Towards new tests of cosmic-ray correlations with BL Lac type objects

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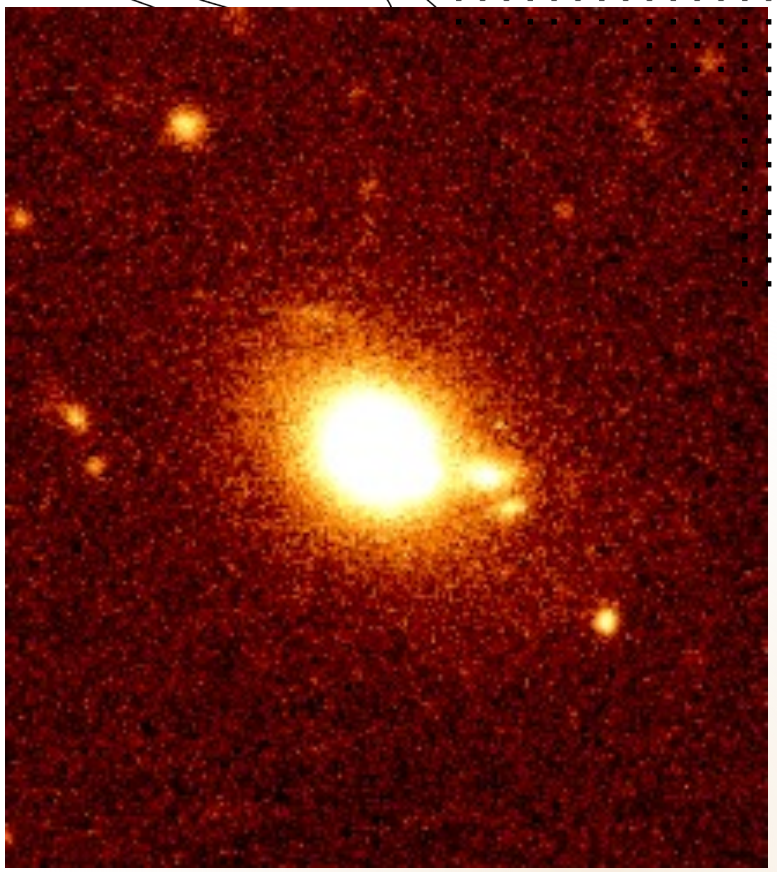
Plan

- Motivation
- Methods
  - Galactic plane isotropy test
  - Whole sphere isotropy test
- Two sets constructed
  - VLBI-set
  - Fermi-set
- Conclusion

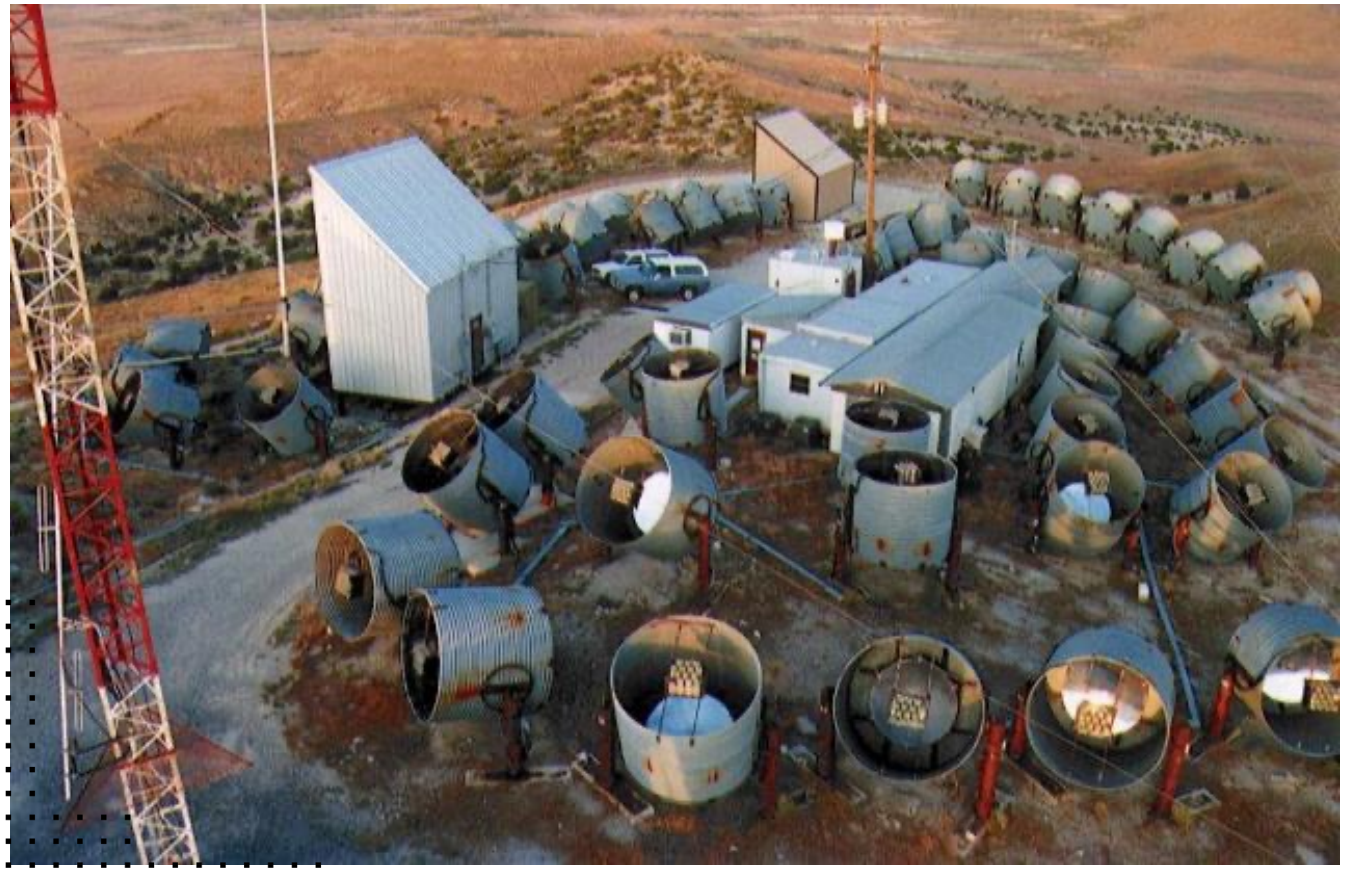
BL Lacertae object



BL Lac type object is a certain type of active galactic nuclei.

In contrast to other types of active galactic nuclei, BL Lacs are characterized by rapid and large-amplitude flux variability and significant optical polarization.

