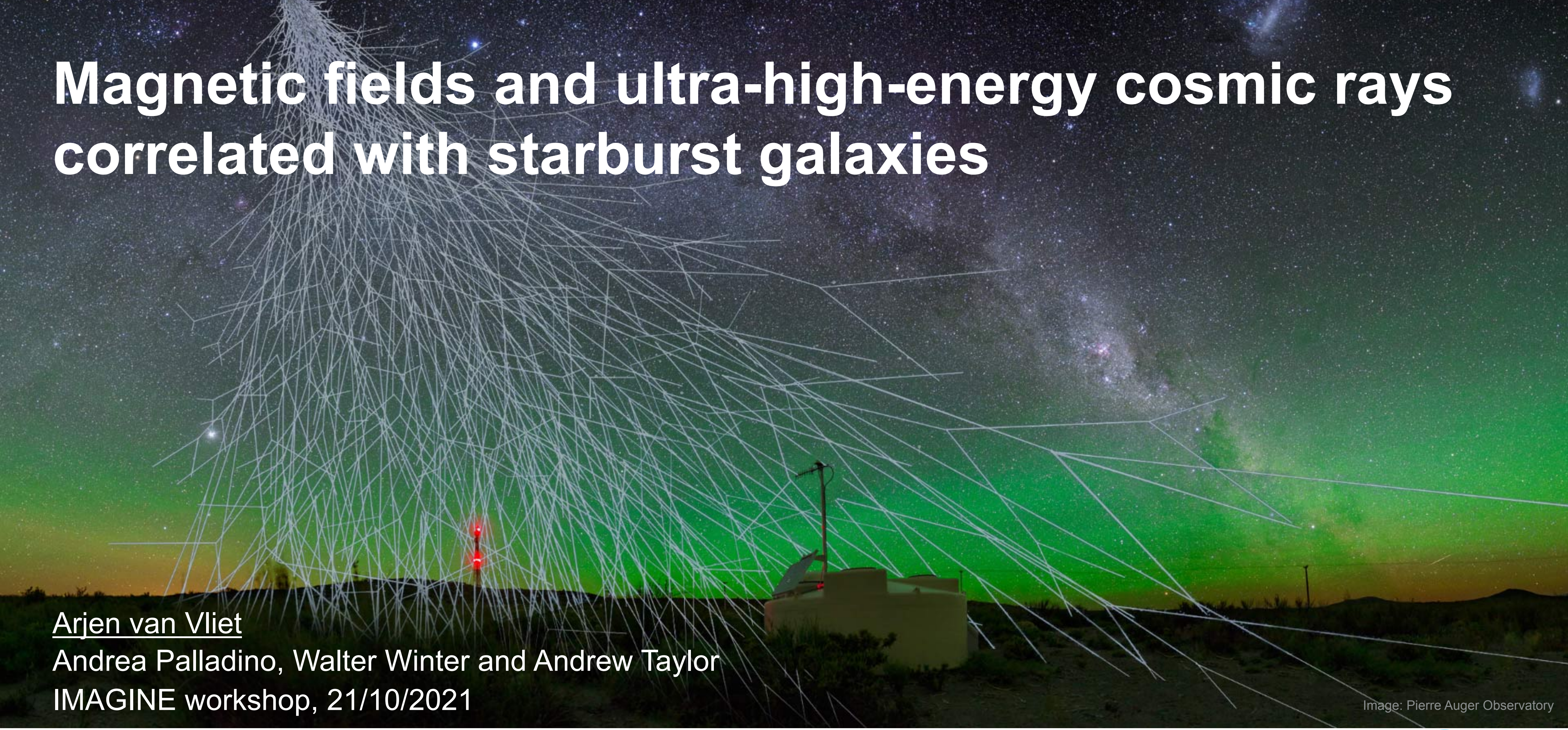
Magnetic fields and ultra-high-energy cosmic rays correlated with starburst galaxies



Arjen van Vliet
Andrea Palladino, Walter Winter and Andrew Taylor
IMAGINE workshop, 21/10/2021

Image: Pierre Auger Observatory

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

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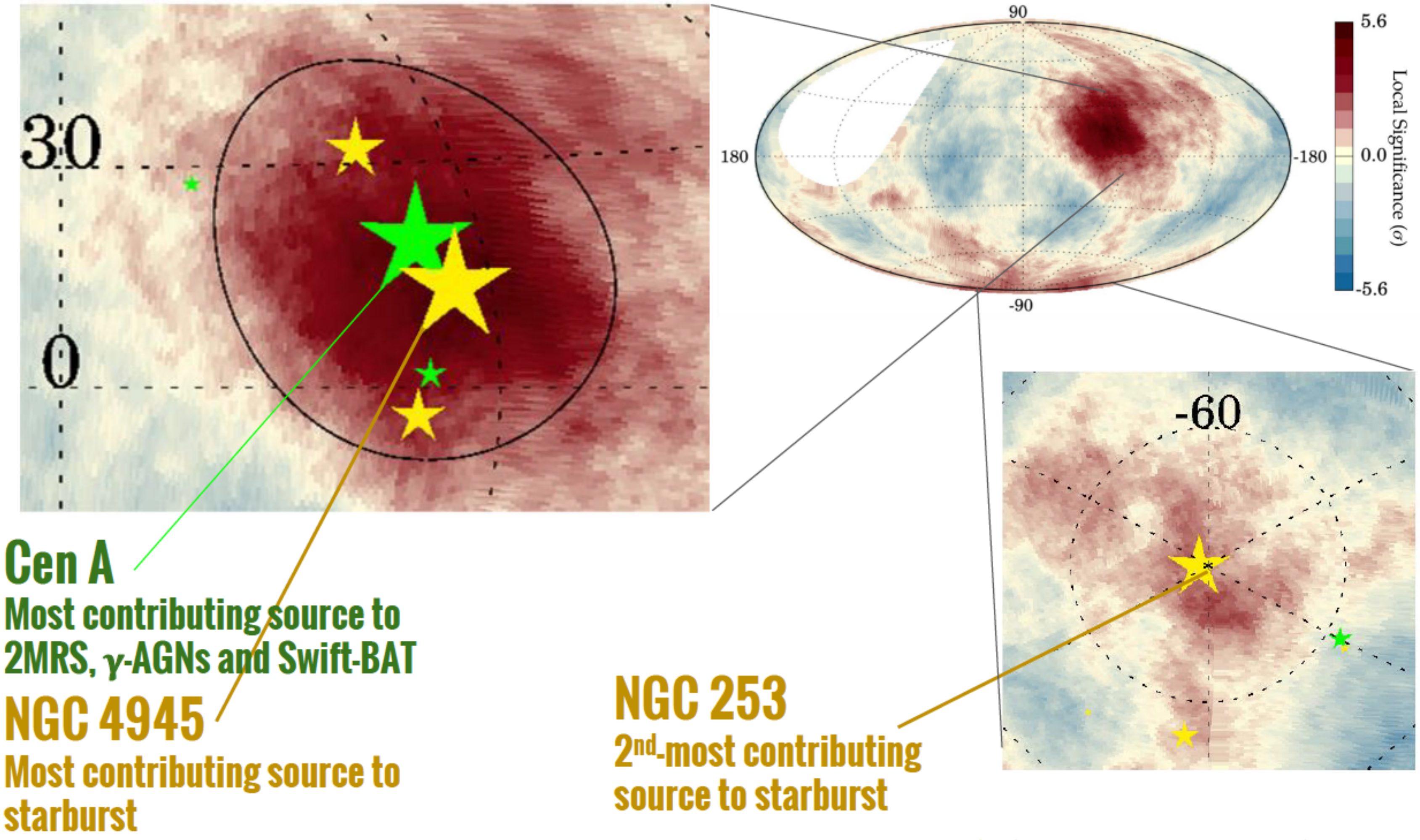
Indication of anisotropy in arrival directions found by Auger

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}°	11^{+5}_{-4}%	29.5	4.5 σ
γ-AGNs	39 EeV	14^{+6}_{-4}°	6^{+4}_{-3}%	17.8	3.1 σ
Swift-Bat	38 EeV	15^{+6}_{-4}°	8^{+4}_{-3}%	22.2	3.7 σ
2MRS	40 EeV	15^{+7}_{-4}°	19^{+10}_{-7}%	22.0	3.7 σ



