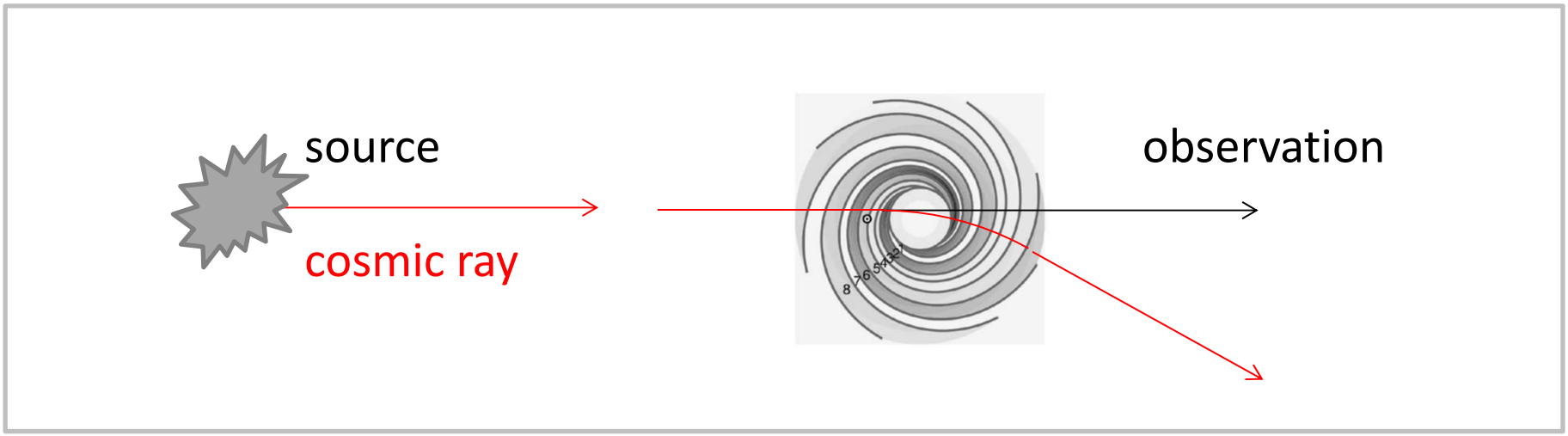
Methods & Observables: Investigation of Magnetic Fields using Ultra-High Energy Cosmic Rays



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23-July-2015

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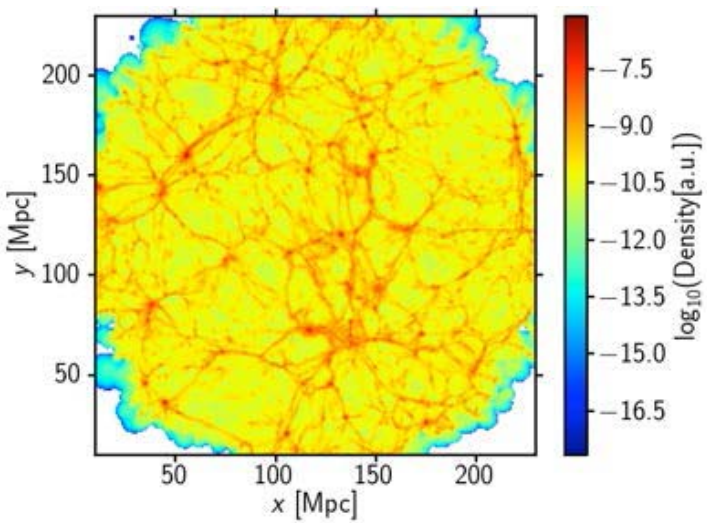
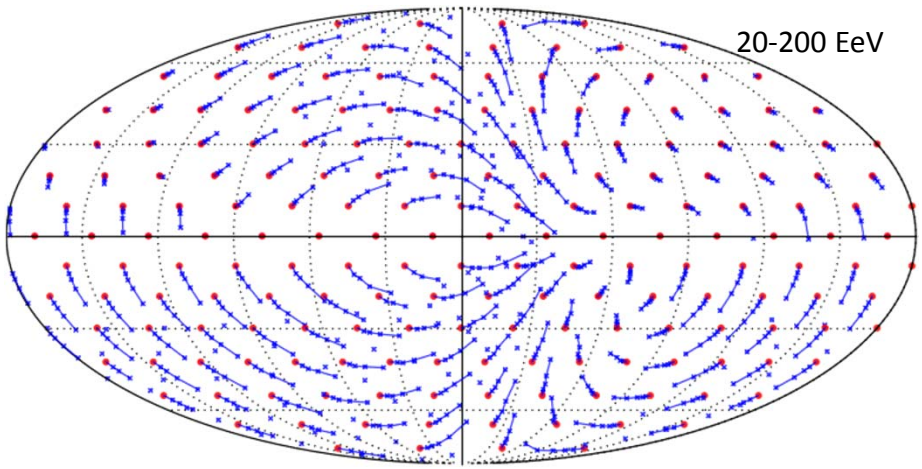
Magnetic fields: key to cosmic ray origin

