Small-scale anisotropy in cosmic ray flux observed by GRAPES-3 at TeV energies

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Outline

- Introduction
- EAS experiments
- GRAPES-3 experiment
- Direction reconstruction
- Results

Introduction

- Cosmic rays (CRs) are high energy ($10^8 - 10^{20}$ eV) charged particles.
- Deflection of CRs in galactic magnetic field leads to isotropic flux.
- Anisotropy $\sim 10^{-4} - 10^{-3}$ of several angular scales observed

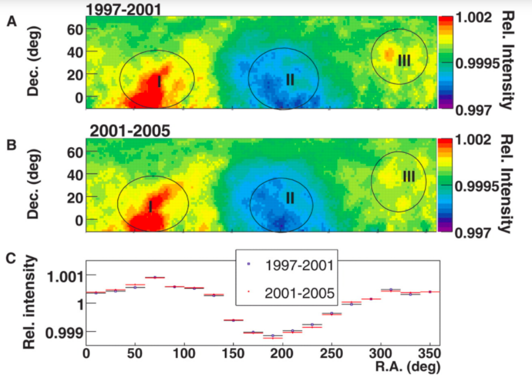


Figure: Observations by Tibet AS-γ

[M Amenomori et al., 2006, Science, 314, 439]

Small-scale anisotropy

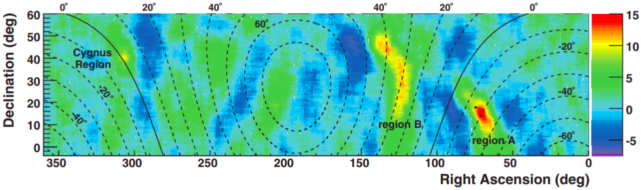


Figure: Small-scale anisotropy observation by Milagro

[A Abdo et al., 2008, PRL, 101,221101]

- Large-scale anisotropy $\sim 10^{-3}$, structures $> 60^\circ$, predominantly described by diffusive propagation of CRs.
- Small-scale anisotropy $\sim 10^{-4}$, structures $\leq 60^\circ$, due to correlated motion of CRs in local turbulent magnetic field, contribution from local sources
- Probe for magnetic field, acceleration and propagation mechanism of CRs.

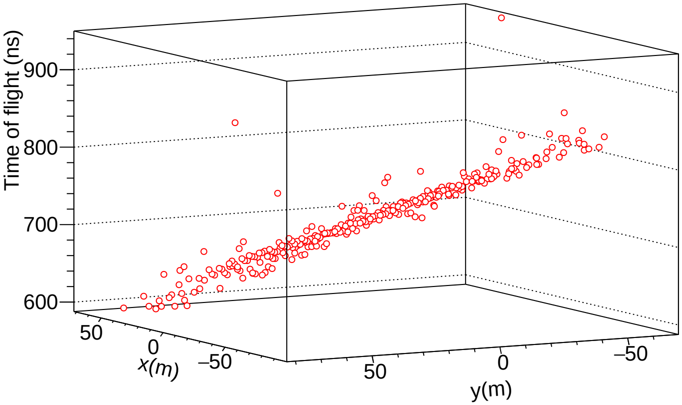
Air shower arrays

GRAPES-3 is closest to the Equator.

GRAPES-3 experiment

- Location: Ooty, India (11.4°N, 76.7°E, 2200 m asl)
- ∼400 plastic scintillators spread over 25000 m^2 with 8 m inter detector separation
- Observables: particle densities and relative arrival times
- Statistics: ∼3 million showers per day
- Muon telescope covering 560 m^2 consisting of 3712 PRCs
- Energy range: 1 TeV - 10 PeV