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

Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	$15^{+5}_{-4}{}^\circ$	$11^{+5}_{-4}\%$	29.5	4.5 σ
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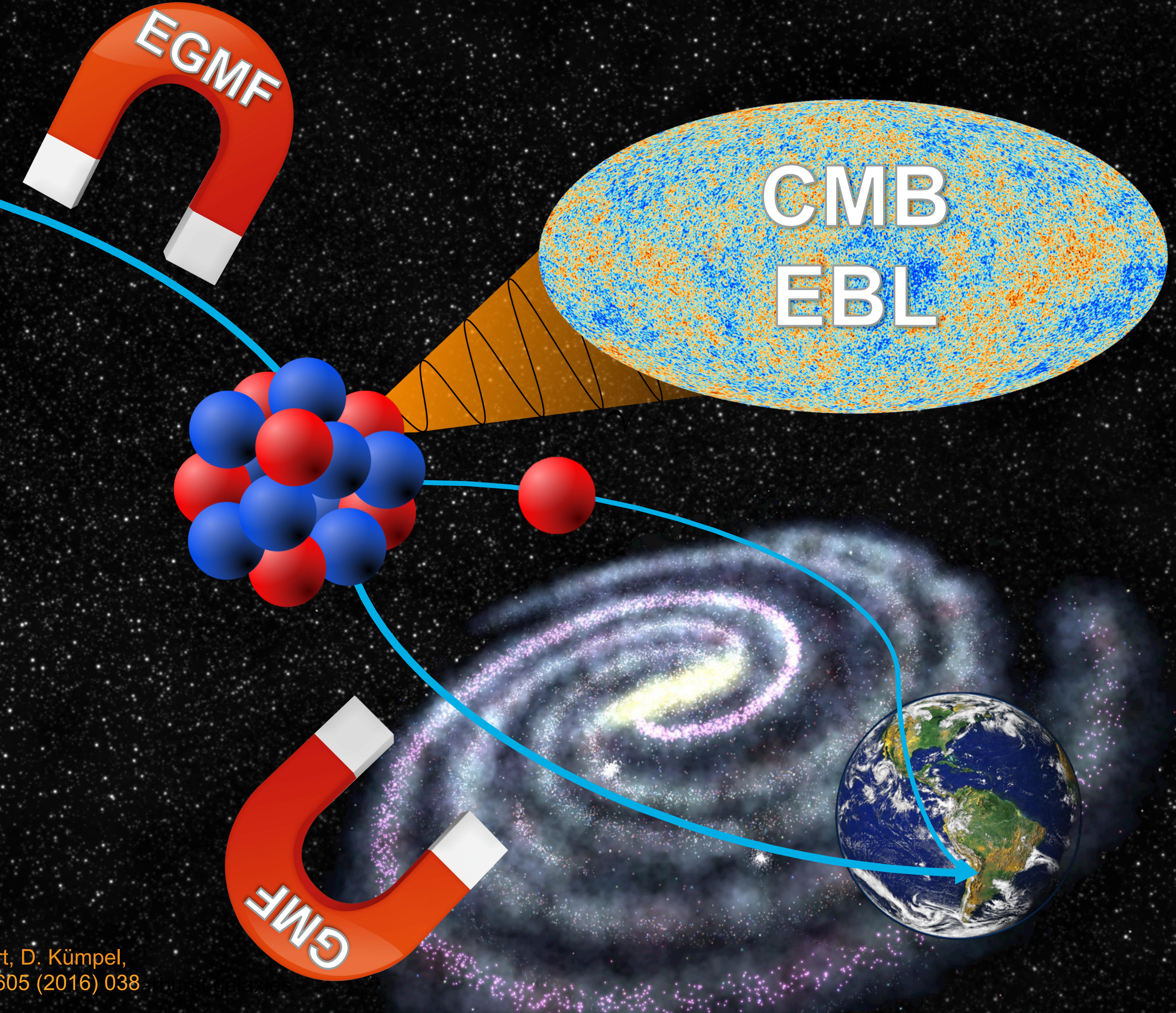
Pierre Auger Collaboration, PoS ICRC2019 206

UHECR



UHECR propagation:

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

CR 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

Our method

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

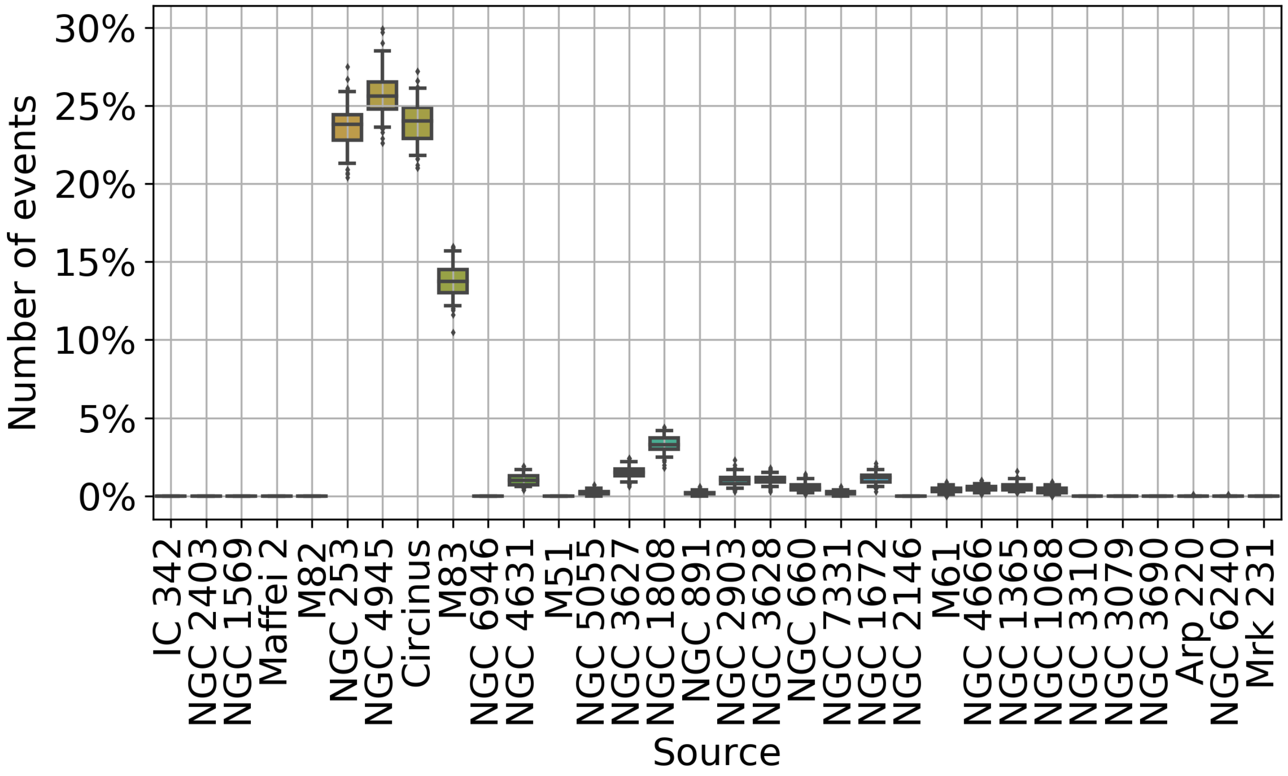
- Simulate UHECR sky maps for specific EGMF and GMF setups and local source densities ρ_0
- Check if these sky maps give θ and f_{aniso} values compatible with what Auger found

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; $0.1 < B_{RMS} < 10$ nG, $0.2 < l_{coh} < 10$ Mpc; $B = B_{RMS} \times \sqrt{l_{coh}}$
- Add deflections from GMF, JF12 model
- Combine catalogue sources with an isotropic contribution from background sources



