Recent Highlights from the Pierre Auger Observatory

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on behalf of the Pierre Auger Collaboration
for the 53rd Rencontres de Moriond
PAO – detection of Ultrahigh energy cosmic rays

- largest cosmic ray detector so far built, covering over 3000 km$^2$

- hybrid detector – combination of two detection techniques allows for cross calibration of the two techniques and eliminates model dependence

- international collaboration of more than 450 scientists from 16 countries of the World

- located in the southern hemisphere, near the town of Malargue, Mendoza province, Argentina

- in operation since 2004, completed in 2008
Hybrid observation

Surface detector

- 1660 Water Cherenkov stations
- 12 tons of ultra pure water
- the volume is observed from the top by three large photo-multipliers
- placed in a triangular grid 1.5 km apart ~ 3000 km²
- solar panel and accumulator cover the energy consumption of the station continuously

+ functions continuously (almost 100% of the time)
- does not observe the longitudinal development of the shower
- primary energy determination depends on simulations
Hybrid observation

Fluorescence detector

- shower particles excite nitrogen in the atmosphere, which then de-excites in 300 – 400 nm band

- amount of light is proportional to the deposited energy

- 24 telescopes in 4 buildings

- 30° by 30° field of view (Schmidt corrector ring),
  - viewing up to 30° above horizon

- functions only during clear, moonless nights (about 15% of the time)

+ observes directly the location of the shower maximum (indicative of primary mass)

+ nearly calorimetric measurement (model independent)
Observatory enhancements

- **HEAT**: 3 telescopes pointing above the standard FOV
  - lowering the energy threshold down to 0.1 EeV

- **AMIGA**: 61 underground muon counters
  - composition and hadronic interaction study

- **INFILL**: 61 WCD in half distance (750 m)
  - extends energy range of SD to $3 \times 10^{17}$ eV (full efficiency)

- **AERA**: 153 radio stations on 17 km$^2$
  - coherent radiation of secondaries in 30-80 MHz band
  - independent energy scale
Observatory layout
Science results include:

- energy spectrum
- arrival directions
- mass composition

- limits on the presence of photons and neutrinos
- cross section of proton-air interaction
- verification of hadronic interaction models

will concentrate on three papers published in the last six months concerning arrival direction
Energy spectrum

- combined from four data sets

- ankle region measured with high precision
  \[ E_{\text{ankle}} = (5.08 \pm 0.06 \pm 0.8) \times 10^{18} \text{ eV} \]

- slope below ankle
  \[ \gamma_1 = (3.293 \pm 0.002 \pm 0.05) \]

  above ankle
  \[ \gamma_2 = (2.53 \pm 0.02 \pm 0.10) \]

- strong suppression above \(10^{19.5}\) eV

- origin is not clear – GZK limit or end of the cosmic accelerator power (composition dependent)
Arrival directions
Large scale distribution

Data set:
- Jan 1, 2004 up to Aug 31, 2016 – total exposure 76 800 km²sr year
- large range of zenith angles up to 80° - 85% sky coverage
- $E > 4$ EeV (full efficiency for inclined showers)

- divided into two energy bins:
  - $4 \text{ EeV} < E < 8 \text{ EeV}$ : ~ 80 000 events
  - $E > 8 \text{ EeV}$ : ~ 30 000 events

- no significant departure from isotropy in the first bin

- In higher energy bin – dipole structure $\sim 5.2 \sigma$ significance

<table>
<thead>
<tr>
<th>Energy (EeV)</th>
<th>Dipole component $d_z$</th>
<th>Dipole component $d_\perp$</th>
<th>Dipole amplitude $d$</th>
<th>Dipole declination $\delta_d$ (°)</th>
<th>Dipole right ascension $\alpha_d$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 to 8</td>
<td>$-0.024 \pm 0.009$</td>
<td>$0.006^{+0.007}_{-0.003}$</td>
<td>$0.025^{+0.010}_{-0.007}$</td>
<td>$-75_{-8}^{+17}$</td>
<td>$80 \pm 60$</td>
</tr>
<tr>
<td>≥8</td>
<td>$-0.026 \pm 0.015$</td>
<td>$0.060^{+0.011}_{-0.010}$</td>
<td>$0.065^{+0.013}_{-0.009}$</td>
<td>$-24_{-13}^{+12}$</td>
<td>$100 \pm 10$</td>
</tr>
</tbody>
</table>
Arrival directions
Large scale distribution

equatorial coordinates
- - - - Galactic plane
* Galactic center

- cosmic ray flux above 8 EeV
- smeared by 45° top-hat function
- 3D dipole, amplitude 6.5%
- pointing to $(\alpha, \delta) = (100°, -24°)$

