Ultra-high-energy cosmic rays and neutrinos, expectations from diffuse fluxes and arrival-direction correlations

Arjen van Vliet

UW-Madison, 15/04/2021

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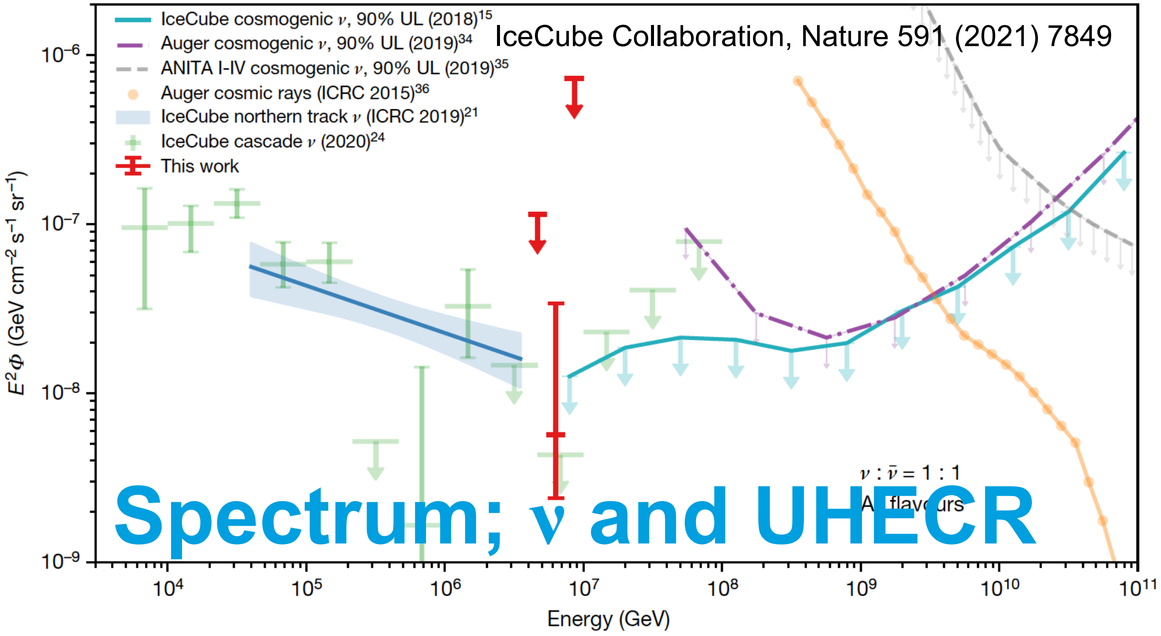
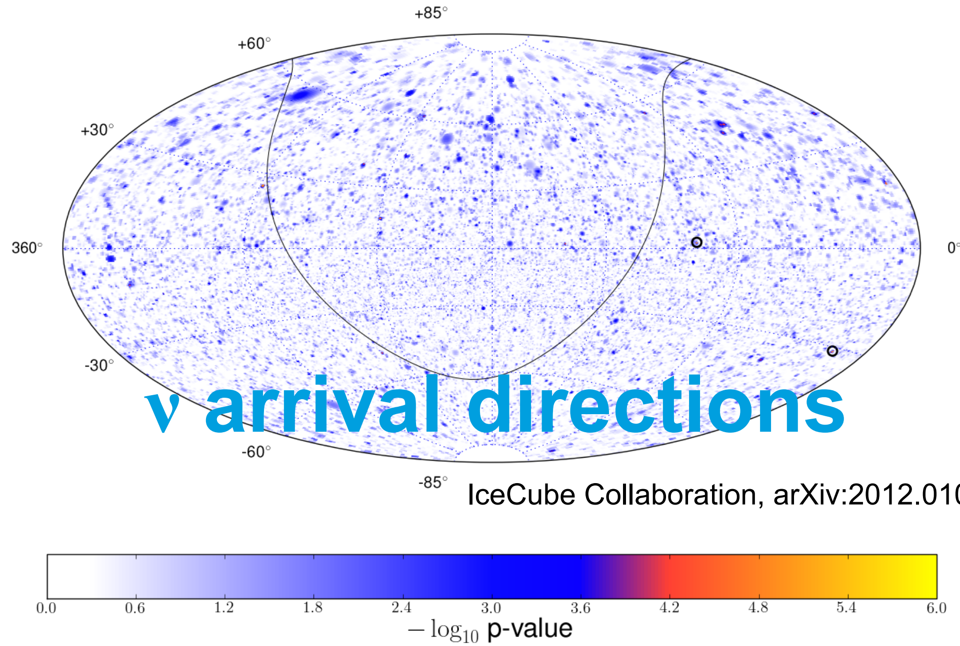
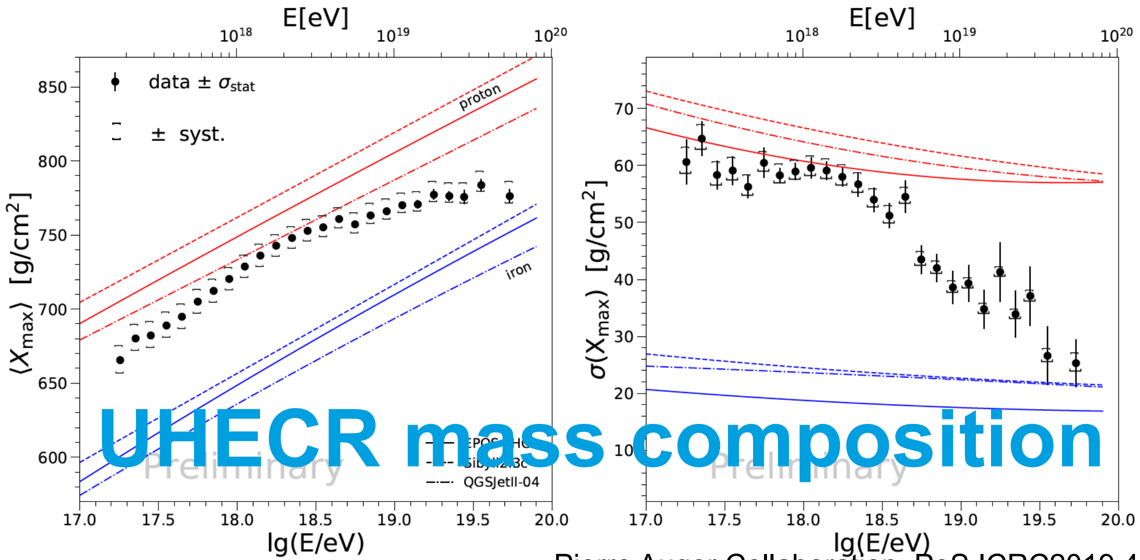
UHECRs and astrophysical neutrinos



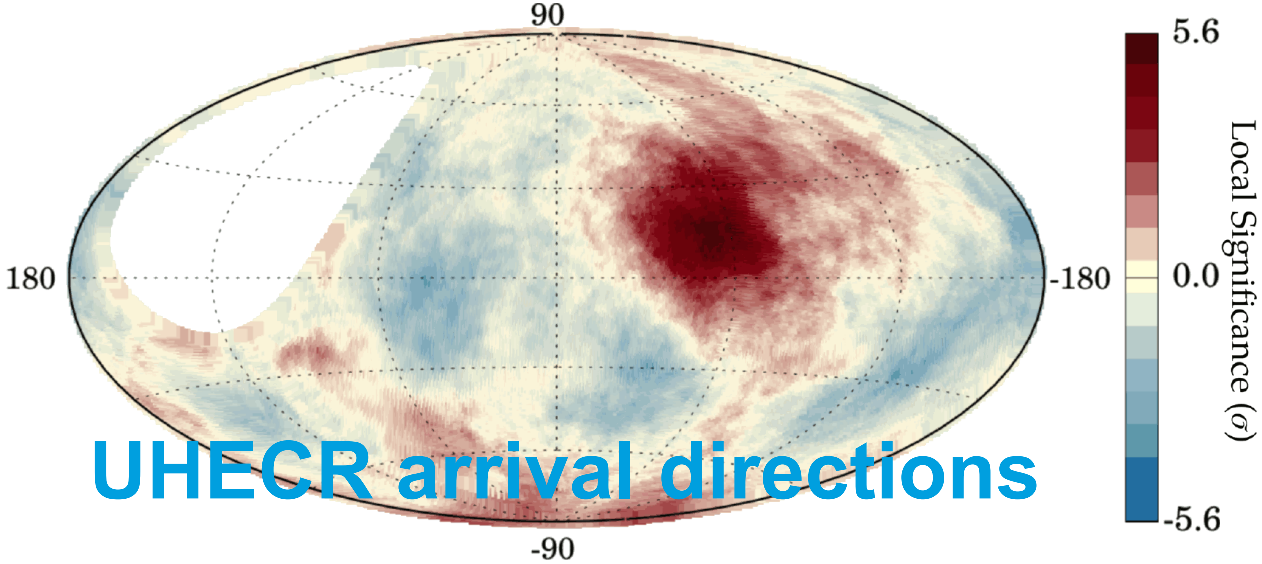
IceCube Collaboration, Nature 591 (2021) 7849



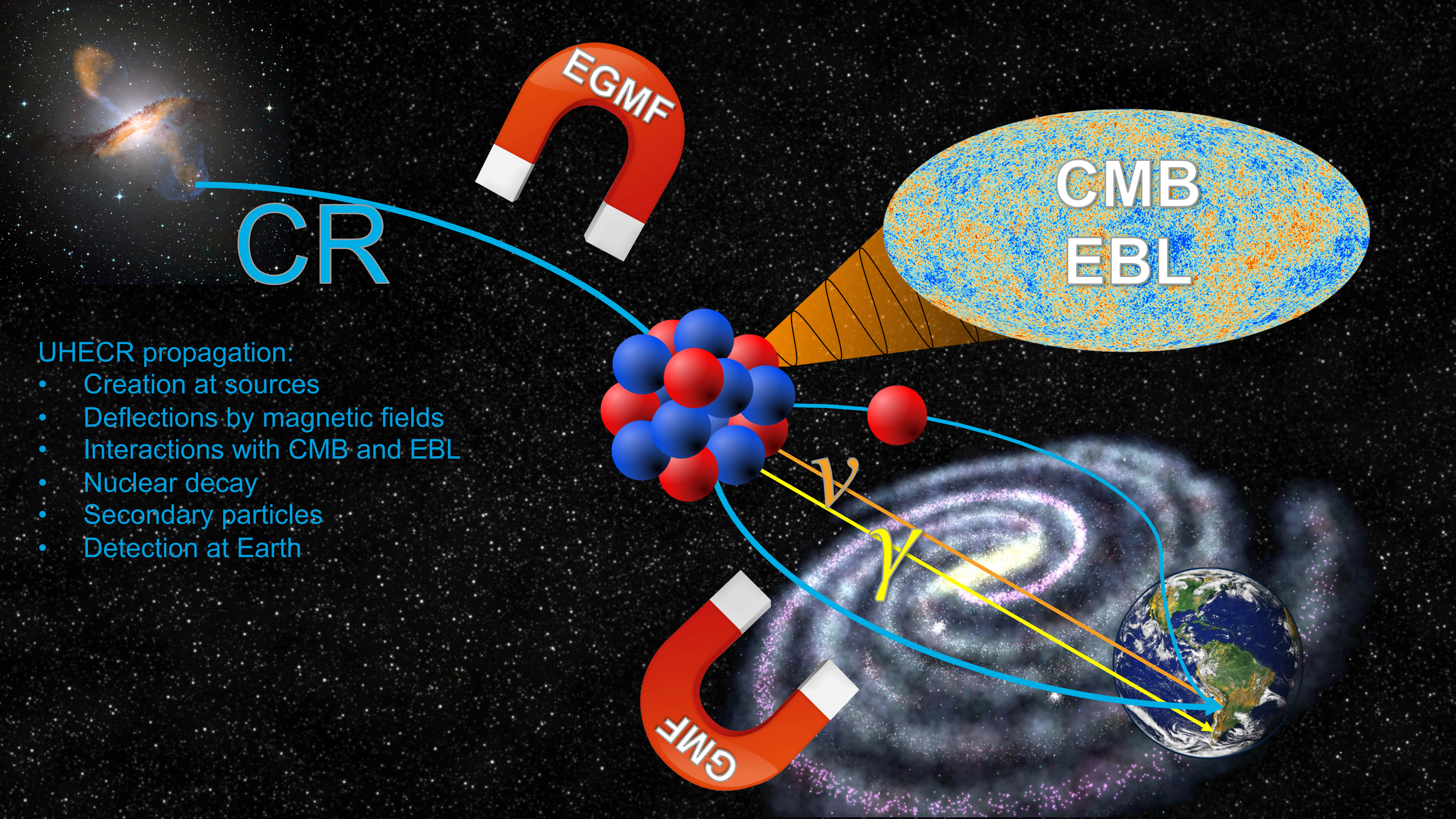
IceCube Collaboration, arXiv:2012.01079



Pierre Auger Collaboration, PoS ICRC2019 482



Pierre Auger Collaboration, PoS ICRC2019 206


EGMF
CMB
EBL
CR
UHECR propagation:
• Creation at sources
• Deflections by magnetic fields
• Interactions with CMB and EBL
• Nuclear decay
• Secondary particles
• Detection at Earth
ν
γ
GMF

Combined fit of UHECR spectrum and composition

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

  Power law with rigidity-dependent cut-off

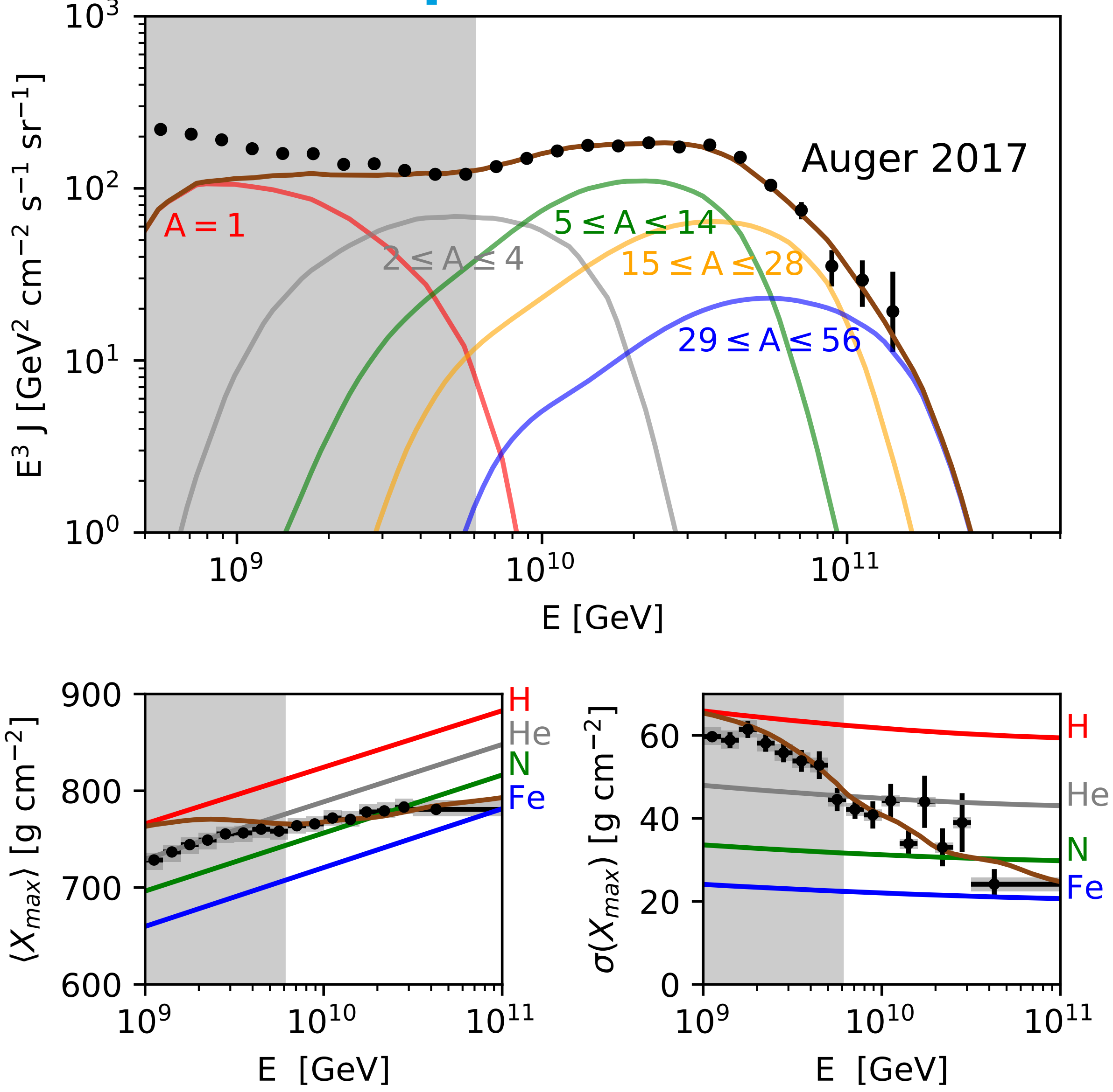
  $$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\alpha} \exp(-E / ZR_{\mathrm{max}})$$

- Emitted particles: p, He, N, Si, Fe
- $\alpha < 1.3$, hard spectral index
- $R_{\mathrm{max}} < 7$ 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