Our method

UHECR spectrum and composition

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

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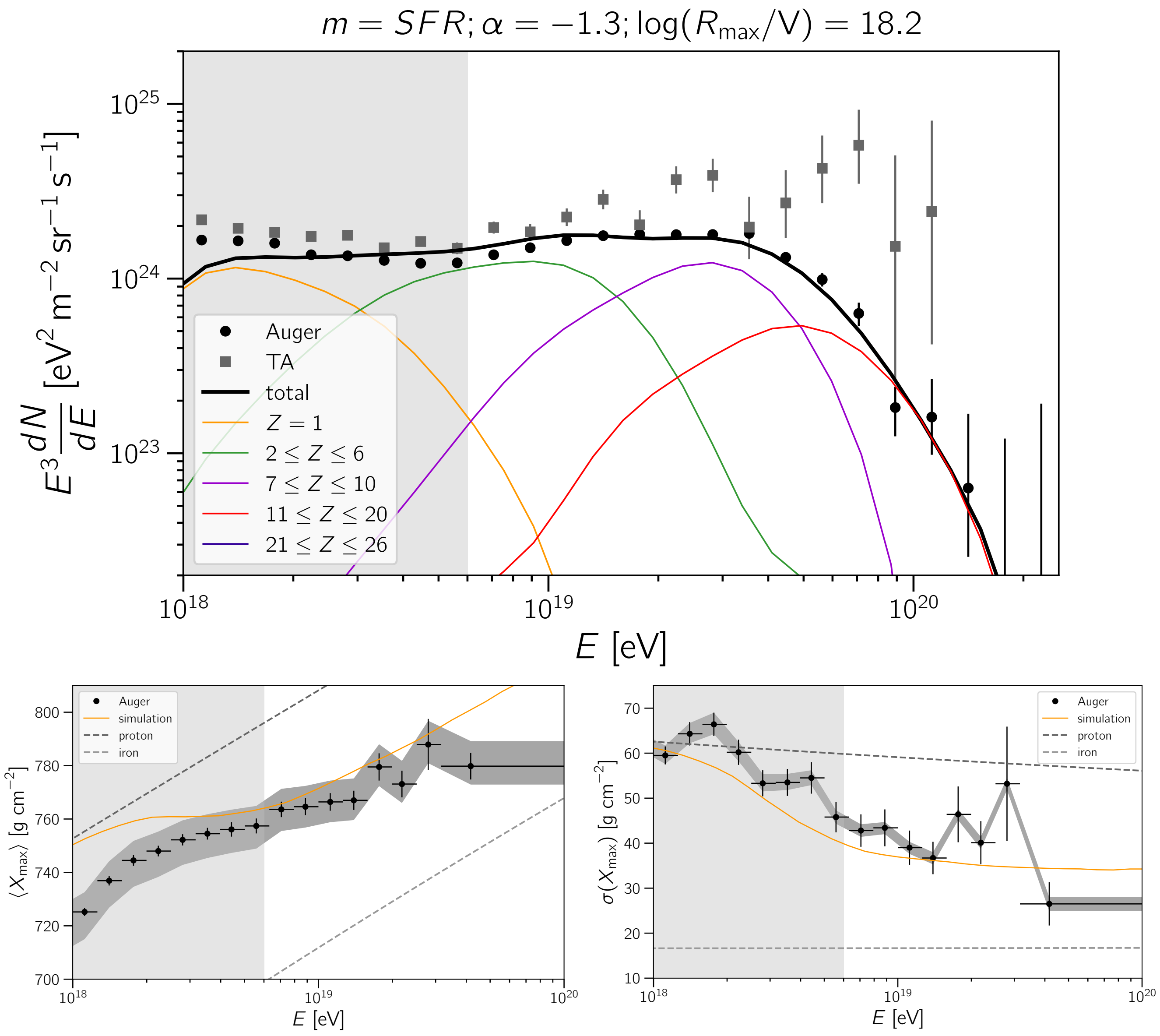

R. Alves Batista, R. M. de Almeida, B. Lago, K. Kotera, JCAP 01 (2019) 002

Our method

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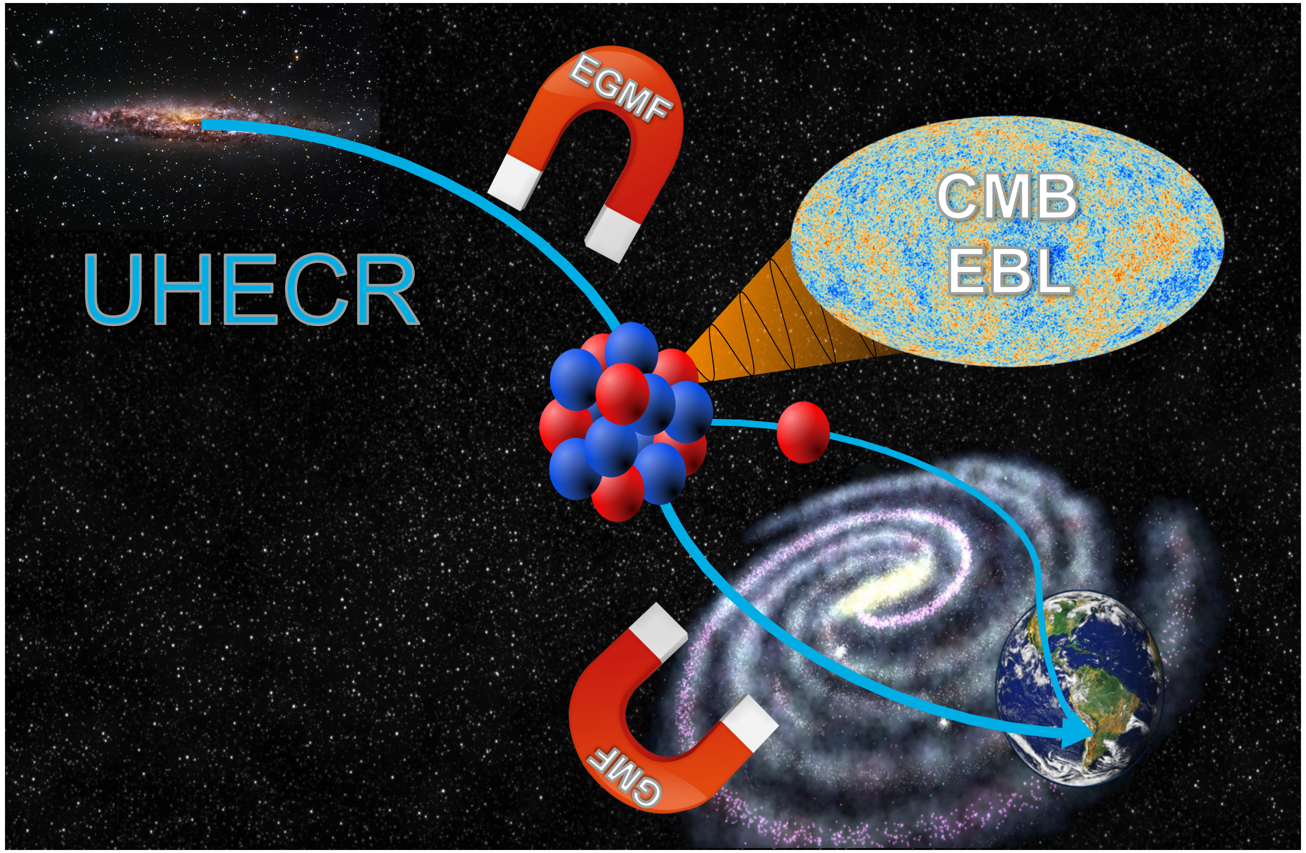

