Ultra-high-energy cosmic rays and neutrinos, expectations for diffuse fluxes and arrival directions

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University of L'Aquila, 18/06/2021

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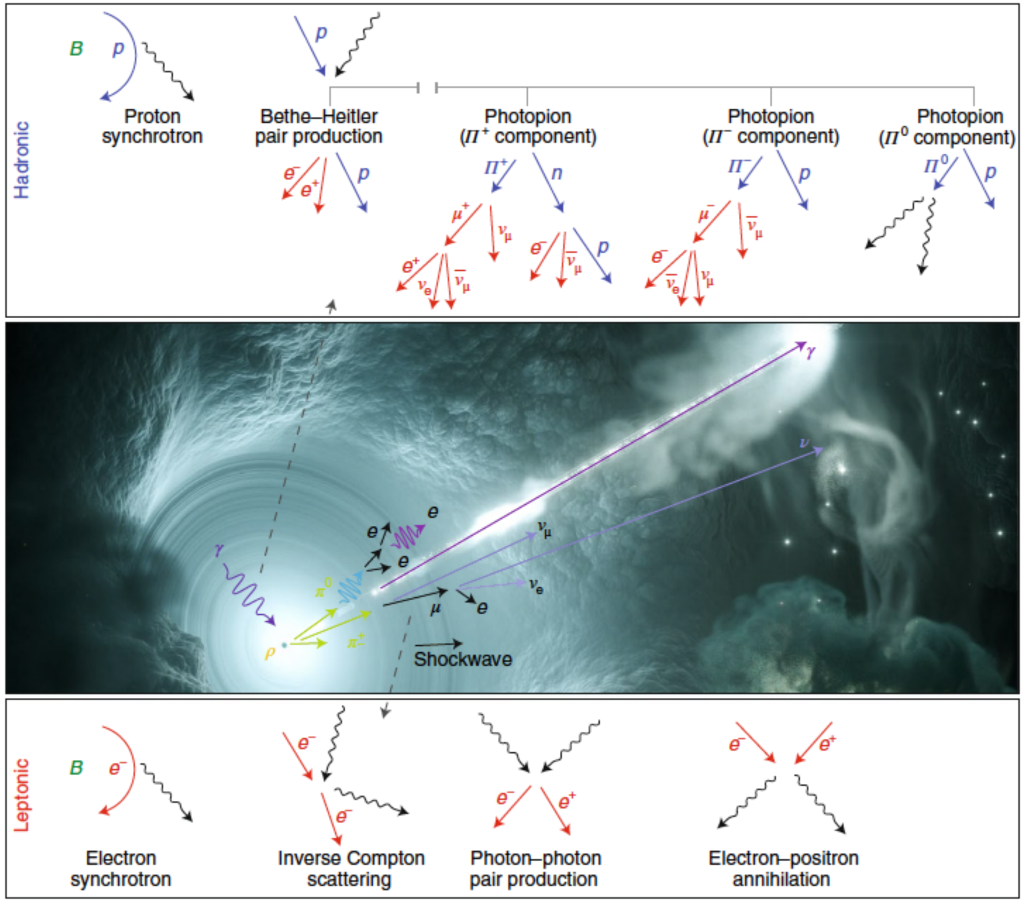
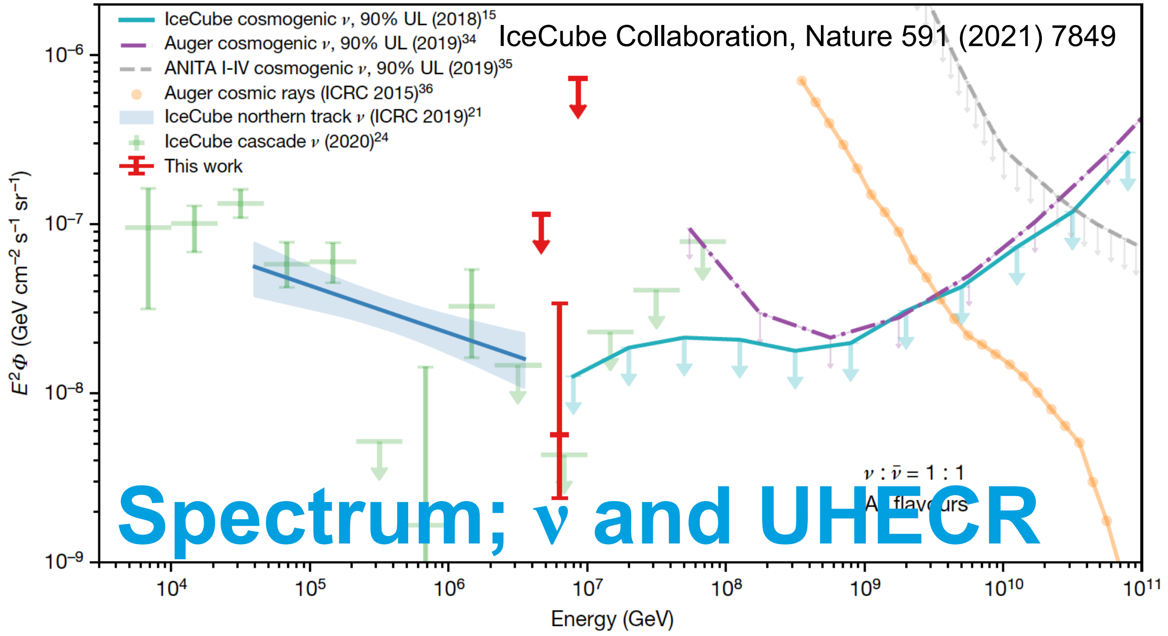
UHECRs and astrophysical neutrinos

- Ultra-high-energy cosmic rays (UHECRs):
  - Nuclei from protons to iron with $E > 10^{18}$ eV (= 10^9 GeV = 1 EeV)
- Main experiments:
  - Pierre Auger Observatory in Argentina
  - Telescope Array in the US
- No identified sources yet
- High-energy astrophysical neutrinos ($E > 10^{14}$ eV), produced by:
  - Cosmic-ray interactions in the sources (source neutrinos)
  - Cosmic-ray interactions when traveling through the Universe (cosmogenic neutrinos)
- Main experiment: IceCube at the South Pole

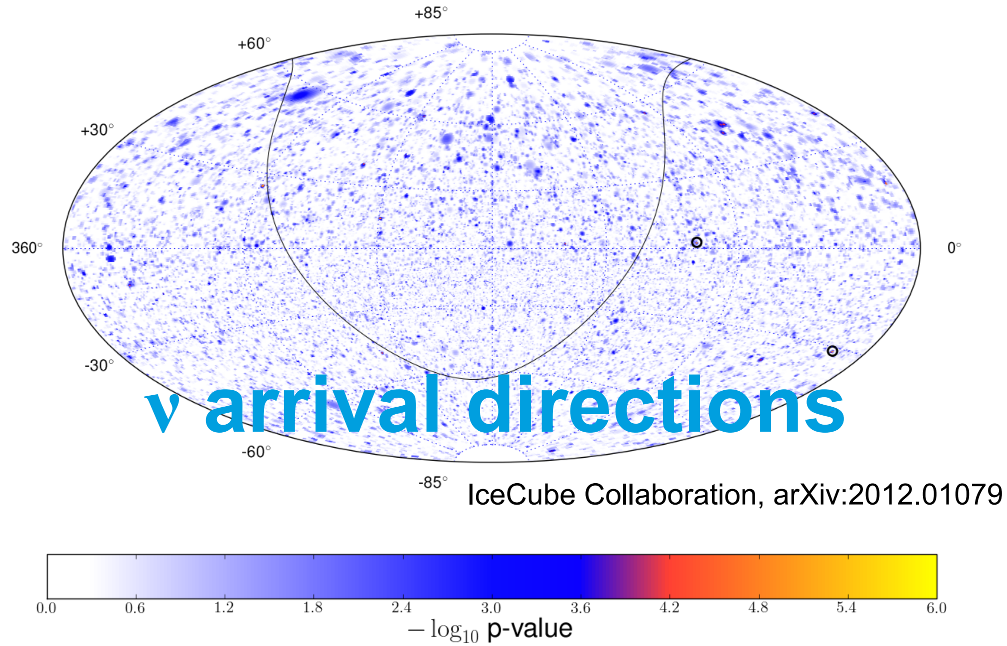


- Possible first identified sources:
  - Active Galactic Nucleus (AGN) TXS 0506+056 (IceCube, Science 361 (2018) 147)
  - Tidal Disruption Event (TDE) AT2019dsg (R. Stein et al., Nature Astron. 5 (2021) 510)

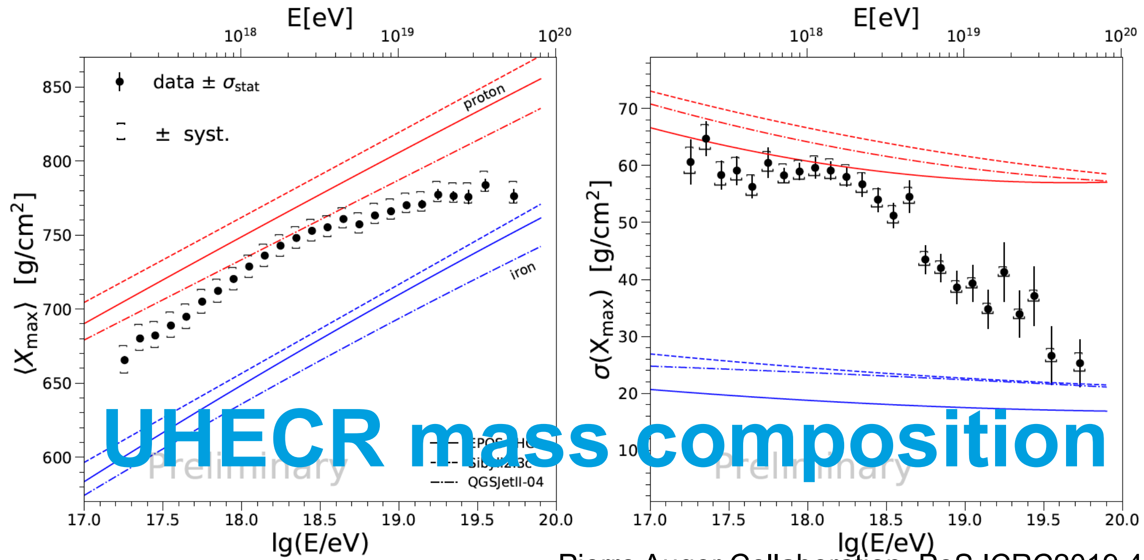
Measurements of UHECRs and astrophysical neutrinos



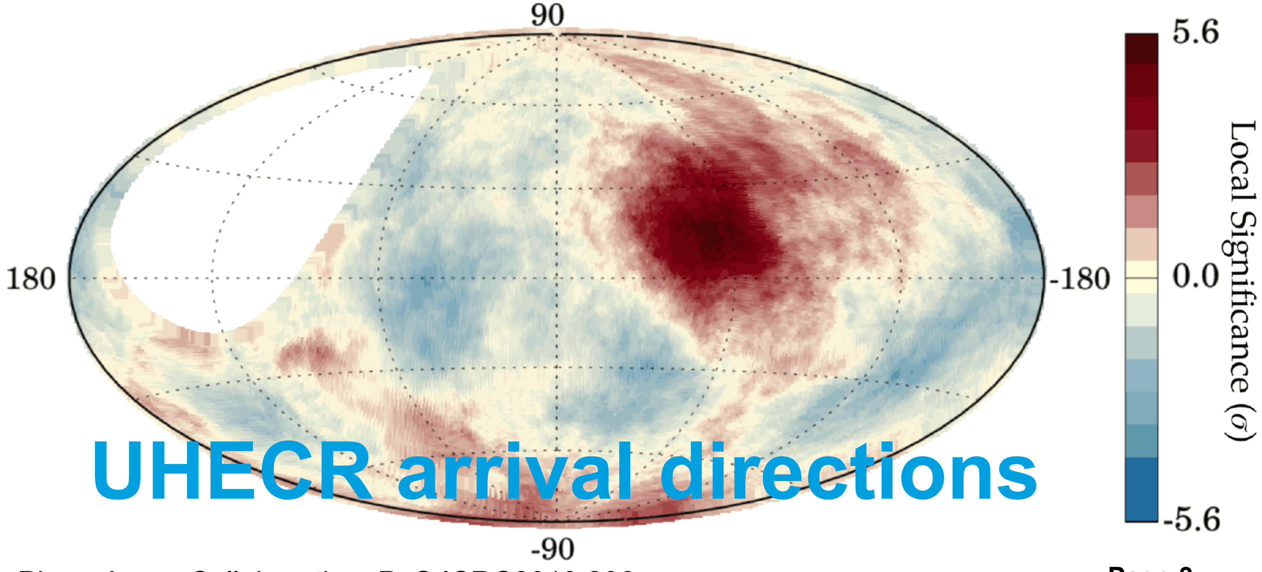
IceCube Collaboration, Nature 591 (2021) 7849



IceCube Collaboration, arXiv:2012.01079



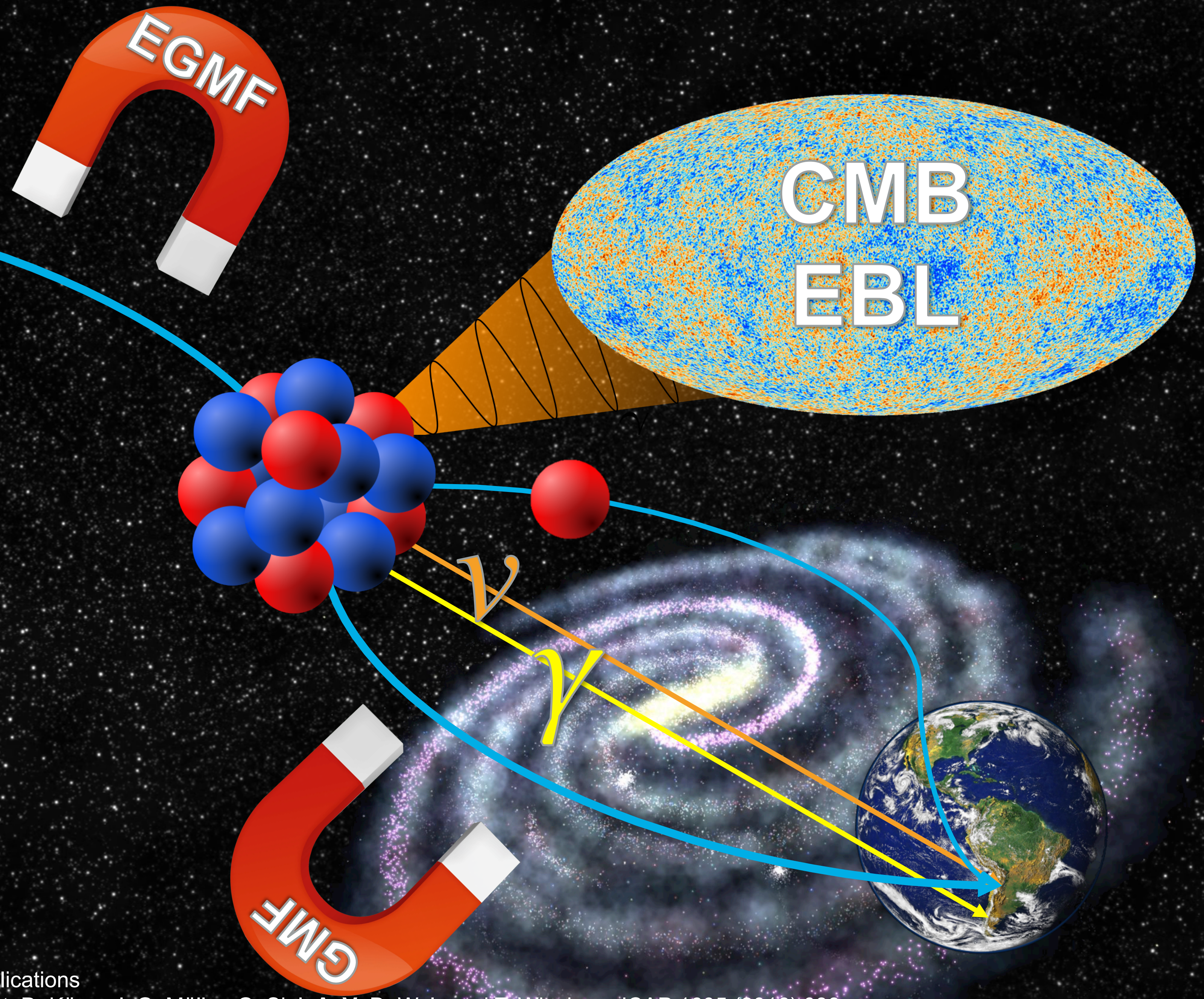
Pierre Auger Collaboration, PoS ICRC2019 482



Pierre Auger Collaboration, PoS ICRC2019 206

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; CRPropa 2+3 used in over 300 publications

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

Combined fit of UHECR spectrum and composition

- Continuous distribution of identical sources
- Spectrum at the sources:

  Power law with rigidity-dependent cut-off

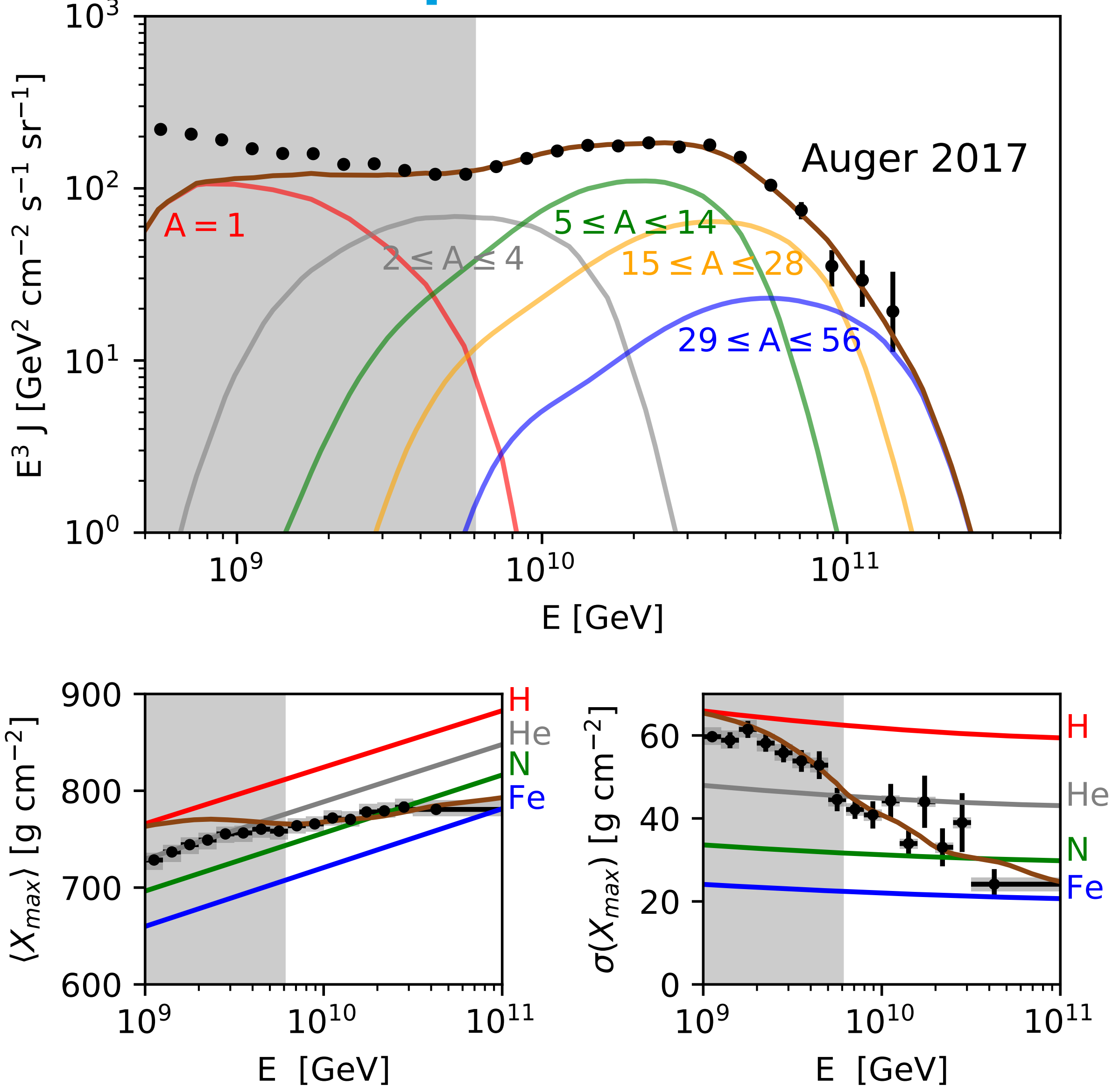
  $$\frac{dN}{dE} \propto E^{-\alpha} \exp(-E / ZR_{max})$$

- α < 1.3, hard injection spectrum
- $R_{max} = E^{i}_{max}/Z$ < 7 EV, low max. rigidity
- Composition at the sources:

  Intermediate to heavy ($Z > 5$)

- **No protons at highest *E***

  See also: Taylor *et al.* (2015), Auger (2017), Romero-Wolf and Ave (2018), Alves-Batista *et al.* (2019), etc.



J. Heinze, A. Fedynitch, D. Boncioli and W. Winter, Astrophys. J. 873 (2019) 88

Cosmogenic neutrino spectra

- Continuous distribution of identical sources
- Spectrum at the sources:

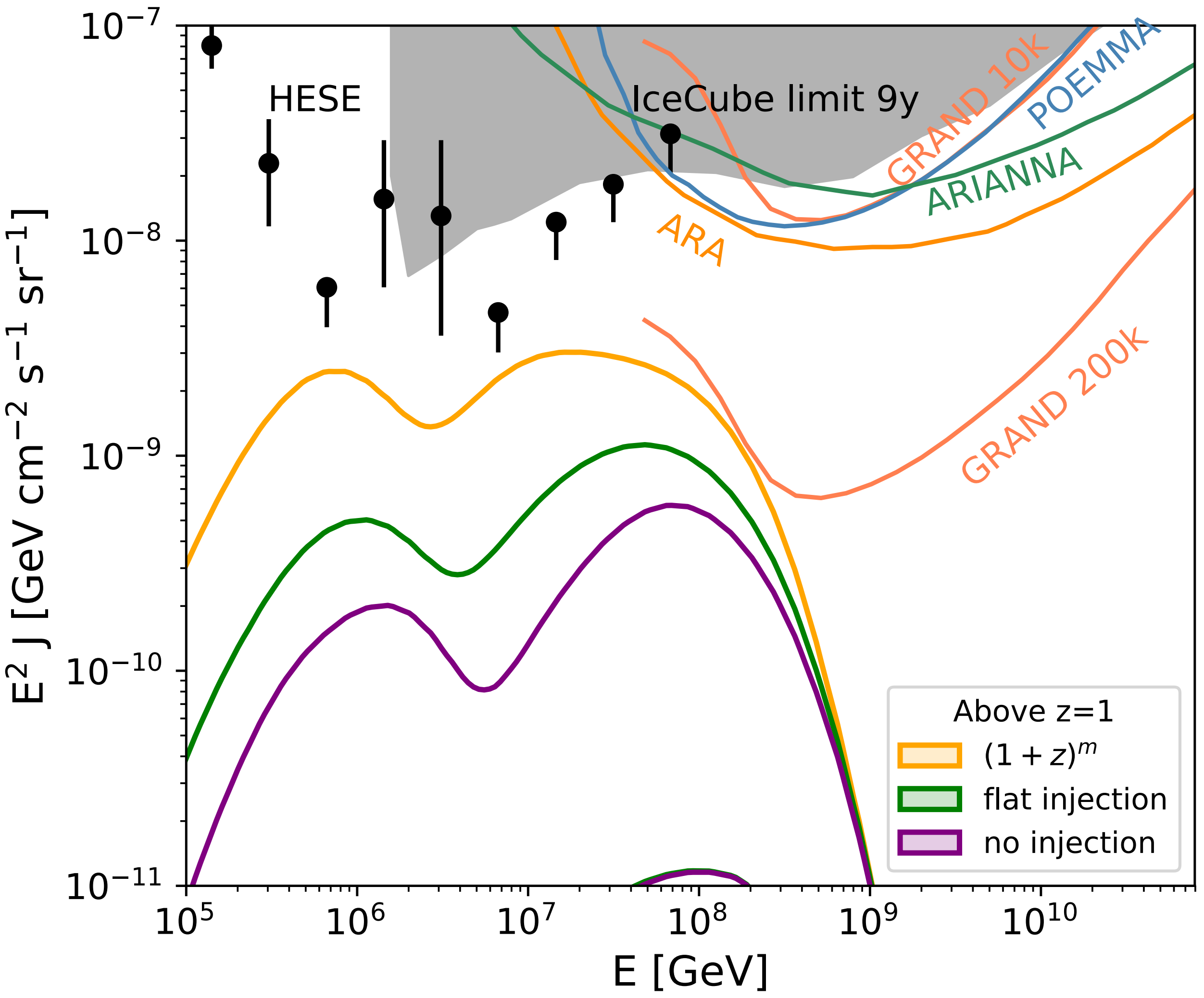
  Power law with rigidity-dependent cut-off

  $$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\alpha} \exp(-E / ZR_{\mathrm{max}})$$

- α < 1.3, hard injection spectrum
- $R_{max} = E^{i}_{max}/Z$ < 7 EV, low max. rigidity
- Composition at the sources:

  Intermediate to heavy ($Z > 5$)

- **No protons at highest *E***
- **Very low cosmogenic neutrino flux**



J. Heinze, A. Fedynitch, D. Boncioli and W. Winter, Astrophys. J. 873 (2019) 88

Additional proton component?

