Recent results on UHE cosmic rays from the Pierre Auger Observatory

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The University of Adelaide, Australia

Photo: Steven Saffi, University of Adelaide

TeVPA Sydney, December 2019
The Pierre Auger Collaboration

Collaboration founded in 1995

Observatory founded in 1999, construction completed in 2008

~500 members, 89 institutions
November 2019
14-15: Scientific Symposium
Guided tour to the Observatory
16: Anniversary Celebration

https://www.auger.org/

We will celebrate in Malargüe
... Join us!

Tour to the field
Workshop where the idea that Auger should be a “hybrid” observatory was born!
The Pierre Auger Observatory

Water-Cherenkov detector
10 m², 1.2 m deep

3000 km²
1661 water-Cherenkov detectors
(on 1500 m or 750 m triangular grid)
27 fluorescence telescopes (4 sites)

Schmidt telescope
3.4 m diameter mirror
2.2 m diameter aperture
440-pixel camera
UV filter and corrector lenses
The Pierre Auger Observatory

**4 Fluorescence Sites**
- 24 telescopes, 1-30° FoV

**Underground Muon Detectors**
- 7 in engineering array phase - 61 aside the Infill stations

**HEAT**
- 3 high elevation FD, 30-60° FoV

**AERA radio antennas**
- 153 graded 17 km²

+Atmospheric monitoring devices
  CLF, XLF, Lidars, …

Water-Cherenkov stations
- SD1500 : 1600, 1.5 km grid, 3000 km²
- SD750 : 61, 0.75 km grid, 25 km²
Energy Scale of the Observatory is Based on Fluorescence Measurements

\[ E_{FD} = E_{cal} + E_{inv} \]

\[ \sigma(E_{FD})/E_{FD} \sim 8\% \]

systematic uncertainty \sim 14\%

A.Aab et al., [Auger Collaboration] PRD 100, 082003 2019
Energy Spectrum

Scaled Flux $E^3 J(E) / (eV^2 km^2 sr^{-1} yr^{-1})$

Auger Measurements

Uncorrelated $\sigma_{sys}$

Sys. Error 14%

SD 750m Array

Auger FD Cherenkov

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

10^{19} \rightarrow 10^{20} [eV]

18.5 \rightarrow 19.5 \rightarrow 20 \rightarrow 

log_{10} (E/eV)

Events 215030
Exposure 60426 km$^2$ sr yr

$J_{raw}$ 1500m $\theta < 60^0$

$J$ unfolded

Energy spectrum

Exposure [km$^2$ sr yr] | Events
--- | ---
SD1500 ($\theta < 60^\circ$) | 60426 | 215030
SD1500 ($\theta > 60^\circ$) | 17447 | 24209
SD750 | 105.4 | 569285
Hybrids | 2248 ($10^{19}$ eV) | 13655
Cherenkov | 286 ($10^{17}$ eV) | 69793

Evolution of spectral slope with energy $\frac{dN}{dE}$.
The energy spectrum

Combined spectrum (components shifted within uncorrelated uncertainties)

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

\[ \gamma_0 = 2.92 \pm 0.05 \]
\[ \gamma_1 = 3.27 \pm 0.05 \]
\[ \gamma_2 = 2.2 \pm 0.2 \]
\[ \gamma_3 = 3.2 \pm 0.1 \]
\[ \gamma_4 = 5.4 \pm 0.6 \]

Events 891972
Exposure \( \sim 80000 \ \text{km}^2 \text{sr yr} \)

\[ E_{01} = 0.15 \pm 0.02 \]
\[ E_{12} = 6.2 \pm 0.9 \]
\[ E_{23} = 12 \pm 2 \]
\[ E_{34} = 50 \pm 7 \]

(energies in EeV units)

Except at the highest energies, uncertainties dominated by systematics

New feature

15 events above \( 10^{20} \ \text{eV} \)
\[ E_{\text{cal}} = \int \frac{dE}{dX} \, dX \]

\[ \sigma_{X_{\text{max}}} \leq 20 \, \text{g/cm}^2 \]
\[ \Delta_{\text{sys}} \leq 10 \, \text{g/cm}^2 \]

\[ \sigma E / E \sim 8\% \]
\[ \Delta_{\text{sys}} \approx 15\% \]
Mass Composition

