Cosmic ray anisotropy study by means of muon bundles

National Research Nuclear University MEPhI, Moscow, Russia

Unique Scientific Facility
Experimental Complex
NEVOD

M.B. Amelchakov, Z.T. Izhbulyakova, S.S. Khokhlov, R.P. Kokoulin, V.V. Shutenko, E.A. Yurina

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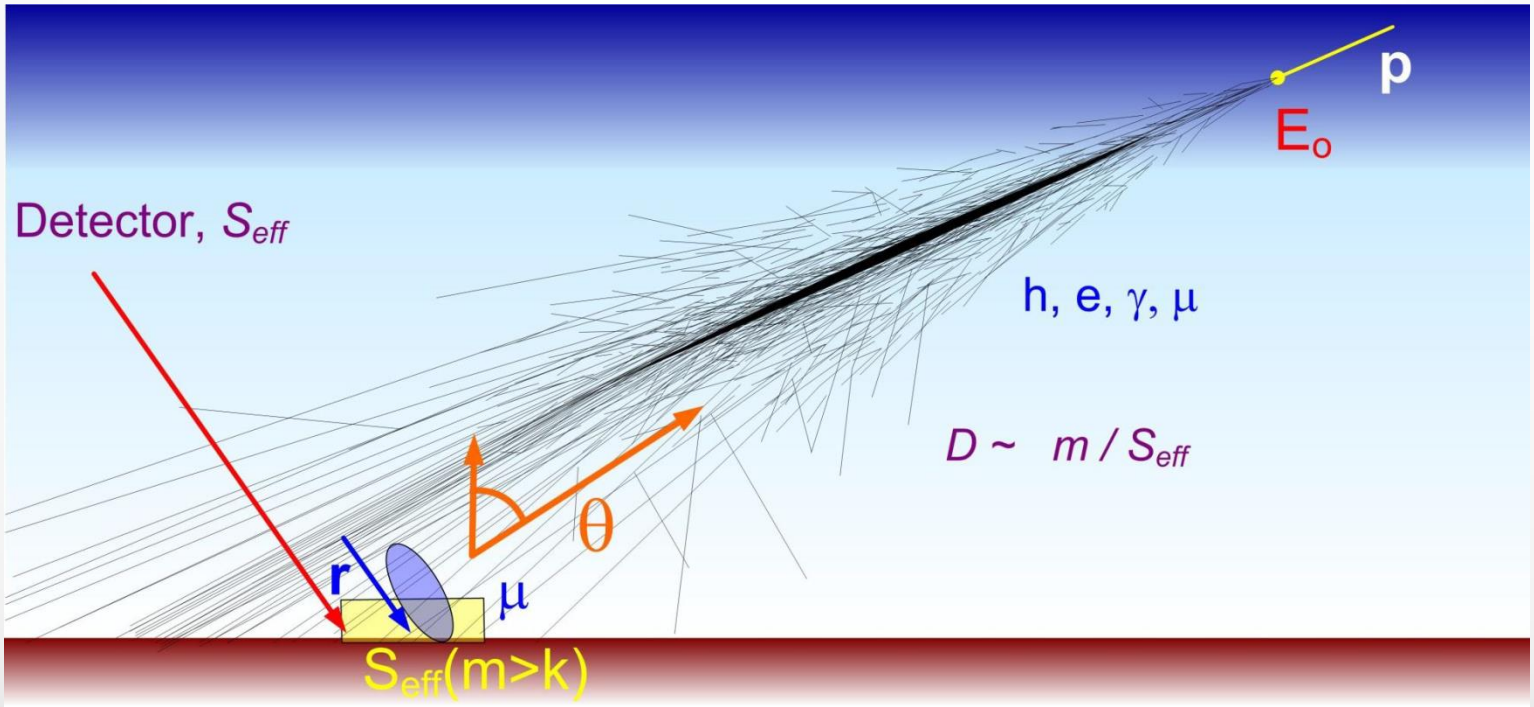
Muon bundles

What are muon bundles?
These are several genetically related muons with quasi-parallel tracks.

They are generated close to the axis of the shower and can reach us in a wide range of zenith angles.

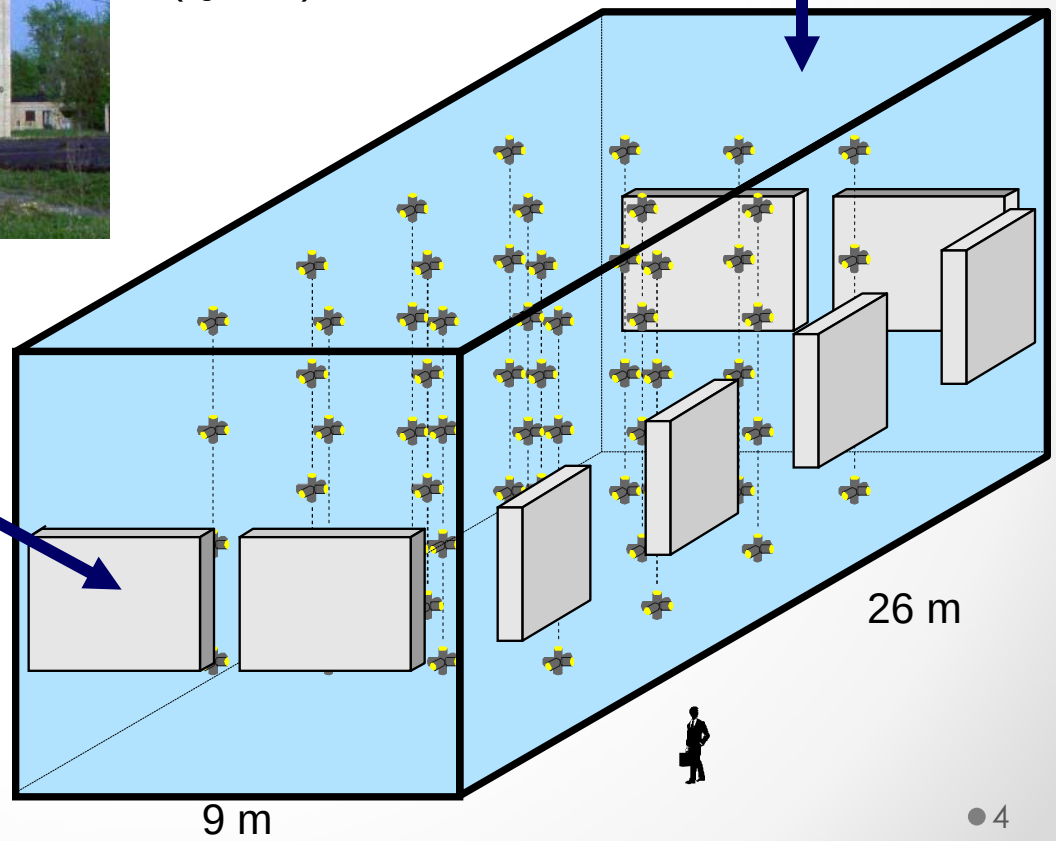
Muon bundles with a good accuracy save directions of primary particles and therefore they can be used to study CR anisotropy.



