Anisotropy studies with the Pierre Auger Observatory

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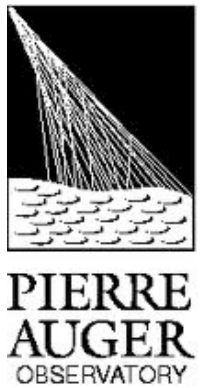
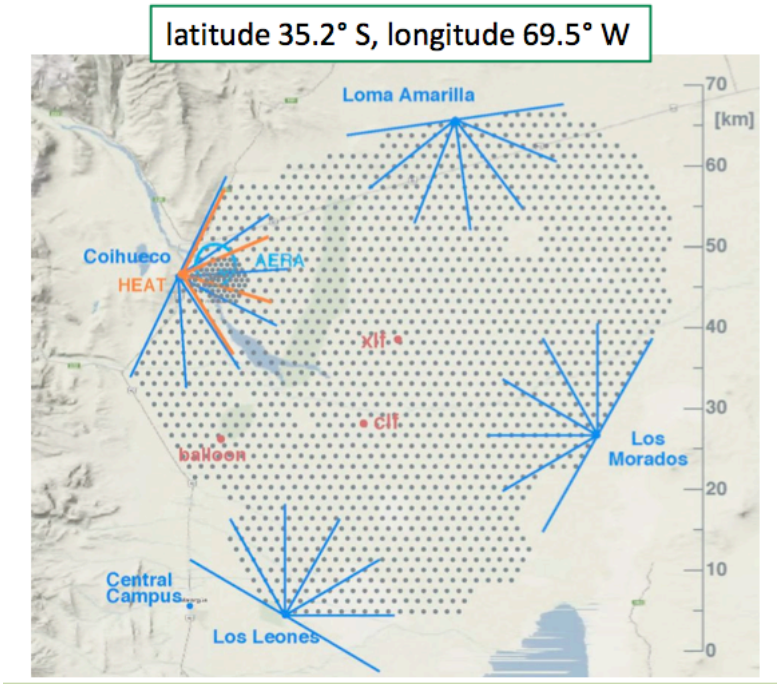


EPSHEP 2013 Stockholm, 18-24 July

The Pierre Auger Observatory

- ✓ designed to study Ultra High Energy Cosmic Rays ($E > 10^{18}$ eV)
- ✓ located near Malargüe, Argentina



Hybrid detector of UHECR

surface + fluorescence detectors

- Surface Detector (SD):

1660 water Cherenkov detectors (regular array) covering 3,000 km^2 on a hexagonal grid with 1,500 m spacing (full efficiency @ 3 × 10^{18} eV)

49 additional detectors (infill array), reduced spacing of 750 m (23.5 km^2 area) enhancing the Observatory capibilities down to 10^{16} eV (full efficiency @ 3 × 10^{17} eV)

- Fluorescence Detector (FD):

27 fluorescence telescopes at 4 sites overlooking the SD array

use subset of events detected simultaneously with the SD and the FD to calibrate the SD signal against FD energies

The Pierre Auger Observatory

✓ designed to study Ultra High Energy

Hybrid detector of UHECR

ce + fluorescence detectors

rgentin

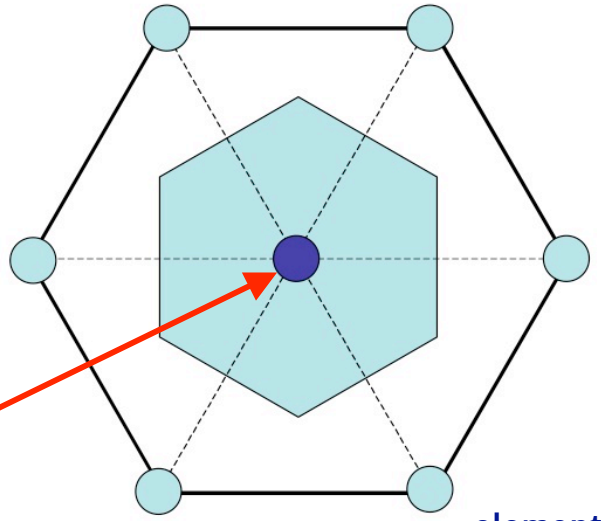
Detector (SD):

ICRC 2013

use events recorded
the SD

The dataset

- events recorded by the Surface Detector array
- January 2004 until December 2012
- zenith angle < 60° (1.5km spacing array)
- zenith angle < 55° (750m spacing array)



