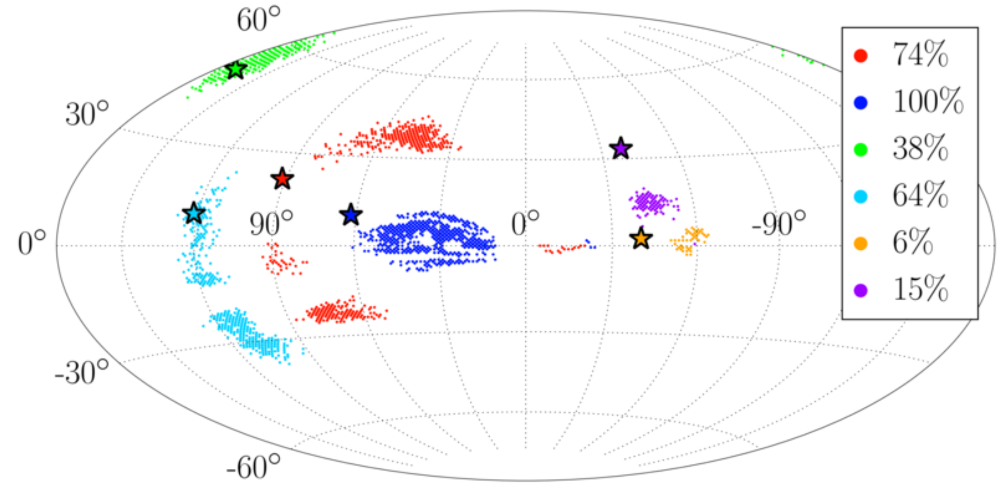
Impact of the galactic magnetic field on cosmic ray arrival

The nuclear window to the extragalactic universe
→ arXiv:1607.01645 (submitted to ApJ)

Search for patterns by combining cosmic ray energy and arrival directions at the Pierre Auger Observatory
→ Eur. Phys. J. C (2015) 75: 269

Arrival scenario for point sources



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22th Sep. 2016

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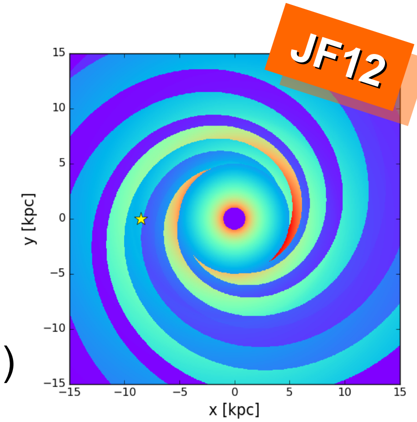
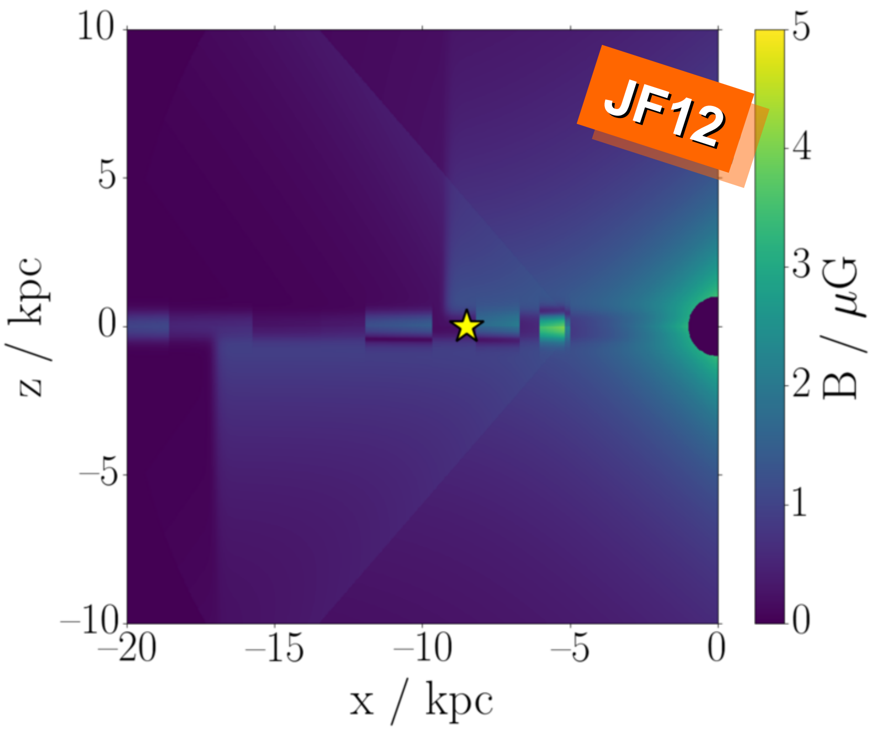
Galactic magnetic field - parametrizations

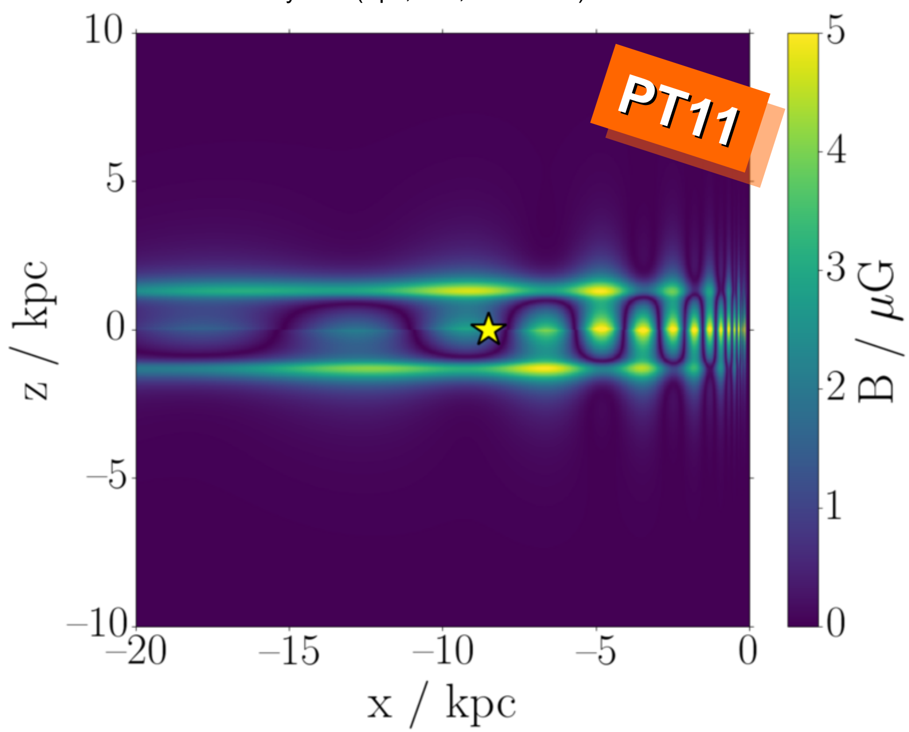
✗ Models tuned to measurements
(e.g. rotation measurements, synchrotron radiation)



Jansson & Farrar (ApJ, 757, 14: 2012)

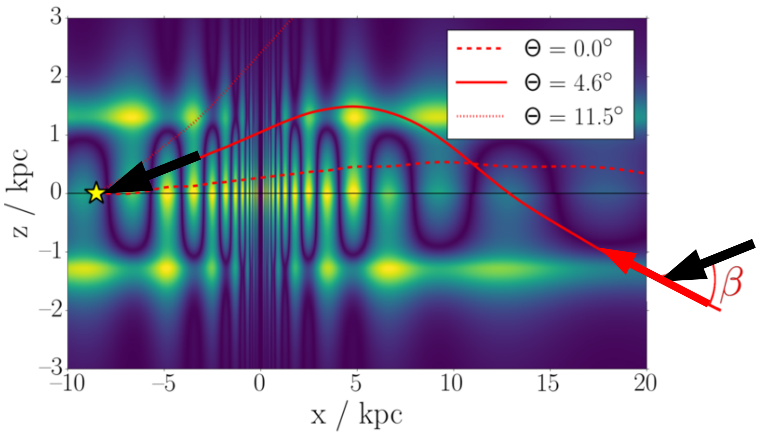


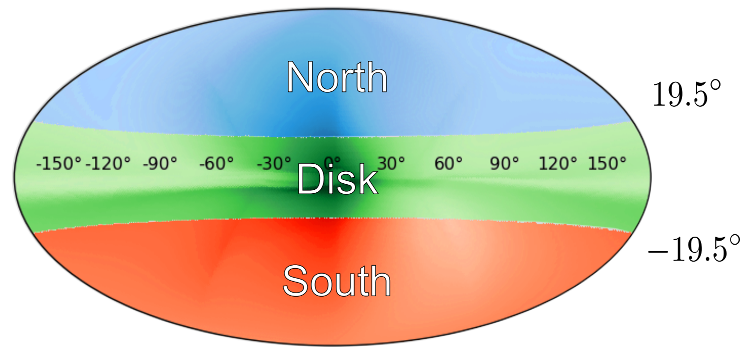
Pshirkov & Tinyakov (ApJ, 738, 192: 2011)

