Anomalous cosmic-ray correlations revisited with a complete full-sky sample of BL Lac type objects

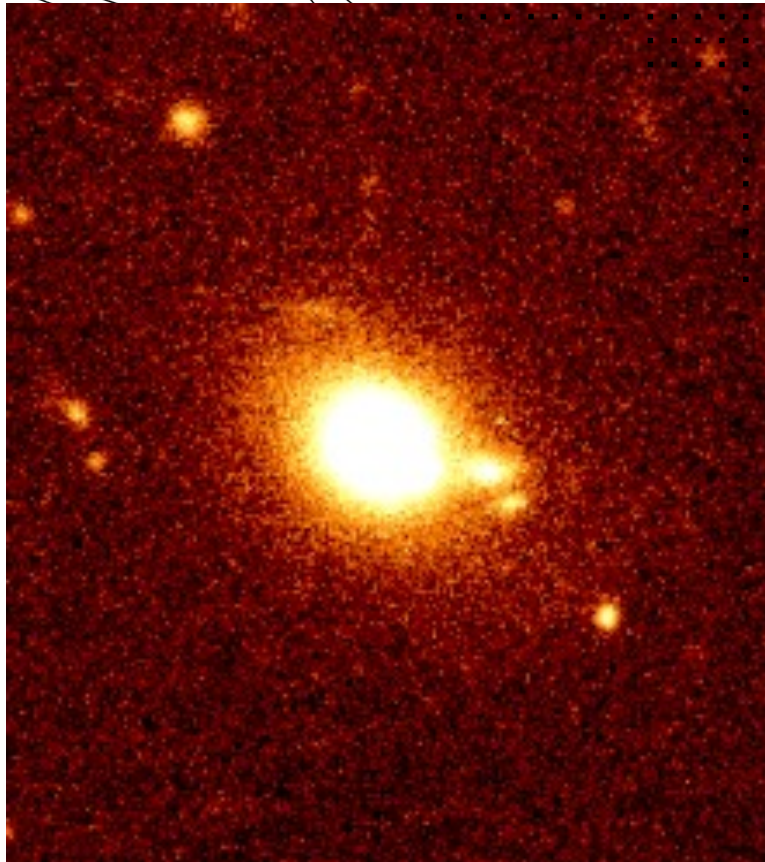**Maria Kudenko**, Sergey Troitsky

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Plan

- Correlations of HiRes cosmic-rays and sample of BLLs constructed by Veron in 2001 tested by Gorbunov et. al. in 2004

- Isotropic sample of BL Lac type objects

- Correlations revisited with full sky-sample of BLLs and HiRes data

- Further steps

BL Lacertae object

BL Lac type object is a certain type of active galactic nuclei with jets pointing to the observer and located at cosmological distances.

In contrast to other types of active galactic nuclei, BL Lacs are characterized by the absence of emission lines with equivalent widths exceeding 5Å.
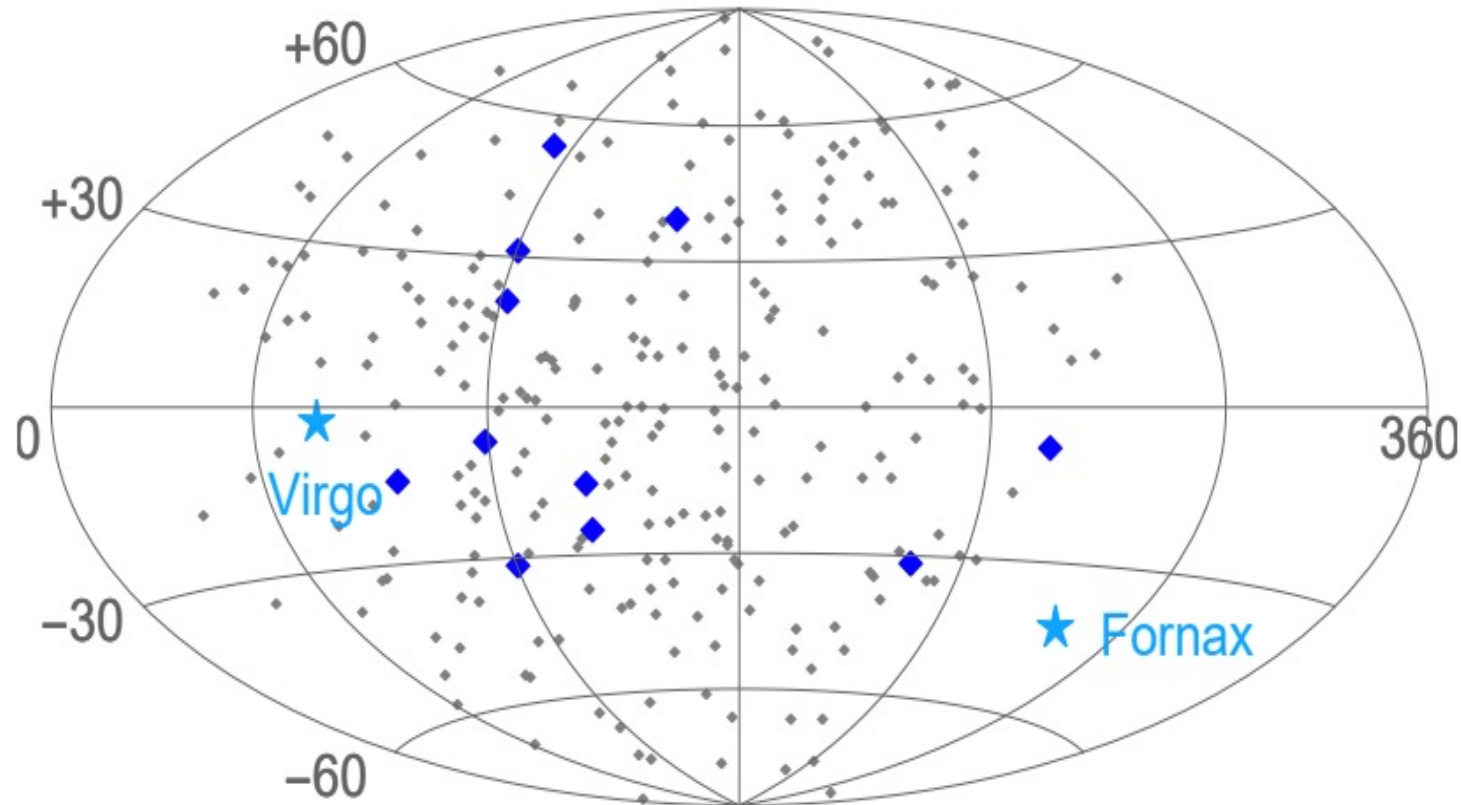
High Resolution Fly's Eye Cosmic Ray Detector

Hight Resolution Fly's Eye Cosmic Ray Detector or HiRes was an ultra-high-energy cosmic ray observatory located in Utah.

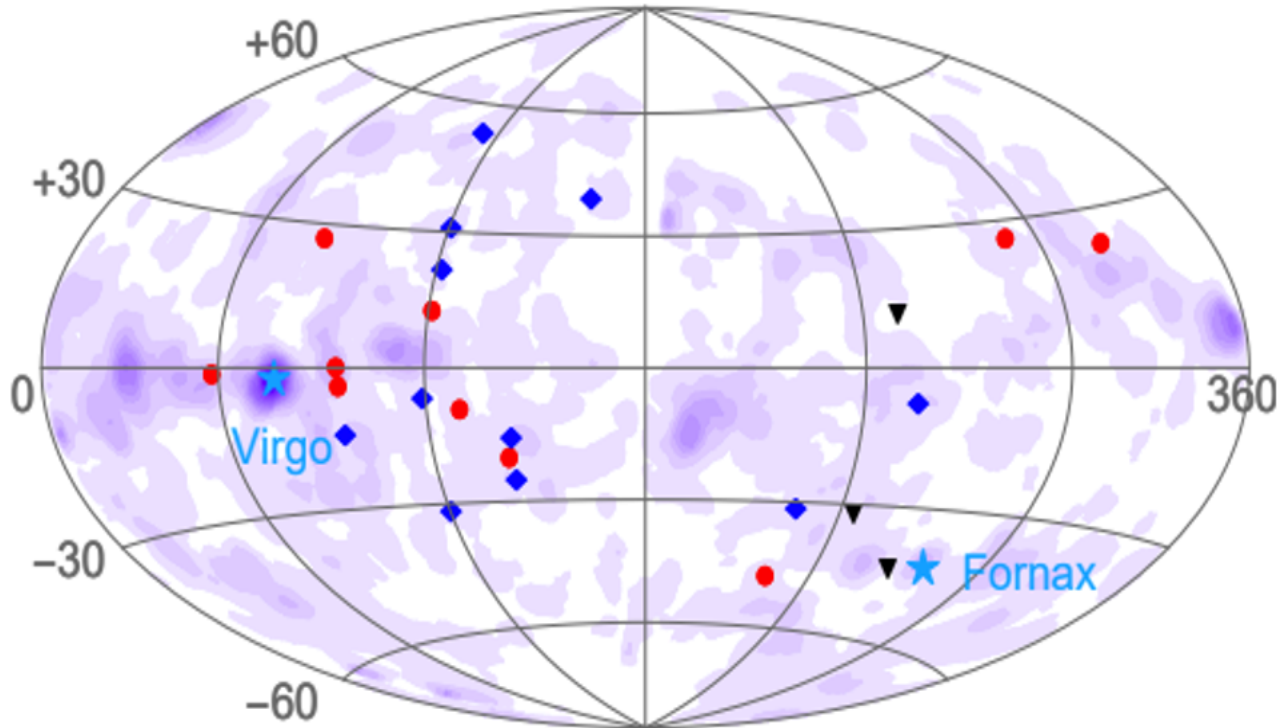HiRes operated from May 1997 until April 2006.

