Faculty of Physics of Moscow State University

The 21st Lomonosov Conference
on Elementary Particle Physics

Unique Scientific Facility
Experimental Complex
NEVOD

National Research Nuclear University
MEPhI, Moscow, Russia

Cosmic-ray anisotropy study by means of detection of muon bundles

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Introduction

A non-uniform distribution of CR sources and magnetic fields in the Galaxy create conditions for CR diffusion which could cause the large scale anisotropy (LSA).

Due to diffusion, the CR flux takes the form of a dipole and can be expressed by the formula

$$I = I_0\left(1 + \vec{r}\vec{D}\right)$$

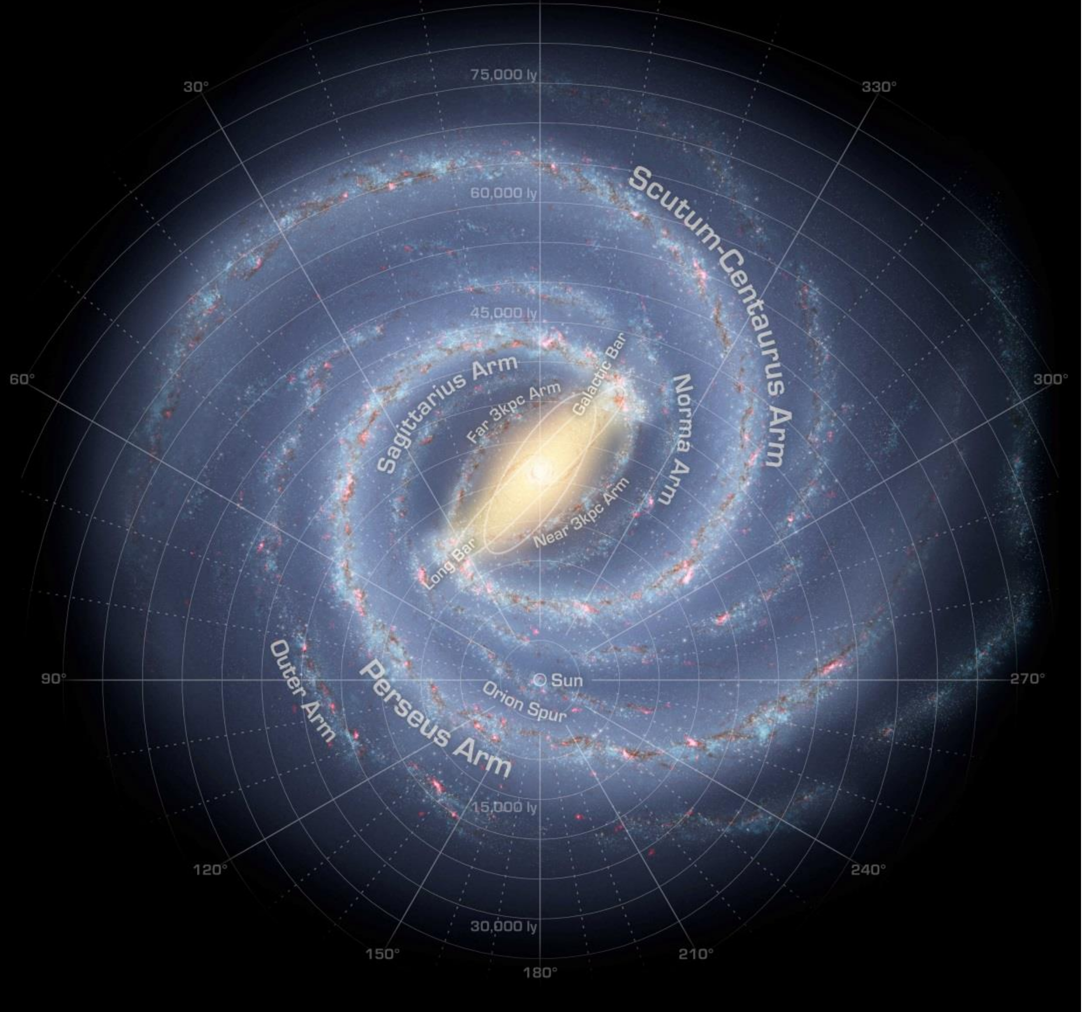
The second equatorial coordinate system is ordinary used to study the CR anisotropy because the equatorial plane of this system coincides with the Earth equatorial plane.

It is impossible to survey the entire celestial sphere from the surface of the Earth. Therefore, the anisotropy parameters estimation is carried out in the projection on the axis of right ascension. The first harmonics of relative deviation of flux corresponds to dipole anisotropy:

$$\frac{\Delta I}{I_0}(\alpha) = b + a\cos(\alpha - \alpha_0)$$

$\boldsymbol{a}$ is the amplitude and $\boldsymbol{\alpha_0}$ is the phase of the anisotropy

Simulated image



LSA sources

1. Diffusion is considered to be the main reason of the LSA.

$$A \sim R^{1/3}$$

(Berezinsky 1990, 21st ICRC)

