3rd Roma International Conference on Astroparticle Physics

Large scale anisotropy studies with the Pierre Auger Observatory

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Ultra High Energy Cosmic Rays

Particles with E ~ 10^{20} eV exist and have been detected

➧ **what are they and where do they come from?**

Complementary studies:

- **Energy spectrum**
- **Mass composition**
- **Arrival directions distribution**

→ LARGE SCALE:

transition from galactic to extra-galactic origin = change in the large scale angular distribution because of different mechanisms of propagation

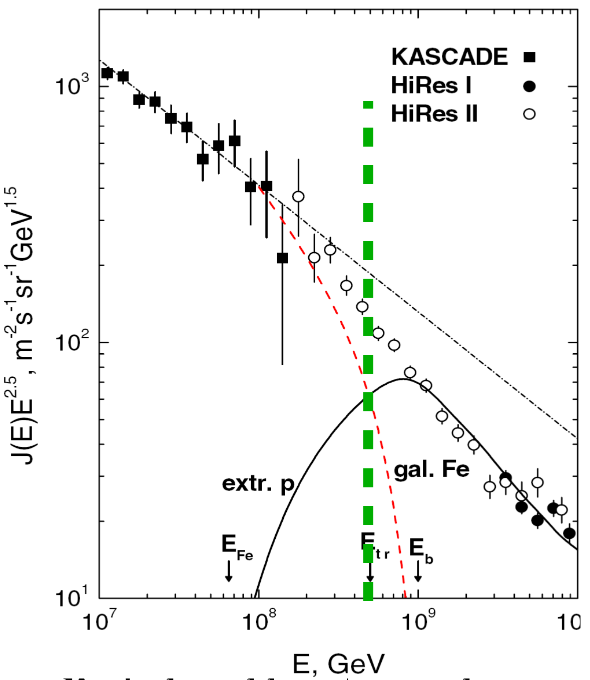
→ SMALL SCALE:

at ultra high E cosmic rays are only slightly deflected by magnetic fields
→ direct way to search for **UHECR sources**

If sources are nearby and not uniformly distributed, an anisotropic arrival directions distribution is expected ("clustering")

Transition galactic-extragal. origin

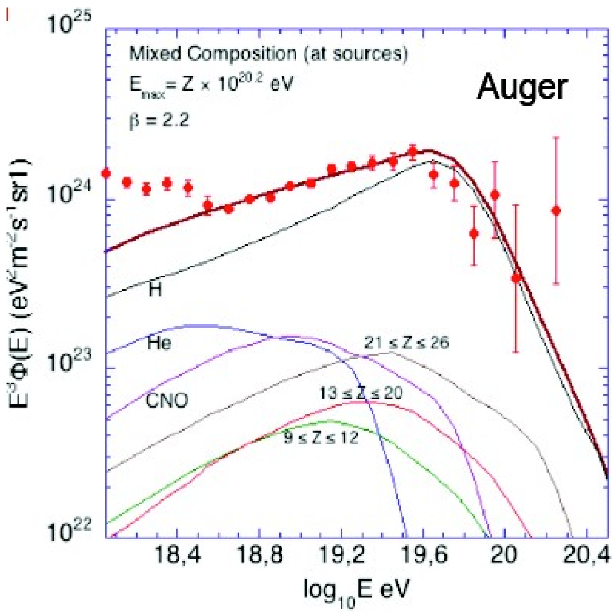
2nd knee model [Berezinsky2006]



- **dip** induced by e^+e^- prod. on CMB
- **2nd knee** = 1st flattening of dip → transition ("rigidity model")
- **ankle** = 2nd flattening of dip

➔ At ~10^{18} eV **extragalactic** (p)

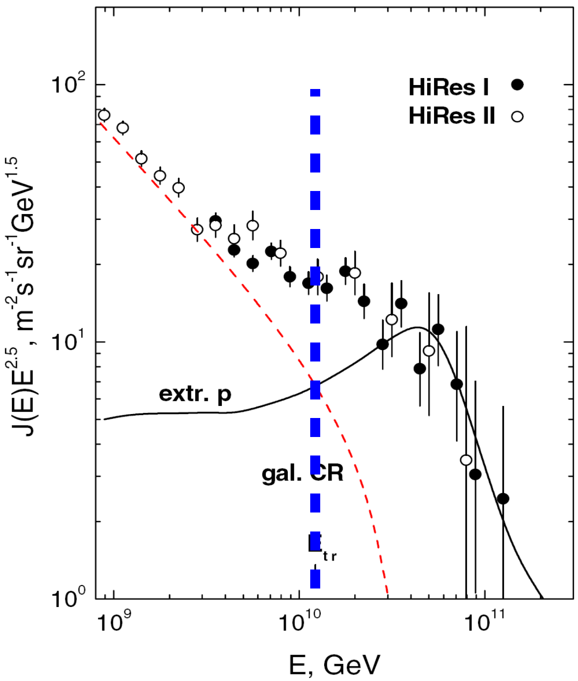
Mixed comp. source model [Allard et al. 2005-2008]



