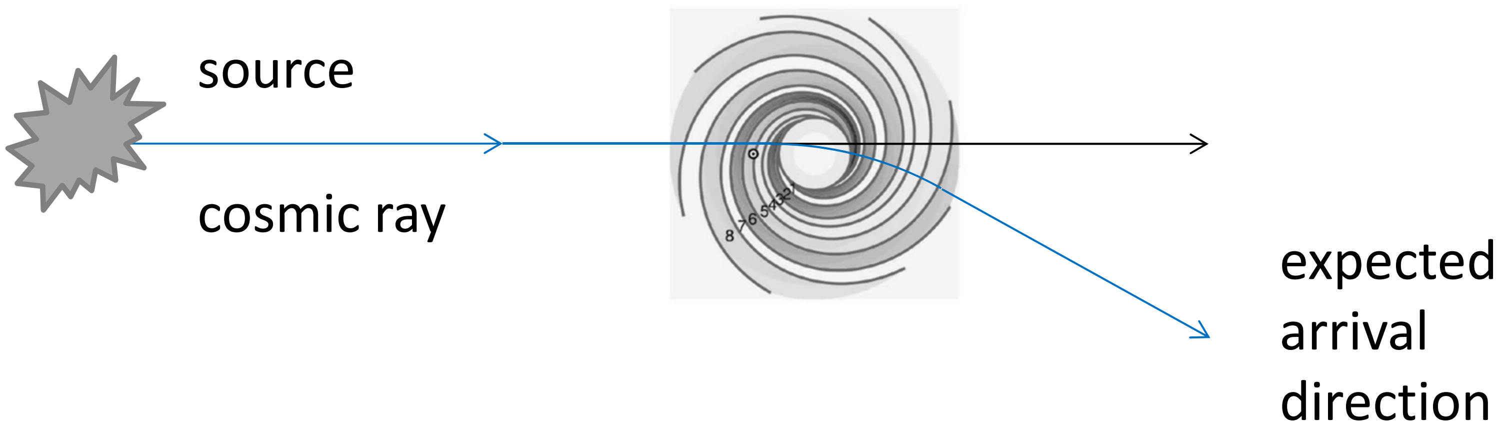
arXiv:1508.03737

Method & Observables: Investigation of Magnetic Fields using Ultra-High Energy Cosmic Rays



GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Martin Erdmann, Gero Müller, Martin Urban

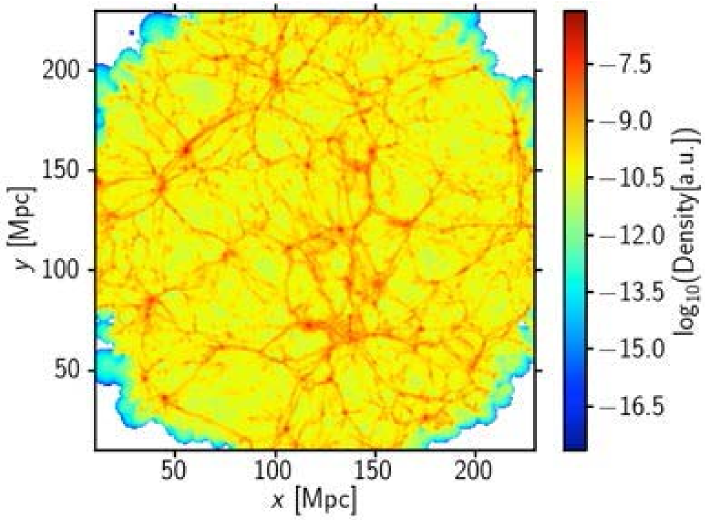
21-Sep-2015

RWTH AACHEN UNIVERSITY

Magnetic fields: key to cosmic ray origin

Extragalactic fields (nG, 10 Mpc)

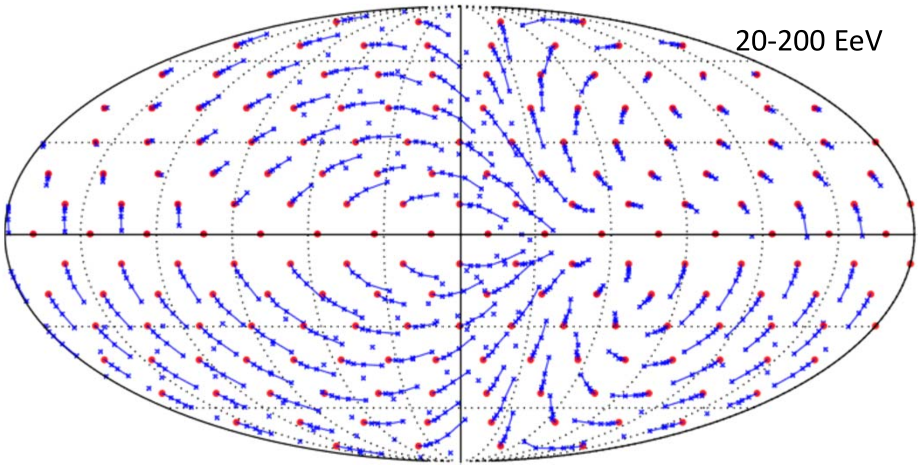
Large scale simulations



(Dolag et al)

Galactic field (μG, 10 kpc)

Parameterizations from 40,000 Faraday rotation & sychrotron radiation measurements



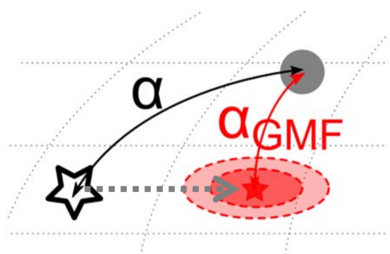
Simulated effect on cosmic rays (Farrar et al)

Pshirkov et al., 2011, ApJ, 738, 192; 2013, MNRAS, 436, 2326
Jansson, Farrar, 2012, ApJ, 757, 14; 2012, ApJ, 761, L11
Beck et al., 2014, arXiv:1409.5120

New analysis concept

Cosmic ray

Source candidate



Simulate expected proton arrival direction

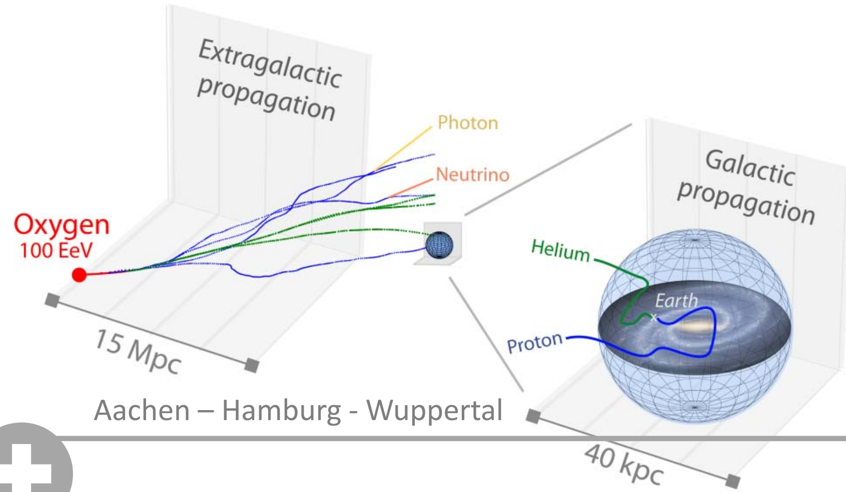
Magnetic field effect

Test validity of source candidates, field parameterizations, and composition without imposing potentially unphysical conditions on measured data

Simulated astrophysical scenario

Signal

- *CRPropa v3*: from 22 sources propagate 10^7 high energy nuclei to edge of Galaxy
- *JF12 regular field*: project cosmic rays to Earth with lensing technique
- *Exposure*: Pierre Auger