General view of the Experimental complex NEVOD

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 feature of DECOR is its vertical deployment and good spatial and angular resolution (1 cm and ~1°).

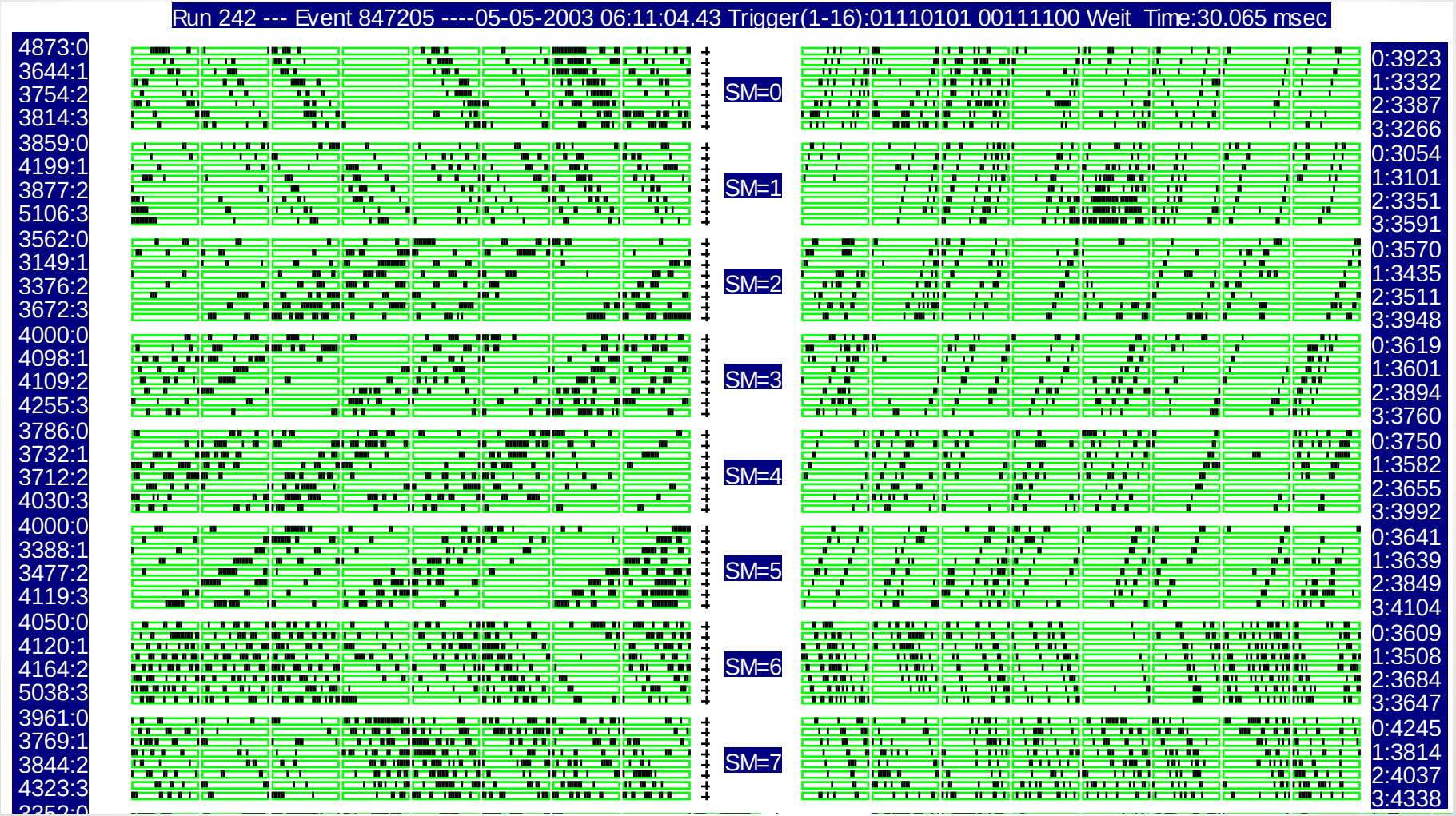
Side view of DECOR supermodules

Eight-layer system of plastic streamer tube chambers with a resistive cathode coating suspended at a distance of 6 cm from each other.

