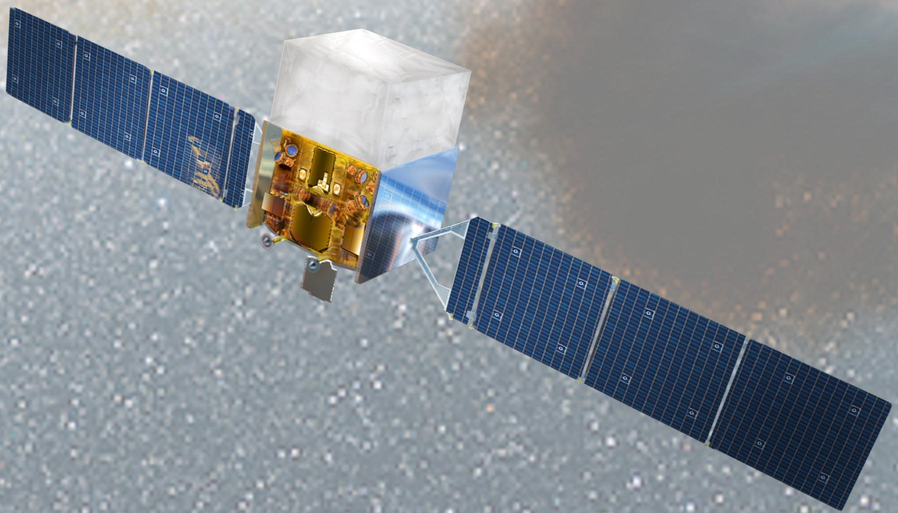
Search for correlations between Fermi LAT very high energy photons and active galactic nuclei

M.Kudenko[1]

[1]INR RAS



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Motivation

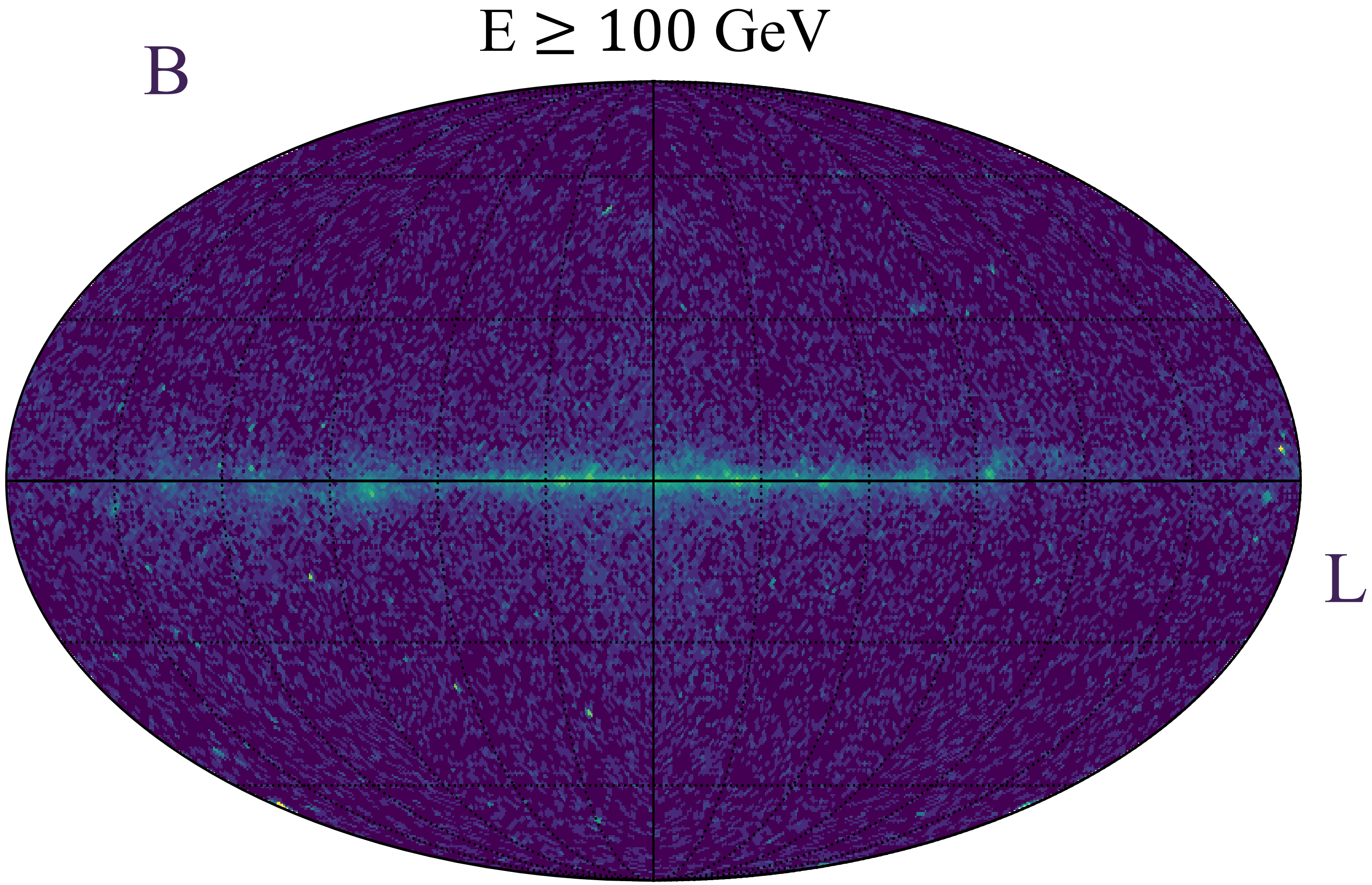
➢Using Fermi LAT data to search for population of radio loud AGNs which also emit gamma rays with energies >100 GeV and which are not present in 4FGL Catalog of Fermi LAT data.