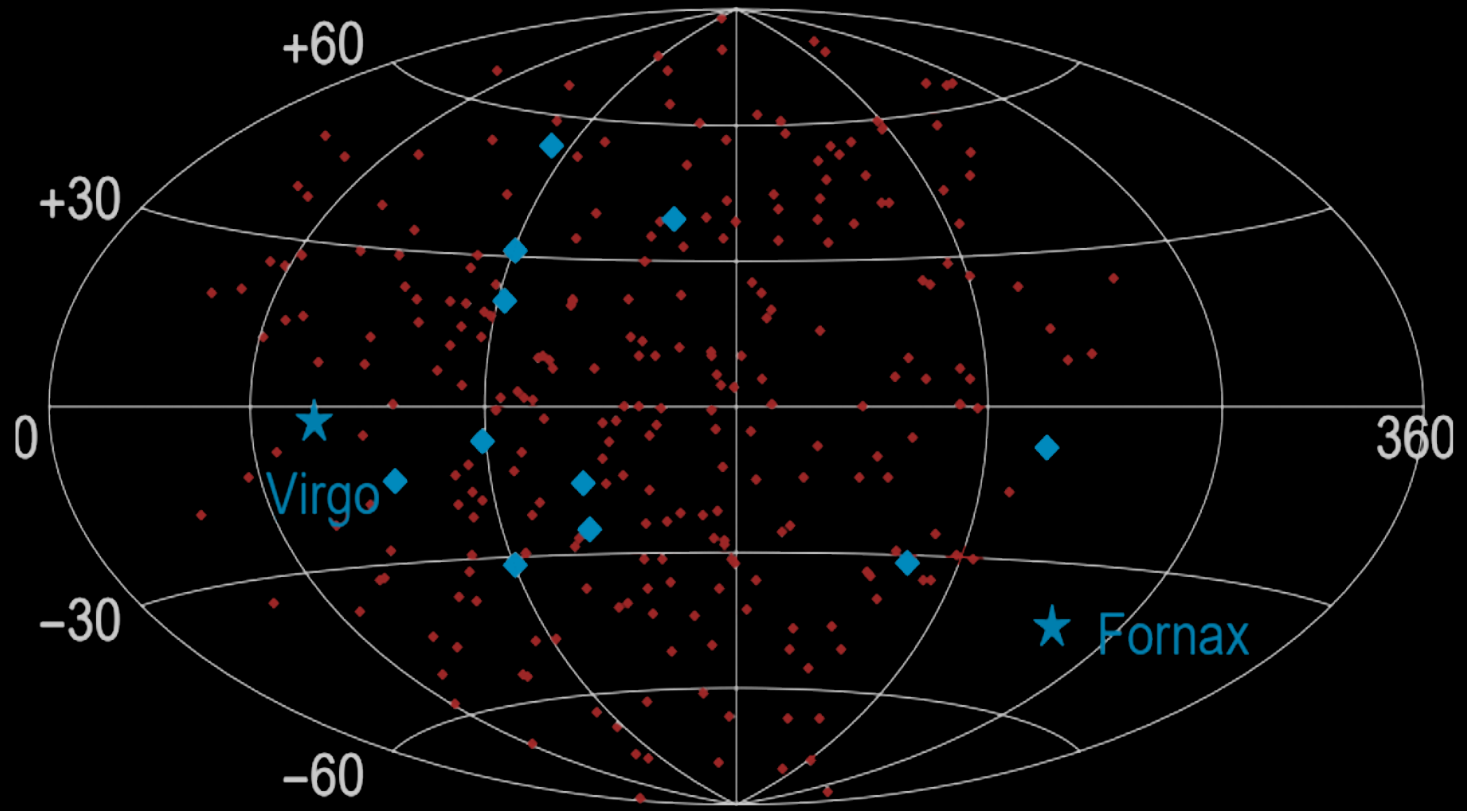
High Resolution Fly’s Eye Detector



Ultra-high energy cosmic ray observatory HiRes..

It operated in west Utah desert from May 1997 until April 2006. HiRes used the “atmospheric fluorescence” technique. It has excellent angular resolution.

Motivation. 2004 Result



Correlations between BLL and UHECR were discovered with the use of HiRes data.

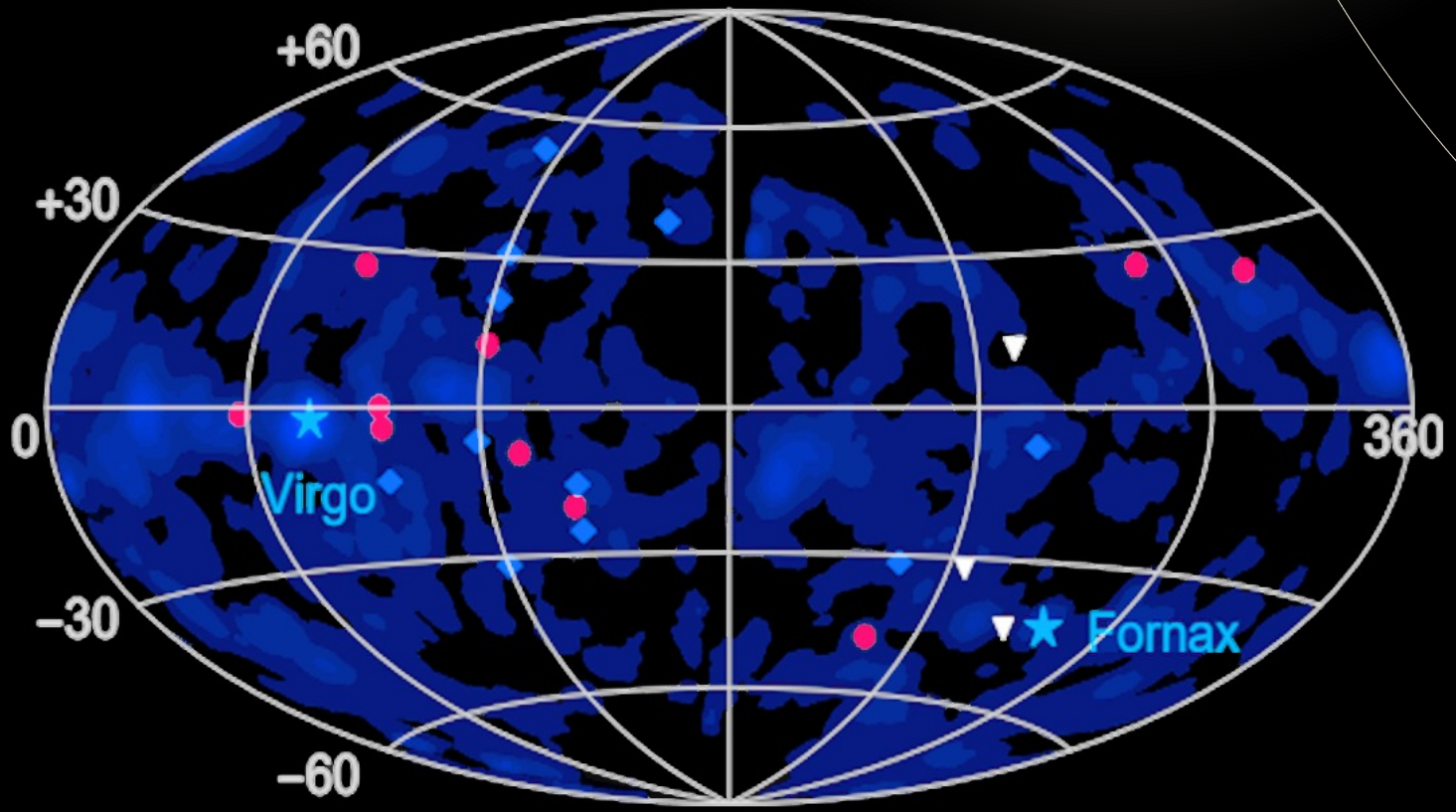
Blue diamonds – correlating BLL objects.

Red dots – other HiRES showers in the sample.

Supergalactic coordinates.

(S. Troitsky, EPJ, 2020)

Motivation. 2004 Result



Correlating objects ate located in regions of higher magnetic field.

Red circles - objects with anomalous hardenings in VHE.

Blue dimonds - air showers correlated with BL Lac type objects.