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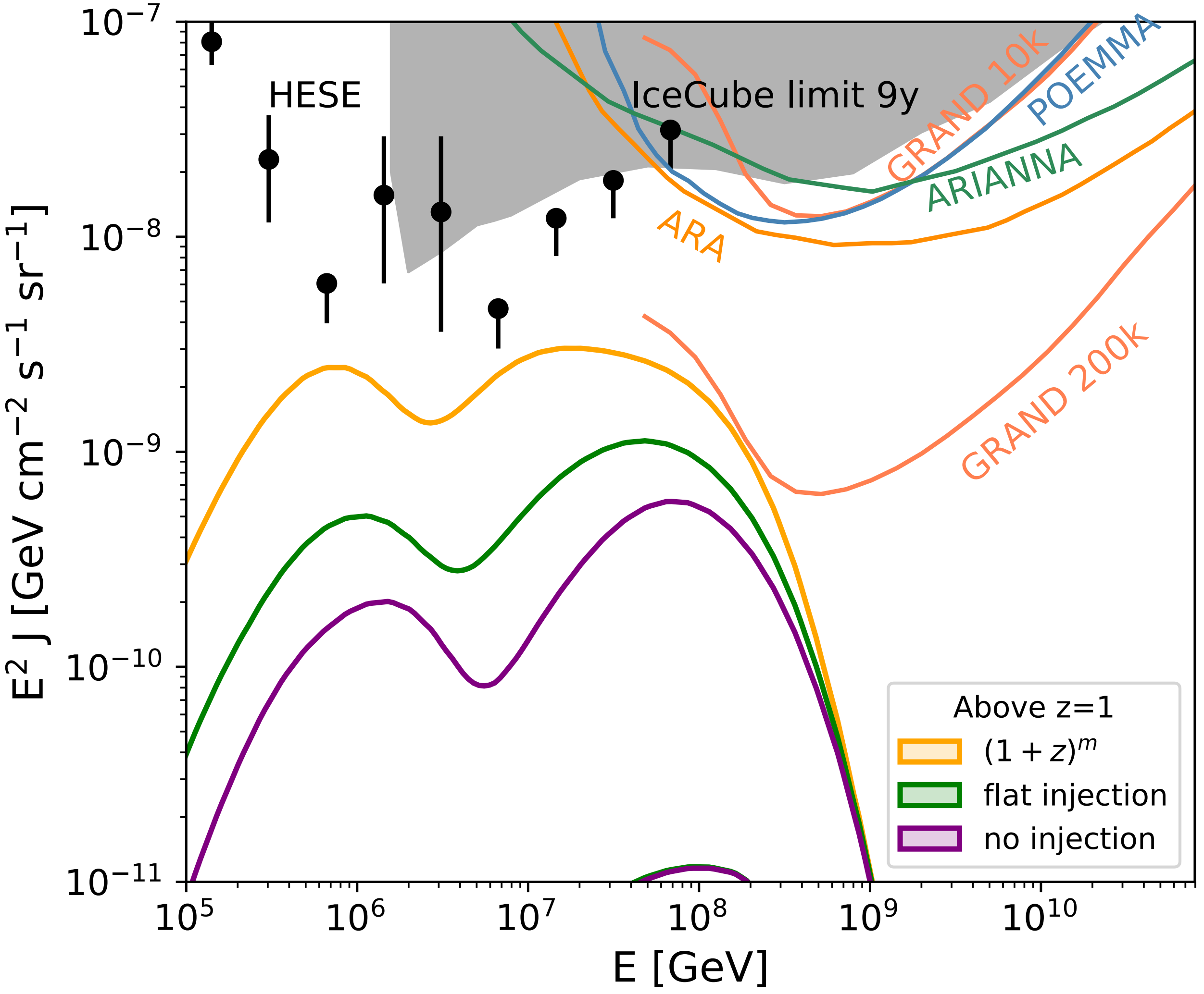
- **Very low cosmogenic neutrino flux**



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

Combined fit of UHECR spectrum and composition

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

  Power law with rigidity-dependent cut-off

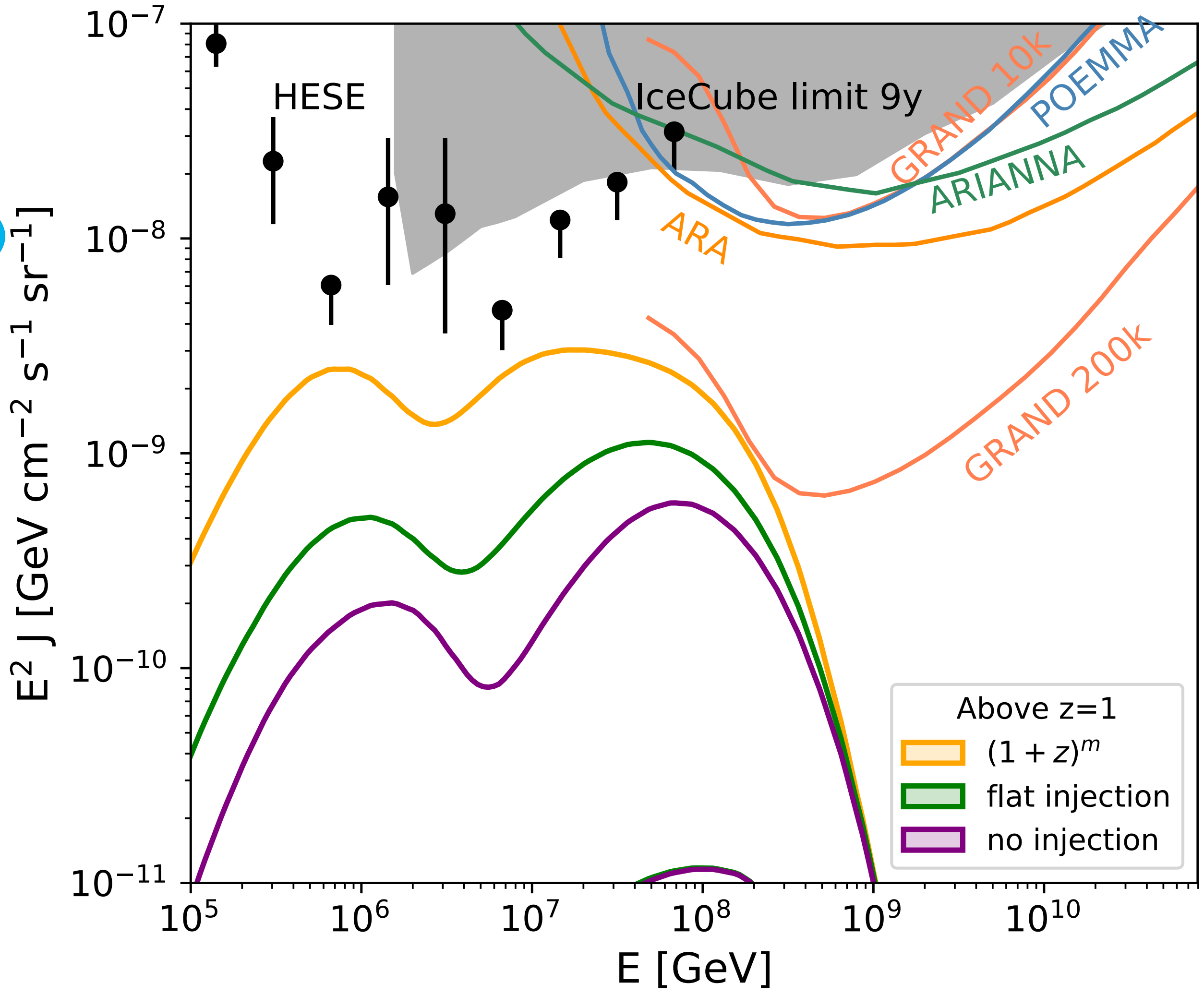
  $$\frac{dN}{dE} \propto E^{-\alpha} \exp(-E / Z R_{max})$$

- $\alpha < 1.3$, hard spectral index
- $R_{max} < 7$ 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)



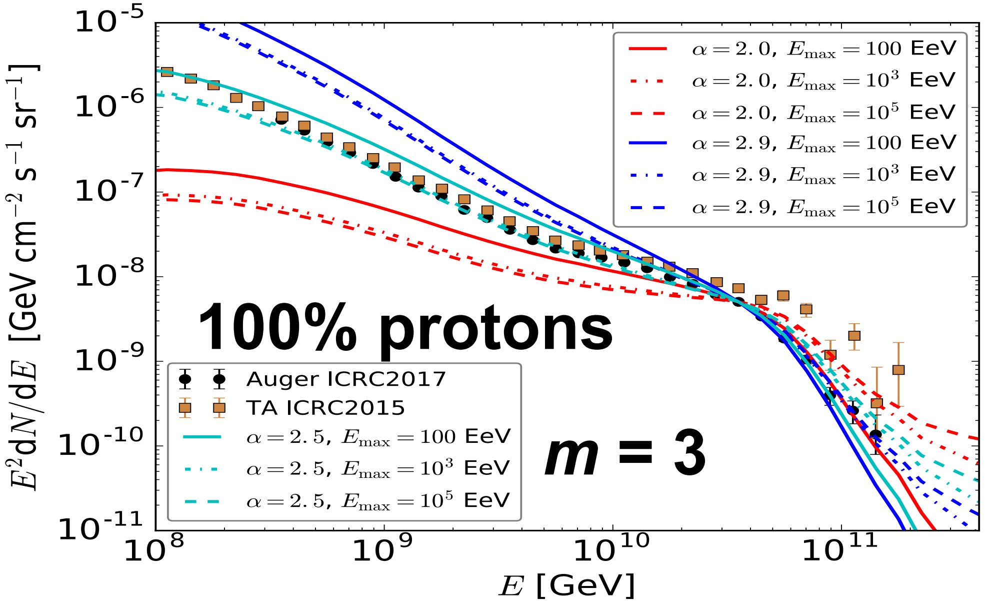
J. Heinze, A. Fedynitch, D. Boncioli and W. Winter, Astrophys. J. 873 (2019) 88

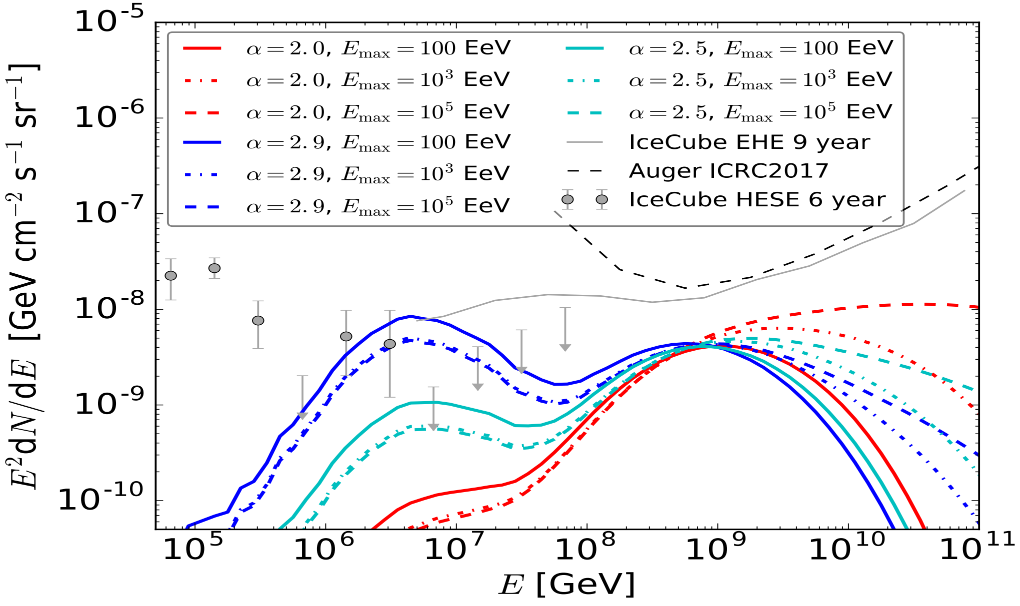
Neutrinos at ~1 EeV

- 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)

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

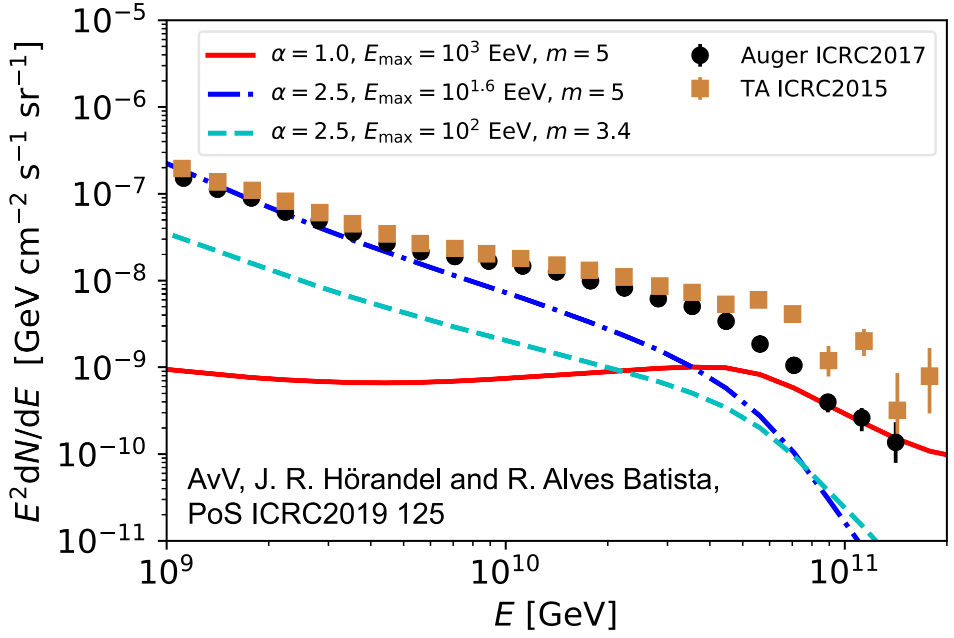
AvV, J. R. Hörandel and R. Alves Batista, PRD 100 (2019) 021302(R)

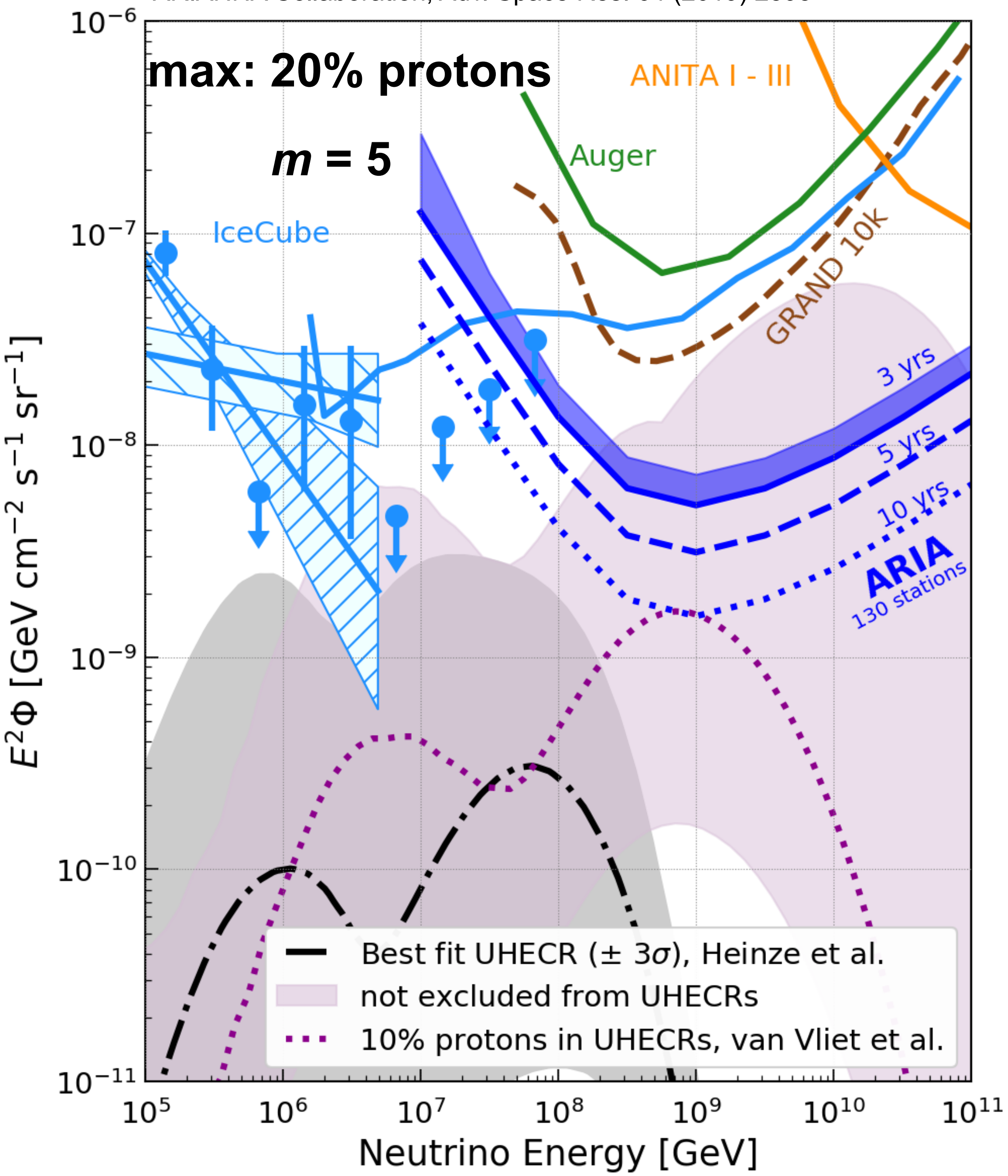




Neutrinos from subdominant proton component

- Cosmogenic neutrino flux for:
  - $1.0 < \alpha < 2.5$
  - $10^{1.6} < E_{max} < 10^3$ EeV
  - EBL model: Franceschini ’08
  - proton fraction $f < 0.2$ at $10^{1.6}$ EeV
  - $m < 5$