- $750\, \text{m array}$
- $1500\, \text{m array}$

Correlation = 0.39
Correlation = 0.46

$X_{\text{max}} \leq 20\, \text{g/cm}^2$
$\Delta_{\text{sys}} \leq 10\, \text{g/cm}^2$

$E_{\text{cal}} = \int \frac{dE}{dX} \, dX$

$\sigma_{E/E} \sim 8\%$
$\Delta_{\text{sys}} \approx 15\%$
Energy Dependence of $X_{\text{max}}$

$X_{\text{max}}$ resolution

~25 g cm$^{-2}$ at $10^{17.8}$ eV

~15 g cm$^{-2}$ for $E > 10^{19}$ eV

$\sigma_{\text{sys}} \leq 10$ g cm$^{-2}$

<table>
<thead>
<tr>
<th>$\log_{10}(E/\text{eV})$</th>
<th>FD</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.5-18.6</td>
<td>1098</td>
</tr>
<tr>
<td>18.6-18.7</td>
<td>834</td>
</tr>
<tr>
<td>18.7-18.8</td>
<td>578</td>
</tr>
<tr>
<td>18.8-18.9</td>
<td>469</td>
</tr>
<tr>
<td>18.9-19.0</td>
<td>356</td>
</tr>
<tr>
<td>19.0-19.1</td>
<td>281</td>
</tr>
<tr>
<td>19.1-19.2</td>
<td>191</td>
</tr>
<tr>
<td>19.2-19.3</td>
<td>131</td>
</tr>
<tr>
<td>19.3-19.4</td>
<td>111</td>
</tr>
<tr>
<td>19.4-19.5</td>
<td>66</td>
</tr>
<tr>
<td>&gt; 19.5</td>
<td>62</td>
</tr>
<tr>
<td>Total</td>
<td>4177</td>
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Mean $X_{\text{max}}$ and its fluctuations from FD

Composition becoming lighter up to $\sim 2 \times 10^{18}$ eV, heavier above this energy

Primary mass not constant with energy, in agreement with more direct fluorescence measurements
Combined fit of spectrum and Xmax data - astrophysics

A. Aab et al. [Auger Collaboration] JCAP 04 (2017) 038

ICRC2019, Madison

Simple model: uniformly distributed identical sources, nuclei accelerated via a rigidity-dependent mechanism.

Result: relatively low maximum acceleration energies, hard spectra and heavy chemical composition.
Large-scale anisotropy

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<th>Energy [EeV] interval</th>
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<th>$d_\perp$</th>
<th>$d_z$</th>
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<th>$\alpha_d$ [°]</th>
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<td>4 - 8</td>
<td>5.0</td>
<td>0.010$^{+0.007}_{-0.004}$</td>
<td>$-0.016 \pm 0.009$</td>
<td>$0.019^{+0.009}_{-0.006}$</td>
<td>$70 \pm 34$</td>
<td>$-57^{+24}_{-20}$</td>
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<td>$\geq 8$</td>
<td>11.5</td>
<td>0.060$^{+0.010}_{-0.009}$</td>
<td>$-0.028 \pm 0.014$</td>
<td>$0.066^{+0.012}_{-0.008}$</td>
<td>$98 \pm 9$</td>
<td>$-25 \pm 11$</td>
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Amplitude increasing with energy

Exposure $> 92000$ km$^2$ sr yr for events with $\theta < 80^\circ$

3D dipole above $8 \times 10^{18}$ eV at ($\alpha, \delta$) = ($98^\circ, -25^\circ$): $(6.6^{+1.2}_{-0.8})\%$

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Amplitude increasing with energy

Search for large scale anisotropies down to 0.03 EeV
- SD1500 + SD750 data,
- East-West method below 2 EeV (to minimise detector systematics)

Predominantly galactic origin below 1-2 EeV, extragalactic origin above

Intermediate-scale anisotropy - blind scan & Cen A

Total SD events with $E>32$ EeV: 2157
Total exposure $101,400$ km$^2$ sr yr

Blind search

Scan ranges:
$32$ EeV $\leq Eth \leq 80$ EeV (1 EeV steps)
$1^\circ \leq \psi \leq 30^\circ$ (1$^\circ$ steps)