2004 Result

Blue diamonds – correlating BLL objects.

Gray dots – other HiRES showers in the sample with $E \geq 10^{19} \, eV$.

Supergalactic coordinates.

(S. Troitsky, EPJ, 2020)

2004 Result

Red circles: objects with anomalous hardenings in VHE.

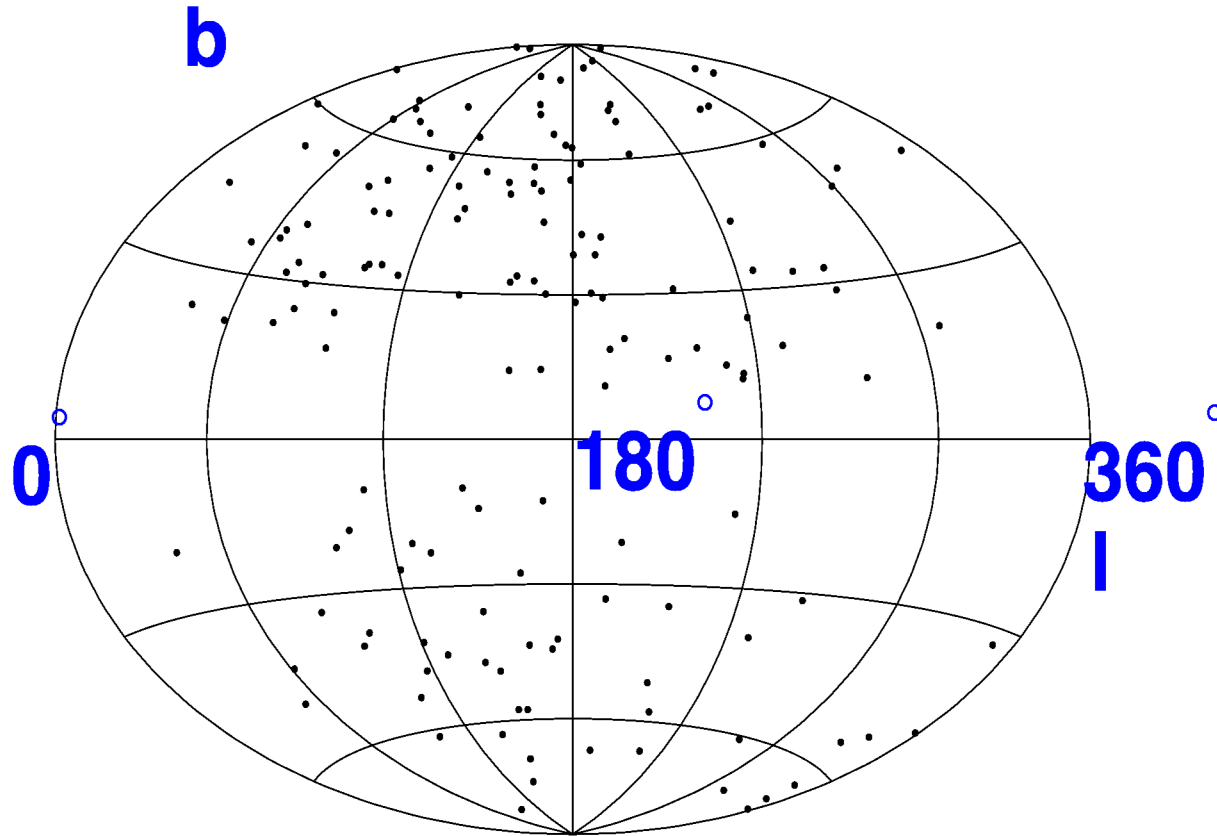Blue dimonds: air showers correlated with BL Lac type objects.

Black triangles: gamma-ray bursts detected in VHE.

Density plot – weighted density of nearby ($\lesssim$ 30Mpc) galaxies.

Supergalactic coordinates.

(S. Troitsky, EPJ, 2021)

BLLac catalog by Veron et al. 2001

b

0   180   360

l

b – Galactic latitude.

l – Galactic longitude.

Map of objects from the catalog in the Galactic coordinates.

It can be seen that the sample is not isotropic, because very small amount of objects is located near the Galactic plane.
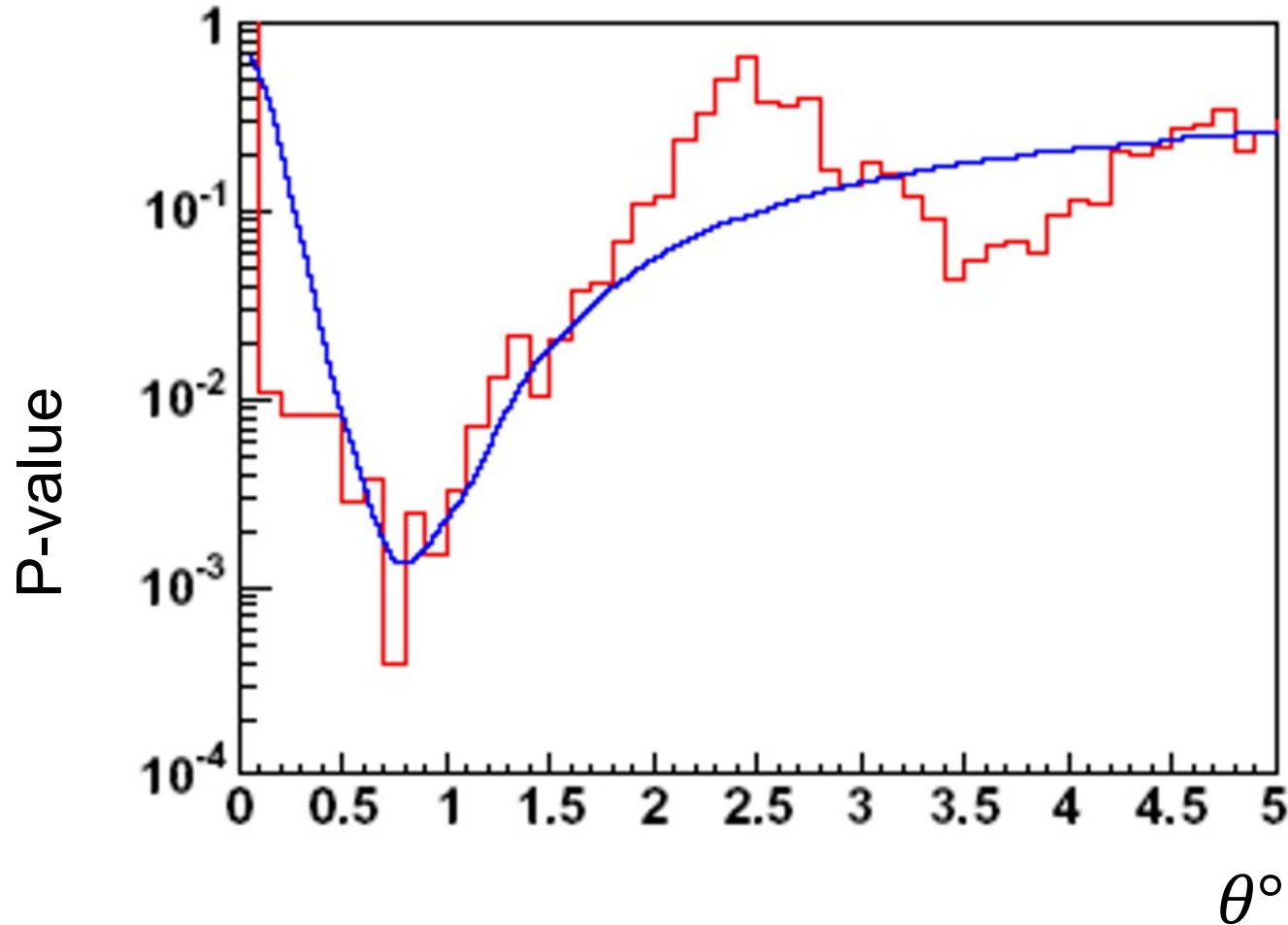
2004 Result

