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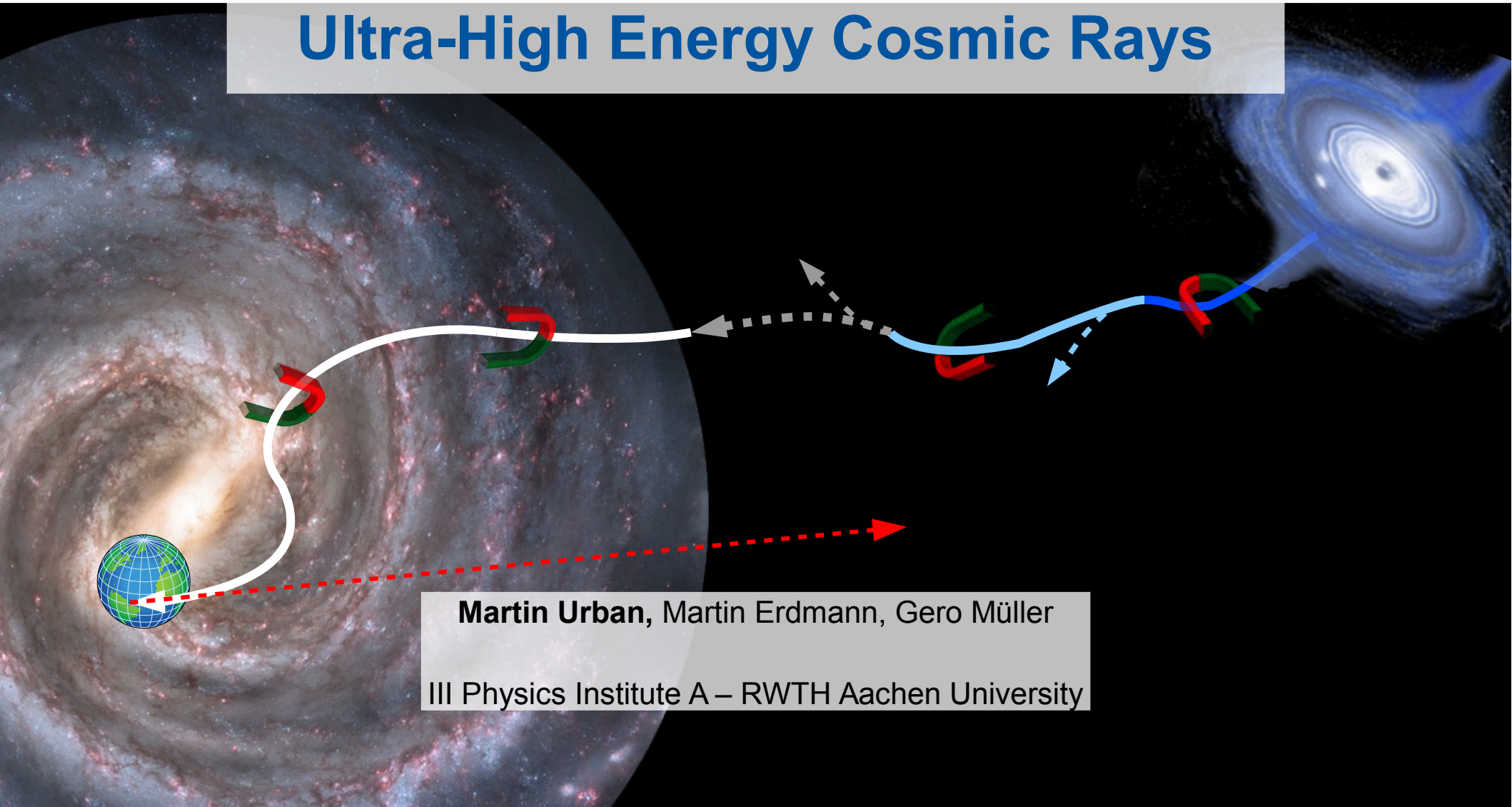
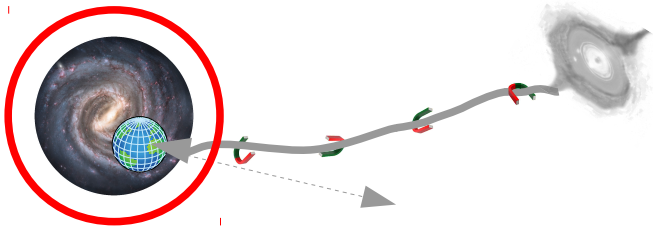
Method for the Investigation of the Galactic Magnetic Field using Ultra-High Energy Cosmic Rays



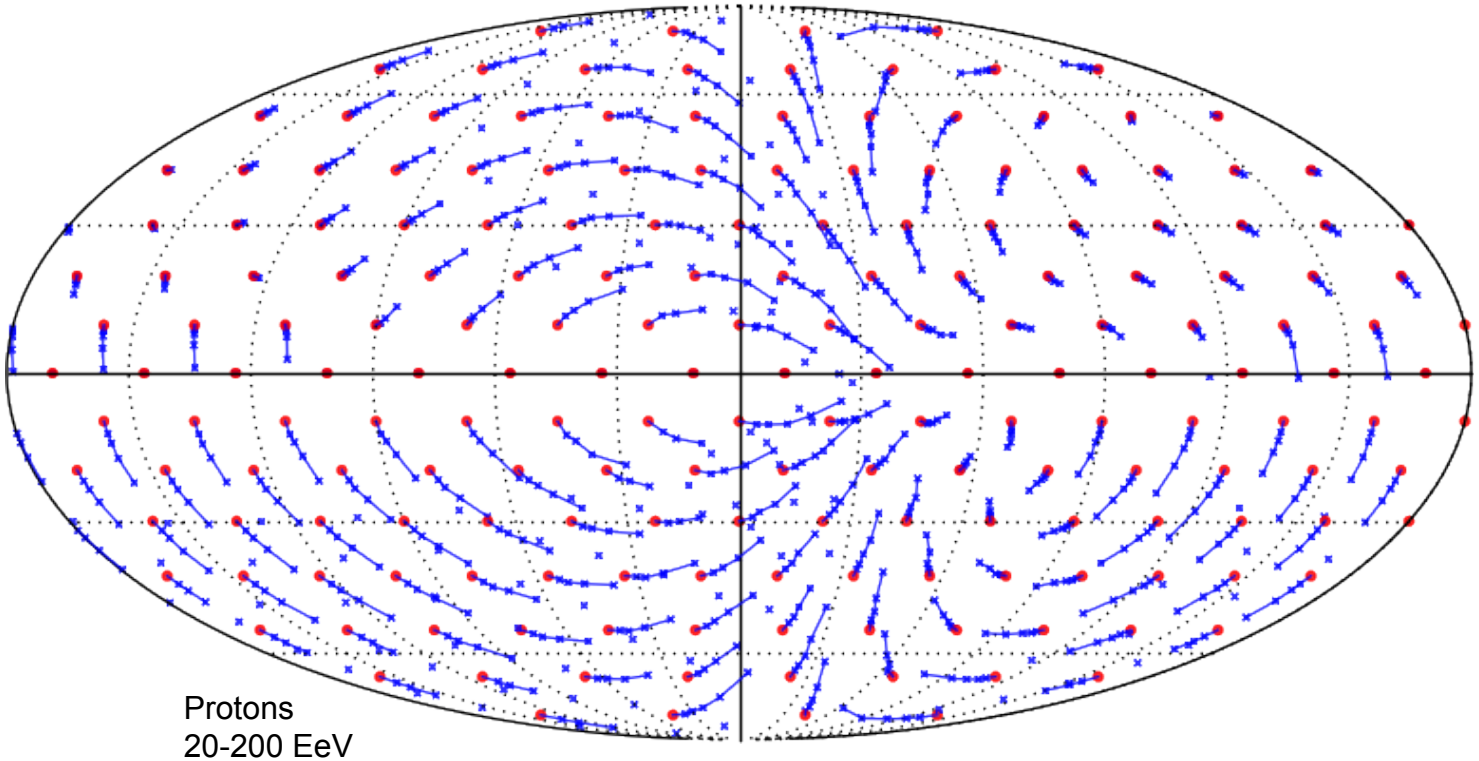
Martin Urban, Martin Erdmann, Gero Müller

III Physics Institute A – RWTH Aachen University

Galactic Magnetic Field

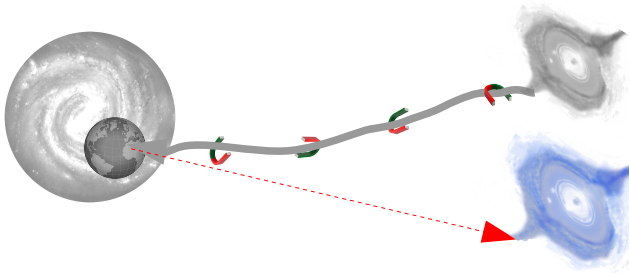


- Recent galactic magnetic field parameterizations predict deflection
  - → Direction and magnitude
  - → Here Janson and Farrar model: JF12

