The Pierre Auger Observatory

Latest results and future perspectives

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Ultra-high energy cosmic rays

$10^{18}$ eV to more than $10^{20}$ eV

What are the sources?

How are they accelerated?

How do they propagate?

How do they interact in the atmosphere?

LHC with Mercury orbit @ $10^{20}$ eV
The Pierre Auger Observatory

Located in Argentina, Province of Mendoza

Area of 3000 km$^2$ (4 x Berlin)

Collaboration includes

- 16 countries
- ∼90 institutions
- ∼450 authors
The Pierre Auger Observatory

Water-Cherenkov stations
- SD1500: 1600, 1.5 km grid, 3000 km²
- SD750: 61, 0.75 km grid, 25 km²
- ~100% duty cycle

4 Fluorescence Sites
- 24 telescopes, 1-30° field of view
- HEAT: 3 high-elevation FD, 30-60° field of view
- ~15% duty cycle

+ Atmospheric monitoring devices
Event reconstruction and energy scale

Longitudinal profile
\[ E \propto \int \frac{dE}{dX} dX \]

Lateral distribution
\[ S(r_{\text{opt}}) \propto E \]

Total energy: \( E_{\text{FD}} = E_{\text{cal}} + E_{\text{inv}} \)

\[ \sigma(E_{\text{FD}})/E_{\text{FD}} \sim 8\% \]
Systematic uncertainty of 14%

Using events which are well reconstructed by both detectors
Energy spectrum

![Graph showing the energy spectrum with the energy axis on a logarithmic scale and the intensity axis on a linear scale. The data points represent the Auger (ICRC 2017) measurement.](image)
Energy spectrum

Extension of energy range by

- update to particle triggers in SD stations
- extension of FD reconstruction to low-energetic air showers (showers with high Cherenkov fraction)

Indication of second knee

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

\[
\begin{align*}
E_{01} &= 0.15 \pm 0.02 \\
E_{12} &= 6.2 \pm 0.9 \\
E_{23} &= 12 \pm 2 \\
E_{34} &= 50 \pm 7 \\
\end{align*}

(energies in EeV units)

Events 891972

Exposure ~80000 km$^2$ sr yr

\[
\gamma_0 = 2.92 \pm 0.05 \\
\gamma_1 = 3.27 \pm 0.05 \\
\gamma_2 = 2.2 \pm 0.2 \\
\gamma_3 = 3.2 \pm 0.1 \\
\gamma_4 = 5.4 \pm 0.6 \\
\]
Evolution of $\langle X_{\text{max}} \rangle$ with energy

$X_{\text{max}}$: depth of shower maximum, one of the most robust observables for mass composition analysis

Change of composition @ $E \sim 2$ EeV
Evolution of \( \langle X_{\text{max}} \rangle \) with energy

\( X_{\text{max}} \): depth of shower maximum, one of the most robust observables for mass composition analysis

Change of composition \( @ E \sim 2 \text{ EeV} \)
Composition is getting lighter below $E \sim 2$ EeV and heavier above.

Decrease of fluctuations above $10^{18.3}$ eV indicates trend towards heavier composition.

No composition data @ and above onset of suppression.

Composition fractions from description of full $X_{\text{max}}$ distribution.
Large scale anisotropy

Energies above 8 EeV

Harmonic analysis in right ascension $\alpha$

Significant dipolar modulation ($5.2\sigma$) above 8 EeV: $(6.6^{+1.2}_{-0.8})\%$ at $(\alpha, \delta) = (98^\circ, -25^\circ)$

Expected if CRs diffuse to Galaxy from sources distributed similar to nearby galaxies

Dipole points $\sim 125^\circ$ away from the galactic center $\rightarrow$ indication for extragalactic origin
Large scale anisotropy

$4 \text{ EeV} \leq E \leq 8 \text{ EeV}$

galactic coordinates

Dipole direction for different energy bins

Amplitude increases with energy.

Energy-independent amplitude is disfavored at the level of $5.1\sigma$
Large scale anisotropy

Search at lower energies

Amplitudes grow with energy from sub-% to above 10%
Phases shift from $\sim$ galactic center direction to $\sim$ opposite direction

Predominantly galactic origin below $\sim$1 EeV, extragalactic origin above
Search for Intermediate-scale Anisotropies

Sky models for two distinct populations of extragalactic gamma-ray emitters

**Intermediate**: experimental resolution \( \sim 1^\circ \) < angular scale < \( 45^\circ \)

**Active Galactic Nuclei**
- 2FHL Catalog (Fermi-LAT, 360 sources)
- \( \phi_{\gamma}(>50 \text{ GeV}) \) as proxy for UHECR flux
- 17 bright nearby sources \( (D < 250 \text{ Mpc}) \)

**Star-forming or Starburst Galaxies**
- Fermi-LAT search list
- \( \phi_{\text{radio}}(>1.4 \text{ GHz}) > 0.3 \text{ Jy} \) as proxy
- 23 brightest objects \( (D < 250 \text{ Mpc}) \)