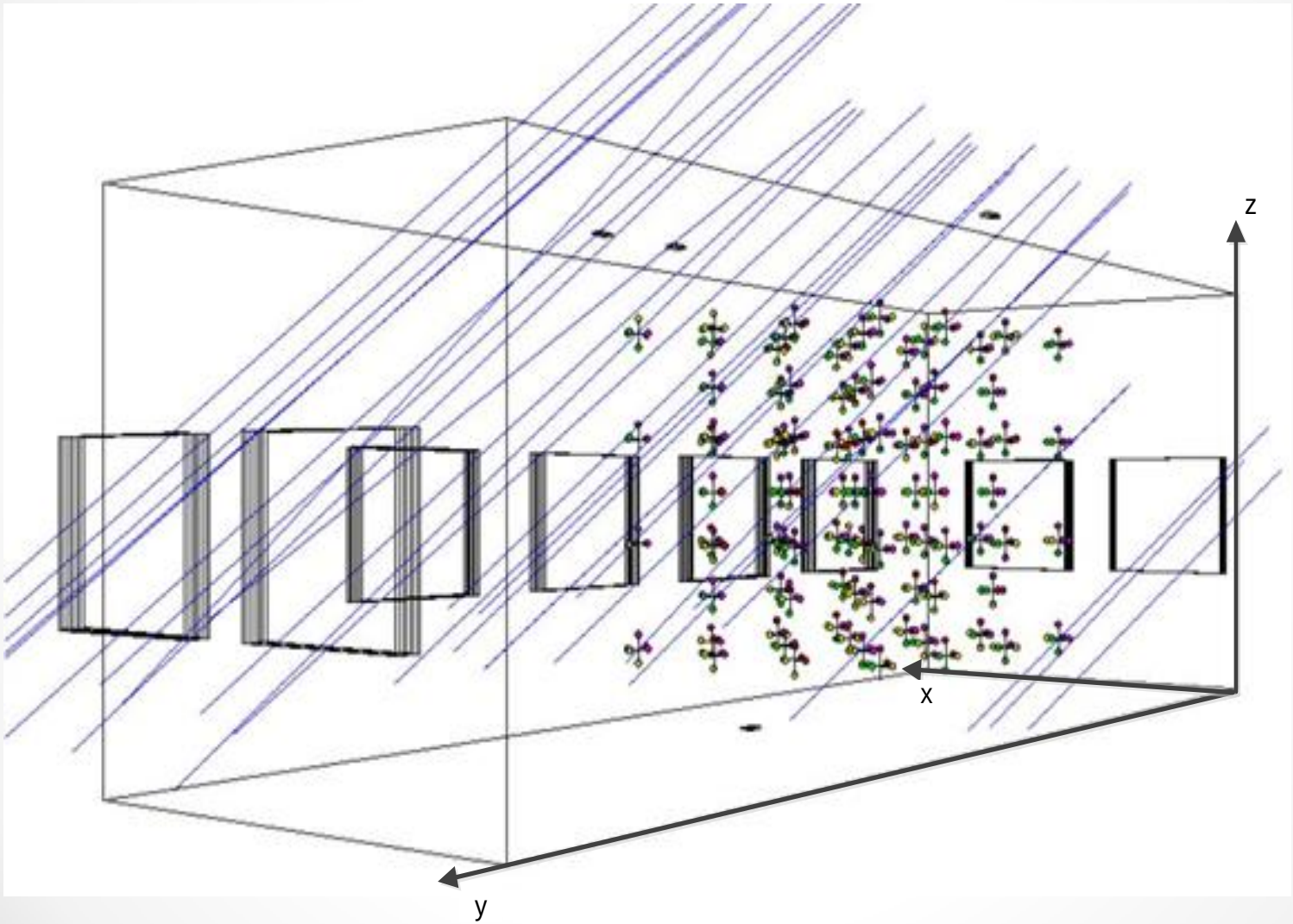
Response of DECOR coordinate-tracking detector for muon bundle event

Horizontal projection

Vertical projection



Geometry reconstruction of muon bundle event



Experimental data

In this work, we use measurement data accumulated from May 3, 2012 to April 13, 2019.

“Live” observation time was 43,290.5 hours (~ 1804 days)

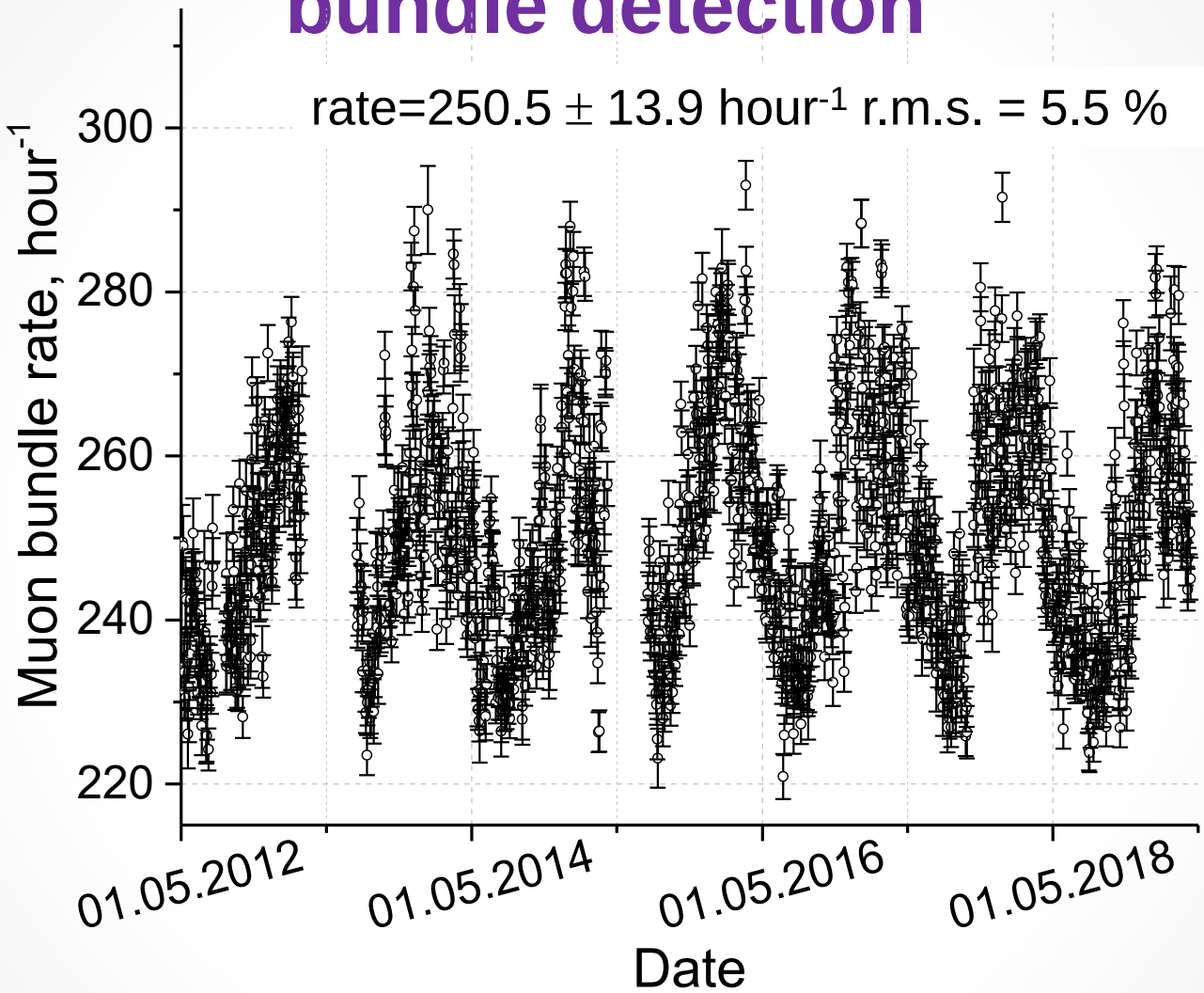
Selection conditions are

- Three parallel tracks in at least three supermodules.
- Zenith angle in the range from 10 ° to 75°.

The number of selected events is about 10.7 millions.

