

Ultra-high-energy cosmic rays from star-forming galaxies constrain the extragalactic magnetic field

Arjen van Vliet

Andrea Palladino, Walter Winter and Andrew Taylor

EPS-HEP2021 conference, 26/07/2021

Image: Pierre Auger Observatory

AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732, submitted to MNRAS

HELMHOLTZ RESEARCH FOR
GRAND CHALLENGES

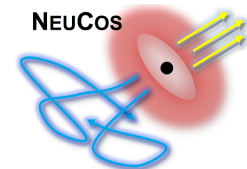


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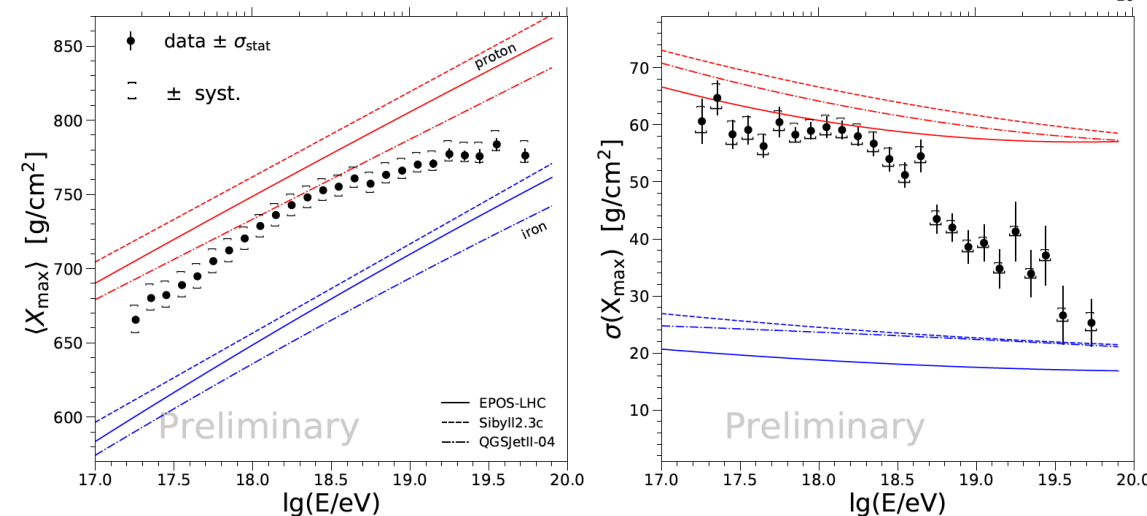
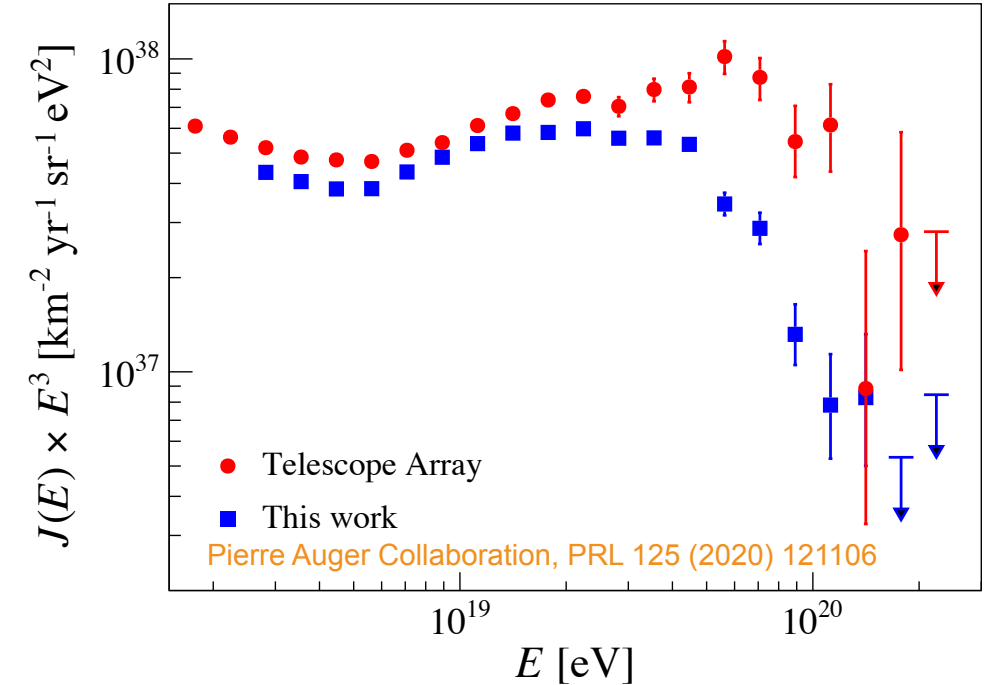
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Ultra-high-energy cosmic rays (UHECRs)

- Nuclei from protons to iron with $E > 10^{18}$ eV (= 1 EeV)
- Main experiments:
 - Pierre Auger Observatory in Argentina
 - Telescope Array in the US
- Features in the energy spectrum
 - 'Ankle' at $\sim 5 \times 10^{18}$ eV
 - 'Instep' at $\sim 14 \times 10^{18}$ eV
 - 'Suppression' at $\sim 47 \times 10^{18}$ eV
- Composition, getting increasingly heavier above the ankle
- No identified sources yet, but indication of anisotropies in the arrival directions have been detected



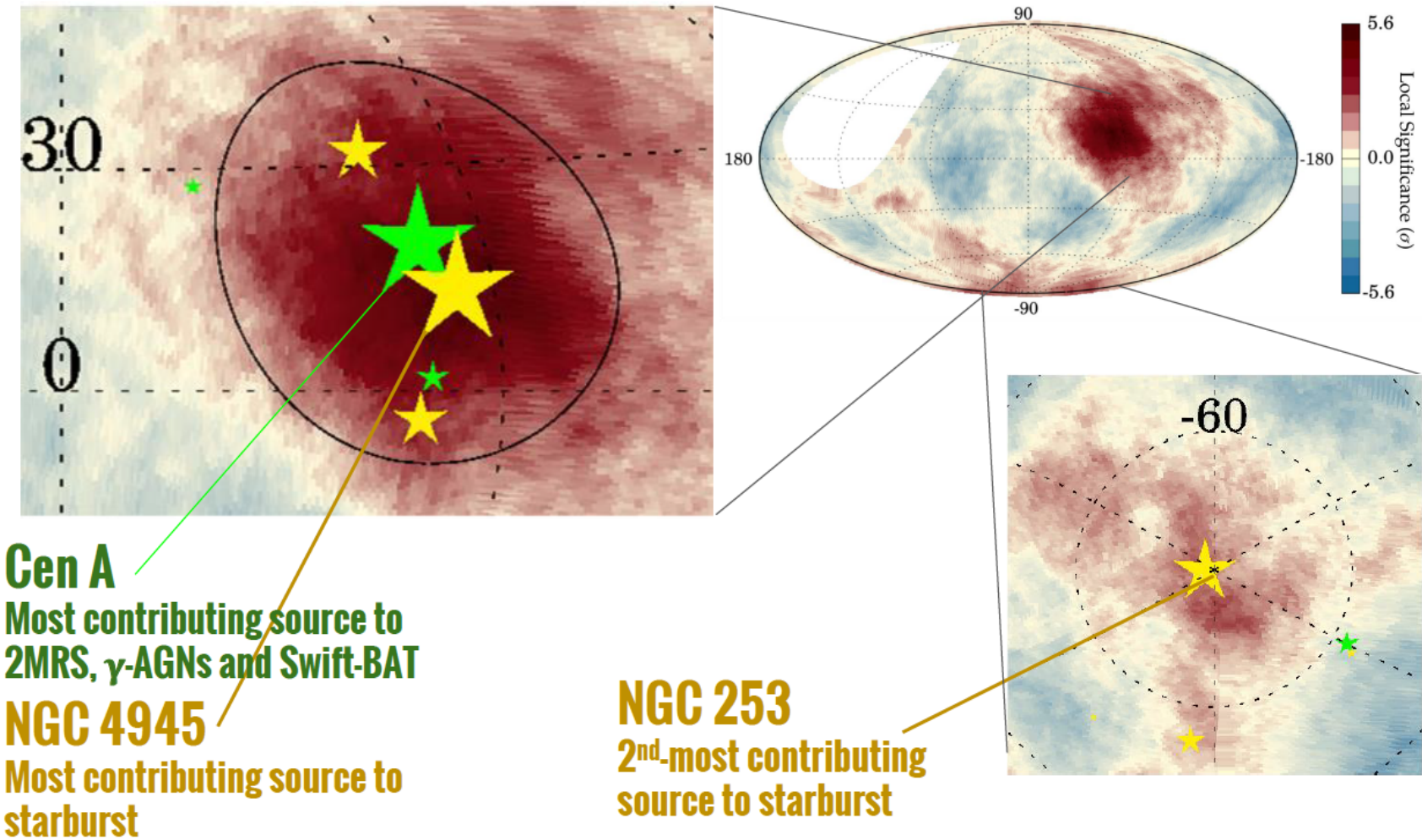
Indication of anisotropy in arrival directions found by Auger