- Continuous distribution of identical sources
- Spectrum at the sources:

  Power law with rigidity-dependent cut-off

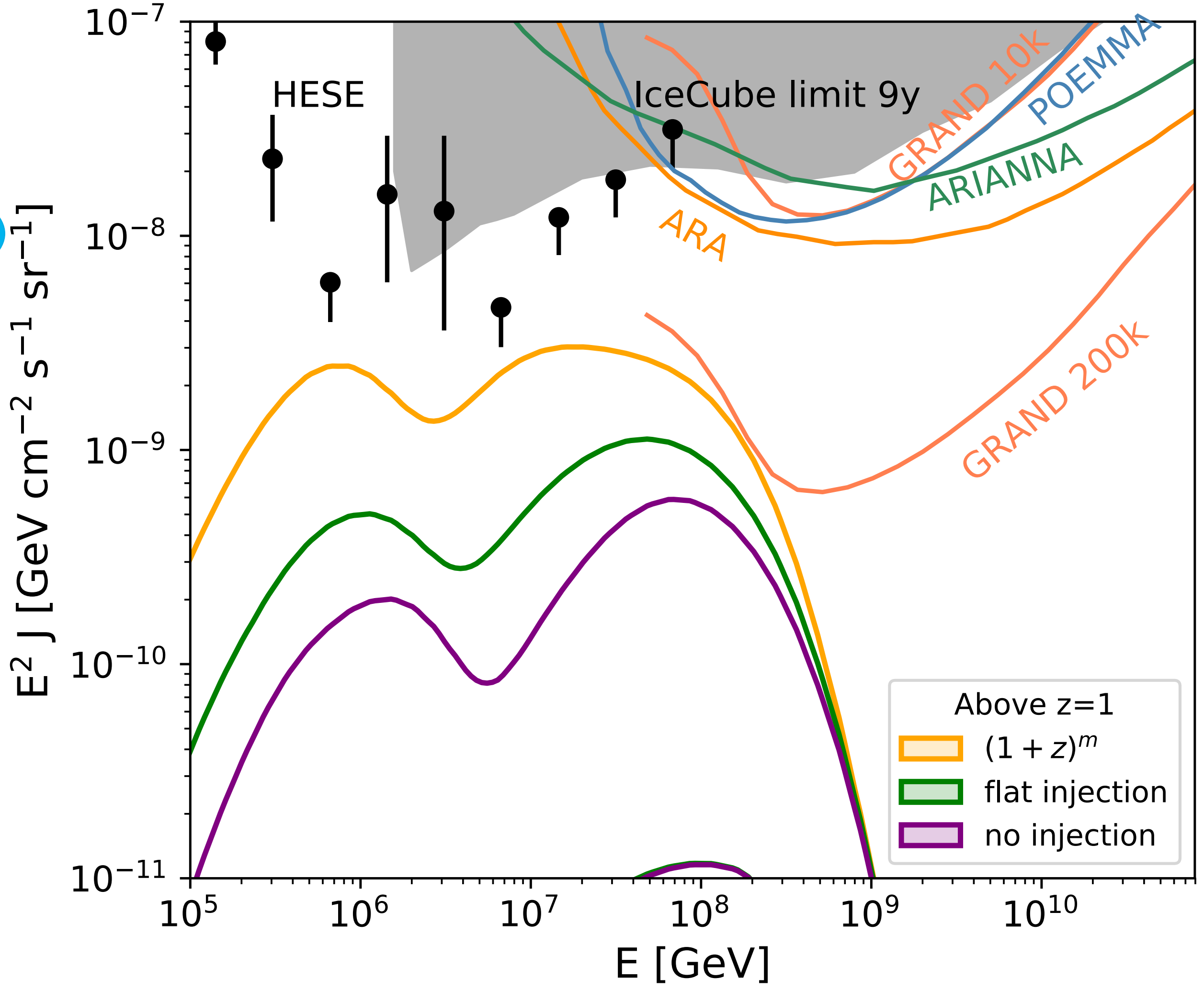
  $$\frac{dN}{dE} \propto E^{-\alpha} \exp(-E / Z R_{max})$$

- $\alpha < 1.3$, hard injection spectrum
- $R_{max} = E^{i}_{max}/Z < 7$ EV, low max. rigidity
- Composition at the sources:

  Intermediate to heavy ($Z > 5$)

- **No protons at highest *E***
- **Very low cosmogenic neutrino flux**
- **Additional proton component can improve fit**

  Muzio *et al*. (2019), Das *et al*. (2021)

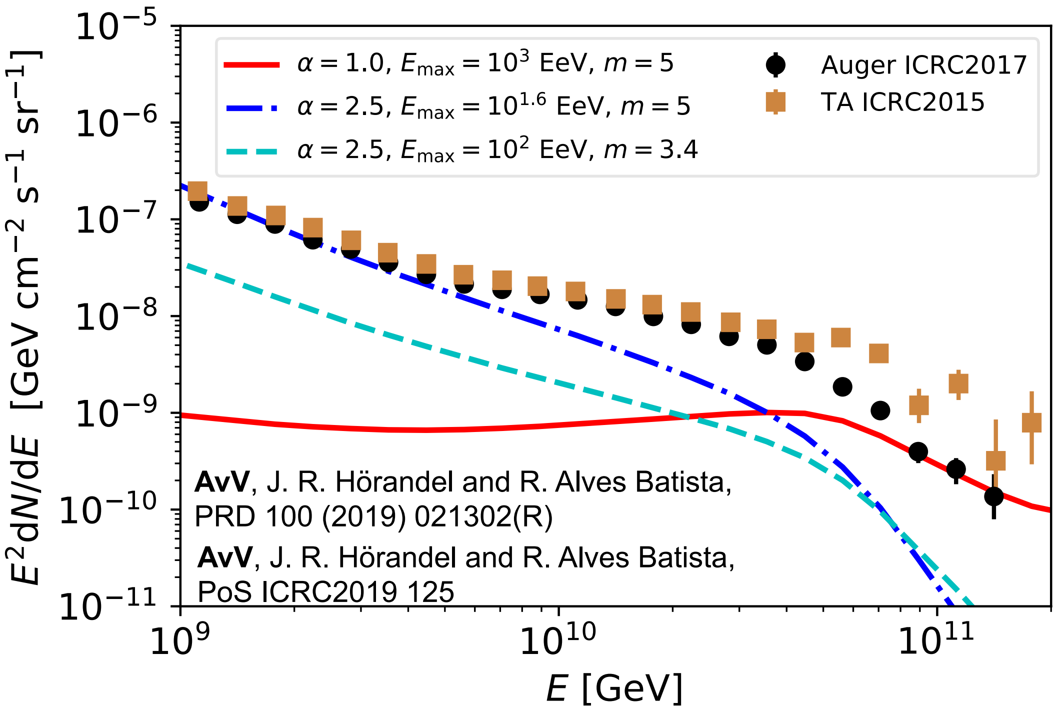


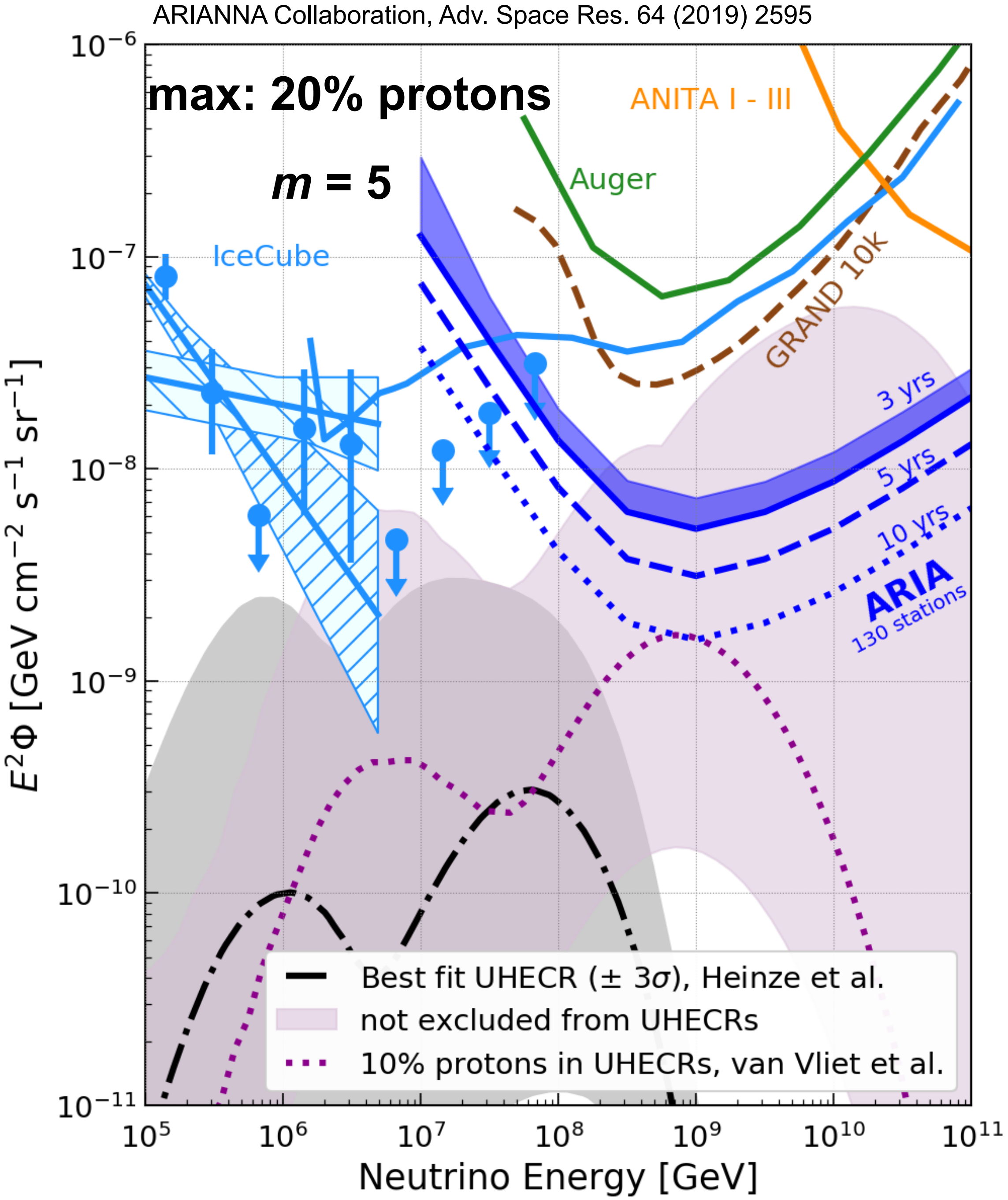
J. Heinze, A. Fedynitch, D. Boncioli and W. Winter, Astrophys. J. 873 (2019) 88

Neutrinos from subdominant proton component

- Cosmogenic neutrino flux for:
  - proton fraction $f \leq 0.2$ at $10^{1.6}$ EeV
  - Source evolution ($z_{max} = 4$, $m \leq 5$):

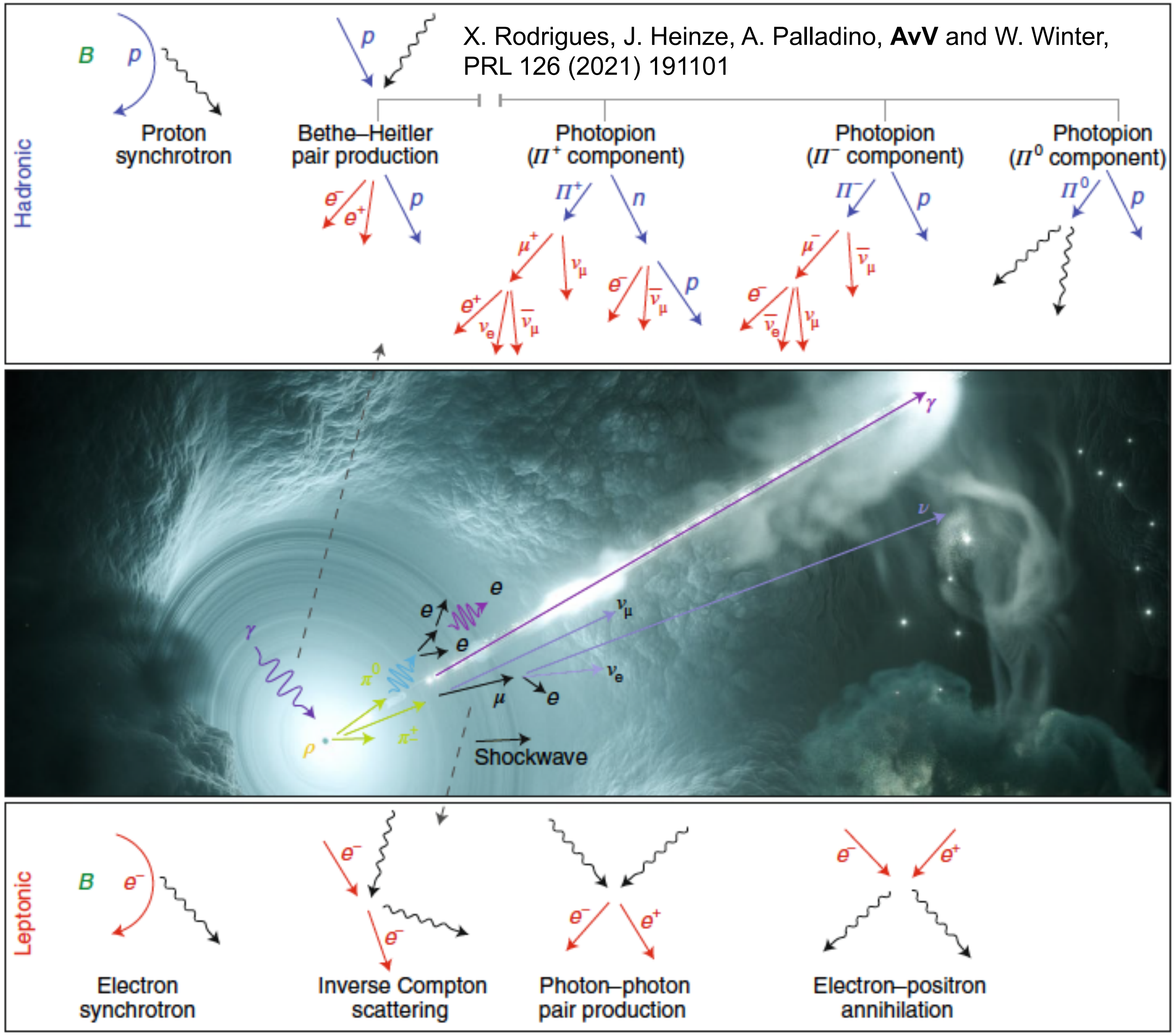
$$\begin{cases} (1+z)^m & \text{for } z < 1.5 \\ 2.5^m & \text{for } z \geq 1.5 \end{cases}$$





UHECRs and neutrinos from AGN

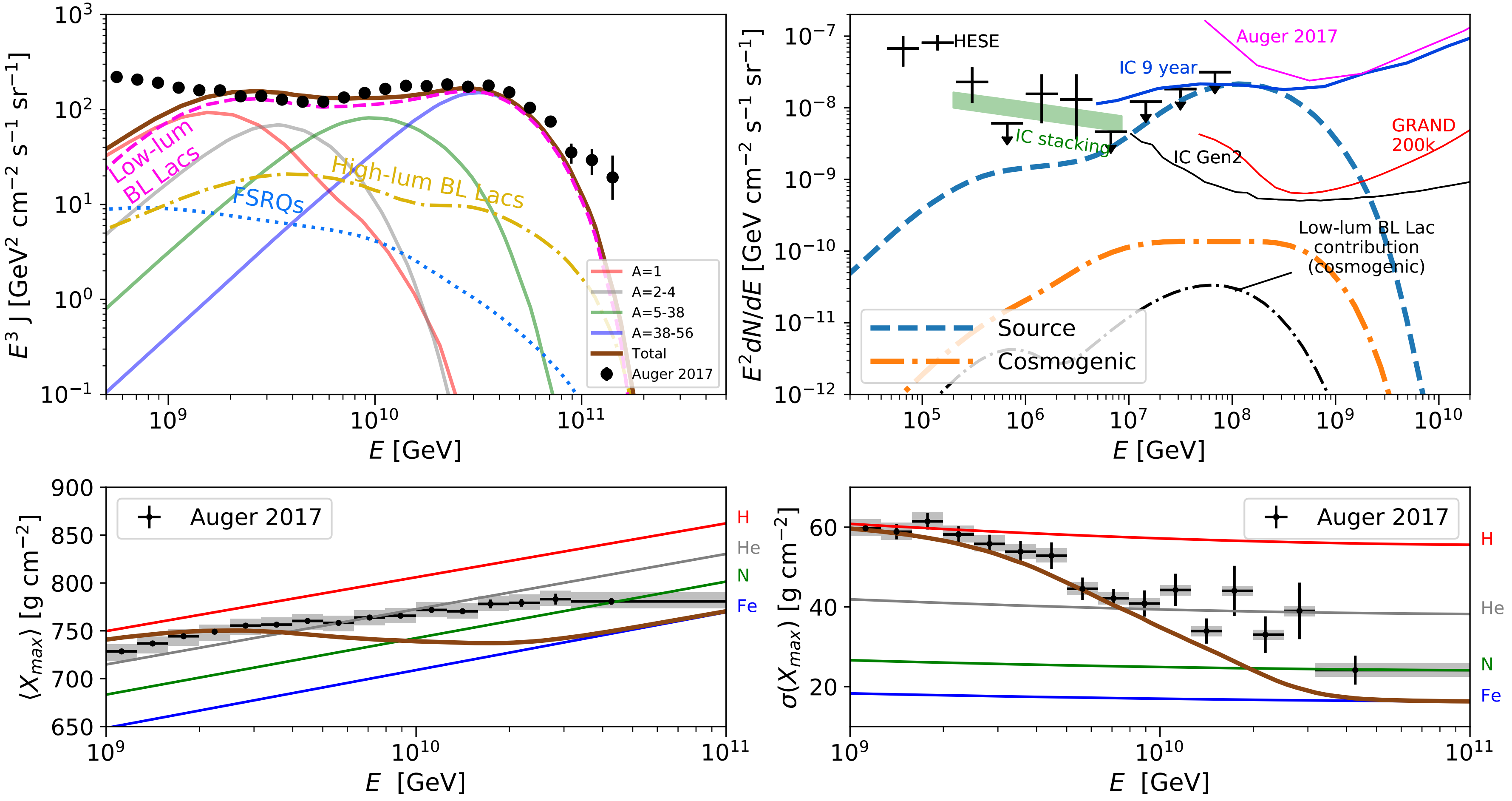
- Simulation of interactions inside the sources
- **Predictions for both source neutrinos and cosmogenic neutrinos**
- BL Lacs:
  - Low photon density
  - Efficient UHECR emitters
  - Inefficient neutrino emitters
  - Rigidity-dependent maximal energy
- FSRQs:
  - High photon density
  - Efficient photohadronic interactions
  - Abundant neutrino production
  - Light UHECR composition emitted



UHECRs and neutrinos from AGN; Results

- Initial composition fixed to Galactic CR composition
- BL Lacs dominate the UHECR spectrum
- Light UHECRs from FSRQs improve composition
- FSRQ source neutrinos dominate neutrino flux
- **Source neutrinos can outshine cosmogenic neutrinos**

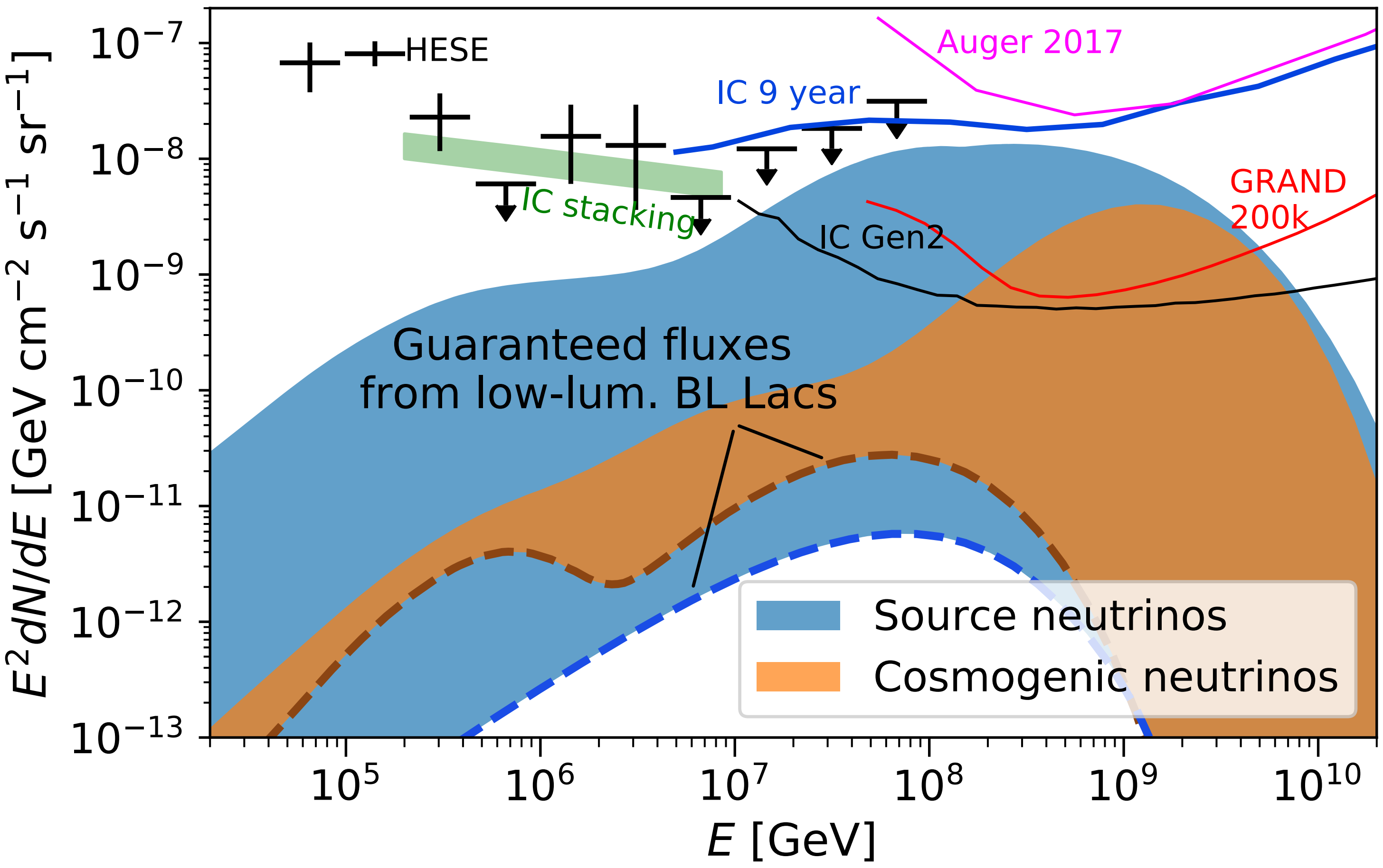
X. Rodrigues, J. Heinze, A. Palladino, **AvV** and W. Winter, PRL 126 (2021) 191101



