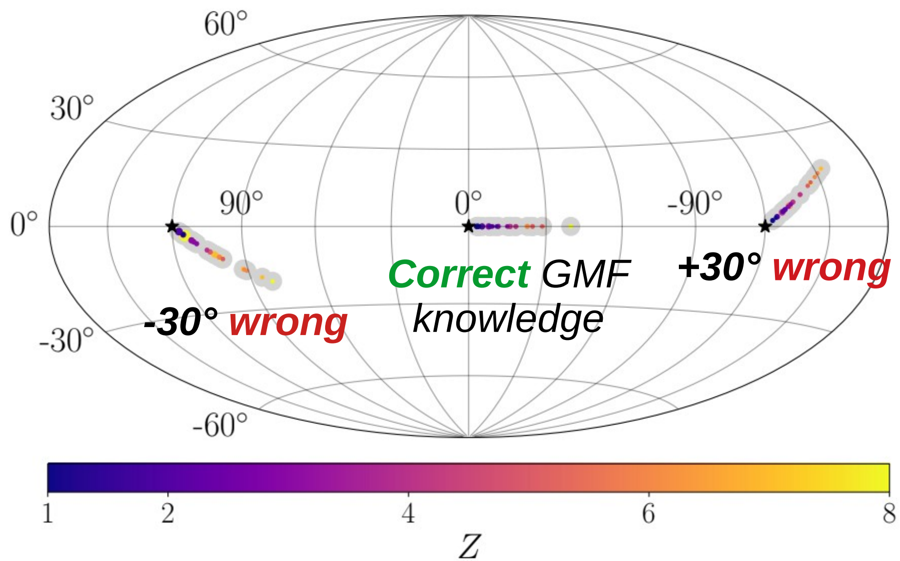
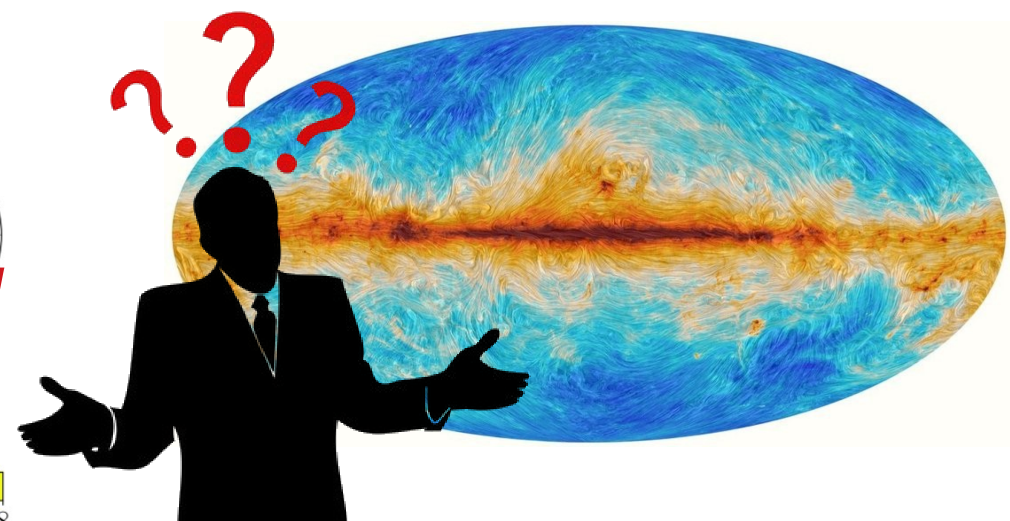
Contracting alignment patterns of mixed composition UHECRs nuclei deflected in the galactic magnetic field

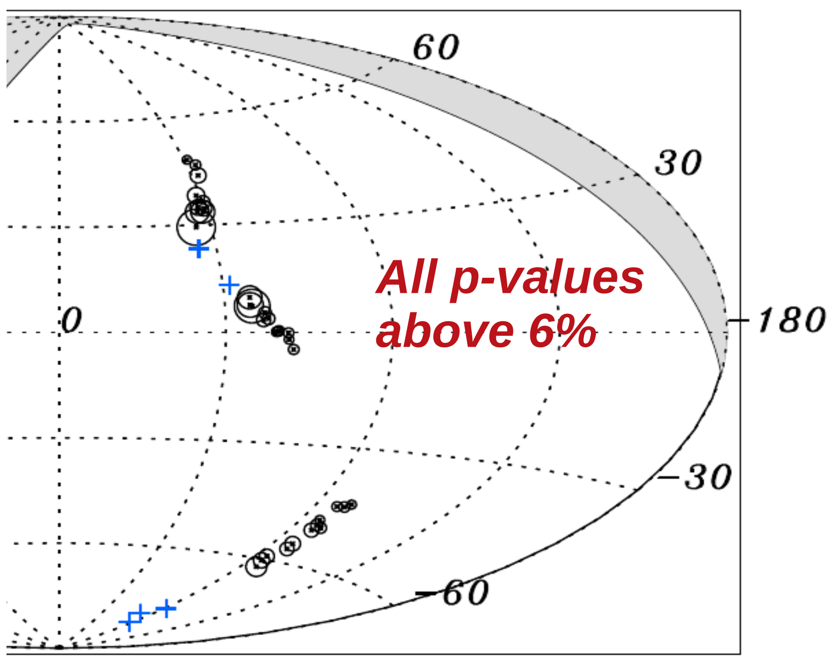


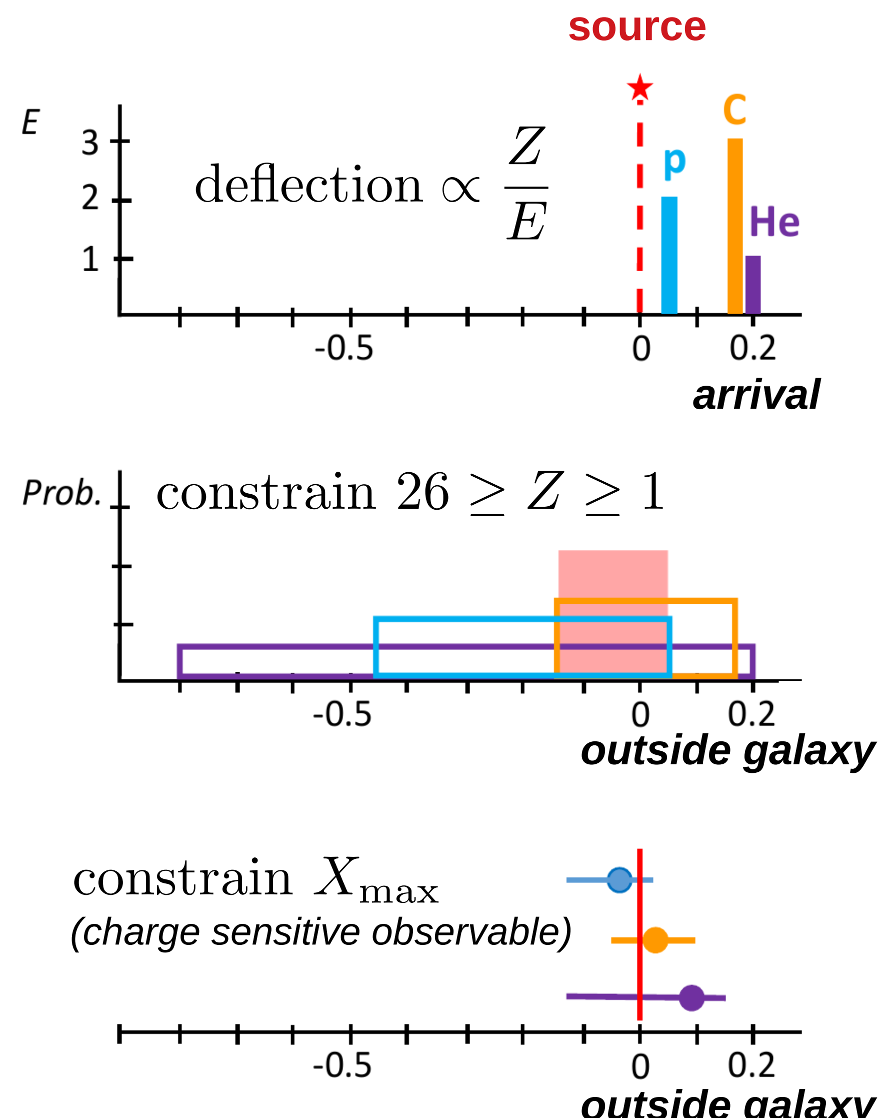


Marcus Wirtz, HAP Workshop 2019, 19.02.2019

Motivation – Search for point source patterns

- ✗ Discovery of a significant energy ordering, would be a discovery of the sources
- ✗ Including charge in "multiplet analysis" would lead to exploding combinatorics

