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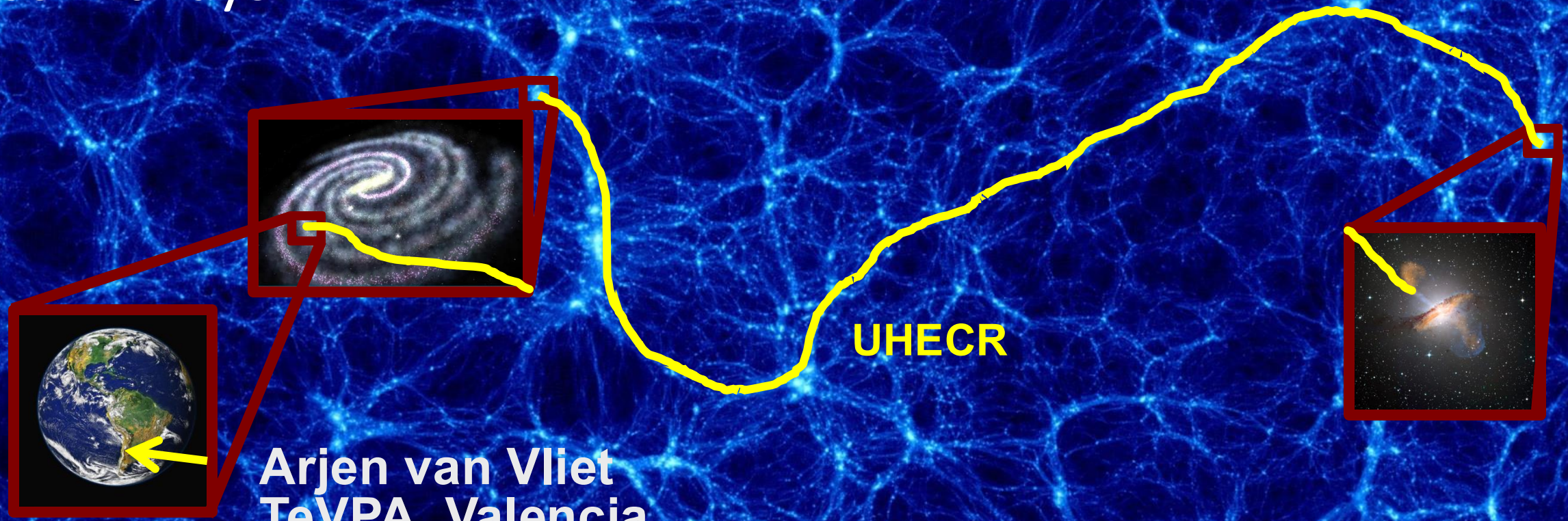
Constraints on magnetic fields from ultra-high-energy cosmic rays



Arjen van Vliet
TeVPA, Valencia

NOV 5TH, 2025

Large-scale structure image by J. Dubinski (U. of Toronto)

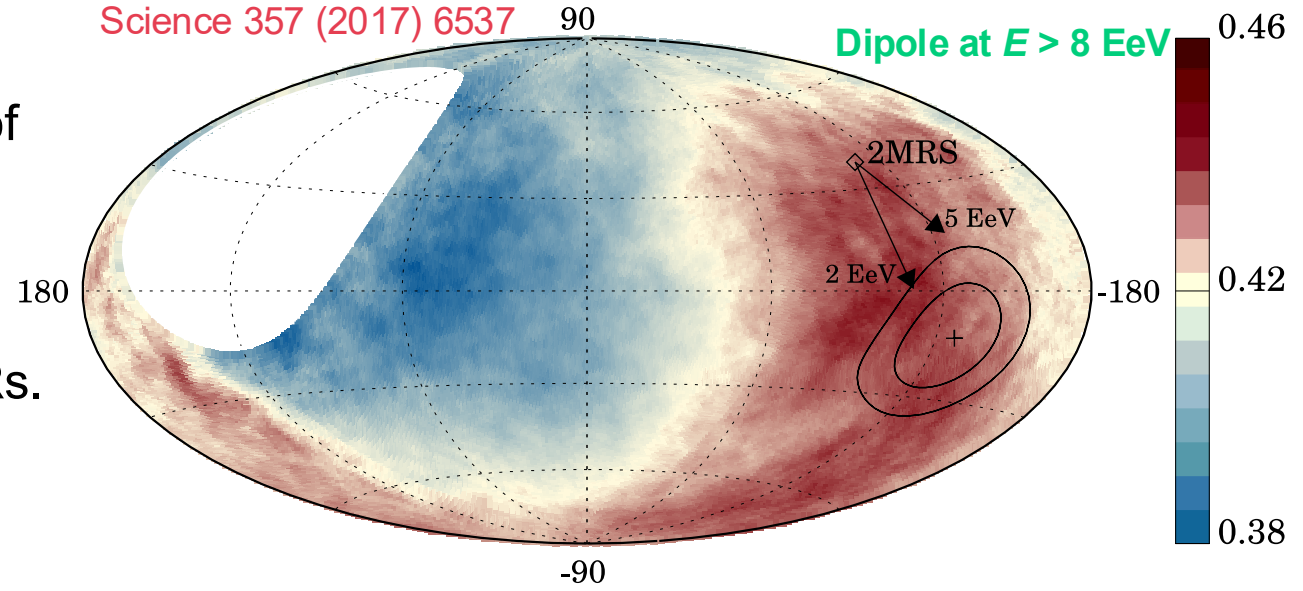
UHECRs; arrival directions

- No clearly confirmed sources yet, but indications of anisotropies in the arrival directions have been detected.
- Dipole at E > 8 EeV.
  - Indication for an extragalactic origin of UHECRs.
- Intermediate-scale anisotropies at E > 38 EeV.

