Observatoř Pierra Augera:
gigantický detektor kosmického záření

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What are ultra-high energy cosmic rays (UHECRs)?

UHECRs are particles with energy above "ankle", say, above $3 \times 10^{18}$ eV.

The most energetic event: Detector Fly’s Eye, Utah, USA, October 15th 1991
$3 \times 10^{20}$ eV $\approx 50$ J

Simon Swordy, 1996
Primary particle interacts with atmosphere

Number of secondary particles is created

Secondaries interact again, and again, ...

Typical shower $10^{20}$ eV: $10^{10}$ particles at ground

Animation color code:
- blue: electrons/positrons
- cyan: photons
- orange: protons
- red: neutrons
- gray: mesons
- green: muons
(10^{-6} thinning)

H.-J. Drescher, Frankfurt University
How to detect UHECRs?

- The number of secondary particles is proportional to energy of primary particle.
- Relative time of detection of individual secondary particles carries information about incident direction of primary particle.
- Types of detectors: ground arrays and fluorescence telescopes.

Primary particle coming from space (proton or light nucleus) hits the atmosphere of the Earth.

Shower of secondary particles originates during collisions with molecules in the atmosphere.

The array of ground detectors is recording and sampling fraction of secondary particles.
Detectors of cosmic rays with ultra-high energies

7 different detectors were in operation during 40 years of measurements and achieved detection of approximately ~ 200 particles with energies over $4 \times 10^{19}$ eV and only ~ 20 particles with energies over $10^{20}$ eV.

Surface detectors:
- Volcano Ranch, USA (1959 – 1963)
- SUGAR, Australia (1968 – 1979)
- Haverah Park, UK (1968 – 1987)
- Yakutsk, Russia (1970 – today)
- AGASA, Japan (1990 – 2004)

Fluorescence detectors:
- Telescope Array (2008 – today)
HiRes Experiment (Dugway, Utah)

HiRes-I
21 mirrors
1 ring, full azimuth, $3^\circ$-$17^\circ$ elevation
Sample & Hold DAQ System

HiRes-II
42 mirrors
2 rings, full azimuth, $3^\circ$-$31^\circ$ elevation
FADC DAQ System
Took data: Dec. 1999-April 2006

Both:
5.1 m² mirrors, 16x16 PMTs

HR I+II data taking:
June 1997-April 2006

K.-H. Kampert, EPS-HEP 2009
Telescope Array (Utah)

Fully Operational since March 2008

507 Plastic Scintillator Detectors cover ~700 km² (1.2km spacing)

3 Fluorescence Telescope Stations overlook the array.

Utah, USA
39.3 ° N, 112.9 ° W
alt. 1400 m

K.-H. Kampert, EPS-HEP 2009
GZK or not to GZK: HiRes vs. AGASA

Is there really GZK-cutoff? Where are the sources?
• Fermi acceleration in magnetic fields.

• We need magnetic fields extremely strong OR filling extremely large regions to accelerate particles above $10^{20}$ eV.

• And still, all parameters have to be finely tuned.

Michael Hillas, 1984
GZK suppression

- Discovered 1966 independently by Greisen and Zatsepin & Kuzmin.
- UHECRs lose energy due to collisions with CMB photons (photon produces pions, nuclei photodisintegrate).
- Threshold for this process is \( \sim 5 \times 10^{19} \text{ eV} \).

Sources of particles with \( E > 10^{20} \text{ eV} \) have to be within “GZK-sphere” (100 Mpc).
Influence of magnetic fields

- Above $10^{19}$ eV - not curved trajectories? - “Cosmic ray astronomy”?
- Not so sure...
- Extragalactic magnetic fields could be very important, especially if UHECRs are mainly iron nuclei.
- And what about Galactic magnetic field?

Particle trajectories in the Galaxy:
- Iron nuclei, $4 \times 10^{19}$ eV
- Turbulent (up to 3x higher intensity than regular), poloidal and toroidal components exist
- Global structure surely spiral
The Pierre Auger Observatory

Mendoza province, Argentina
The Pierre Auger Observatory

More than 250 PhD scientists from more than 60 institutions from 15 (+2) countries.

Participating countries:
Argentina, Australia, Bolivia*, Brazil, Czech Republic, France, Germany, Italy, Mexico, Netherlands, Poland, Portugal, Slovenia, Spain, United Kingdom, USA and Vietnam*

* - associated countries
The construction of the southern site in Argentina is completed.

Northern hemisphere? (Original idea, but not likely...)

Southern hemisphere: Malargüe, Mendoza province, Argentina

See www.augernorth.org for details

Lifetime of the observatory: 15 - 20 yrs
The Pierre Auger Observatory = hybrid detector of cosmic rays

• The array of surface Cherenkovov detectors will be accompanied with system of fluorescence telescopes, which will observe faint UV/visible light during clear nights. This fluorescence light origins as by-product during the interactions of shower particles with the atmosphere.
**Ground detectors:**
*Covered surface:* 3000 km²
*Number of detectors:* 1600
*Type of detector:* Detector of Cherenkov radiation, each consisting of 12 000 litres of ultrapure water and equipped with 3 photomultipliers.
*Spacing between detectors:* 1.5 km.
Fluorescence detectors of the Pierre Auger Observatory