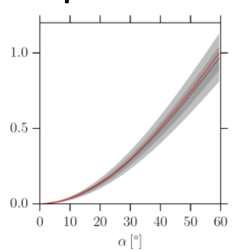


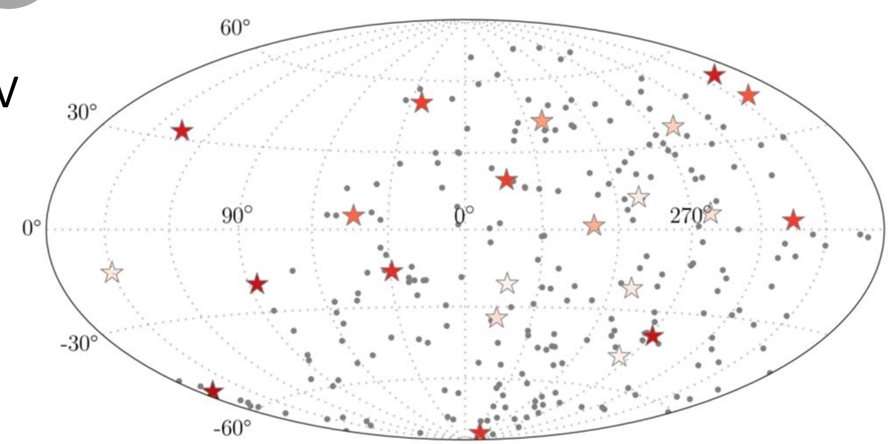
Background

Isotropic cosmic rays

„Data“

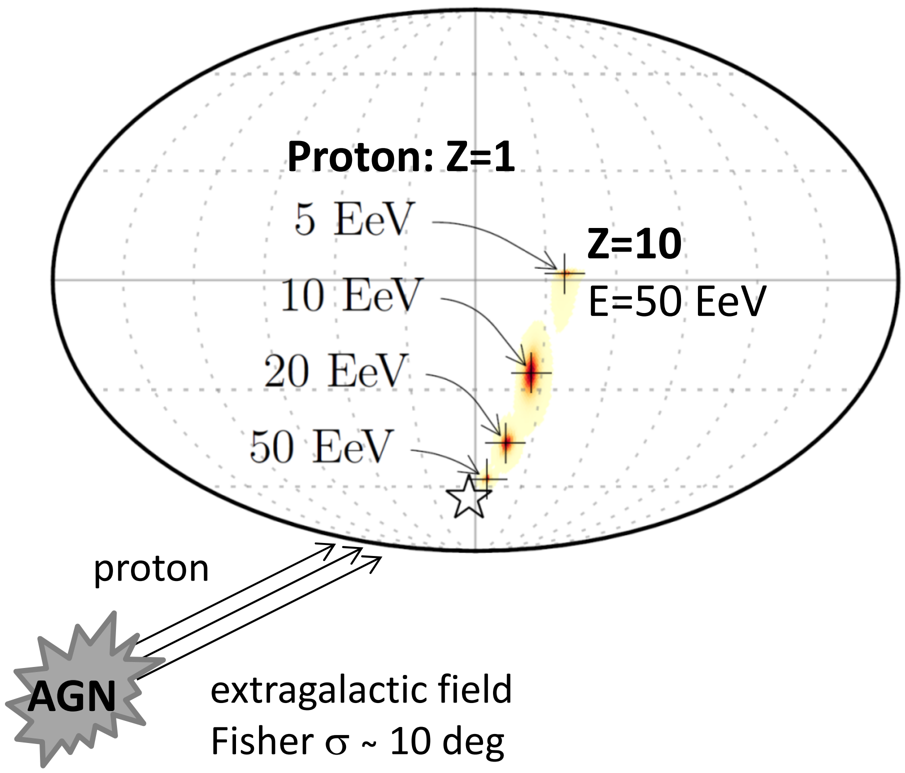
- **10 % signal + 90 % isotropy**
- 231 cosmic rays with E ≥ 52 EeV
- 22 AGN sources
- no sign: 2pt-autocorrelation



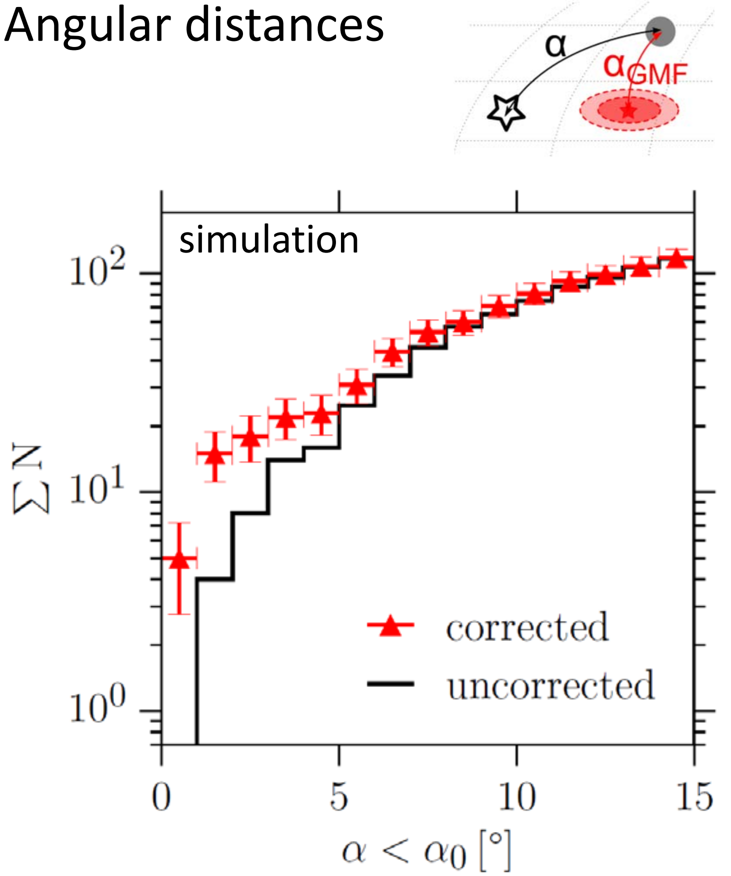


Analysis: expected arrival directions

Galactic field lenses



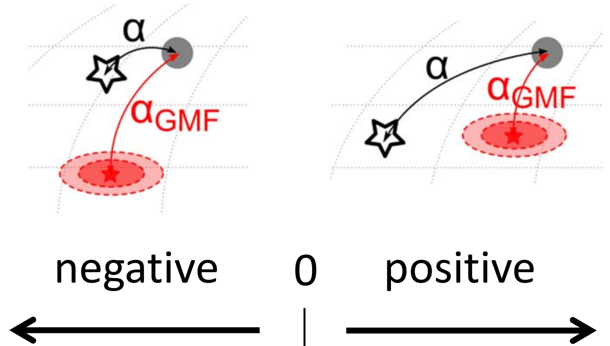
Angular distances



For sufficiently strong galactic field: proton identification to some extent

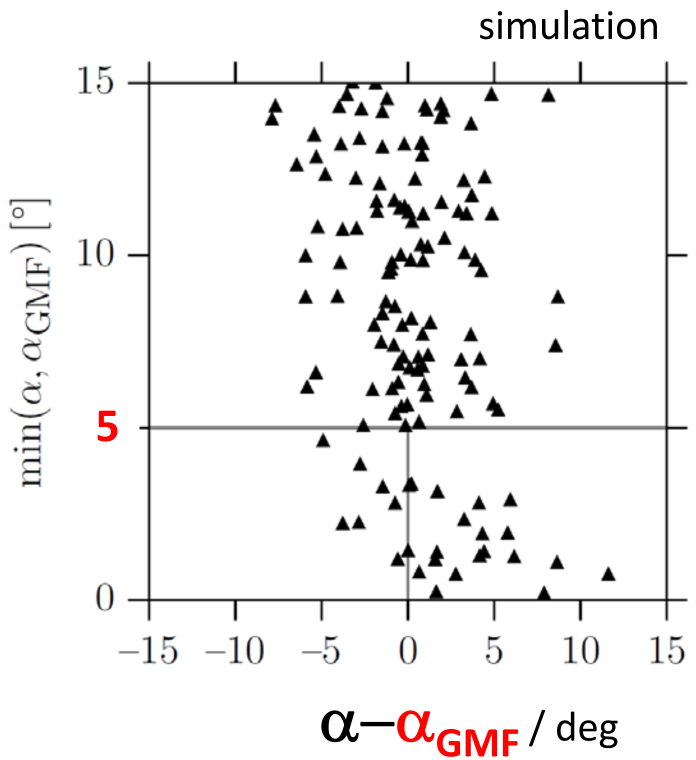
Observable 1: Change in angular distances

