Extragalactic magnetic fields and directional correlations of ultra-high-energy cosmic rays with local galaxies and neutrinos

Arjen van Vliet
Andrea Palladino, Walter Winter, Andrew Taylor and Anna Franckowiak

THAT meeting, 19/05/2021

Image: Pierre Auger Observatory

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Looking for correlations between UHECRs and neutrinos

- Searches by IceCube + ANTARES + Auger + TA
- **No significant correlations found yet**

Search for correlations of high-energy neutrinos and ultrahigh- energy cosmic rays

ANTARES and IceCube and Telescope Array Collaborations (Lisa Schumacher (Aachen, Tech. Hochsch.) for the collaboration)

May 24, 2019 - 4 pages

EPJ Web Conf. 207 (2019) 02010
(2019)
DOI: 10.1051/epjconf/201920702010
Conference: C18-10-02.1 (EPJ Web Conf., 207 (2019) 02010)
Proceedings
e-Print: arXiv:1905.10111 [astro-ph.HE] | PDF
Experiment: ANTARES, ICECUBE, AUGER, TELESCOPE-ARRAY

Search for a correlation between the UHECRs measured by the Pierre Auger Observatory and the Telescope Array and the neutrino candidate events from IceCube and ANTARES

ANTARES and IceCube and Pierre Auger and Telescope Array Collaborations (J. Aublin (APC, Paris) *et al.*) *Show all 14 authors*

May 10, 2019 - 5 pages

EPJ Web Conf. 210 (2019) 03003
(2019)
DOI: 10.1051/epjconf/201921003003
Conference: C18-10-08.1
Proceedings
e-Print: arXiv:1905.03997 [astro-ph.HE] | PDF
Experiment: ANTARES, ICECUBE, AUGER, TELESCOPE-ARRAY

Search for correlations between the arrival directions of IceCube neutrino events and ultrahigh-energy cosmic rays detected by the Pierre Auger Observatory and the Telescope Array

IceCube and Pierre Auger and Telescope Array Collaborations (M.G. Aartsen (Adelaide U.) *et al.*) *Show all 870 authors*

Nov 30, 2015 - 40 pages

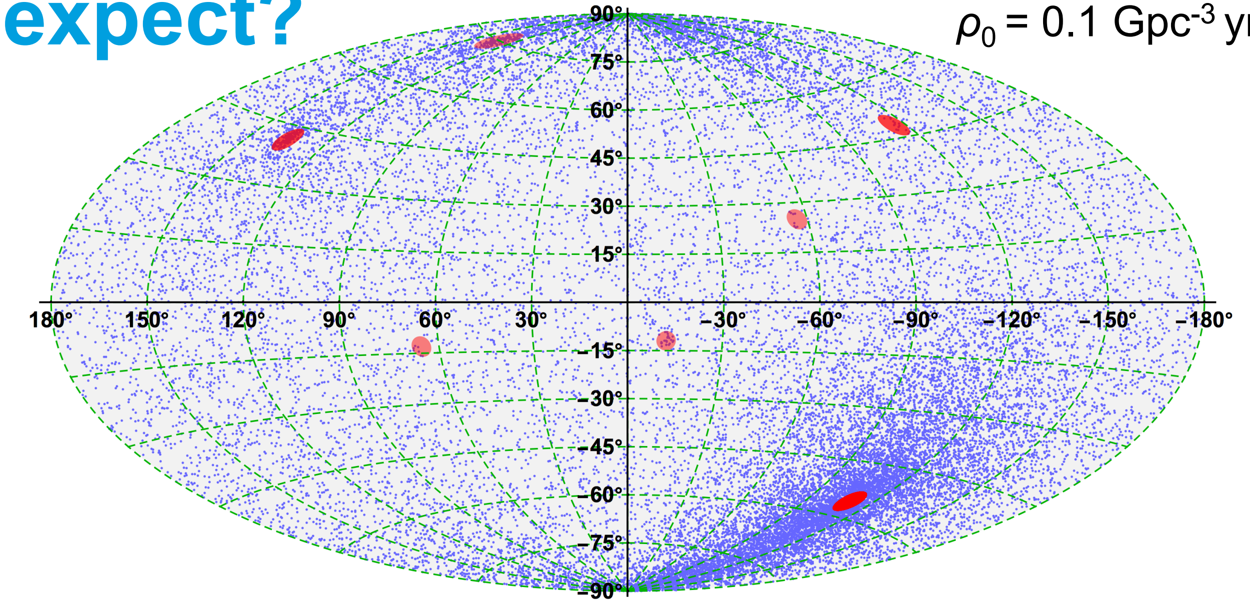
JCAP 1601 (2016) 037
(2016-01-20)
DOI: 10.1088/1475-7516/2016/01/037
FERMILAB-PUB-15-520-AD-AE-CD-TD
e-Print: arXiv:1511.09408 [astro-ph.HE] | PDF
Experiment: AUGER, IceCube, TELESCOPE-ARRAY

How many correlations do we expect?

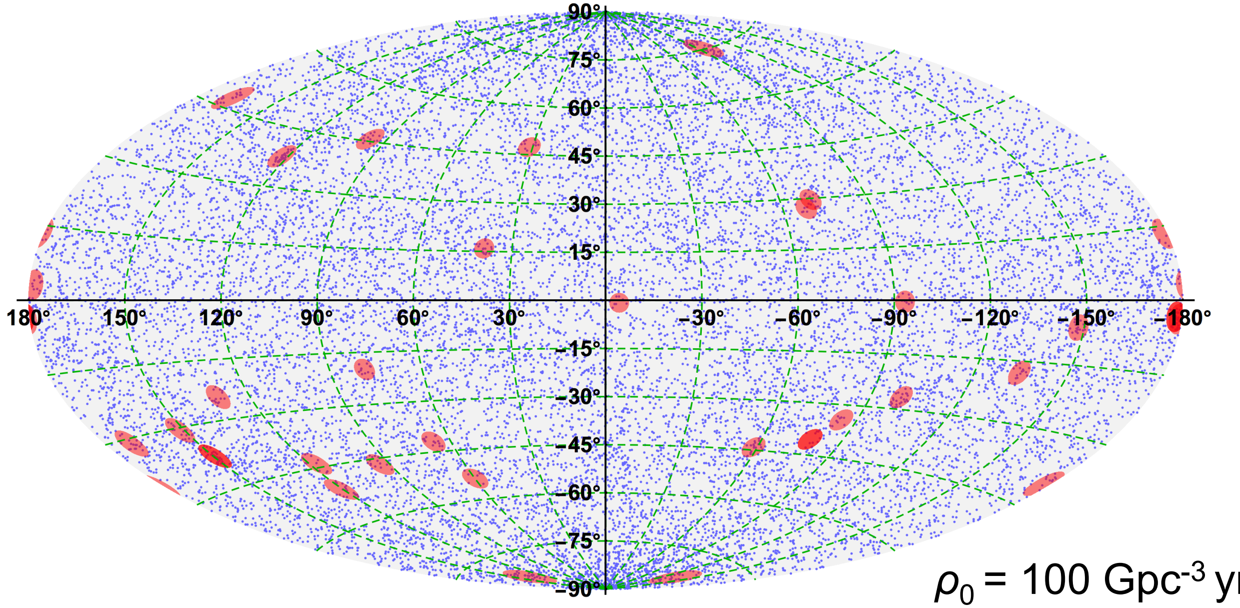
A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- Depends on
  - Energy-losses of UHECRs
  - Source evolution with redshift
  - Deflections in extragalactic magnetic field
  - Deflections in Galactic magnetic field
  - Density of the sources
- **Test most positive scenario:** all UHECRs and HE neutrinos are produced by the same source class
- Neutrinos: through-going muon sample of IceCube (36 neutrinos with E > 200 TeV)
  IceCube Collaboration ICRC 2017
- UHECRs: 135k with $E > 10^{18.5}$ eV (~ number of UHECRs measured by Auger + TA)

$\rho_0 = 0.1\ \mathrm{Gpc^{-3}\ yr^{-1}}$



36 neutrinos; 10^5 cosmic rays; $E_{CR} > 10^{19}$ eV

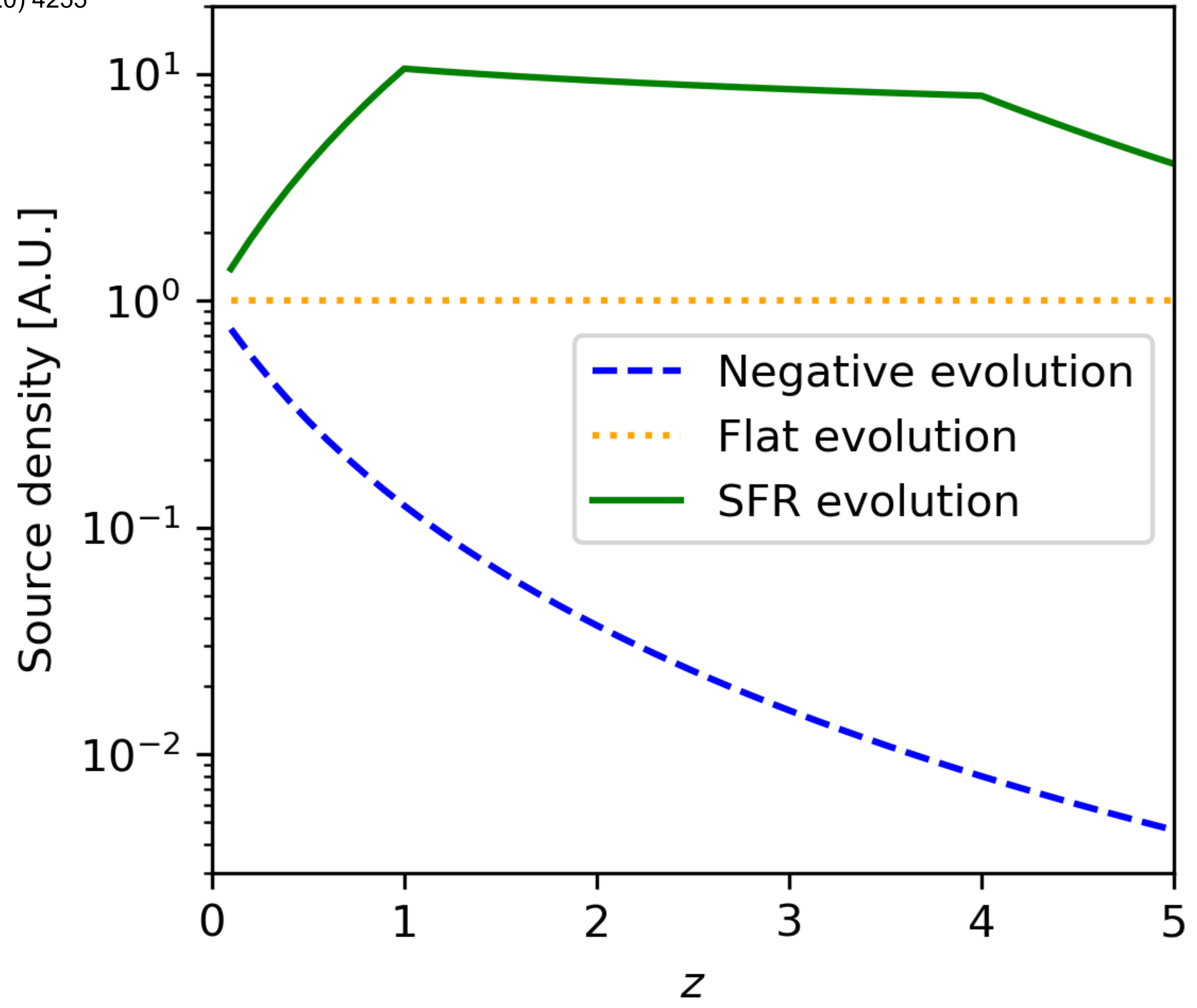


$\rho_0 = 100\ \mathrm{Gpc^{-3}\ yr^{-1}}$

Source evolution with redshift

A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- Test 3 different scenarios
- Negative evolution:
  - Low-luminosity BL Lacs
  - TDEs
- Flat evolution
- Star Formation Rate evolution:
  - Normal galaxies
  - Starburst galaxies
  - GRBs