Possible ranges for source and cosmogenic neutrinos

- Allowing for different acceleration efficiencies of FSRQs
- **Source neutrinos can outshine cosmogenic neutrinos**
- Source neutrinos possibly identified and disentangled with different techniques
  - Stacking searches
  - Flare analyses
  - Multi-messenger follow-up
- Guaranteed flux from BL Lacs up to EeV energies

X. Rodrigues, J. Heinze, A. Palladino, **AvV** and W. Winter, PRL 126 (2021) 191101



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

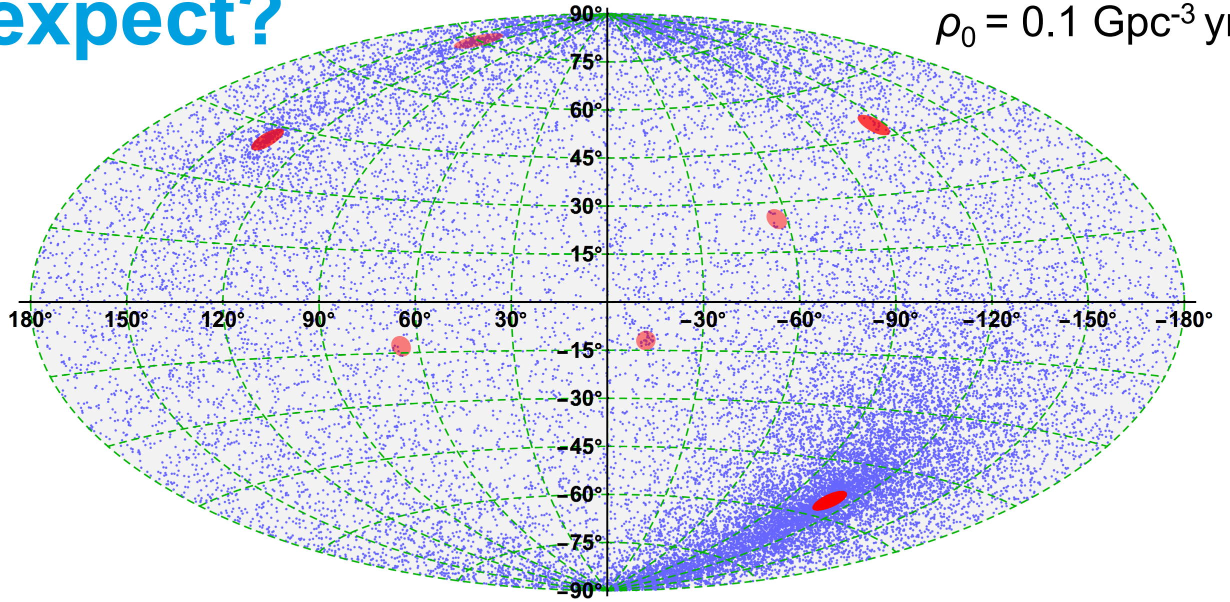
JCAP 1601 (2016) 037
(2016-01-20)
DOI: 10.1088/1475-7516/2016/01/037
FERMILAB-PUB-15-520-AD-AE-CD-TD
e-Print: arXiv:1511.09408 [astro-ph.HE] | PDF
Experiment: AUGER, IceCube, TELESCOPE-ARRAY

How many correlations do we expect?

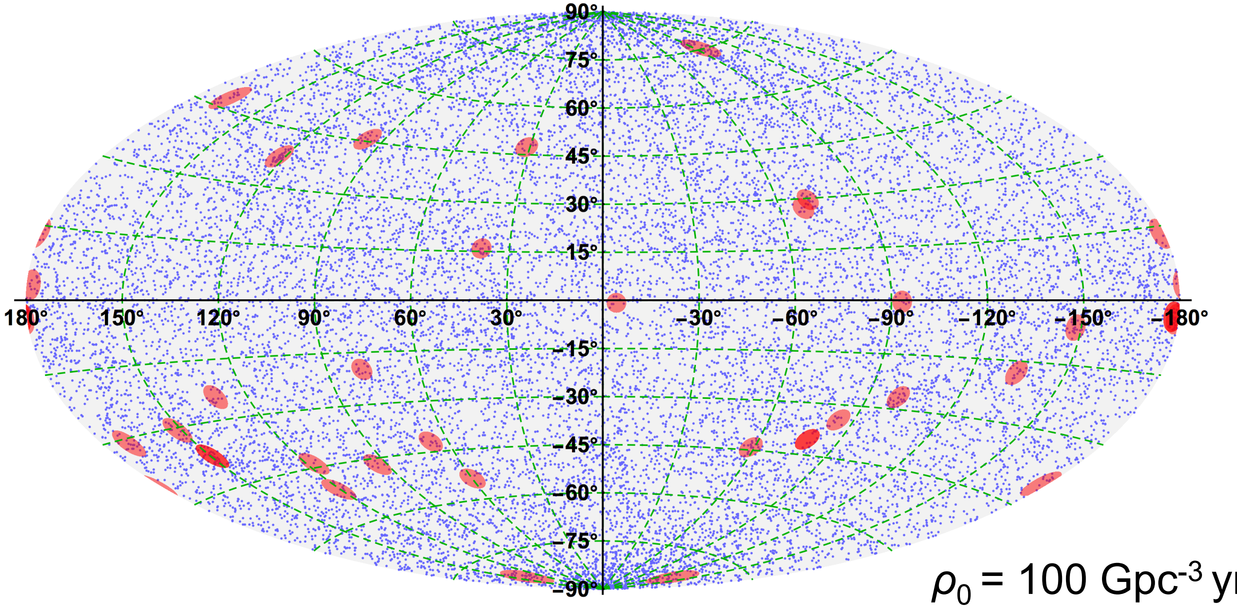
A. Palladino, **AvV**, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- **Test most positive scenario for UHECR-ν correlations**
- 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)
- UHECRs: 135k with $E > 10^{18.5}$ eV (~ number of UHECRs measured by Auger + TA)
- Influenced by
  - Source evolution with redshift
  - Energy-losses of UHECRs
  - Deflections in extragalactic magnetic field
  - Deflections in Galactic magnetic field
  - Density of the sources ρ_0

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



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



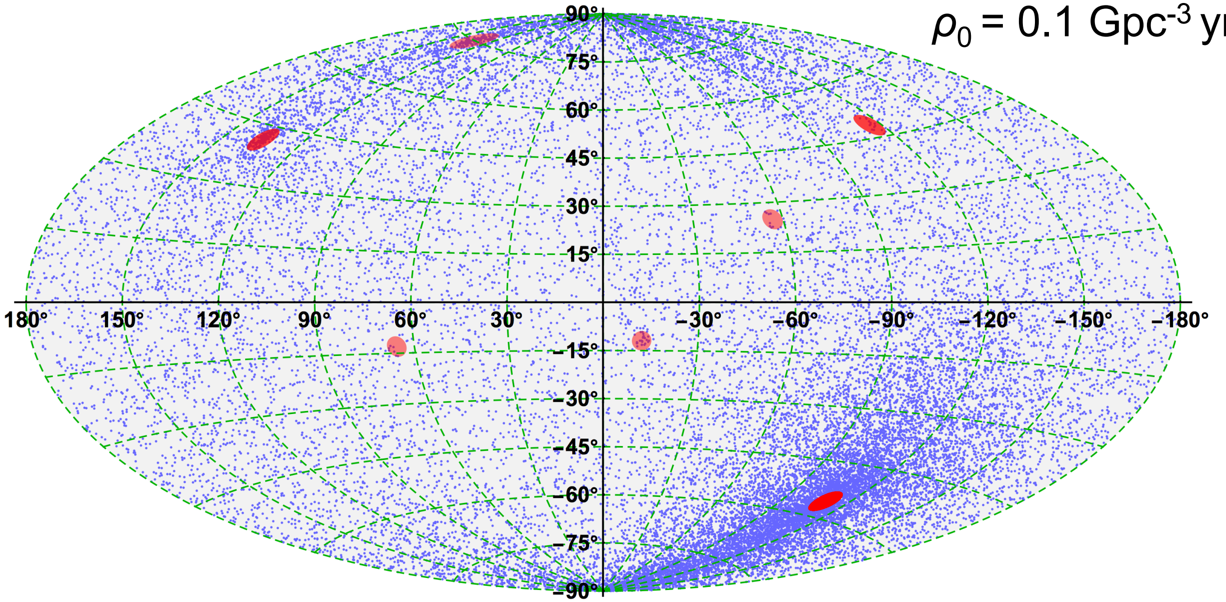
$\rho_0 = 100\ \mathrm{Gpc^{-3}\,yr^{-1}}$

Neutrino multiplets

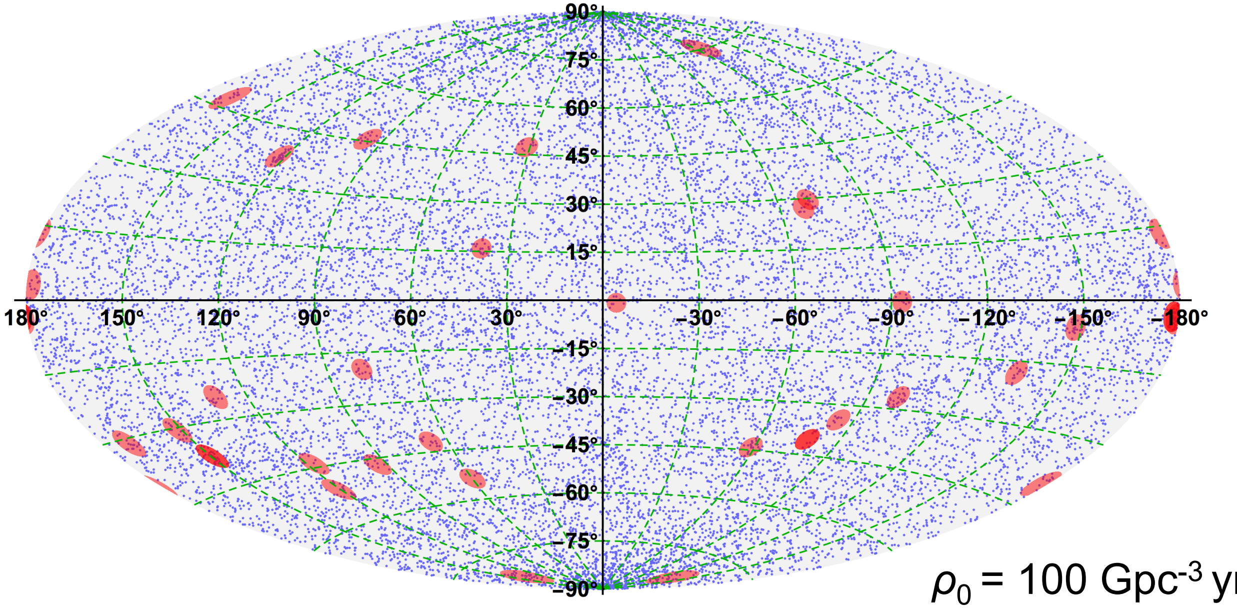
A. Palladino, **AvV**, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- 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
- Influenced by
  - Source evolution with redshift
  - Density of the sources ρ_0
  - Neutrino luminosity
- **Strongly constrains local density**

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



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

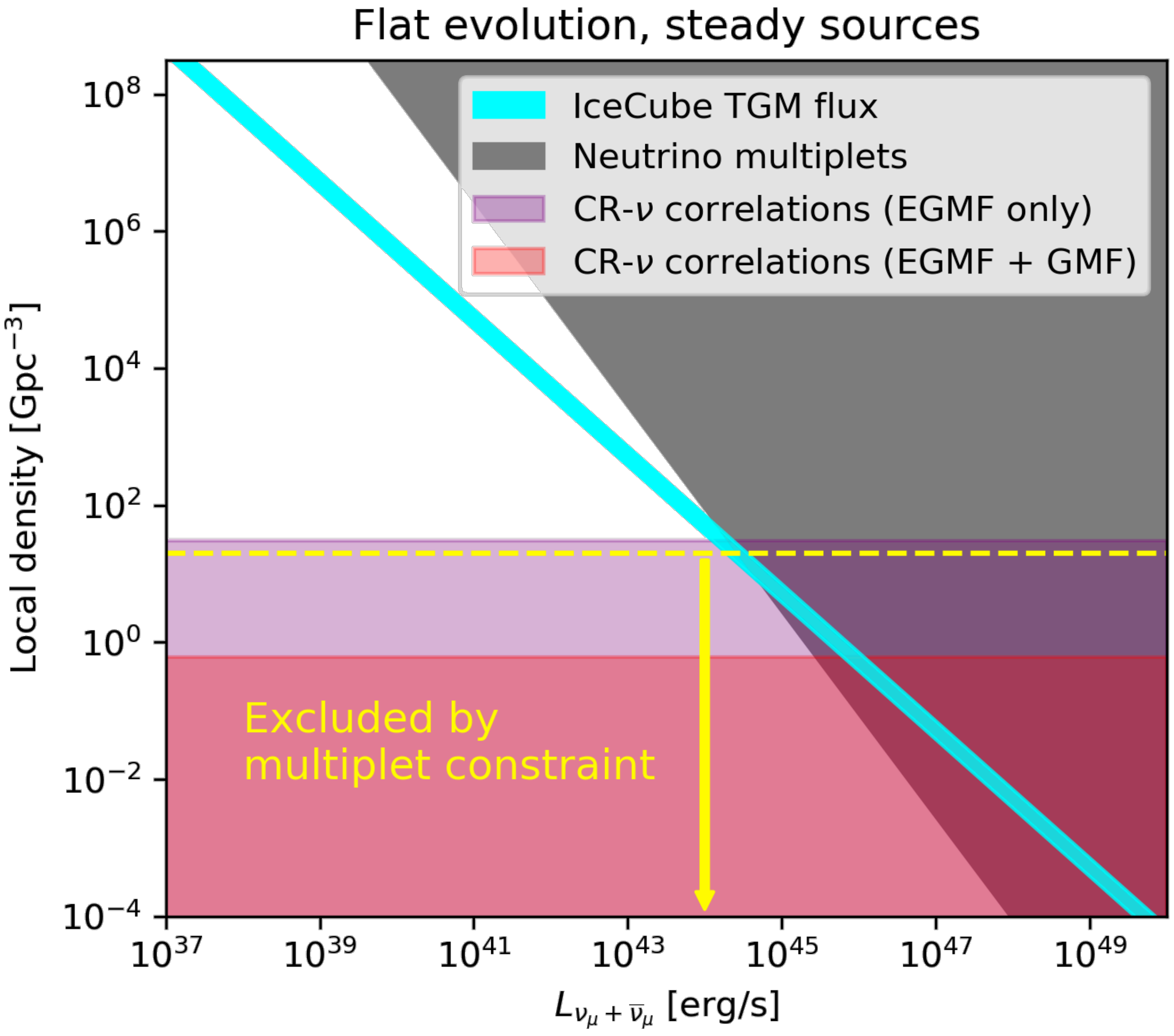


$\rho_0 = 100\ \mathrm{Gpc^{-3}\,yr^{-1}}$

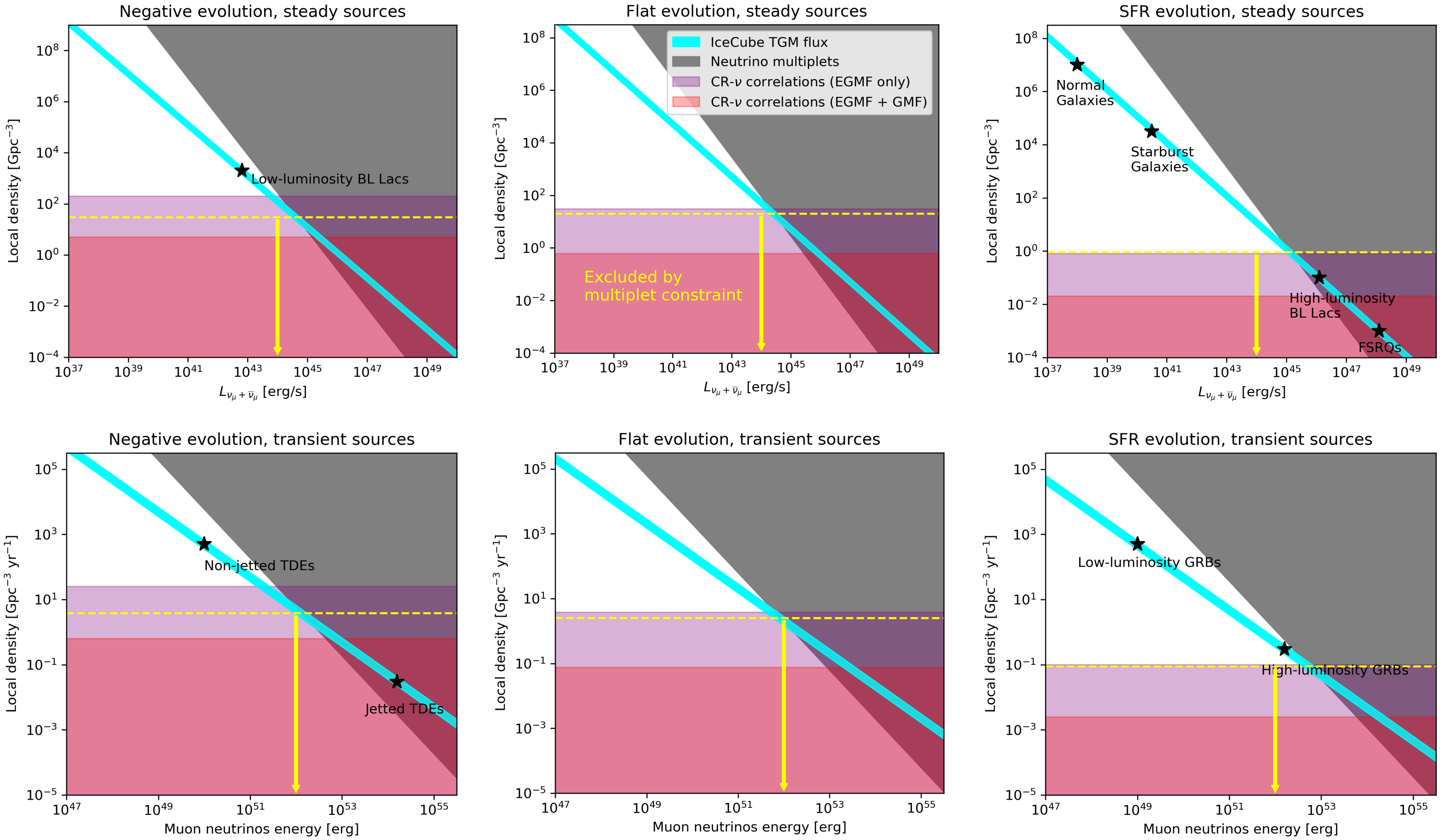
Results as a function of the source density

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

- **Neutrino flux**
- **Neutrino multiplets:** 90% region for presence of at least one neutrino multiplet in IceCube through-going muon flux
- **UHECR-neutrino correlations:** Region for at least 50% chance of observing 5σ excess in neutrino-UHECR correlations
  - assuming the IceCube TGM flux is reproduced



Results for different source evolutions; steady vs. transient

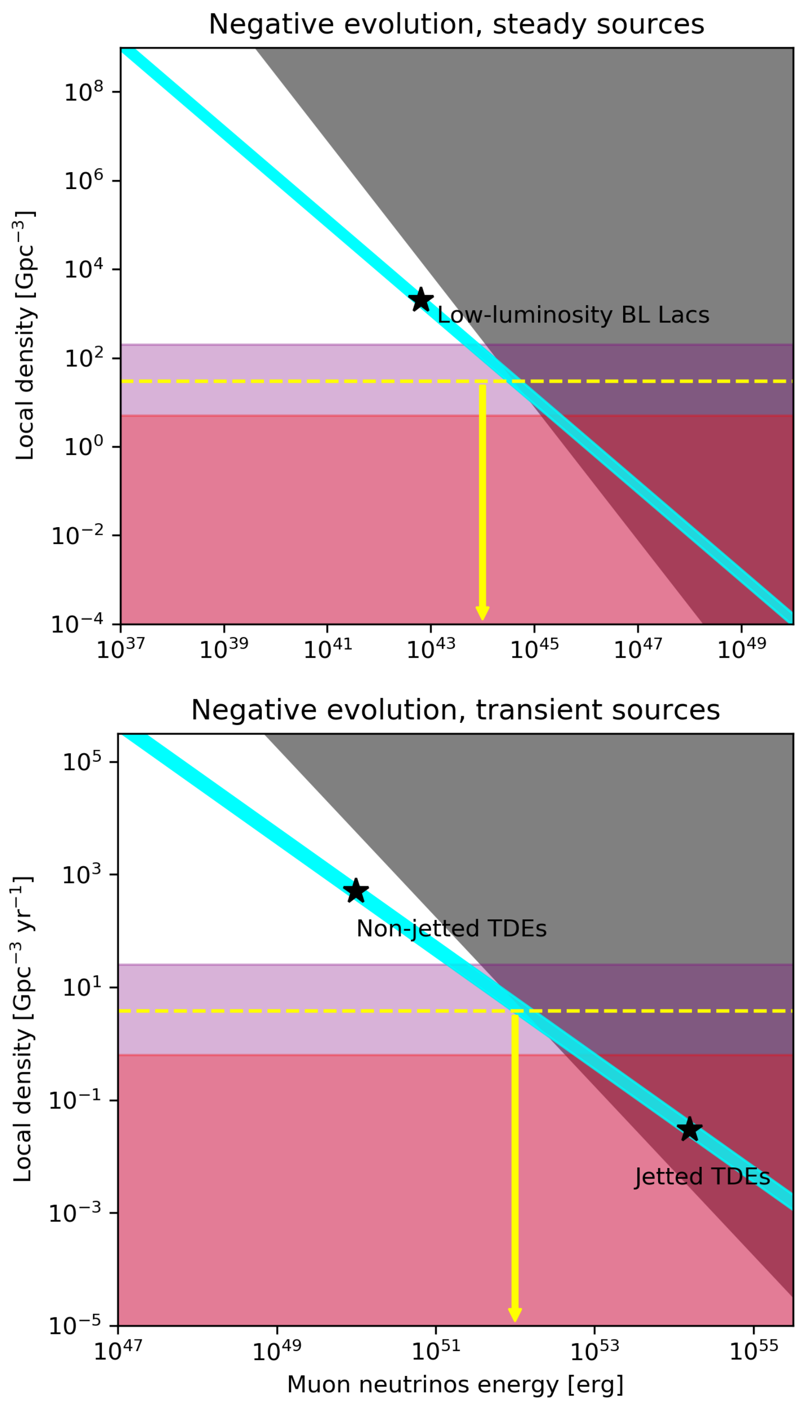


A. Palladino, **AvV**, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

UHECR-ν 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 and 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

