Ultra-High Energy Cosmic Rays and fundamental physics

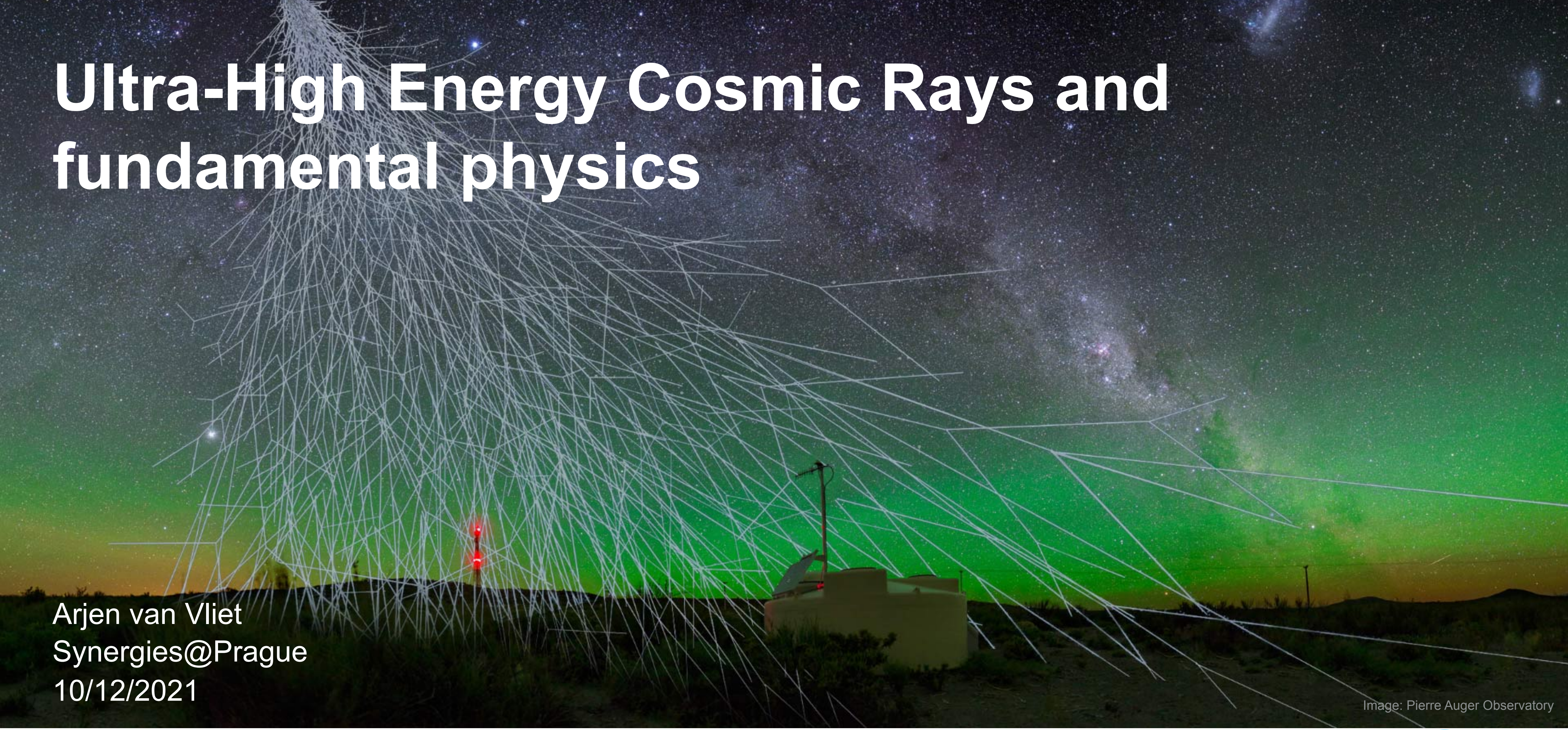

Image: Pierre Auger Observatory

Arjen van Vliet
Synergies@Prague
10/12/2021

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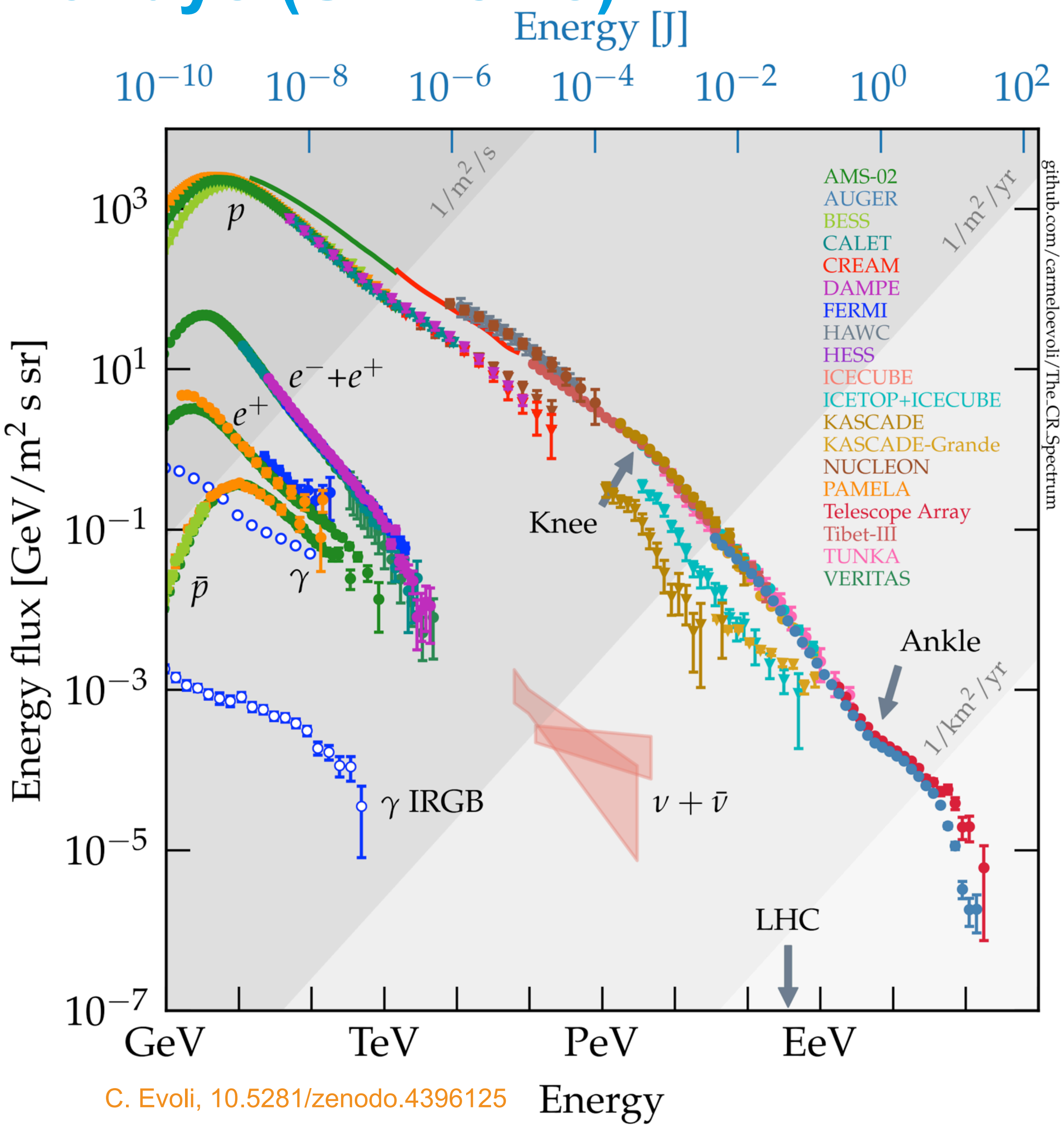
Ultra-high energy cosmic rays (UHECRs)

- Nuclei from protons to iron with $E > 10^{18}$ eV (= 1 EeV)
- Main experiments:
  - Pierre Auger Observatory in Argentina
  - Telescope Array in the US
- Features in the energy spectrum
  - ‘Ankle’ at ~5×10^{18} eV
  - ‘Instep’ at ~14×10^{18} eV
  - ‘Suppression’ at ~47×10^{18} eV
- Composition, getting increasingly heavier above the ankle
- No identified sources yet, but indication of anisotropies in the arrival directions have been detected



C. Evoli, 10.5281/zenodo.4396125

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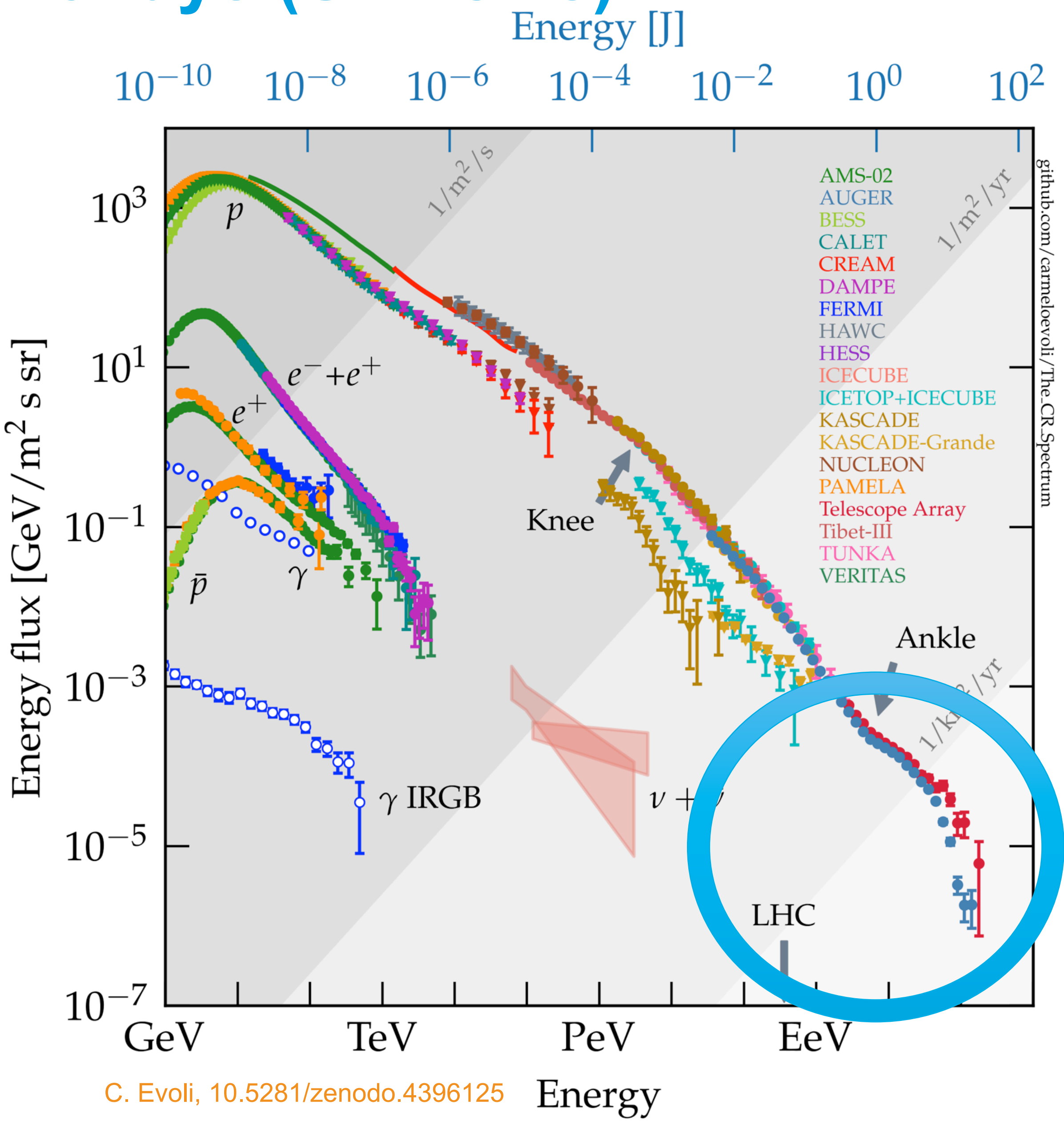

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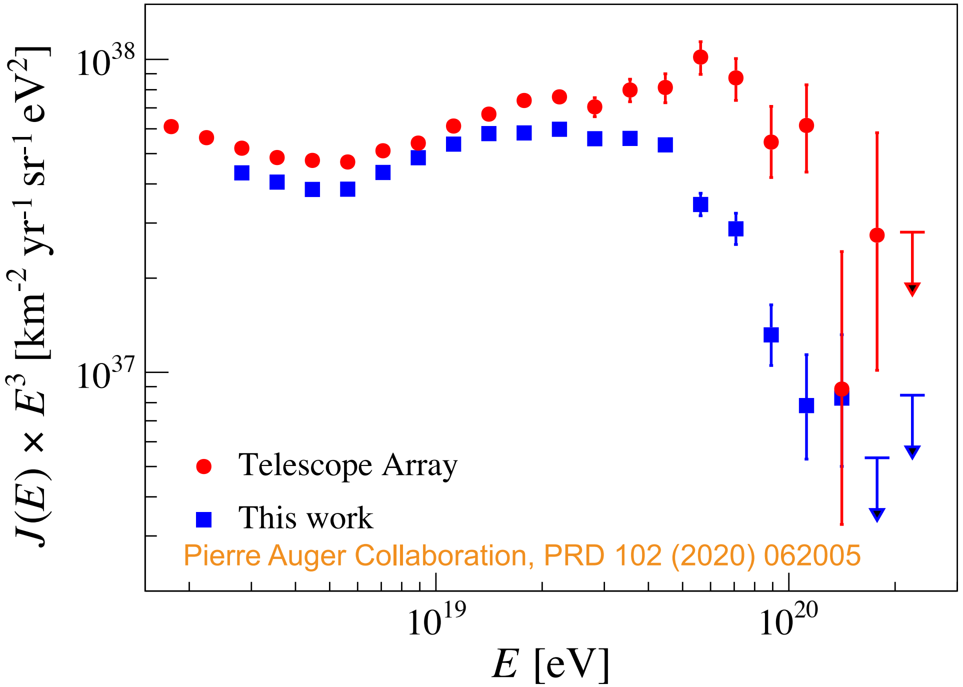
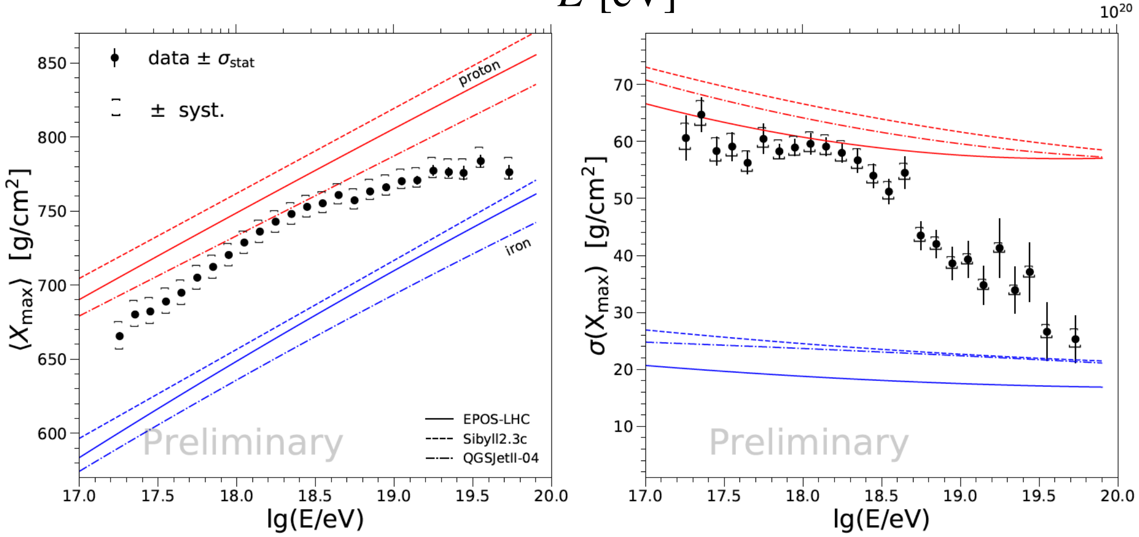


Pierre Auger Collaboration, PRD 102 (2020) 062005



Pierre Auger Collaboration, PoS ICRC2019 482

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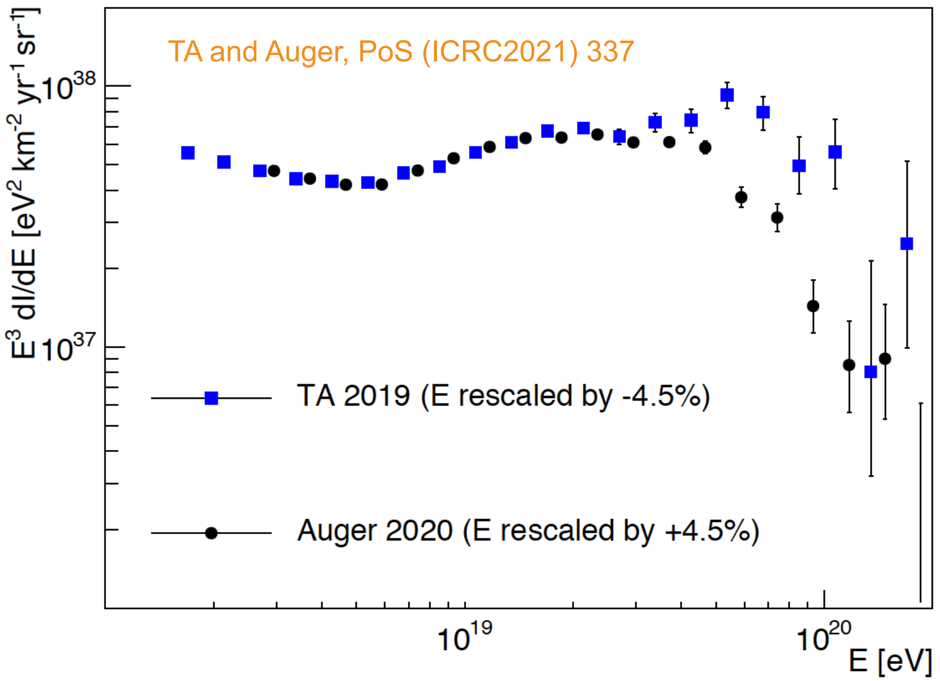

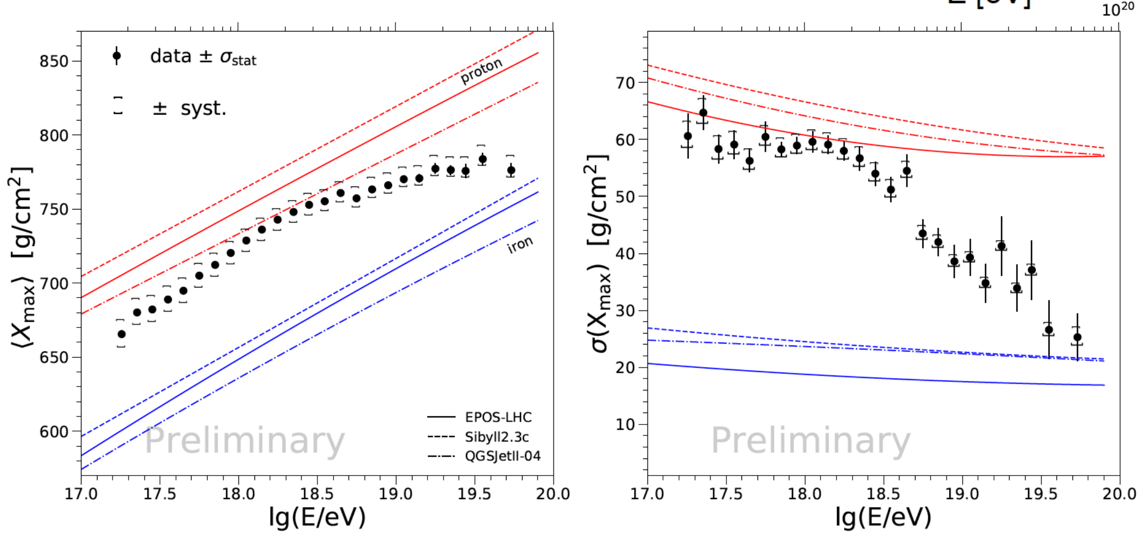

Pierre Auger Collaboration, PoS ICRC2019 482

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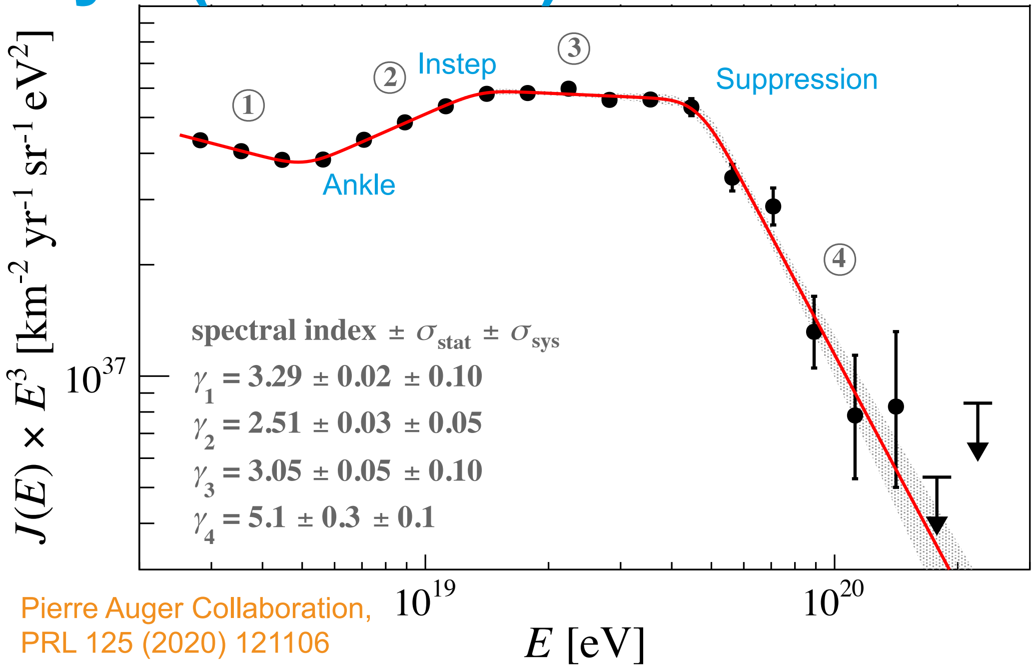
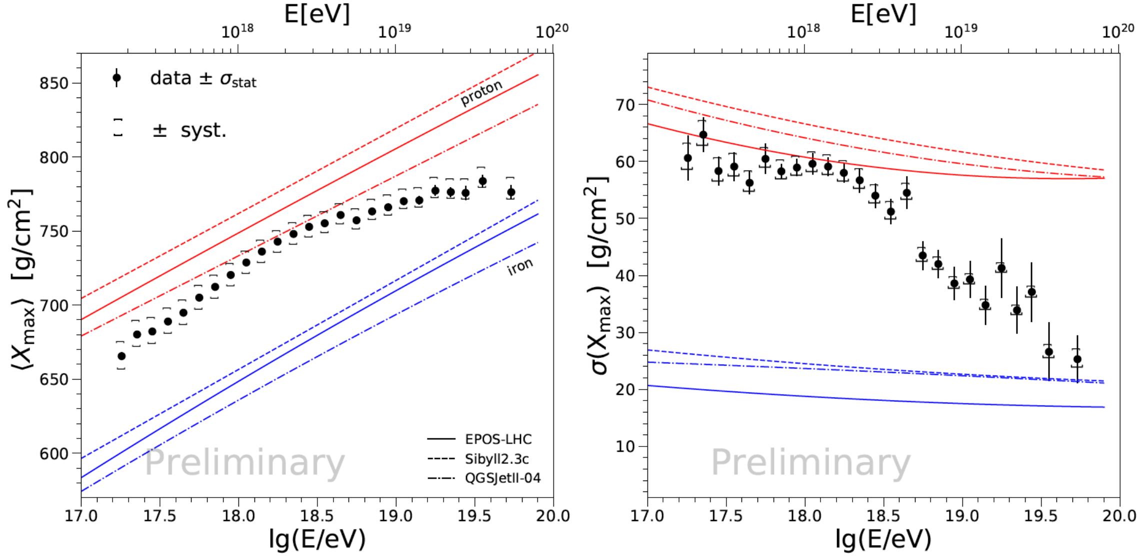


