Recent results from the Pierre Auger Observatory

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Main questions regarding Ultra-High Energy Cosmic Rays:

What are they
Which are the sources
How they get accelerated
What produces the changes in the spectrum & composition
How do they propagate, effects of Galactic and X-gal B fields
What are the effects of interactions with the CMB or EBL
Are neutrinos & photons produced
How are the hadronic interactions at the highest E

Main CR observables:

Spectrum, composition and anisotropies
at the highest energies, only few cosmic rays arrive per km$^2$ per century!

to see some, huge detectors are required
The Pierre Auger Observatory

Malargüe, Argentina

3000 km²

the Auger Collaboration: ~ 400 scientists, 17 countries, taking data since 2004

Argentina Australia Belgium Brazil Czech-Republic France Germany Italy Mexico Netherlands Poland Portugal Slovenia Spain USA Colombia Romania
HYBRID CONCEPT

Surface Detector
1660 water-Cherenkov stations

SD1500:
1,5 km grid
3,000 km²

SD750:
750 m grid
24 km²

FD: Fluorescence Detector
24 telescopes in 4 locations

MD: AMIGA
muon detectors

HEAT: 3 higher elevation telescopes

AERA: radio detection
17 km²

AERA:
35.15° S 69.2° W ~ 1400 m a.s.l.
HYBRID CR AIR SHOWER DETECTION

\[ S_{1000} \]

\[ E_{\text{surface}} = f(S_{1000}, \theta) \]

\[ \sigma x_{\text{max}} \leq 20 \text{ g/cm}^2 \]
\[ \Delta_{\text{sys}} \leq 10 \text{ g/cm}^2 \]

\[ X_{\text{max}} \]

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

\[ \sigma_E / E \sim 8\% \]
\[ \Delta_{\text{sys}} \approx 15\% \]
WATER-CHERENKOV SURFACE DETECTORS  
( ~100% duty cycle)

SD1500:
fully efficient for $E > 2.5\,EeV$ ($\theta < 60^\circ$), $> 4\,EeV$ ($\theta < 80^\circ$)

* Vertical spectrum: $\theta < 60^\circ$ and strict trigger requirement  
(all 6 stations around hottest one be active)
→ Exposure [1/04 - 9/18]: $6 \times 10^4$ km$^2$ yr sr

* anisotropies $E>4\,EeV$: $\theta < 80^\circ$ and relaxed trigger  
(hottest station surrounded by 5 or 6 active stations)
→ Exposure [1/04 - 1/21]: $1.1 \times 10^5$ km$^2$ yr sr

* also study muon content, signal rise time, ...

SD750:
fully efficient for $E > 0.3\,EeV$ for $\theta < 55^\circ$), $E>0.1\,EeV$ for $\theta < 40^\circ$ & new trigger
* Measure spectrum and large scale anisotropies down to ~0.1 EeV

FLUORESCENCE DETECTORS
(~13% duty cycle)
Measure $X_{\text{max}}$ → composition, used for E calibration, p-air cross section, spectrum down to ~10$^{16}$ eV,  
observation of Elves, ...
inflection identified at ~13 EeV (steepening), no declination dependence observed
slight offsets between different spectra related to E calibrations
Nuclei behave as \( A \) nucleons with \( E_n = E/A \) → less penetrating, smaller fluctuations
change in $X_{\text{max}}$ slope around 2 EeV

A large spread $\sigma$ can be due to light composition or to admixture of different masses
Inferred composition depends on hadronic model assumption

Composition becomes light approaching 2 EeV and heavier for increasing energies

Very little mass admixture above 10 EeV
$X_{\text{max}}$ from SD signal rise-times

Deeper showers have larger em fraction → longer rise times

Trend towards heavier masses persists at highest energies

[Todero-Peixoto ICRC2019
Phys Rev D 2017 122003-20]
Trying to explain both spectrum and composition in mixed composition scenarios with power-law sources and rigidity cutoff:
favor scenarios with hard spectra (\(dN/dE \sim E^{-1}\)) and low rigidity cutoff (few EV)

Low rigidity cutoff required to avoid admixture of light elements at highest energies

Suggests that suppression is, to a large extent, due to maximum acceleration at the sources

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hard spectra required to avoid too many heavy elements near the ankle

alternatively, source spectrum could be softer (\(\sim E^{-2}\)) but low rigidity CRs don’t have enough time to reach us due to slow diffusion in B fields (magnetic horizon)?