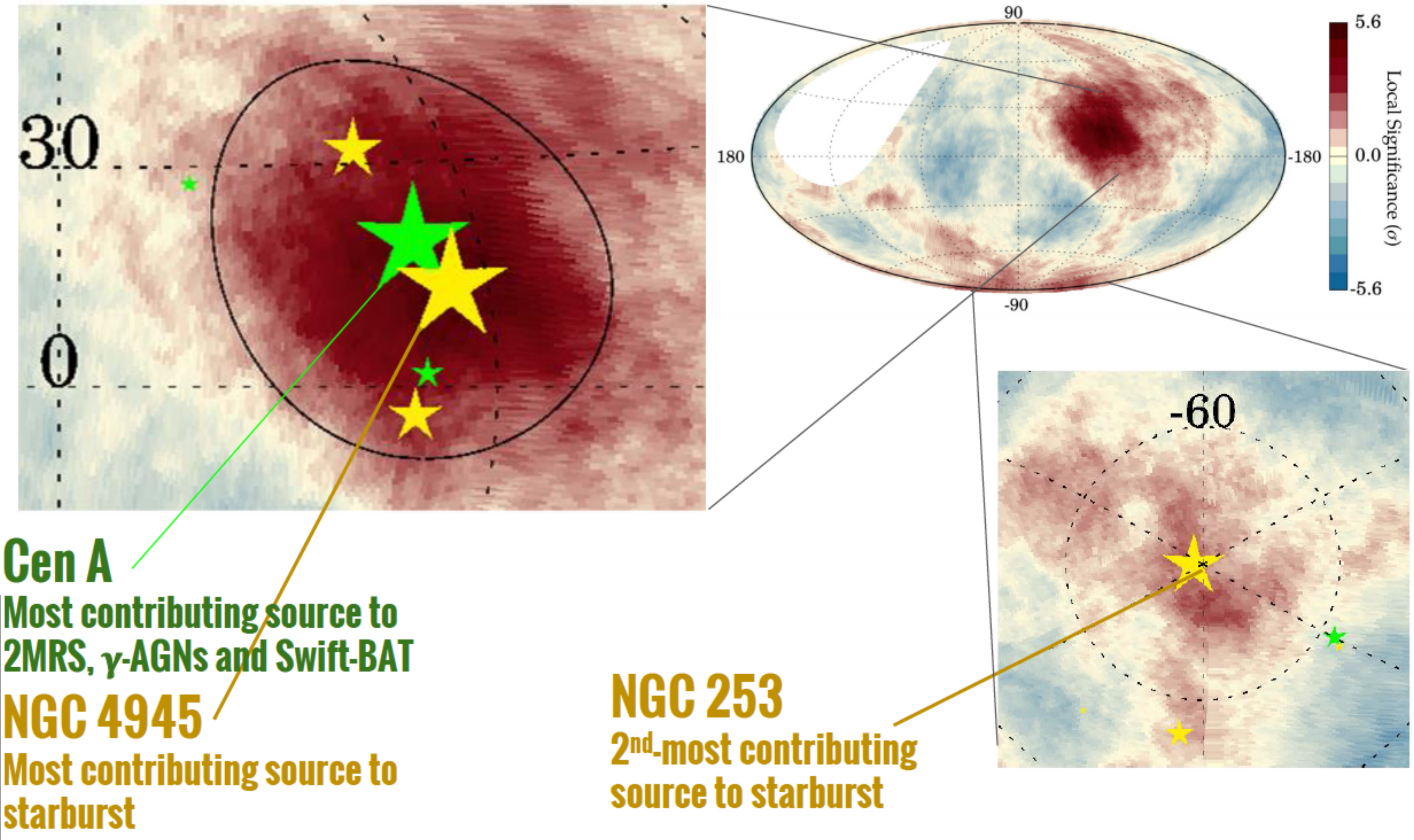


Correlations between UHECRs and source positions

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

- Indications of anisotropy found by Auger
- Largest significance for correlation with starburst/star-forming 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	$4.5\,\sigma$
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	$3.7\,\sigma$



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 and a larger isotropic background
- 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

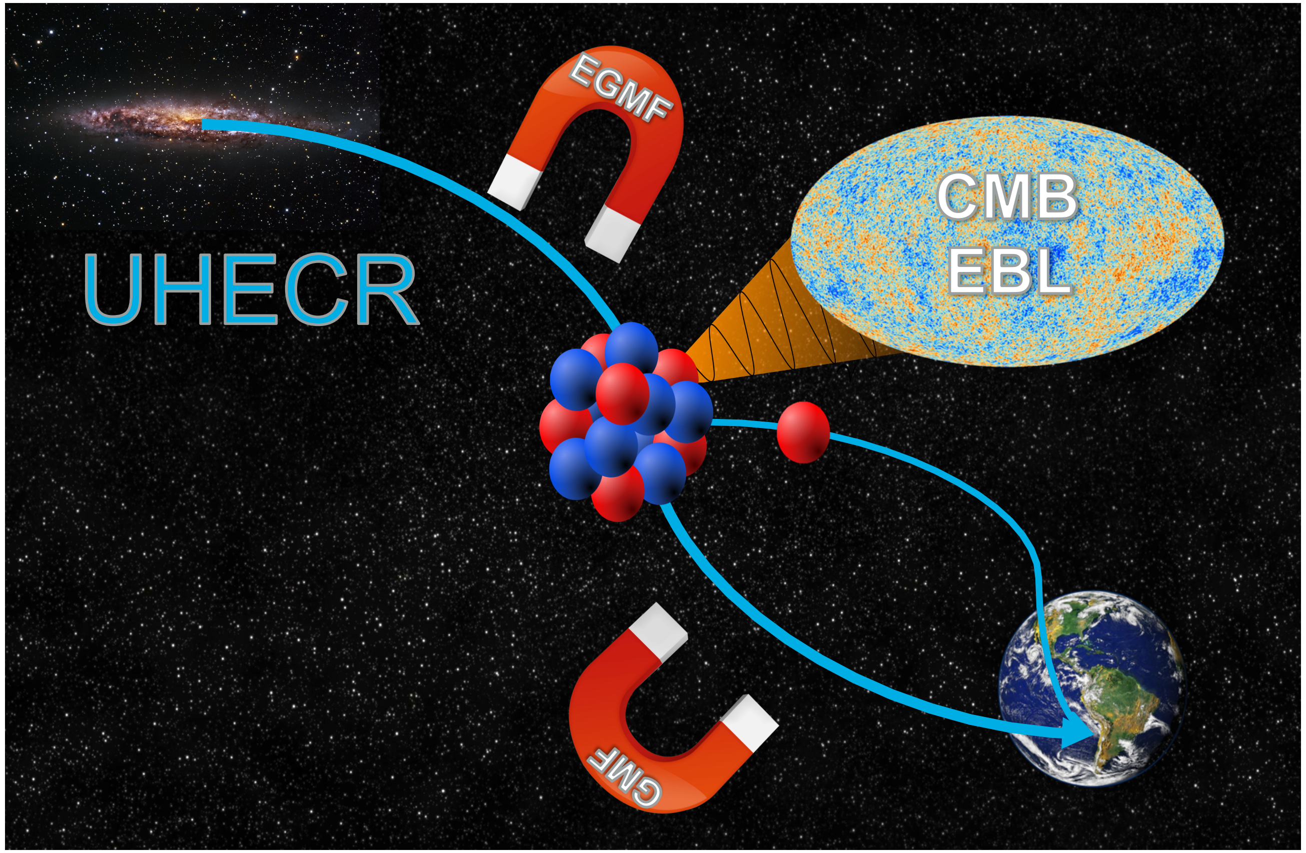
Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	$15^{+5}_{-4}{}^{\circ}$	$11^{+5}_{-4}\%$	29.5	4.5 σ
γ-AGNs	39 EeV	$14^{+6}_{-4}{}^{\circ}$	$6^{+4}_{-3}\%$	17.8	3.1 σ
Swift-Bat	38 EeV	$15^{+6}_{-4}{}^{\circ}$	$8^{+4}_{-3}\%$	22.2	3.7 σ
2MRS	40 EeV	$15^{+7}_{-4}{}^{\circ}$	$19^{+10}_{-7}\%$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

Our method

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

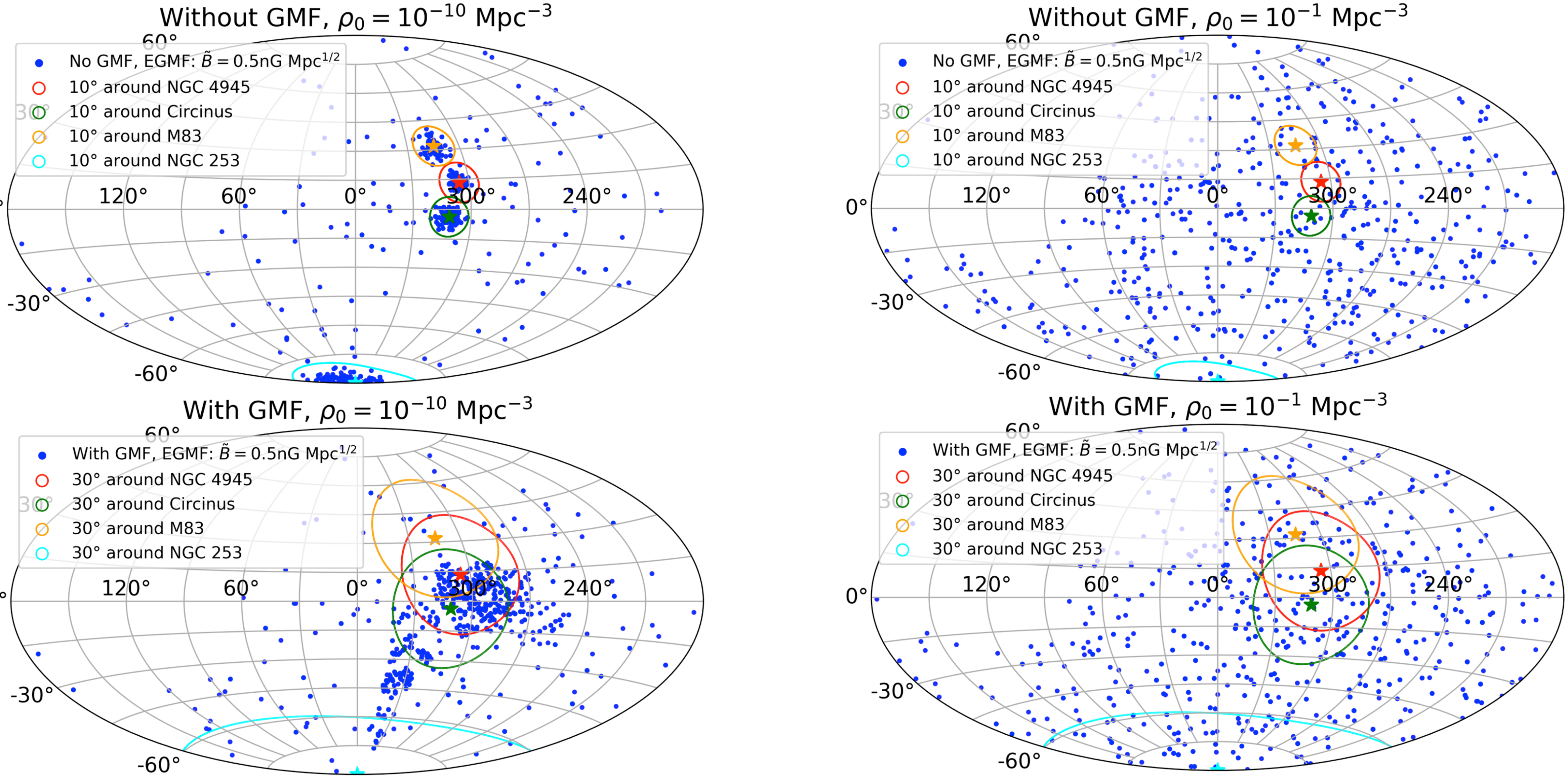
- Simulate UHECR sky maps for specific EGMF and GMF setups and local source densities ρ_0
- Check if these sky maps give θ and f_{aniso} values compatible with what Auger found

- 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 and GMF
- Combine UHECRs from catalogue sources with a diffuse contribution



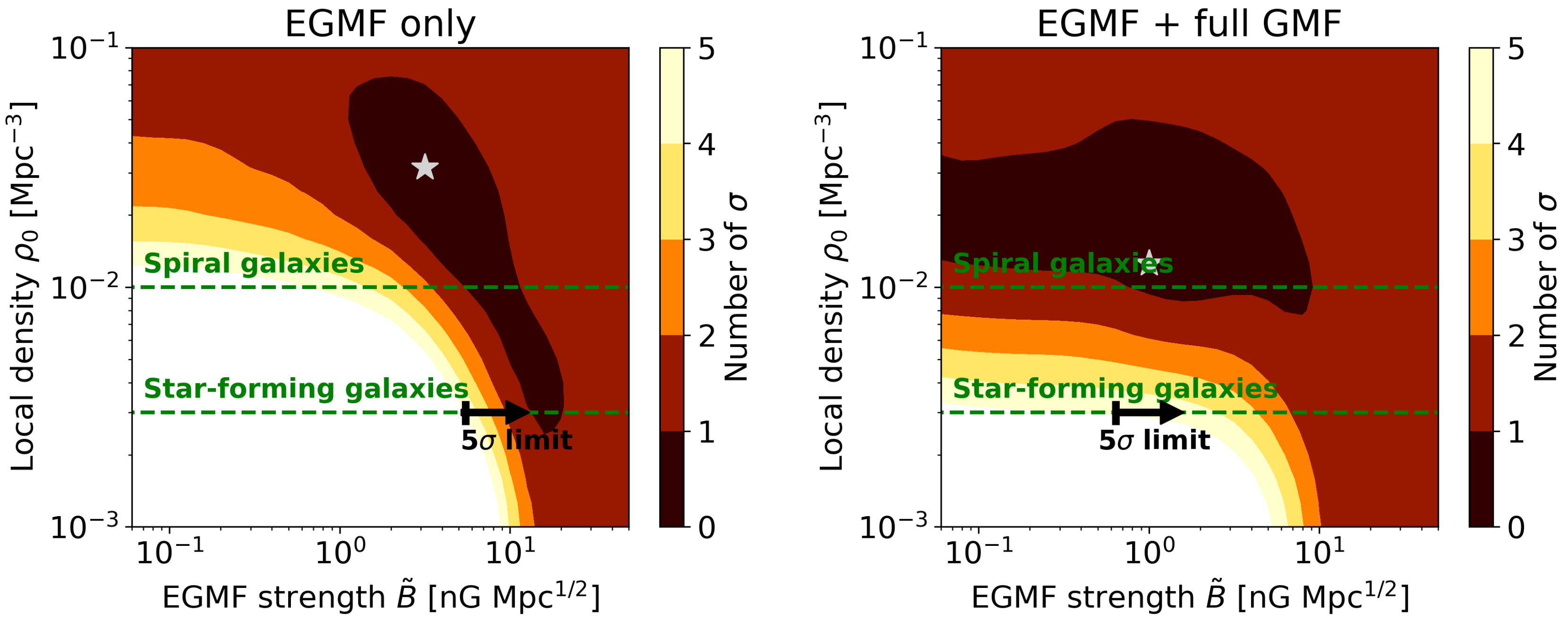
Example sky maps

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

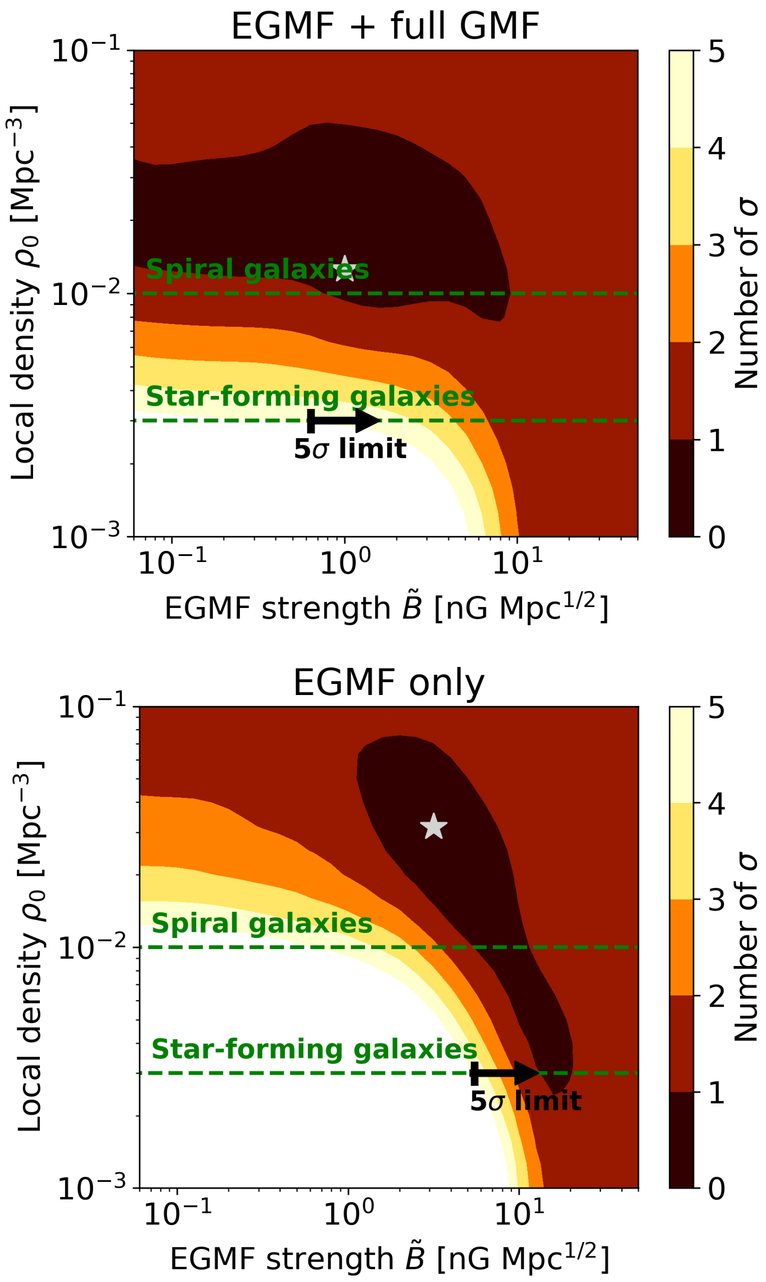


	EGMF only	EGMF + full GMF
5σ lower limit on $\tilde{B}$ for $\rho_0 = 3 \cdot 10^{-3}$ Mpc^{-3}	$\tilde{B} > 5.5$ nG Mpc$^{1/2}$	$\tilde{B} > 0.64$ nG Mpc$^{1/2}$
Best-fit point	$\tilde{B} = 3.2$ nG Mpc$^{1/2}$; $\rho_0 = 3.2 \cdot 10^{-2}$ Mpc^{-3}	$\tilde{B} = 1.0$ nG Mpc$^{1/2}$; $\rho_0 = 1.3 \cdot 10^{-2}$ Mpc^{-3}
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}

Preliminary 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



Summary

- Neutrino limits at ~1 EeV are able to constrain the proton fraction and source evolution of UHECR sources
- The combination of a large proton fraction and a strong source evolution is already ruled out
- Strong potential for upcoming experiments, to detect cosmogenic neutrinos and source neutrinos in the UHE range
- Source neutrinos could even outshine cosmogenic neutrinos, allowing for additional techniques to identify the sources
- Arrival-direction correlations between HE neutrinos and UHECRs not expected
- Arrival-direction correlations of UHECRs with star-forming galaxies suggest the presence of strong local extragalactic magnetic fields ($B > 0.64$ nG Mpc$^{1/2}$) or very numerous UHECR sources ($\rho_0 > 3 \times 10^{-3}$ Mpc^{-3})

Backup slides

Calculation of expected correlations

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

- Monte Carlo simulation following:

  i. **create source list** for specific source density ρ_0 randomly, distributed isotropically in the sky, distances following source evolutions with redshift (figure on slide 4)

  ii. assign **probabilities to observe a neutrino** from the source to each source, following figure on slide 6

  iii. assign **probabilities to observe a cosmic ray** from the source to each source, following figure on slide 8

  iv. randomly extract **36 observed neutrinos** from source list (through-going muon sample from IceCube ‘17)

  v. randomly extract **200k observed cosmic rays** from source list (roughly number of cosmic rays measured by Auger + TA with E>$10^{18.5}$ eV), with deflections following figures on slides 9 and 10

  vi. count number of **‘signal’ cosmic rays** within certain angular distance from the neutrino positions

  vii. determine expected number of **‘background’ cosmic rays** assuming a purely isotropic distribution

  viii. determine **optimal angular window** (order of 20° - 30°) with parameter scan

  ix. determine **significance** as number of σ, $N\sigma \geq 5$ cases are considered to be significant

  x. **repeat** 10^3 times for each combination of ρ_0 and source evolution

  xi. determine which fraction of maps give a significant **expected correlation**

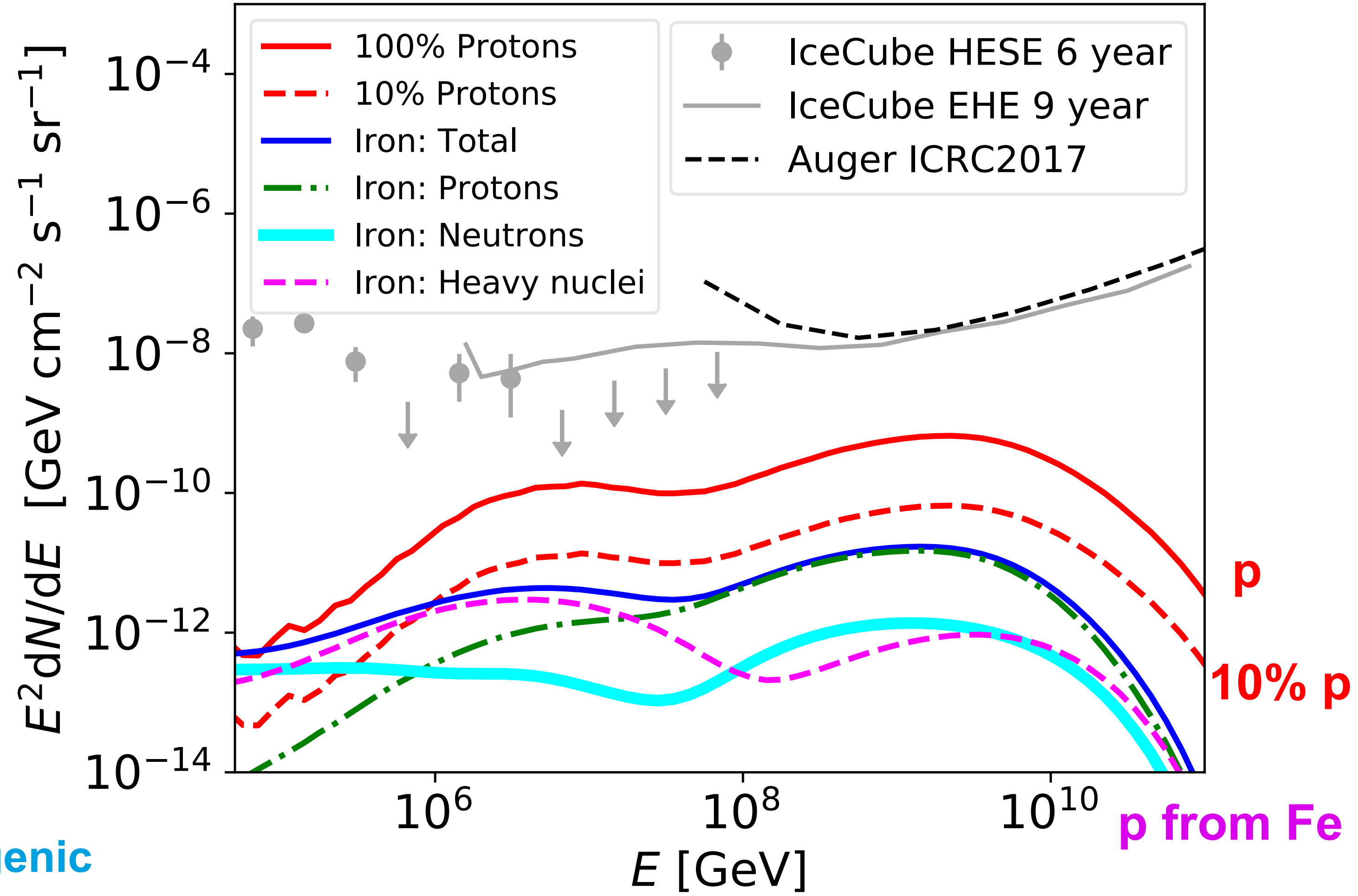
Cosmogenic neutrinos; protons vs. iron

- Continuous distribution of identical sources
- Spectrum at the sources:

  Power law with rigidity-dependent cut-off

  $$\frac{dN}{dE} \propto E^{-\alpha} \exp(-E / ZR_{max})$$
- $\alpha = 2.5$
- $R_{max} = 200$ EV
- Composition at the sources:

  Pure proton vs. pure iron
- Comoving source evolution
- EBL: Gilmore *et al*. 2012
- **Protons especially important for cosmogenic neutrino production**

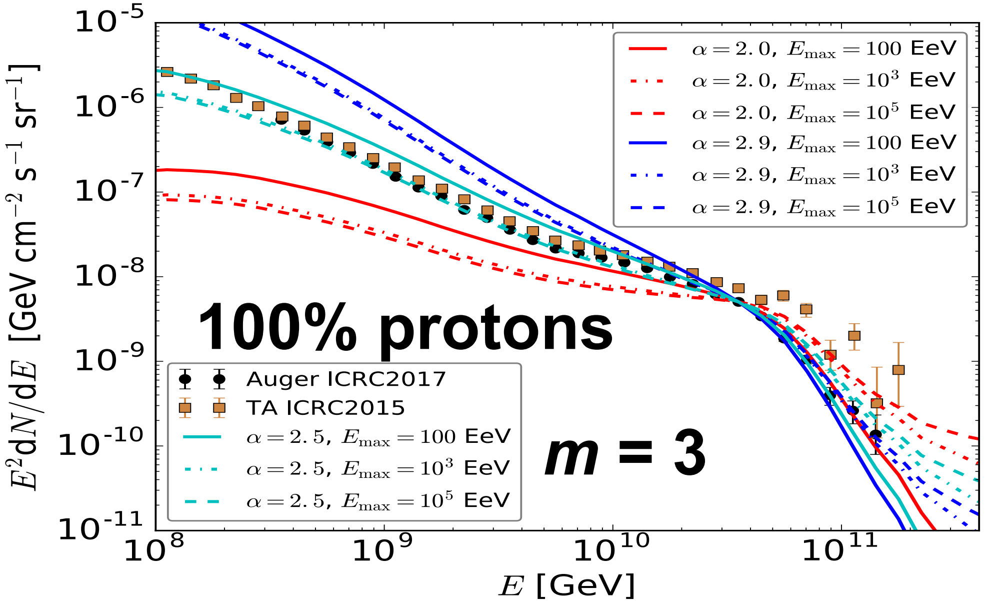


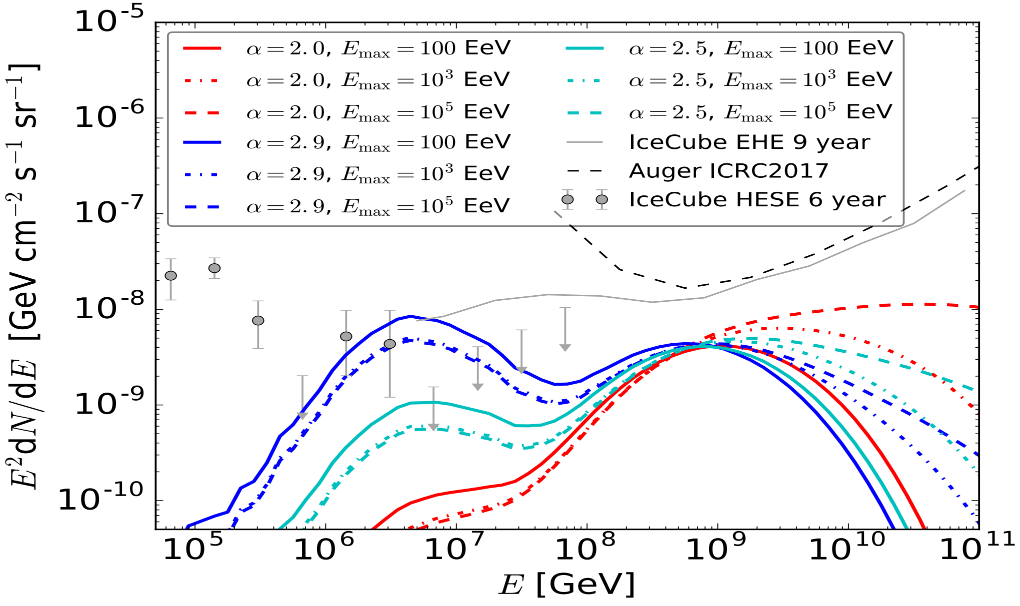
Neutrinos at ~1 EeV

- Cosmogenic neutrino flux depends on:
  - Spectral index α
  - Max. rigidity R_{max}
  - EBL model
  - Composition (proton fraction at Earth, f)
  - Source evolution
- Sweet spot at ~1 EeV, only depends on:
  - Composition (proton fraction)
  - Source evolution (z_{max} = 4)

$$\text{SE} = \begin{cases} (1+z)^m & \text{for } m \leq 0 \\ (1+z)^m & \text{for } m > 0 \text{ and } z < 1.5 \\ 2.5^m & \text{for } m > 0 \text{ and } z \geq 1.5 \end{cases}$$

AvV, J. R. Hörandel and R. Alves Batista,
PRD 100 (2019) 021302(R)





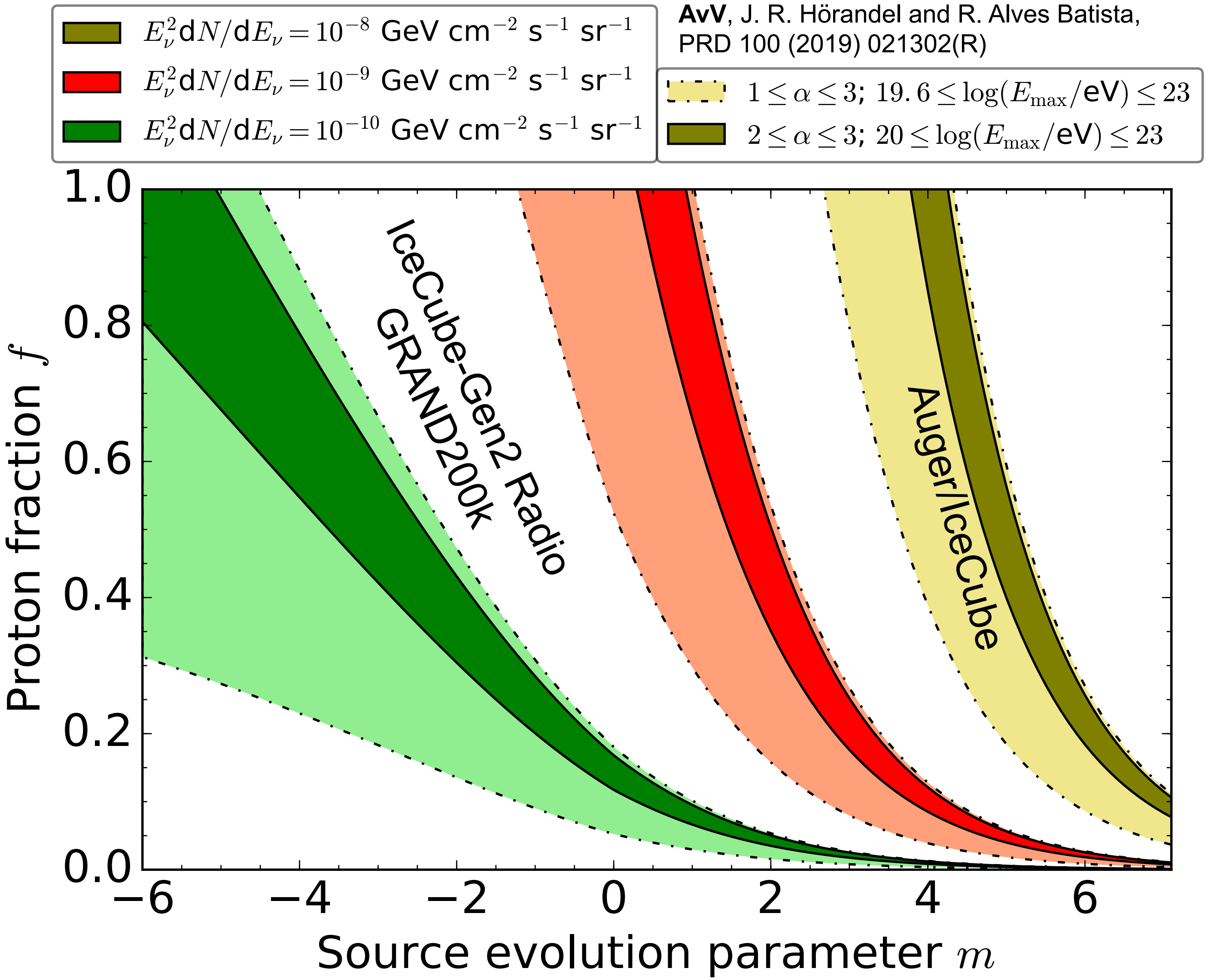
Proton fraction vs. source evolution

- Single-flavour neutrino flux at ~1 EeV
- Auger and IceCube are both close to

  ~10^{-8} GeV cm^{-2} s^{-1} sr^{-1}
- Top-right part of parameter space already constrained
- Combination of a large proton fraction and strong source evolution ruled out

See also: Pierre Auger Collaboration, JCAP 10 (2019) 022

AvV, J. R. Hörandel and R. Alves Batista, PRD 100 (2019) 021302(R)



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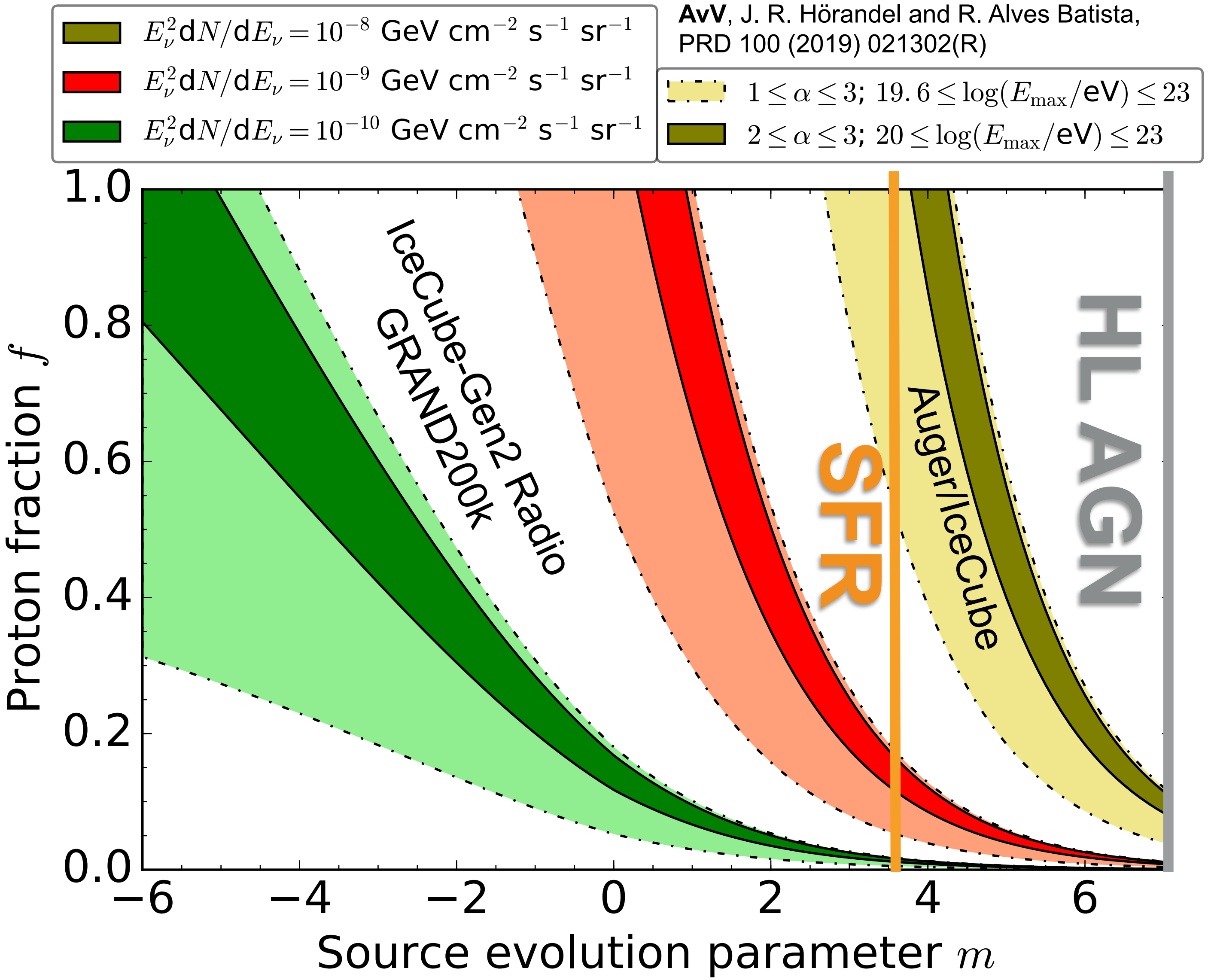
AvV, J. R. Hörandel and R. Alves Batista, PRD 100 (2019) 021302(R)



Current sensitivity

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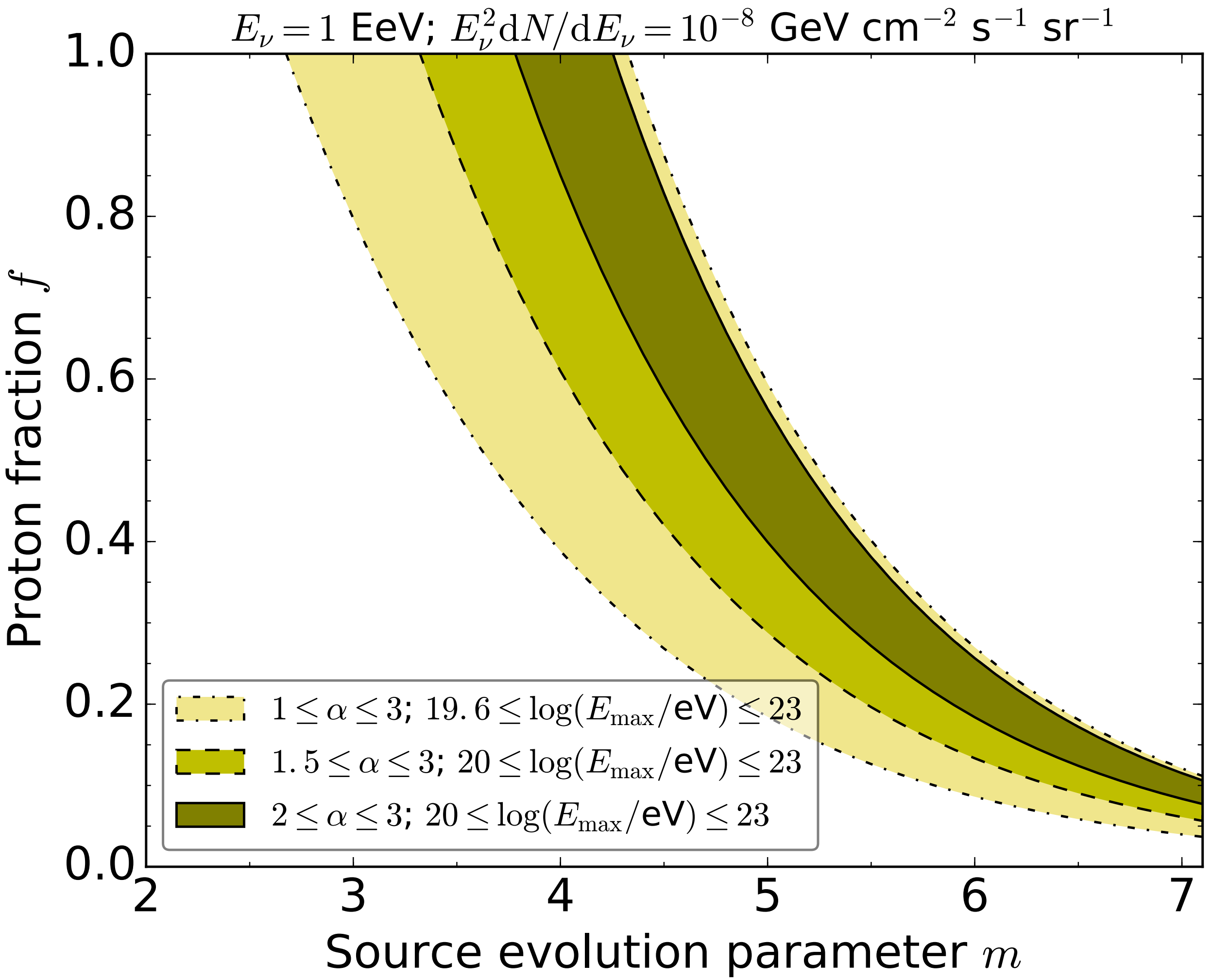

AvV, J. R. Hörandel and R. Alves Batista, PoS(ICRC2019)125

Current sensitivity

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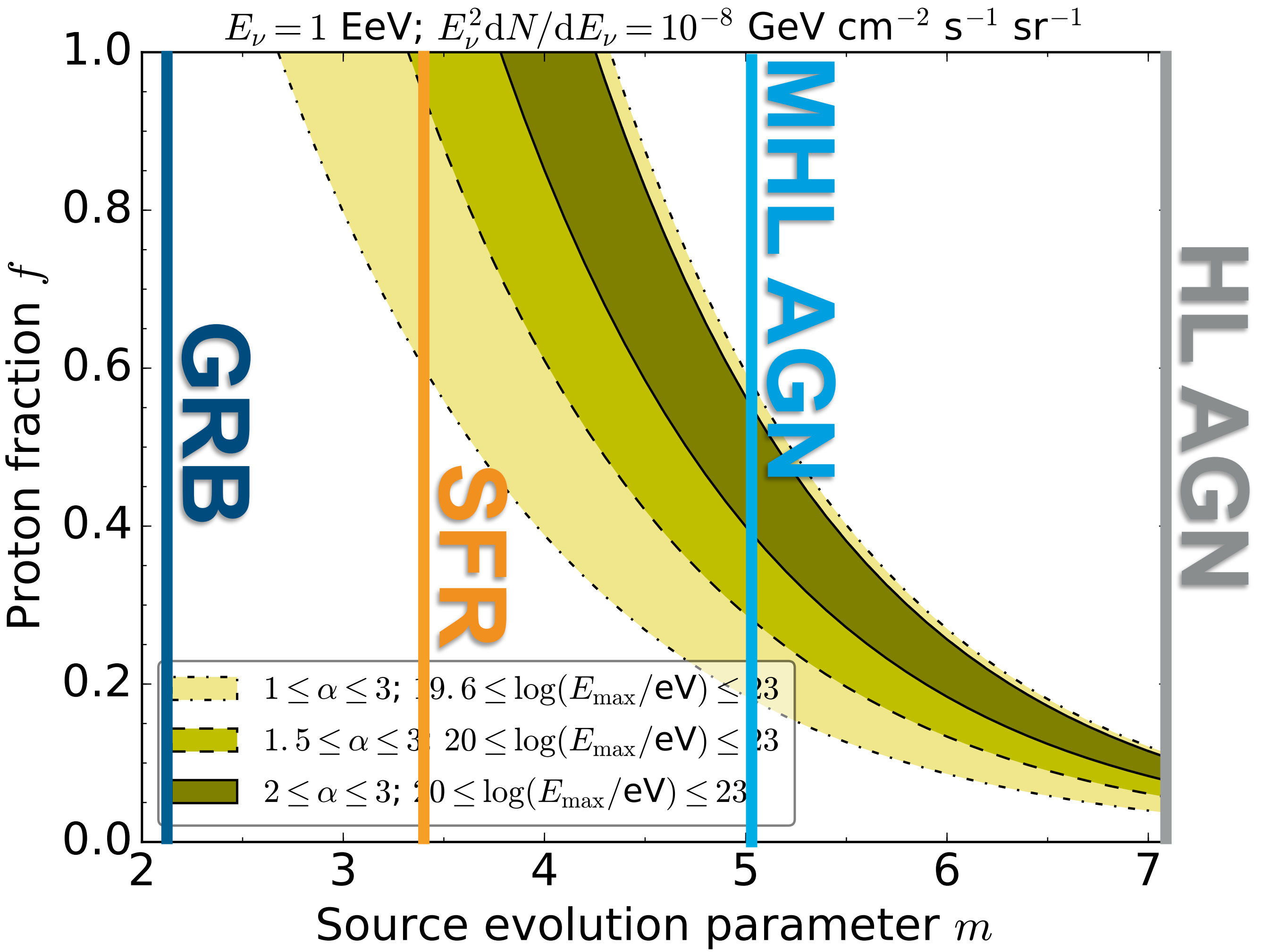