Pierre Auger Collaboration, PRL 125 (2020) 121106



Pierre Auger Collaboration, PoS ICRC2019 482

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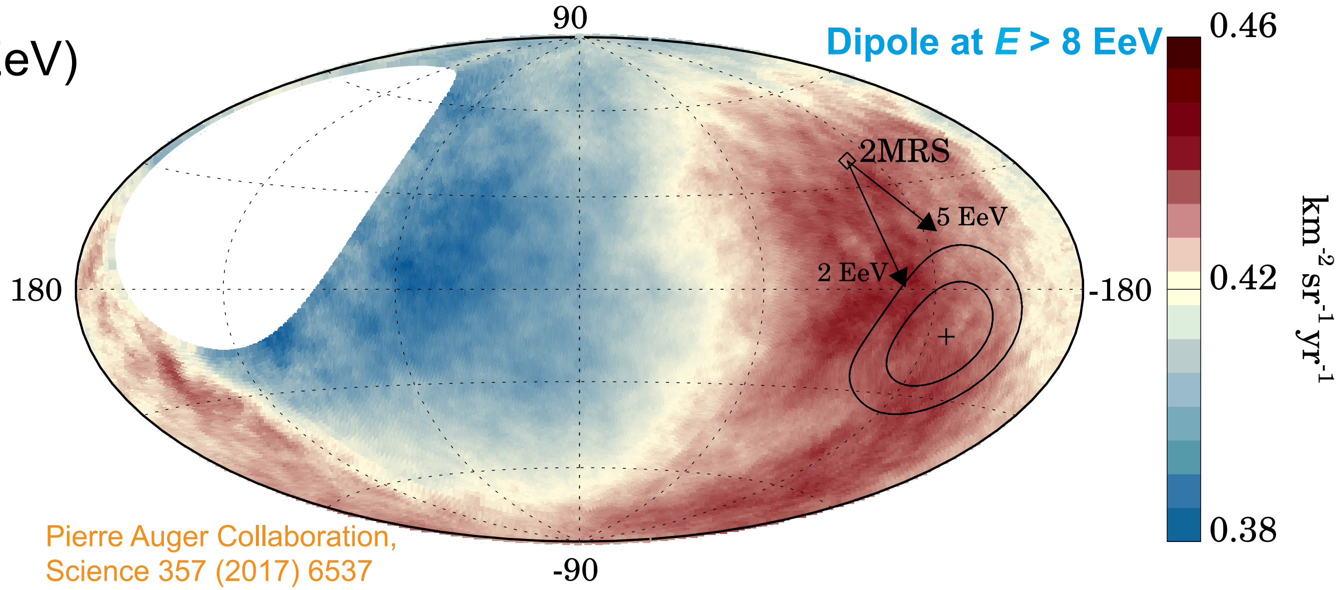
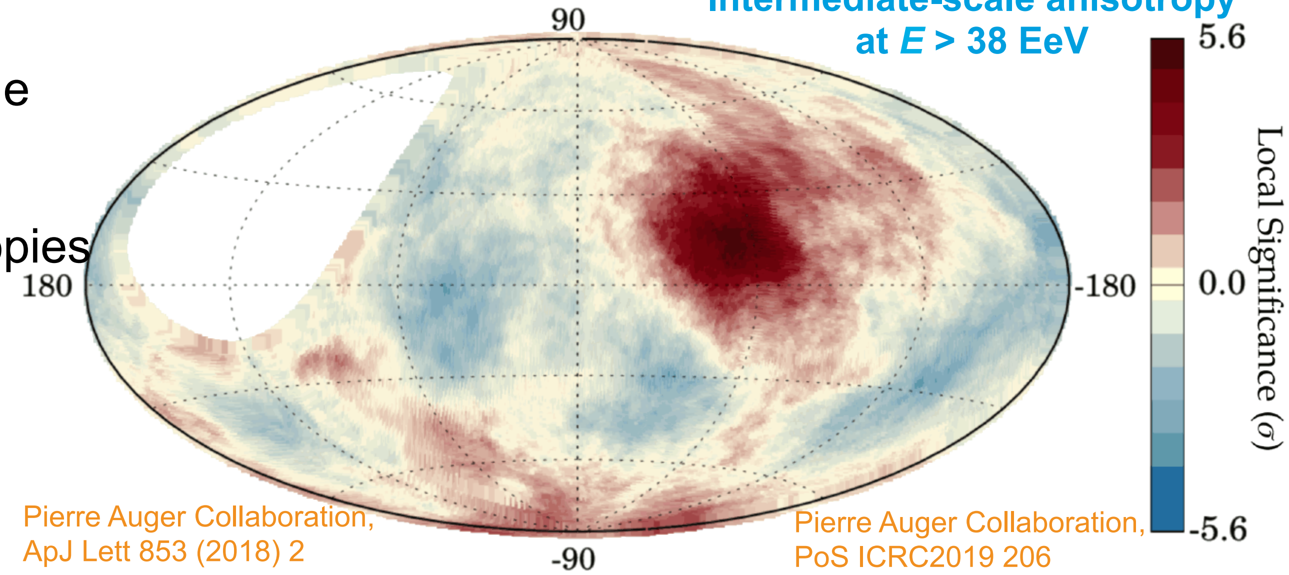
Dipole at E > 8 EeV



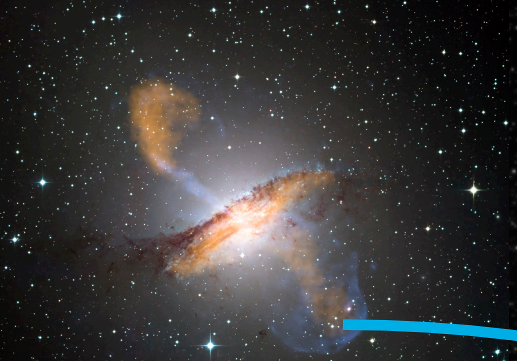
Pierre Auger Collaboration, Science 357 (2017) 6537

Intermediate-scale anisotropy at E > 38 EeV



Pierre Auger Collaboration, ApJ Lett 853 (2018) 2

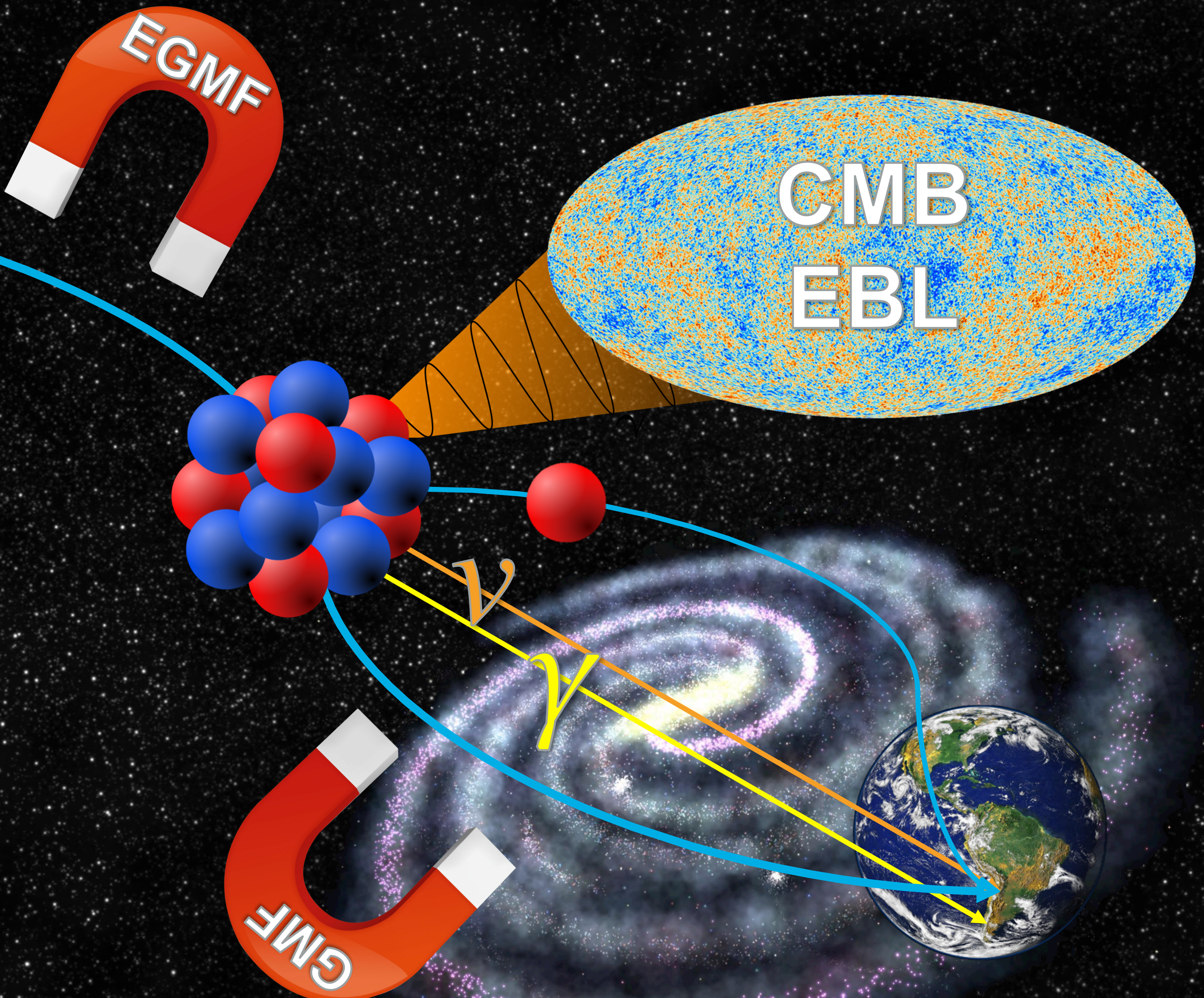
Pierre Auger Collaboration, PoS ICRC2019 206



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

Combined fit of UHECR spectrum and composition

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

  Power law with rigidity-dependent cut-off

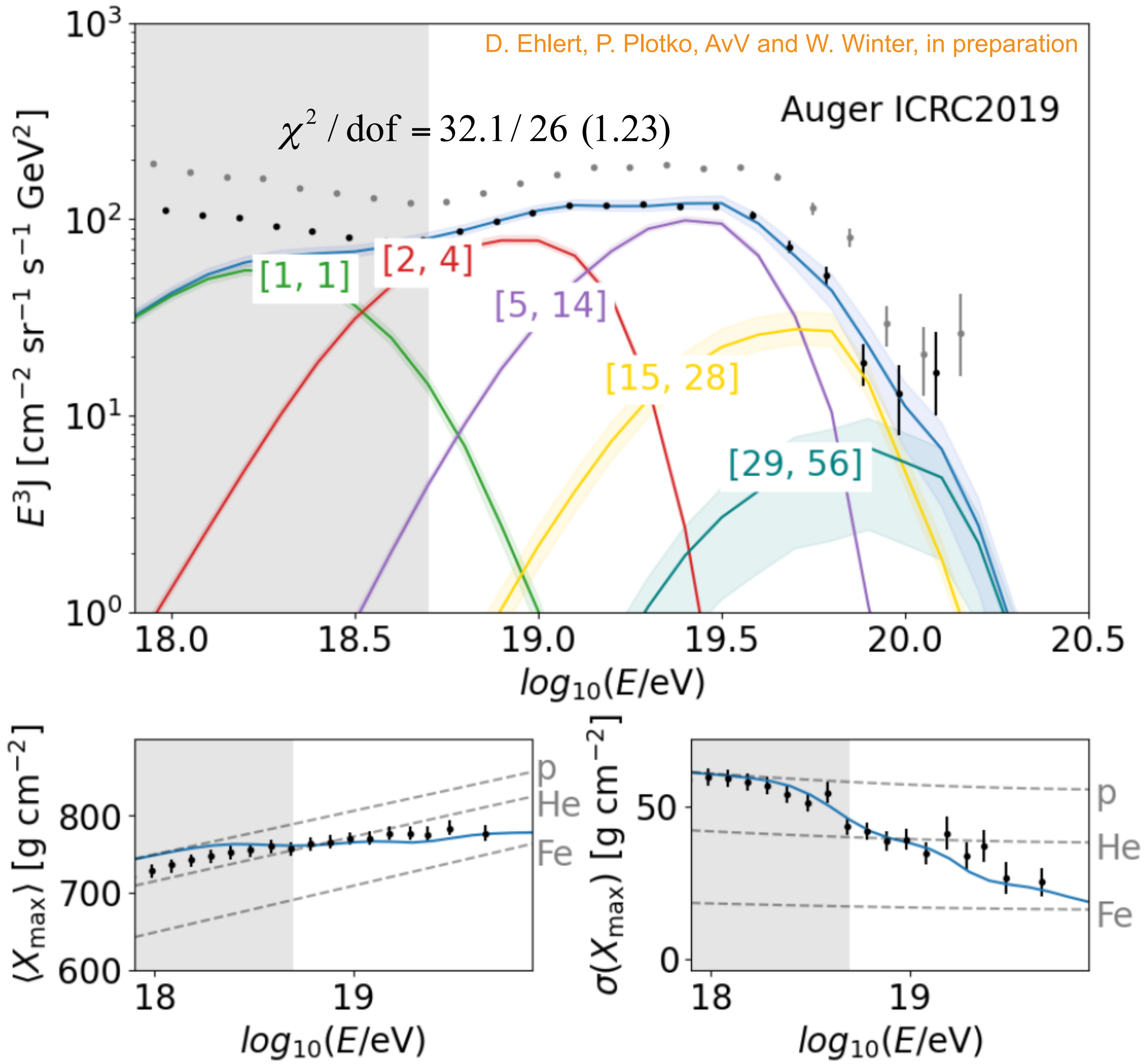
  $$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\gamma} \exp(-E / Z R_{\max})$$
- $\gamma < 1.3$, hard injection spectrum
- $R_{\max} = E^{i}_{\max}/Z < 7$ EV, low max. rigidity
- Composition at the sources:

  Intermediate to heavy ($Z > 5$)
- Source evolution with redshift:

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

  m not strongly constrained

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



Cosmogenic neutrino spectra

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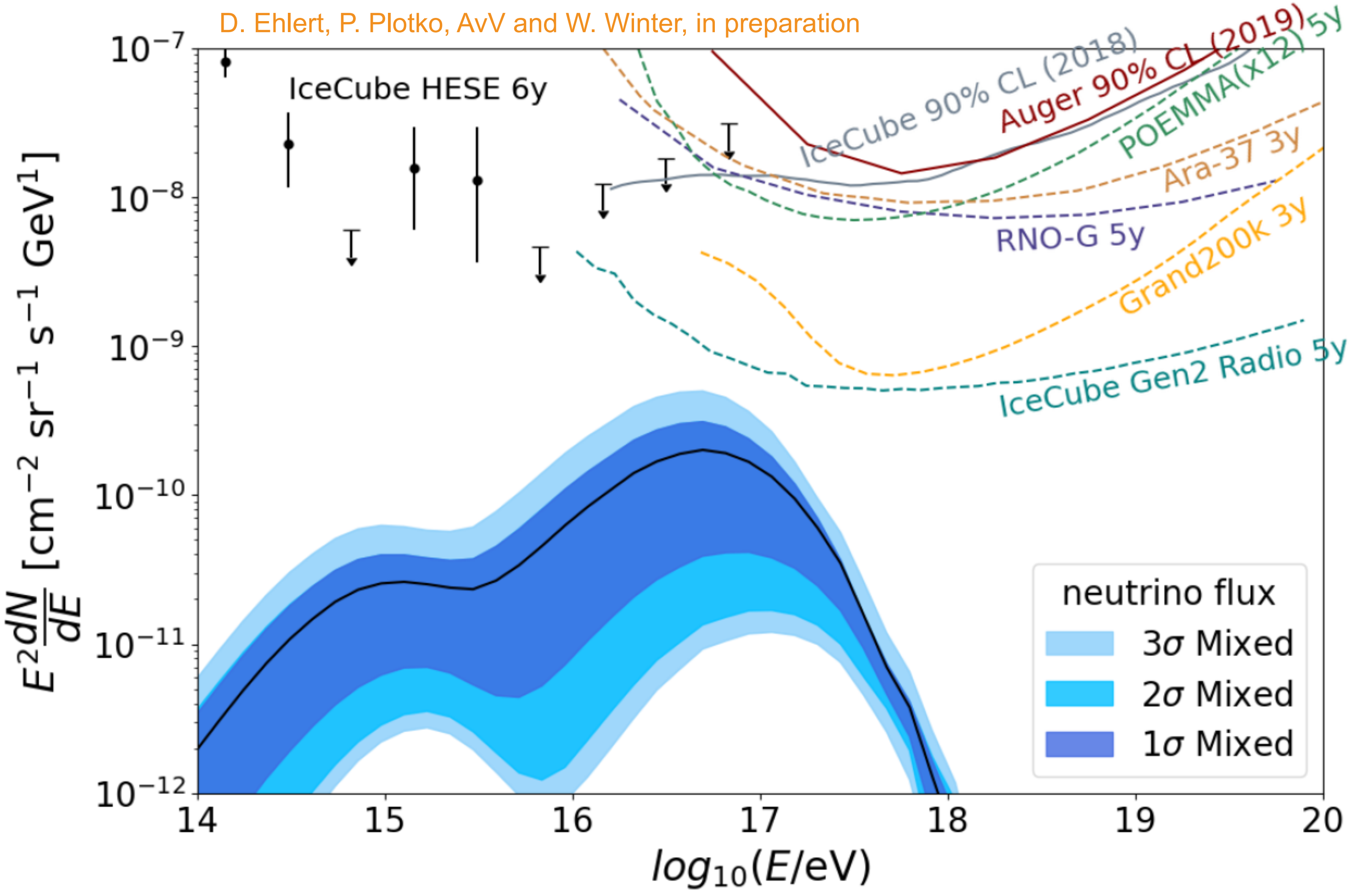
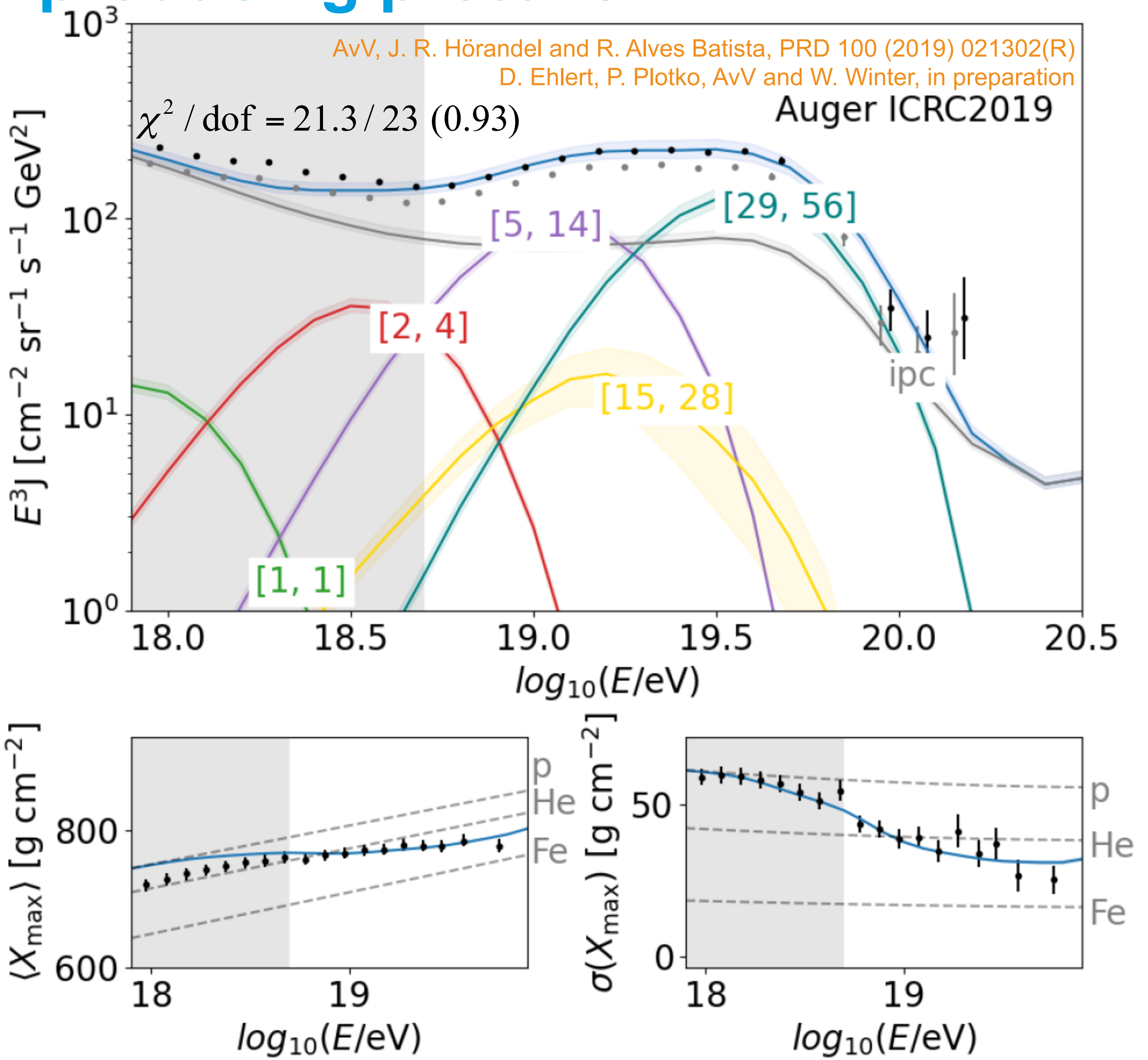
- **Very low cosmogenic neutrino flux**



Additional source population producing protons?

