Recent results from the Pierre Auger Observatory

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Outline

Direct observation
Indirect observation (air shower detectors)

Energy spectrum
Anisotropy
Mass composition
Hadronic interactions
Photons
Neutrinos

Pierre Auger Observatory + extensions AMIGA HEAT Radio
Pierre Auger Observatory

AMIGA Radio

Coihueco + HEAT

Malargüe, Argentina
1400 m a.s.l.

Los Morados

Loma Amarilla

Surface detector (SD)
1660 stations
Fluorescence detector (FD)
27 fluorescence telescopes

18 countries
70 institutes
~450 scientists

Exposure > 20000 km² sr yr
600 events / year > 10^{19} eV
15 events / year > 10^{19.7} eV
Measurement principle

Loma Amarilla

Coihueco

Los Morados

Los Leones

cross-calibrated to FD

**Table:**

<table>
<thead>
<tr>
<th>$\sigma$</th>
<th>SD</th>
<th>FD</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>10% - 20%</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>22% (sys)</td>
<td>22% (sys)</td>
</tr>
<tr>
<td>$X_{max}$</td>
<td></td>
<td>20 g cm$^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13 g cm$^{-2}$ (sys)</td>
</tr>
<tr>
<td>$\theta, \phi$</td>
<td>0.5° - 2°</td>
<td>0.6°</td>
</tr>
</tbody>
</table>

Duty cycle

100 %

13 %
Energy spectrum

Physics Letters B 2010


- Auger
  flux corrected for detector smearing effects (unfolding)

SD flux $\sigma_{\text{sys}}$ 6 %
FD flux $\sigma_{\text{sys}}$ <10 %

flux in agreement if
Auger energy +16 %
or
HiRes energy −16 %
Anisotropy

sky map of CR arrival directions in galactic coordinates

active galaxies closer than 75 Mpc from Véron-Cetty & Véron catalogue

color indicates exposure

Auger SD data
69 events with $E > 10^{19.7}$ eV (data up to end of 2009)

21 correlations out of 55 events

$P(\text{data|isotropy}) = 0.3\%$ (not $P(\text{isotropy|data})$)

Correlation signal became weaker
No strong correlation with other catalogs
Auto-correlation not conclusive
Some excess near Centaurus A
Mass composition: FD

\[ \langle X_{\text{max}} \rangle = \alpha (\ln E - \langle \ln A \rangle) + \beta \]

Elongation rate (no \( \beta \)-dependency)

\[ D_{10} = \frac{d\langle X_{\text{max}} \rangle}{d \ln E} \approx \alpha \left( 1 - \frac{d\langle \ln A \rangle}{d \ln E} \right) \ln(10) \]

sudden change at \( 10^{18.24} \) eV suggests change in \( \frac{d\langle \ln A \rangle}{d \ln E} \)

\[ \text{RMS}(X_{\text{max}})^2 = \text{RMS}^2(\text{depth of first interaction}) + \text{RMS}^2(\text{shower development}) \]

data suggests transition from light/mixed to heavy composition or drastic change in hadronic interactions
Mass composition: SD

- Rise time
- XAsymMax = \ln(\sec(\theta)) of max. radial signal asymmetry
- \(X_{\text{max}}\) affects some secondary SD observables
  \(\rightarrow\) more events, less resolution

\(X_{\text{max}}\) affects some secondary SD observables

energies used in anisotropy study

Cross-calibrated to \(X_{\text{max}}\):

- XAsymMax
- Rise time (relative to benchmark)

Signal trace recorded in every SD station

Proton QGSJETII03
Fe QGSJETII03
Proton SIBYLL2.1
Fe SIBYLL2.1
Auger - ICRC2007
XAsymMax
Rise time

\(X_{\text{max}}\) affects some secondary SD observables

\(\rightarrow\) more events, less resolution

\(10\% \quad 50\%\)
Hadronic interactions

Air showers → soft QCD at E_{cm} > 100 TeV
No theoretical framework, models are based on phenomenology and extrapolations