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

Pierre Auger Collaboration, *PoS ICRC2019* 206

- Largest post-trial significance for correlation with starburst/star-forming 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

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



ICRC 2019 presentation by L. Caccianiga

Constraints on extragalactic magnetic fields and local source density

AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732, submitted to MNRAS

- Galactic and extragalactic magnetic fields (GMF and EGMF) deflect UHECRs
- θ : optimal angular width around sources, measure for the deflection of UHECRs from those sources
- A larger local source density means more contributing sources, reducing the expected level of anisotropy
- f_{aniso} : fraction of UHECRs from the catalogue sources, directly related to the source density
- Auger results can be used to constrain magnetic fields and local source density

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Pierre Auger Collaboration, PoS ICRC2019 206

UHECR

UHECR propagation:

- Creation at sources
- Deflections by magnetic fields
- Interactions with CMB and EBL
- Nuclear decay
- Detection at Earth

CR $\overrightarrow{\text{Propa}}$

See crpropa.desy.de
 R. Alves Batista, A. Dundovic, M. Erdmann, K.-H. Kampert, D. Kümpel,
 G. Müller, G. Sigl, **AvV**, D. Walz and T. Winchen, JCAP 1605 (2016) 038

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Our method

AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732, submitted to MNRAS

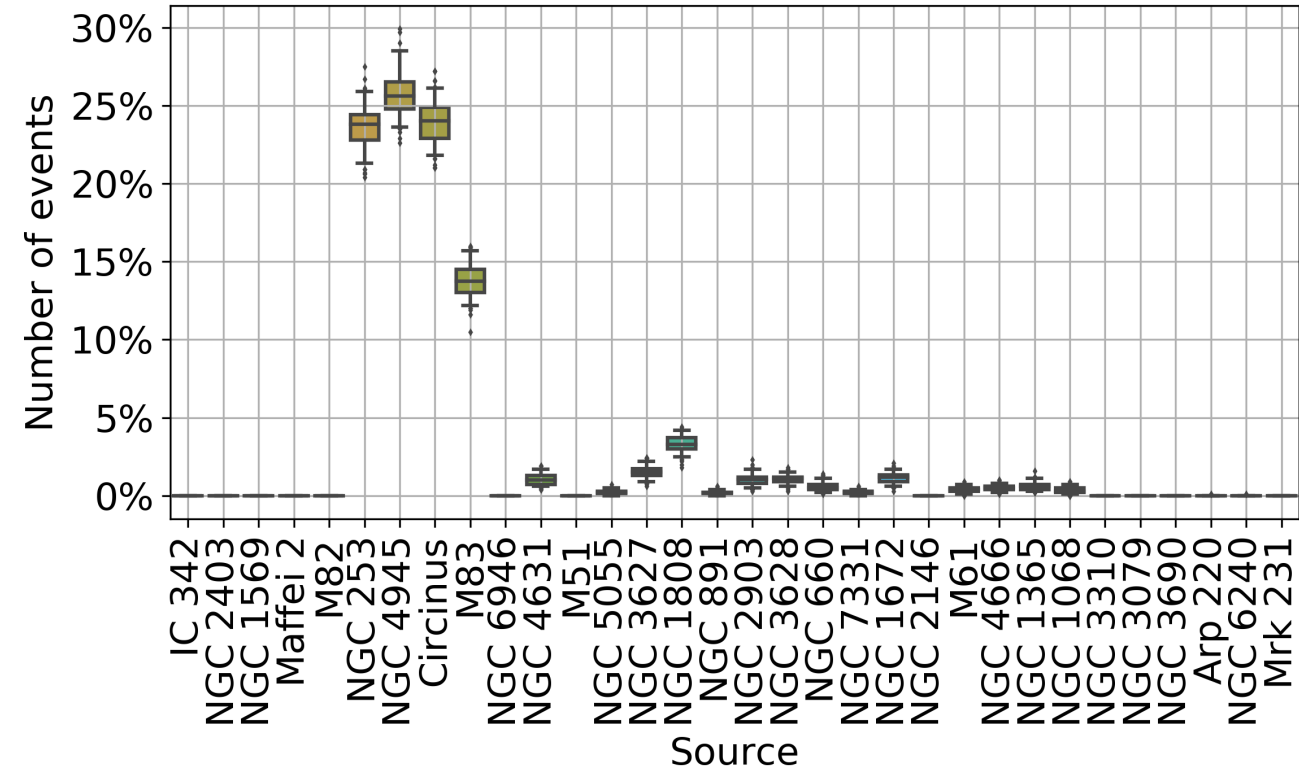
- Simulate UHECR sky maps for specific EGMF and GMF setups and local source densities ρ_0
- Check if these sky maps give θ and f_{aniso} values compatible with what Auger found

Our method

4 important sources

AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732, submitted to MNRAS

- Simulate UHECR sky maps for specific EGMF and GMF setups and local source densities ρ_0
- Check if these sky maps give θ and f_{aniso} values compatible with what Auger found
- Focus on 4 most important sources
- UHECR source spectra and composition from fits to spectrum and composition of Auger
- Simulate deflections from catalogue sources in EGMF
 - random Kolmogorov fields; $0.1 < B_{\text{RMS}} < 10$ nG, $0.2 < l_{\text{coh}} < 10$ Mpc; $B = B_{\text{RMS}} \times \sqrt{l_{\text{coh}}}$
- Add deflections from GMF, JF12 model
- Combine catalogue sources with an isotropic contribution from background sources