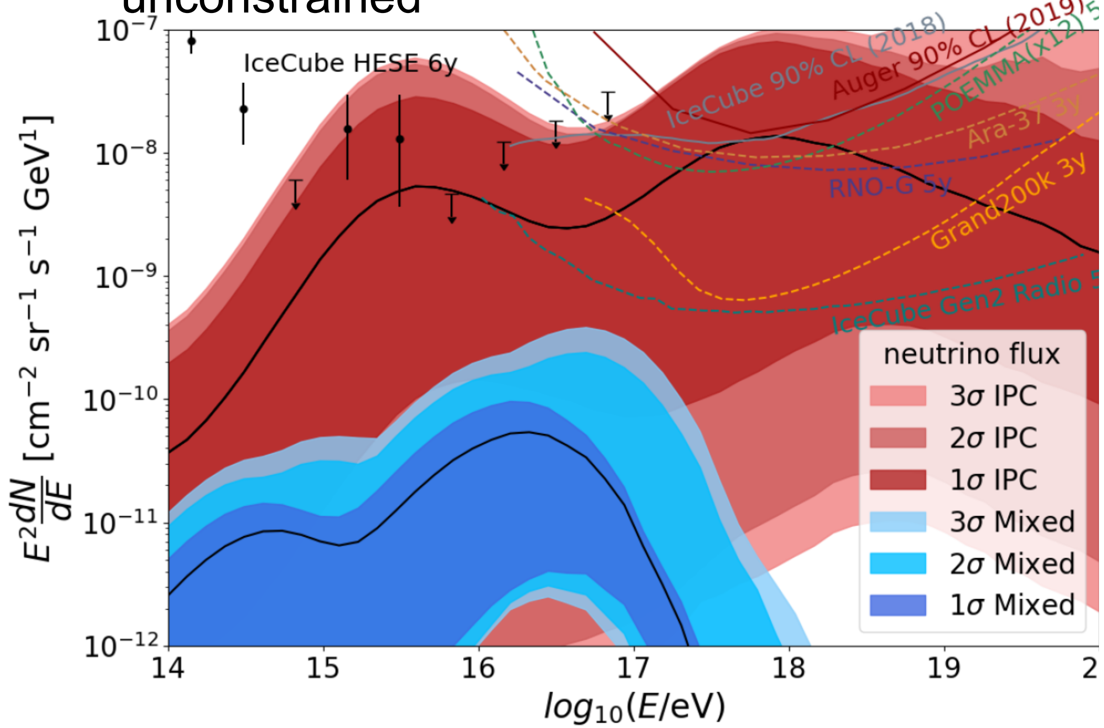
- Assumptions
  - Continuous distribution of identical sources
  - Rigidity-dependent maximum energy
- No protons at highest *E*
- But these assumptions might not be realistic
- **Additional proton component can improve the fit and significantly increases the expected cosmogenic neutrino flux**

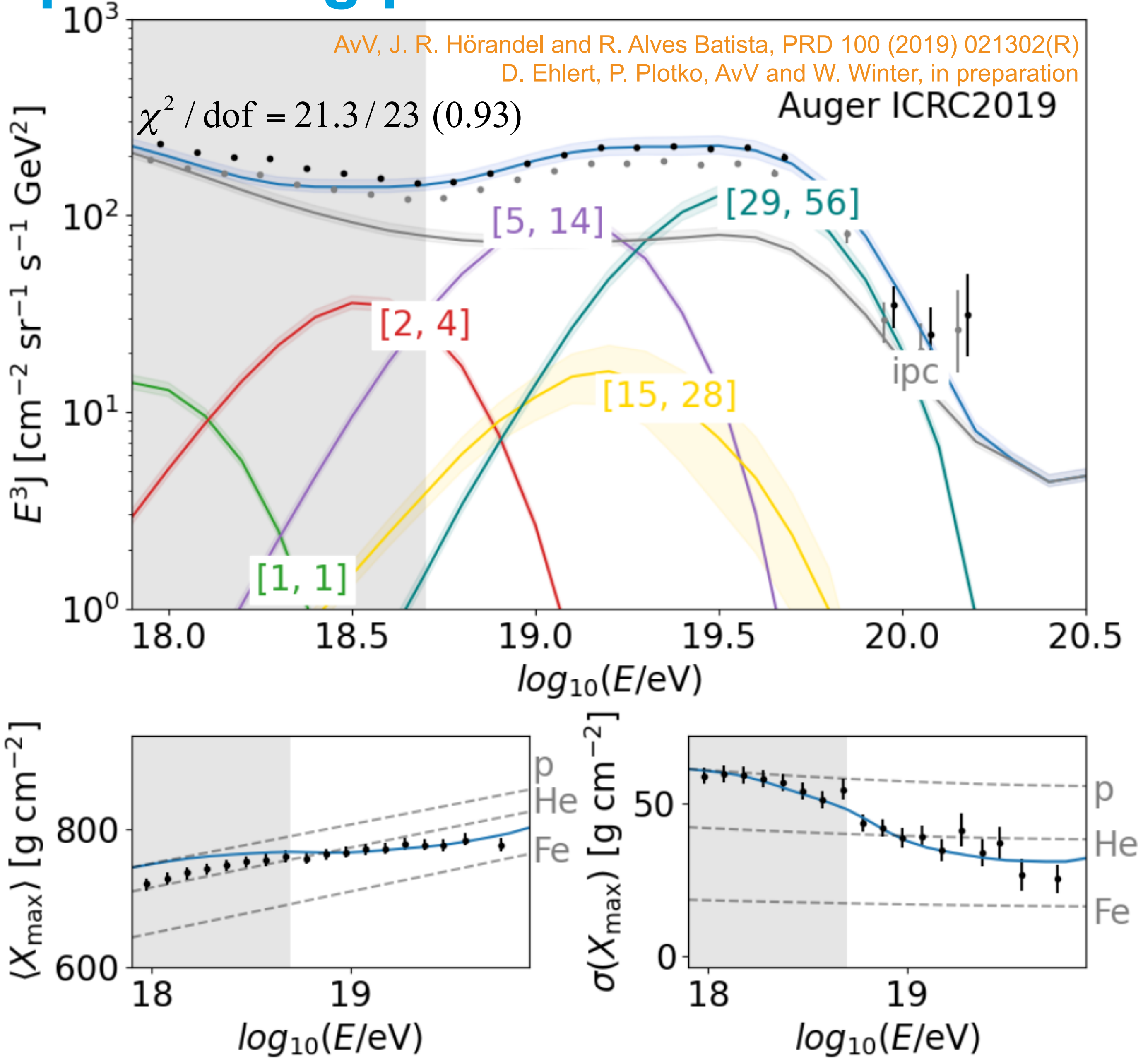
See also: Muzio *et al.* (2019), Das *et al.* (2021)



Additional source population producing protons?

- Improved fit quality, possibly more realistic assumptions, significantly enhanced cosmogenic neutrino flux
- Large number of protons at the highest energies: UHECR astronomy with AugerPrime?
- Large uncertainty because the source evolution of the proton component is basically unconstrained





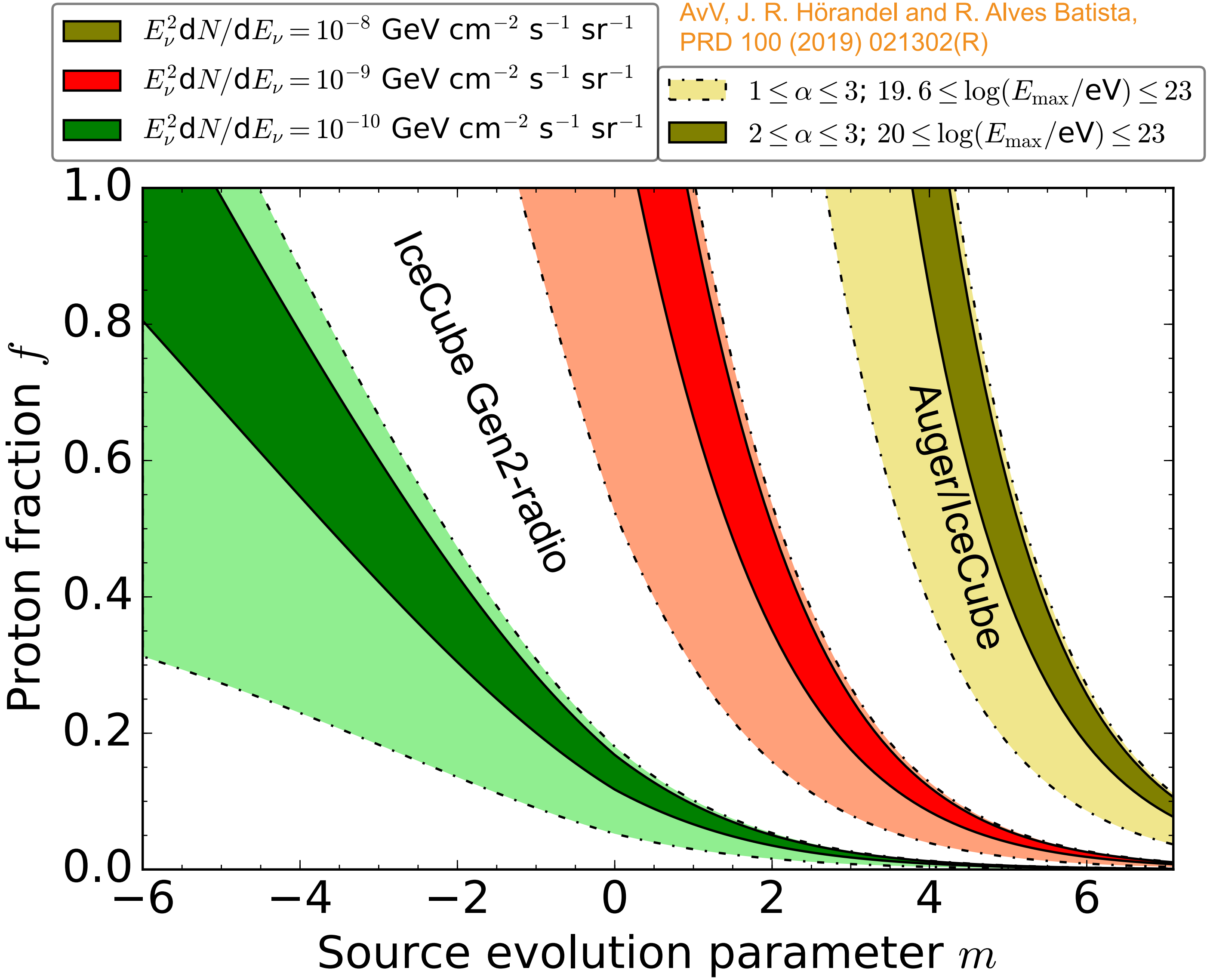
Proton fraction vs. source evolution

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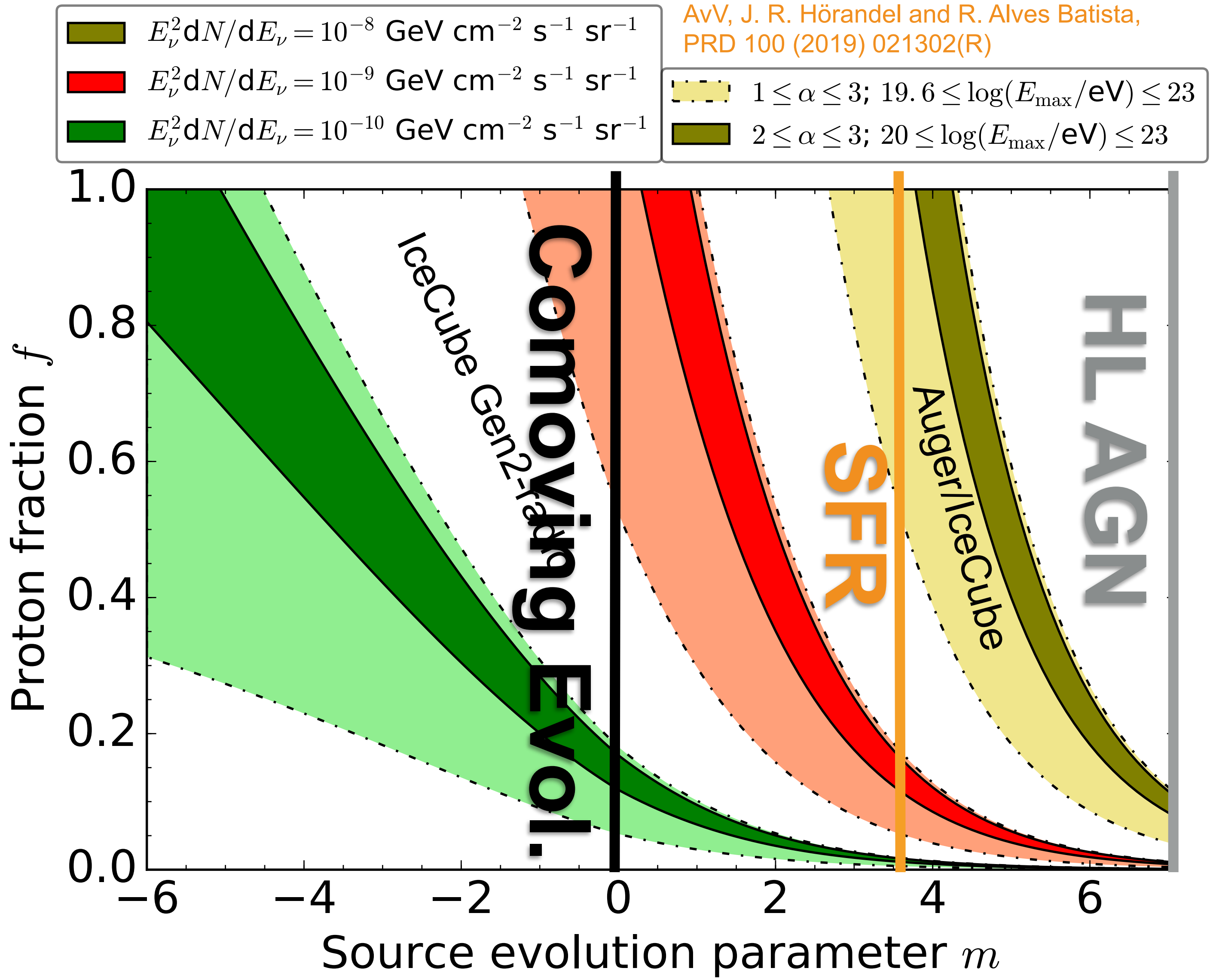
See also: Pierre Auger Collaboration, JCAP 10 (2019) 022

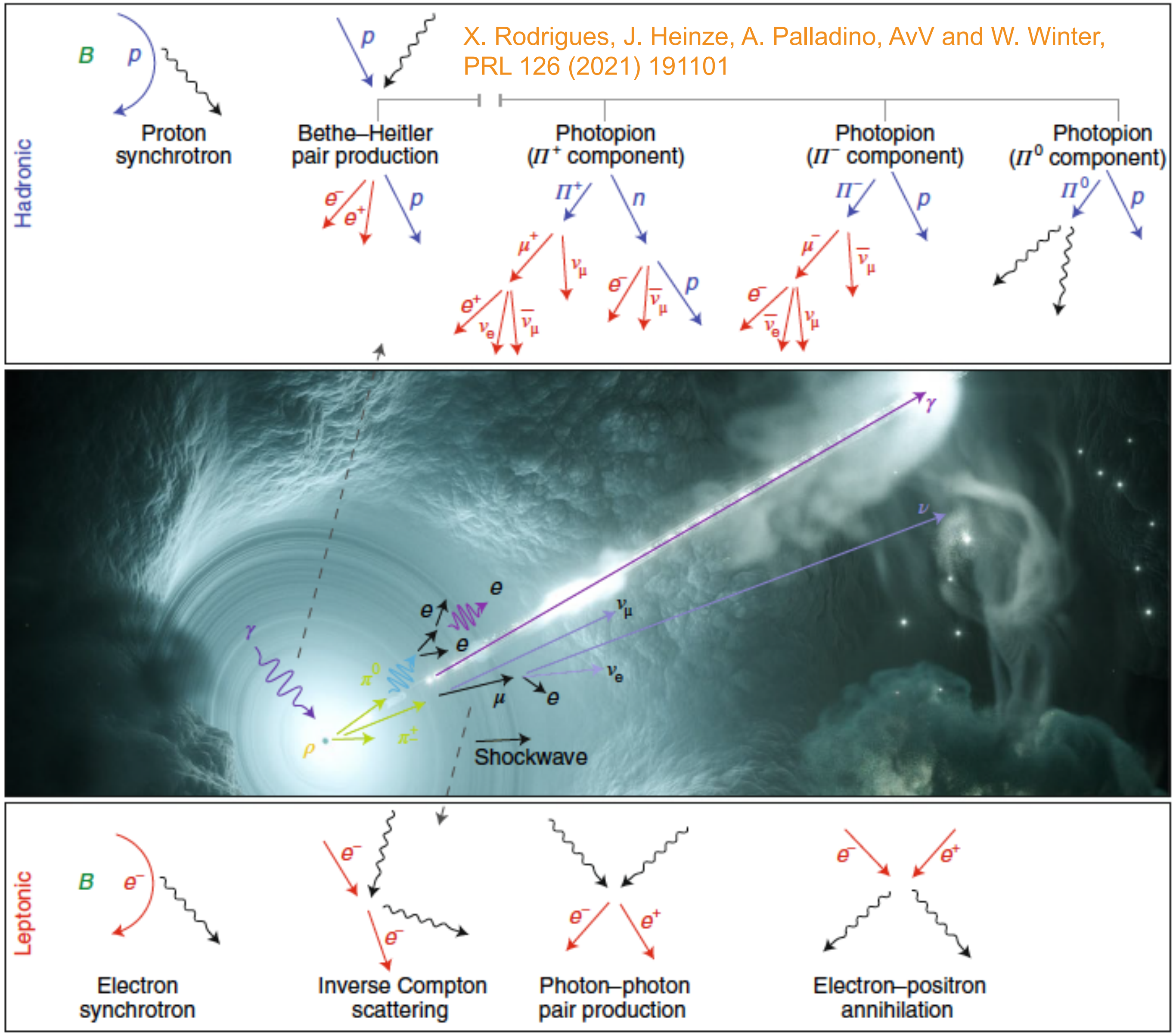
- Link source evolution to specific source classes

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



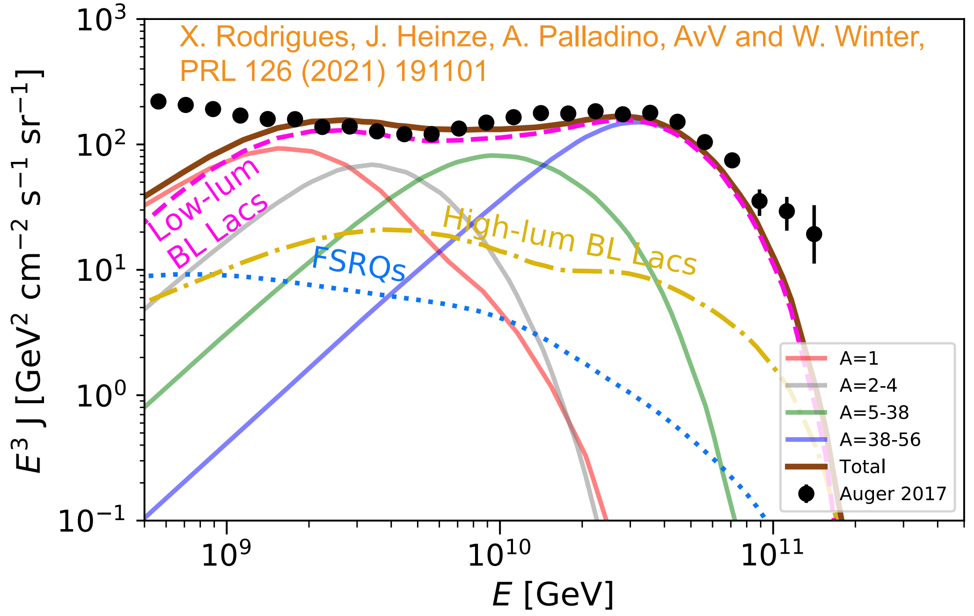
Source neutrinos: UHECRs and neutrinos from AGN

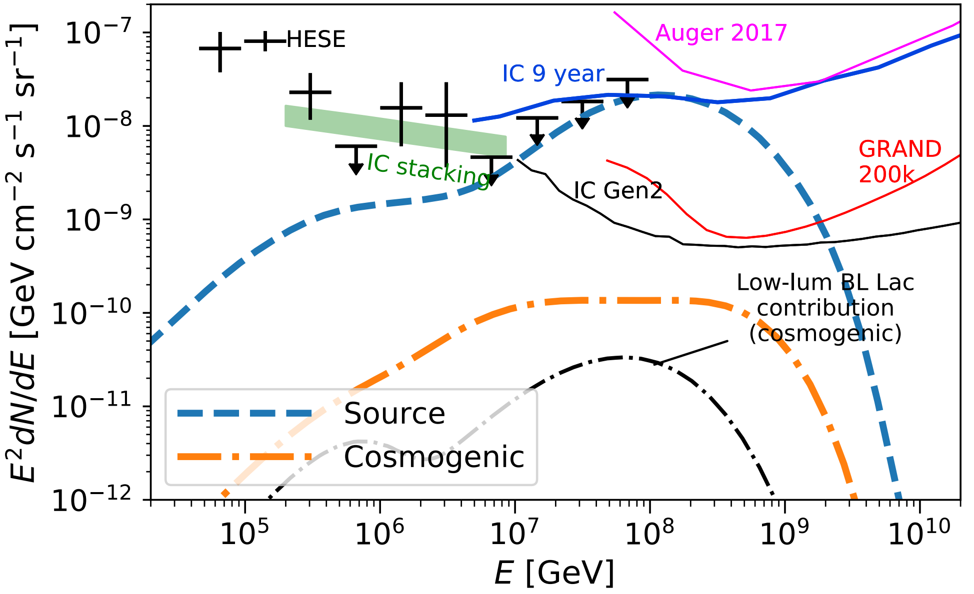
- Simulation of interactions inside the sources
- **Predictions for both source neutrinos and cosmogenic neutrinos**
- BL Lacs:
  - Low photon density
  - Efficient UHECR emitters
  - Inefficient neutrino emitters
  - Rigidity-dependent maximal energy
- FSRQs:
  - High photon density
  - Efficient photohadronic 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**
- Source neutrinos possibly identified and disentangled with different techniques
  - Stacking searches
  - Flare analyses
  - Multi-messenger follow-up





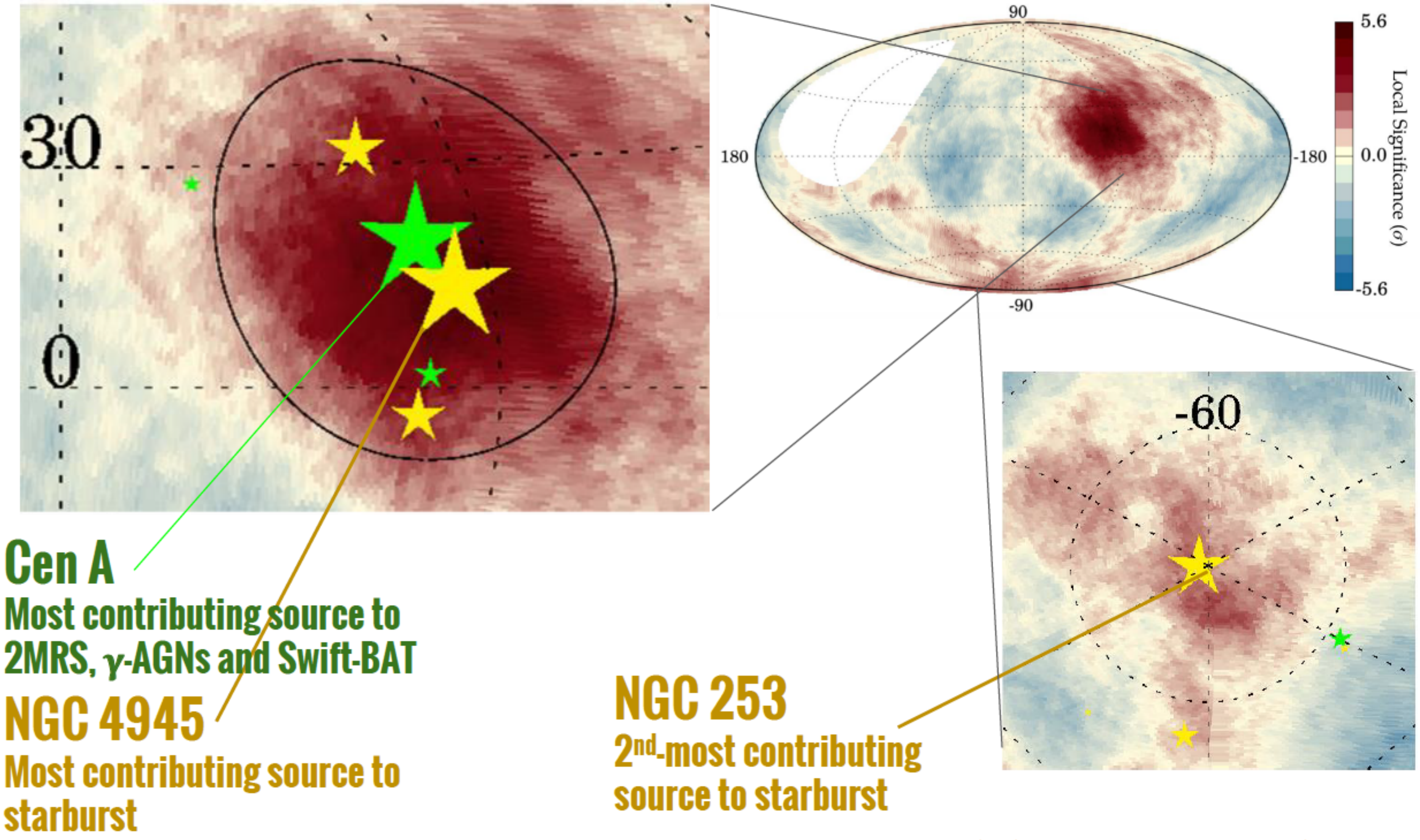
Indication of anisotropy in arrival directions found by Auger