Extragalactic fields (nG, 10 Mpc)



Large scale simulation (Dolag et al)

Galactic field (μG, 10 kpc)



Simulated effect on cosmic rays (Farrar et al)

Parameterizations from 40,000 Faraday rotation & sychrotron radiation measurements

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

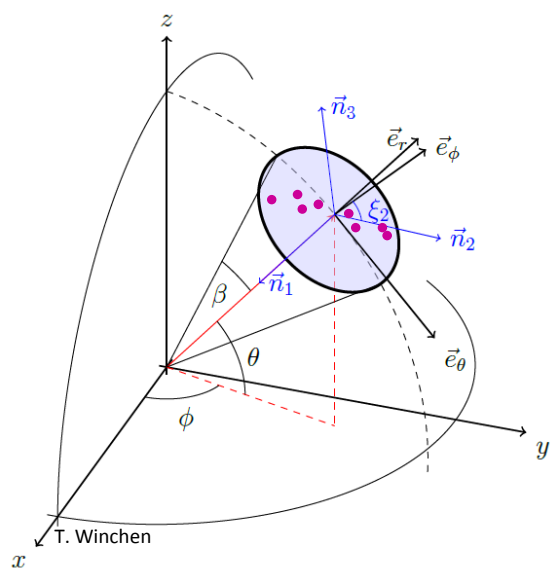
Thrust observable transferred to sky

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

Principal axes, thrust major & minor

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

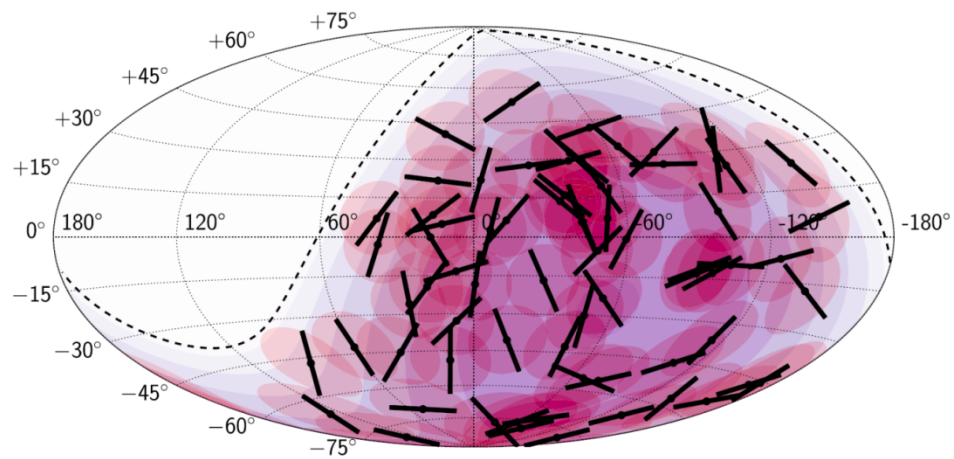
ω = acceptance factor



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

Thrust major directions at highest energy cosmic rays

Seed E>60EeV
thrust calculation E>5EeV within 0.25 rad



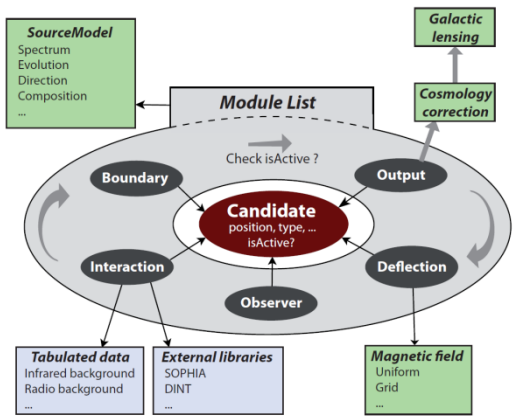
Results of thrust analysis are being compared with galactic field parameterizations

Cosmic ray propagation

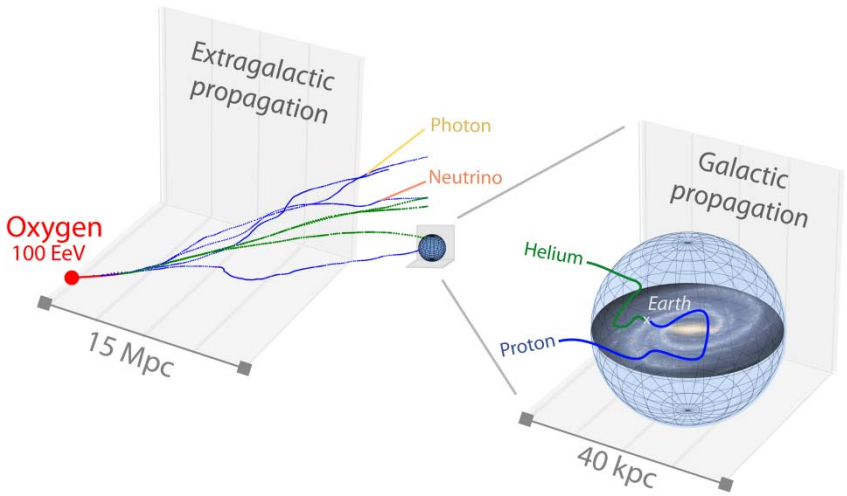
CRPropa 3.0 R.A.Batista, M.E., C.Evoli, K-H.Kampert, D.Kuempel, G.M. , G.Sigl, A.van Vliet, D.Walz, T.Winchen

