EXPLORING COSMIC RAYS AT THE HIGHEST-ENERGY FRONTIER WITH THE PIERRE AUGER OBSERVATORY

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The main goals: to study cosmic-ray particles at energies above $10^{18}$ eV, look for possible sources, find out primary composition.

Main results: ankle and cut-off in spectrum clearly measured, anisotropy studied in large and small scales, composition in primary nuclei studied, search for neutrinos, photons, and neutrons performed.

Auger challenges for beyond 2015:
Origin of the cut-off: GZK or exhaustion of sources,
Proton fraction at highest energies,
Constrain hadronic interaction models/new physics,
Improve knowledge of composition with upgraded detector.
The Pierre Auger Observatory

Location:
Malargüe, Mendoza, Argentina

Surface Detector (SD):
Total area 3000 km$^2$
1660 water Cherenkov detectors @ 1500 m
71 water Cherenkov detectors @ 750 m spacing (Infill) (~30 km$^2$)

Fluorescence Detector (FD)
24+3 fluorescence telescopes at four locations

Muon Detectors
61 detectors along the Infill

AERA radio antennas (MHz)
124 in the Infill area
R&S GHz antennas
AMBER/MIDAS/EASIER
One of the fluorescence telescopes (FD)

- Mirror 3 m²
- Aperture, corrector ring and filter
- 440 pixel camera
- 10 MHz sampling
One of the surface detectors (SD)

- Communication Antenna
- GPS Antenna for timing
- Electronics enclosure 40 MHz sampling
- Solar Pannel
- Battery Box
- 3 photomultiplier tubes of 9 inches
- Tank in polyethylene containing 12000 l water
Hybrid detection:

**Fluorescence Detector:**
- Almost calorimetric energy measurement
- 13% duty cycle
- Complex acceptance calculation

**Surface Detector Array:**
- ~100% duty cycle
- Simple geometrical acceptance
- Extracting primary mass depends on models

Combining both techniques allows:
- Cross calibration in energy
- Better angular resolution
What do we have? A puzzle...
Energy Spectrum

- Data from the SD / FD provide **four independent measurements**;
- The **four spectra agree** within statistical and systematic uncertainties.

Energy Spectrum

\[ J(E; E > E_a) \propto E^{-\gamma_2} \left[ 1 + \exp \left( \frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1} \]

\[ \gamma_1 = 3.23 \pm 0.07 \]

\[ \log_{10}(E_{\text{ankle}}/\text{eV}) = 18.7 \]

\[ \gamma_2 = 2.63 \pm 0.04 \]

\[ \log_{10}(E_{1/2}/\text{eV}) = 19.63 \]

130 000 events

\[ \log_{10}(E_{\text{ankle}}/\text{eV}) = 18.7 \]

\[ \gamma_1 = 3.23 \pm 0.07 \]

\[ \log_{10}(E_{1/2}/\text{eV}) = 19.63 \]

Parameter | Result $\pm \sigma_{\text{stat}} \pm \sigma_{\text{sys}}$
--- | ---
$\log_{10}(E_a/\text{eV})$ | $18.72 \pm 0.01 \pm 0.02$
$\gamma_1$ | $3.23 \pm 0.01 \pm 0.07$
$\gamma_2$ | $2.63 \pm 0.02 \pm 0.04$
$\log_{10}(E_{1/2}/\text{eV})$ | $19.63 \pm 0.01 \pm 0.01$
$\log_{10} W_c$ | $0.15 \pm 0.01 \pm 0.02$

Energy spectrum and models

Mass composition measurements (FD)
Mass Composition

High-quality hybrid data: anti-bias cuts for a direct data-model composition.

Average mass composition: $X_{\text{max}}$ and $<\ln A>$

- All models show a trend to $<\ln A>$ increasing from light to medium with $E$;
- The mix is between light/medium-mass nuclei (not only $p$-$\text{Fe}$);
- Dispersion: spread reflects mixture at sources and propagation effects.
Update on $X_{\text{max}}$ measurements: coming soon

- data from 12/2004 – 12/2012
- energies $> 10^{17.8}$ eV
- 19947 high-quality FD events
- resolution: 26 g/cm$^2$ @ $10^{17.8}$ eV, 15 g/cm$^2$ @ $10^{19.3}$ eV.
- new $X_{\text{max}}$ distributions will be released soon....
Composition implications: what is also being studied

- Simulated $X_{\text{max}}$ distributions with same mean/dispersion and different compositions.
- In this example, EPOS-LHC used to generate $10^4$ events.
Preliminary results:

- A mixture of simply protons and iron nuclei does not describe the data over the whole energy range;
- All models give similar predictions of protons and iron fractions;
- Data are better fit when intermediate masses are included;
- Strong energy dependence of resulting proton fractions, decreasing at higher energies;
- None of the models predicts a significant iron contribution.
Another approach to estimate mass composition: muon production depth (SD)

Reconstruction of $X^\mu$ of an event with $E=(95\pm3)$ EeV, $\theta=59^\circ$ (Gaisser-Hillas fit)
$X_{\text{max}}^\mu$ distributions for proton and iron showers @ 30 EeV

