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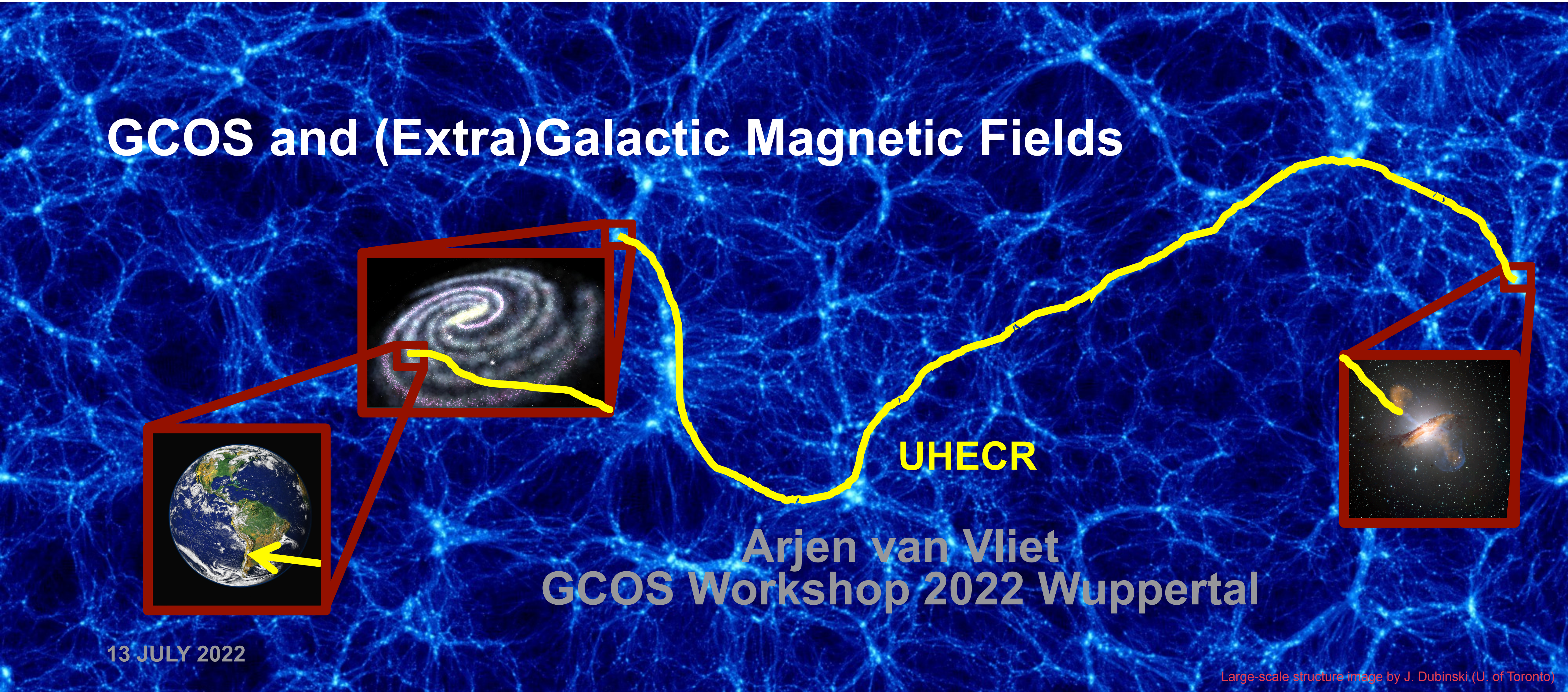
GCOS and (Extra)Galactic Magnetic Fields



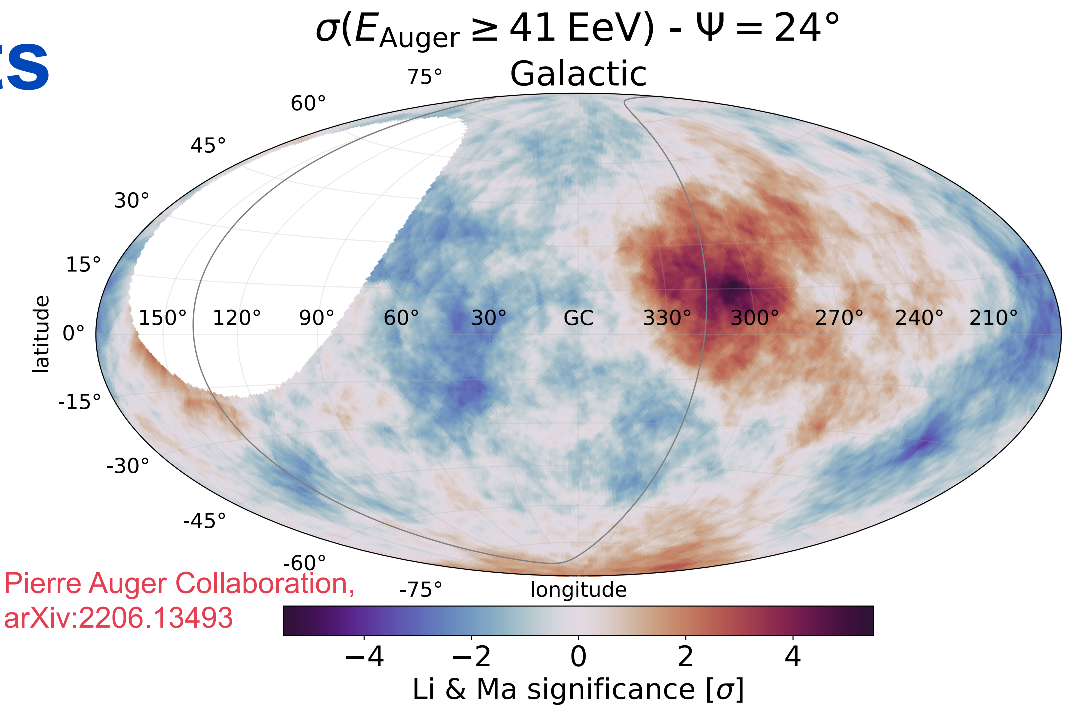
Arjen van Vliet
GCOS Workshop 2022 Wuppertal

13 JULY 2022

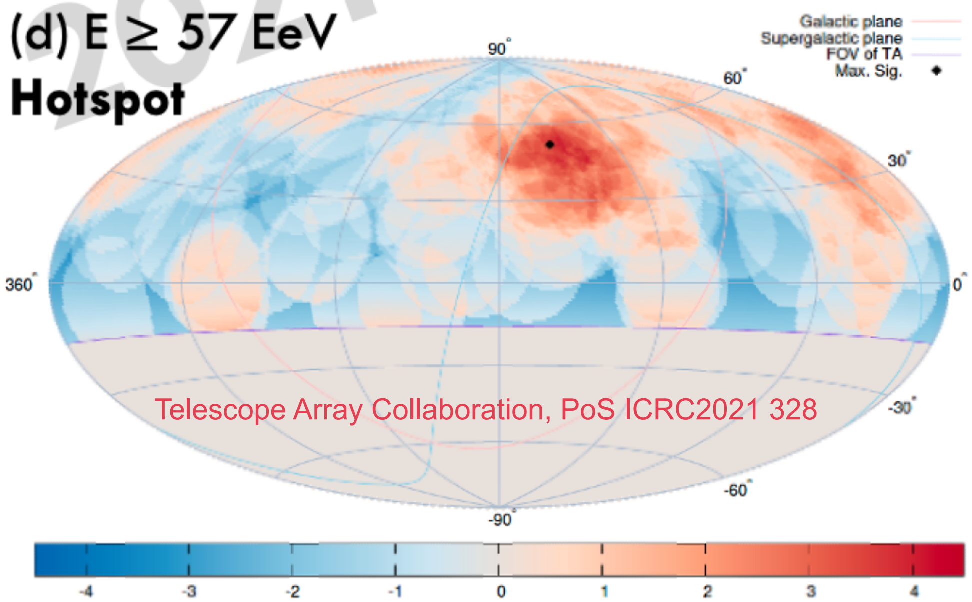
Large-scale structure image by J. Dubinski (U. of Toronto)

UHECR status when GCOS starts

- GCOS after AugerPrime and after TAx4
- Current status at the highest energies: several “hot spots” at intermediate angular scales in different positions in the sky.
    - Pierre Auger Collaboration: ‘4σ evidence for a deviation in excess of isotropy at intermediate angular scales’ (arXiv: 2206.13493)
    - Telescope Array Collaboration: Hot spot at 3.2σ post-trial significance, new excess around Perseus-Pisces supercluster at 4.2σ local Li-Ma significance (ICRC 2021)

