Highlights from the Pierre Auger Observatory

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Outline

• The Observatory
  – description, philosophy, quality of the data

• The Astrophysics – understanding the origin of UHECR
  – spectrum, mass composition, anisotropy;
  – photon & neutrino limits; shower physics

• Summary
Surface detector (SD)

Over 1600 detectors in operation, covering 3000 square kilometres

July 2009
Fluorescence detector (FD)

+3 new HEAT telescopes!
Auger is a Hybrid detector

- **SD** provides a huge aperture (easily calculable), with robust detectors. Good angular resolution, and promising mass composition indicators.

- **FD** can provide near calorimetric energy measurements, a direct view of shower maximum, and precise directions (hybrid method). But duty cycle is only 10-15%
Two Key Aspects of the Auger Observatory Philosophy

• Where possible, minimise use of simulations in the production of key scientific outputs
  – e.g. SD energy spectrum, elongation rate (~ minimal use)
  – not always possible (e.g. hybrid spectrum)

• Take advantage of Auger's hybrid nature and other cross-checks, e.g.
  – FD calibrates SD energy scale
  – hybrid directions cross-check SD directions
  – SD cross-checks FD trigger efficiency
  – ....
“hybrid” reconstruction (FD + one SD station) → excellent geometrical reconstruction

\[ E_{\text{tot}} \propto \int_0^\infty \frac{dE}{dX} \, dX \]
Hybrid event
-sometimes also “stereo”
- here independent hybrid reconstructions

$E = (1.88 \pm 0.14) \times 10^{19} \text{ eV}$

$E = (1.85 \pm 0.19) \times 10^{19} \text{ eV}$

(Statistical error, including contributions from geometry, atmosphere)
Surface Detector Quality

Angular resolution: better than 1 degree for events with \( \geq 6 \) tanks (from timing uncertainties measured in dual-tank stations; verified by hybrid)

Resolution in \( S(1000) \): better than 10% above \( 10^{19} \) eV (stat+sys) (verified by hybrid)
The Energy Spectrum
M. Roth, this afternoon

- **Fluorescence Detector**
  - fluorescence light emitted in proportion to energy deposit
  - atmosphere as calorimeter
  - near independent of mass and model

- **Surface Detector**
  - energy parameter is signal at 1000m from shower core $S(1000)$

"Hybrid" spectrum and calibration of SD spectrum

SD spectrum - huge exposure
Fluorescence Method – beautiful technique, but care required!

- Fluor. yield ~ 4 photons/m/electron
- Very moderate change in 0-10km region (the important region)
- Because yield is the result of competition between excitation by air shower and collisional de-excitation

Yield vs electron energy – it scales like energy deposit dE/dX

This means that fluorescence light is a DIRECT measure of energy deposited in the atmosphere by the shower

The atmosphere is a calorimeter!
Complication: light received at detector is
- fluorescence light
- direct and scattered Cherenkov light

- isotropic fluorescence emission
- forward beamed direct Cherenkov light
- Rayleigh- and Mie-scattered Cherenkov light
The atmosphere

We must monitor the state of
- the molecular atmosphere
- aerosol distribution and scattering properties
- night-time cloud

UV lasers

radiosondes

lidars

cloud detection

infra-red cameras and lidar
An example of Auger's philosophy...

- **Fluorescence Detector**
  - fluorescence light emitted in proportion to energy deposit
  - atmosphere as calorimeter
  - near independent of mass and model

- **Surface Detector**
  - energy parameter is signal at 1000m from shower core $S(1000)$

"Hybrid" spectrum and calibration of SD spectrum

SD spectrum - huge exposure
Convert all $S(1000)$ to $S_{38}$ – the $S(1000)$ expected at $\theta=38$ deg.

Shows the attenuation of $S(1000)$ with zenith angle. Measured from data not simulated.