arXiv:1307.2643v1

Modern programming design suited for high statistics simulations



Propagation of nuclei from sources to observer including the relevant interactions & magnetic field deflections



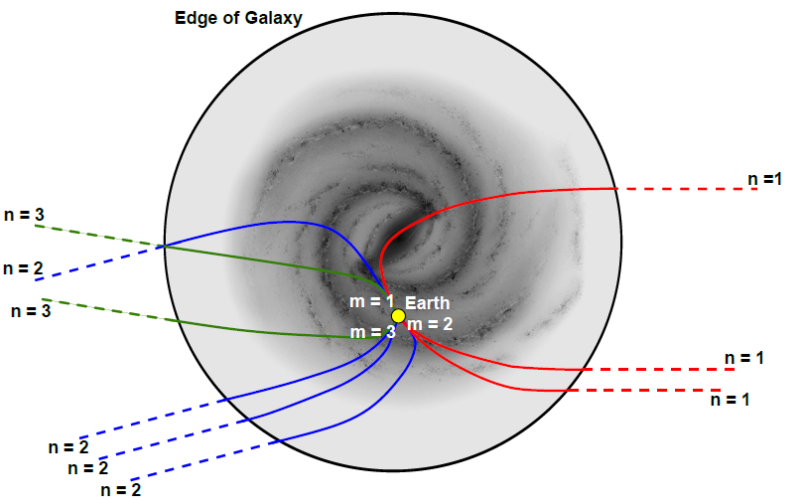
Interactive for you
https://vispa.physik.rwth-aachen.de/

most valuable tool for comparisons with data

Galactic magnetic lenses

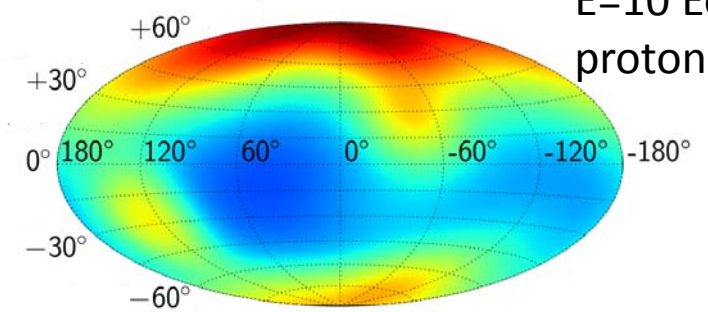
H-P Bretz, M.E., P. Schiffer, D., T. Winchen, AP 54C (2014) 110

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



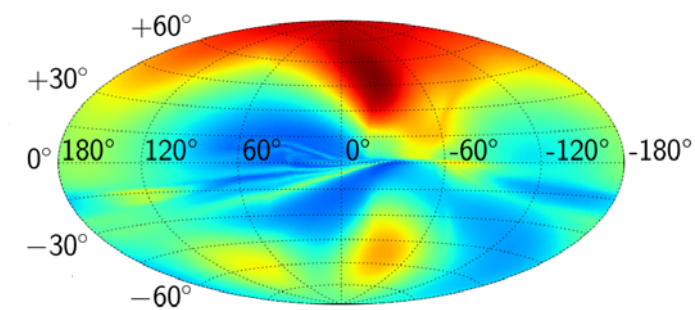
Simulated probability distribution of extragalactic arrival

E=10 EeV protons



Probability distribution projected onto the Earth

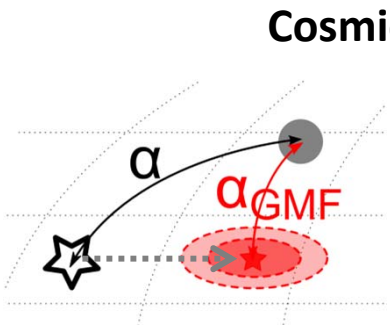
Galactic field: Jansson, Farrar 2012



Lenses suited for sources at Mpc distance from the observer

New Analysis Concept

Source hypothesis: **AGN** (Active Galactic Nuclei)