For given set of sources and fixed angle θ, the number of pairs "cosmic ray-source" separated by angular distance less or equal than θ were calculated. After that real data was replaced by large number of randomly generated Monte Carlo set of cosmic rays and the same procedure was repeated. This was made in order to calculate the p-value measuring how often this or larger number of pairs can be observed by chance.

θ
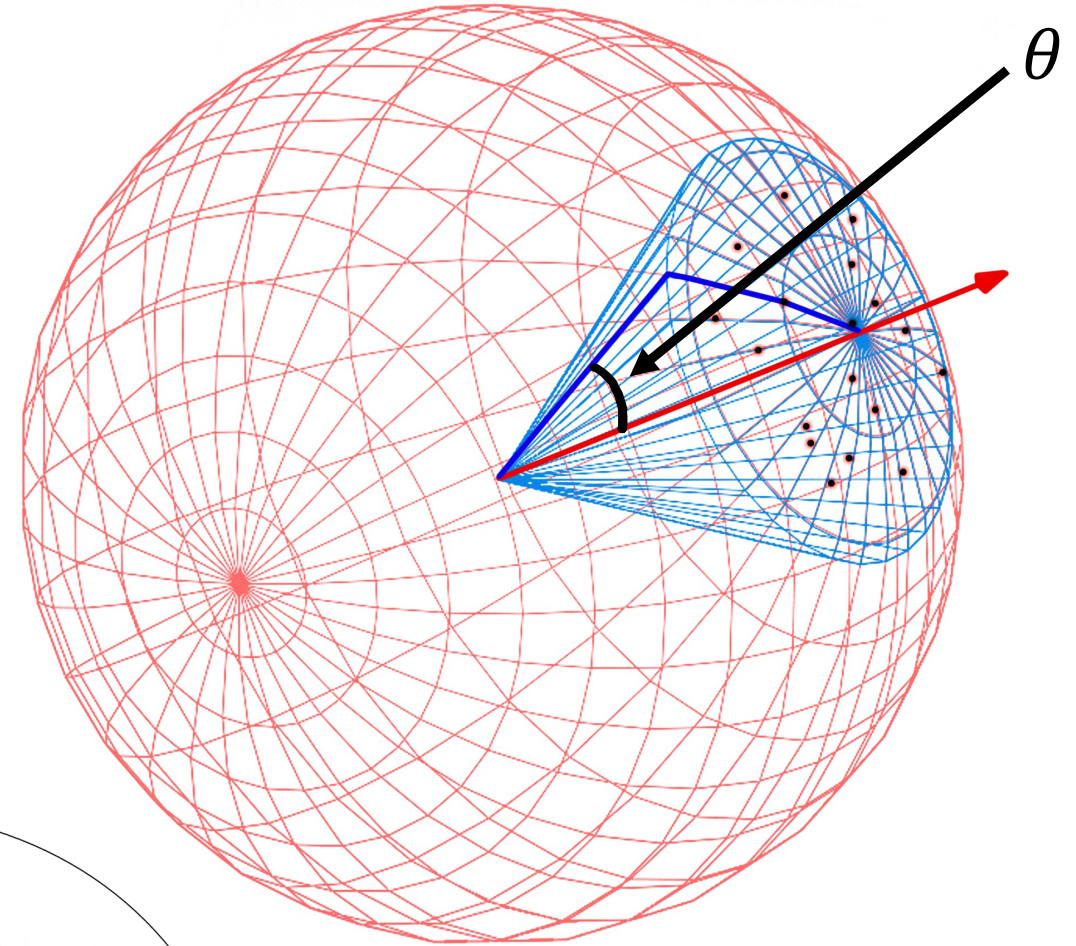
2004 Result

- 156 BLL objects with uncorrected visual magnitude $V < 18^m$

- 271 events with $E \geq 10^{19} \; eV$

- 11 pairs "BLL-cosmic ray" observed

- 3 pairs expected for isotropy

- P-value $= 10^{-3}$

- HiRes angular resolution 0.6°

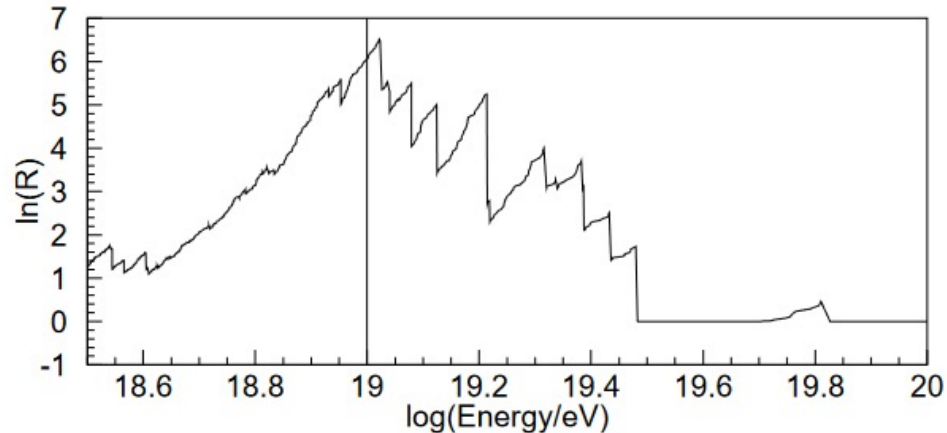(D. Gorbunov et al., JETP letters, 2004)

2004 Result confirmation

FIG. 1.— ln $\mathcal{R}$ result as a function of minimum energy threshold of the HiRes data set. The 10^{19} eV energy threshold of the published data is indicated.

TABLE 2

HIRES — BL LAC CORRELATION RESULTS: FRACTION $\mathcal{F}$ OF SIMULATED HIRES SETS WITH STRONGER CORRELATION SIGNAL.

Source Sample (# Obj.)	All Energies	$E > 10\,\mathrm{EeV}$
"BL" (157)	2×10^{-4}	2×10^{-4}
"HP" (47)	0.3	6×10^{-3}
"BL"+"HP" (204)	5×10^{-4}	10^{-5}

NOTE. — Correlations are with confirmed BL Lacs in Table 2 of the Veron 10th Catalog (Veron-Cetty & Veron 2001), classified as either "BL" or "HP," with $m < 18$.

- Same data set and internal information
- All observed events
- Likelihood, not pair counting
- Same 156($\pm$1) BL Lacs
- Correlations confirmed and extended to lower energies

(HiRes Collaboration, ApJ, 2006)