✓Key idea № 1: no masking of the Galactic plane

✓Key idea № 2: no usage of Fermi tools due to a lot of model dependent assumptions

✓Key idea № 3: implementation of methods from cosmic ray analysis in order to detect fainter gamma emitters

Fermi LAT data



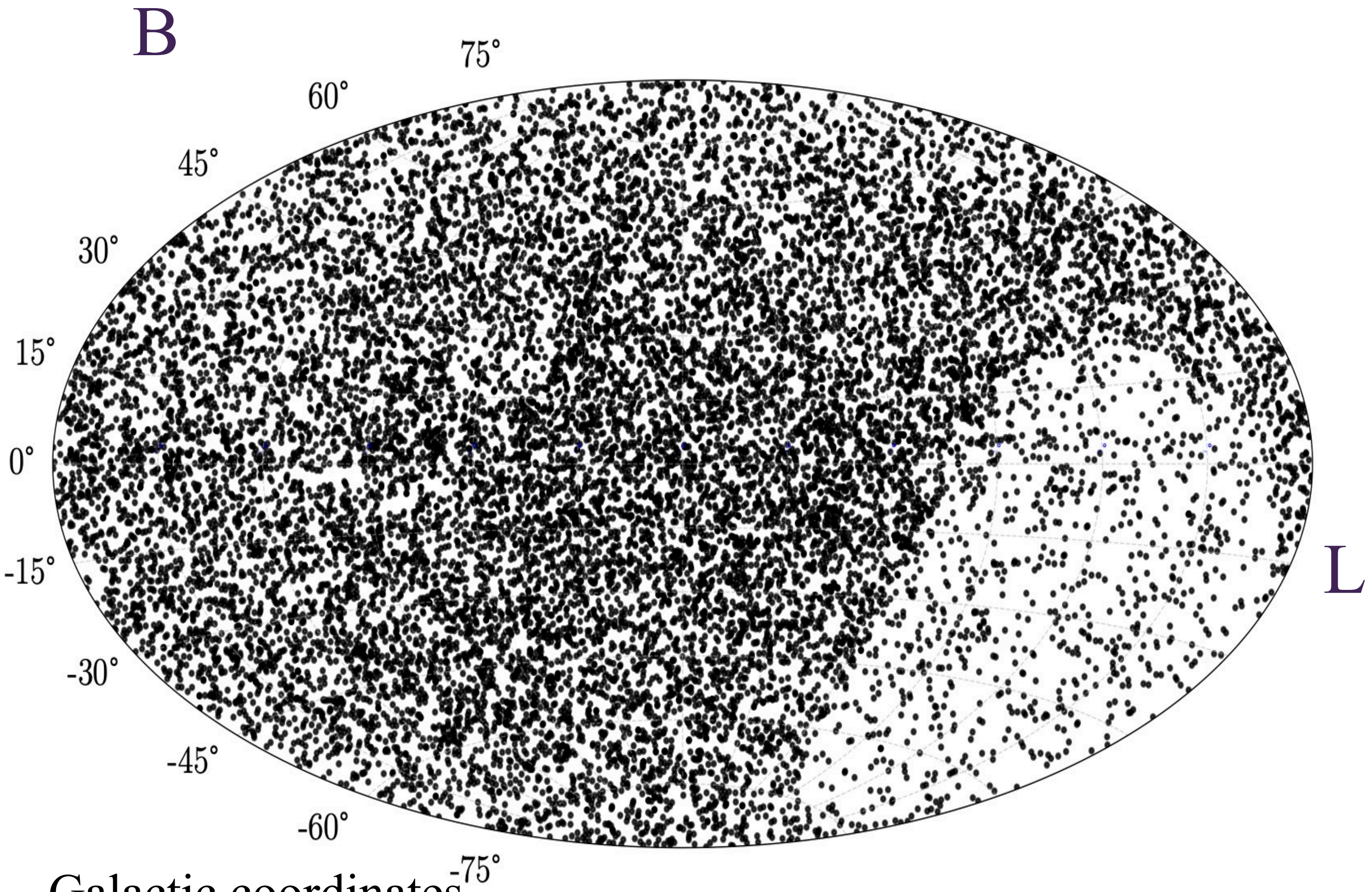
Galactic coordinates

Fermi LAT:
"P8R3_SOURCE_V3"

$E_\gamma \geq 100$ GeV

Front converted events

Sample of blazars



Galactic coordinates

Radio-loud blazar-like objects with identified Fermi LAT sources excluded.

15 716 objects.

(Petrov & Kovalev, 2025, ApJS)

Pair-counting method

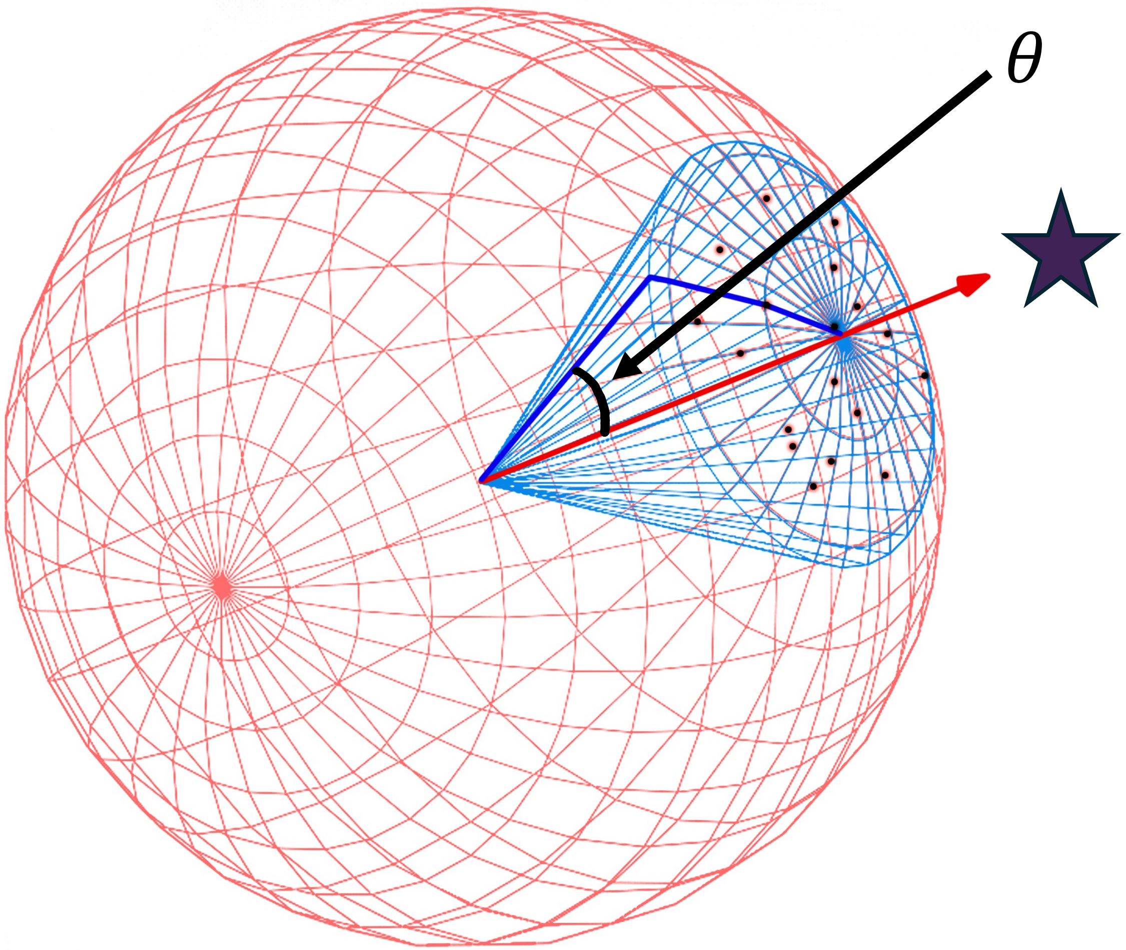
<u>H0.</u> There is no physical connection between sources and gamma (or cosmic) rays.