elemental cell

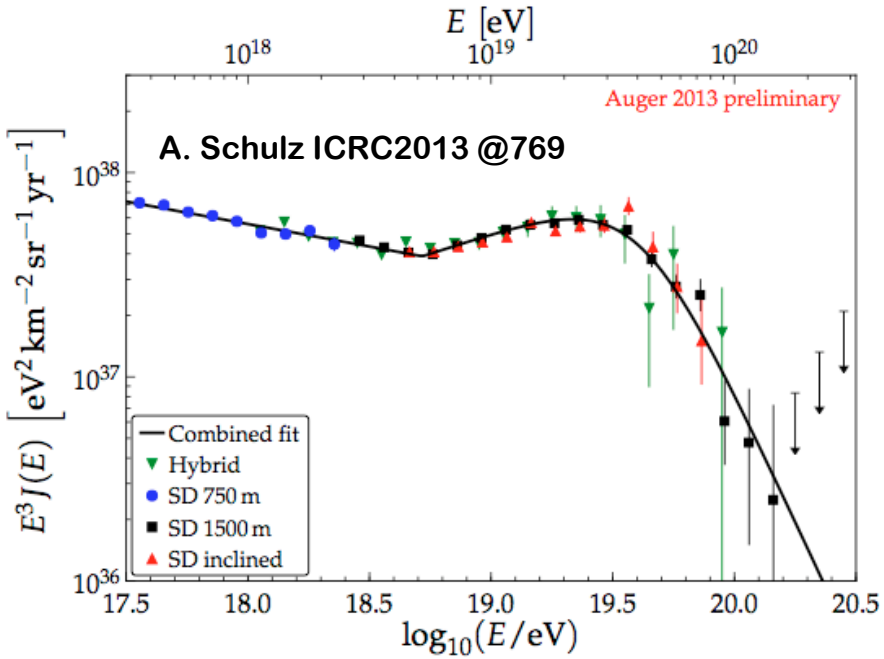
- **station with the highest signal** surrounded by a complete hexagons of working stations
- periods of unstable data acquisition removed

necessary for a good estimate of the detector's exposure at low energies

same quality cut is used to select events recorded with the infill array and the regular array

Cosmic Rays Observables

Spectrum (see I. Maris talk)



- ankle model
  transition Gal-ExtraGal. component at ankle
  (flat Fe → steep E.G. proton)
- dip model
  transition Gal-ExtraGal. at 2nd knee
  (ankle → e^+e^- production)
- mixed model
  transition Gal-ExtraGal. at ankle
  (flat Fe → mixed E.G. component)

Mass composition: evidence of light component until ~ $10^{18.3}$ eV

(E.J. Ahn ICRC2013 @0690)

Anisotropy studies: **large scale anisotropies, point source analysis**

provide complementary informations to understand the nature and origin of cosmic rays

Large Scale Anisotropies

- transition from galactic to extragalactic component should induce a significant change in the large scale angular distribution of cosmic rays

Galactic + heavy CR (sources on Galactic Plane) → few % dipole pattern

Isotropic E.G. proton (Compton Getting effect) → % dipole pattern

General method

$$\frac{dN(\Delta E,(n))}{d\Omega} = \int_{\Delta E} E^{-\gamma}\omega(E,\mathbf{n})\phi(\mathbf{n})dE$$

$$\omega(t,\theta,\psi,E) = n_{cell}(t)\cdot a_{cell}(\cos\theta)\cdot\epsilon(\theta,\psi,E)$$

- control of systematics at % level (angle independent energy estimator, estimation of exposure)
- expansion of $\phi(\mathbf{n})$ in angular function of (dec, R.A.)

L. S. A.: first harmonic analysis in R.A.

The Pierre Auger Collabration, Astropart. Phys. 34 (2011), 627-639

- expansion of $\phi(n)$ in right ascension R.A. (no declination dependence in exposure)

$$\Phi(\alpha) = \Phi_O \cdot (1 + r\cos(\alpha - \phi))$$

- First harmonic modulations are small ⇒ account for spurious modulations (experimental and atmospheric)

Method: Modified Rayleigh (E > 1 EeV)

Fourier coefficients $a = \frac{2}{N}\sum_{i=1}^{N} w_i \cos\alpha_i$ $b = \frac{2}{N}\sum_{i=1}^{N} w_i \sin\alpha_i$

amplitude $r = \sqrt{a^2 + b^2}$ phase $\varphi = \arctan\frac{b}{a}$

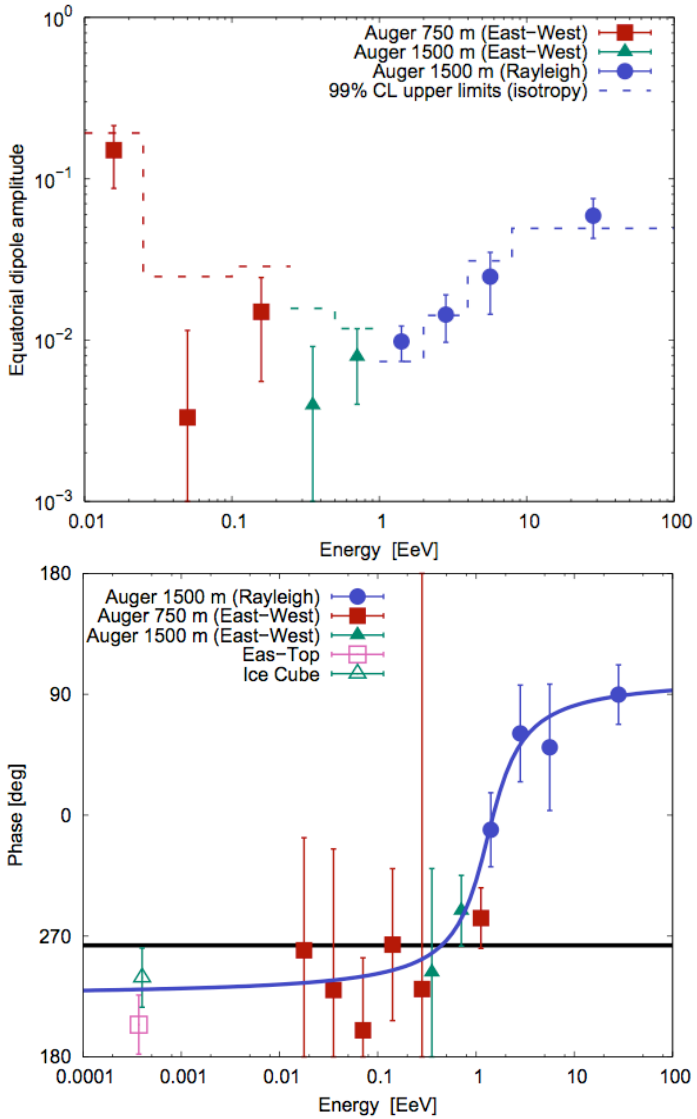
- energy assignement corrected for weather and geomagnetic effects
- w_i accounting for the dead time, growth and tilt of the array

