The Pierre Auger Observatory
Status - First Results - Plans

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Pierre Auger Observatory: Science Objectives

- understand the nature, origin and propagation of UHECR
  - point sources?
  - An-/Isotropy of arrival directions?
  - GZK cut-off or continuing spectrum or other structures?
  - primary particle mass, type?
  - acceleration or decay of exotics?

- measure cosmic rays with high statistics and quality
  - aperture > 7 000 km²sr @10¹⁹eV in each hemisphere
  - ~ degree angular resolution, zenith angle θ°... 90°
  - primary particle discrimination (light, heavy, γ, ν)
  - calorimetric energy calibration

⇒ hybrid design: surface detectors and fluorescence telescopes
  - measurement of direction, energy and composition of primaries
The Pierre Auger Project

High statistics
Hybrid detection
Full sky coverage

1992 Paris workshop
1996 Design report
1999 Ground breaking
2001 Engineering array
2003 Construction phase
2008 Completion

Northern Observatory
4000 detectors 20,000 km²

Southern Observatory
1600 detectors 3,000 km²
Southern Pierre Auger Observatory completed July 2008

1600 surface detector stations: water-Cherenkov tanks (triangular grid of 1.5 km)

4 fluorescence detectors (24 telescopes in total)

2 laser stations balloon station

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2 laser stations balloon station
Surface array in the Argentinean Pampa
Water Cherenkov Detector

- Communications antenna
- GPS antenna
- Electronics enclosure
- Solar panels
- Battery box
- Plastic tank with 12 tons of very pure water
- 3 photomultiplier tubes looking into the water collect light left by the particles
Fluorescence Telescopes
six telescopes each viewing 30° by 30°
One of 24 fluorescence telescopes

PMT camera with 440 pixels, 1.5° FoV per pixel, 10 MHz

UV transmitting filter, corrector lens, safety curtain

3.4 m segmented mirror (aluminum alloy, glass)
Surface detector events

More than 650,000 events (T5 trigger, used in analysis)

Example: $E > 10^{20}$ eV, $\theta \approx 45^\circ$

Tank signal in units of the signal of a vertical muon
Golden hybrid events

Hybrid events ~120,000
Golden hybrid events ~ 15,000

Lateral distribution

Shower longitudinal profile
Other types of Auger events

Event 200718905882  (9.7.2007)

Event 200716104390  (11.6.2007)
Other types of Auger events

Event 200717001509 (19.6.2007)

Event 3618809 (25 June 2007): 59 stations,
Golden hybrid events: many cross checks possible

Independent profile reconstructions

Event 200716104390 (11.6.2007)
Energy calibration of surface detector by Hybrid events

Fluorescence detector energy

\[ E_{\text{prim}} = f_{\text{corr}} \cdot \int \frac{dE_{\text{ion}}}{dX} \, dX \]
Energy spectrum

- 661 events

Data: 1 Jan 2004 - 31 Aug 2007

Energy spectrum: Other methods

Transition from galactic to extragalactic cosmic ray sources? Greisen-Zatsepin-Kuzmin (GZK) cutoff?
Comparison with GZK suppression models

- Observed flux suppression is due entirely to GZK effect
- Observed flux suppression is signature of maximum acceleration energy
- Observed flux suppression is due to both source cutoff and GZK effect

Pure proton model
(Berezinsky et al.)

Mixed composition model
(Allard et al., Hillas)
Composition: measurement of longitudinal profile

Field of view bias needs to be accounted for

$X_{\text{low}}$, $X_{\text{up}}$ are determined from data, no simulation needed

(Unger et al., ICRC 2007)
Composition: mean depth of shower maximum

Sys. uncertainty: ±15 g/cm²

D_{10}^p = 71±5 g/cm²

D_{10}^i = 40±4 g/cm²

(Note: not consistent with muon data and current interaction models)
Photon limit: using surface detector data

- Signal rise time
  - Total signal
  - Muons
  - Electrons
  - $t_{1/2} = 81.39$ ns

- Shower front curvature
  - Data
  - MC: photons

- Graph showing deviation from $R_e$ and rise time
  - MC Photons
  - Data
Limit on fraction of photons in UHECR flux

Integral photon flux limit

Many exotic source scenarios excluded

Many exotic source scenarios excluded
Neutrino limit: horizontal air showers

nearly horizontal air showers from extremely high energy $\nu_e$ or $\nu_\mu$ neutrinos

air showers from skimming $\nu_\tau$ neutrinos
Flux limits for neutrinos

Data: 1 Jan 2004 – 31 Aug 2007
PRL 100 (2008) 211101
Arrival directions: Galactic center point source search

Significance plots

Dark red: more events than expected
Light red: fewer events than expected

AGASA: would have 16σ
SUGAR: would have 30σ in Auger

No confirmation of previous indications for excess from GC region

Astropart. Phys. 27 (2007) 244
Anisotropy of ultra-high energy cosmic rays

Veron-Cetty: 472 AGN (z < 0.018, ~75 Mpc)
318 in field of view of Auger

Auger: 27 events above $5.7 \times 10^{19}$ eV,
20 correlated within 3.1°,
5.7 expected
Possible correlation with nearby AGNs?