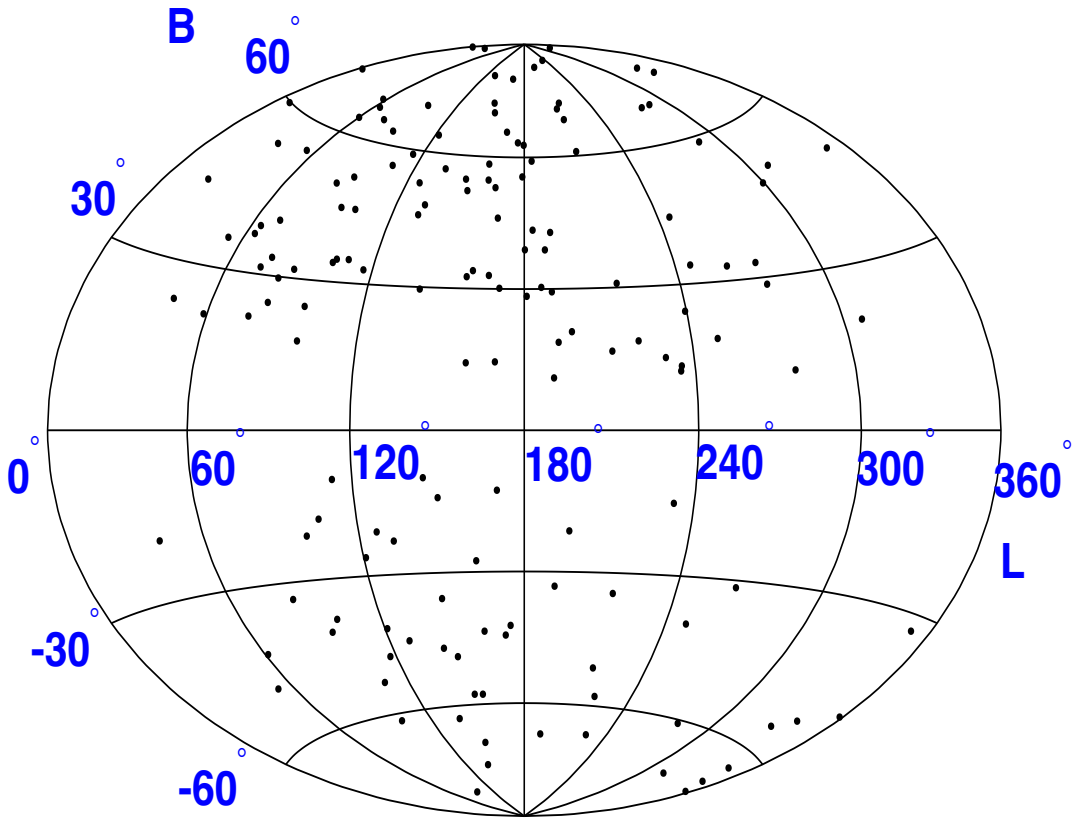
White triangles - gamma-ray bursts detected in VHE .

Density plot - weighted galaxy distribution.

Supergalactic coordinates.

(S. Troitsky EPJ, 2021)

Motivation. BLLac catalog by Veron et al. 2001



Map of objects from the catalog in the galactic coordinates.

B – galactic latitude.

L – galactic longitude.

It can be seen that the sample is not isotropic, because very small amount of objects is located near the galactic plane.

Motivation

- In 2004 was obtained a very interesting result with the use of HiRes data. It was shown that there are directional correlations between cosmic rays and BL Lac type objects.

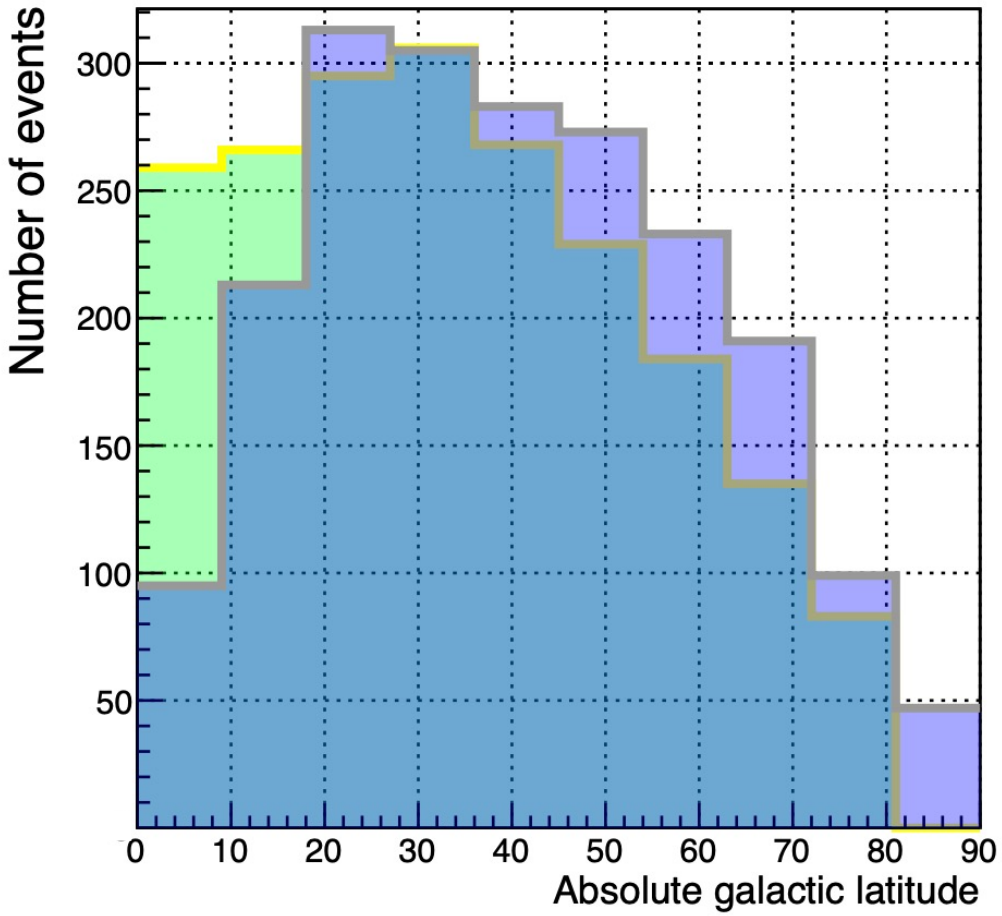
New sets need to be constructed in order to check results of paper published in 2004.

Steps to construct an isotropic set

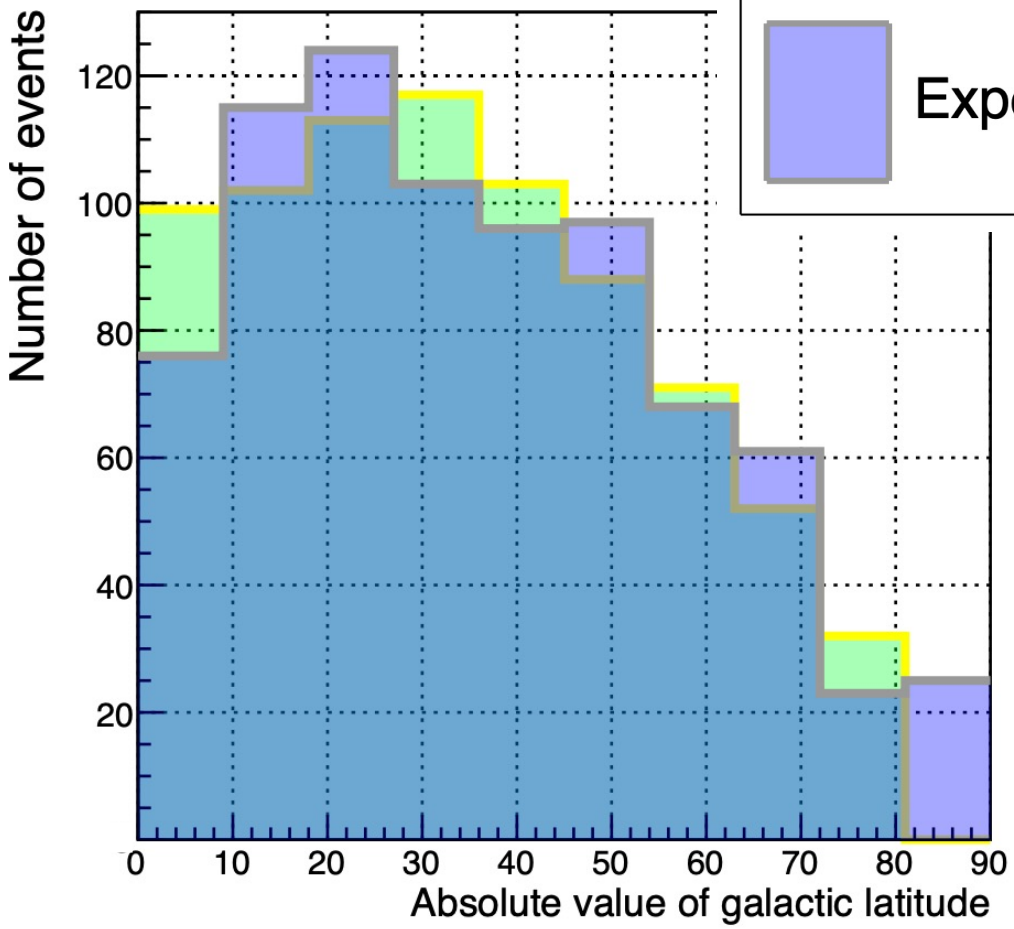
- Take a set of blazar-like objects detected in certain energy range.
- Apply constraints on corrected visual magnitude to select visually bright objects.
- Make a galactic plane isotropy test and apply flux constraints if needed.
- Make a whole sphere isotropy test and apply flux constraints if needed.