- **ankle** = transition
- EGCR source composition ~ GCR
- source spectrum ∝ $E^{-(2.2\text{-}2.3)}$, (2nd knee model $E^{-(2.6\text{-}2.7)}$)

➔ At ~10^{18} eV **galactic** (mixed)

Ankle model [Linsley 1963]



- **2nd knee** = break of gal. Fe component
- **ankle:** gal. magnetic field loses its efficiency→ transition
- $S_{gal.CR}$ =obs.S_{tot}- calculated $S_{extr.p}$

➔ At ~10^{18} eV **galactic** (heavy)

LS anisotropy studies at PAO

[Pierre Auger Coll., Astropart. Phys. 34 (2011) 627]

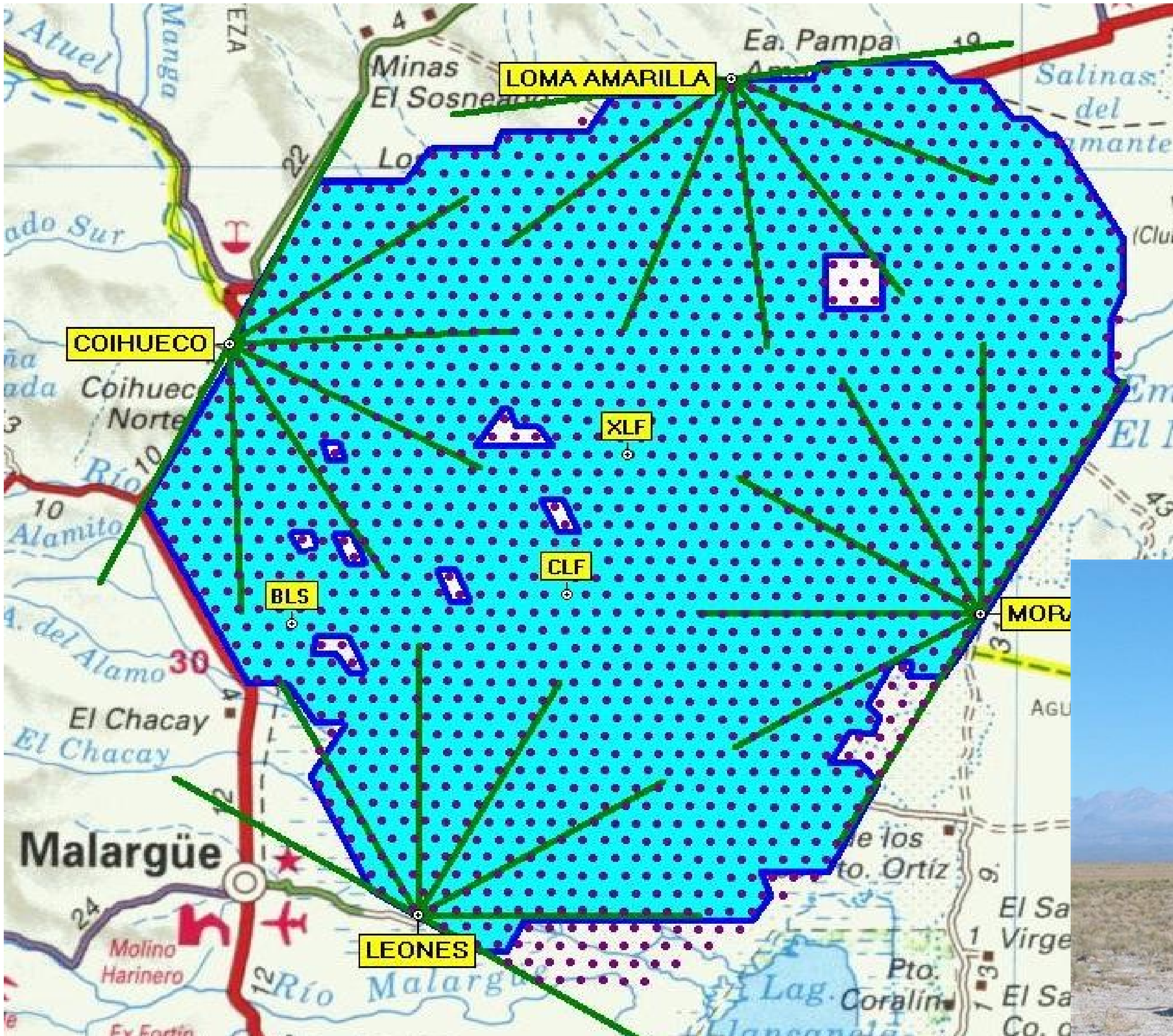
At energies ~ 10^{18} eV, the aims of this search are:

- study the **evolution of the galactic anisotropy** and possibly identify the energy of **transition from galactic to extra-gal. origin** of UHECRs
  - ✔ **if galactic:** **%-level modulation** (amplitude depends on assumed gal. magnetic field, charges of particles, distribution of sources, …)
  - ✔ **if extra-gal.:** **no structure except for a CMB-dipole (~ 0.6 %)**
    at higher energies: GZK cut-off → sources → anisotropy
- test the excess of 4% (4 s.d.) reported by **AGASA** in the 1-2 EeV energy range (even if in a different hemisphere)

⇓

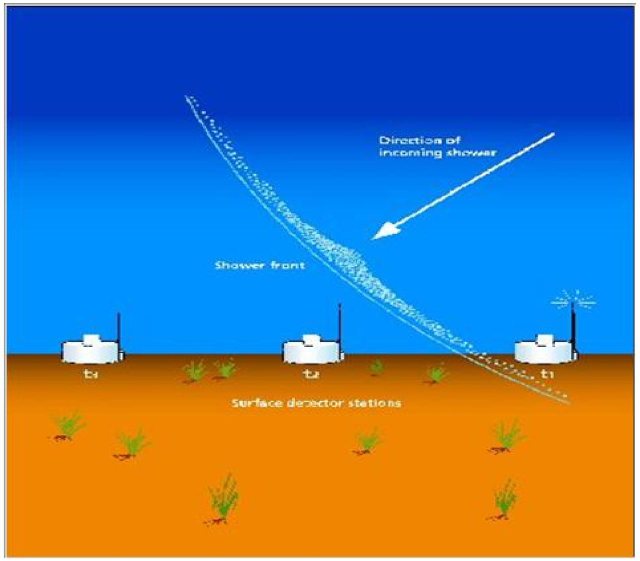
Data collected by the **Pierre Auger Observatory** allow us to perform large scale analyses with a **sensitivity** at the **%-level** at **EeV energies**

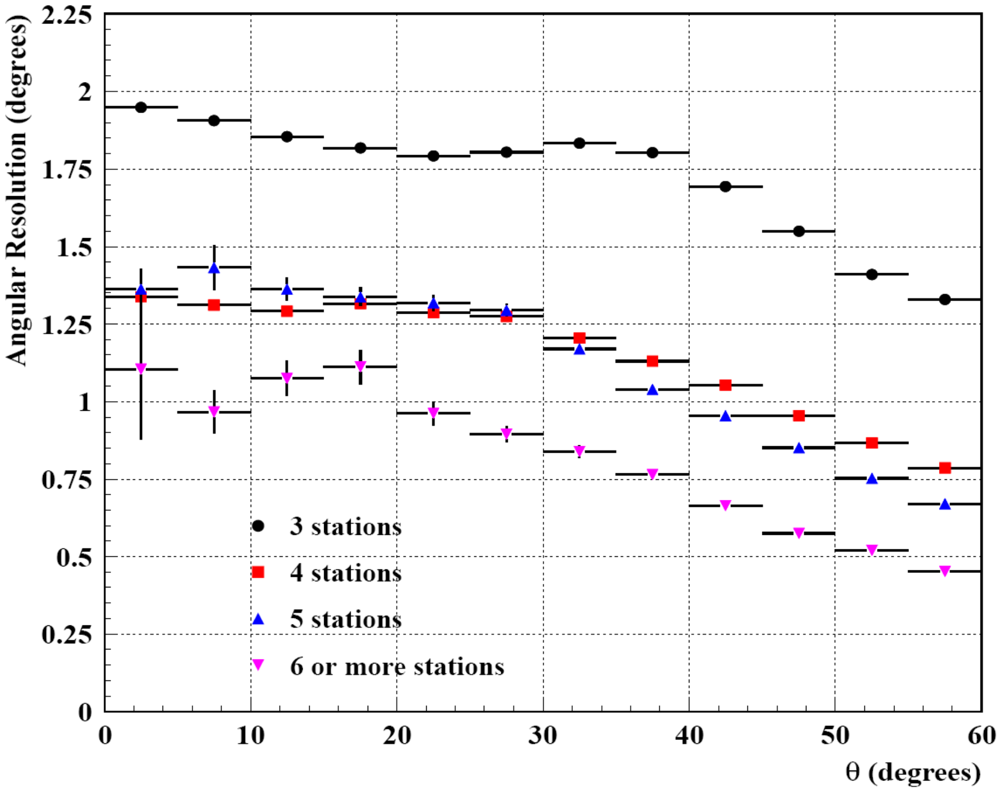
Pierre Auger Surface Detector



SD angular resolution

Arrival direction determined **from the delays** among the hit tanks → fit to the arrival times of the shower front at the SD