- 12th Veron-Cetty & Veron catalogue of AGN
- Data set: Jan1st, 2004 to May 27th, 2006, well-contained events
- Scan over angular distance, maximum redshift, energy threshold

Minimum: 12 out of 15 correlated with nearby AGNs (3.2 expected)

\[ \Delta \alpha = 3.1^\circ, E_{\text{min}} = 5.6 \times 10^{19} \text{ eV}, z_{\text{max}} = 0.018 \text{ (75 Mpc)} \]

Uncorrected chance probability: \( P \sim 2 \times 10^{-6} \)

*Science 318 (2007) 939
Astropart. Phys. 29 (2008) 188*
Anisotropy of ultra-high energy cosmic rays

Hammer-Aitoff projection, Equatorial coordinates

Galactic plane

Correlated events (20)

Uncorrelated events (7)

Supergalactic plane
Arrival direction distribution is anisotropic

Independent measure: autocorrelation function
Could it be that AGNs are indeed the sources?

Assumption: all AGNs of the VC catalogue have same injection power

Expectation: ~6 events from Virgo cluster, none observed
(excluded at 99% level for complete distribution)

(Paper: Gorbunov et al., arXiv:0711.4060 [astro-ph])

Possible interpretations:

• AGNs have different injection power (predicted by Biermann, Falcke et al.)
• Sub-class of AGNs are sources
• AGNs are not sources, sources are distributed similar to AGNs
• ...

Note:

• AGNs are standard Seyfert galaxies (not very powerful)
• Anisotropy of distribution independent of source catalogue
• Correlation with supergalactic plane
• HiRes stereo data

Auger Enhancements: investigating the ankle

Deviation from $E^{-2.6}$ flux

Mean mass number
Infill array of water Cherenkov detectors

Simulated acceptance

Threshold for infill array $\sim 10^{17}$ eV
AMIGA: Auger Muons and Infill for the Ground Array

Existing tank array 1500m

Infill array 750m
42 additional detectors
Area ~ 23.5 km²

Infill array 433m
24 additional detectors
Area ~ 5.9 km²

Each of the 85 detectors:
pair of Cherenkov tank and muon counter

em. + μ

μ ~3m
HEAT: High Elevation Auger Telescopes

- 3 ``standard´´ Auger telescopes tilted to cover 30 - 60° elevation
- Custom-made metal enclosures
- Also prototype study for northern Auger Observatory
HEAT: High Elevation Auger Telescopes

First telescope in operation
AERA: Auger Engineering Radio Array

Aims:
• Establish radio detection technique
• Establish test self-trigger concepts for $E > 5 \times 10^{17}$ eV
• Calibrate radio signal
• Investigation of transition from galactic to extragalactic CR

Plan:
• Array of 20 km$^2$
• 30 - 80 MHz, 200 Ms/s
• 20 prototype antennas by end 2009
• 150 antennas by end of 2011
AERA: Auger Engineering Radio Array

First prototype of DAQ system
Go for highest energies

Auger-South results
- Suppression of flux (like GZK effect)
- Anisotropy \( E > 6 \times 10^{19} \) eV
- Mixed cosmic ray composition at lower energy
- Photon fraction small
- Neutrino flux low

Auger-North: GZK suppression region
Northern Auger Observatory: Motivation and aims

• **The sources of UHECR**
  - Anisotropy ⇒ correlations ⇒ source classes
  - Study individual sources with spectra and composition on the whole sky

• **The acceleration mechanism**
  - Composition evolves from source to here
  - Proton beam !? calibration !
  - $E >> 10^{20}$ eV still difficult; $E_{\text{max}}$ ?

• **Propagation and cosmic structure**
  - Map galactic B-field
  - Matter within 100 Mpc
  - Extragalactic B-field small ?

• **Particle physics at 350 TeV**
  - Mass and $X_{\text{max}}$
  - Had. interactions, cross sections ?
  - New physics, Lorentz invariance

• **Multi-messenger astrophysics**
  - Combine the data from photons, neutrinos and charged particles !
  - Sources within field of view of IceCube
$E > 6 \times 10^{19} \text{ eV}$
Particle physics with air showers

(a) Correlation with sources allow identification of particles
(b) Propagation leads to either light or heavy composition

Allard et al., arXiv:0805.4779 [astro-ph]
Auger-North detector layout

- Optimized for science and costs
- Surface array with 4000 stations: \(20,000 \text{ km}^2\) with \(\sqrt{2}\)-mile = 2.3 km grid
- Infill array with 400 stations: \(2,000 \text{ km}^2\) with 1-mile = 1.6 km grid
- 39 fluorescence telescopes
Current status and timeline

2009:
R&D array, funded (10 detector stations)

2009-2011:
Science reviews

2012: Begin of construction (5 years)

Auger-South: $55M
Auger-North: $120M
special thanks to Ralph Engel, Matthias Kleifges