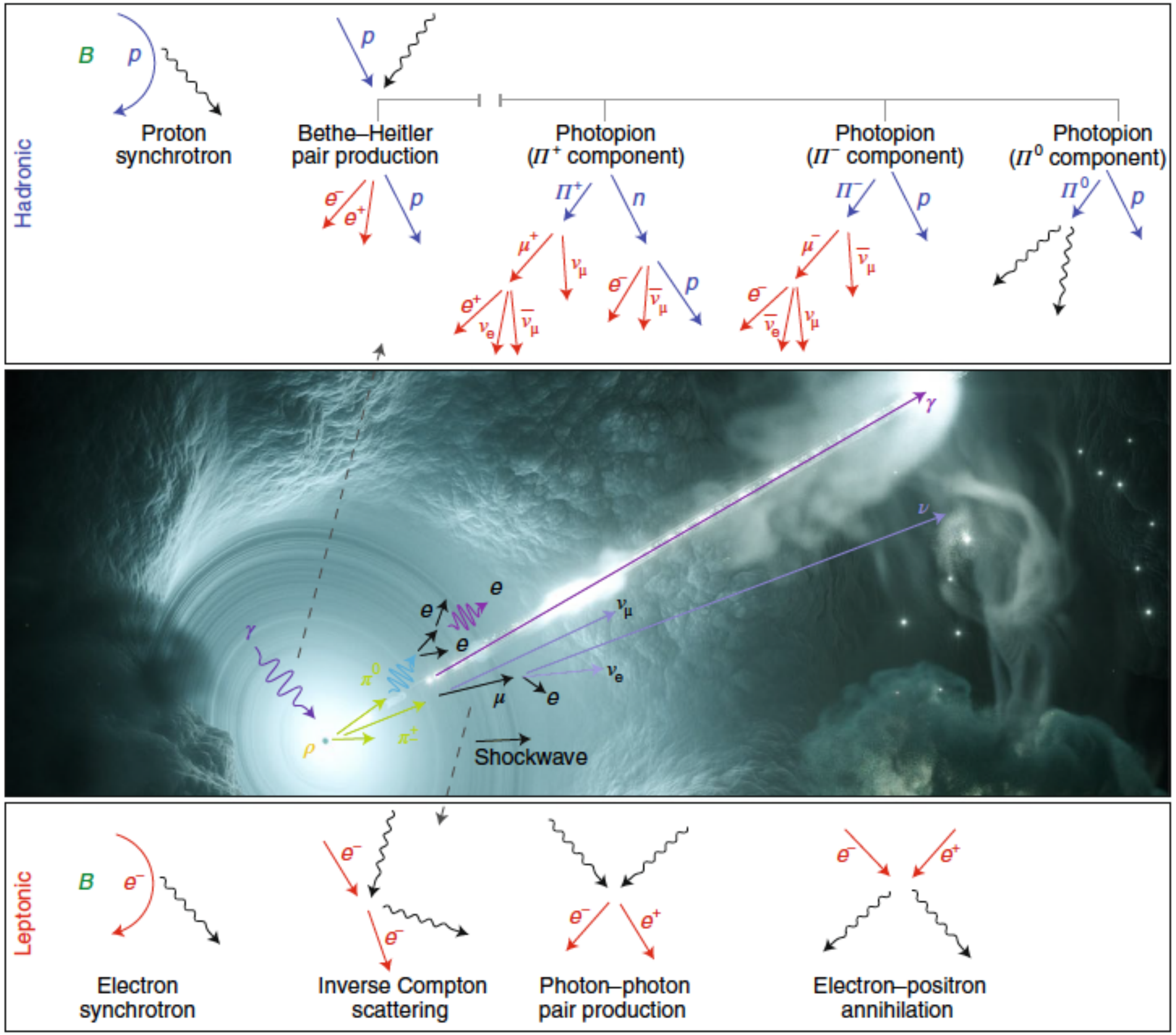
AvV, J. R. Hörandel and R. Alves Batista, PoS(ICRC2019)125

UHECR sources also produce high-energy neutrinos

- Neutrinos produced in
  - Photopion production
  - *pp* interactions
  - β-decay

$$ {}^{A}_{Z}\mathrm{N} \rightarrow {}^{A}_{Z\pm1}\mathrm{N}' + e^{\pm} + \nu_e / \bar{\nu}_e $$

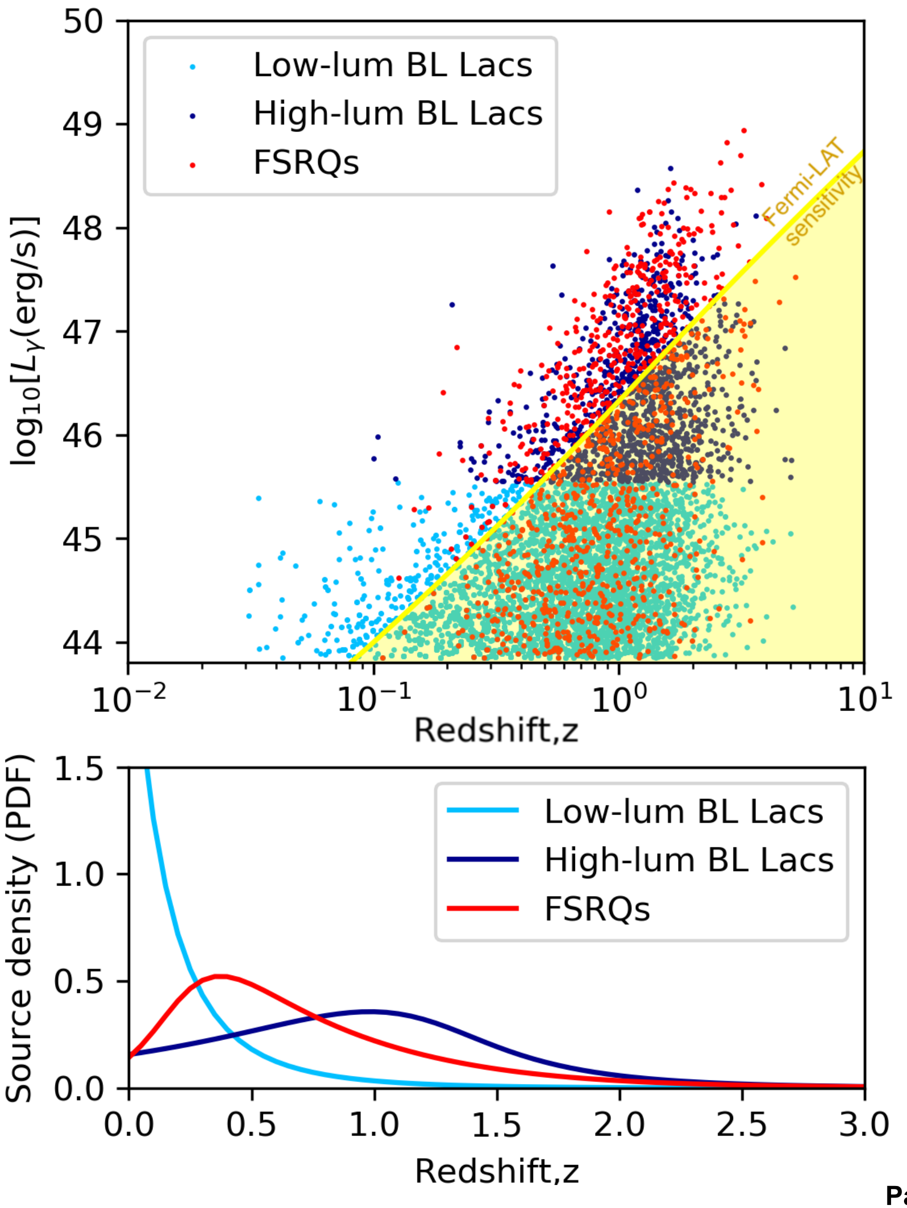
- **Correlation between UHECRs and HE neutrinos?**



UHECRs and neutrinos from AGN

- 3 AGN subpopulations
  - Low-luminosity BL Lacs
  - High-luminosity BL Lacs
  - FSRQs
- Simulation of interactions inside the sources
- **Predictions for both source neutrinos and cosmogenic neutrinos**
- Evolution model consistent with diffuse γ-ray background
- Photon spectrum in the sources determined by L_γ
- BL Lacs: one-zone model where UHECR interact with non-thermal radiation produced in the AGN jet
- FSRQs: additional target photons from the broad line region and the dust torus

X. Rodrigues, J. Heinze, A. Palladino, **AvV** and W. Winter, PRL 126 (2021) 191101



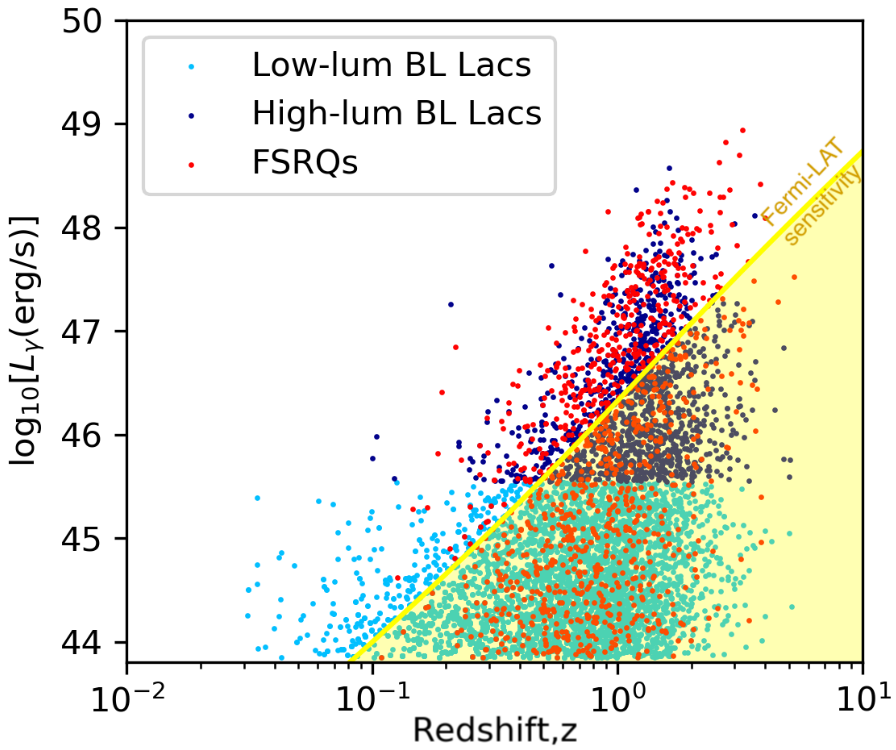
Simulation setup

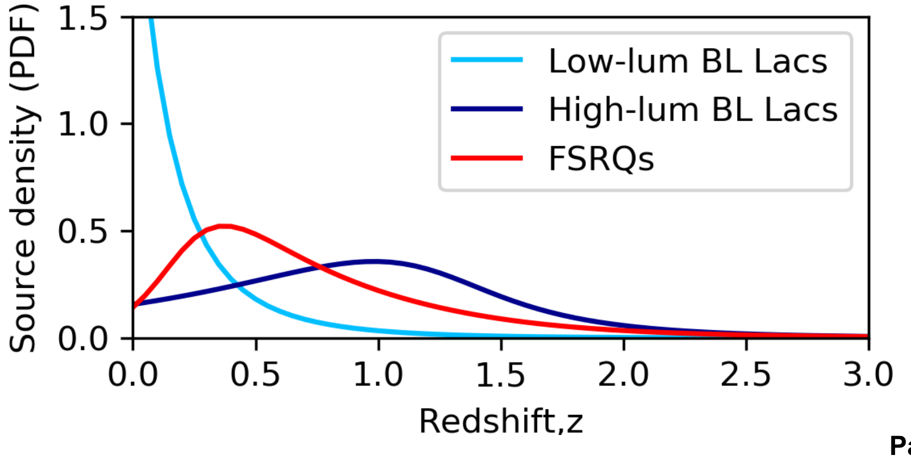
- Mass composition fixed to Galactic CR composition
  - p, He, N, Fe = [1.00, 0.46, 0.30, 0.14]
- E^{i}_{max} determined by energy losses and acceleration efficiency
- UHECR injection spectrum:

$$\frac{dN}{dE} \propto E^{-2} \exp(-E / E^{i}_{max})$$

- AGN properties:
  - Baryonic loading (different for Low-lum. BL Lacs vs. FSRQs)
  - UHECR acceleration efficiency (the same for all sources)
  - Size of the radiation zone (fixed, r = 0.1 pc)
  - Escape mechanism (fixed, Bohm-like diffusion)

X. Rodrigues, J. Heinze, A. Palladino, **AvV** and W. Winter, PRL 126 (2021) 191101

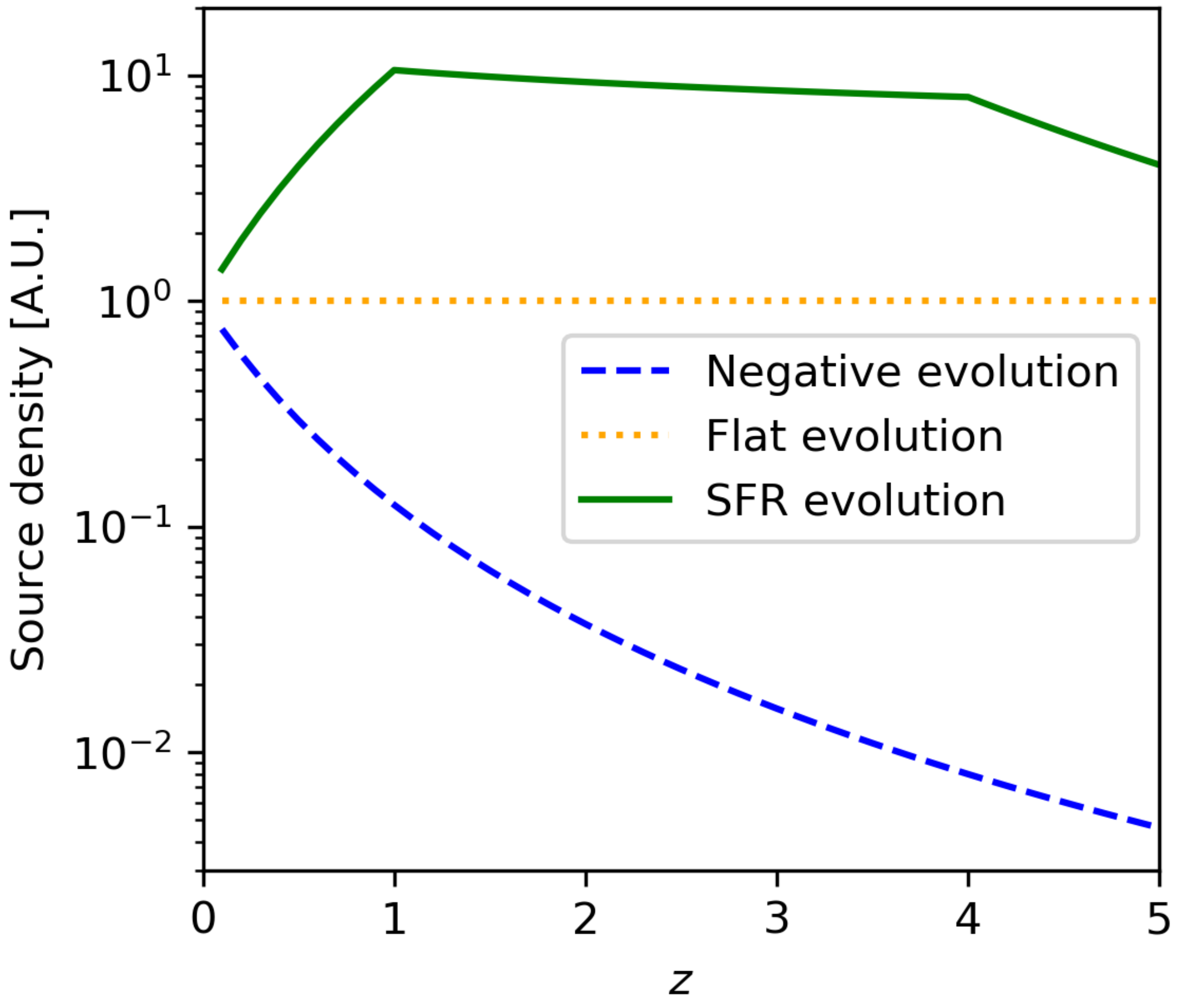




Source evolution with redshift

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
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- Star Formation Rate evolution:
  - Normal galaxies
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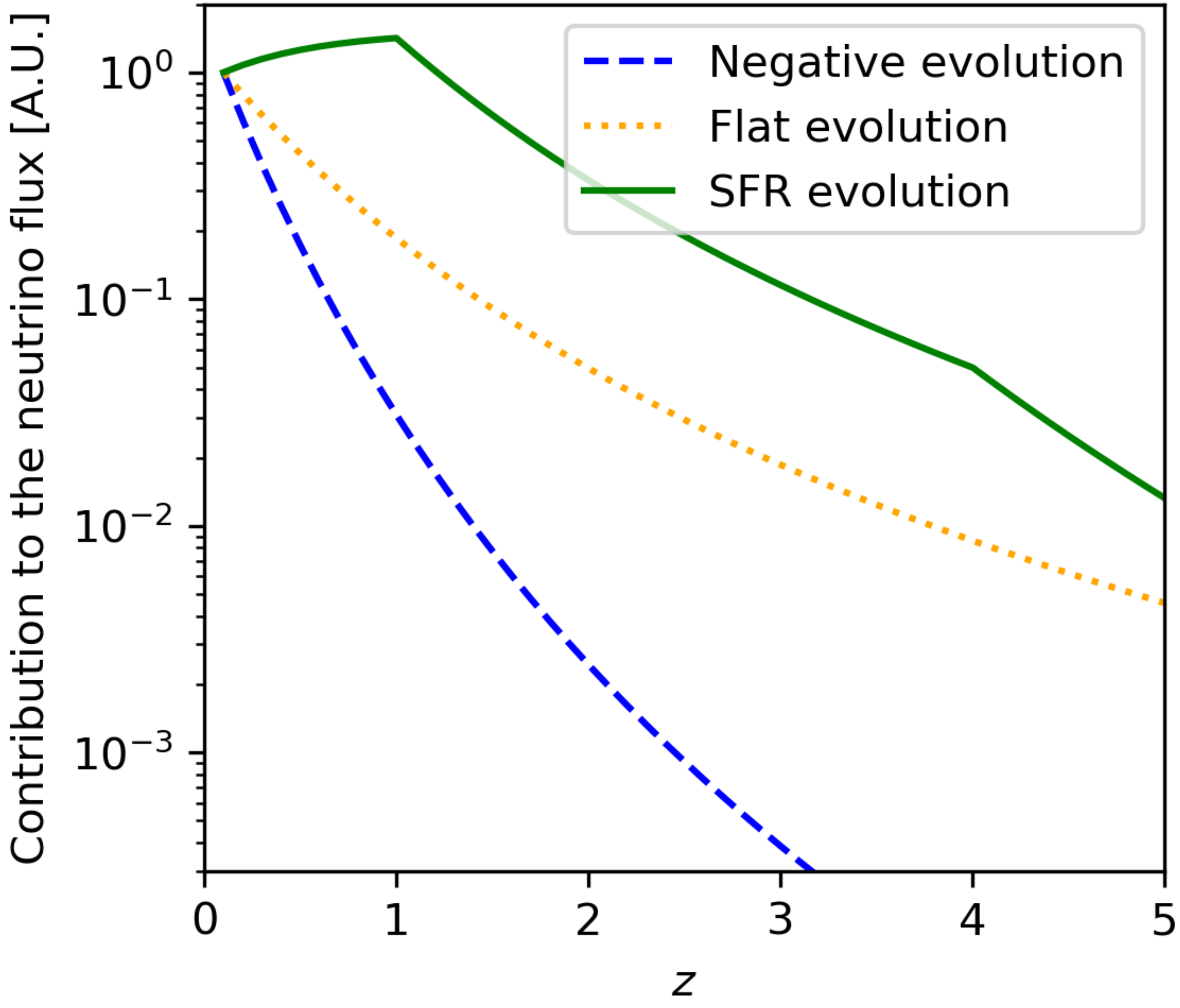


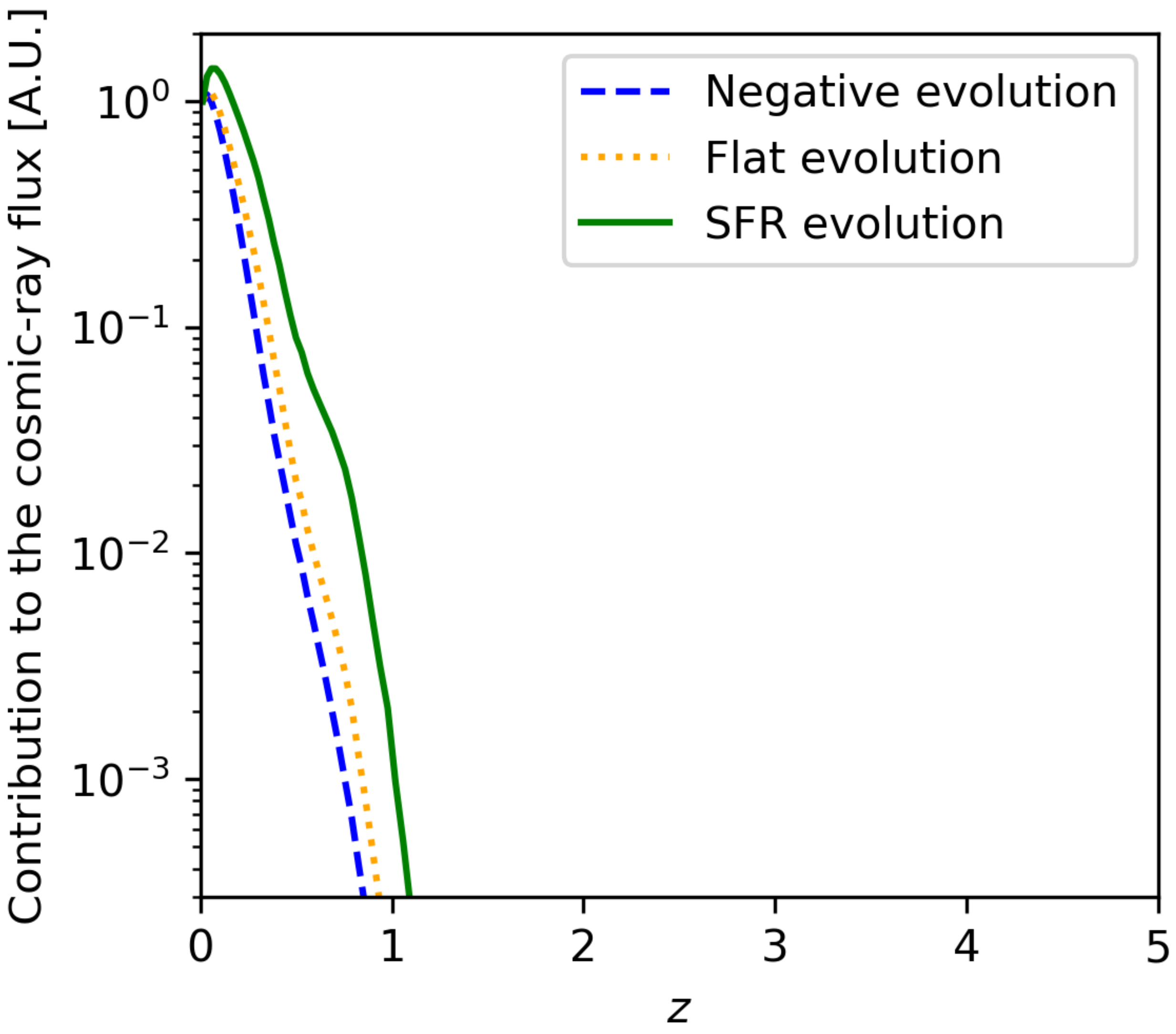
Energy losses of UHECRs

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

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

$\rho(z)$	γ	$R_{\max}/\mathrm{V}$	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