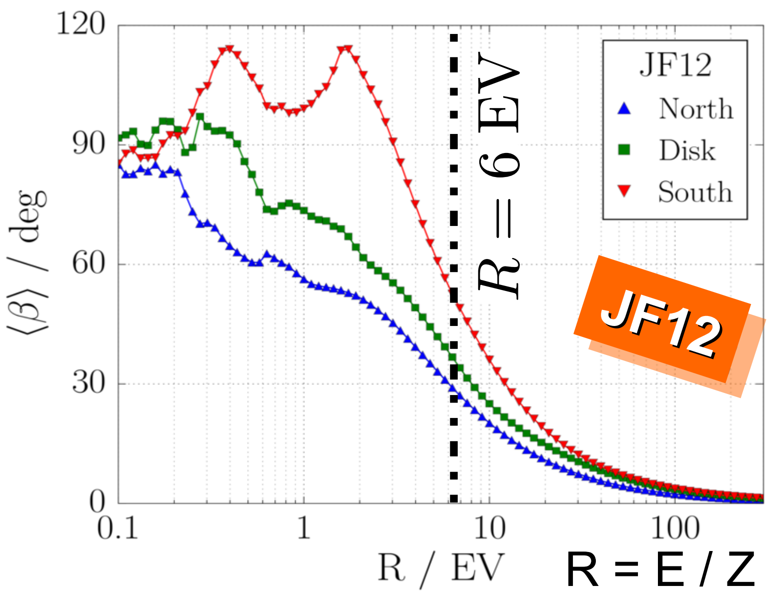


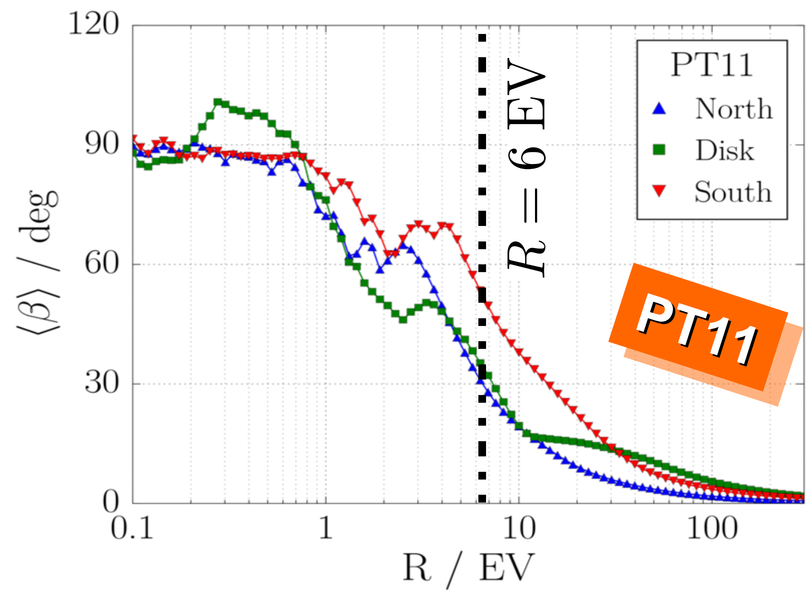
⇨ How do they effect cosmic ray propagation?

Angular deflections



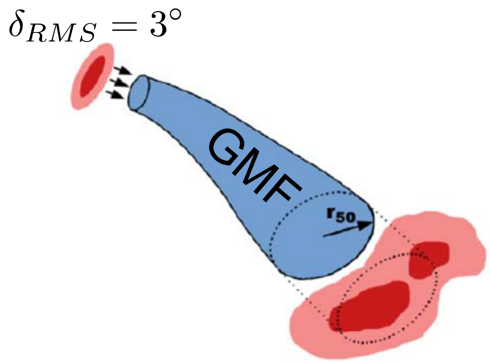




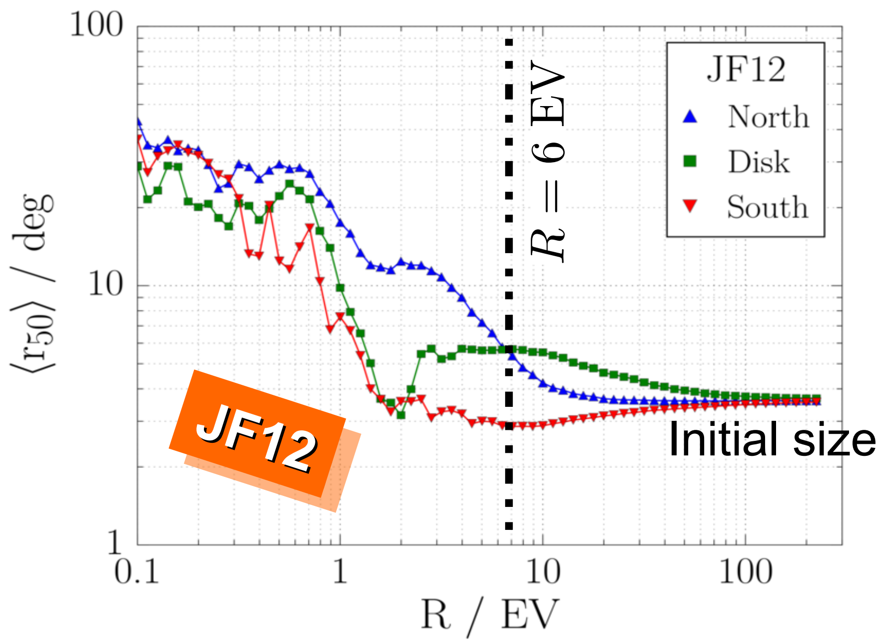


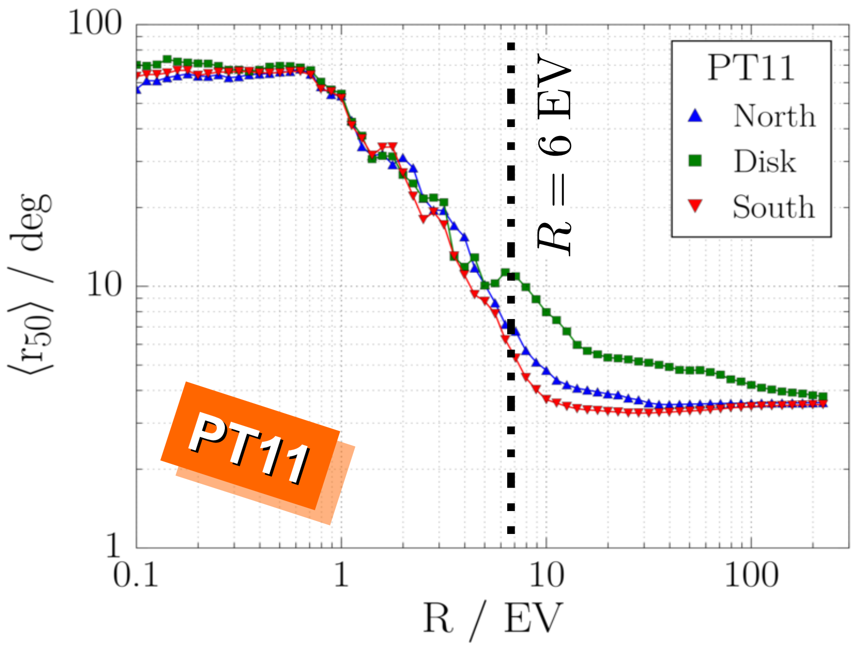
✗ Moderate deflections for rigidities E / Z > 6 EV

Dispersion by field



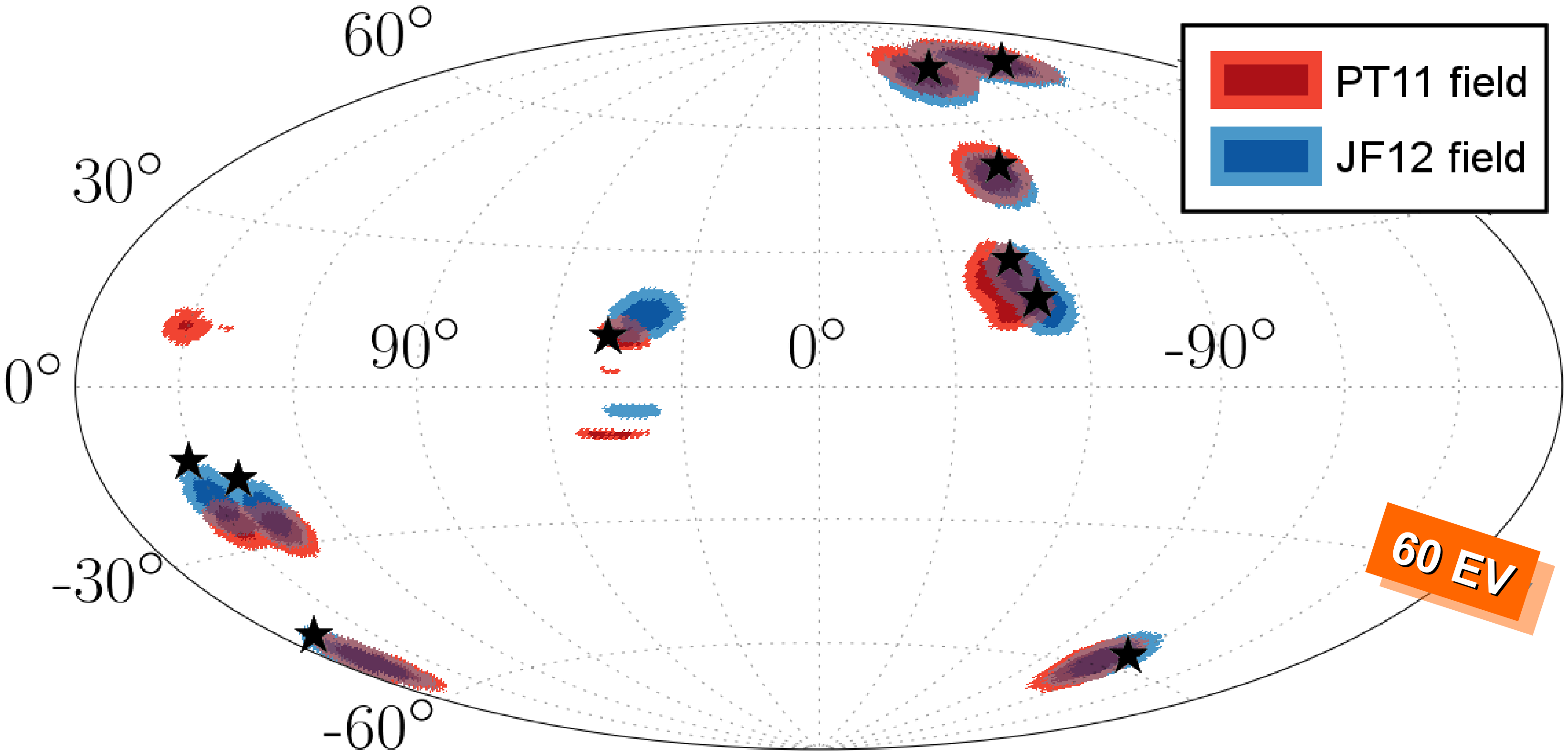
r50=smallest radius containing 50% of arrival probability

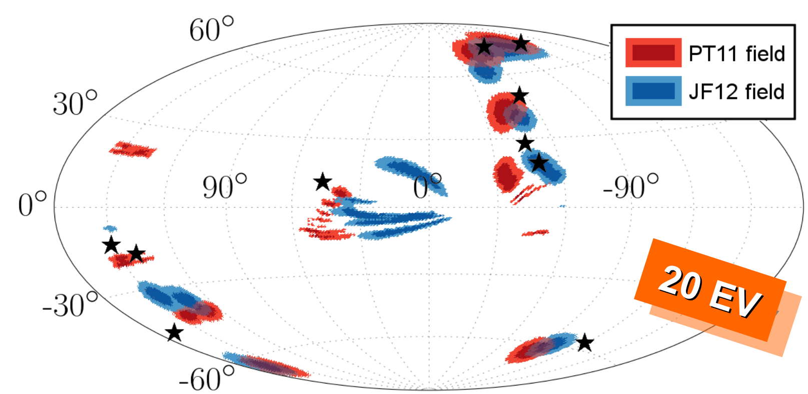




- ✗ Defocusing and focusing effects depending on energy and direction
- ✗ Size for R > 6 EV is mostly conserved !