Primary particles energy $\gtrsim$ 1 PeV
(*Bogdanov A. G. et al, 2010, Phys. Atom. Nucl. 73, 1852*)

Seasonal variations in the rate of muon bundle detection



This atmospheric effect produces noise for CR anisotropy measurements.

Atmospheric effect correction

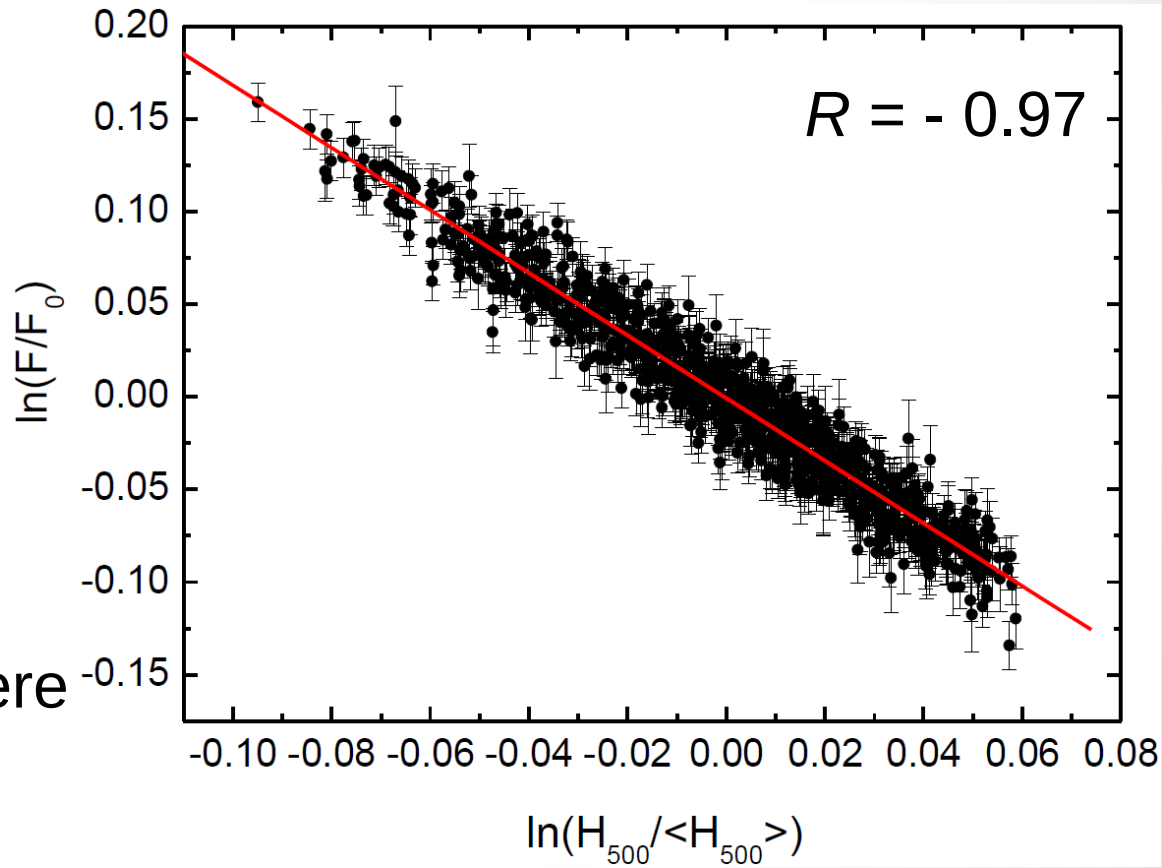
The muon bundle rate closely correlates with the altitude of the 500 mbar residual pressure level.

(*Yurina E. A. et al, 2019, J. Phys.: Conf. Series 1189, 012010*)

$$F = F_0 \left(\frac{H_{500}}{\langle H_{500} \rangle} \right)^{\alpha}$$

$\langle H_{500} \rangle = 5520$ m

$\alpha = -1.689 \pm 0.011$

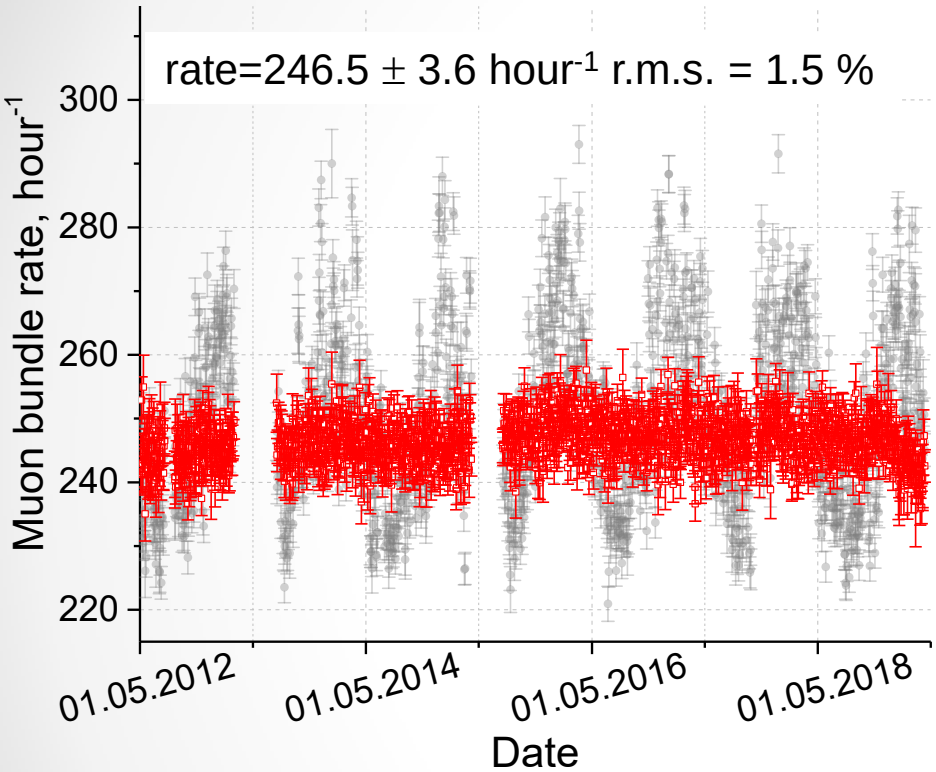


Data on H_{500} values were taken from the GDAS database:

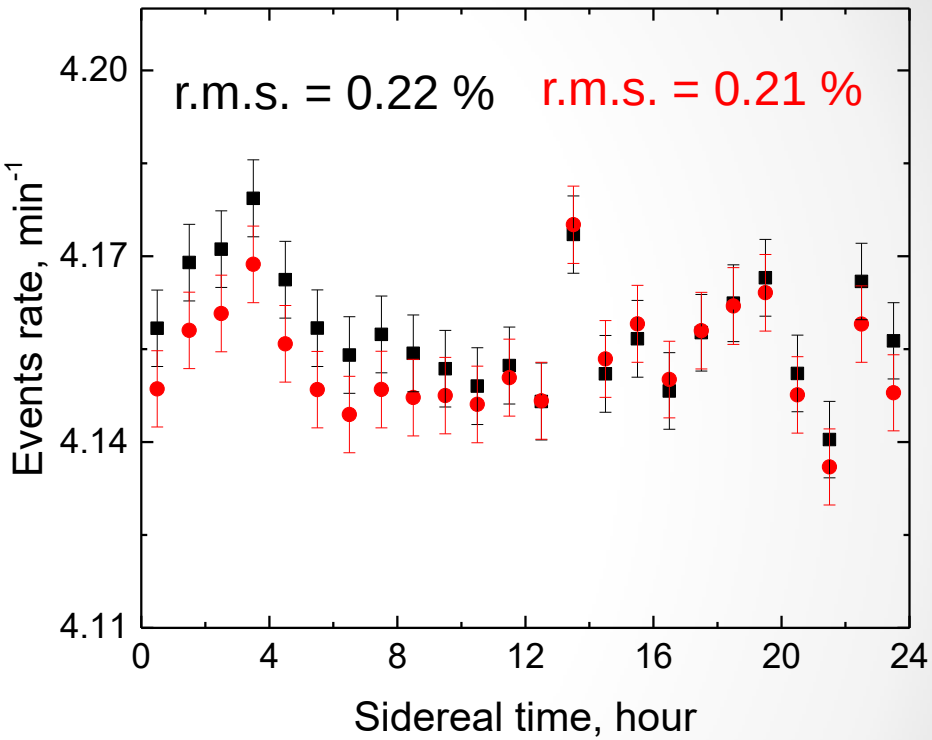
NOAA Air Resources Laboratory (ARL) 2015 http:/ready.arl.noaa.gov/gdas1.php

Muon bundle rate after correction

The muon bundle rate after correction



Sidereal time dependence



R.m.s was been reduced several times, and seasonal effect practically eliminated.

We do not see significant changes

Anisotropy search method

Anisotropy search method is based on the comparison of the expected and the measured number of events

Relative deviation:

$$r = \frac{N_{\text{meas}} - N_{\text{exp}}}{N_{\text{exp}}}$$

error estimate:

$$\Delta r = \frac{\Delta N_{\text{meas}}}{N_{\text{exp}}} = \frac{\sqrt{N_{\text{meas}}}}{N_{\text{exp}}}$$

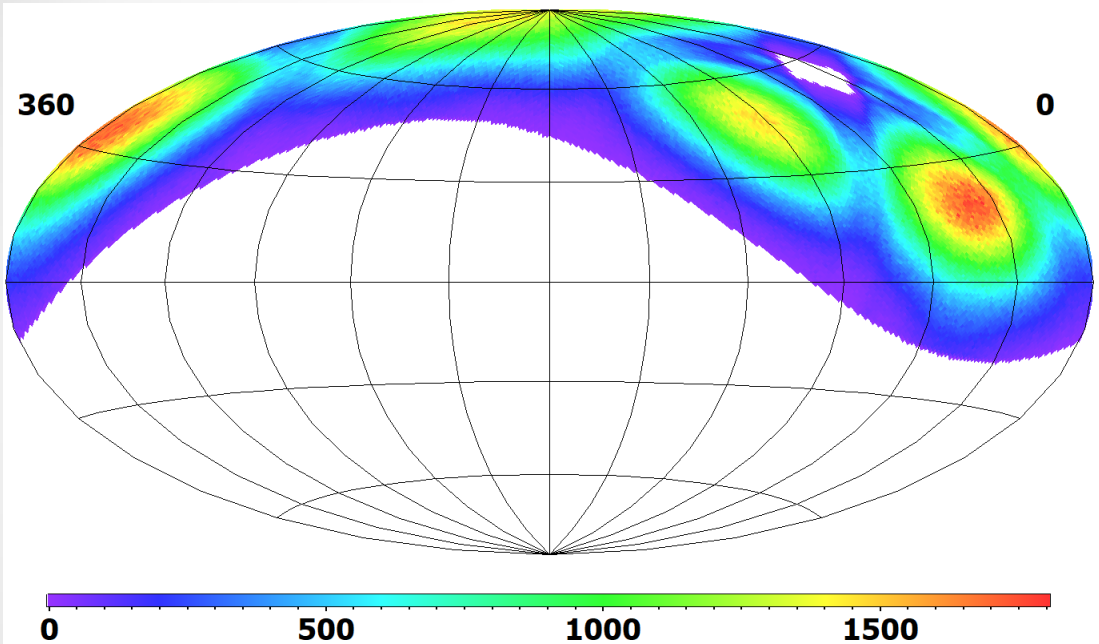
For data projected on the right ascension axis, we use the approximation function:

$$f(\alpha) = A\cos(\alpha - \varphi)$$

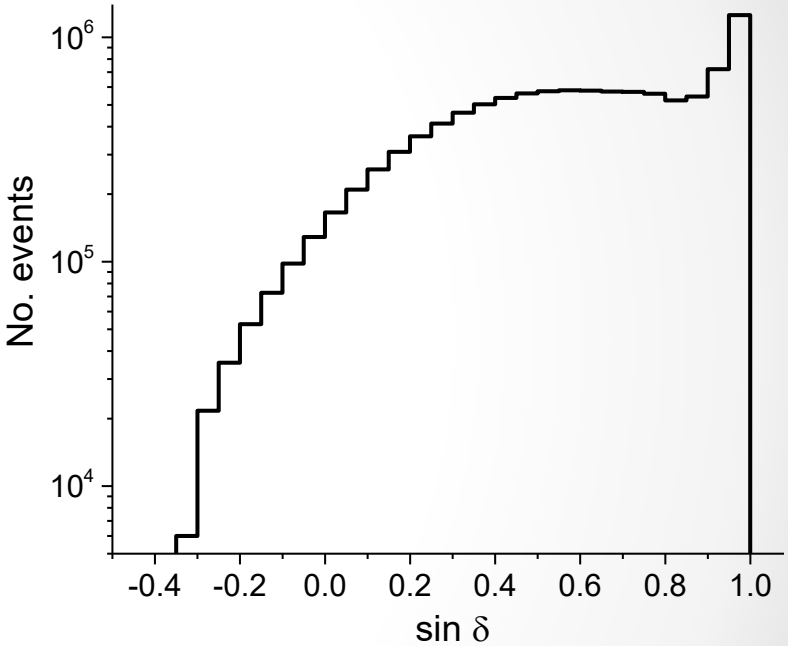
A is the anisotropy amplitude, φ is the phase.