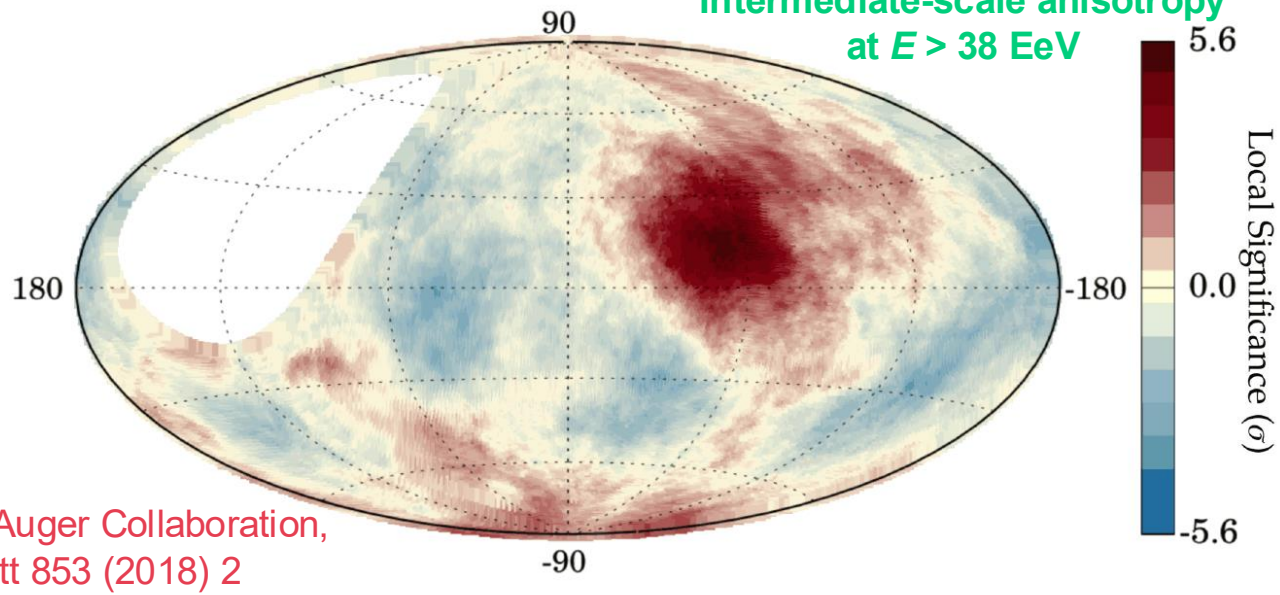
Larmor radius: $r_L = \frac{E}{ZeB}$

Pierre Auger Collaboration,
Science 357 (2017) 6537

Dipole at E > 8 EeV



Intermediate-scale anisotropy at E > 38 EeV

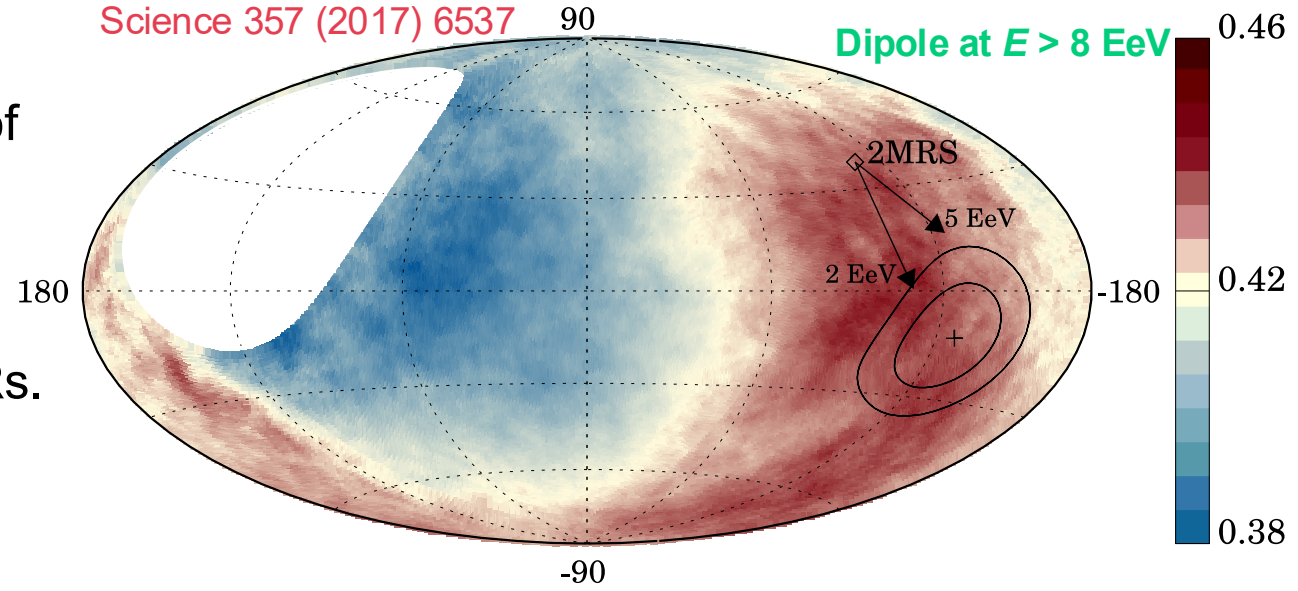


Pierre Auger Collaboration,
ApJ Lett 853 (2018) 2

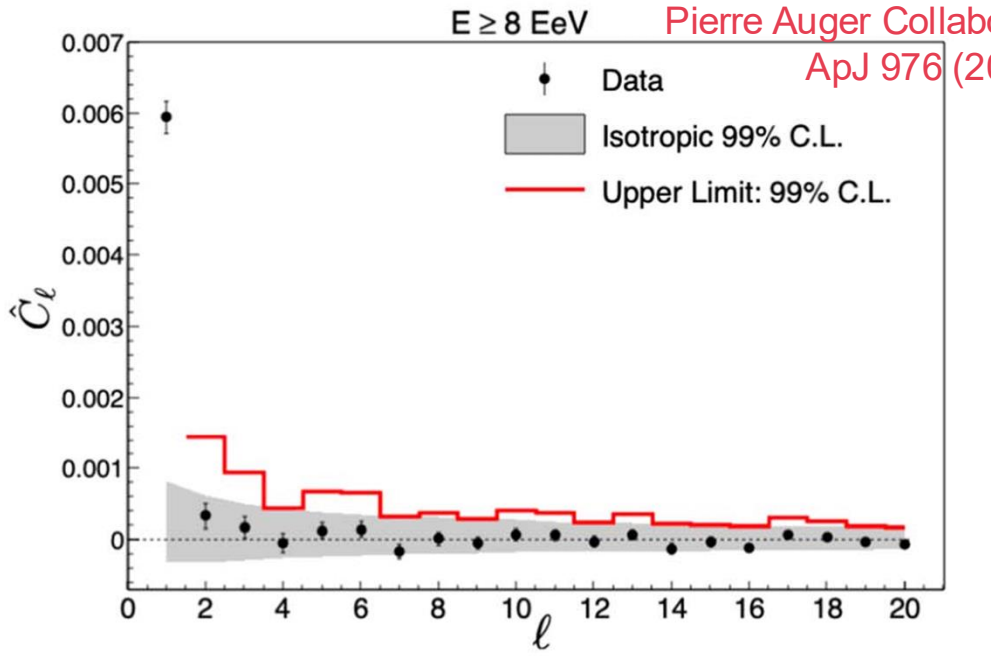
UHECRs; dipole

- No clearly confirmed sources yet, but indications of anisotropies in the arrival directions have been detected.
- Dipole at $E > 8$ EeV.
  - Indication for an extragalactic origin of UHECRs.
  - 6.8σ significance
  - Amplitude: ~7%
  - No significant quadrupole or other multipole moments.
- Possible origin:
  - Inhomogeneous distribution of the local large-scale structure (e.g. Lang et al. 2021; Ding et al. 2021; Allard et al. 2022; Bister & Farrar 2024)
  - The existence of one or more bright local sources combined with UHECR propagation through Galactic (GMFs) and/or extragalactic magnetic fields (EGMFs) (e.g. Mollerach & Roulet 2019; Eichmann et al. 2022; Mollerach & Roulet 2024)

Pierre Auger Collaboration, Science 357 (2017) 6537

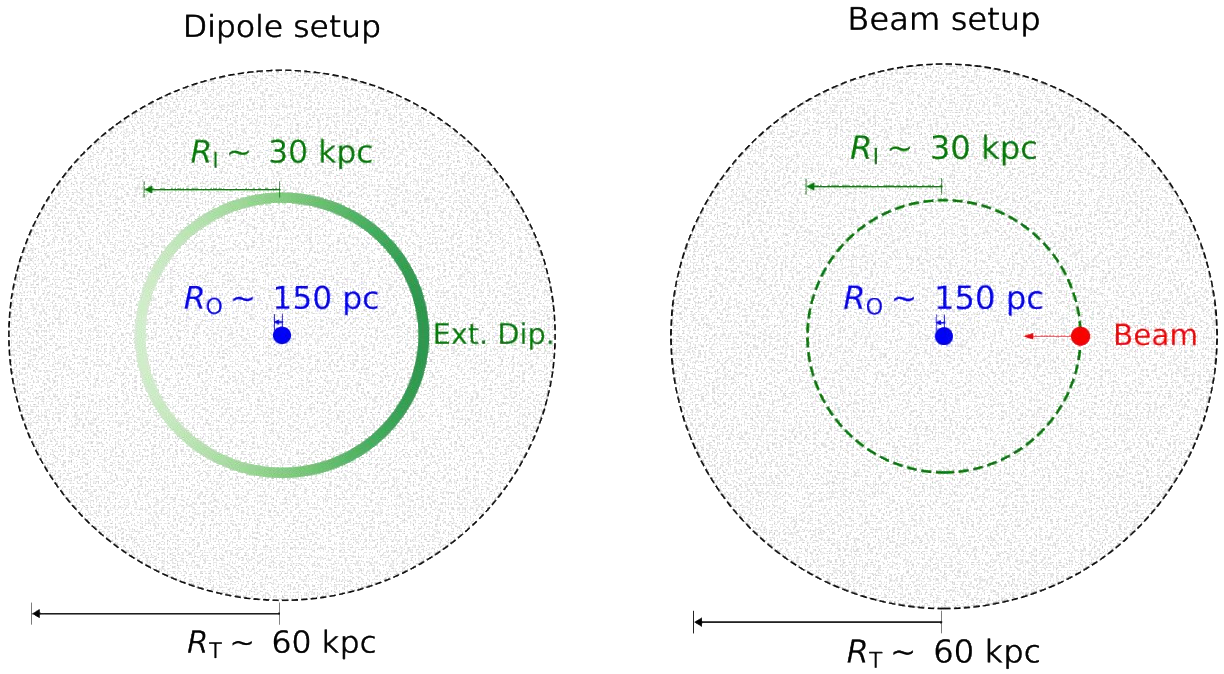


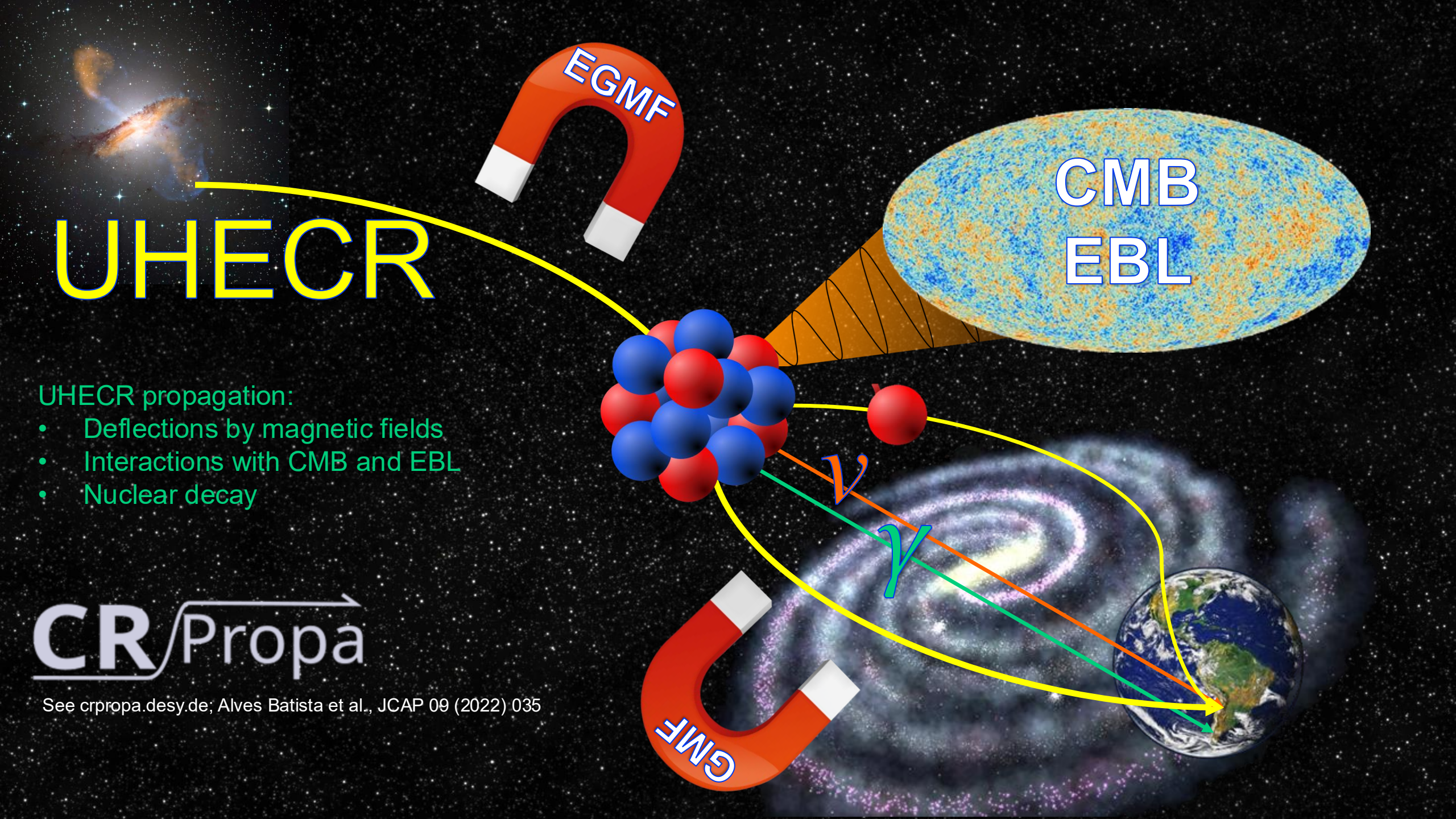
Pierre Auger Collaboration, ApJ 976 (2024) 48



Giant, turbulent Galactic magnetic field halo

- Can we see the difference between the two possible origin scenarios? Shaw, AvV, Taylor, MNRAS, 543 (2025) 3242
- Assume: a giant, turbulent Galactic magnetic field halo
- Motivation:
  - Indications that a considerable level of thermal gas pressure exists out in the halo of the Milky Way and other local galaxies of a similar mass (Martynenko 2022; Bregman et al. 2022; Hopkins et al. 2022; Zhang et al. 2024)
  - Consistent with recent radio observations of the circumgalactic medium region of local galaxies (Heesen et al. 2023)
- Track cosmic rays through a giant, turbulent Galactic magnetic field halo for different extragalactic distributions:
  - Pure dipole
  - One or more beams