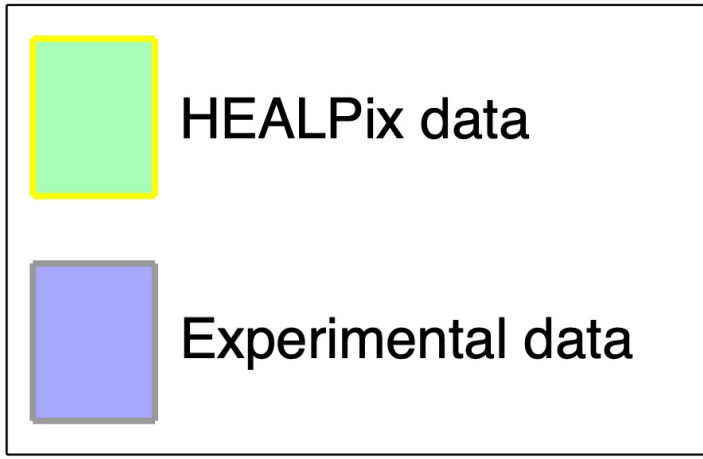
Galactic plane isotropy test

No flux constraints

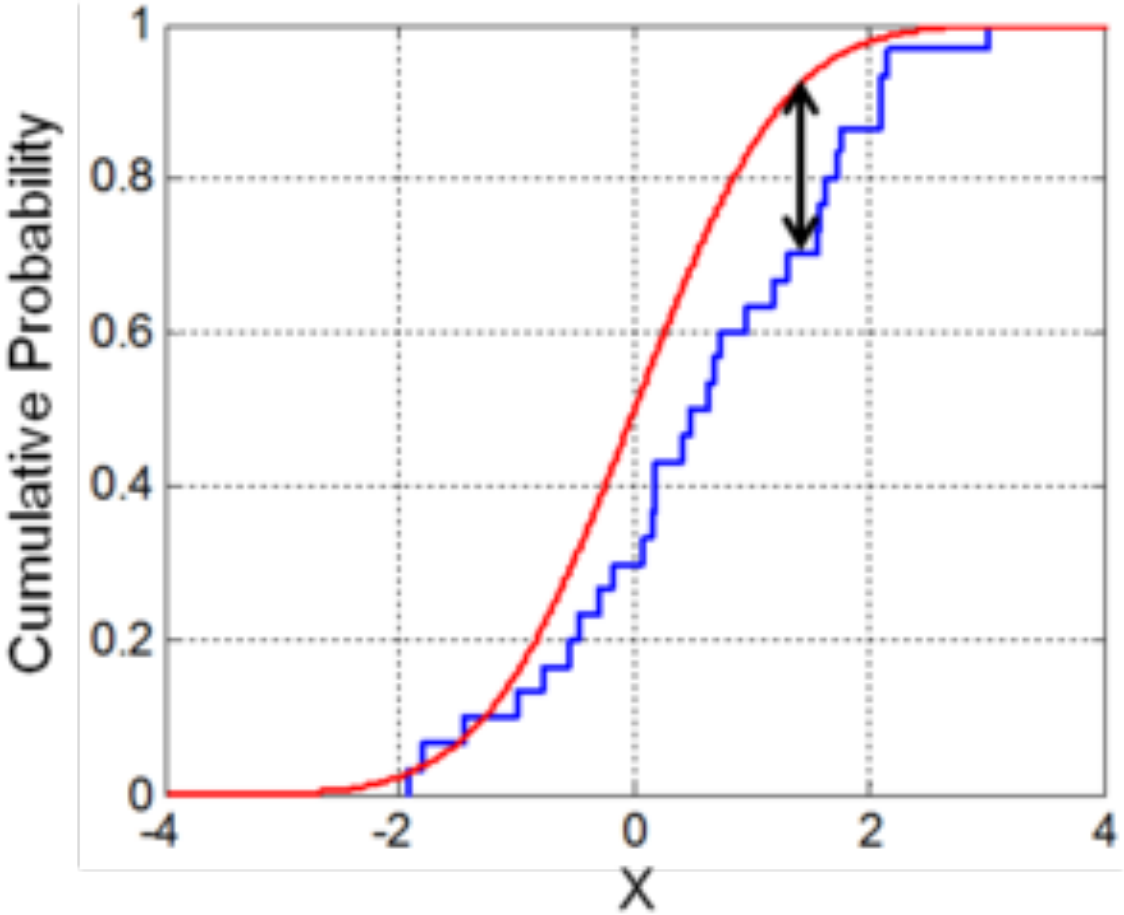


With flux constraints





Kolmogorov-Smirnov probability test



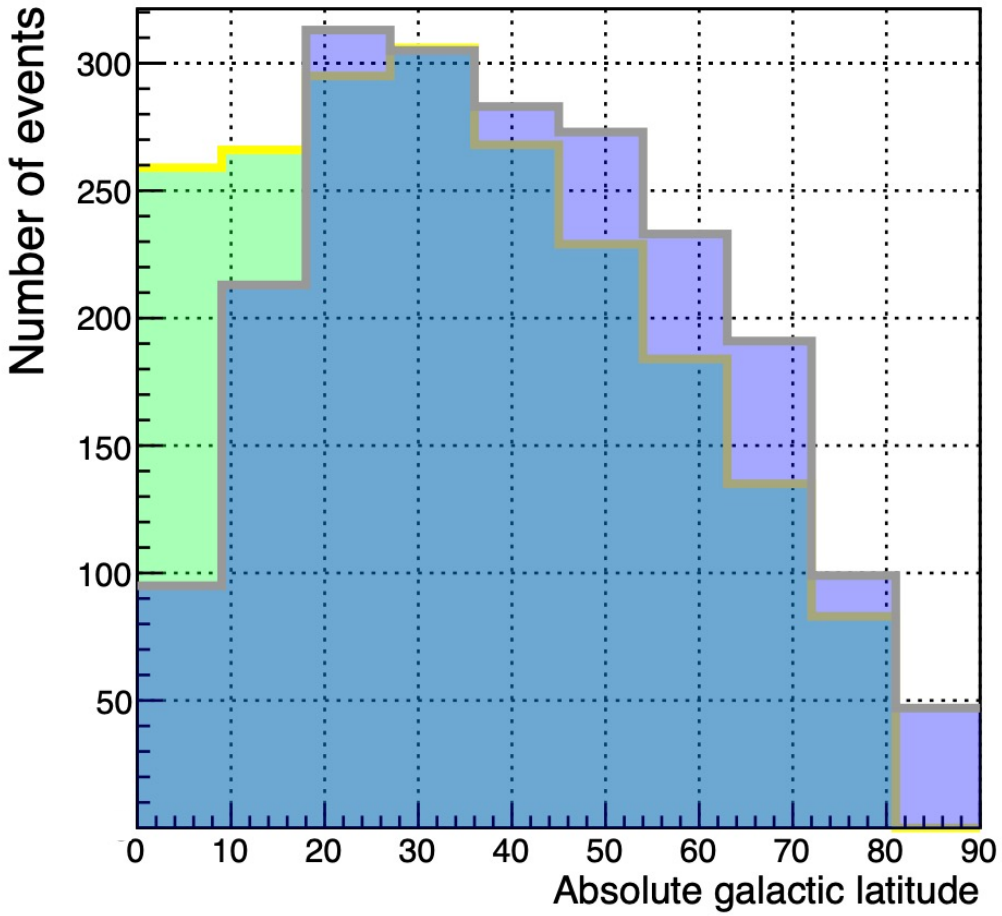
- Red line – model cumulative distribution function (CDF).
- Blue line – empirical cumulative distribution function or histogram.
- Black arrow – supremum of differences between model CDF and empirical CDF.