Investigate connection
\( X_{\text{max}}, N_e, N_\mu \) (Mean, RMS) ↔ cross-section, multiplicity, elasticity, A

\[
\langle X_{\text{max}} \rangle \quad \text{X-section, multiplicity, elasticity}
\]
\[
\text{RMS}(X_{\text{max}}) \quad \text{X-section}
\]
\[
\langle N_e \rangle \quad \text{X-section, multiplicity, elasticity}
\]
\[
\text{RMS}(N_e) \quad \text{X-section, multiplicity}
\]
\[
\langle N_\mu \rangle \quad \pi^{+/0} \text{ ratio, \textit{multiplicity}}
\]
\[
\text{RMS}(N_\mu) \quad \text{elasticity}
\]

\( N_\mu \) can be observed with SD at \( \theta > 60^\circ \), shape information in signal traces & AMIGA

Unfortunately, \( \langle \ln A \rangle \) seems to change, too → need to separate effects or do combined fit

\( f_{19} \) energy dependent scale factor

Muon excess

Considerably more muons found in data than in air shower simulations

- Hybrid event re-simulation (SD, FD)
- Shower universality (SD, ⟨FD⟩)
- Signal trace: muon jump method (SD)
- Signal trace: smoothing method (SD)

AMIGA will investigate radial muon distribution

All methods based partly on simulations, different systematics, compatible results

QGSJET II-3/iron
QGSJET II-3/proton

N_{\mu^\pm}^{rel.} (1000 \text{ m}) at 10 \text{ EeV}

Energy scale rel. to FD
Photon searches

Ultra-high energy photons vs. hadrons
Photon-air cross section is smaller
→ deeper $X_{\text{max}}$, very few muons
Smaller theoretical uncertainties!

Discriminants
FD: $X_{\text{max}}$
SD: rise time & shower front curvature
(combined with principal component analysis)
Photon limits

Neutrino limits  

Look for very deeply penetrating showers with active em-component at ground level

assumptions:
\[ \nu - \text{flux} \propto E^{-2} \]
\[ \nu_e : \nu_\mu : \nu_\tau = 1:1:1 \]

\( \nu \)-exposure computed with simulations (largest source of uncertainty)
Summary and outlook

Energy spectrum ++
Reduce energy scale systematics
To come: low energy extension (HEAT, AMIGA)

Anisotropy +?
Analyses ready, waiting for data...

Mass composition ++
FD ++
SD?
To come: low energy extension (HEAT, AMIGA)

Hadronic interactions ?

Photon limits ++
Reducing systematics, increase efficiency

Neutrino limits ++
Reducing systematics, increase efficiency
AMIGA

Auger Muon and Infill Ground Array (AMIGA)
low energy extension $10^{17}$ eV < $E$ < $10^{18}$ eV + dedicated muon counters
Part of 750m-Infill takes data since 2008, muon counters to come

30 m² scintillators buried 2.25 m deep
DAQ coupled to standard Infill stations
HEAT
High Elevation Auger Telescopes (HEAT)
low energy extension $10^{17}$ eV < $E$ < $10^{18}$ eV
DAQ since 2009
Backup
FD exposure

![Graph showing data and MC results for FD exposure across different energy ranges.](image)

- **Data:** $18.0 < \log_{10} (E/eV) < 18.5$
- **Data:** $18.5 < \log_{10} (E/eV) < 19.0$
- **MC:** $18.0 < \log_{10} (E/eV) < 18.5$
- **MC:** $18.5 < \log_{10} (E/eV) < 19.0$

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![Exposure vs. log_{10} (E/eV) for proton and iron.](image)

- **Exposure [km^2 sr yr]**
  - **Proton**
  - **Iron**

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![Relative difference across core-telescope distance.](image)

- **Core-telescope distance [km]**
- **log_{10} (E/eV)**
Anisotropy

Cen-A study

Two point auto-correlation
Rise time and XAsymMax

\[ t_{ij} \approx (0.00053 \pm 0.00008) x_{\text{max}}^{-4.0 \pm 0.6} \]

\[ \chi^2/\text{NDF} = 0.45 \]

Probability = 0.87

1.00 \leq \sec \theta \leq 1.40
Hadronic model influence

Proton

Iron

Mean $X_{\text{max}}$ [g/cm$^2$]
RMS $X_{\text{max}}$ [g/cm$^2$]

$f_{19}$