2. Relative movements (Compton-Getting effect)

$$A = (\gamma + 2)\frac{w}{v}$$

γ is the index of the differential energy spectrum;

w is the detector velocity

v is CR particles velocity

Movement	Speed, km/s	Amp.
Earth around the Sun	30	**~ 10^{-4}**
Sun with respect to LSR	20	**~ 10^{-4}**
Sun around the center of MW	240	**~ 10^{-3}**

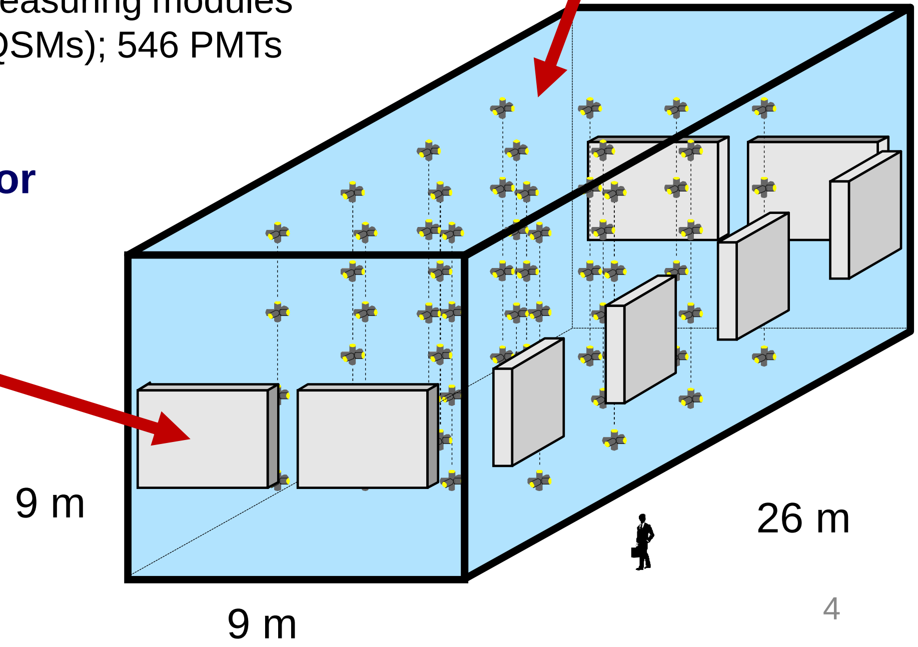
Experimental setup

Cherenkov water detector
NEVOD
(2000 m^3 volume)

Spatial lattice of
91 quasi-spherical
measuring modules
(QSMs); 546 PMTs

Coordinate-tracking detector
DECOR
(total area ~ 70 m^2)

8 supermodules (SMs)
of streamer tube chambers



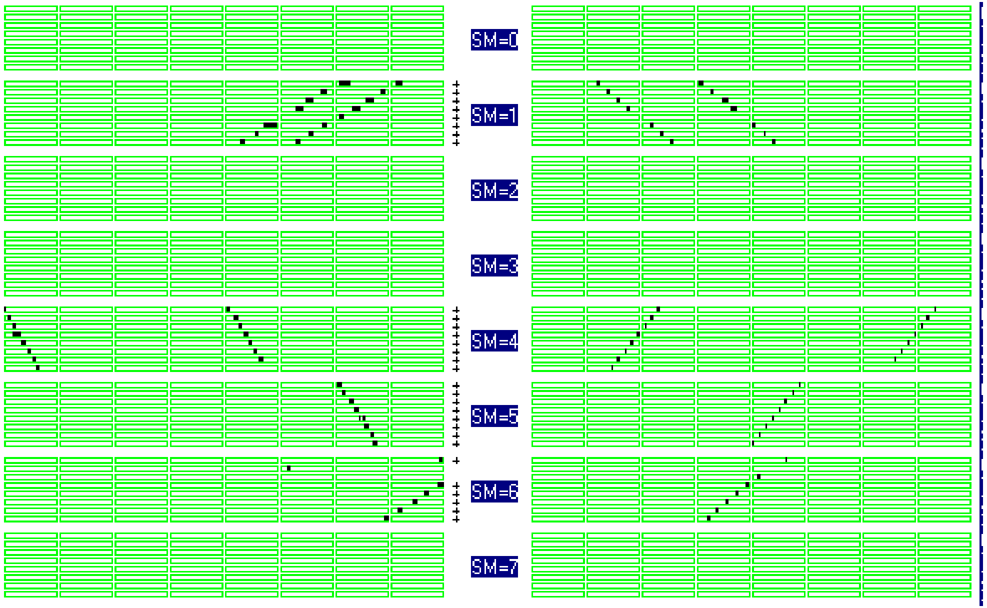
The main features of DECOR are its vertical deployment and good spatial and angular resolution (1 cm and ~1°).