$E=30$ EeV, $\theta = [55^\circ, 65^\circ]$  
EPOS-LHC
MPD analysis:

- Data from 01/2004 – 12/2013
- Energies $> 20$ EeV
- Zenith angles $[55^\circ, 65^\circ]$
- Distances from the core $[1700, 4000]$ m
- 481 events selected
- Systematic uncertainty $17$ g/cm$^2$
- Resolution $100$ (80) g/cm$^2$ @ $10^{19.3}$ eV for $p$ (Fe)
  - $50$ g/cm$^2$ @ $10^{20}$ eV
Mean reconstructed MPD

Muonic elongation rate:

\[ D_{10}^\mu = d\langle X_{\text{max}}^\mu \rangle / d \log E \left[ g/cm^2/\text{decade} \right] \]

**Predictions:**
- 35.9 ± 1.2 (proton)
- 48.0 ± 1.2 (iron)

- Data are bracketed by QGSJetII-04 and fall below EPOS-LHC predictions;
- Data show a flatter trend than predicted for pure \( p \) or Fe showers.
Mean logarithmic mass from MPD and $X_{\text{max}}$

$\langle \ln A \rangle$ from $X_{\text{max}}$ and MPD for EPOS LHC

Consistency of the two $X_{\text{max}}$ allows one to constrain hadronic interaction models.
Correlation of the highest energy cosmic rays with nearby extragalactic matter

VCV: 21/55 events correlating (11.6 expected)
Probability=0.3%
Latest update on the correlation of the highest energy cosmic rays with nearby extragalactic matter

- Isotropy rejected with a 99% C.L.;
- Signal $2\sigma$ above the expected for isotropy: $(33\pm5)\%$ (28/82) instead 21%;
- The proton fraction is small: consistent with $X_{max}$ results.

Large-scale anisotropy: Equatorial dipole amplitude and phase

no clear evidence of anisotropy.. interesting....

prescription still running....
Large-scale anisotropy search

Reconstructed amplitude of the dipole

Reconstructed declination and right ascension of the dipole
Joint Auger and Telescope Array analysis: full-sky coverage

$E > 10^{19}$ eV

Flux sky map in km$^{-2}$ yr$^{-1}$ sr$^{-1}$ using a multipolar expansion up to $\ell = 4$. Significance sky map smoothed out at a 15° angular scale.

Auger: 8259 events
TA: 2130 events
Looking for photons, neutrinos, neutrons....

**Photons:**

**Neutrons from our Galaxy:**

**Neutrinos:**
Summary of the discussion

• The ankle in the spectrum and the change in composition just about a few $10^{18}$ eV; hints of anisotropy on large scale;

• A suppression of the flux above $5 \times 10^{19}$ eV; three events above $10^{20}$ eV; no data for Xmax; point source anisotropy at 2σ.

• EeV photons, galactic neutrons, neutrinos still not detected.

• Constrains on hadronic interaction models: cross section and muon content in showers.
Open questions...

• Is there a (small) proton component at UHE?

• Does the lack of Galactic neutrons indicate that there are no protons at energies around the ankle? No proton sources in our Galaxy?

• Does the suppression reflect the GZK effect ($E^{1/2}$ lower than expected) or otherwise the exhaustion of the sources? Composition studies indicate increasing primary masses; no photons and neutrinos as indirect evidence.
## Possible scenarios:

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<th>Scenario</th>
<th>Description</th>
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| **photodisintegration** | Sources accelerate nuclei up to a $E_{\text{max}}$  
Light elements are fragments of heavier nuclei  
Cut-off would be due to energy loss of nuclei in photodisintegration  
Light elements appear at $E$ shifted by the ratio $M_{\text{daughter}}/M_{\text{parent}}$  
N-Si nuclei at the sources, no protons |
| **maximum energy** | Sources accelerate nuclei up to a $E_{\text{max}} \propto Z$  
Composition in the source similar to the Galactic one  
Cut-off: $E_{\text{max}}$ would be reached in the source  
Composition getting heavier for increasing energy  
Protons at the ankle are of extragalactic origin, no GZK $\gamma$ or $\nu$ |
| **proton dominance** | The all particle flux consists of extragalactic protons  
The source has a cut-off energy  
Cut-off: energy loss processes for protons is pion-photoproduction  
Ankle due to pair production of protons on CMB photons  
New physics to explain heavier composition at UHE |

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*Special thanks to A. Castellina, Vulcano Workshop 2014*
Coming back to the beginning of this talk...
Plan for the future:

Motivation: find out origin of the cut-off and composition:
- GZK or $E_{max}$ of sources?
- Proton fraction at UHE?
- Help to constrain hadronic interaction models.

Continue operation up to 2023 with upgraded detectors, improving:
- electronics,
- discrimination of muonic/electromagnetic components.
Conclusion

• Rich harvest of data;
• Broad Science Program;
• Stable operation + Enhancements;
• Experimental Breakthroughs;
• First $\sigma_{p\text{-}air}$ & $\sigma_{pp}$ well above LHC energies;
• Anisotropies stabilizing;
• Photons and neutrinos nearing GZK regime.
ACKNOWLEDGEMENTS

THANKS FOR YOUR ATTENTION!