BLLac catalog by Veron et al. 2001

b

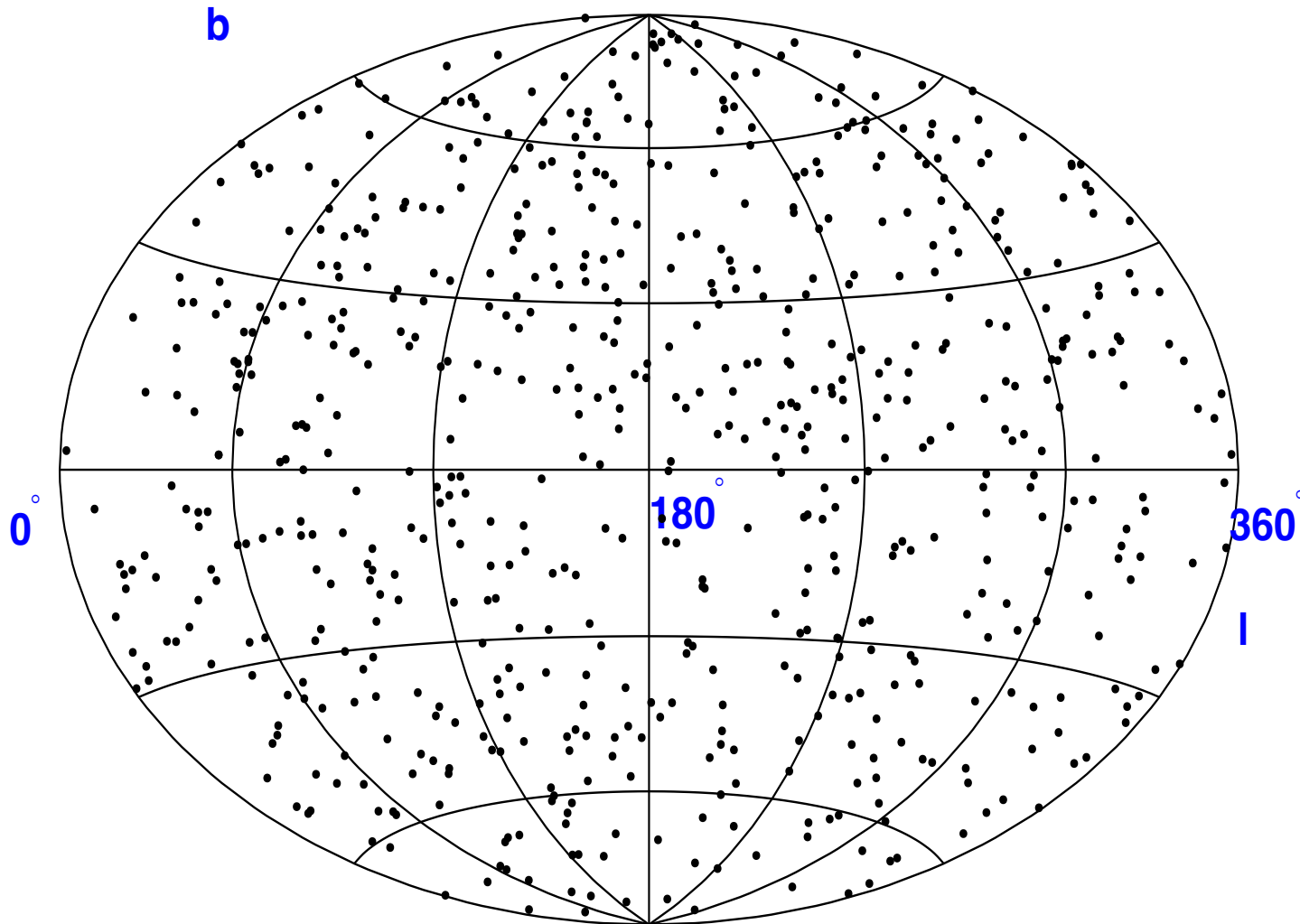**0** **180** **360**

l
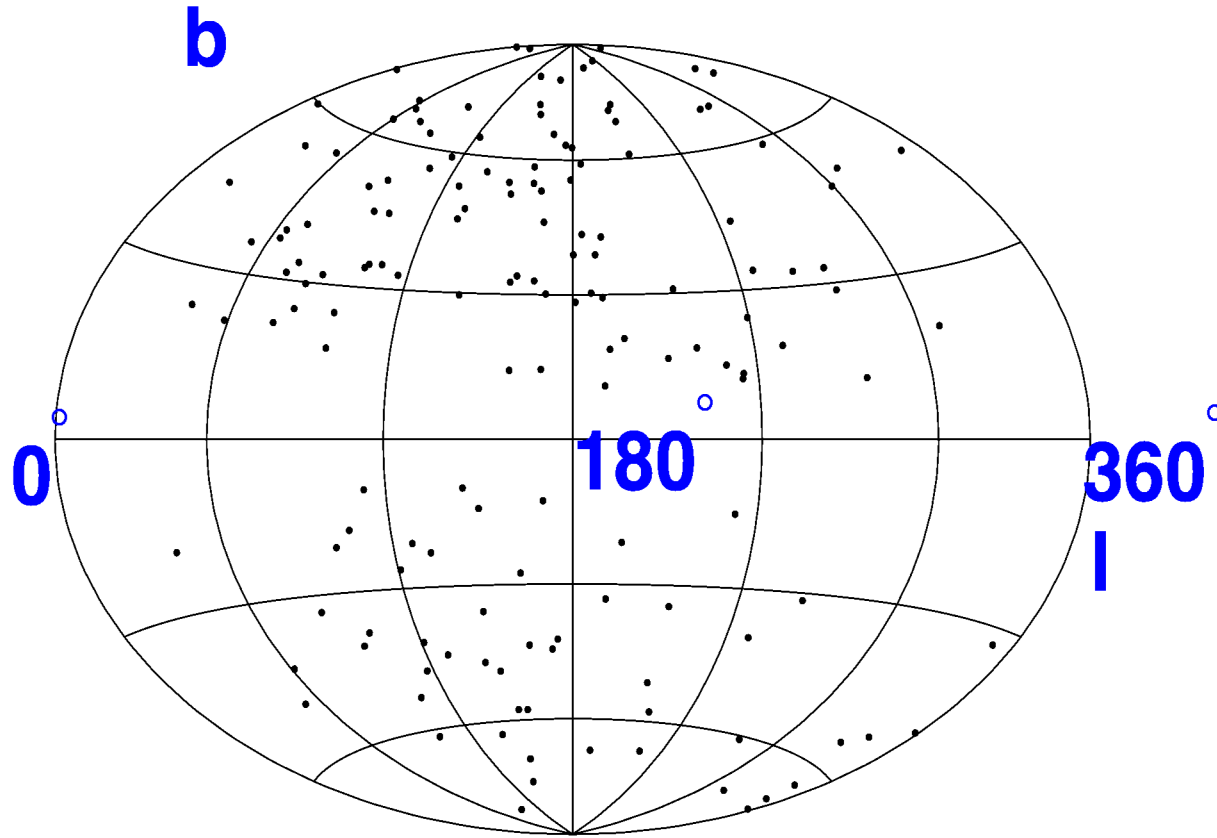
Map of objects from the catalog in the Galactic coordinates.

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.

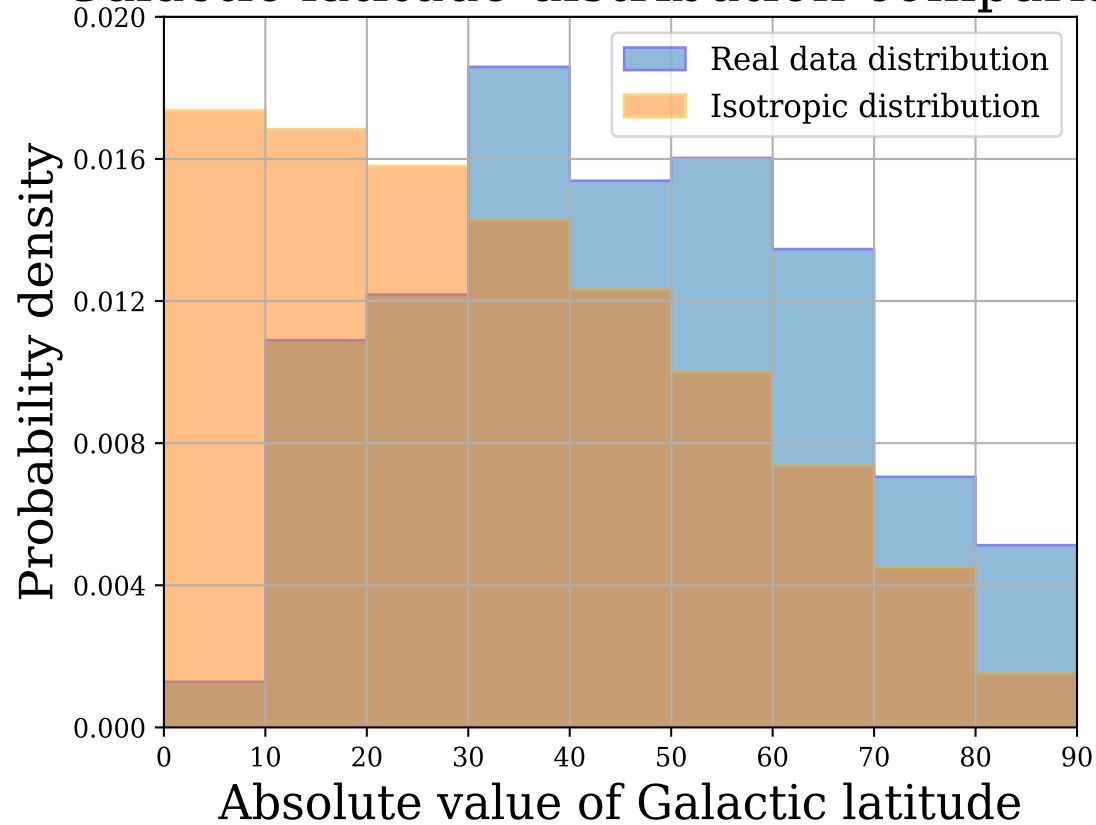# An isotropic sample of optically selected blazars