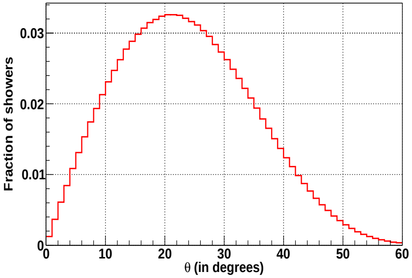
Direction reconstruction

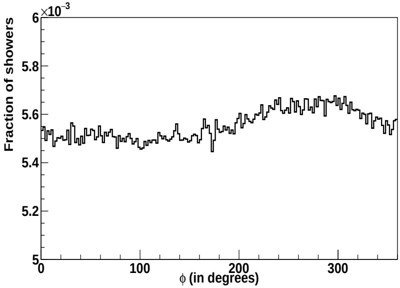


Planar fit is performed on arrival times to estimate direction of the shower

Direction reconstruction

Zenith and azimuthal angle distributions

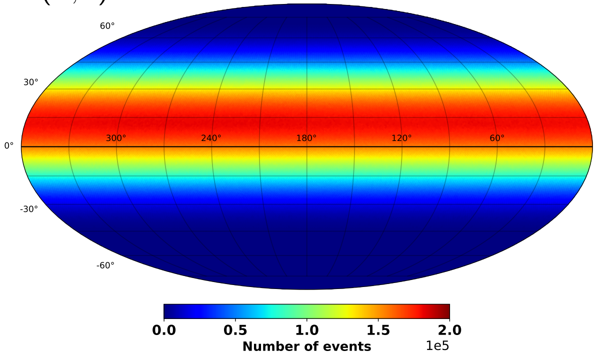




Non-uniform exposure of sky as distributions are non-uniform

Analysis

- Data period: 1st Jan, 2013 - 31st Dec, 2016
- Successful direction reconstruction, $\theta \leq 60^\circ$
- Number of events : 3.7×10^9
- Median energy : 19.4 TeV
- Local coordinates are converted to Equatorial coordinates, $(t, \theta, \phi) \rightarrow (\alpha, \delta)$



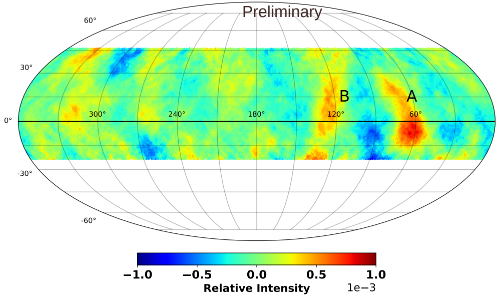
Analysis method

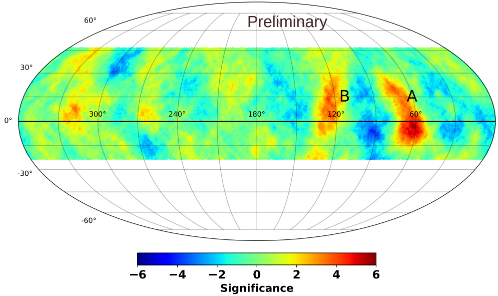
- Non-uniform sky exposure due to detector acceptance, breaks in DAQ, temperature and pressure effects.
- Background estimated from data set itself using the method of time-scrambling
- Event times are scrambled within a time window of 4 hrs. Anisotropic structures of angular width $< 60^\circ$ are destroyed.
- Background generated having similar sky exposure as data.
- Background subtracted to obtain the signal. Relative intensity,

$$\delta I = \frac{N_{ij}}{N_{oj}} - 1$$

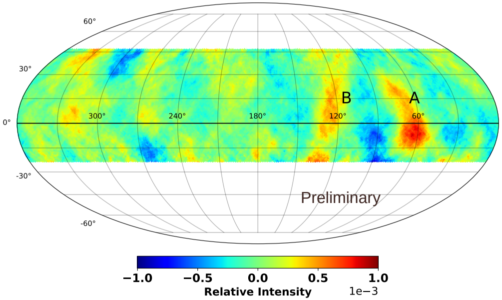
  N_{ij} : No. of events in the j-th pixel of data map. N_{oj} : No. of events in the j-th pixel of scrambled map
- Significance is calculated using Li-Ma formula from the likelihood ratio[The Astrophys. J. 272:317]

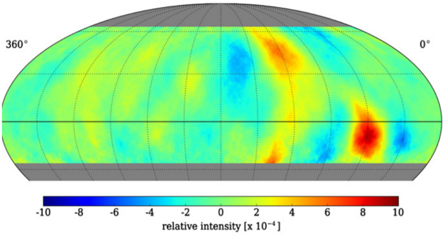
Results


Preliminary
60°
30°
0°
-30°
-60°
300°
240°
180°
120°
60°
B
A
−1.0
−0.5
0.0
0.5
1.0
Relative Intensity
1e−3