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 (2021) stab3495

- 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

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Pierre Auger Collaboration, PoS ICRC2019 206

Our method

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS (2021) stab3495

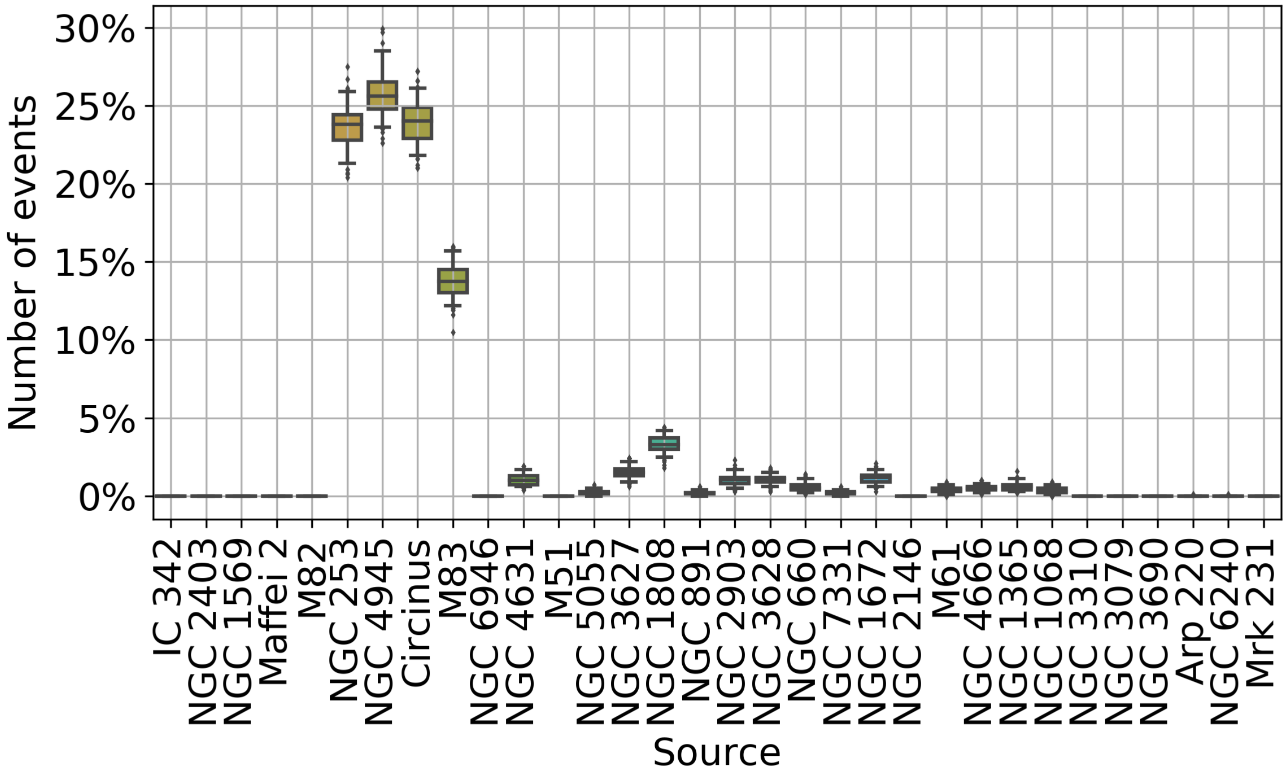
- Simulate UHECR sky maps for specific EGMF and GMF setups and local source densities ρ_0
- Check if these sky maps give θ and f_{aniso} values compatible with what Auger found

Our method

4 important sources

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS (2021) stab3495

- Simulate UHECR sky maps for specific EGMF and GMF setups and local source densities ρ_0
- Check if these sky maps give θ and f_{aniso} values compatible with what Auger found
- Focus on 4 most important sources
- UHECR source spectra and composition from fits to spectrum and composition of Auger
- Simulate deflections from catalogue sources in EGMF
  - random Kolmogorov fields; $0.1 < B_{RMS} < 10$ nG, $0.2 < l_{coh} < 10$ Mpc; $B = B_{RMS} \times \sqrt{l_{coh}}$
- Add deflections from GMF, JF12 model
- Combine catalogue sources with an isotropic contribution from background sources



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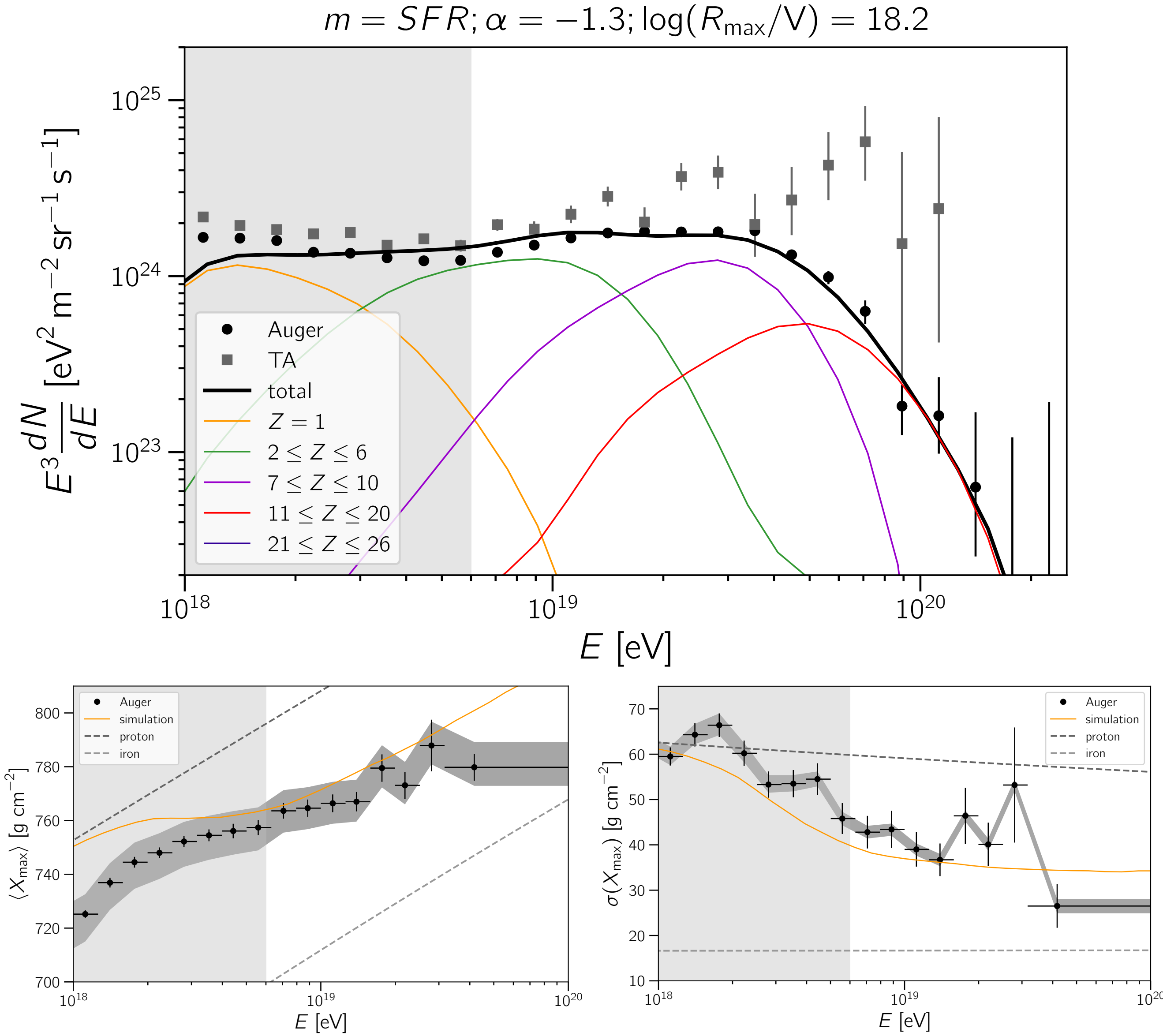

R. Alves Batista, R. M. de Almeida, B. Lago and K. Kotera, JCAP 01 (2019) 002

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AvV, A. Palladino, A. Taylor and W. Winter, MNRAS (2021) stab3495

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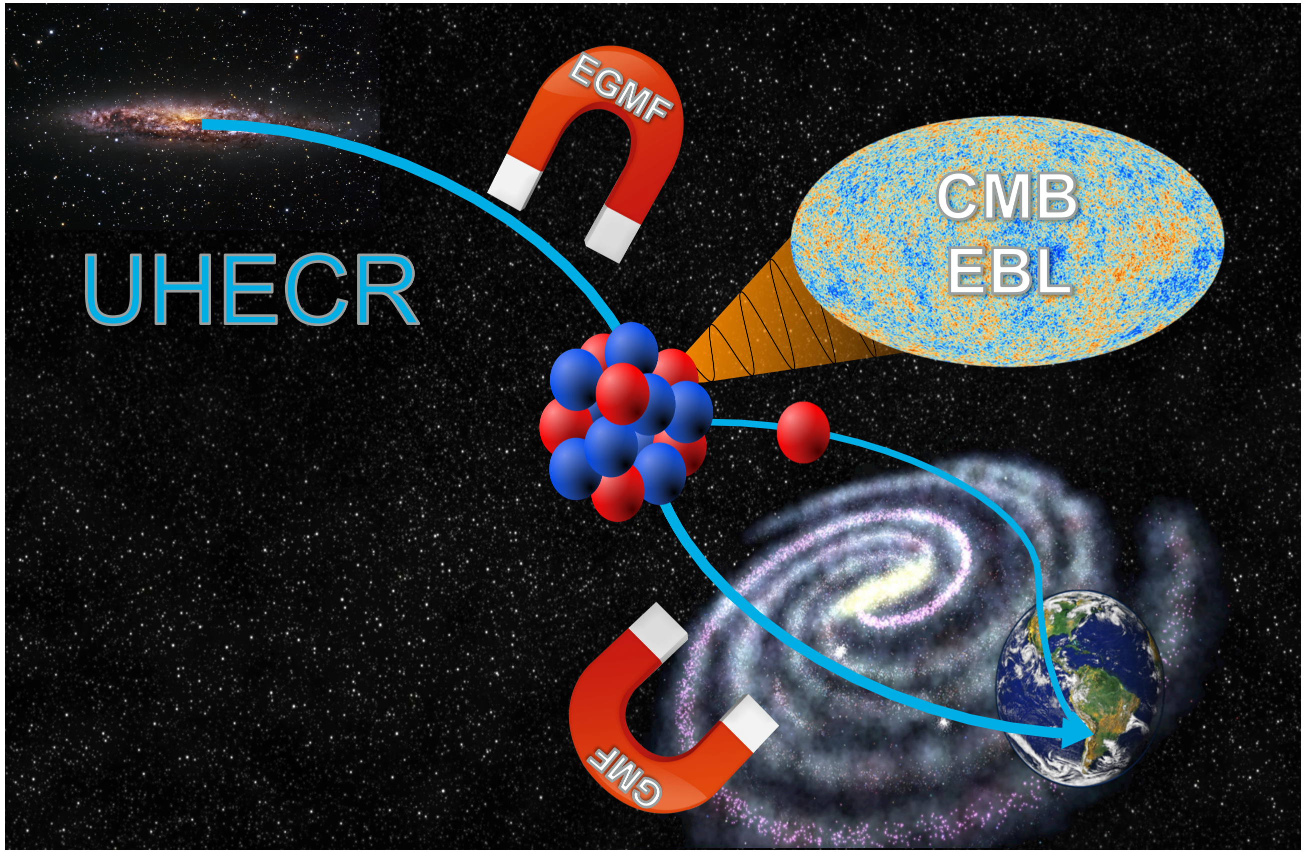

Our method

Source density

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS (2021) stab3495

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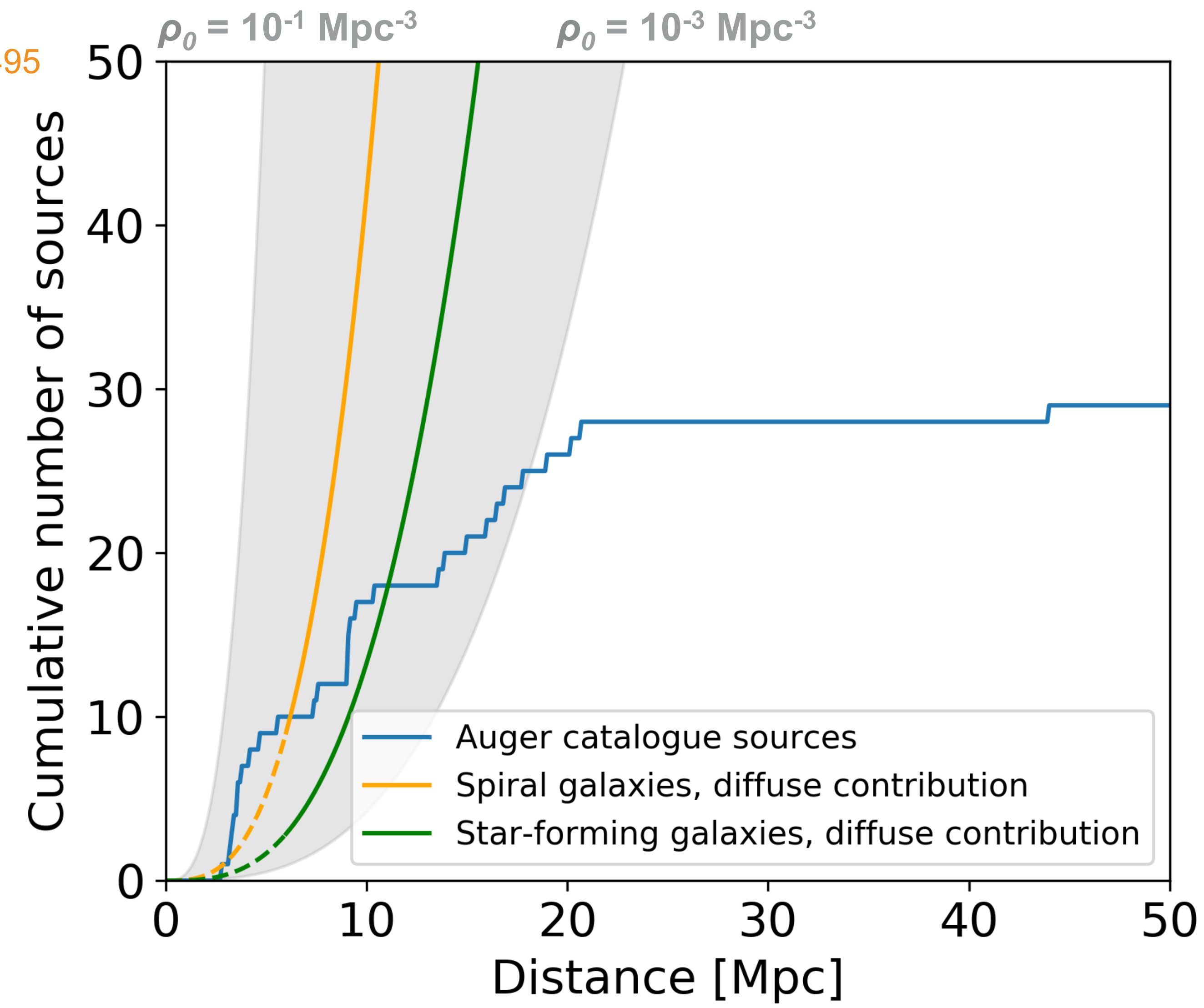
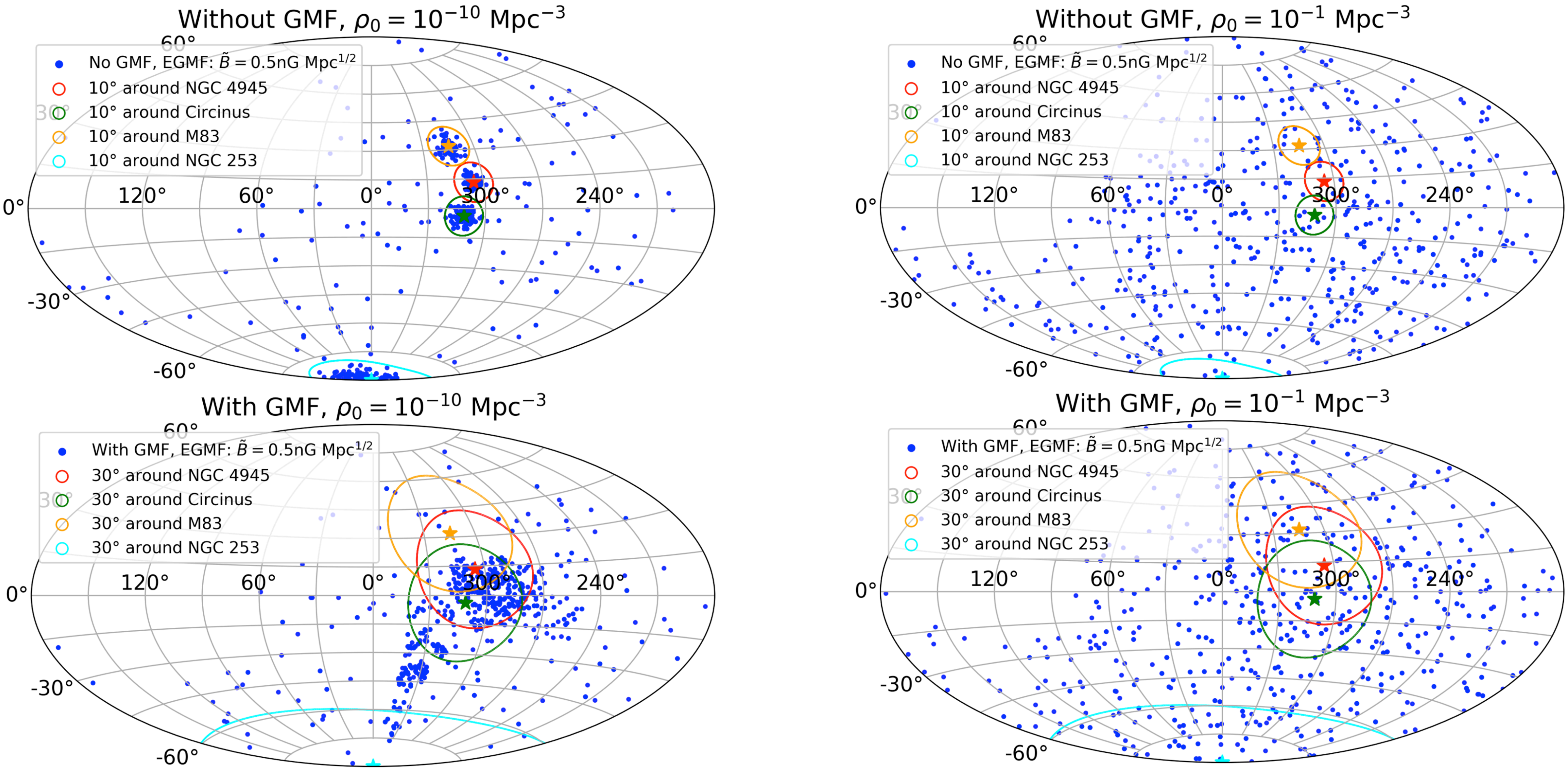


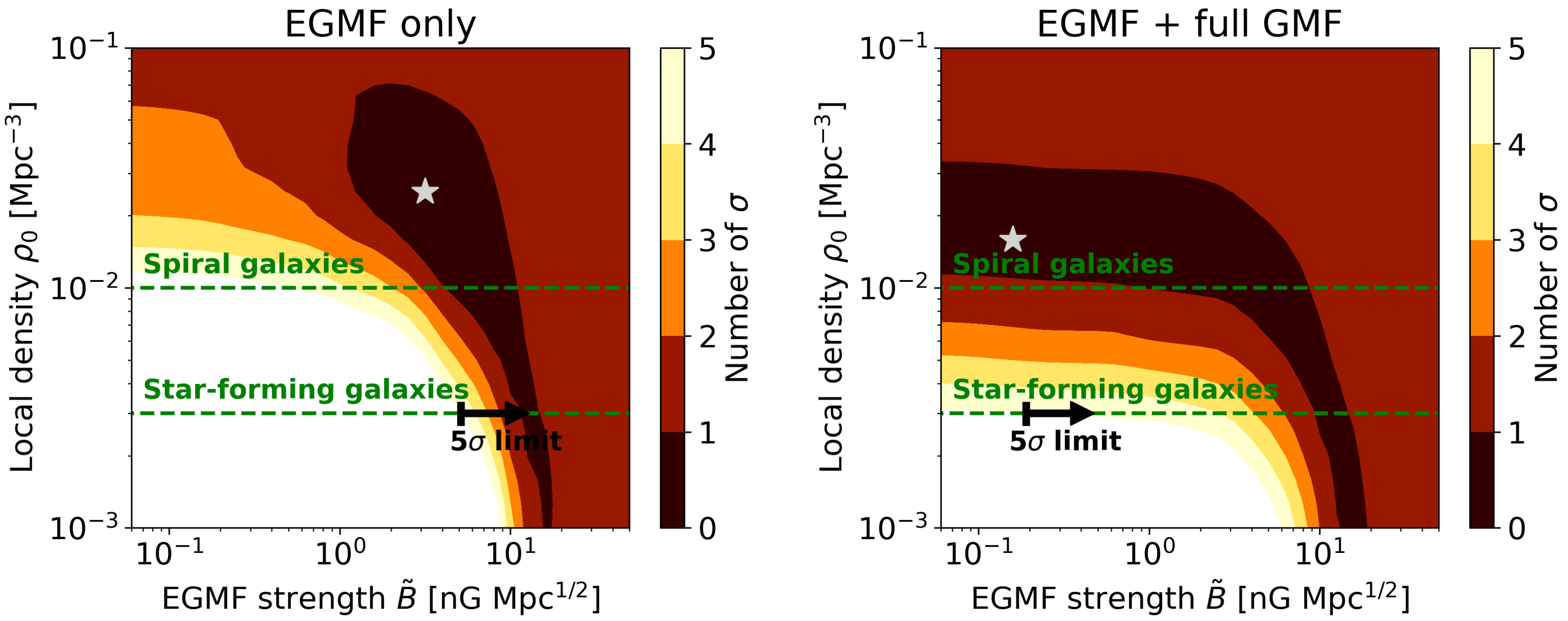
Example sky maps

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS (2021) stab3495



Preliminary results from scanning over ρ_0 and B

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS (2021) stab3495

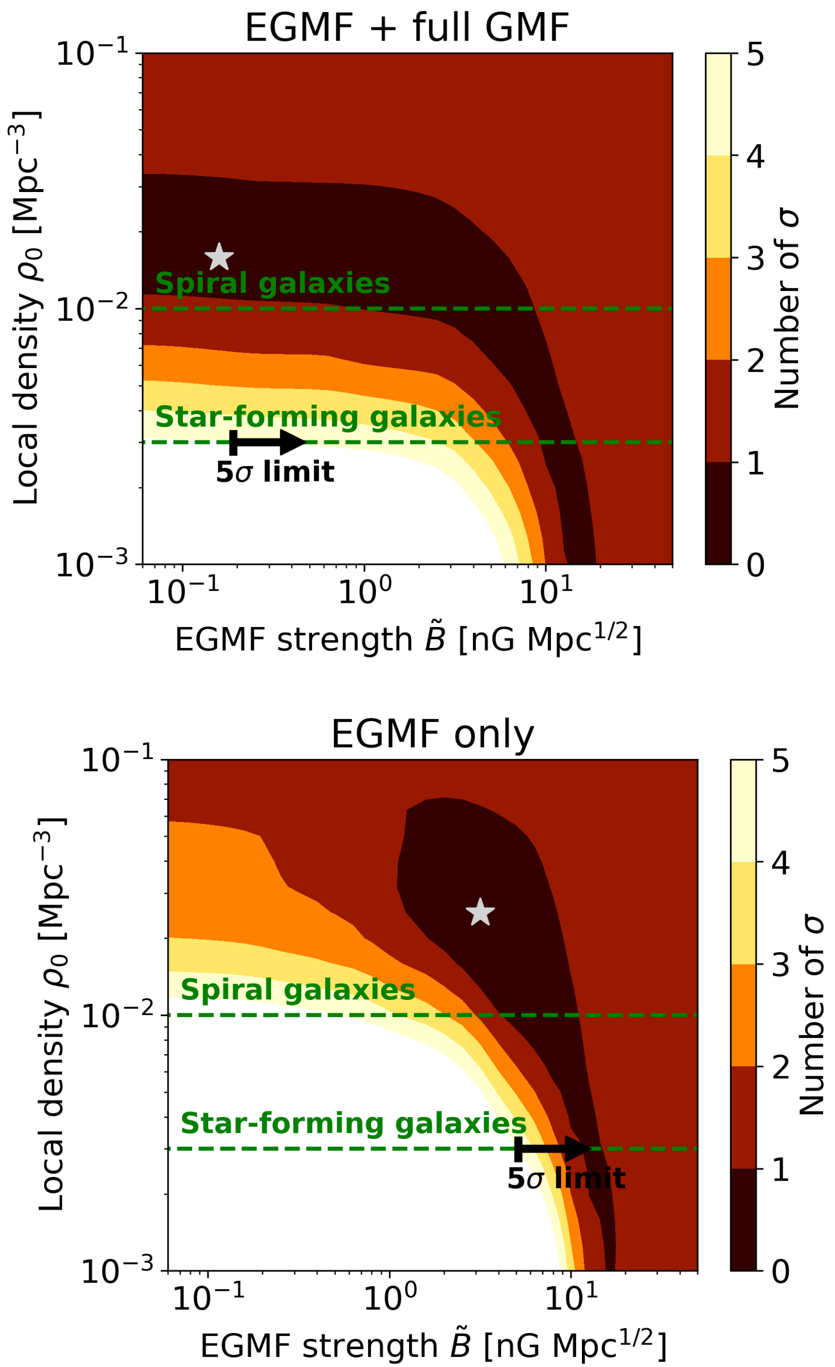


	EGMF only	EGMF + full GMF
5σ lower limit on $\tilde{B}$ for $\rho_0 = 3 \cdot 10^{-3}$ Mpc^{-3}	$\tilde{B} > 5.1$ nG Mpc$^{1/2}$	$\tilde{B} > 0.19$ nG Mpc$^{1/2}$
Best-fit point	$\tilde{B} = 3.2$ nG Mpc$^{1/2}$; $\rho_0 = 2.5 \cdot 10^{-2}$ Mpc^{-3}	$\tilde{B} = 0.16$ nG Mpc$^{1/2}$; $\rho_0 = 1.6 \cdot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