East-West method (E < 1 EeV) **(astro-ph/1106.2651)**

- $I_E(\alpha^0)$ - $I_W(\alpha^0)$ allows us to reduce systematic effects
- Reduced sensitivity

L. S. A.: first harmonic analysis in R.A.

I. Sidelnik ICRC2013 @0739



Amplitude of the dipole ($d_\perp \sim r/\langle\cos\delta\rangle$)

- **dashed line**: 99% C.L upper bound on on statistical fluctuations from isotropy
- 3 bins above 1 EeV have low probability to arise from isotropy

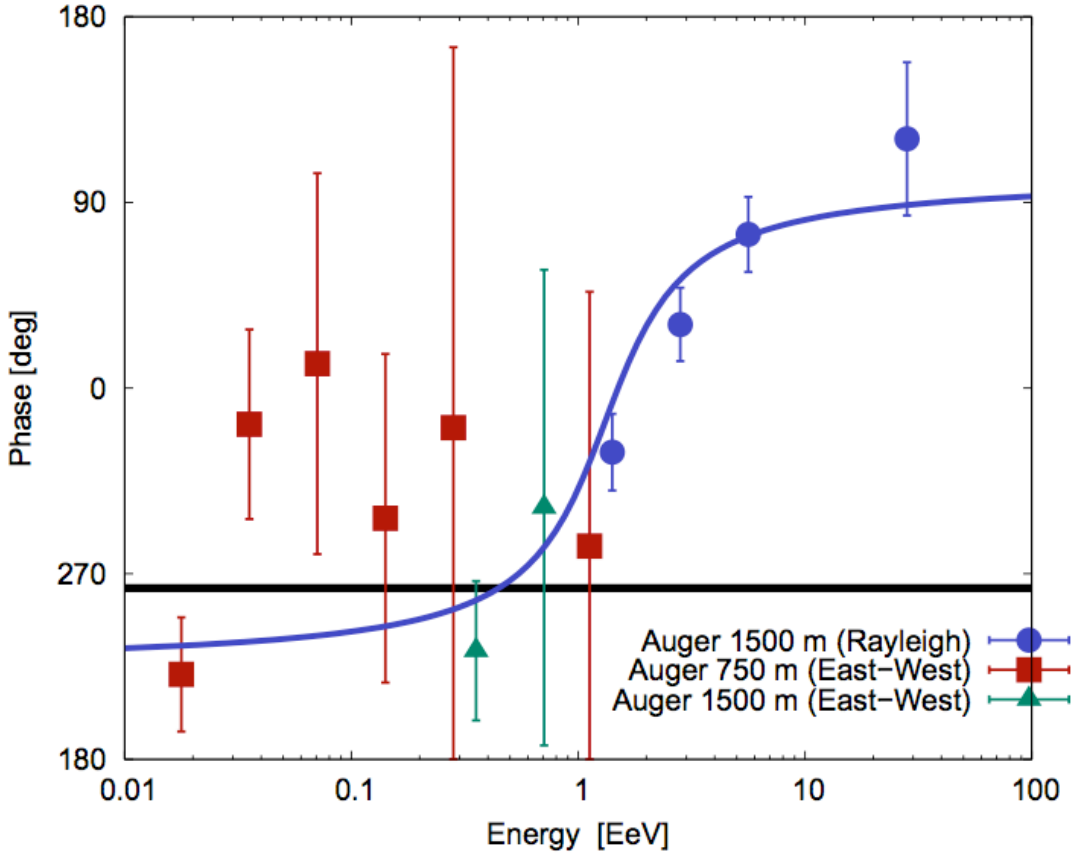
P(1-2 EeV) = 0.03%
P(2-4 EeV) = 0.9%
P(>8 EeV) = 0.1%

Phase of the first harmonic

- hint of a smooth transition from a common phase of $\alpha \approx 270^\circ$ in the bins below 1 EeV to $\alpha \approx 90^\circ$ above 4 EeV (α_{GC} 268.4°)

prescription to check with new data at 99% C.L.

Midterm status of the prescription



- started on the 25 June 2011
- constancy of phase at E < 1EeV with the Infill data
- transition in phase at high energies

Phase on the first harmonic with events from 25 June 2011 to 31 December 2012

L. S. A.: 3D Method

Rogerio M. de Almeida ICRC2013@0768

Expansion in Spherical Harmonics

$$\Phi(\mathbf{n}) = \sum_{l\geq 0} \sum_{m=-l}^{m=l} a_{lm} Y_{ln}(\mathbf{n})$$

$$\omega(\mathbf{n}) \cdot \Phi(\mathbf{n}) = \sum_{l\geq 0} \sum_{m=-l}^{m=l} b_{lm} Y_{ln}(\mathbf{n})$$

$$a_{lm} = \sum_{l'=0}^{l_{max}} \sum_{m=-l'}^{l'} [K^{-1}_{l_{max}}]^{l'\,m'}_{lm}\, b_{l'\,m'}$$