Response of DECOR for muon bundle event

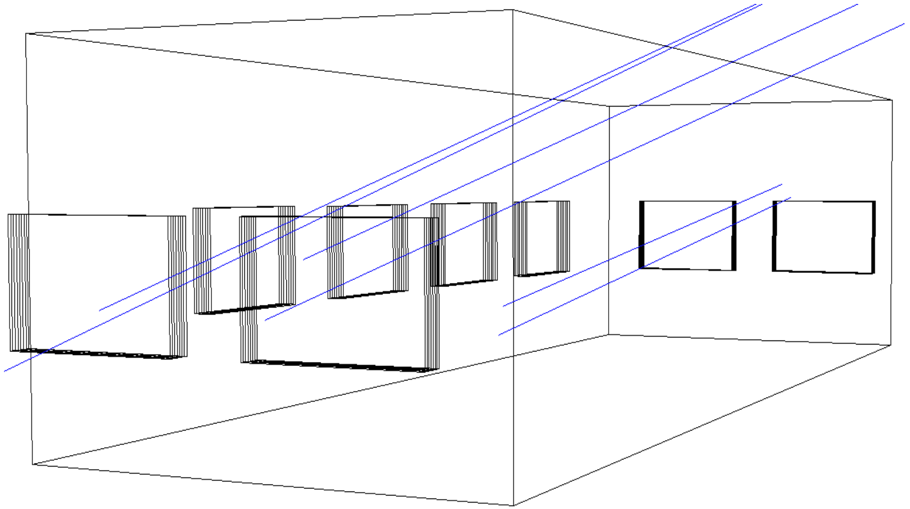
Tracks identification

X-projection

Y-projection



3D reconstruction



6 tracks

$\theta = 60°, \varphi = 211°$

Experimental data

Data accumulation was carried out for about 10 years

The total "live time" of the observation was 57,271 hours (~ 2,386 days).

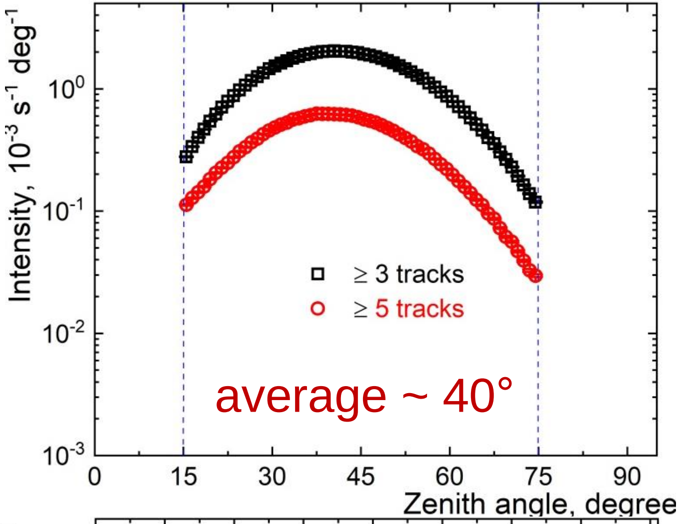
We used two samples of events with different selection conditions:

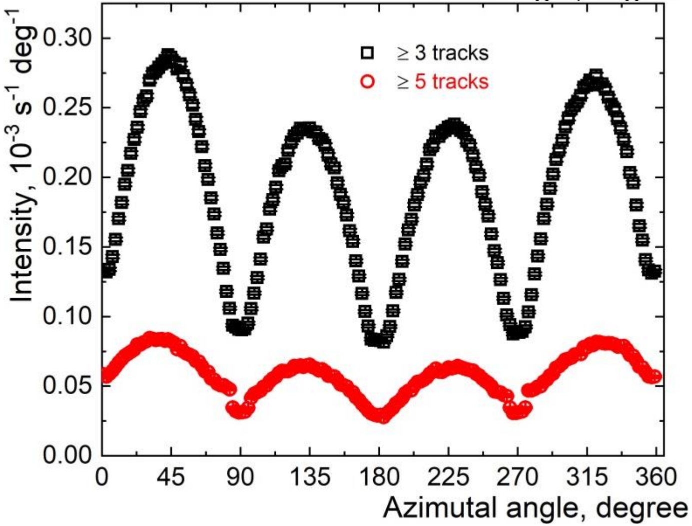
1. $\geq$ 3 tracks in at least 3 SM
2. $\geq$ 5 tracks in at least 3 SM

The zenith angle was limited to the range [15°, 75°]

The number of events in two samples was 14 and 4 million, respectively, which points to different effective energies.

The average zenith angle of arrival is about 40 degrees. There are four distinguished azimuth directions.





Expected distribution in case of an isotropic flux

The anisotropy is defined as the relative deviation from the isotropic component.