It's a nonparametric test of the equality of two one-dimension probability distributions.

X – experimental values.

Galactic plane isotropy test

No flux constraints



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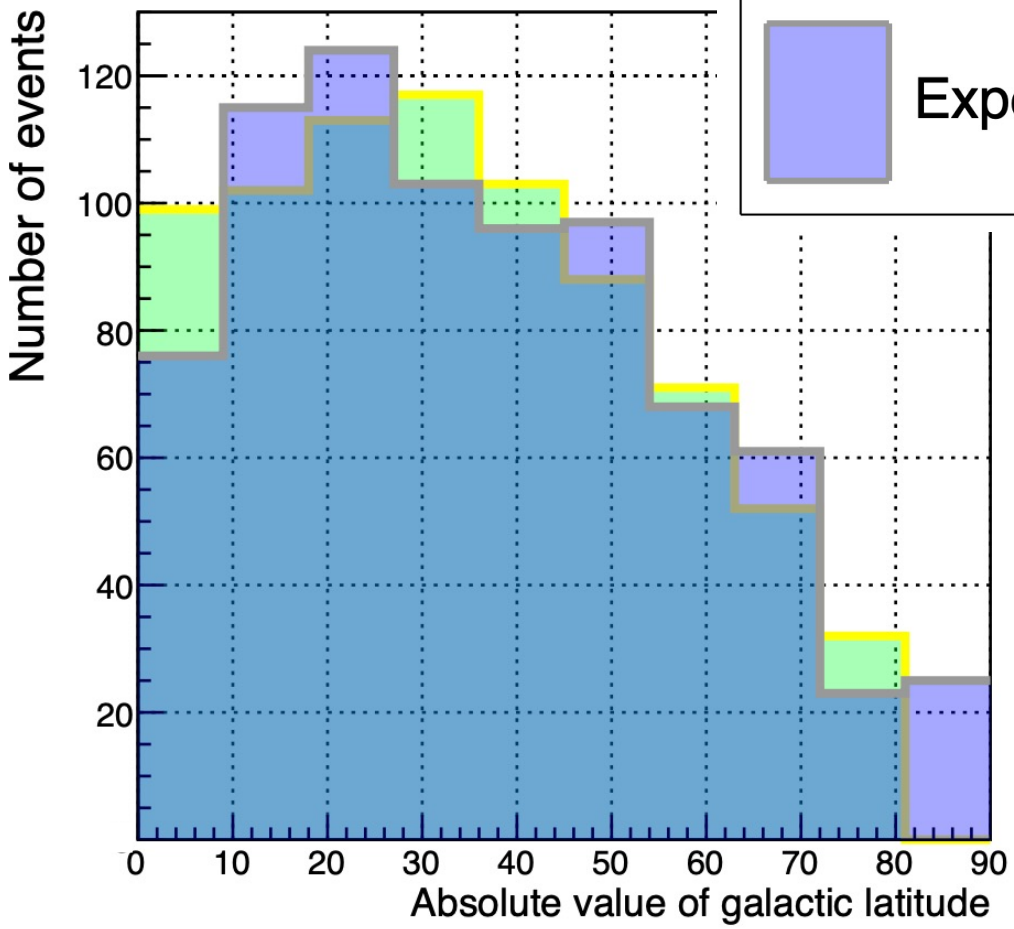
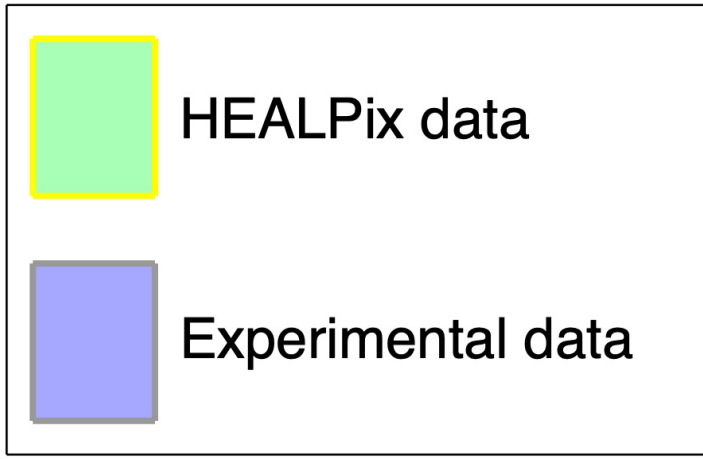




Pixelization HEALPix

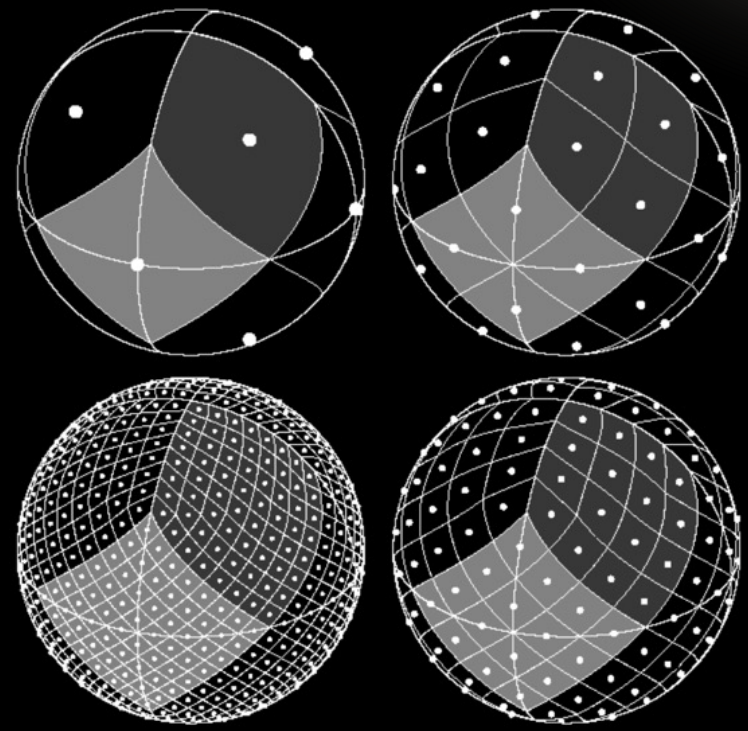
Pixelization HEALPix on the sphere:

- Light-gray shading - one of the eight (four north, and four south) identical polar base-resolution pixels.
- Dark-gray - one of the four identical equatorial base-resolution pixels.