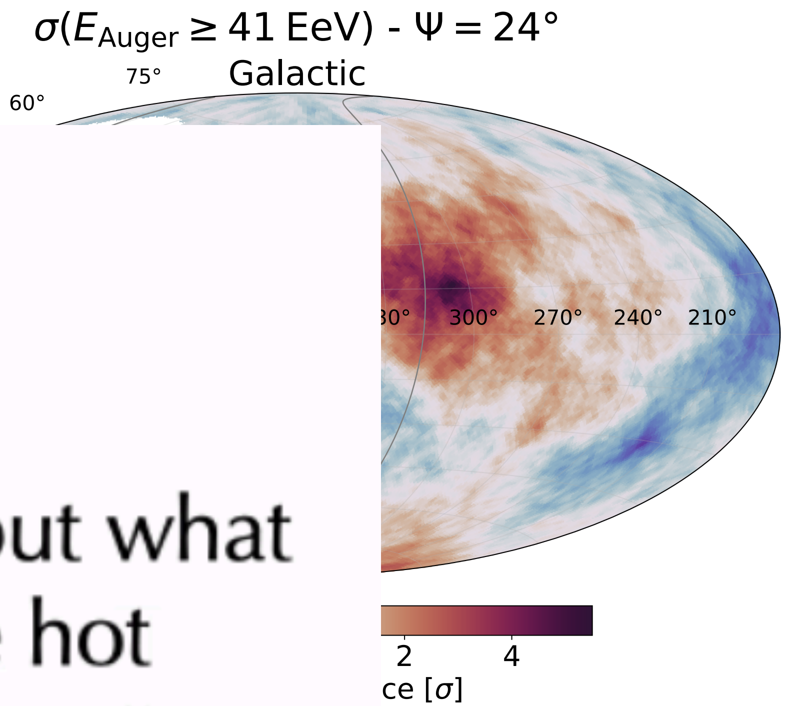


Pierre Auger Collaboration, arXiv:2206.13493



Telescope Array Collaboration, PoS ICRC2021 328

UHECR status when GCOS starts



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- Current status at the
  "hot spots" at interme
  different positions in t
  - Pierre Auger Colla
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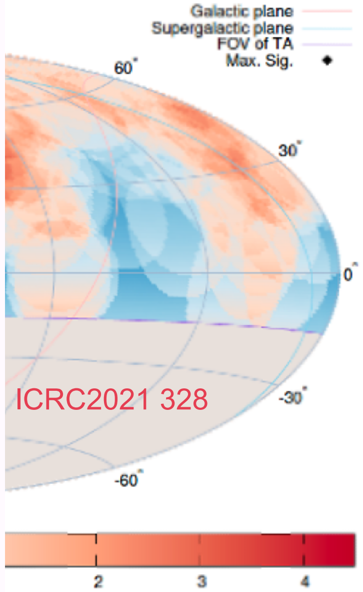
    intermediate angu
    2206.13493)
  - Telescope Array C
    3.2σ post-trial sig
    around Perseus-P
    local Li-Ma signific

By 2030:

- The TA hot spot may be confirmed at 5σ level (but what sources hide behind the hot spot may remain a mystery!)
- One or more classes of UHECR sources may be discovered by Auger.

Fred Sarazin



ICRC2021 328

Magnetic fields

- What can we learn from GCOS anisotropy measurements if some nearby sources are identified?
- ‘Identifying the sources of UHECRs indeed runs parallel to deducing properties of Galactic and extragalactic magnetic fields, and constraints on one of these will enhance our understanding of the other.’ (Pierre Auger Collaboration, arXiv:2206.13493)
- **Use UHECRs to constrain (E)GMFs**
- Energy, charge and search radius together give a direct indication for the magnetic deflections on the way.
- Signal fraction gives an indication for the source density.

Catalog	E_{th} [EeV]	Fisher search radius, Θ [deg]	Signal fraction, α [%]	TS_{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, arXiv:2206.13493

What do we need?

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

$$\frac{E}{Z}\theta_{\mathrm{rms}} \approx \frac{ec\sqrt{D}}{2}\sqrt{\lambda}B_{\perp}$$

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

$$\frac{E}{Z}\sin\theta = \frac{ecD}{2}B_{\perp}$$

- Event-by-event rigidity will be a huge benefit!

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

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Current status of magnetic fields

Nuisances:

- GMF $\rightarrow$ learn about Galactic magnetism!
  what we know:
  - coherent and random fields $O(\mu\text{G})$)
  - coherence length few pc to tens of pc
  - global GMF models
- EGMF $\rightarrow$ learn about primordial magnetism!
  what we know:
  - ≤ 1 nG, but filaments, voids etc.
  - coherence length $\leq$ Mpc
  - UHECR charge $\rightarrow$ learn about hadronic interactions!

Michael Unger

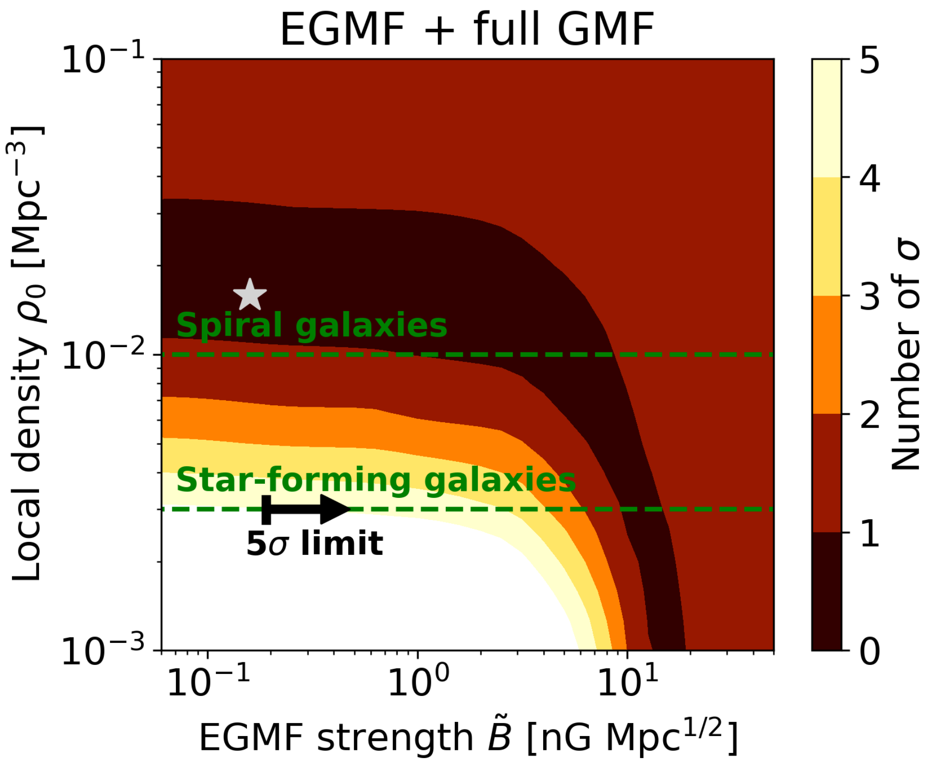
GMF better known in the disc than in the halo. For UHECRs, the halo is especially important. Extent of magnetic fields in the halo also largely uncertain.

Opportunity for significant contributions from UHECRs.

Assuming starburst galaxies as UHECR sources

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS 510 (2021) 1289

	EGMF + full GMF
5σ lower limit on $\tilde{B}$ for $\rho_0 = 3 \cdot 10^{-3}$ Mpc^{-3}	$\tilde{B} > 0.19$ nG Mpc$^{1/2}$
Best-fit point	$\tilde{B} = 0.16$ nG Mpc$^{1/2}$; $\rho_0 = 1.6 \cdot 10^{-2}$ Mpc^{-3}
90% C.L. region	$\tilde{B} < 22$ nG Mpc$^{1/2}$; $\rho_0 < 4.3 \cdot 10^{-2}$ Mpc^{-3}



See also: Bray & Scaife 2018; Boulanger et al. (IMAGINE) 2018

$$\sqrt{\lambda} B_\perp < 2.2 \text{ nG}$$

Conclusions

- Main science case: detecting UHECR sources. But what if this already happened before GCOS?
- Current knowledge on the GMF in the halo and on the EGMFs is very limited.
- Potential for significant contributions from GCOS towards constraining (extra)galactic magnetic fields.
- Event-by-event rigidity will be a huge benefit.

