THE PIERRE AUGER OBSERVATORY: COSMIC ACCELERATORS AND THE MOST ENERGETIC PARTICLES IN THE UNIVERSE

Johannes Blümer
Victor Hess 1912

Pierre Auger 1938

John Linsley 1962

rate
counter
separation

LOG N

1 2 3

rate
counter
separation

LOG X

0.1 m. 1 m. 4 m. 10 m. 100 m. 300 m.

1 km
Atmospheric depth $[g/cm^2]$ vs Altitude [km]

- Electrons
- Muons \(\times 10\)
- Hadrons \(\times 10\)

\(\pi^0\) decay feeds electromagnetic part
\(\pi^\pm\) decay feeds muonic part
element abundances: 15 My in galaxy & halo energy density ~like light, magnetic field, CMB; equiv. to 3 SN/century at 10% eff.

powerlaw spectrum $dN/dE \sim E^{-3}$

10 decades in energy; flux range very large

stochastic acceleration in shocked plasma, confined by mag. fields

knee: p drop out first; end of SN acceleration?

isotropic directions

ankle: harder component, extragalactic

GZK: flux suppression above 60 EeV

acceleration to 100 EeV using LHC technology would require Mercury’s orbit; acceleration time: >800 years...
Cherenkov telescopes

particle detector arrays

Fluorescence telescopes

Radio antenna

HYBRID detection: more than one method!
Greisen Zatsepin-Kuzmin (GZK) effect: protons scatter with the CMB:
threshold effect above $6 \times 10^{19}$ eV:
\[ p + \gamma_{3K} \rightarrow \Delta(1232) \rightarrow p\pi^0 \rightarrow p\gamma \quad \text{or} \quad n\pi^+ \rightarrow p\gamma^+\nu \]
\[ 2E_p\epsilon > (m^2_\Delta - m^2_p) \]
\[ \epsilon = \text{meV, 400 cm}^{-3} \]
Hillas condition and diagram: $E_{\text{max}} \sim \beta Z B L$

- **Neutron Stars**
- **Gamma Ray Bursts**
- **White Dwarfs**
- **Active Galactic Nuclei**
- **Protons**
- **Iron**
- **Radio Lobes**
- **Galaxy Clusters**
- **Galactic Disk**
- **Galactic Halo**
- **SNR**
- **others**
GZK horizons
(uniform source distribution)

\[ E = 6 \times 10^{19} \text{ eV} \]
1. Argentina
2. Australia
3. Bolivia*
4. Brazil
5. Croatia*
6. Czech Republic
7. France
8. Germany
9. Italy
10. Mexico
11. Netherlands
12. Poland
13. Portugal
14. Slovenia
15. Spain
16. UK
17. USA
18. Vietnam*

* associated countries
1660 water Cherenkov detectors covering 3000 km²

4 x 6 fluorescence telescopes
fluorescent detectors
surface detectors
1 of 3 PMTs

12 m³ pure water in Tyvek liner

FADC traces, Energy = 1.2 \times 10^{19} \text{ eV}, \text{ zenith} = 13°
The surface detectors are self-calibrating by single muons. VEM = Vertical Equivalent Muon. The fluorescence telescopes are calibrated piece by piece on an absolute scale. It is an optical calorimeter! The absolute fluorescence yield is the currently biggest source of uncertainties on energy. The RMS is 17%. The fluorescence telescopes are calibrated piece by piece on an absolute scale. It is an optical calorimeter!
Energy spectrum

$E^3 J(E) \text{[km}^{-2} \text{yr}^{-1} \text{sr}^{-1} \text{eV}^2]$}

$18 \quad 18.5 \quad 19 \quad 19.5 \quad 20 \quad 20.5$

$\log_{10}(E/eV)$

$\sigma_{\text{sys}}(E) = 22\%$

Auger

power laws

power laws + smooth function

Energy spectrum

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$\log_{10}(E/eV)$

$\sigma_{\text{sys}}(E) = 22\%$

Auger

power laws

power laws + smooth function
the depth of the shower maximum, $X_{\text{max}}$, is the best estimator for the primary mass.
energy spectrum: convoluted information about sources, propagation, particle id

shower profiles: best estimator for the mass of the primary particle

very small fluctuations... all showers develop alike???

models assume no change in particle physics...

fluctuations of $X_{\text{max}}$

relative intensity $\frac{\text{de}}{dX}$
photon and neutrino limits

Photon showers have a distinct shape and can be ‘readily’ identified. Only neutrino induced showers can have large zenith angles (≈ 90°) and still interact close to the detector.

Single flavour neutrino limits (90% CL)

This limits the ‘exotic models’...
In total **27 events** measured at \( E > 57 \) EeV

out of which **20 correlate**

5.6 expected (\( p=0.21 \))

Net chance for isotropic distr. \( P < 10^{-5} \)
Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects

Journalists: "cosmic rays come from black holes".