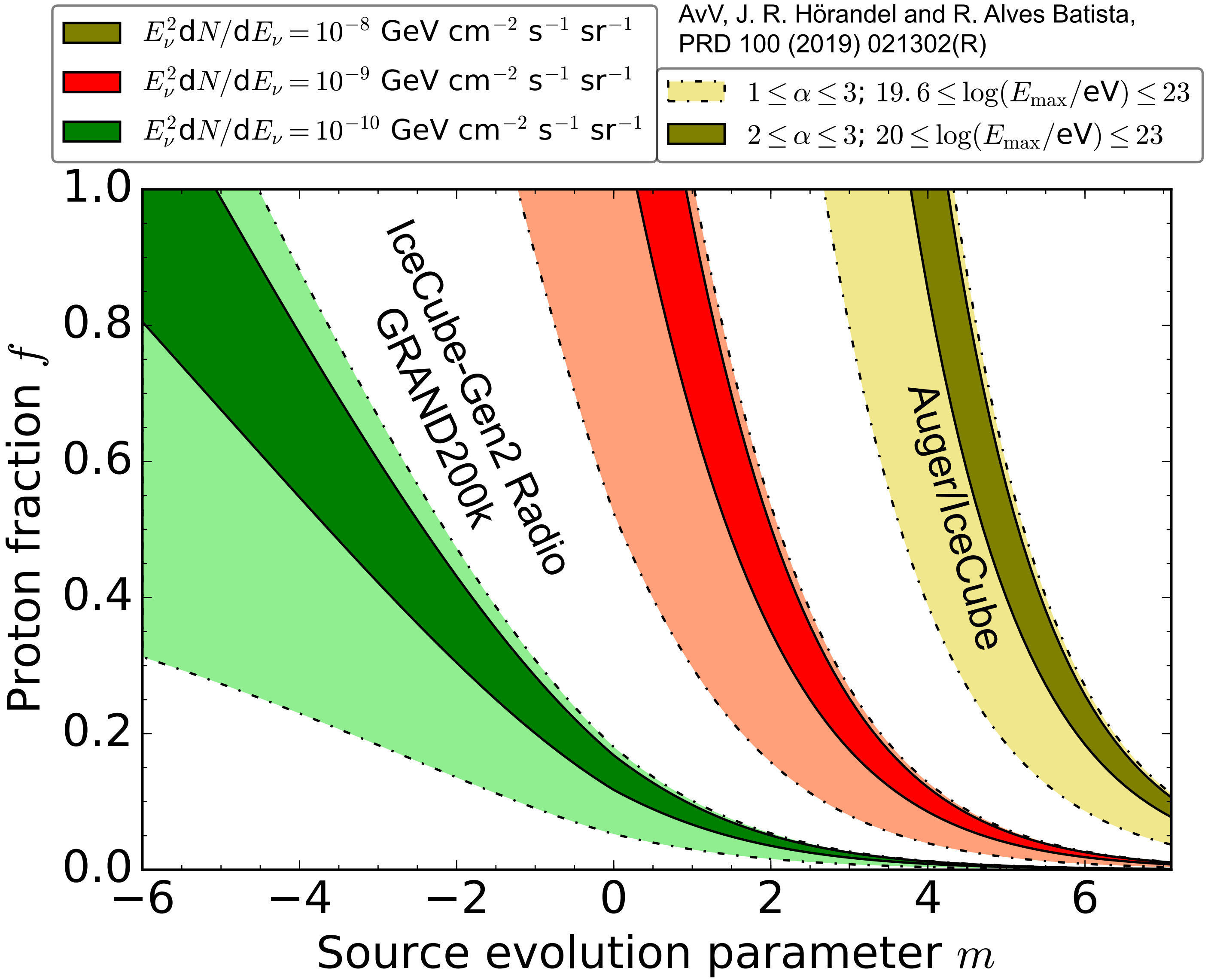


Proton fraction vs. source evolution

- Single-flavour neutrino flux at ~1 EeV
- Auger and IceCube are both close to $\sim 10^{-8}$ 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)

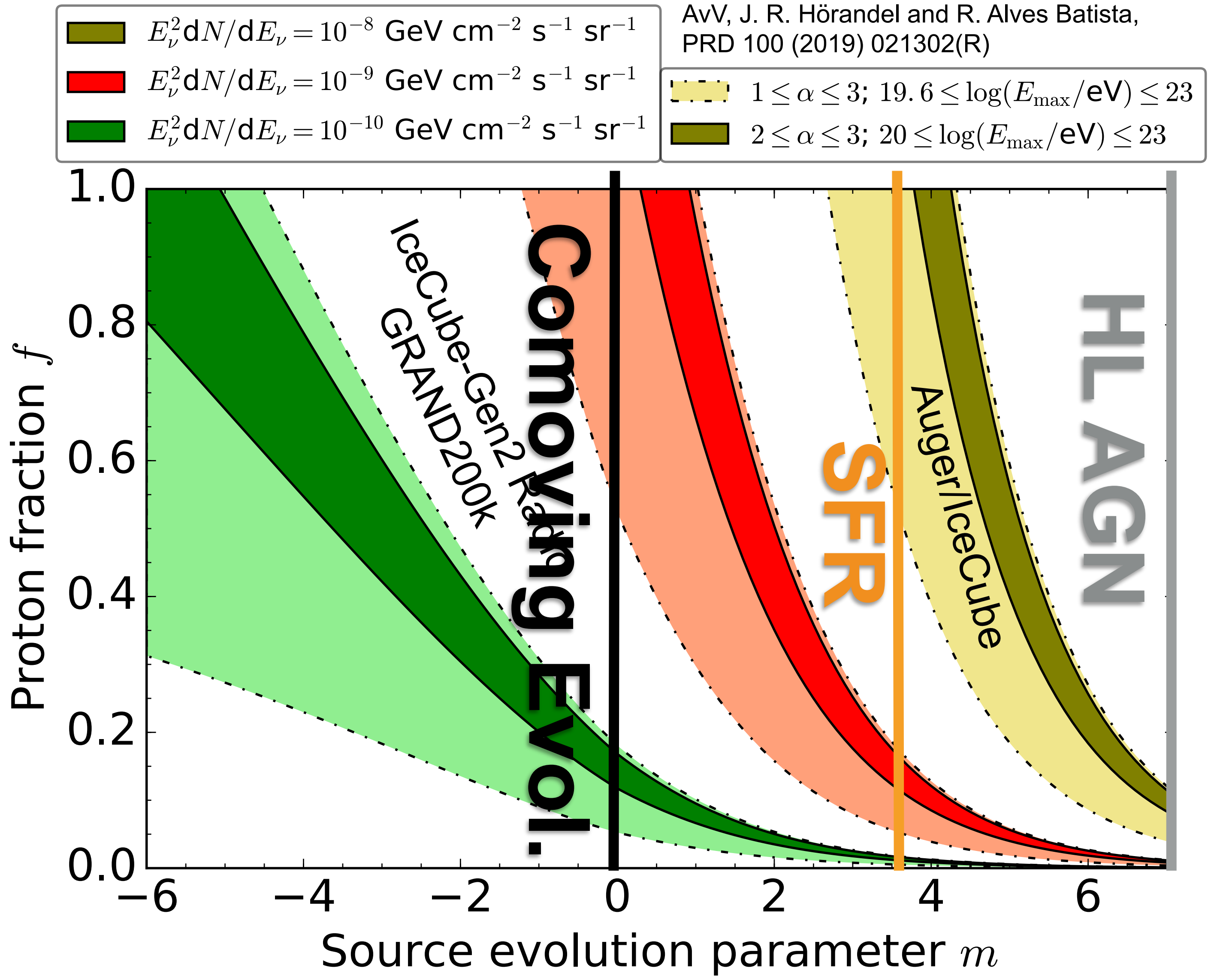


Proton fraction vs. source evolution

- 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

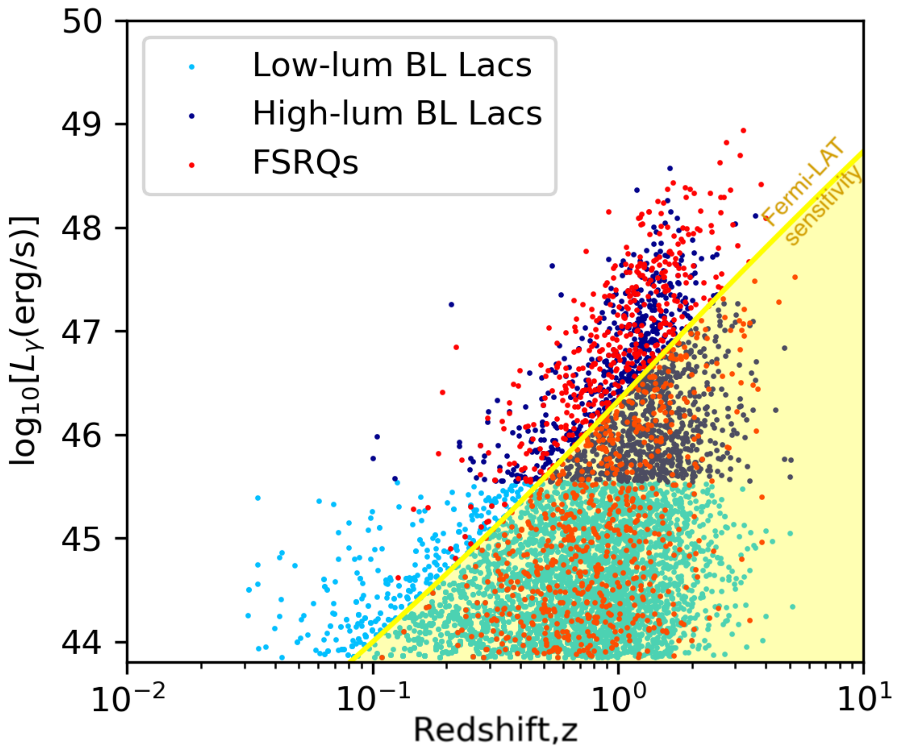
AvV, J. R. Hörandel and R. Alves Batista, PRD 100 (2019) 021302(R)

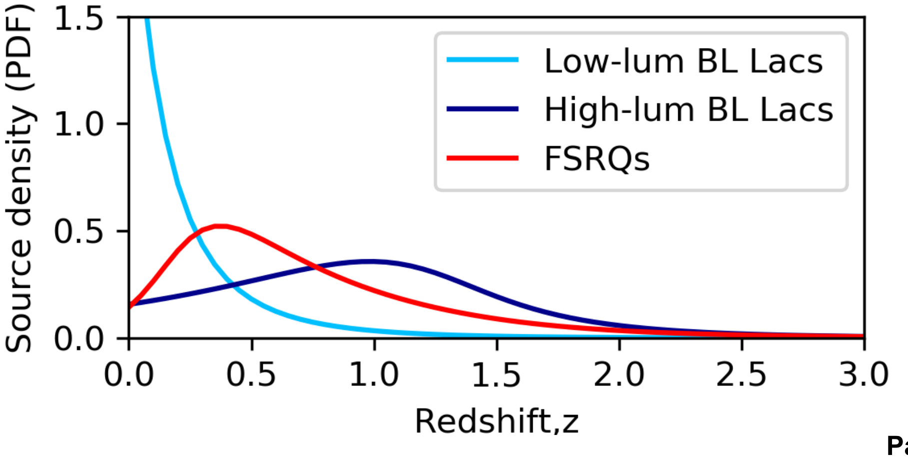


UHECRs and neutrinos from AGN

- 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, arXiv:2003.08392, accepted for publication in PRL

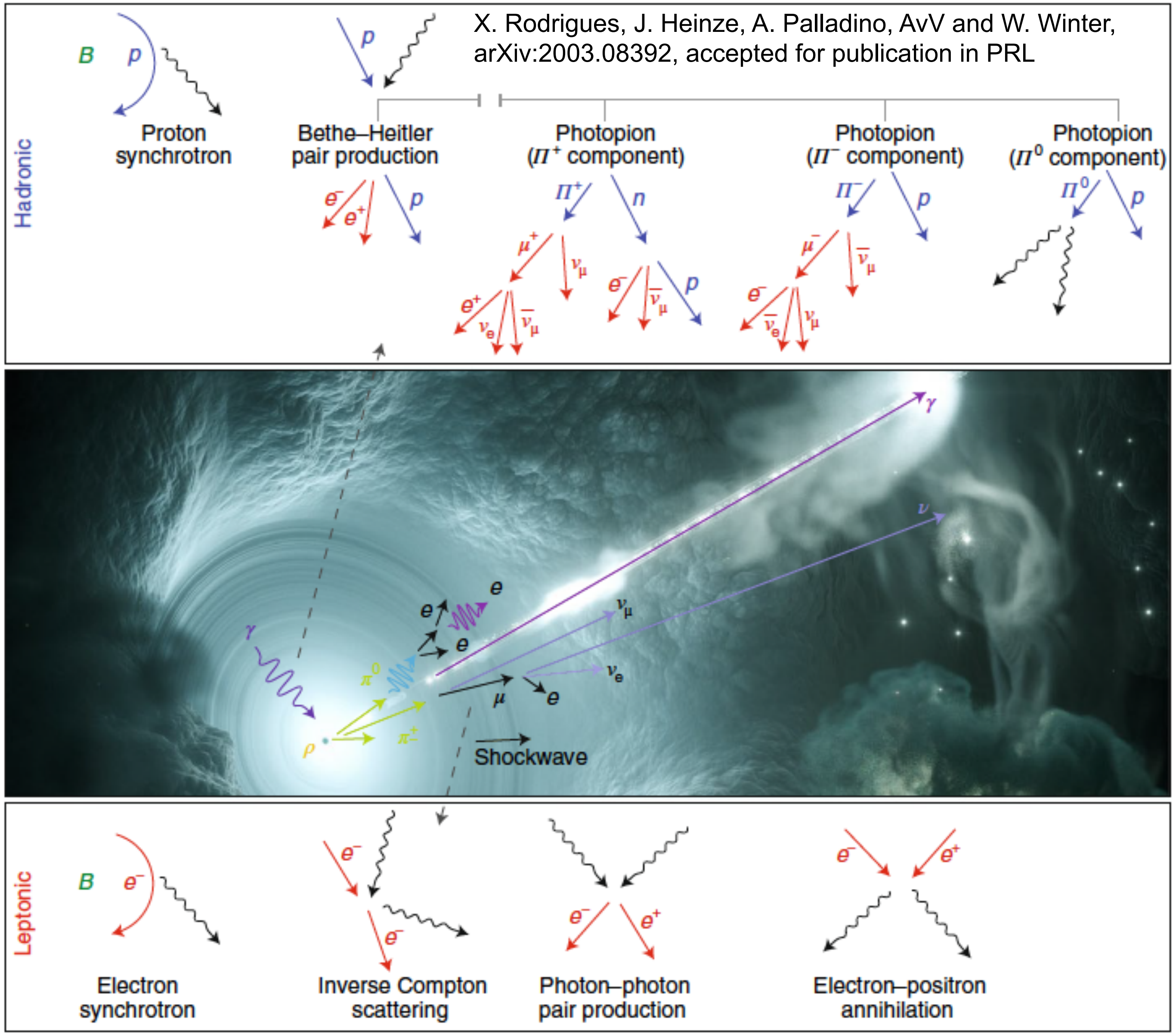




UHECRs and neutrinos from AGN

Low-luminosity BL Lacs vs. FSRQs

- Low-luminosity BL Lacs:
  - Low photon density
  - Efficient UHECR emitters
  - Inefficient neutrino emitters
  - Rigidity-dependent maximal energy
- FSRQs (and high-luminosity BL Lacs):
  - High photon density
  - Efficient photohadronic interactions
  - Abundant neutrino production
  - Light UHECR composition emitted



UHECRs and neutrinos from AGN

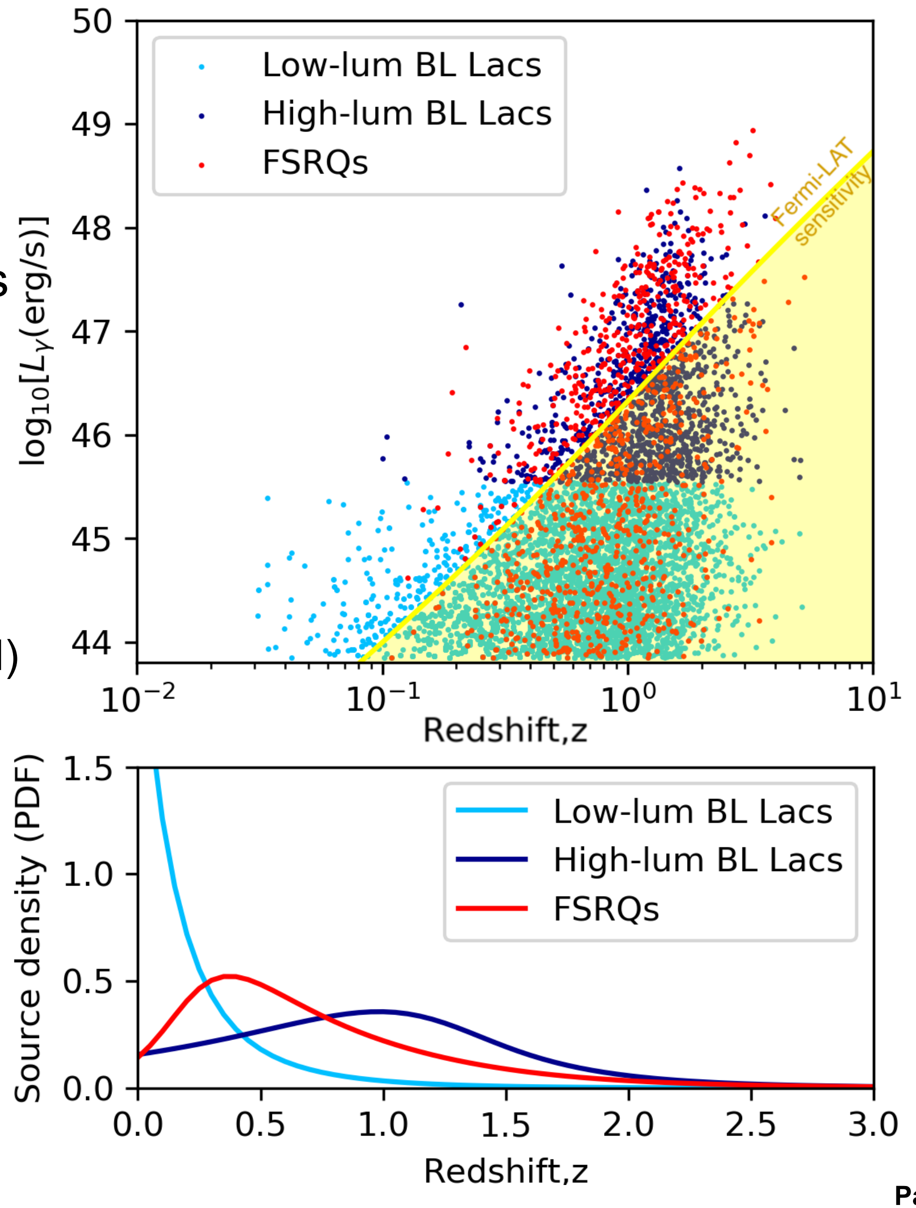
Simulation parameters

- 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 timescales
- 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. High-lum. AGN)
  - UHECR acceleration efficiency (the same for all sources)
  - Size of the radiation zone (fixed, r = 0.1 pc)
  - Escape mechanism (fixed, Bohm-like diffusion)
- Different acceleration mechanisms in different AGN populations?

