p)^{N-i}, \qquad p = p(\psi, z_{\max}, \delta), \quad N = N(E_{\text{th}}), \quad k = k(\psi, z_{\max}, E_{\text{th}})$$

$p \ldots$ exposure-weighted fraction of the sky accessible to observation by Auger which is covered by windows of radius ψ centred on the selected sources

$P \ldots$ the probability that k or more out of a total of N events from an isotropic flux are correlated by chance with the selected objects at the chosen angular scale

D. Nosek

Running Prescription

$\psi = 3.1°,\ z_{\max} = 0.018 \rightarrow p = 0.21,$ $E_{\rm th} = 56$ EeV

$$P = \sum_{i=k}^{N} \binom{N}{i} p^i (1-p)^{N-i}$$ CL : $\alpha = 1\%$ $p_{\rm cut} = 0.23\%$

N	k	P [%] $p = 0.21$	$P_{\rm a}$ [%] $p_{\rm a} = 0.57$	$P_{\rm b}$ [%] $p_{\rm b} = 0.80$	$p_{\rm s}$ [%]	$p_{\rm t}$ [%]
4	4	0.19	11	41	0.19	0.19
6	5	0.20	19	66	0.13	0.32
8	6	0.16	26	80	0.07	0.40
10	7	0.12	31	88	0.04	0.44
12	8	0.08	36	93	0.02	0.47
...	...	...	...	...	...	...
31	14	0.22	93	100	0.05	0.87
33	15	0.14	93	100	0.01	0.89
34	15	0.21	95	100	0.03	0.92

27 May 2006 – 25 May 2007: $N/k = 8/6$

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