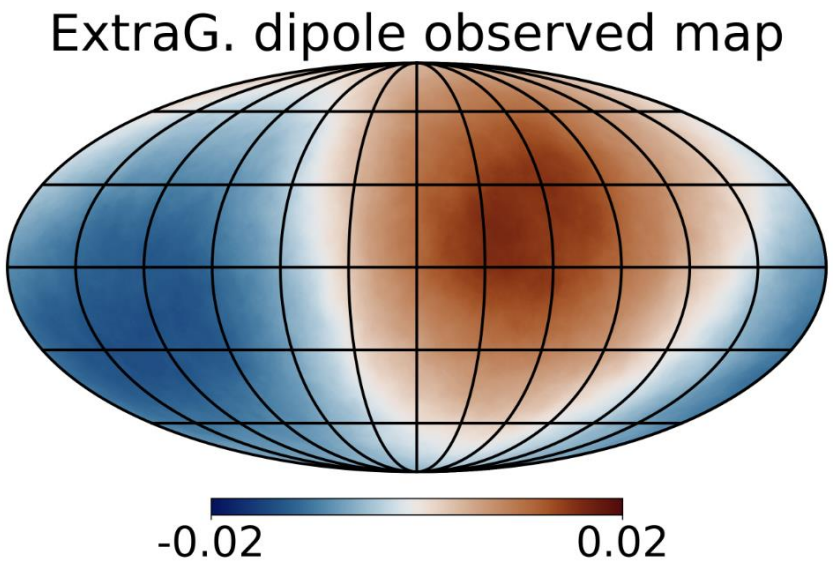


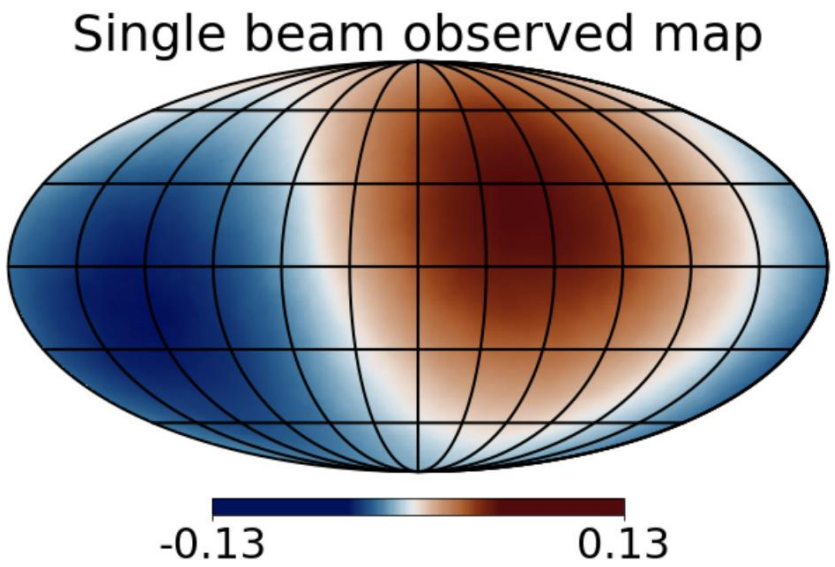

UHECR
EGMF
CMB
EBL
UHECR propagation:
• Deflections by magnetic fields
• Interactions with CMB and EBL
• Nuclear decay
ν
γ
GMF
CRPropa
See crpropa.desy.de; Alves Batista et al., JCAP 09 (2022) 035

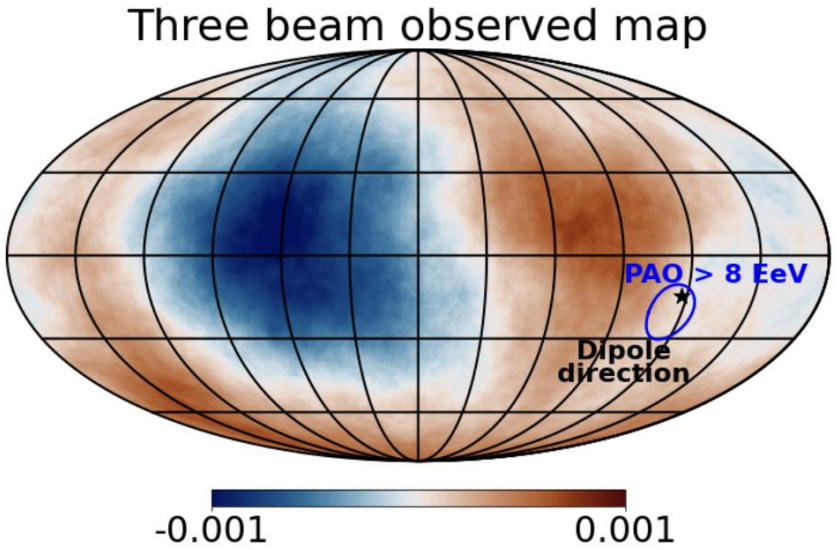
Simulated Observed Skymaps

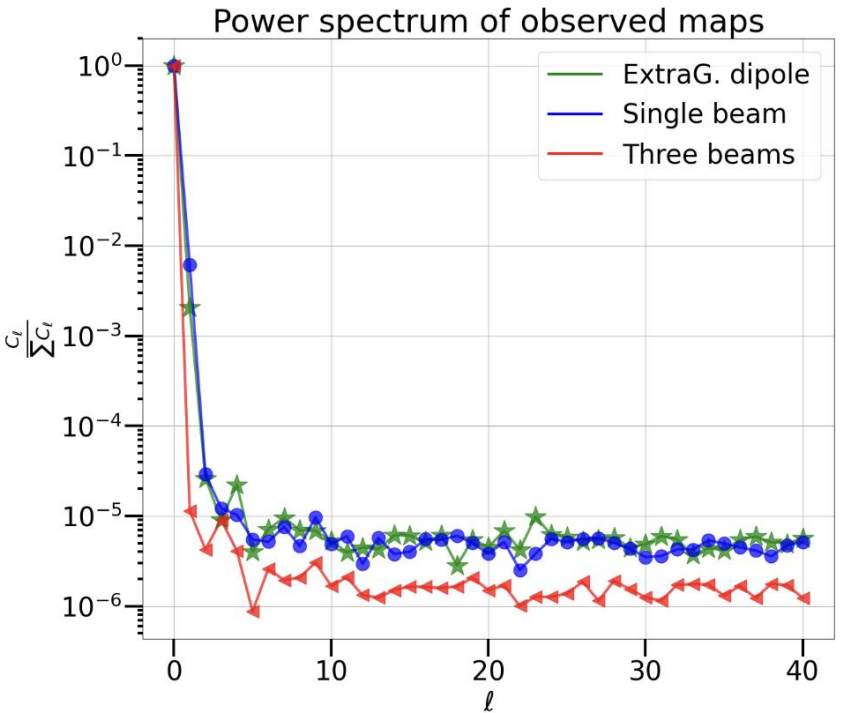
Shaw, AvV, Taylor, MNRAS, 543 (2025) 3242

- For the same scattering length of 80 kpc, where $L_{\rm scat} \propto \frac{r_L^2}{L_{\rm coh}}$
- Dipole can be extracted in all 3 cases. Most significant dipole for the 1-beam case, least significant dipole for the 3-beam case.





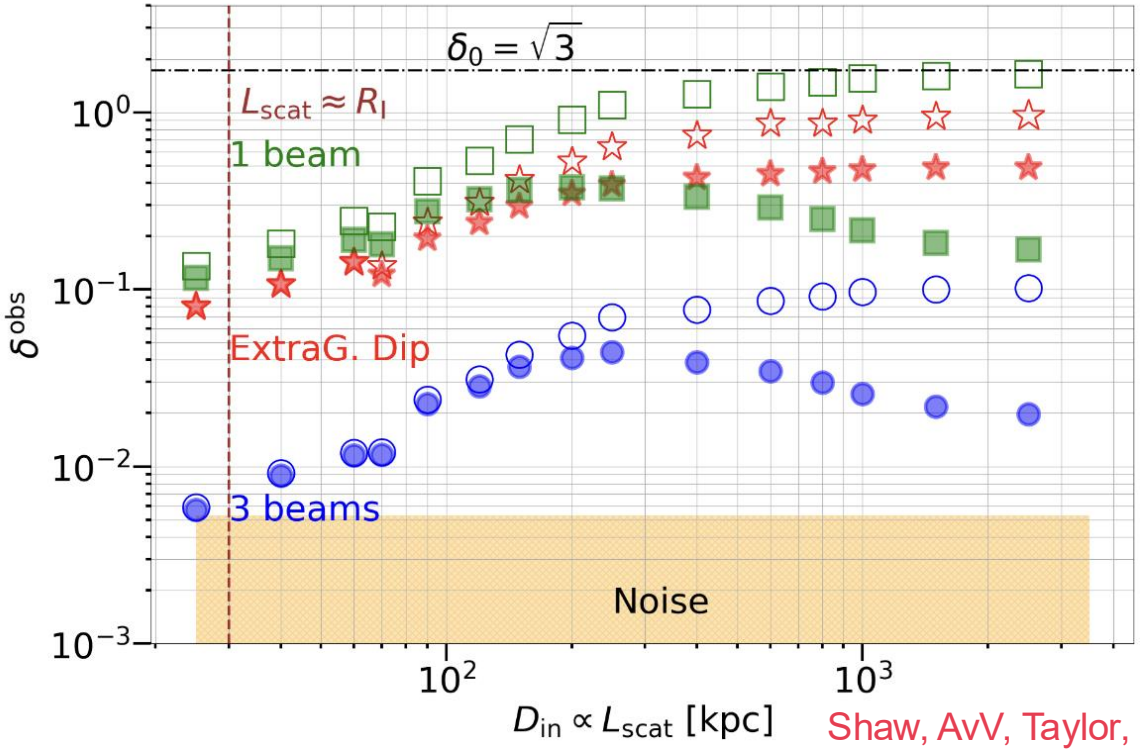




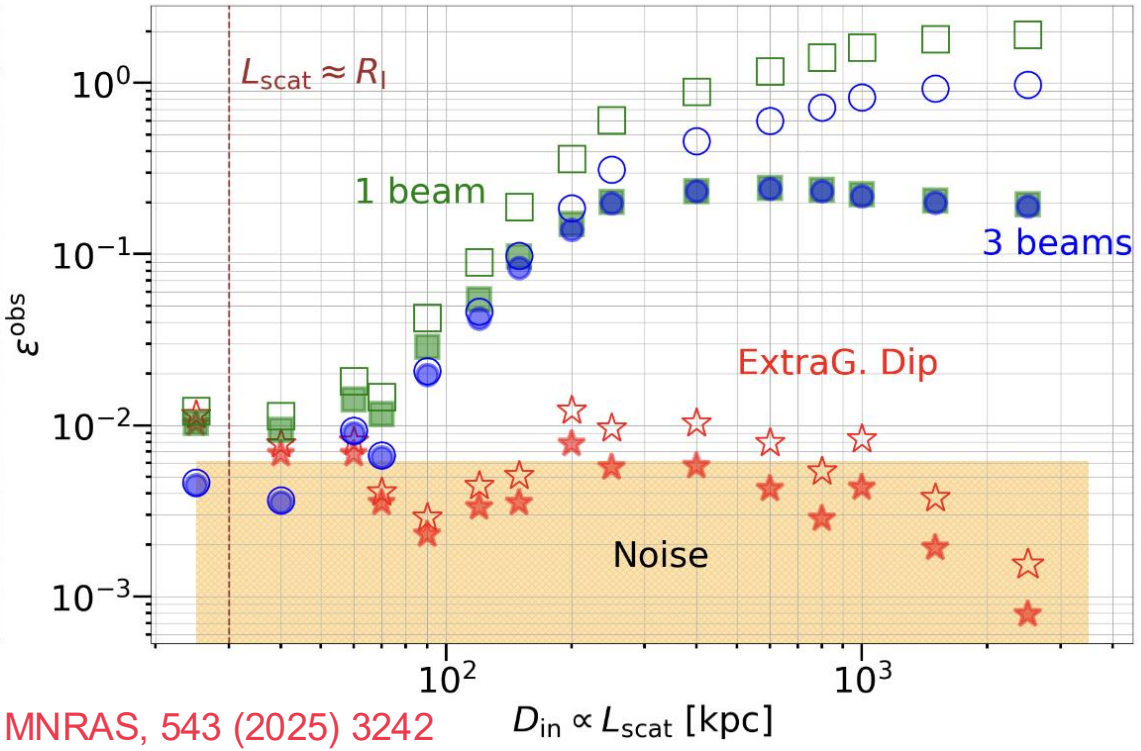
Dipole vs Quadrupole

- Expected dipole and quadrupole increase for increased scattering length.
  - Dipole and quadrupole get suppressed by magnetic-field deflections.
- Exception: quadrupole of the Extragalactic Dipole scenario.
- The Quadrupole can distinguish between different scenarios, especially at larger scattering lengths (rigidities).