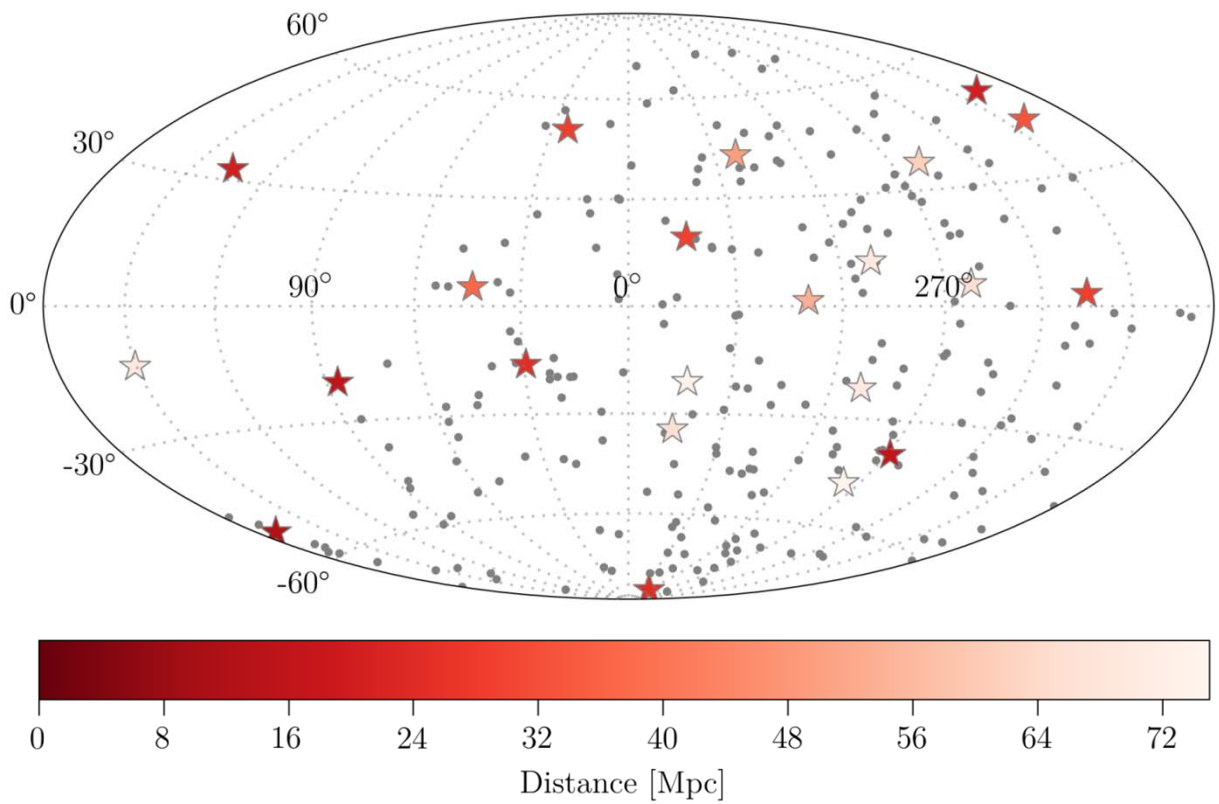
Simulate expected proton arrival direction

test validity of source candidates & field parameterization without imposing possibly unphysical conditions on measured data

Simulated cosmic rays

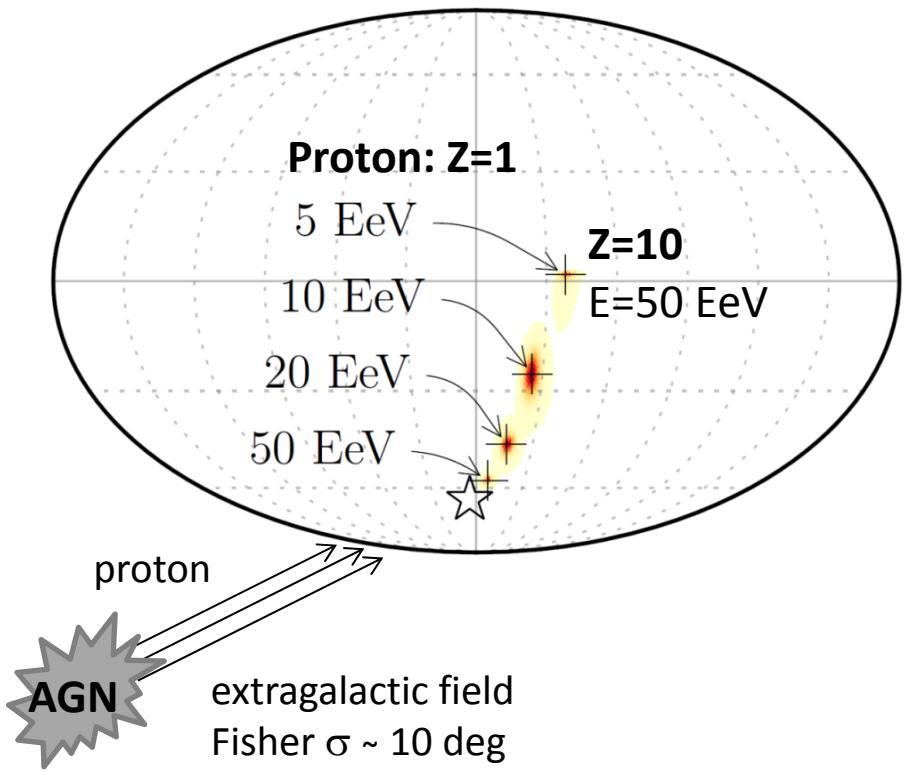
22 sources: **AGN**
(near IceCube published Neutrinos)