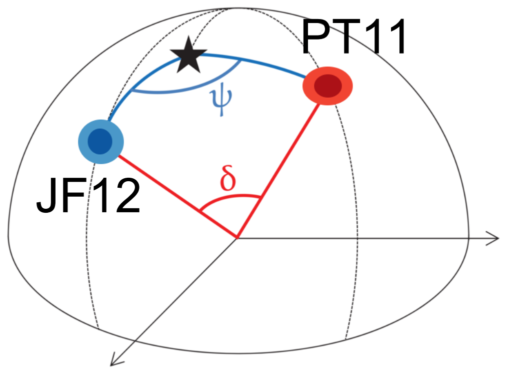
Example arrival distributions

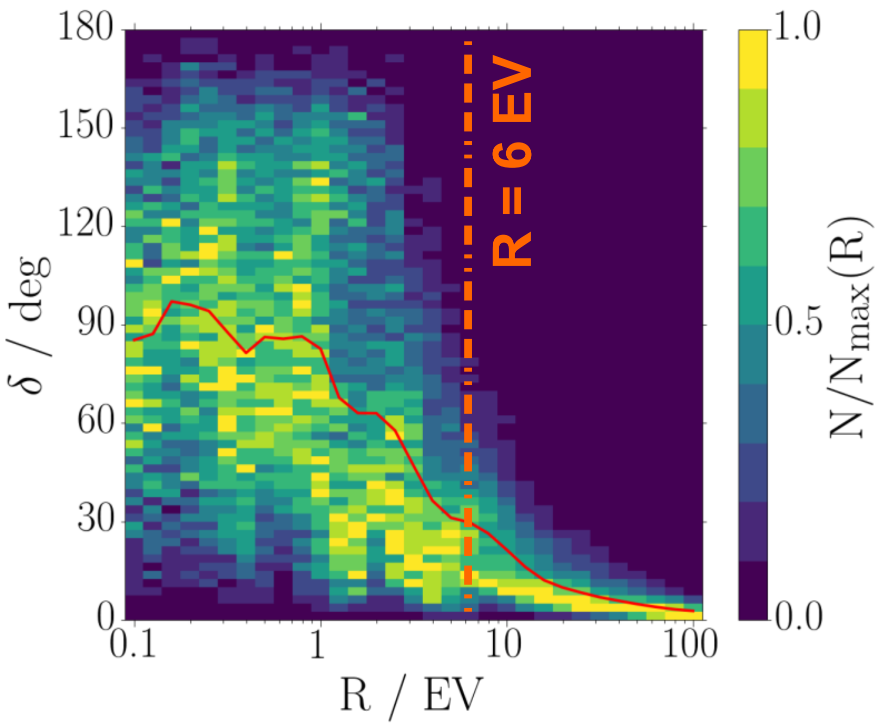


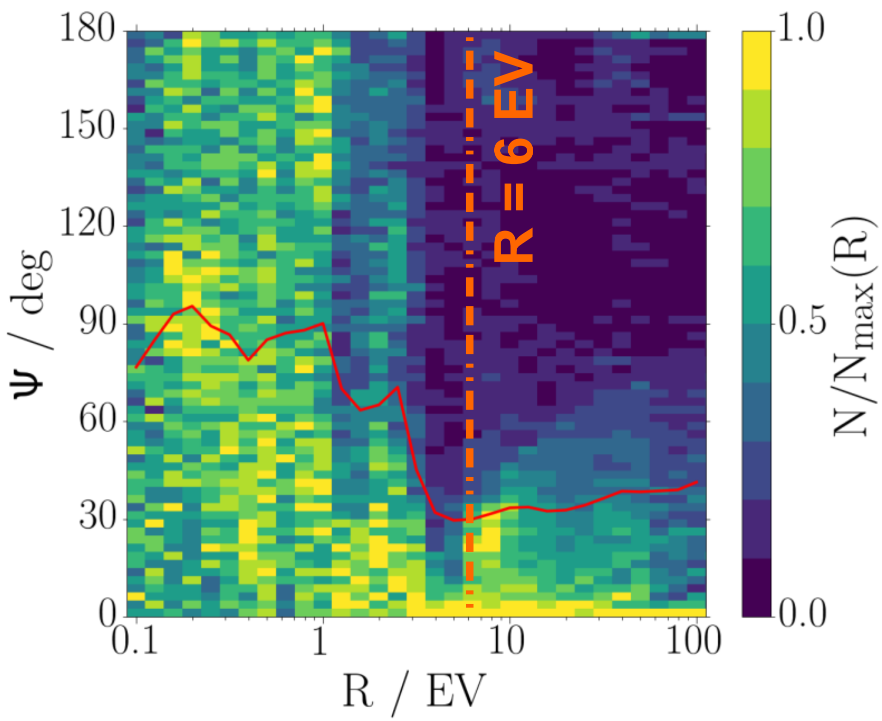


- ✗ Displacements of JF12 and PT11 match mostly
- ✗ Large deflections → point into same directions

Reliability of magnetic field corrections

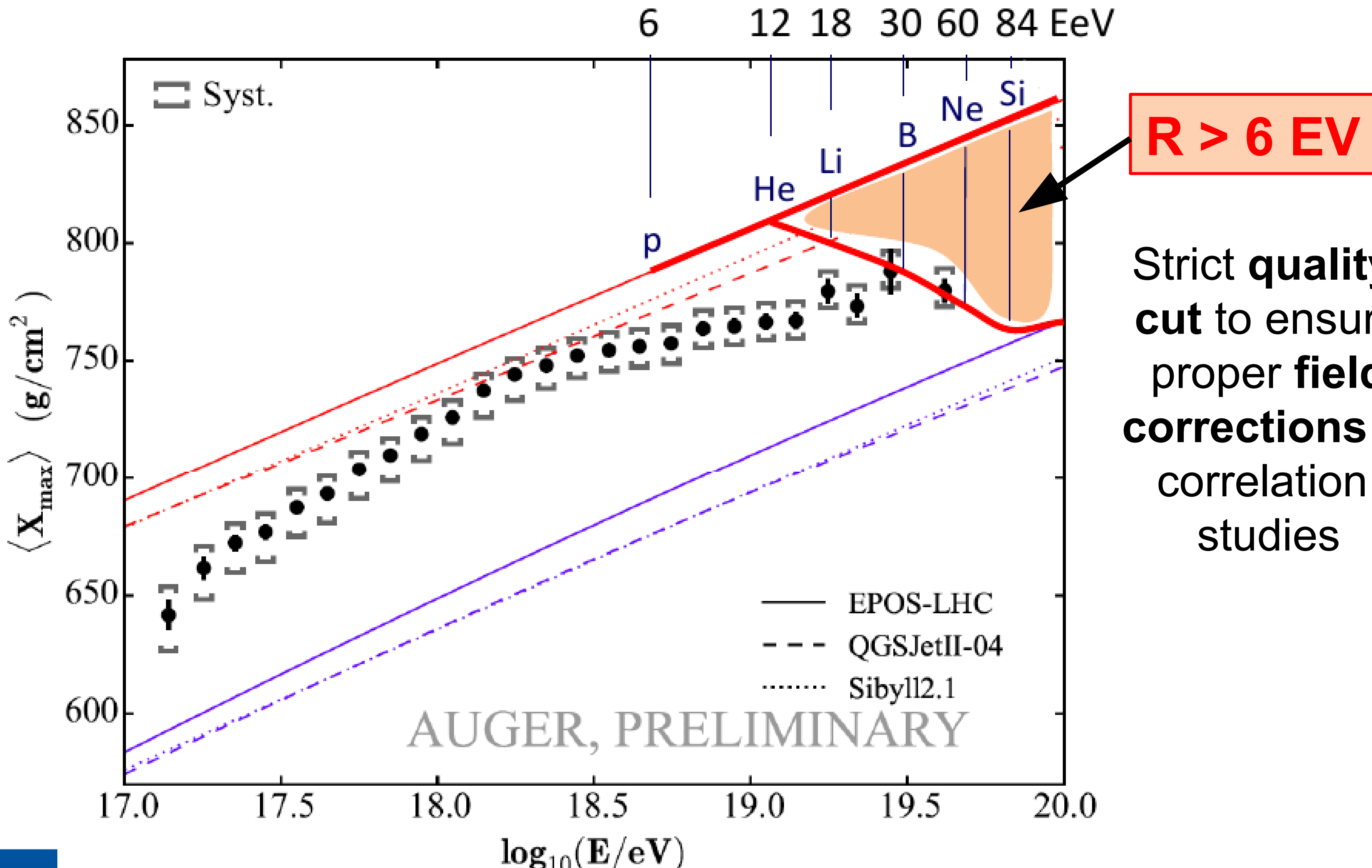






✗ Above 6 EV the differences in the magnetic field deflections are acceptable

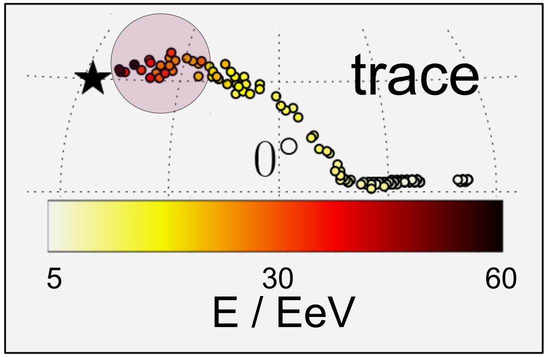
The nuclear window to the extragalactic universe