**Likelihood ratio analysis**
- smearing angle \( \Psi \)
- \( H_0 : \text{isotropy} \)
- \( H_1 : (1 - f) \times \text{isotropy} + f \times \text{fluxMap}(\Psi) \)
- \( \text{TS} = 2 \log(H_1/H_0) \)
Search for Intermediate-scale Anisotropies

**NGC 253**
- 2.5 Mpc

**NGC 1068**
- 16.7 Mpc

**Starburst**
- \( f = 10\% \), \( \Psi = 13^\circ \)
- 3.9\( \sigma \)

**NGC 4945**
- M 83
- 3.7 Mpc

**CenA**
- 4 Mpc

**AGN**
- \( f = 7\% \), \( \Psi = 7^\circ \)
- 2.7\( \sigma \)
Searches for cosmogenic neutrinos

**Production**: \( N + \gamma_{\text{CMB}} \rightarrow N + \pi^\pm \) and \( \pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \) and \( \mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu (\nu_\mu) + \nu_e (\bar{\nu}_e) \)

**Identification**: Highly inclined showers.  
**Nuclei**: no electromagnetic component. **Neutrinos**: deep showers, large electromagnetic component.
Assumption of differential neutrino flux: $dN(E_\nu)/dE_\nu = k \cdot E_\nu^{-2}$

$k \sim 4.4 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
Upgrade - Motivations

Study the origin of suppression at the highest energies

Mass composition at the highest energies

Select light primaries for charged particle astronomy

Improve estimates of neutrino and gamma flux

Improve measurement of shower components to deepen the study of hadronic interactions at ultra-high energies

Improve sensitivity to composition by disentangling the electromagnetic and muonic components
Upgrade to AugerPrime

+ extended dynamic range and new electronics of the SD, extended duty cycle of the FD

Complementarity of particle response used to discriminate electromagnetic and muonic components

hybrid: $E_{\text{rad}}$ from radio, muons from water-Cherenkov stations
Upgrade to AugerPrime

→ 12 upgraded stations (Engineering Array) since 2016 with new electronics, higher sampling, large dynamic range
→ SSD preproduction array: 80 stations (since 03/2019)
→ 356 SSD stations already deployed
+ Underground Muon detector, + largest radio detector
Summary

**Spectrum** → high statistics measurement from $10^{17.5}$ eV to $\sim 10^{19.5}$ eV, 15 events above $10^{20}$ eV

**Mass composition** → light @ ankle, mixed @ higher energies

**Arrival direction** → dipolar modulation @ large scales
→ amplitude increasing with energy

→ @ intermediate scales, most significant excess found for densely-populated region, significance of starburst model increased with more data

**Neutrino search** → constraints on p-dominated sources

*Thanks for your attention!*
Backup slides
Intermediate scale anisotropy

Search for event excess using a blind search

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

Scan ranges:
$32$ EeV $\leq E \leq 80$ EeV in $1$ EeV steps
$1^\circ \leq \psi \leq 30^\circ$ in $1^\circ$ steps

Cen A (active galactic nucleus)

NGC 4945 (starburst galaxy)

Most significant excess found for $E > 38$ EeV with a local significance of $5.6\sigma$ ($2.5\sigma$ post-trial)
Intermediate scale anisotropy

Matching with candidate sources

**Assumption**: bright objects have a higher contribution to the CR flux

Likelihood analysis $TS = 2 \log [L(\Psi, f)/L(f=0)]$. $\Psi$ = search radius, $f$ = anisotropy fraction

<table>
<thead>
<tr>
<th>Catalog</th>
<th>$E$/EeV</th>
<th>$\Psi/\degree$</th>
<th>$f/%$</th>
<th>TS</th>
<th>Post-trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starburst</td>
<td>38</td>
<td>$15^{+5}_{-4}$</td>
<td>$11^{+5}_{-4}$</td>
<td>29.5</td>
<td>4.5$\sigma$</td>
</tr>
<tr>
<td>$\gamma$-AGNs</td>
<td>39</td>
<td>$14^{+6}_{-4}$</td>
<td>$6^{+4}_{-3}$</td>
<td>17.8</td>
<td>3.1$\sigma$</td>
</tr>
<tr>
<td>Swift-Bat</td>
<td>38</td>
<td>$15^{+6}_{-4}$</td>
<td>$8^{+4}_{-3}$</td>
<td>22.2</td>
<td>3.7$\sigma$</td>
</tr>
<tr>
<td>2MRS</td>
<td>40</td>
<td>$15^{+7}_{-4}$</td>
<td>$19^{+10}_{-7}$</td>
<td>22.0</td>
<td>3.7$\sigma$</td>
</tr>
</tbody>
</table>

Arrival direction of CRs above 38 EeV best matched by model with $\sim 11\%$ clustered around nearby & bright starburst galaxies

*flux attenuation due to propagation*
Point-like sources of UHE $\nu$

Steady sources

- Complementary energy range to IceCube and ANTARES
- Good sensitivity at EeV energies in a broad declination range
- Best sensitivity where sources spend more time in Earth-skimming field of view

* DG = downward-going high/low

Transient sources

- Example of transient sources: 21 binary black hole mergers detected by Ligo-Virgo
- 24h follow-up search after BBH merger
- No neutrinos found
- Sensitivity improved by combining the sources