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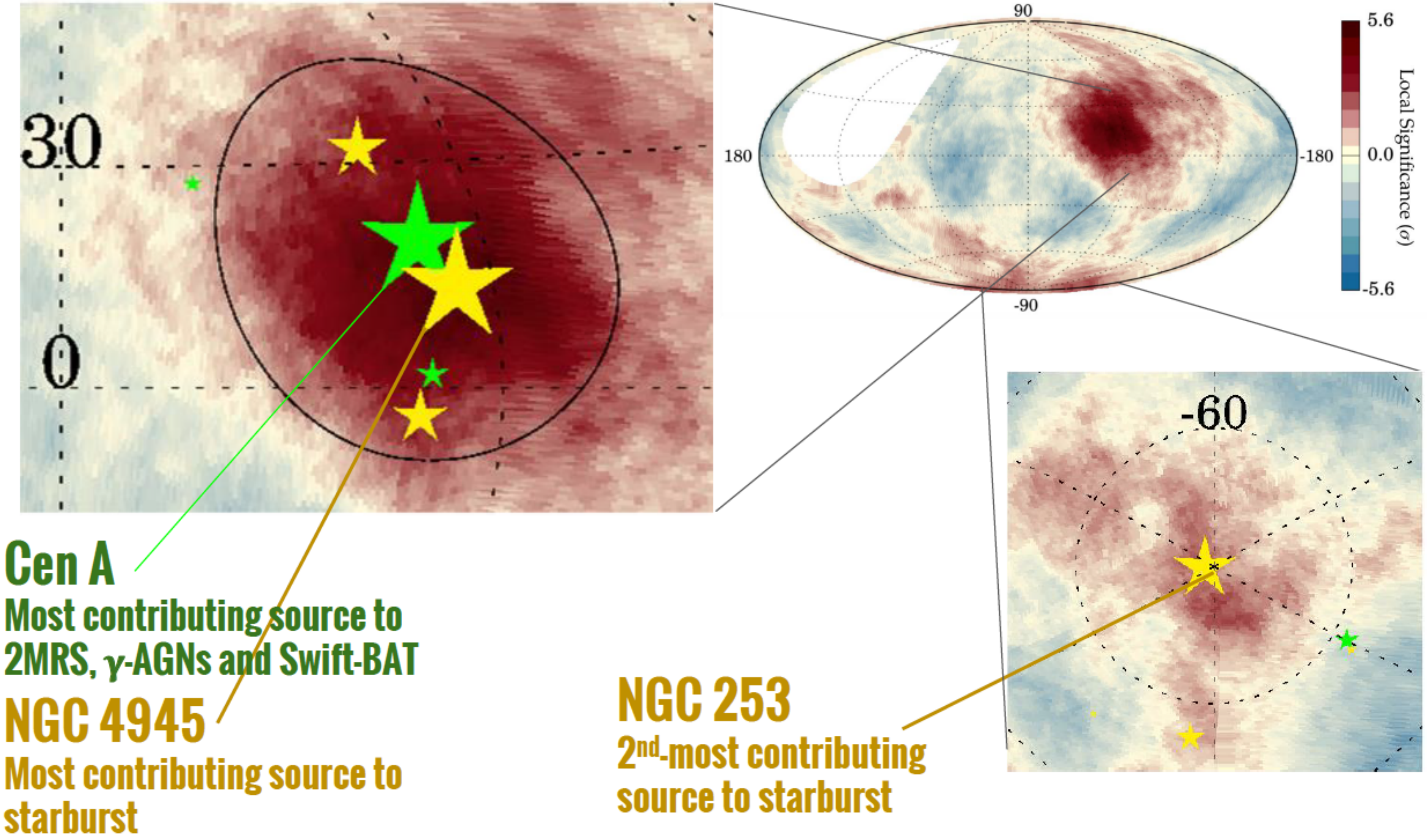
Thank You

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, MNRAS 510 (2021) 1289

- 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
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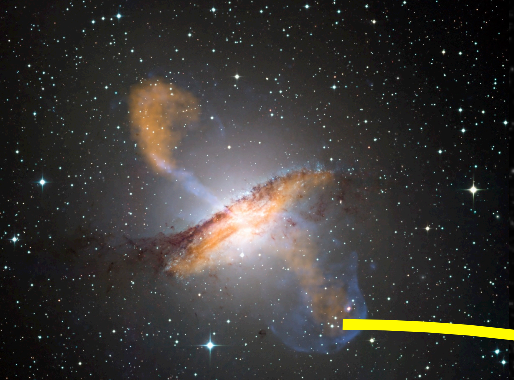
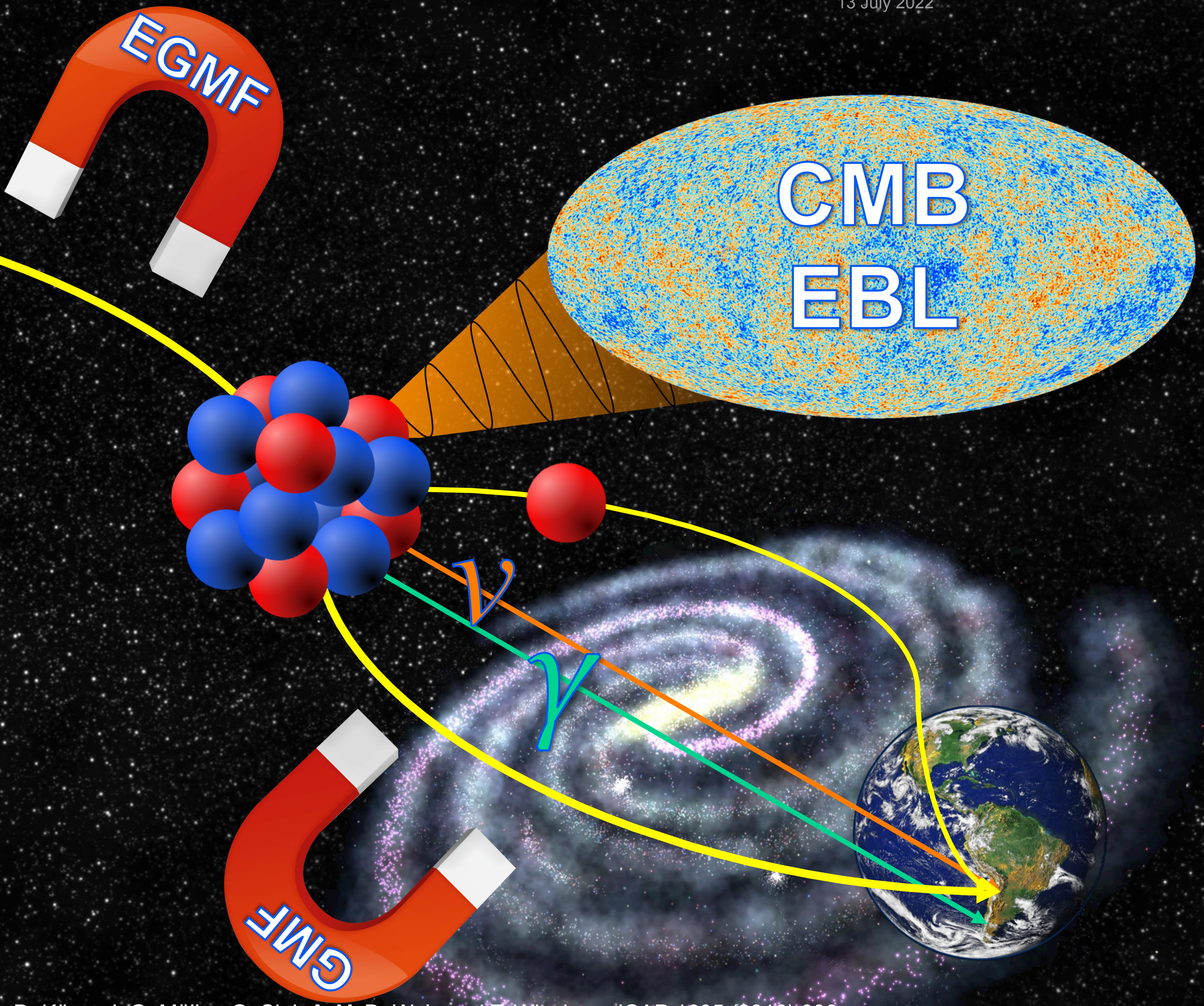
Pierre Auger Collaboration, PoS ICRC2019 206



UHECR



UHECR propagation:

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

CRPropa

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

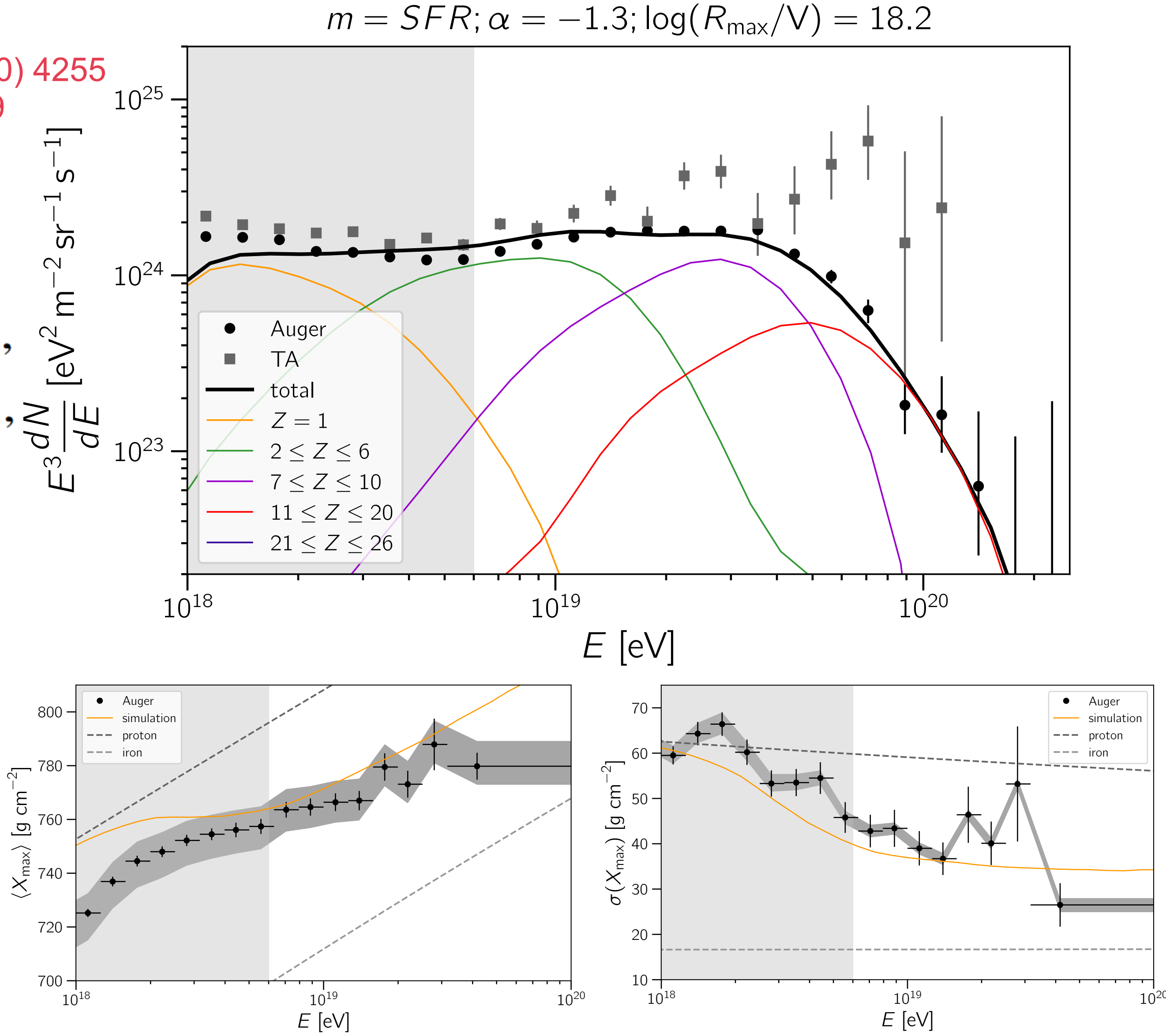
Our method

A. Palladino, **AvV**, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255
AvV, A. Palladino, A. Taylor and W. Winter, MNRAS 510 (2021) 1289

- UHECR source spectra and composition from fits to the spectrum and composition of Auger

$$\frac{dN_i}{dE} \propto \begin{cases} f_i E^{-\gamma} & \text{for } E < Z_i R_{\max}, \\ f_i E^{-\gamma} \exp\left(1 - \frac{E}{Z_i R_{\max}}\right) & \text{for } E \geq Z_i R_{\max}, \end{cases}$$

$\rho(z)$	γ	R_{max}/V	f_p	f_{He}	f_N	f_{Si}
Neg.	1.42	$10^{18.85}$	0.07	0.34	0.53	0.06
Flat	−1.0	$10^{18.2}$	0.6726	0.3135	0.0133	0.0006
SFR	−1.3	$10^{18.2}$	0.1628	0.8046	0.0309	0.0018



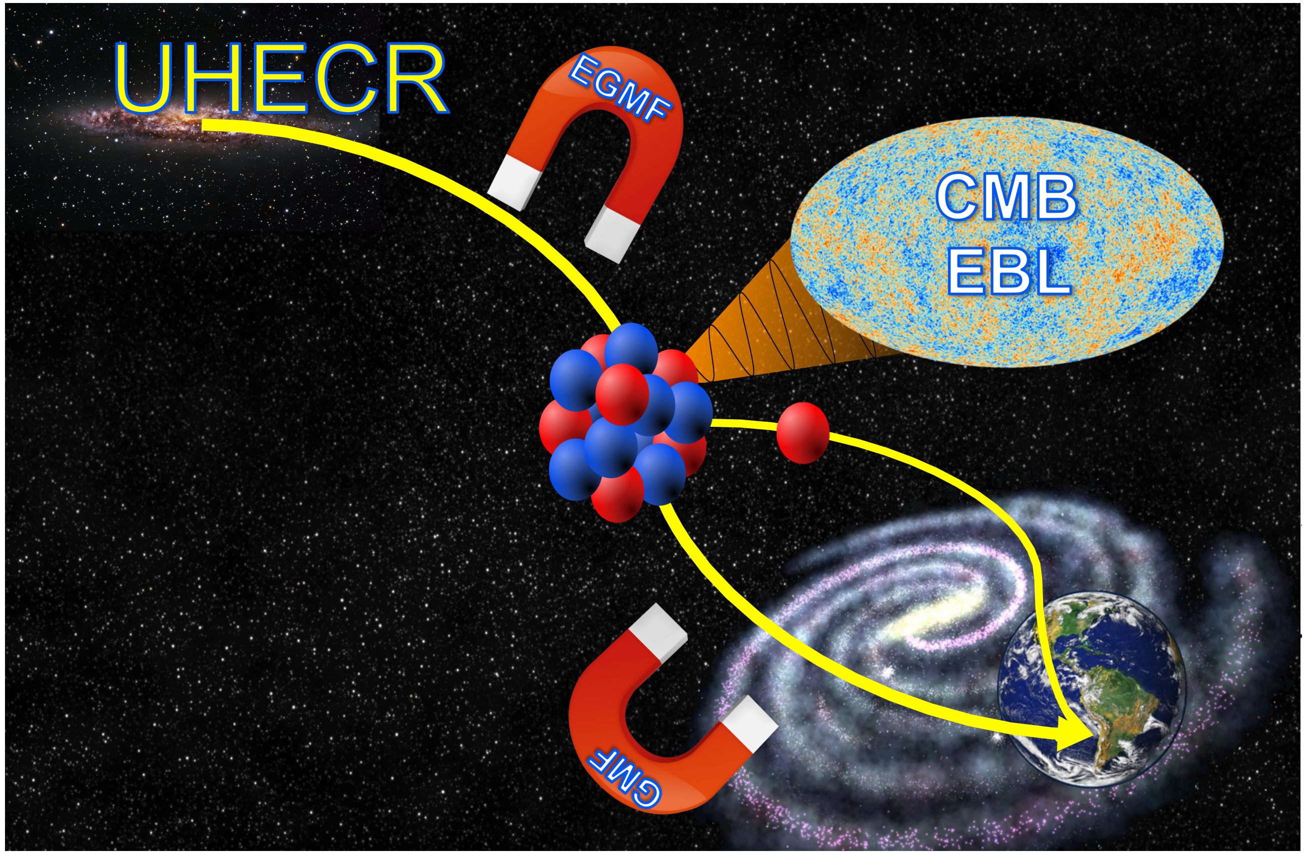
R. Alves Batista, R. M. de Almeida, B. Lago and K. Kotera, JCAP 01 (2019) 002

Our method

A. Palladino, **AvV**, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255
AvV, A. Palladino, A. Taylor and W. Winter, MNRAS 510 (2021) 1289

- Simulate deflections from the sources in EGMF
  - Local galaxies correlations: 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 the GMF, JF12 model

R. Jansson, G. R. Farrar, Astrophys. J. 757 (2012) 14
R. Jansson, G. R. Farrar, Astrophys. J. 761 (2012) L11
G. R. Farrar, M. S. Sutherland, JCAP 05 (2019) 004