In the lower energy range: **ang. res. < 2°**

→ sufficient to perform searches for large scale patterns in arrival directions

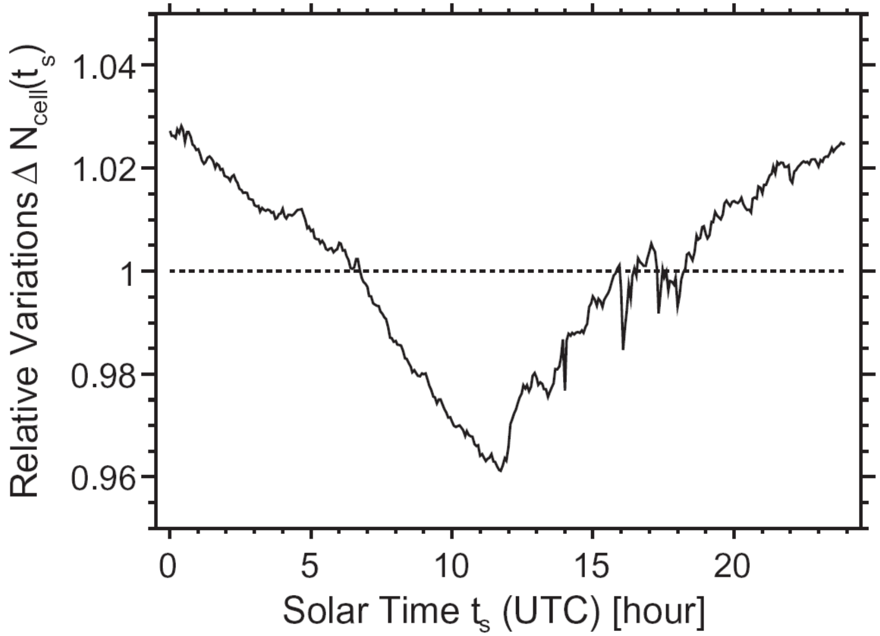
Experimental effects

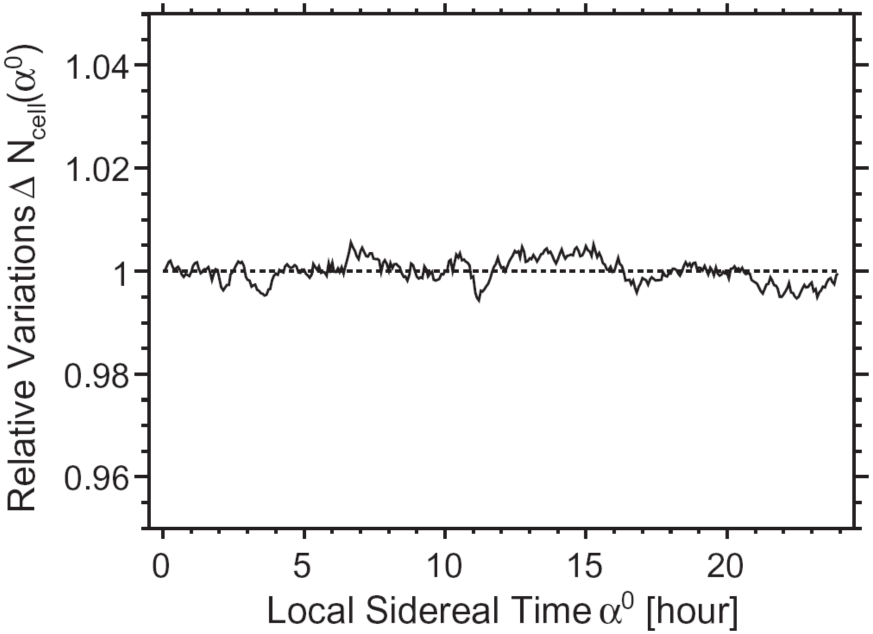
✔ A ***genuine dipolar anisotropy*** in the R.A. distribution of the events induces a modulation in the distribution of t_{arr} of events with T = 1 sidereal day

✔ A dipolar modulation of ***experimental origin*** with T= 1 solar day may induce a ***spurious dipolar anisotropy*** in the R.A. distribution

Difficulties: control of the sky exposure (with the corresponding accuracy)

- increase of experiment dimensions → deployment of tanks over the array
- instabilities and dead times of the apparatus
- atmospheric and instrumental effects





Rayleigh analysis weighted by exposure

[Mollerach & Roulet, JCAP 0508 (2005) 004]

- Classical Rayleigh formalism slightly modified to account for non-uniform exposure

- Measure the residual modulation after correcting for:
  - ✔ **non-uniform acceptance in Right Ascension:** weight each event by the inverse of the R.A. dependent exposure ω_i