[Mollerach&ER, JCAP 2013]
being charged nuclei, CRs get deflected by Galactic (and extra-galactic) magnetic fields

\[ \delta \approx 3^\circ Z \frac{B}{3 \mu G} \frac{L}{kpc} \frac{6 \times 10^{19} eV}{E} \]

E/Z = 10 EeV

E/Z = 1 EeV

astronomy with CRs may become possible at the highest energies
Large angular scale anisotropies could originate from:

- anisotropies in the distribution of extragalactic CR sources
- diffusive propagation from individual sources
- diffusive escape from the Galaxy

They can be present at all energies

Localized anisotropies at small (few degrees) or intermediate (few tens degrees) angular scales may appear at the highest energies as CR trajectories straighten up
above 4 EeV, SD1500 fully efficient up to $80^\circ \rightarrow$ cover 85% of the sky $(\text{dec} < 45^\circ)$

**equatorial dipole ($d_\perp$), NS component ($d_z$), total amplitude ($d$) and direction**

<table>
<thead>
<tr>
<th>Energy [EeV] interval</th>
<th>$N$</th>
<th>$d_\perp$</th>
<th>$d_z$</th>
<th>$d$</th>
<th>$\alpha_d$ [$^\circ$]</th>
<th>$\delta_d$ [$^\circ$]</th>
</tr>
</thead>
<tbody>
<tr>
<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>69 $\pm$ 46</td>
<td>$-57^{+24}_{-20}$</td>
</tr>
<tr>
<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>
</tr>
<tr>
<td>8 - 16</td>
<td>10.3</td>
<td>$0.056^{+0.012}_{-0.010}$</td>
<td>$-0.011 \pm 0.016$</td>
<td>$0.057^{+0.014}_{-0.008}$</td>
<td>97 $\pm$ 12</td>
<td>$-11 \pm 16$</td>
</tr>
<tr>
<td>16 - 32</td>
<td>20.2</td>
<td>$0.075^{+0.023}_{-0.018}$</td>
<td>$-0.07 \pm 0.03$</td>
<td>$0.10^{+0.03}_{-0.02}$</td>
<td>80 $\pm$ 17</td>
<td>$-44 \pm 14$</td>
</tr>
<tr>
<td>$\geq$ 32</td>
<td>39.5</td>
<td>$0.13^{+0.05}_{-0.03}$</td>
<td>$-0.09 \pm 0.06$</td>
<td>$0.16^{+0.06}_{-0.03}$</td>
<td>152 $\pm$ 19</td>
<td>$-34^{+19}_{-20}$</td>
</tr>
</tbody>
</table>

has $P = 1.4 \times 10^{-9}$ (6σ)
Energy dependence of dipolar modulation

The dipole direction away from the Galactic Center is close to the outer spiral arm in all energy bins above 4 EeV.

The amplitude of the dipole increases with energy, suggesting that at these energies CRs are predominantly extragalactic.

Mathematically, the dipole amplitude $d$ can be expressed as:

$$d(E) = d_{10} \times (E/10 \text{ EeV})^\beta$$

where $d_{10} = 0.051 \pm 0.007$ and $\beta = 0.96 \pm 0.16$.

Consistent with expectations, the data is shown to be consistent with models with a source density of $10^{-4}$ Mpc$^{-3}$ from PRD92 (2015) 063014.