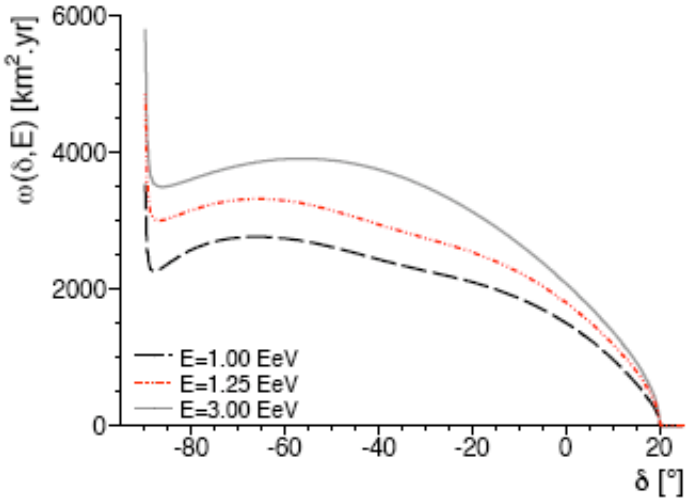
- any anisotropy fingerprint is encoded in the set of spherical harmonics coefficients a_{lm}
- observed angular distribution is modulated by the exposure function (account for partial sky coverage)
- extract multipolar moments with partial sky coverage (**JCAP0802:009, 2008**)

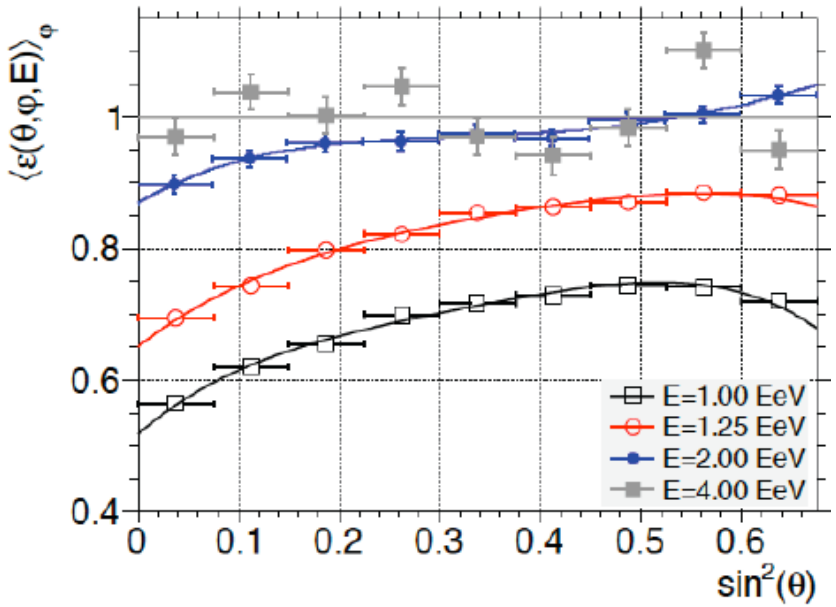
- **dipole vector and quadrupole tensor of special interest**
- **need to fix L_{max} (maximum order of expansion)**
- **resolution on a_{lm} decrease with L_{max}**
- **data θ<55°, correct for geomagnetic and atmospheric effects**

Directional Exposure

- **in searching anisotropies it is crucial to determine the directional exposure**

- above 3 EeV exposure determined by geometric considerations
- below 3 EeV the exposure depends on the efficiency