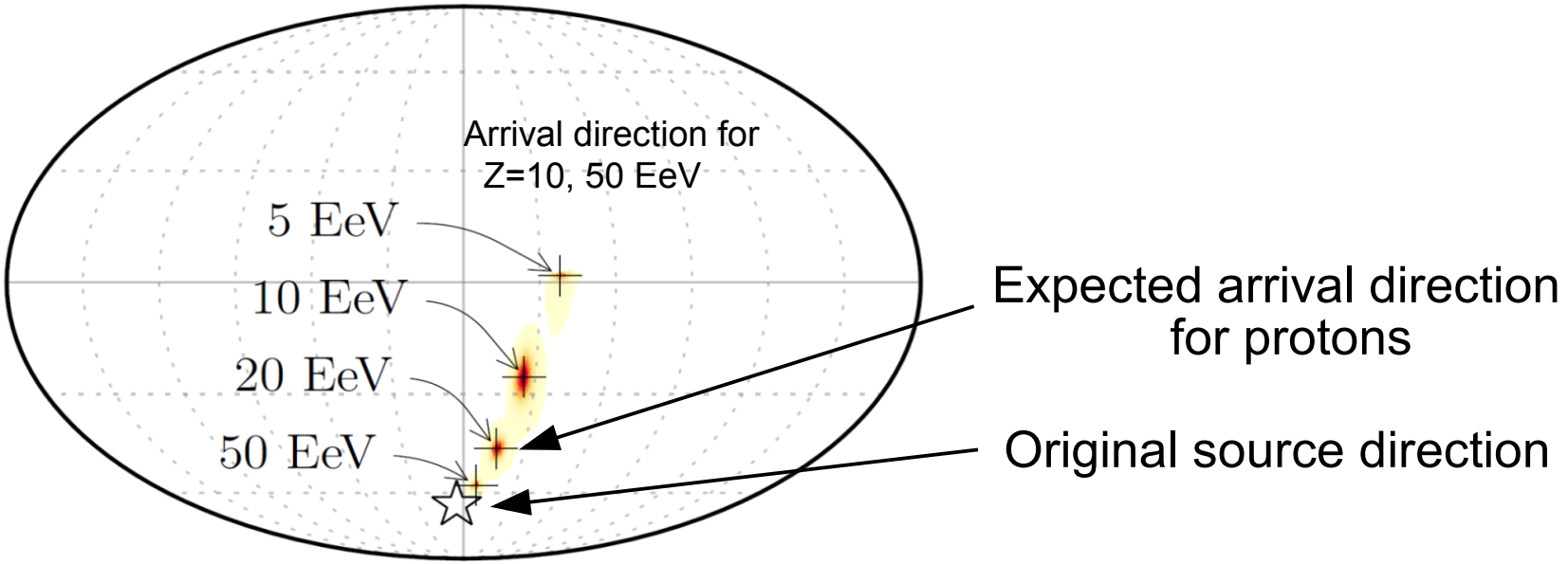


Protons
20-200 EeV
Galactic Coordinates
Jansson, Farrar, 2012, ApJ, 757, 14; 2012, ApJ, 761, L11

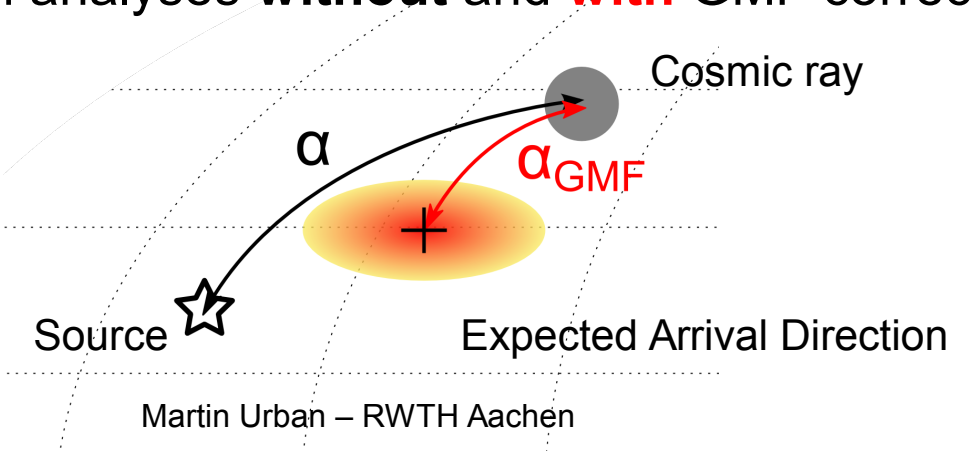
Expected Arrival Direction



- Only calculated for protons
- Implemented as magnetic field lens
  - → Rigidity dependent transformation matrix



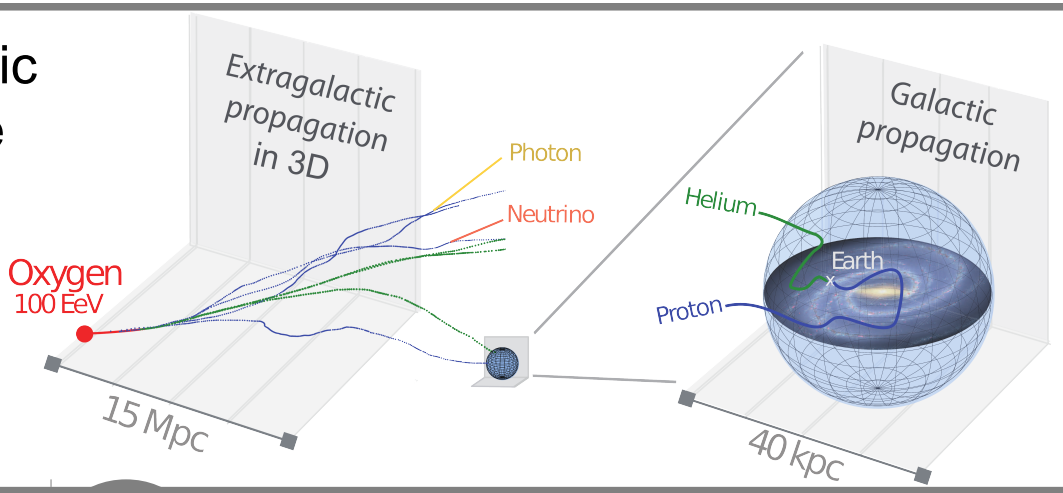
- Compare correlation analyses **without** and **with** GMF correction



Astrophysical Simulation

Signal

- Propagate 10^7 high energetic nuclei from sources to edge of Galaxy (CRPropa 3)
- Send cosmic rays to Earth using lensing technique with JF12 regular field lens