Our method

Source density

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

- Simulate UHECR sky maps for specific EGMF and GMF setups and local source densities ρ_0
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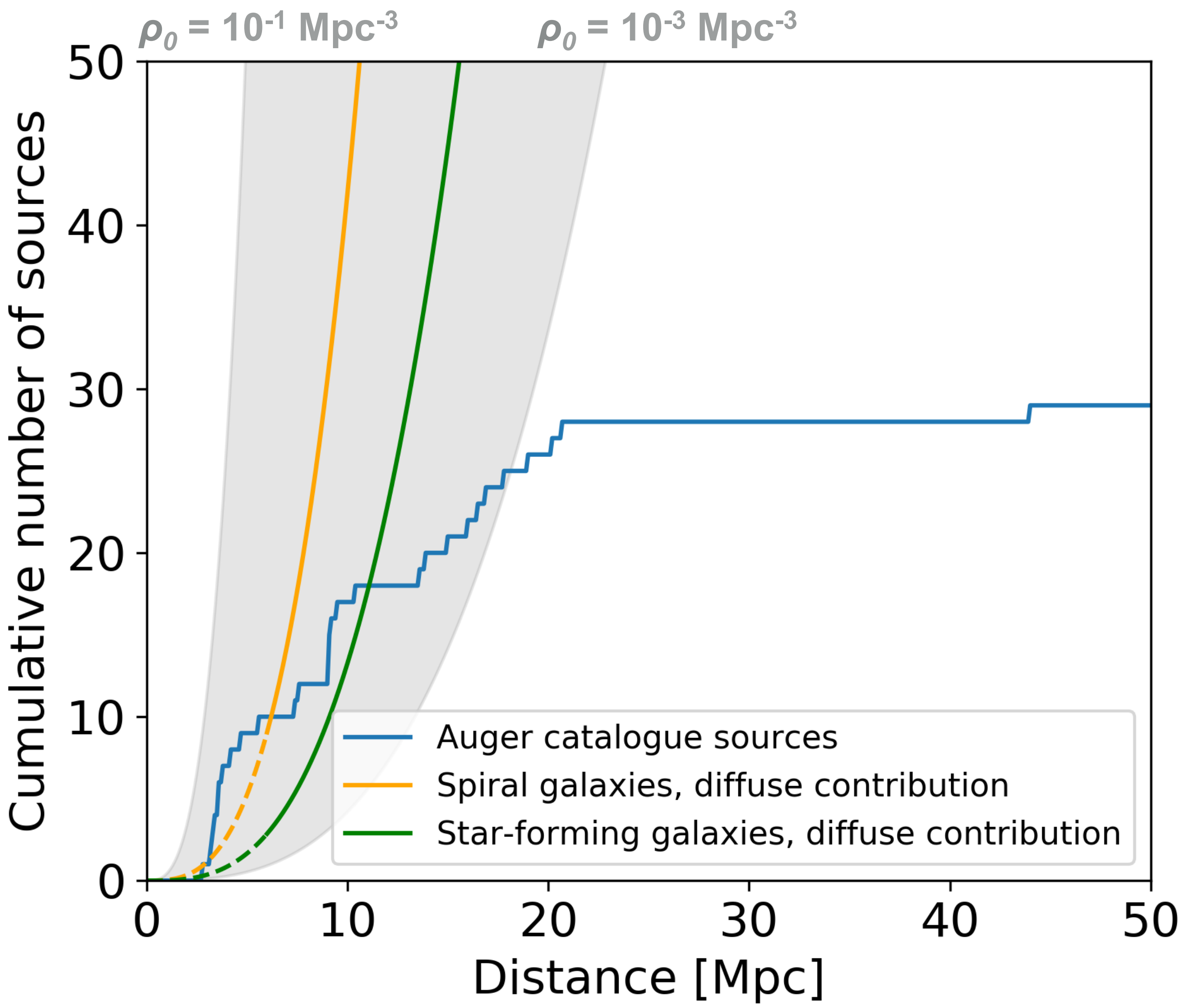
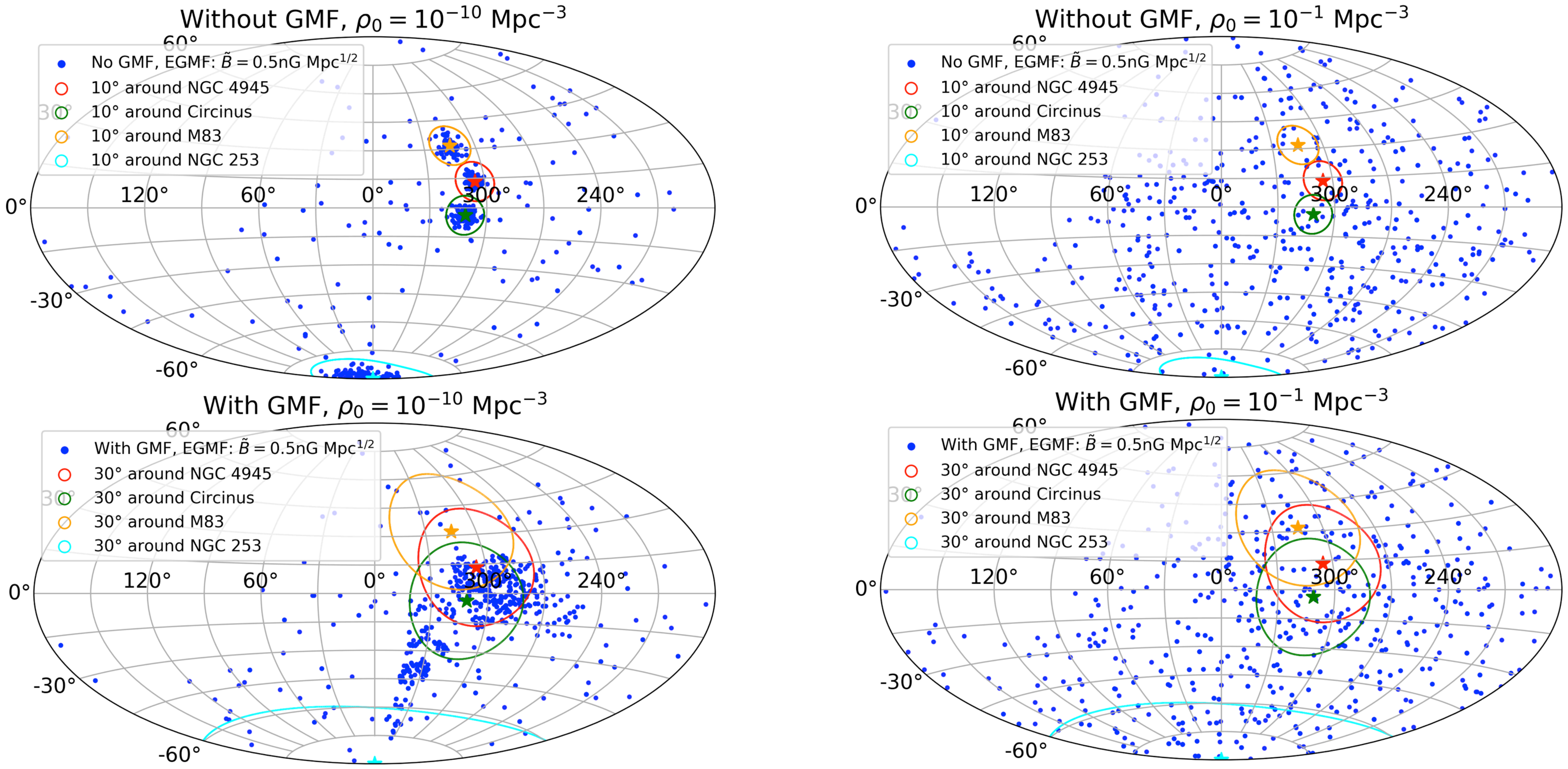