Dipole



Quadrupole

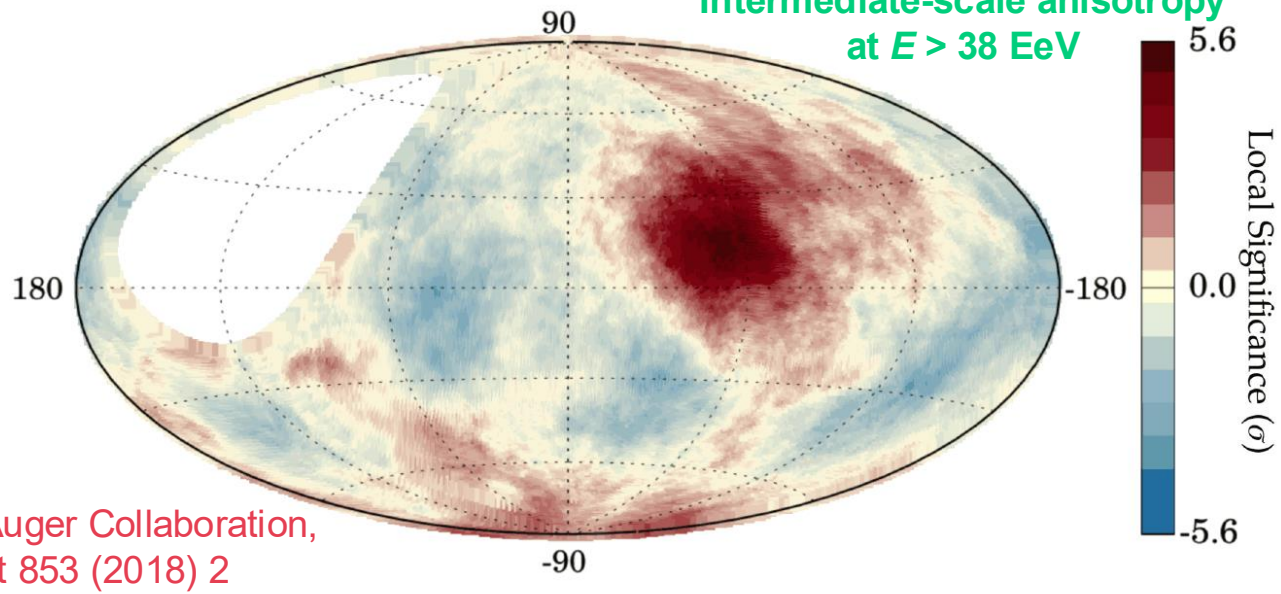


Shaw, AvV, Taylor, MNRAS, 543 (2025) 3242

Intermediate-scale anisotropies at the highest energies

- No identified sources yet, but indications of anisotropies in the arrival directions have been detected.
- Intermediate-scale anisotropies at $E > 38$ EeV.

Larmor radius: $r_L = \frac{E}{ZeB}$



Pierre Auger Collaboration, ApJ Lett 853 (2018) 2

Catalog	$E_{\rm th}$ [EeV]	Fisher search radius, Θ [deg]	Signal fraction, α [%]	$\mathrm{TS}_{\rm max}$	Post-trial p-value
All galaxies (IR)	40	16^{+11}_{-6}	16^{+10}_{-7}	18.0	7.9×10^{-4}
Starbursts (radio)	38	15^{+8}_{-4}	9^{+6}_{-4}	25.0	3.2×10^{-5}
All AGNs (X-rays)	39	16^{+8}_{-5}	7^{+5}_{-3}	19.4	4.2×10^{-4}
Jetted AGNs (γ-rays)	39	14^{+6}_{-4}	6^{+4}_{-3}	17.9	8.3×10^{-4}

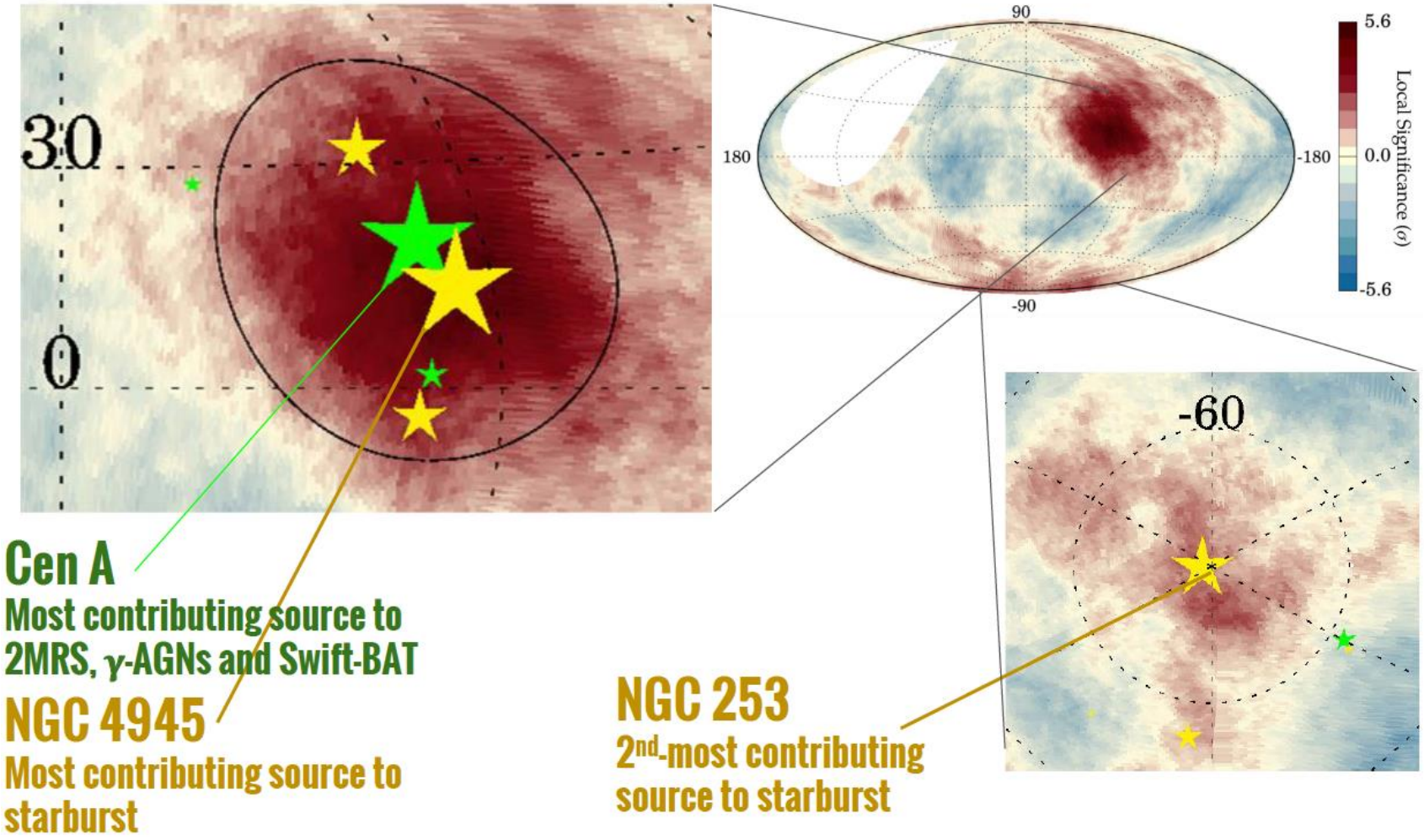
Pierre Auger Collaboration, Astrophys. J. 935 (2022) 170

UHECRs; intermediate-scale anisotropies

Pierre Auger Collaboration, Astrophys. J. Lett. 853 (2018) 2

Pierre Auger Collaboration, Astrophys. J. 935 (2022) 170

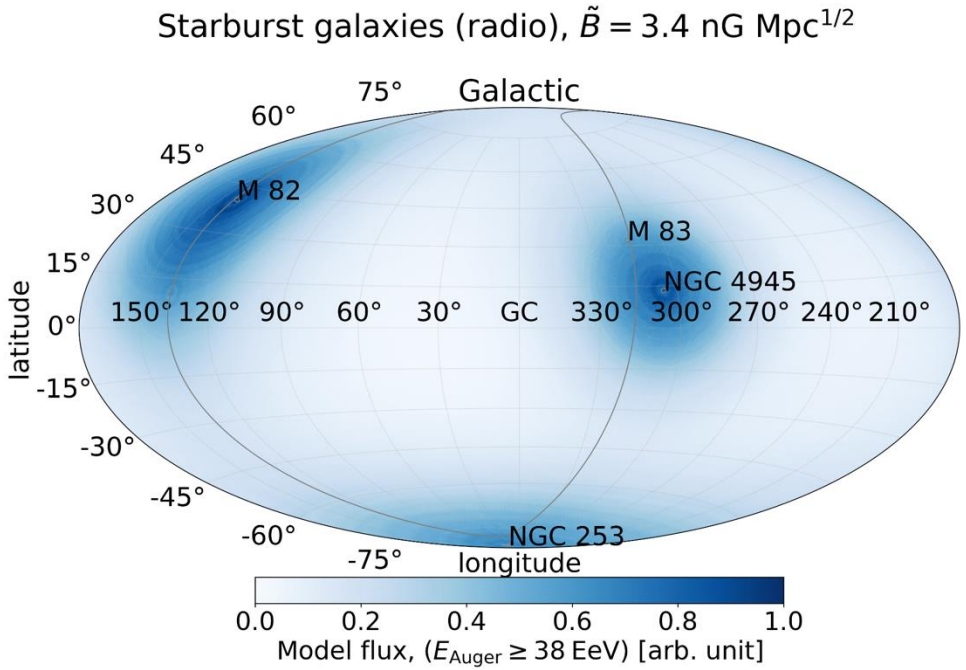
- Largest post-trial significance for correlation with starburst galaxies.
- Catalogue of 32 nearby galaxies
- Most important sources:
  - NGC 253, NGC 4945, Circinus and M83
  - 4 nearest sources in the catalogue within the field of view of Auger



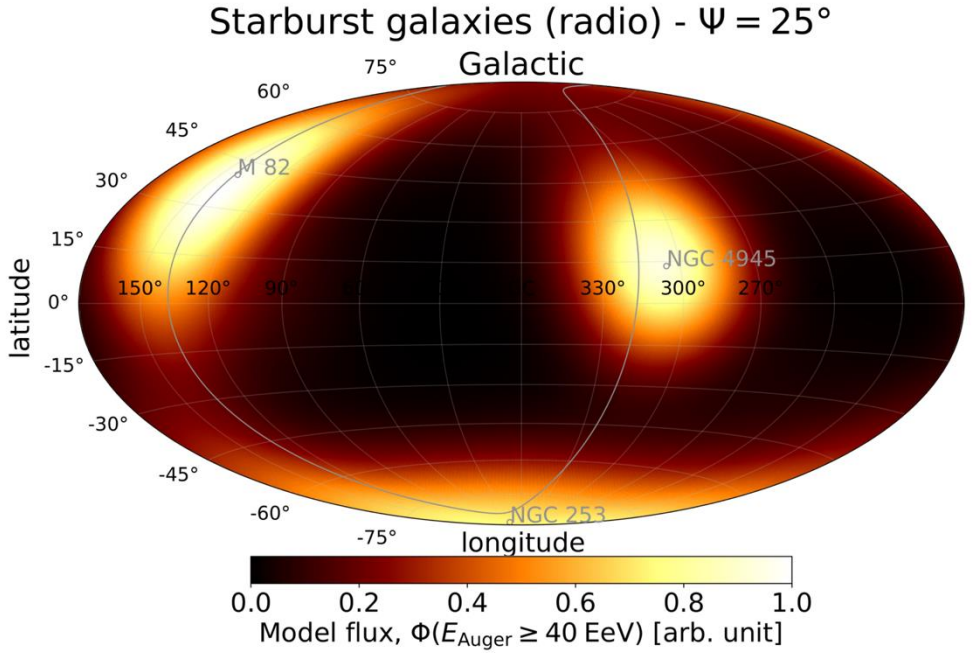
ICRC 2019 presentation by L. Caccianiga

Auger's analysis, including magnetic fields

- Redo Auger's analysis, using EGMFs instead of a Fisher distribution around sources.
- Neglect GMF: conservative limit on the strength of the EGMF.
- Starburst galaxies catalog: similar results for appropriate magnetic-field strength.