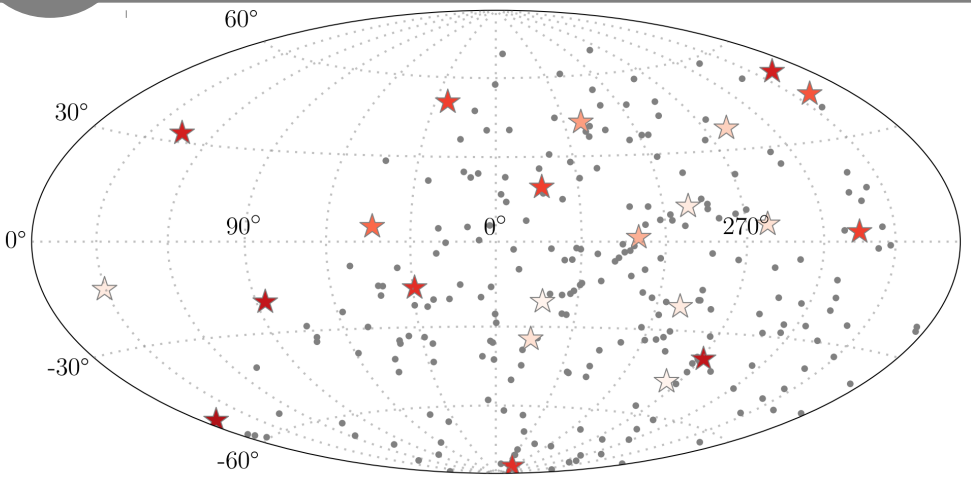
Background

- Isotropy using geometric exposure of Pierre Auger experiment

MC Data

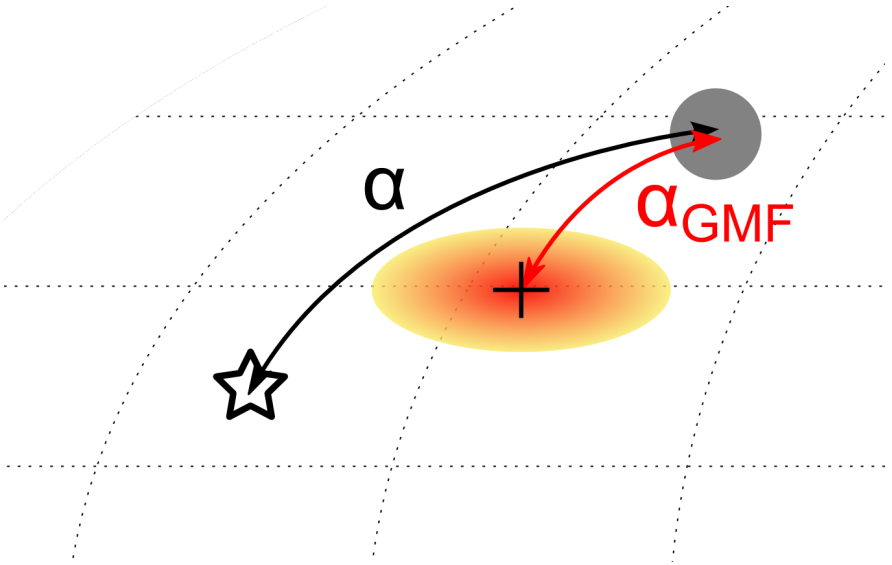
- **10 % signal + 90 % isotropy**
- 231 events with E ≥ 52 EeV

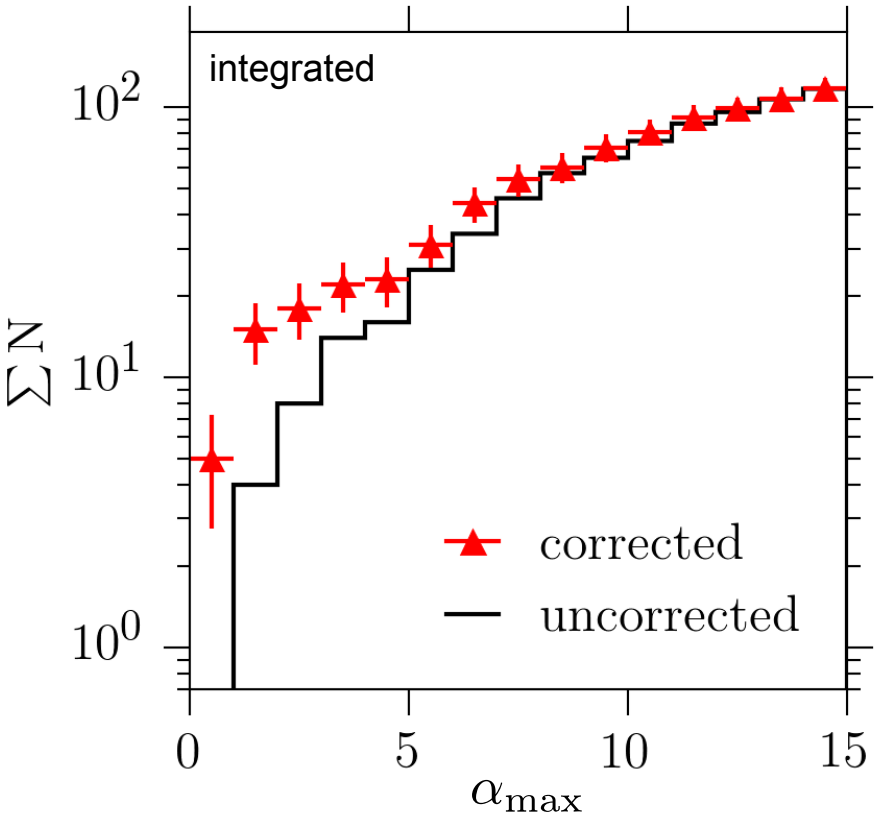
  Like published dataset by Auger collaboration
- 22 sources



Angular distance

- Angular distances between cosmic ray and closest
  - → Source (uncorrected)
  - → Energy dependent expected arrival direction (corrected)



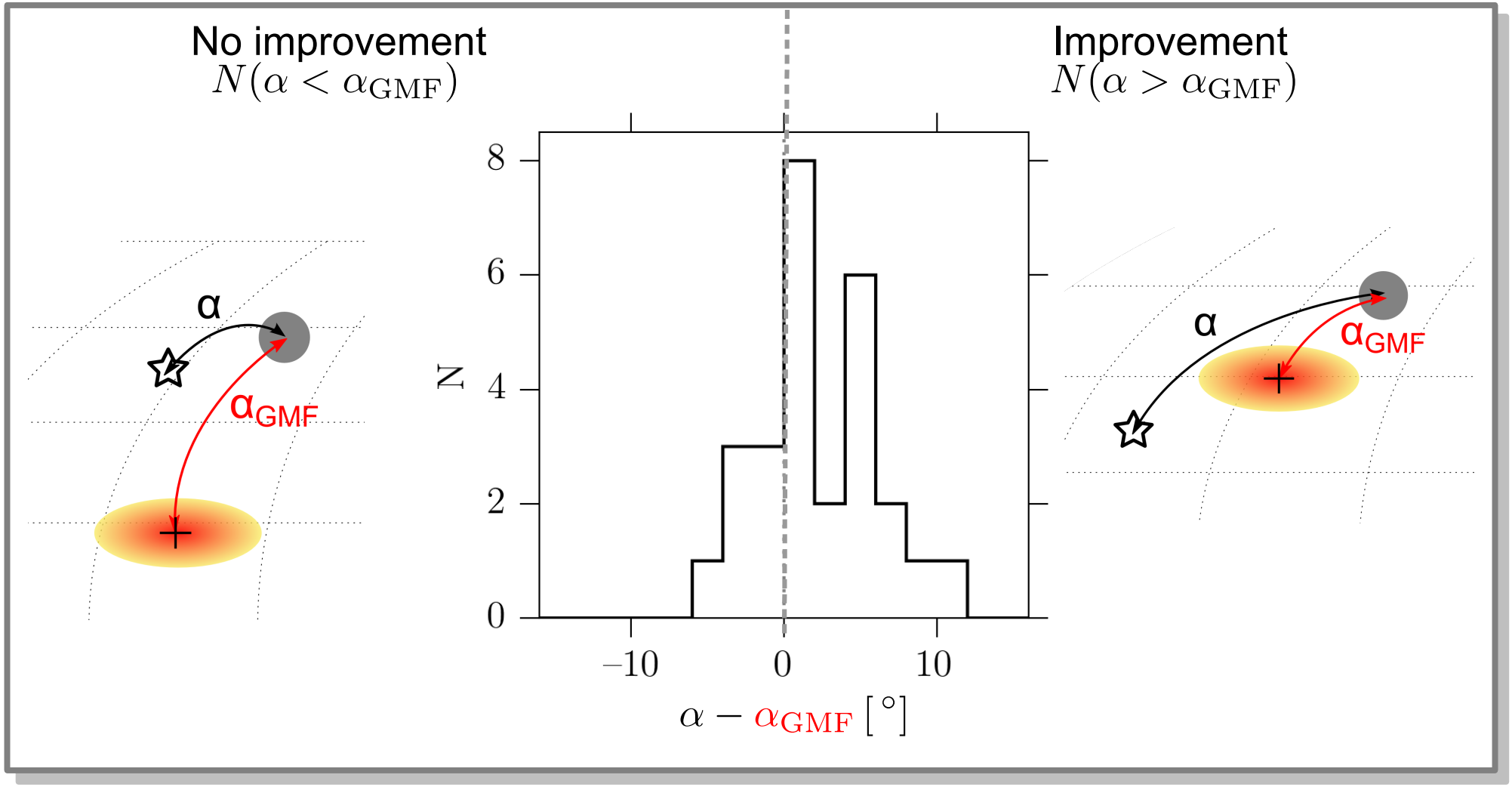


- Protons at small angles
- Preselection:
  - → e.g. α, $\alpha_{GMF} < \alpha_{max} = 5°$