- Isotopic set of 561 radio and gamma loud blazars

- Corrected for the Galactic absorption GAIA DDR3 G-band magnitude $G_{corr} < 18^m$

(arXiv:2312.07508,

Kudenko, Troitsky)
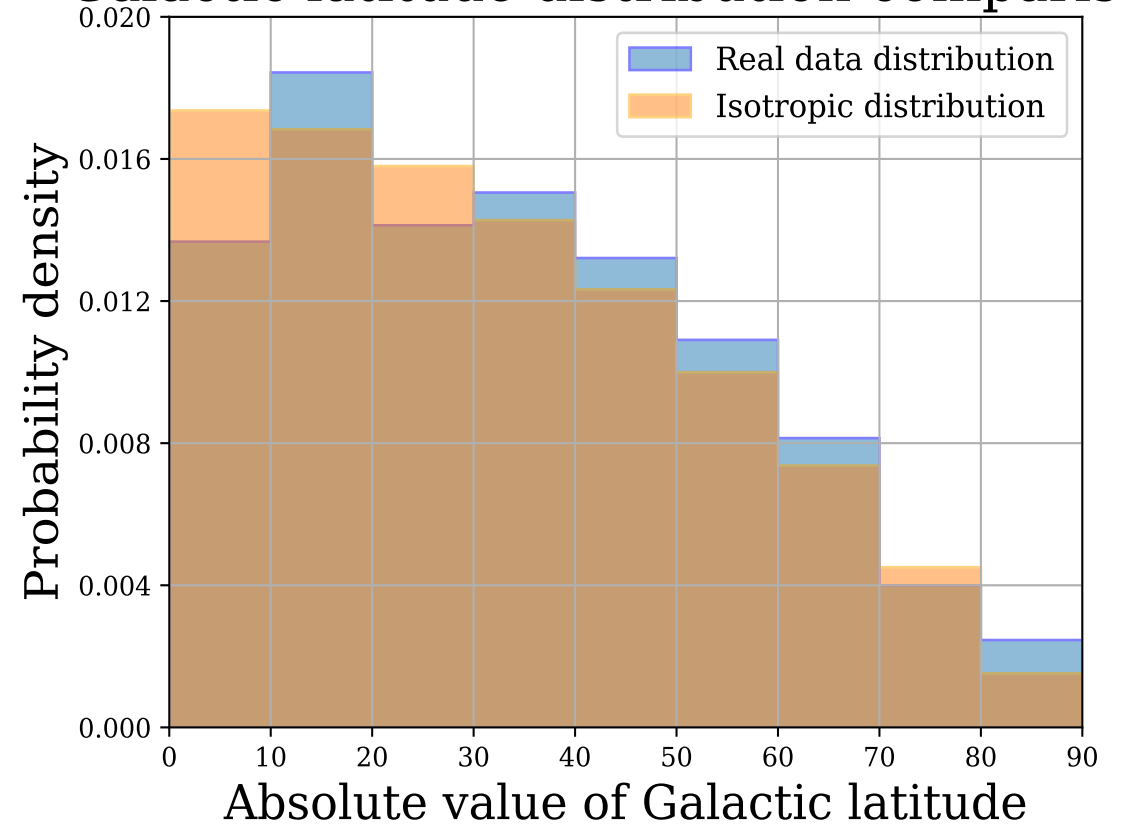
Galactic latitude distribution

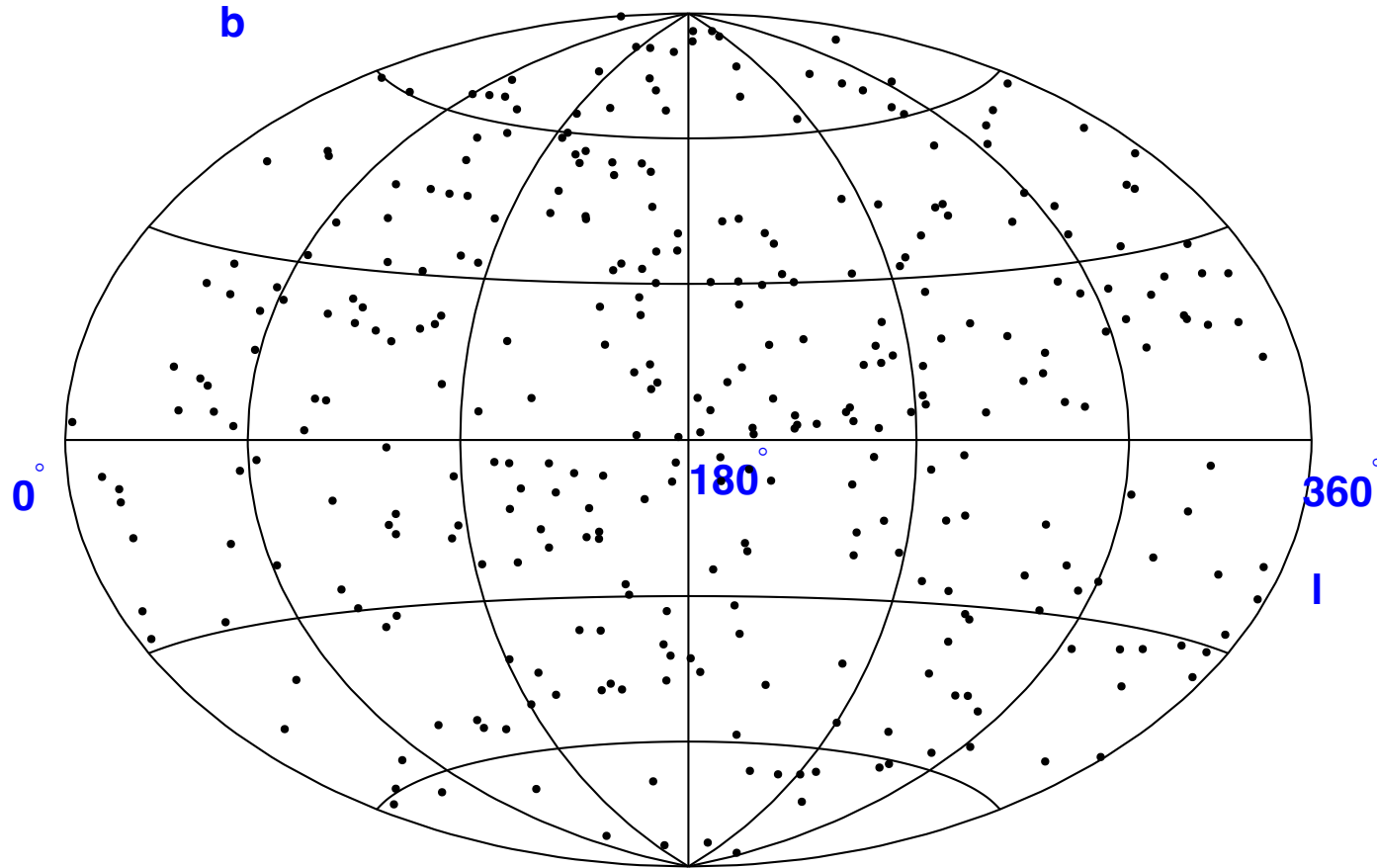Sample of 156 objects used in 2004
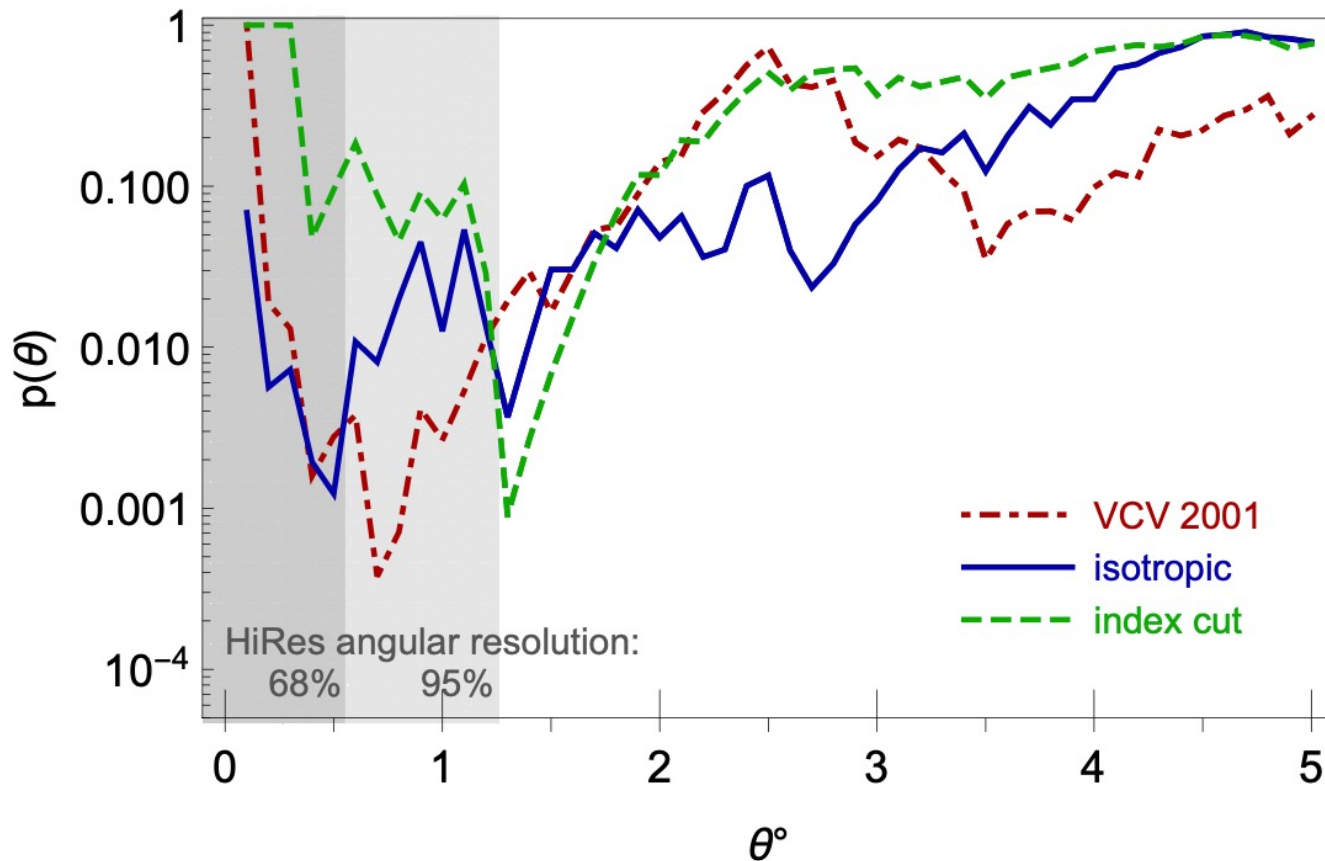
Isotopic set of 561 objects