Angular Difference $\alpha - \alpha_{GMF}$



No: distance smaller w/o field corrections

YES: smaller distance with field corrections

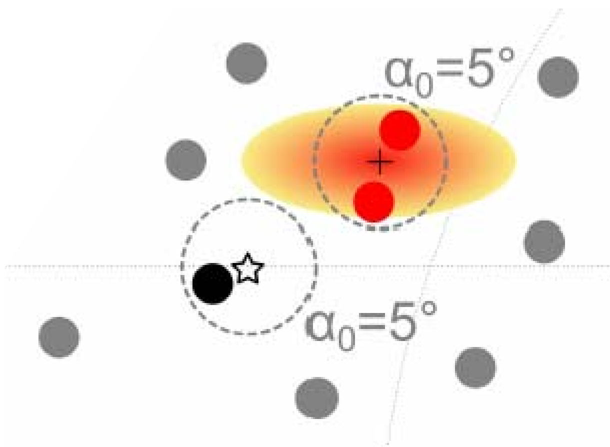


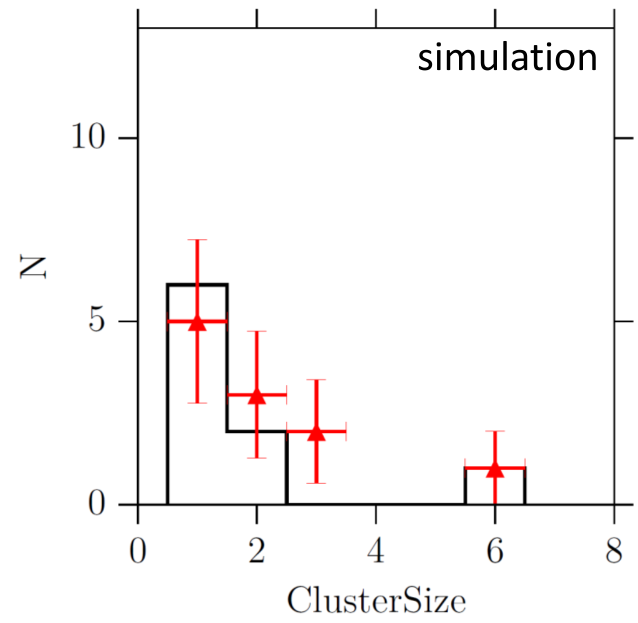
Positive asymmetry:

$$A \equiv 2\,\frac{N(\alpha > \alpha_{\mathrm{GMF}}) - N(\alpha < \alpha_{\mathrm{GMF}})}{N(\alpha > \alpha_{\mathrm{GMF}}) + N(\alpha < \alpha_{\mathrm{GMF}})} = 0.96$$

Observable 2: Change in clustering strength

Cluster size: correlating events
- with a source
- with an expected arrival direction



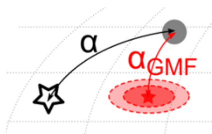


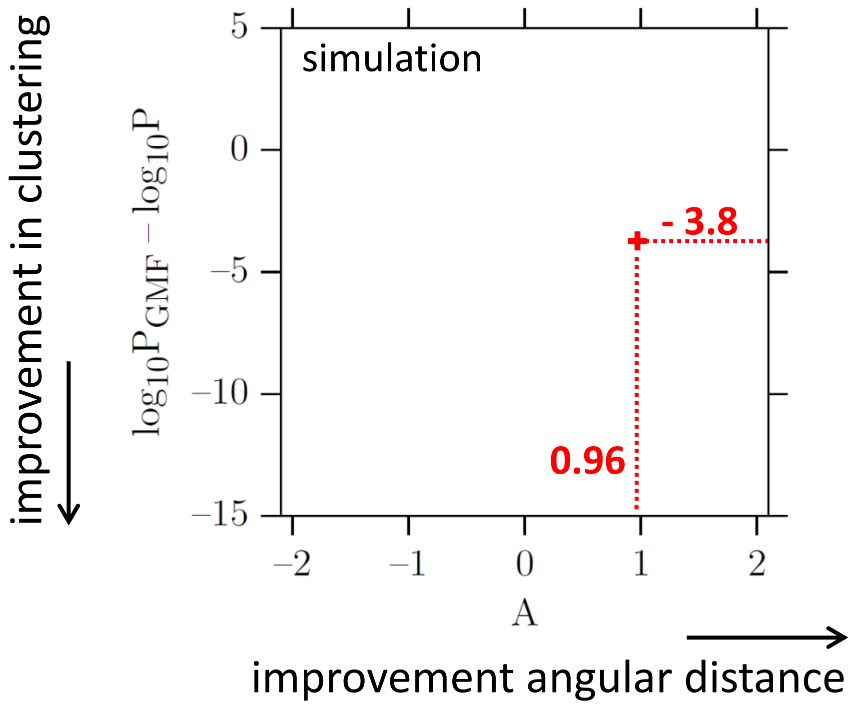
multinomial probability (trivial clustering)
- w/o field: lg P = -11.5
- with field: lg P = -15.3

Clustering improvement by magnetic field corrections: **Δlg P = -3.8**

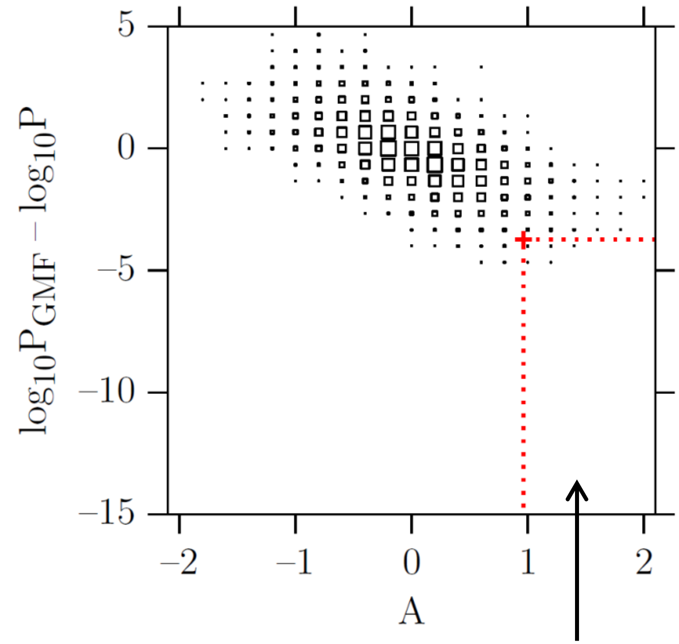
Combine: clustering & angular asymmetry

regular JF12 field, correct sources





- Isotropic cosmic rays
- Arbitrary galactic field patterns
- Typical field strength of galactic field



only 0.05% show improvement

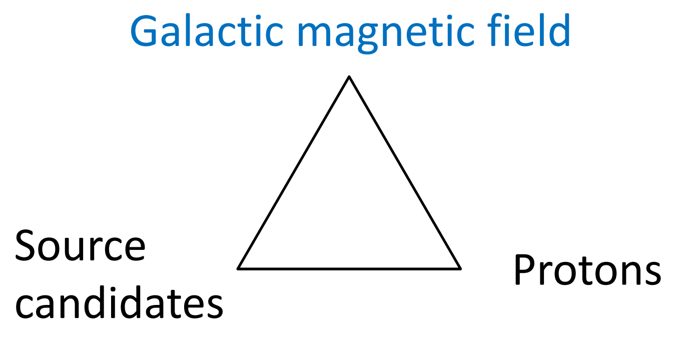
Results differ from isotropic cosmic rays & arbitrary field patterns (>3σ)

Test assumptions of combined model

A) Vary galactic field parameterization

assume to be correct:

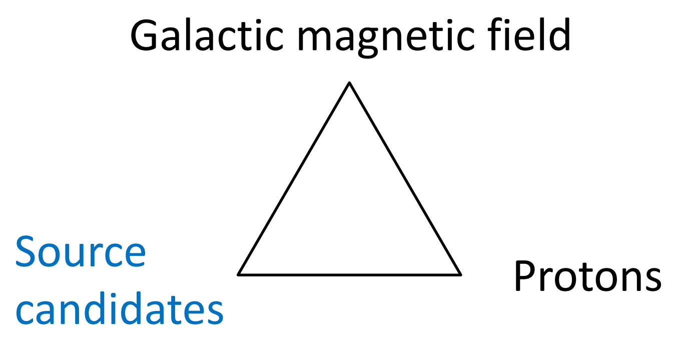
sources and composition



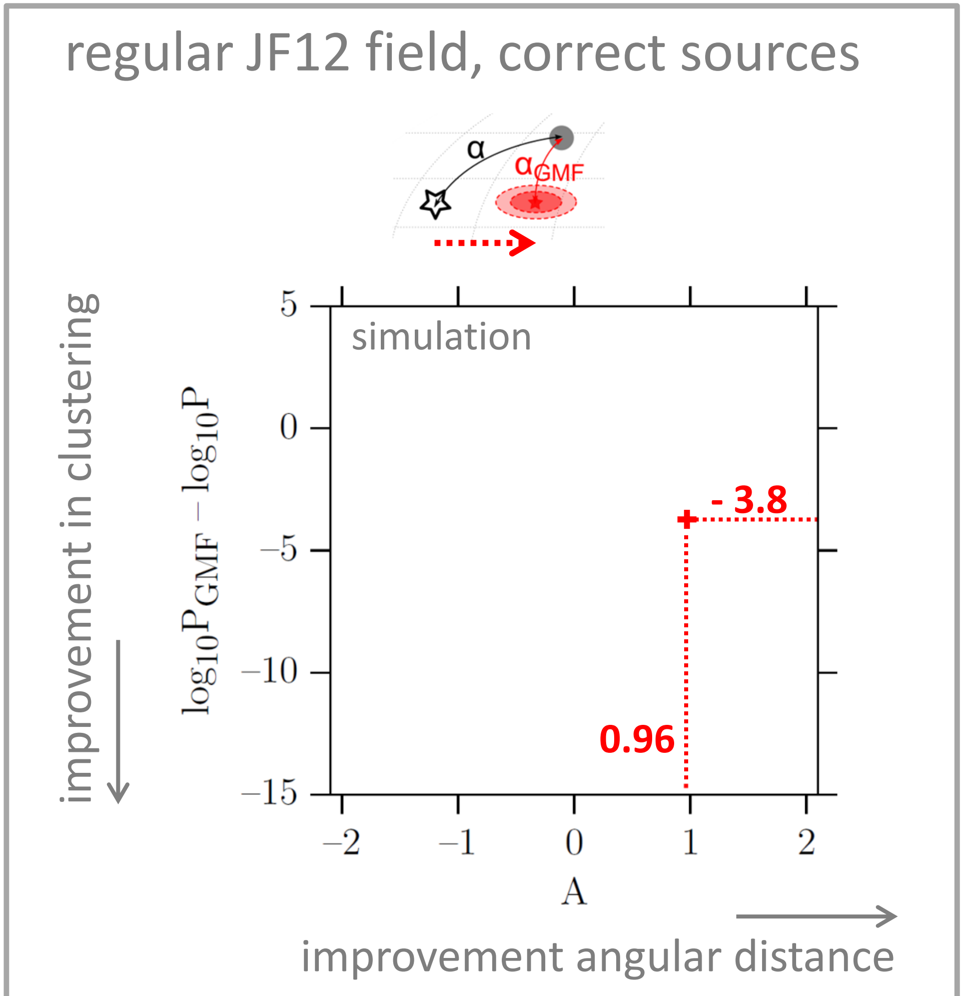
B) Vary source candidates

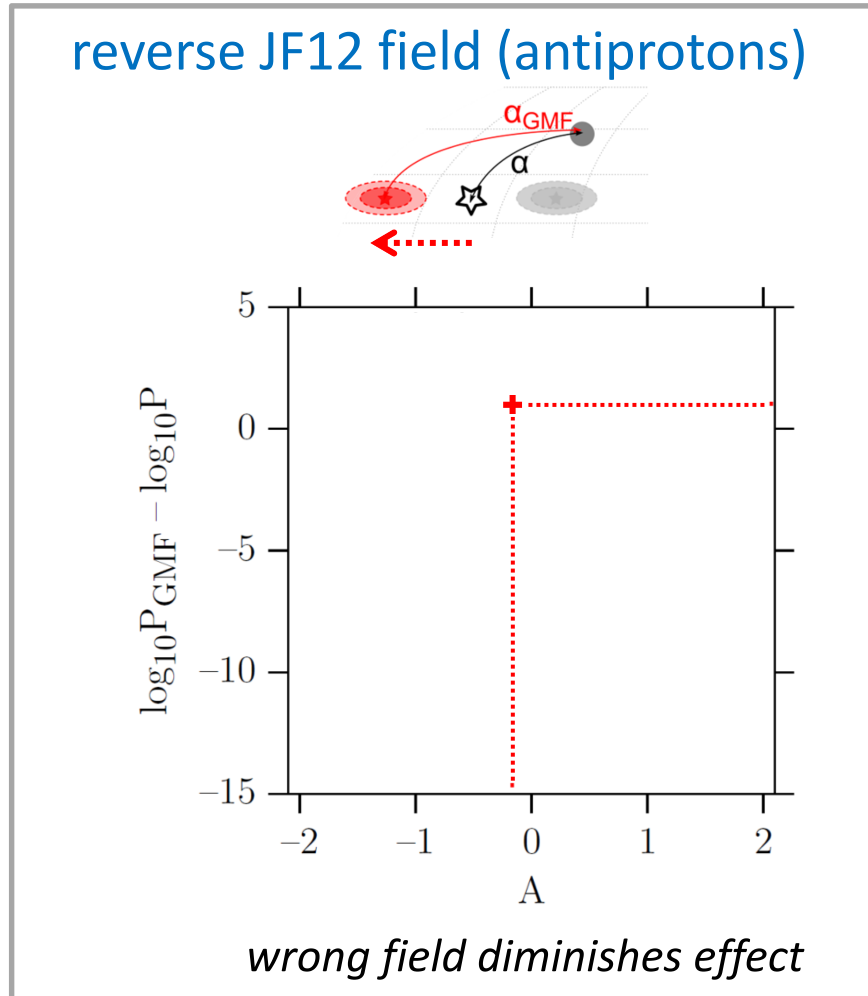
assume to be correct:

galactic field and composition



A) Reversing the galactic field orientation

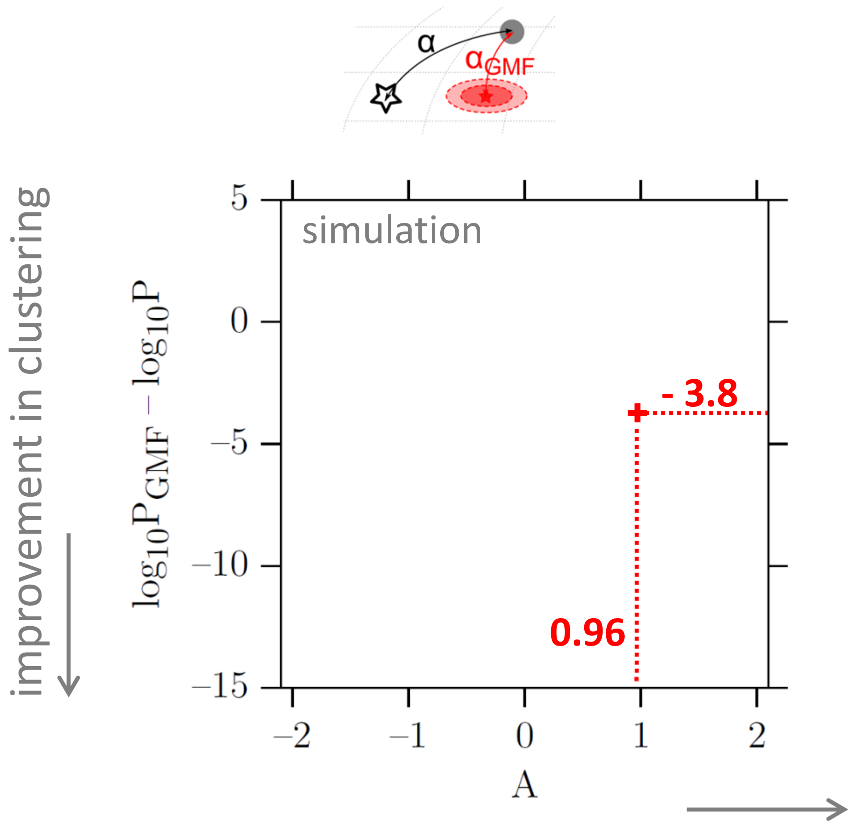




Directional characteristics of galactic magnetic field: expect striking effect

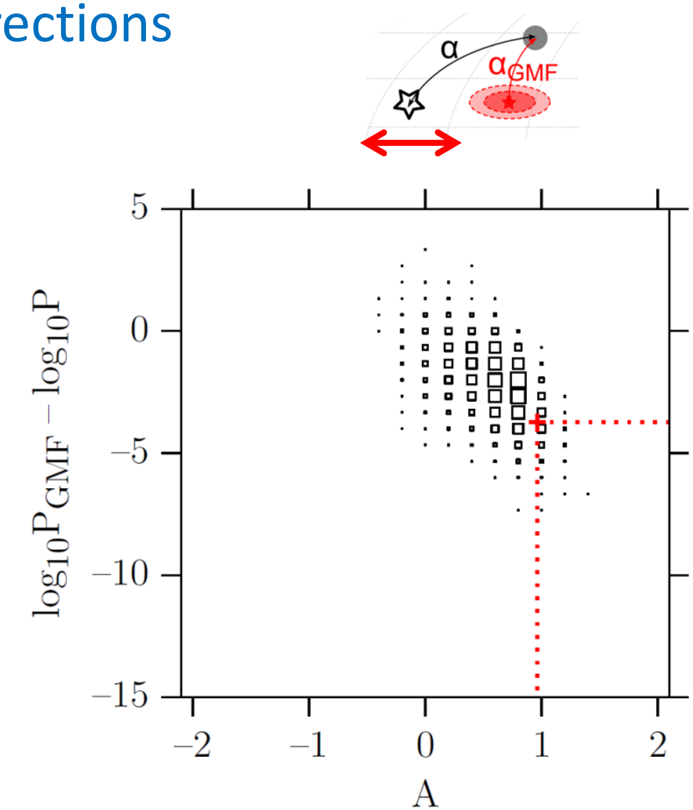
B) Sensitivity to source directions

regular JF12 field, correct sources



improvement angular distance

15 deg uncertainty in source directions



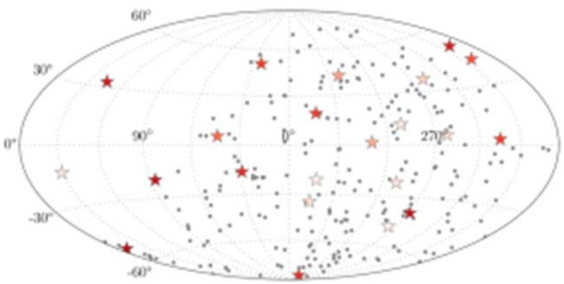
directional uncertainty reduces sensitivity

Source directions are important

Sensitivity to signal in isotropic background

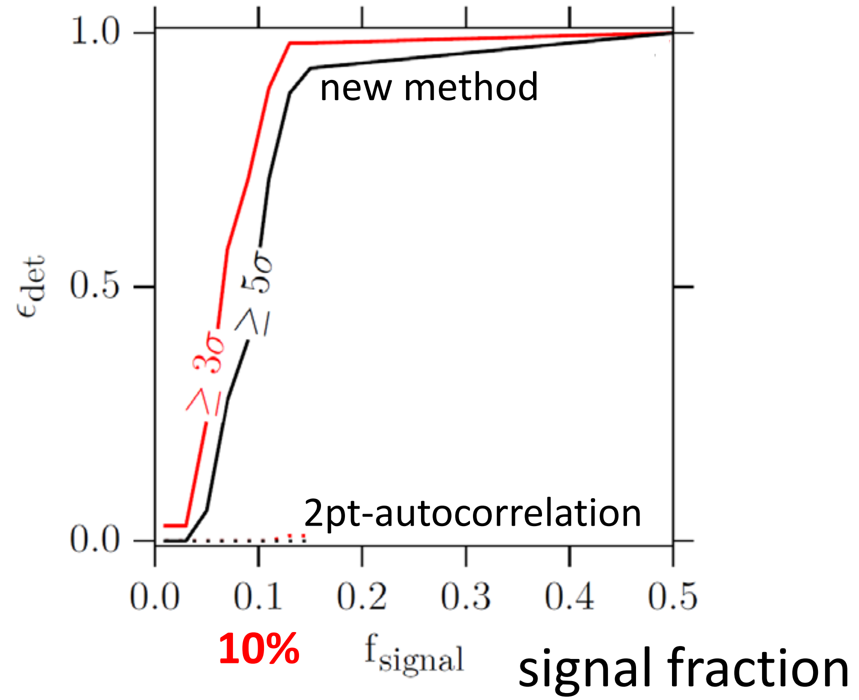
Simulated data sets

f_{signal} **signal** + (1-f_{signal}) **isotropy**



Signal detection efficiency

each from 100 realizations using regular JF12 field, correct sources

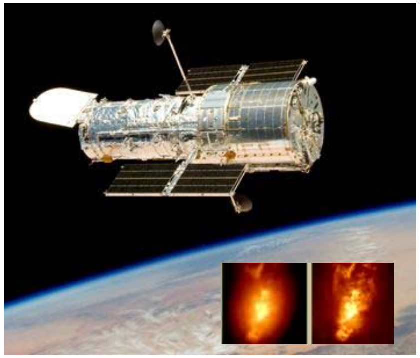


Method sensitive at 10% signal fraction

Conclusions

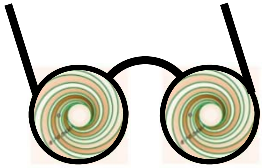
- Improved source correlation method
  - expected arrival directions include field deflections
- Method exhibits sensitivity to
  - galactic magnetic field structure
  - source directions
  - 10% percent signal fraction

ESA/Hubble



Cosmic Ray Observatories

with magnetic field corrections



investigations of cosmic particle origin and acceleration enter new phase

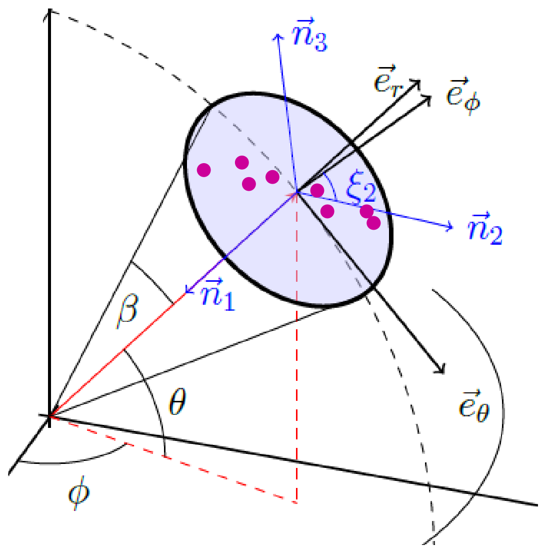
BACKUP

Magnetic field directions by cosmic rays?

Principal axes decomposition (thrust)

$$T_k = \max_{\mathbf{n}_k} \left(\frac{\sum_i |\omega_i^{-1} \, \mathbf{p}_i \cdot \mathbf{n}_k|}{\sum_i |\omega_i^{-1} \, \mathbf{p}_i|} \right)$$