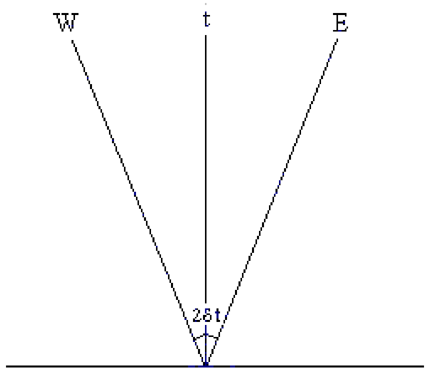
$$a = \frac{2}{\Omega} \sum_{i=1}^{N} \omega_i \cos \alpha_i \qquad b = \frac{2}{\Omega} \sum_{i=1}^{N} \omega_i \sin \alpha_i$$

$$r = \sqrt{a^2 + b^2} \qquad \phi = \arctan \frac{b}{a} \qquad P = \exp\left(-r^2 \Omega / 4\right)$$

  - ✔ **weather effects:** correct the energy assignment for weather effects
    - ✗ below 1 EeV w.e. affect *also* the detection efficiency
      → this method can be **reliably applied only above 1 EeV**

East-West method
[R.Bonino et al., submitted to ApJ]

- **Differential method** originally proposed in *Nagashima, Il Nuovo Cimento 1989*



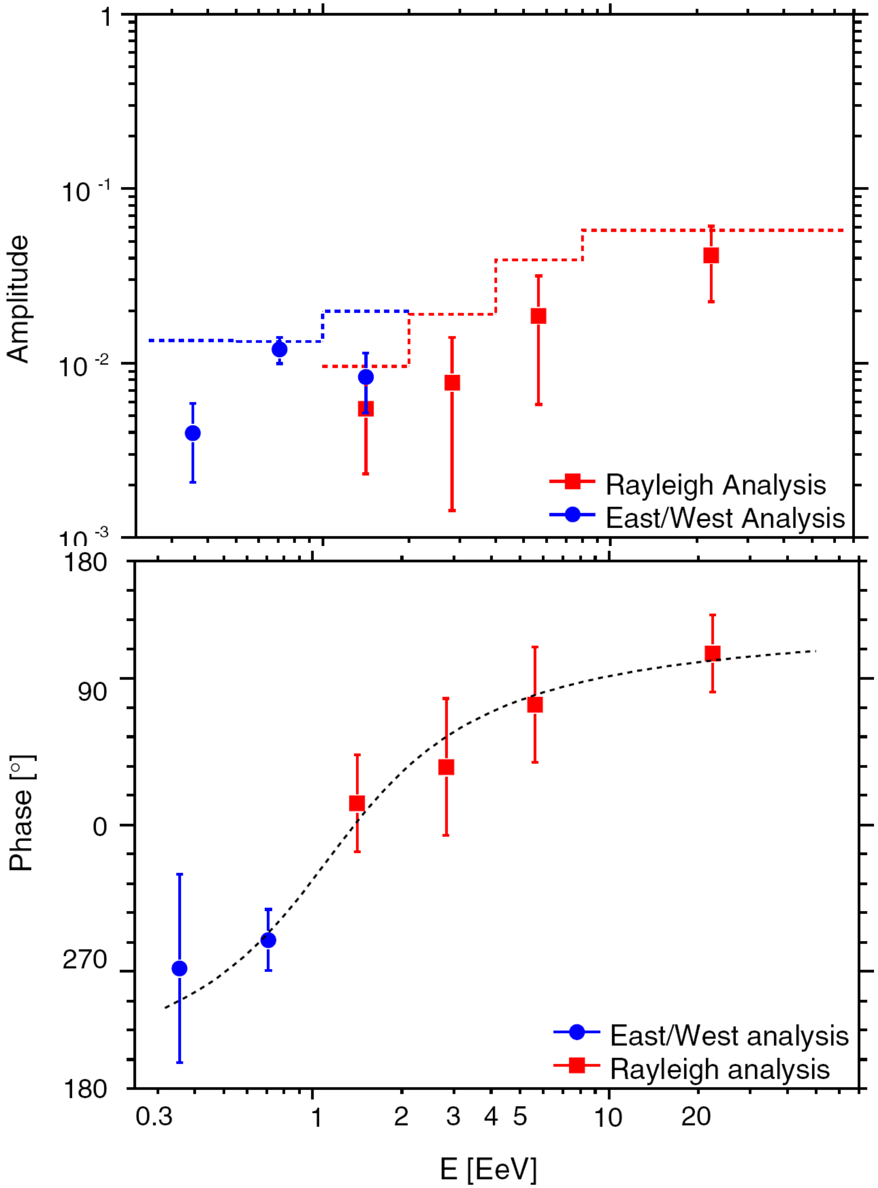
$$\frac{dI}{dt} \simeq \frac{E(t) - W(t)}{<h>}$$

- Instantaneous exposure for E and W events is the same, *i.e.* both sectors are equally affected by detector instabilities and weather conditions

- Standard harmonic analysis on the differences E-W

- The **difference between counts from the E and the W sectors** allows us to remove direction-independent phenomena (of experimental origin):
  - ✔ **no correction** is needed
  - ✗ **reduced sensitivity** → higher statistics required (4 times more events)