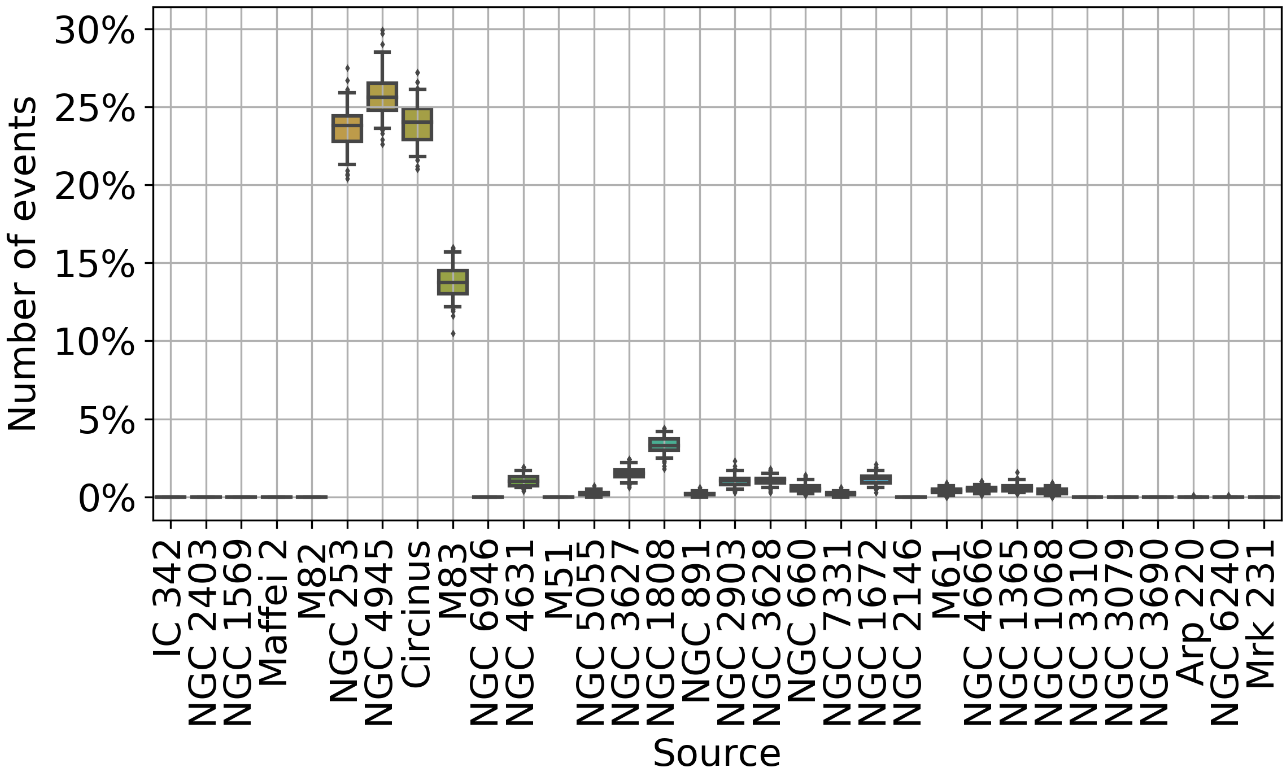


Local galaxies correlations; Our method

4 important sources

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS 510 (2021) 1289

- Simulate UHECR sky maps for specific EGMF and GMF setups and local source densities ρ_0
- Check if the UHECR sky maps give θ and f_{aniso} values compatible with the analysis of Auger
- **Focus on 4 most important sources**
- Combine 4 catalogue sources with an isotropic contribution from background sources



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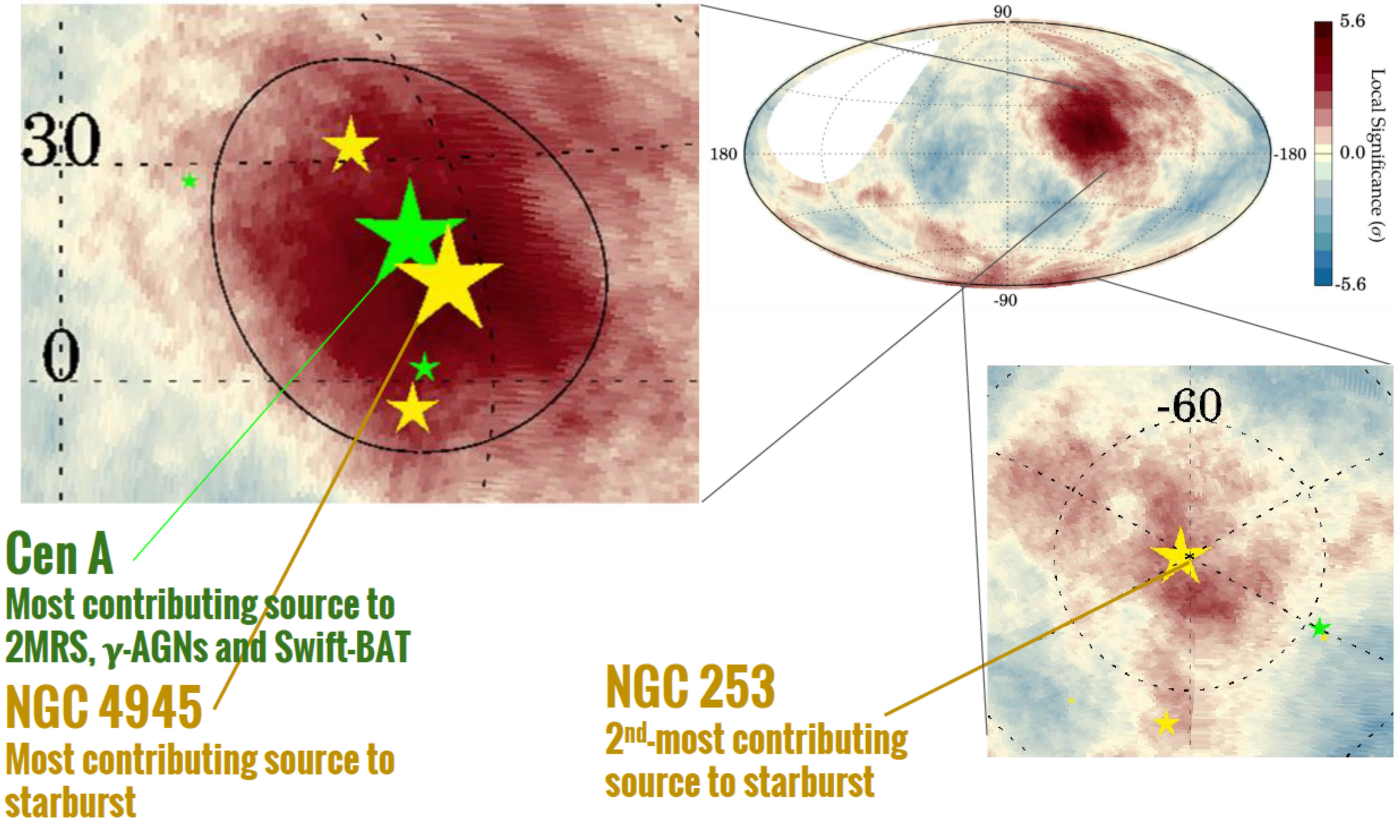

