Ultra High Energy Cosmic Rays Anisotropy searches in data of the Pierre Auger Observatory

Gabriella Cataldi ⁽¹⁾ (for the Pierre Auger collaboration⁽²⁾)



(1)INFN Lecce, Italy(2)The Pierre Auger Observatory Malargüe, Argentina



The Pierre Auger Observatory

 ✓ designed to study Ultra High Energy Cosmic Rays (E > 10¹⁸ eV)
✓ located near Malargüe, Argentina



Hybrid detector of UHECR

surface + fluorescence detectors

 Surface Detector (SD): 1660 water Cherenkov detectors covering 3,000 km² on a hexagonal grid with 1,500 m spacing (full efficiency @ 3 x 10¹⁸ eV)

49 detectors (infill array), reduced spacing of 750 m (23.5 km² area) allows a lower energy detection (full efficiency @ 3×10^{17} eV)

Fluorescence Detector (FD):

27 fluorescence telescopes at 4 sites overlooking the SD array

use events recorded independently by SD and FD to calibrate the SD measurements to FD energy

The Pierre Auger Observatory



station with the highest signal surrounded by a complete hexagons of working stations



6 telescopes with a FOV of 30° x 30°



FD Detector

Anisotropy studies: Large Scale Anisotropy

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

Above 1 EeV anisotropies could be imprinted in the distribution of arrival directions as the result of the escape of UHECRs from the Galaxy up to the ankle energy.

If UHECRs have a predominant extragalactic origin their angular distribution is expected to be isotropic to a high level.

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

Method (multiple expansion):

Raileigh method (E > 1 EeV) Classical formalism derived from Fourier analysis of right ascension including normalized weights (w_i) to correct for varying exposure of the SD.

East-West method (E < 1 EeV) (astro-ph/1106.2651) Differential method taking advantage of East/West symmetry of the SD detection probability at any single point in time (no local effects).

Event rate difference from East and West sectors at sidereal time is sensitive to right ascension modulation of amplitude and phase.

G. Cataldi

L.S.A: First Armonic analysis in R.A



I. Sidelnik ICRC2013 @0739

Amplitude of the dipole

- dashed line: 99% C.L upper bound 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 dipole

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 this transtion in the phase

L.S.A: Midterm status of the prescription



Phase on the first harmonic with events from 25 June 2011 to 31 December 2012 Prescription to check with new data at 99% of C.L.

- Started on the 25 June 2011
- Constancy of phase at E < 1EeV with infill data
- Transition in phase at high energies

L.S.A: 3D Method

Expansion in Spherical Harmonics

 Any anisotropy fingerprint is encoded in the set of spherical harmonics coefficients

 Observed angular distribution is modulated by the exposure function

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



Rogerio M. de Almeida ICRC2013@0768



Similar results obtained from the LSA in R.A. Hints for large scale anisotropies above 1 EeV

Anisotropy: 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 $d = 9.2 E/EeV [kpc], r_{GAL} = 15 kpc$
- Neutrons are electrically neutral, they 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 excesses in the data The Pierre Auger Collaboration, ApJ, 760 (2012) 148

targeted search, search over selected sources list

F. Salesa ICRC2013 @1125

N.S.: Blind search

- 4 energy bins: [1-2] EeV, [2-3] EeV, E > 3 EeV, E > 1 EeV
- $\theta < 60^{\circ}$, optimized target search form 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)

Flux upper limit map 95% C.L. Li-Ma Significance Histogram ($E \ge 1 \text{ EeV}$) $E \ge 1 \, EeV$ Number of Targets 01 1 Observed 60 Expected 30 10³ Gaussian 120 0 180 60 300 240 10² -30 -60 Galactic 10⁰ -2 2 -4 0 4 0.0025 0.035 $1/(km^2 yr)$ Li-Ma Significance $[\sigma]$ $E > 1 EeV flux UL \sim 0.0114 neutron/km² yr$ (energy flux limit 0.083 eV/cm² s)

No deviation from isotropy in each energy bin

N.S.: 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 $1.05 \times A.R.$ where A.R. is the average angular resolution
- 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: $p_i = P(n_i, b_i)$

 combined p-value (P): probability that the product of the p-values in isotropic simulations is less or equal to the value of 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

Anisotropy: Correlation Analysis

The Pierre Auger Collaboration, Astroparticle Physics, 34 (2010) 314-326

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 correlation of the arrival directions of cosmic rays with E > 55 EeV with the positions of "nearby" AGNs (z<0.018) of the VCV catalog 68% CI 95% CI 0.9 99 7% CI f = k/Ndata 0.8 **Correlating fraction** k: correlating events 0.7 N: total number 0.6 0.5 up to June 2011 0.4 0.3 $f = (33\pm5)\%$ 0.2 $f_{ISO} = 21\%$ 0.1 0 10 20 30 40 50 60 70 80 0 Number of events (excluding exploratory scan) G. Cataldi Tübingen, September 2013

Anisotropy: Correlation Analysis

The 69 events with Energy > 55 EeV detected by the Pierre Auger Observatory

Blue circles of radius 3.1° centered at the positions of the 318 AGNs < 75 Mpc in the VCV catalog.



The exposure weighted fraction of the sky covered by the blue circles is 21%. Chance probability for a isotropic source distribution < 1%

CONCLUSIONS

Large scale analysis

Hints of dipole structures in the arrival directions above 1 EeV

Transition in phase at high energy \Rightarrow prescription running Point search analysis

- At $E \ge 1$ EeV flux limit ≈ 0.083 eV cm⁻² s⁻¹
- No excesses in targeted search with different classes of sources

Correlation analysis

Chance probability for a isotropic source distribution < 1%