Conclusions

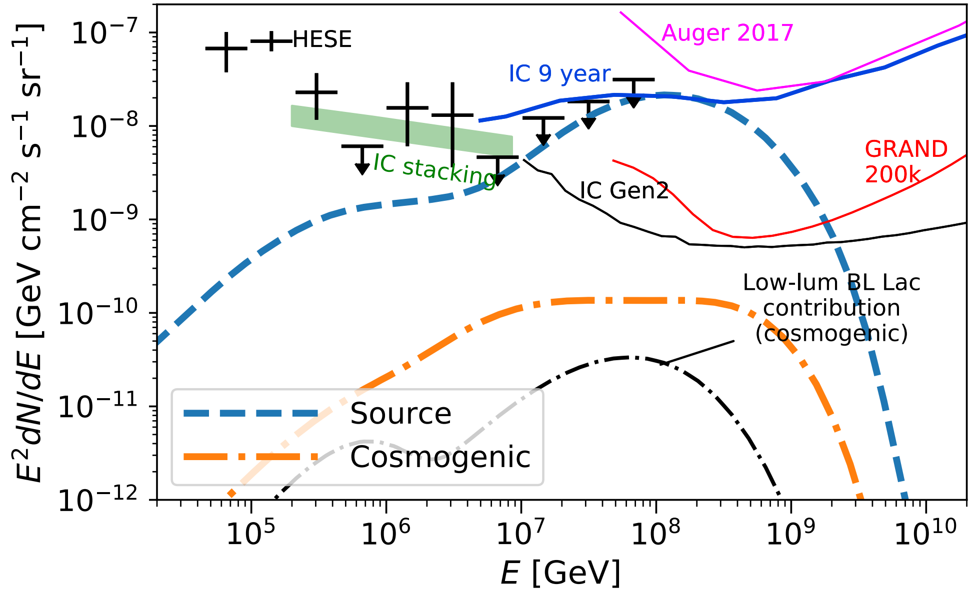
AvV, A. Palladino, A. Taylor and W. Winter, MNRAS (2021) stab3495

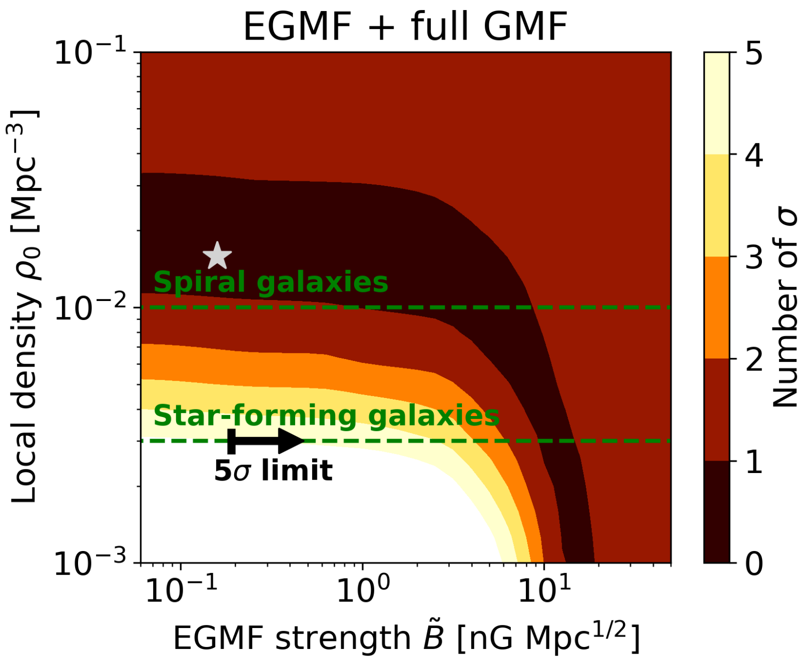
- Main assumption: overdensities in UHECR sky maps by Auger are produced by local star-forming galaxies
- If true, and the background UHECRs come from the same source class, a 5σ lower limit on the EGMF is obtained: $\boldsymbol{B > 0.19}$ **nG Mpc$^{1/2}$**
- Allowing for the full range of ρ_0:
  - 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: $\boldsymbol{B < 22}$ **nG Mpc$^{1/2}$**; $\boldsymbol{\rho_0 < 0.084}$ **Mpc^{-3}**
  - Best-fit point for a source density close to, or even denser than, that of spiral galaxies



Summary

- UHECR spectrum and composition fits under the simplest assumptions give very low cosmogenic neutrino fluxes
- However, the fits can be improved by adding an independent proton component
- Strong potential for future neutrino detectors
  - To detect cosmogenic neutrinos in the UHE range
  - To constrain the combination of proton fraction and source evolution
  - To determine the dominant source class if AugerPrime gives the proton fraction
- Source neutrinos could even outshine cosmogenic neutrinos, allowing for additional techniques to identify the sources
- Relatively strong EGMFs are required to explain the anisotropy results of Auger, if UHECRs are indeed produced by star-forming galaxies

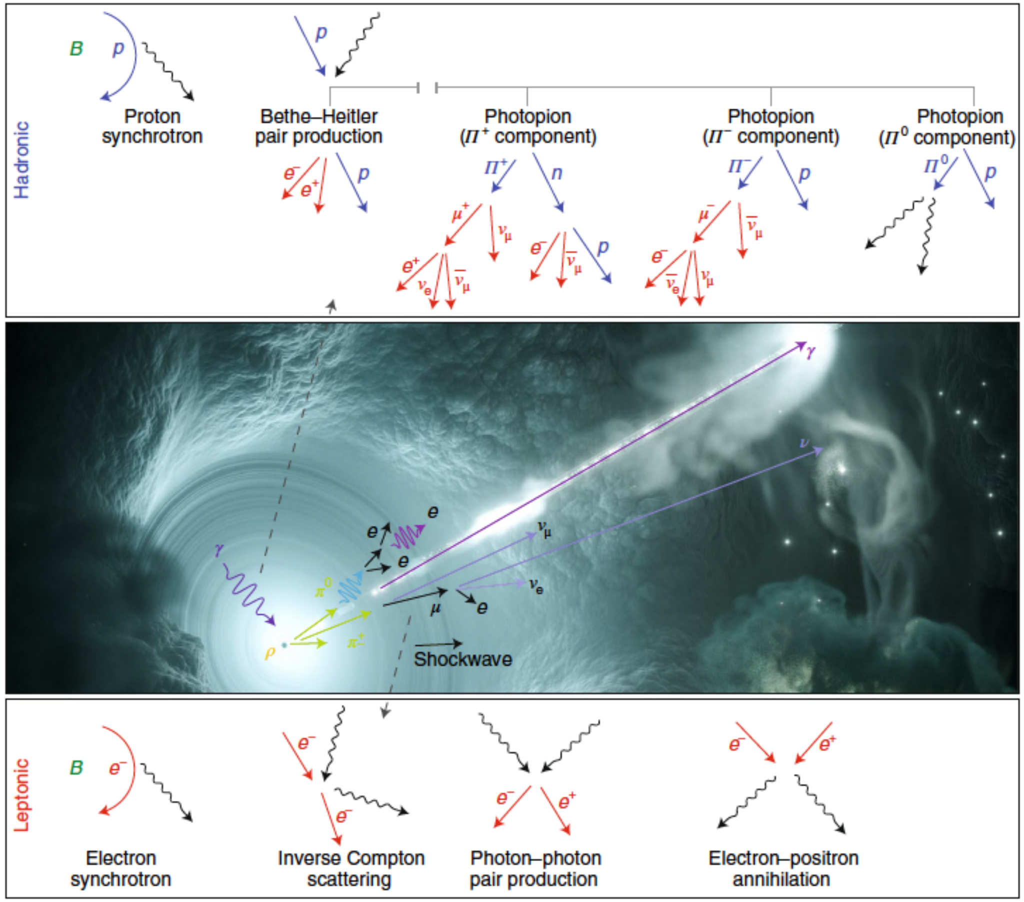




Backup slides

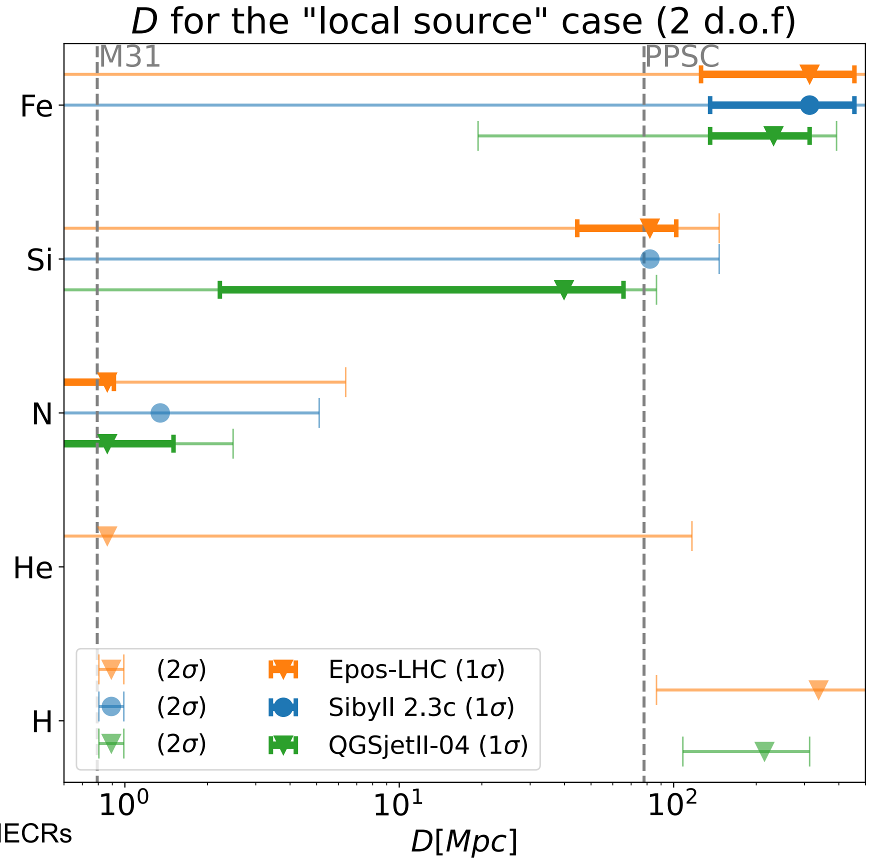
UHECRs and astrophysical neutrinos

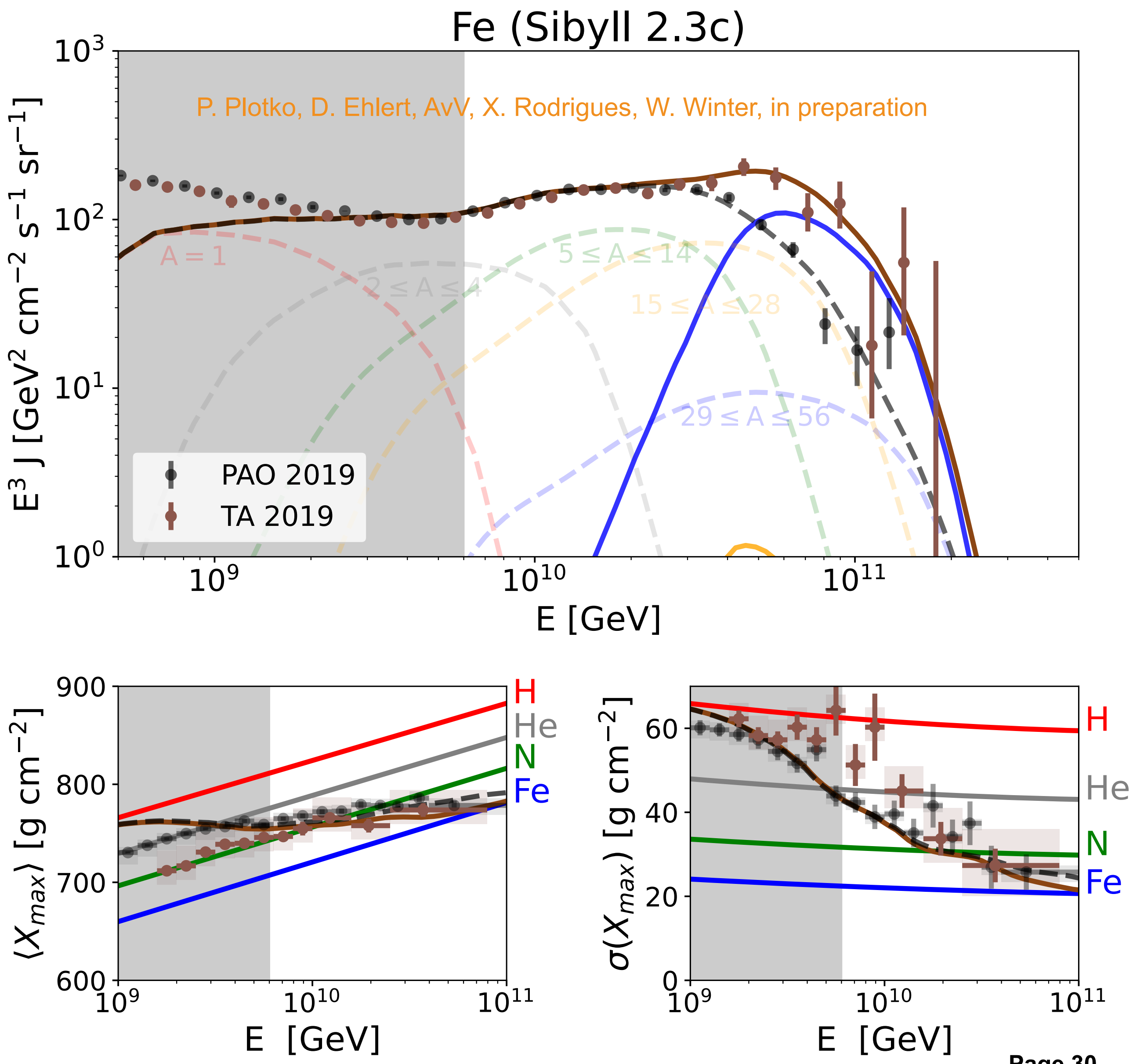
- Ultra-high-energy cosmic rays (UHECRs):
  - Nuclei from protons to iron with $E > 10^{18}$ eV (= 10^9 GeV = 1 EeV)
- Main experiments:
  - Pierre Auger Observatory in Argentina
  - Telescope Array in the US
- No identified sources yet
- High-energy astrophysical neutrinos ($E > 10^{14}$ eV), produced 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)



Explaining the Auger and TA spectra with a local source

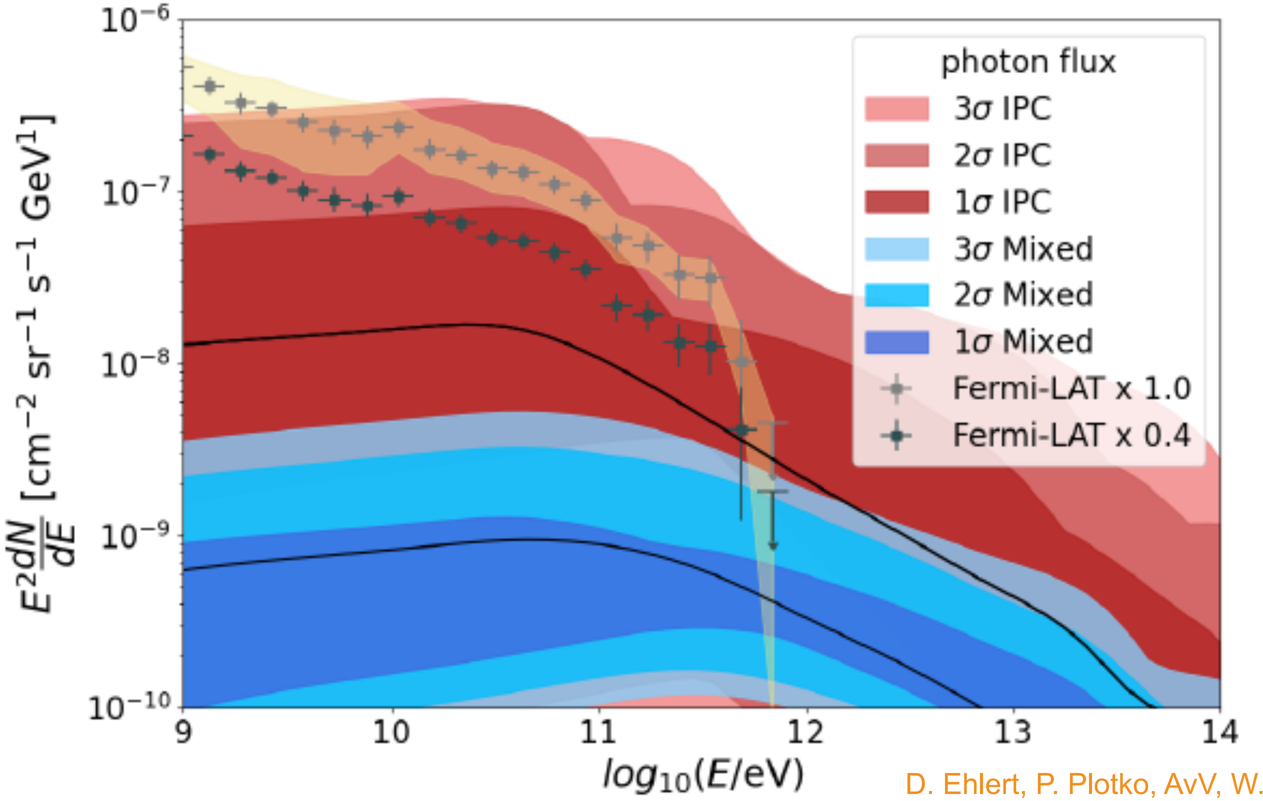
- Discrepancy in the UHECR spectra at the highest energies measured by Auger and TA
- Can be explained by adding a local source in the Northern hemisphere, only observable by TA

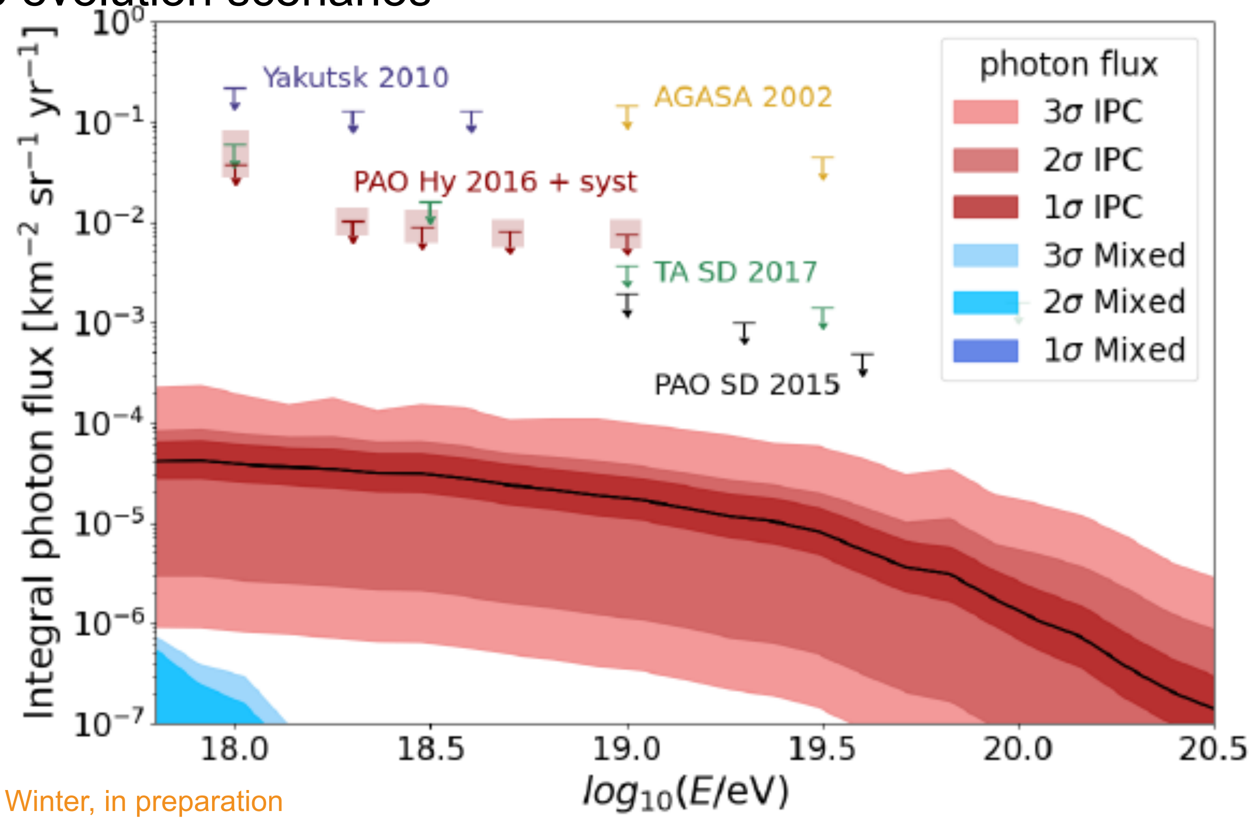




Cosmogenic photons from the 2nd source population

- Fermi LAT's isotropic gamma-ray background (IGRB) is quite constraining
- Unresolved point sources produce ~60-100% of the IGRB ➔ rescaling by 0.4
- However, additional uncertainties might play a role due to possible effects of uncertainties in the EBL model and in the EGMF strength
- Limits on UHE photons are not constraining at the moment, but it is interesting to note that the highest UHE photon fluxes are produced by negative source evolution scenarios