Observation aperture

If the Earth would not rotate,
the map of events would look like this:



Declination distribution
of recorded events



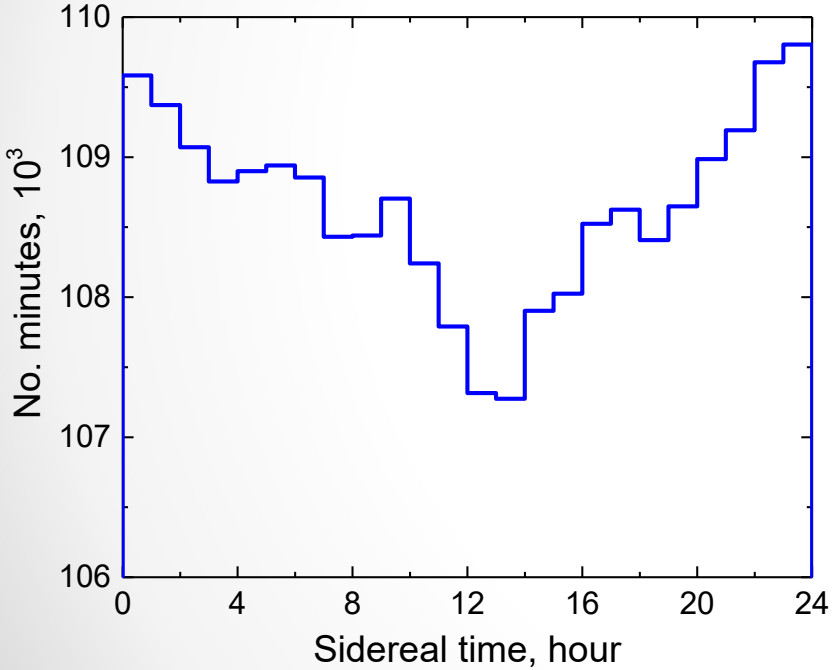
1 pixel corresponds to 2.6×10^{-4} sr

In the absence of the anisotropy, the distribution of expected events should be uniformly spread in right ascension.

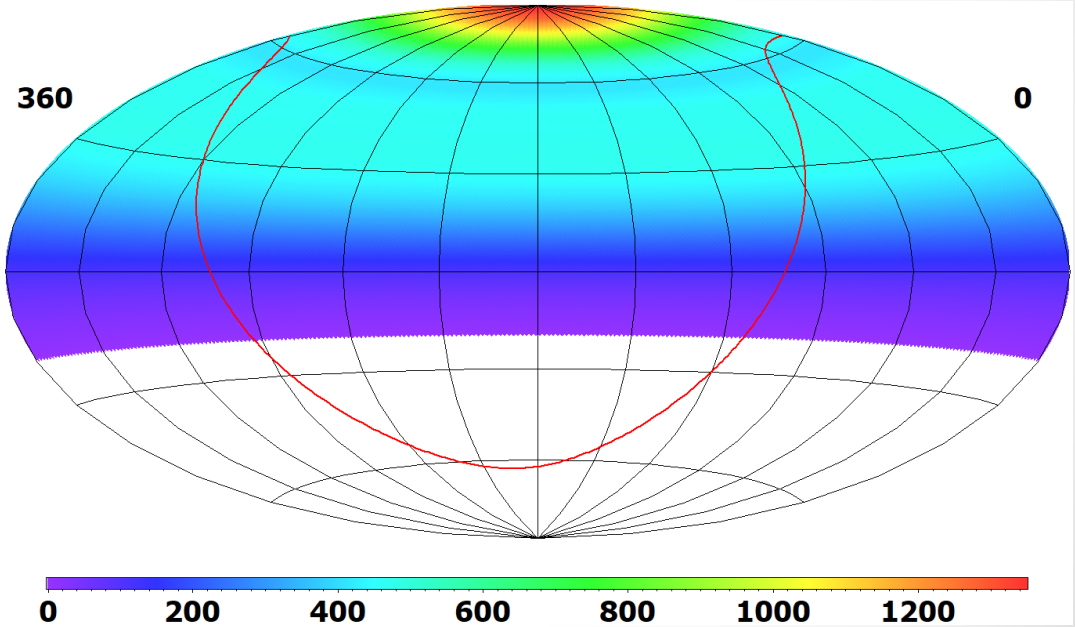
Expected distribution

We spread events throughout the celestial sphere in proportion to the “live” time of observation.