Moving clockwise from the upper left panel the grid is hierarchically subdivided with the grid resolution parameter equal to $N_{side} = 1, 2, 4, 8$ and the total number of pixels equal to

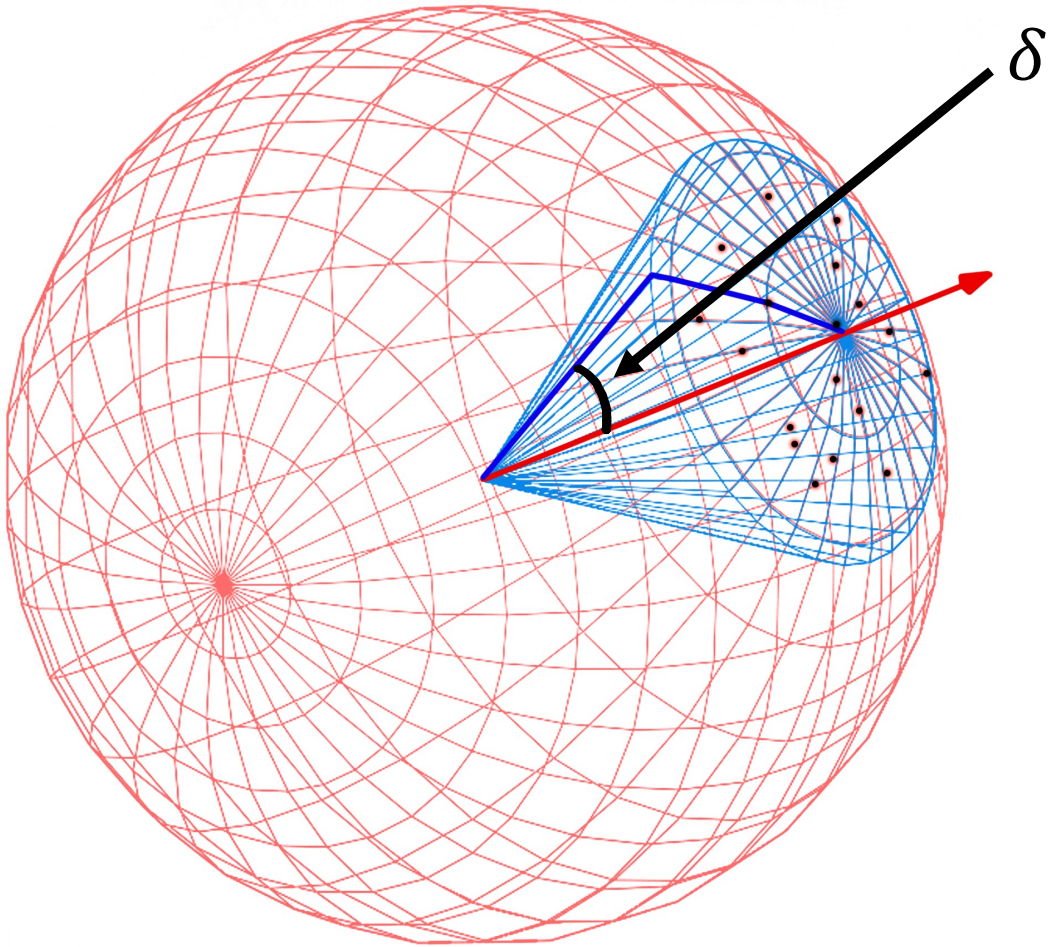
$N_{pix} = 12 \cdot N_{side} = 12, 48, 192, 768.$

Górski K. M et. al. (2004).



Whole sphere isotropy test

For a given set of objects, fixed direction on the sphere (represented by center of HEALPix pixel) and angle δ the amount of objects separated from the chosen direction by the angular distance less than δ is calculated.



Whole sphere isotropy test

It is expected that distribution of the amount of objects located in the cones around directions of healpix pixels' centers is binomial with average value described by this formula:

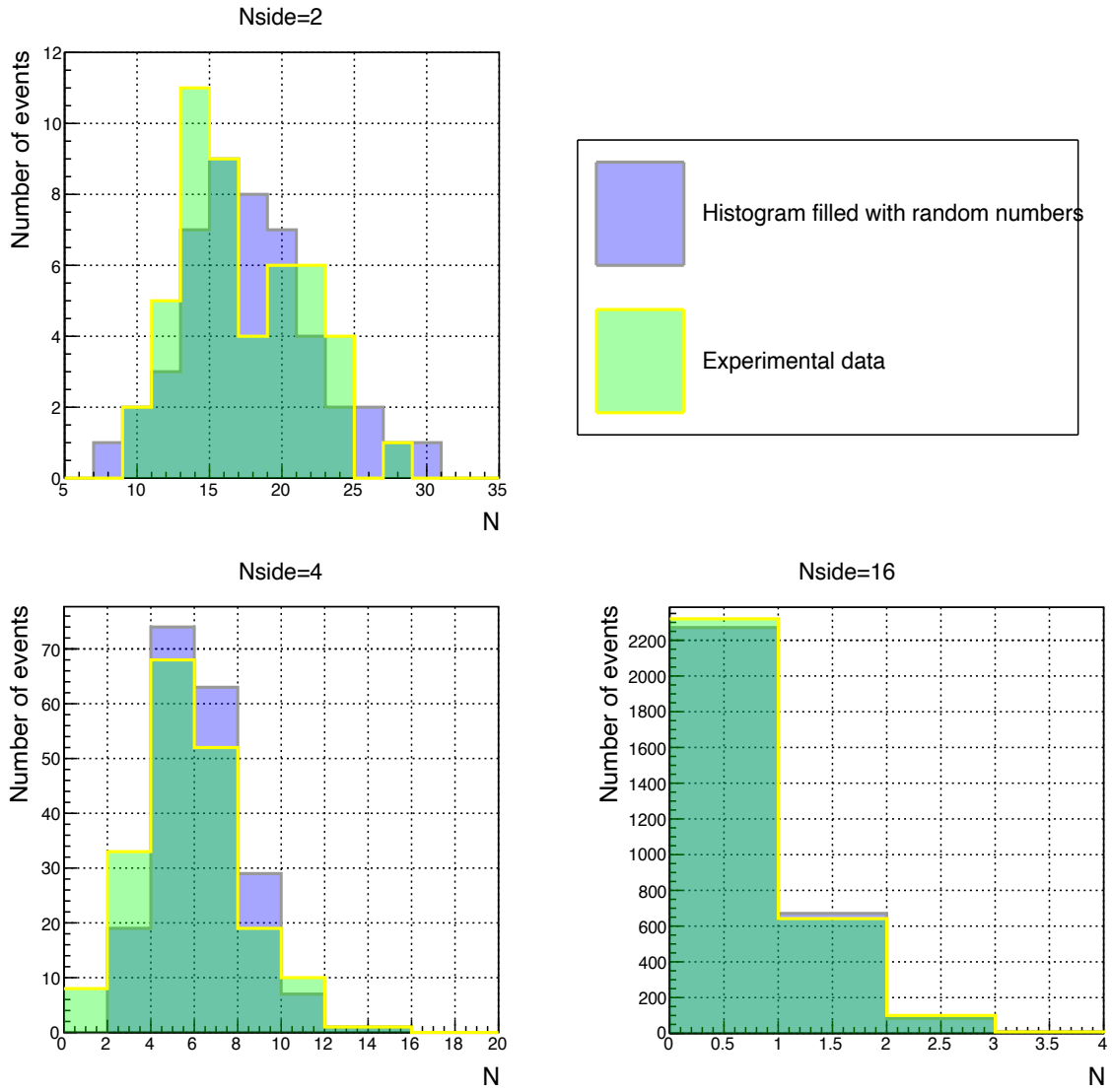
$$< N > = \ N_0 \cdot sin^2 \frac{\delta}{2} ,$$

Where N_0 - amount of objects in the set, δ – cone angle.