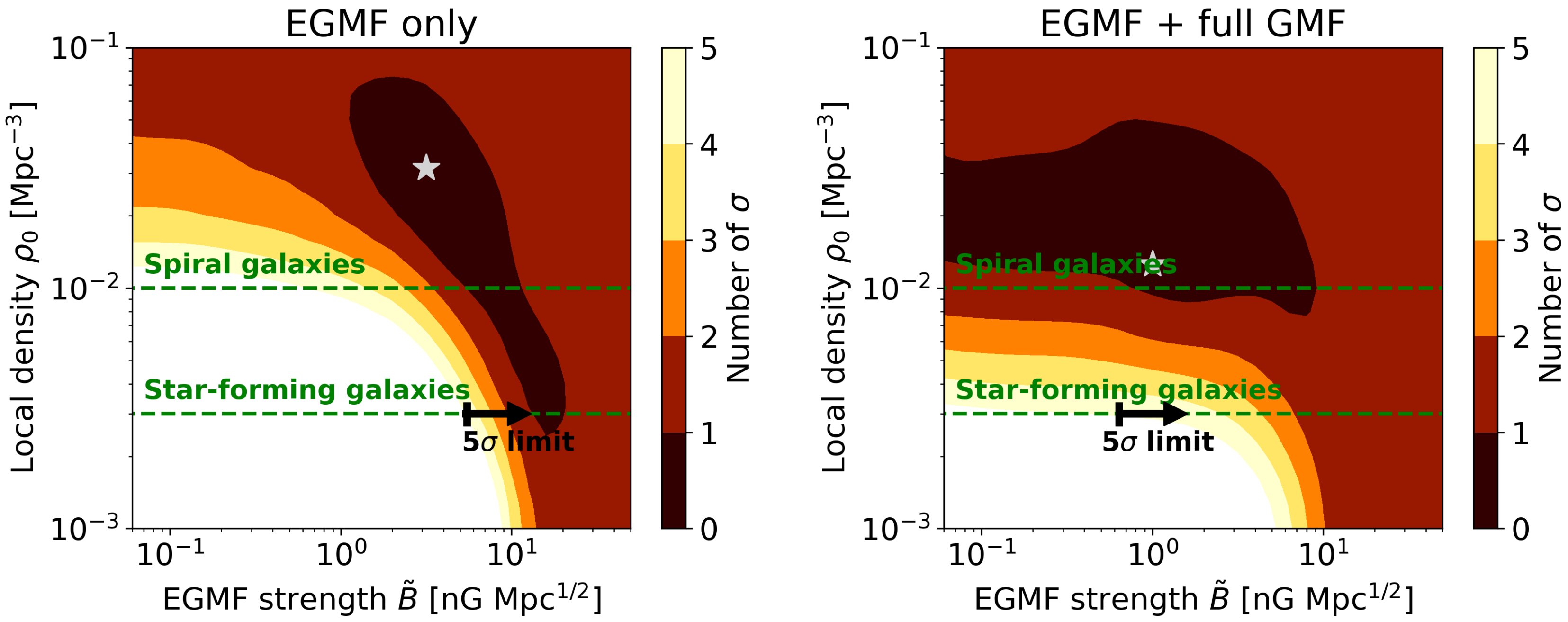
Example sky maps

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

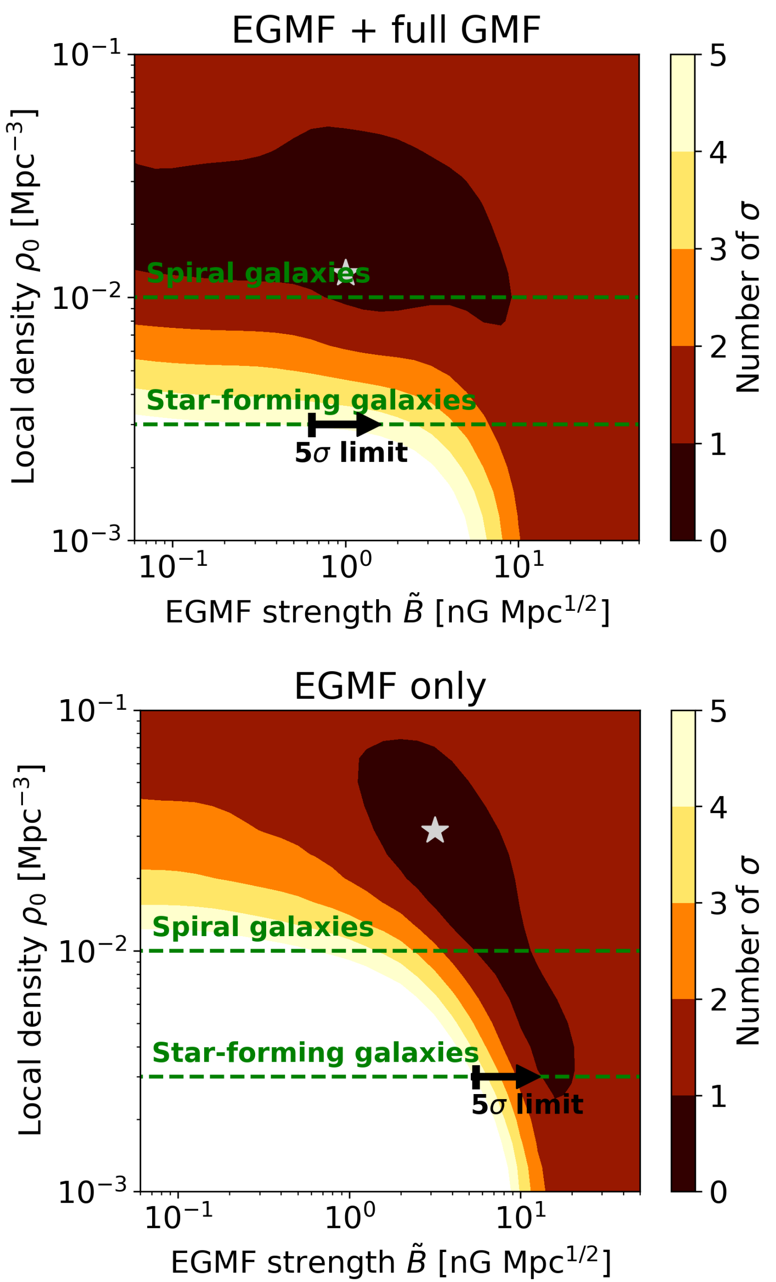


	EGMF only	EGMF + full GMF
5σ lower limit on $\tilde{B}$ for $\rho_0 = 3 \cdot 10^{-3}\ \mathrm{Mpc}^{-3}$	$\tilde{B} > 5.5$ nG $\mathrm{Mpc}^{1/2}$	$\tilde{B} > 0.64$ nG $\mathrm{Mpc}^{1/2}$
Best-fit point	$\tilde{B} = 3.2$ nG $\mathrm{Mpc}^{1/2}$; $\rho_0 = 3.2 \cdot 10^{-2}\ \mathrm{Mpc}^{-3}$	$\tilde{B}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

Conclusions

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

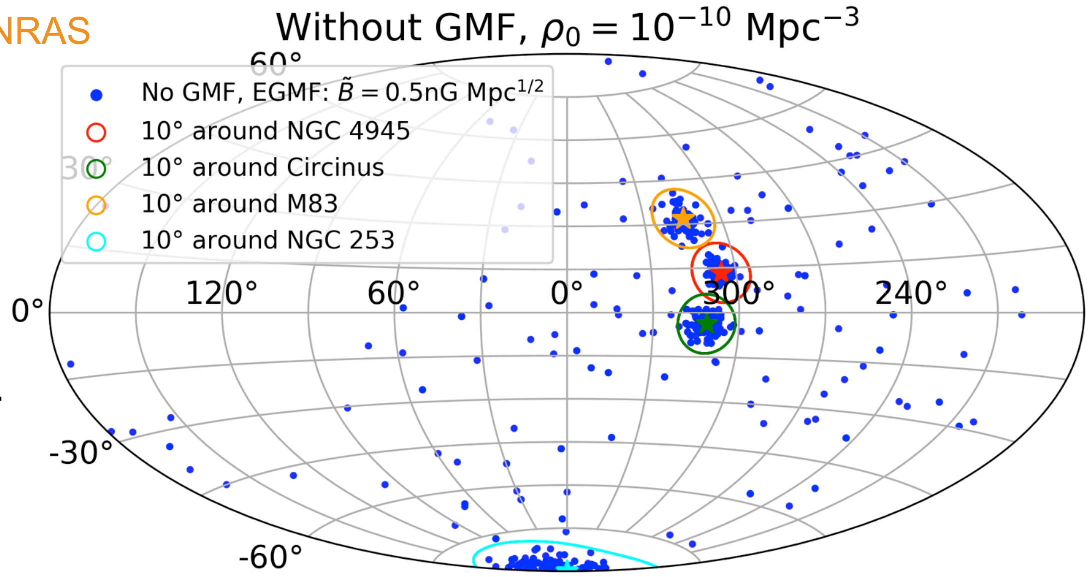
- Main assumption: overdensities in UHECR sky maps by Auger are produced by local star-forming galaxies
- If true, and the background UHECRs come from the same source class, a 5σ lower limit on the EGMF is obtained: **B > 0.64 nG Mpc$^{1/2}$**
- Allowing for the full range of ρ_0:
  - Anti-correlation 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 nG Mpc$^{1/2}$; ρ_0 < 0.09 Mpc^{-3}**
  - Best-fit point for a source density close to, or even denser than, that of spiral galaxies