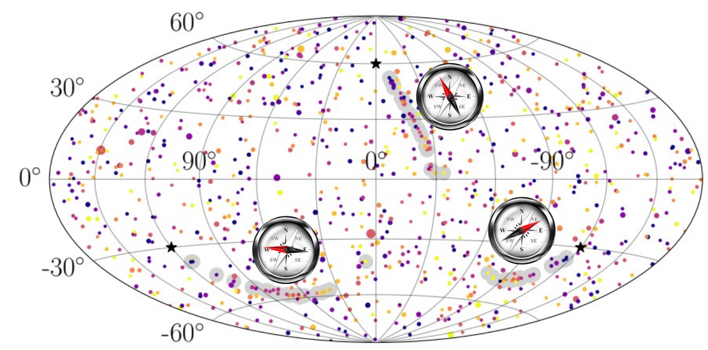




Overview

I. **Contracting alignment patterns**: Simultaneous fit to all cosmic ray charges (~1000) with Tensorflow, to contract alignment patterns given a galactic magnetic field model
(M. Erdmann, L. Geiger, D. Schmidt, M. Urban, M. Wirtz, Astroparticle Physics, 108, 74-83, 2019)

II. **Compass method**: Multi dimensional fit to the galactic magnetic field using strongest occurrences of UHECR aligments



Contracting alignment patterns

Fit Concept

- ✗ Contracting mixed composition multiplets by a fit to all charges and “source positions” with a suitable loss term and a galactic mangnetic field model

“charge” / “source”

$$\begin{pmatrix} \hat{Z}_i \\ \vec{\hat{s}}_i \end{pmatrix} \Longrightarrow T_{\mathrm{GMF}}\left(\vec{\hat{s}}_i, \hat{Z}_i / E_i\right) \Longrightarrow \vec{\hat{p}}_i \Longrightarrow \textsc{Loss}$$

“Fit parameter” *“Transformation”* *“Observed direction”*

- ✗ Defining loss term:

$$L = D + \lambda_C \cdot C + \lambda_Q \cdot Q$$

Minimizing loss by backpropagation technique

“Distance loss”

Keeps arrival directions

$$\frac{1}{N}\sum_i \|\vec{p}_i - \vec{\hat{p}}_i\|^2$$

“Cluster loss”

Clusters source positions in as few directions as possible (preferred along GMF axis)

“Charge loss”

Keeps charges compatibel with their energy and shower depth information

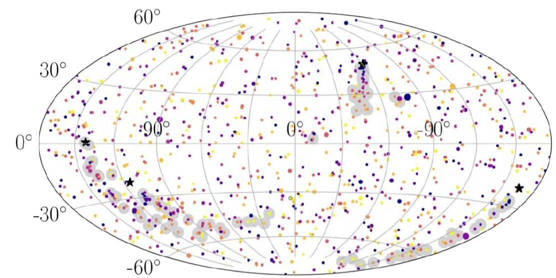
Loss terms

$$L = D + \lambda_C \cdot C + \lambda_Q \cdot Q$$

Three components drive the fit

Distance loss (arrival directions within uncertainties)

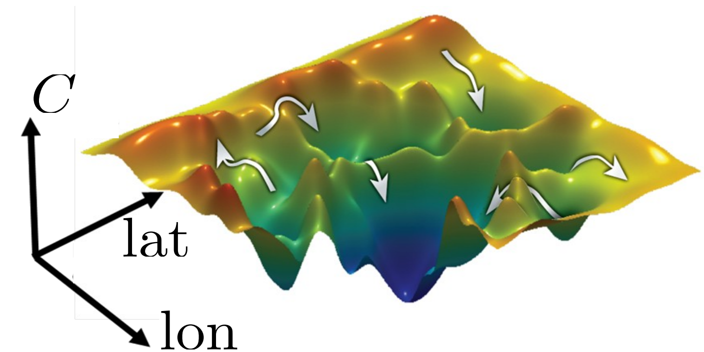
$$D = \frac{1}{N} \sum_i \|\vec{p}_i - \vec{\hat{p}}_i\|^2$$



Entropy like cluster loss (minimize “potential energy”)

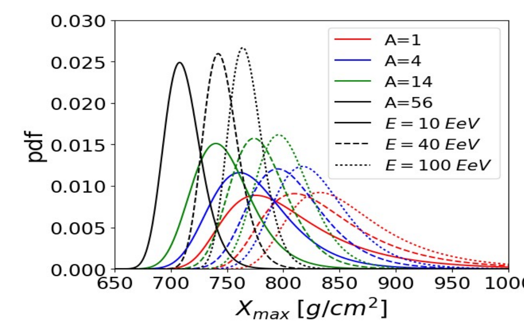
$$C = -\frac{1}{N^2} \sum_i \sum_j \exp((\vec{s}_i \cdot \vec{s}_j - 1)/\sigma_{i,j}^2)$$

“Elliptical fisher distribution”



Compatibility with shower depth distribution

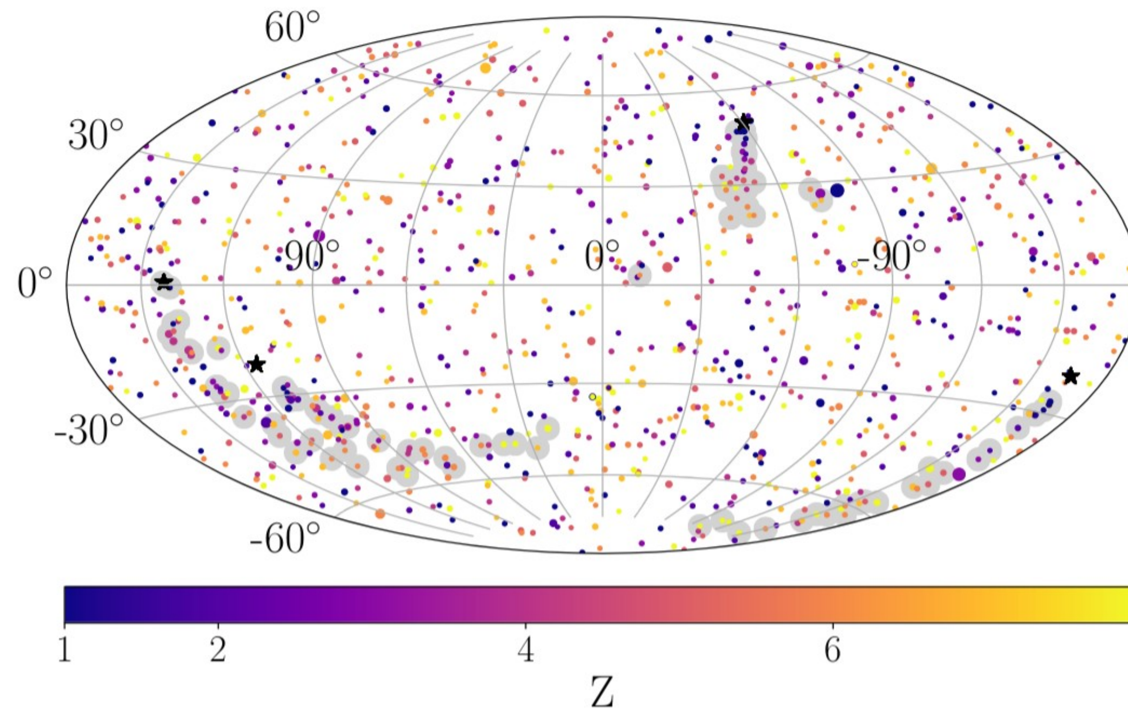
$$Q = \left[\frac{\chi^2}{\mathrm{ndf}} - 1\right]^2 = \left[\frac{1}{N} \sum_i \frac{(X_{\max,i} - \mu_i)^2}{\mathrm{Var}(G(\hat{A}_i, E_i))} - 1\right]^2$$



Scenario for realistic deflection model

- ✗ Cosmic rays follow AUGER energy spectrum, E > 40 EeV
- ✗ Charge uniform up to CNO group (Z = 1 … 8)
- ✗ 4 sources each emitting 25 CRs + 900 background CRs
- ✗ Deflection model:
  JF12 galactic field model
  + rigidity dependent smearing

$$\sigma = \frac{0.5 \cdot Z}{E/\mathrm{EeV}}\,\mathrm{rad}$$



⇨ How to transport gradients over an arbitrary galactic field transformation?