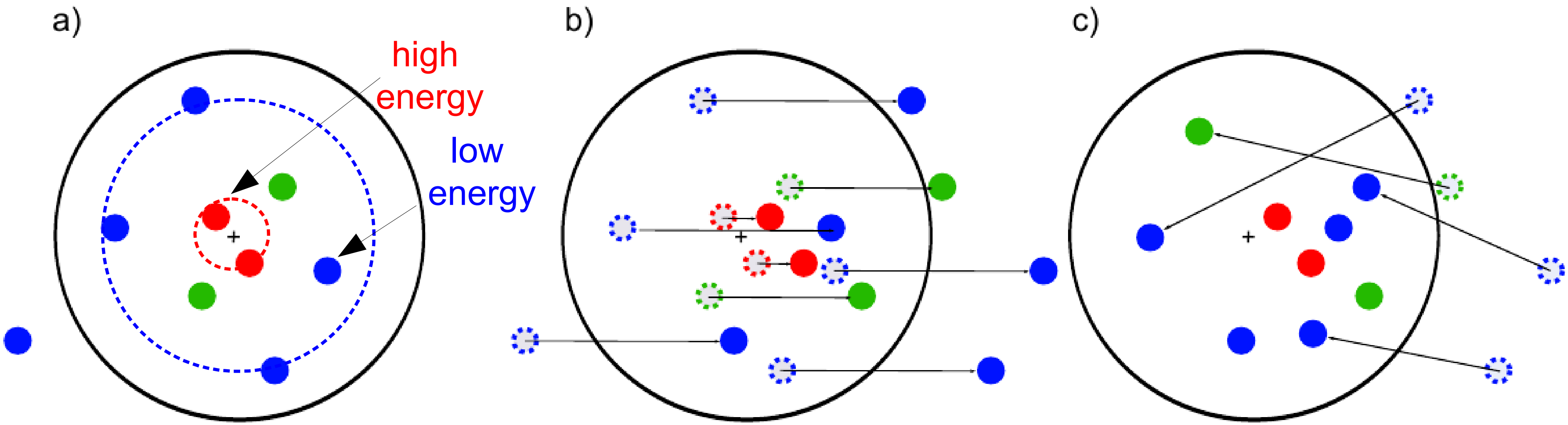
Strict **quality cut** to ensure proper **field corrections** in correlation studies

Search for patterns in CR arrival - mockup data

Analysis done by Tobias Winchen
Eur. Phys. J. C (2015) 75: 269

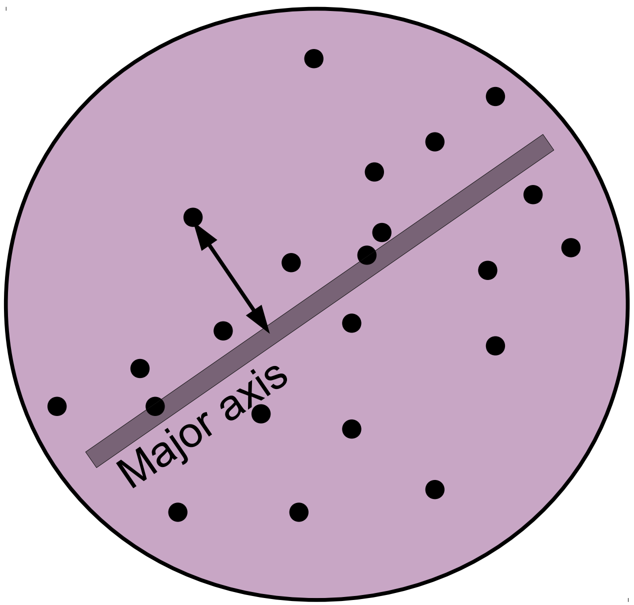


$$\delta_{RMS} = C_T/E \qquad \alpha = C_C/E$$



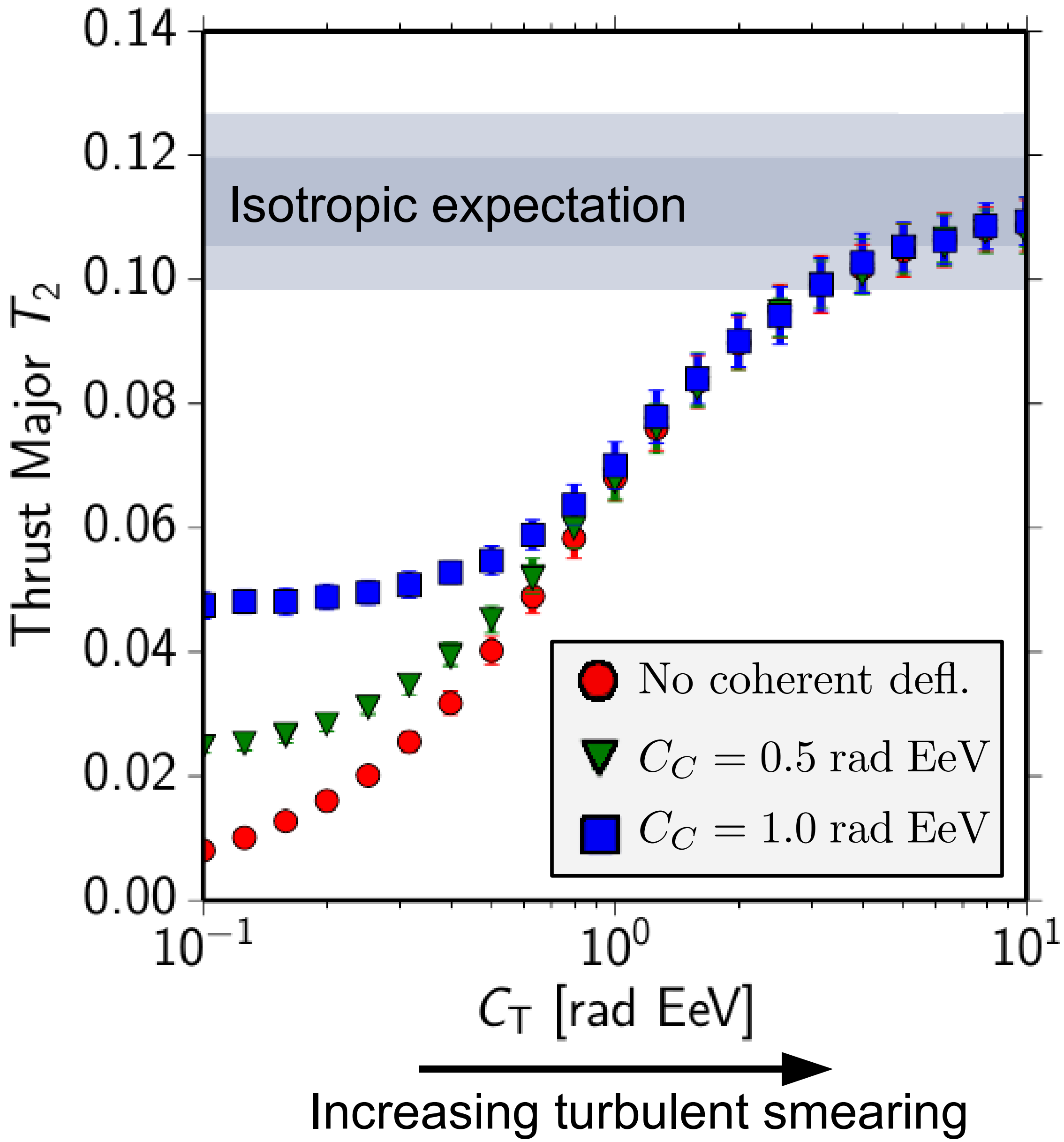
- ✗ Turbulent deflections → Fisher smearing
- ✗ Coherent deflection → angular shift
- ✗ Outlier added as random background

Thrust major axis - Expectations



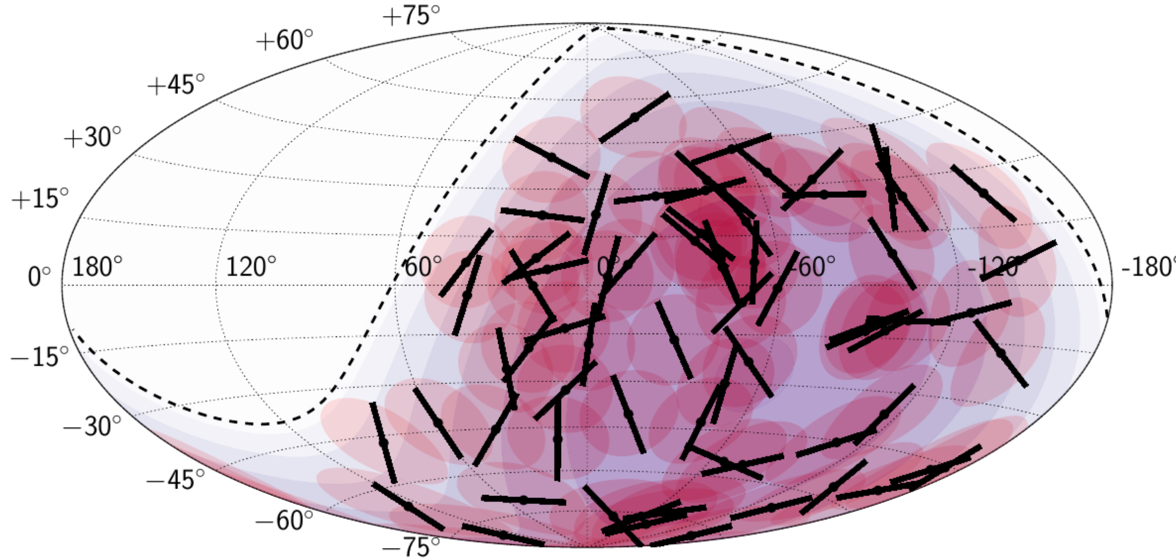
Region of interest (ROI)

- ✗ Turbulent components diminishes observability
- ✗ Strength T2 of thrust major axis increases with coherent deflections