Al-Zetoun, AvV, Taylor and Winter, arXiv:2506.16169

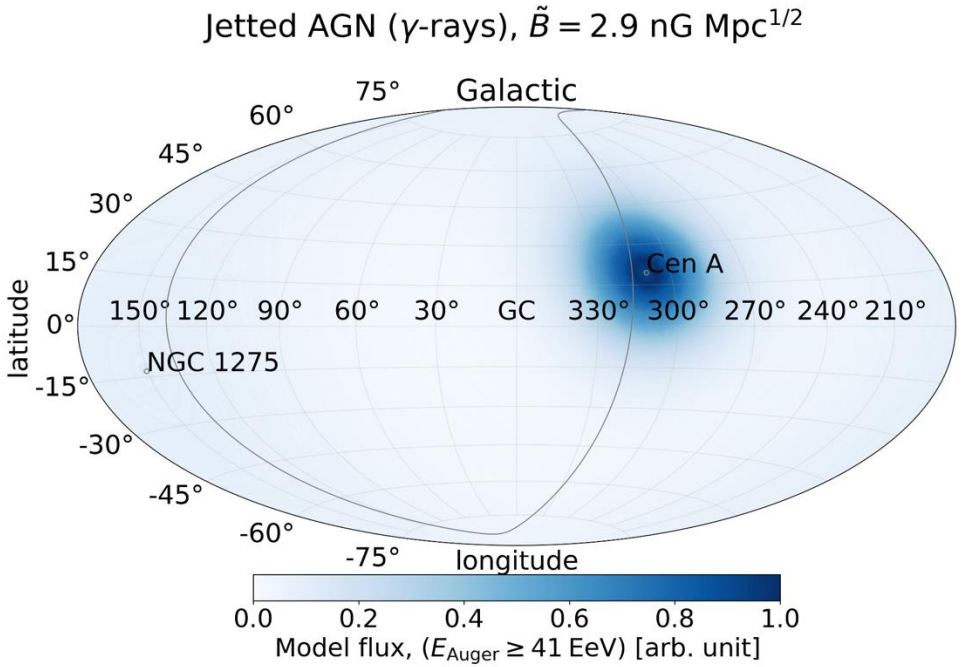


Auger

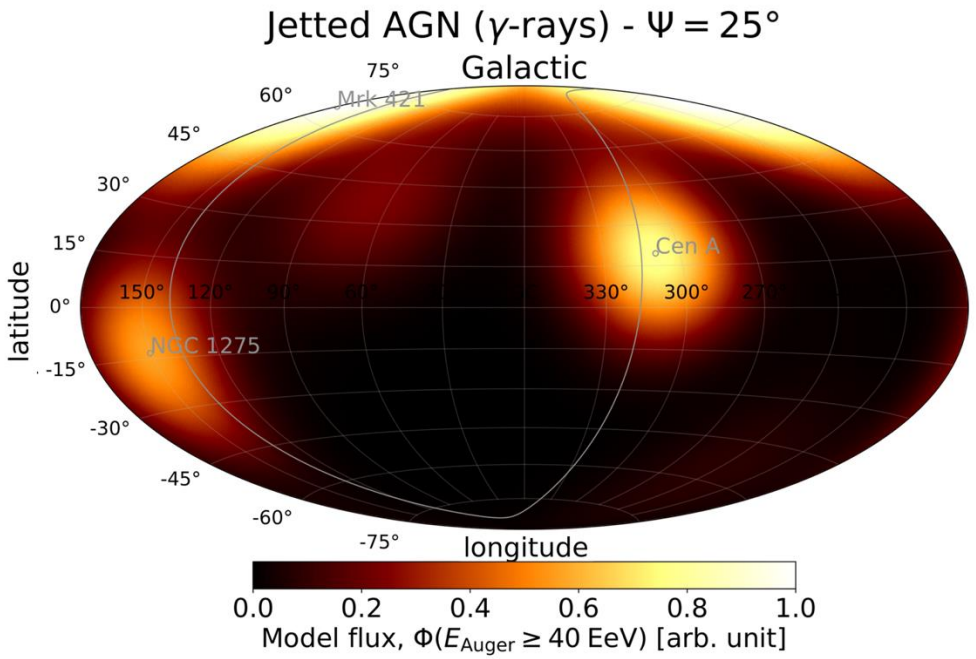
Pierre Auger Collaboration, Astrophys. J. Lett. 935 (2022) 170

Auger's analysis, including magnetic fields

- Redo Auger's analysis, using EGMFs instead of a Fisher distribution around sources.
- Neglect GMF: conservative limit on the strength of the EGMF.
- Jetted AGN catalog: different results due to additional distance dependence.



Al-Zetoun, AvV, Taylor and Winter, arXiv:2506.16169

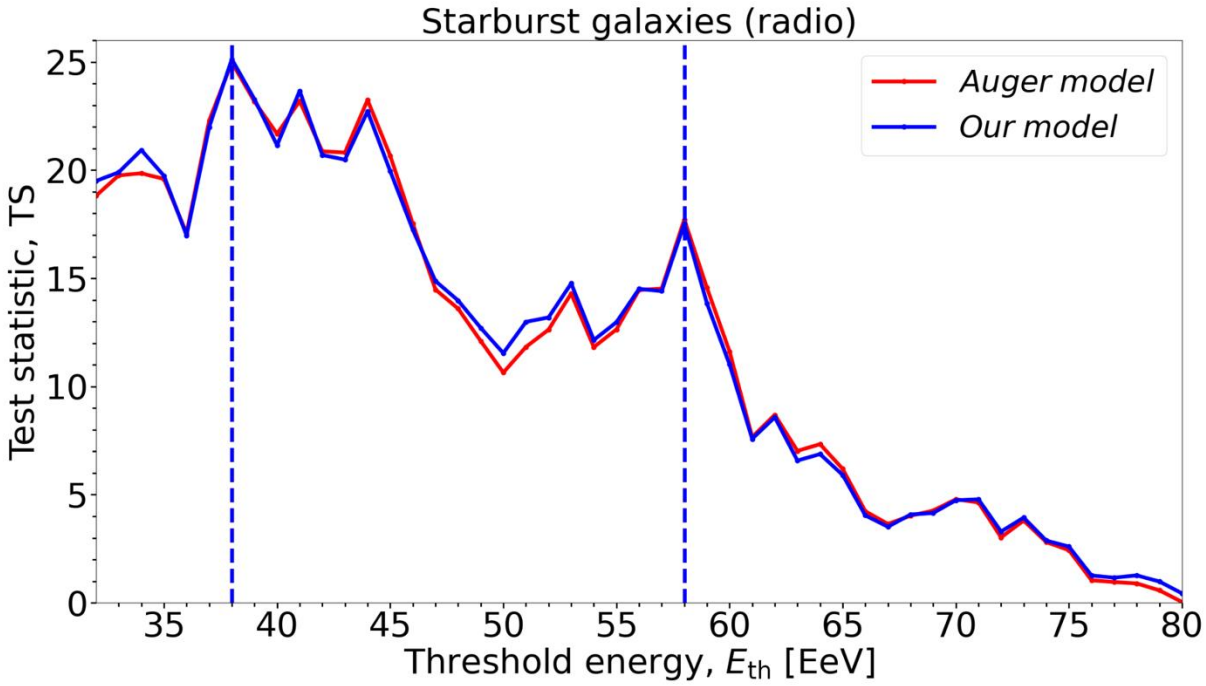


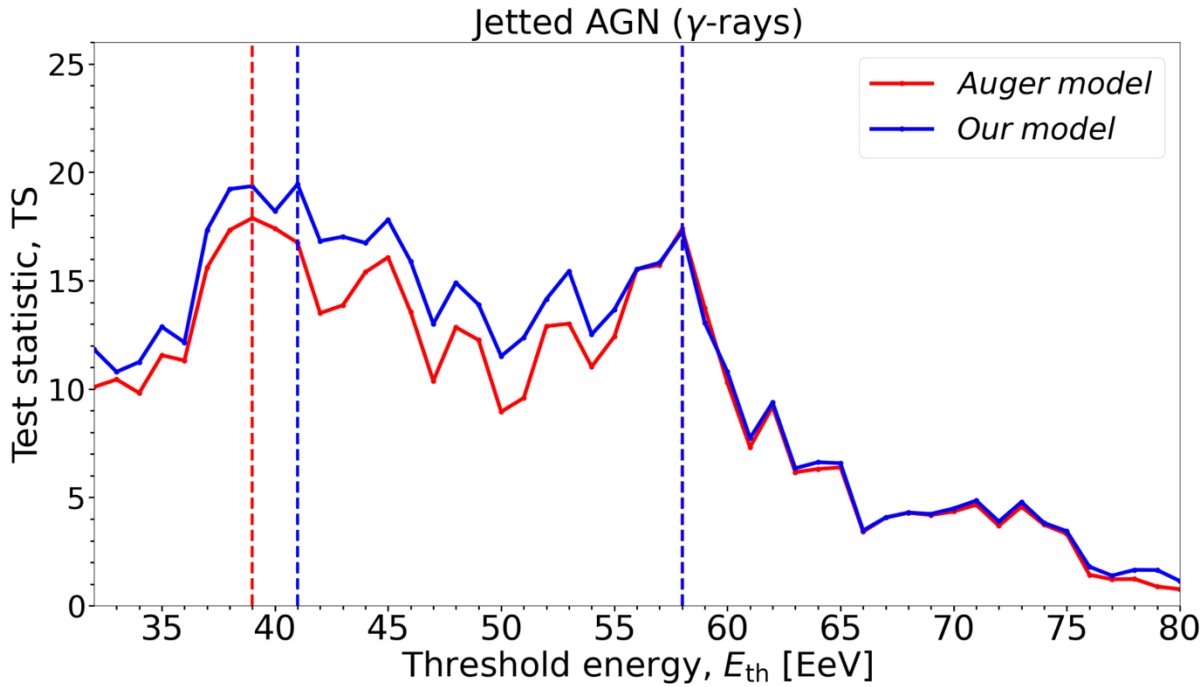
Auger

Pierre Auger Collaboration, Astrophys. J. Lett. 935 (2022) 170

Test statistic comparison

- Scan over threshold energy, signal fraction, magnetic-field strength (instead of angular width around source)
- Compare with Auger's UHECR data