Auger:
... We have demonstrated the anisotropy of the arrival directions of the highest-energy cosmic rays and their extragalactic origin. Our observations are consistent with the hypothesis that the rapid decrease of flux measured by the Pierre Auger Observatory above 60 EeV is due to the GZK effect and that most of the cosmic rays reaching Earth in that energy range are protons from nearby astrophysical sources, either AGN or other objects with a similar spatial distribution....
equal exposure polar projection: 2007 same data as Science paper

**AGN**

Auger events
E > 3 EeV

Auger events
E > 55 EeV

[Beatty & Westerhoff 2008]
Distribution of angular separations between the 58 events with $E > 55$ EeV and the closest AGN in the VCV catalog within 75 Mpc
Bin > 55 EeV contains the 58 highest energy events (Jan 1 2004 to April 4 2009)

[Jim Cronin, Blois 2009]

Isotropic probability with 2pt-Rayleigh correlation

27 events as of 2007
Total number of events (excluding exploratory scan) 5 10 15 20 25 30 35 40

$p_{iso} = 0.21$

Data ± 1σ

Data ± 2σ

[paper reference: Auger ICRC 2009]
cumulative number of events with $E \geq 55 \text{ EeV}$ as a function of angular distance [°] from Cen A
Preliminary conclusions

- First precise energy spectrum from 1 EeV to above 100 EeV
- Fluorescence detection of showers sets the energy scale to ± 22%,
  - biggest contribution from absolute fl. yield
- Ankle at 2-3 EeV: transition from galactic to extragalactic cosmic particles
- Flux suppression at 50-60 EeV: GZK effect or maximum accelerator energy?
- With increasing energy air showers develop higher up in the atmosphere and show less fluctuations – astrophysics and/or particle physics? E.g. heavier particles or higher cross section?
- Arrival directions of cosmic rays become abruptly anisotropic above 50-60 EeV, in coincidence with the flux suppression.
- Cosmic ray arrival directions correlate with the distribution of nearby (<75 Mpc) extragalactic objects; several reference maps are being tested. The correlating fraction is (38 ± 6)% [was (69^{+11}_{-13})% initially].
- The reference-free anisotropy is a robust feature.
"This could be the discovery of the century. Depending, of course, on far down it goes."
Auger had always been designed as a two-instrument, full-sky coverage cosmic ray observatory.
Auger North

4400 tanks on 20,000 km²
39 telescopes
<table>
<thead>
<tr>
<th></th>
<th>Auger South</th>
<th>Auger North</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>$35^\circ$ S, $69^\circ$ W</td>
<td>$38^\circ$ N, $102^\circ$ W</td>
</tr>
<tr>
<td><strong>Altitude</strong></td>
<td>1,300 - 1,500 [m a.s.l.]</td>
<td>1,300 [m a.s.l.]</td>
</tr>
<tr>
<td><strong>Area</strong></td>
<td>3,000 km$^2$</td>
<td>20,000 km$^2$</td>
</tr>
<tr>
<td><strong>Number of SD stations</strong></td>
<td>1,600</td>
<td>4,000</td>
</tr>
<tr>
<td>(infill)</td>
<td></td>
<td>(400)</td>
</tr>
<tr>
<td><strong>SD spacing</strong></td>
<td>1,500 m</td>
<td>2,300 m</td>
</tr>
<tr>
<td>(infill)</td>
<td></td>
<td>(1,600 m)</td>
</tr>
<tr>
<td><strong>PMT sensors / SD station</strong></td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td><strong>Communications network</strong></td>
<td>SD-tower radio</td>
<td>peer-to-peer</td>
</tr>
<tr>
<td><strong>SD array 50% efficient at</strong></td>
<td>0.7-1 EeV</td>
<td>8-10 EeV</td>
</tr>
<tr>
<td><strong>SD array 100% efficient at</strong></td>
<td>3 EeV</td>
<td>80 EeV</td>
</tr>
<tr>
<td><strong>FD stations</strong></td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td><strong>FD telescopes</strong></td>
<td>24 ($4 \times 6$)</td>
<td>39 ($2 \times 12 + 2 \times 6 + 1 \times 3$)</td>
</tr>
<tr>
<td><strong>Begin construction</strong></td>
<td>1999</td>
<td>2012</td>
</tr>
<tr>
<td><strong>End construction</strong></td>
<td>2008</td>
<td>2016</td>
</tr>
</tbody>
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Final conclusions

- First precise energy **spectrum** from 1 EeV to above 100 EeV
- Optical fluorescence detection of showers set the **energy scale** to ± 22%,
  - biggest contribution from absolute fl. yield
- **Ankle** at 2-3 EeV: transition from galactic to extragalactic cosmic particles
- Flux suppression at 50-60 EeV: **GZK effect or maximum accelerator energy?**
- With increasing energy **air showers develop** higher up in the atmosphere and show less fluctuations – **astrophysics and/or particle physics? E.g. heavier particles or higher cross section?**
- Arrival directions of cosmic rays become abruptly **anisotropic** above 50-60 EeV, in coincidence with the flux suppression
- **Cosmic ray arrival directions correlate with the distribution of nearby (<75 Mpc) extragalactic objects**; several reference maps are being tested. The correlating fraction is (38 ± 6)% [was (69+11-13)% initially] -- need more data
- Many open important questions remain to be answered – **Auger North** is needed with a much larger (x7) aperture. A complementary approach (detection from space, ~less precise, even larger statistics) is **JEM-EUSO**.
... and because the Universe is expanding ever further, we just need a bigger telescope!