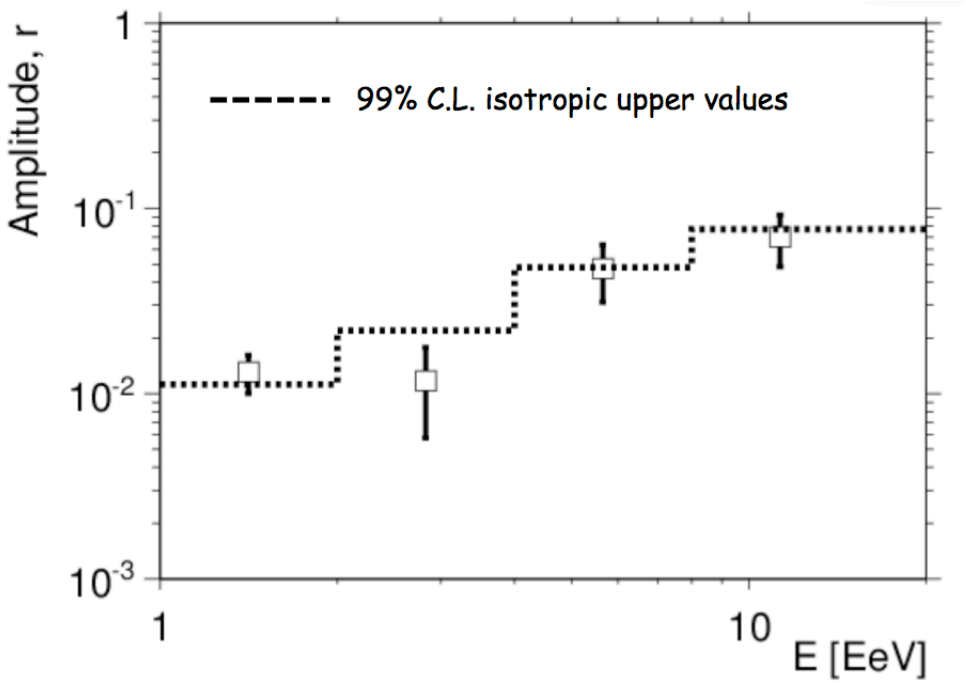


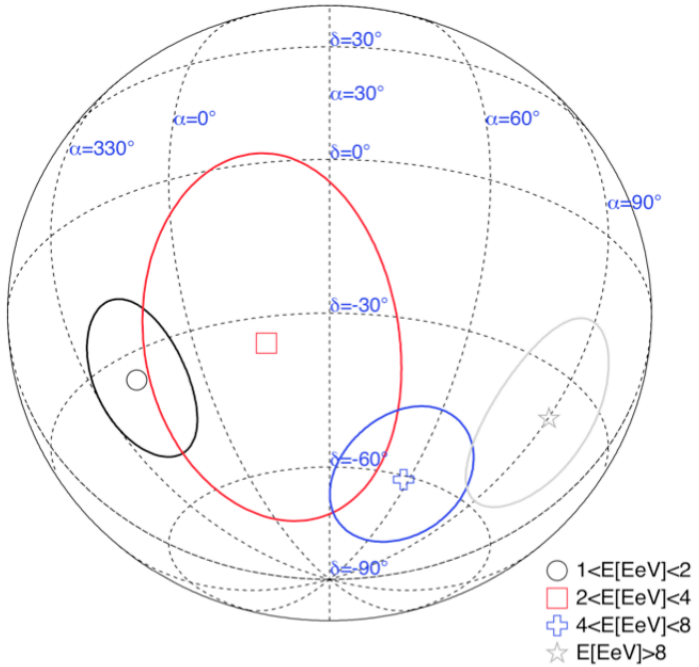
Empirical approach: based on quasi invariance of the zenithal distribution to large scale anisotropies for zenith angles less than ~ 60°

$$\langle \epsilon(\theta,\varphi,E)\rangle_\varphi = \frac{1}{\mathcal{N}}\frac{dN(\sin^2\theta,E)}{d\sin^2\theta}$$

Dipole search ($l_{max} = 1$)

$$\Phi(\mathbf{n}) = \frac{\Phi_0}{4\pi}(1 + r\mathbf{d}\cdot\mathbf{n})$$





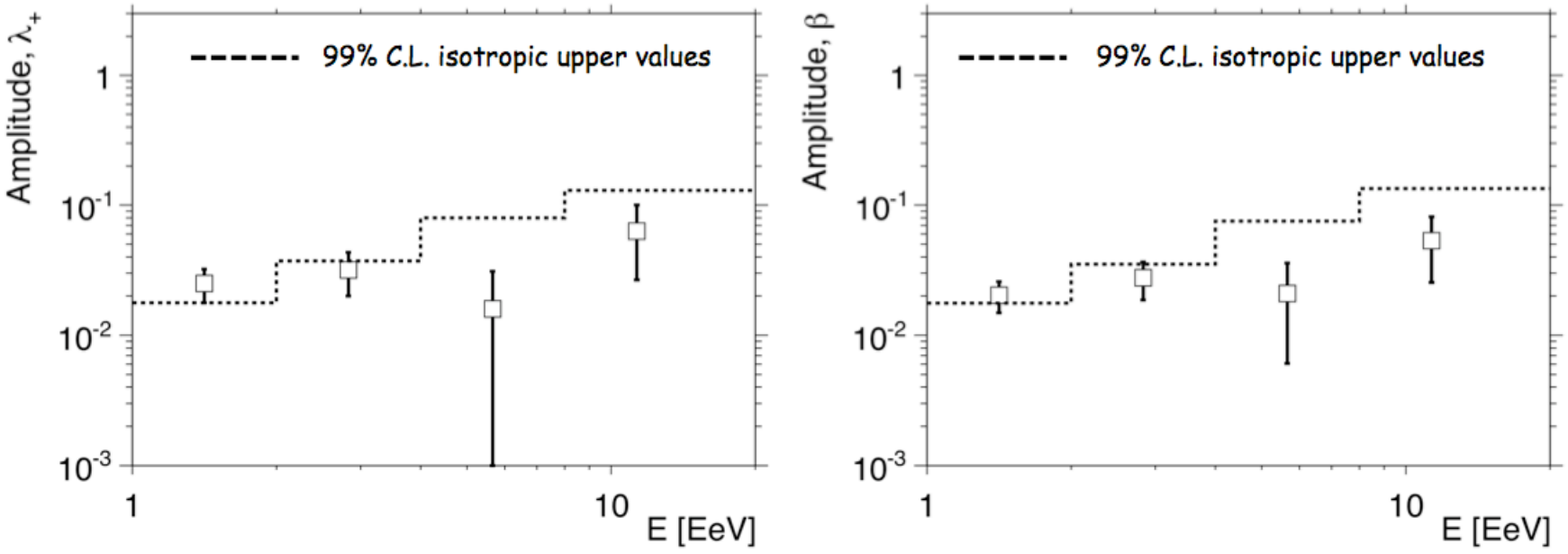
similar to the results obtained from first harmonic analysis in R.A.