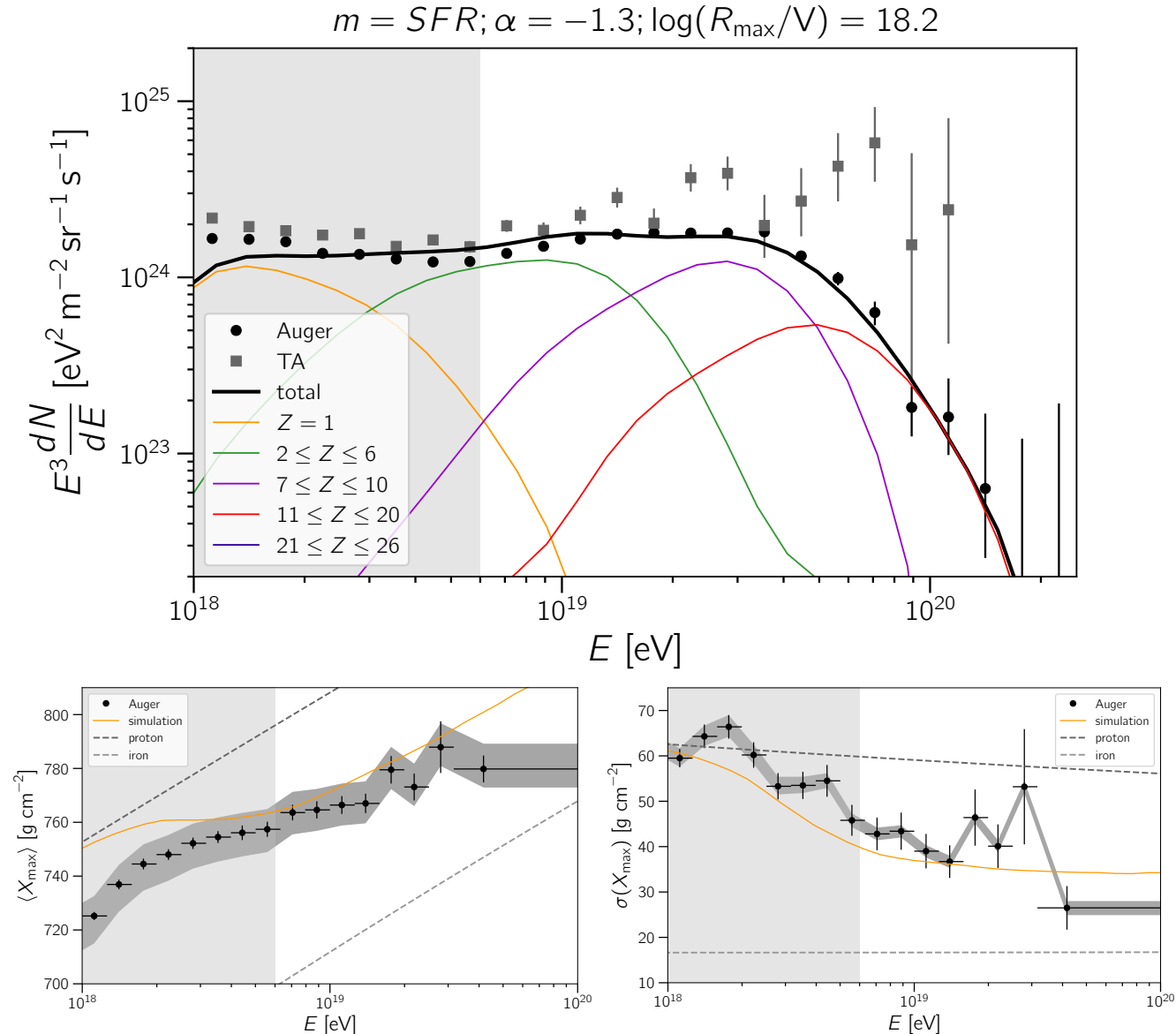
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UHECR spectrum and composition

AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732

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DESY. UHECRs from star-forming galaxies constrain the EGMF strength



R. Alves Batista, R. M. de Almeida, B. Lago, K. Kotera, JCAP 01 (2019) 002

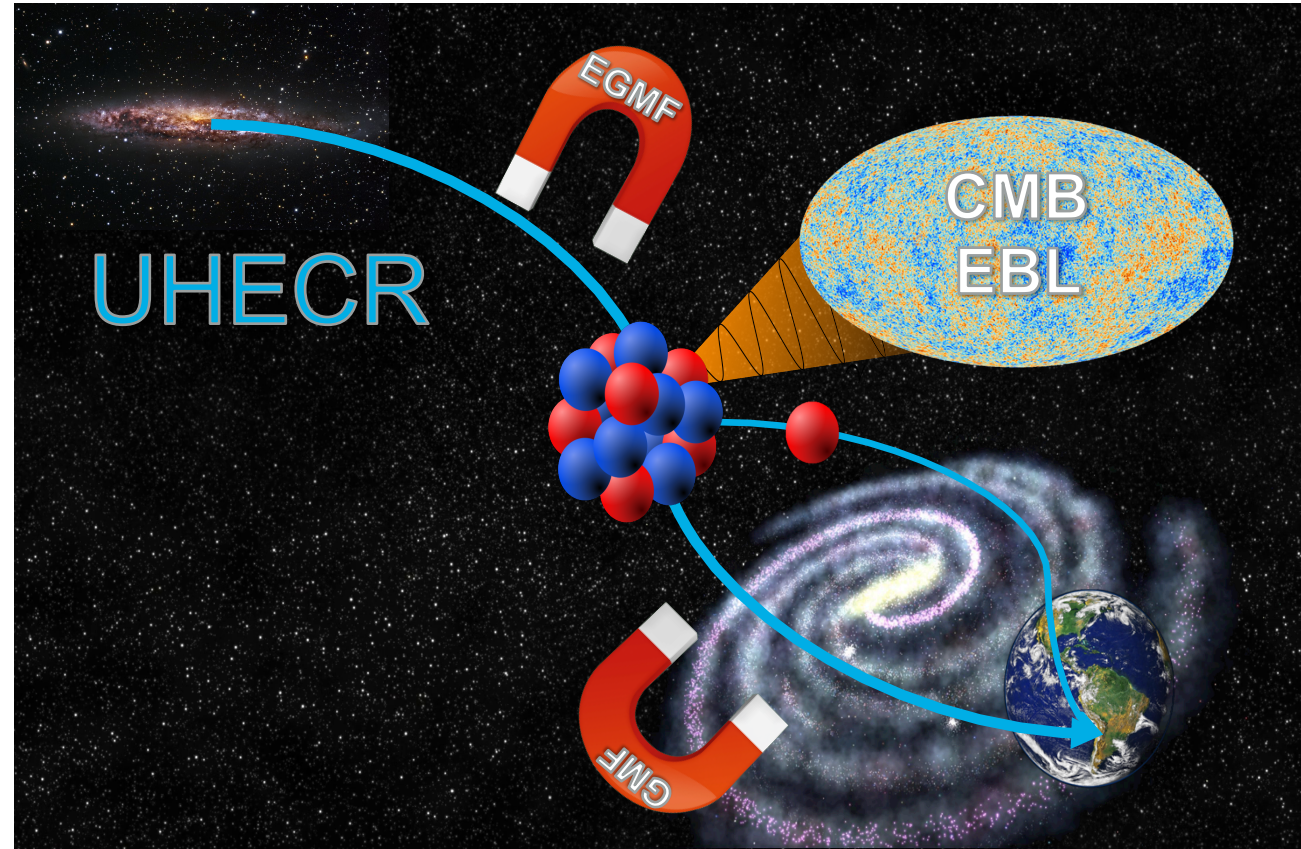
Our method

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DESY. UHECRs from star-forming galaxies constrain the EGMF strength