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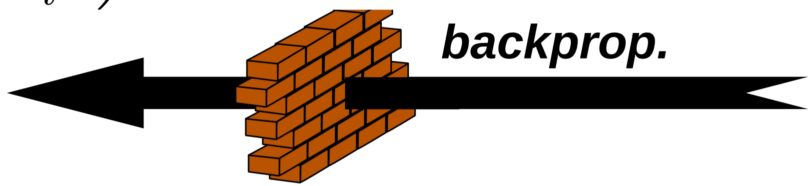
MagNet – Deep neural network for GMF transformation

✗ The transformation of directions outside our galaxy to observed directions is not differentiable (depends on magnetic field model)

$$\begin{pmatrix}\hat{Z}_i\\ \vec{\hat{s}}_i\end{pmatrix} \Longrightarrow T_{\mathrm{JF12}}\left(\vec{\hat{s}}_i, \hat{Z}_i/E_i\right) \Longrightarrow \vec{\hat{p}}_i \Longrightarrow \textsc{Loss}$$



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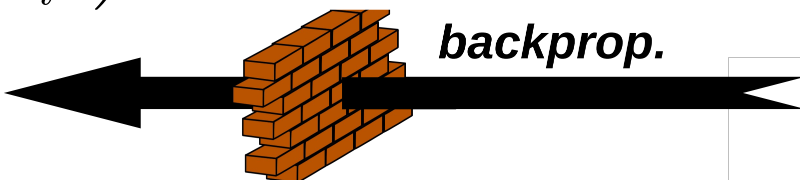
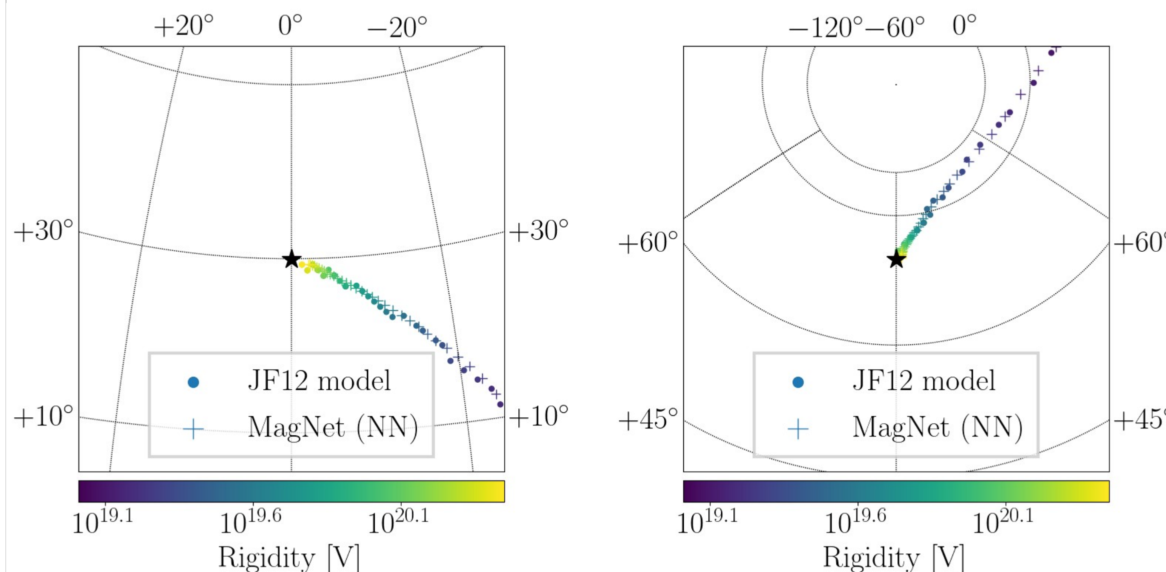


- ✗ Deep neural network learns (5 layers, 100 nodes):

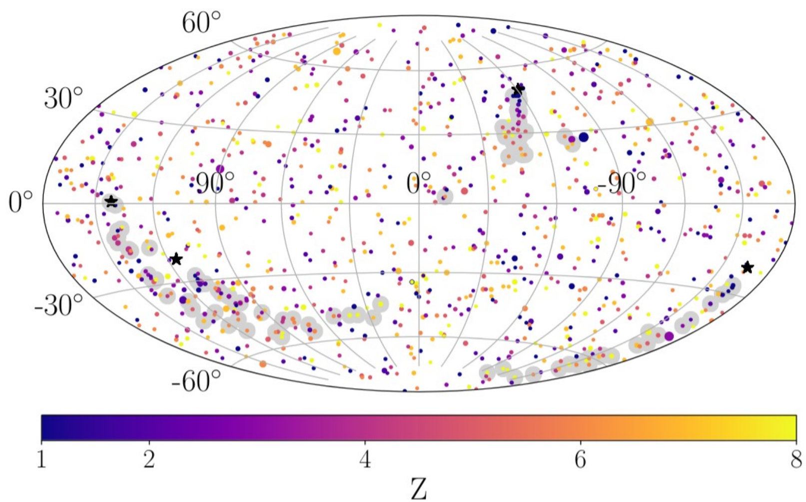
$$T_{\mathrm{GMF}}\left(\vec{s}_i, R_i\right) \Longrightarrow \vec{\hat{p}}_i$$

Network is able to interpolate between simulated spatial points and rigidities

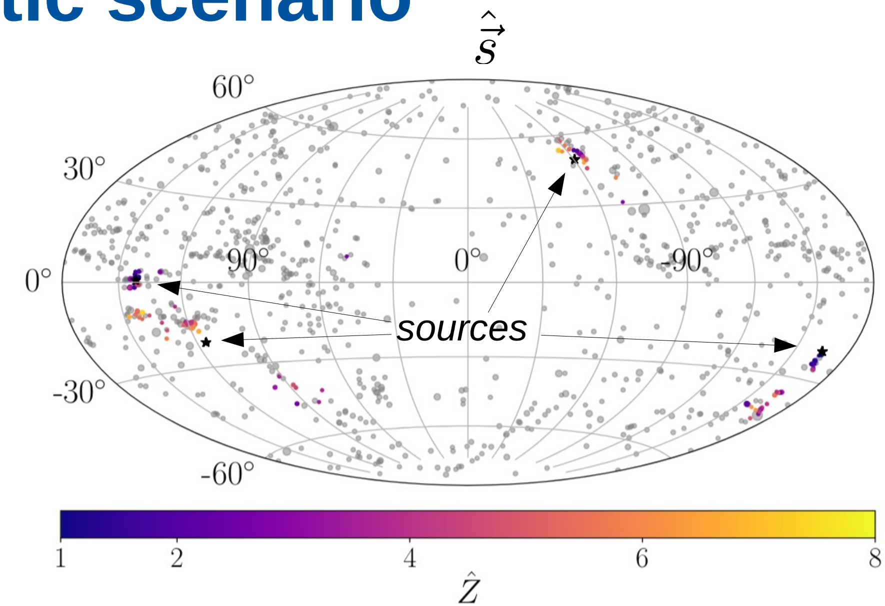


Fit results on realistic scenario

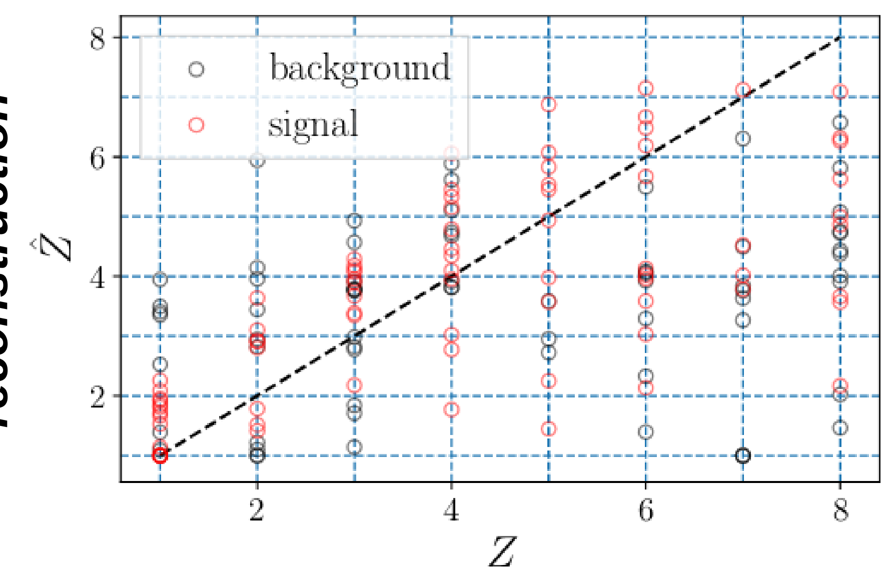
- ✗ Cosmic rays follow AUGER energy spectrum, E > 40 EeV
- ✗ Charge uniform up to CNO group (Z = 1 … 8)
- ✗ 4 x 25 signal; 900 isotropic CRs
- ✗ Deflection: JF12 model + blurring