231 **cosmic rays**, energy E>52 EeV
(observatory exposure: Pierre Auger)
7% proton signal
93% background (e.g. heavy nuclei)

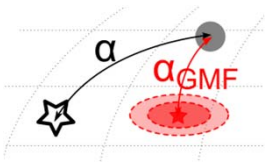


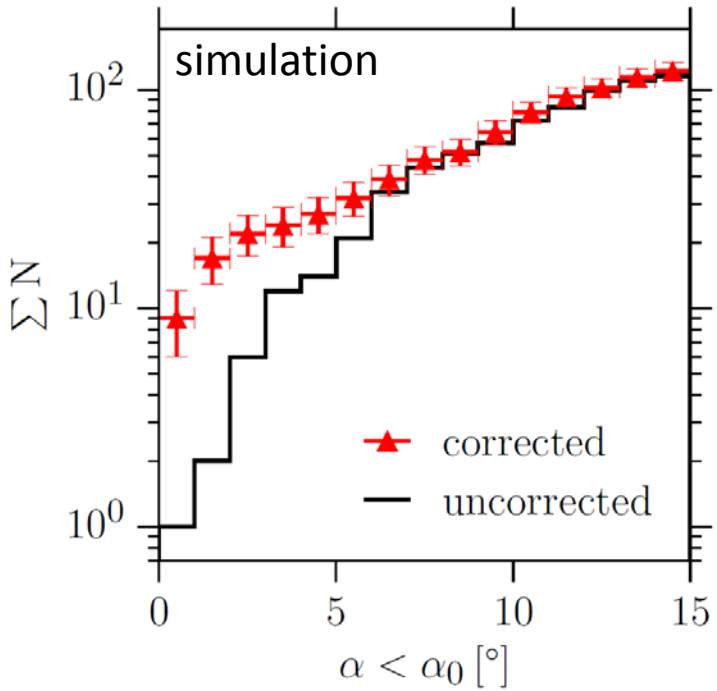
Expected Arrival Directions

Galactic field lenses



Angular distances

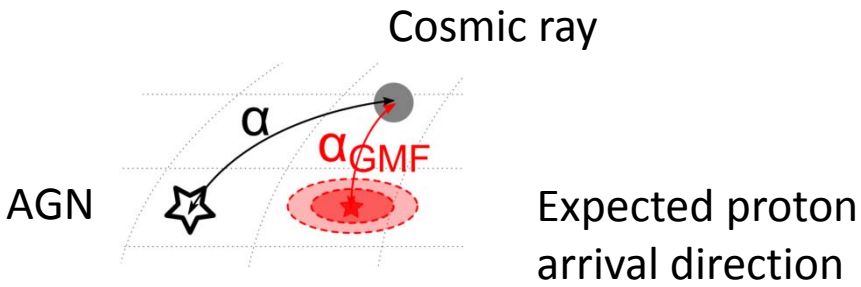




for sufficiently strong galactic field: proton identification to some extent

Gradient Observables

1) Change in angular distances $\alpha - \alpha_{GMF}$



2) Change in clustering strength (singlets, doublets,…)