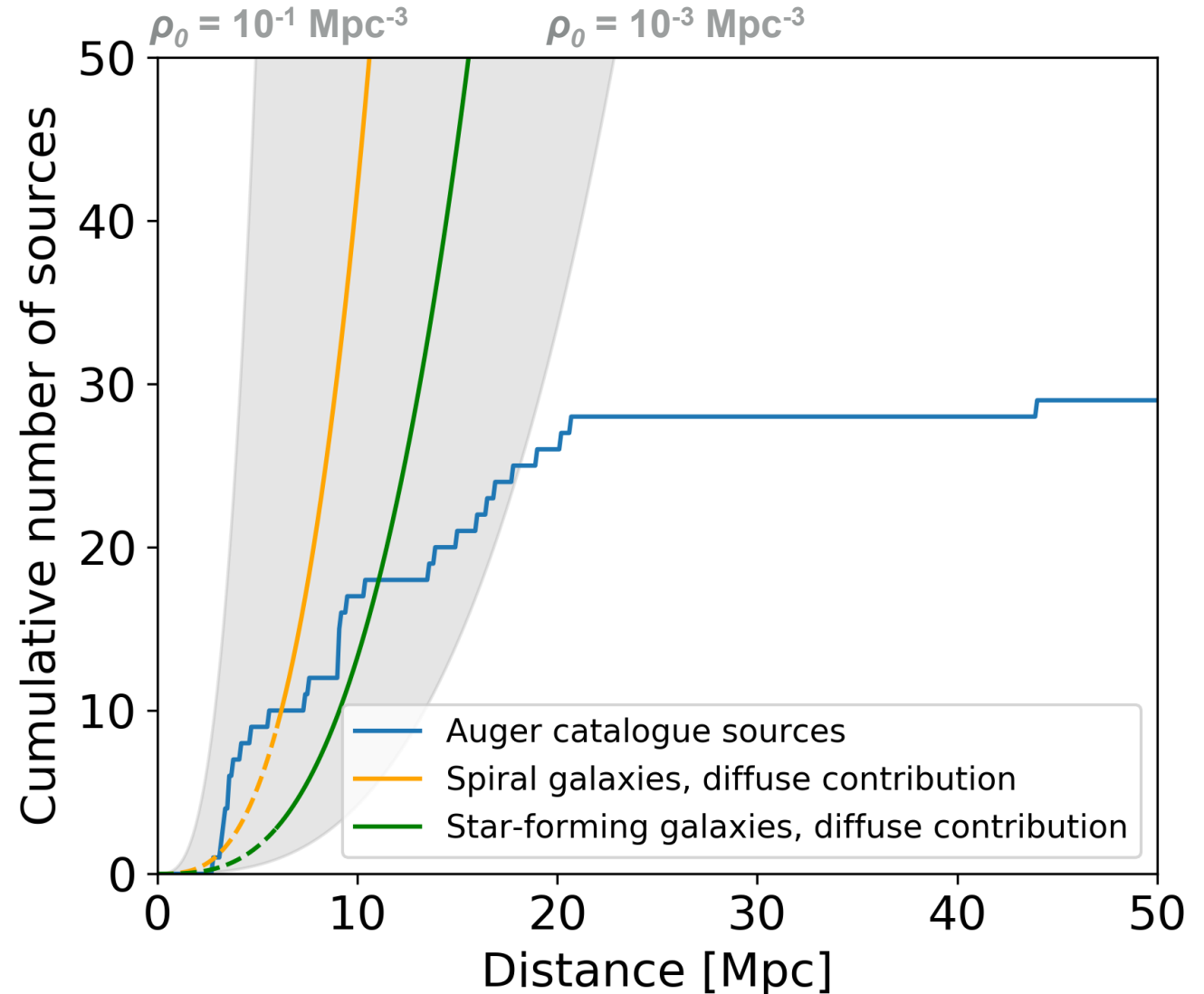


Our method

Source density

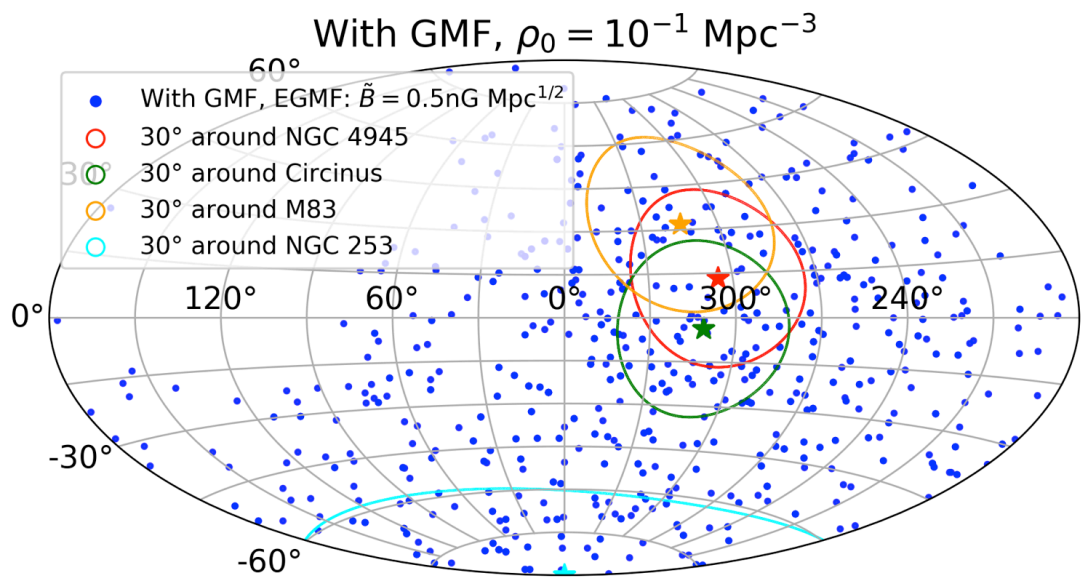
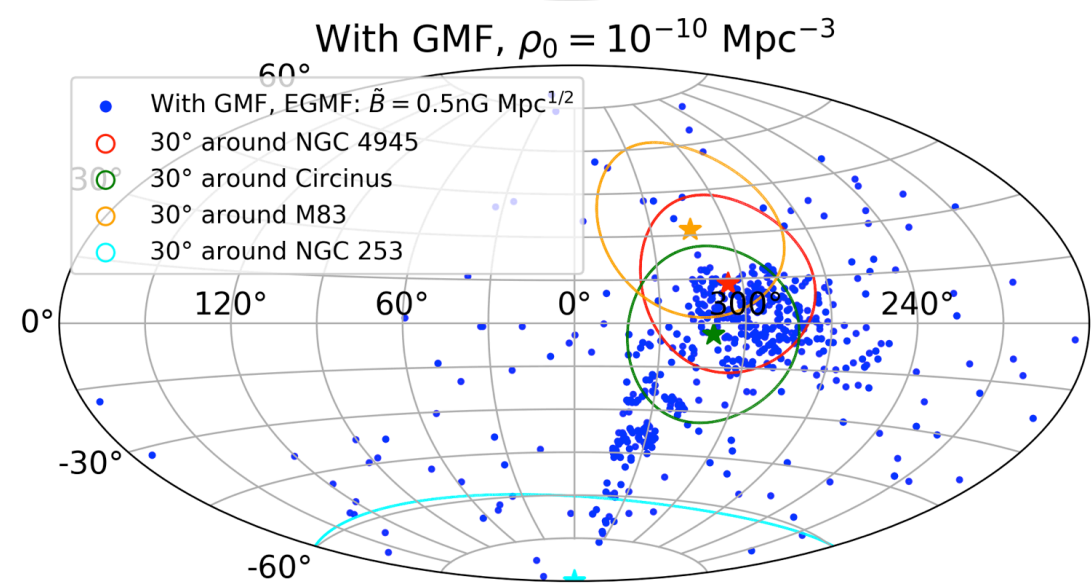