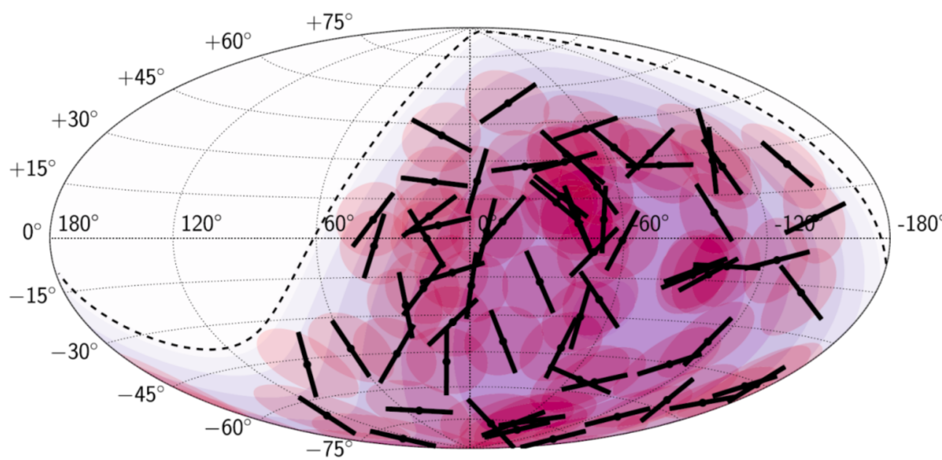
ω = acceptance factor



M.E., T. Winchen, ICRC 2013, arXiv:1307.8273

Thrust major directions

- Seed cosmic rays E>60EeV
- thrust calculation E>5EeV within 0.25 rad



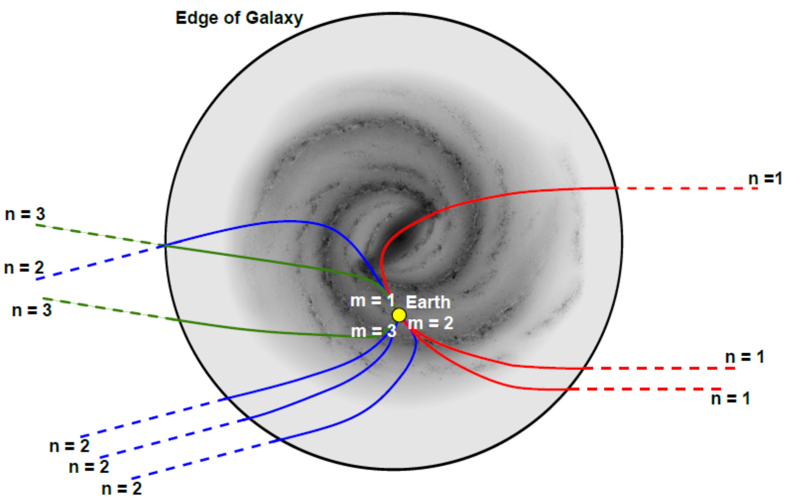
The Pierre-Auger Collab., Eur. Phys. J. C 75 (2015) 269

Limits on magnitude of magnetic fields and number of sources

Galactic magnetic lenses

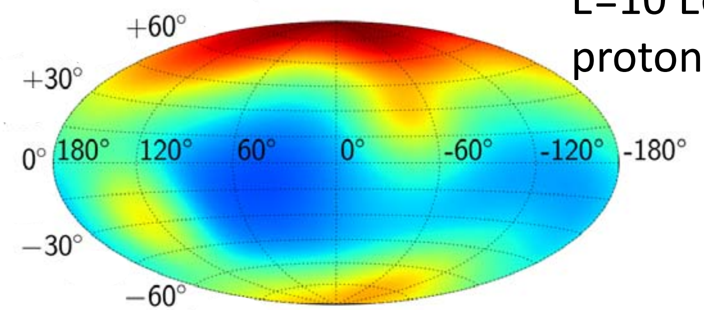
H-P Bretz, M.E., P. Schiffer, D., T. Winchen, AP 54C (2014) 110

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



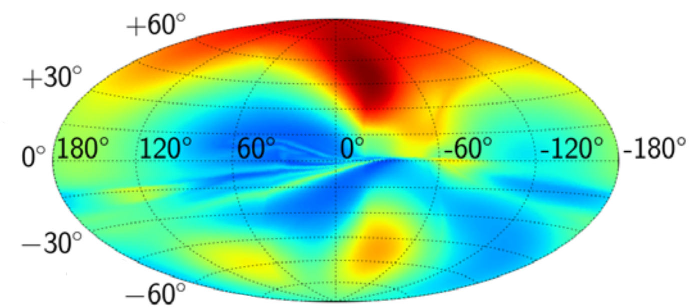
Simulated probability distribution of extragalactic arrival

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

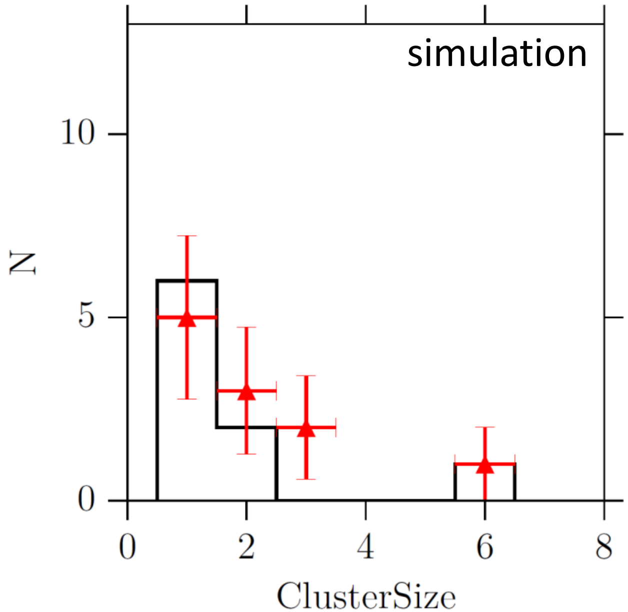
Multinomial probability

Cluster size

< 5 deg

AGN

expected arrival direction



singlet doublet …

Multinomial probability

=probability of cluster configuration

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

N : total number of cosmic rays

N_{hit} : number of cosmic rays correlating with sources $N_{hit} = \Sigma n_i$

p_{iso} : summed average source hit probability $p_{iso} = \Sigma p_i$

i : source identifier

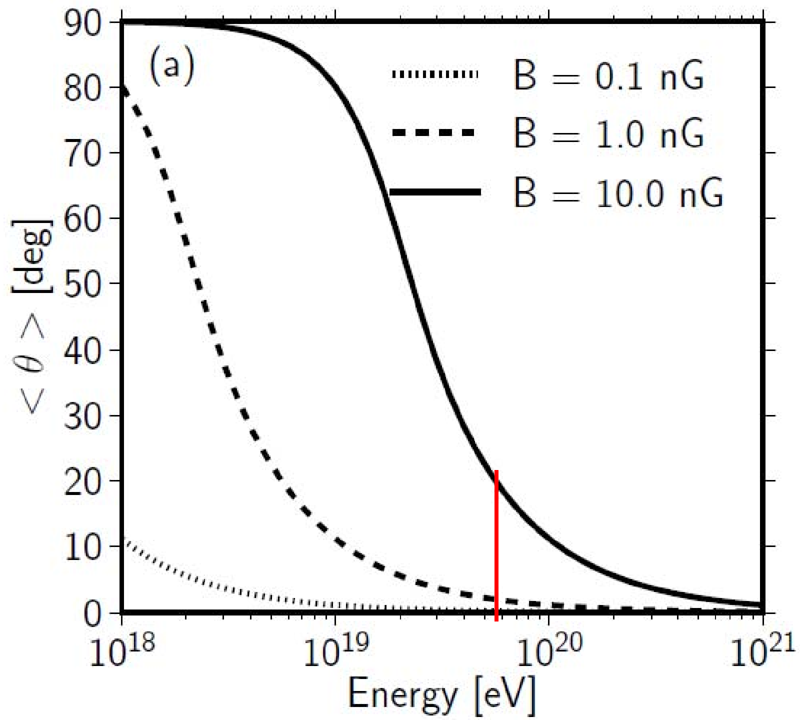
p_i : source *i* average hit probability