Magnetic Field Observable: Angular Asymmetry

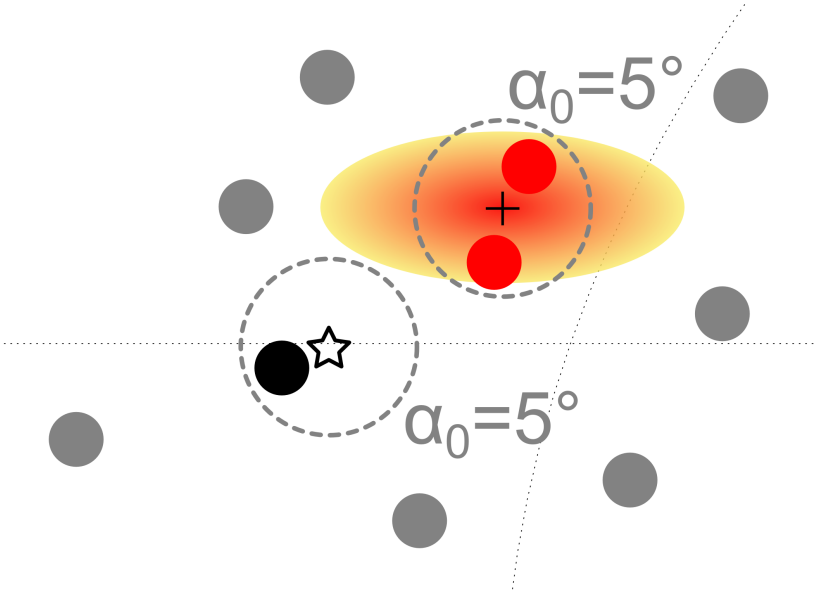
- Change in angular distance: $A \equiv 2\dfrac{N(\alpha > \alpha_{\mathrm{GMF}}) - N(\alpha < \alpha_{\mathrm{GMF}})}{N_{\mathrm{tot}}}$

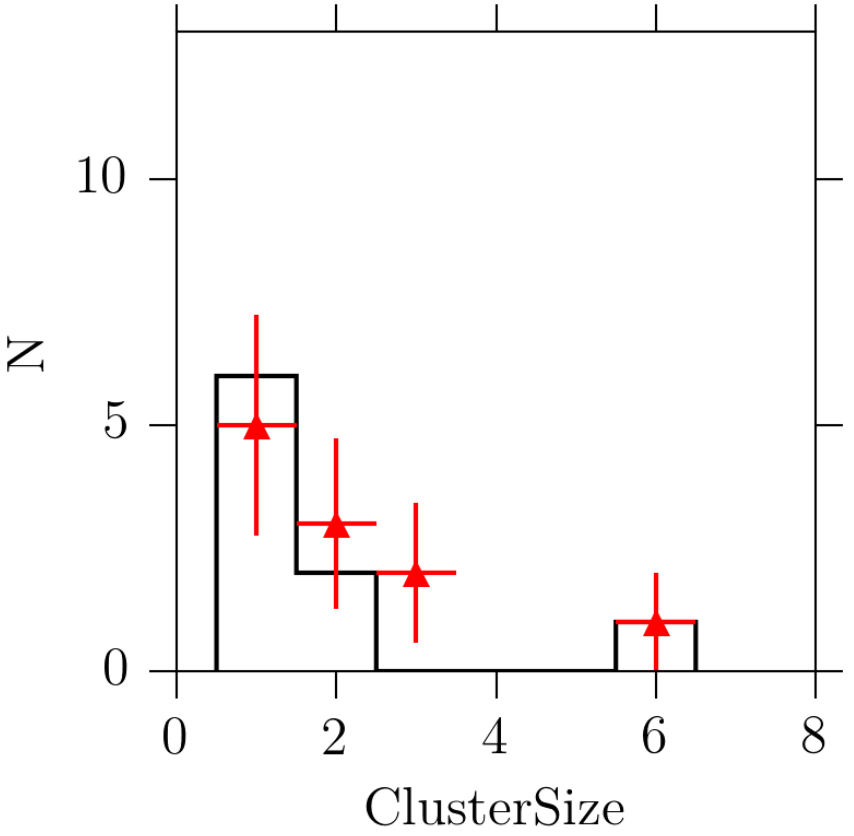
$$= 0.96$$



Magnetic Field Observable: Clustering

- Number of correlating events
  - → per source
  - → Expected arrival direction



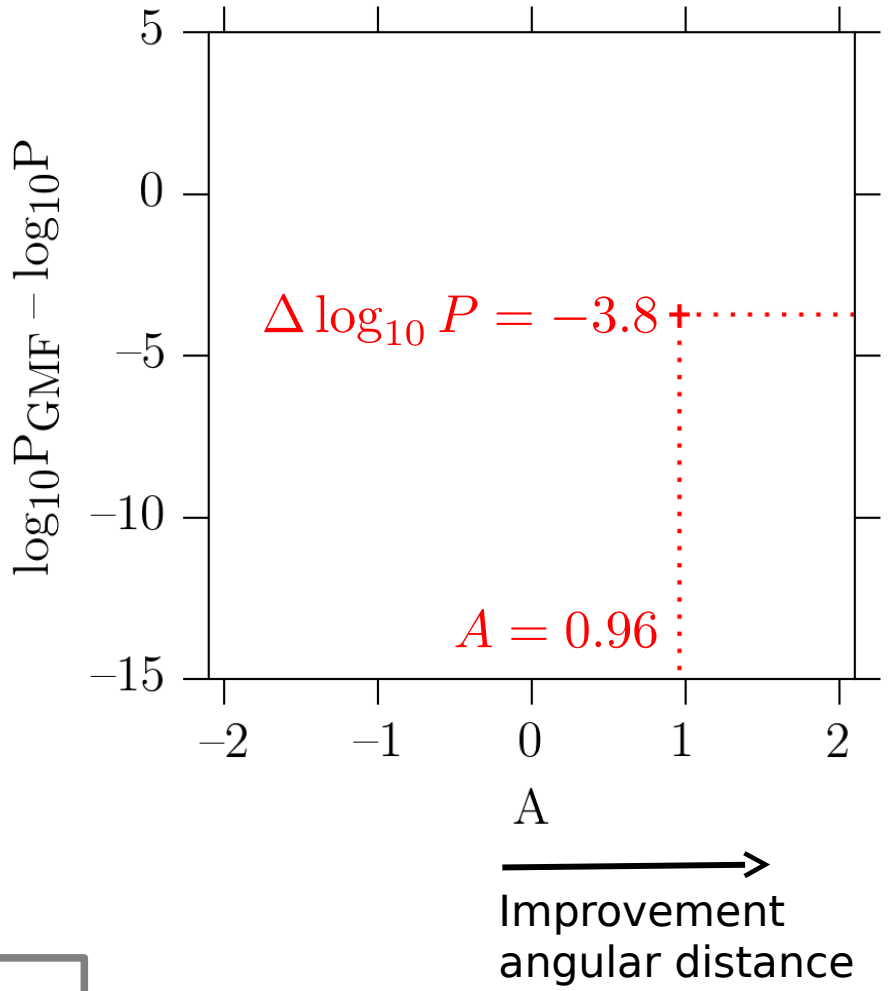


- Cluster distribution probability
  - → P = multinomial distribution
- Observable: $\Delta \log_{10}P = \log_{10}(P_{GMF}) - \log_{10}(P) = -3.8$

Combine observables

- Astrophysical simulations
  - → 231 cosmic rays
  - → JF12 regular field

+ Expected arrival directions:
  - → AGN sources
  - → JF12 regular field



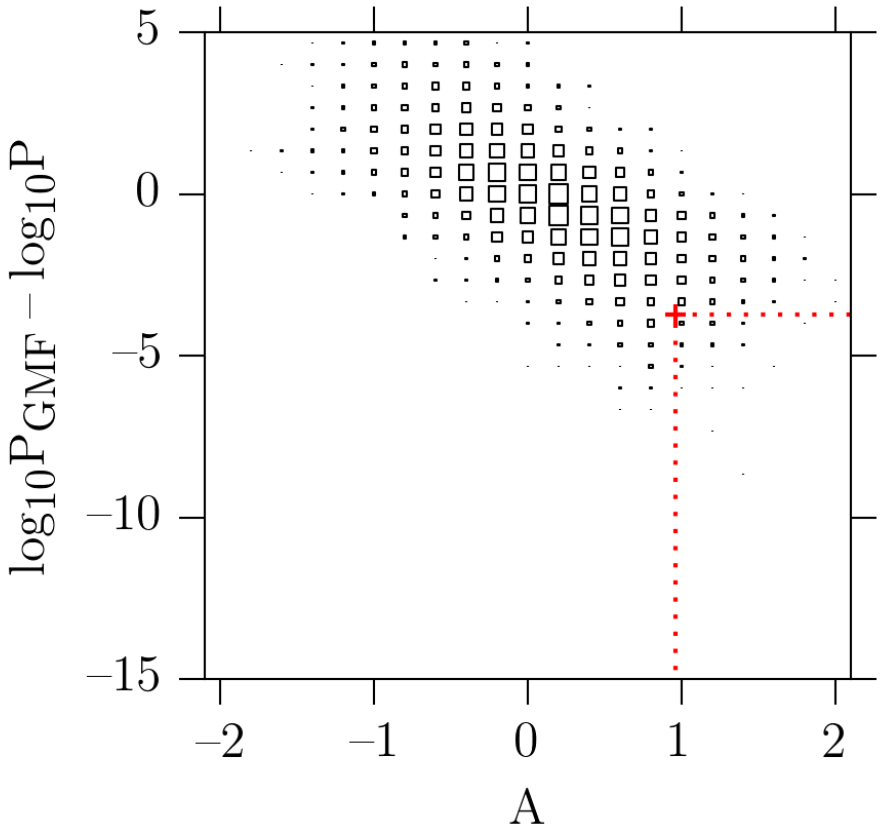
⇨ Investigate different hypotheses

Random Sources

- Astrophysical simulations
  - → 231 cosmic rays
  - → JF12 regular field

- \+ Expected arrival directions:
  - → AGN sources
  - → JF12 regular field

- ☐ **Random source directions**
  - → 10000 variations
  - → 0.47 % show improvement in both observables



