Highlights from the Pierre Auger Observatory

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for the Auger collaboration

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Pierre Auger Project
Detection of Ultra High Energy Cosmic Rays

18 countries, 476 scientists

Malargüe, Mendoza province, Argentina
Two detection techniques

Fluorescence telescopes
- 30° x 30° field of view
- 440 PMT camera

Cherenkov water tanks
- 12 tons of water
- 3 PMTs (9 inch)
- 1.5 km apart
24 telescopes in 4 buildings

1663 water Cherenkov Detectors

Covering 3000 km²
Science results

- Energy spectrum
- Anisotropy
- Photon limit
- Neutrino limit
- Mass composition
Energy spectrum

- Model independent energy determination

- GZK suppression
  (about right for protons)
- or maximum accelerator energy reached?

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Energy spectrum

Shifted spectra agree in shape
Anisotropy

Auger events with $E > 10^{19}$ eV

No enhancement along galactic disk: UHE particles are extragalactic

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Anisotropy

Auger events with $E > 55$ EeV, $D < 75$ Mpc correlation with VCV catalogue, $< 3.1^\circ$)

→ Suggests proton primary
Anisotropy

Auger events with $E > 55$ EeV

Current signal: $p = 0.38 \ (+0.07 \ -0.06)$

Was $p = 0.69 \ (+11 \ -13) \ \ (Science2007)$
**Anisotropy**

Excess in Cen A region

Auger events with $E > 55$ EeV

- Red stars (left) – 58-month Swift-BAT (X-rays) catalog
  AGNs, size proportional to assigned weight
- Density map (right) - 5° smoothing

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Anisotropy
Excess in Cen A region

Angular Distance: CR - Cen A

4% chance prob. for isotropic distribution
**Xmax**: height of shower maximum, grows with \( \log(\text{E}) \)

- \( p \): penetrate deeper, larger \( X \max \)
- \( \text{Fe} \): develop earlier, smaller \( X \max \)

  difference about 70 g/cm\(^2\)

- \( \text{Xmax}(p) \) fluctuates much more than \( \text{Xmax(Fe)} \)
- \( \text{RMS}(\text{Xmax}(p)) \approx 60 \text{ g/cm}^2 \quad \text{RMS}(\text{Xmax(Fe)}) \approx 20 \text{ g/cm}^2 \)

  largely due to \( \sigma_{\text{inel}} \) of primary particle.

  \( 1 \text{ Fe} \approx 56 \text{ protons of E}_0 /56 \)
Xmax prediction

\[ \langle X_{\text{max}} \rangle \ (\text{g/cm}^2) \]

- Auger 2009
- Yakutsk 2005
- Yakutsk 2001
- HiRes 2004
- HiRes-MIA
- Fly’s Eye
- TUNKA

\[ E_{\text{lab}} \ (\text{eV}) \]

Proton
Iron
Gamma with preshower
From North
From South

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Mass Composition

![Graphs showing the relationship between energy (E) and maximum range (Xmax) for different mass compositions. The graphs illustrate that the proton and iron mass compositions show distinct behaviors, with iron having a lower maximum range compared to protons at the same energy, especially at the highest energies.]
**Photon limit**

Current limit ~2% - ruling out some top down scenarios

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Sensitivity to neutrino showers

nearly horizontal showers:
- atmosphere $>> 1000 \text{ g/cm}^2$

- full el.mag.
- curved shower front,
- broad arrival time dist.

$P, Fe$

- no el.mag.,
- plane shower front,
- sharp arrival time dist.
Neutrino limit
No neutrino candidate observed yet

Single flavour neutrino limits (90% CL)

Maximum sensitivity where the highest GZK neutrino flux is expected
**Muon content**

Discrepancy (baryon and pion spectra) among models

Much more muons in EPOS – different approach to baryon production (collective effects)

![Graph showing muon content vs energy for different models](image)

3 times less baryons = 40 % less muons (~difference between proton and iron)
Muon Density @ 1000 m

- EPOS consistent with Auger data
- intermediate mass needed for \( <X_{\text{max}} > \), RMS \( (X_{\text{max}}) \) and muons
- QGSJETII underestimates the number of muons

![Graph showing ratio of S_{1000m} (QGSJETII p) compared to EPOS models for proton (1.99) and iron (1.99). The graph includes data for PAO. The plot shows the ratio of muon density at 1000 m with energy \( E=10^{19} \text{ eV} \).]
In order to explain the data as primary protons the cross section would have to grow enormously at high energies
Auger south enhancements

Lower the energy threshold to 0.1 EeV

- **HEAT**: view the atmosphere above FD
- **AMIGA**: infill and muon counters
- **AERA**: coherent radiation of secondaries at radio frequencies

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Auger south + enhancements $E > 10^{17}$ eV

+ CERN experiments

**LHCf:** testing very forward region, laboratory equivalent energy of $10^{17}$ eV

**TOTEM:** $p$-$p$ cross-section at similar energies

- Particle physics at $10^{19}$ eV
Summary

- Spectrum with clear suppression above $10^{19.5}$ eV
- Anisotropy above 55 EeV (weaker but still present)
- Excess in Cen A region
- Photon limit disfavours top-down scenarios
- Shower maxima suggest heavy composition at highest energies
- Discrepancies in hadronic interaction models puzzles remain...
- AUGER south upgrade to extend the sensitivity down to $10^{17}$ eV
- need more statistics

We continue to pursue the idea of AUGER NEXT