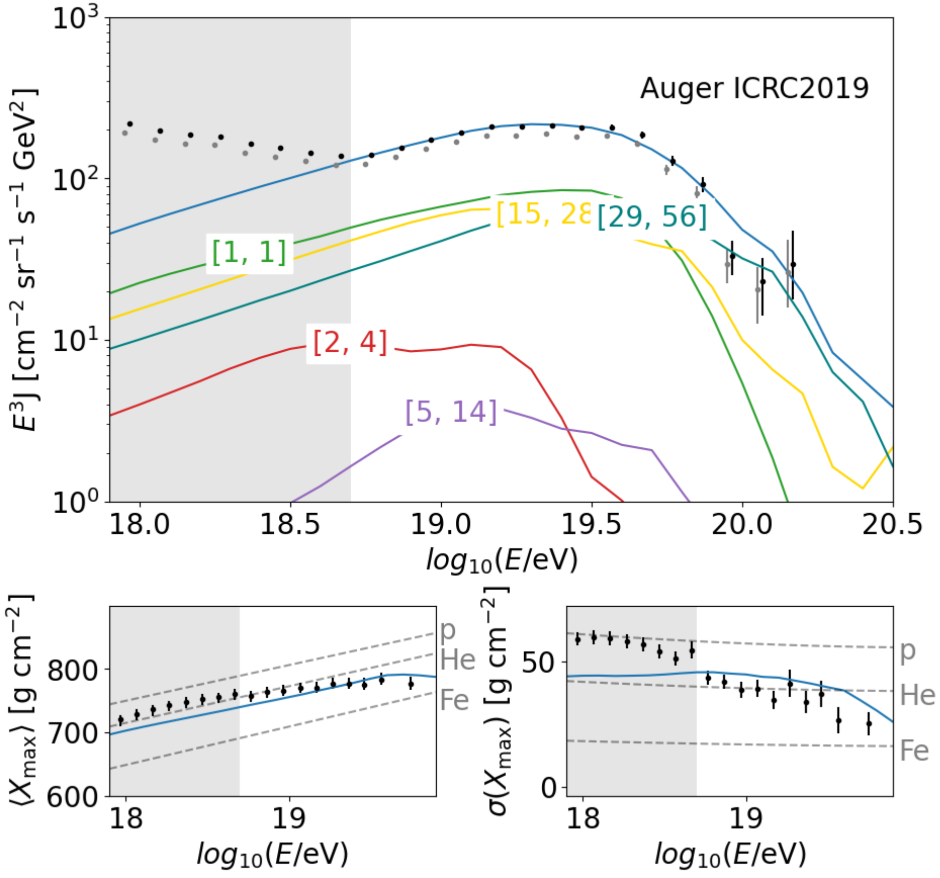


D. Ehlert, P. Plotko, AvV, W. Winter, in preparation

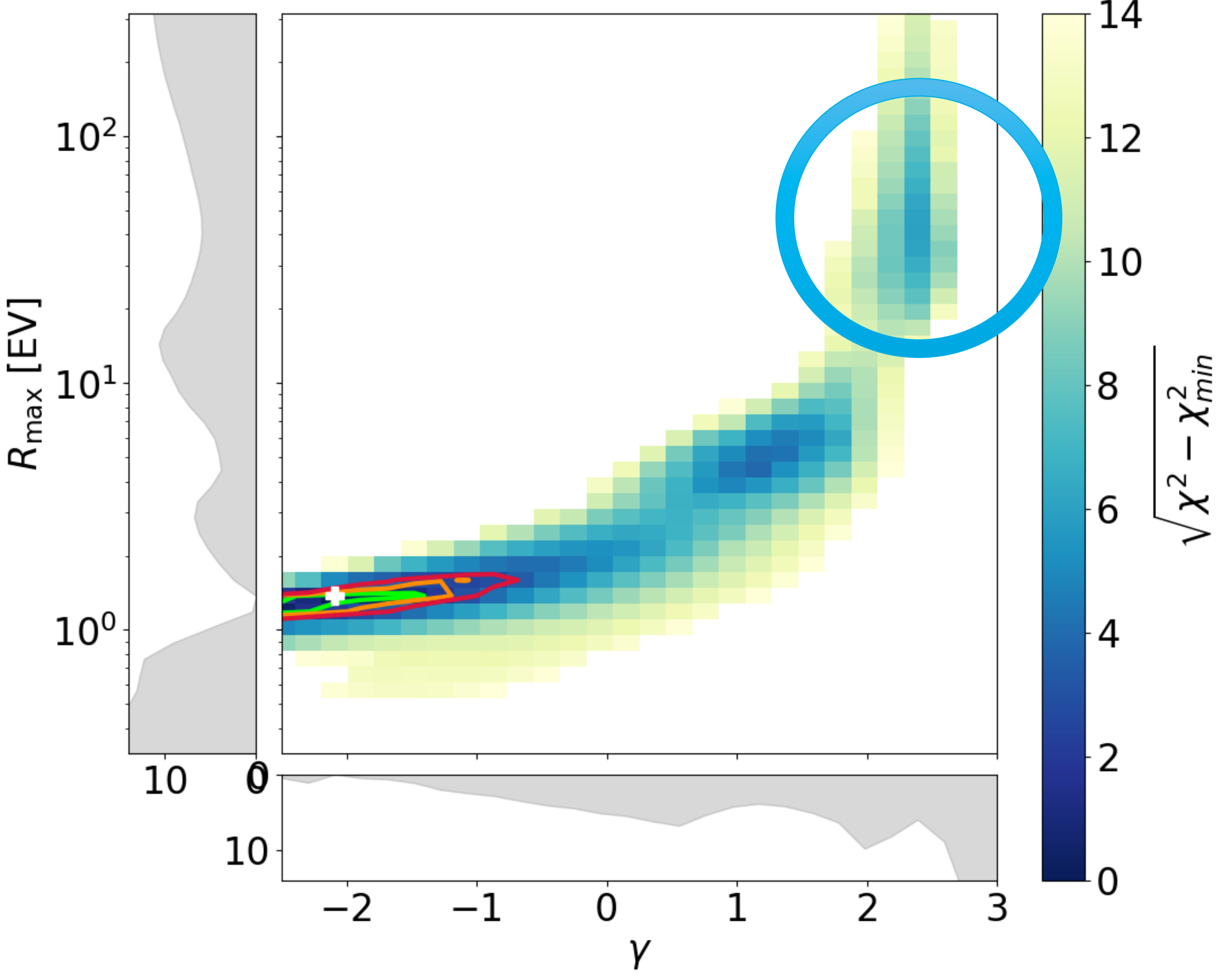
Other possibilities

2^{nd} minimum in the combined fit

- $\gamma > 2$, Fermi acceleration?
- $R_{max} > 30$ EV, protons reach higher energies
- Composition at the sources: ~50% protons



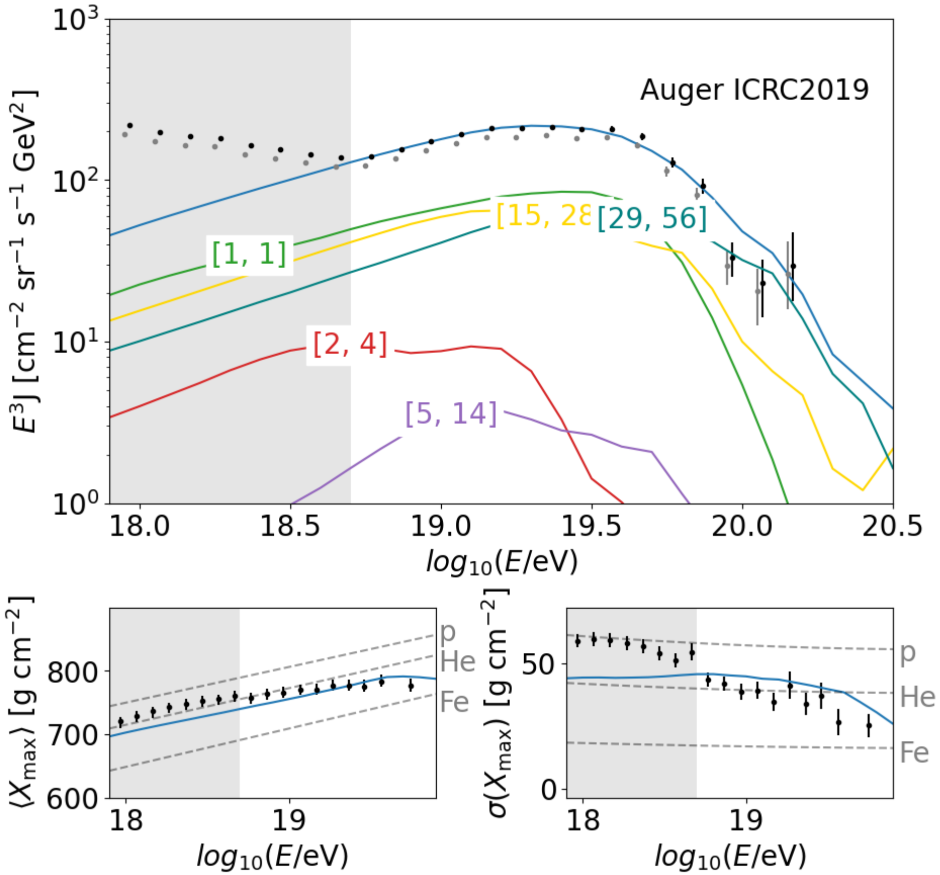
D. Ehlert, P. Plotko, AvV, W. Winter, in preparation



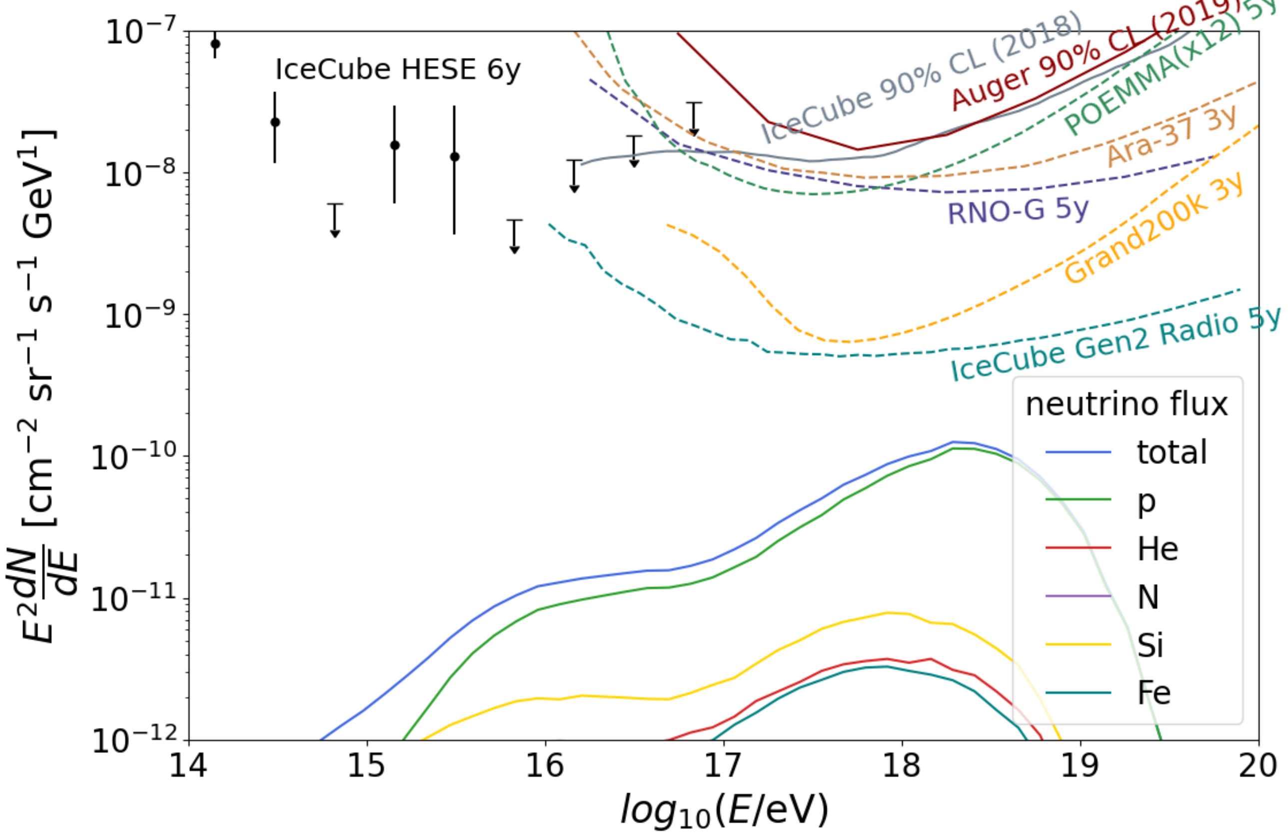
Other possibilities

2nd minimum in the combined fit

- Not a very good fit, excluded at ~6σ
- Not many neutrinos due to negative source evolution



D. Ehlert, P. Plotko, AvV, W. Winter, in preparation

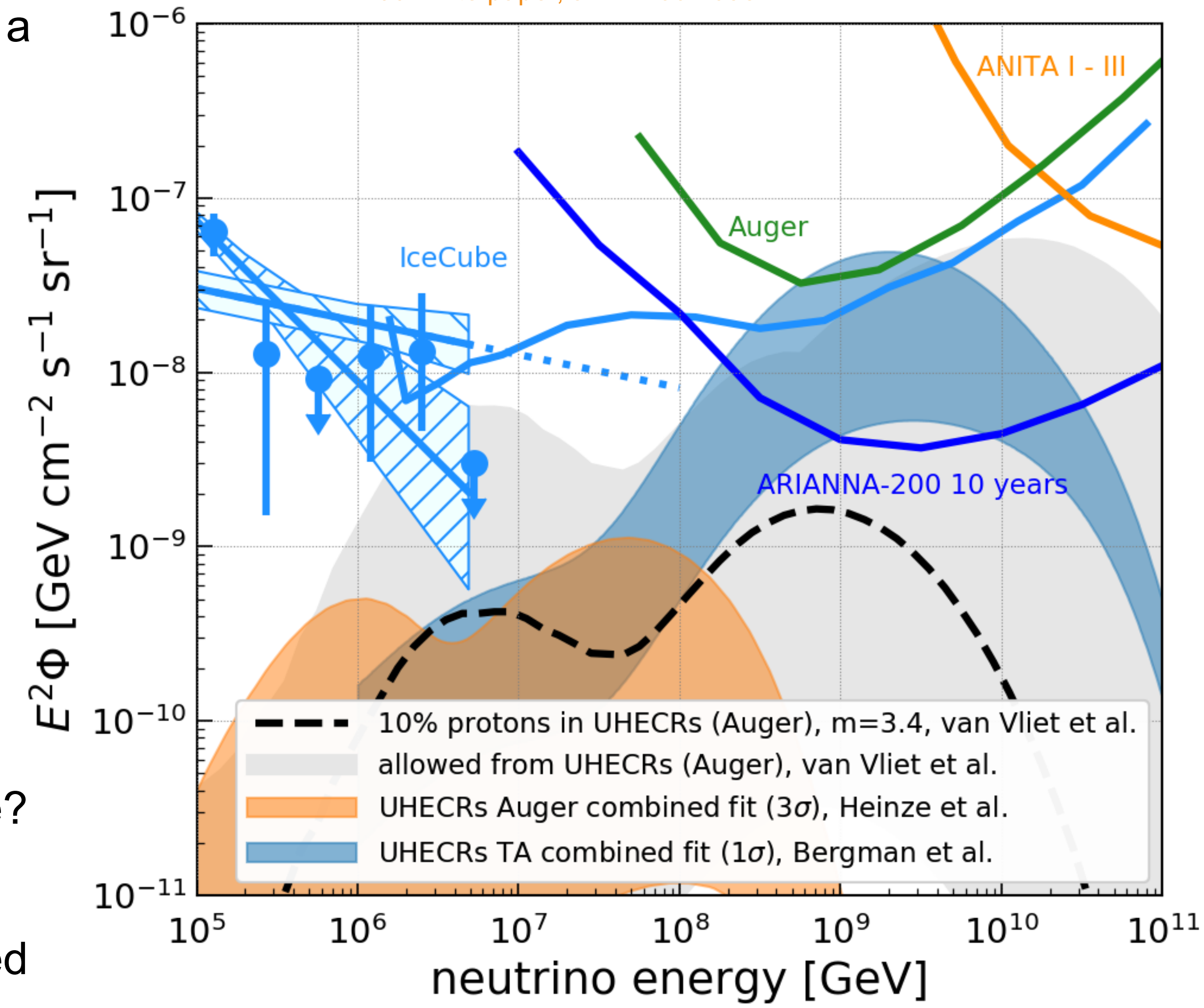


Other possibilities

Fit to Telescope Array data instead of Auger data

- TA claims a lighter composition than Auger, and has a stronger UHECR flux at the highest energies
  - See also: D. Bergman, PoS (ICRC2021) 338
- However, both spectrum and composition of TA and Auger in good agreement (within energy scale uncertainties) for E < 30 EeV
- Both spectra in good agreement in the same declination band
- No indication of declination dependence in the spectrum of Auger
- TA spectrum does show declination dependence for E > 30 EeV, local source in the northern hemisphere?
- No reason to expect a difference between TA and Auger, as far as cosmogenic neutrinos are concerned

ARIANNA-200 white paper, arXiv:2004.09841



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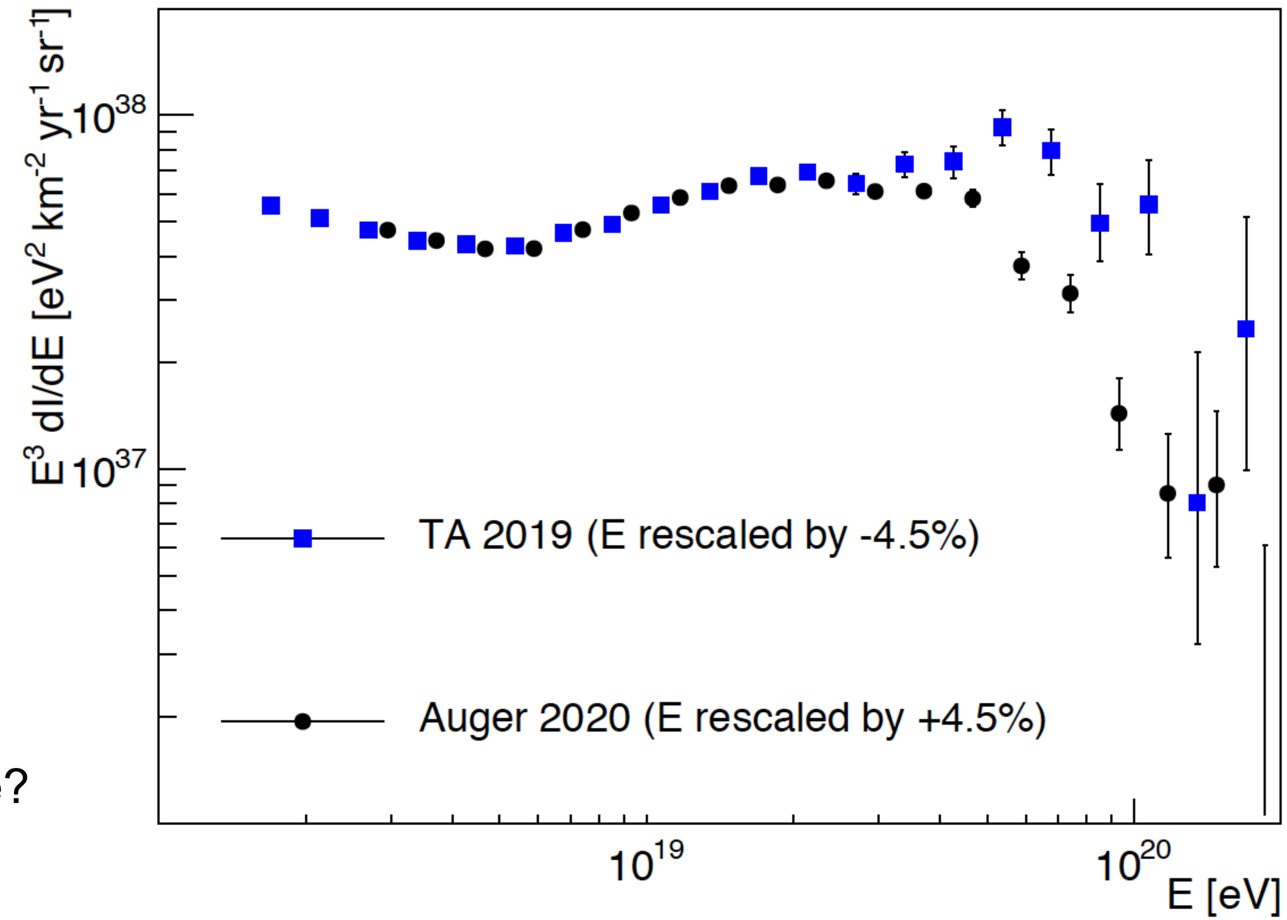
TA and Auger, PoS (ICRC2021) 337



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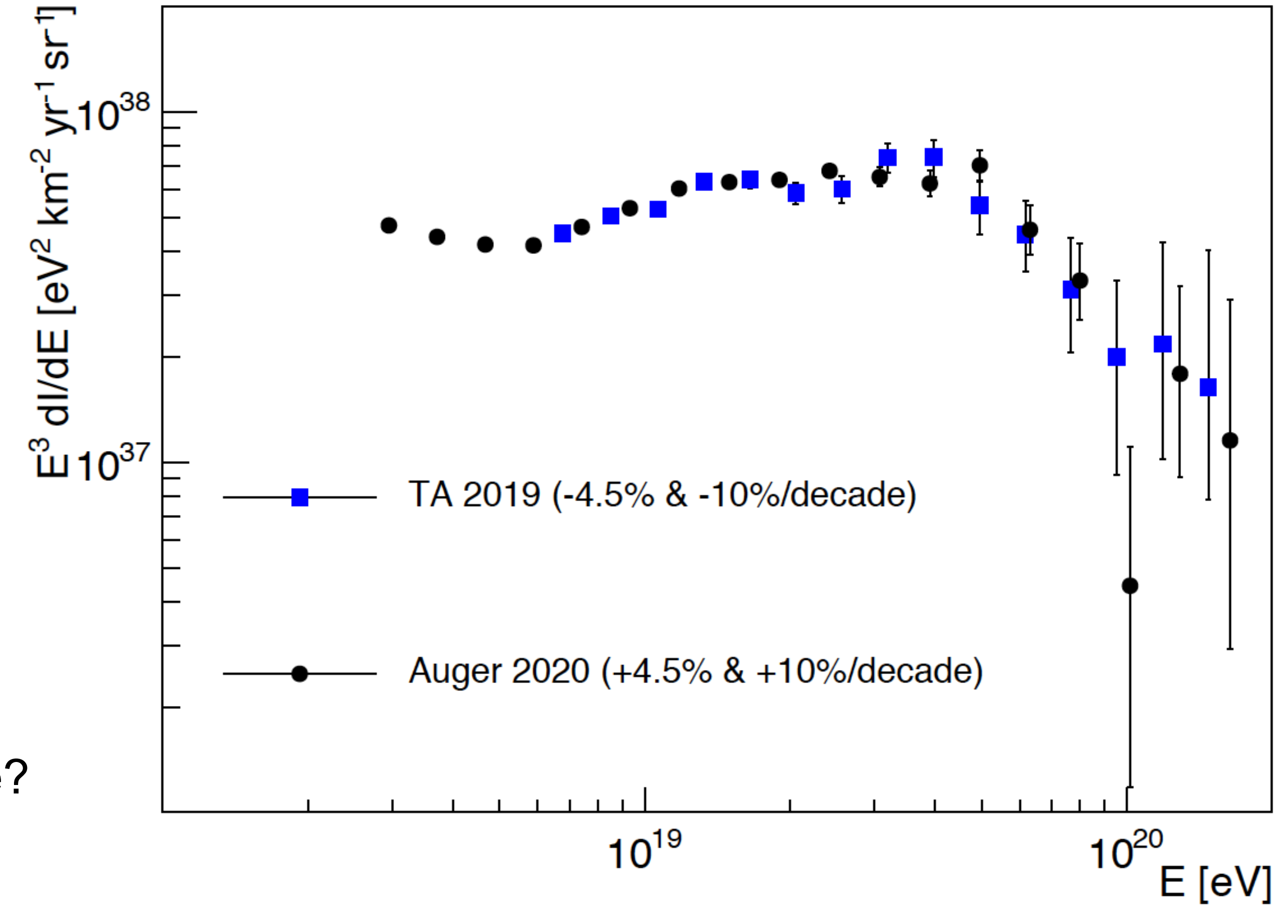
TA and Auger, PoS (ICRC2021) 337