Adiabatic energy losses of neutrinos

A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- Test 3 different scenarios
- Negative evolution:
  - Low-luminosity BL Lacs
  - TDEs
- Flat evolution
- Star Formation Rate evolution:
  - Normal galaxies
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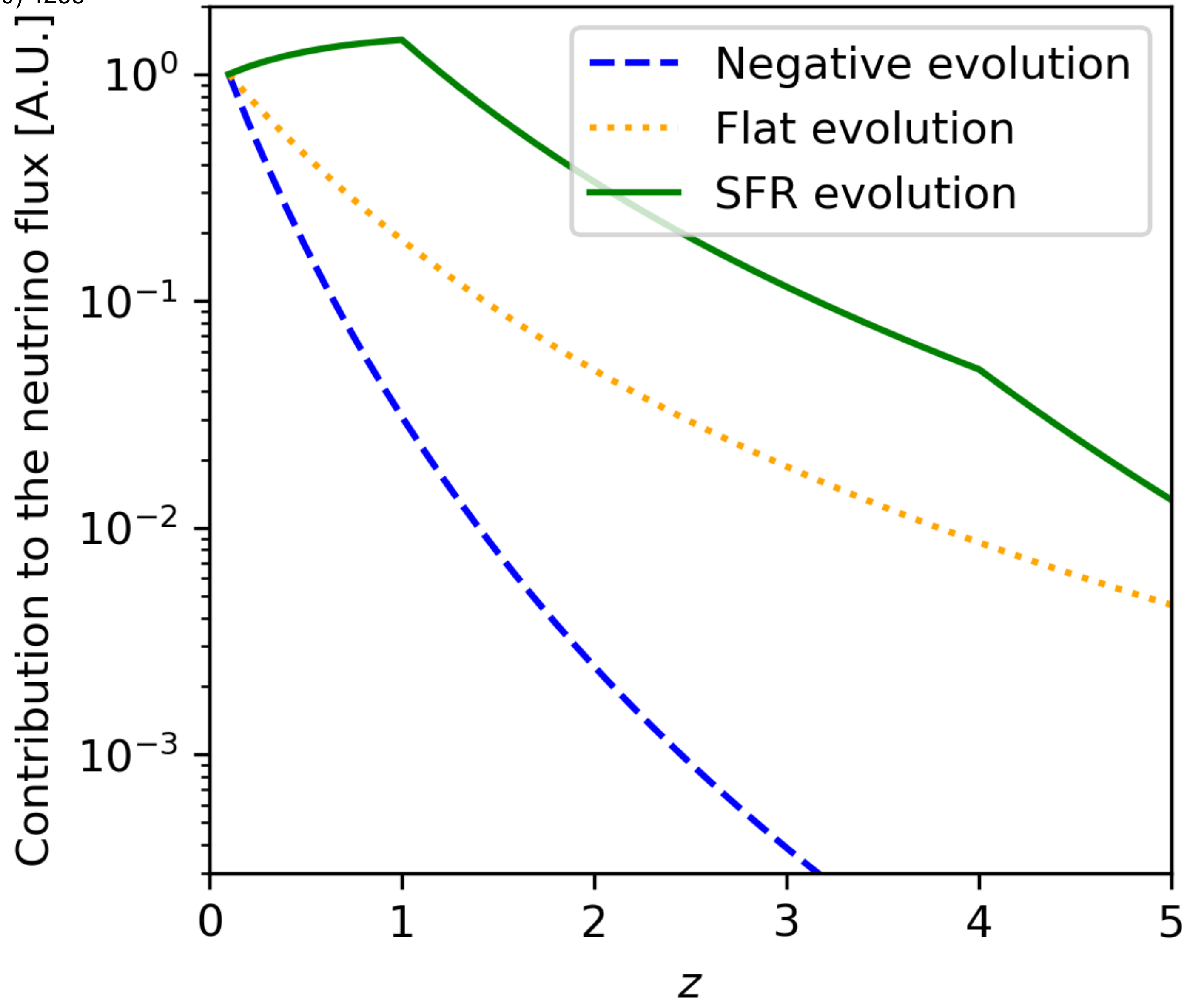


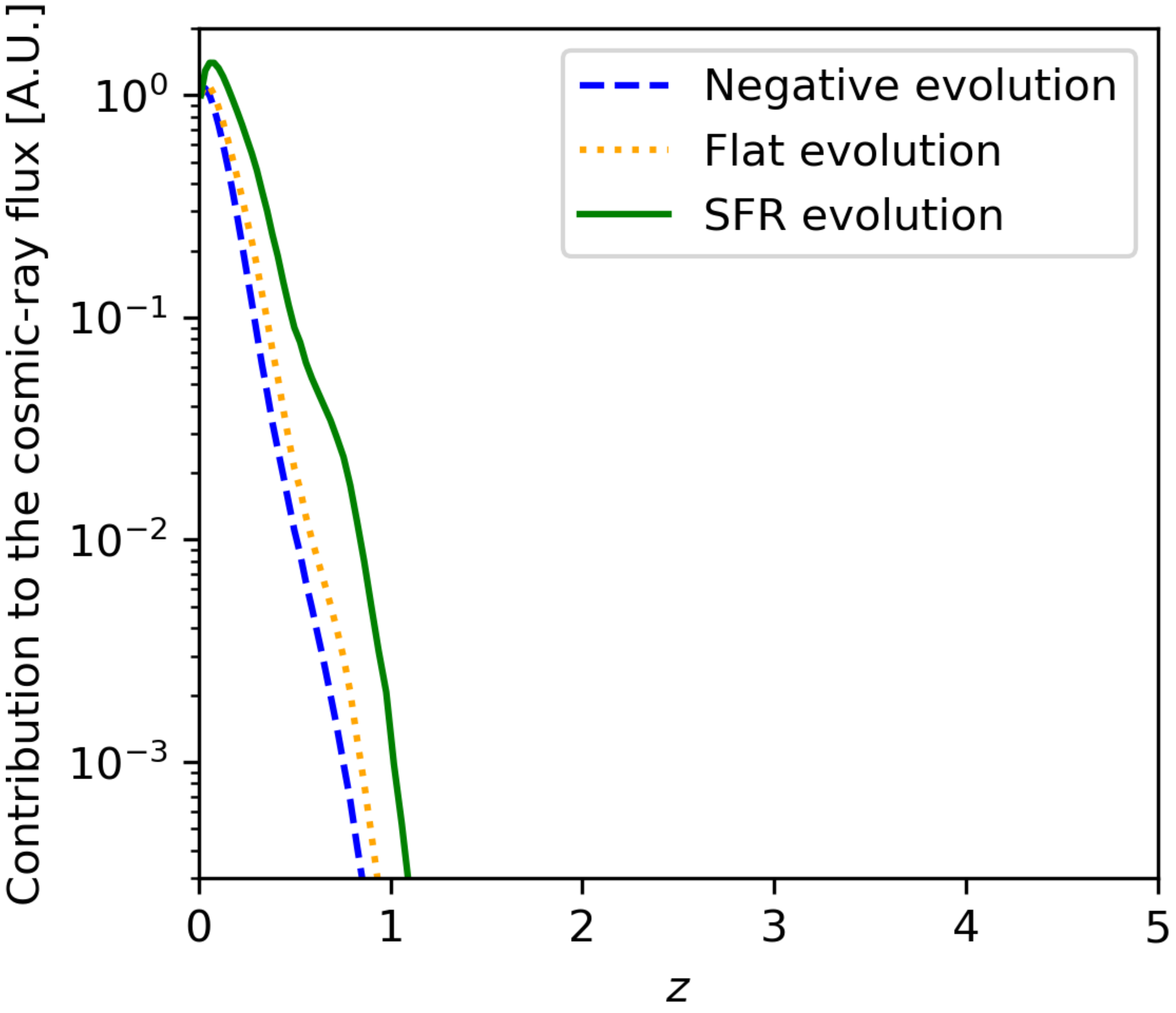
Energy losses of UHECRs

A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- 1D simulation with CRPropa, including all relevant interactions
- For E_{CR}>$10^{18.5}$ eV
- For scenarios that fit Auger spectrum and composition

$\rho(z)$	γ	$R_{\rm max}/{\rm V}$	$f_{\rm p}$	$f_{\rm He}$	$f_{\rm N}$	$f_{\rm Si}$
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

Auger, JCAP 04 (2017) 038
R. Alves Batista *et al.*, JCAP 01 (2019) 002



Deflections in extragalactic magnetic fields

A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- 3D simulation with CRPropa
- For E_{CR}>$10^{18.5}$ eV
- For the same scenarios that fit Auger spectrum and composition
- In the EGMF model with the smallest deflections of Hackstein *et al*. 2018

$\rho(z)$	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
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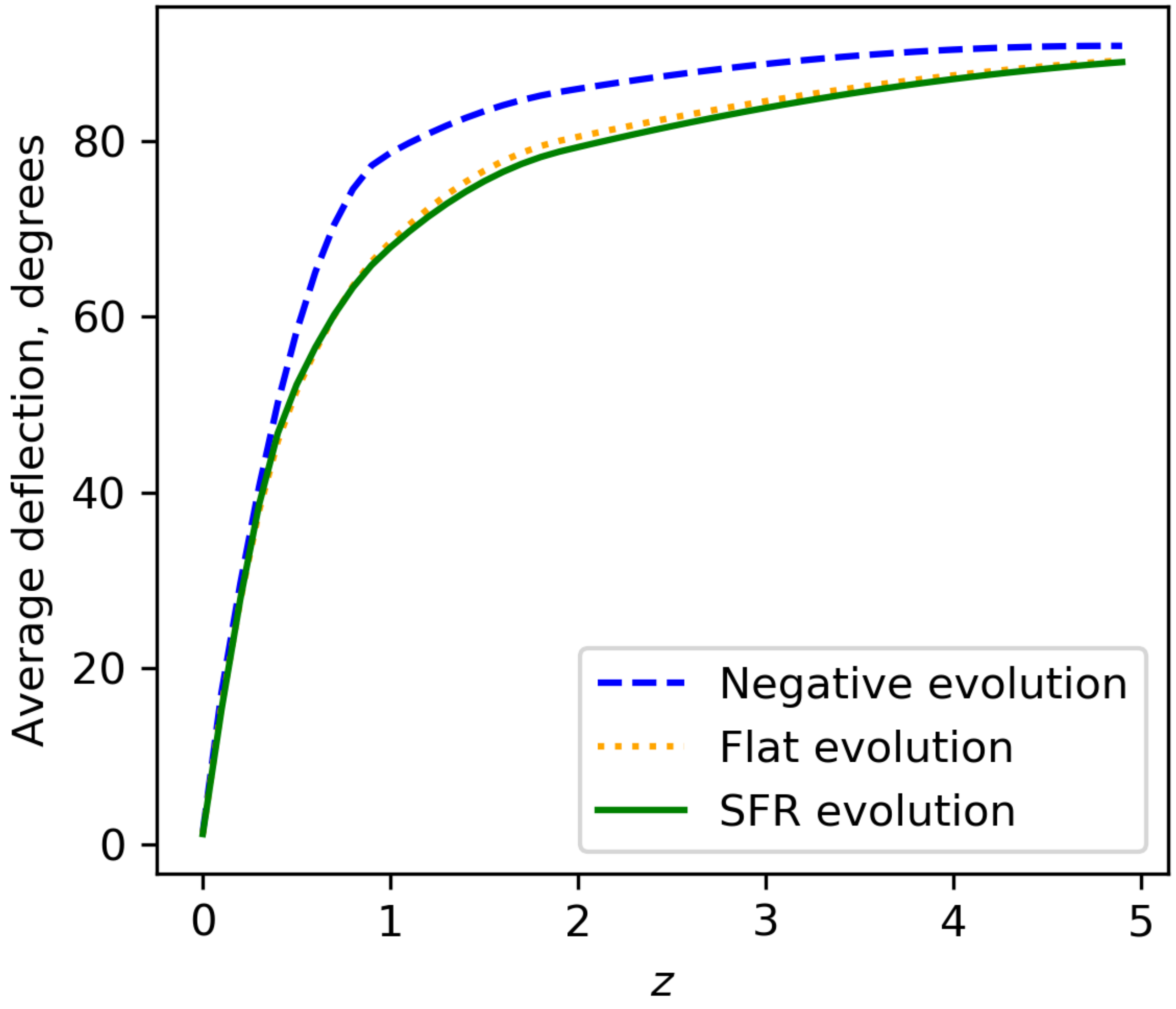
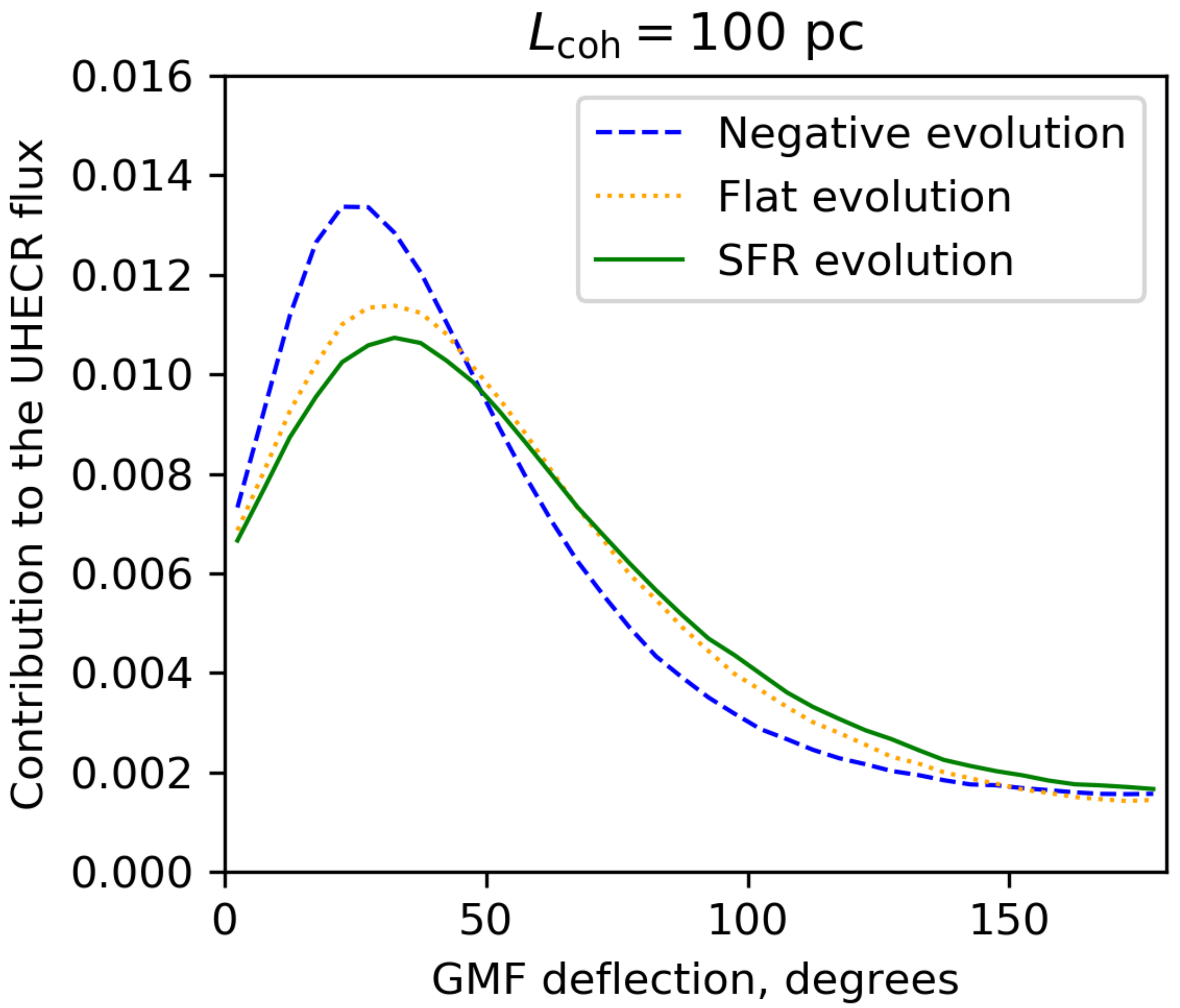