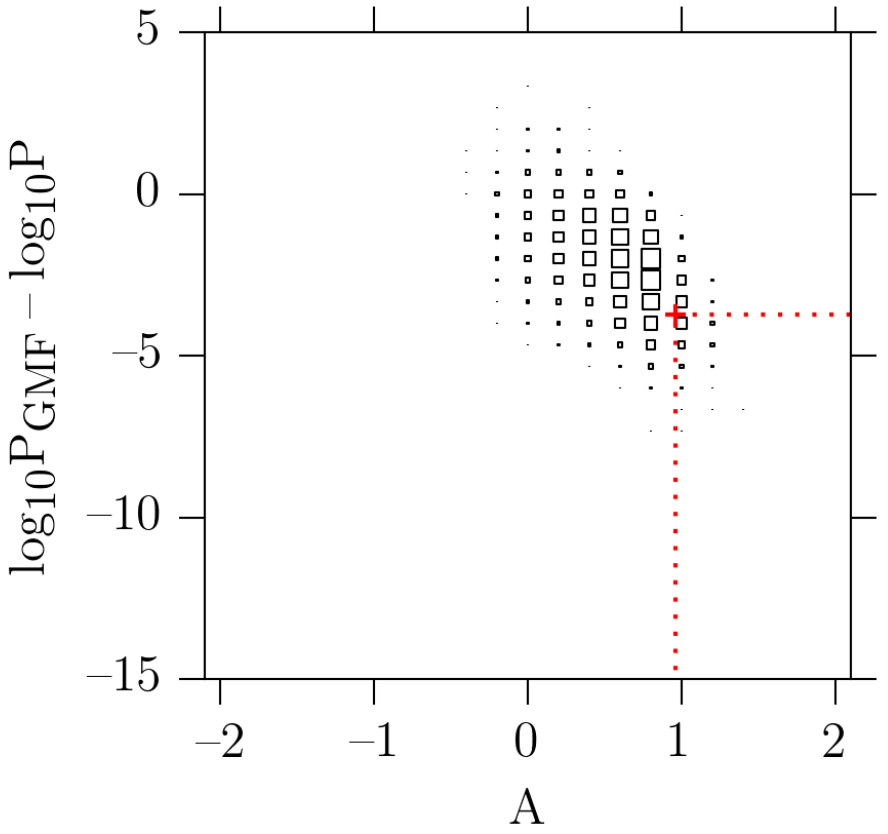
Source directions important

Uncertainty in Source Direction

- Astrophysical simulations
  - → 231 cosmic rays
  - → JF12 regular field

+ Expected arrival directions:
  - → AGN sources
  - → JF12 regular field

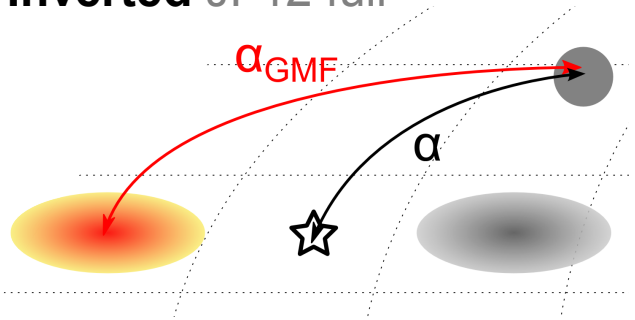
☐ **AGN with 15° directional uncertainty**
  - → 10000 variations



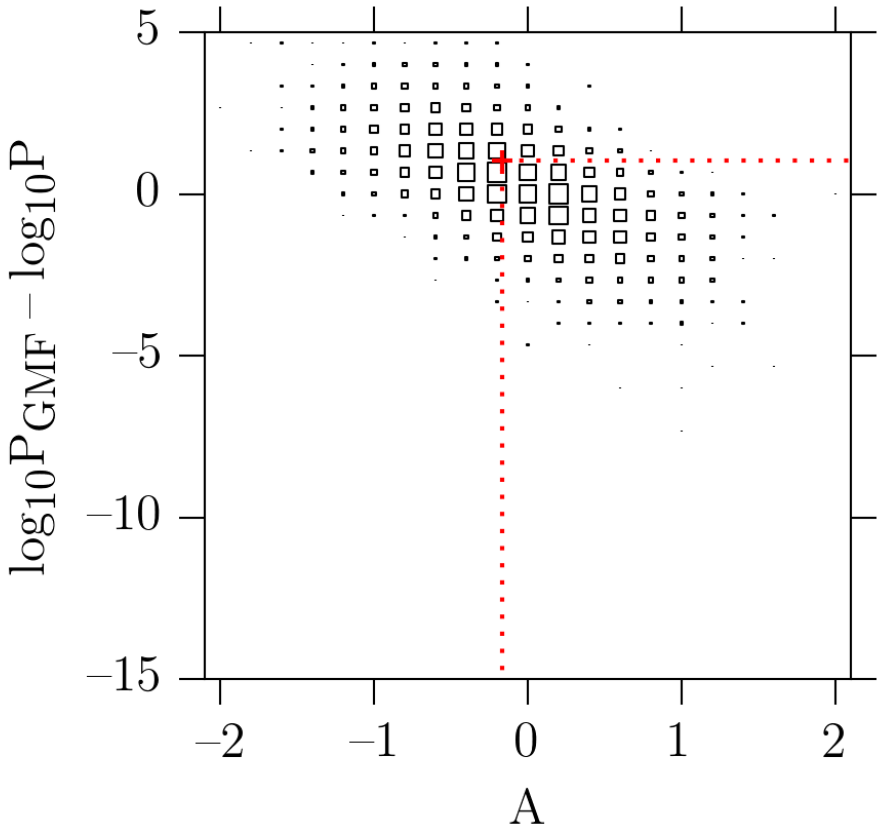
Large uncertainties reduce sensitivity

Directional characteristics of galactic magnetic field

- Astrophysical simulations
  - → 231 cosmic rays
  - → JF12 regular field
- \+ Expected arrival directions:
  - → AGN sources
  - → **Inverted** JF12 full