An isotropic sample of BL Lacs

- Objects with the absence of emission lines with equivalent width exceeding 5 $\mathring{A}$ were selected (Veron criteria).
- 336 objects
- Still isotropic sample
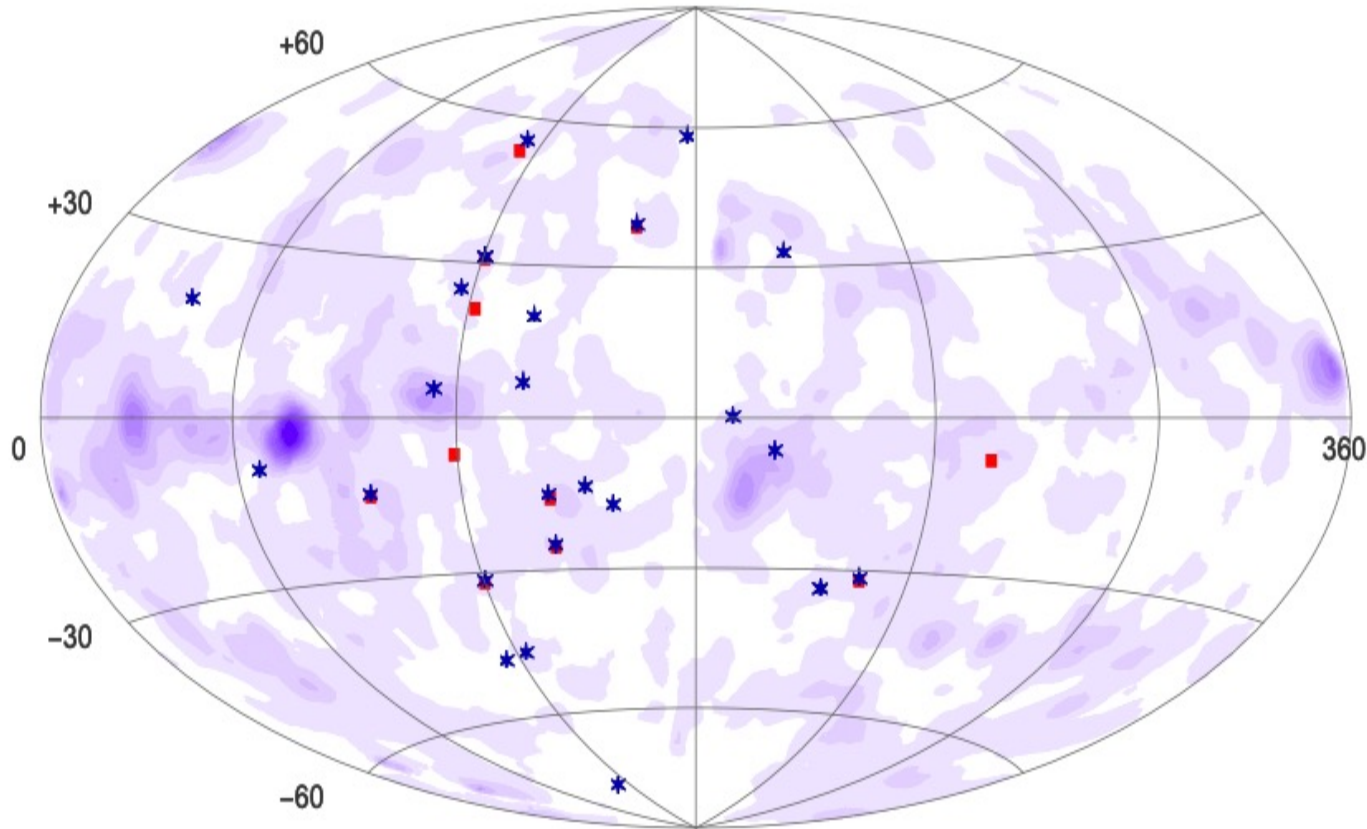- Good for correlation search

(arXiv:2312.07508)

Revisited result

- 336 BLL objects with corrected for the Galactic absorption GAIA DDR3 G-band magnitude $G_{corr} <$ 18^m (isotropic)
- 76 objects with $\alpha_{ox} < 1$ (index cut)
- 271 HiRes events with $E \geq 10^{19}\ eV$

(Kudenko, Troitsky, JETP letters 2024)

Revisited result

Sky map with positions of BL Lacs associated with HiRes cosmic rays (supergalactic coordinates).

Red circles: the sample used in 2004, $\theta = 0.8°$

Blue stars: the isotropic sample, $\theta = 1.3°$

Shading represents the weighted density of galaxies

(arXiv:2312.07525)

Further steps

- Search for cosmic ray correlation in TA SD 15 year data with the use of Veron catalog and new isotropic catalog of BL Lacs.

- Check whether correlating objects are the same and whether they are located near large scale structures.

- Search for correlations with the use of TA data with higher angular resolution.