Deflections in the Galactic magnetic field

A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- GMF model: Jansson and Farrar ‘12
- Deflection parameterised as function of rigidity in Farrar and Sutherland ‘19
- Combine with rigidity distribution obtained from 1D simulation with CRPropa

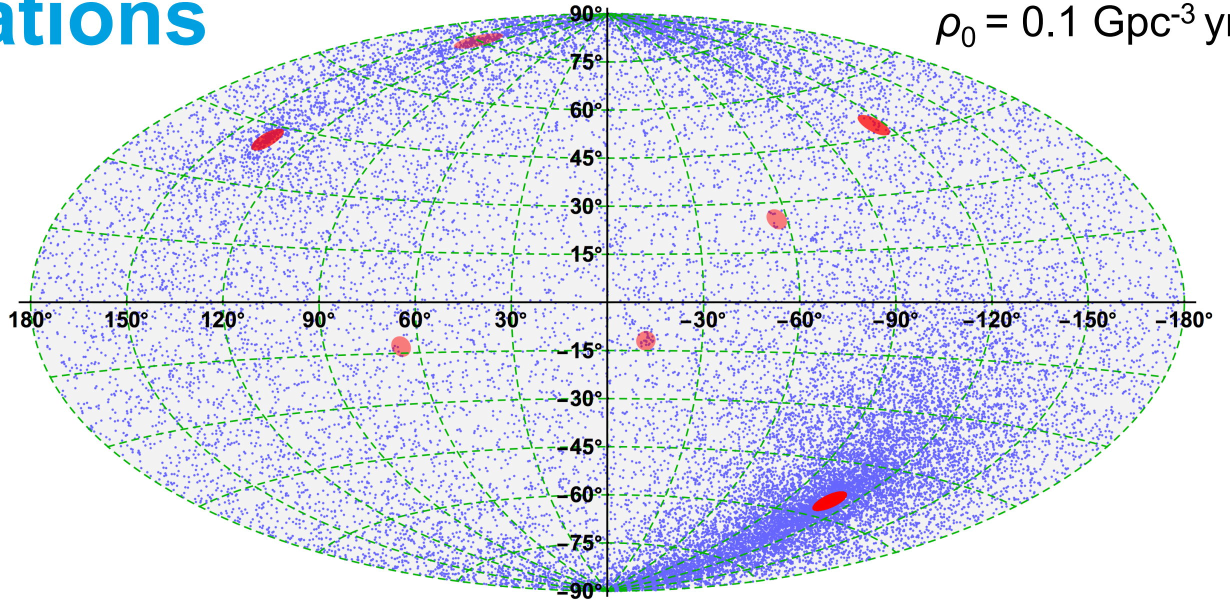


Calculation of expected correlations

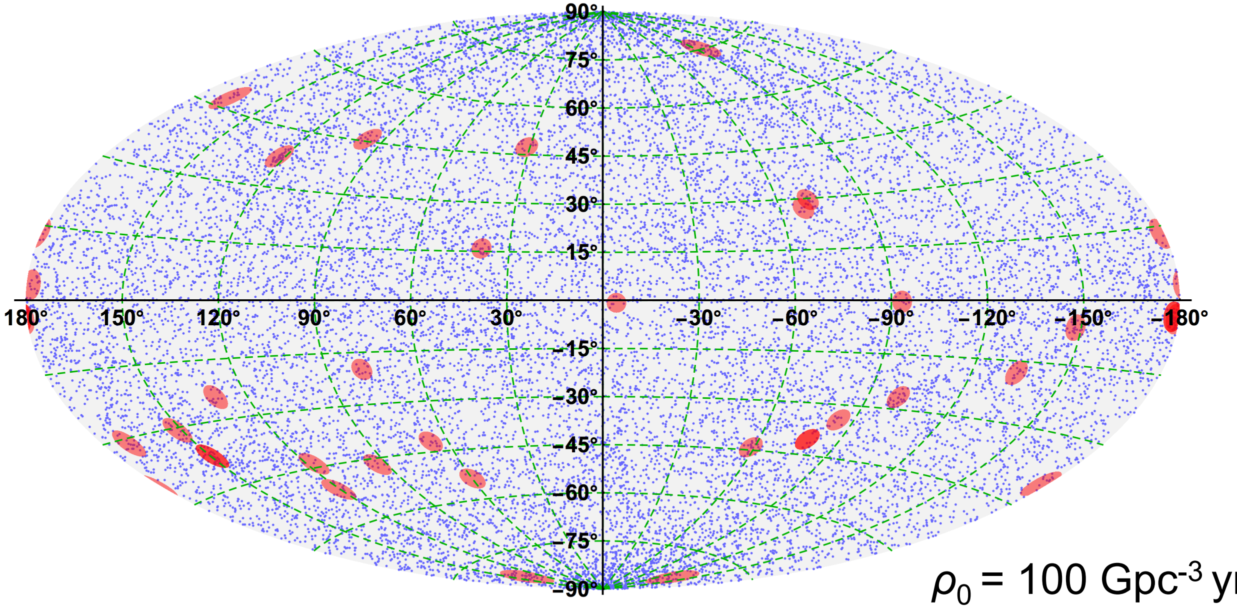
A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- Create sky maps from a list of random sources with a specific source density ρ_0, with 36 neutrinos and 135k cosmic rays
- Determine optimal angular window and significance with parameter scan
- Repeat 10^3 times for each combination of ρ_0 and source evolution
- Determine which fraction of maps give a significant expected correlation

$\rho_0 = 0.1\ \mathrm{Gpc^{-3}\ yr^{-1}}$



36 neutrinos; 10^5 cosmic rays; $E_{CR} > 10^{19}$ eV

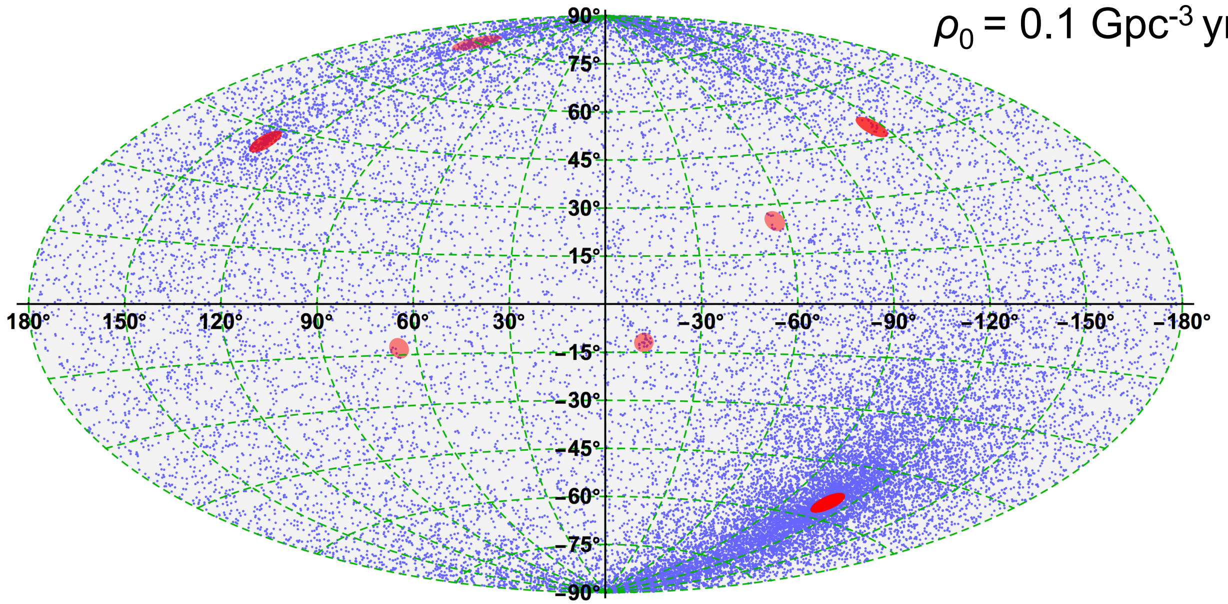


$\rho_0 = 100\ \mathrm{Gpc^{-3}\ yr^{-1}}$

Neutrino multiplets

A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- No HE neutrino multiplets (2 or more neutrinos from the same source) observed so far
- Use the same method as for neutrino-UHECR correlation to determine the probability to observer neutrino multiplets
- Depends on local source density, source evolution and neutrino luminosity
- **Strongly constrains local density**, if source class powers diffuse neutrino flux