- ☐ **Isotropic cosmic ray arrival directions**
  - → 10000 variations

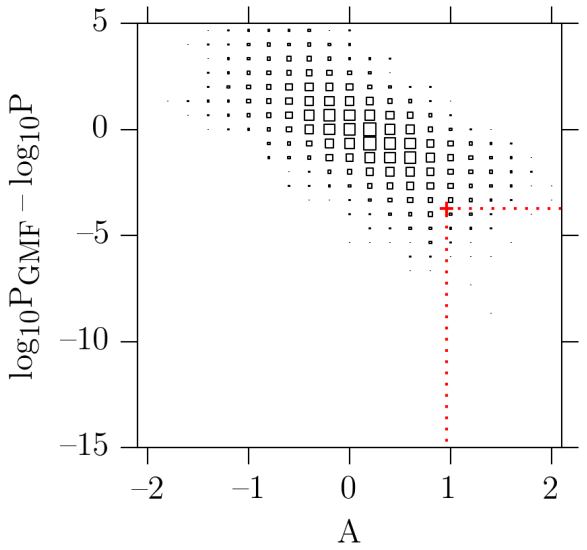


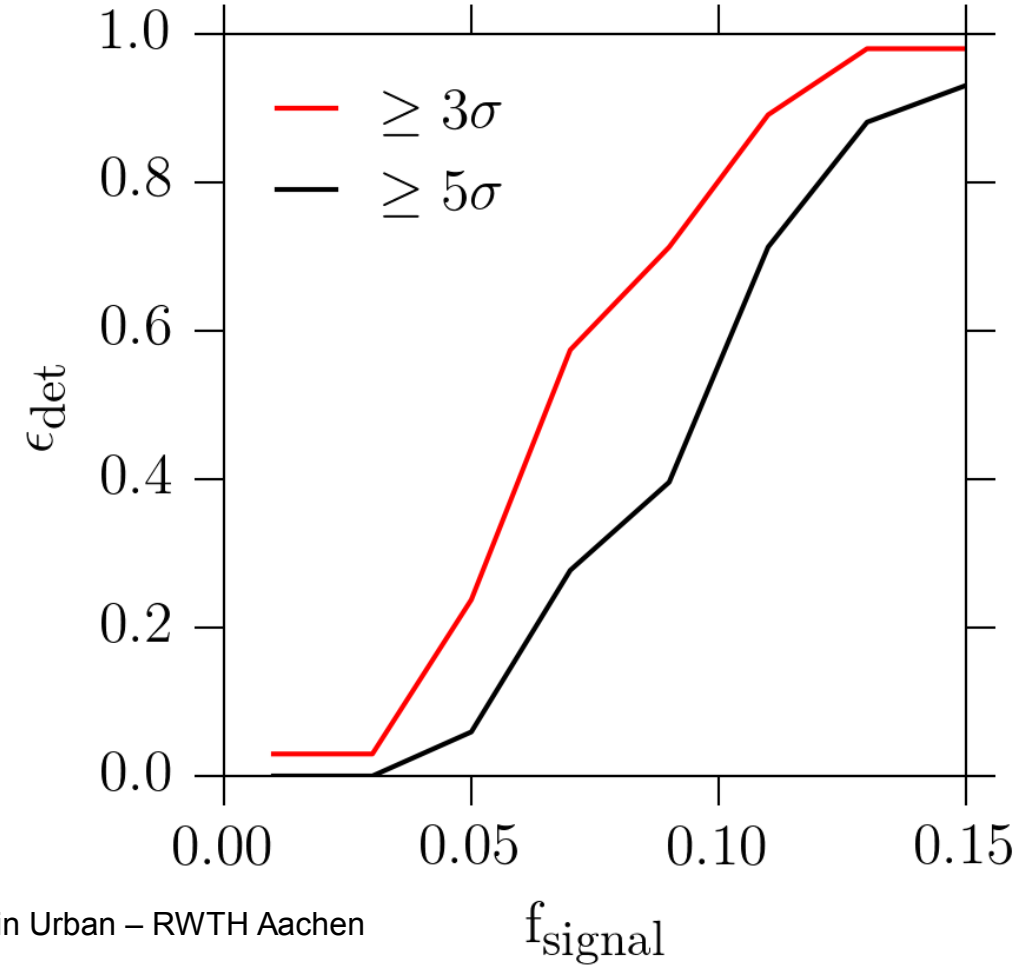
Correct characteristics of magnetic field is essential to detect signal

Sensitivity to detect signal in isotropic background

- Scan of signal fraction
- 100 different signal realizations for each signal fraction f_{signal}

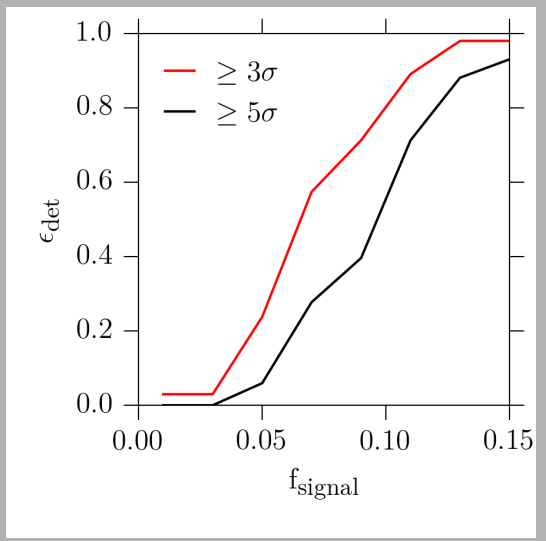
  → Detection efficiency ε_{det}: Number of simulations with ≥ 3 (5) σ difference from isotropy





Summary

- Enhanced correlation method: expected arrival directions
  - → Include deflections in magnetic field
- Observables for magnetic field investigations
  - → Angular asymmetry
  - → Clustering
- Analysis method
  - → is sensitive to galactic magnetic field structure
  - → is sensitive to selected source positions
  - → is sensitive to few percent signal fractions



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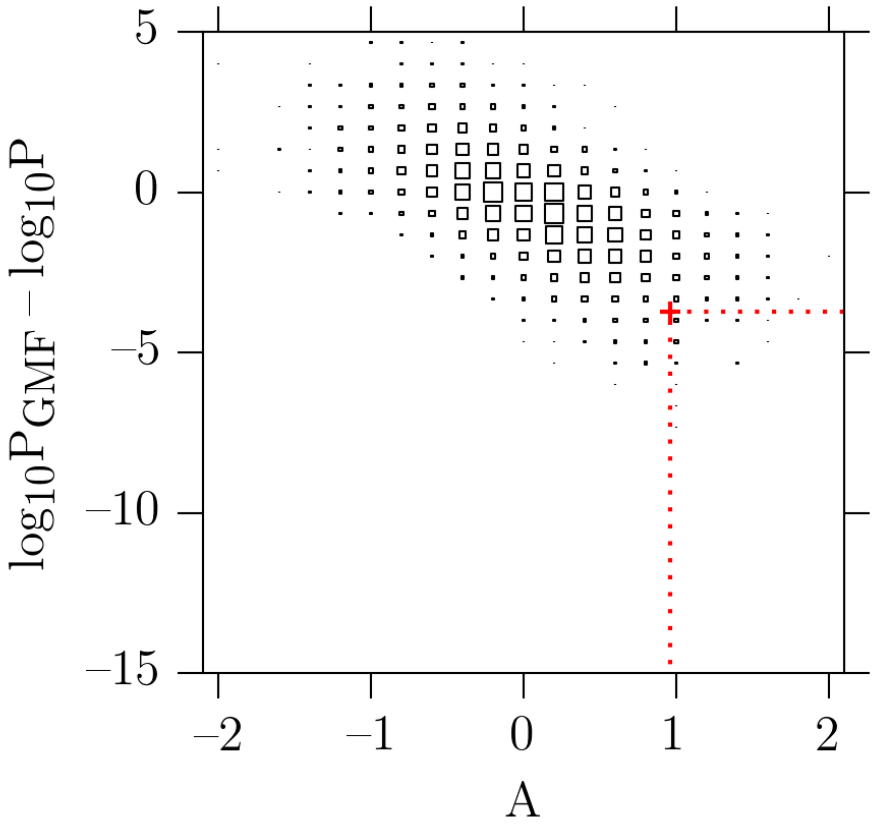
BACKUP

Are the correlated cosmic rays unique?

- Astrophysical simulations
  - → 231 cosmic rays
  - → JF12 regular field
- \+ Expected arrival directions:
  - → AGN sources
  - → JF12 regular field

- ☐ **Isotropic cosmic ray arrival directions**
  - → 10000 variations
  - → 0.29 % show improvement in both variables