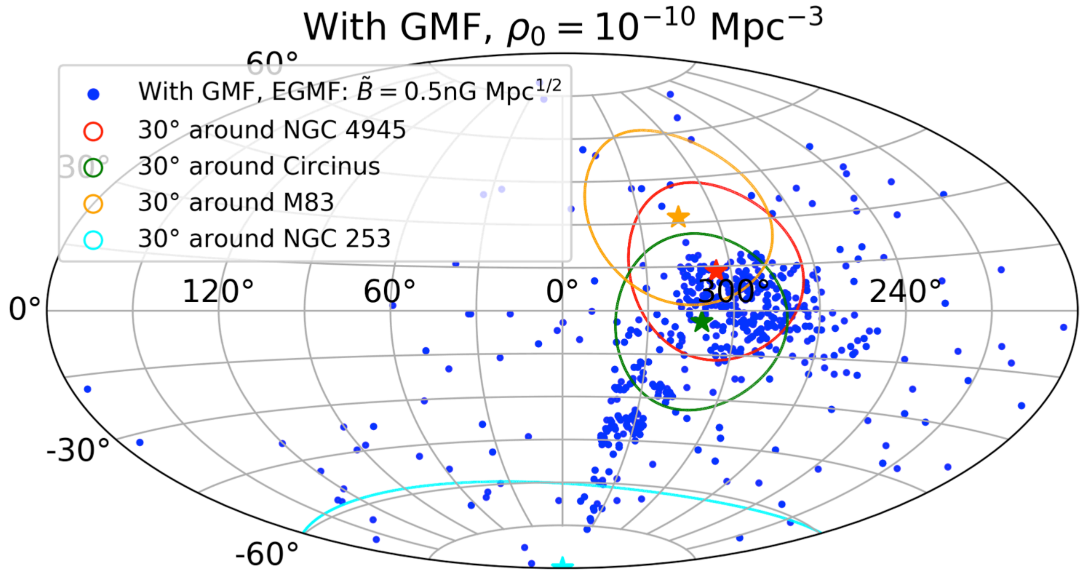


Outlook

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

- Extend to different source classes: AGN
  - Lower local source density, but Cen A at roughly the same distance as the dominant nearby star-forming galaxies
  - Comparatively strong EGMF expected
- Include different GMF models, or parameter scan of GMF parameters
  - Computationally intensive, but still viable
  - Current analysis not sensitive to direction of deflection, but it might be possible to improve on that
  - Indication for problems with the JF12 model, if overdensities in UHECR sky maps by Auger are indeed produced by local star-forming galaxies
  - Include in the IMAGINE framework?

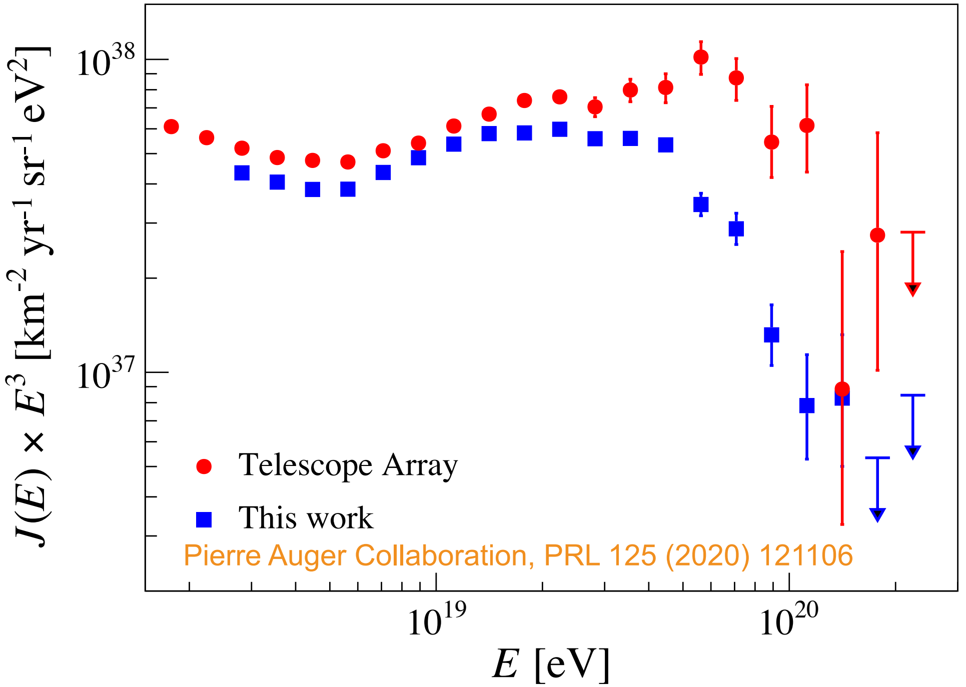




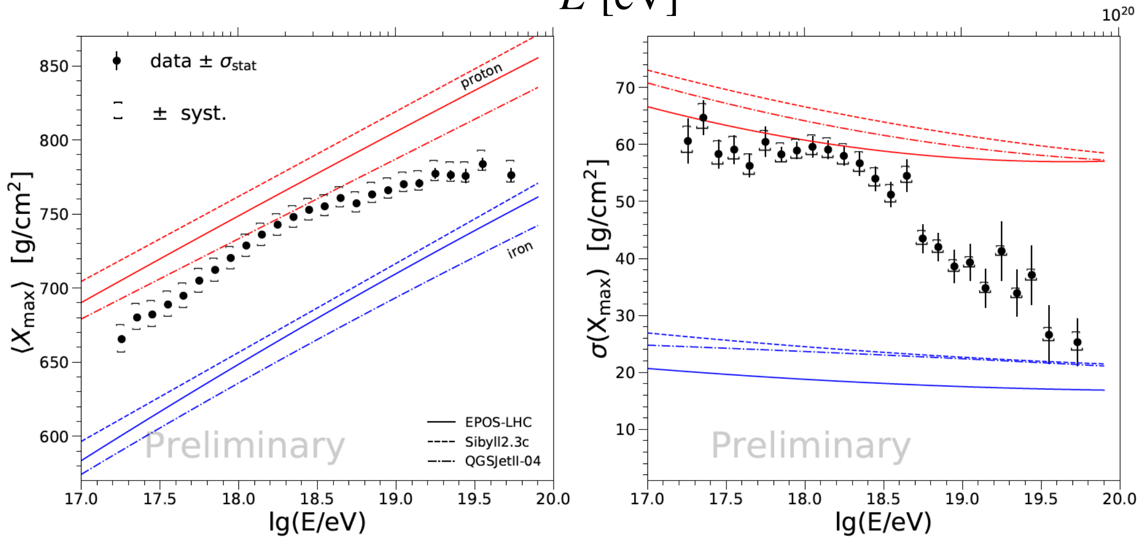
Backup slides

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 ~5×10^{18} eV
  - 'Instep' at ~14×10^{18} eV
  - 'Suppression' at ~47×10^{18} eV
- Composition, getting increasingly heavier above the ankle
- No identified sources yet, but indication of anisotropies in the arrival directions have been detected