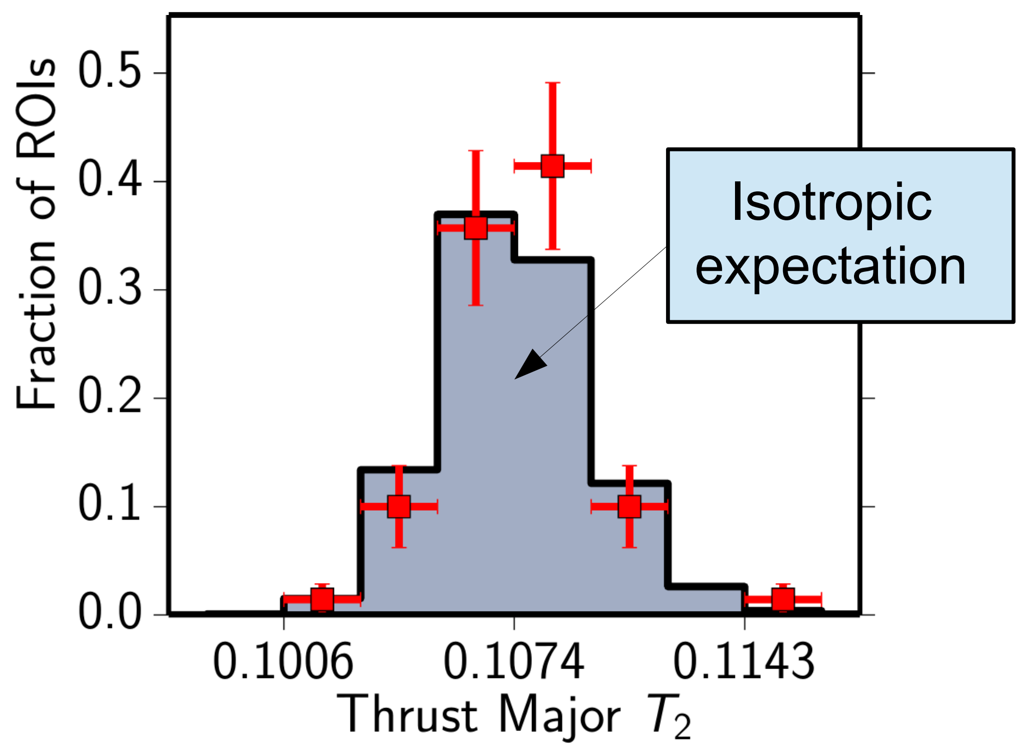
Observations

- ✗ Cut E > 5 EeV ensures extragalactic origin
- ✗ ROIs (~14°) defined by high energy events E > 60 EeV → seeds 70 ROIs



⇨ Strength T_2 of major axis not significant / Also found axis are not stable

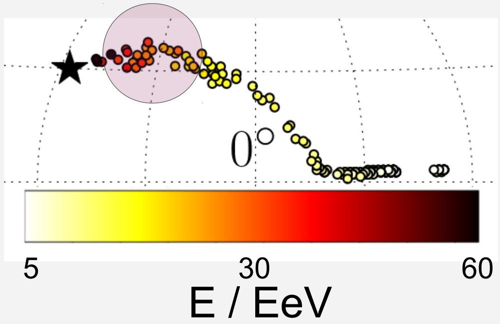
⇨ Limits on extragalactic scenarios (source density, turb defl. C_T)



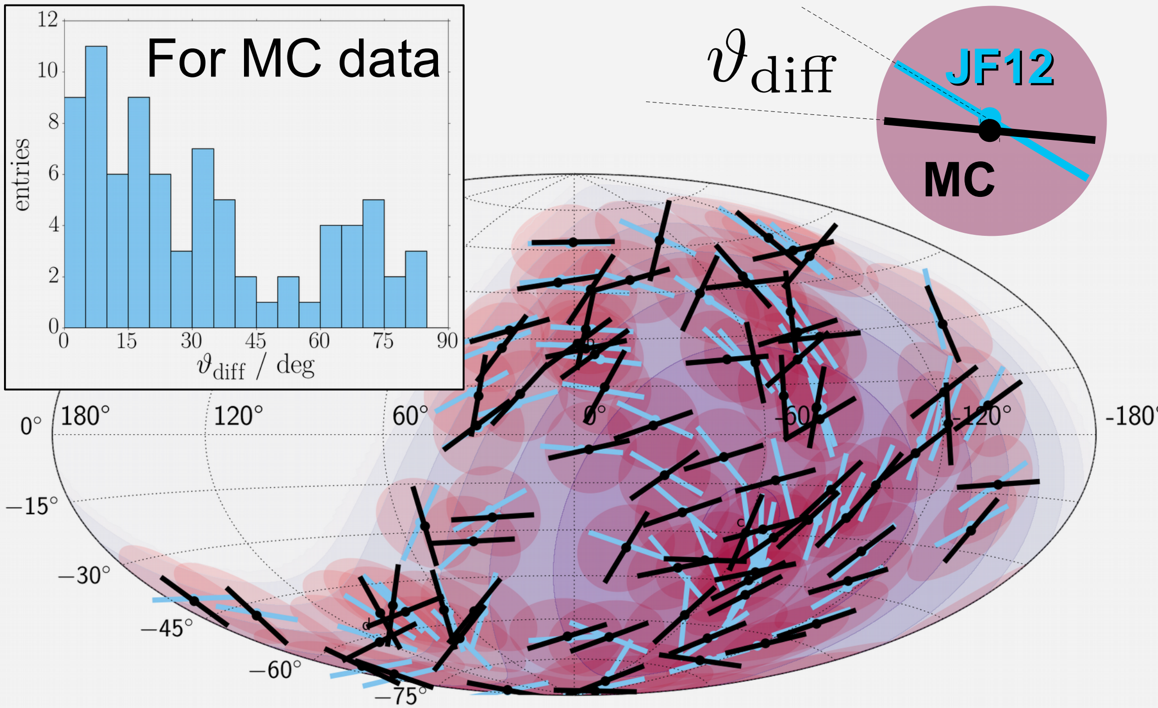
Outlook

1) Choose of threshold and ROIs

- ✗ Rigidity threshold at 6 EV instead of E > 5 EeV
- ✗ Patterns typically arise strongest ~20° away from the source position



2) Compare patterns with GMF model expectations



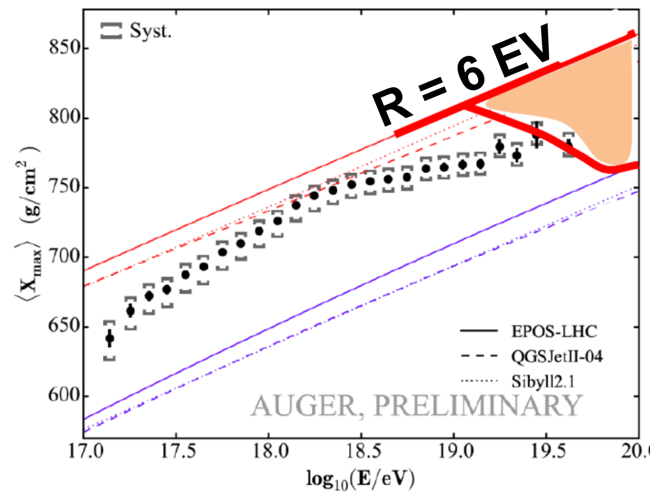
Conclusion

✗ Current galactic magnetic field parameterizations are adopted to numerous measurements (rotation measures, synchrotron radiation)

✗ Reliable galactic field correction can be achieved above $E/Z \approx 6\ \mathrm{EeV}$
→ deflections, dispersions, multiple images …
→ models JF12 and PT11 as measure for our knowledge

✗ Patterns caused by coherent deflections are expected
→ no evidence in thrust auto correlation measurements
→ limits on extragalactic scenarios
→ Outlook: compare to galactic field parametrization

Nuclear window



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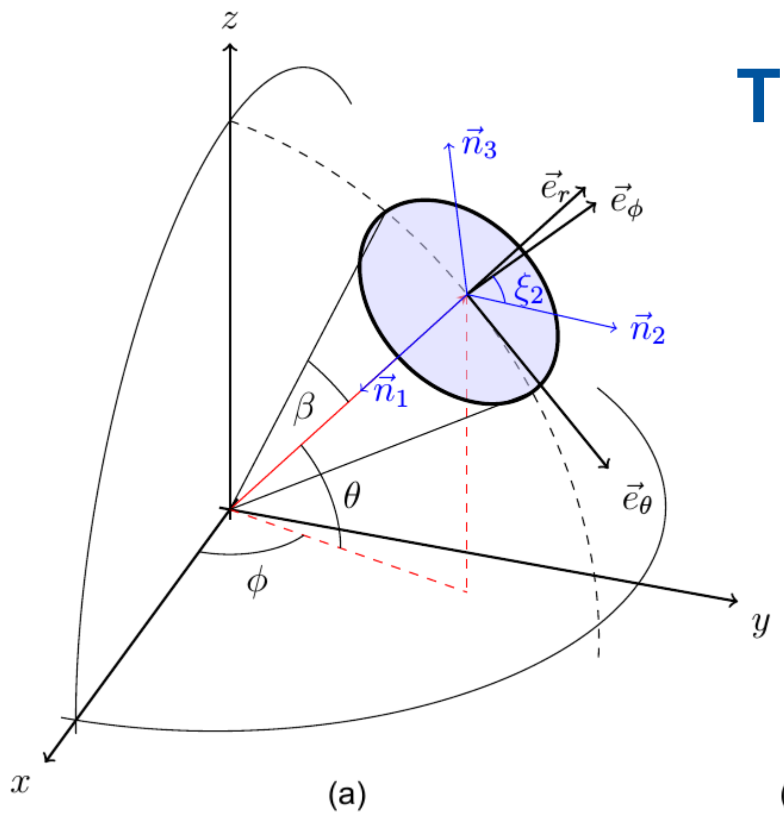
Backup

Thrust axis



$$T_k = \max_{\vec{n}_k} \left(\frac{\sum_i |E_i \vec{n}_k|}{\sum_i |E_i|} \right)$$