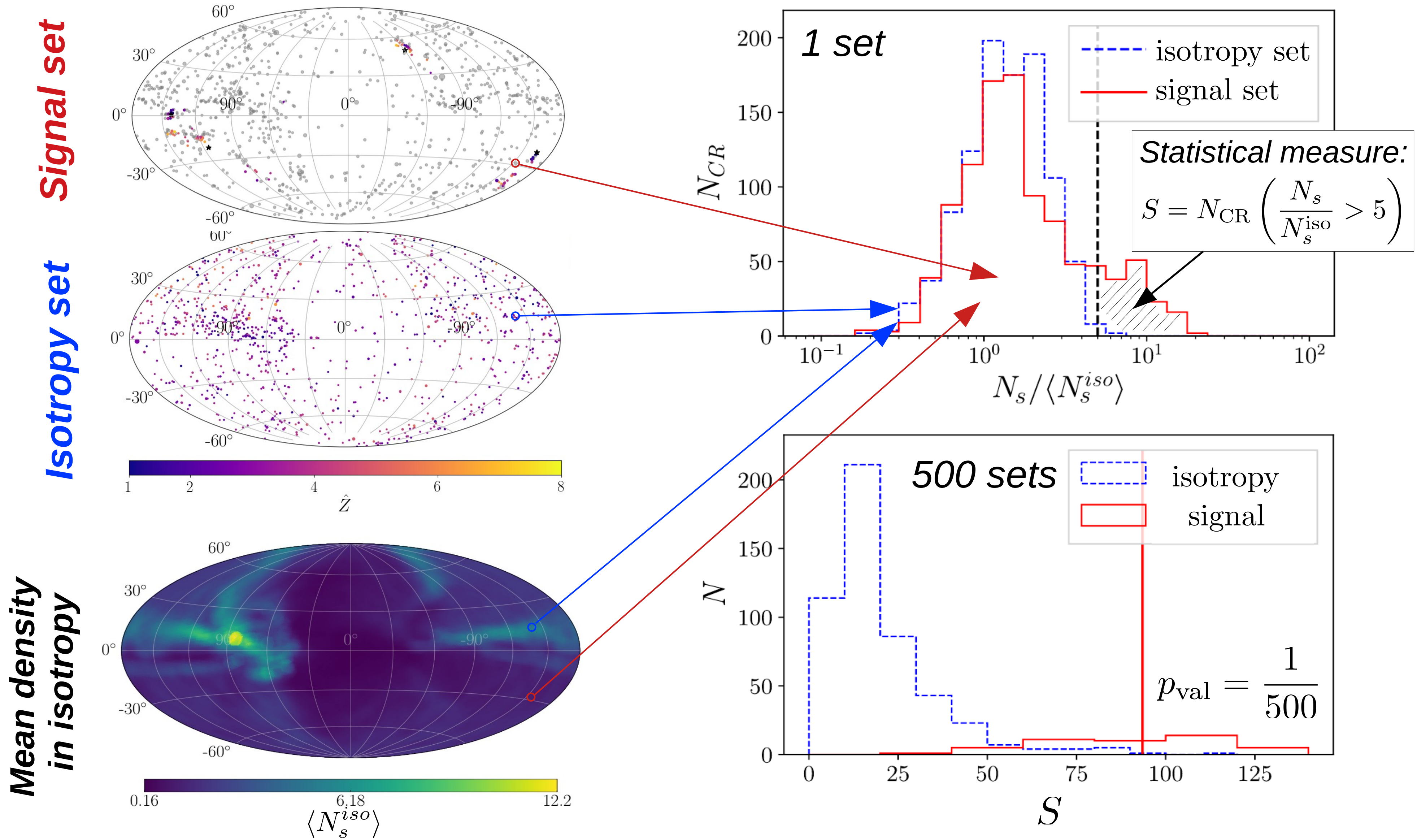
Found cluster



Charge reconstruction

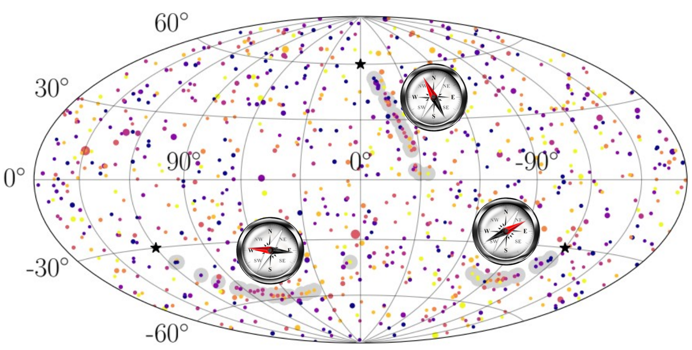


Evaluate sensitivity on realistic scenario



“How to deal with unknown galactic magnetic field?”

Compass method



Parametrize new deflection model

- ✗ Most important uncertainty in the galactic magnetic field for cosmic ray deflection is the directional deflection

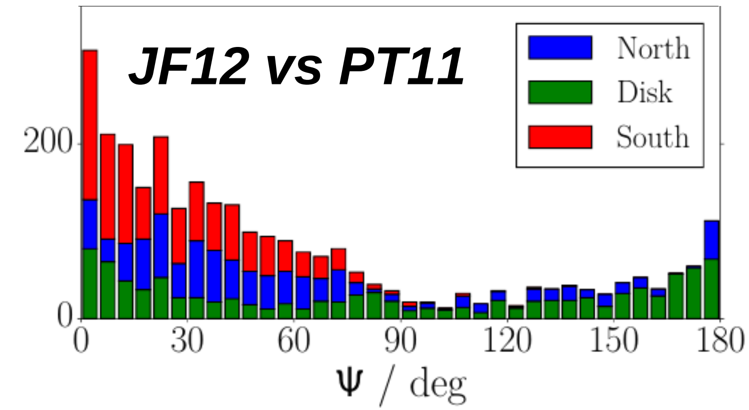
- ✗ Fit parameters for the GMF uncertainties defined for few fixed points on sphere:

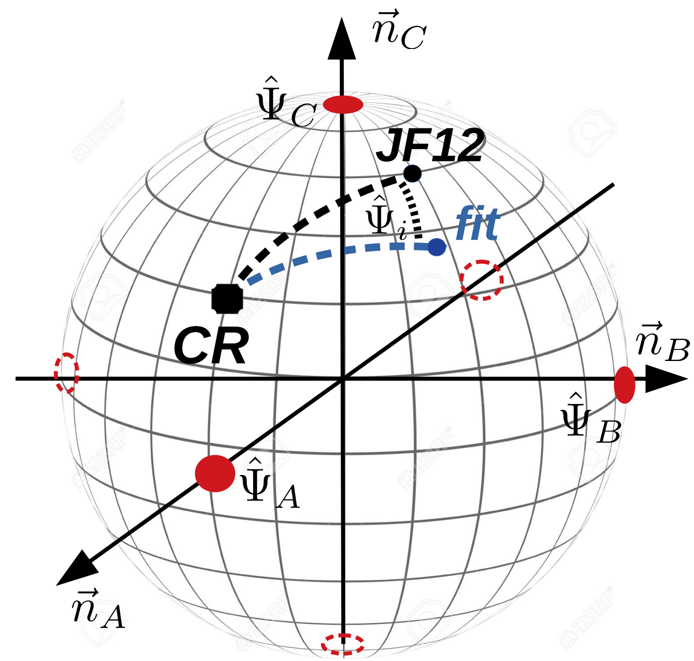
$$\underline{\hat{\Psi}} = \left(\hat{\Psi}_A, \hat{\Psi}_B, \ldots\right)$$

- ✗ For the $\hat{\Psi}_i$ angle of a certain cosmic ray, interpolate values of the different regions:

$$\hat{\Psi}_i = \frac{\sum_k \exp((\vec{p}_i \cdot \vec{n}_k)/r^2_{\mathrm{inter}}) \cdot \hat{\Psi}_k}{\sum_k \exp((\vec{p}_i \cdot \vec{n}_k)/r^2_{\mathrm{inter}})}$$

⇒ Using Healpy nside=2 (48 points) as interpolation points





Fit concept

- ✗ Define ellipses around all observed cosmic rays, with major axis aligned with the local Psi

$$L = C + \lambda_{MF} \cdot MF$$

by varying the Psi fit parameters

Entropy like cluster loss (minimize “potential energy”)

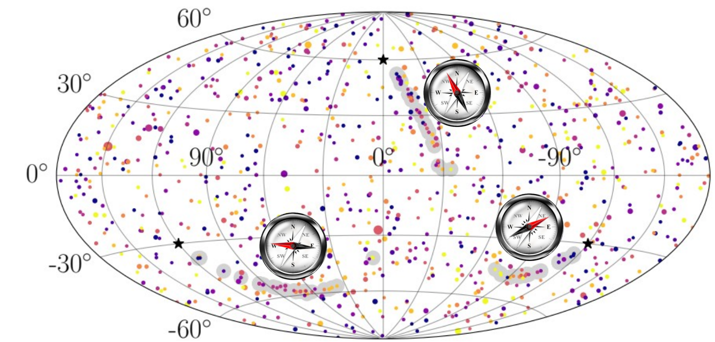
$$C = -\frac{1}{N^2} \sum_i \sum_j \exp((\vec{p}_i \cdot \vec{p}_j - 1)/\sigma(\Psi_i, \vec{p}_j)^2)$$

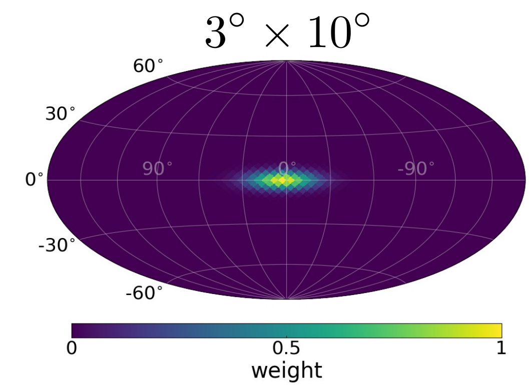
“Elliptical Fisher distribution”