X. Rodrigues, J. Heinze, A. Palladino, AvV and W. Winter, arXiv:2003.08392, accepted for publication in PRL

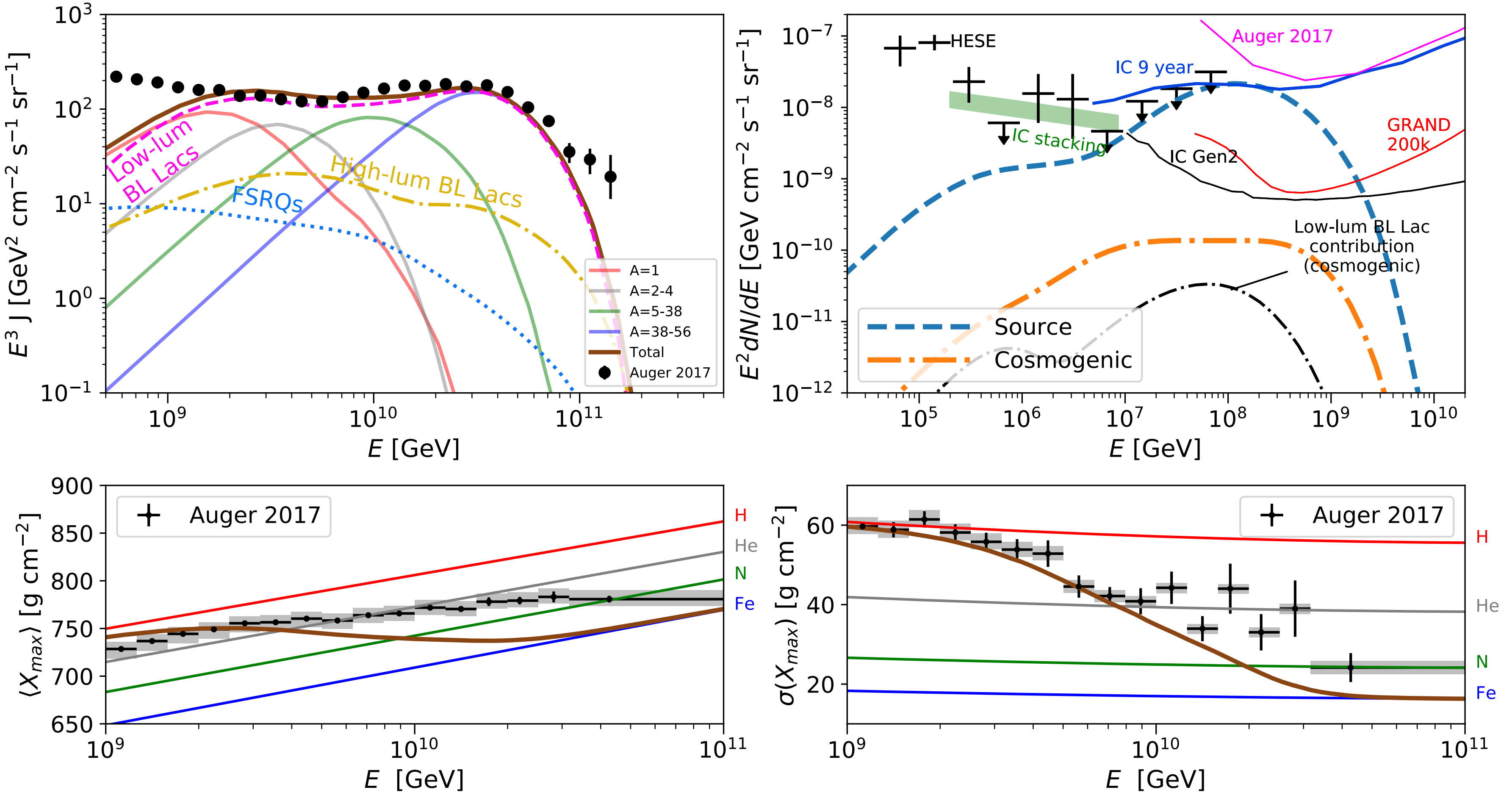


UHECRs and neutrinos from AGN

Results

X. Rodrigues, J. Heinze, A. Palladino, AvV and W. Winter, arXiv:2003.08392, accepted for publication in PRL

- Low-lum. BL Lacs dominate the UHECR spectrum
- Light UHECRs from FSRQs improve composition
- FSRQ source neutrinos dominate neutrino flux
- **Source neutrinos can outshine cosmogenic neutrinos**

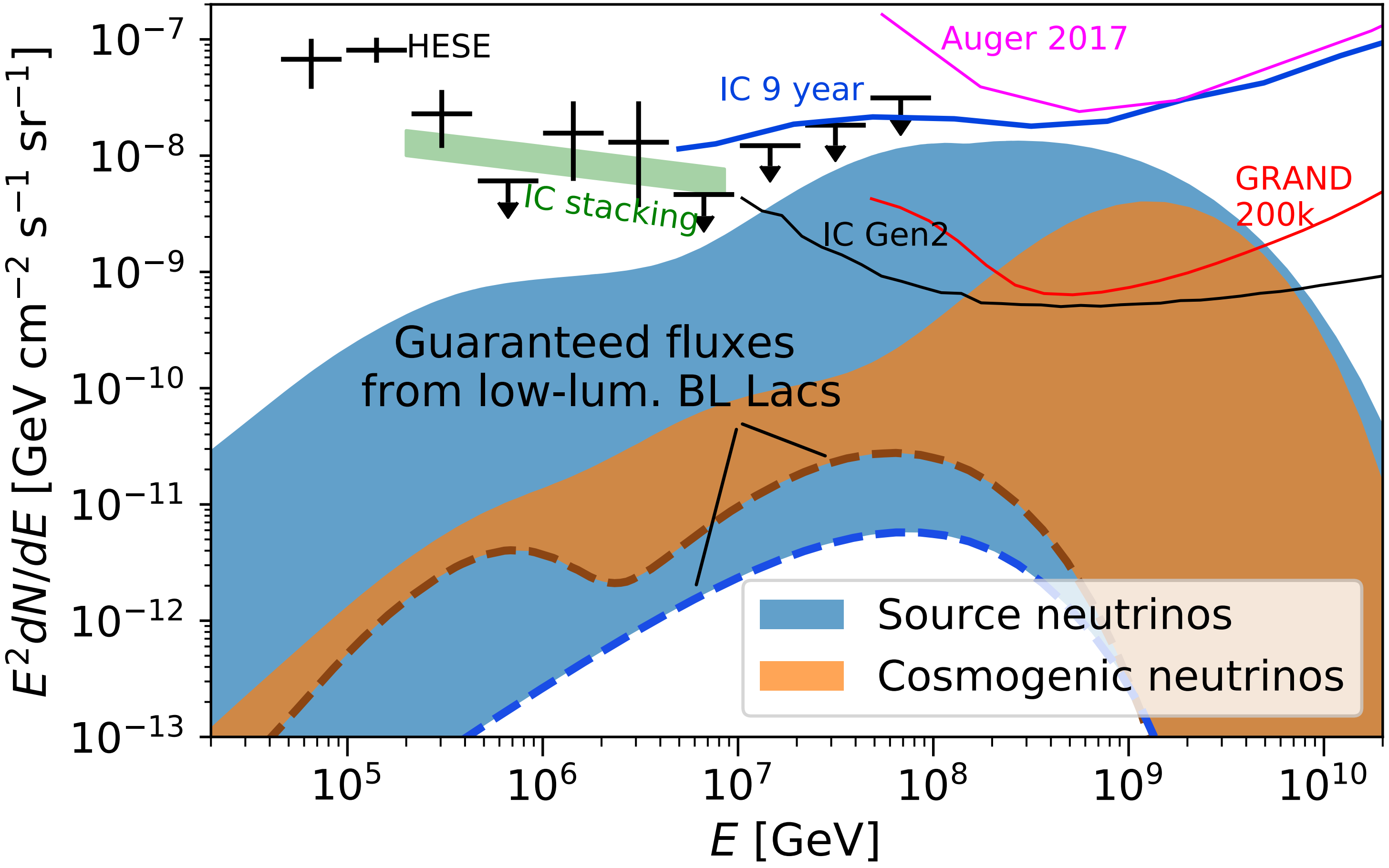


UHECRs and neutrinos from AGN

Possible ranges for source neutrinos 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 low-lum. BL Lacs up to EeV energies

X. Rodrigues, J. Heinze, A. Palladino, AvV and W. Winter, arXiv:2003.08392, accepted for publication in PRL



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

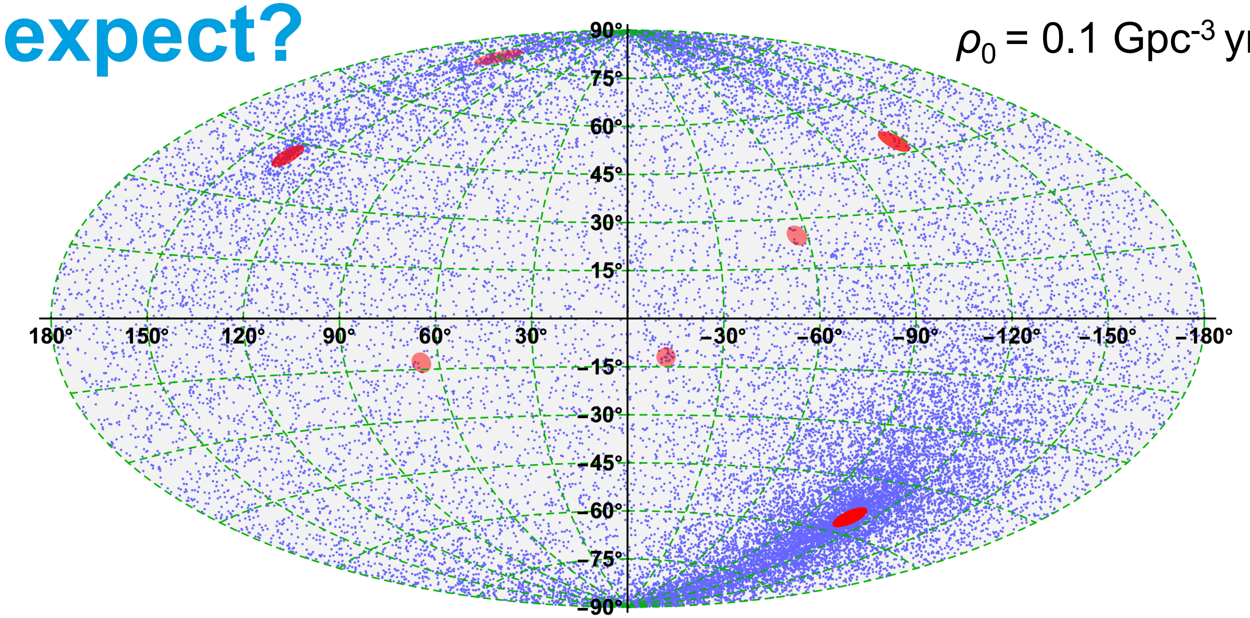
JCAP 1601 (2016) 037
(2016-01-20)
DOI: 10.1088/1475-7516/2016/01/037
FERMILAB-PUB-15-520-AD-AE-CD-TD
e-Print: arXiv:1511.09408 [astro-ph.HE] | PDF
Experiment: AUGER, IceCube, TELESCOPE-ARRAY

How many correlations do we expect?

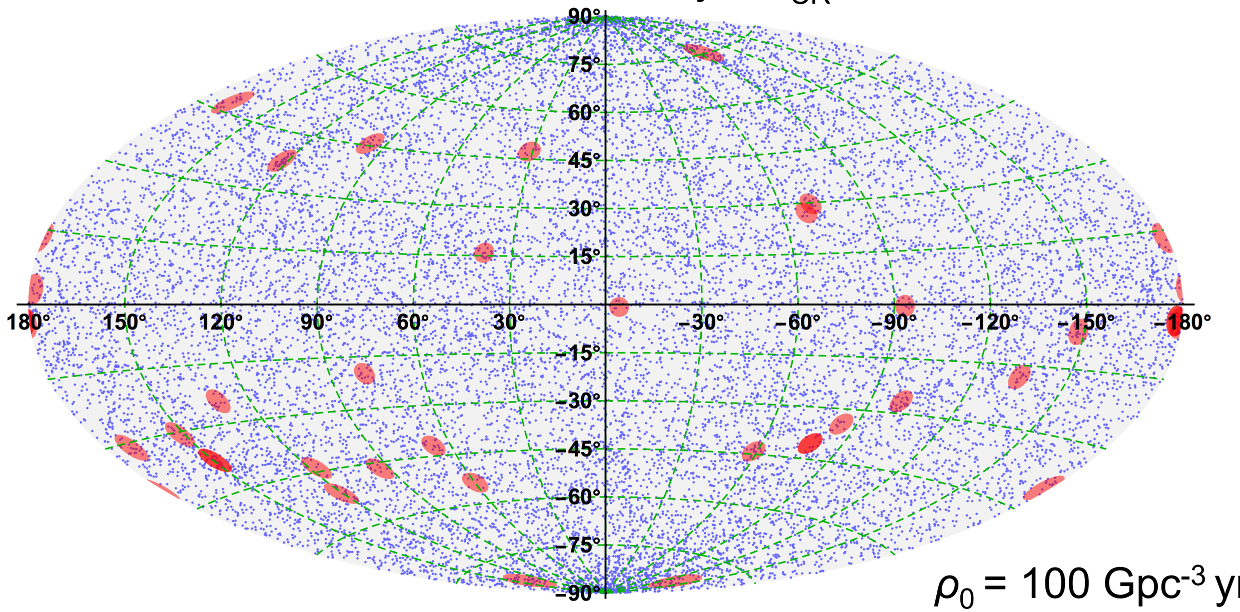
A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- 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)