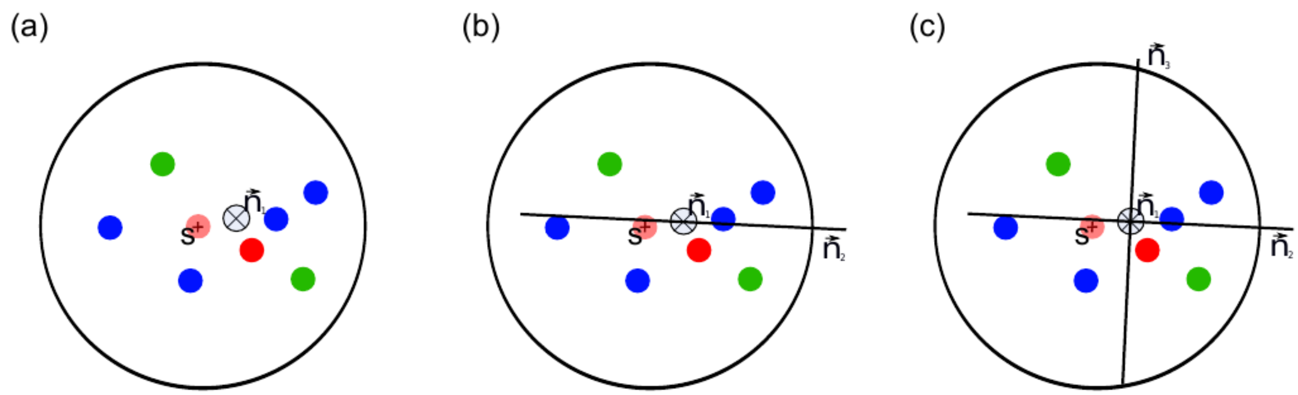
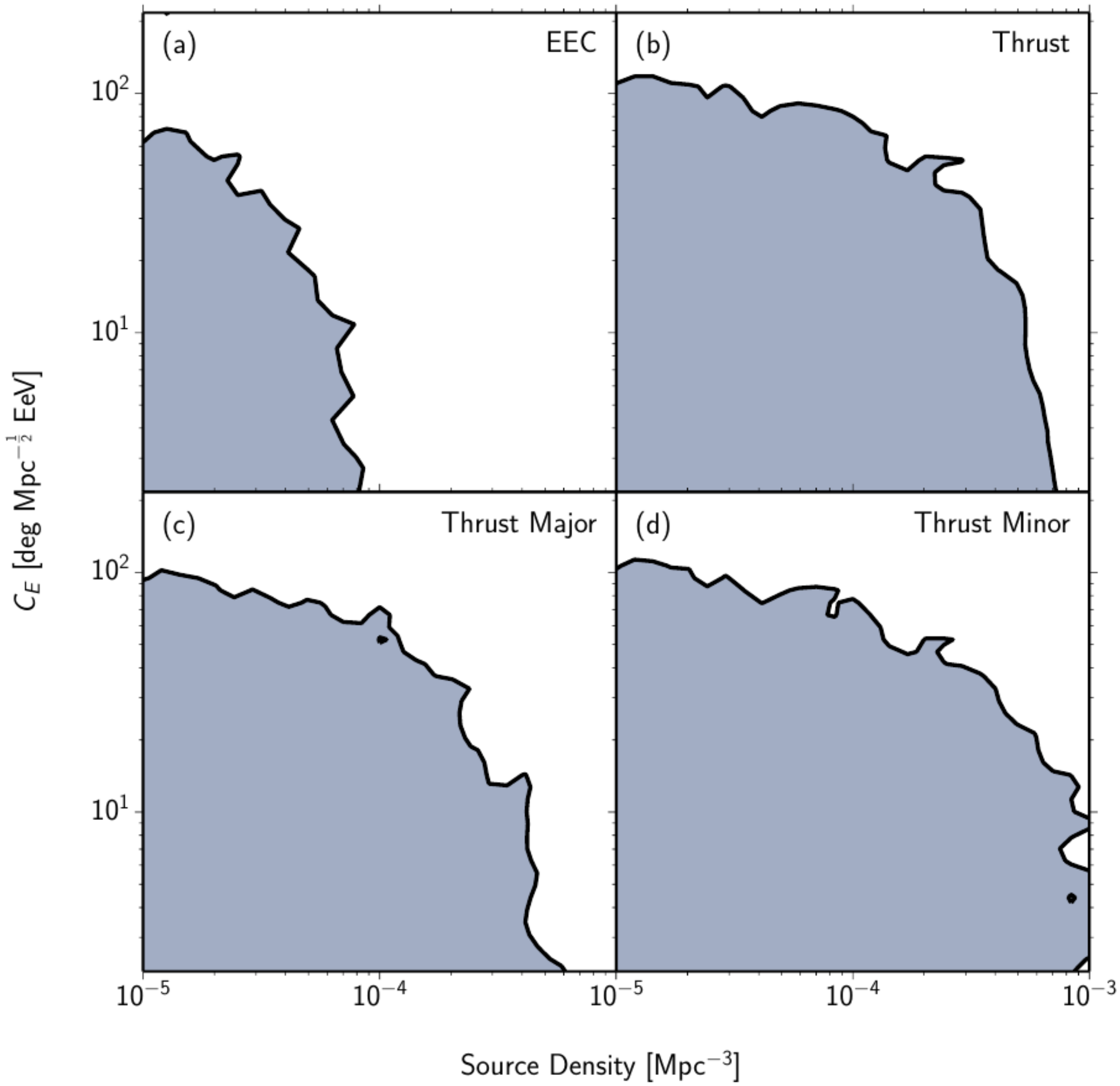


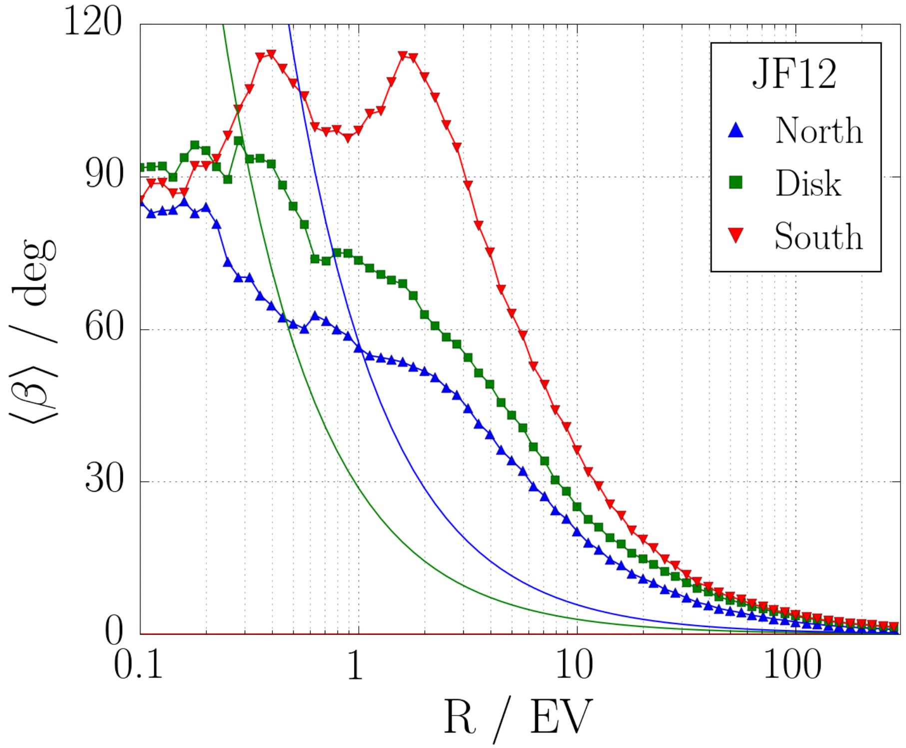
Figure 4.2: Successive calculation of the thrust observables $T_{1,2,3}$ and axes $\vec{n}_{1,2,3}$ in three steps (a–c). Dots mark arrival directions of UHECR with energy denoted by the color.