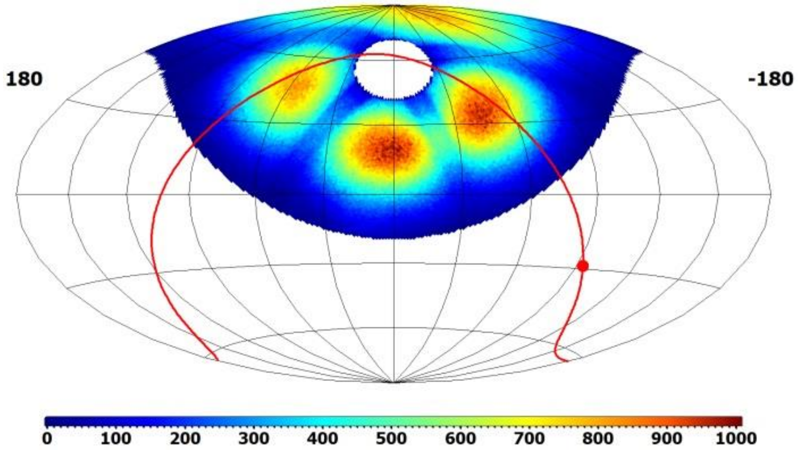
$$A = \frac{I - I_0}{I_0}$$

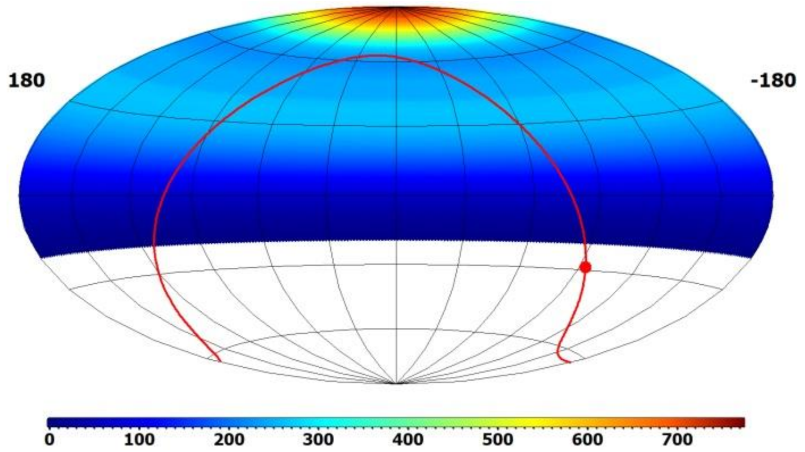
How to determine the isotropic flux (I_0)?

Fix local sidereal time

Aperture image (**AI**)

Normalization of **AI** to the “live time” of observation for any values of sidereal time



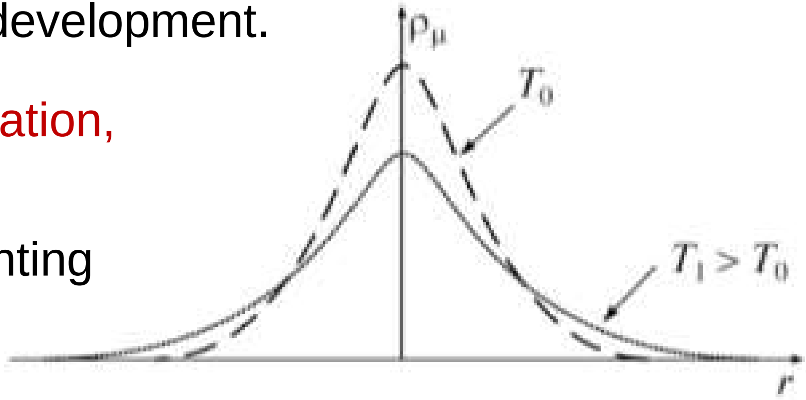


Atmospheric effects correction method

Muon bundles are generated as a result of EAS development.

Atmospheric parameters affect the level of generation, so the form of the LDF changes.

The result of the influence is a change in the counting rate of muon bundles in the detector.



The atmospheric effects correction method was developed on the basis of the analysis of variations in the counting rate of muon bundles. The correlation dependence determines the relationship between the counting rate (F) and the height (H_{500}) of the atmospheric layer with a residual pressure of 500 mbar.

$$F(t) = F_0 \left(\frac{H_{500}(t)}{H_0} \right)^{\lambda} = \eta(t) F_0$$

$\lambda \sim -1.67$

$H_0 \sim 5.5\ km$

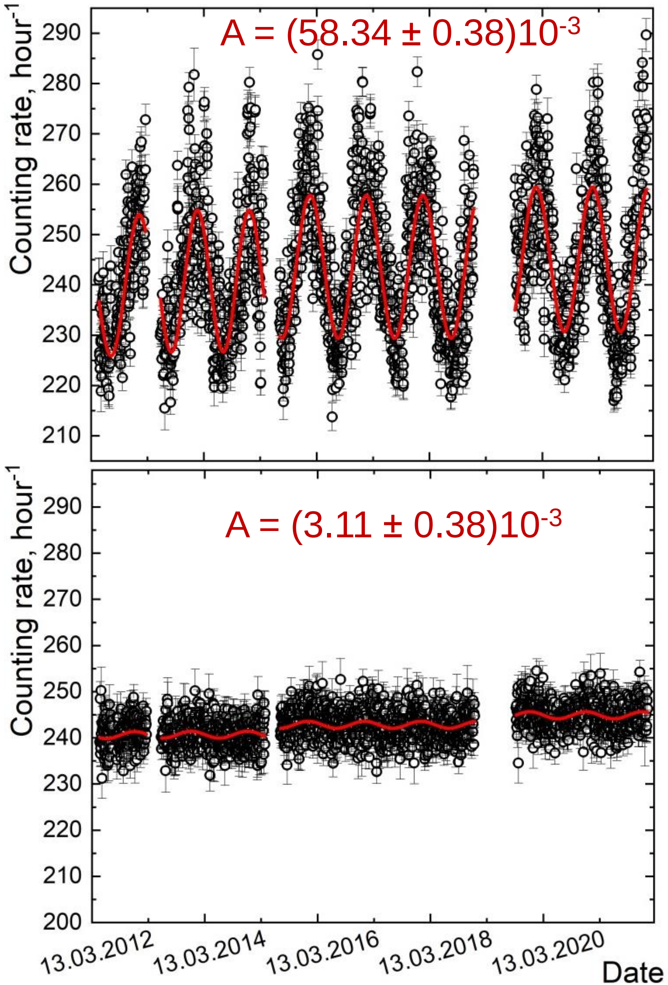
$F_0 \sim 240\ h^{-1}$ $\sim 70\ h^{-1}$