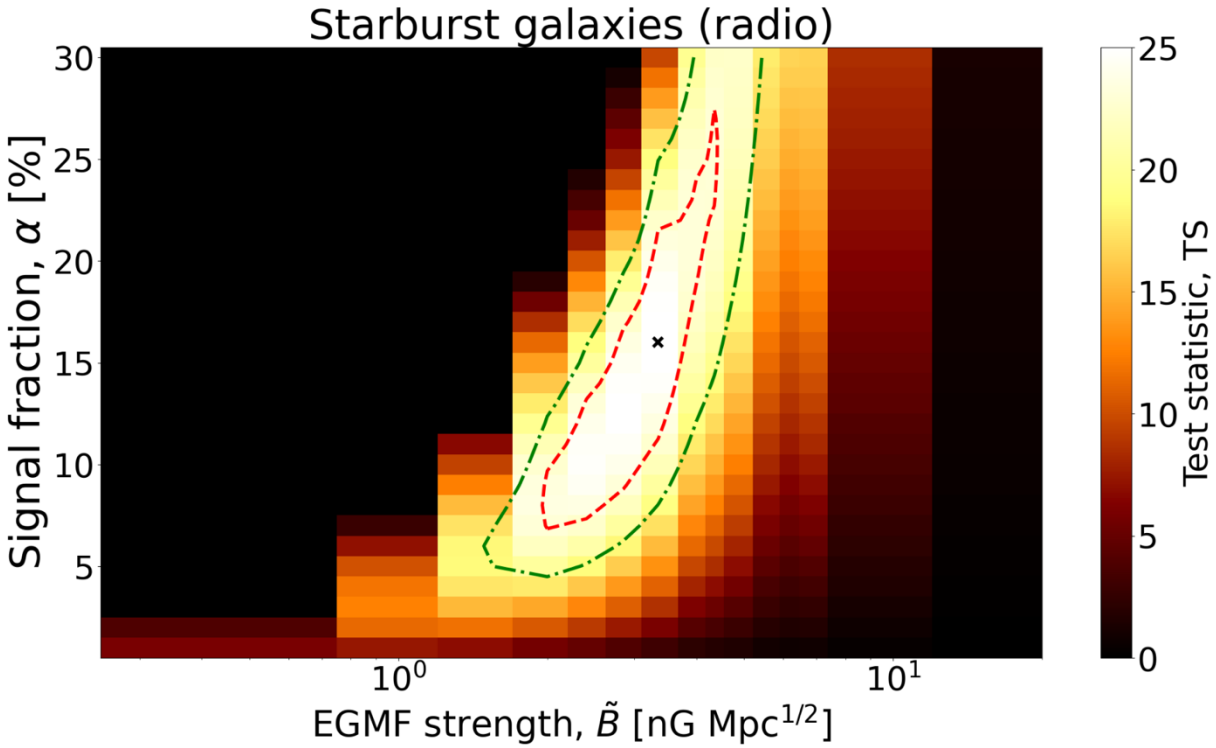


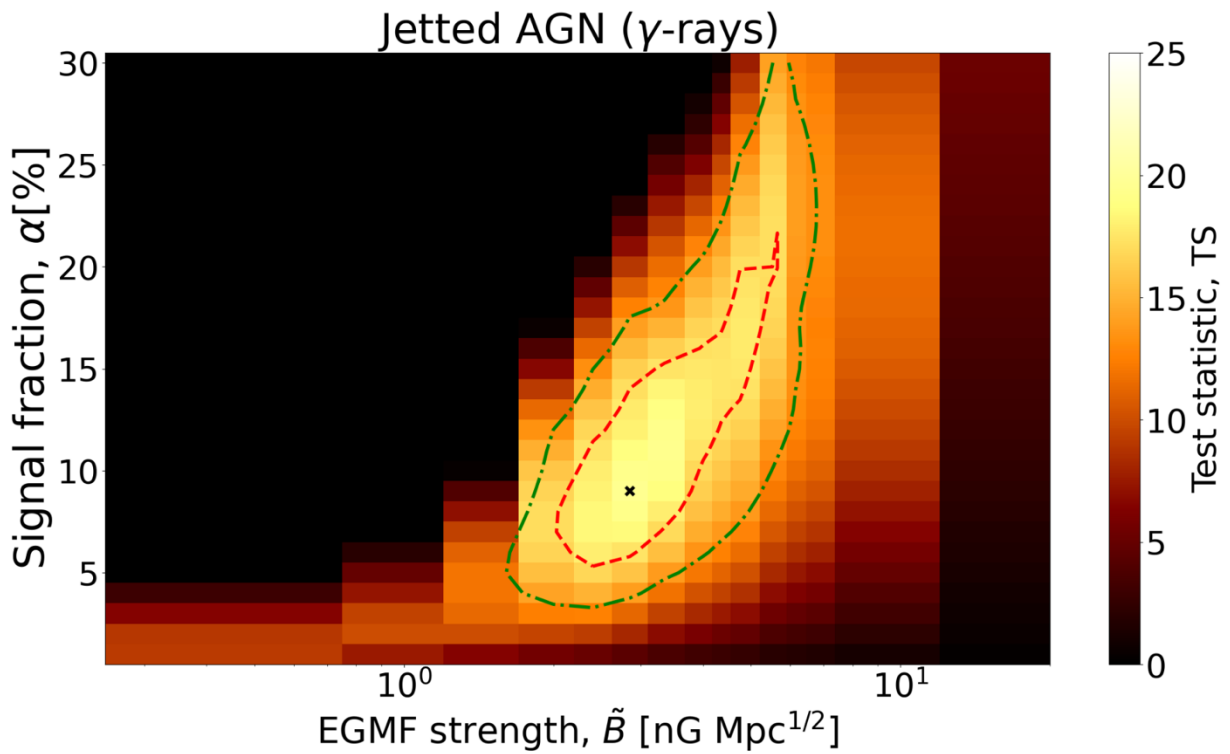


Al-Zetoun, AvV, Taylor and Winter, arXiv:2506.16169

EGMF strength

- EGMF only, no GMF
- Provides upper limit on EGMF strength
- 90% C.L. upper limit: $\tilde{B} < 4.4$ nG Mpc$^{1/2}$ (Starburst galaxies); $\tilde{B} < 6.7$ nG Mpc$^{1/2}$ (Jetted AGN)





Al-Zetoun, AvV, Taylor and Winter, arXiv:2506.16169

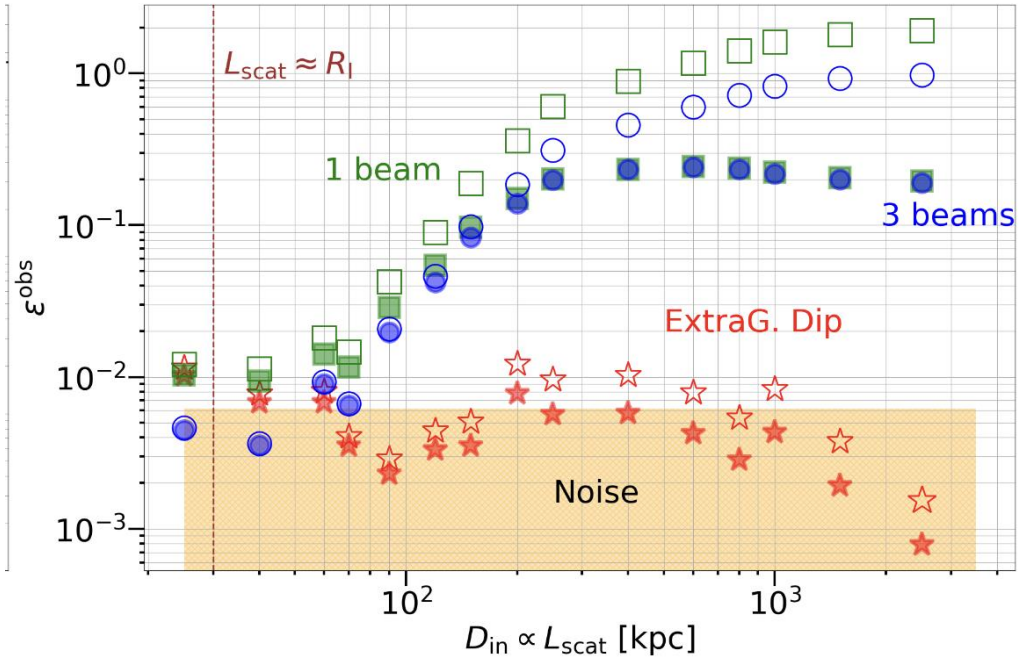
Conclusions

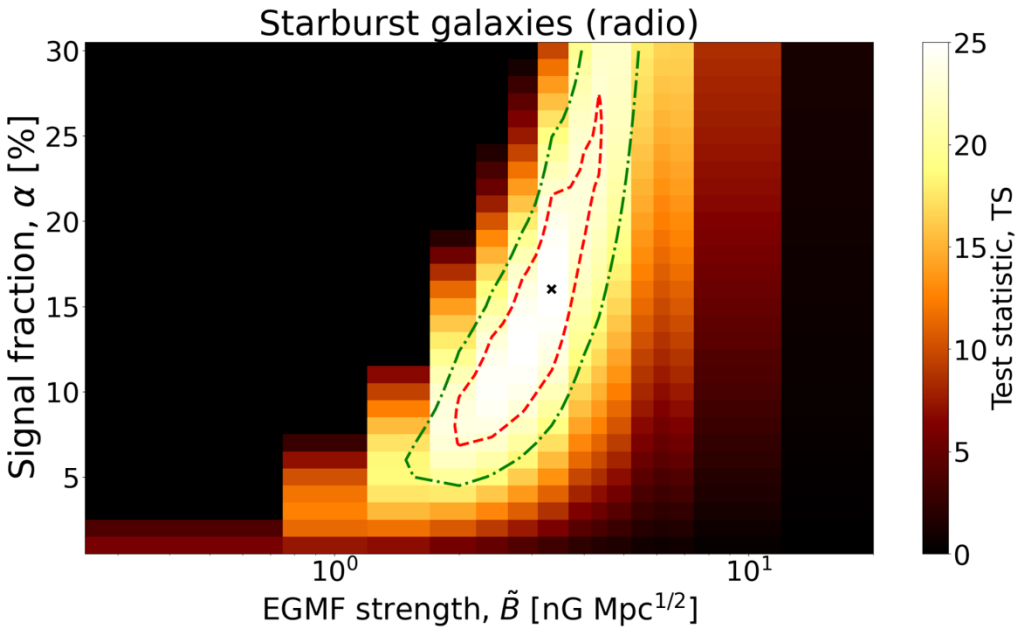
- **Dipole/Quadrupole:**
- Quadrupole in UHECRs can distinguish between different UHECR origin scenarios, even if the dipole cannot.