One should simulate datasets under H0 and for fixed angle θ calculate the number of pairs “gamma ray — source” separated by angular distance less or equal than θ.

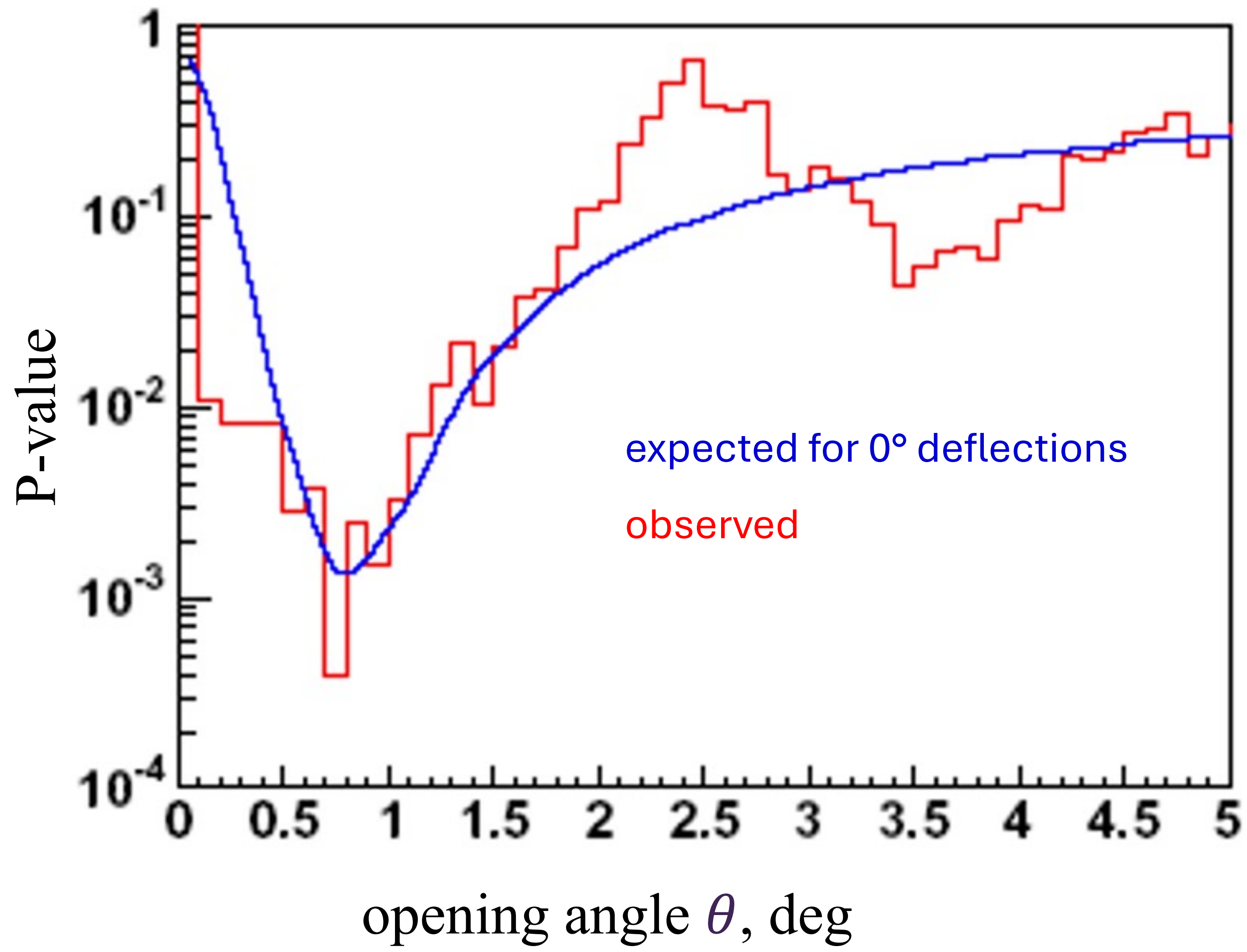
After that perform the same procedure for real data and calculate p-value.

Low p-value → excess of events around objects from the sample.

Scan over θ can be performed.



Pair-counting method



The resulting curve will look like this.

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

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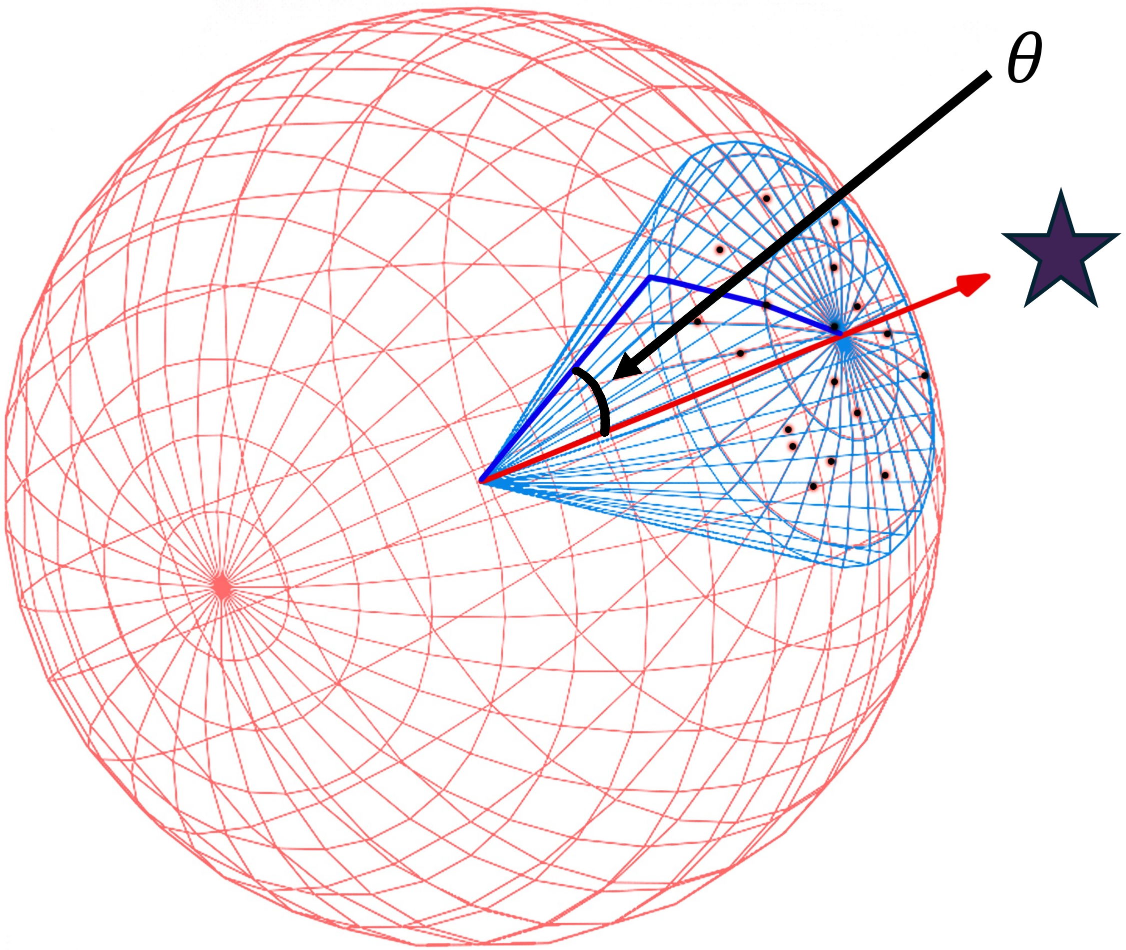