hints for large scale anisotropies above 1 EeV

Quadrupole search ($l_{max} = 2$)

$$\Phi(\mathbf{n}) = \frac{\Phi_0}{4\pi}(1 + r\mathbf{d}\cdot\mathbf{n} + \lambda_+(\mathbf{q}_+\cdot\mathbf{n})^2 + \lambda_0(\mathbf{q}_0\cdot\mathbf{n})^2 + \lambda_-(\mathbf{q}_-\cdot\mathbf{n})^2)$$

$$\beta \equiv \frac{(\lambda_+ - \lambda_-)}{(2 + \lambda_+ + \lambda_-)} = \frac{\Phi_{max} - \Phi_{min}}{\Phi_{max} + \Phi_{min}}$$



Hints of moments higher than dipole at EeV energies

Neutron Search

Motivation

- if TeV gamma rays are produced in pion-producing interactions sources should emit also neutrons
- at EeV energies neutrons still can reach us from Galactic sources
  $d = 9.2\ E/\mathrm{EeV}\ [\mathrm{kpc}]$, $r_{GAL} = 15$ kpc
- neutrons are electrically neutral → point back directly to the sources
- event clusterings would be indicative of a neutron cosmic ray flux
- neutrons produced showers that are indinstinguishable from those iniziated by protons

Method

- **blind search analysis,** search for excess in the data

  The Pierre Auger Collaboration, ApJ, 760 (2012) 148

- **targeted search,** search over selected candidate sources list

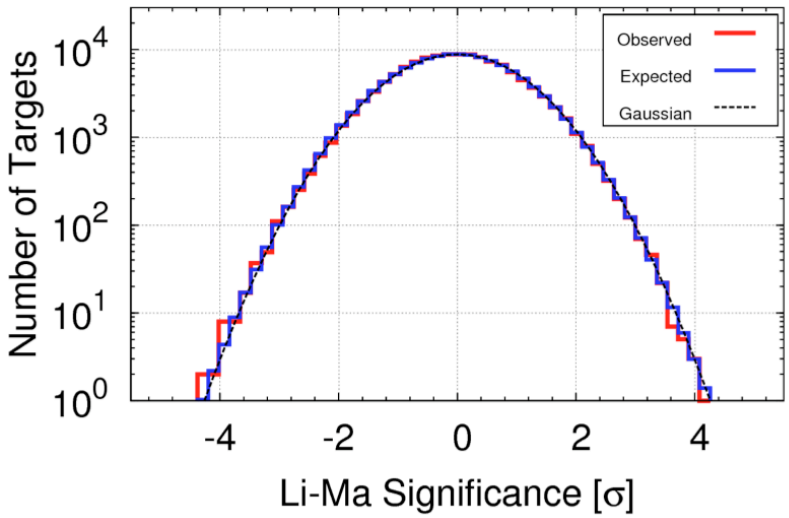
  F. Salesa ICRC2013 @1125

Neutron Search - Blind Search

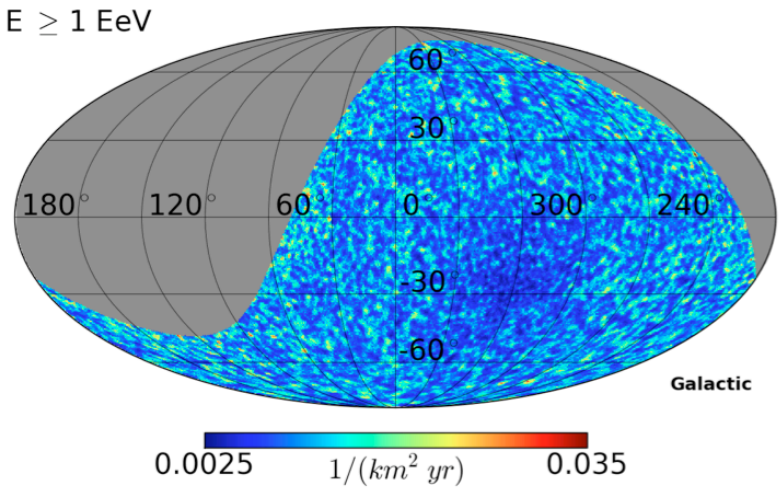
- 4 energy bins: [1-2] EeV, [2-3] EeV, E > 3 EeV, E > 1 EeV
- optimized target search from 1.36° to 0.69° for E > 3 EeV
- 10,000 simulated data set (real events scrambled)
- significance: T.-P.Li, Y.-Q.Ma, (**ApJ 1983, 272: 317-324**)

No deviation from isotropy in each energy bin

Li-Ma Significance Histogram (E ≥ 1 EeV)



Flux upper limit map 95% C.L.



E > 1 EeV flux UL ~ 0.0114 neutron/km^2 yr
(energy flux limit 0.083 eV/cm^2 s)

Neutron Search - Targeted Search

Candidate source lists (Magnetars, x-ray binaries microquasars gamma ray pulsars from Fermi catalog, HESS catalogs, Galactic Plane, Galactic Center)

Method

- target radius is 1.05° × A.R. where A.R. = A.R. (dec.)
- observed (n_i) number of events in each target
- expected number of events (b_i) is taken from average of 10,000 simulated data set (real event scrambled) in each target
- p-value (p_i) from Poisson statistics: pi = P(≥n_i, b_i)
- combined p-value (P): $\mathrm{P} = P(\Pi_{i=1}^{N} p_i^{sim} \leq \Pi_{i=1}^{N} p_i^{obs})$ probability that the product of the p-values in isotropic simulations is less or equal to the value or the observed p-values
- also weights are included in the combined p-value P to favour sources with greater exposure and larger electromagnetic flux