  Shaw, AvV, Taylor, MNRAS, 543 (2025) 3242

- **Intermediate-scale anisotropies:**
- Conservative assumptions: neglect GMF.
  - 90% C.L. upper limits: $\tilde{B} < 6.7$ nG Mpc$^{1/2}$.
  - Limit on average EGMFs in between sources and Milky Way, not necessarily in voids

  Al-Zetoun, AvV, Taylor and Winter, arXiv:2506.16169





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Thank You

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Simplified description of UHECR deflections

- For turbulent magnetic fields (spread around the source position):

UHECRs $\frac{E}{Z}\theta_{\mathrm{rms}} \propto \frac{ec\sqrt{D}}{2}\sqrt{\lambda B_{\perp}}$ Magnetic-field properties

- For a uniform magnetic field (shift of the source position):

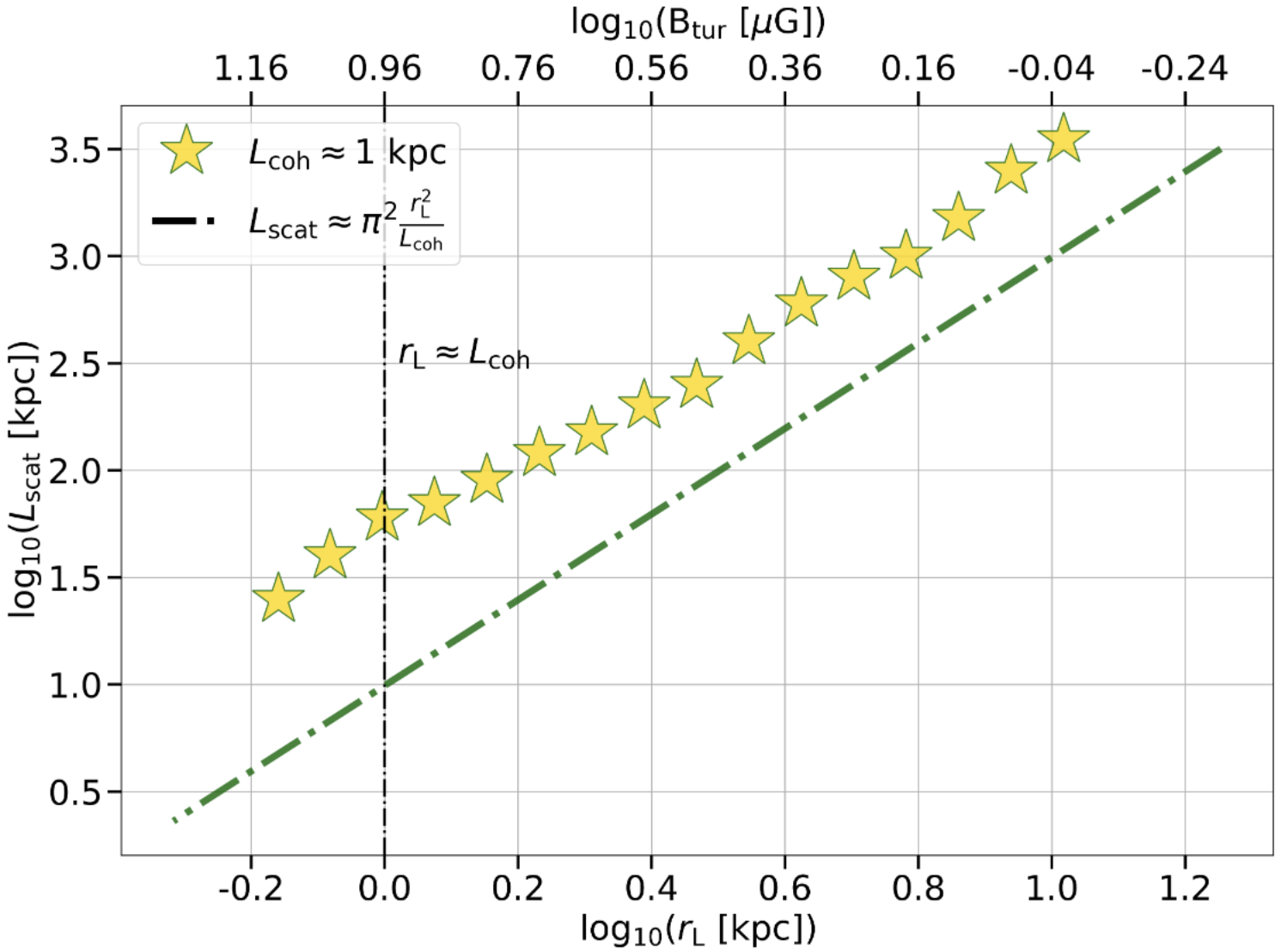
UHECRs $\frac{E}{Z}\sin\theta = \frac{ecD}{2}B_{\perp}$ Magnetic-field properties

- Event-by-event rigidity (Auger Prime) will be a huge benefit!

Scattering length

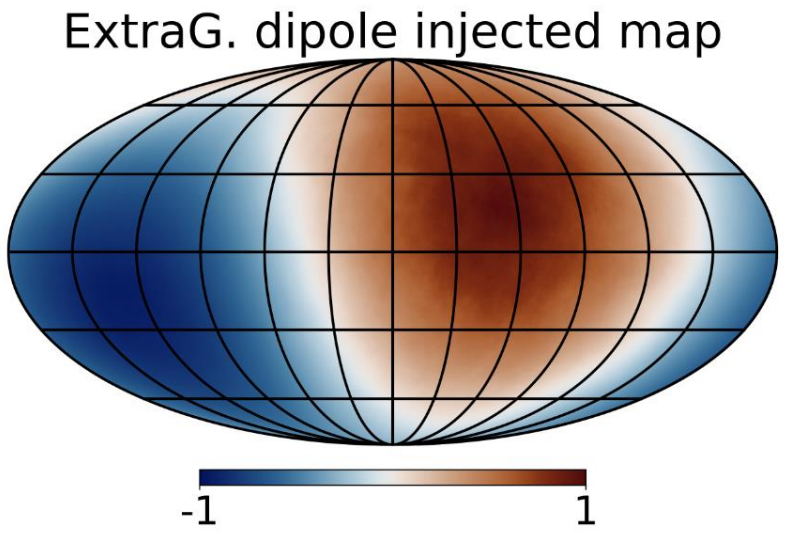
- Scattering length as a function of the Larmor radius and EGMF strength

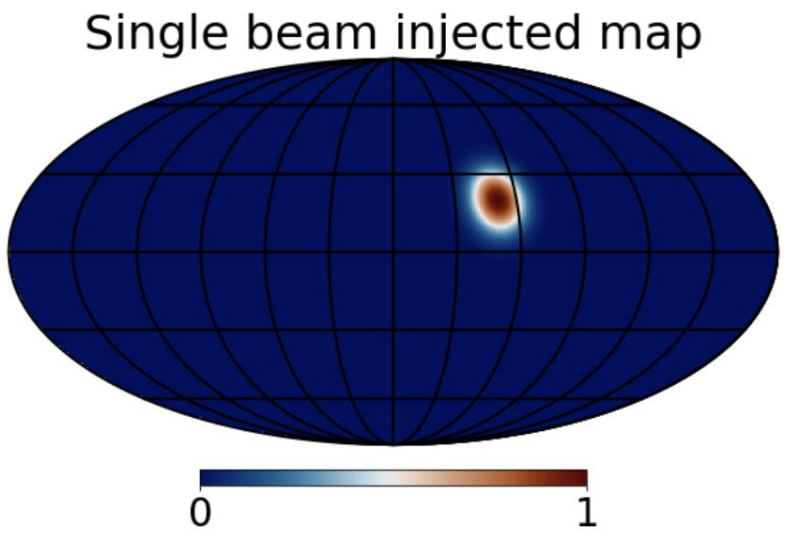
Shaw, AvV, Taylor, MNRAS, 543 (2025) 3242