Yurina et al. 2019, Journal Physics: Conference Series

H_0 and ***F_0*** averaged values over a long period of time:

How the method does work?

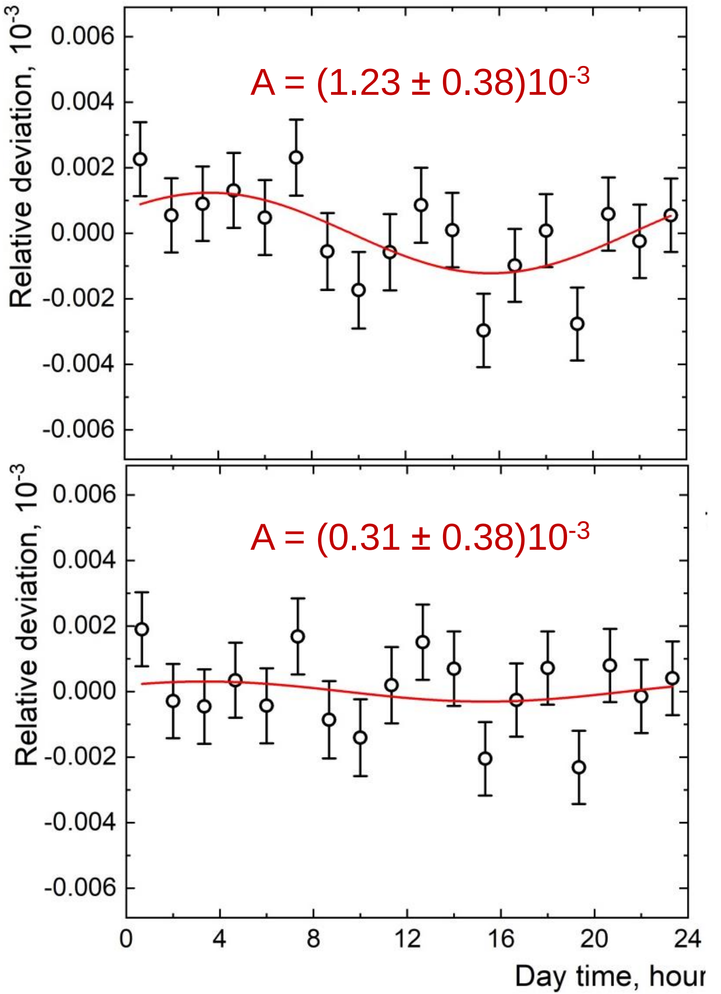
Seasonal



before correction

after correction

Diurnal



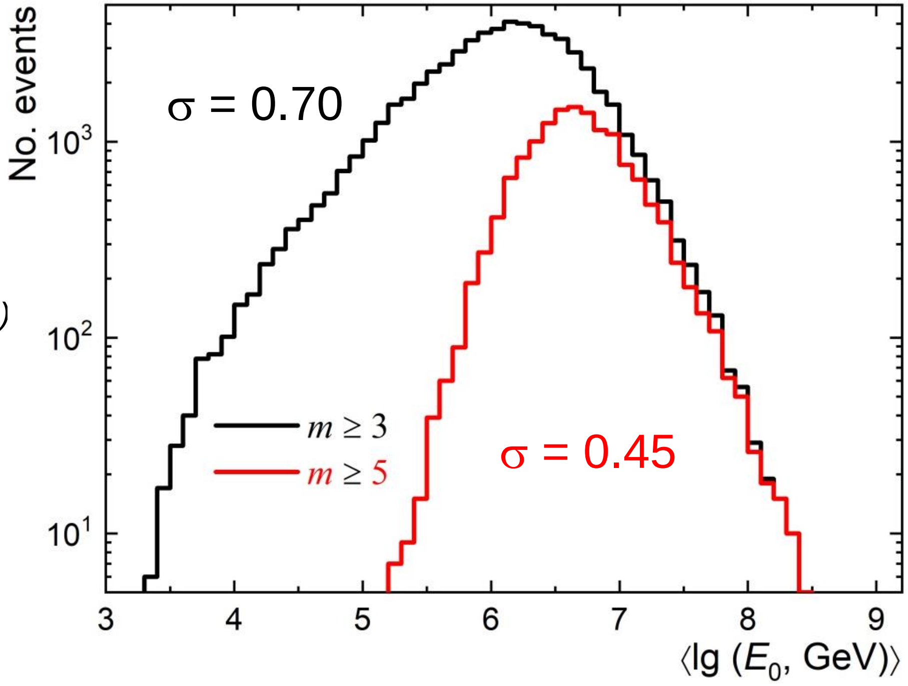
Primary energy estimation

Estimation of the energy of primary particles was carried out with simulated events using the spectra of local muon density measured for various zenith angles.