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



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

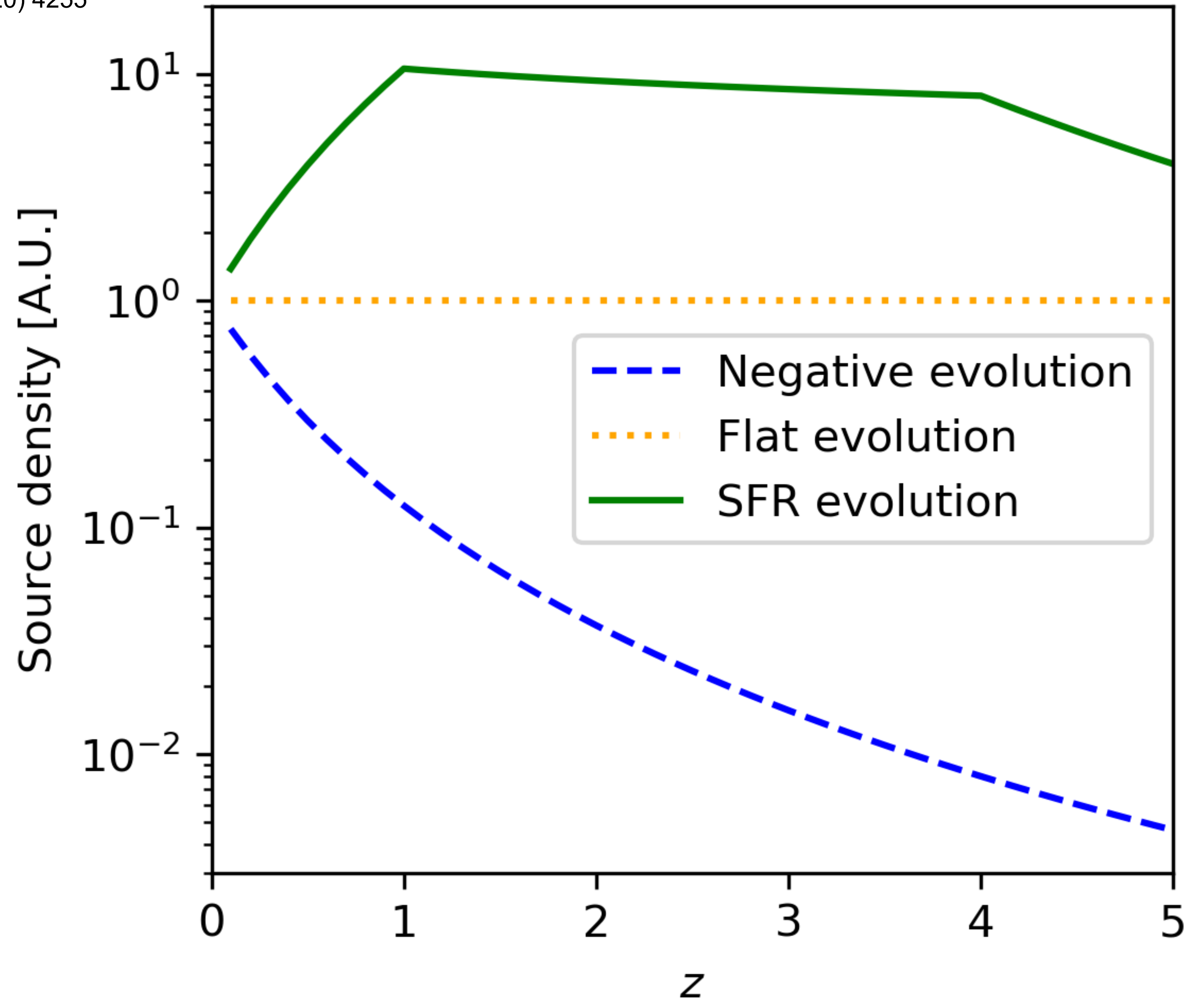


$\rho_0 = 100$ Gpc^{-3} yr^{-1}

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

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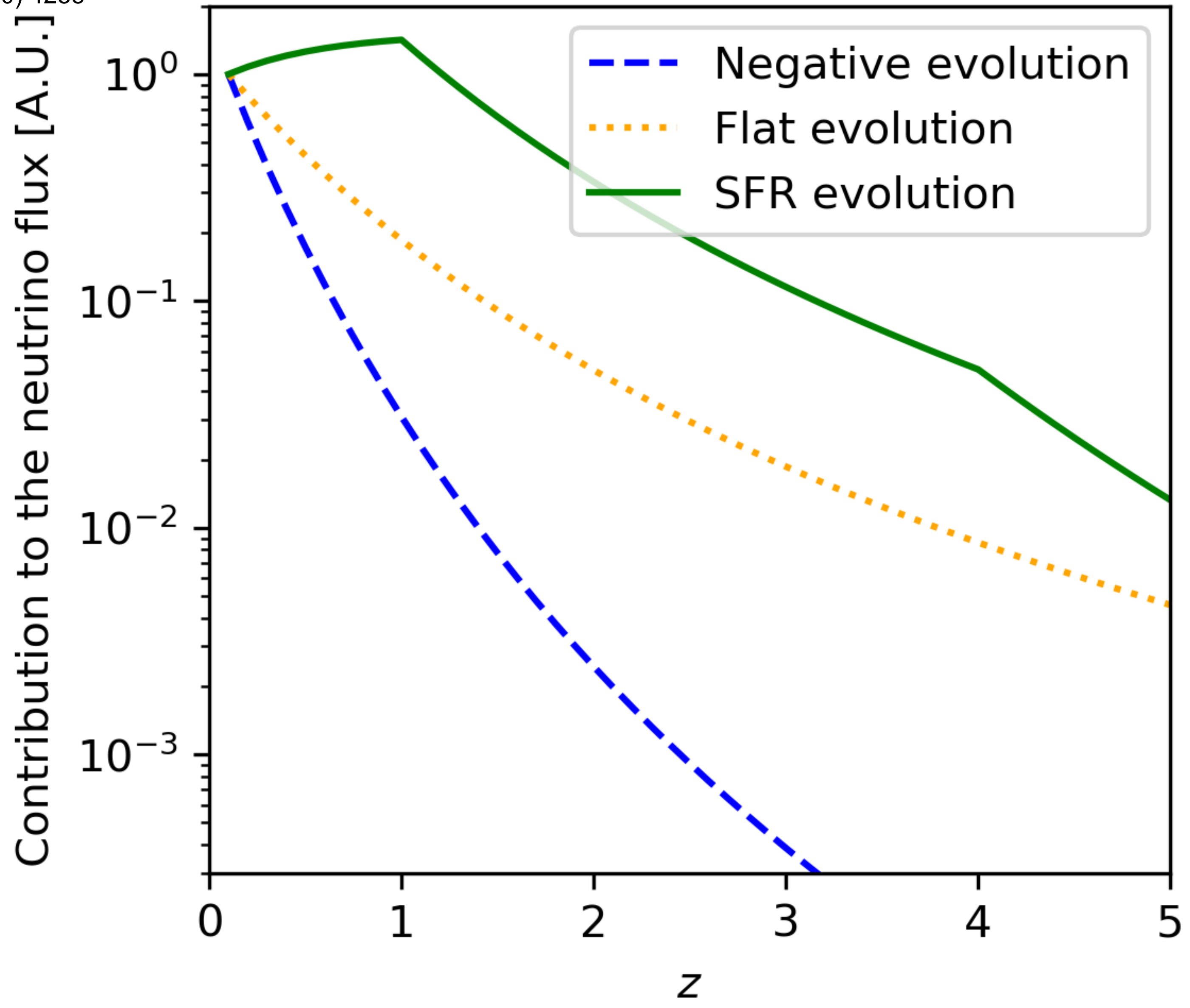


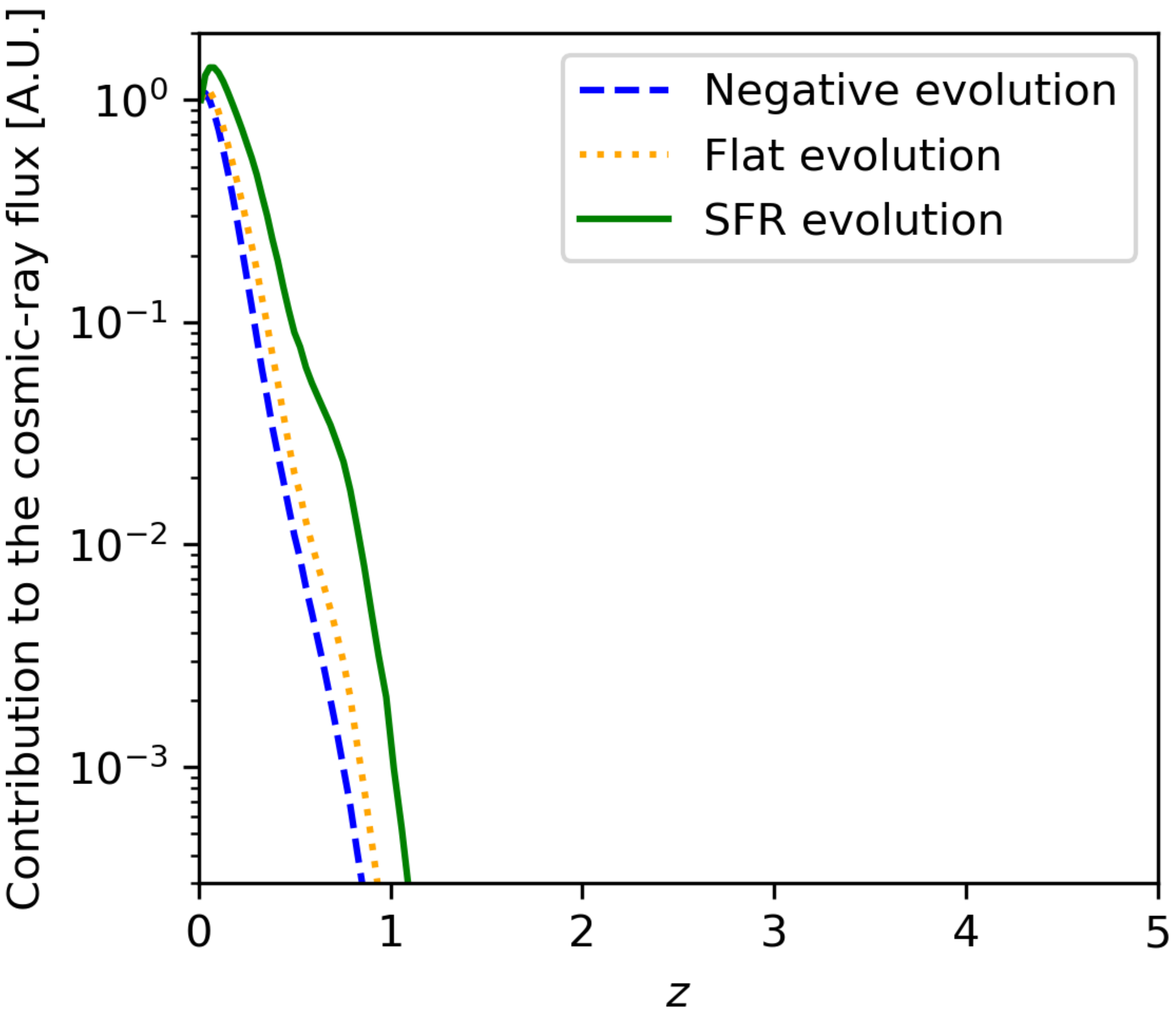
Energy losses of UHECRs

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_{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

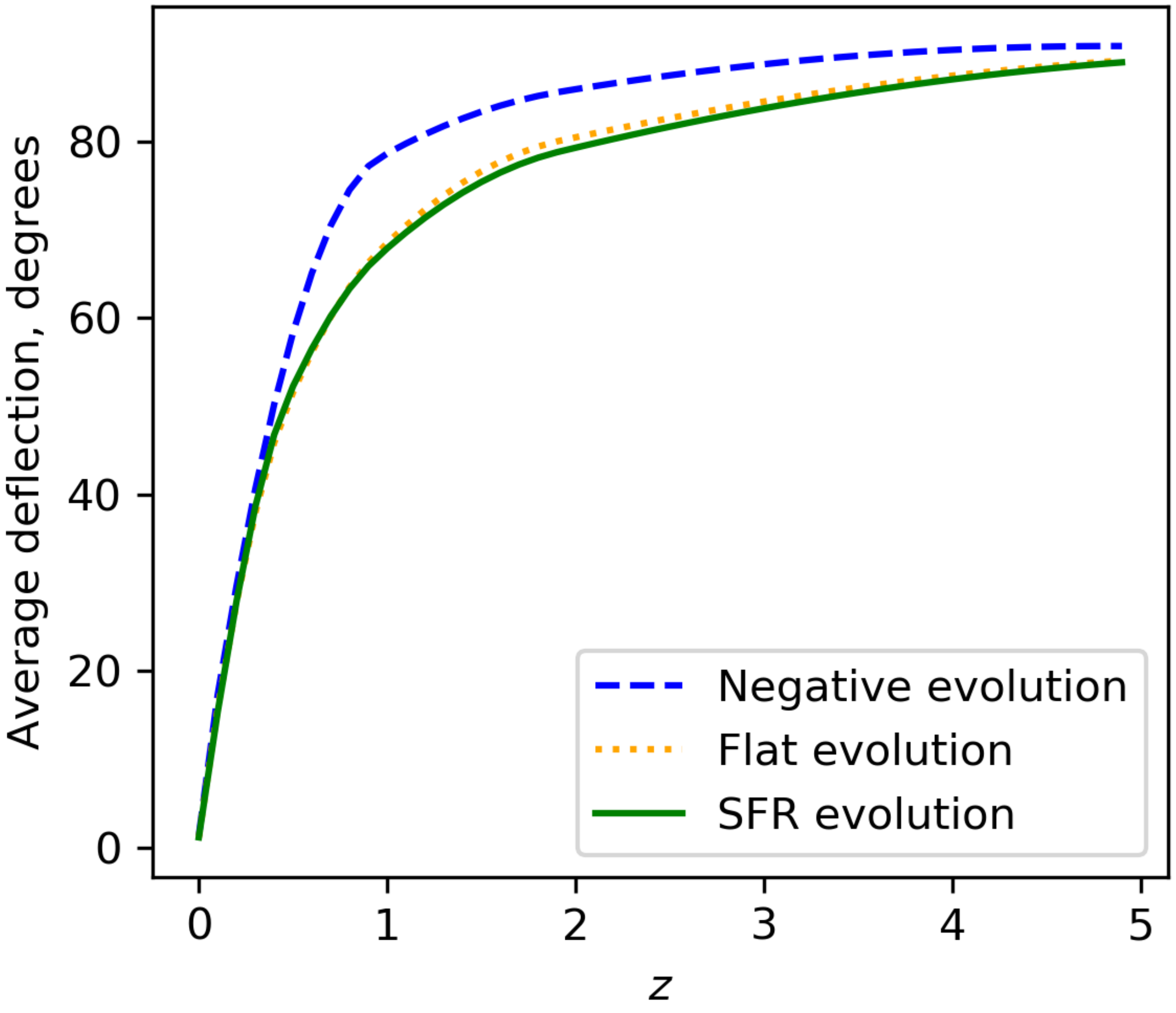
Auger, JCAP 04 (2017) 038
R. Alves Batista *et al.*, JCAP 01 (2019) 002



Deflections in extragalactic magnetic fields

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

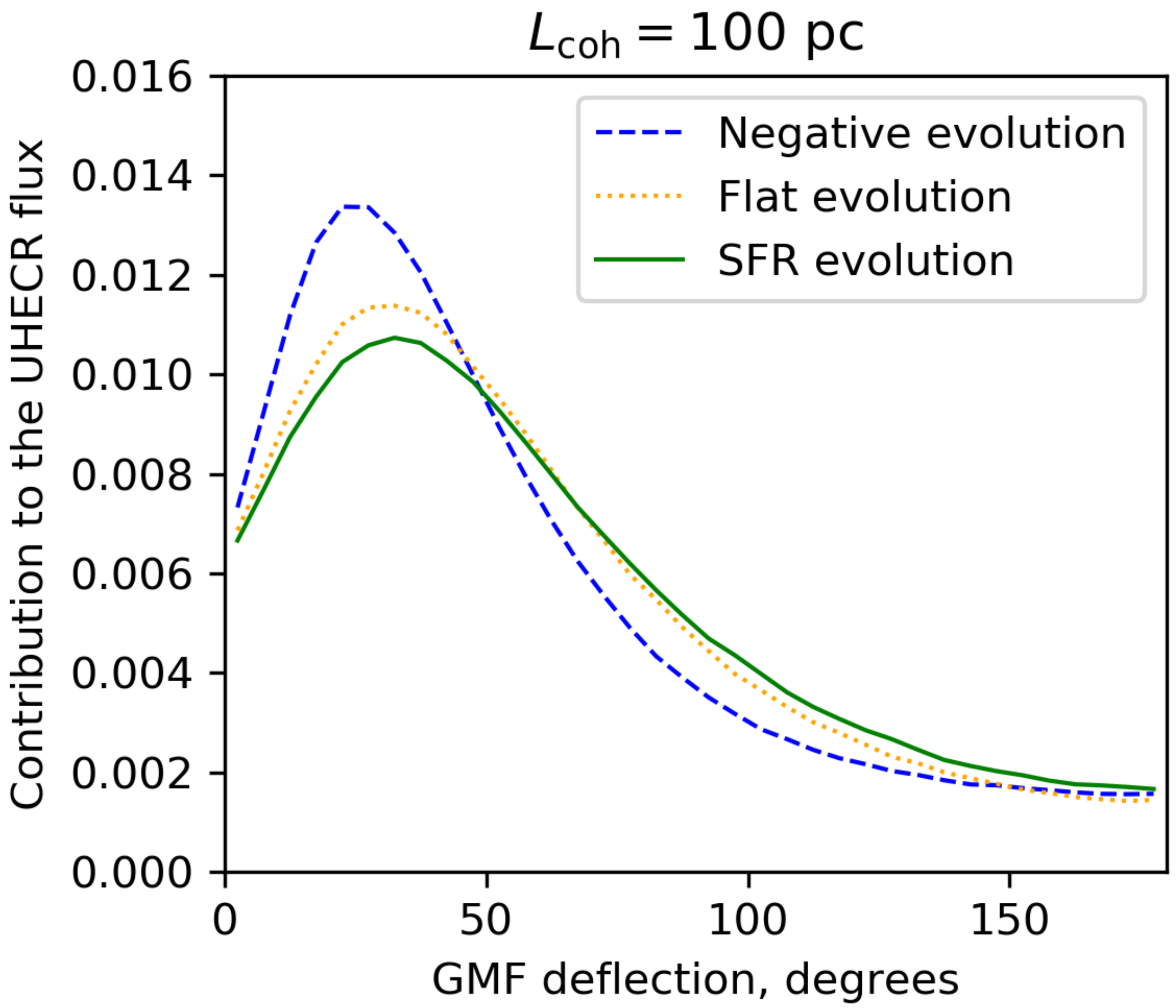
- 3D simulation with CRPropa
- For E_{CR}>$10^{18.5}$ eV
- For the same scenarios that fit Auger spectrum and composition
- In the EGMF model with the smallest deflections of Hackstein *et al*. 2018