Most significant excess for $E>38$ EeV
$$(\alpha=202^0, \delta=-45^0) \sim 2^0 \text{ from CenA}$$

2.5% post-trial chance probability

Centaurus A

$3.9 \sigma$ effect (post-trial)
for $E>37$ EeV, $28^0$ window

**Intermediate-scale anisotropy - catalog search**

**γ AGNs**
3FHL catalog < 250 Mpc
33 sources (CenA, Fornax A, M87…)
Flux proxy $\phi (>10 \text{ GeV})$

**Starburst Galaxies**
32 sources (Circinus, M82, M83,…)<250 Mpc
Flux proxy $\phi (>1.4 \text{ GHz}), > 0.3 \text{ Jy}$

**Swift-BAT**
>300 radio loud and quiet sources
<250 Mpc
$\phi > 13.4 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$

**2MRS**
$\sim 10^4$ sources with $D > 1 \text{ Mpc}$
<250 Mpc
Flux proxy K-band flux.

**Likelihood analysis**

$$TS = 2 \log \left[ \frac{L(\psi, f_{\text{anis}})}{L(f_{\text{anis}} = 0)} \right]$$

<table>
<thead>
<tr>
<th>Catalog</th>
<th>$E_{\text{th}}$</th>
<th>TS</th>
<th>Local p-value</th>
<th>post-trial</th>
<th>$f_{\text{aniso}}$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starburst</td>
<td>38 EeV</td>
<td>29.5</td>
<td>$4 \times 10^{-7}$</td>
<td>4.5 $\sigma$</td>
<td>11$^{+3}_{-4}$%</td>
<td>15$^{+5}_{-4}$°</td>
</tr>
<tr>
<td>γ-AGN</td>
<td>39 EeV</td>
<td>17.8</td>
<td>$1 \times 10^{-4}$</td>
<td>3.1 $\sigma$</td>
<td>6$^{+4}_{-3}$%</td>
<td>14$^{+6}_{-4}$°</td>
</tr>
<tr>
<td>Swift-BAT</td>
<td>38 EeV</td>
<td>22.2</td>
<td>$2 \times 10^{-5}$</td>
<td>3.6 $\sigma$</td>
<td>8$^{+4}_{-3}$%</td>
<td>15$^{+6}_{-4}$°</td>
</tr>
<tr>
<td>2MRS</td>
<td>40 EeV</td>
<td>22.0</td>
<td>$2 \times 10^{-5}$</td>
<td>3.6 $\sigma$</td>
<td>19$^{+10}_{-7}$%</td>
<td>15$^{+7}_{-4}$°</td>
</tr>
</tbody>
</table>

*(given source smearing, clearly some overlap between catalogs)*
Intermediate-scale anisotropy - catalog search

Rejection of isotropy hypothesis

[Jan 2004-Apr 2017] 4.0σ for SBGs
[Jan 2004-Aug 2018] 2.7σ for γ-AGN

ICRC2019
[Jan 2004-Aug 2018] 4.5σ for SBGs
[Jan 2004-Aug 2018] 3.1σ for γ-AGN

Significance increasing with time!
Cosmogenic neutrino and photon limits

Neutrinos

\[
p + \gamma \rightarrow n + \pi^+ \\
\rightarrow \mu^+ + \nu_\mu \\
\rightarrow e^+ + \nu_\mu + \nu_e
\]

\[
k = \frac{N_{up}}{\int_{E_\nu} E_\nu^2 \epsilon_{tot}(E_\nu) dE_\nu}
\]

\[
p + \gamma \rightarrow p + \pi^0 \\
\rightarrow \gamma + \gamma
\]

Maximum sensitivity around EeV
\[k \ (90\% \ CL) < 4.4 \times 10^{-9} \ \text{GeV cm}^{-2} \ \text{s}^{-1} \ \text{sr}^{-1}\]

Most sensitive EAS detector for \[E_r > 0.2 \ \text{EeV}\]

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Exclusion of a significant region of parameter space \((z_{\text{max}}, m)\) from non-observation of neutrinos

Excluded: high max \(z\) of CR acceleration and/or rapid source evolution
Muon content in air showers - hadronic interaction physics

In the energy range $3 \times 10^{17}$ eV to $2 \times 10^{18}$ eV simulations fail to reproduce muon densities.