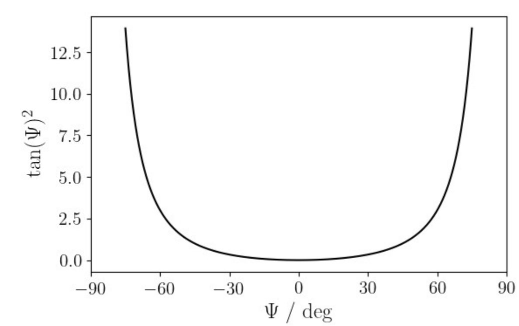
Penalize too large deviations from model prediction

$$MF = \sum_{\hat{\Psi}_k \in \underline{\hat{\Psi}}} \tan(\hat{\Psi}_k)^2$$

Fit avoids values Psi > 90°







Benchmark simulation

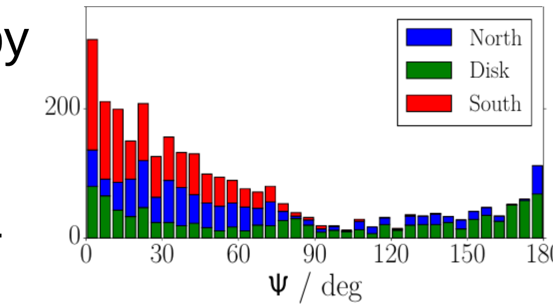
Astrophysical scenario

- Auger energy spectrum, E > 40 EeV
- 4 sources each emitting 25 CRs + 900 background CRs
- Charges uniformly between 1 and 8
- Deflection model:
  JF12 galactic field model
  + rigidity dependent smearing

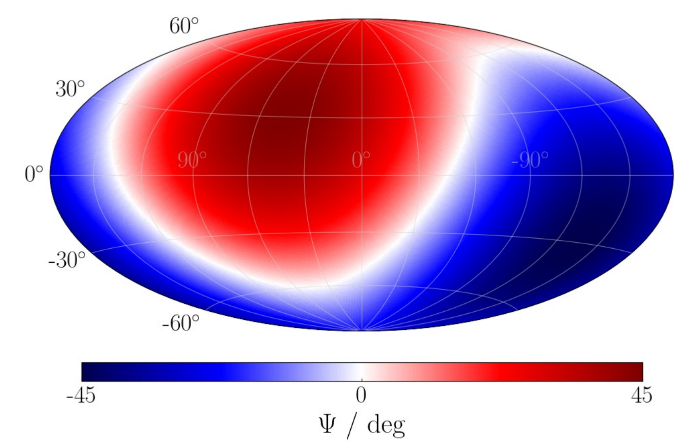
$$\sigma = \frac{1.0 \cdot Z}{E/\mathrm{EeV}}\,\mathrm{rad}$$

Simulated GMF uncertainty

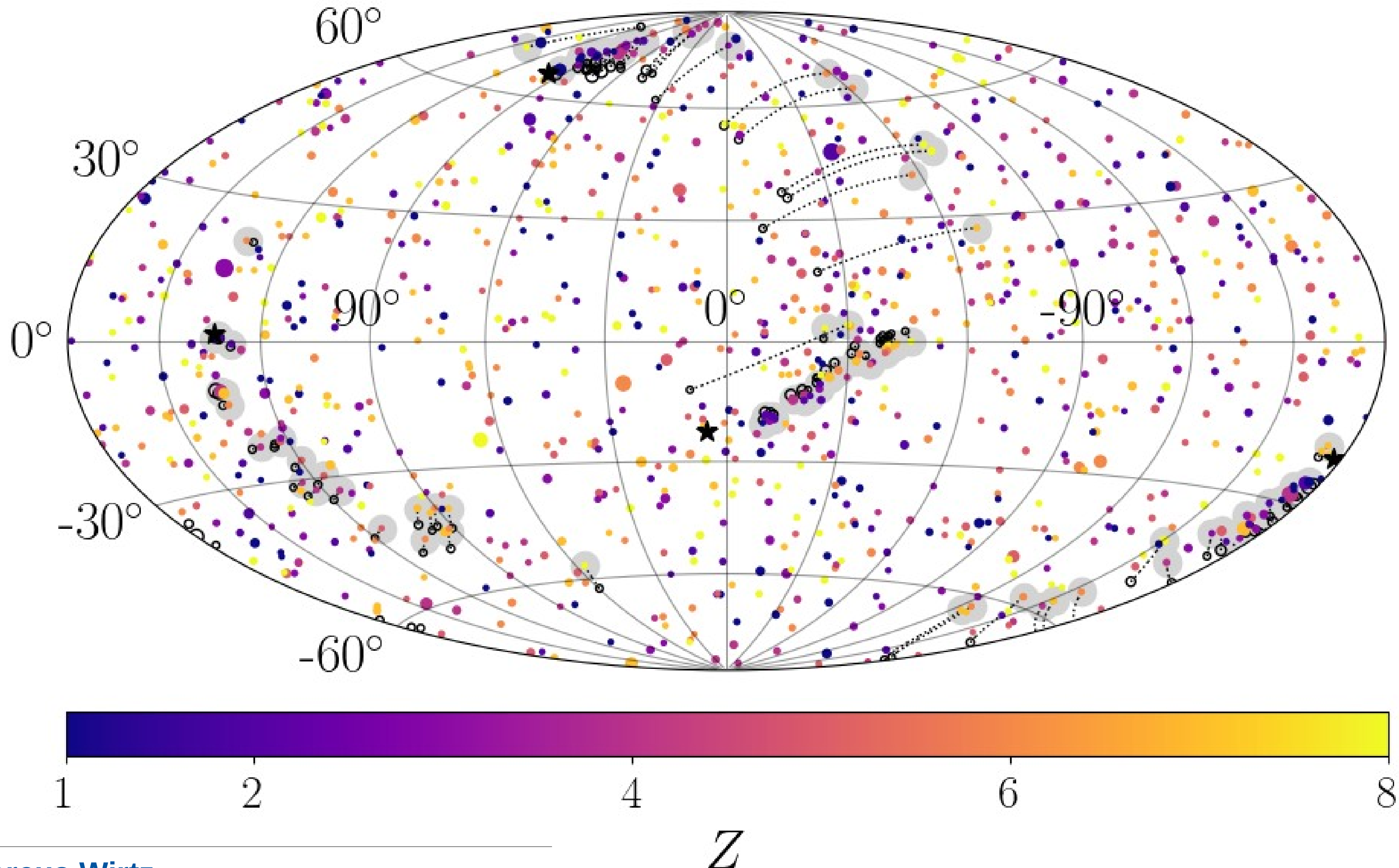
- Motivated by differences between JF12, PT11



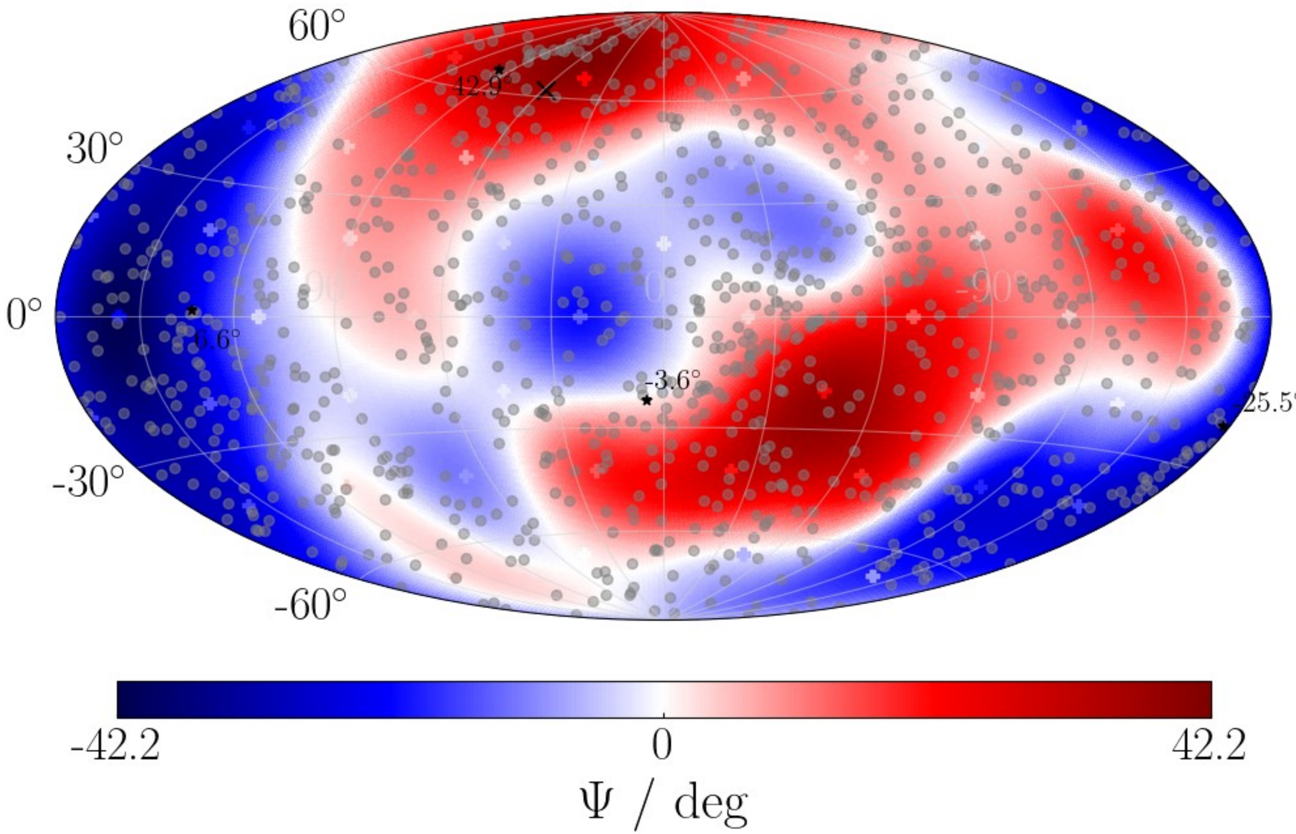
- Create a dipolar modulation of the psi angle, with random direction and amplitude of 45 degrees