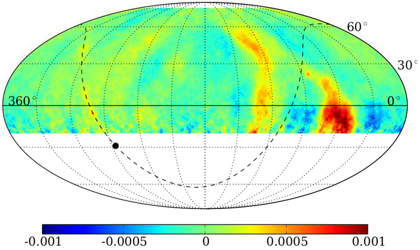

Preliminary
60°
30°
0°
-30°
-60°
300°
240°
180°
120°
60°
B
A
−6
−4
−2
0
2
4
6
Significance

Comparison with other experiments



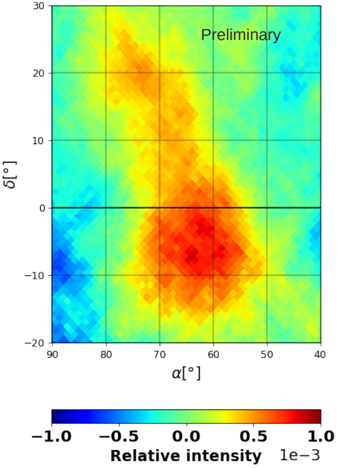


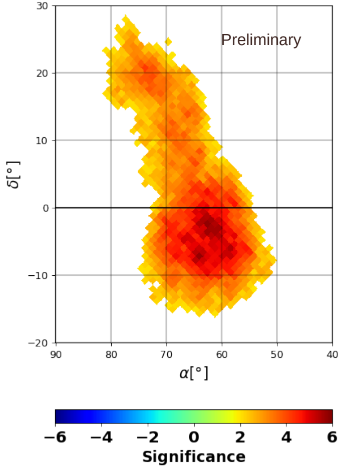
(a) HAWC



(b) ARGO-YBJ

Region A

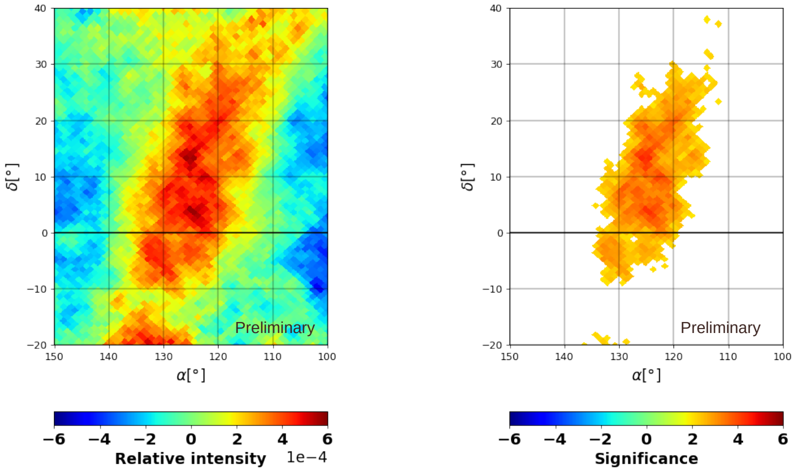




Relative intensity : $(6.5 \pm 1.3) \times 10^{-4}$,

Significance : 6.8σ

Region B

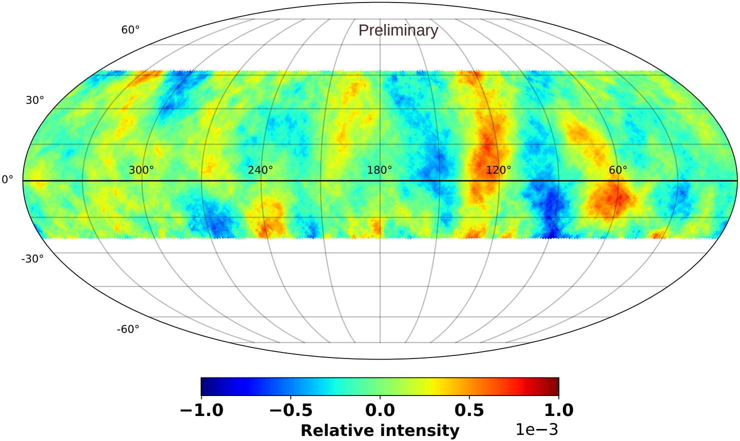


Relative intensity : $(4.9 \pm 1.4) \times 10^{-4}$,

Significance : 4.7σ

Showers with muon content

Models suggesting that the structures may be attributed to gamma ray flux from sources like Crab and Geminga. Showers generating one or more muon tracks in the muon detector used for the analysis. Events : 2.6×10^9