38% (53%) increase in $< N_\mu >$ at 1EeV needed for EPOS-LHC (QGSJetII-04)

(consistent with a number of other measurements at Auger)

Fluctuations in the muon content of air showers

Observing very inclined air showers with the main surface detector array

Fluctuations in the muon number — a probe of the first interaction at ultra-high energy.

Post-LHC models give a good description of particle production in the first interaction.
AugerPrime - science case for the upgrade

- Study the highest energy cosmic rays (spectral suppression region) with mass composition information
- Select light primaries for charged particle astronomy
- Provide better estimates of the UHE neutrino and photon fluxes. Establish potential for future experiments.
- Better measure shower components, study hadronic physics, search for non-standard physics

Auger operations extended to beyond 2025

So far, event by event mass estimates limited to 13% FD duty cycle
AugerPrime - deployment underway

Mass-composition information for all events, including the very highest energies.

- Engineering array (12 stations) since 2016, scintillator (SSD), new electronics (faster sampling, increased dynamic range)
- Pre-production SSD array (80 stations) since March 2019.
- 559 SSD stations installed up to now (Nov 2019)
- Underground muon detector (UMD) construction continues
- New: 3000 km² radio detector

Water-Cherenkov detector (WCD) with new surface scintillator detector (SSD) and new radio antenna.
Significance of distinguishing two different realisations of Scenario 1 (maximum rigidity model):
- as it predicts, i.e. no protons at UHE
- adding 10% protons

>5σ in 5 years of operations

Conclusion and Outlook

- Auger continues to provide a rich array of results, including increasingly significant anisotropies.

- AugerPrime will offer mass (charge) estimates for 100% of events (improved sky maps).

- We will double our exposure in the next 10 years, before any future observatory takes over.
Backup
Agree in the ankle region $10^{18.4} \text{ eV} < E < 10^{19.4} \text{eV}$ after rescaling

Difference above $10^{19.4} \text{ eV}$ persists after locking energy scales of experiments
Full sky search with Auger and Telescope Array

Large Scale Anisotropy

Energy threshold
- 8.86 EeV (Auger)
- 10 EeV (Telescope Array)

Events
- ~31000 events

Intermediate Scale Anisotropy

Energy threshold
- 40 EeV (Auger)
- 53.2 EeV (Telescope Array)

Events
- 969 events

Blind search
- ($\alpha=12^h50^m, \delta=-50^\circ$), 4.7 local sign (2.6 post-trial)
- ($\alpha=9^h30^m, \delta=+54^\circ$), 4.2 local sign (1.5 post-trial)

Local Sheet
- 26% higher flux in a band of $\pm24^\circ$ around the Local Sheet (global significance $2.8\sigma$)

Agreement with Auger alone, smaller uncertainty
Hint for a quadrupole moment

$\begin{align*}
  d_x &= (-0.7 \pm 1.1_{\text{stat}} \pm 0.01_{\text{calib}})\% \\
  d_y &= (+4.2 \pm 1.1_{\text{stat}} \pm 0.04_{\text{calib}})\% \\
  d_z &= (-2.6 \pm 1.3_{\text{stat}} \pm 1.4_{\text{calib}})\% (\pm 1.9_{\text{tot}})
\end{align*}$
Summary

\( \langle X_{\text{TA}}^{\text{Auger}} \rangle < \langle X_{\text{max}}^{\text{Auger}} \rangle \) for almost all energies

agreement within (stat + sys) errors

\( \sigma(X_{\text{TA}}^{\text{Auger}}) > \sigma(X_{\text{max}}^{\text{Auger}}) \) for \( \lg(E/\text{eV}) = 18.6 - 19.0 \)

Next: comparison to Auger ICRC (2017) data and energies \( \lg(E/\text{eV}) > 19.0 \)