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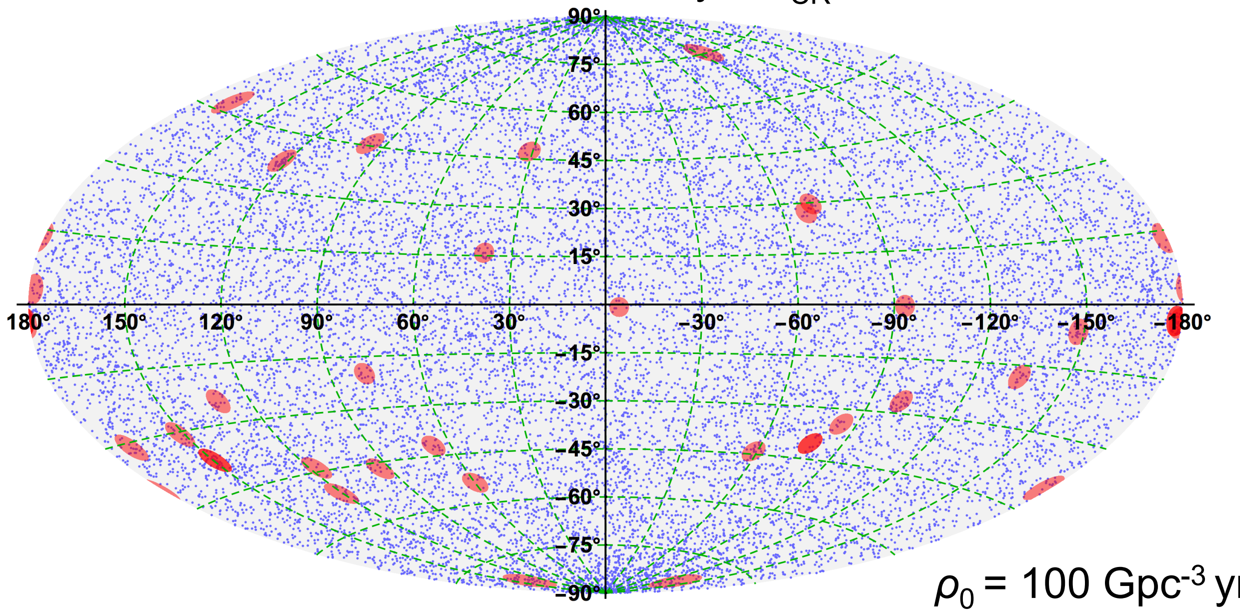
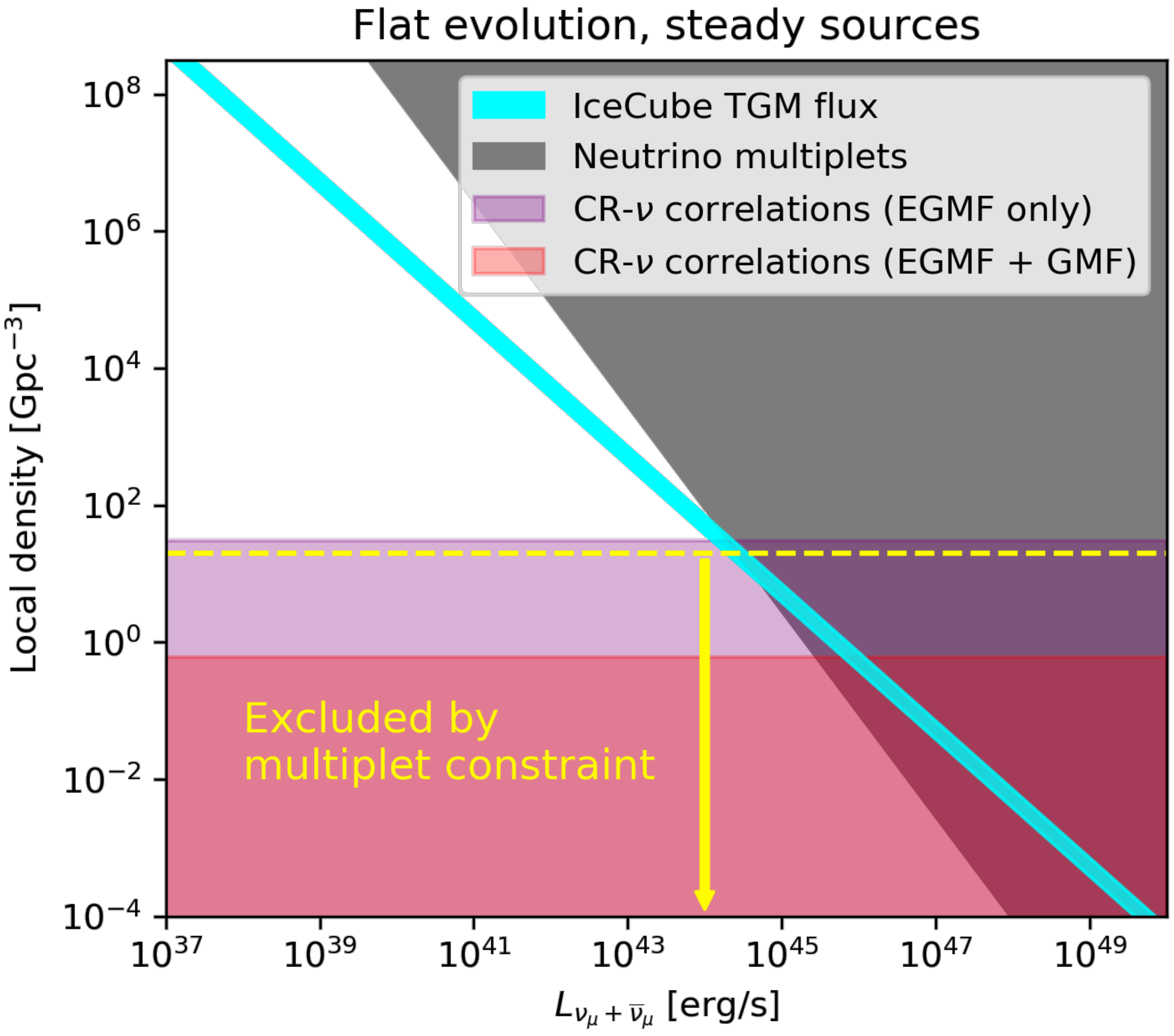


$\rho_0 = 100\ \mathrm{Gpc^{-3}\ yr^{-1}}$

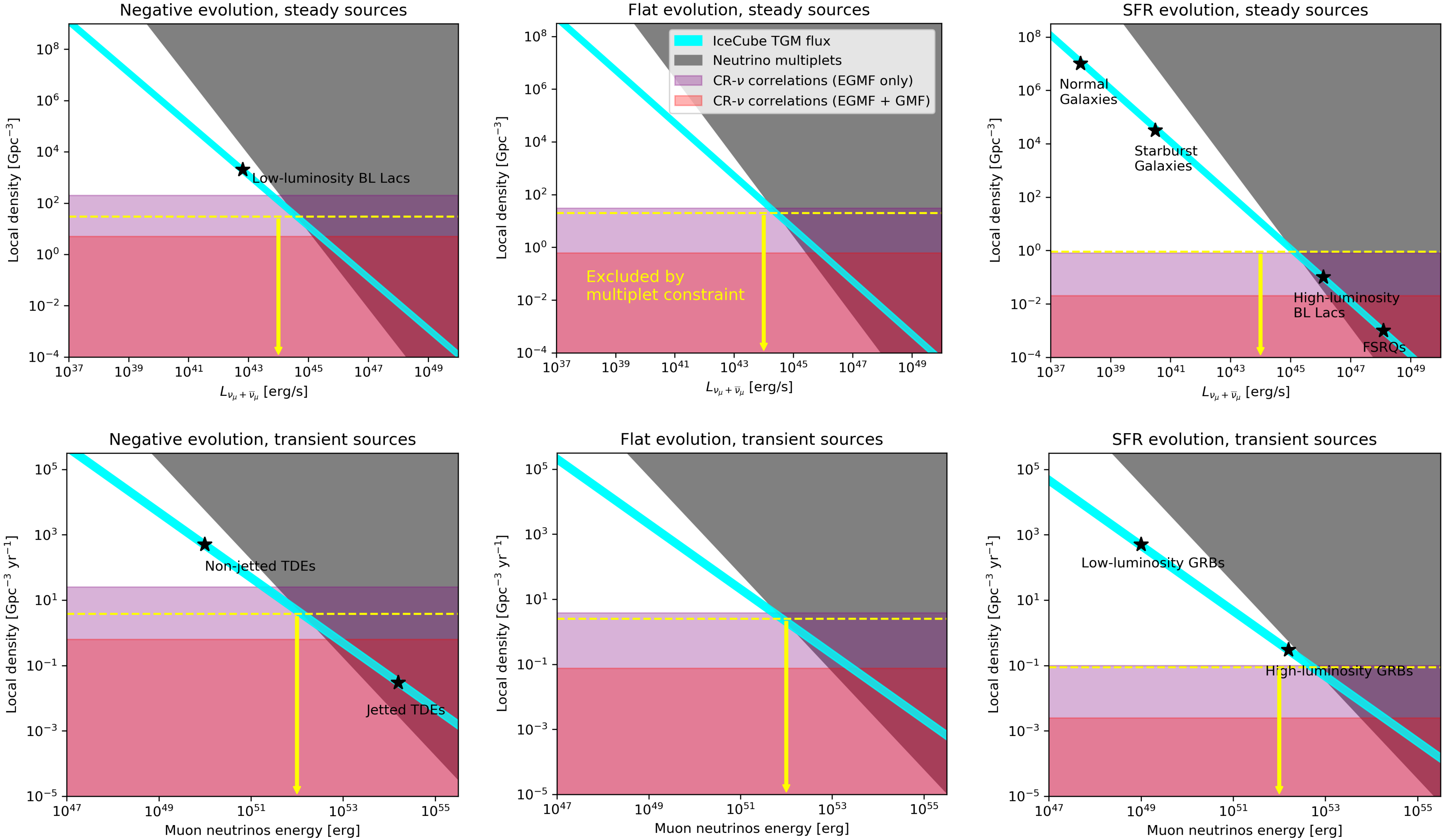
Results as a function of the source density

A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- 90% region for presence of at least one neutrino multiplet in IceCube through-going muon flux
- Agrees with IceCube '19 analyses
- Region for at least 50% chance of observing 5σ excess in neutrino-UHECR correlations
  - assuming the IceCube TGM flux is reproduced



Results as a function of the source density

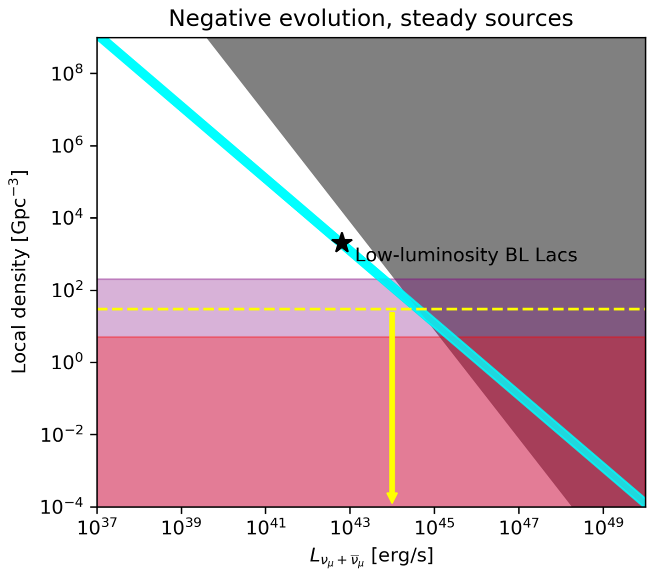


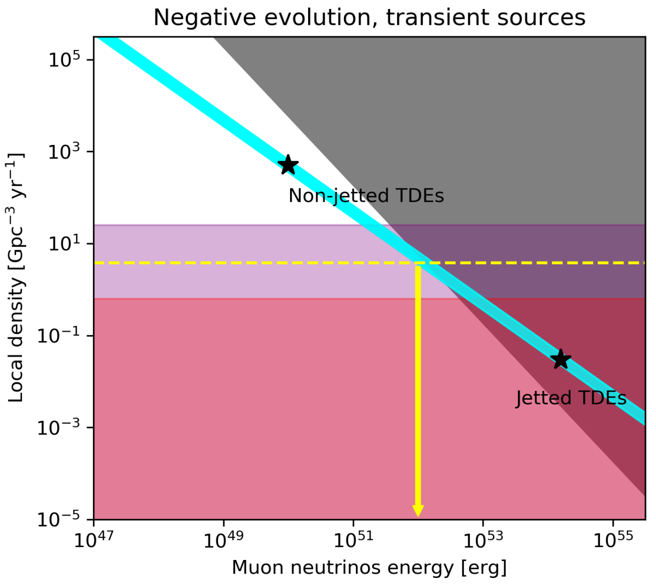
A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

Neutrino-UHECR correlations, conclusions

A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- Expected neutrino-UHECR correlations limited by non-observation of neutrino multiplets
- Best chance of finding neutrino-UHECR correlations for sources with negative source evolution
- In this case ρ_0<10 Gpc^{-3}
- If IceCube does not observe any neutrino multiplets in the next few years, it is very unlikely that a correlation between neutrinos and UHECRs will be found





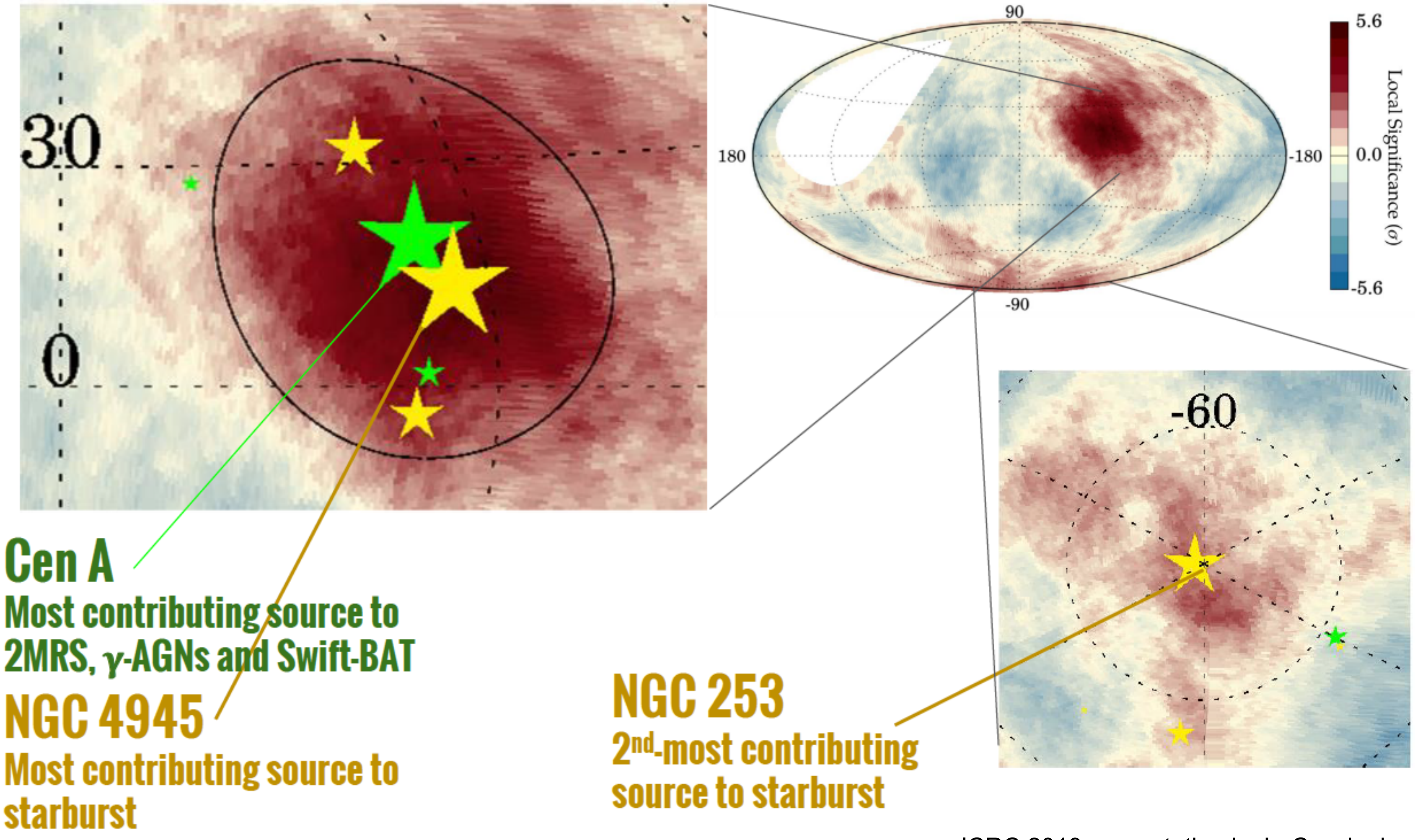
Correlations between UHECRs and source positions