Results

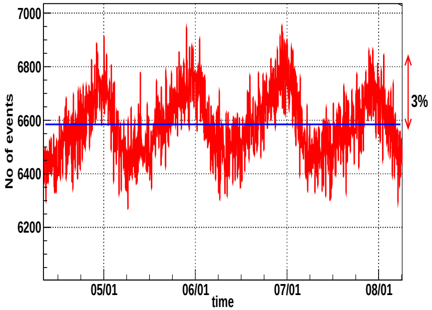
Structure	Without muon cut ($\times 10^{-4}$)	With muon cut ($\times 10^{-4}$)
A	(6.5 ± 1.3)	(5.5 ± 1.5)
B	(4.9 ± 1.4)	(5.7 ± 1.8)

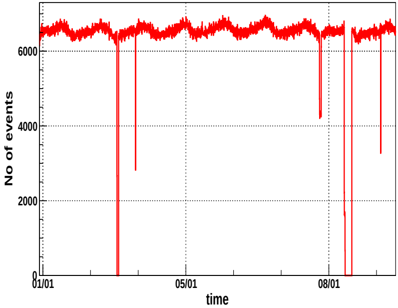
No statistically significant changes are observed in the strength of both the structures.

Summary

- Anisotropic structures, regions A and B have been observed with significance of 6.8σ and 4.7σ respectively.
- The structures are similar to observations by other experiments namely, Milagro, ARGO-YBJ and HAWC.
- By using the muon track information, it can be concluded that the primary contribution to the observed structures is the CR flux and not the gamma ray flux.

Detector and atmospheric effects





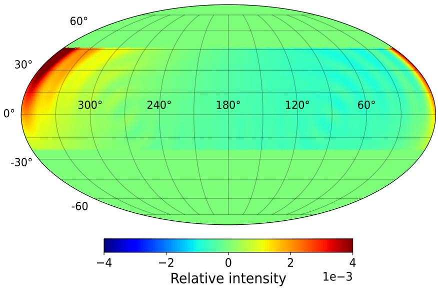
Time-scrambling method

- $(t, \theta, \phi) \rightarrow (\alpha, \delta)$ Data map (Signal+Background) α: RA, δ: declination
- Background map using time scrambling algorithm
- 20 random times within Δt from recorded time sample are assigned to each event
- Random times are chosen from recorded data sample, the breaks in DAQ are taken care of.
- Changes right ascension of the event keeping declination same
- Any structure within $w = \Delta t \times 15^\circ / hr$ is destroyed
- Relative intensity, $\delta I = \frac{N_{ij}}{N_{oj}} - 1$
  where, N_{ij} : No of events in the j-th pixel of data map
  N_{oj} : No of events in the j-th pixel of background map
- Significance is calculated using Li-Ma formula from the likelihood ratio[APJ 272:317-324]

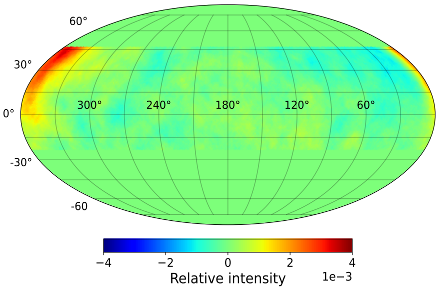
$$S = \sqrt{2N_{on} ln[\frac{1+\alpha_s}{\alpha_s} \frac{N_{on}}{N_{on}+N_{off}}] + 2N_{off} ln[(1+\alpha_s)\frac{N_{off}}{N_{on}+N_{off}}]}$$

Simulated data: Results

Data and scrambled maps are smoothed with top-hat function of smoothing radius 10°. Relative intensity, $\delta I = \frac{N_{ij}}{N_{oj}} - 1$
where, N_{ij} : No of events in the j-th pixel of data map, N_{oj} : No of events in the j-th pixel of background map



(a) Input anisotropy



(b) After time scrambling

Power spectrum

Simulation

$$a_{\ell m} = \Sigma_{i=0}^{NPix} \delta I(\delta_i, \alpha_i) Y_{\ell m}(\delta_i, \alpha_i) \Omega_i$$

$$C_\ell = \frac{\Sigma_m |a_{\ell m}|^2}{2\ell + 1}$$