The mean logarithmic energy of primary particles is related to the density and direction of muon bundles by the following expression:

$$\langle \lg(E_0, \mathrm{GeV}) \rangle \approx 7.03 + 1.07\,\lg(D, \mathrm{m}^{-2}) + 3.80\,\lg(\sec\theta)$$

(Bogdanov et al. 2010 , PhAN)

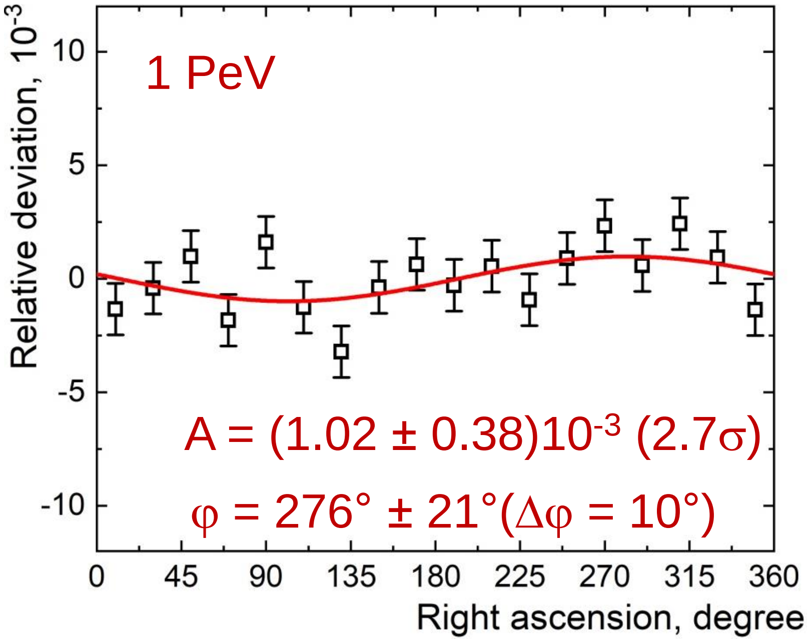


To account for the randomness of the EAS core positions relative to detector location, it is necessary to add (in squares) 0.4 to the obtained values of σ.

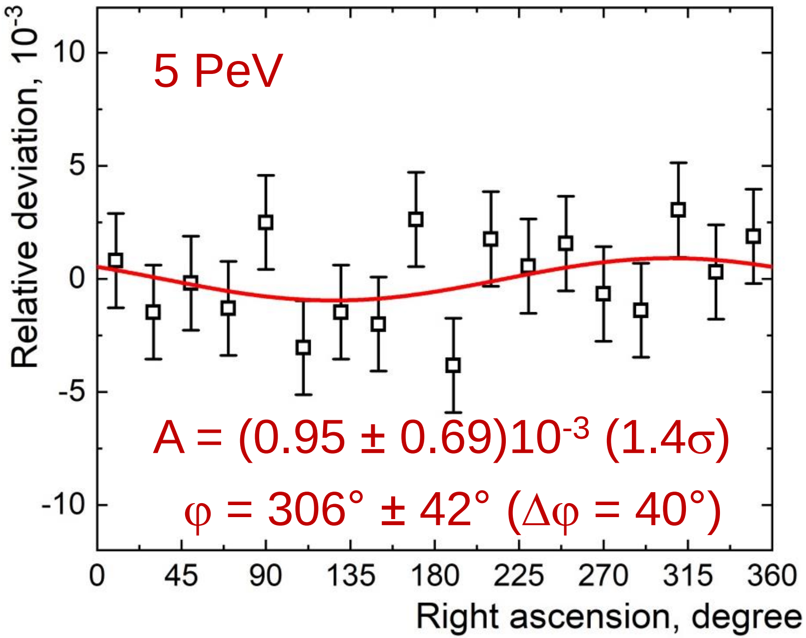
Selection	≥ 3 tracks	≥ 5 tracks
lg (E_0, GeV)	6.1 ± 0.8	6.7 ± 0.6