- Tests of nature of primary particles of correlating events.
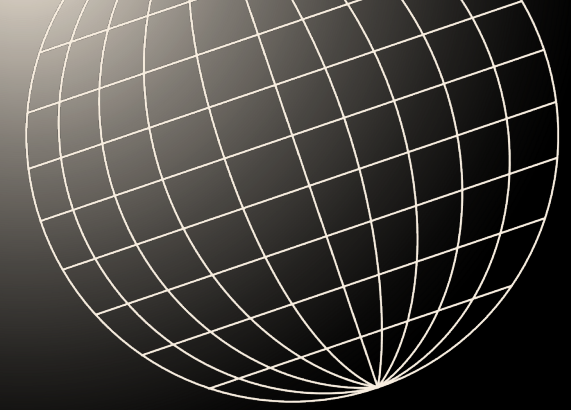
Thank you for your attention!

# Backup

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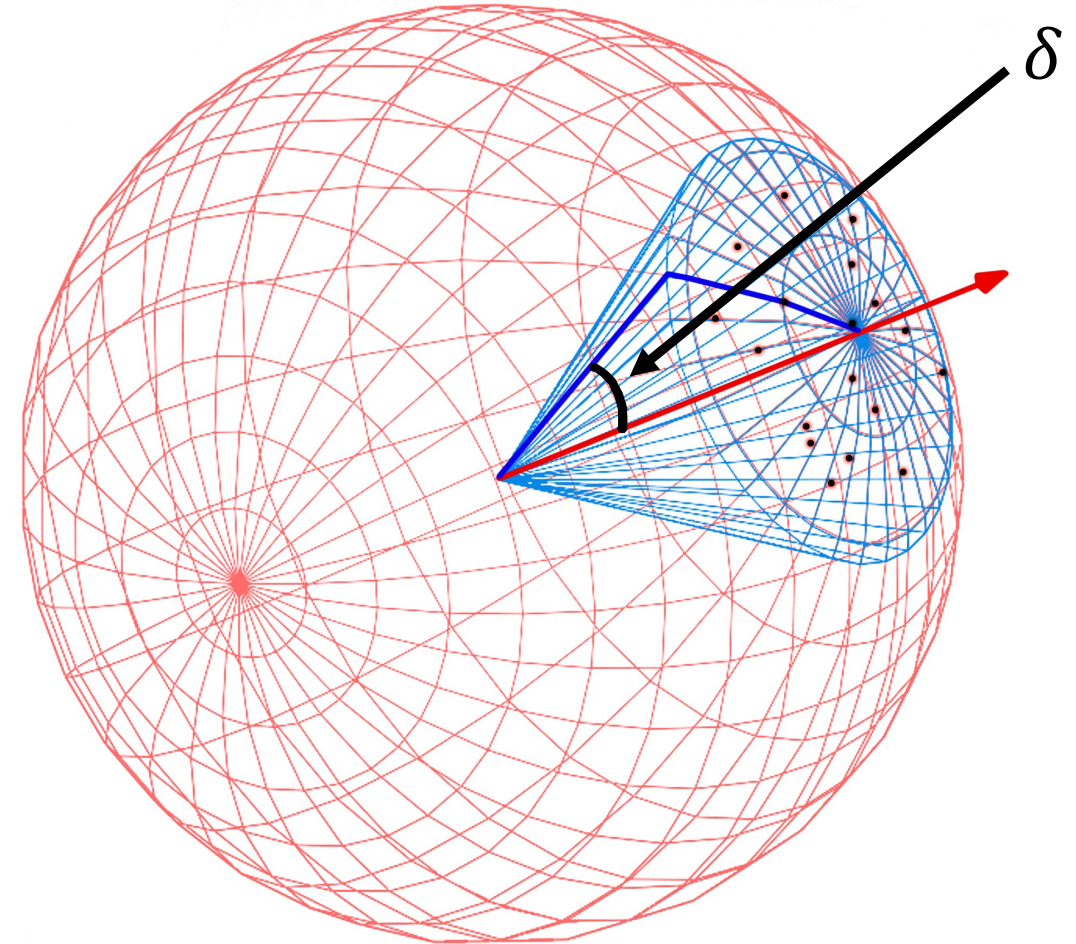
$N_{pix} = 12 \cdot N_{side} = 12, 48, 192, 768.$

Górski K. M et. al. (2004).
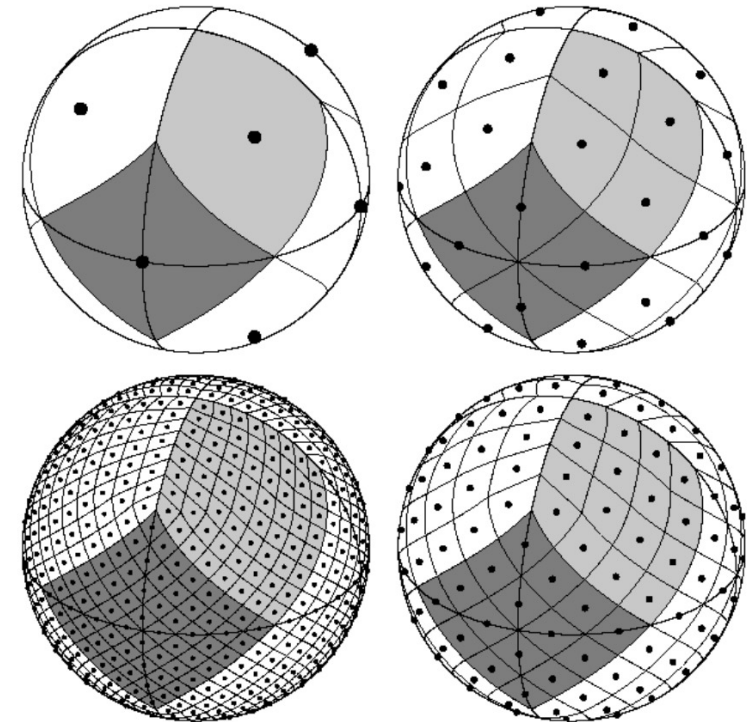
Whole sphere isotropy test

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.
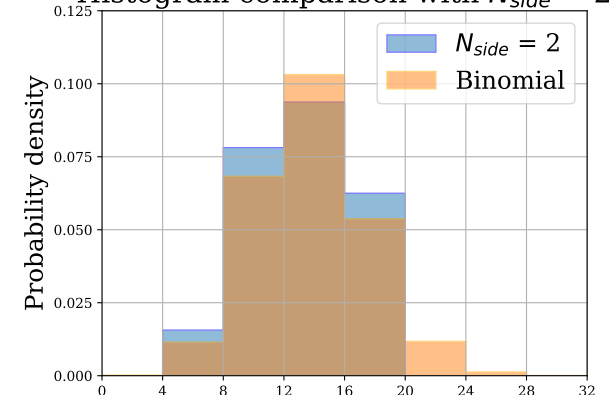
Whole sphere isotropy test

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.
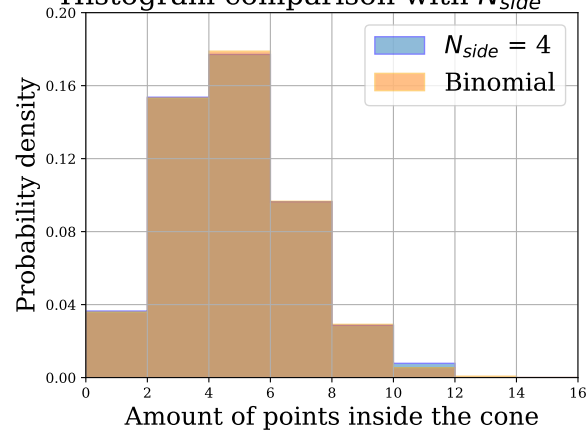
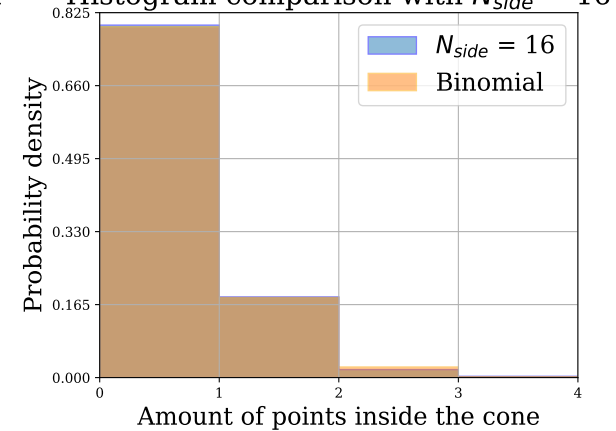