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<u>Option 1.</u>

Simulate Fermi LAT photons in the absence of sources from the sample.

- ➢ Too model dependent and time consuming.

<u>Option 2.</u>

Simulate samples of radio-loud objects.

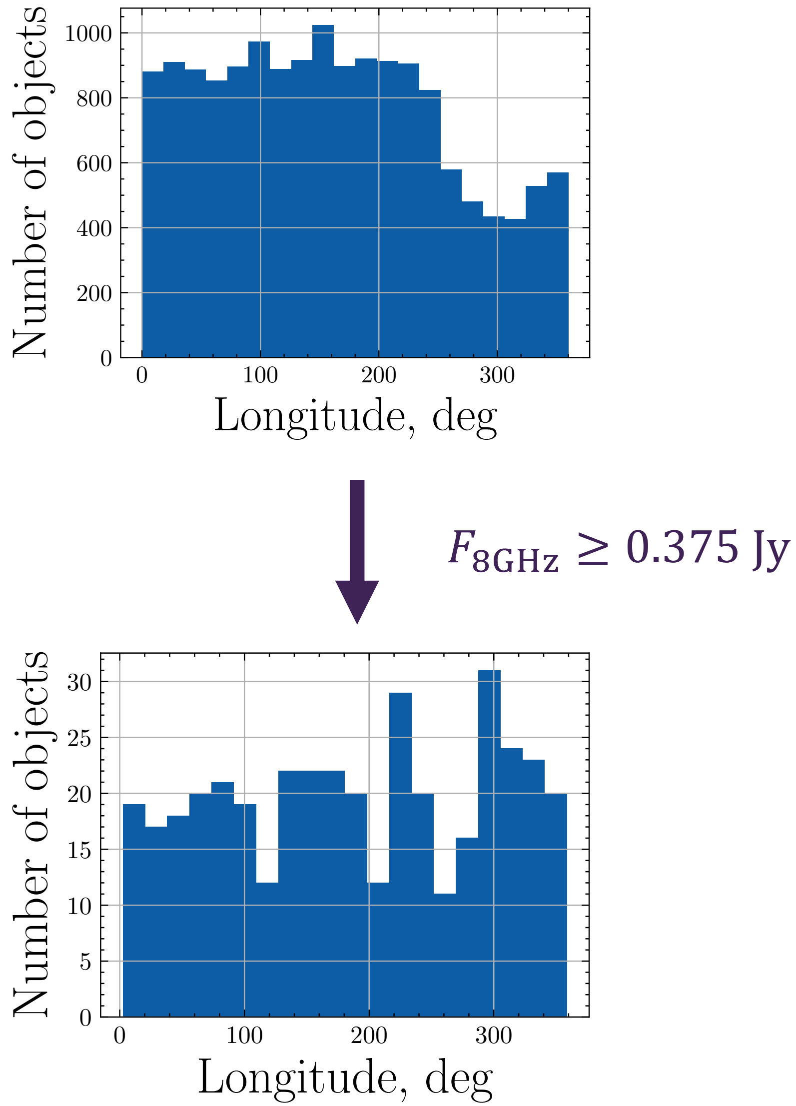
- ➢ Unknown catalogue selection function.
- ✓ A flux cut at 8 GHz allows to select a subsample of objects uniformly distributed in longitude.

Subsample selection

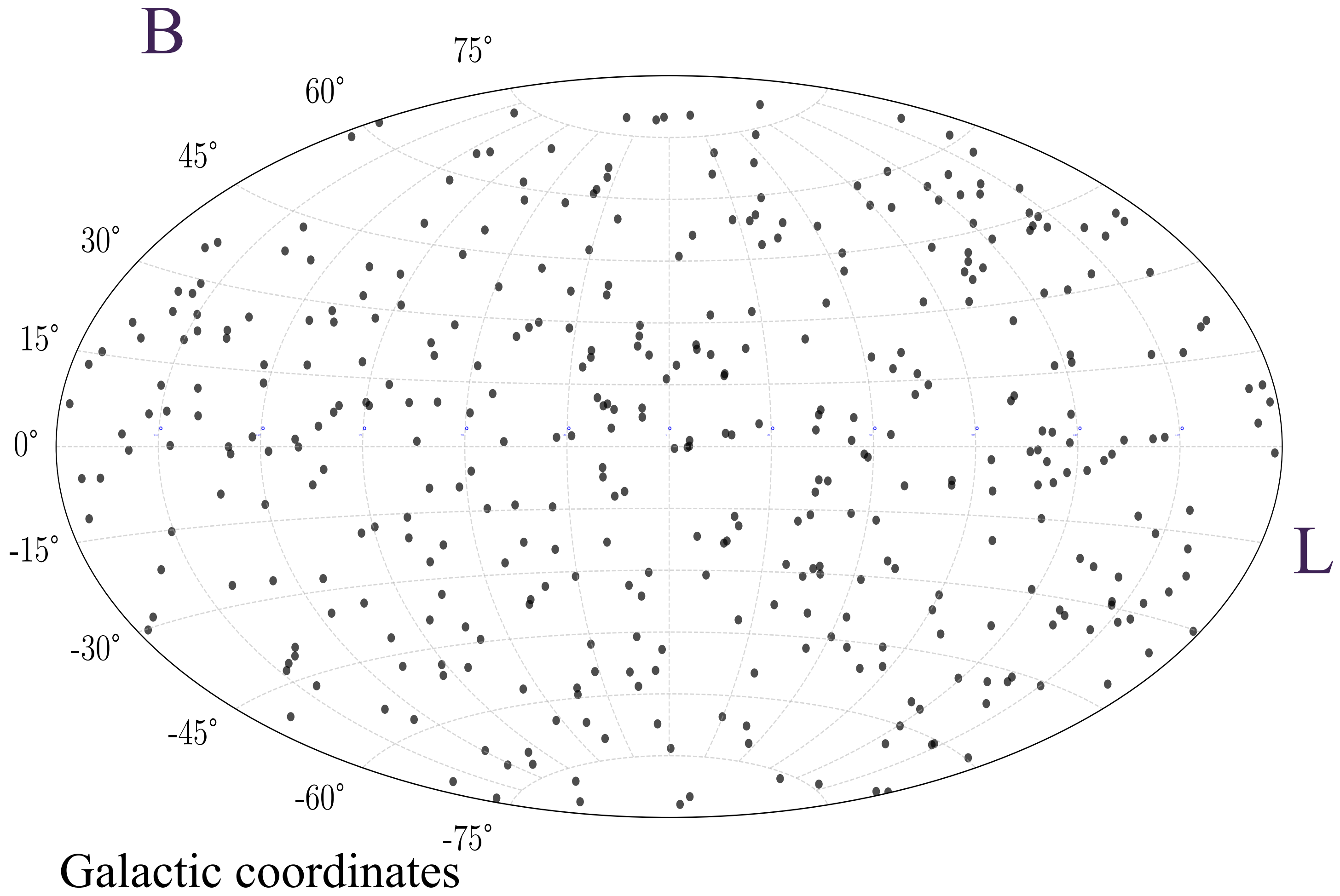
<u>Criterion 1.</u> Uniformity of global longitude distribution.