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

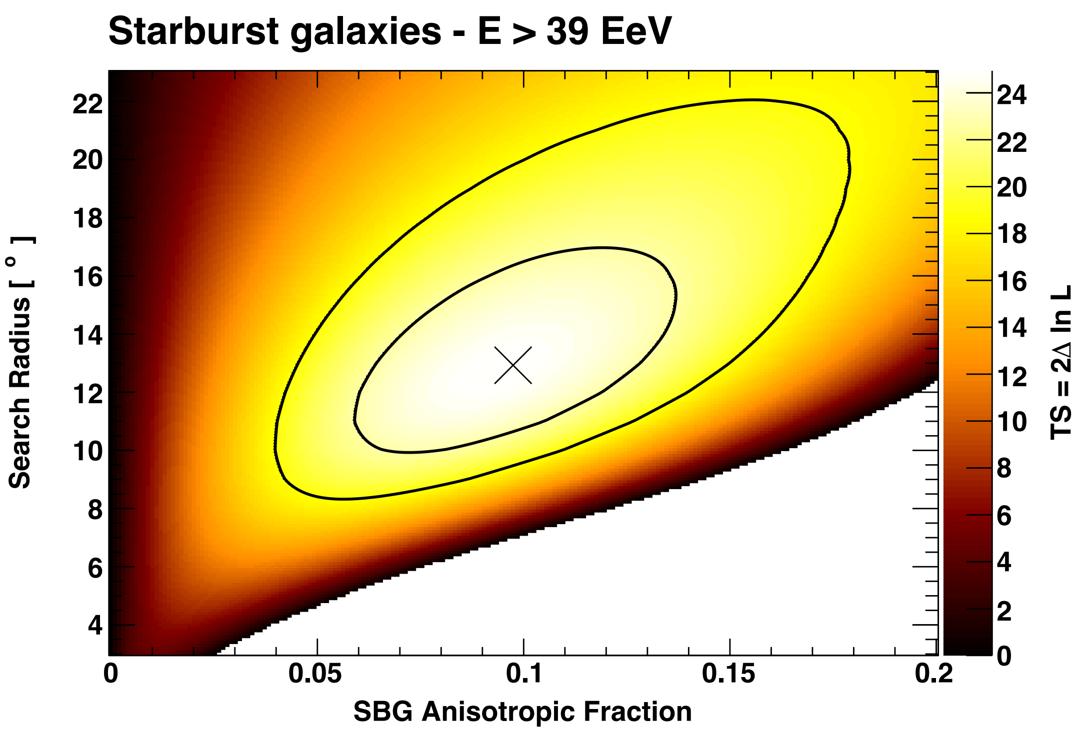


ICRC 2019 presentation by L. Caccianiga

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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Constraints on extragalactic magnetic fields and local source density

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

- 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

Our method

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

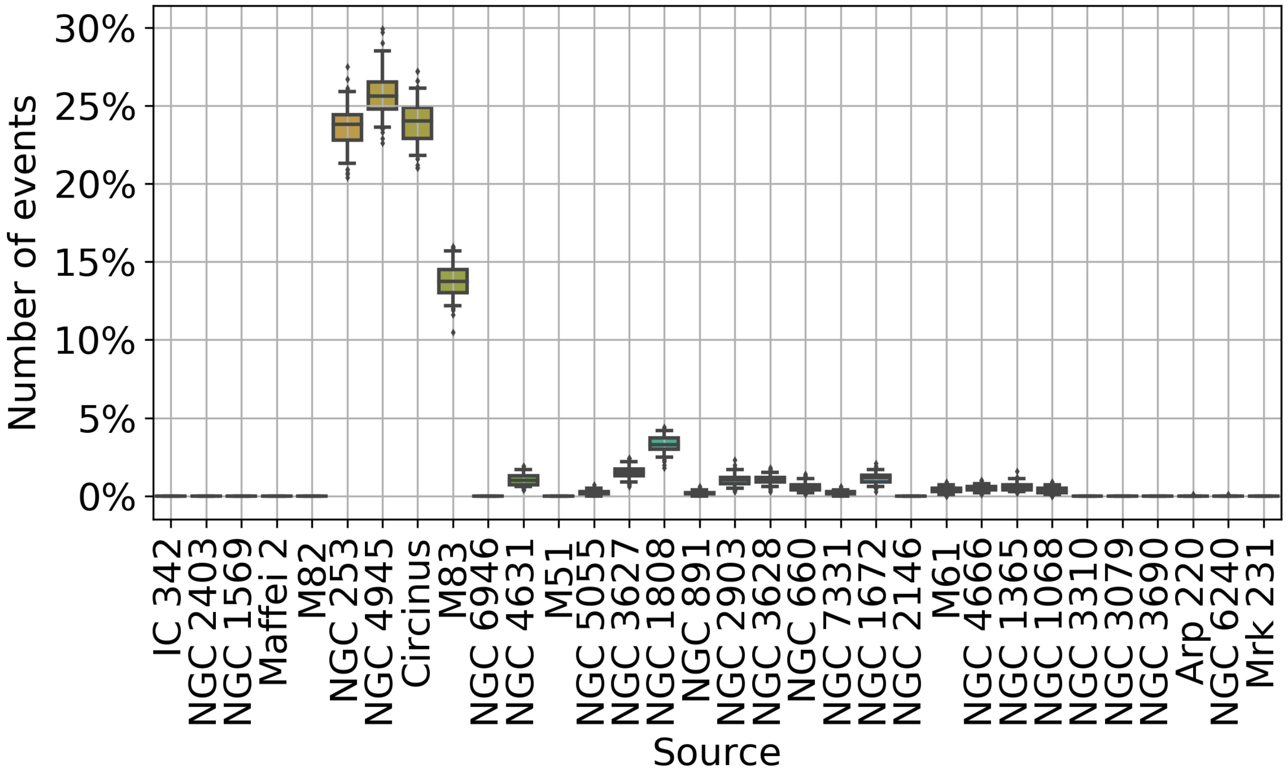
- Simulate UHECR sky maps for specific EGMF and GMF setups and local source densities ρ_0
- Check if these sky maps give θ and f_{aniso} values compatible with what Auger found

Our method

4 important sources

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

- 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



Our method

UHECR spectrum and composition

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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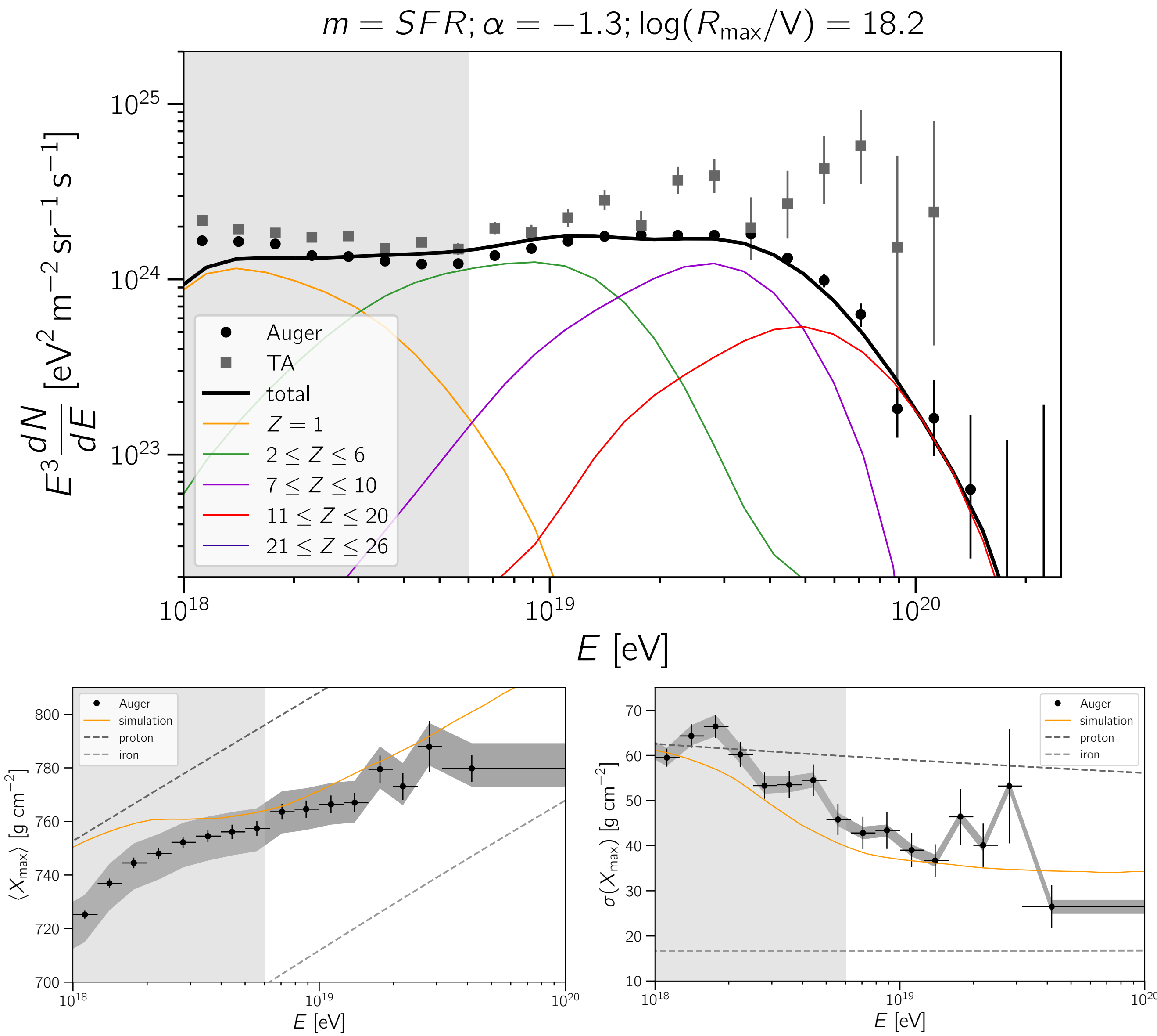

R. Alves Batista, R. M. de Almeida, B. Lago, K. Kotera, JCAP 01 (2019) 002

Our method

Deflections in magnetic fields

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
- Check if these sky maps give θ and f_{aniso} values compatible with what Auger found
- Focus on 4 most important sources
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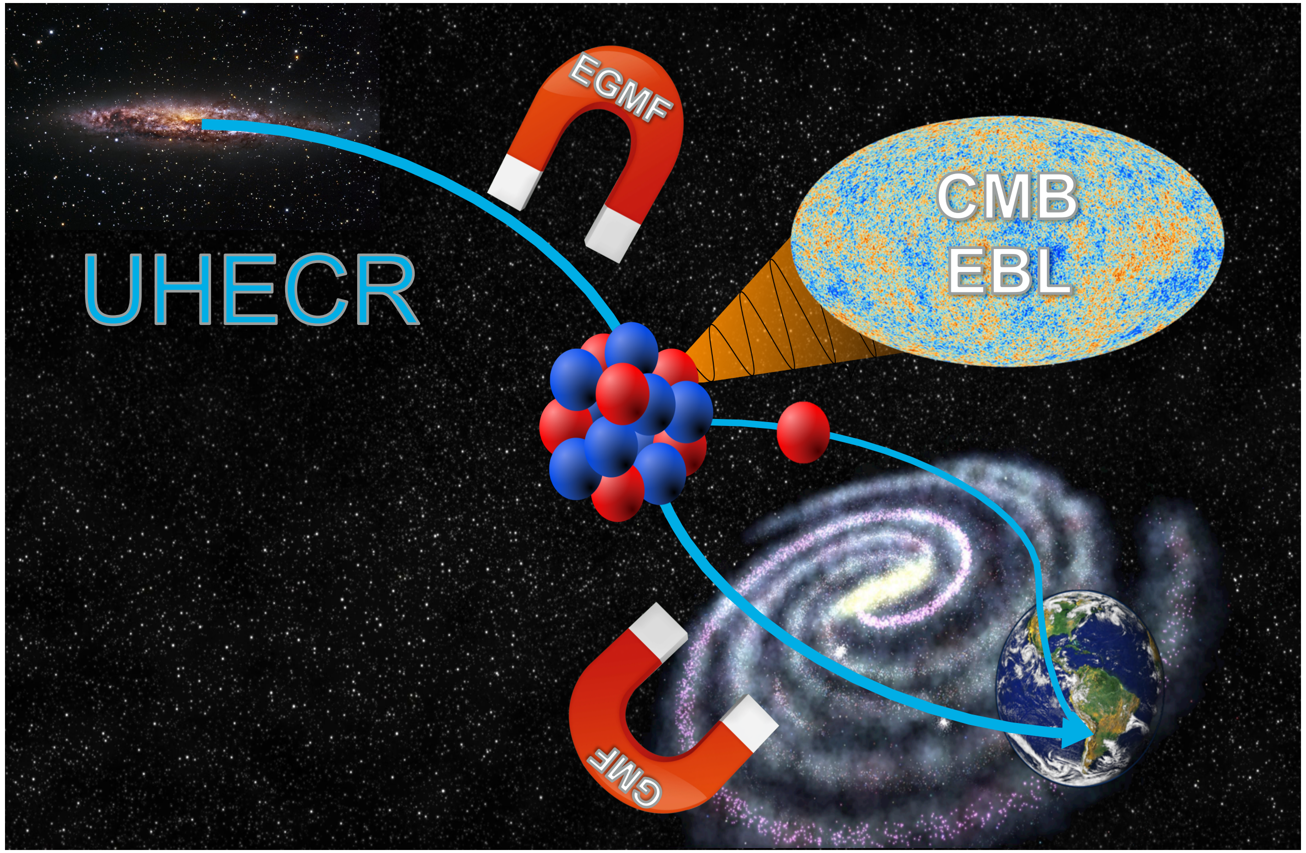