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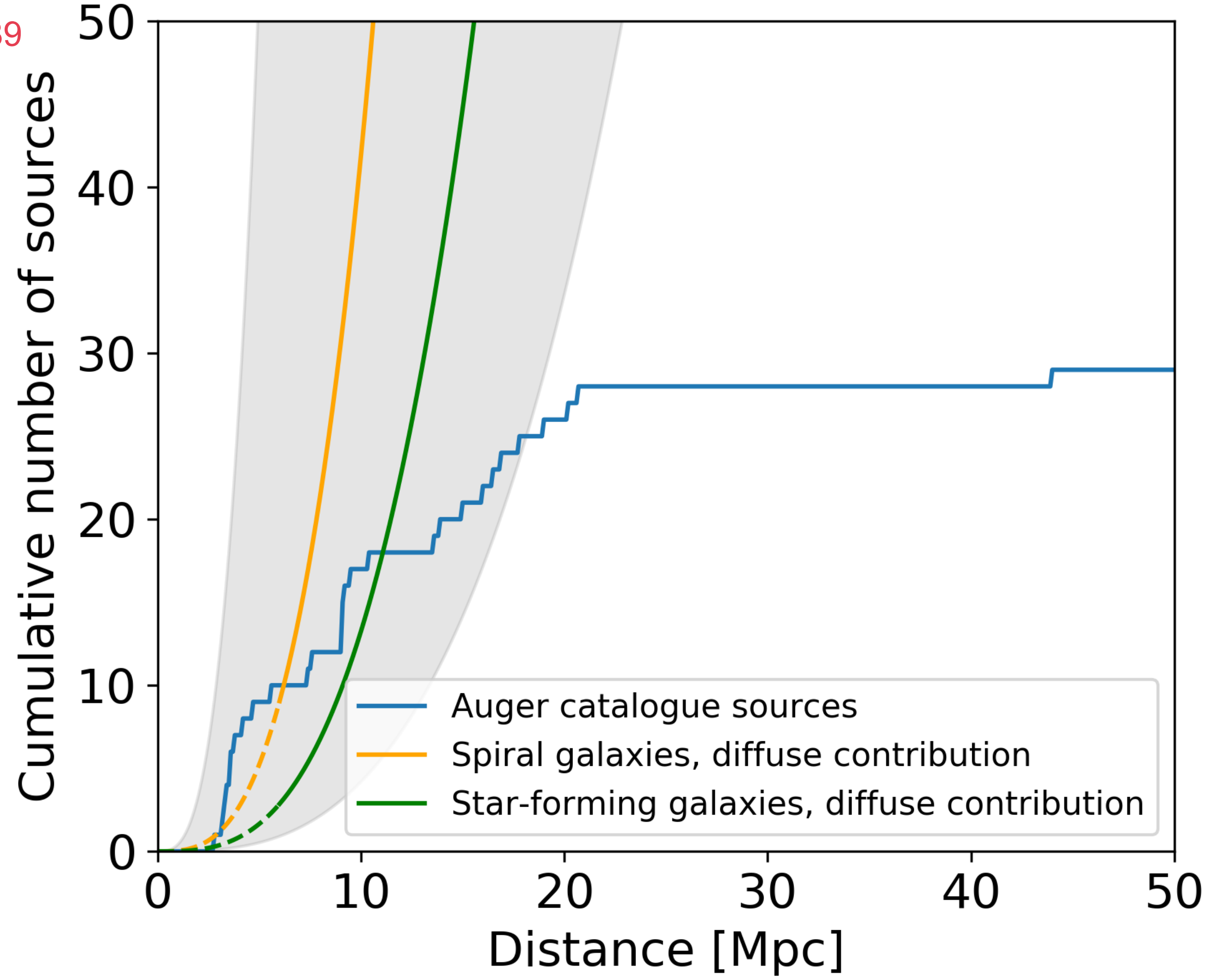
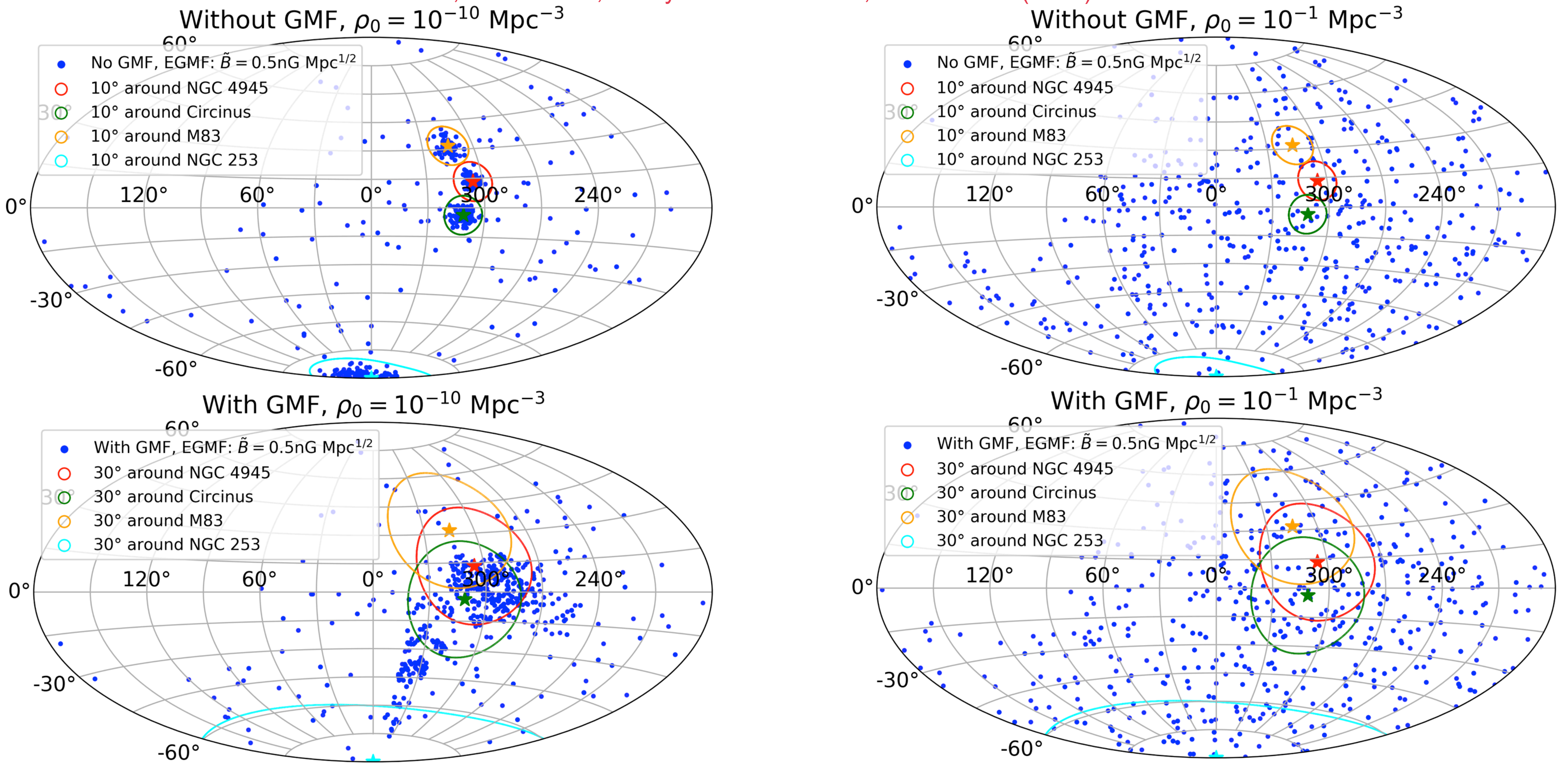


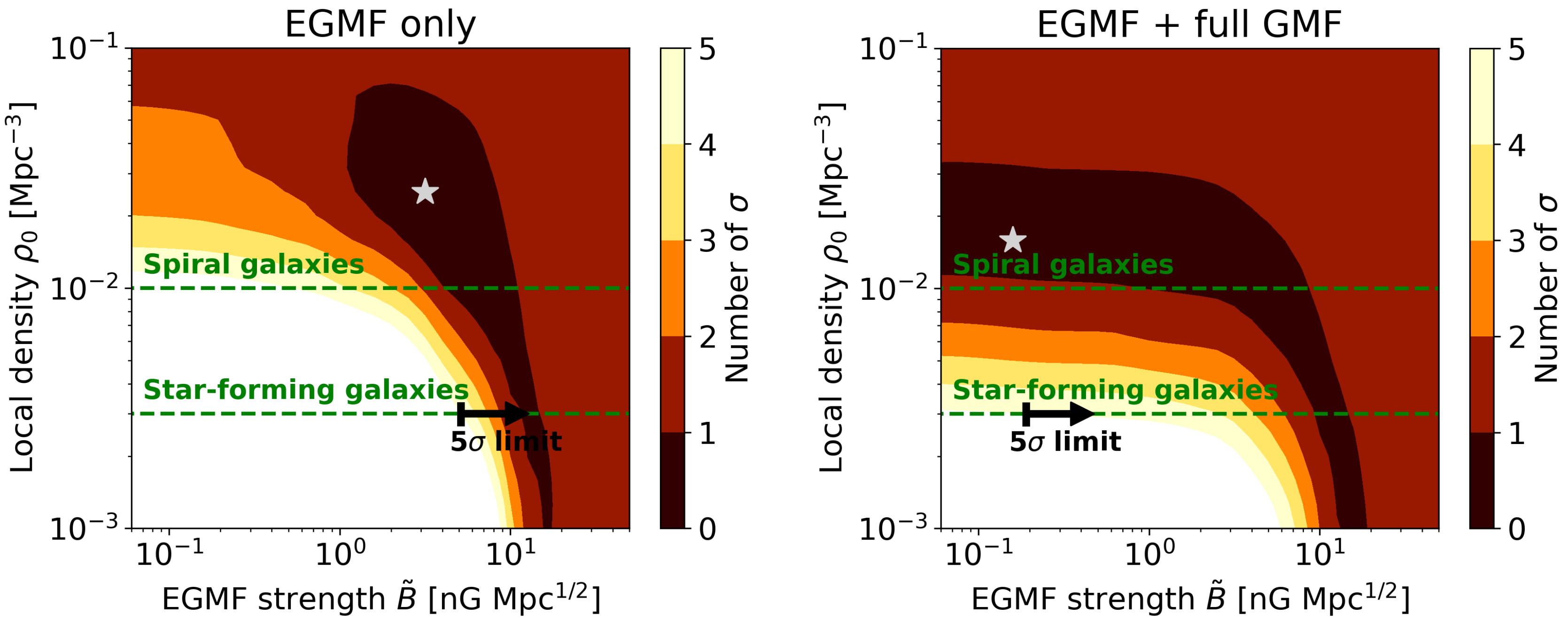
Local galaxies correlations; Example sky maps