Results: energy bins

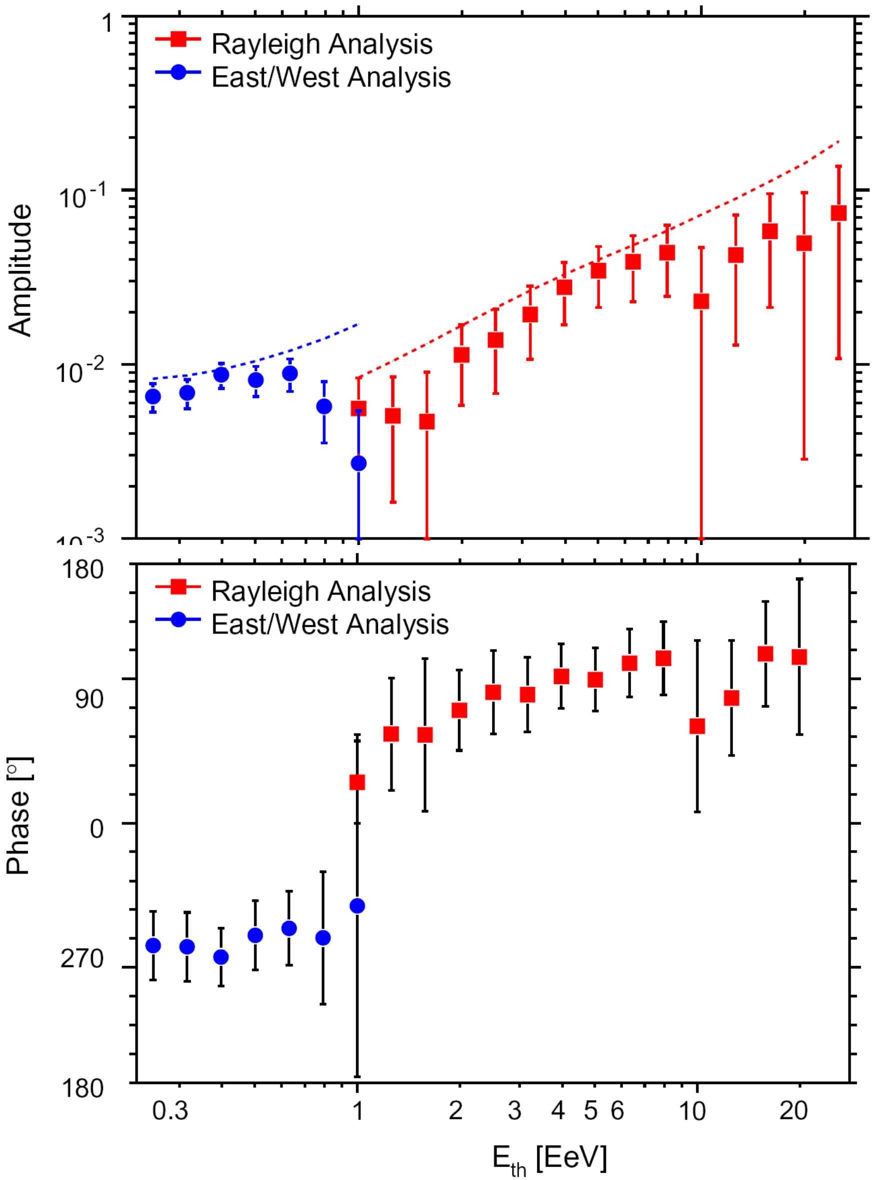


✔ **Amplitudes:** below the 99% c.l. upper bounds resulting from fluctuations of isotropic distrib. (*dashed lines*) → no evidence of anisotropy

✔ **Phases: smooth transition** at 1 EeV from 270° (compatible with R.A.$_{GC}$) to ~100° → intriguing

➔ **Real transition?** 1.8 times the present statistics is needed to confirm it at 99% c.l.

Results: energy thresholds



In this analysis:

✗ bins are strongly correlated

✔ useful to optimize the detection of an eventual genuine signal spread over a large energy range