n_i : number of cosmic rays associated with source *i*

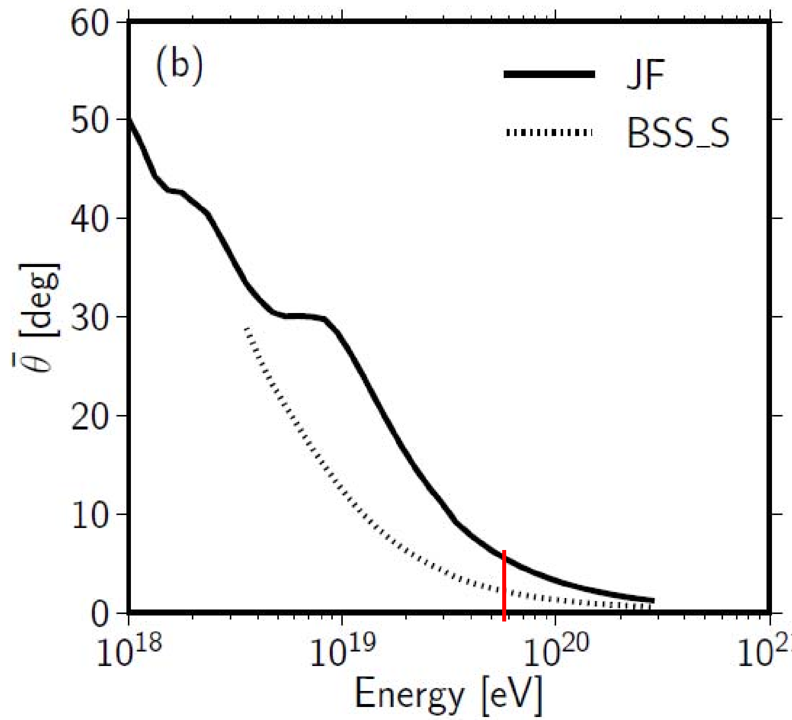
Mean deflection of protons in fields

Mean deflection of protons with E>55 EeV from 10 Mpc distance

Extragalactic field

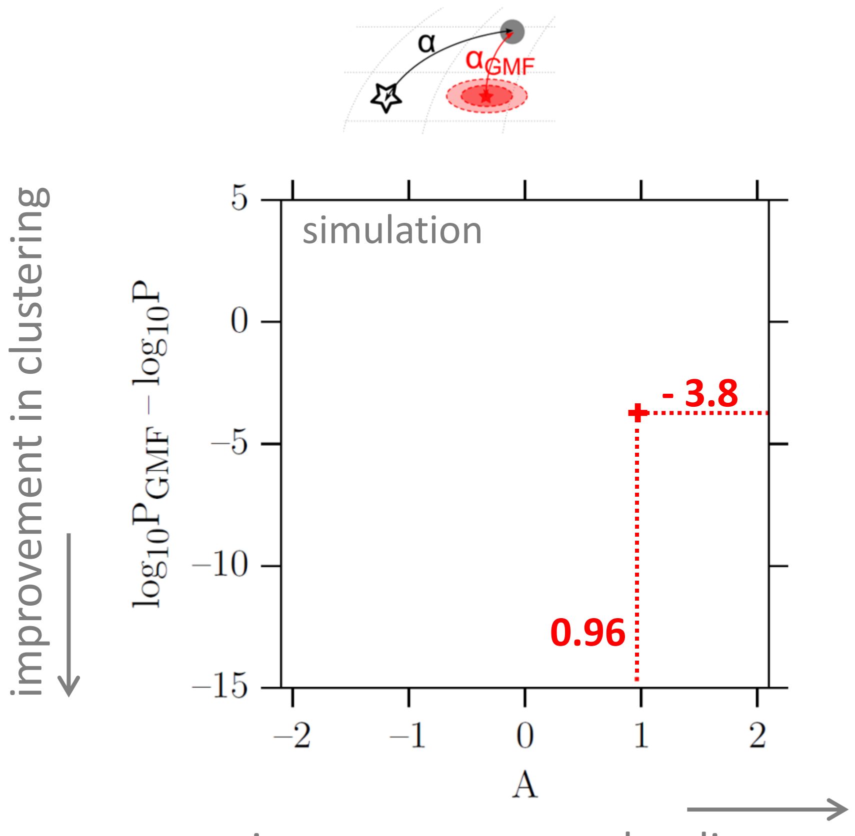


Galactic field

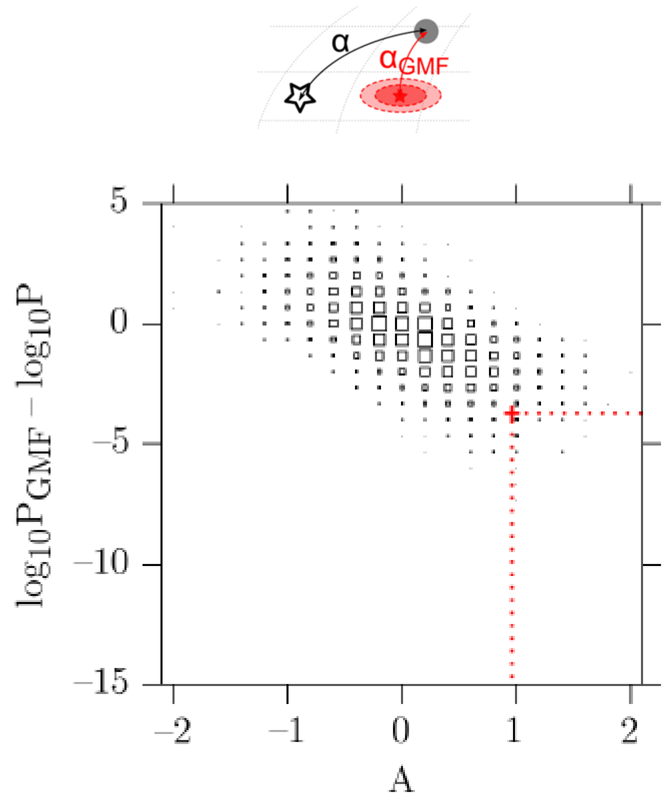


Does field move any cosmic rays→sources?