<u>Criterion 2.</u> Uniformity of longitude distribution within local latitude bands on different angular scales.

<u>Criterion 3.</u> Reproducibility of the angular structure of the real sample by fixing latitudes and uniformly randomizing longitudes.



Resulting subsample



Subsample of radio-loud AGNs with $F_{8\mathrm{GHz}} \geq 0.375$ Jy.

398 objects.

This sample is consistent with uniform longitudinal distribution according to three criteria above.

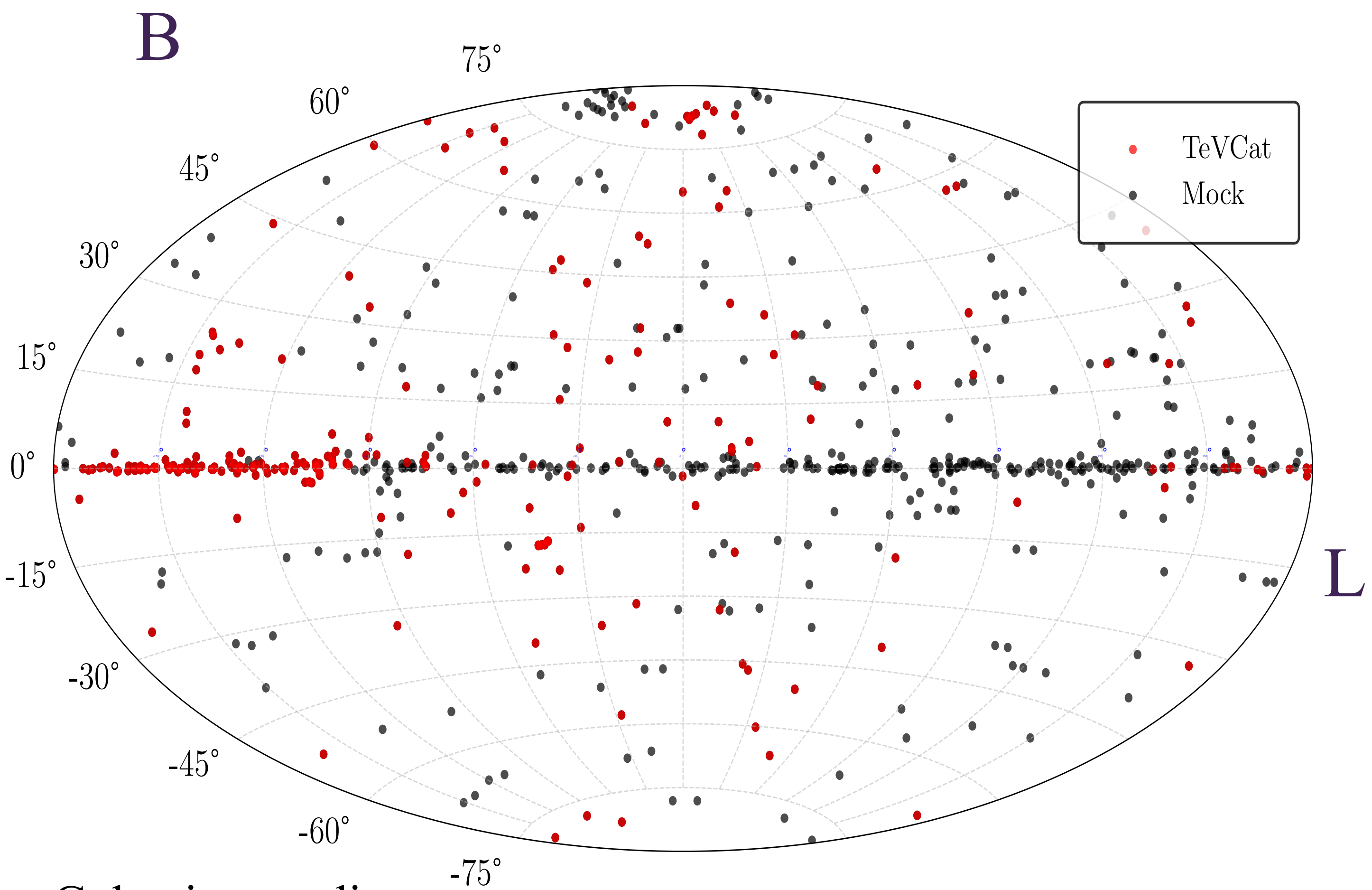
Intuition

Simulated samples are too different from real data due to some deviation from longitudinal uniformity.

Minimal p-value is unrealistically low in the absence of sources (false positive)

Additional validation on pre-defined samples is needed.