Benchmark simulation



Reconstructed Psi angle for galactic field correction



- ✗ Interpolation scheme provides psi angles which can change on intermediate scales
- ✗ The psi angles of the 4 sources [43°, 7°, -4°, -26°] are well reconstructed

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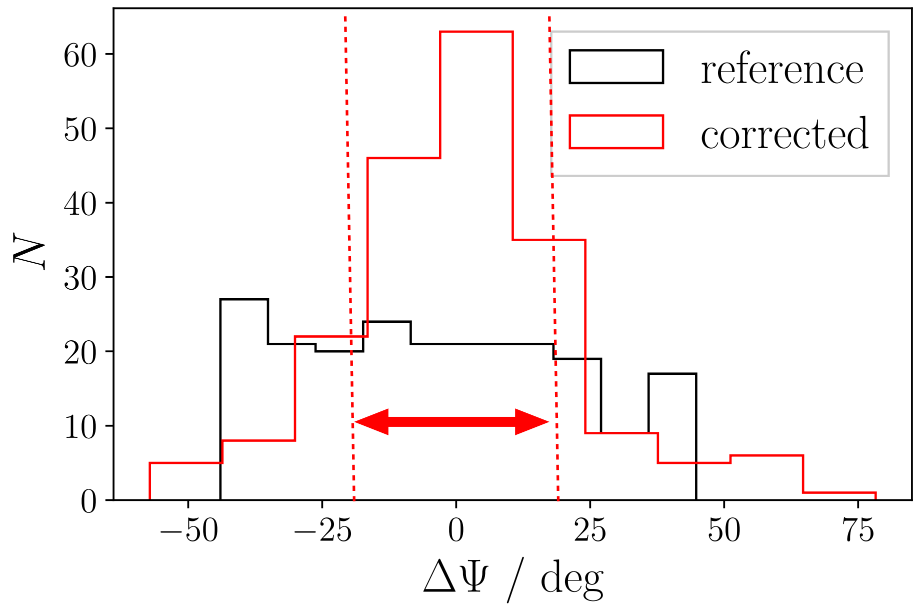
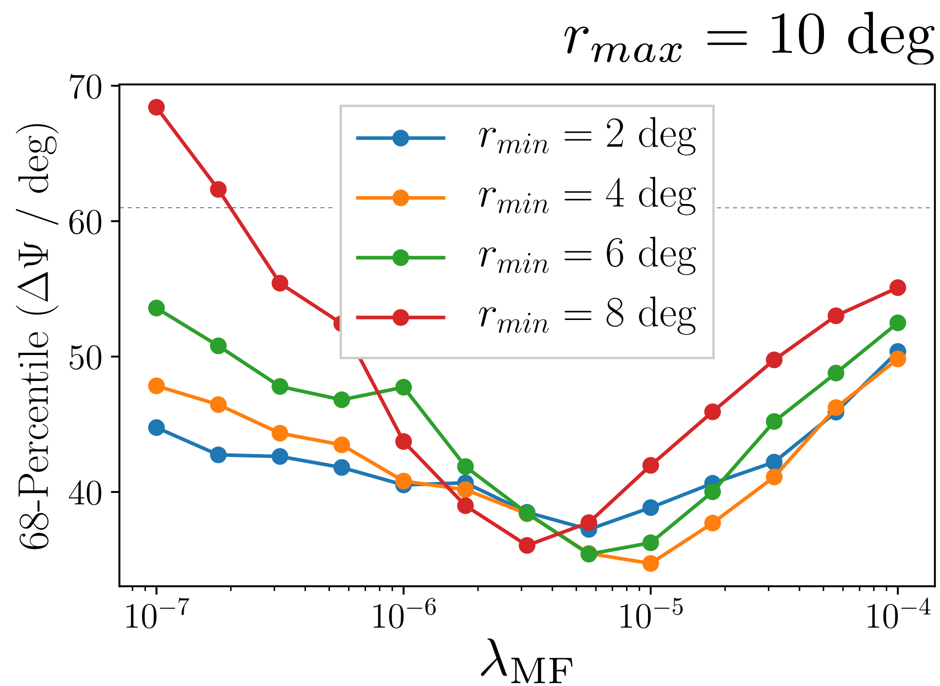
Reconstruction quality





- ✗ Deviation before and after re-construction for 200 scenarios
- ✗ Fit clearly decreases the width of the psi deviation

- ✗ Width of the psi distribution as function of the loss weight, for different ellipse widths
- ✗ Scale of roughly 2:1 in the ellipse shape yields best reconstruction

Summary

Contracting alignment patterns

- ✗ Multi-dimensional tensorflow based fit, to contract aligned patterns in the arrival directions of UHECRs to their sources
- ✗ Works well on simulated astrophysical scenarios, given that deflections in the galactic magnetic field are known

Compass method

- ✗ Approach to fit a deflection model itself by elliptical potentials around each cosmic ray, which rotate according to the local alignments
- ✗ First benchmark studies show a promising reconstruction quality even in high turbulent scattering

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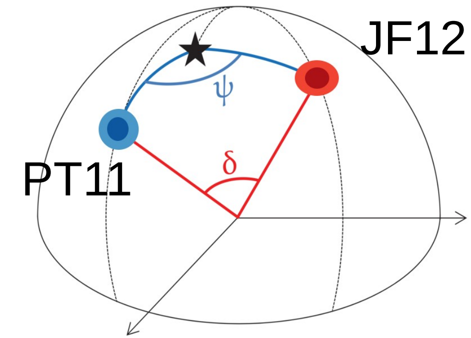
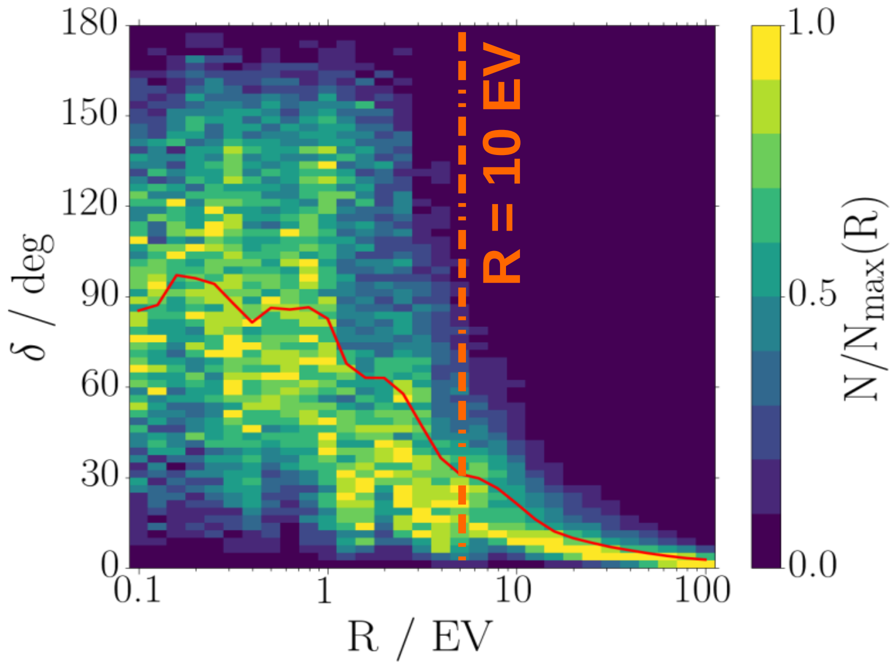
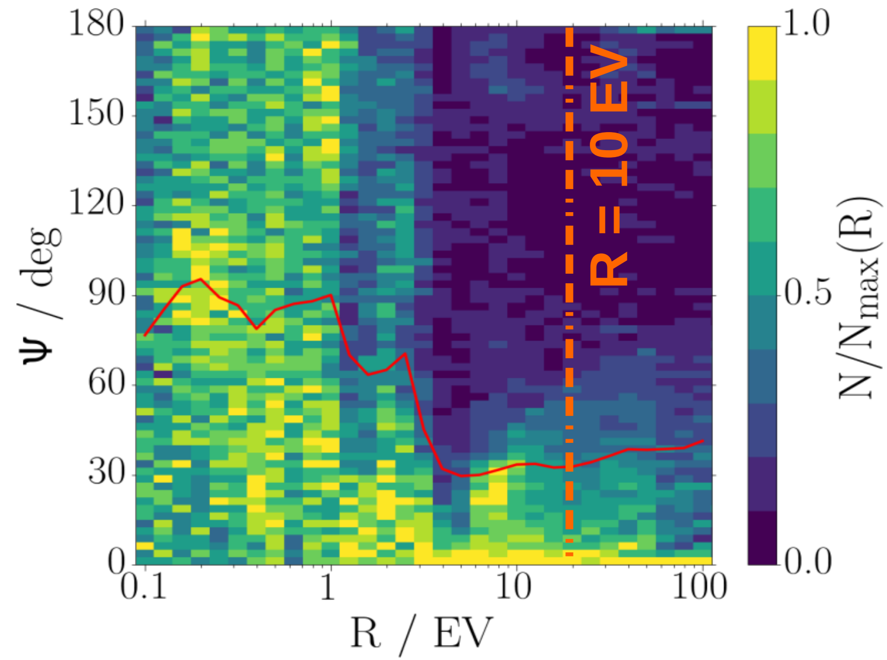
Backup

