Indications of anisotropy at large scales in the arrival directions of CRs detected at the Pierre Auger Observatory

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PIERRE AUGER OBSERVATORY

ICRC
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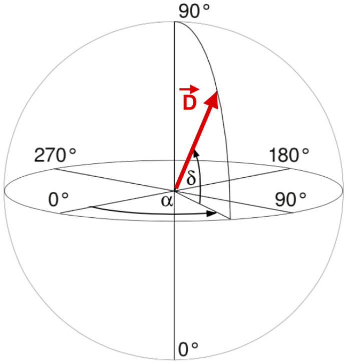
Large scale anisotropy studies

- Together with the energy spectrum and mass composition → Nature and origin of cosmic rays
- Transition from a galactic to an extragalactic origin → significant change in the large scale angular distribution of cosmic rays expected

- Analyses rely on a harmonic expansion of the cosmic rays flux distribution
- Reconstruct the dipole/quadrupole patterns in cosmic rays arrival directions (amplitude and direction)

This contribution

- The **phase of the first harmonic** from 10 PeV to the highest energies
- **Dipole search** above 4 EeV



The Pierre Auger Observatory

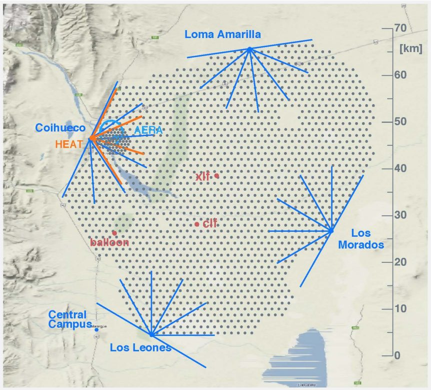
- Designed to study Ultra High Energy Cosmic Rays (E $>10^{18}$ eV)

Fluorescence detectors (FD)

27 telescopes at 4 sites overlooking the SD array

Surface detectors (SD)

- The 1500 m array :
  - Surface : 3000 km^2
  - $E > 0.1$ EeV (full eff. above 3 EeV)
- The 750 m array :
  - Surface : 23.5 km^2
  - $E > 0.01$ EeV (full eff. above 0.3 EeV)



Ability to perform large scale anisotropy studies over 4 orders of magnitude in energy

Analysis methods (1)

Systematic effects

- Low amplitudes expected (% level) $\rightarrow$ careful consideration of spurious modulations
- Modulation of any detector property in time $\rightarrow$ modulations of the measured event rate in right ascension

Varying weather effects

- Atmospheric conditions affect the shower development
- *Correction :* Energy estimation at **reference values of pressure and density**, and correction of the energy on an **event-by event basis**
- Effect of the order of $\sim$1%

Varying exposure

- Growth of the detector, detector down times...
- *Correction :* Using the instantaneous **monitoring of the detector size**
- Effect of the order of $\sim$0.5%

Analysis methods (2)

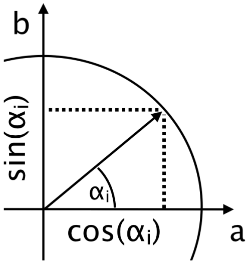
The Rayleigh analysis

- The Rayleigh method to study (first) harmonic modulations [Linsley, 1975] is directly obtained from discrete Fourier analysis
- Fourier coefficients :

$$a_n^\alpha = \frac{2}{\tilde{N}} \sum_{i=1}^{N} w_i \cos(n\alpha_i) \,, \;\; b_n^\alpha = \frac{2}{\tilde{N}} \sum_{i=1}^{N} w_i \sin(n\alpha_i),$$

where w_i accounts for variations in the operating size of the detector, and $\tilde{N} = \sum_{i=1}^{N} w_i$

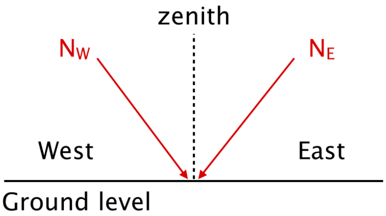
- Amplitude $r = \sqrt{a^2 + b^2}$ and phase $\phi = \arctan(b/a)$
- Uncertainties $\sigma = \sqrt{\frac{2}{N}}$ and $\sigma_\phi = \frac{1}{r}\sqrt{\frac{2}{N}}$
- All measured energies are corrected for atmospheric effects *before* subdividing the event set into energy bins and using the Rayleigh method