Galactic latitude distribution comparison
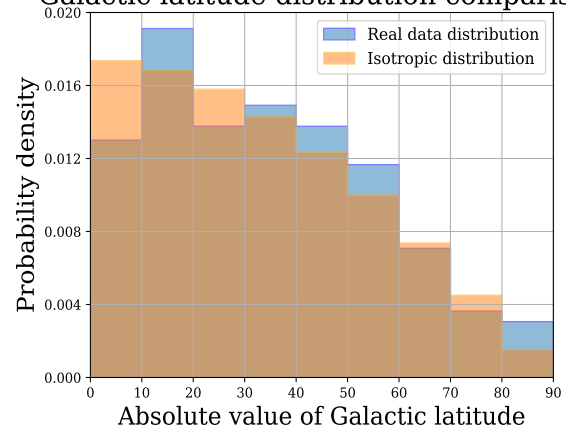
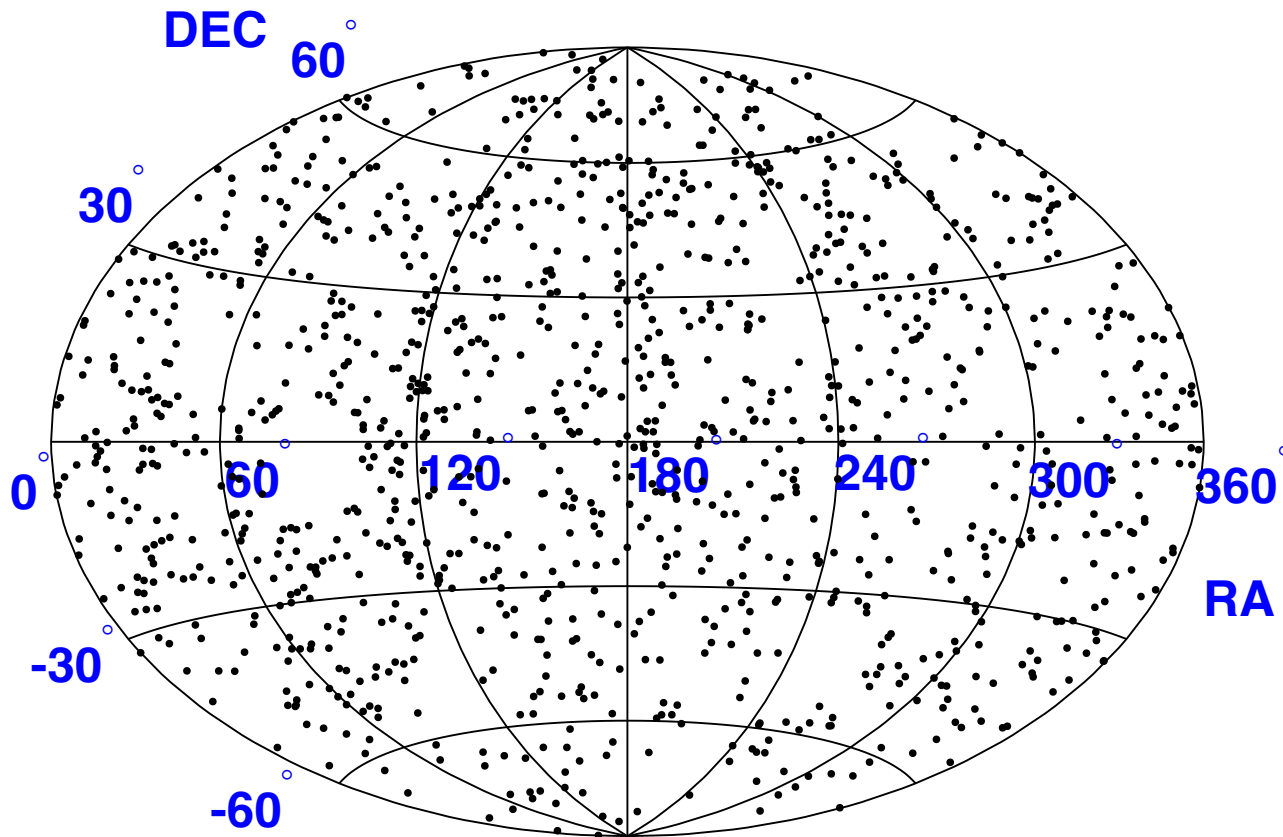Histogram comparison with $N_{side} = 2$

Histogram comparison with $N_{side} = 4$

Histogram comparison with $N_{side} = 16$

VLBI-set

This set consists of radio-loud objects detected in the experiments with very long baseline interferometry (VLBI).
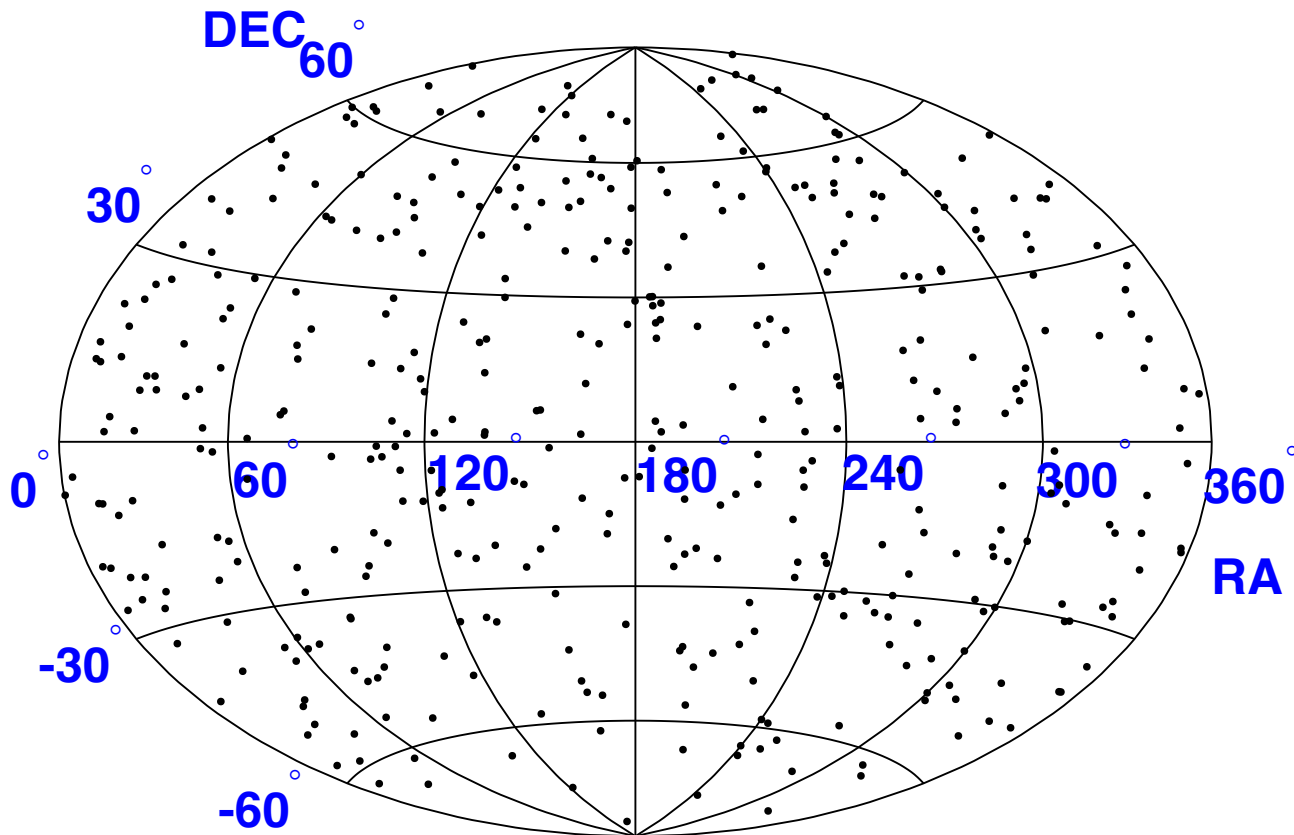
- m<18, where m – corrected visual stellar magnitude. Stellar magnitude of all objects was corrected via the model Amores&Lepine A2. This is made in accordance with paper of 2004.

- $F_{8Ggz} \geq 0.41\ Jy$, 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 **256 objects** was constructed.

Fermi-set

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

- m < 18, where m – corrected visual stellar magnitude.

- $F_{1-100GeV} \geq 3.8 \cdot 10^{-10} \frac{photons}{sm^2 \cdot s}$, where $F_{1-100GeV}$ – flux in energy range 1-100 GeV.

An isotropic set of **523 objects** was constructed.