Science 357 (22 September 2017) 1266
Arrival directions
Large scale distribution

- indication of extragalactic origin
- distribution of nearby galaxies is also dipolar
  - 2MRS catalogue dipole points 55° away

Science 357 (22 September 2017) 1266
Search for neutrinos in correlation with GW

signatures of a neutrino at PAO
Search for neutrinos associated with GW170817

- binary neutron star merger
- GW detected by LIGO-VIRGO
- associated short GRB by Fermi-GBR and INTEGRAL
- UV, optical and IR observation
- location in NGC 4993 ~ 40 Mpc distance
- X-ray and radio detection followed

no neutrino candidate found in ± 500 seconds, nor in a period of next 14 days, compatible with expectations for GRB observed off-axis multimessenger observation by many instruments
Arrival directions
Hints of intermediate scale anisotropy

**Data set:**
- 5514 events above 20 EeV
- zenith angles up to 80°

**4 sky models:**
- \(\gamma\)AGN: blazars and radio-loud AGNs selected from 2FHL catalog of Fermi-LAT
- SBG: 23 starburst galaxies from the list examined by Fermi-LAT
- Swift-BAT X-ray sources
- 2MRS IR catalog (includes both AGN and SBG)

- statistical analysis performed – likelihood ratio test between sky model and isotropic model
- test statistics maximized with respect to two parameters: search radius and a fraction of anisotropy
Arrival directions
Hints of intermediate scale anisotropy

\textbf{top: starburst galaxies}

\begin{itemize}
  \item [Observed Excess Map - \(E > 39\) EeV]
  \item [Model Excess Map - Starburst galaxies - \(E > 39\) EeV]
  \item [Residual Excess Map - Starburst galaxies - \(E > 39\) EeV]
  \item [Observed Excess Map - \(E > 60\) EeV]
  \item [Model Excess Map - Active galactic nuclei - \(E > 60\) EeV]
  \item [Residual Excess Map - Active galactic nuclei - \(E > 60\) EeV]
\end{itemize}

\textbf{bottom: \(\gamma\)AGN}

\begin{itemize}
  \item [Beam size \(N_{\text{beam}} = 40\)]
  \item [Beam size \(N_{\text{beam}} = 15\)]
\end{itemize}

\begin{itemize}
  \item [Beam size \(N_{\text{beam}} = 10\)]
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highest significance \(4.0\sigma\) achieved for SBG fraction 10% an search radius 13°
other models are favored against isotropy with significances 2.7-3.2\(\sigma\)

\textbf{astro-ph.HE: 1801.06160}
Mass composition

How we do it:

\[
\begin{align*}
\text{depth } X \text{ (g/cm}^2) & \quad \text{number of particles} \\
X_1 & \quad \text{first interaction} \\
\Delta X_1 & \\
\Delta X_{\text{max}} & \\
\text{Fe} & \\
p &
\end{align*}
\]
Mass composition from the fluorescence detector only

- composition is mixed
- mixture is energy dependent - getting heavier with energy
- missing information in the flux suppression region
Upgrade motivation

- **mass composition information in the flux suppression region**
  - distinguish between propagation effect and maximum energy from astrophysical sources

- **search for a proton flux at highest energies**
  - reach sensitivity to a contribution as low as 10%

- **air shower physics and hadronic multiparticle production studies**
  at energies beyond LHC reach (muon excess compared to interaction models)
SD upgrade implementation

- scintillation panel above each SD station
  - separating the electromagnetic and muonic part of the shower

- faster and more powerful electronics

- small PMT in the tank
  - increase the dynamic range, study the hadronic interaction

Timeline

- prototype currently running

- 2018-2019
  - production and deployment

- data taking until 2025
  - roughly double the statistics with composition sensitivity