Signal sample

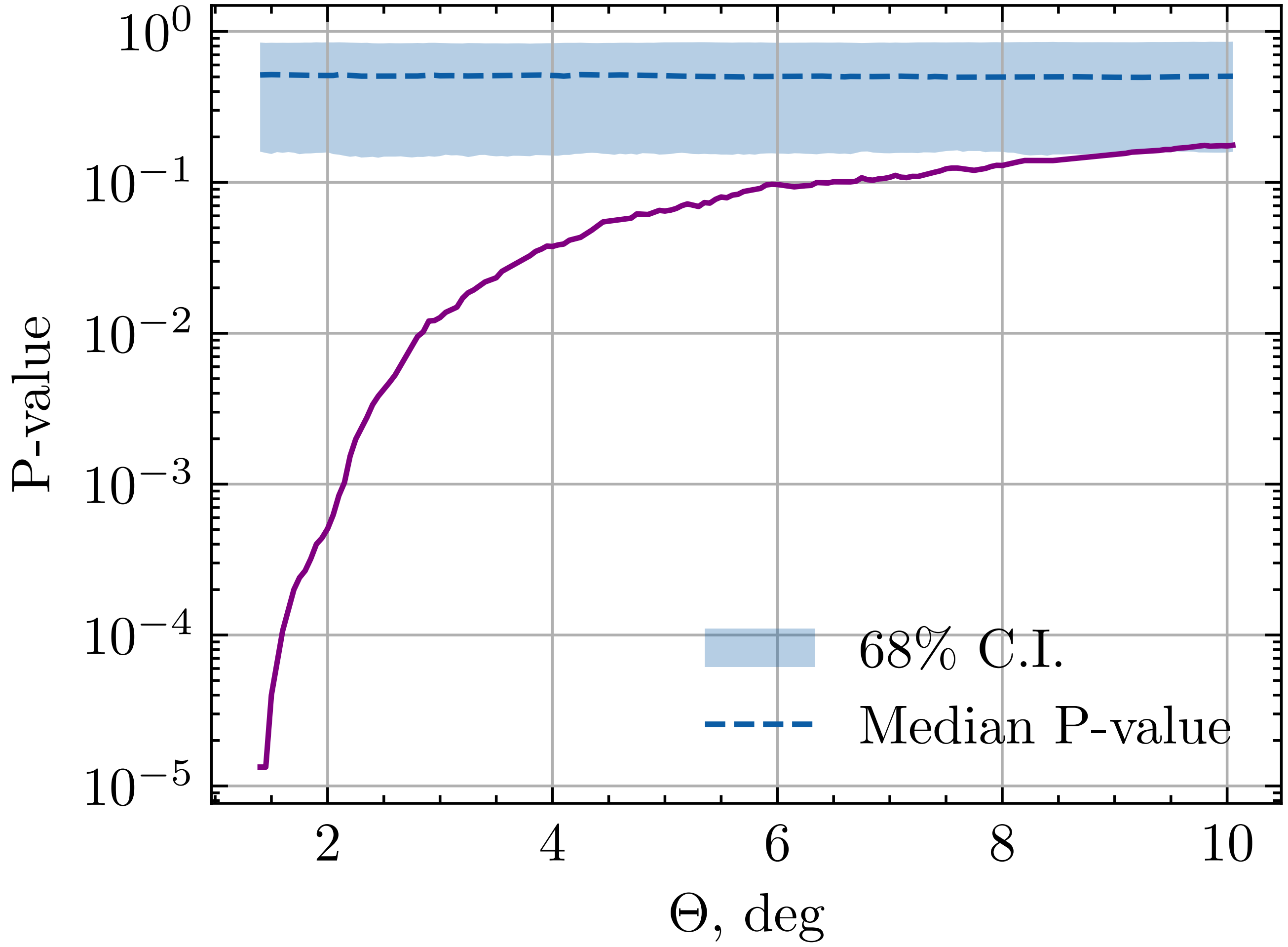


Galactic coordinates

As a signal sample objects from catalogue of TeV sources were used (TeVCat).

To fulfill longitudinal uniformity criteria mock objects were added with the use of kernel density estimation.
229 objects from TeVCat.
420 additional mock objects.

Signal sample

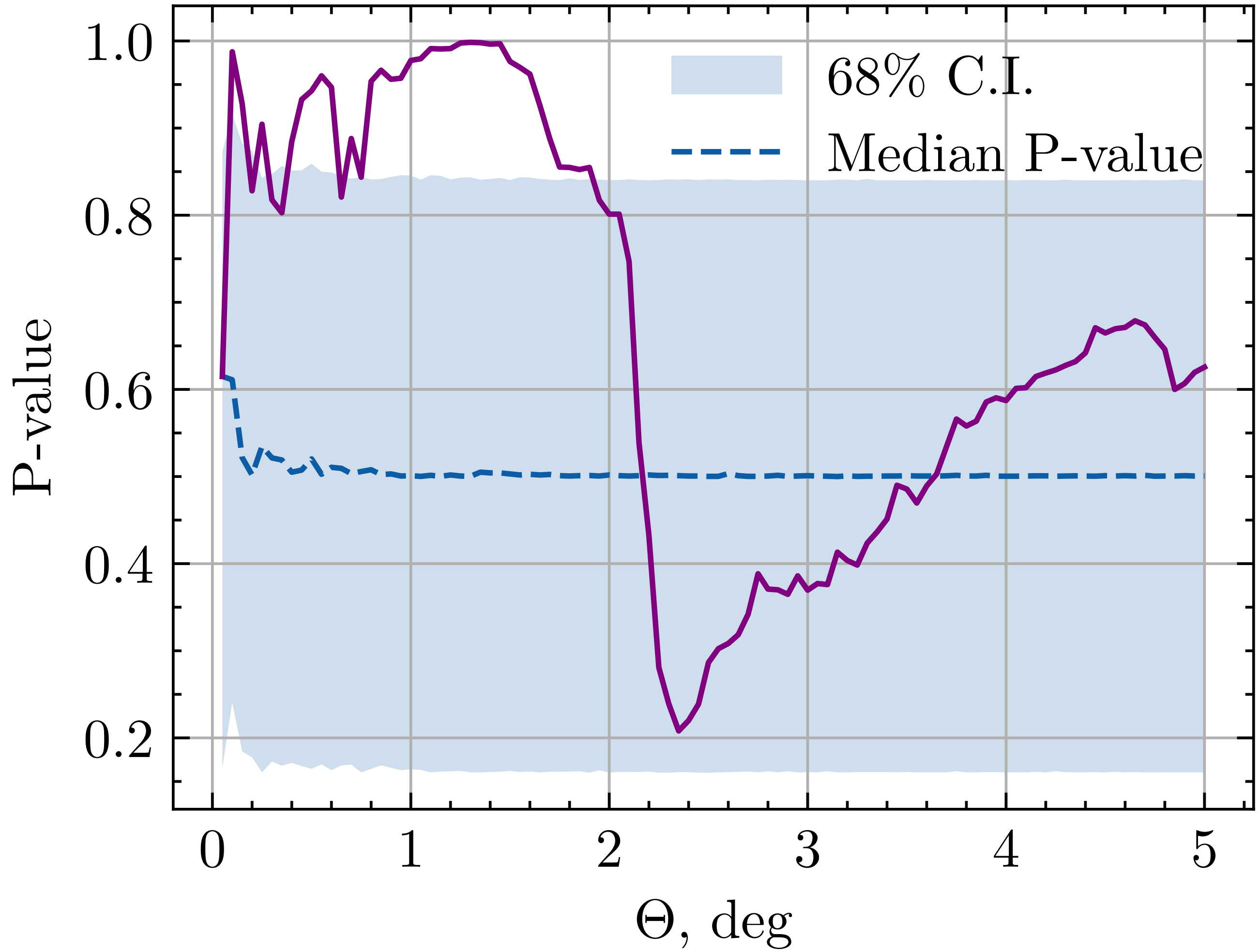


As a signal sample catalogue of TeV sources was used (TeVCat).