[ER ICRC2019]
We are falling towards a region with more galaxies $\rightarrow$ dipole of the CMB
In this direction there are more galaxies, there should also be more CR sources
extragalactic dipole direction gets shifted towards spiral arms by Galactic B field

Galactic coordinates

GC

outer spiral arm

observed dipole $E > 8 \text{ EeV}$

2MRS dipole

dipole direction outside Galaxy

dipole direction after accounting for Galactic B field for $E/Z = 32, 16, 8$ and $4 \text{ EeV}$

(using Jansson&Farrar 2012 B field model)
phases shift, from around the GC to almost opposite direction

Suggests transition from anisotropies of Galactic origin below ~1 EeV to extragalactic origin above few EeV

Extragalactic component could be sizeable below 1 EeV, as long as it is sufficiently isotropic.
OVERDENSITIES, most significant excess for $E > 38$ EeV and $27^\circ$ radius

(RA=202, dec=-45)
obs/exp = 188/125

Figure 1: Map in Galactic coordinates of the local significance found when searching for excesses in circular windows with $27^\circ$ radius above 38 EeV. The post-trial p-value for the most significant excess is 2.5%. See [ApJ 804 (2015) 15; ApJ Lett. 853 (2018) L29]
Starburst Galaxy catalog compiled by Fermi team (weighted by radio-flux)
AGNs observed by Fermi: mostly Cen A + M87 + Blazars (weighted by gamma flux)
2MRS Galaxies (weighted by IR flux)
Swift-BAT AGNs (weighted by X-ray flux)
Only neutrinos can produce young horizontal showers

0 events observed → bounds scale linearly with exposure
Neutrinos searched in Auger, IceCube and Antares nothing observed \(\rightarrow\) flux upperbounds

Still waiting for simultaneous GW, \(\gamma\) and \(\nu\) observation

(CRs, being charged, arrive much much later)

Also didn’t see UHE\(\nu\) from TXS 0506+056 at Auger [ApJ 2020]
THE FUTURE: ONGOING UPGRADE

SSD: Scintillators on top of the Surface Detectors (2019-2021)

additional scintillator detectors on top of each station
refurbished electronics
small PMT to increase dynamic range

This will make it possible to separate muonic and electromagnetic signals
→ allow for composition measurements event by event
- do astronomy with light nuclear component
and help to understand:
- origin of the flux suppression at highest energies
- proton contribution at the highest energies
- EAS physics and hadronic multiparticle production

AMIGA:
Scintillators underground in Infill

RADIO UPGRADE:
AERA: 17 km²
→ 3000 km²
BACKUP
more muons are produced than expected → hadronic models need revision
fluctuations OK → not just the first interaction, but cumulative effect in shower
Xmax distribution sensitive to depth of first interaction → to p-air cross-section

\[ \Lambda_{\eta} = 55.8 \pm 2.3 \text{ g/cm}^2 \]

18<logE<18.5 would be steeper for larger cross section

p-air cross section looks 'normal'

also pp cross section can be inferred
p-p CROSS SECTION CAN BE INFERRED
Dipole allowing also for the presence of quadrupolar components

Dipole and quadrupole components in the two energy bins. The $x$ axis is in the direction $\alpha = 0^\circ$

<table>
<thead>
<tr>
<th>Energy [EeV]</th>
<th>$d_i$</th>
<th>$Q_{ij}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 - 8</td>
<td>$d_x = -0.001 \pm 0.008$</td>
<td>$Q_{zz} = -0.003 \pm 0.039$</td>
</tr>
<tr>
<td></td>
<td>$d_y = 0.008 \pm 0.008$</td>
<td>$Q_{xx} - Q_{yy} = -0.004 \pm 0.028$</td>
</tr>
<tr>
<td></td>
<td>$d_z = -0.014 \pm 0.022$</td>
<td>$Q_{xy} = 0.006 \pm 0.014$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_{xz} = -0.008 \pm 0.018$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_{yz} = -0.005 \pm 0.018$</td>
</tr>
<tr>
<td>$\geq 8$</td>
<td>$d_x = -0.004 \pm 0.012$</td>
<td>$Q_{zz} = 0.032 \pm 0.061$</td>
</tr>
<tr>
<td></td>
<td>$d_y = 0.054 \pm 0.012$</td>
<td>$Q_{xx} - Q_{yy} = 0.077 \pm 0.048$</td>
</tr>
<tr>
<td></td>
<td>$d_z = -0.011 \pm 0.035$</td>
<td>$Q_{xy} = 0.038 \pm 0.024$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_{xz} = 0.015 \pm 0.029$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_{yz} = -0.016 \pm 0.029$</td>
</tr>
</tbody>
</table>