Our method

Source density

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

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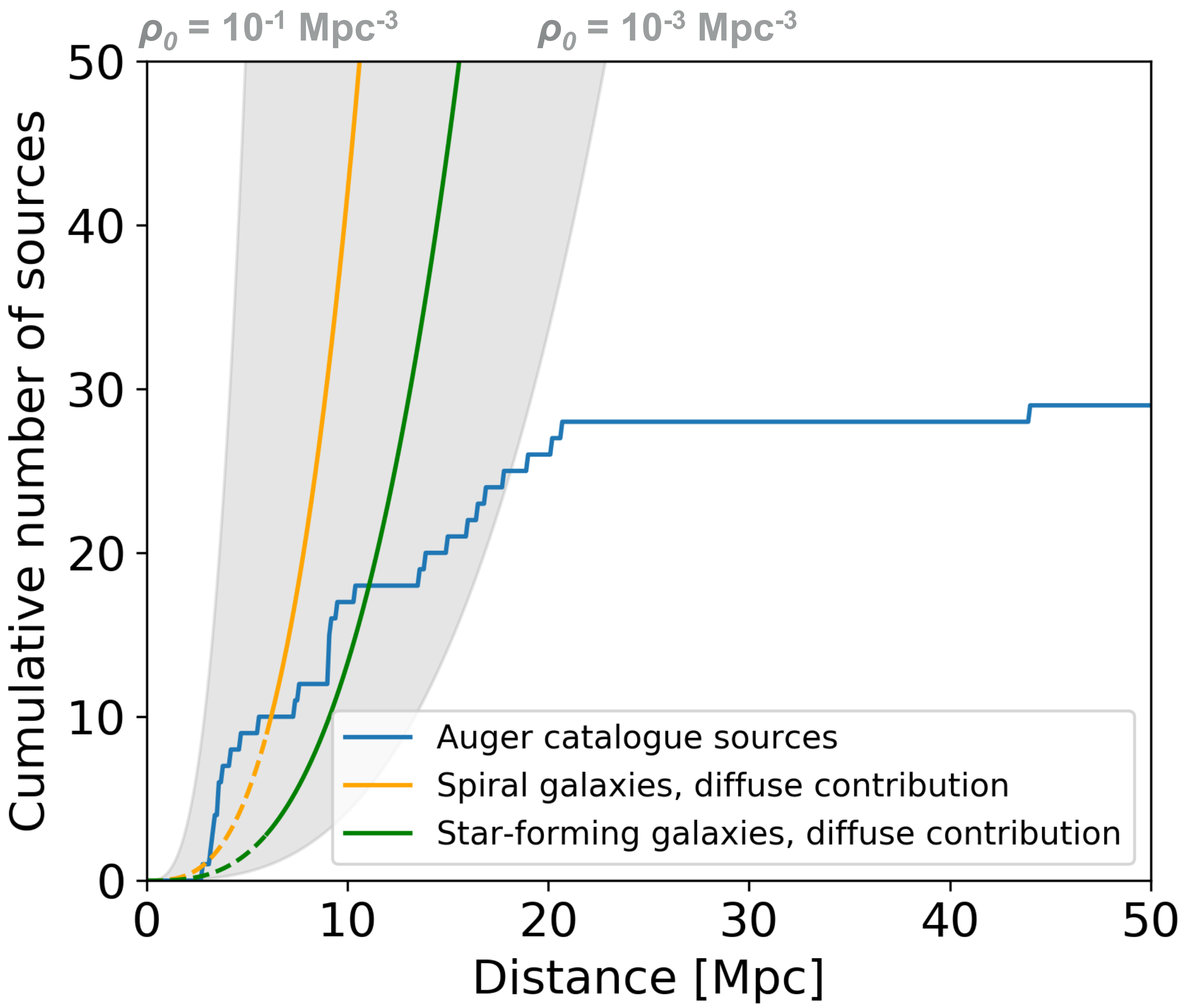
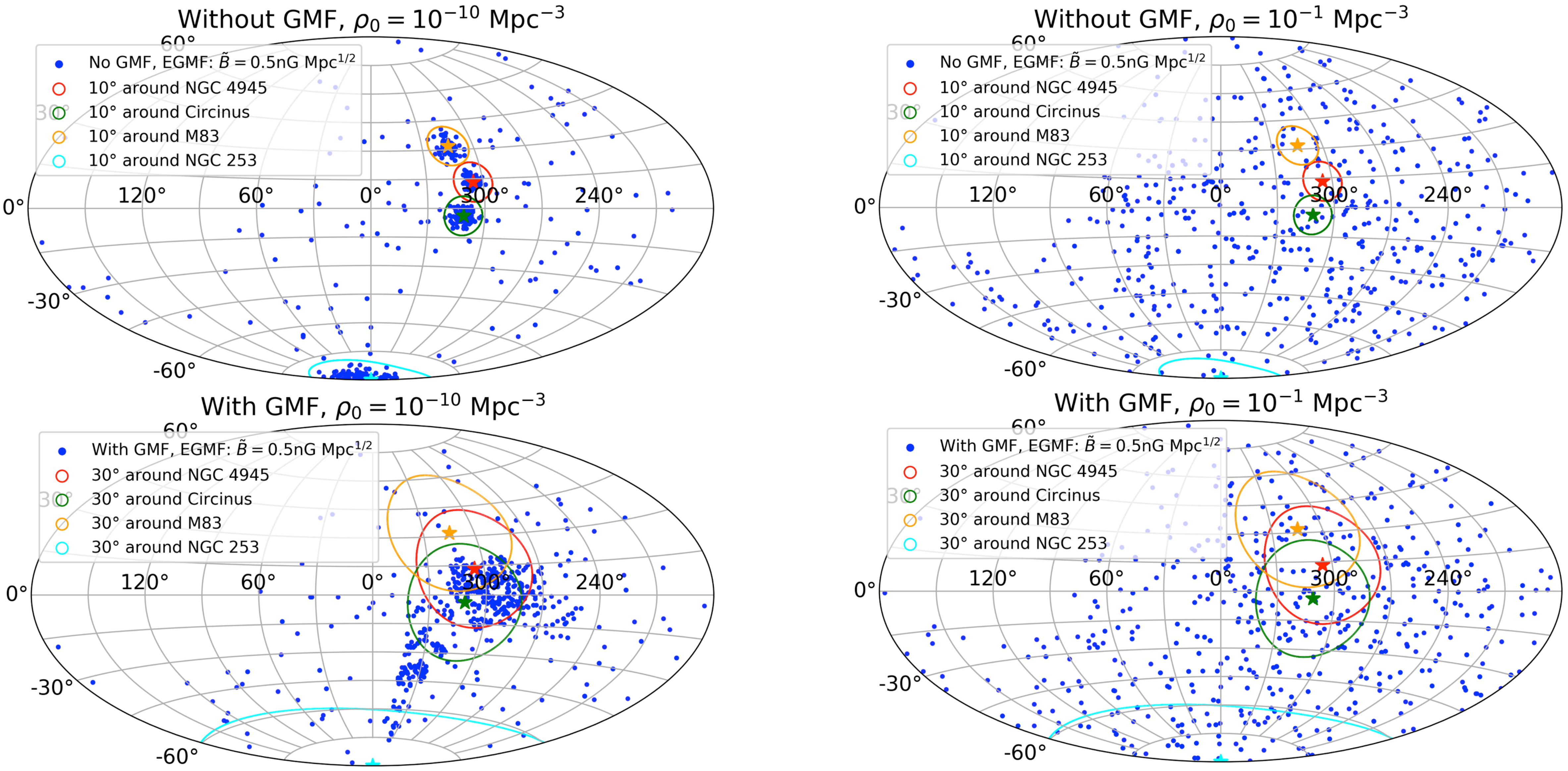


Example sky maps

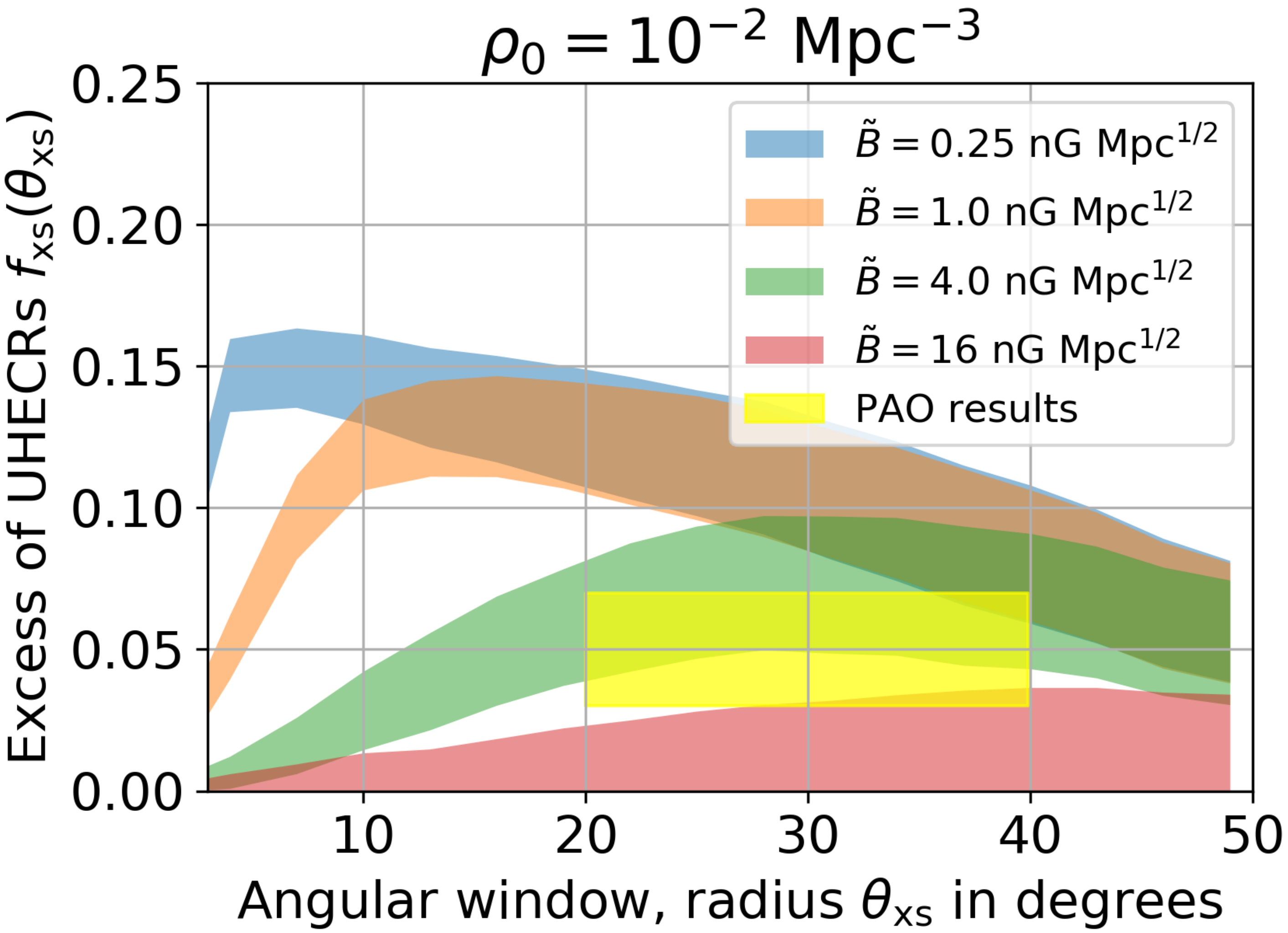
AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732