Effects of the different model parameters and assumptions

- Fit parameters
  - Maximum rigidity R_{max}
  - Spectral index γ
  - Source evolution with redshift m
  - Composition
- Implemented interaction models
  - EBL model
  - Hadronic interaction model for air showers
  - (Photodisintegration model)

R. Alves Batista, D. Boncioli, A. di Matteo, AvV, JCAP 05 (2019) 006
J. Heinze, A. Fedynitch, D. Boncioli, W. Winter, Astrophys. J. 873 (2019) 88
R. Alves Batista, D. Boncioli, A. di Matteo, AvV, D. Walz, JCAP 10 (2015) 063

- Assumptions
  - Continuous distribution of identical sources
  - Rigidity-dependent maximum energy

D. Ehlert, P. Plotko, AvV, W. Winter, in preparation

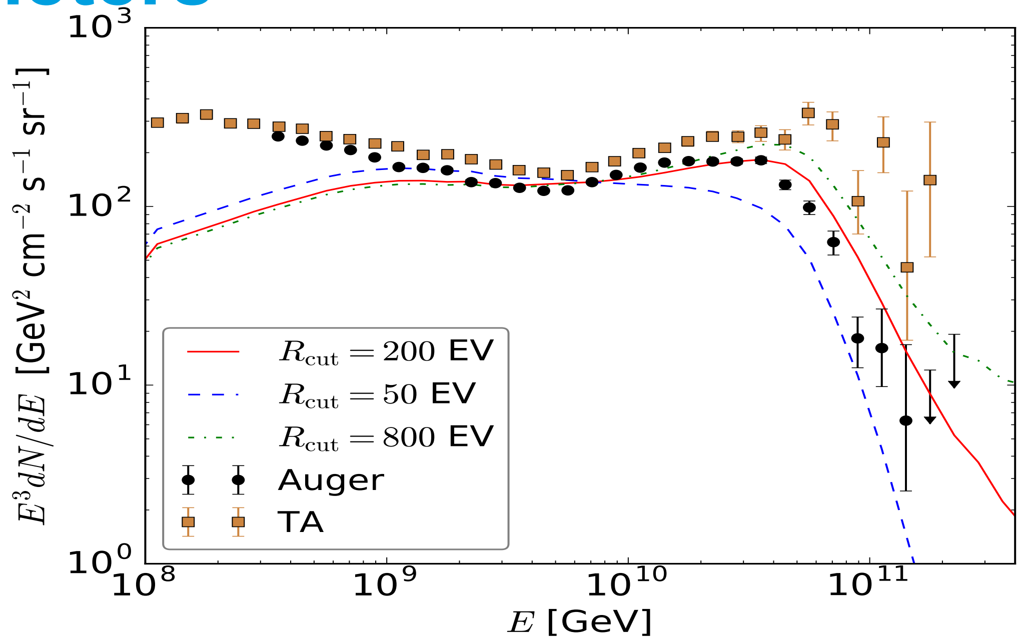
	EPOS-LHC	Sibyll 2.3	QGSJet-II-04
R_{max} [EV]	$1.19^{+0.19}_{-0.16}$	$3.85^{+0.61}_{-0.53}$	$1.38^{+0.22}_{-0.19}$
γ	$-2.50^{+0.20}_{-?}$	$1.57^{+0.20}_{-0.20}$	$-1.89^{+0.20}_{-0.61}$
m	$1.50^{+0.75}_{-0.75}$	$-6.00^{+1.50}_{-?}$	$-1.5^{+3.00}_{-2.30}$
L_0 $[10^{44} \frac{\text{erg}}{\text{Mpc yr}}]$	$3.21^{+0.12}_{-0.12}$	$1.80^{+0.15}_{-0.15}$	$2.24^{+0.20}_{-0.18}$
$\delta_E[\%]$	$-14.0^{+1.2}_{-?}$	$6.7^{+3.2}_{-3.5}$	$-4.6^{+3.0}_{-2.9}$
$I_A^9[\%]$	H: $5.8^{+1.0}_{-1.0}$	H: $0^{+1.9}_{-0}$	H: $15.1^{+1.1}_{-0.9}$
	He: $14.7^{+1.0}_{-1.0}$	He: $22.3^{+2.8}_{-2.2}$	He: $16.2^{+0.9}_{-0.9}$
	N: $69.2^{+1.3}_{-1.8}$	N: $32.2^{+5.5}_{-6.9}$	N: $56.0^{+1.8}_{-1.8}$
	Si: $9.2^{+2.2}_{-1.5}$	Si: $43.2^{+5.0}_{-3.8}$	Si: $11.8^{+2.2}_{-1.9}$
	Fe: $1.1^{+0.5}_{-0.7}$	Fe: $2.2^{+1.9}_{-0.6}$	Fe: $0.9^{+0.6}_{-0.6}$
χ^2/dof	32.1/26	32.7/26	111.5/26

Effects of the different model parameters

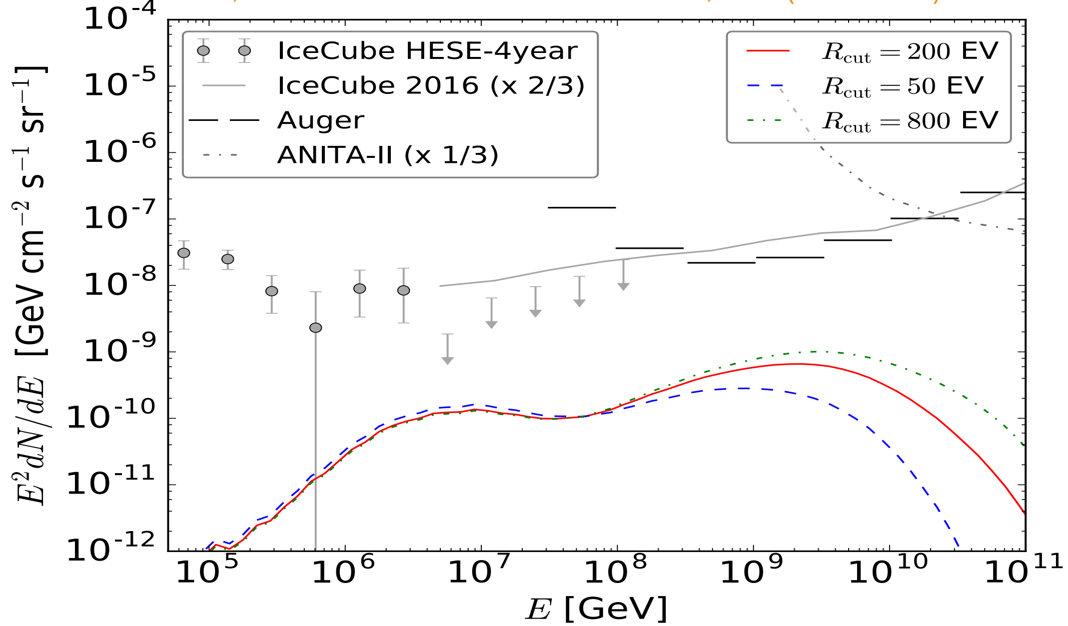
Maximum rigidity

Reference simulation:

- 1D simulation including neutrinos
- Homogeneous distribution of identical sources
- Initial CR type: protons
- Injection spectrum: $\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\alpha} \exp(-E / ZR_{\mathrm{cut}})$
- Cut-off rigidity: R_{cut} = 50, 200, 800 EV
- Injection index: α = 2.5
- Source evolution: comoving (m = 0)
- EBL: Gilmore *et al.* 2012



AvV, J. R. Hörandel and R. Alves Batista, PoS (ICRC2017) 562

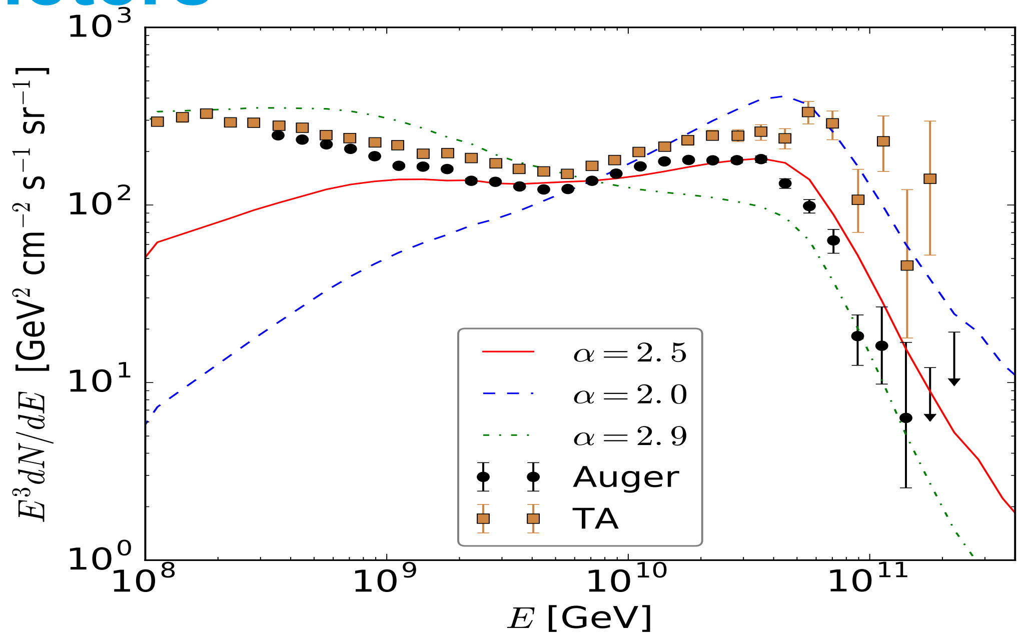


Effects of the different model parameters

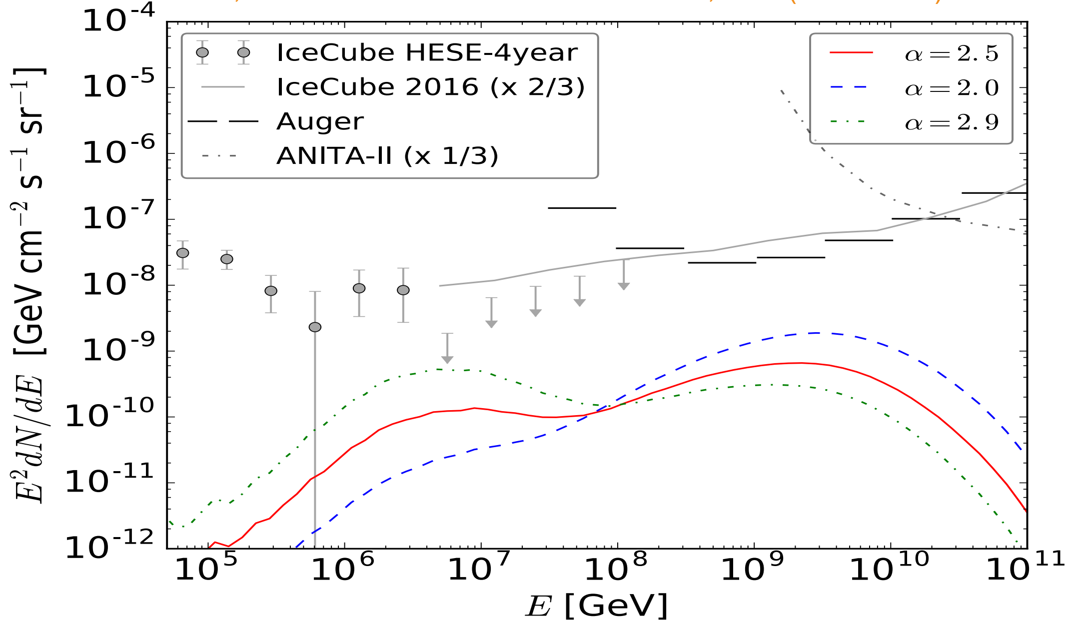
Spectral index

Reference simulation:

- 1D simulation including neutrinos
- Homogeneous distribution of identical sources
- Initial CR type: protons
- Injection spectrum: $\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\alpha} \exp(-E / ZR_{\mathrm{cut}})$
- Cut-off rigidity: R_{cut} = 200 EV
- Injection index: α = 2.0, 2.5, 2.9
- Source evolution: comoving (m = 0)
- EBL: Gilmore *et al.* 2012



AvV, J. R. Hörandel and R. Alves Batista, PoS (ICRC2017) 562

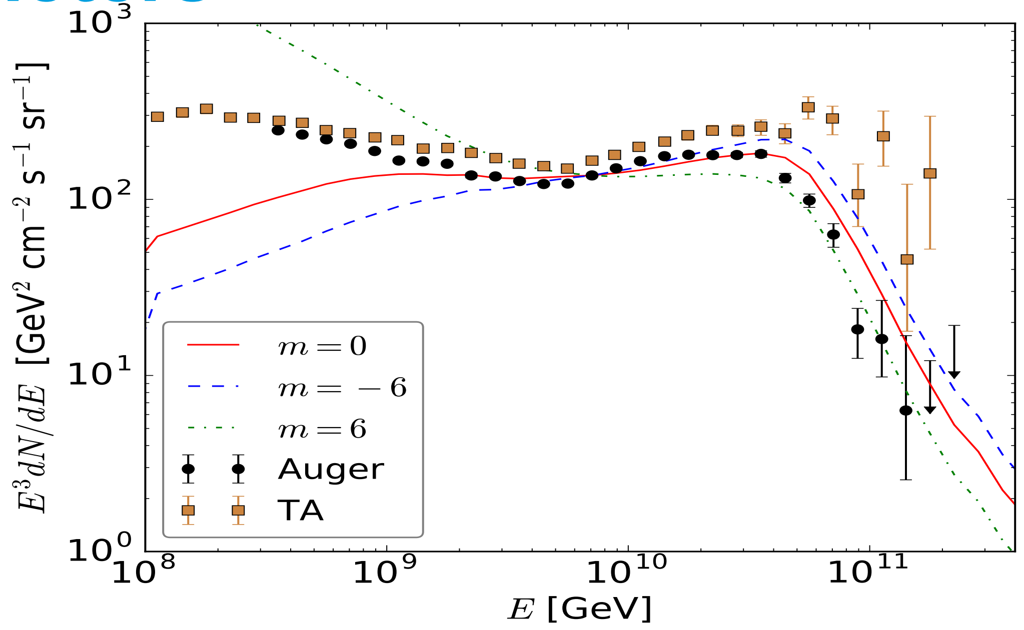


Effects of the different model parameters

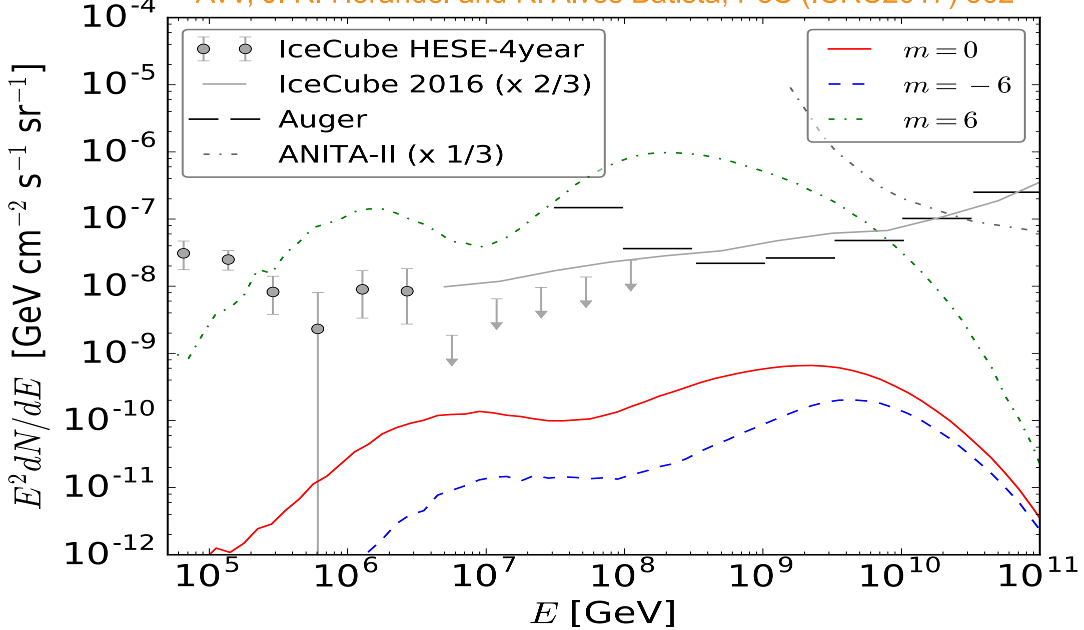
Source evolution

Reference simulation:

- 1D simulation including neutrinos
- Homogeneous distribution of identical sources
- Initial CR type: protons
- Injection spectrum: $\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\alpha} \exp(-E / ZR_{\mathrm{cut}})$
- Cut-off rigidity: R_{cut} = 200 EV
- Injection index: α = 2.5
- Source evolution: m = -6, 0, 6
- EBL: Gilmore *et al.* 2012
- **Source evolution strongly affects the cosmogenic neutrino flux**



AvV, J. R. Hörandel and R. Alves Batista, PoS (ICRC2017) 562

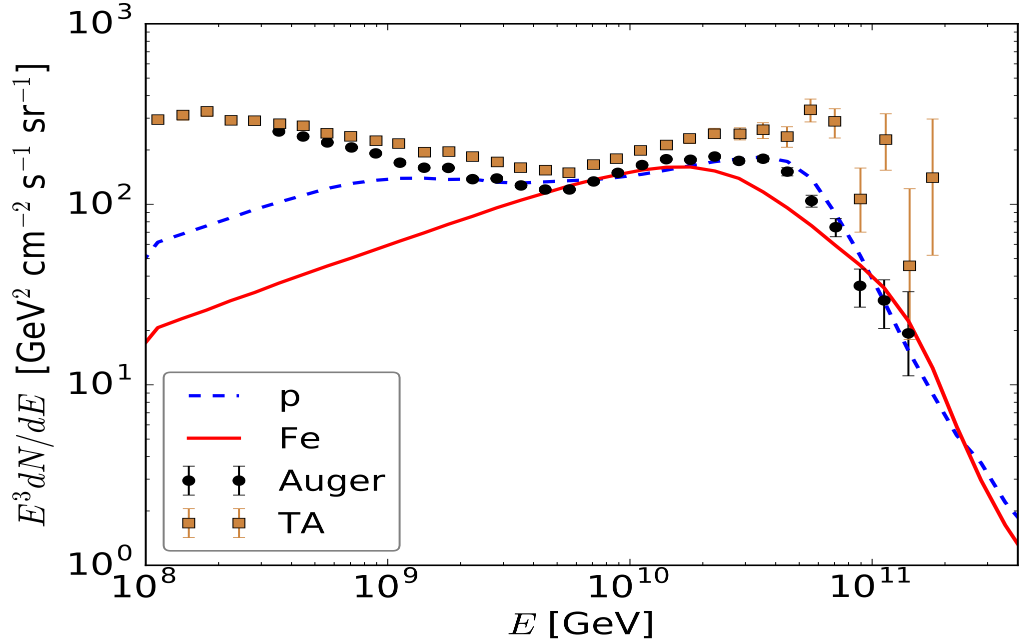


Effects of the different model parameters

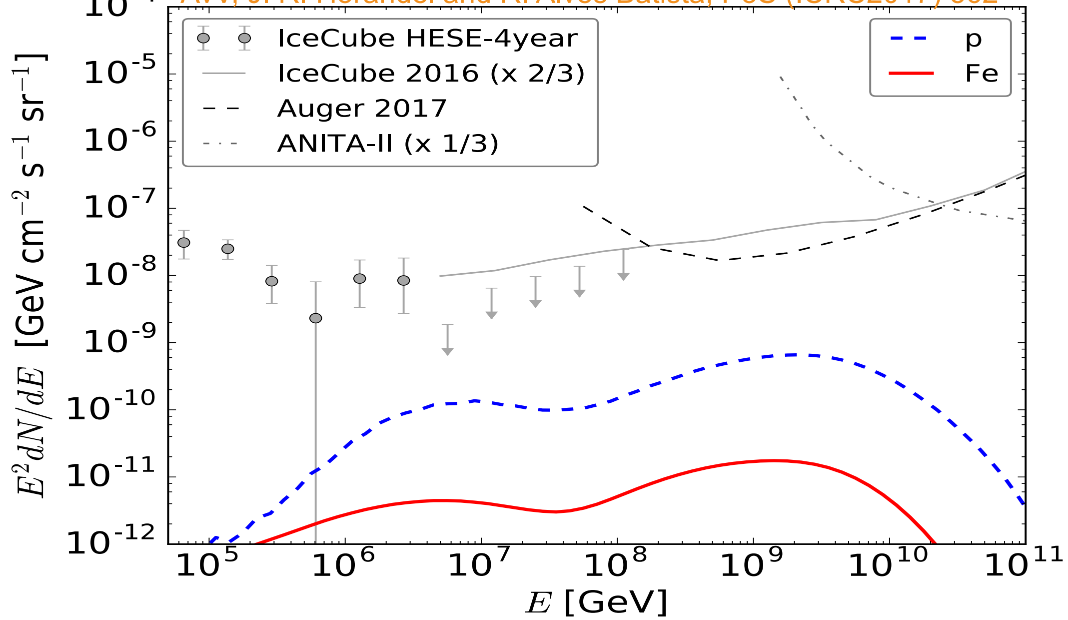
Composition

Reference simulation:

- 1D simulation including neutrinos
- Homogeneous distribution of identical sources
- Initial CR type: protons vs. iron
- Injection spectrum: $\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\alpha} \exp(-E / ZR_{\mathrm{cut}})$
- Cut-off rigidity: R_{cut} = 200 EV
- Injection index: α = 2.5
- Source evolution: comoving (m = 0)
- EBL: Gilmore *et al.* 2012
- **Protons especially important for cosmogenic neutrino production**