Analysis methods (3)
The East-West method

- Difficult to keep under control the trigger effects below 1 EeV down to the 1% level
- The E-W method is insensitive to local effects taking advantage of the symmetry of the setup

- N_E and N_W are related to the amplitude r and phase ϕ of a first harmonic modulation
- $N_E(\tau) - N_W(\tau) \propto r\, sin(\tau - \phi)$, where τ is the local sidereal time
- 2.5 times less sensitive than the Rayleigh method

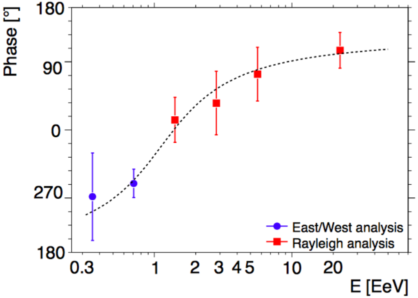


Phase of the first harmonic

Phase prescription

- A change in phase is potentially indicative of a *real* underlying anisotropy

- Hint of a smooth phase transition from $\sim 270°$ to $\sim 100°$ in the EeV energy range [P. Abreu et al., 2011]



Test with an independent data set

- Data set posterior to 25 June 2011
- Additional exposure of 21,000 km^2
- Likelihood ratio test with $p < 0.5\%$ around predefined values :
  - $\Phi_0^{\mathbf{750\ m}} = 263° \pm 19°$
  - $\phi_0^{\mathbf{1500\ m}}(E) = \phi_0 + \phi_E \arctan\left(\frac{\log_{10}(E/\text{EeV}) - \mu}{\sigma}\right)$,

    $\phi_0 = -16° \pm 49°$, $\phi_E = 76° \pm 64°$,

    $\mu = 0.12 \pm 0.23$, $\sigma = 0.26 \pm 0.39$

Phase of the first harmonic

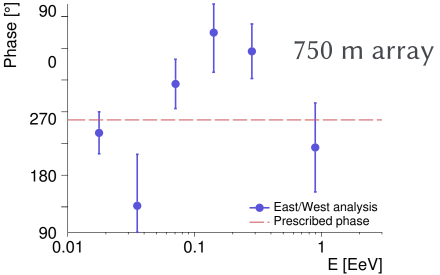
Status of the phase prescription

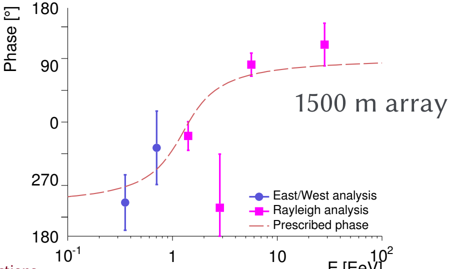
Analysis details

- Data set : 25 Jun 2011 $\rightarrow$ 31 Dec 2014
- $\theta < 60^\circ$
- Active detector surrounded by six active neighbors

At (almost) the end of the prescription

- Phase alignment is uncertain (p-values : 40% (750 m array), 7% (1500 m array))
- Additional exposure of **1,900 km^2 sr yr** needed to establish/reject the consistency in phases at 99% CL



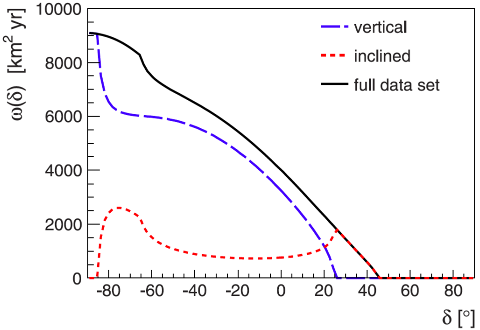


Dipole search above 4 EeV

- Events with $\theta < 60°$ (*vertical* events) + events with $60° < \theta < 80°$ (*inclined* events)
- Extension of the fraction of covered sky from 71% to 85%
- Increase of 30% in the number of events

The analysis

- Data set : 1 January 2004 $\rightarrow$ 31 December 2013
- Absence of trigger effects for events with $E \geq 4$ EeV
- Two Rayleigh analysis ; RA and azimuth
- Account for atmospheric and geomagnetic effects, and tilt of the array