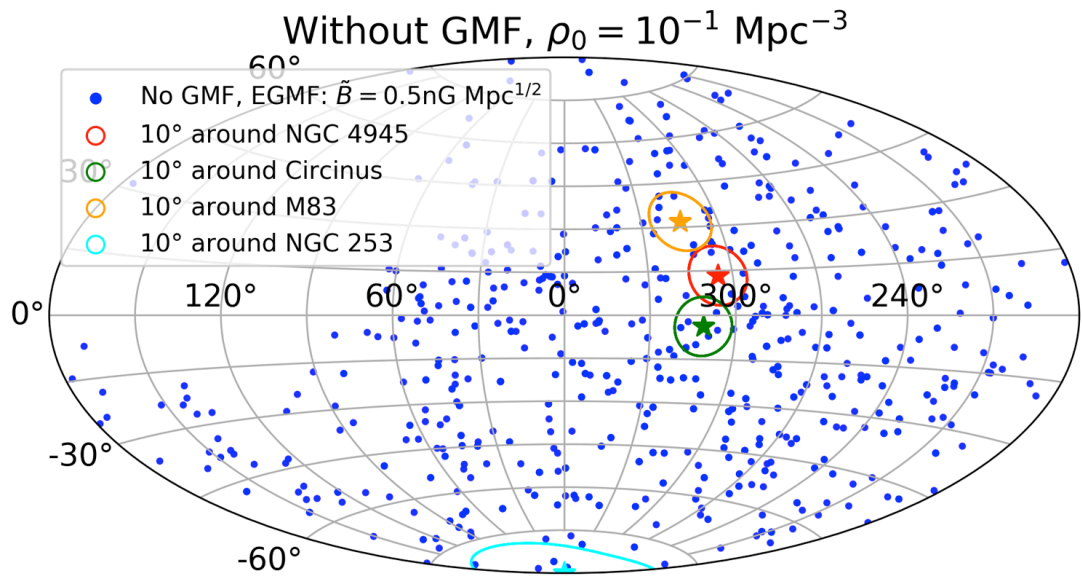
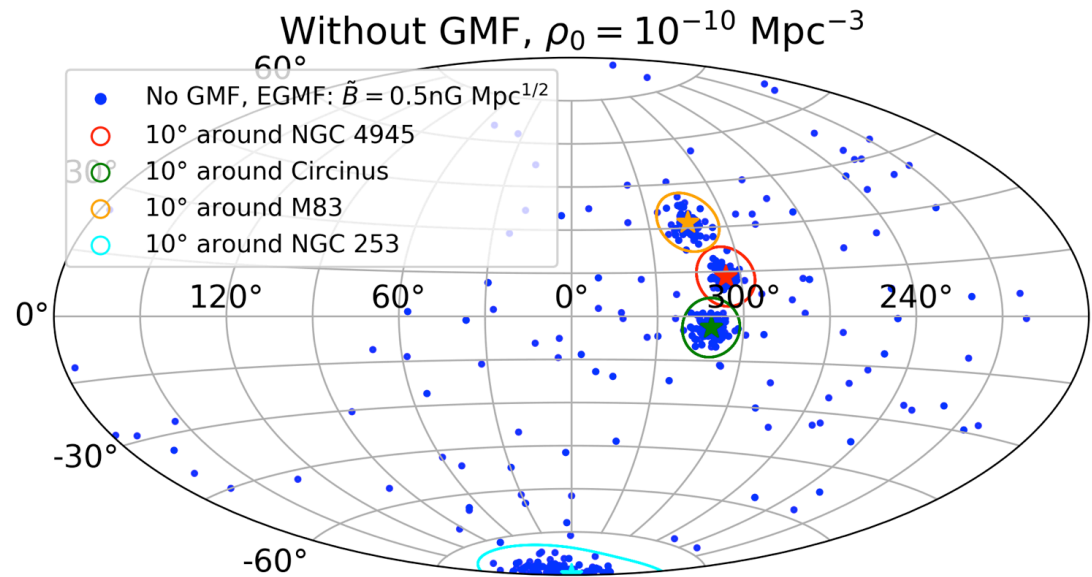
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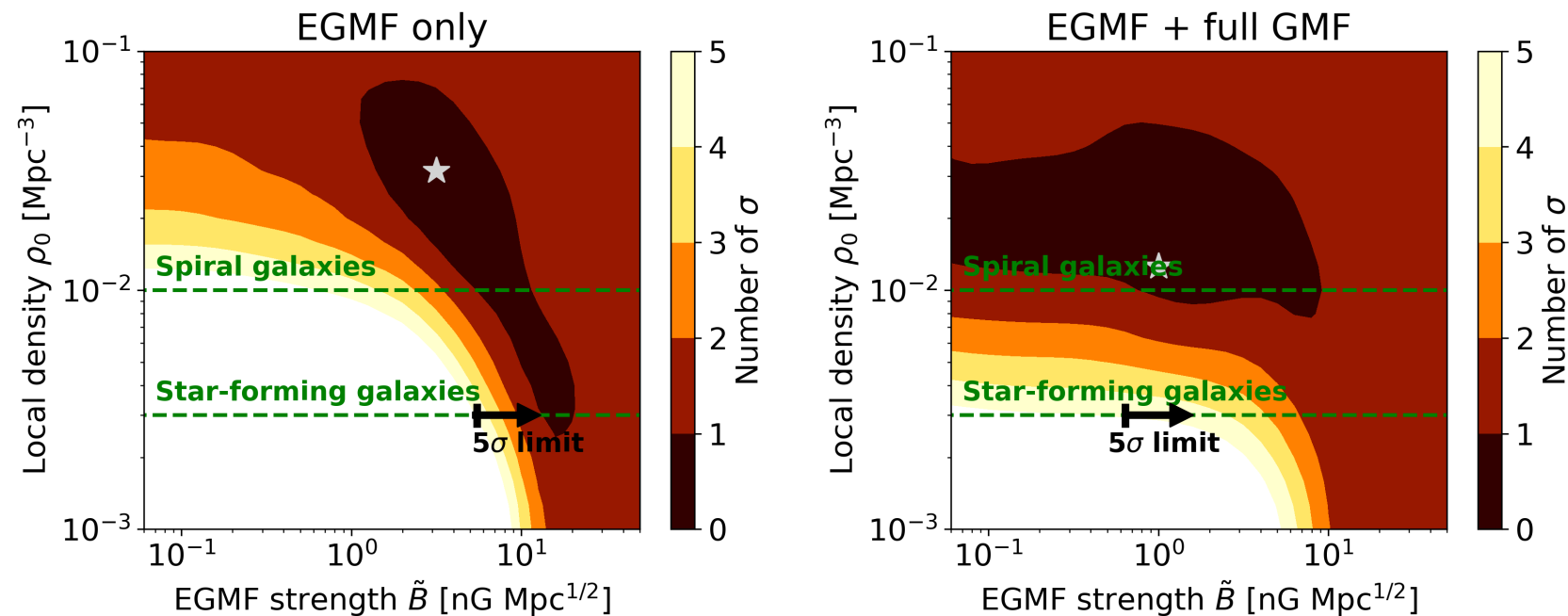
Example sky maps

AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732, submitted to MNRAS



Preliminary results from scanning over ρ_0 and B

AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732, submitted to MNRAS

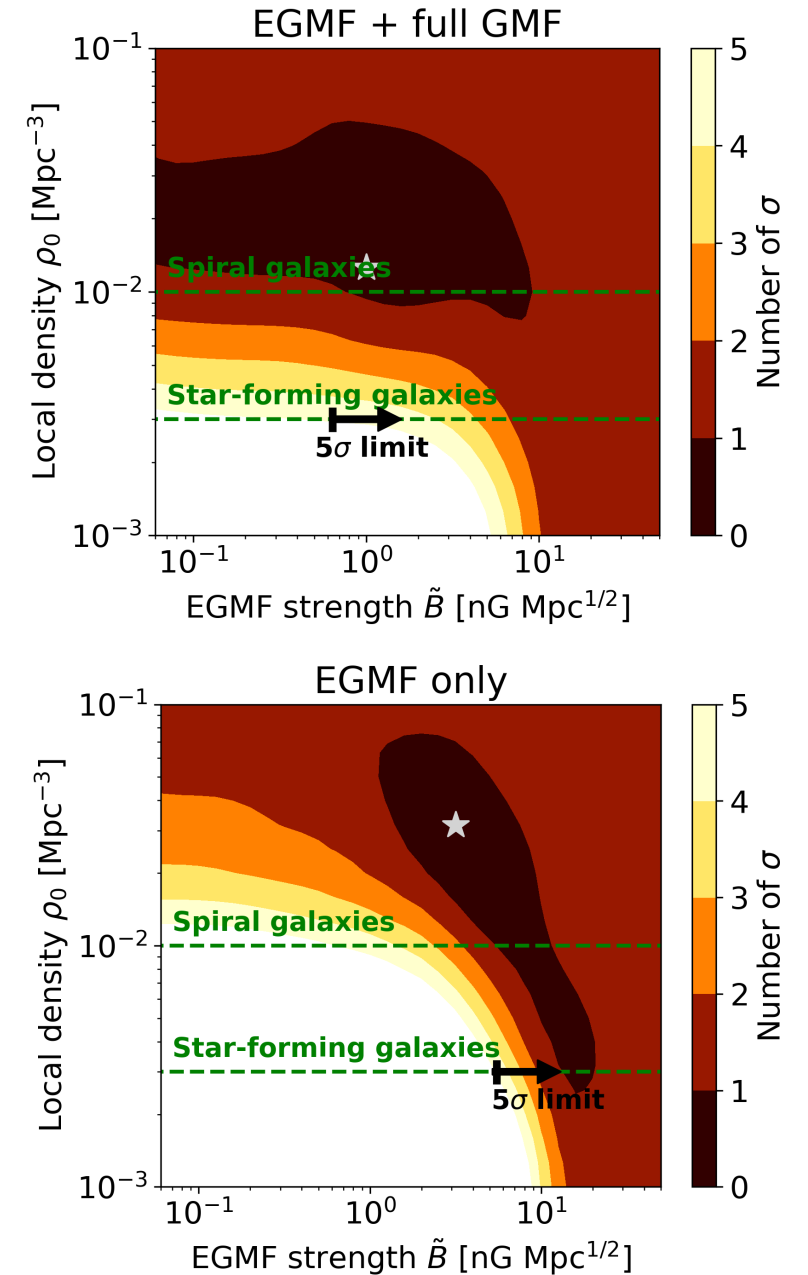


	EGMF only	EGMF + full GMF
5 σ lower limit on $\tilde{B}$ for $\rho_0 = 3 \cdot 10^{-3} \text{ Mpc}^{-3}$	$\tilde{B} > 5.5 \text{ nG Mpc}^{1/2}$	$\tilde{B} > 0.64 \text{ nG Mpc}^{1/2}$
Best-fit point	$\tilde{B} = 3.2 \text{ nG Mpc}^{1/2};$ $\rho_0 = 3.2 \cdot 10^{-2} \text{ Mpc}^{-3}$	$\tilde{B} = 1.0 \text{ nG Mpc}^{1/2};$ $\rho_0 = 1.3 \cdot 10^{-2} \text{ Mpc}^{-3}$
90% C.L. region	$0.89 < \tilde{B} < 24 \text{ nG Mpc}^{1/2};$ $1.9 \cdot 10^{-3} < \rho_0 < 9.0 \cdot 10^{-2} \text{ Mpc}^{-3}$	$\tilde{B} < 22 \text{ nG Mpc}^{1/2};$ $\rho_0 < 6.3 \cdot 10^{-2} \text{ Mpc}^{-3}$

Conclusions

AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732, submitted to MNRAS

- Main assumption: overdensities in UHECR sky maps by Auger are produced by local star-forming galaxies
- If true, and the background UHECRs come from the same source class, a 5σ lower limit on the EGMF is obtained: $B > 0.64 \text{ nG Mpc}^{1/2}$
- Allowing for the full range of ρ_0 :
 - Anti-correlation between source density and EGMF: isotropization by strong magnetic fields or large source densities
 - Too strong isotropization destroys observed correlations:
 - 90% C.L. upper limits: $B < 24 \text{ nG Mpc}^{1/2}$; $\rho_0 < 0.09 \text{ Mpc}^{-3}$
 - Best-fit point for a source density close to, or even denser than, that of spiral galaxies



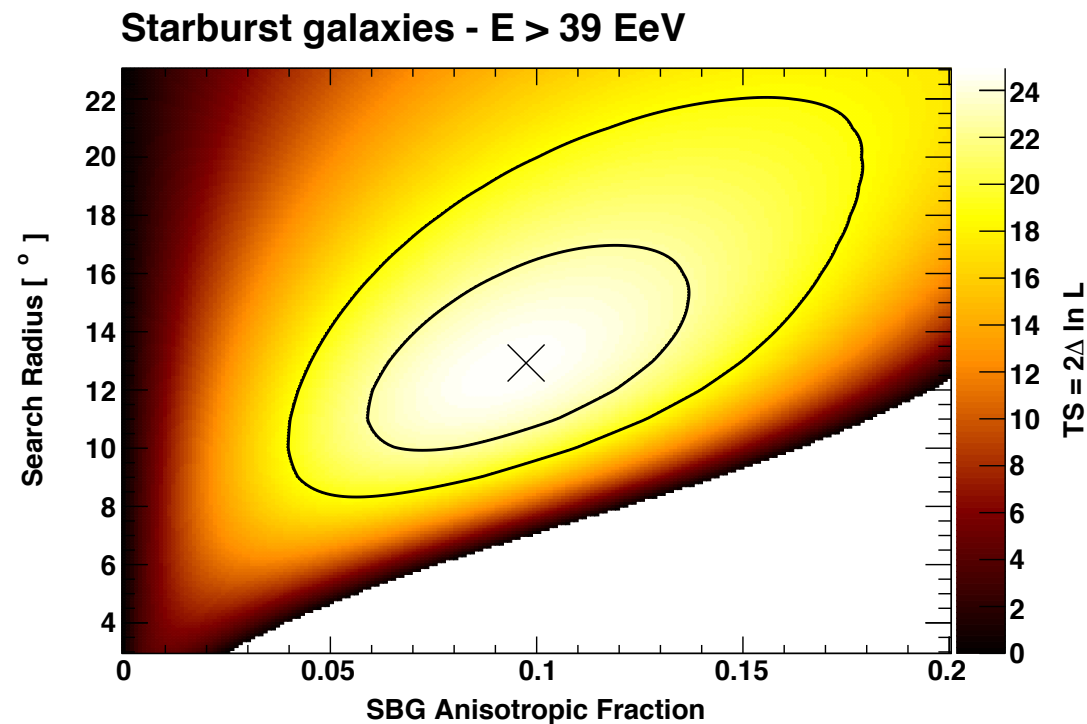
Backup slides

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 $\times$ probability density map
 - Compared with isotropic probability density map