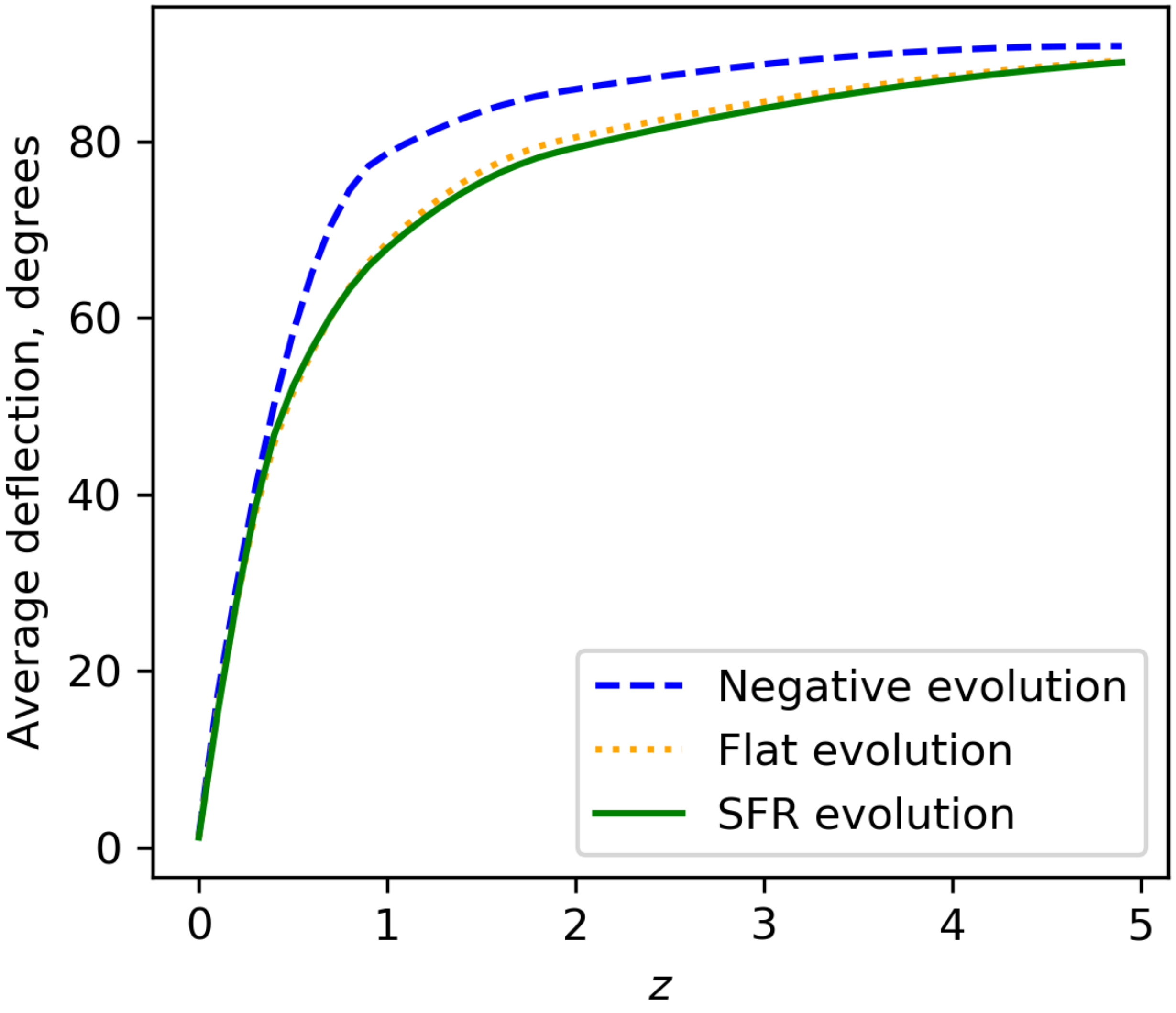
Auger, JCAP 04 (2017) 038
R. Alves Batista *et al.*, JCAP 01 (2019) 002



Deflections in extragalactic magnetic fields

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

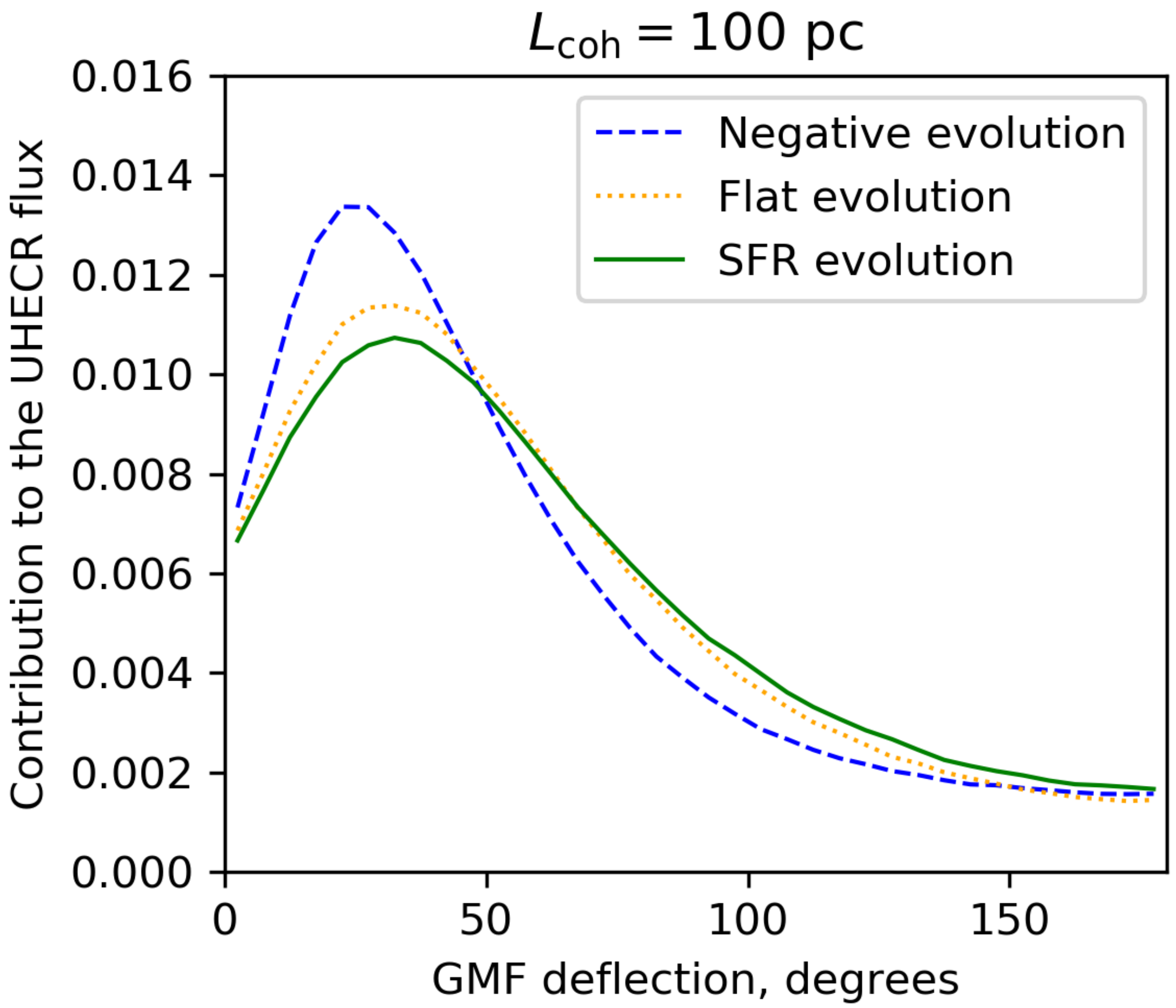
- Simulation with CRPropa, including all relevant interactions
- For E_{CR}>$10^{18.5}$ eV
- For scenarios that fit UHECR spectrum and composition of Auger
- In the weakest EGMF model of Hackstein *et al*. 2018



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
- Combined with rigidity distribution obtained from simulation with CRPropa

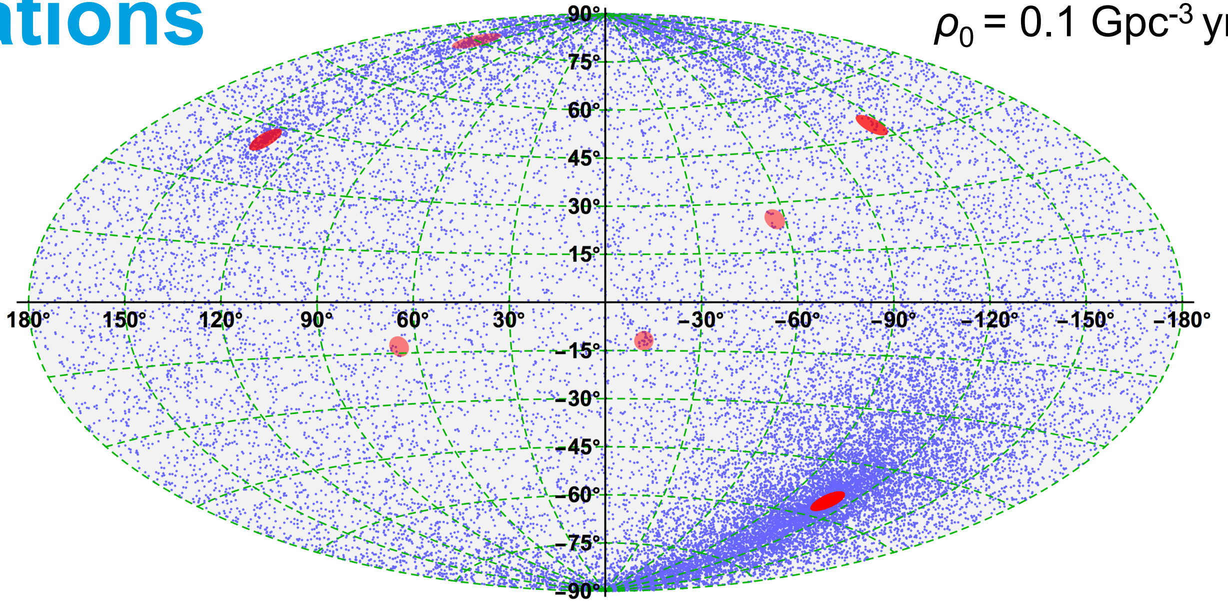


Calculation of expected correlations

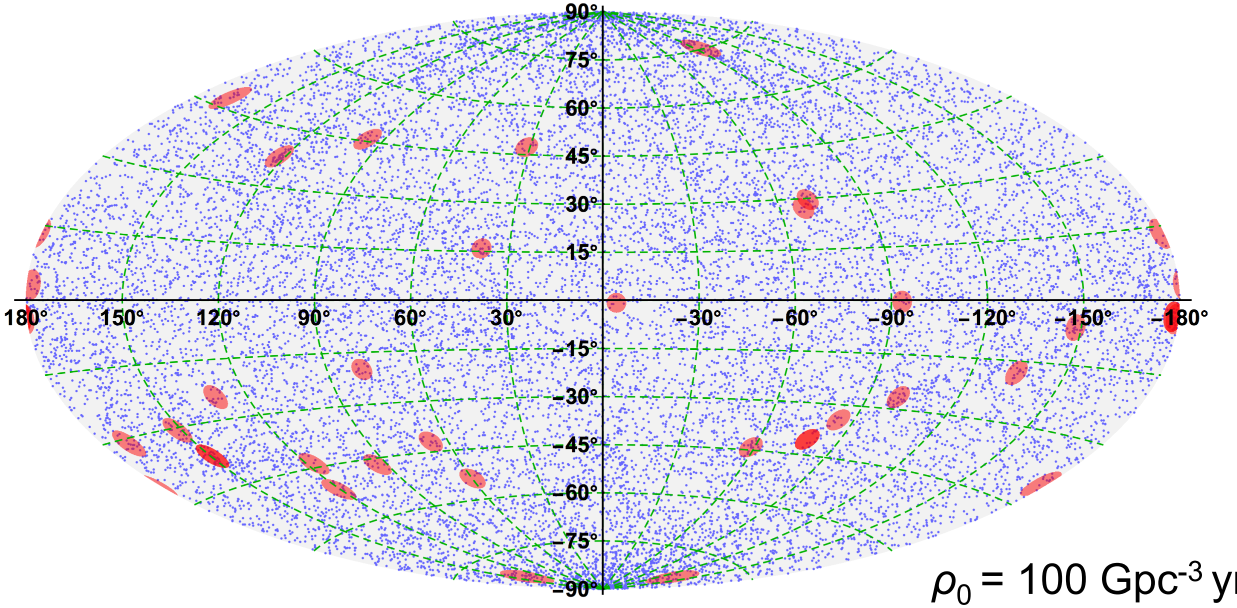
A. Palladino, **AvV**, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- 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

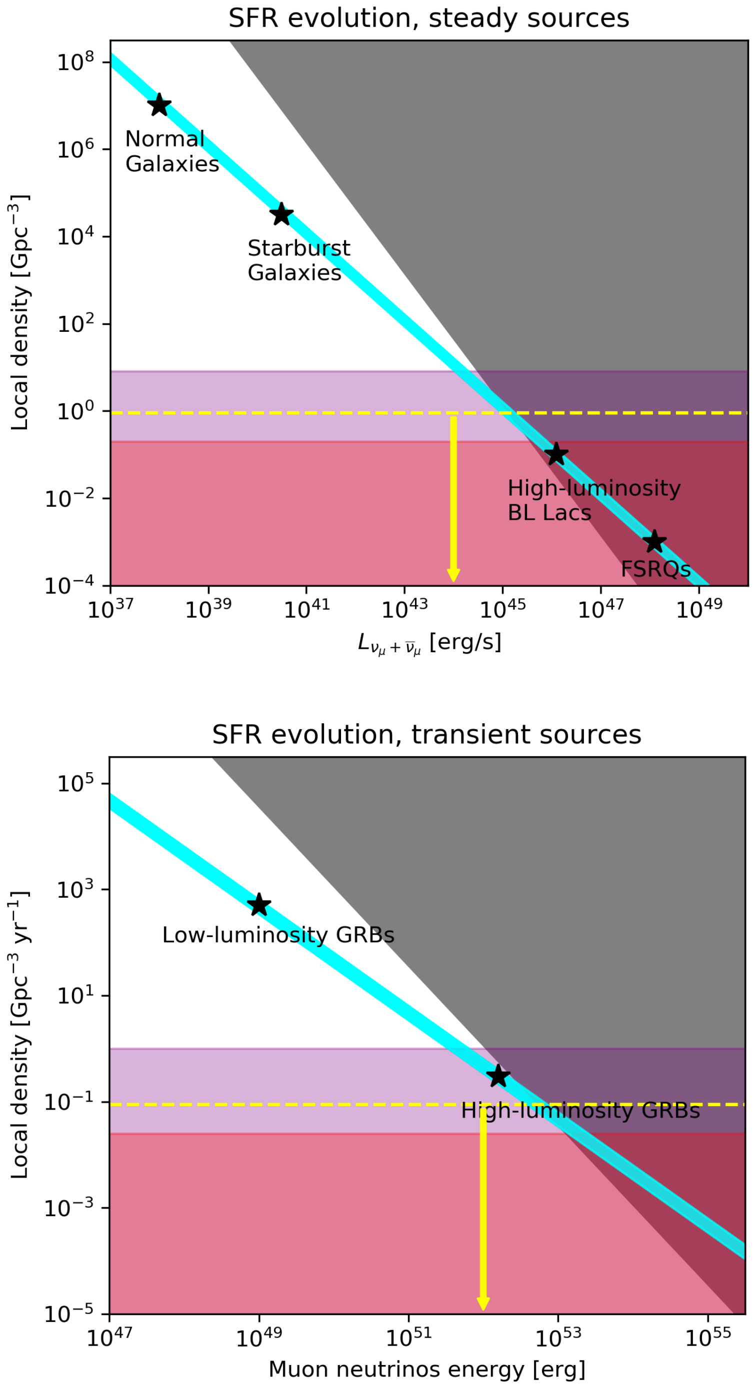


$\rho_0 = 100\ \mathrm{Gpc^{-3}\ yr^{-1}}$

Pure-proton scenario

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

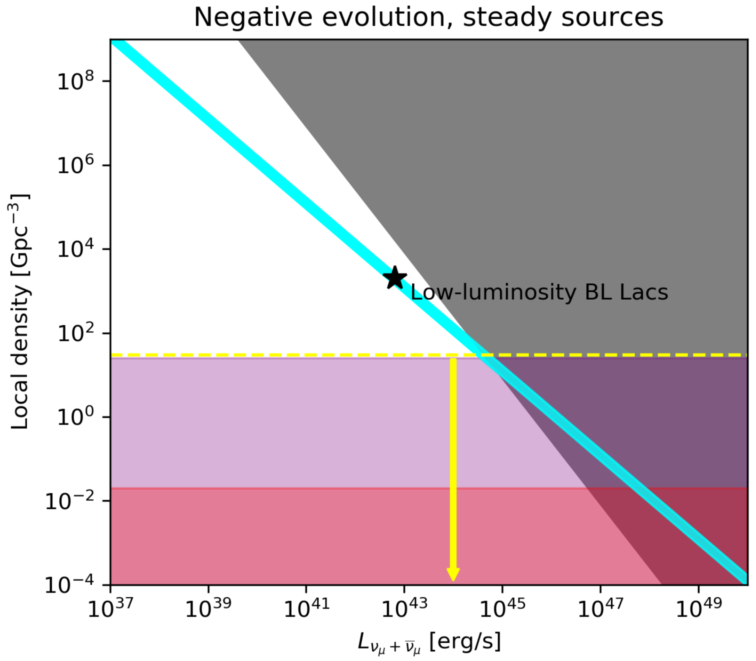
- Excluded by UHECR composition measurements, but instructive as most optimistic case for UHECR-neutrino correlations
- Even in this case, when the GMF is included, no UHECR-neutrino correlations are expected

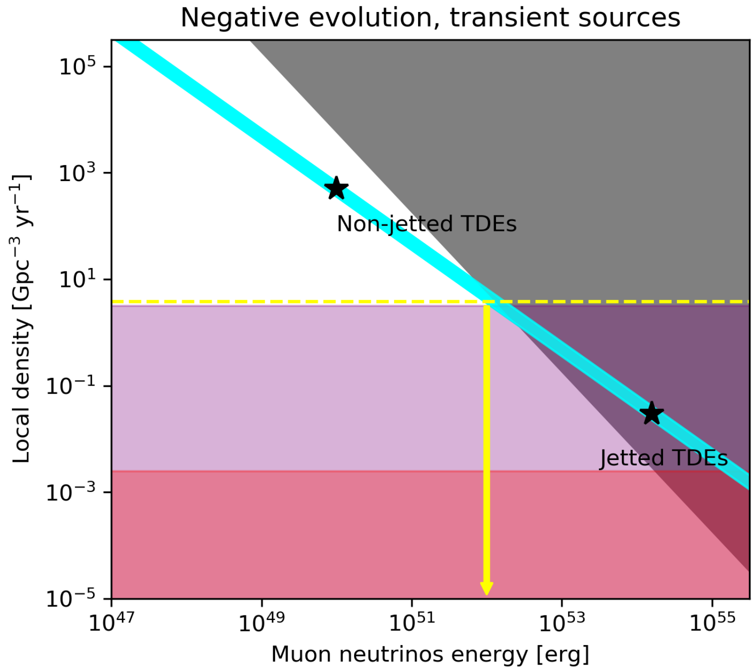


UHECRs with E > 50 EeV

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

- Higher energy threshold for UHECRs:
  - Less deflections
  - But also: less events and smaller source distances
- In this case even fewer UHECR-neutrino correlations are expected

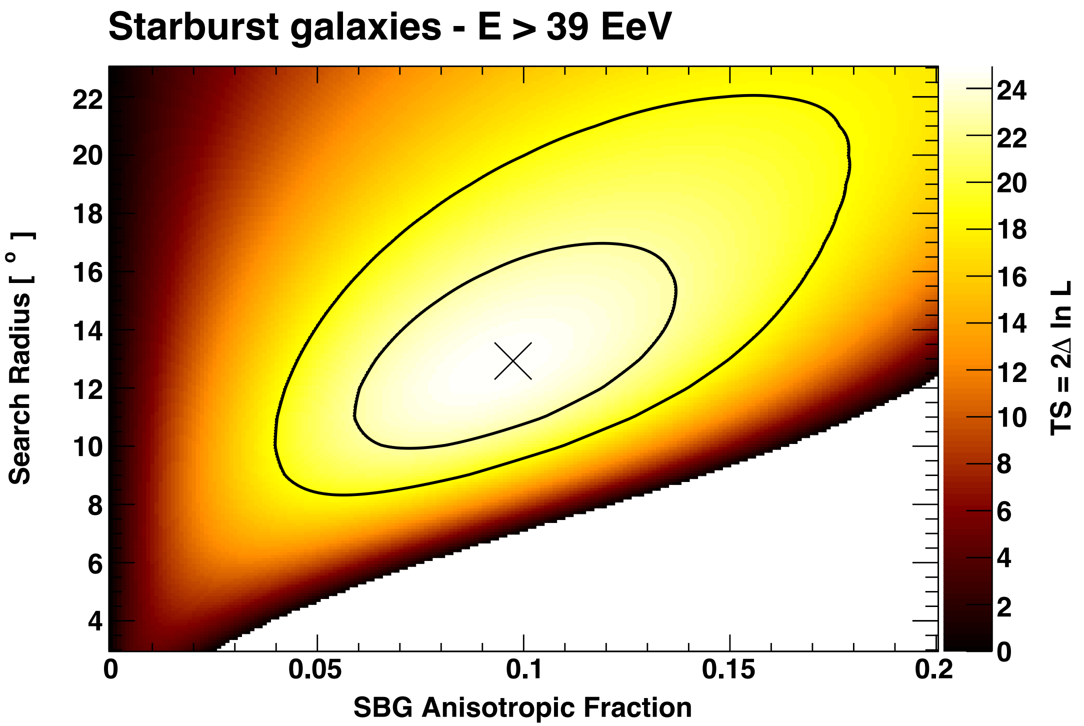




The analysis performed by Auger

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

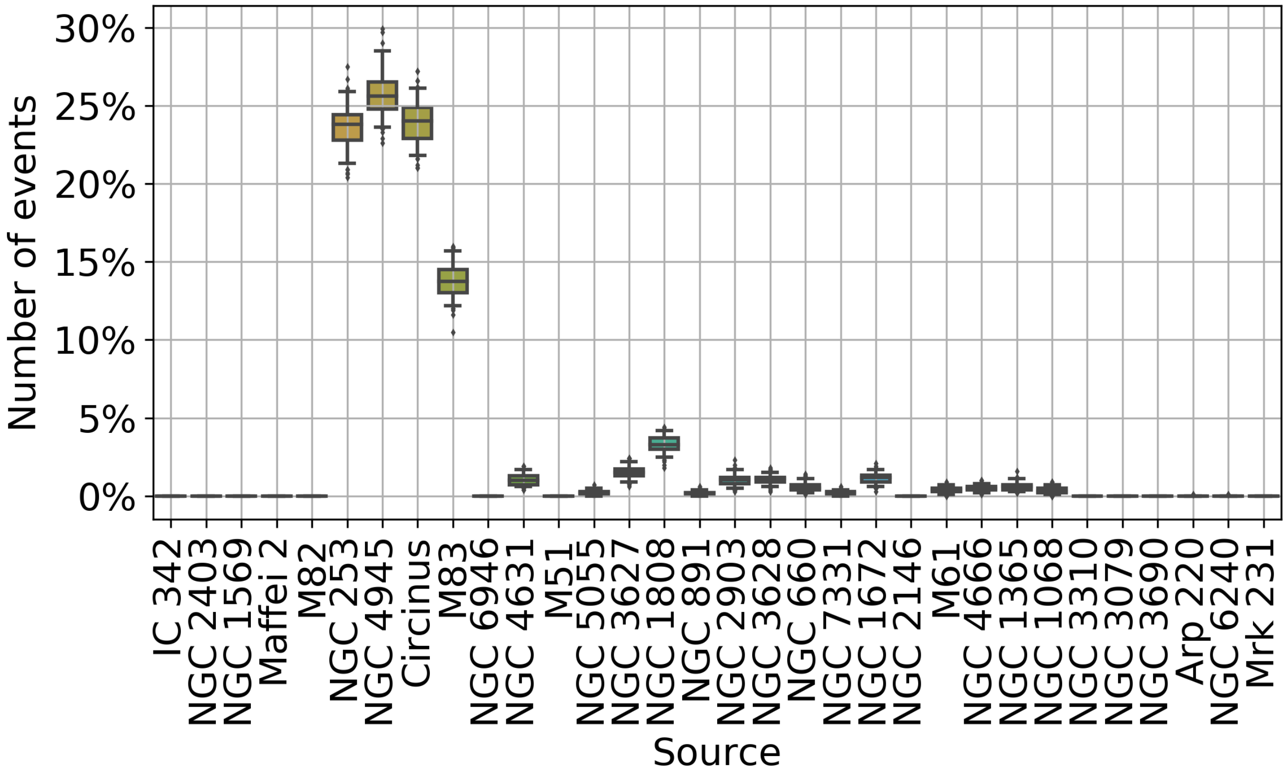


Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	15^{+5}_{-4}°	11^{+5}_{-4}%	29.5	4.5 σ
γ-AGNs	39 EeV	14^{+6}_{-4}°	6^{+4}_{-3}%	17.8	3.1 σ
Swift-Bat	38 EeV	15^{+6}_{-4}°	8^{+4}_{-3}%	22.2	3.7 σ
2MRS	40 EeV	15^{+7}_{-4}°	19^{+10}_{-7}%	22.0	3.7 σ