Anisotropy search results in the projection on the right ascension axis

3 or more tracks

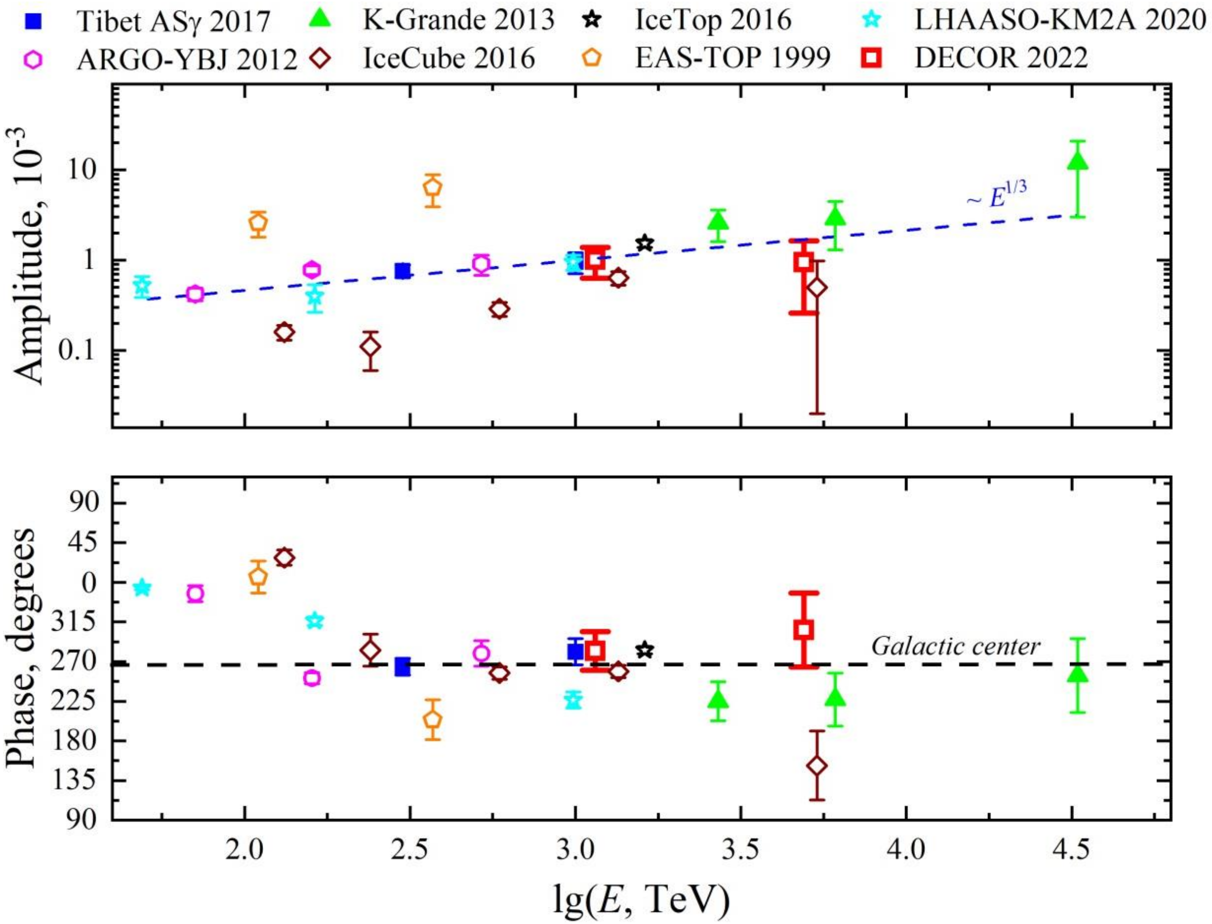


5 or more tracks



The degree of deviation of the CR flux relative to isotropic one is a tenth of percent in PeV energy region. The phases correspond to the direction to the center of the Galaxy for both samples.

Dipole anisotropy estimates in a wide primary energy range



Conclusion

For the first time the multiplicity of muon bundles detected at the surface of the Earth is used for the study of the energy dependence of cosmic ray anisotropy.

For muon bundles, the influence of the atmospheric changes can be practically eliminated by controlling just one parameter – the altitude of the atmospheric layer with a residual pressure of 500 mbar.

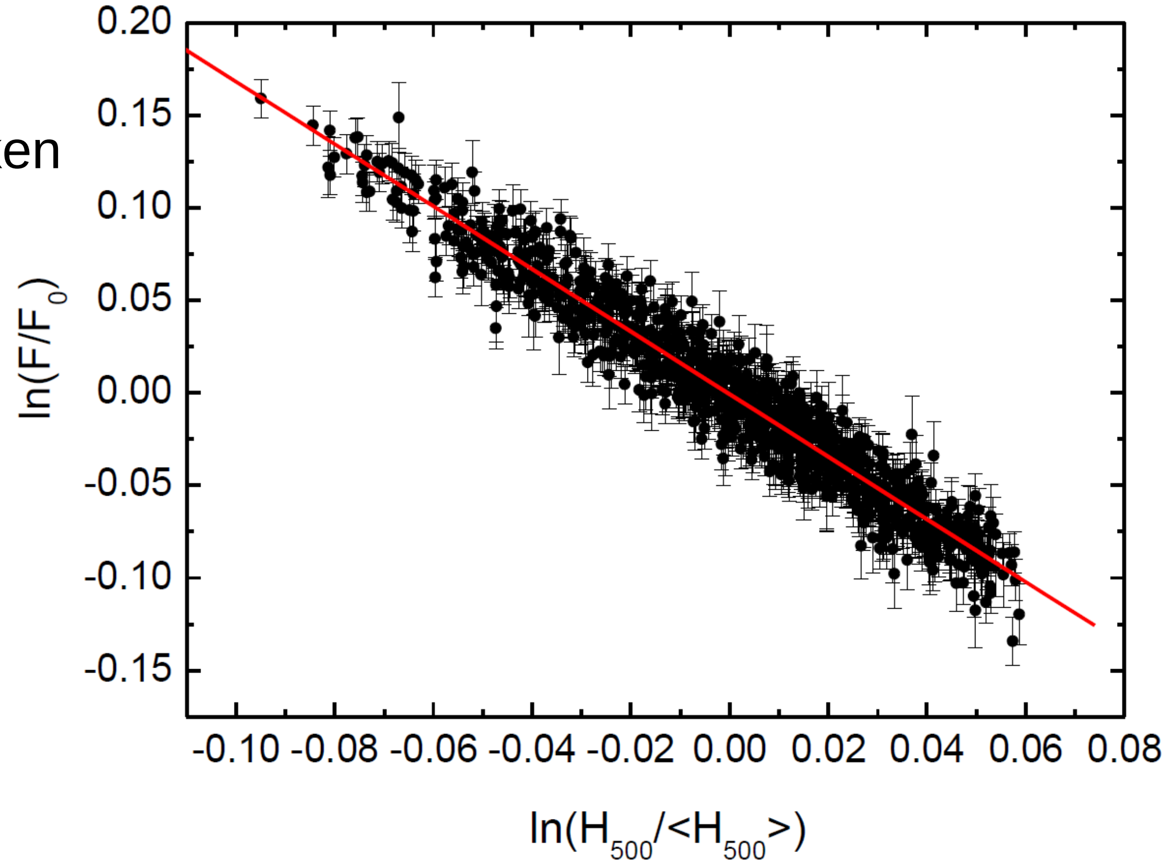
The obtained dipole anisotropy parameters are consistent with the theory of diffuse propagation of CR from the center of the Galaxy for the mean logarithmic energies of primary particles about 1 PeV and 5 PeV.