Combined SD/FD energy resolution ~20%
Excellent agreement with expectation

FD calibrates SD simulation-free (apart from missing energy correction)
- data up to end December 2008. Exposure 12,790 km² sr y.
- spectrum corrected for resolution effects (~15% resolution at lower energy, improving to ~10%).
- compared with power law extrapolation, flux drops to 50% at logE=19.6. Significance ~20σ. **Consistent** with GZK suppression.
"Hybrid" Spectrum

allows spectrum measurement at lower energies

Data to May 2008. Requires
- careful MC evaluation of exposure, including measured atmospheric and detector conditions
- quality cuts and anti-bias cuts to minimise influence of mass composition on exposure
Combined Hybrid and SD Spectra

Auger and HiRes spectra consistent within systematic errors (22% and 17% respectively)

Nature of suppression?
Protons and iron nuclei have very similar energy loss lengths, which both become $<100\text{Mpc}$ beyond $\log E \sim 19.5$. Could both produce a spectral suppression at Earth.

The observed spectral suppression may also be due to the average injection spectrum at the sources.
Mass Composition
M. Unger (tomorrow)

Fluorescence detector measurements of $X_{\text{max}}$.

SD measurements (e.g. asymmetry) coming soon.

Interpretation requires simulations, significant model dependence
Q: At a given energy, what range of depths must be visible for an unbiased estimate of $X_{\text{max}}$?

A: at this energy, $X_{\text{low}}<600\text{g/cm}^2$, $X_{\text{up}}>900\text{g/cm}^2$

For every real shower, simulate a range of $X_{\text{max}}$ for its true energy and geometry. Determine uncertainty in reconstructed $X_{\text{max}}$ for every realization.

Require that $X_{\text{max}}$ uncertainty be less than 40 g/cm$^2$ between $X_{\text{low}}$ and $X_{\text{up}}$. If so, event is accepted as having an unbiased measurement of $X_{\text{max}}$
Resolution of the reconstructed $X_{\text{max}}$

The detector resolution of the reconstructed $X_{\text{max}}$ is estimated using MC simulations.

This resolution is validated by comparing $X_{\text{max}}$ measurements from two independent FD detectors.

![Graph showing data and MC simulations]

Pierre Auger Collaboration, PRL 104, 091101 (2010)
Auger’s $X_{\text{max}}$ results

The data favor a break in the $X_{\text{max}}$ vs energy curve at:

$$E_b = 10^{18.25 \pm 0.05} \text{ eV}$$

an energy close to the ankle in the energy spectrum.

At energies above $E=2 \times 10^{18}$ eV the small elongation rate,

$$D_{10} = 24 \pm 3 \text{ g cm}^{-2} / \text{decade}$$

and the decreasing trend of the RMS($X_{\text{max}}$) suggest a composition change towards a heavier composition

Pierre Auger Collaboration, PRL 104, 091101 (2010)
Are Changes to Hadronic Physics Responsible?

- Protons at highest energies?
- Can vary assumptions about hadronic interaction models
- Find that mean $X_{\text{max}}$ is easier to influence than the RMS
- extreme changes to proton-air cross-section required to explain RMS

1000 proton showers at $10^{19.5}\text{eV}$

- Equivalent c.m. energy $\sqrt{s_{\text{pp}}}$ [GeV]
- Cross section (proton-air) [mb]
- RMS $X_{\text{max}}$ [g/cm$^2$]

R. Ulrich et al. ICRC09 arXiv:09060418
Anisotropy

A. Letessier-Selvon
tomorrow

- **Prescription:** used early dataset to define energy cut, catalog and redshift cut, angle. First published November 2007, *Science*

- AGN correlation now weaker than first indicated, but is apparently still present (38 +/- 6 % compared with 21% for isotropy).

- Tension with mass composition result?