Pre-trial p-value $\leq 10^{-5}$.

✓ **As expected, statistically significant correlations are present.**

Mock sample

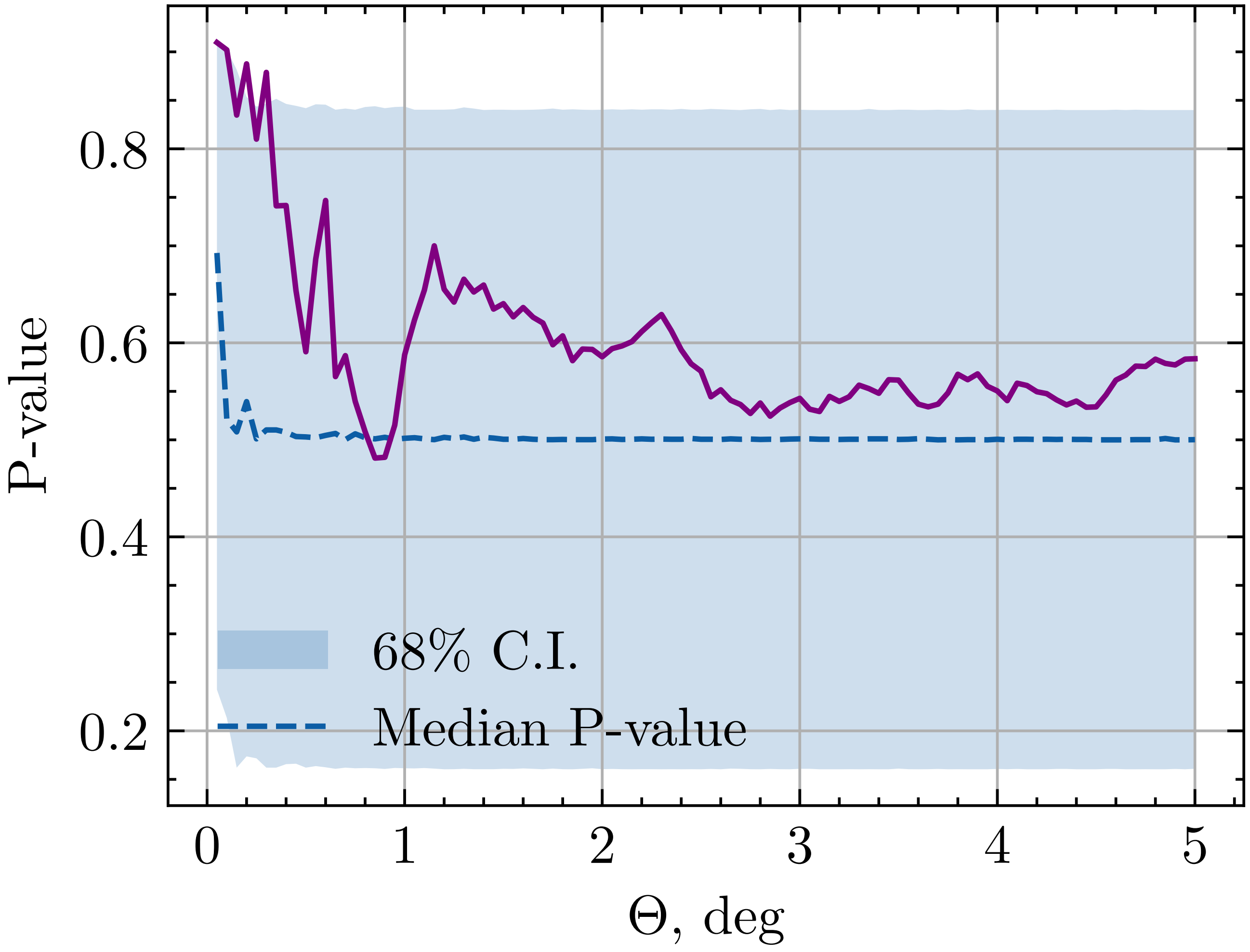


In case of positive result due to deviation from uniformity (as discussed in Intuition) all objects from signal sample were shifted 30° north.
Shift keeps sample structure, but kills physical connection.

Pre-trial p-value = 0.208.