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS 510 (2021) 1289



Local galaxy correlations; results

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS 510 (2021) 1289

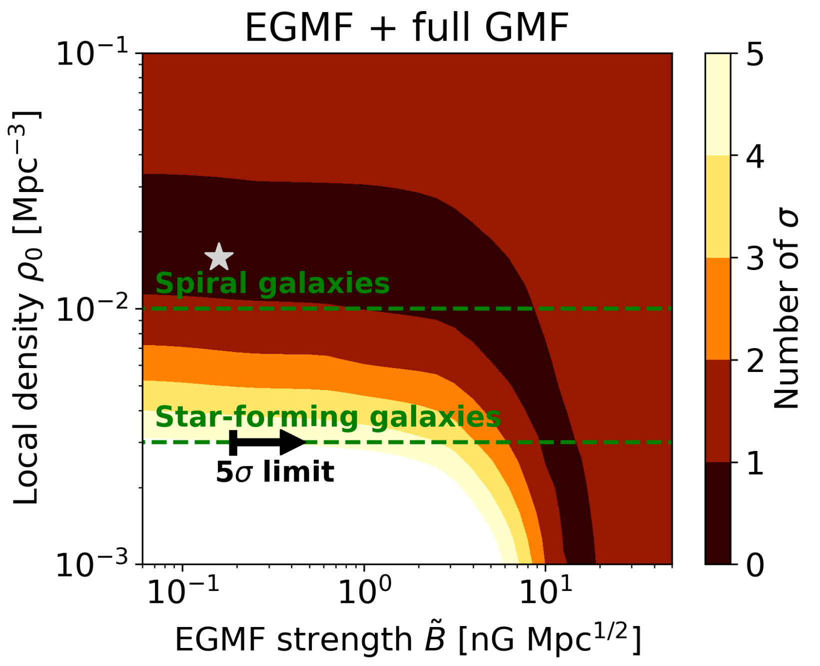


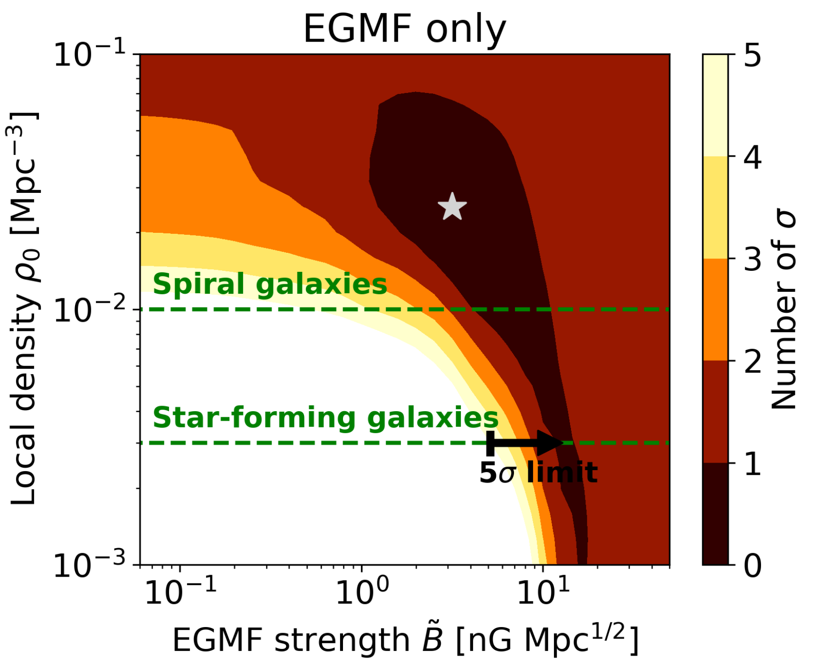
	EGMF only	EGMF + full GMF
5σ lower limit on $\tilde{B}$ for $\rho_0 = 3 \cdot 10^{-3}$ Mpc^{-3}	$\tilde{B} > 5.1$ nG Mpc$^{1/2}$	$\tilde{B} > 0.19$ nG Mpc$^{1/2}$
Best-fit point	$\tilde{B} = 3.2$ nG Mpc$^{1/2}$; $\rho_0 = 2.5 \cdot 10^{-2}$ Mpc^{-3}	$\tilde{B} = 0.16$ nG Mpc$^{1/2}$; $\rho_0 = 1.6 \cdot 10^{-2}$ Mpc^{-3}
90% C.L. region	$\tilde{B} < 22$ nG Mpc$^{1/2}$; $\rho_0 < 8.4 \cdot 10^{-2}$ Mpc^{-3}	$\tilde{B} < 22$ nG Mpc$^{1/2}$; $\rho_0 < 4.3 \cdot 10^{-2}$ Mpc^{-3}

Local galaxy correlations; conclusions

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS 510 (2021) 1289

- 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: $\tilde{B} > 0.19\ \mathrm{nG\ Mpc}^{1/2}$
- 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: $\tilde{B} < 22\ \mathrm{nG\ Mpc}^{1/2}$; $\rho_0 < 0.084\ \mathrm{Mpc}^{-3}$
  - Best-fit point for a source density close to, or even denser than, that of spiral galaxies