Reliability of galactic magnetic field models







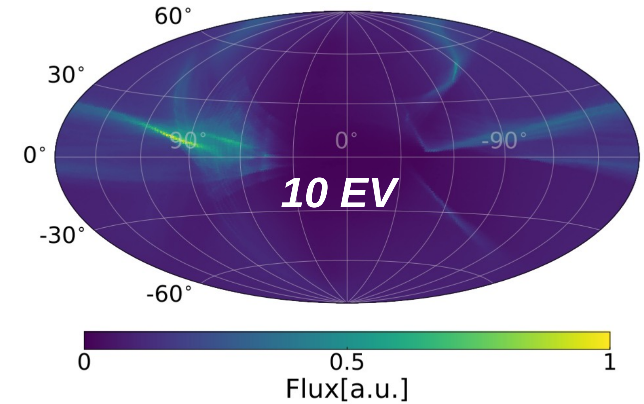
B1

Directional differences between GMF models in median below 40° (remaining offset: blurring)

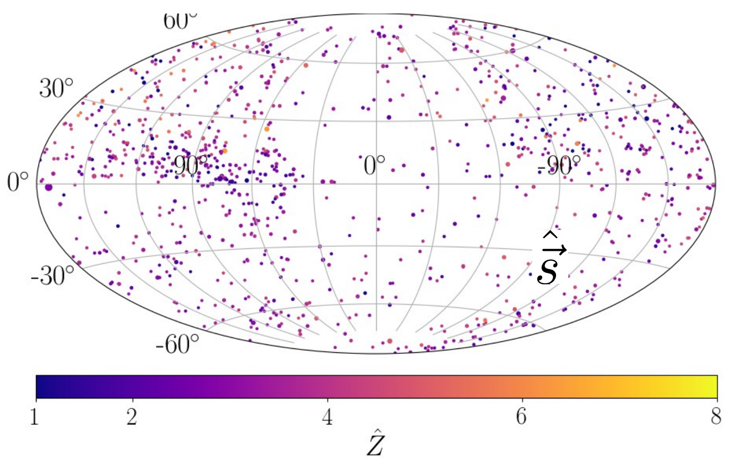
Fit results on isotropy...

- ✗ Cosmic rays follow AUGER energy spectrum, E > 40 EeV
- ✗ Charge uniform up to CNO group (Z = 1 … 8)
- ✗ Arrival directions isotropic