Compare with Auger results

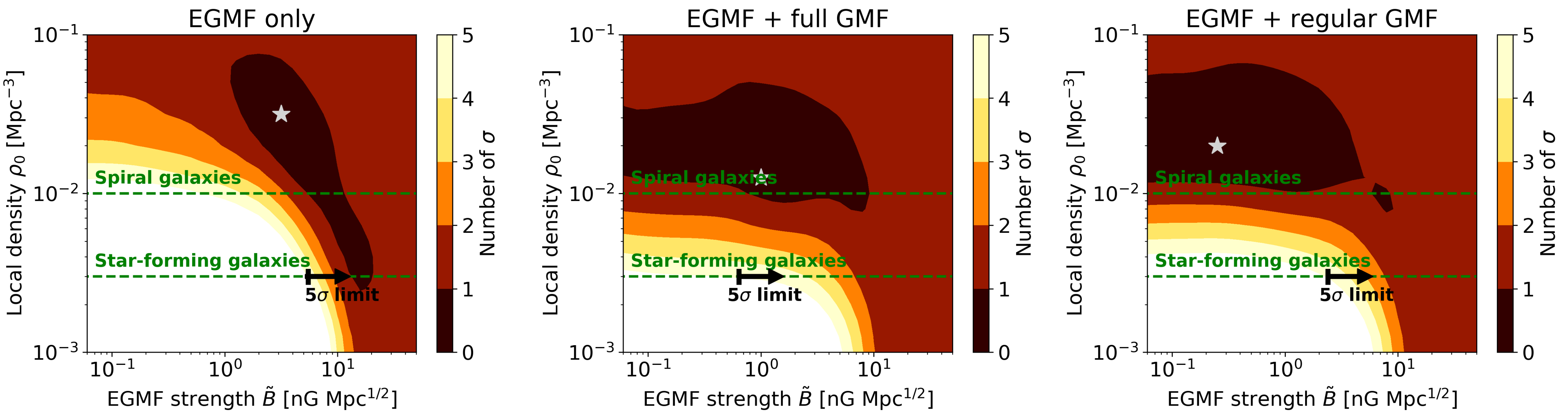
AvV, A. Palladino, A. Taylor and W. Winter, arXiv:2104.05732

- 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



Results from scanning over ρ_0 and B

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

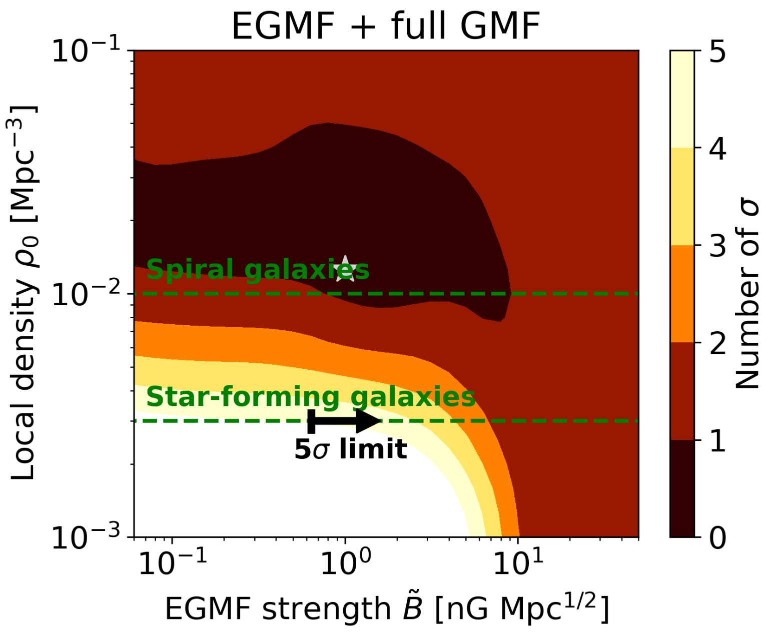


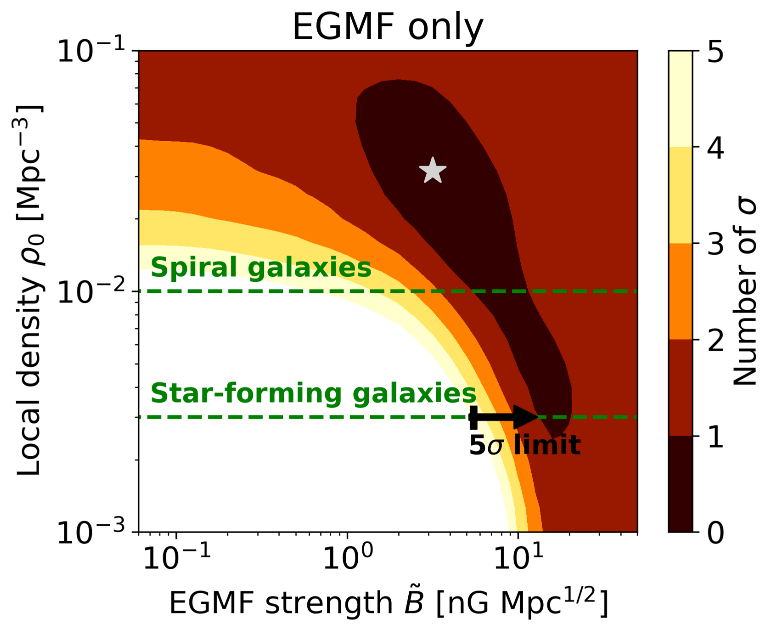
	EGMF only	EGMF + full GMF	EGMF + regular GMF
5σ lower limit on $\tilde{B}$ for $\rho_0 = 3 \cdot 10^{-3}$ Mpc^{-3}	$\tilde{B} > 5.5$ nG Mpc$^{1/2}$	$\tilde{B} > 0.64$ nG Mpc$^{1/2}$	$\tilde{B} > 2.4$ nG Mpc$^{1/2}$
Best-fit point	$\tilde{B} = 3.2$ nG Mpc$^{1/2}$; $\rho_0 = 3.2 \cdot 10^{-2}$ Mpc^{-3}	$\tilde{B} = 1.0$ 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}

Conclusions

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

- 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$^{1/2}$; $\rho_0 < 0.09$ Mpc^{-3}**
  - Best-fit point for a source density close to, or even denser than, that of spiral galaxies
- Possible additional science case for UHECR detectors: improve our understanding of the GMF and local EGMF



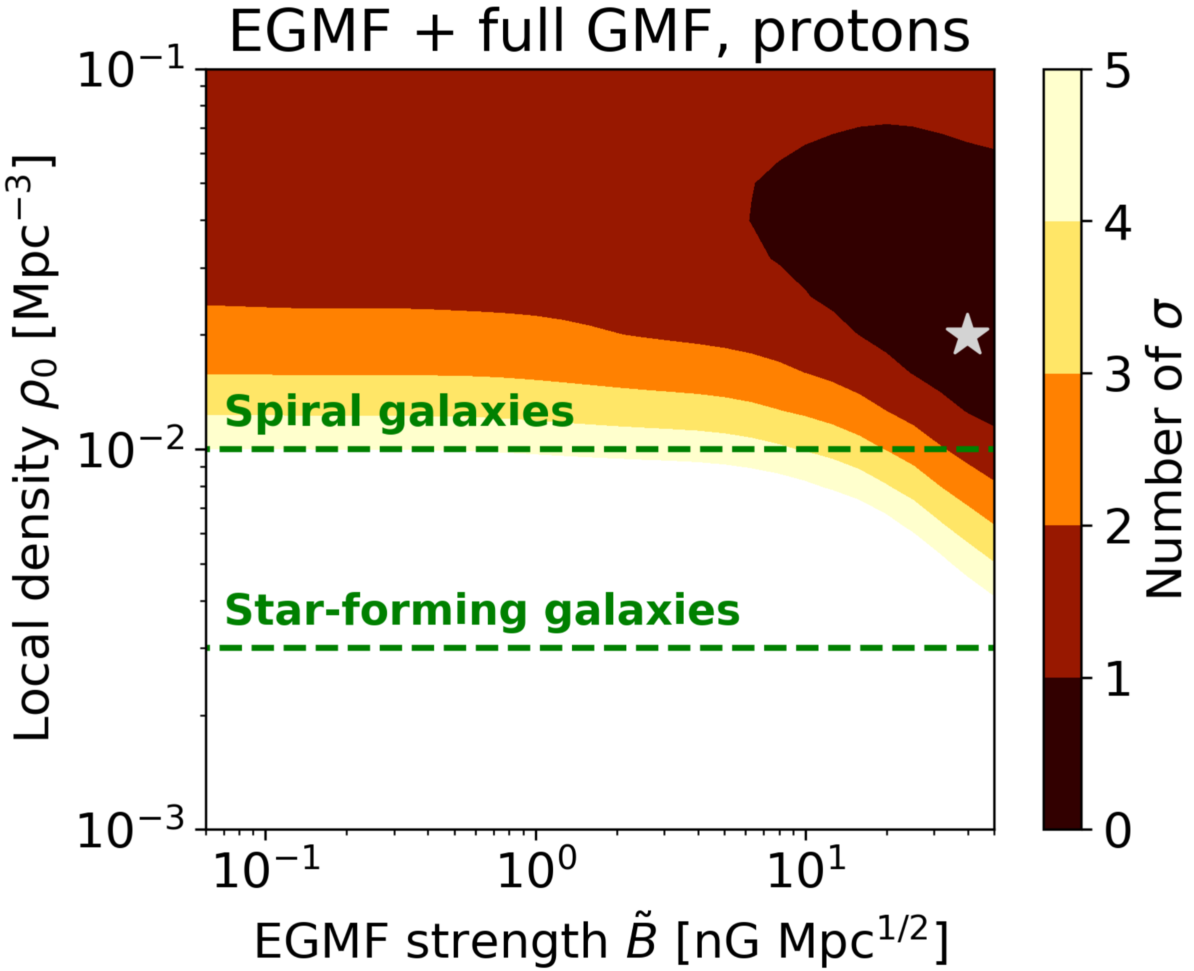


Backup slides

Pure-proton scenario

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

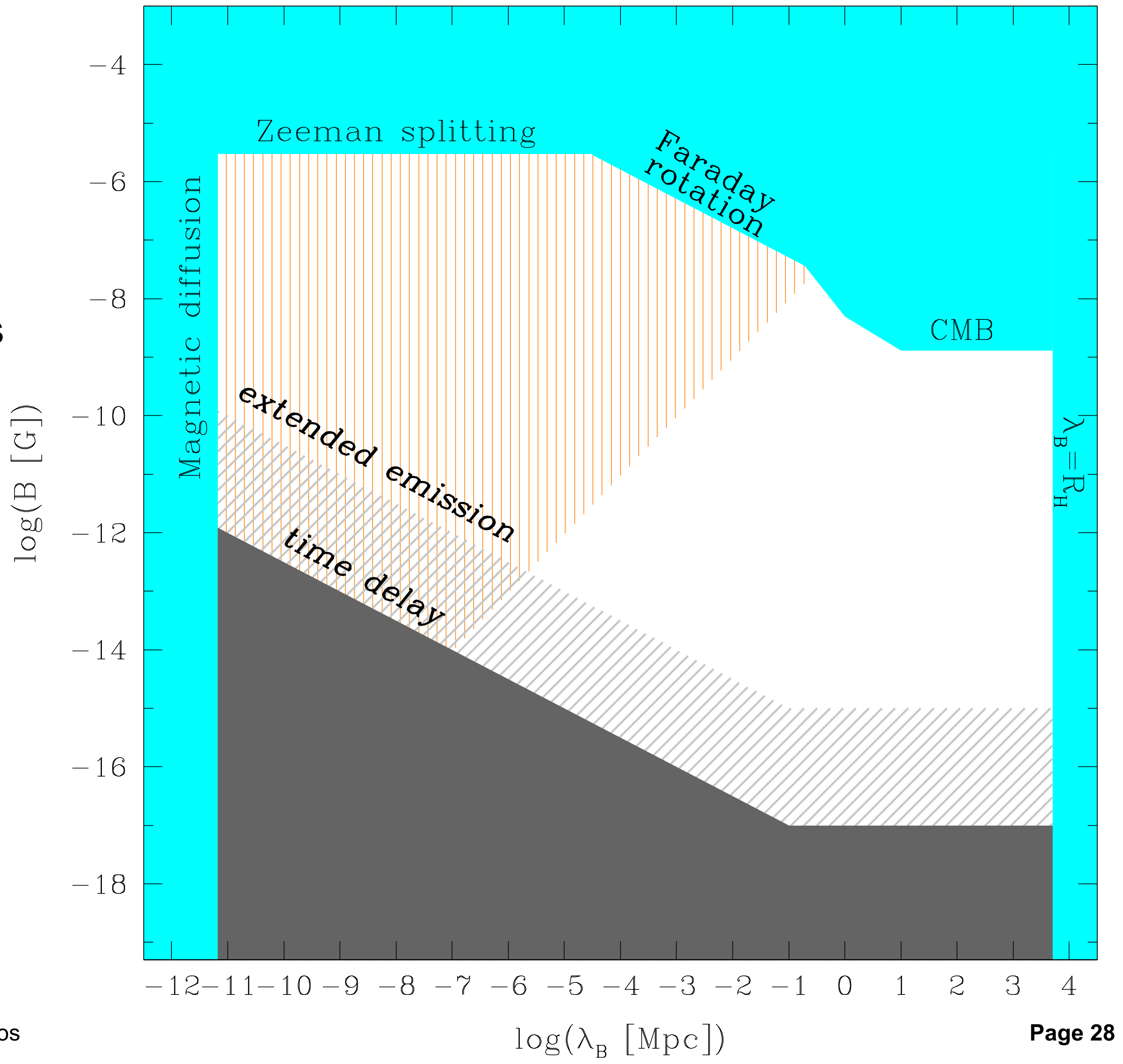
- Extreme scenario with minimized deflections
- Requires very large local density ρ_0
- Not possible to reproduce Auger results for a local density of star-forming galaxies, for the values of B we considered