Pierre Auger Collaboration, PRL 125 (2020) 121106

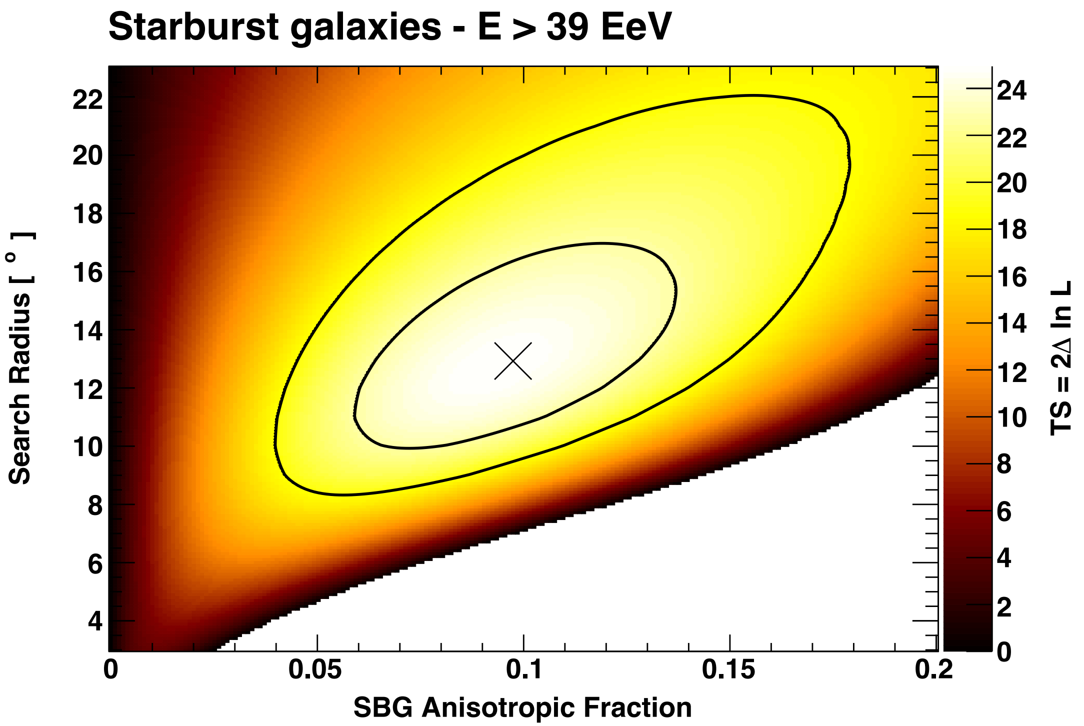


Pierre Auger Collaboration, PoS ICRC2019 482

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



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Starburst	38 EeV	15^{+5}_{-4}°	11^{+5}_{-4}%	29.5	4.5 σ
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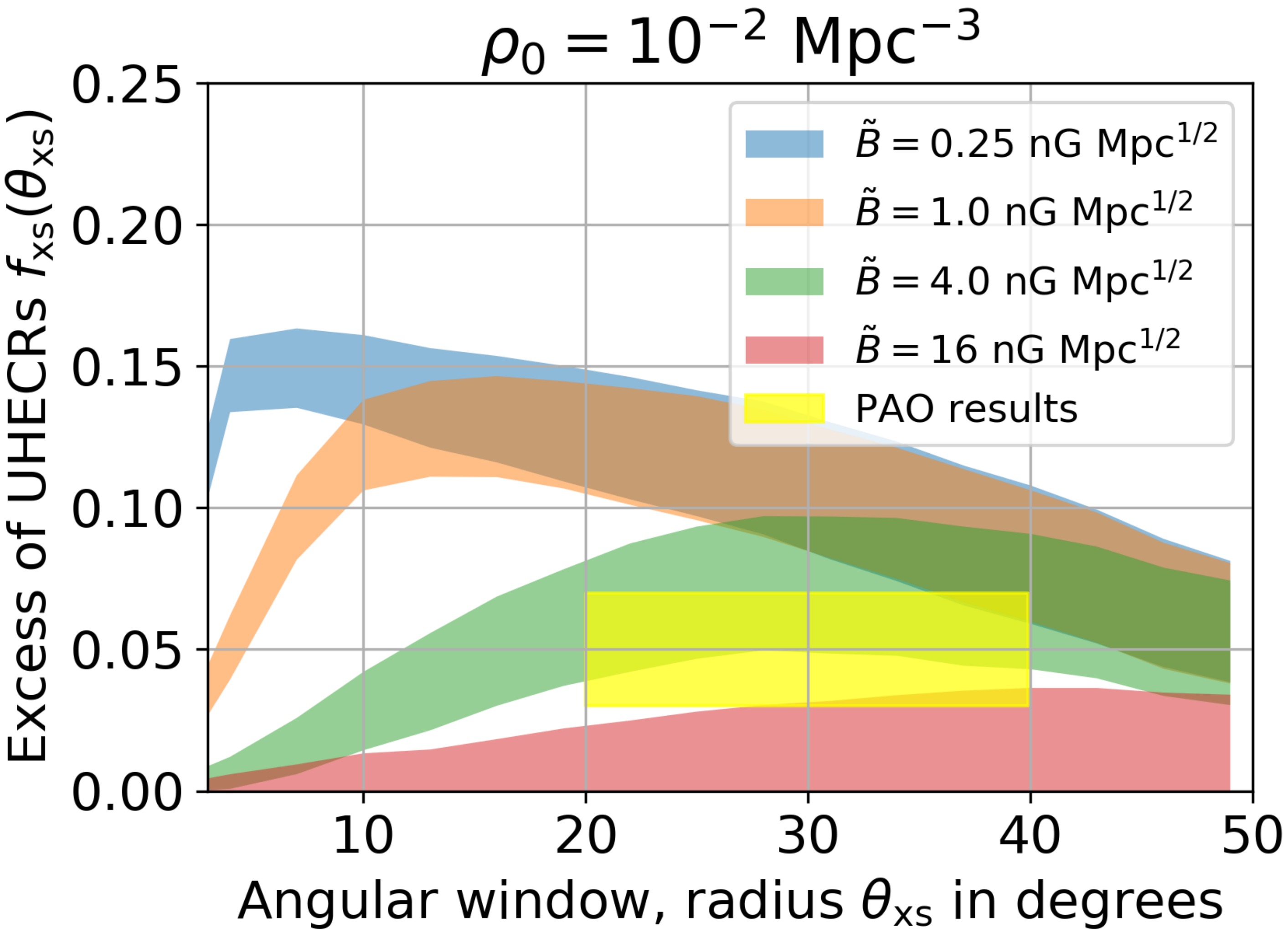
2MRS	40 EeV	15^{+7}_{-4}°	19^{+10}_{-7}%	22.0	3.7 σ

Compare with Auger results

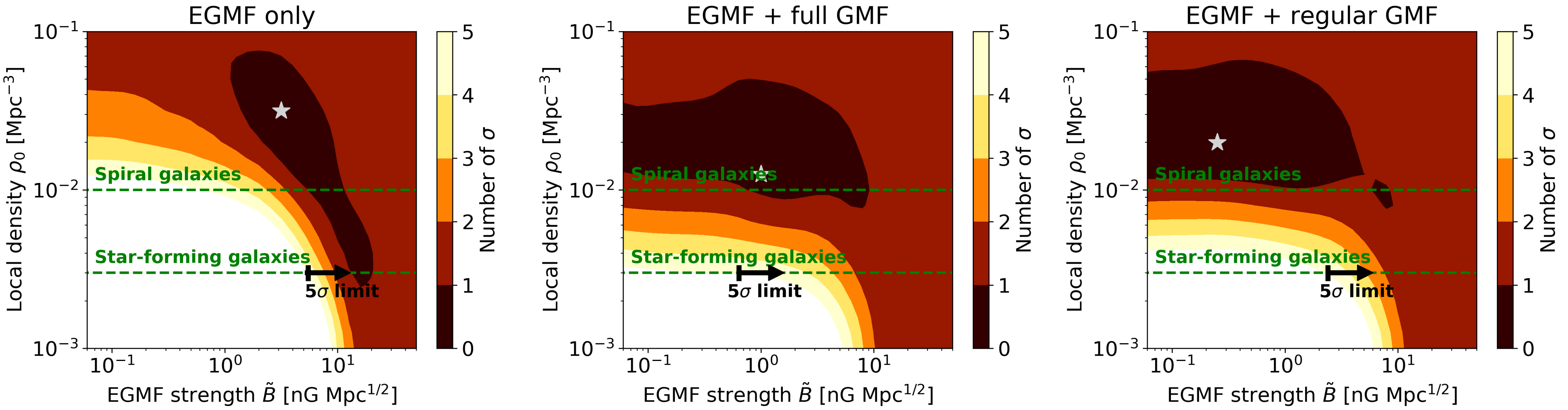
AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732, submitted to MNRAS