“Live” observation time



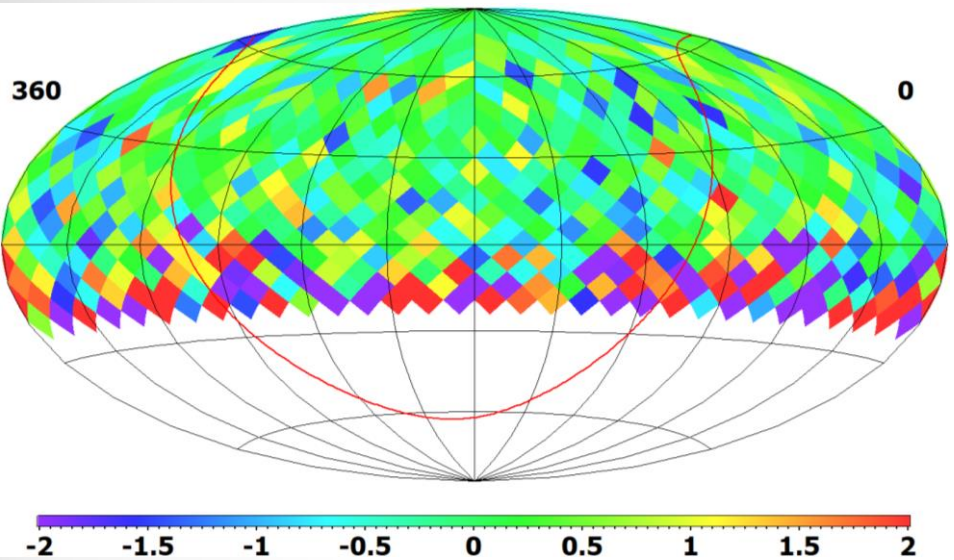
Expected event distribution



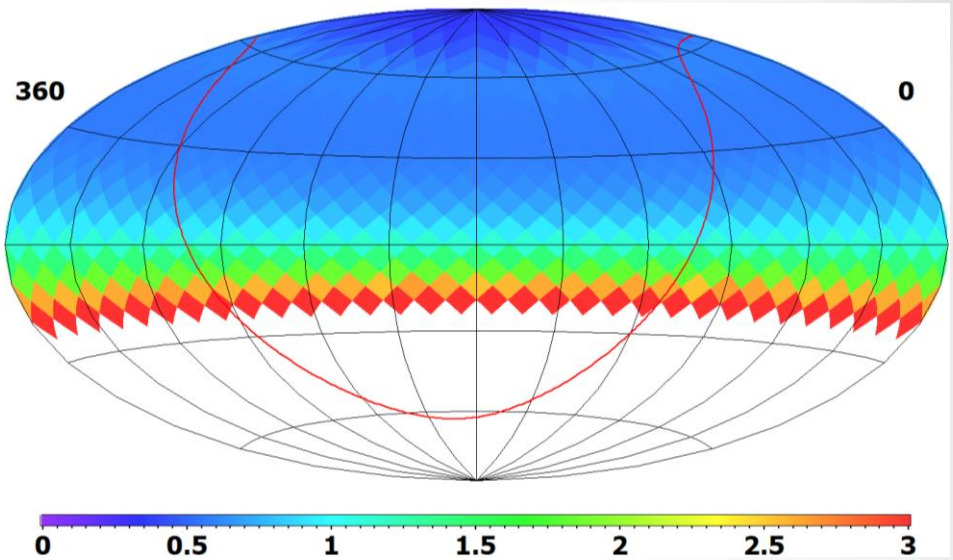
1 pixel corresponds to 2.6×10^{-4} sr

Anisotropy map

Relative deviation



Error estimate

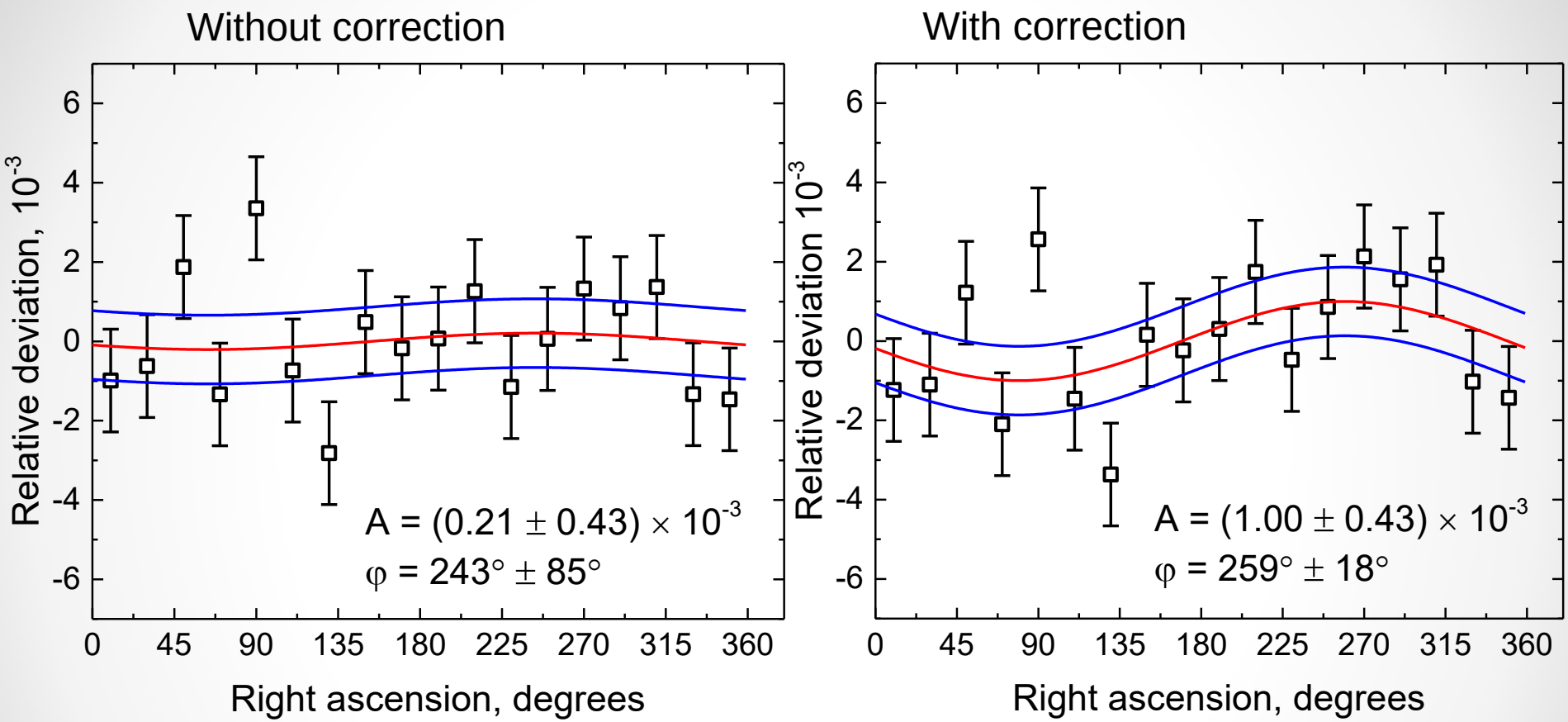


Scales in %

1 pixel corresponds to 16.4×10^{-3} sr

Visually, dipole anisotropy is not seen in the projection onto the celestial sphere.