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

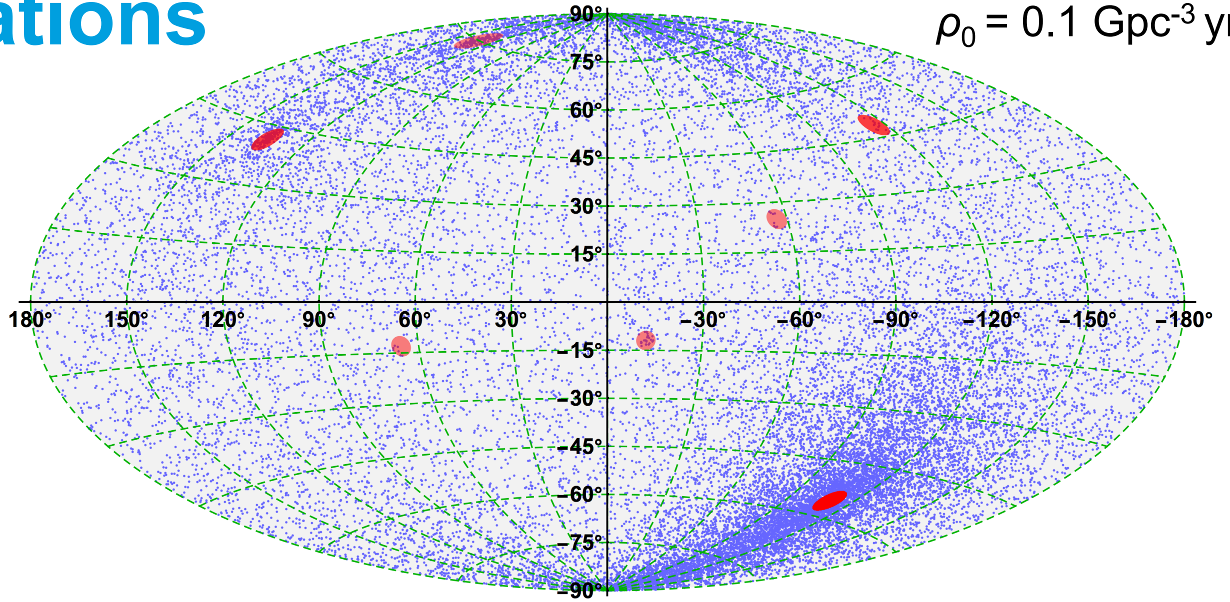


Calculation of expected correlations

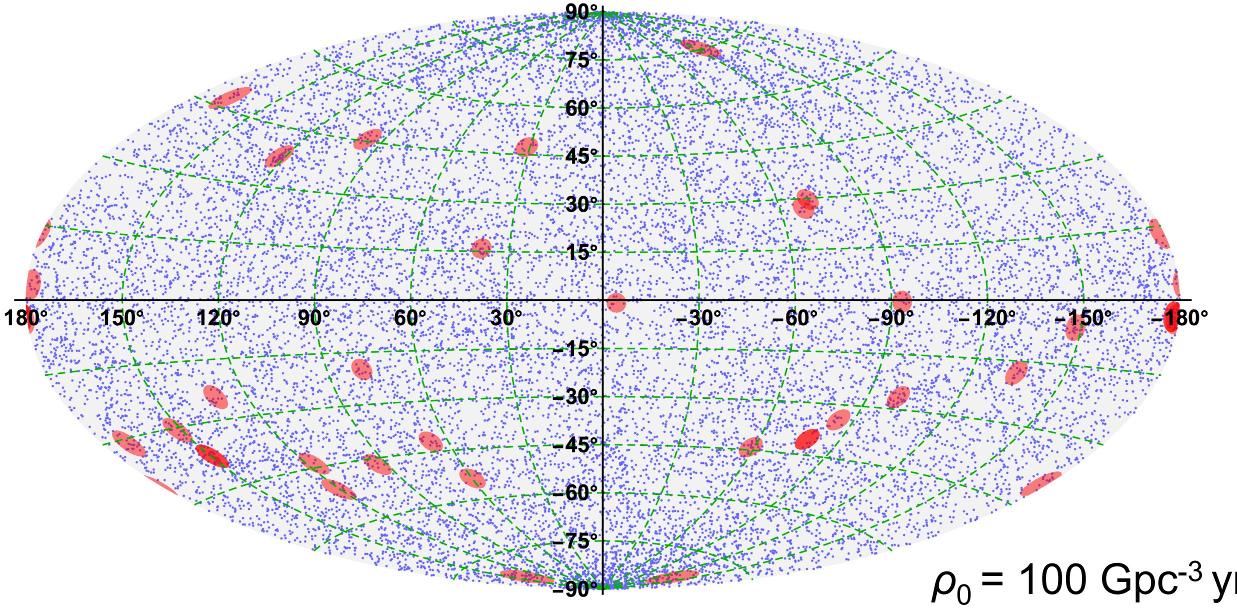
A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- 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

ρ_0 = 0.1 Gpc^{-3} yr^{-1}



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



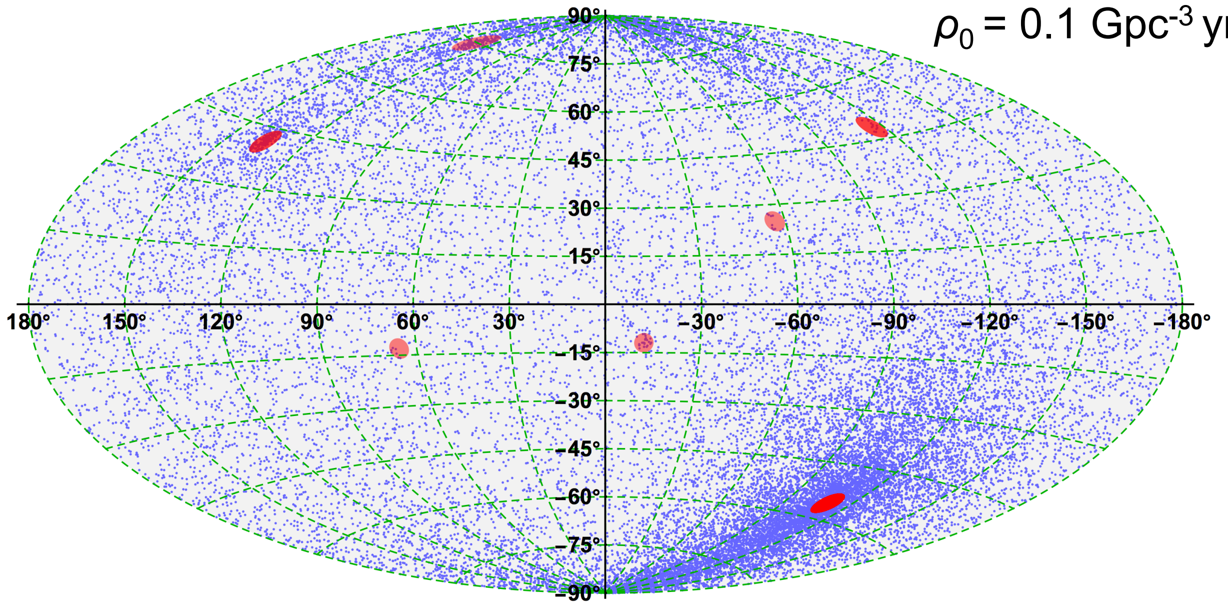
ρ_0 = 100 Gpc^{-3} yr^{-1}

Neutrino multiplets

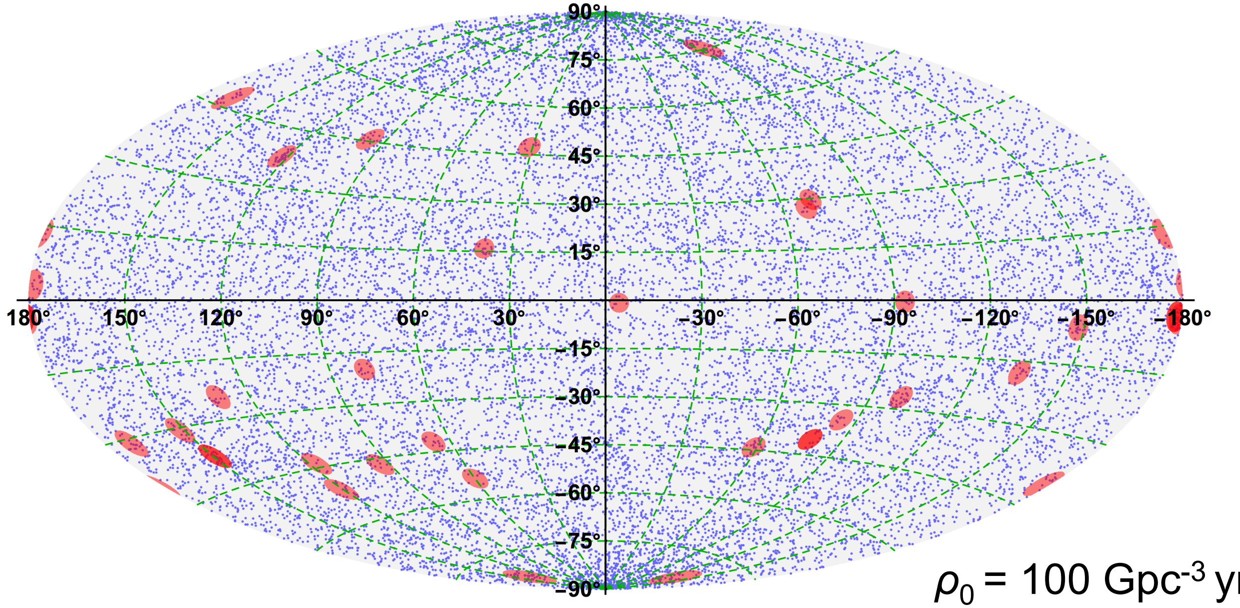
A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

- 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

ρ_0 = 0.1 Gpc^{-3} yr^{-1}



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

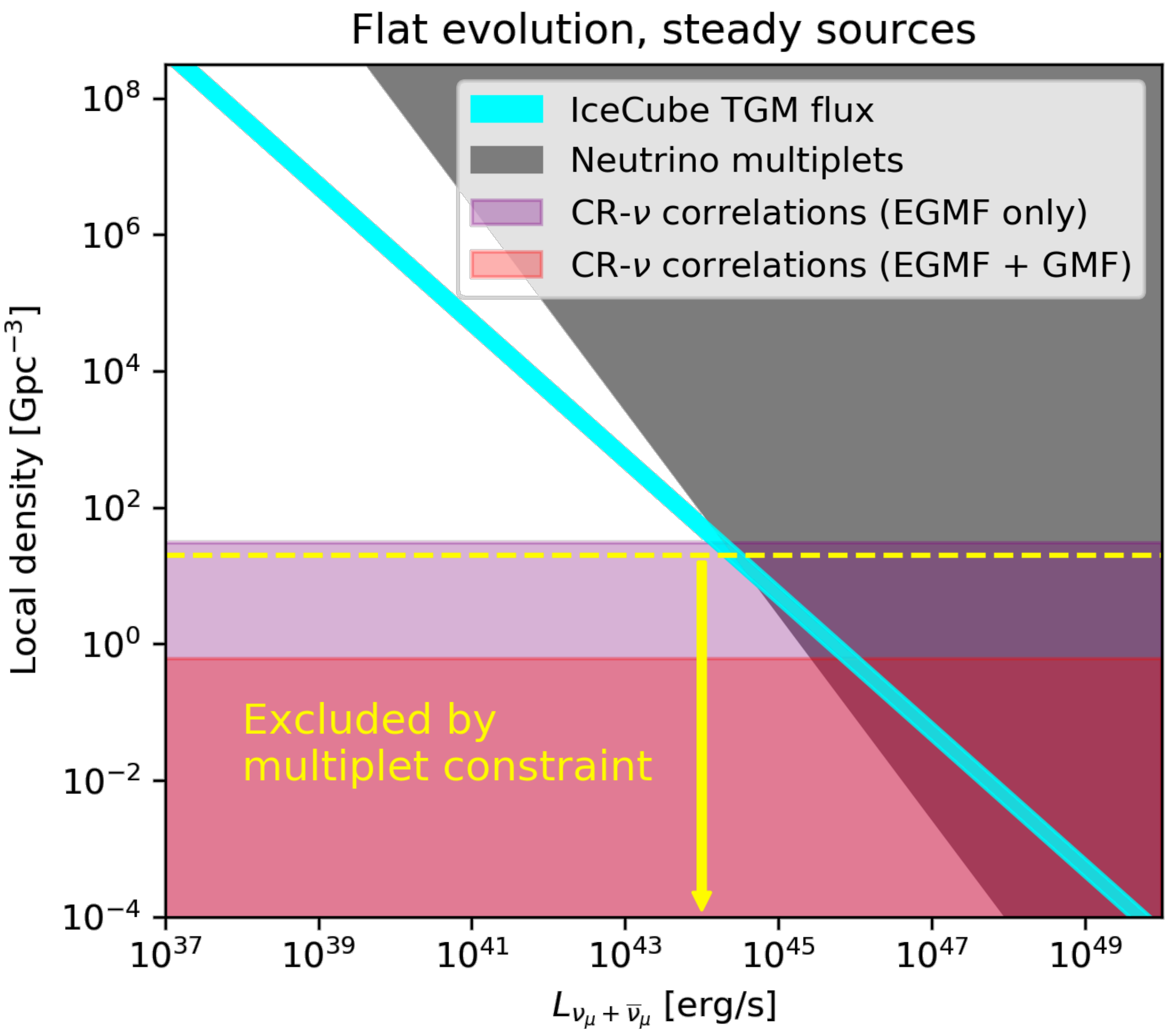


ρ_0 = 100 Gpc^{-3} yr^{-1}

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



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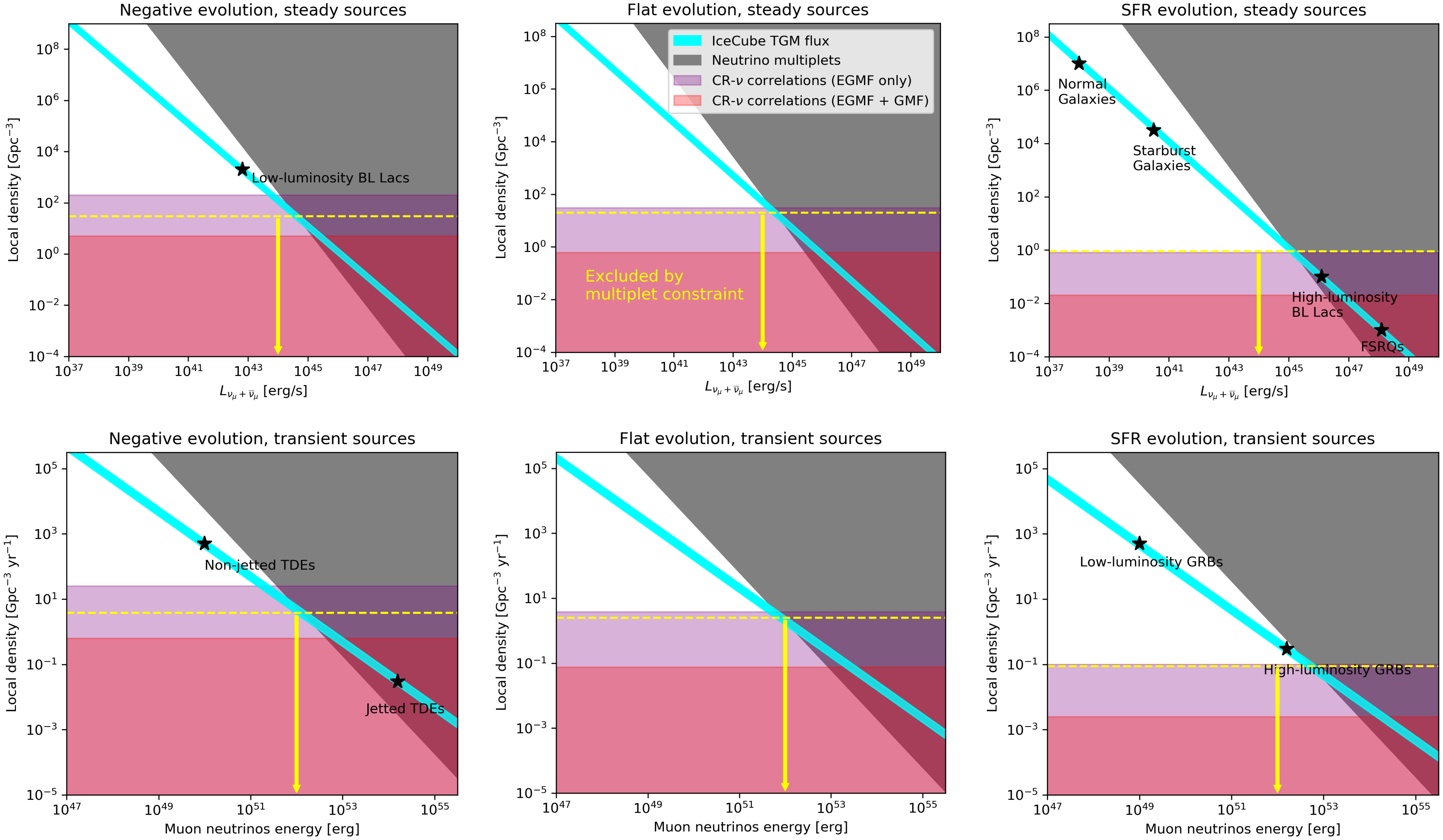


A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255

Neutrino-UHECR correlations, conclusions

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 $\rho_0 < 10\ \mathrm{Gpc}^{-3}$
- 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

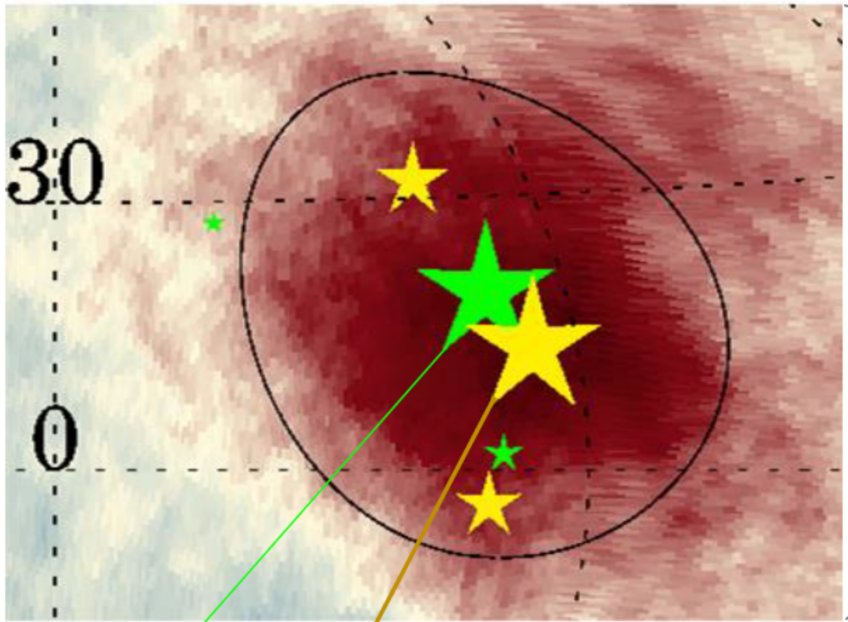
UHECR correlations with star-forming galaxies