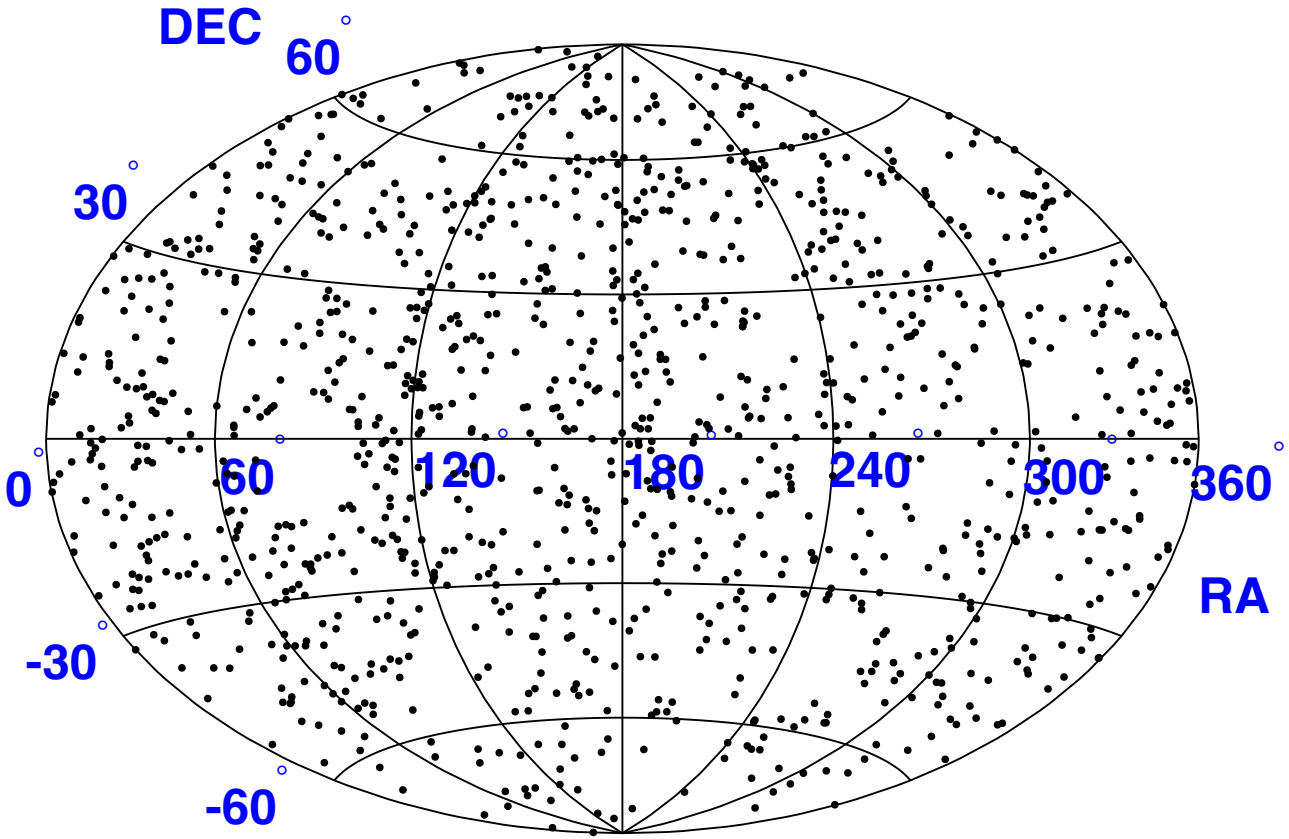
Constructed distribution is compared to binomial distribution with the use of Kolmogorov-Smirnov test in a same way as was described for galactic isotropy test.

Whole sphere isotropy test

Procedure described above is repeated for three sets of HEALPix pixels with different resolution parameters and cone angles. Each cone angle is chosen in a way to cover the distance between to pixels' centers as much as possible.



VLBI-set



This set consists of radio-loud objects detected in the experiments with very long baseline interferometry (VLBI).

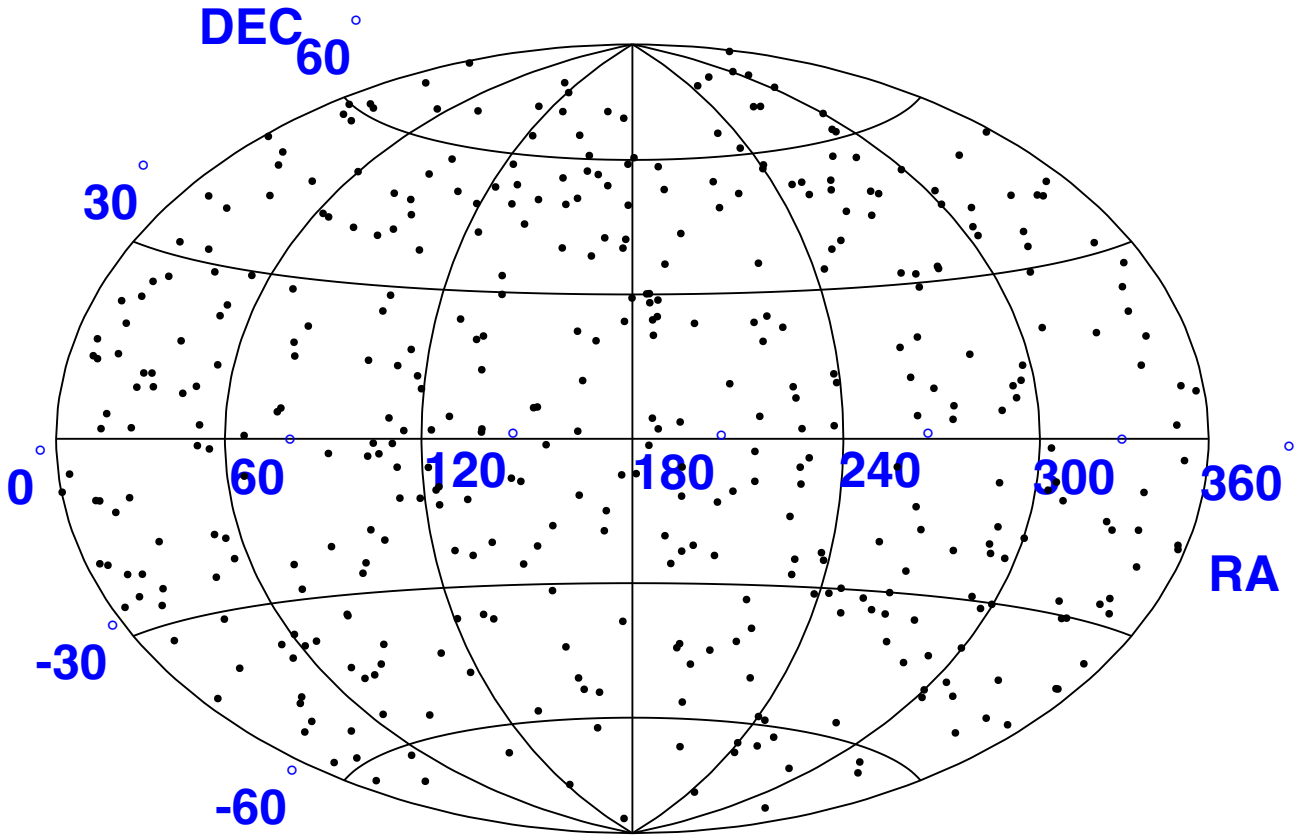
- m<18, where m – corrected visual stellar magnitude. Stellar magnitude of all objects was corrected via the model Amores&Lepine A2. This is made in accordance with paper of 2004.

- $F_{8Ggz} \geq 0.055\,Jy$, where F_{8GHz} – $photon\ flux\ at\ 8\ GHz$ in Jy*.