EGMF limits

- 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

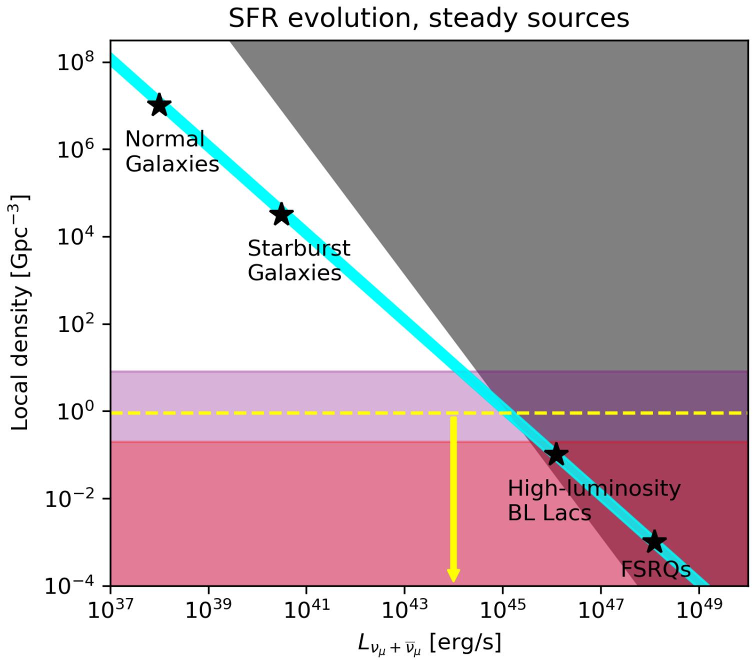
A. Taylor, I. Vovk, A. Neronov, A&A 529 (2011) A144

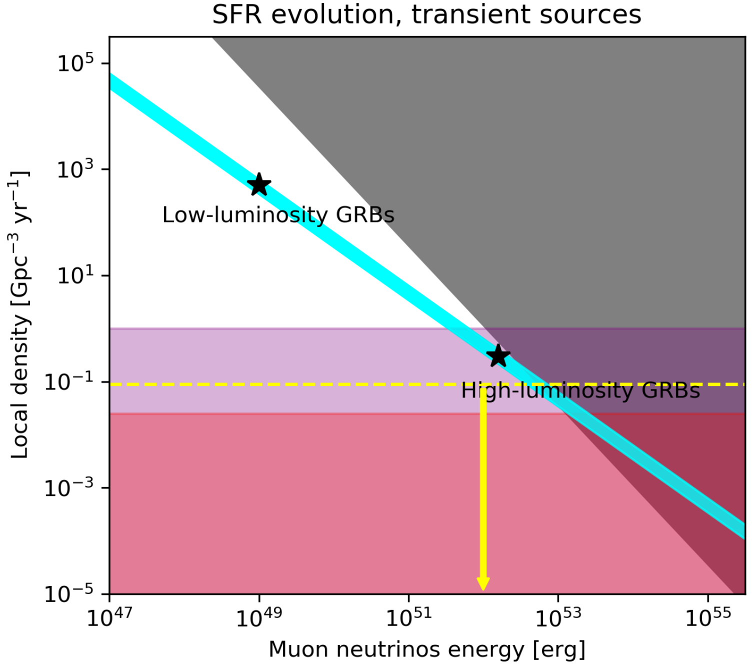


Pure-proton scenario

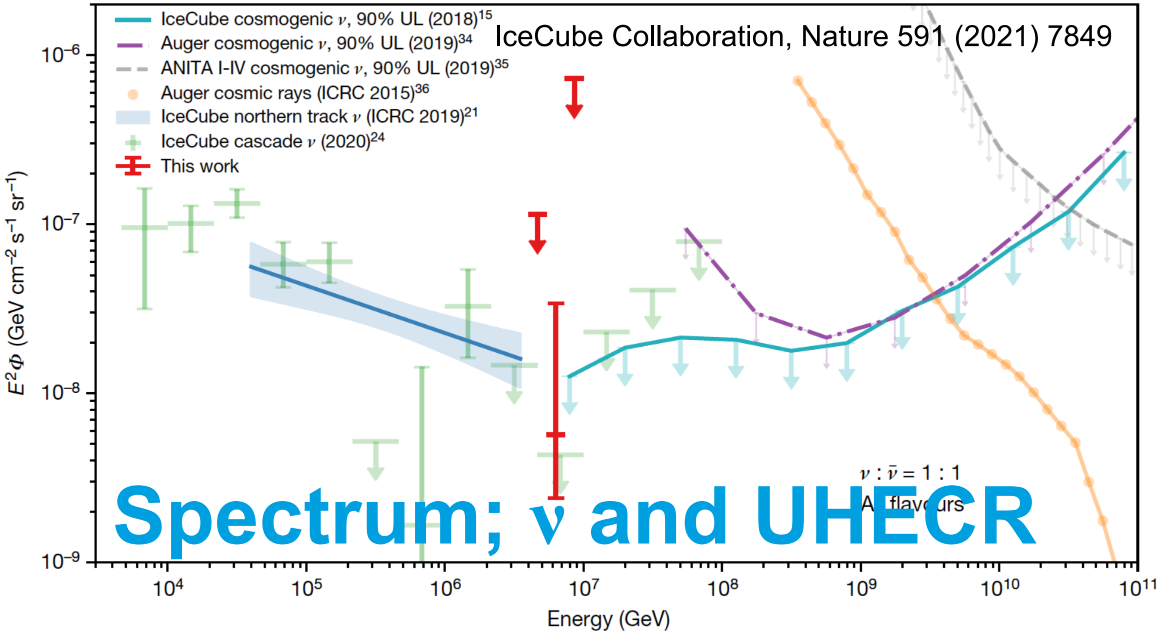
A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- Excluded by UHECR composition measurements, but instructive as most optimistic case for UHECR-neutrino correlations
- Even in this case, when the GMF is included, no UHECR-neutrino correlations are expected

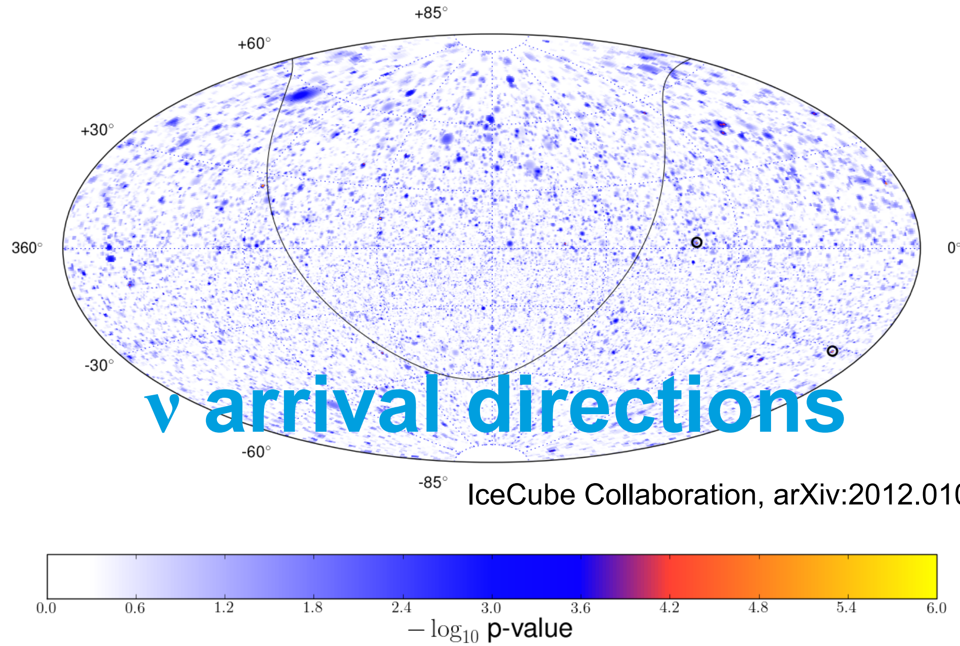




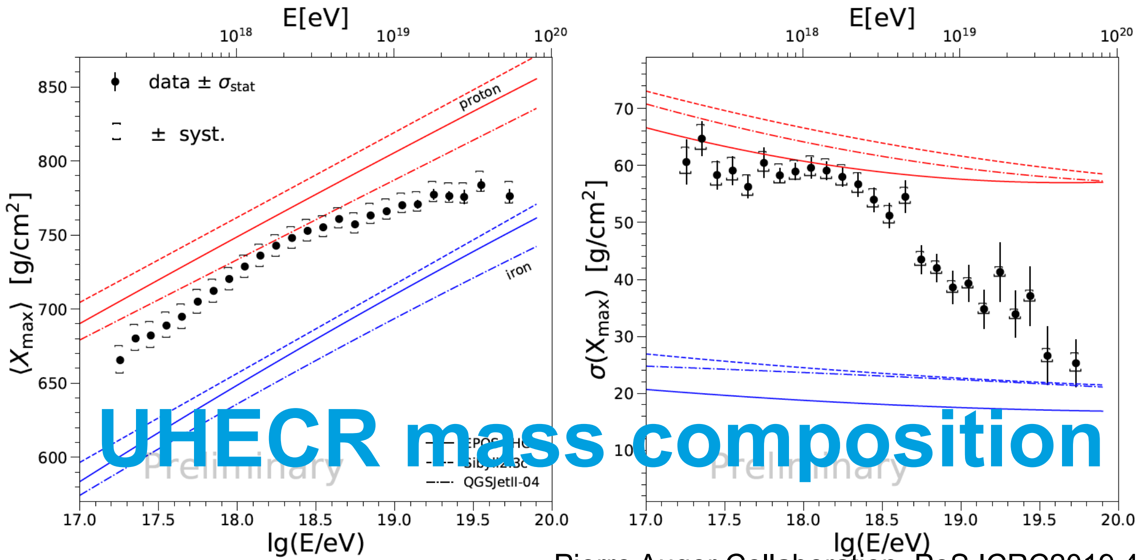
UHECRs and astrophysical neutrinos



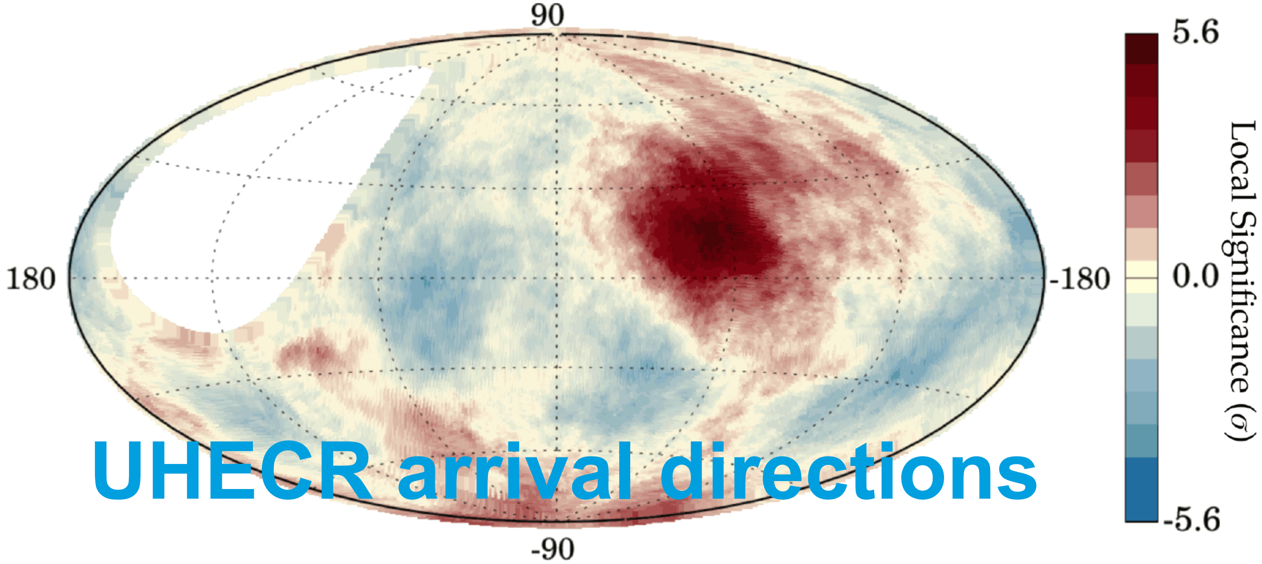
IceCube Collaboration, Nature 591 (2021) 7849



IceCube Collaboration, arXiv:2012.01079



Pierre Auger Collaboration, PoS ICRC2019 482



Pierre Auger Collaboration, PoS ICRC2019 206

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