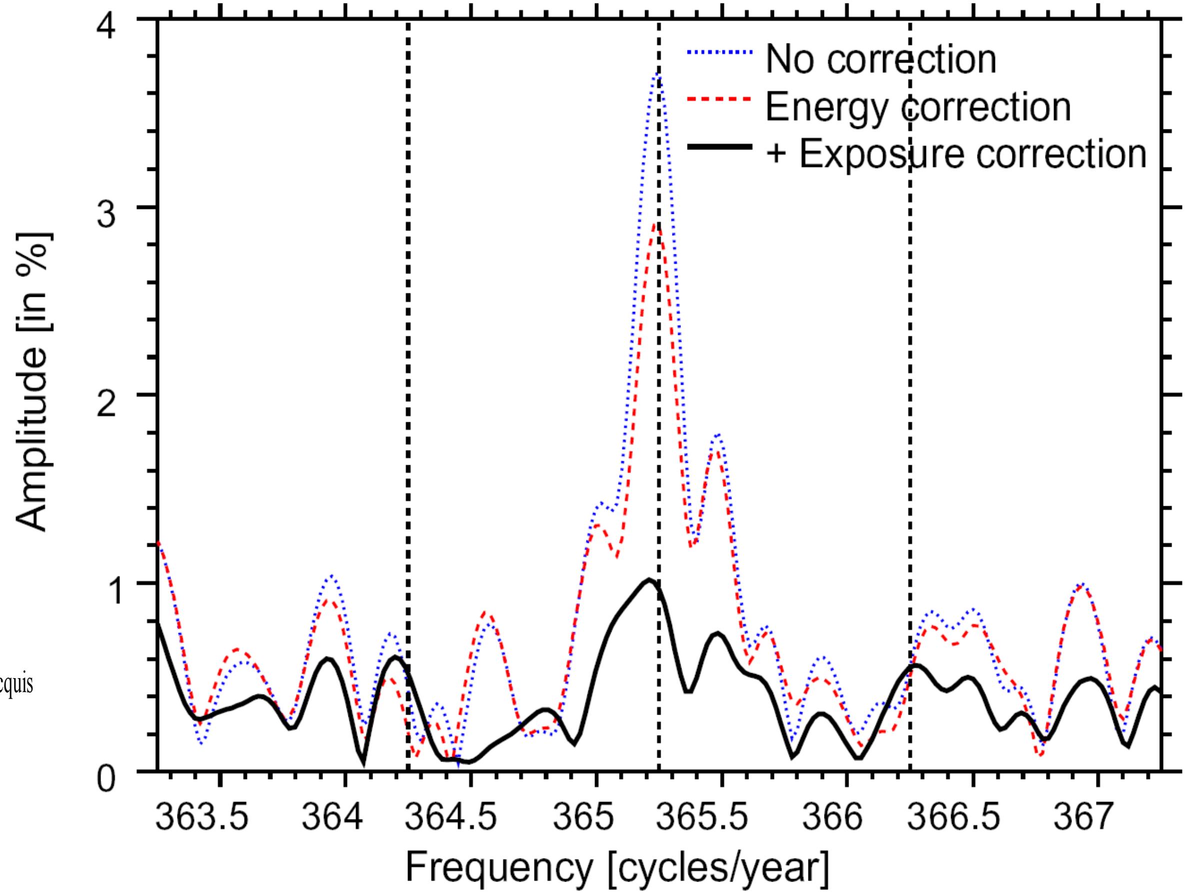
➔ **No evidence of significant anisotropy**

Check of corrections

Fourier time analysis: designed to disentangle any sidereal modulation from the solar and the anti-sidereal ones, without the knowledge of the exposure

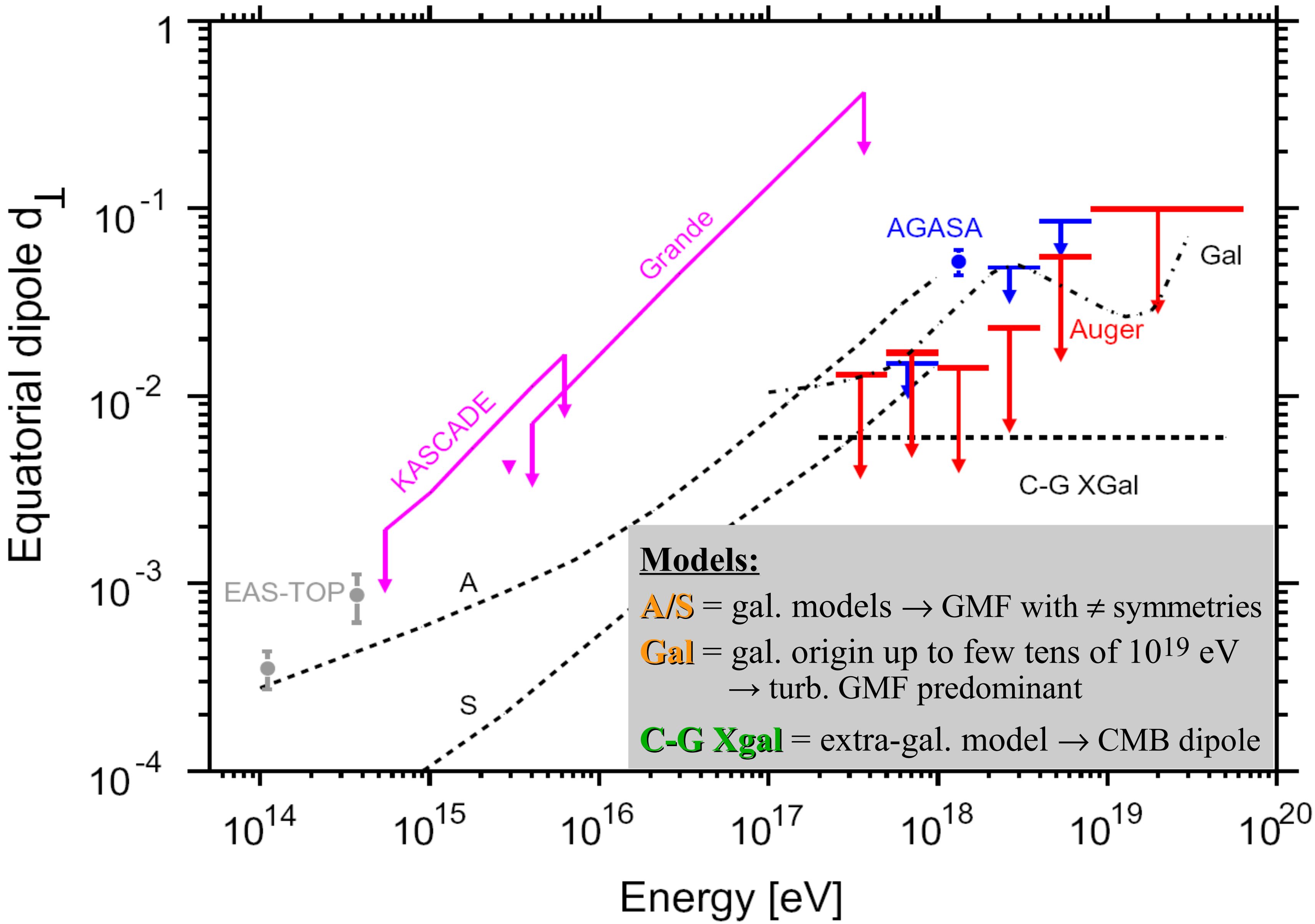
[Billoir & Letessier-Selvon, Astropart. Phys. 29 (2008) 14]