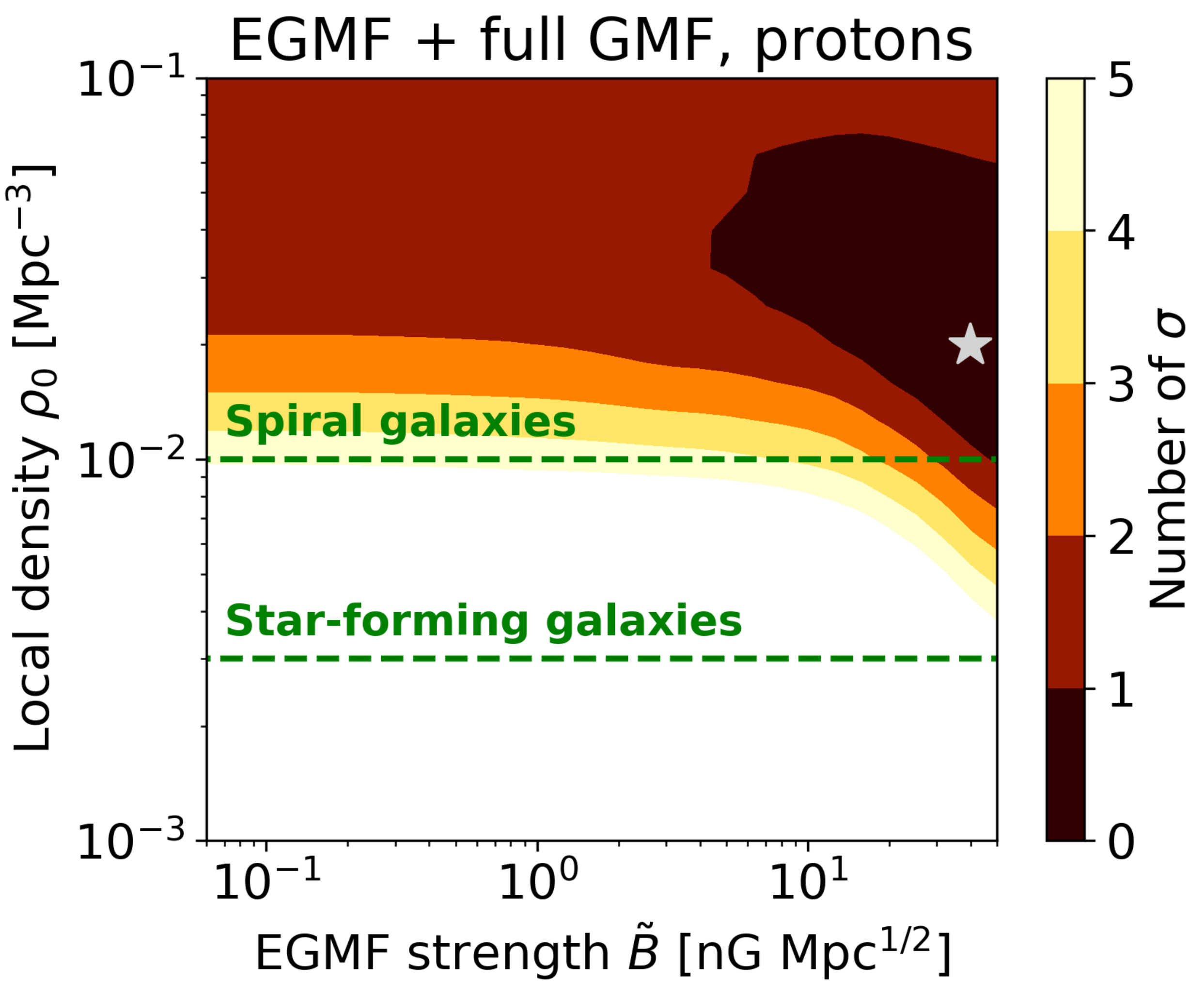




Pure-proton scenario

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS 510 (2021) 1289

- **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**

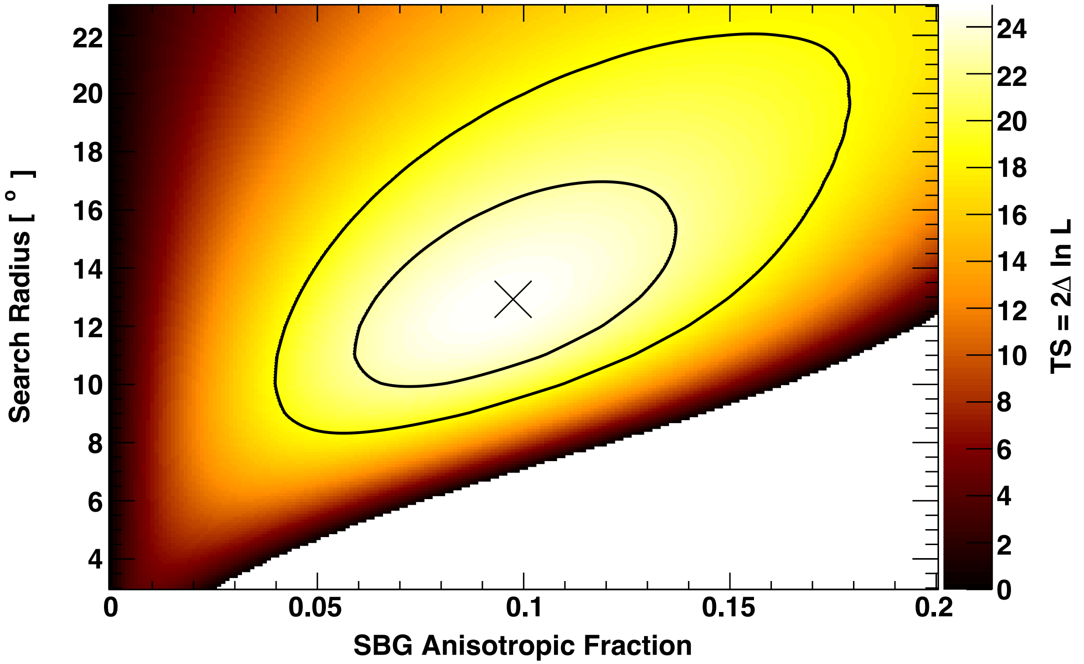


The analysis performed by Auger

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

Starburst galaxies - E > 39 EeV



Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
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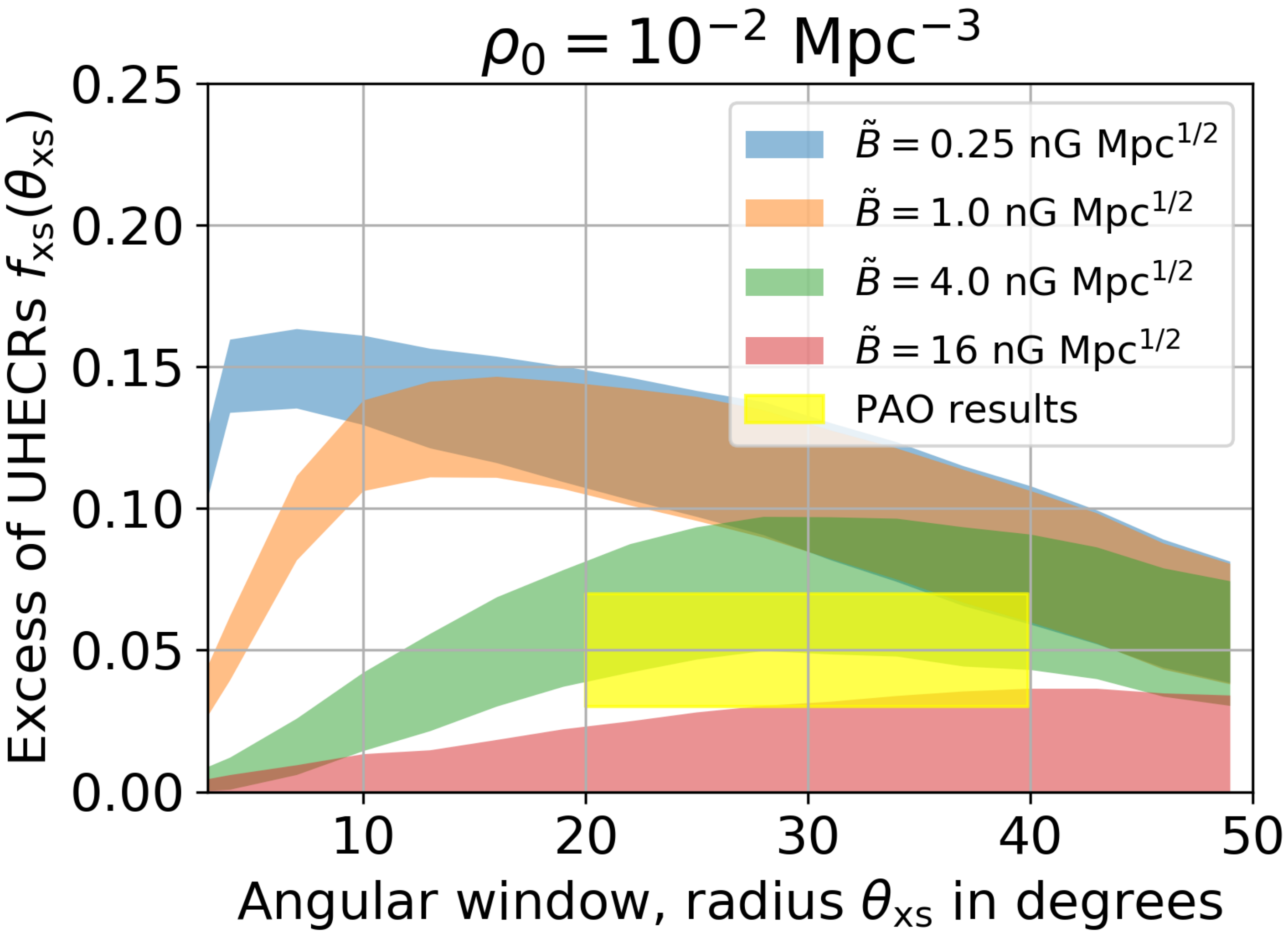
Compare with Auger results

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS 510 (2021) 1289

- **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

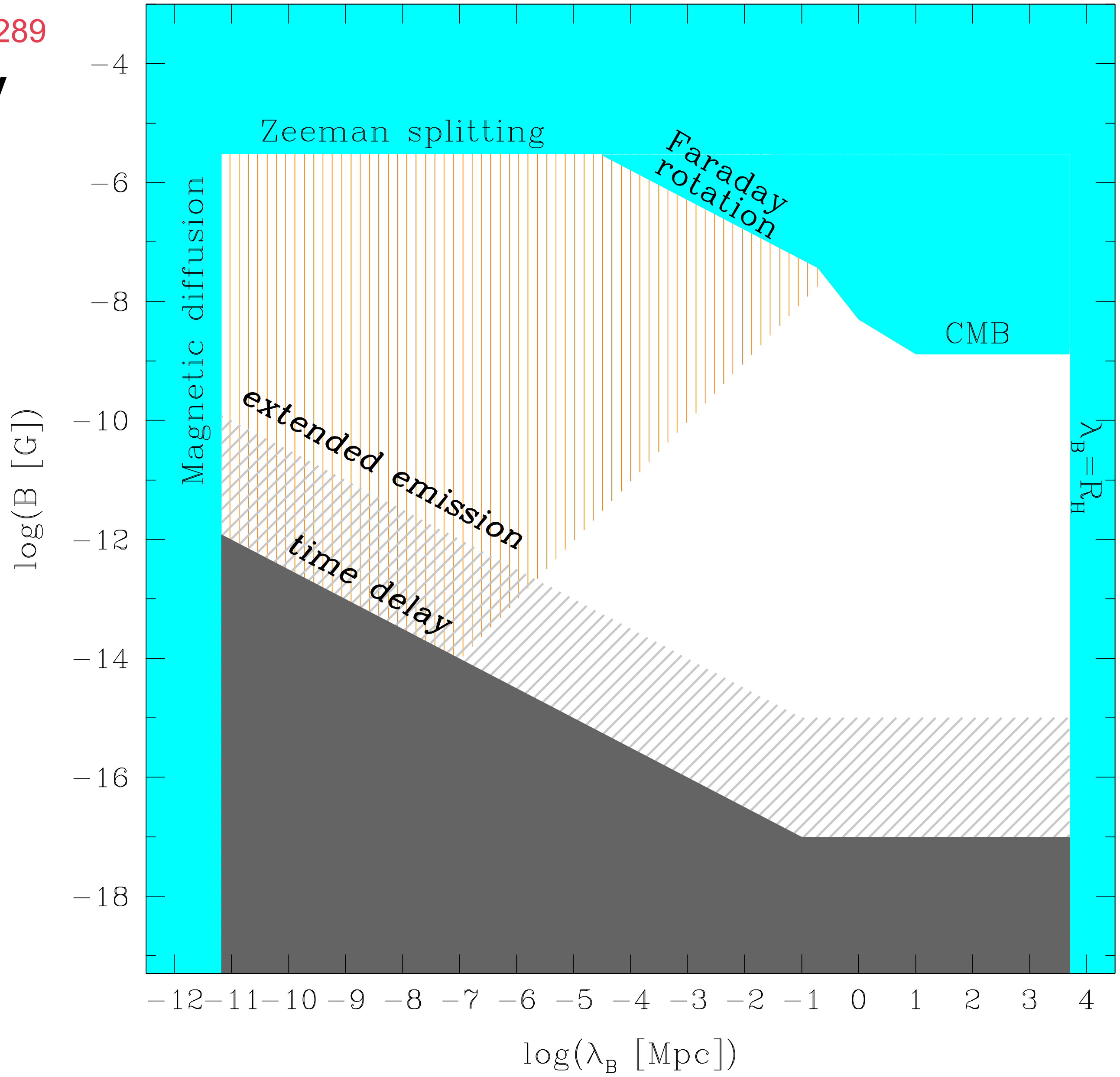


EGMF limits

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS 510 (2021) 1289

- **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



Explaining the Auger and TA spectra with a local source

- Discrepancy in the UHECR spectra at the highest energies measured by Auger and TA
- Can be explained by adding a local source in the Northern hemisphere, only observable by TA