count cosmic rays clustering at AGN

count cosmic rays clustering at expected arrival direction

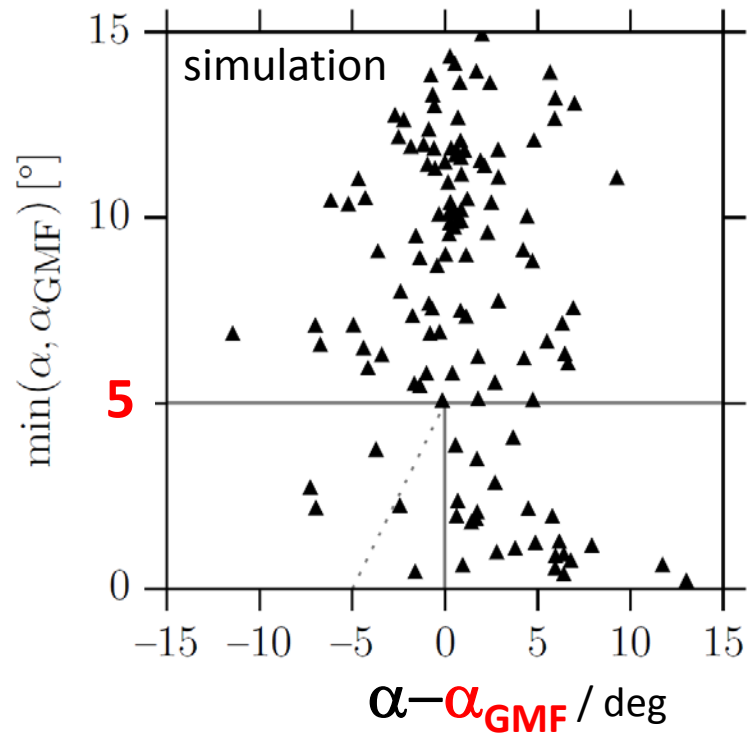
1) Angular asymmetry

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

negative 0 positive

No: distance smaller without correction

YES: smaller distance with field corrections



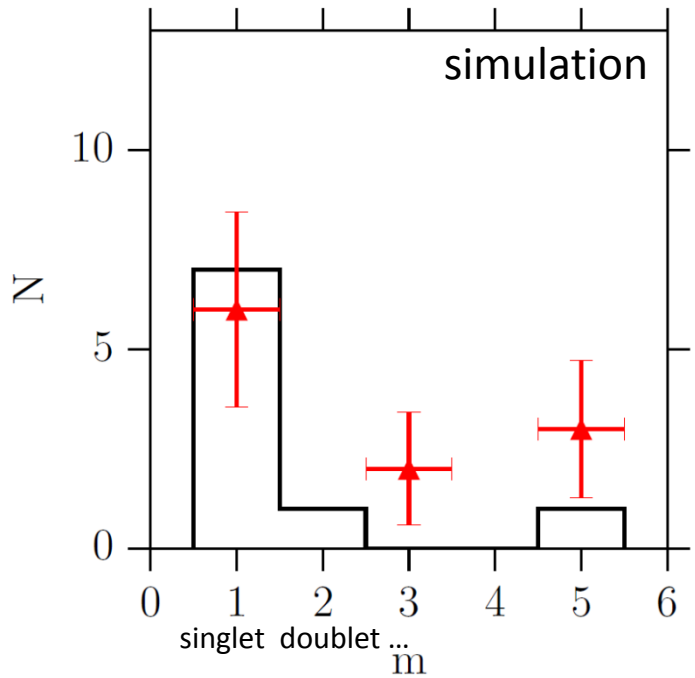
Positive asymmetry: $$A \equiv 2\,\frac{N(\alpha > \alpha_{GMF}) - N(\alpha < \alpha_{GMF})}{N(\alpha > \alpha_{GMF}) + N(\alpha < \alpha_{GMF})} = 1.3$$

2) Clustering strength

Cluster size

AGN expected arrival direction

< 5 deg



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 neutrinos $N_{hit} = \Sigma n_i$

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

i : neutrino identifier

p_i : neutrino i average hit probability

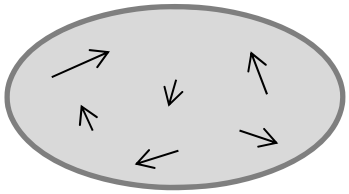
n_i : number of cosmic rays associated with neutrino i

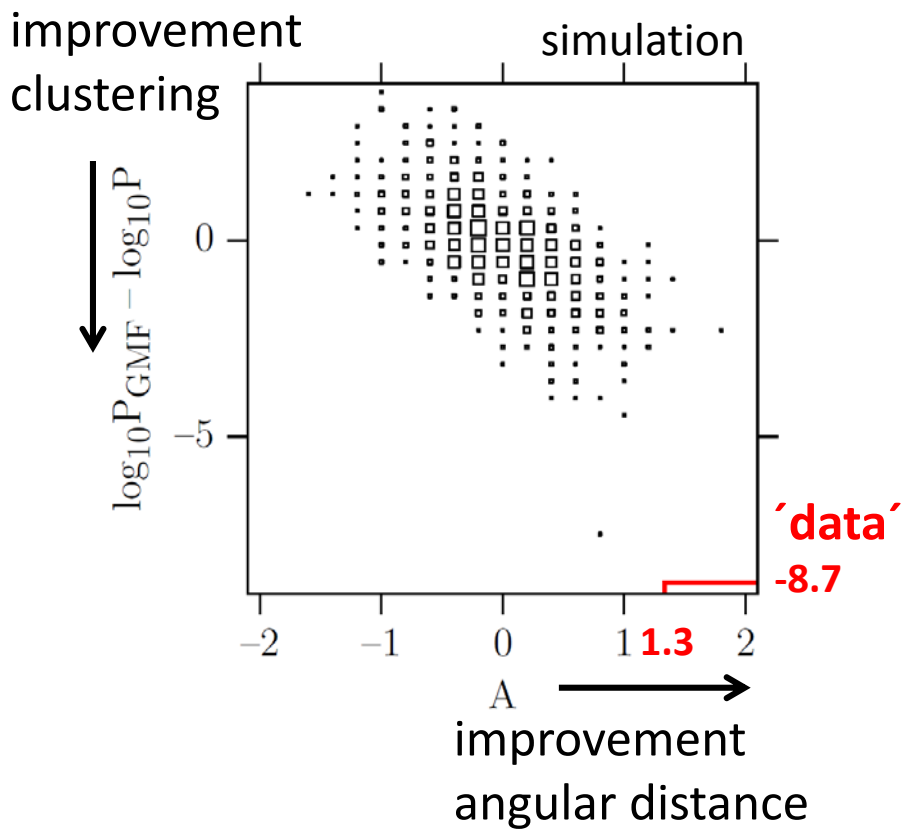
Simulated data multinomial probability
w/o field: lg P = -9.5, with field: lg P = -18.2