*1 Jy = $10^{-26}\frac{Wt}{m^2 \cdot Hz} = 10^{-23}\frac{erg}{s \cdot sm^2 \cdot Hz}$

An isotropic set of **1177 objects** was constructed.

Fermi-set



This set consists of objects from 4FGL catalogue Fermi LAT.

- $m < 18$, where m – corrected visual stellar magnitude.
- $F_{1-100GeV} \geq 7 \cdot 10^{-10} \frac{photons}{sm^2 \cdot s}$, where $F_{1-100GeV}$ – flux in energy range 1-100 GeV.

An isotropic set of **424 objects** was constructed.

Conclusion

- Two isotropic sets of objects were constructed.
- With them results obtained in 2004 with HiRes data could be checked.
- With the use of these sets it is possible to search for directional correlations of cosmic rays with BL Lac type objects in Telescope Array data.

Thank you for your attention!

This work is supported by contract on Russian Science Foundation № 22-12-00253.

Backup

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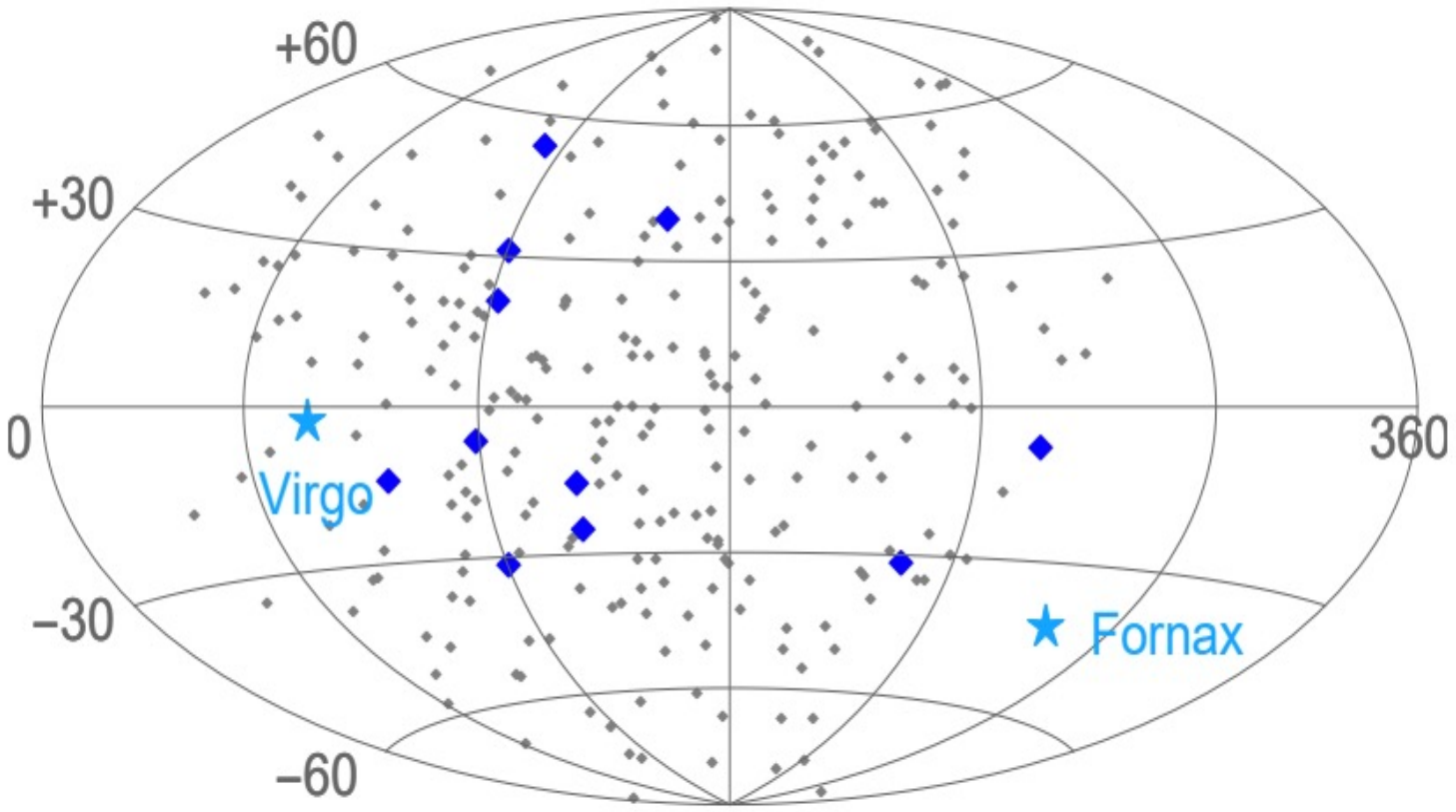

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(S. Troitsky, EPJ, 2020)

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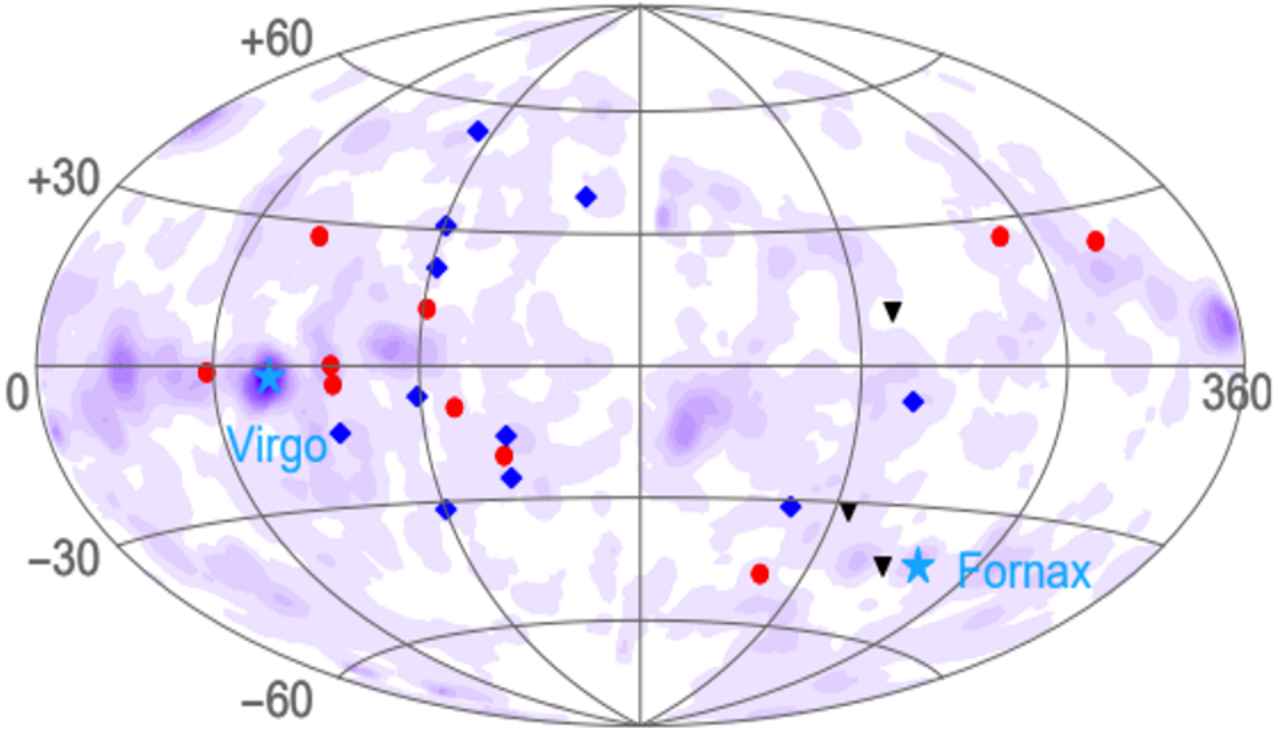

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