- 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

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

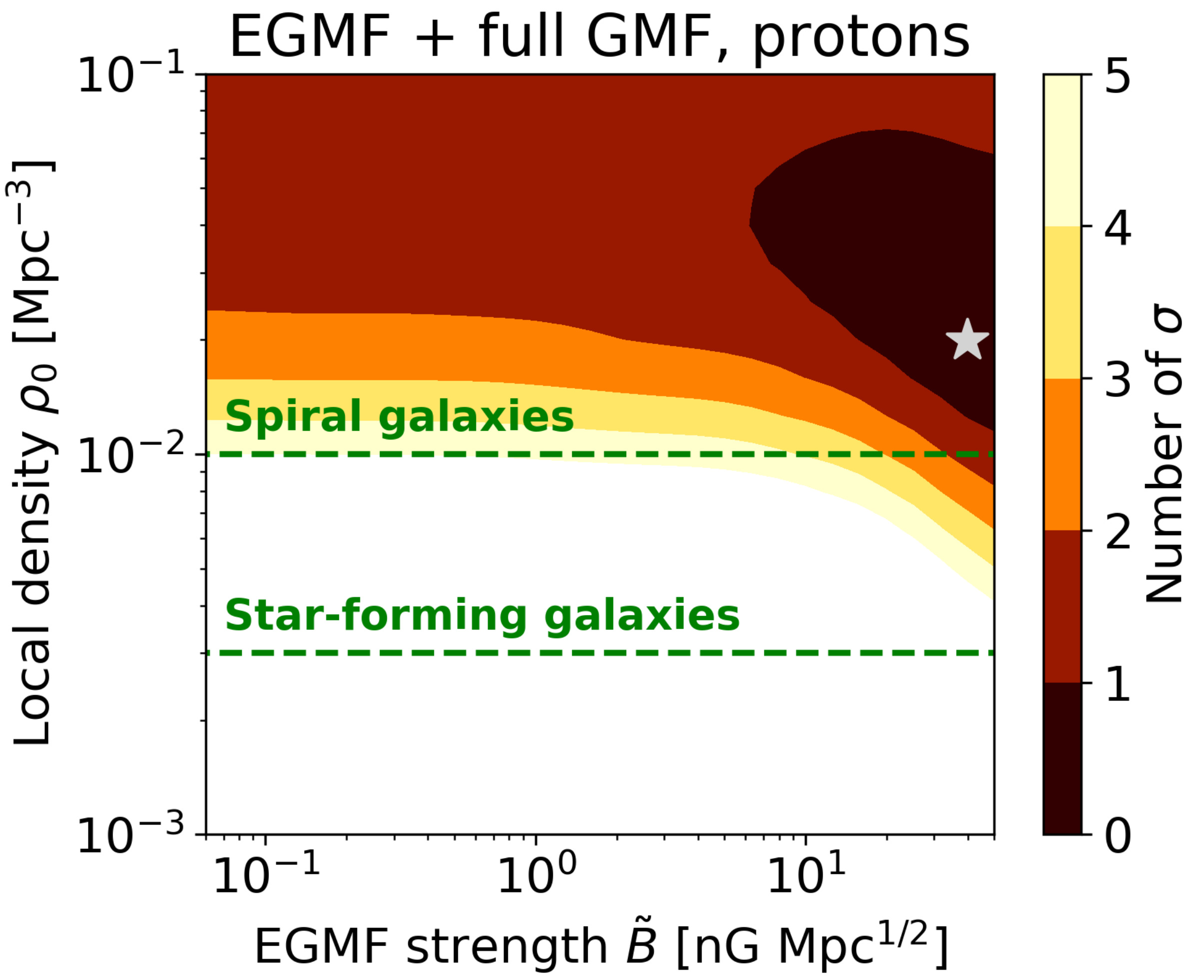


	EGMF only	EGMF + full GMF	EGMF + regular GMF
5σ lower limit on $\tilde{B}$ for $\rho_0 = 3 \cdot 10^{-3}$ Mpc^{-3}	$\tilde{B} > 5.5$ nG Mpc$^{1/2}$	$\tilde{B} > 0.64$ nG Mpc$^{1/2}$	$\tilde{B} > 2.4$ nG Mpc$^{1/2}$
Best-fit point	$\tilde{B} = 3.2$ nG Mpc$^{1/2}$; $\rho_0 = 3.2 \cdot 10^{-2}$ Mpc^{-3}	$\tilde{B} = 1.0$ nG Mpc$^{1/2}$; $\rho_0 = 1.3 \cdot 10^{-2}$ Mpc^{-3}	$\tilde{B} = 0.25$ nG Mpc$^{1/2}$; $\rho_0 = 2.0 \cdot 10^{-2}$ Mpc^{-3}
90% C.L. region	$0.89 < \tilde{B} < 24$ nG Mpc$^{1/2}$; $1.9 \cdot 10^{-3} < \rho_0 < 9.0 \cdot 10^{-2}$ Mpc^{-3}	$\tilde{B} < 22$ nG Mpc$^{1/2}$; $\rho_0 < 6.3 \cdot 10^{-2}$ Mpc^{-3}	$\tilde{B} < 12$ nG Mpc$^{1/2}$; $5.1 \cdot 10^{-3} < \rho_0 < 7.4 \cdot 10^{-2}$ 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

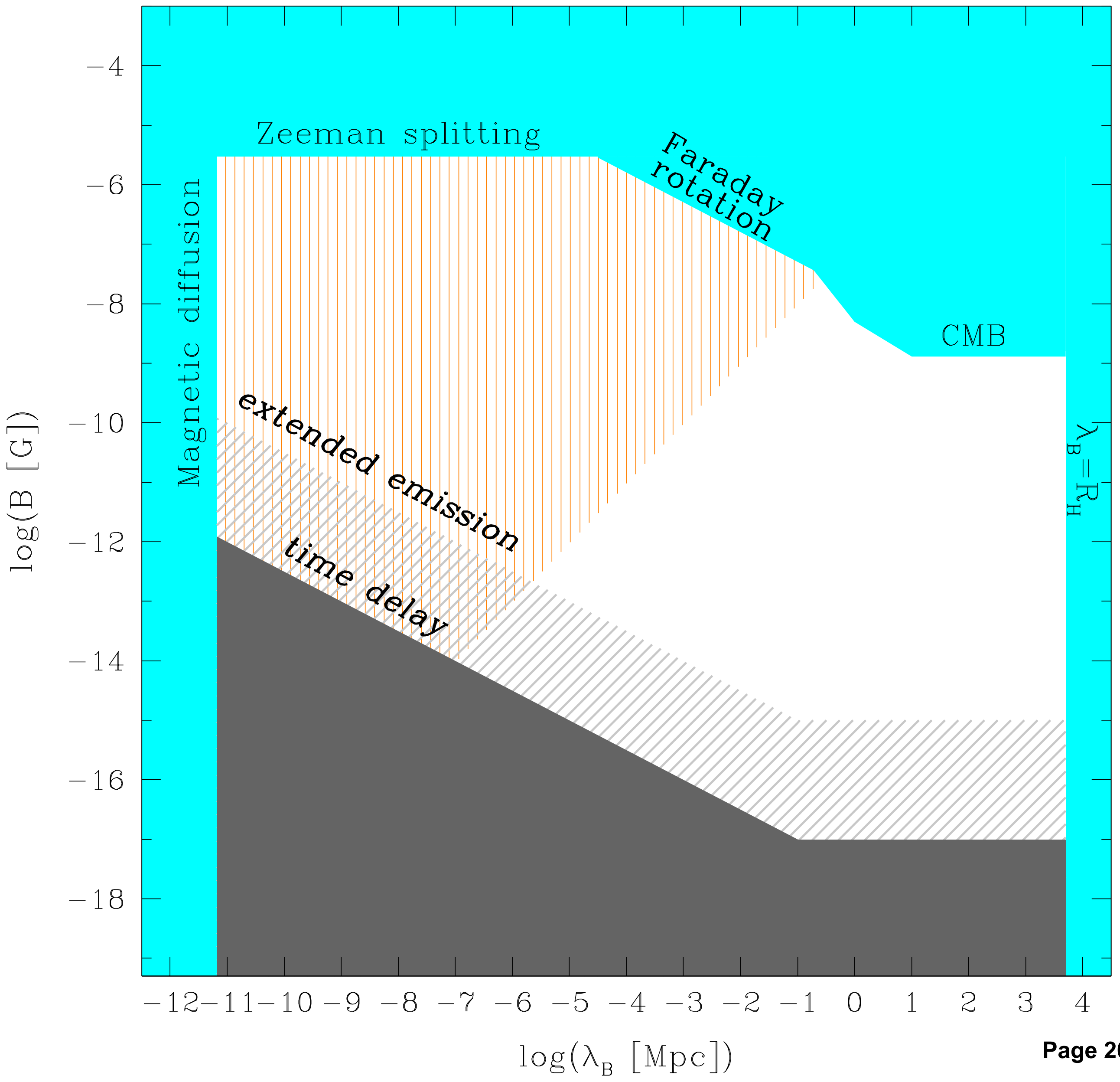


EGMF limits

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 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



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