Dipole search above 4 EeV

Right ascension distribution

E(EeV)	k	r_k^α	ϕ_k^α	$P(\geq r_k^\alpha)$
4-8	1	0.0031	15°	0.88
	2	0.0013	99°	0.98
>8	1	0.044	95°	$6.4\ 10^{-5}$
	2	0.028	36°	0.021

- **k=1** : Larger number of events $\rightarrow$ significance of the measurement has grown to about **4** σ
- **k=2** : 2% probability to arise by chance$\rightarrow$ less significant

Azimuth distribution

- A non-vanishing b_1^Φ $\rightarrow$ A dipolar component of the flux along the rotation axis of the Earth

E(EeV)	b_1^Φ	$P(\geq b_1^\Phi)$
4-8	-0.0142	0.024
>8	-0.024	0.015

- The a_2^Φ coefficient that probes the quadrupolar component is **compatible with zero**
- a_1^Φ and b_2^Φ coefficients are **compatible with zero** as expected

Dipole search above 4 EeV

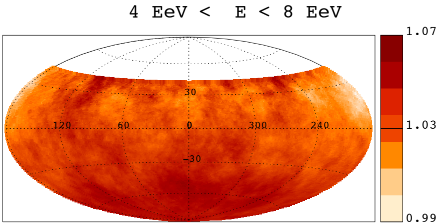
Pure dipole hypothesis

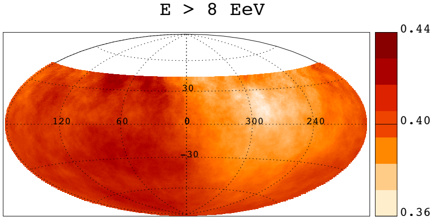
- *Equatorial component* : $d_\perp \simeq r_1^\alpha / < \cos(\delta) >$
- *Component along the Earth rotation axis* : $d_z = b_1^\Phi / (\cos(l_{obs}) < \sin(\theta) >)$

E(EeV)	d	δ_d	α_d
4-8	0.027 ±0.012	-81°± 17°	15°± 115°
>8	0.073 ± 0.015	-39°±13°	95°± 13°

- Quadrupole components not significant

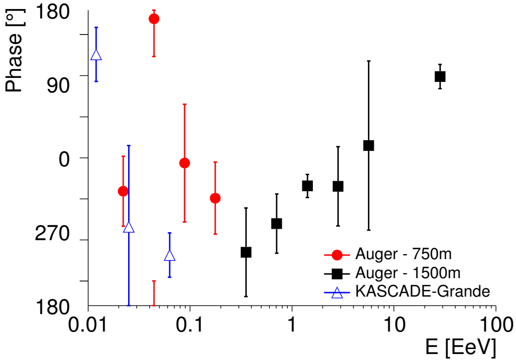
- Sky maps of the flux of CRs smoothed over 45° for the two energy bins
- Maximum difference in the flux of CRs : [4-8 EeV] : 8%, [>8 EeV] : 21%

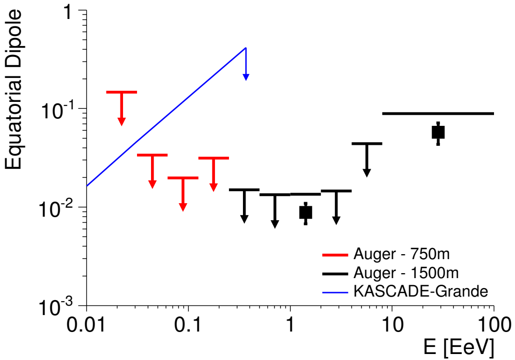




Summary

- Results on the phase measurements (left) and upper limits on equatorial amplitudes (right) **from 10 PeV to the highest energies**





Conclusion

- Different approaches were explored by the Pierre Auger Collaboration in revealing large-scale anisotropies imprinted on the CR arrival directions
- More exposure needed to conclude about the prescribed phase values
- **Phase transition** suggestive of a progressive domination by the flux of extragalactic CRs
- Upper limits on amplitudes are **at the % level** over a wide energy range
- **5.7% equatorial dipole amplitude** above 8 EeV

Thank you for you attention !