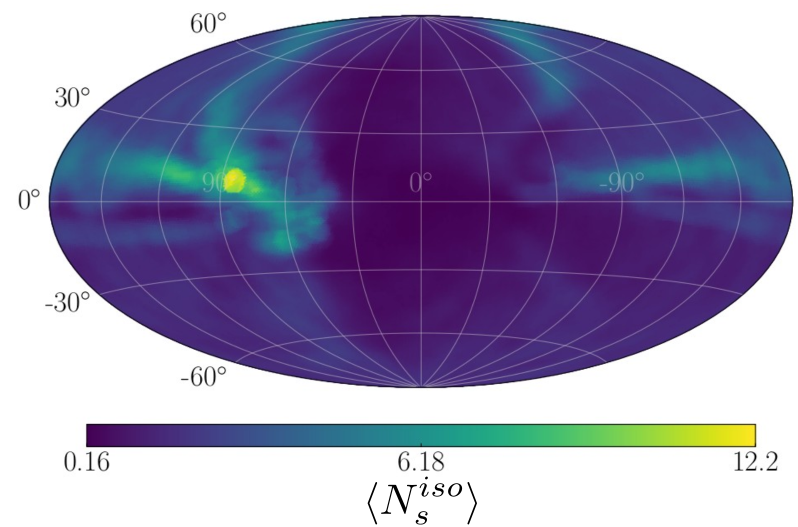
For comparison:
Isotropic backtracking



Converged fit result

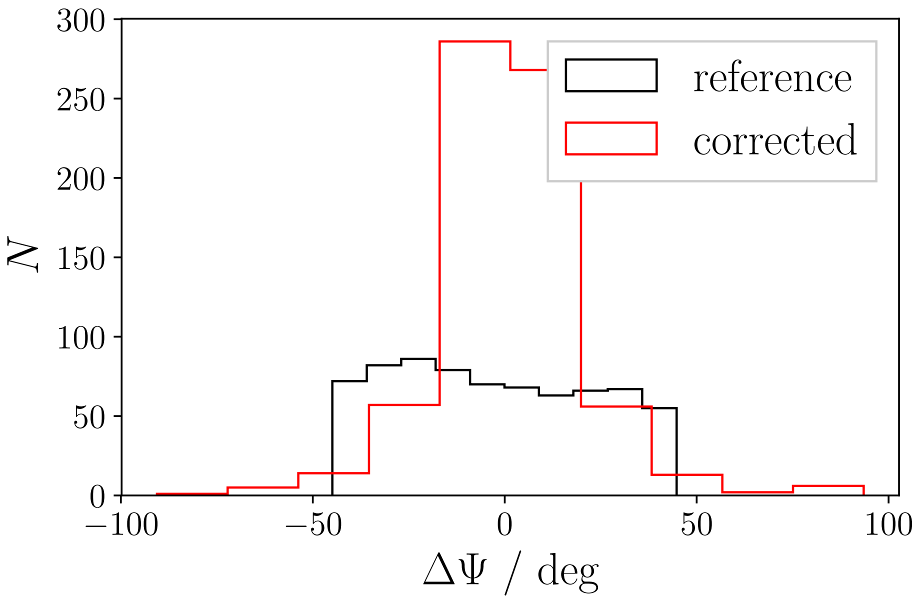


Run 500 times and create mean isotropic 5°- tophat map

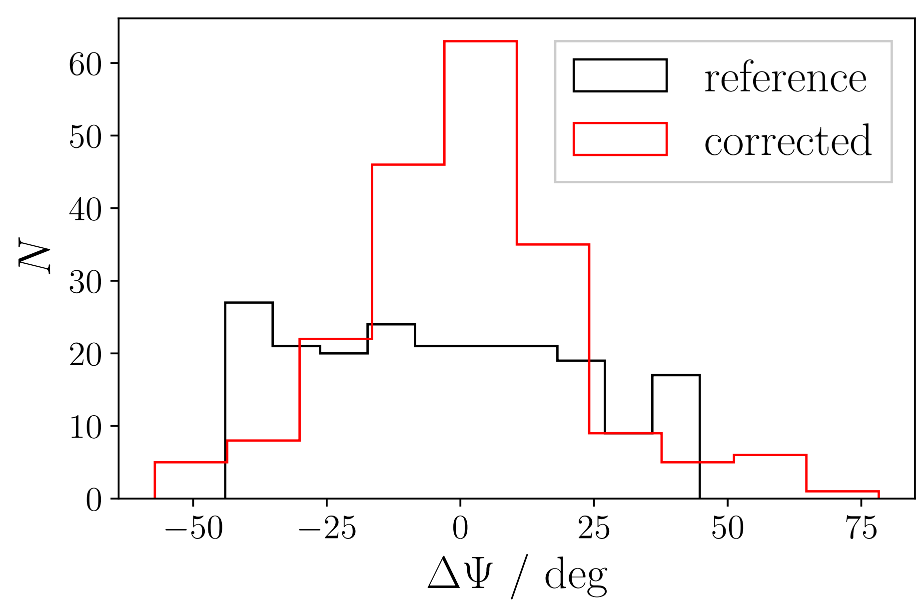


Compass method – Reconstruction on only coherent

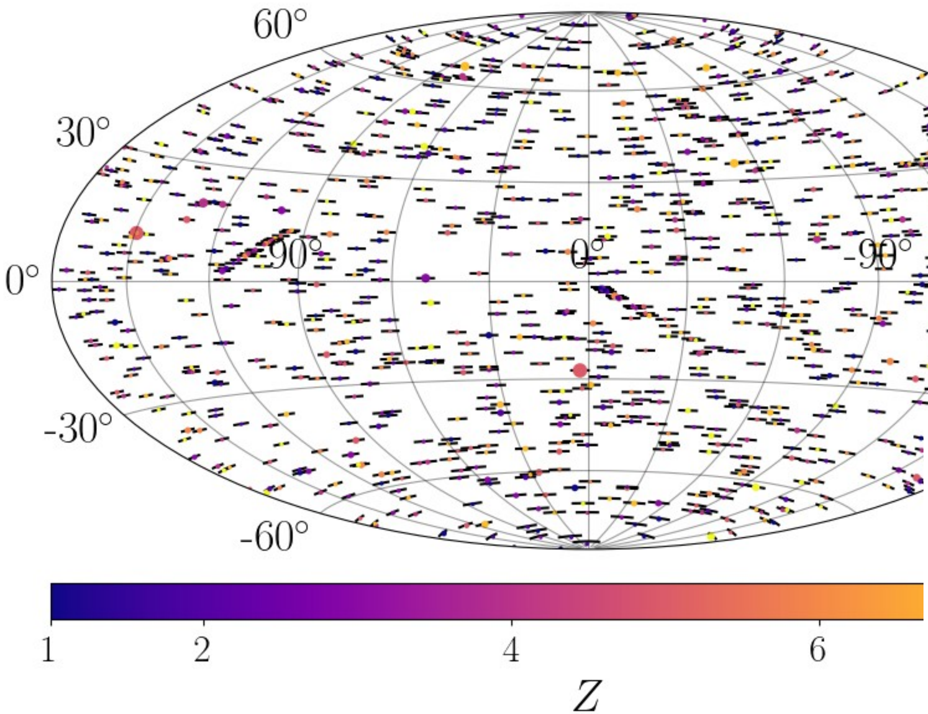
$$\sigma = 0\,\mathrm{rad}$$

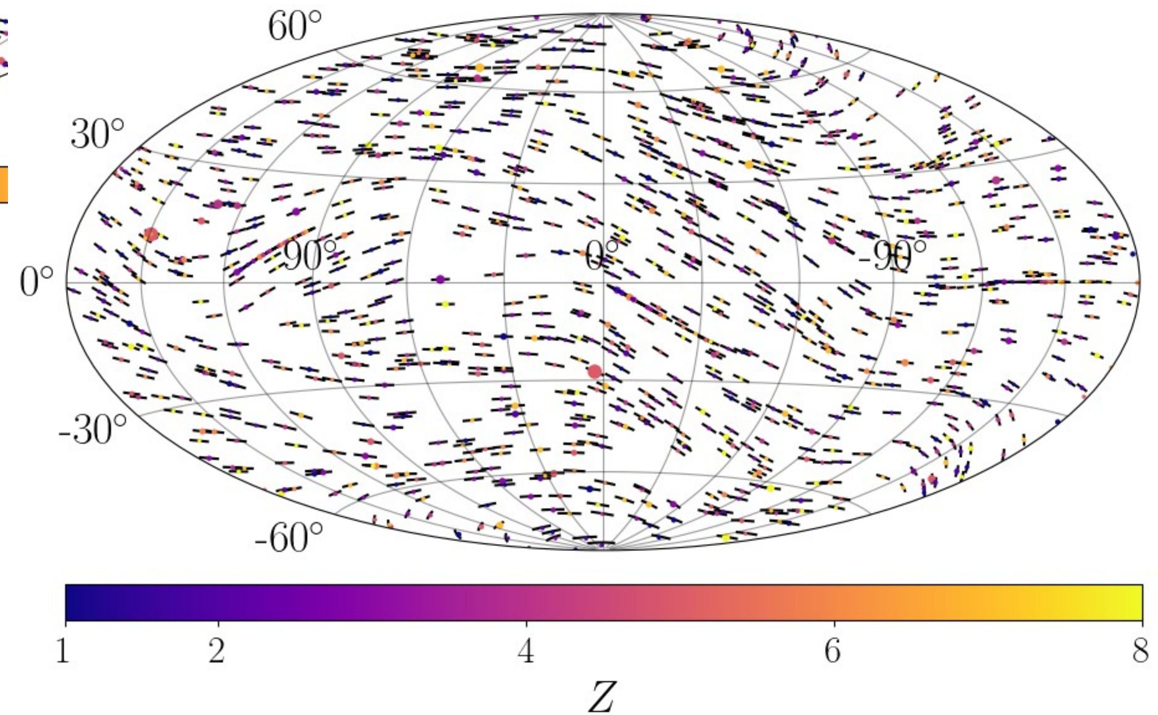


$$\sigma = \frac{1.0 \cdot Z}{E/\mathrm{EeV}}\,\mathrm{rad}$$



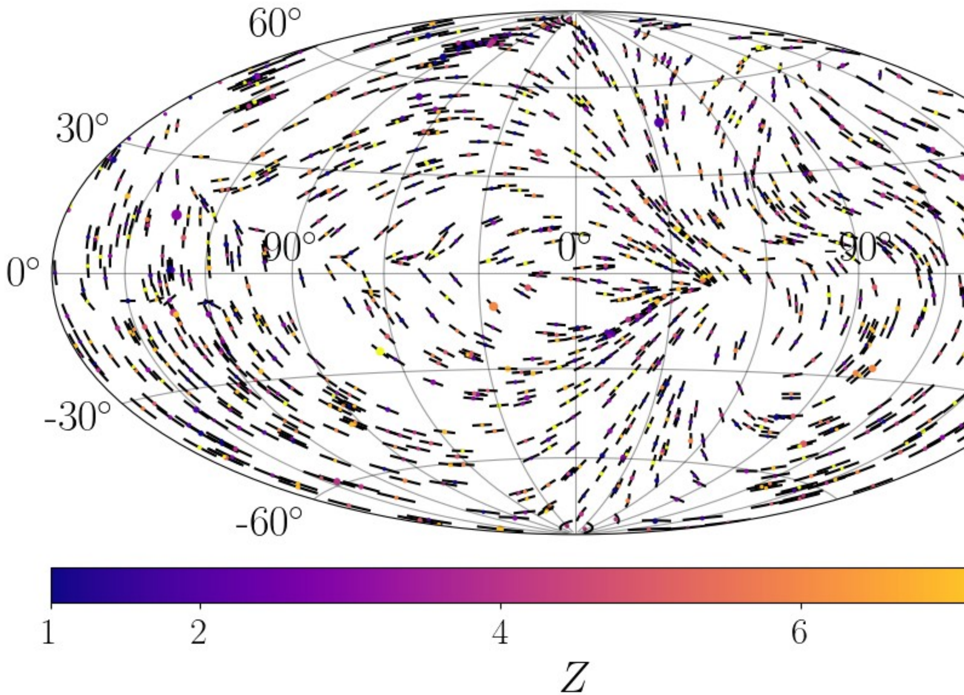
Compass visualization – Toy setup

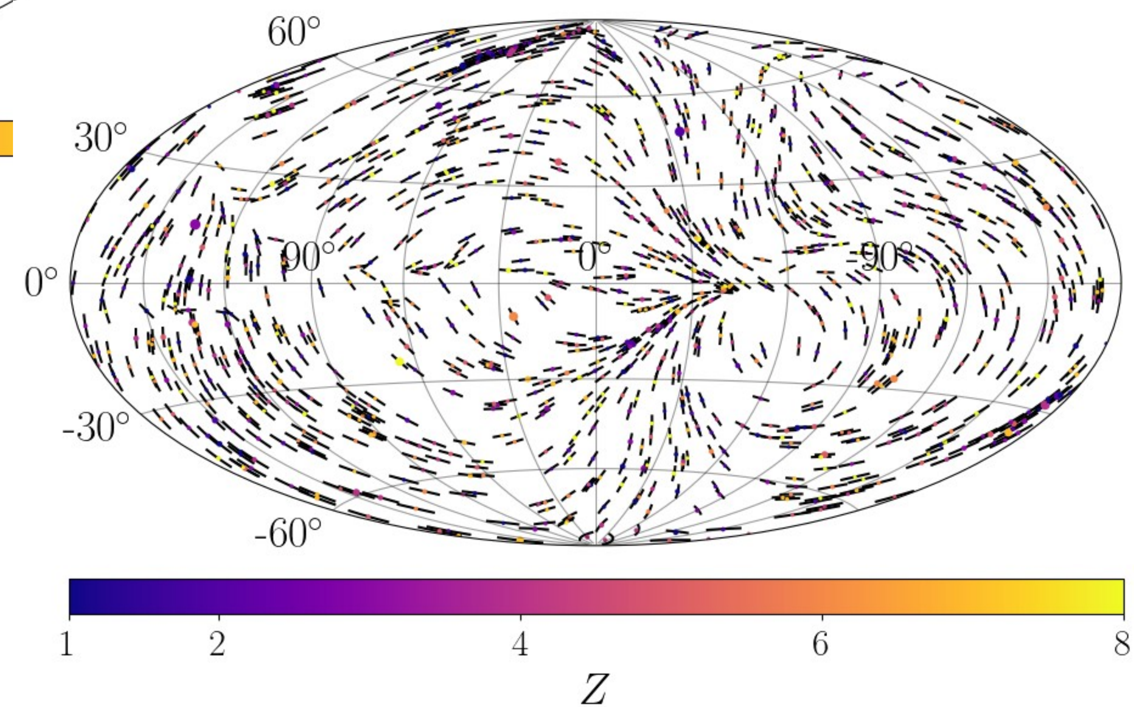




B4

Compass visualization – JF12 model





B5