- Interesting feature is the clustering (20° scale) around direction of Cen A

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**Update on the correlation of the HECR with nearby extragalactic matter, PA Collab., Astropart. Phys. 34 (2010) 314**

degree of correlation $P_{\text{data}} = k/N$

21/55 events now correlate 0.3% chance of finding this degree of correlation from an isotropic distribution.
Cross-Correlation analysis $E > 55$ EeV.

- "a posteriori" analysis, but interesting
- excess of correlating pairs (event+catalog object) within separation angle above isotropic expectation
- there is an excess of pairs, but significance is difficult to evaluate

Photon and Neutrino Limits

- **Photons**
  - FD and SD techniques
  - top-down models highly constrained
  - GZK photons ~ within reach (but 20 years for current aperture)

- **Neutrinos**
  - SD limits from “young” inclined showers
  - up-going (tau) and down-going (all flavours)
  - cosmogenic neutrinos within reach within lifetime of Auger south, if they exist.
Auger Enhancements/New Techniques

Infill and Muon Detector (AMIGA)

... and several experiments testing feasibility of molecular bremsstrahlung detection (Sunday)
Summary

- This is what we see:
  - a significant spectral suppression above $10^{19.6}$ eV
  - a weaker AGN correlation, but with interesting future targets
  - a change in shower development with $E$ – mass increase, or hadronic physics? RMS results are striking. Tension with anisotropy?
  - no photons and neutrinos so far, several exotic models ruled out

- What must we do next? (J. Bluemer, Sunday)
  - continue accumulating 7000 km$^2$sr exposure every year
  - continue to develop new analysis (e.g. SD mass composition)
  - extend energy reach downwards
  - work with other experiments to understand differences
  - strive for larger area, longer exposure, new cheaper techniques

- UHECR physics is rich
  - clues are more puzzling than some would have expected, but not “disappointing”
  - anisotropy is a key measurement, but mass and energy information is crucial!
Backup Slides
Systematic Uncertainties in FD Energies
(typically much larger than statistical errors on individual events)

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescence yield</td>
<td>14%</td>
</tr>
<tr>
<td>P,T and humidity</td>
<td>7%</td>
</tr>
<tr>
<td>effects on yield</td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>9.5%</td>
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<tr>
<td>Atmosphere</td>
<td>4%</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>10%</td>
</tr>
<tr>
<td>Invisible energy</td>
<td>4%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>22%</td>
</tr>
</tbody>
</table>

(significant work underway to reduce these uncertainties)
Results (total number of events 3764)

Mean $X_{\text{max}}$ and RMS($X_{\text{max}}$) Vs energy

A reduction in the elongation rate (left) accompanied by a reduction in the RMS of the $X_{\text{max}}$ distribution (right).

Indication of an increase in the mean mass of cosmic rays?

Pierre Auger Collaboration, PRL 104, 091101 (2010)
The data suggest a break in the $<X_{\text{max}}>$ vs energy curve.

\[ \chi^2 / \text{Ndf} = 9.7 / 9 \]

\[ \chi^2 / \text{Ndf} = 35.6 / 11 \]

\[ D_{10} = 106^{+35}_{-21} \text{ g/cm}^2 \text{ per decade} \]

\[ D_{10} = 24 \pm 3 \text{ g/cm}^2 \text{ per decade} \]

\[ E_0 = 10^{18.25 \pm 0.05} \text{ eV} \]

\[ D_{10} = 33 \pm 2 \text{ g cm}^{-2} \text{ per decade} \]

uncertain, but rapid elongation interesting!

very slow elongation

J. Bellido et al. 31st ICRC Lodz (2009)
Some simple models

• Uniform distribution of sources
• cosmological evolution of source luminosity \((1+z)^m\), source spectrum \(E^{-\beta}\). \(E_{\text{max}} = 10^{20.5}\) eV
• No serious attempt at modelling, but better agreement with data with
  – protons and rapid evolution of sources \(m=5\), or
  – iron and no evolution (galactic source required for ankle)
• Simple examples now, promise of future capabilities