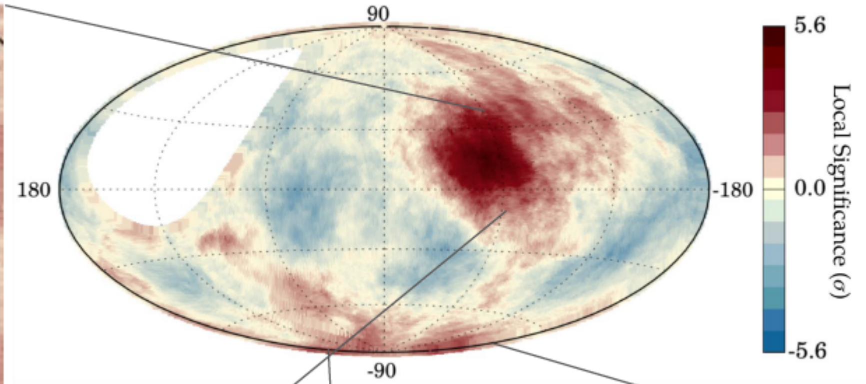
Indication of anisotropy in arrival directions found by the Pierre Auger Collaboration

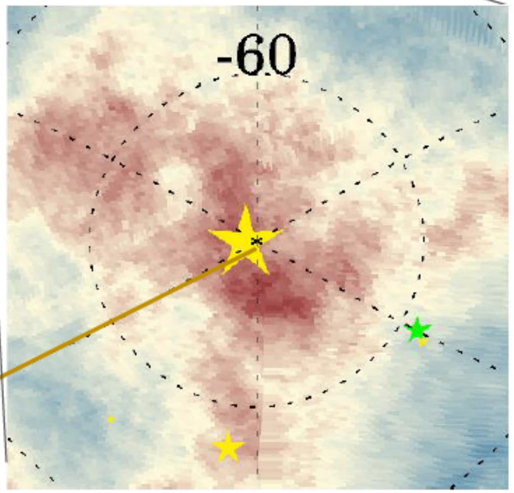
Pierre Auger Collaboration, Astrophys. J. Lett. 853 (2018) 2

Pierre Auger Collaboration, PoS ICRC2019 206

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

Cen A
Most contributing source to 2MRS, γ-AGNs and Swift-BAT

NGC 4945
Most contributing source to starburst

NGC 253
2nd-most contributing source to starburst

ICRC 2019 presentation by L. Caccianiga

UHECR correlations with star-forming galaxies

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

Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
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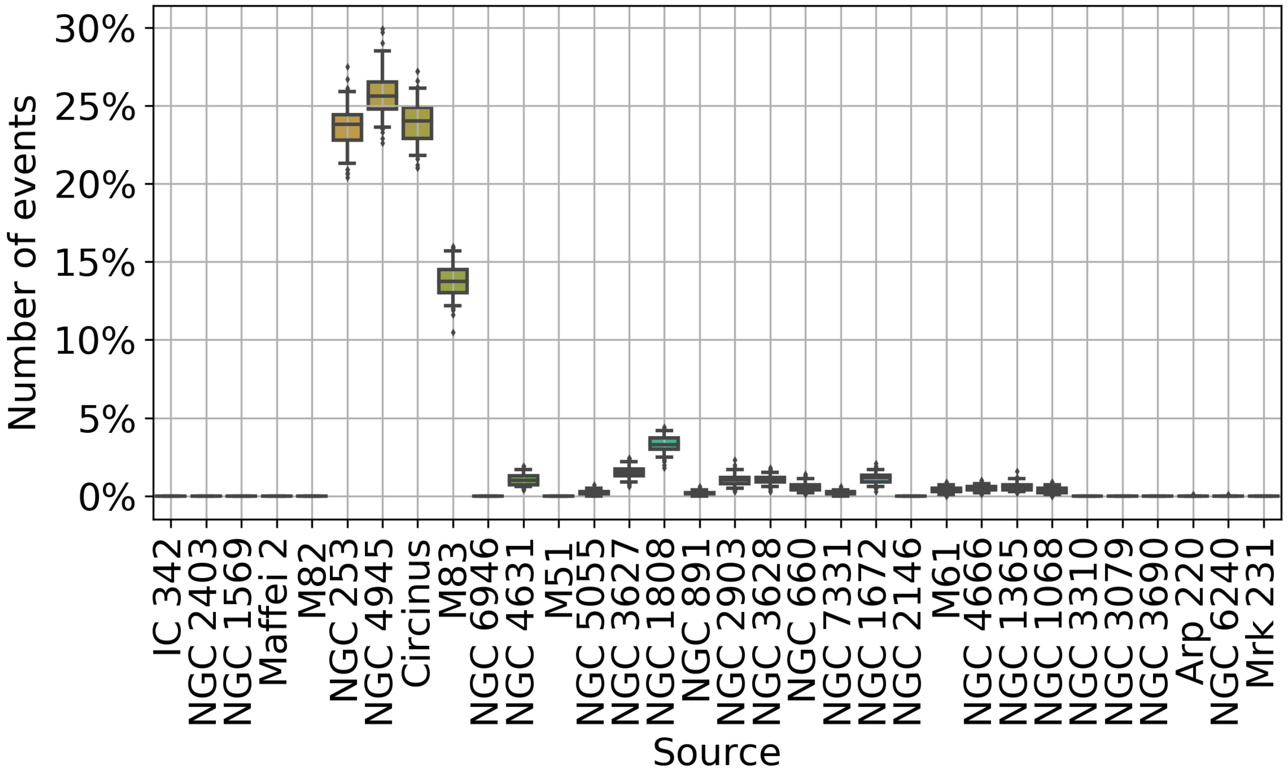
UHECR correlations with star-forming galaxies

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 the Pierre Auger Collaboration found
- Focus on 4 most important sources
- Combine catalogue sources with a diffuse contribution
- 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



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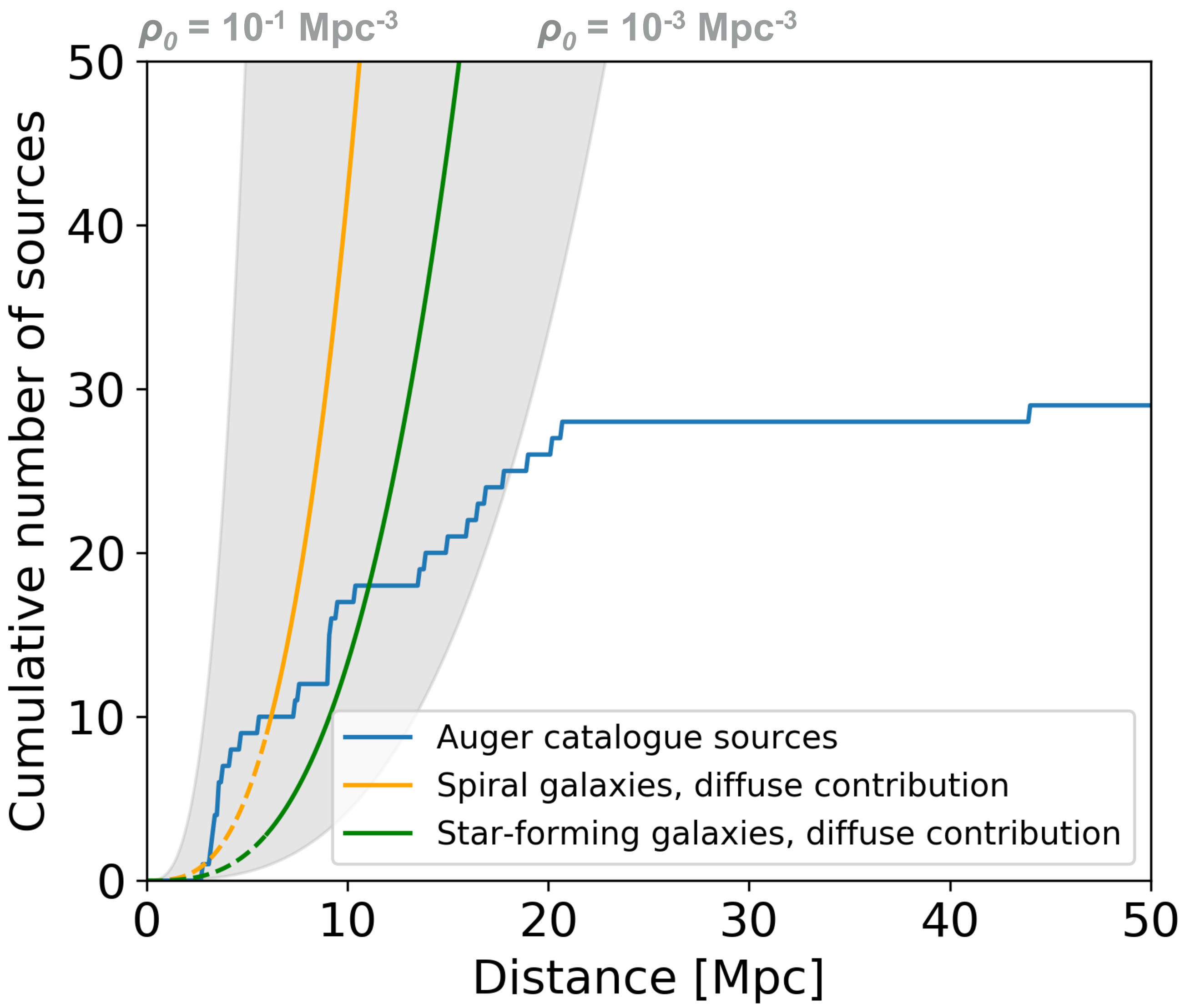
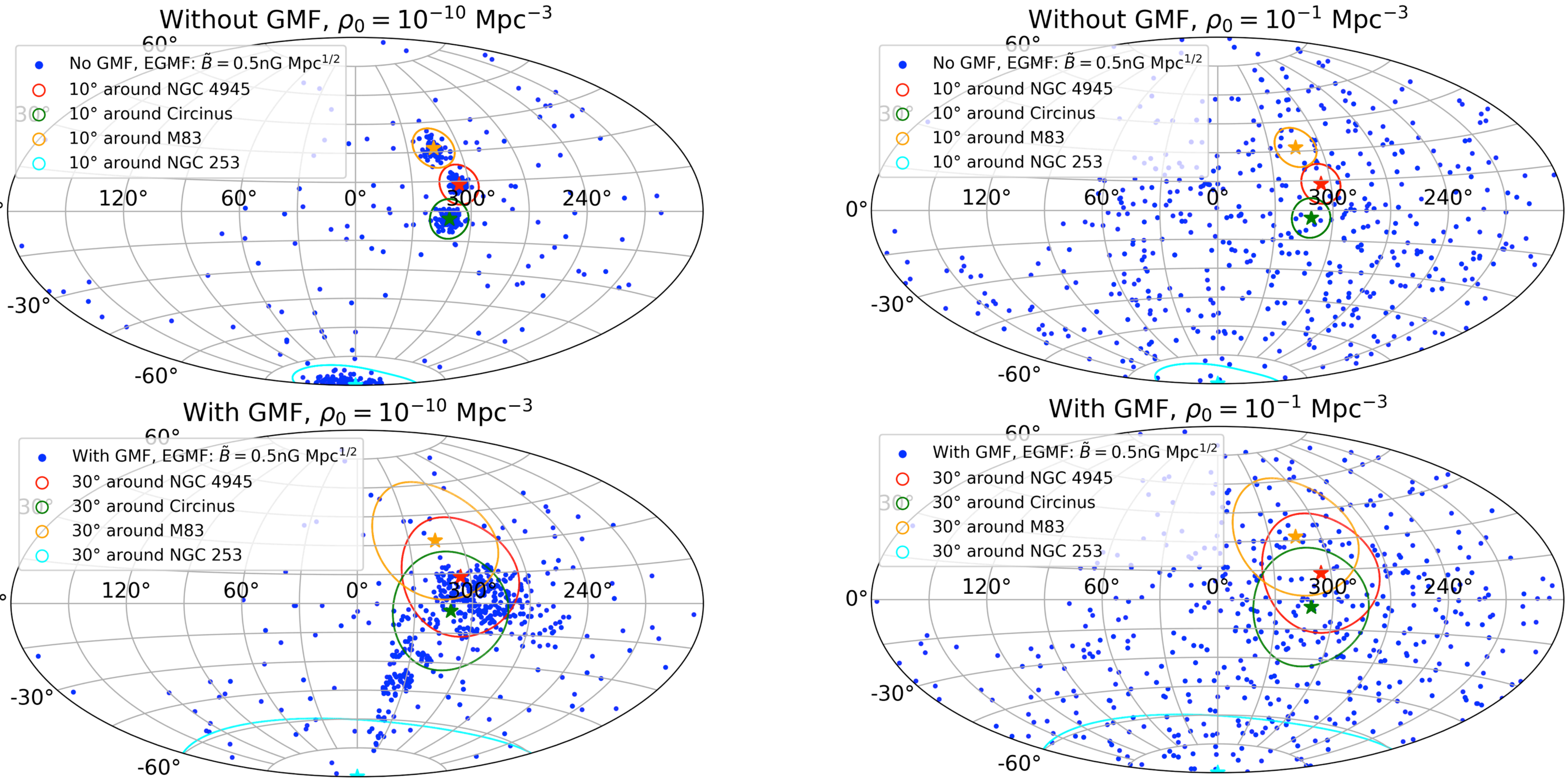


UHECR correlations with star-forming galaxies

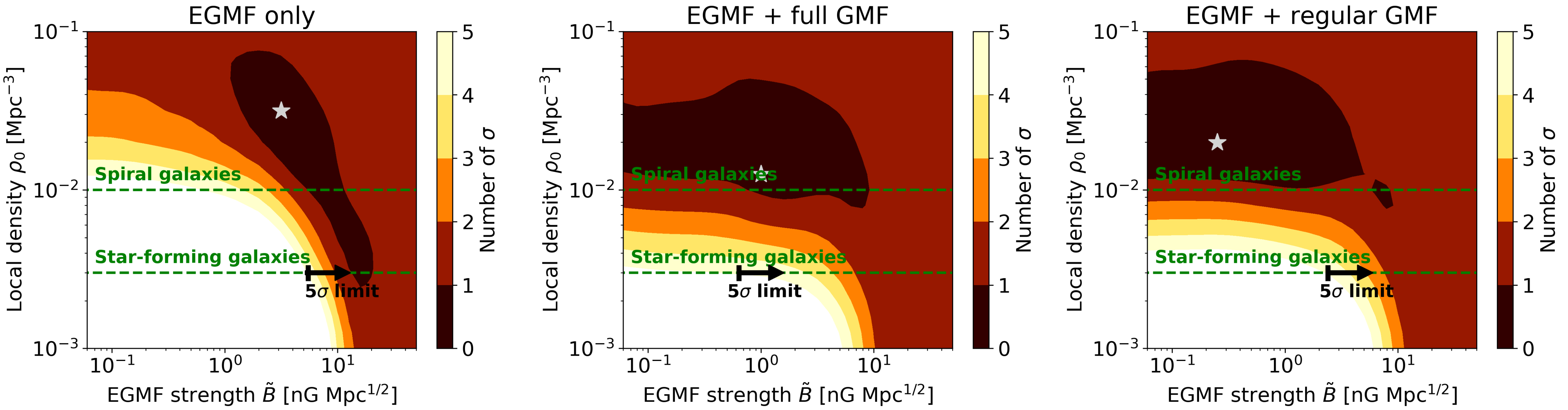
Example sky maps

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



UHECR correlations with star-forming galaxies

Results from scanning over ρ_0 and B

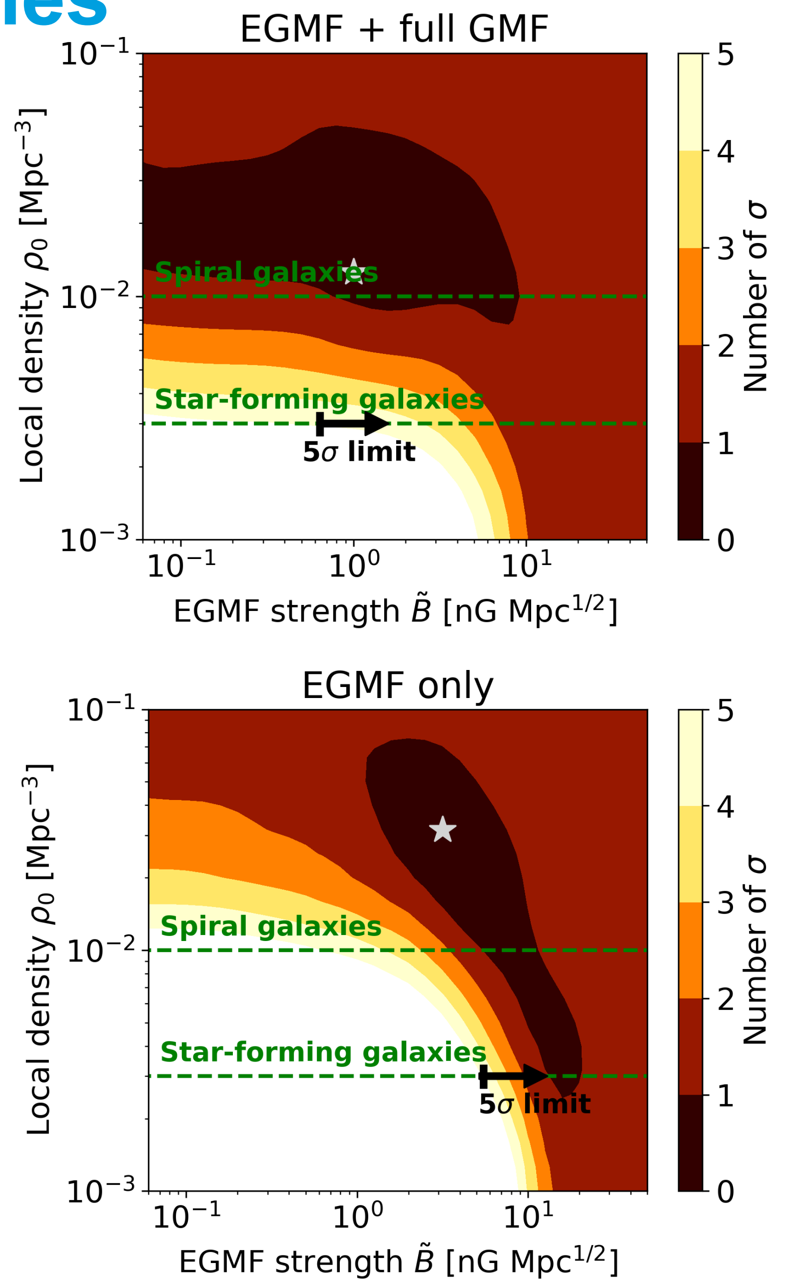


	EGMF only	EGMF + full GMF	EGMF + regular GMF
5σ lower limit on $\tilde{B}$ for $\rho_0 = 3 \cdot 10^{-3}$ Mpc^{-3}	$\tilde{B} > 5.5$ nG Mpc$^{1/2}$	$\tilde{B} > 0.64$ nG Mpc$^{1/2}$	$\tilde{B} > 2.4$ nG Mpc$^{1/2}$
Best-fit point	$\tilde{B} = 3.2$ nG Mpc$^{1/2}$; $\rho_0 = 3.2 \cdot 10^{-2}$ Mpc^{-3}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