Fluorescence telescopes:
Number of telescopes: 24
Mirrors: 3.6 m x 3.6 m with field of view 30° x 30°, each telescope is equipped with 440 photomultipliers.
Evolution of the hybrid detector

Production of scientific data since late 2003.
Example Surface Array Event
($\Theta \sim 48^\circ$, $\sim 70$ EeV)

Some flash ADC traces
Example Hybrid Event
(Θ~ 30º, ~ 8 EeV)
20 May 2007  \( E \sim 10^{19} \text{ eV} \)
Energy estimation, atmospheric monitoring

<table>
<thead>
<tr>
<th>Term</th>
<th>Error(%)</th>
<th>Term</th>
<th>Error(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light collection</td>
<td>5</td>
<td>Atmosphere (aerosols)</td>
<td>10</td>
</tr>
<tr>
<td>Detector photometric calibration</td>
<td>12</td>
<td>Atmosphere (clouds)</td>
<td>5</td>
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<tr>
<td>Geometric reconstruction</td>
<td>2</td>
<td>Atmosphere (density profile)</td>
<td>2</td>
</tr>
<tr>
<td>Correction for Missing Energy</td>
<td>3</td>
<td>Fluorescence yield</td>
<td>15</td>
</tr>
</tbody>
</table>

Quadrature Sum = 23

Current estimates of systematic errors of the FD energy measurement
Comparison of integrated aperture

Currently (Nov 2013) ~ 20 x AGASA
Auger Observatory results
• No spectrum from SD only!

• Relation between particle density parameter $S(1000)$ and FD energy using selected hybrid events

• Aperture from SD

• Combining advantages of FD technique (calorimetric measurement of energy) and of SD technique (well defined aperture; 100 % duty cycle)
Ground Array calibrated by Fluorescence Obs.

795 events
$E_{\text{max}} = 6 \times 10^{19} \text{ eV}$

Applied by Auger and Telescope Array

K.-H. Kampert, EPS-HEP 2009
Auger Energy Spectrum

For more details see arXiv:0906.2189
Mass Composition

For more details see arXiv:0906.2319
Or talk by Michael Unger: http://web.phys.ntnu.no/~mika/unger2.pdf
Shower Profile
FD mass composition results

\[ \chi^2 / \text{Ndf} = 9.7 / 9 \]

\[ D_1 = 106 \pm 35 \]
\[ D_2 = 24 \pm 3 \]
\[ \log(E_b/\text{eV}) = 18.2 \pm 0.1 \]

\[ \chi^2 / \text{Ndf} = 2.2 / 9 \]

\[ D_1 = 5 \pm 20 \]
\[ D_2 = -26 \pm 4 \]
\[ \log(E_b/\text{eV}) = 18.3 \pm 0.1 \]
• Elongation rate flattens at high energy
• Fluctuations decrease with energy
• Two options (both can be simultaneously true):
  1.) Cosmic rays heavier at high energy
  2.) Hadronic models at UHE energy need modification
Hadronové složení

lehké \quad těžké!

\[ \sigma_{\text{nové}}(10\text{EeV}) = f_{19} \sigma_{\text{model}}(10\text{EeV}) \]

a nebo je to jinak – např.,
že prudce roste účinný
průřez?
Účinný průřez

a nebo je to jinak – např., že prudce roste účinný průřez?

Budoucnost: Měření účinného průřezu i na observatoři AUGER
Jak poznat foton?

Hadronové a fotonové spršky se značně liší. Najít v datech primární fotony lze podle maxima spršky (FD) a podle počtu mionů (SD).
Photon limit
Jak poznat neutrino?

„Mladá“ horizontální sprška!

- elektromagnetická komponenta
- široká časová distribuce signálu
- velké zakřivení
- strmá laterální distribuce

~30 atm

Nebo pod horizontálou jdoucí \( \nu \)

1 atmosféra           3 atmosféry

„Mladé“ spršky:

- tvrdé miony
- úzká časová distribuce signálu
- malé zakřivení
- plochá laterální distribuce

čelo mladé spršky

čelo staré spršky

„Staré“ spršky

- široká časová distribuce signálu
- velké zakřivení
- strmá laterální distribuce
The best agreement is with the distribution of nearby active galaxies.

Black dots – arrival directions of CRs with $E > 55$ EeV
Blue circles – active galactic nuclei (AGNs) with distance < 75 Mpc
– in agreement with our expectations (GZK cutoff)
So, what are active galactic nuclei?

- galaxies with supermassive black holes in their centers; black hole mass in order of $10^7 - 10^8$ solar masses; enough matter nearby to be swallowed
Seyfert galaxies are most common in our selection.
However, we have to be careful…

Red circles – (again) AGNs closer than 75 Mpc
Black dots – all galaxies closer than 75 Mpc (HyperLEDA catalogue)

Distribution of ordinary galaxies (and matter in general) and of AGNs is very similar!

So, our first guess that the particles with the highest energies come from AGNs is not correct → we need more data from both South and North …
Anizotropie

„Míra korelace“ klesla z 70% na 40%, ale izotropie je stále vyloučena
• Velice nadějný kandidát
• Nejbližší AGN (4 Mpc)
• Zdroj fotonů do škály TeV
• AUGER: přebytek událostí – 12 událostí do 18°, 2,7 události očekáváno, pravděpodobnost 2%