Clustering improvement by magnetic field corrections: **Δlg P = -8.7**

Comparison with chance effects

- **AGN** nominal directions
- Typical field strength of galactic magnetic field
- Arbitrary **field directions**
- Isotropic **cosmic rays** (observatory)



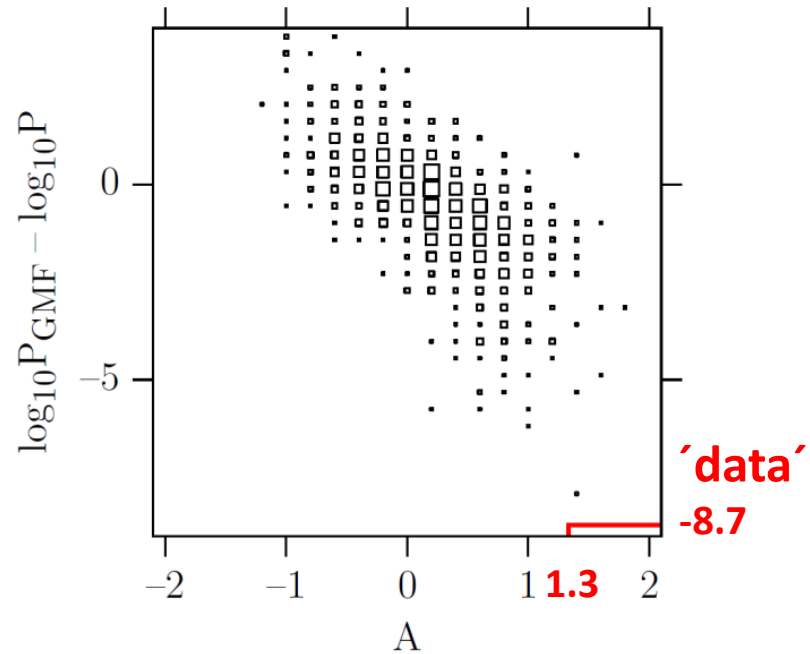


Observables away from chance distributions

Test of sources

Are AGN directions important, magnetic field could move cosmic rays towards them anyway?

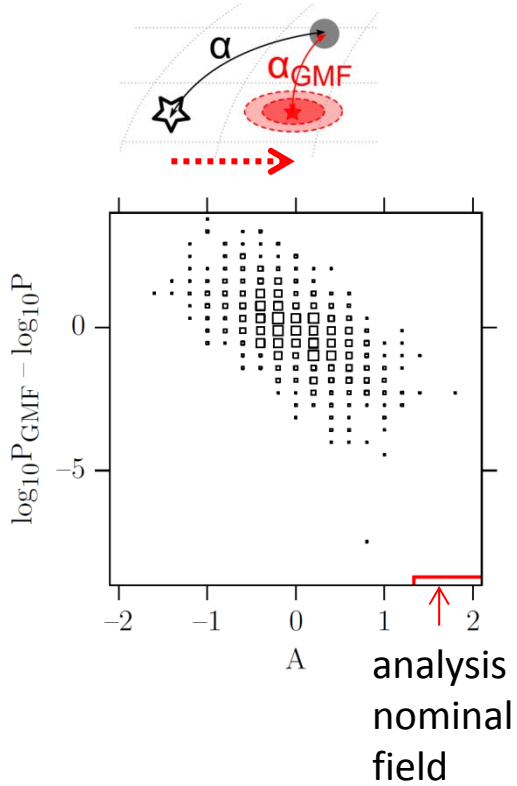
- Nominal cosmic ray arrival directions
- Nominal galactic magnetic field
- Isotropic **AGN** directions