- Fourier transform of modified time distrib.: $\tilde{t}_i = t_i + \alpha_i - \alpha_i^0$
- Compare sidereal signal to:
  - antisidereal signal
  - average noise in other freq.
- Frequency resolution $\Delta f \sim 1/T_{acquis}$



➔ Spurious modulation of experimental origin are under control

Upper limits



Conclusions

- ✔ Search for cosmic ray large scale anisotropy at $E > 2 \cdot 10^{17}$ eV with the Auger data set by adopting **2 complementary analyses**

- ✔ Both analyses **account for** the **non-uniformity in acceptance** and the **weather effect systematics** → **spurious modulations under control**

- ✔ **No significant large-scale pattern observed**
  ⇒ upper limits at 99% c.l. have been set:
  - ➔ ***First constraints on some theoretical models*** : models predicting anisotropies > 2% below 4 EeV are excluded
  - ➔ Anisotropy reported by AGASA (4% for 1<E<2 EeV) not confirmed

- ✔ **In the near future:**
  - profit from Infill array → lower energy threshold
  - multipolar LS search

Harmonic Analysis

Rayleigh analysis *[J. Linsley, Phys. Rev. Lett. 34 (1975)]* = traditional way to study a modulation in right ascension of CRs arrival directions, as the one expected e.g. if the CR distribution has a significant dipolar component .

$$A = \frac{2}{N}\sum_{i=1}^{N}\cos\alpha_i \quad \text{and} \quad B = \frac{2}{N}\sum_{i=1}^{N}\sin\alpha_i$$

First harmonic amplitude and **phase**: $r = \sqrt{A^2 + B^2} \quad \text{and} \quad \Psi = \text{atan}\frac{B}{A}$

Probability for the observed amplitude to arise just as a statistical fluctuation of an isotropic distribution: $P = \exp(-r^2/4N)$

The analysis can be done in:

- *solar time* → detector instabilities + weather modulations
- *sidereal time* → modulation due to a genuine large scale pattern in the sky
- *anti-sidereal time* → to correct apparent sidereal modulations

[F.J.M.Farley and J.R.Storey, Proc. Phys. Soc. A 67 (1954)]

Results: Energy Windows

[EeV]	r_{sid}[%]	Prob [%]	Phase (°)	(99%c.l.)
0.25 - 0.5	0.4	67	262	1.3
0.5 - 1	1.2	2	281	1.7
1 – 2	0.5	22	15	1.4
2 – 4	0.8	47	39	2.3
4 – 8	1.8	35	82	5.5
> 8	4.1	9	117	9.9

DATA SET:

- Events recorded by SD from 1 January 2004 to 31 December 2009
- Highest quality cuts + periods with strong instabilities erased → duty cycle ~ 85%
- $3 \cdot 10^5$ events above 1 EeV, $3 \cdot 10^4$ above 3 EeV

UPPER LIMITS:

- *below 1 EeV* → East-West method
- *above 1 EeV* → generalized Rayleigh analysis
- calculated according to the distribution drawn from a population characterized by an anisotropy of unknown amplitude *[J.Linsley PRL 1975]*