regular JF12 field, correct sources



Isotropic cosmic rays

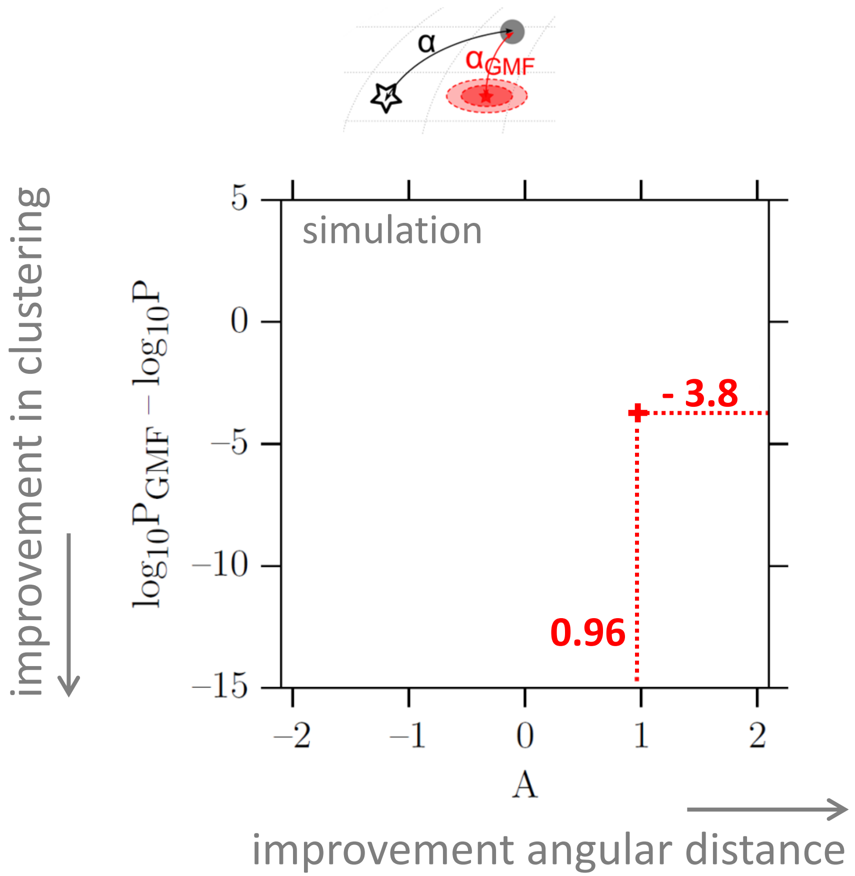


no sensitivity

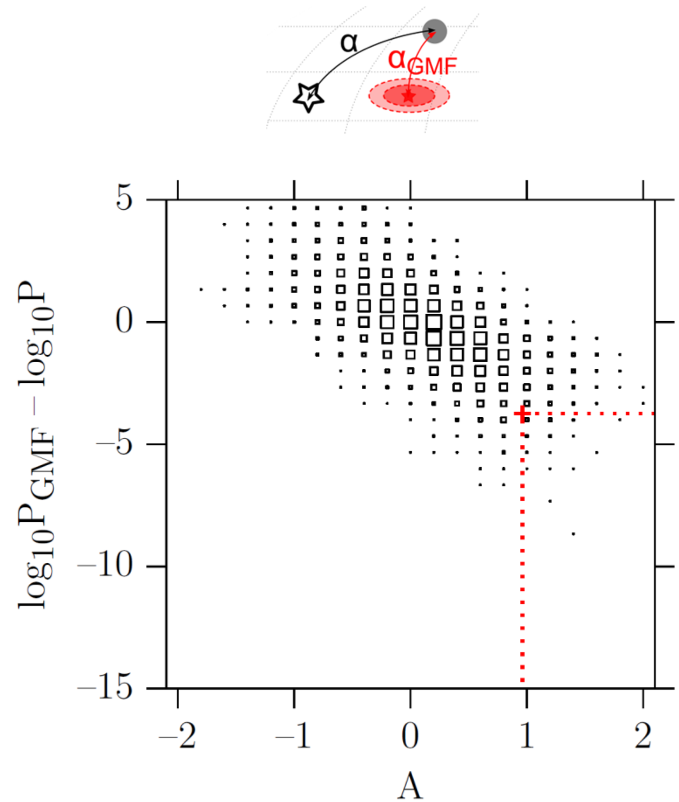
Directional correlations of sources and cosmic rays can be distinguished

Does field move cosmic rays→any sources?

regular JF12 field, correct sources



Isotropic source directions

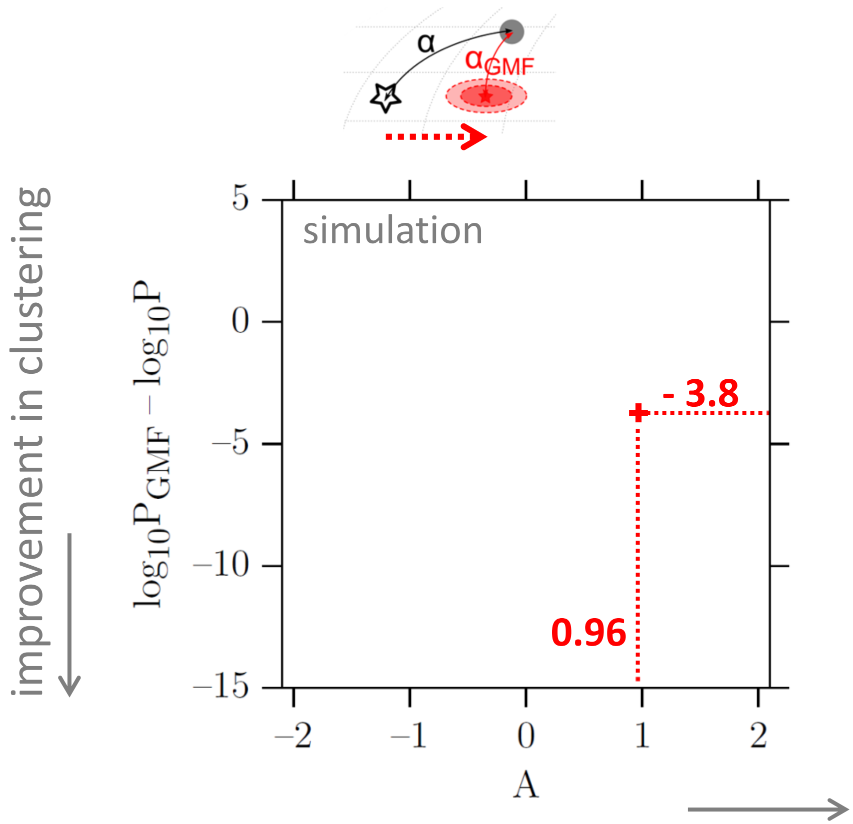


no sensitivity

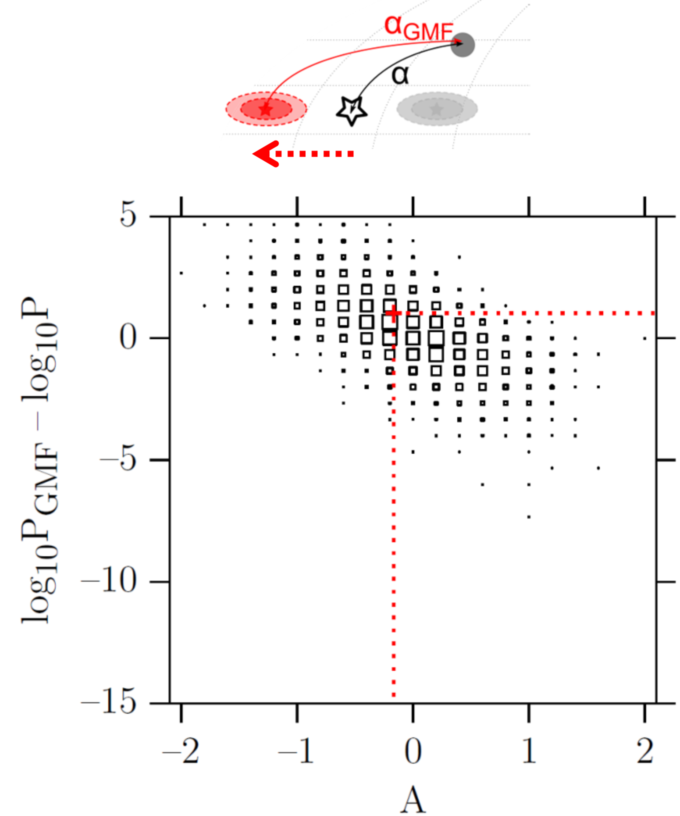
Directional correlations of sources and cosmic rays can be distinguished

Reversing the galactic field orientation

nominal JF12 field, correct sources



reverse JF12 field (antiprotons)

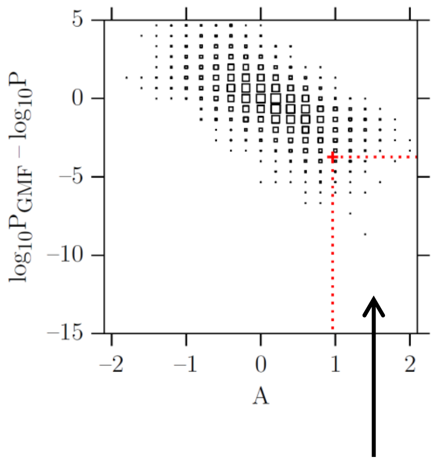


wrong field diminishes effect

Directional characteristics of galactic magnetic field: expect striking effect

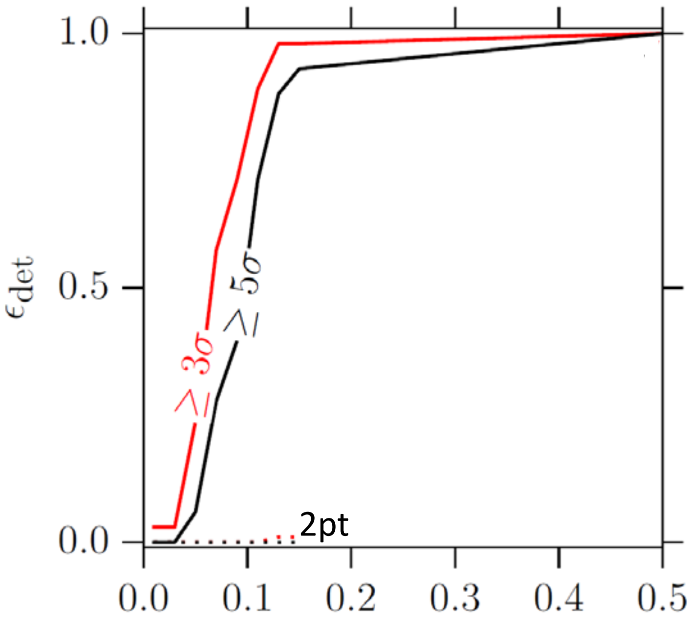
Sensitivity study: signal fraction

For each signal fraction f_{signal} =1,...,50%
simulated 100 signal realizations



Detection efficiency ε_{det} = number of simulations with ≥3 (5) σ difference from isotropic simulations

Signal detection efficiency
for nominal JF12 field, correct sources



Method sensitive at 10% signal fraction