NO SIGNIFICANT SMALL COMBINED (or INDIVIDUAL) p-value

conclusions

Large scale analysis

- hints of dipole structures in the arrival directions of CR above 1 EeV
- transition in phase at high energy ⇒ prescription running
- hints of moments higher than dipole at EeV energies

Point search analysis

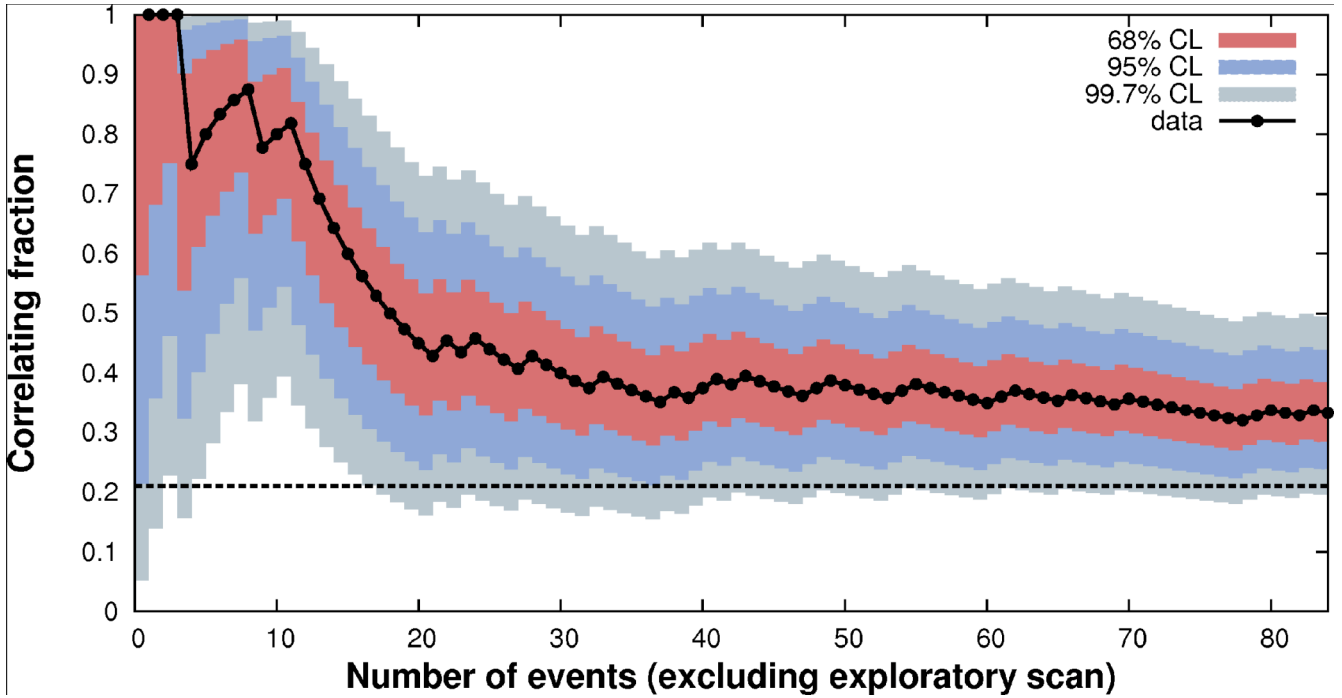
- at $E \geq 1$ EeV flux limit ≈ 0.083 eV cm^{-2} s^{-1}
- no excess in targeted search with different classes of sources

from these results the scenario of proton stationary galactic sources emitting in all directions is disfavored