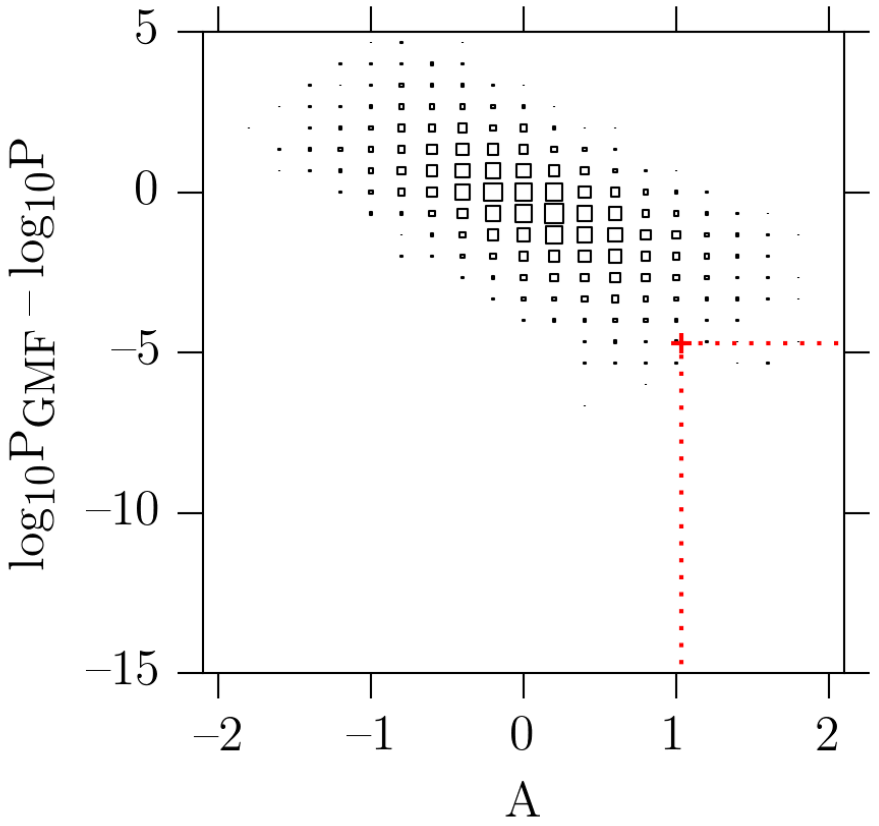


Correlated cosmic rays can be found by the method

Random Component of Galactic Magnetic Field

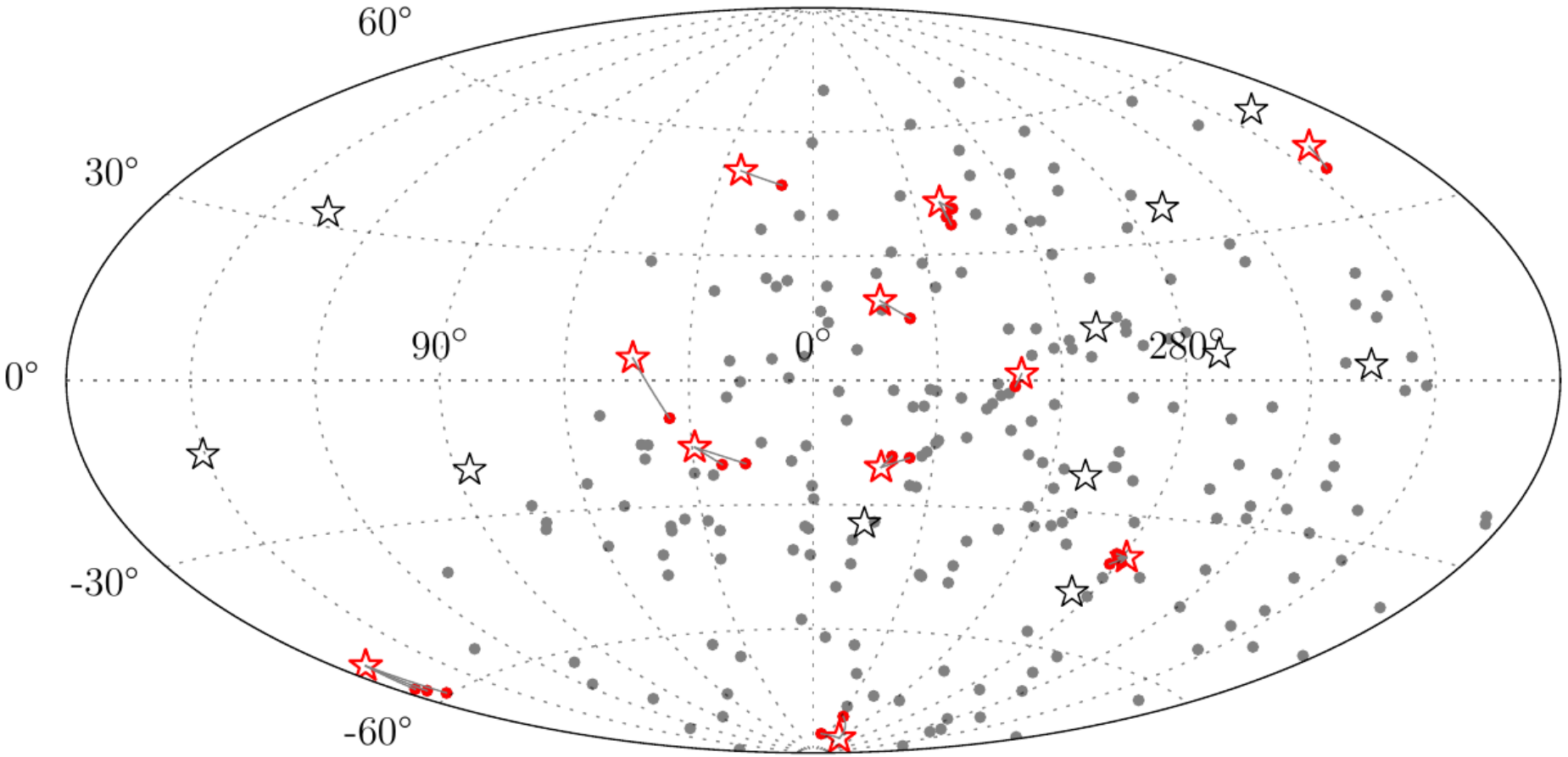
- Astrophysical simulations
  - → 231 cosmic rays
  - → JF12 regular field
- \+ Expected arrival directions:
  - → AGN sources
  - → **JF12 regular + striated + random**

- ☐ **Isotropic cosmic ray arrival directions**
  - → 10000 variations
  - → 0.10 % show improvement in both variables



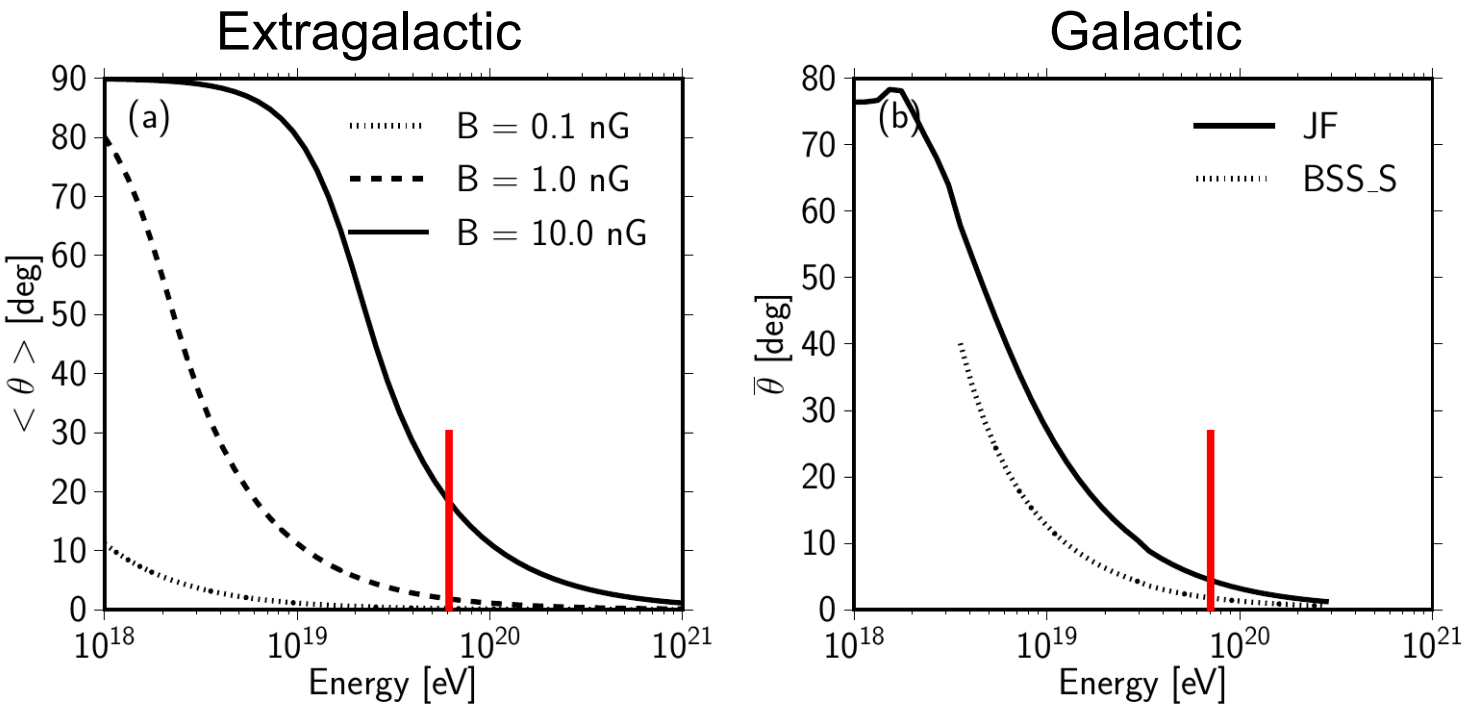
Random component has no effect on analysis