Source catalog

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 a diffuse contribution



UHECR spectrum and composition

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
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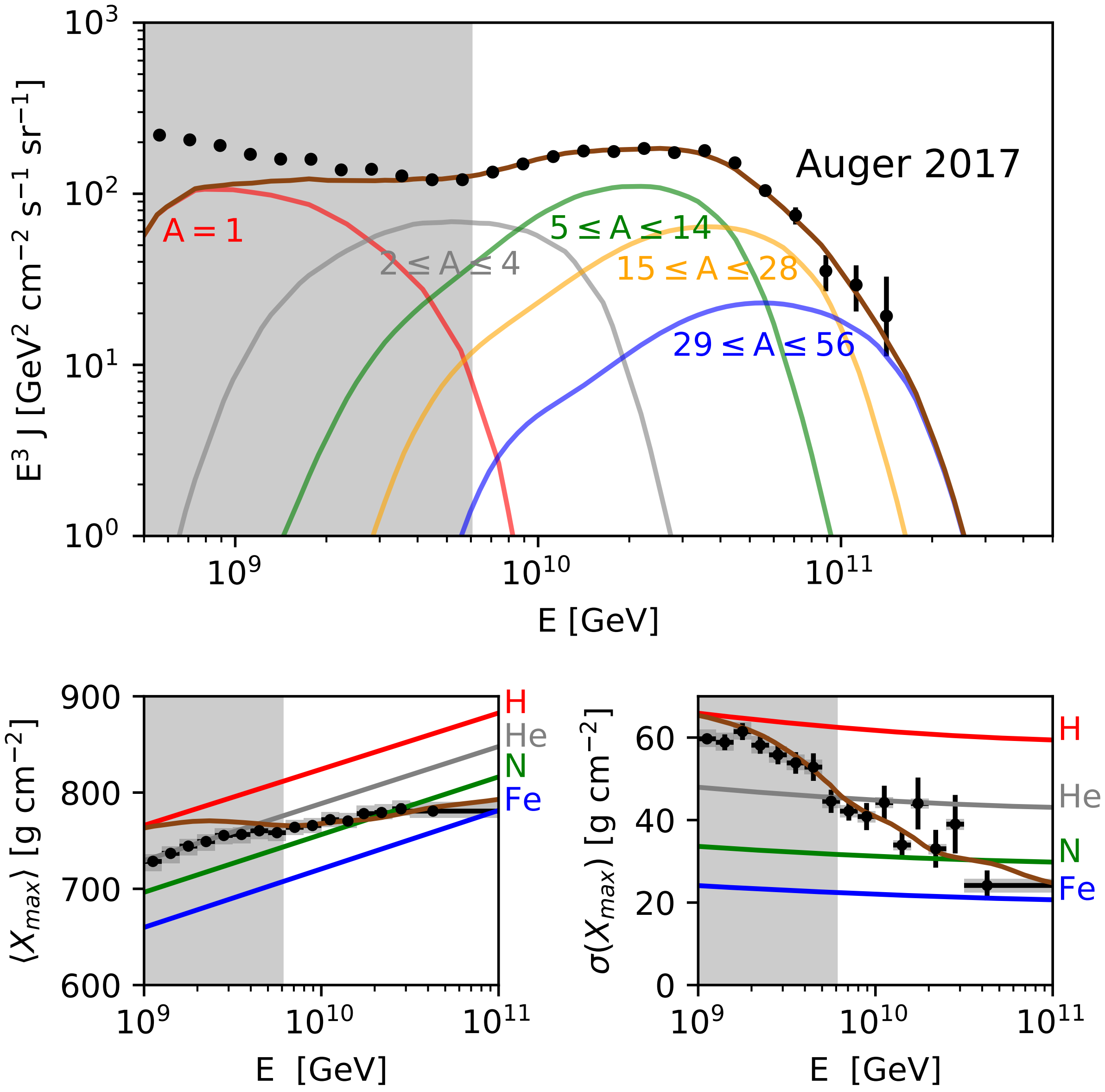

J. Heinze, A. Fedynitch, D. Boncioli and W. Winter, Astrophys. J. 873 (2019) 88

Deflections in magnetic fields

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
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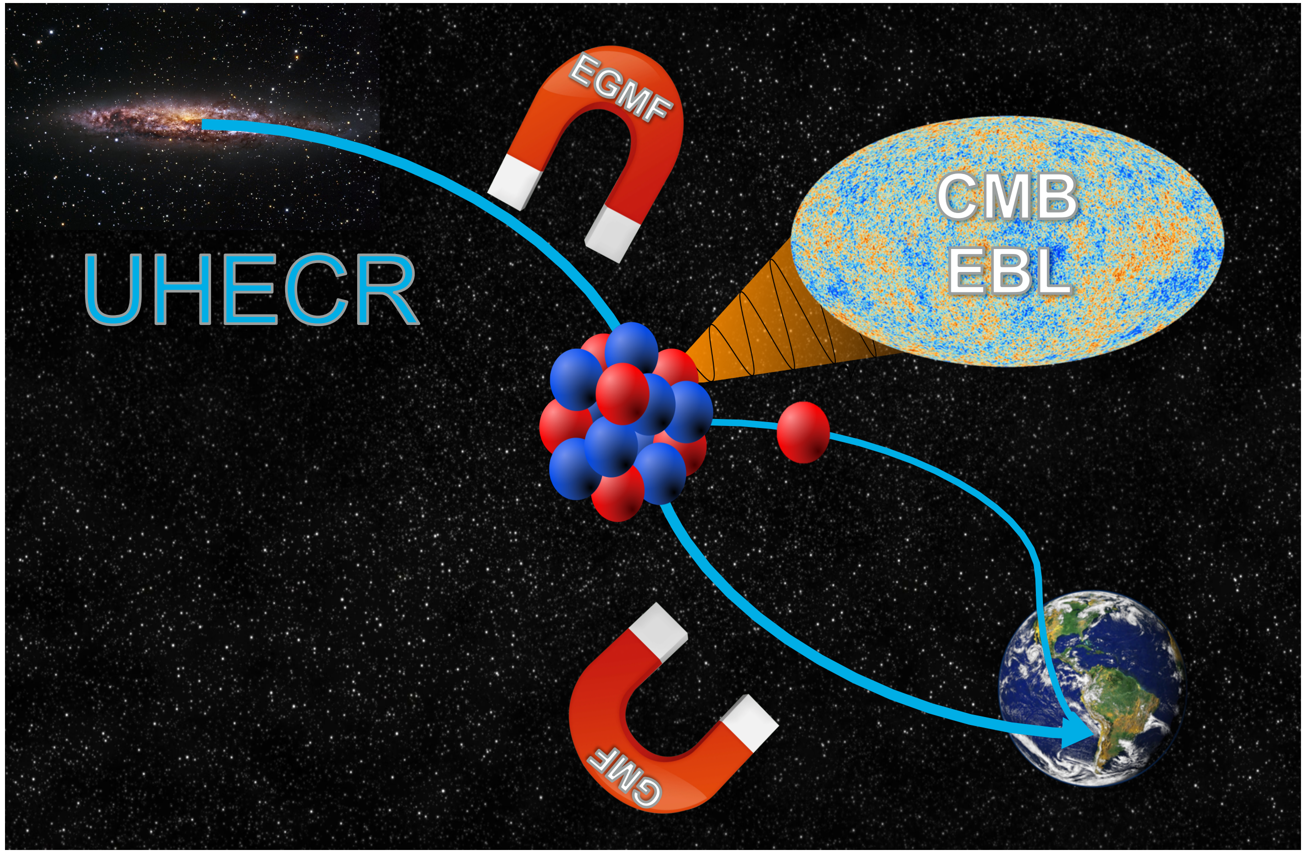

Our method

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

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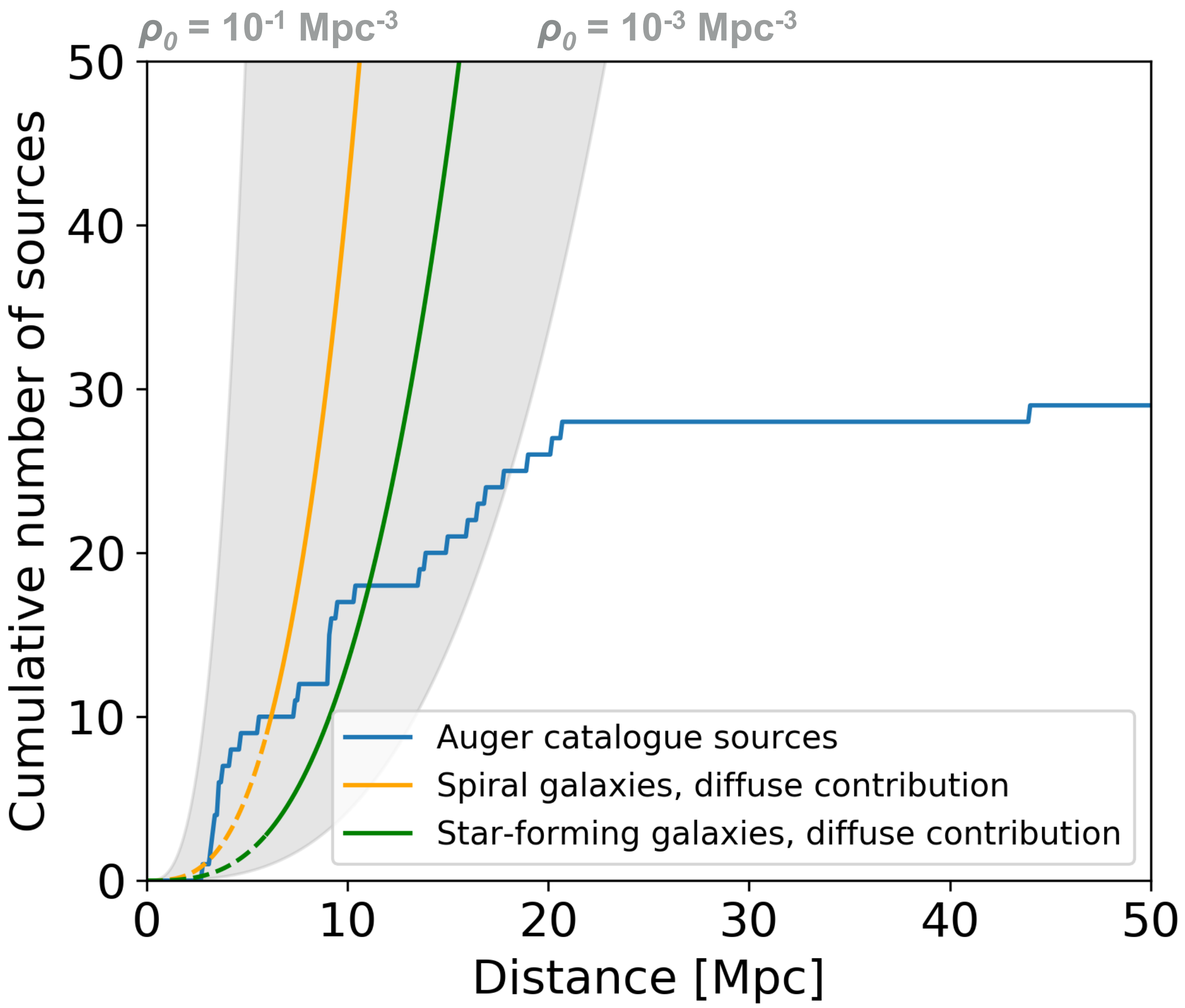
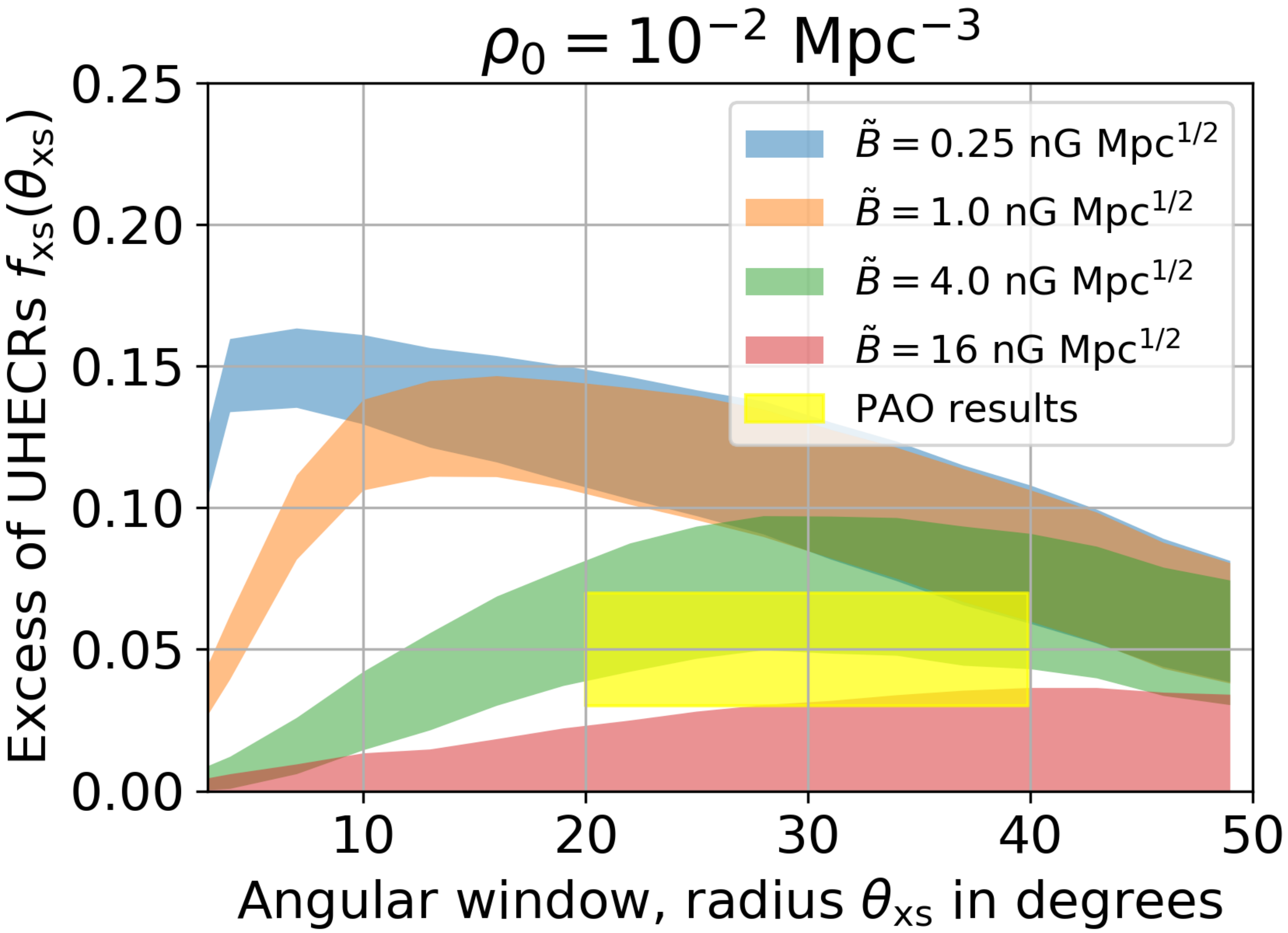


Compare with Auger results

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

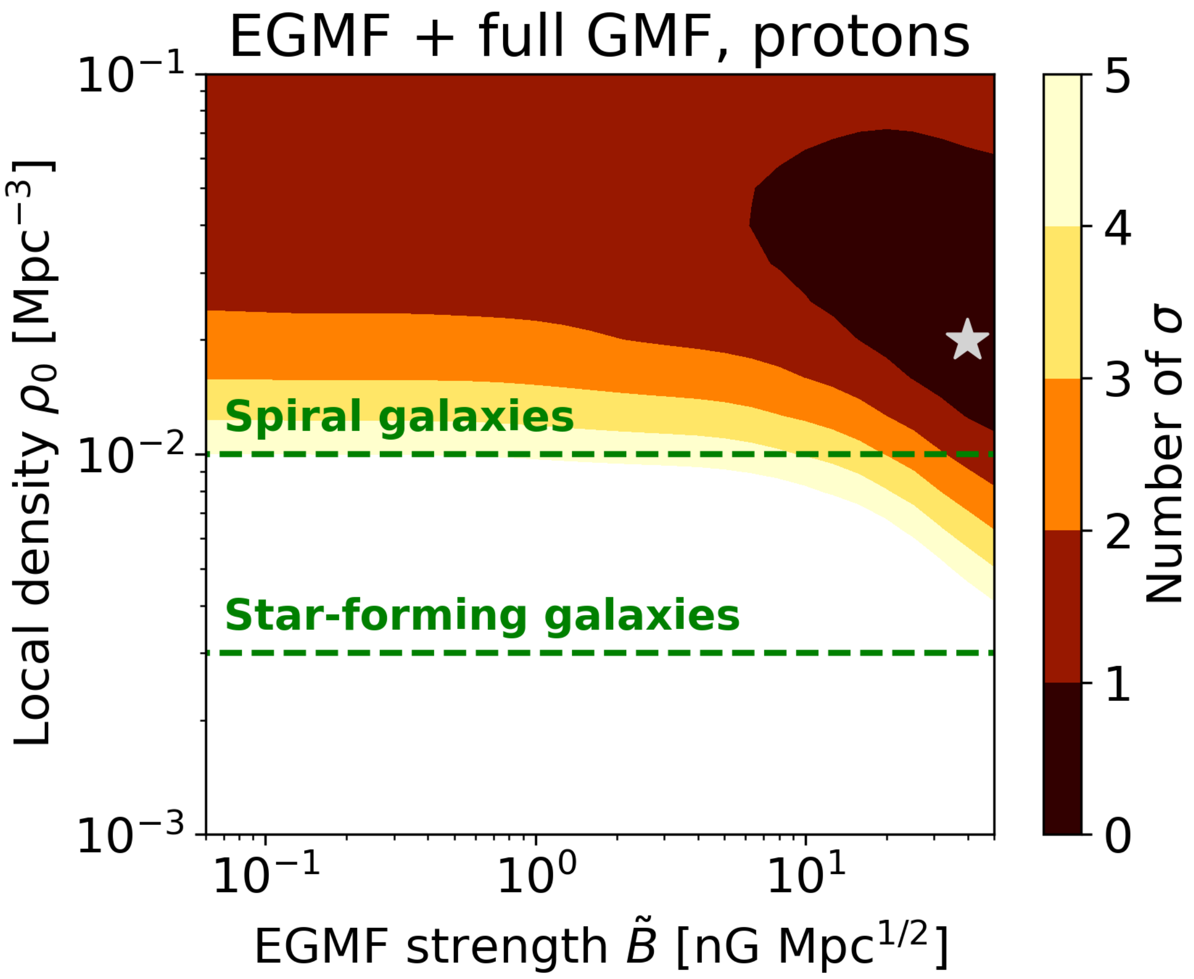
- For each simulated sky map we produce with our method we determine the optimal angular window θ_{xs} and maximum excess f_{xs} of UHECRs
- Compare with results of Auger analysis
- Scan over B and ρ_0
- 3 different scenarios:
  - EGMF only
  - EGMF + full GMF
  - EGMF + regular GMF



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



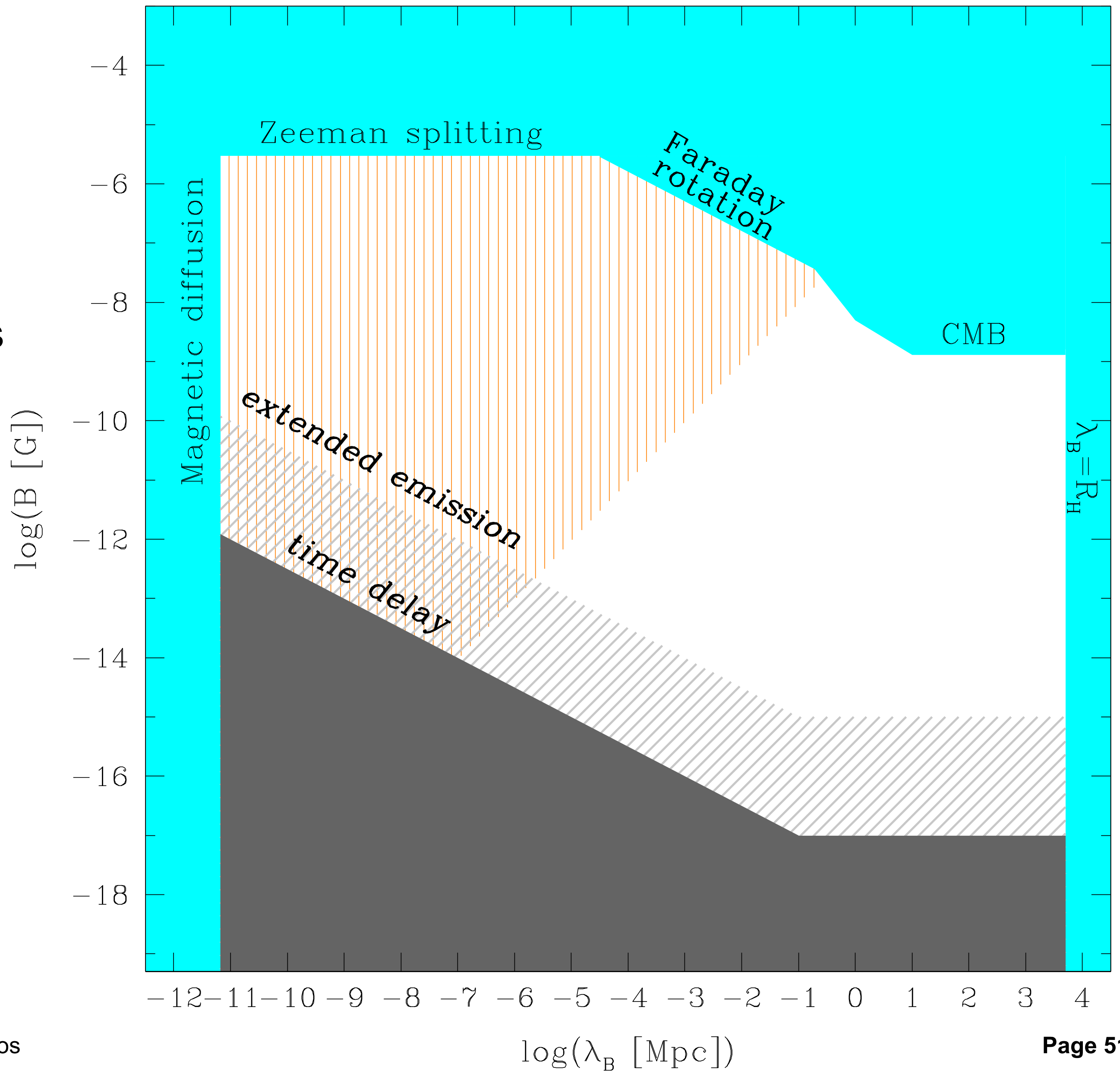
EGMF limits

- 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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