First harmonic parameters of the CR anisotropy

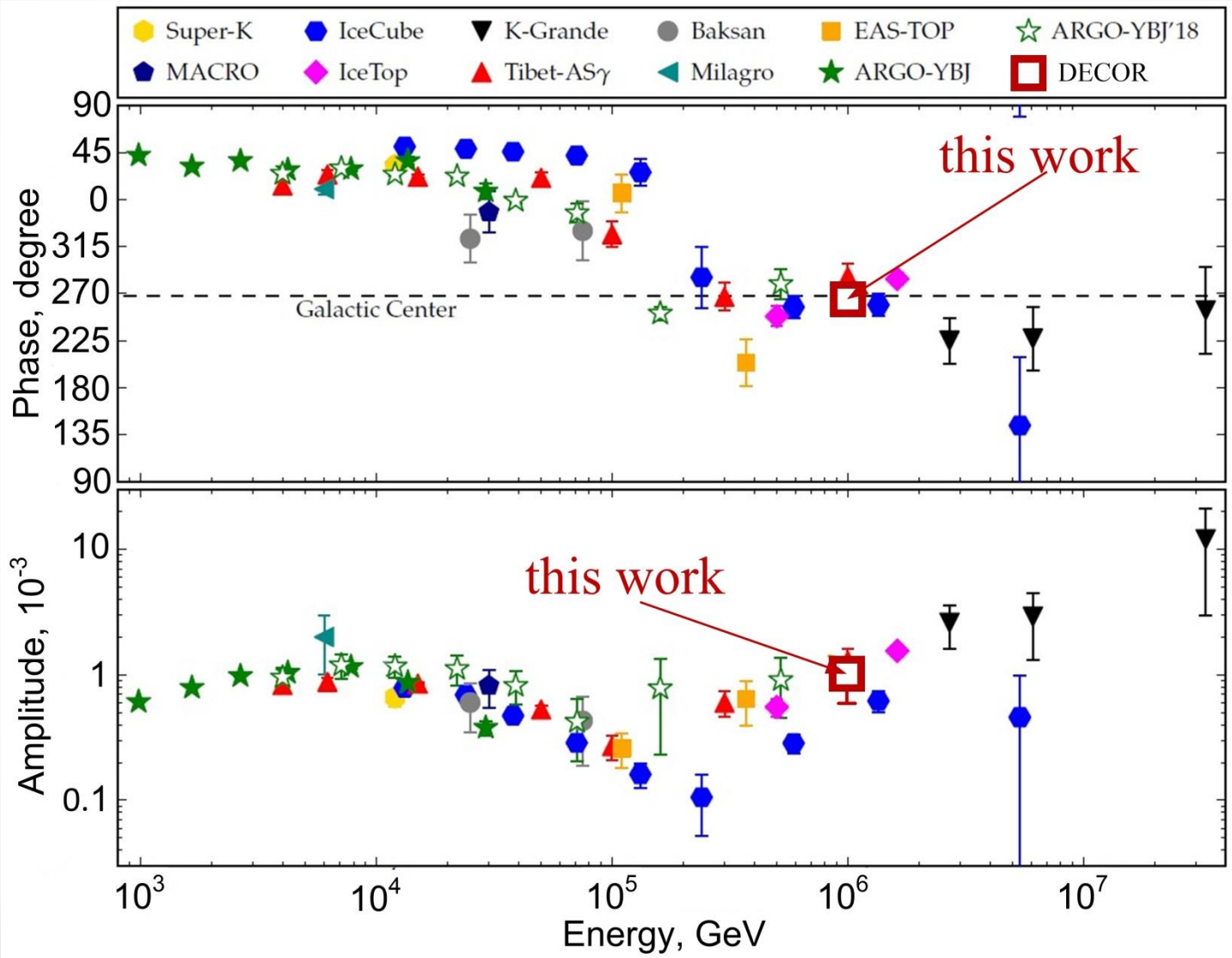


Red line is best fit. Blue lines are $\pm 2\sigma$.

Atmospheric effect hampers observation of the CR anisotropy on the Earth surface

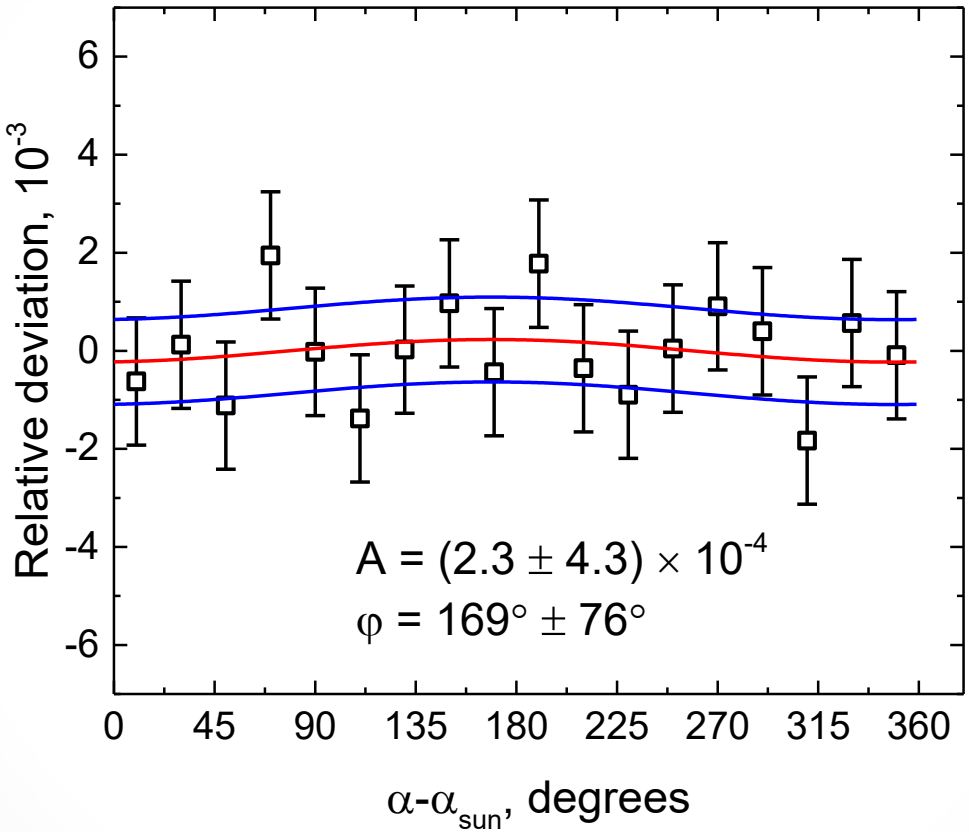
The energy dependences of the first harmonic parameters of the CRs anisotropy

From: Markus Ahlers article: arXiv:1811.08136v1 [astro-ph.HE] 20 Nov 2018



Compton-Getting effect estimation for Earth rotation around the Sun

Dependence of the relative deviation on the right ascension regarding the **Sun** position



With the available statistics, this effect is not seen.

Conclusion

- Muon bundles on the Earth's surface can be used to search for CR anisotropy.
- The developed correction method makes it possible to practically eliminate the noise from atmospheric effects.
- The results of measurements with a statistical significance of 2σ indicates the presence of CR anisotropy.
- The results of the study in this work are consistent with the results obtained at other facilities.

Grazie!!!