Correlations of cosmic rays with expected arrival direction within 5°



Motivation for 5 ° cut

- Mean deflection for E > 55 EeV
- 10 Mpc distance
- Protons

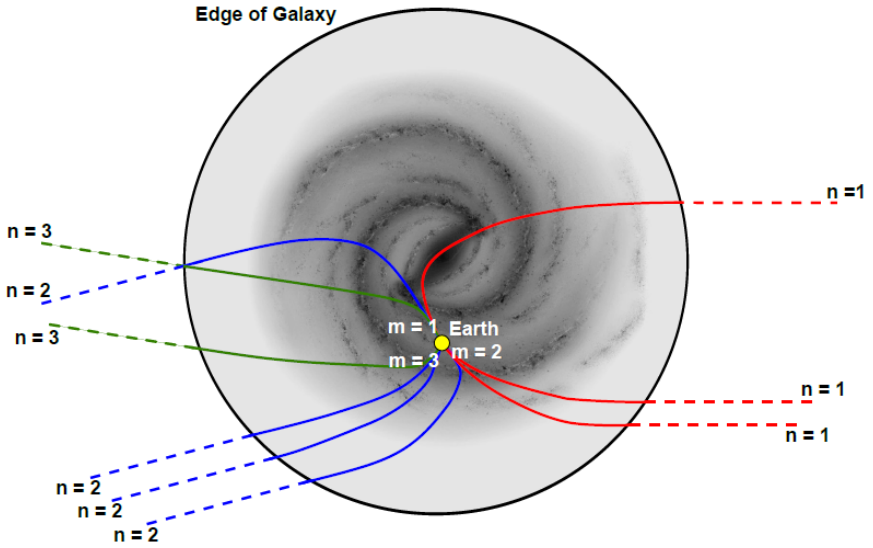


H.-P. Bretz et al., Astropart.Phys. C54 (Feb., 2014) 110–117, 1302.3761.

Galactic Magnetic Lenses

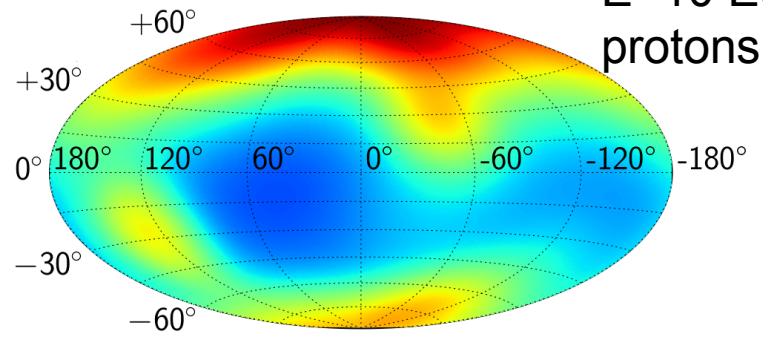
H-P Bretz, M.E., P. Schiffer, D., T. Winchen, AP 54C (2014) 110

Probability of a particle entering galaxy in pixel *n* is observed in direction *m*



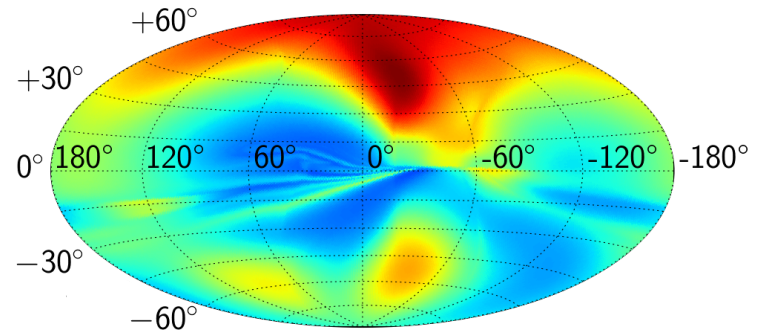
Simulated probability distribution of extragalactic arrival

E=10 EeV protons



Probability distribution projected onto the Earth

Galactic field: Jansson, Farrar 2012



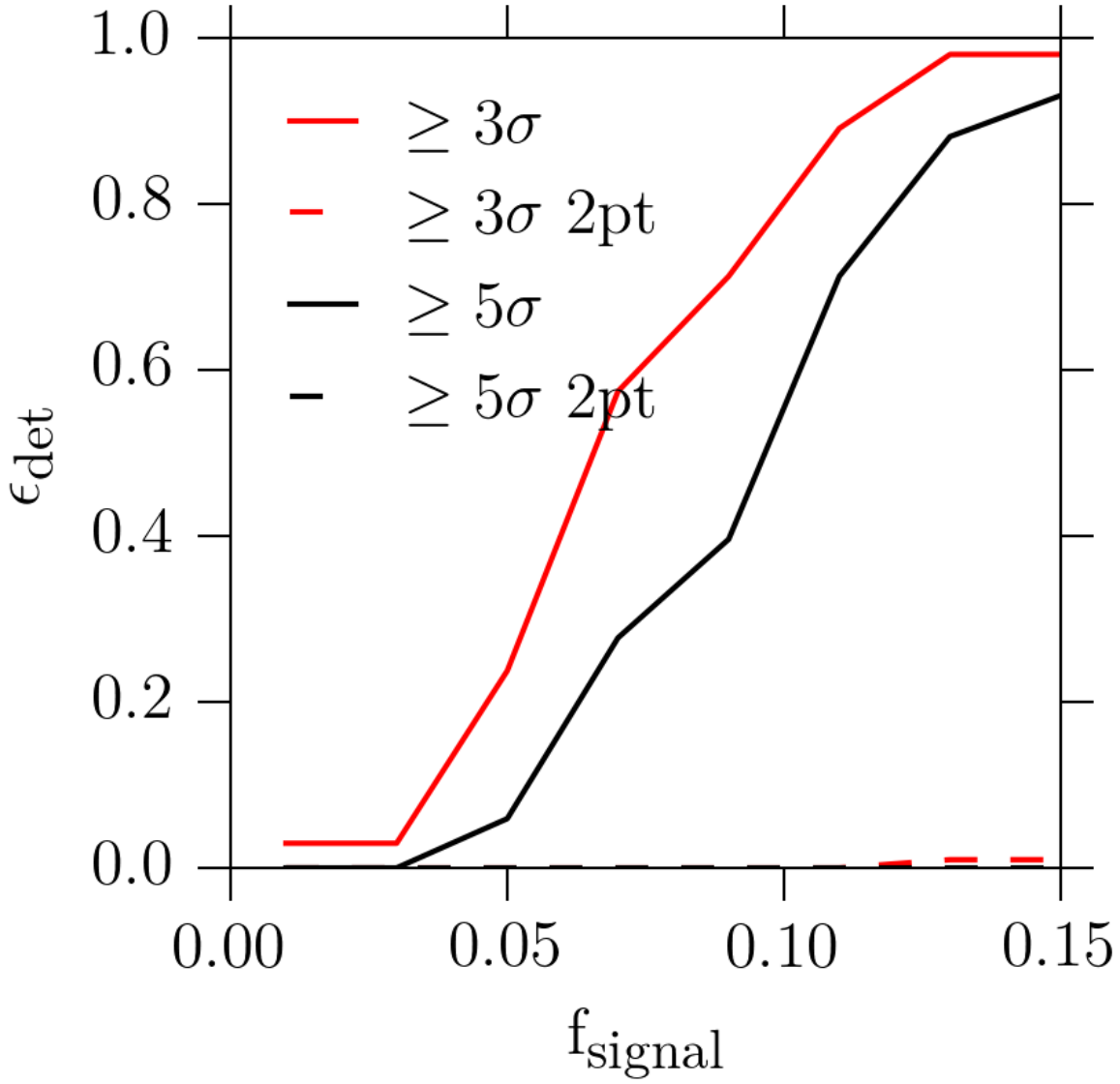
Lenses suited for sources at Mpc distance from the observer

Multinomial Probability

- Probability of cluster configuration

$$P(n_1, \ldots, n_{22}, N - N_{\text{hit}}) = \frac{N!}{n_1! \cdots n_{22}!(N - N_{\text{hit}})!} p_1^{n_1} \cdots p_{22}^{n_{22}} (1 - p_{\text{iso}})^{N - N_{\text{hit}}}$$

- → N: Total number of cosmic rays
- → N_{hit}: Number of cosmic rays correlation with neutrinos $N_{\text{hit}} = \sum_i n_i$
- → p_{iso}: summed average source hit probability
- → i: source identifier
- → p_i source average hit probability
- → n_i: number of cosmic rays associated with source i

Sensitivity with Two-Point-Autocorrelation

- No signal visible in two-point-autocorrelation