UHECR correlations with star-forming galaxies

Conclusions

- 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 $\mathrm{Mpc}^{1/2}$) or very numerous UHECR sources ($\rho_0 > 3 \times 10^{-3}$ Mpc^{-3})

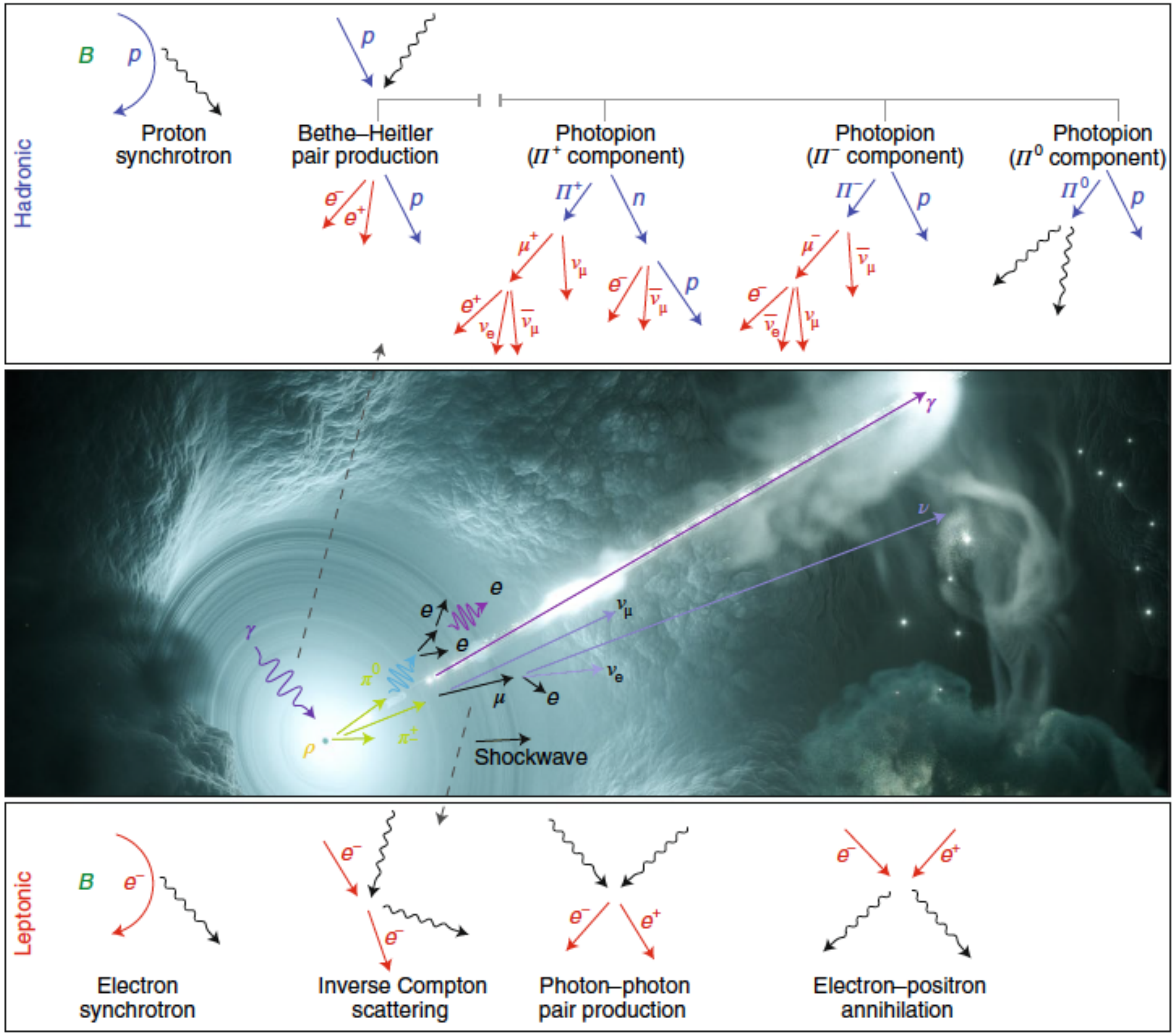
Backup slides

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?**



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:

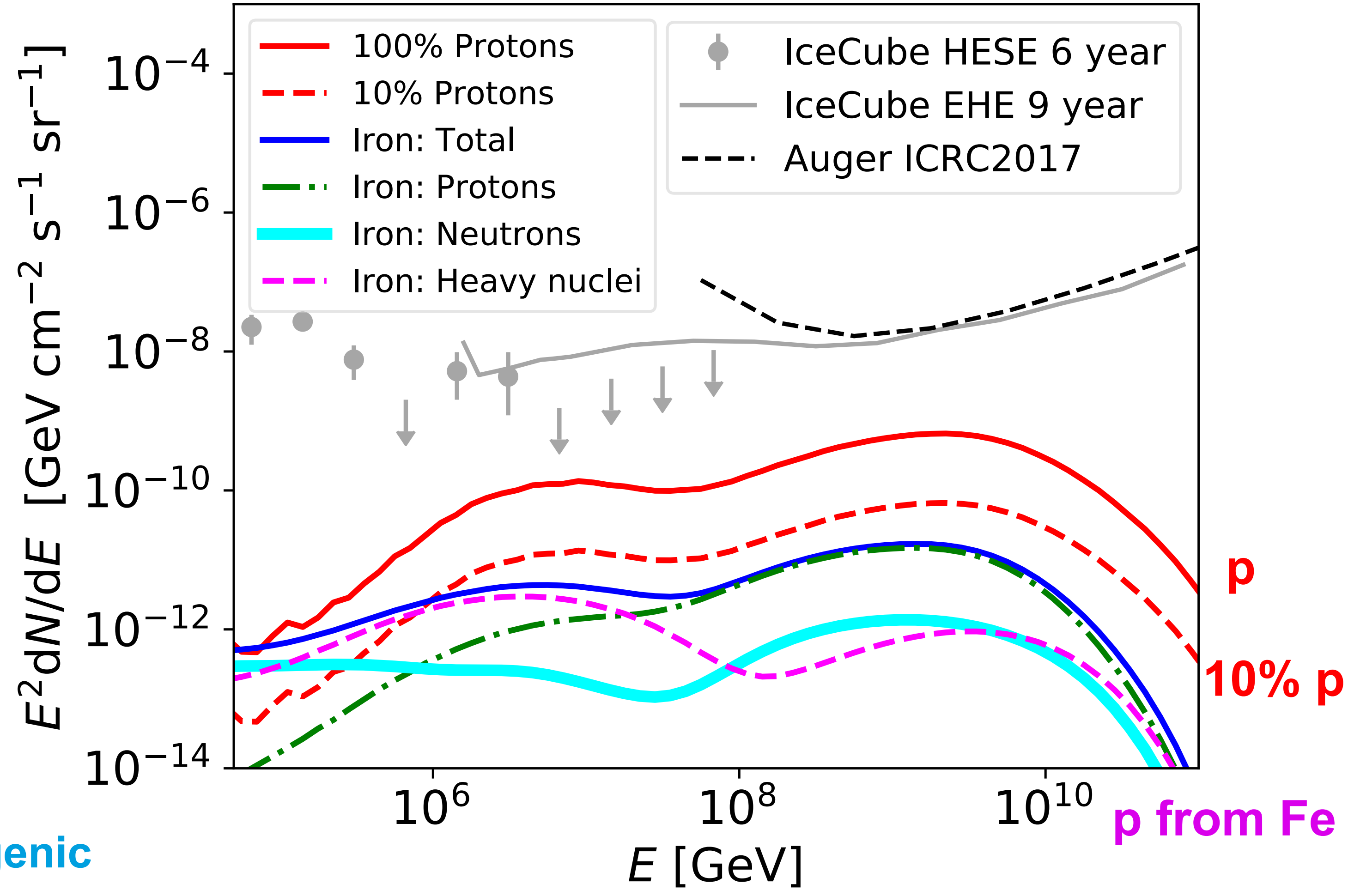
  Power law with rigidity-dependent cut-off

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

- $\alpha = 2.5$
- R_{max} = 200 EV
- Composition at the sources:

  Pure proton vs. pure iron

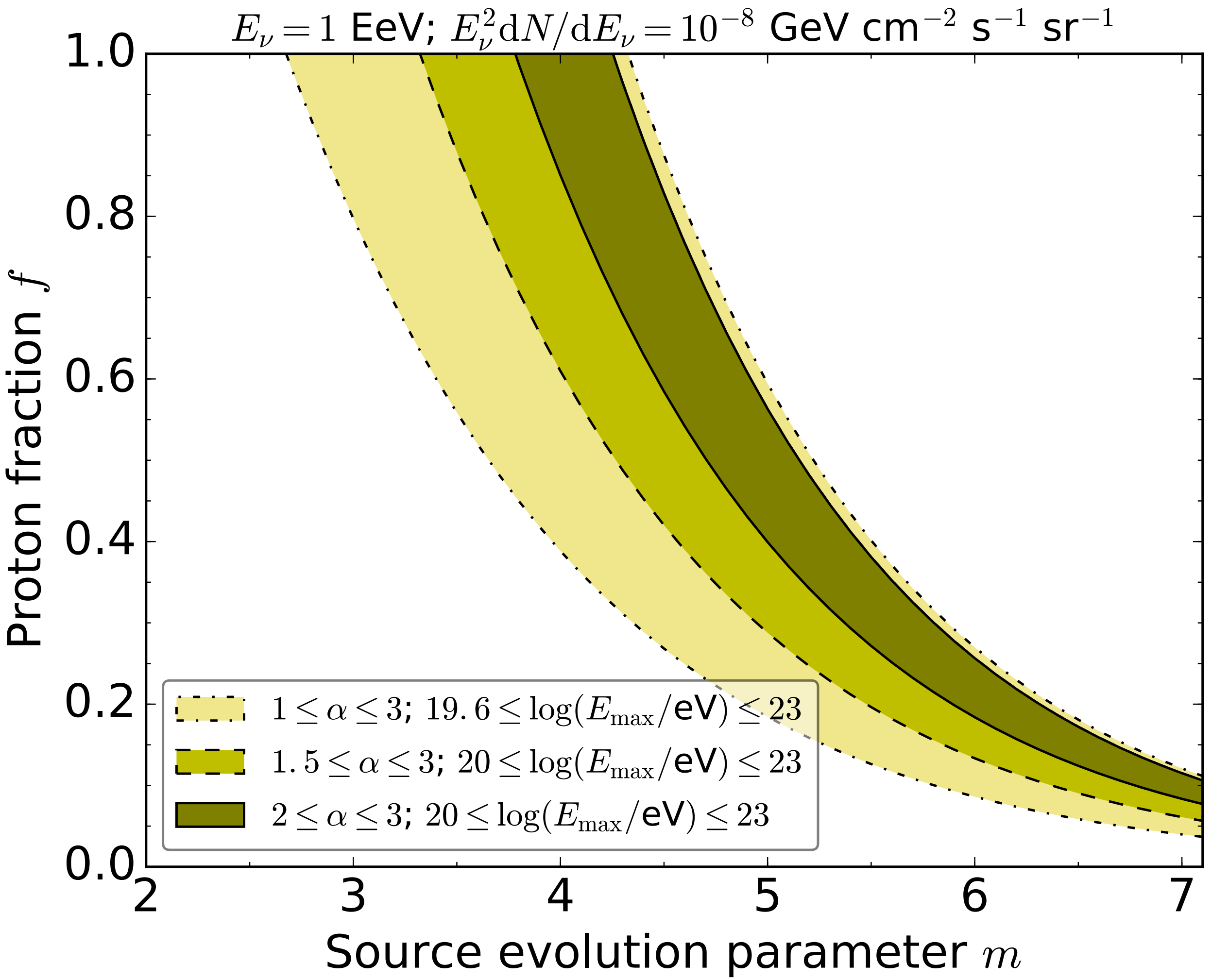
- Comoving source evolution
- EBL: Gilmore *et al*. 2012
- **Protons especially important for cosmogenic neutrino production**



Current sensitivity

- 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



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

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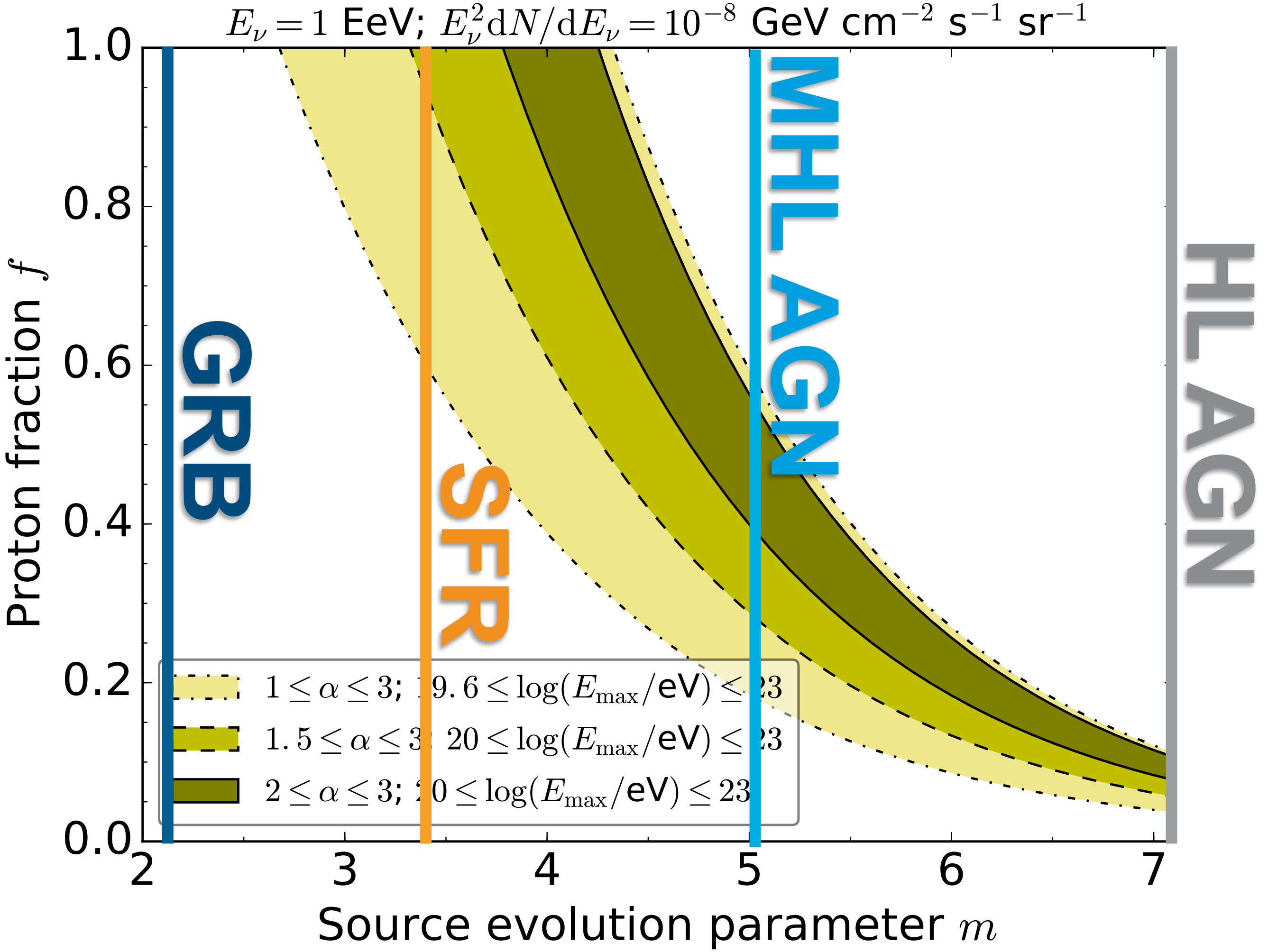

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