Back up

VCV Correlation analysis

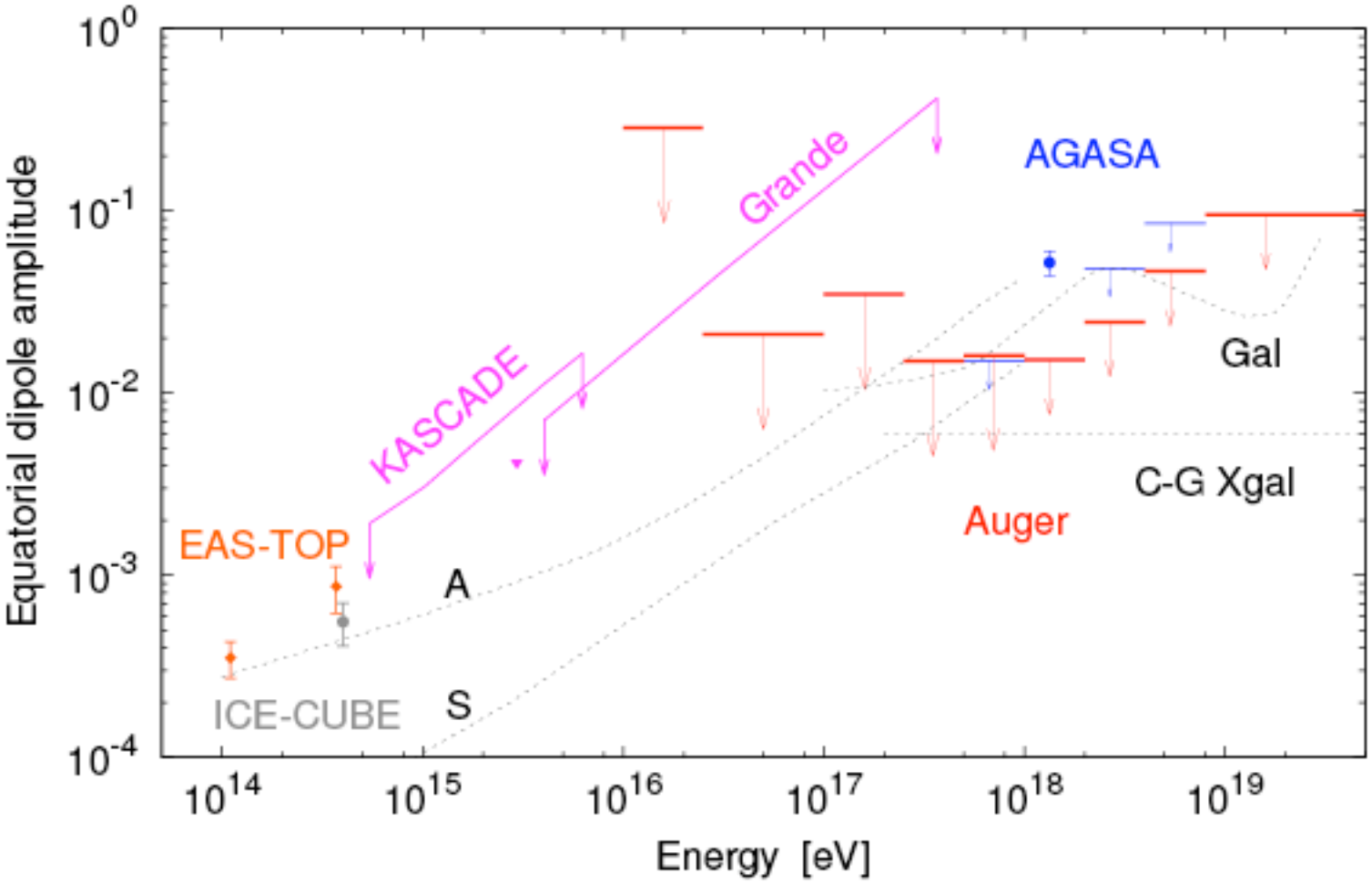
reject the isotropy of cosmic rays with E > 55 EeV with prescription at 99% C.L.
The Pierre Auger Collaboration,Science, 34 318(2007) 938



f = k/N
k: correlating events
N: total number

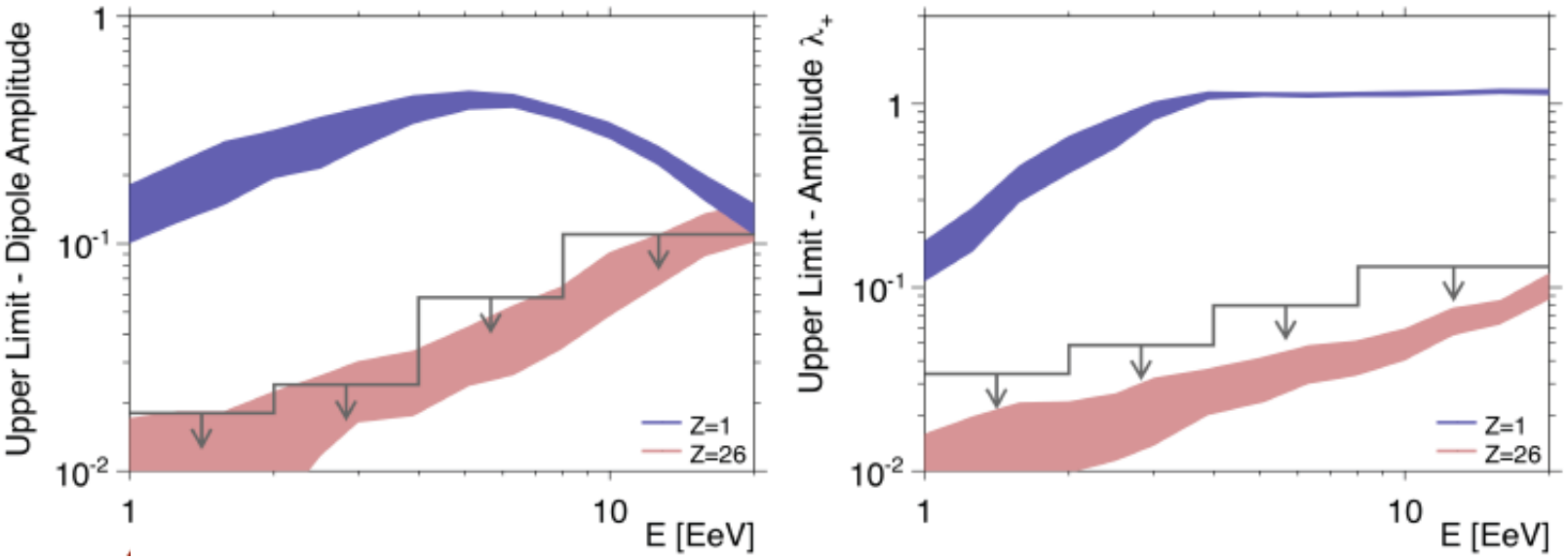
up to June 2011
f = (33±5)%
f_{ISO} = 21%

Upper limits on the equatorial dipole (99% C.L.)



Upper limits on dipole and quadrupole amplitudes

- **generic estimates of the amplitudes expexted from stationary galactic sources**



Galactic magnetic filed → regular field (disk and halo) + turbulent field

BSS model: Symmetric with respect to the galactic plane (logarithmic spiral model with Reversal direction in two arms)

Anti-symmetric with respect to the galactic Plane and purely toroidal

According to a Kolmogorov power spectrum