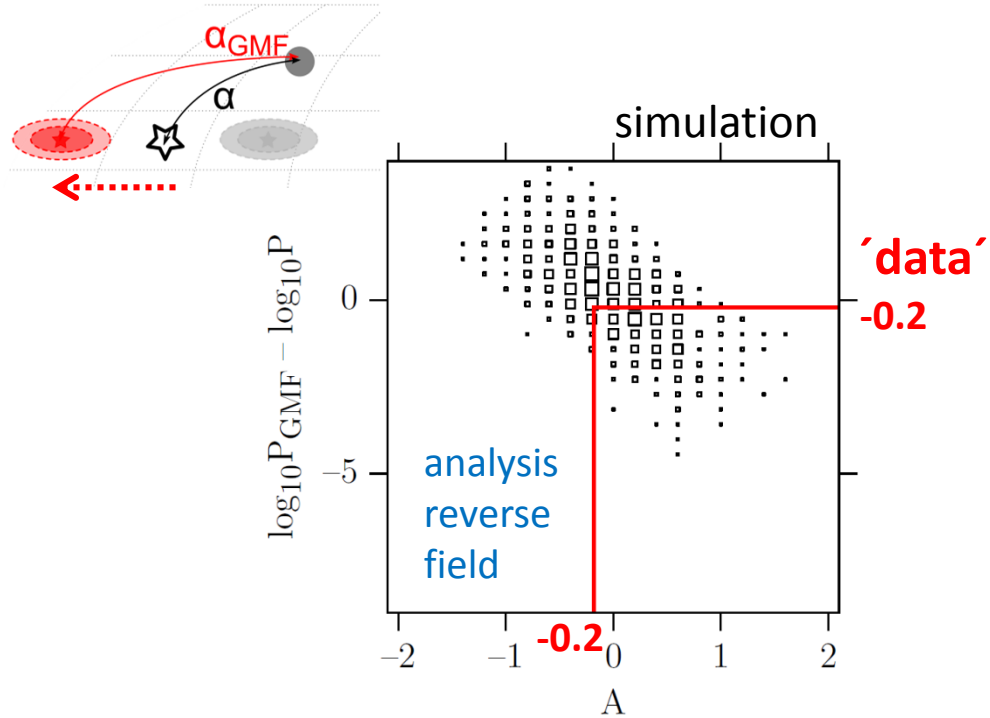
Directional correlations of sources and cosmic rays can be distinguished

Galactic field direction

nominal field



reverse field (antiprotons)



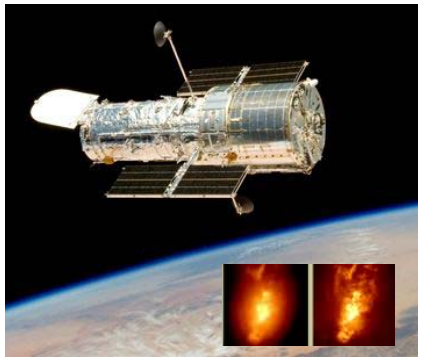
diminishes effect

Directional characteristics of galactic magnetic field: expect striking effect

Conclusions

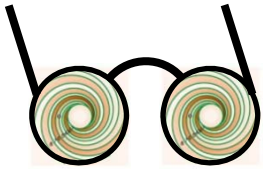
- Development of new methods & observables for understanding magnetic field effects on cosmic rays
- New analysis procedure for galactic magnetic field corrections

ESA/Hubble



Cosmic Ray Observatories

with magnetic field corrections



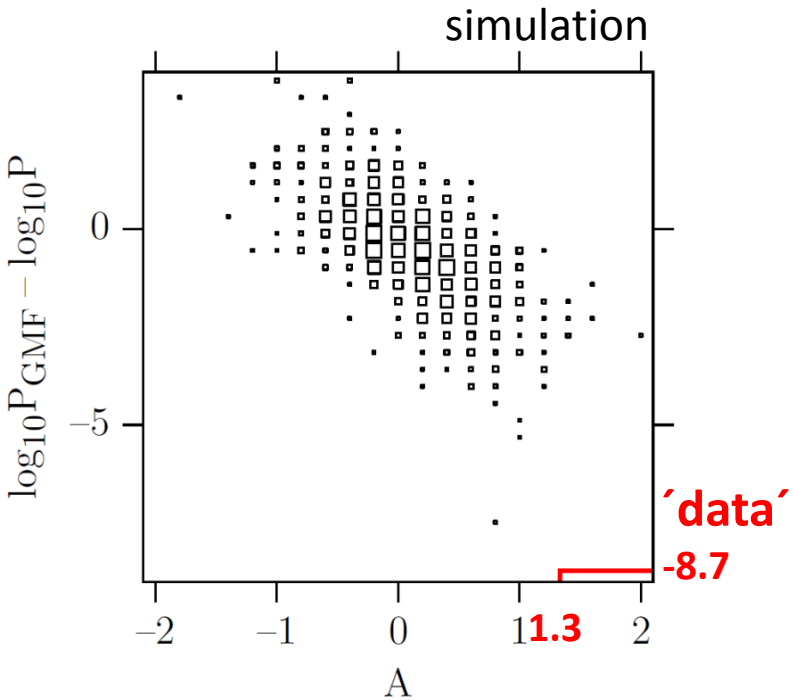
investigations of cosmic particle origin and acceleration enter new phase

BACKUP

Test of sources

Does magnetic field move arbitrary cosmic rays towards AGN directions?

- Nominal **AGN** directions
- Nominal galactic magnetic **field**
- Isotropic **cosmic ray** arrival directions



Directional correlations of sources and cosmic rays can be distinguished