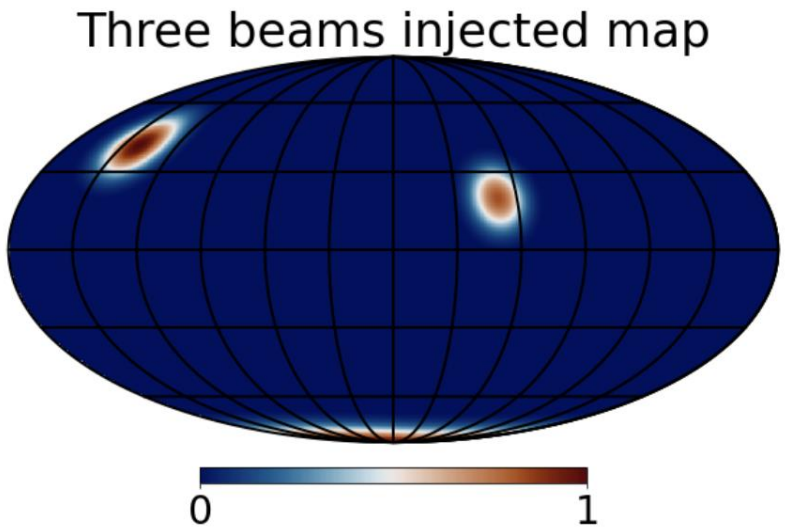


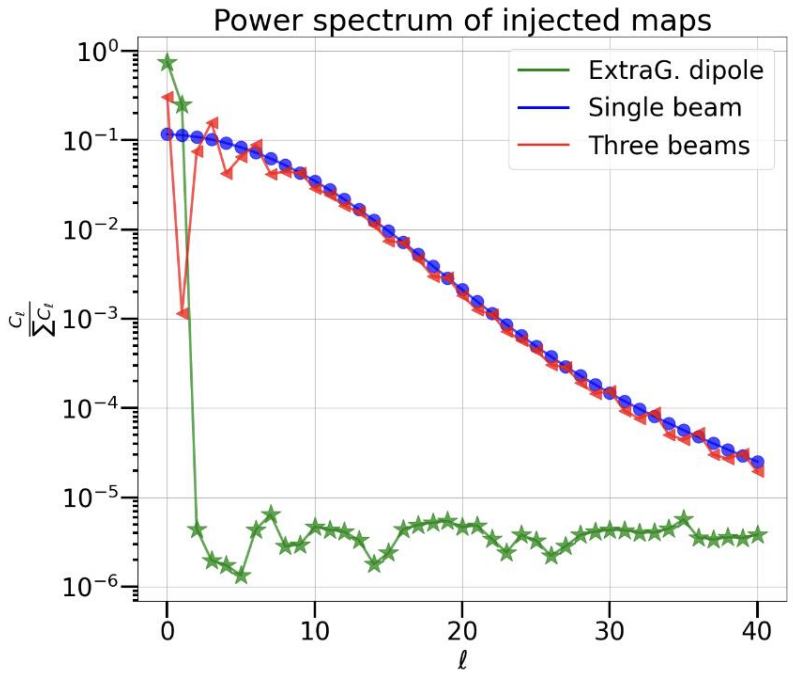
Injected maps

Shaw, AvV, Taylor, MNRAS, 543 (2025) 3242



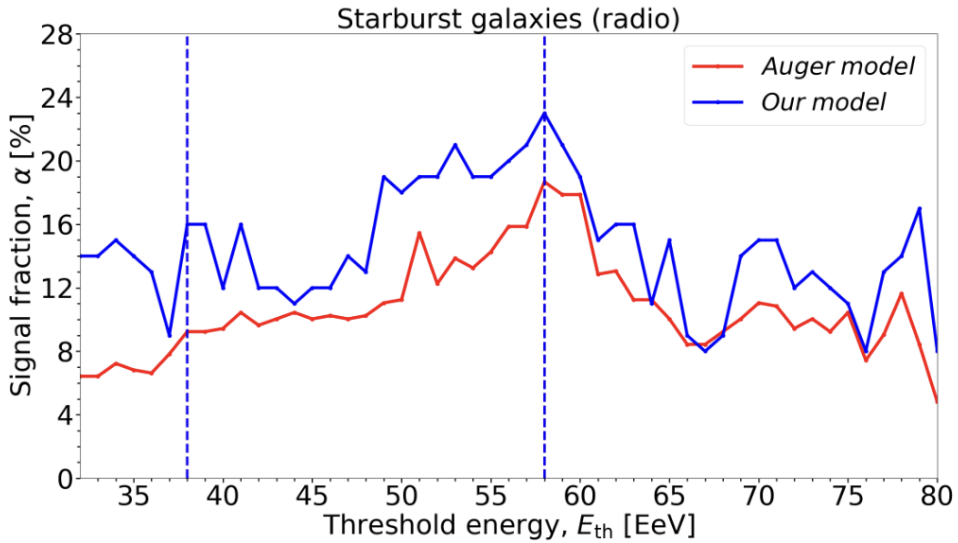


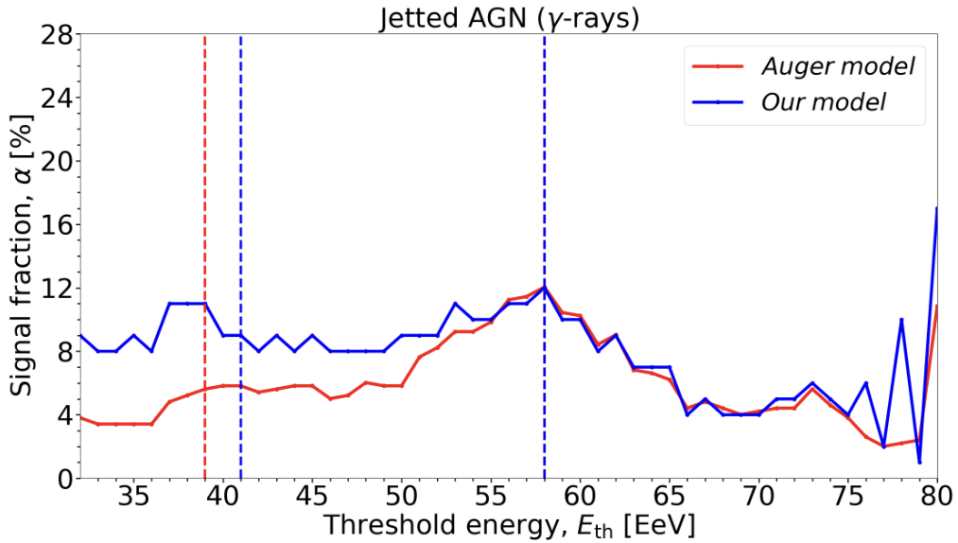


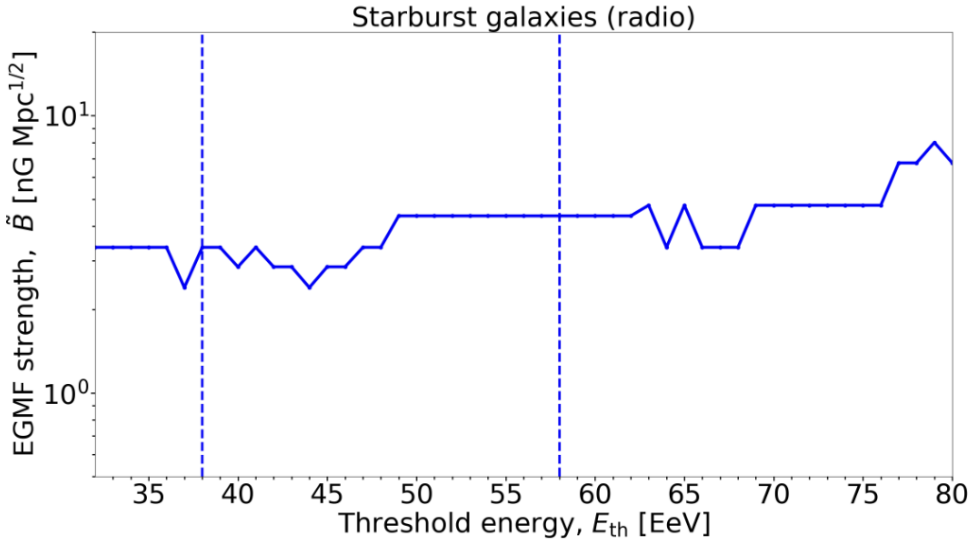


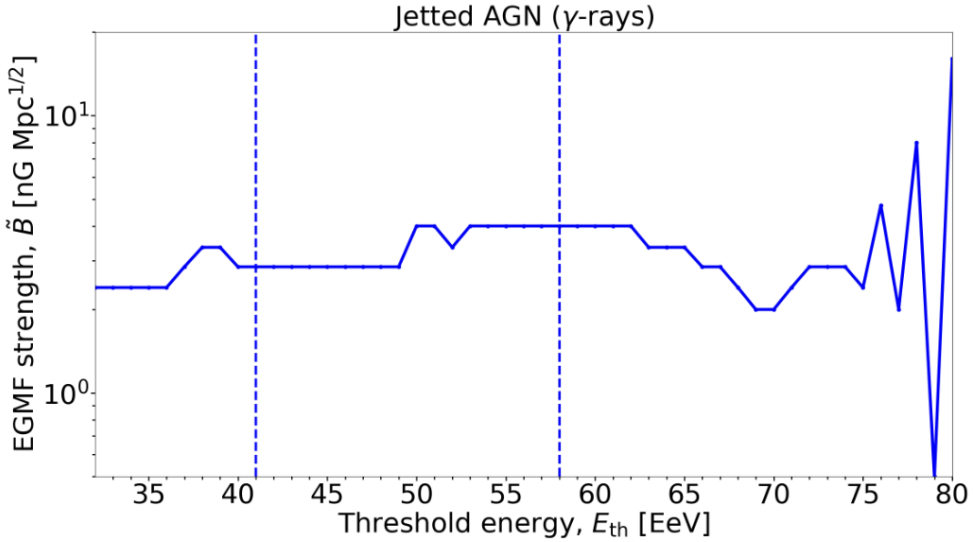
Signal fraction and EGMF strength

A. Al-Zetoun, AvV, A. M. Taylor and W. Winter, arXiv:2506.16169









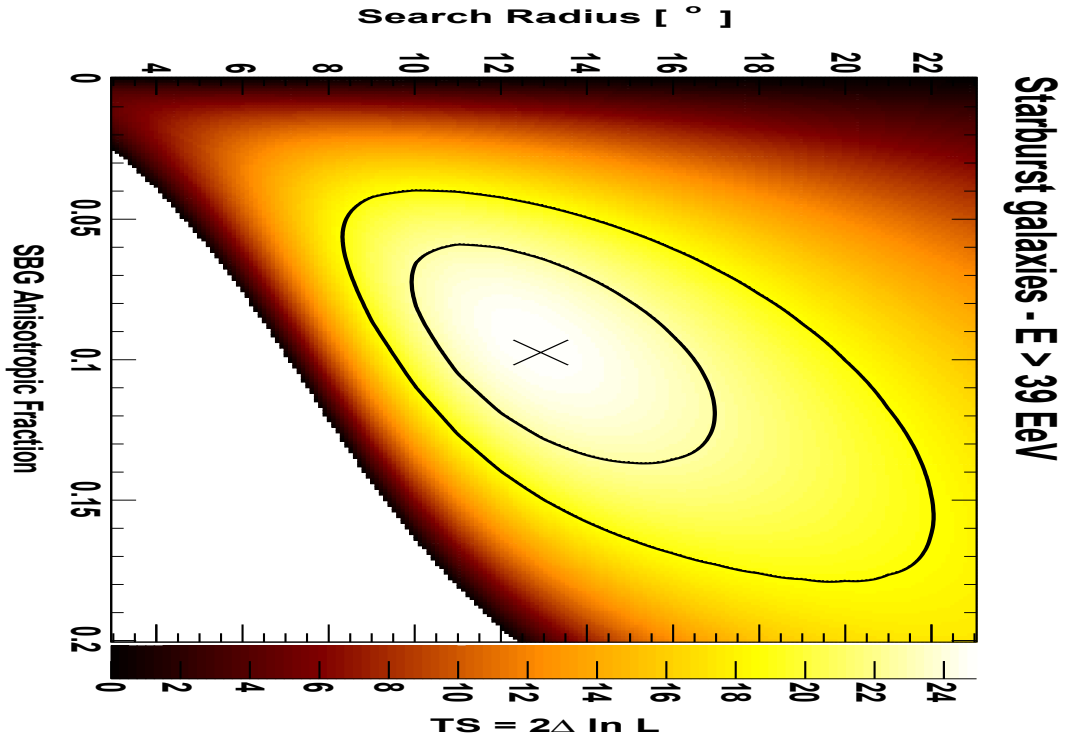
Magnetic-field limits from other UHECR papers

- Both upper limits and lower limits on the strength of EGMFs can be obtained from UHECR measurements, under specific assumptions.
- Conservative assumptions: UHECRs anisotropy produced in sources at ~3-4 Mpc distance.
  - 90% C.L. upper limits: $\beta_{\mathrm{EGMF}} \lesssim 20$ nG Mpc$^{1/2}$. AvV, Palladino, Taylor and Winter, MNRAS 510 (2021) 1289
  - Limit on average EGMFs in between sources and Milky Way, not necessarily in voids.
- More aggressive assumptions: typical source distance of ~70 Mpc, and Auger or TA hotspot, or assume continuous sources following the LSS of the Universe.
  - Limit at the level of $\beta_{\mathrm{EGMF}} \lesssim 0.2$ nG Mpc$^{1/2}$. Bray and Scaife 2018,
  - Limit more likely to actually correspond to EGMFs in voids.
- Lower limit obtained assuming JF12 GMF deflections and source densities not too large:
  - $\beta_{\mathrm{EGMF}} \gtrsim 0.2$ nG Mpc$^{1/2}$. AvV, A. Palladino, A. M. Taylor and W. Winter, MNRAS 510 (2021) 1289
  - Limit on average EGMFs in between sources at ~3-4 Mpc and Milky Way, not necessarily in voids.

The analysis performed by Auger

Pierre Auger Collaboration, Astrophys. J. Lett. 853 (2018) 2 Pierre Auger Collaboration, PoS ICRC2019 206

- **Catalogue of 32 nearby star-forming galaxies**
- **Probability density maps, 2 components:**
  - Isotropic component (equal probability everywhere)
  - Anisotropic component from the star-forming galaxies
- **Anisotropic component:**
  - Fisher distribution centred on the source coordinates (width θ)
  - Source flux proportional to radio emission + attenuation factor from UHECR energy losses
- **Ratio between isotropic and anisotropic component: f_{aniso}**
- **Maximum-likelihood analysis:**
  - Location of UHECR events × probability density map
  - Compared with isotropic probability density map



Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	$15^{+5}_{-4}{}^{\circ}$	$11^{+5}_{-4}\%$	29.5	$4.5\,\sigma$
γ-AGNs	39 EeV	$14^{+6}_{-4}{}^{\circ}$	$6^{+4}_{-3}\%$	17.8	$3.1\,\sigma$
Swift-Bat	38 EeV	$15^{+6}_{-4}{}^{\circ}$	$8^{+4}_{-3}\%$	22.2	$3.7\,\sigma$
2MRS	40 EeV	$15^{+7}_{-4}{}^{\circ}$	$19^{+10}_{-7}\%$	22.0	$3.7\,\sigma$