no significant quadrupolar components
→ dipolar amplitudes consistent with dipole only results
## EQUATORIAL DIPOLE RESULTS ABOVE 0.3 EeV

<table>
<thead>
<tr>
<th></th>
<th>$E$ [EeV]</th>
<th>$N$</th>
<th>$d_\perp$</th>
<th>$\alpha_d$ [°]</th>
<th>$P(\geq d_\perp)$</th>
<th>$d_\perp^{99}$</th>
<th>$d_\perp^{UL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>East-West (SD750)</td>
<td>0.03125 - 0.0625</td>
<td>432,155</td>
<td>0.010$^{+0.010}_{-0.004}$</td>
<td>112 ± 71</td>
<td>0.54</td>
<td>0.028</td>
<td>0.033</td>
</tr>
<tr>
<td></td>
<td>0.0625 - 0.125</td>
<td>924,856</td>
<td>0.006$^{+0.006}_{-0.003}$</td>
<td>-44 ± 68</td>
<td>0.50</td>
<td>0.016</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>0.125 - 0.25</td>
<td>488,752</td>
<td>0.002$^{+0.008}_{-0.002}$</td>
<td>-31 ± 108</td>
<td>0.94</td>
<td>0.019</td>
<td>0.020</td>
</tr>
<tr>
<td>East-West (SD1500)</td>
<td>0.25 - 0.5</td>
<td>770,316</td>
<td>0.006$^{+0.005}_{-0.003}$</td>
<td>-135 ± 64</td>
<td>0.45</td>
<td>0.015</td>
<td>0.018</td>
</tr>
<tr>
<td></td>
<td>0.5 - 1.0</td>
<td>2,388,467</td>
<td>0.005$^{+0.003}_{-0.002}$</td>
<td>-99 ± 43</td>
<td>0.20</td>
<td>0.008</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>1 - 2</td>
<td>1,243,103</td>
<td>0.0018$^{+0.0047}_{-0.0002}$</td>
<td>-69 ± 100</td>
<td>0.87</td>
<td>0.011</td>
<td>0.011</td>
</tr>
<tr>
<td>Fourier (SD1500)</td>
<td>2 - 4</td>
<td>283,074</td>
<td>0.005$^{+0.004}_{-0.002}$</td>
<td>-11 ± 55</td>
<td>0.34</td>
<td>0.010</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>4 - 8</td>
<td>88,325</td>
<td>0.010$^{+0.007}_{-0.004}$</td>
<td>69 ± 46</td>
<td>0.23</td>
<td>0.018</td>
<td>0.026</td>
</tr>
<tr>
<td></td>
<td>8 - 16</td>
<td>27,271</td>
<td>0.056$^{+0.012}_{-0.010}$</td>
<td>97 ± 12</td>
<td>$2.3 \times 10^{-6}$</td>
<td>0.033</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>16 - 32</td>
<td>7,664</td>
<td>0.075$^{+0.023}_{-0.018}$</td>
<td>80 ± 17</td>
<td>$1.5 \times 10^{-3}$</td>
<td>0.063</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\geq$ 32</td>
<td>1,993</td>
<td>0.13$^{+0.05}_{-0.03}$</td>
<td>152 ± 19</td>
<td>$5.3 \times 10^{-3}$</td>
<td>0.12</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\geq$ 8</td>
<td>36,928</td>
<td>0.060$^{+0.010}_{-0.009}$</td>
<td>98 ± 9</td>
<td>$1.4 \times 10^{-9}$</td>
<td>0.028</td>
<td>-</td>
</tr>
</tbody>
</table>