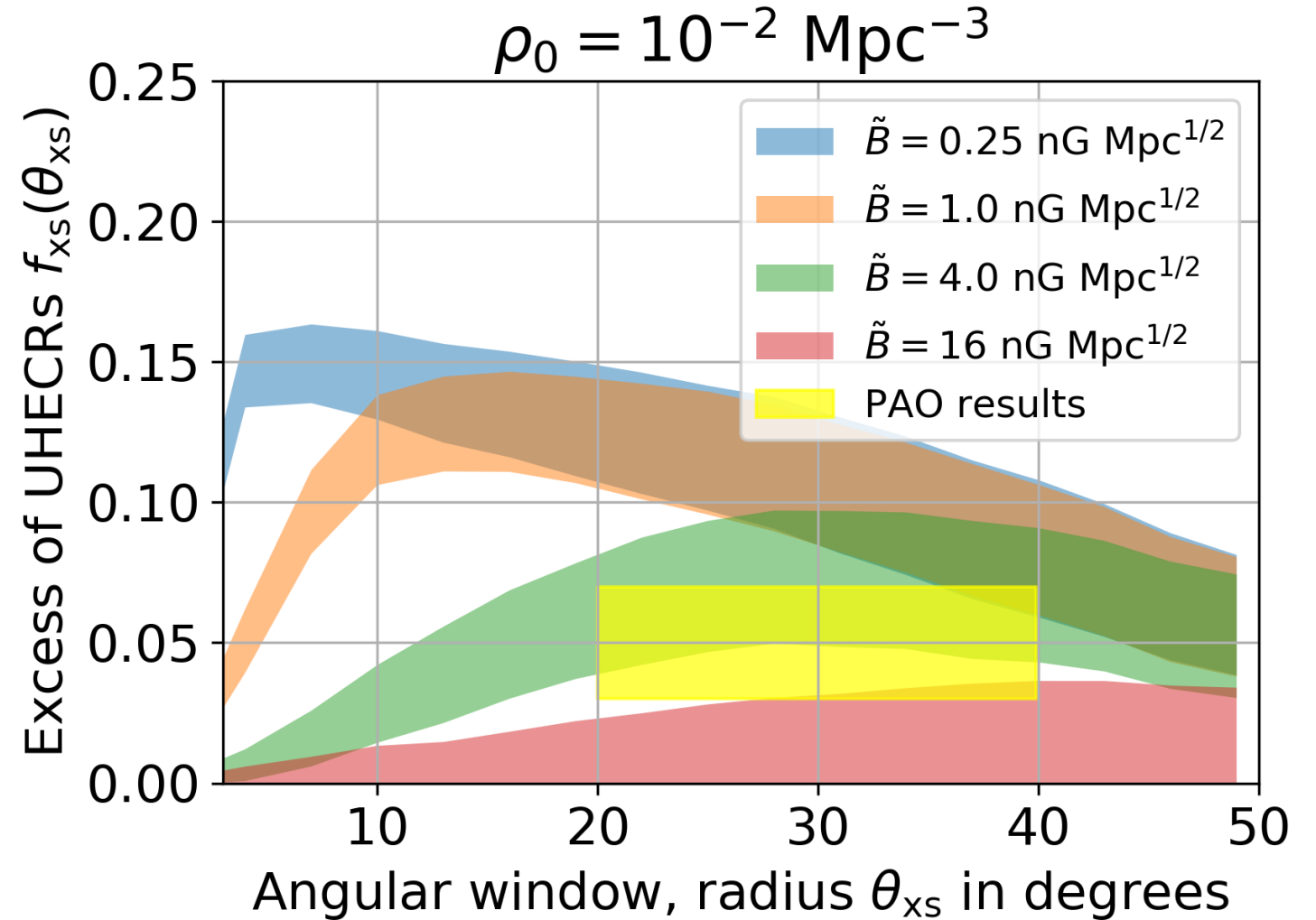


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Compare with Auger results

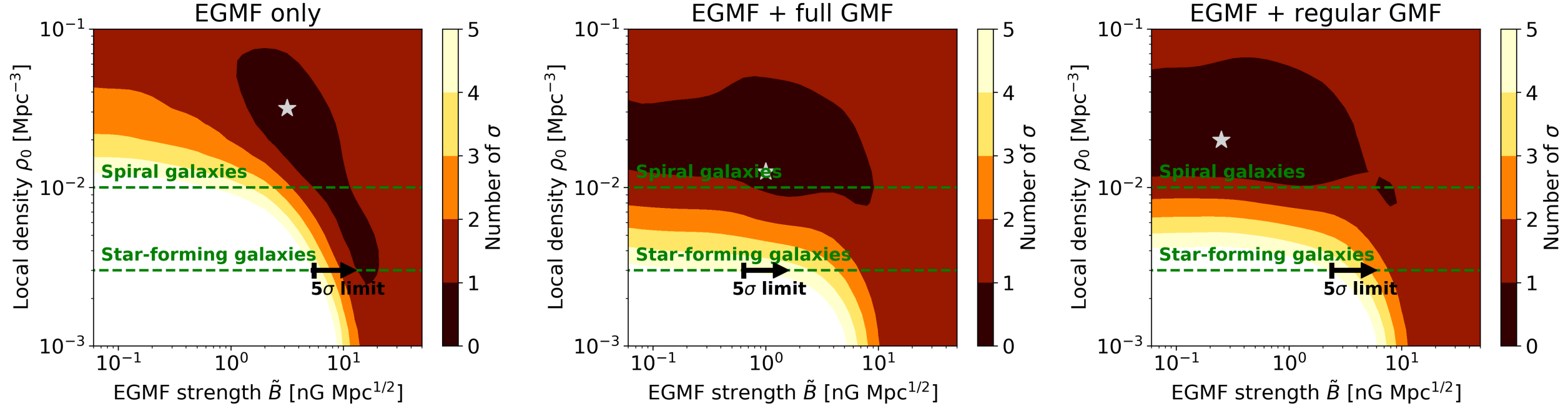
AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732, submitted to MNRAS

- For each simulated sky map we produce with our method we determine the optimal angular window θ_{xs} and maximum excess f_{xs} of UHECRs
- Compare with results of Auger analysis
- Scan over B and ρ_0
- 3 different scenarios:
 - EGMF only
 - EGMF + full GMF
 - EGMF + regular GMF



Preliminary results from scanning over ρ_0 and B

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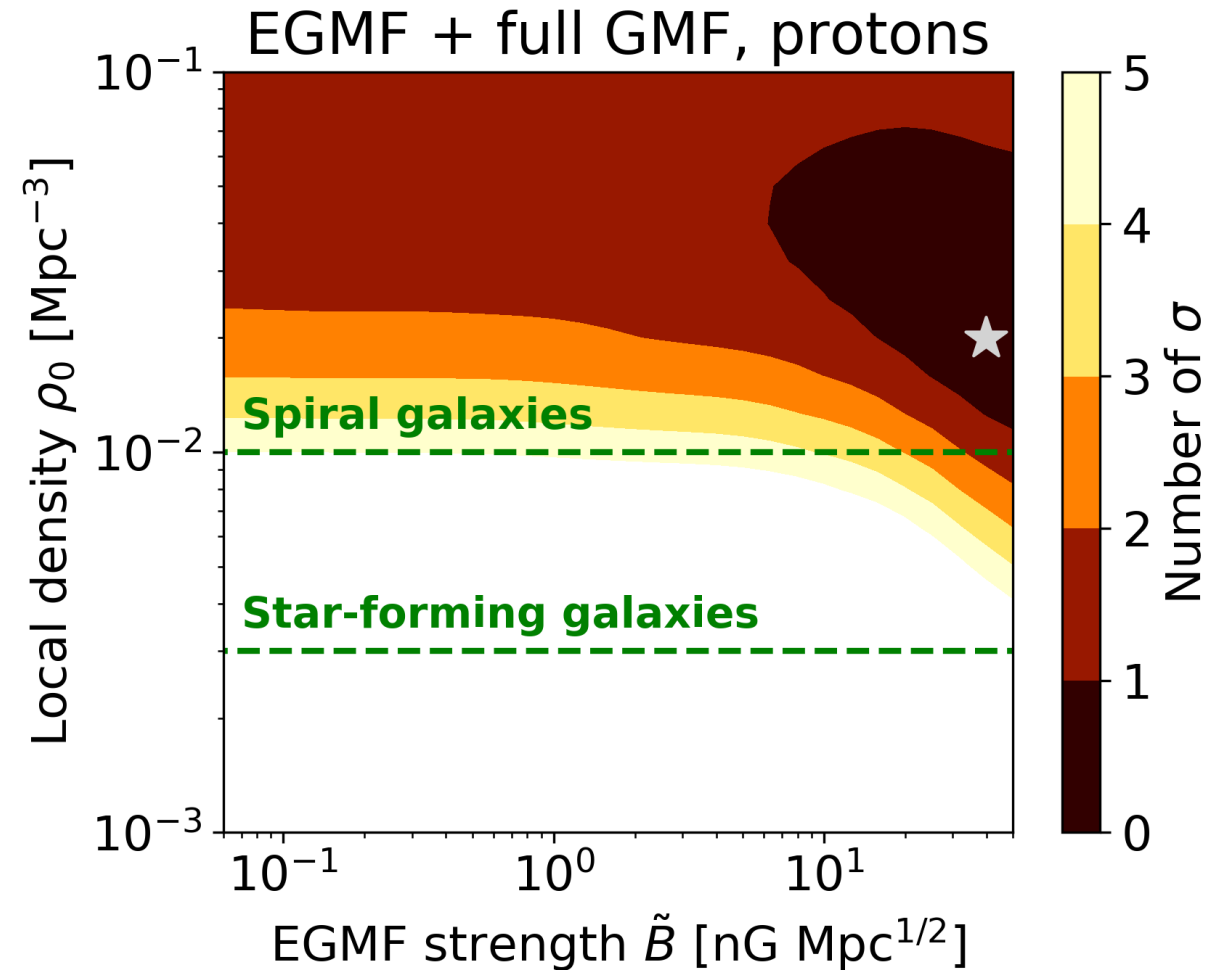