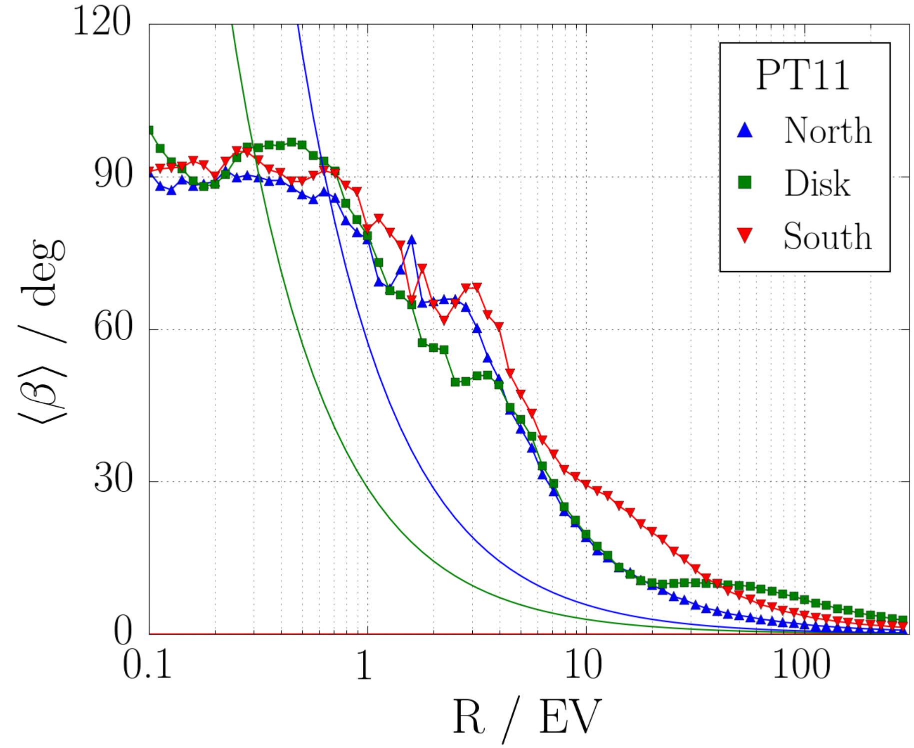
Limits on extragalactic scenarios

$$C_T = C_E \cdot \sqrt{D}$$



Coherent delfection parameter





C_C = 0.5 rad EeV

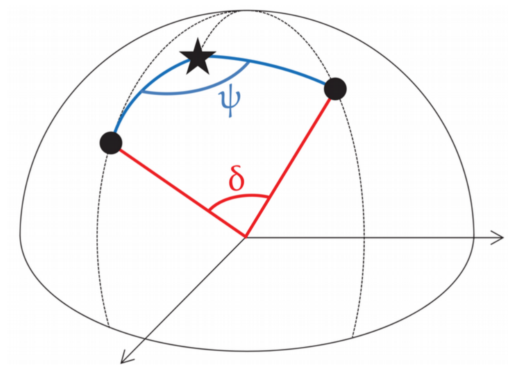
C_C = 1.0 rad EeV

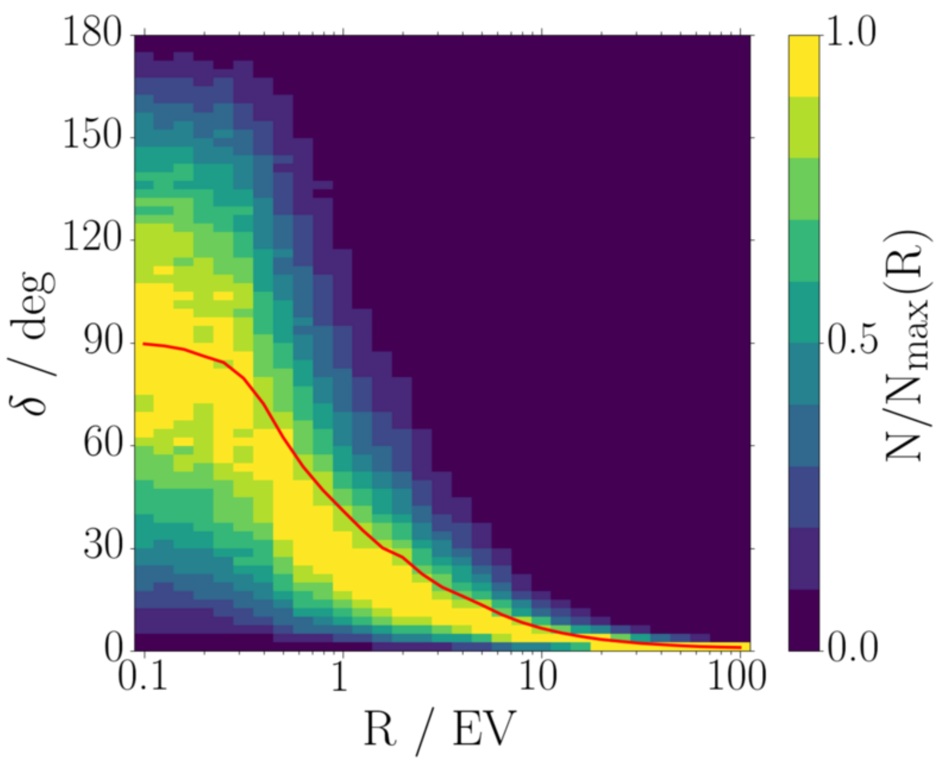
Turbulent delfection parameter

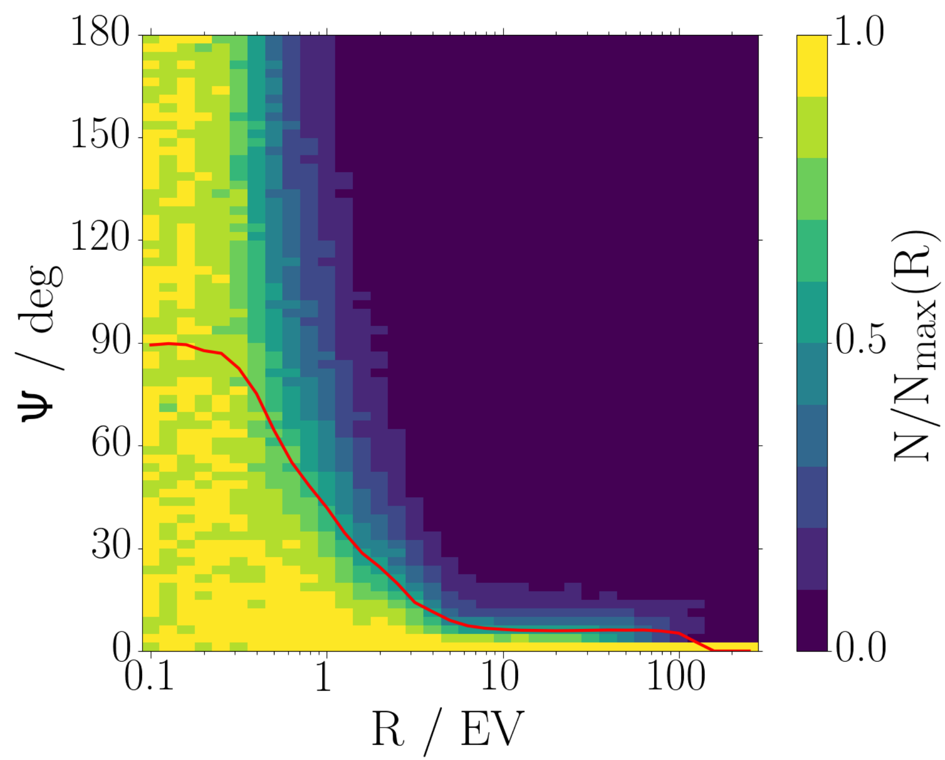
$$\delta_{\mathrm{RMS}} \simeq \frac{C_{\mathrm{T}}}{E}. \tag{7}$$

A value of $C_{\mathrm{T}} = 1\,\mathrm{rad\,EeV}$ is equivalent to an RMS of the deflection angle $\delta_{\mathrm{RMS}} = 5.7°$ for 10 EeV particles. For example, using the usual parametrization for deflections in turbulent magnetic fields [26, 27] this corresponds to the expected deflection of 10 EeV protons from a source at a distance $D \approx 16\,\mathrm{Mpc}$ propagating through a turbulent magnetic field with coherence length $\Lambda \approx 1\,\mathrm{Mpc}$ and strength $B \approx 4\,\mathrm{nG}$.

Two realizations of random fields - striated and turbulent (JF12)