Thank you for your attention!!!

Correlation

Data on H_{500} values were taken from the GDAS database:

$$F(t) = F_0\left(\frac{H_{500}(t)}{H_0}\right)^{\lambda}$$



NOAA Air Resources Laboratory (ARL) 2015 http:/ready.arl.noaa.gov/gdas1.php

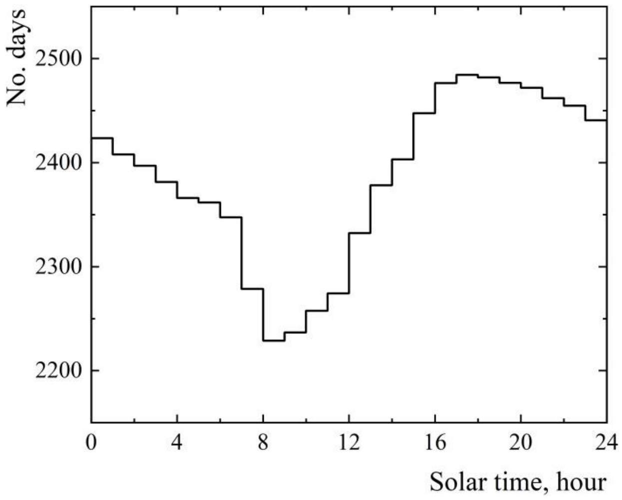
Hammer-Aitoff equal-area projection

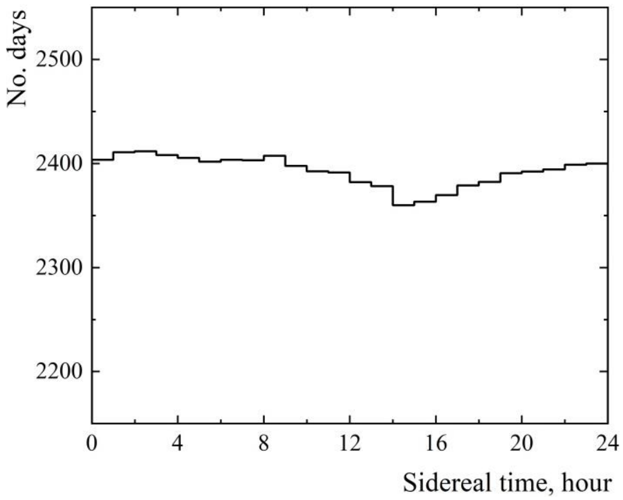
(Calabretta M.R. & Greisen E.W. 2002, Astronomy and Astrophysics*)*

The HEALPix grid resolution parameter N_{side} is set to 64. It corresponds to sell size of about 2.6×10^{-4} sr on the celestial sphere.

“live time”

The “live time” of observation is the part of detector operation time after subtraction of the time required for hardware and software processing of events.





The distribution of “live time” within the solar (left) and sidereal (right) day.

Systematic error

Accounting for the residual seasonal variations allowed us to check the influence of this effect on the final fits. As a result, this correction has led to an increase of the estimates of the dipole anisotropy amplitude by $(+0.04 \pm 0.01) \times 10^{-3}$, the phases shifted by less than 1°. These values may be considered as systematic uncertainties of the anisotropy parameters. Noteworthy, they are much less than the statistical errors.

$$A = (1.02 \pm 0.38)10^{-3} + (0.04 \pm 0.01)10^{-3}$$

$$\varphi = 276° \pm 21° \pm 1°$$