✓**No signs of correlations here.**

Results

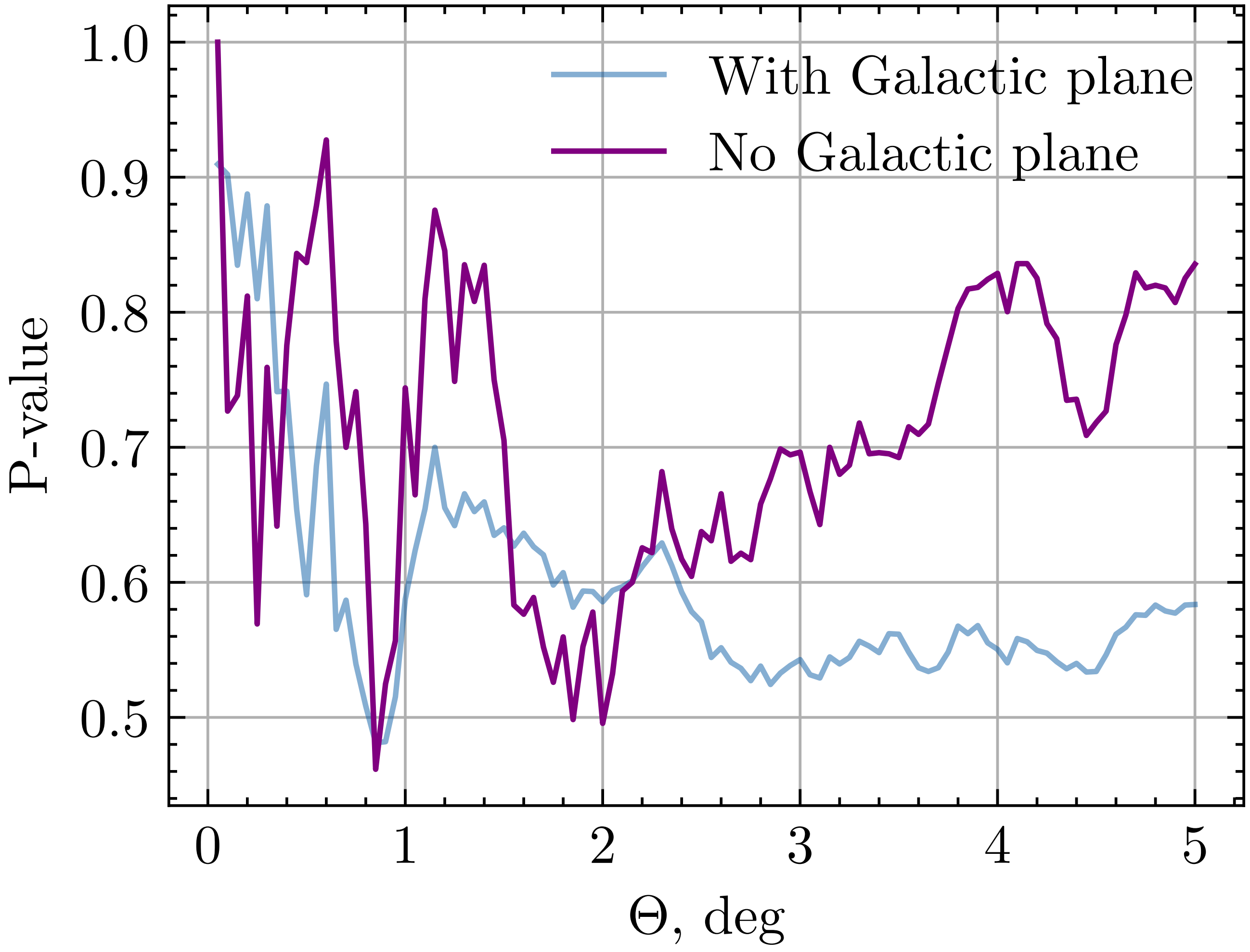


Sample of 398 radio-loud AGNs.

Pre-trial p-value = 0.426.

- **No signs of statistically significant correlations here.**

Results



Sample of 398 radio-loud AGNs.

- **No signs of statistically significant correlations here.**

Conclusion

- Data-driven approach for constructing samples of sources without prior knowledge about catalogue selection function was developed.
- The analysis pipeline was validated with the use of mock samples of objects.
- No statistically significant correlations between selected radio-loud AGNs and Fermi LAT front-converted photons were found.
- A small number of individual off-plane candidates could be identified for follow-up studies.

Thank you for your attention!

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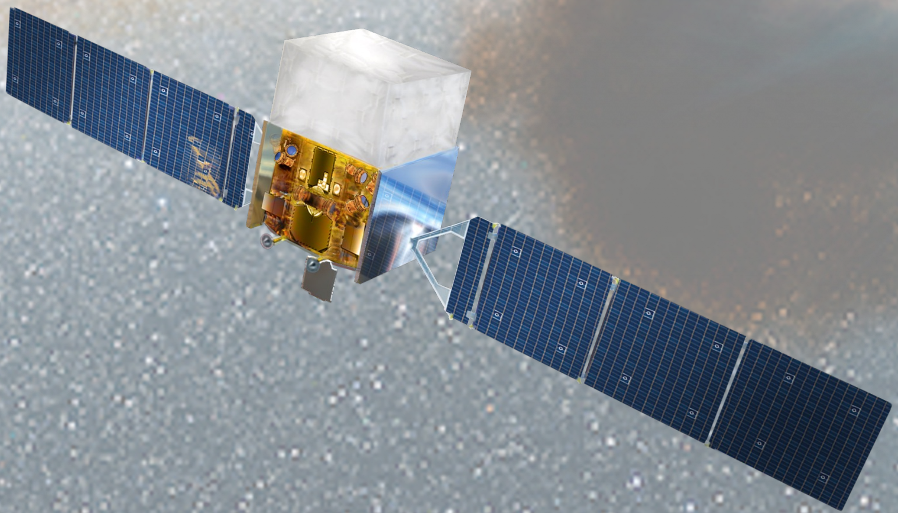
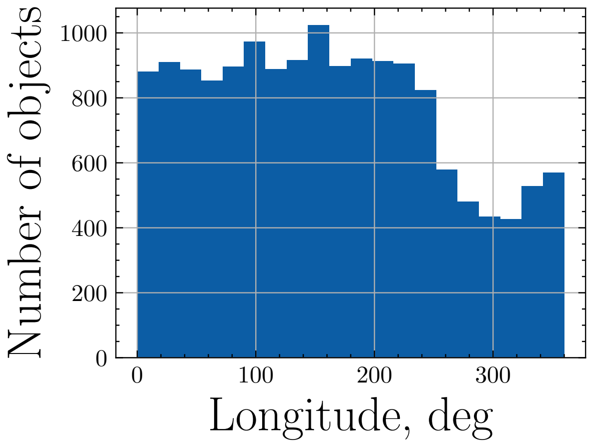


Selection of objects

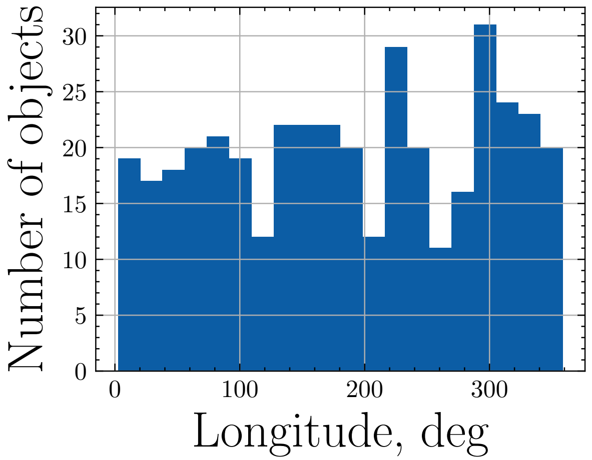
Criterion 1. Global longitude distribution of the selected subsample should be consistent with a uniform distribution.

Criterion 2. Longitude distribution of the selected subsample should be consistent with a uniform distribution within local latitude bands and on different angular scales.

Criterion 3. The angular structure of the real sample should be reproducible by mock samples with fixed latitudes and uniformly randomized longitudes.



$F_{8\mathrm{GHz}} \geq 0.375$ Jy



Kernel density estimation

Kernel density estimation (KDE) – is a non-parametric method to estimate the probability density function of a random variable.

Probability density function is defined as follows:

$$f_h(\mathbf{x}) = \frac{1}{n}\sum_{i=1}^{n} K_h(\mathbf{x}, \mathbf{x}_i),$$

where n – total number of objects, $\mathbf{x}_i$ - coordinate of an objects,

h - bandwidth,

$$K_h(\mathbf{x}, \mathbf{x}_i) = \frac{\exp(2\cos(\mathbf{x}\cdot\mathbf{x}_i)/h^2)}{2\pi h^2 \sinh 2/h^2}$$