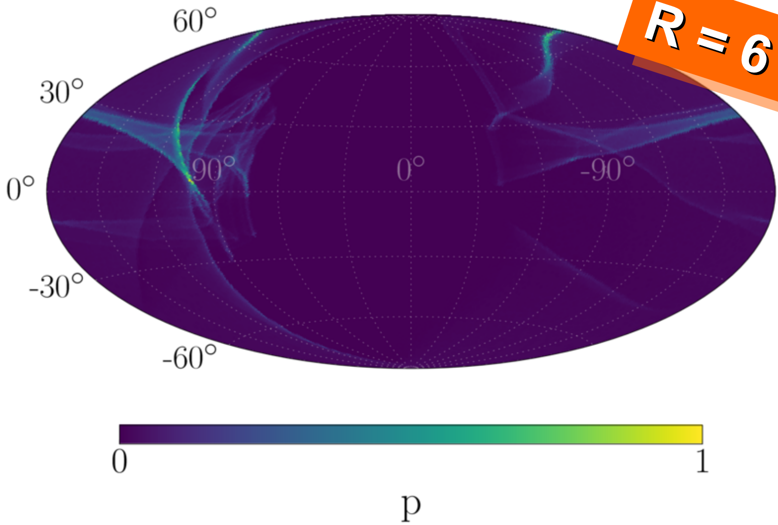


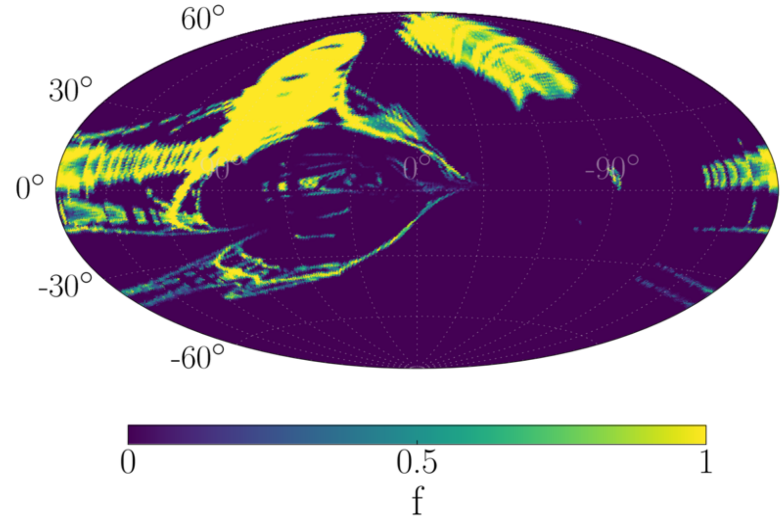


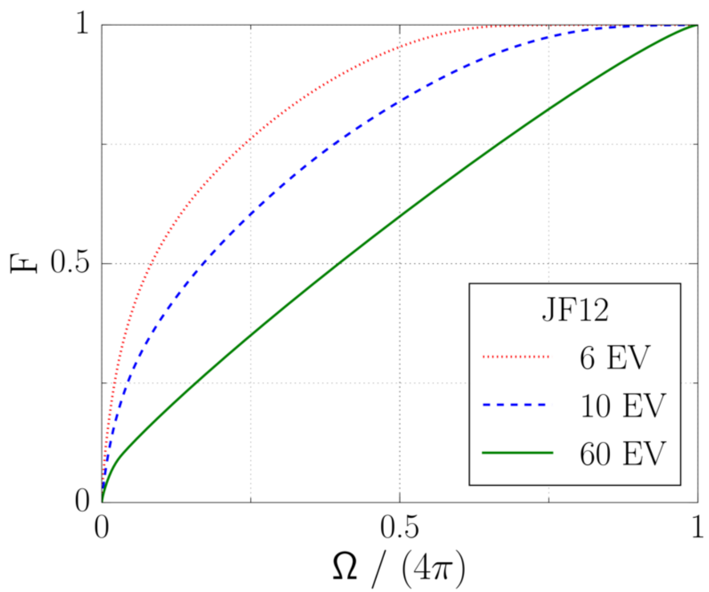


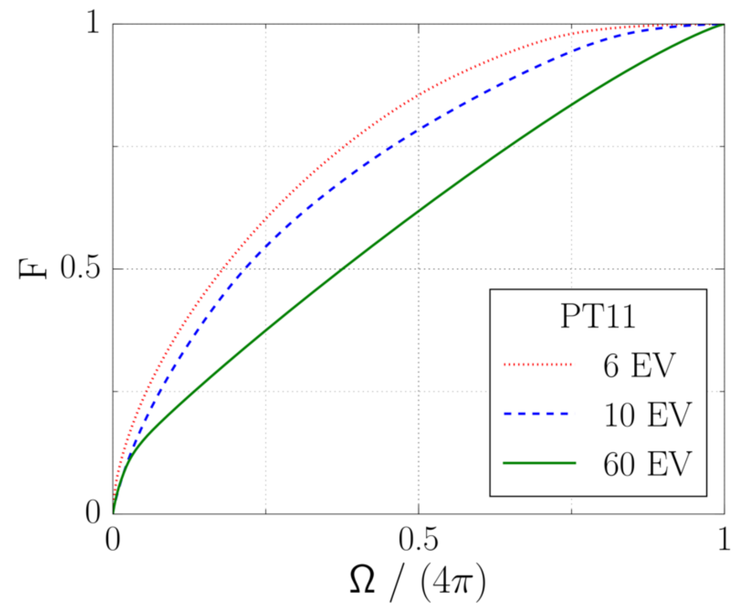
Field transparency

R = 6 EV



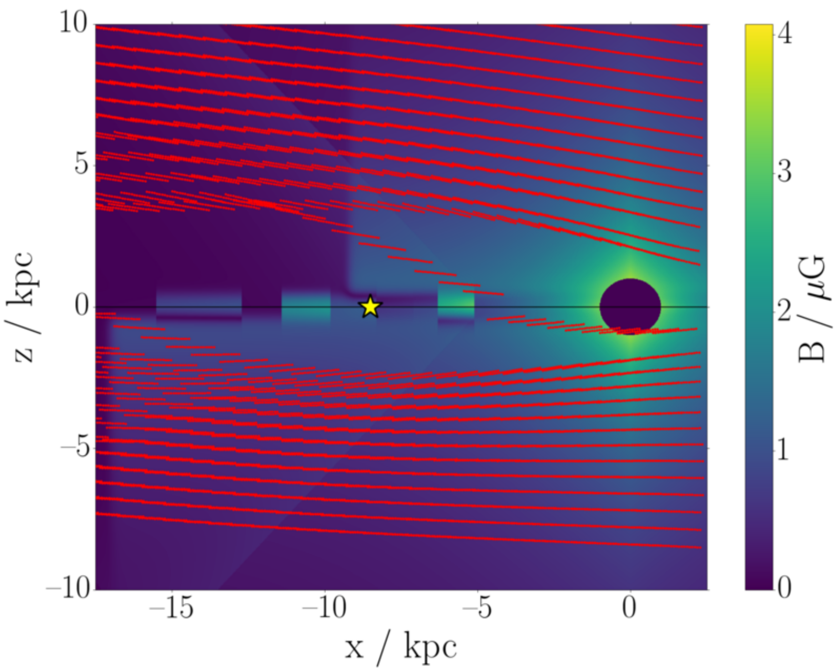


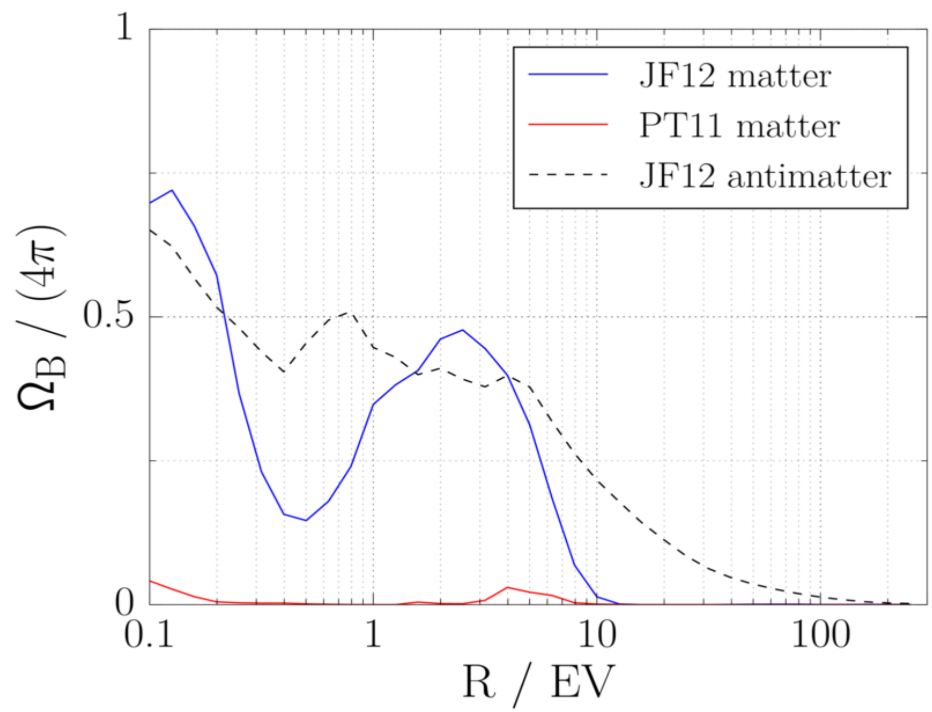




Blind regions

- ✗ Blind spot for antimatter in JF12 field even at high energies
- ✗ For energies below $E \approx 10\ \mathrm{EeV}$: blind regions also for matter





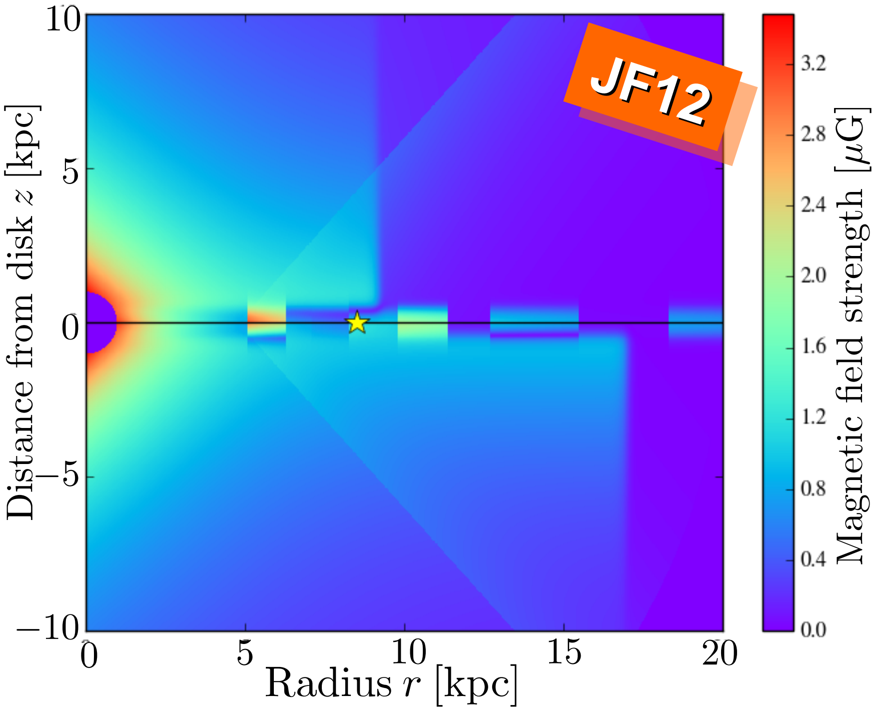
Gyro-radius

High energy gyro-radius:

$$R_{gyro} \approx \frac{1.1}{Z} \cdot \frac{E[EeV]}{B[\mu G]}$$

Example: 6 EeV proton and $B = 2\ \mu G$:

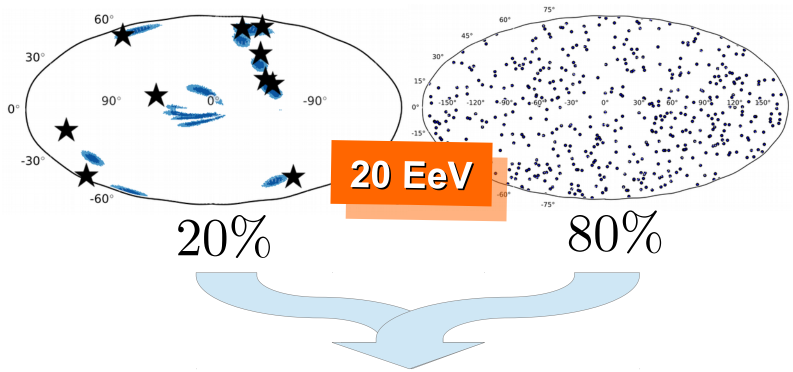
$$R_{gyro} \approx 3\ \text{kpc}$$



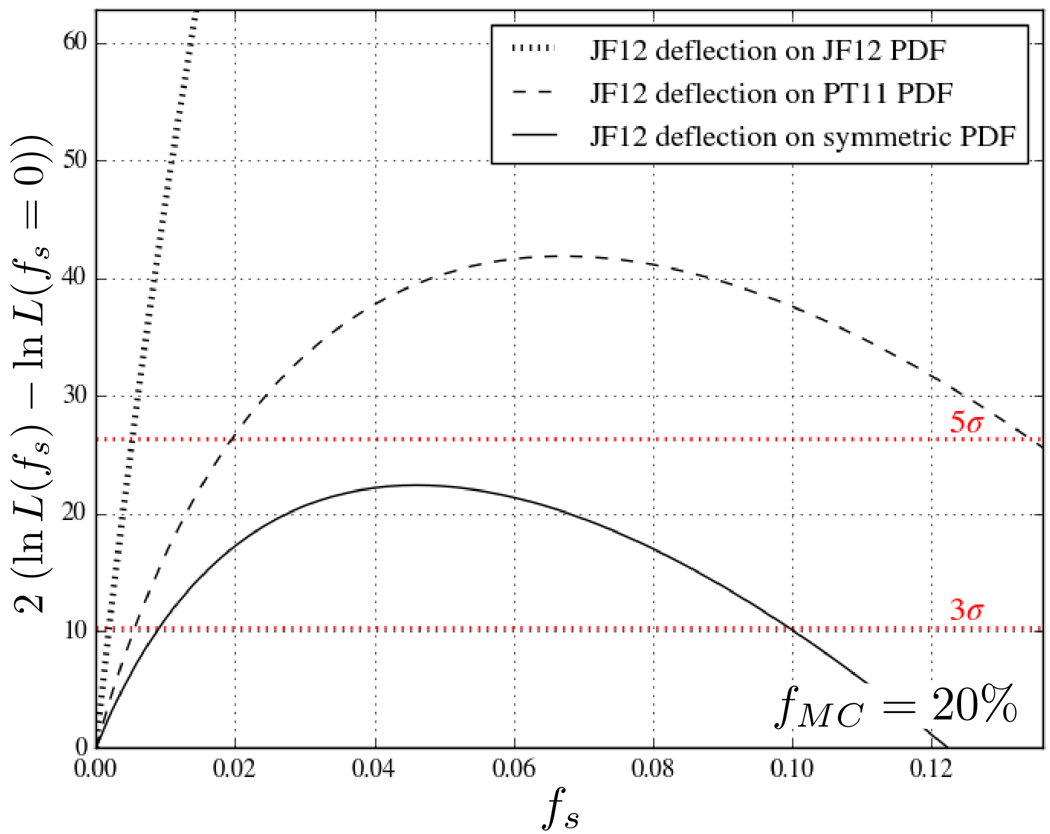
Search for cosmic ray origin

Plug in assumed probability density function (PDF)

$$\ln L(f_s) = \sum_{i=1}^{N} \ln \left[f_s P(R, l_i, b_i, l'_i, b'_i) + (1 - f_s) B \right]$$



✗ Testing for $P(R, l_i, b_i, l'_i, b'_i)$ different probability density functions (PDF)



⇨ PT11 instead of symmetric PDF improves sensitivity!

Significances

Plug in assumed probability density function (PDF)

$$\ln L(f_s) = \sum_{i=1}^{N} \ln \left[f_s \, P(R, l_i, b_i, l'_i, b'_i) + (1 - f_s)\, B \right]$$