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Best-fit point	$\tilde{B} = 3.2 \text{ nG Mpc}^{1/2};$ $\rho_0 = 3.2 \cdot 10^{-2} \text{ Mpc}^{-3}$	$\tilde{B} = 1.0 \text{ nG Mpc}^{1/2};$ $\rho_0 = 1.3 \cdot 10^{-2} \text{ Mpc}^{-3}$	$\tilde{B} = 0.25 \text{ nG Mpc}^{1/2};$ $\rho_0 = 2.0 \cdot 10^{-2} \text{ Mpc}^{-3}$
90% C.L. region	$0.89 < \tilde{B} < 24 \text{ nG Mpc}^{1/2};$ $1.9 \cdot 10^{-3} < \rho_0 < 9.0 \cdot 10^{-2} \text{ Mpc}^{-3}$	$\tilde{B} < 22 \text{ nG Mpc}^{1/2};$ $\rho_0 < 6.3 \cdot 10^{-2} \text{ Mpc}^{-3}$	$\tilde{B} < 12 \text{ nG Mpc}^{1/2};$ $5.1 \cdot 10^{-3} < \rho_0 < 7.4 \cdot 10^{-2} \text{ Mpc}^{-3}$

Pure-proton scenario

AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732, submitted to MNRAS

- Extreme scenario with minimized deflections
- Requires very large local density ρ_0
- Not possible to reproduce Auger results for a local density of star-forming galaxies, for the values of B we considered

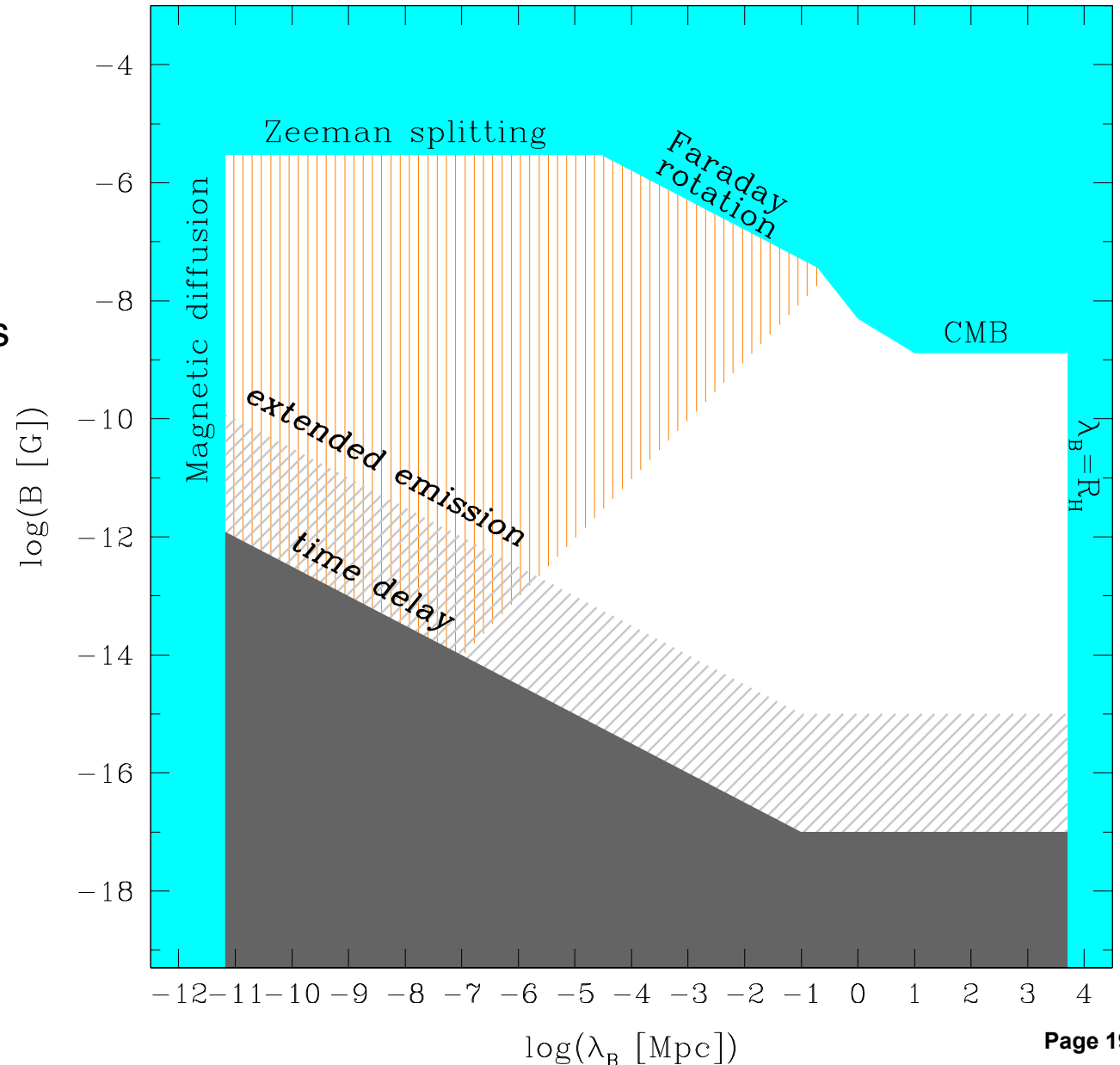


EGMF limits

AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732

- Upper limits on EGMF strength from Faraday rotation, CMB anisotropy, Zeeman splitting
- Lower limits on EGMF from simultaneous GeV-TeV observations of blazars
- Our result: If overdensities in UHECR sky maps by Auger are produced by local star-forming galaxies, and the background UHECRs come from the same source class: $B > 0.64 \text{ nG Mpc}^{1/2}$
- However, this is for the EGMF between local galaxies (<5 Mpc) and the Milky Way, not necessarily comparable with general limits on EGMFs in intergalactic voids

A. Taylor, I. Vovk, A. Neronov, A&A 529 (2011) A144



Contact

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