AvV, J. R. Hörandel and R. Alves Batista, PoS (ICRC2017) 562



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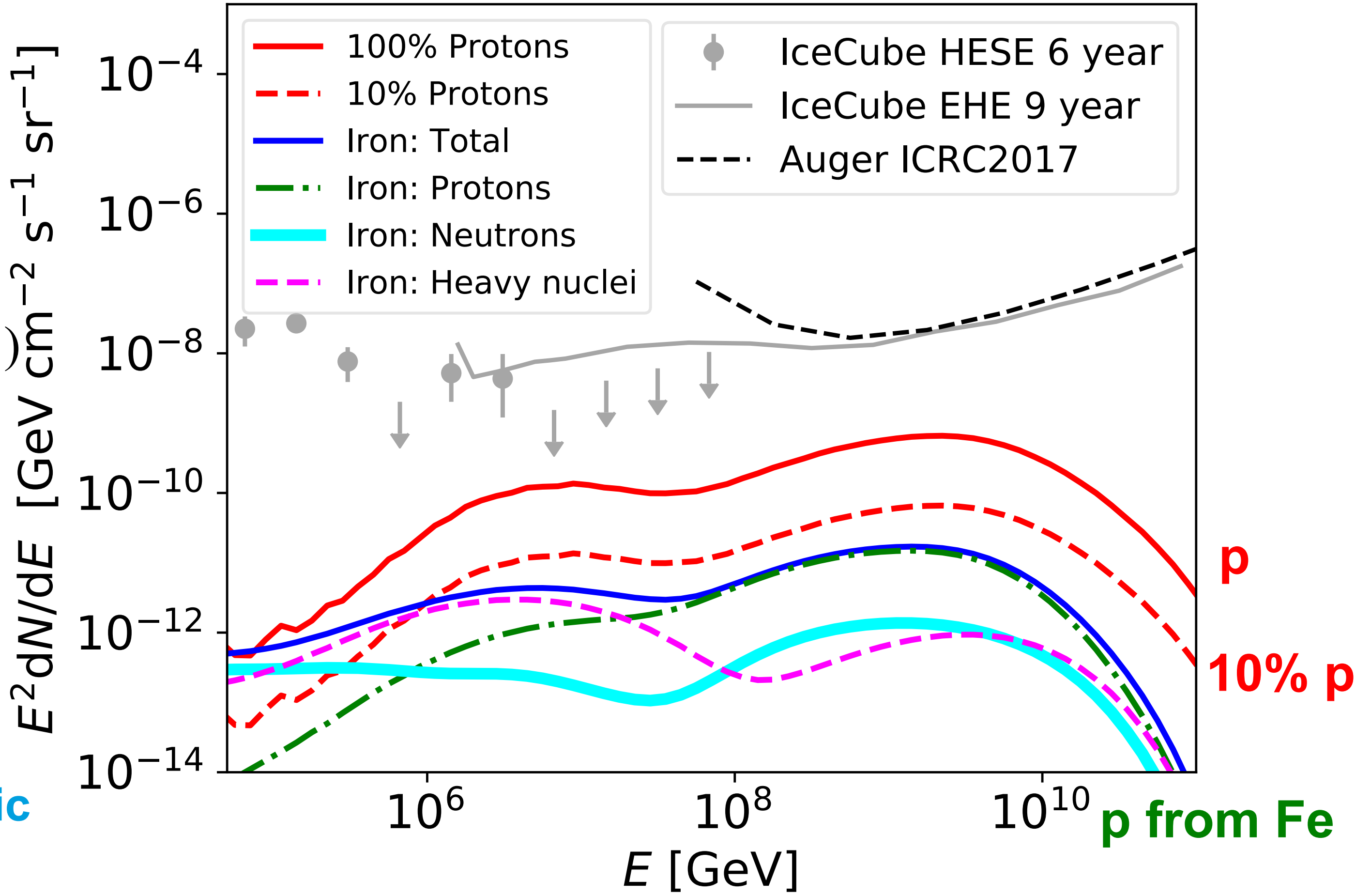

Effects of the different model parameters

EBL models

Reference simulation:

- 1D simulation including neutrinos
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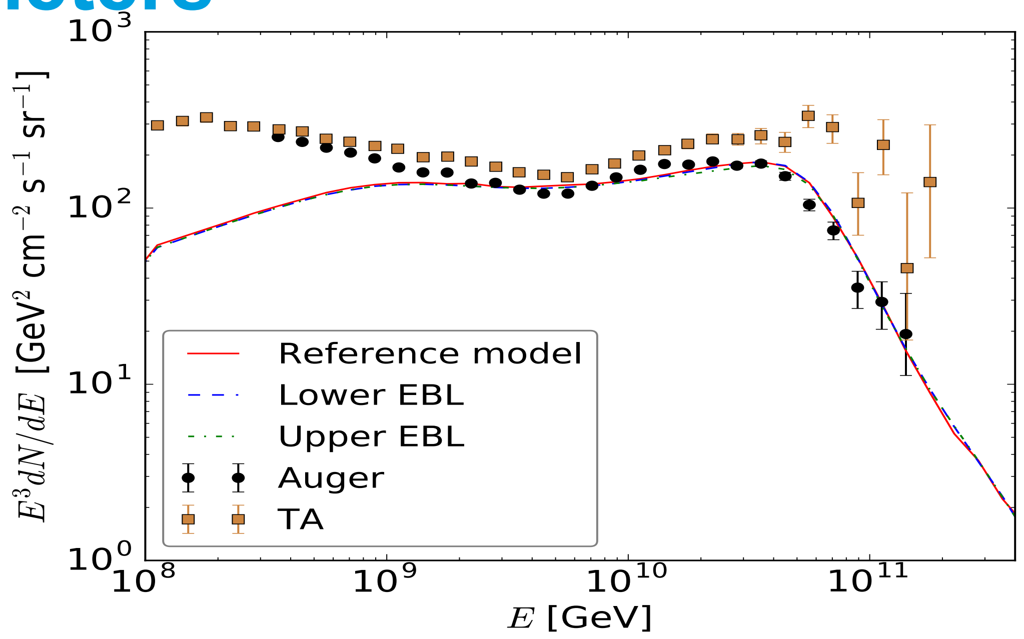
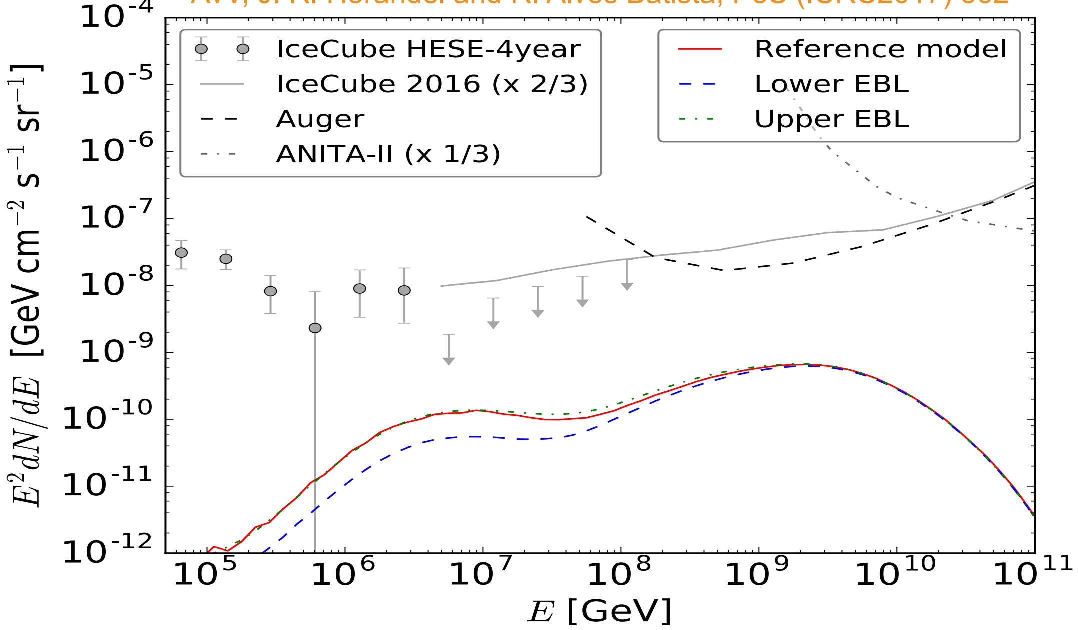
- Initial CR type: protons
- Injection spectrum: $\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\alpha} \exp(-E / ZR_{\mathrm{cut}})$
- Cut-off rigidity: R_{cut} = 200 EV
- Injection index: α = 2.5
- Source evolution: comoving (no evolution)
- EBL: Gilmore *et al.* 2012, Stecker 2016 upper and lower



AvV, J. R. Hörandel and R. Alves Batista, PoS (ICRC2017) 562



Effects of the different model parameters

Hadronic interaction models for air showers

D. Ehlert, P. Plotko, AvV, W. Winter, in preparation

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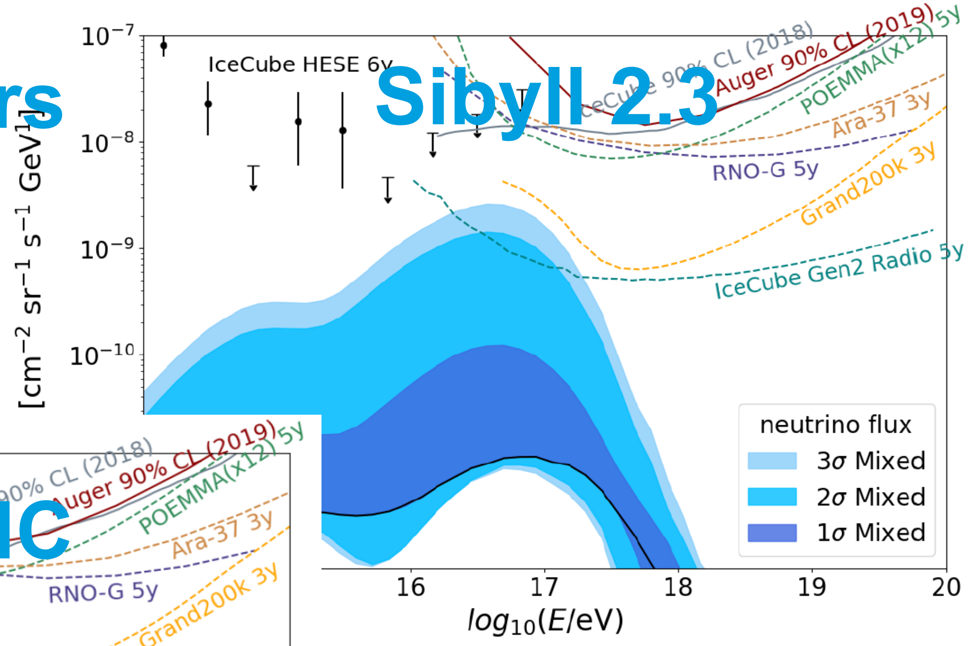
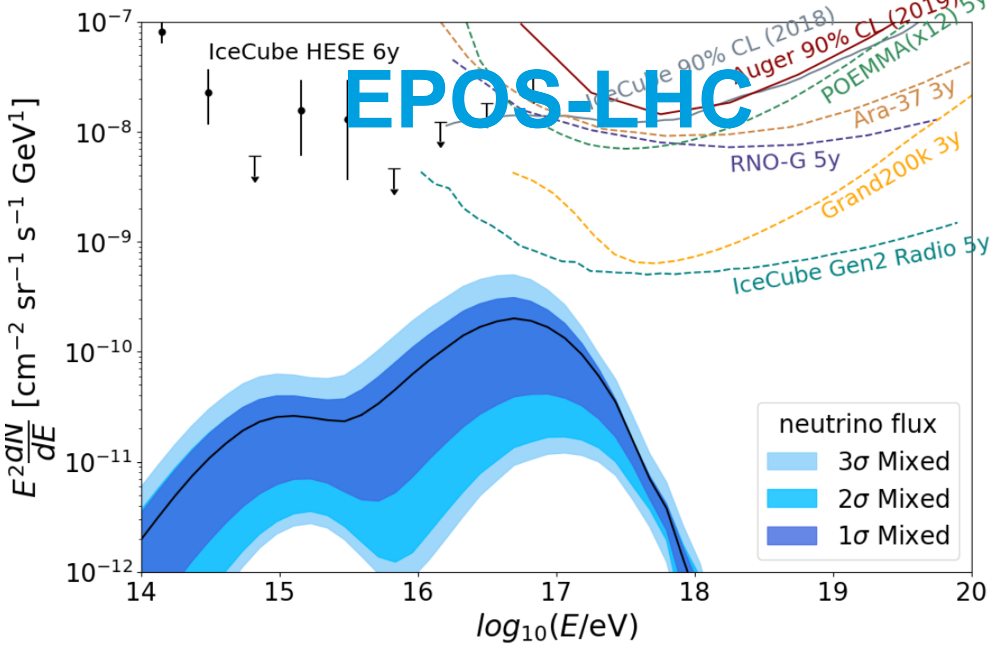
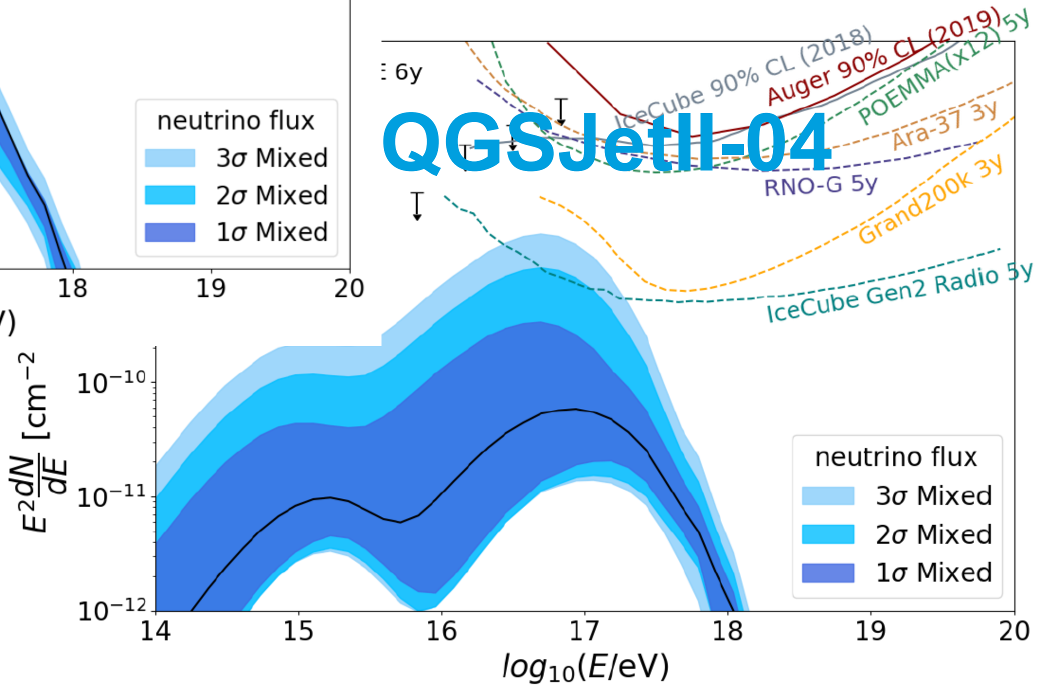


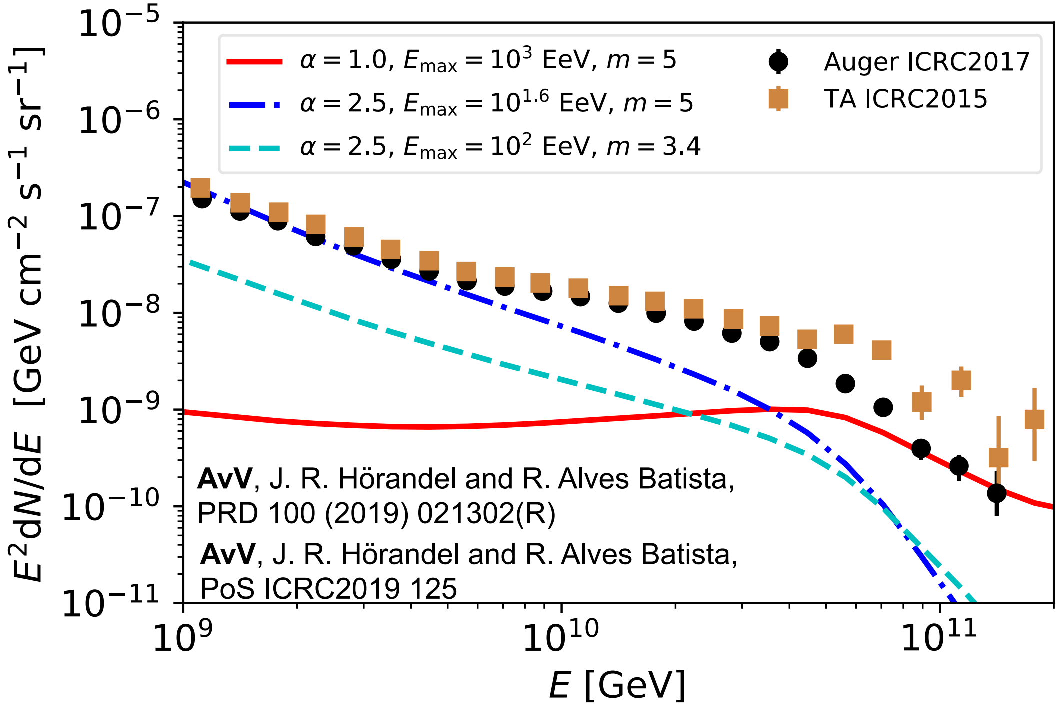


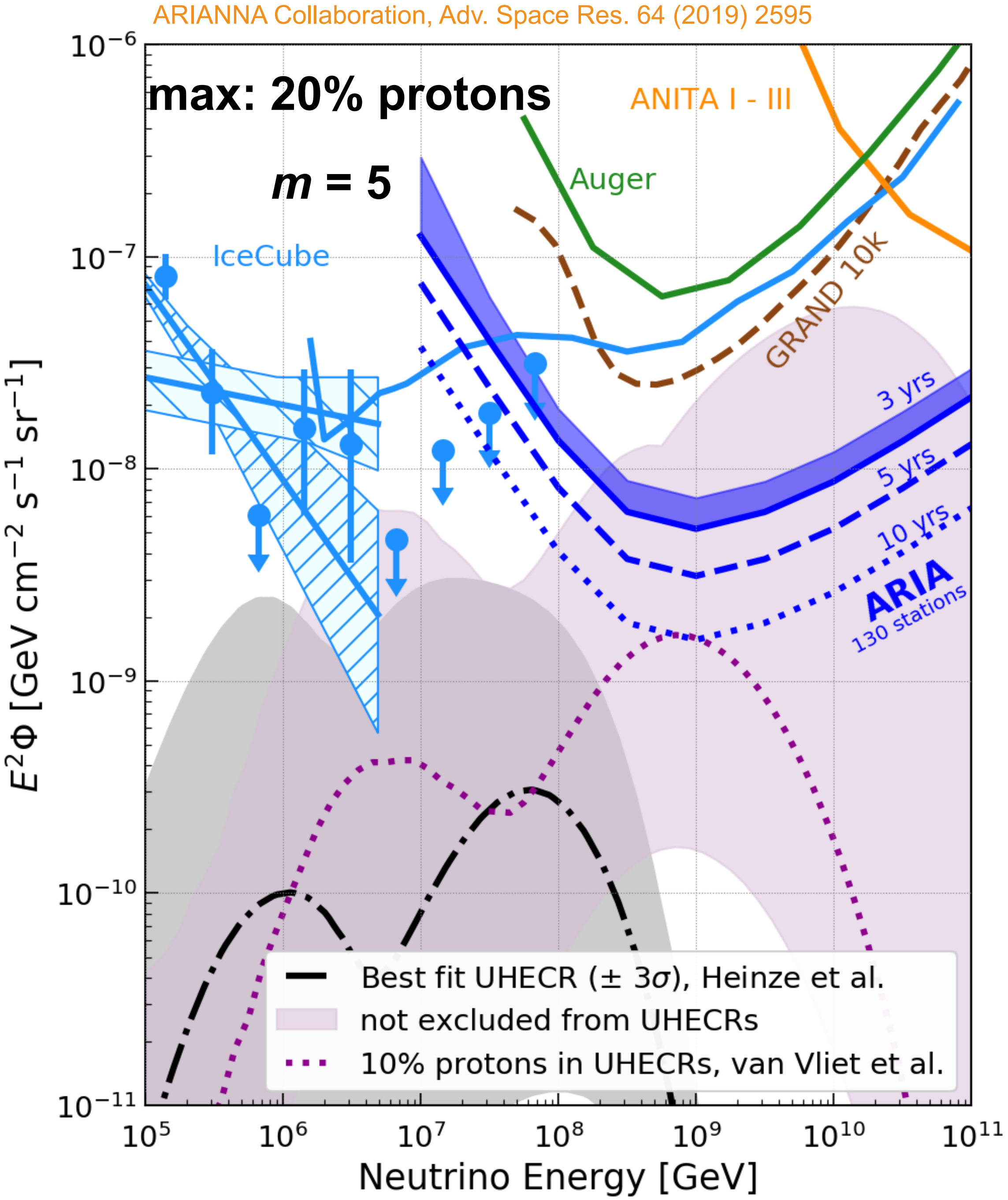


Neutrinos from subdominant proton component

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

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



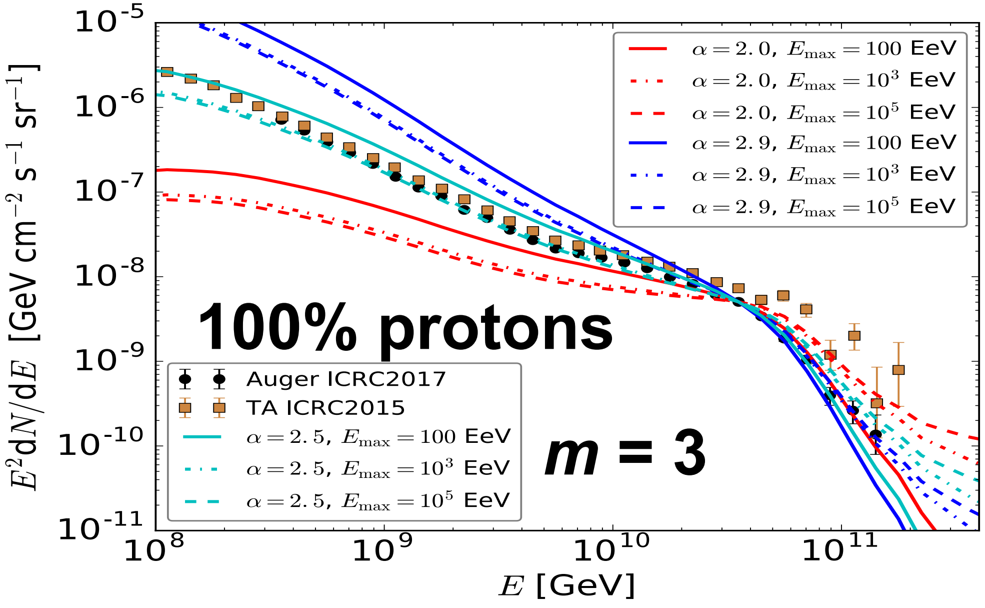


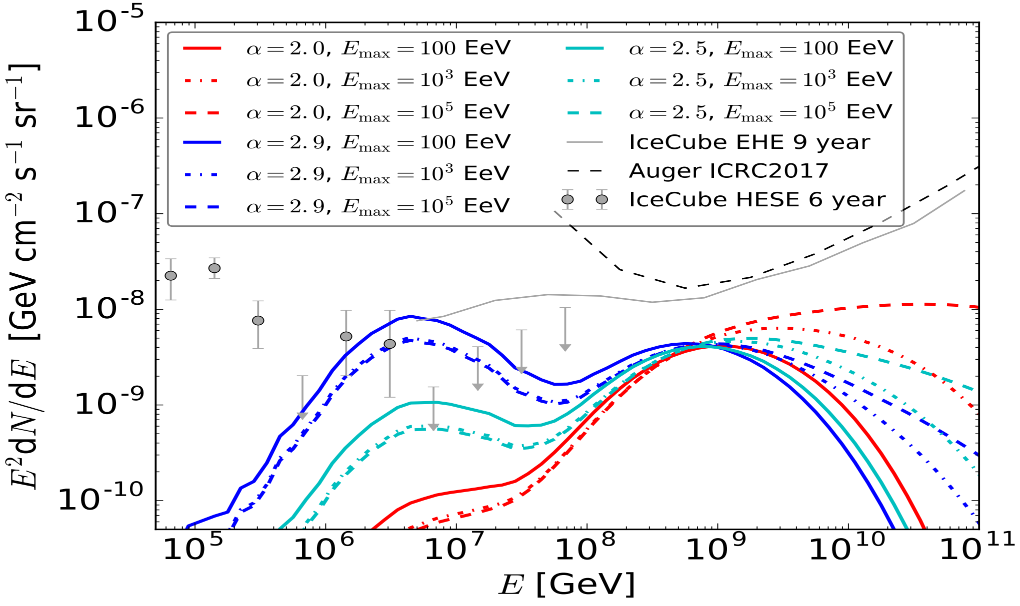
Neutrinos at ~1 EeV

- 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)

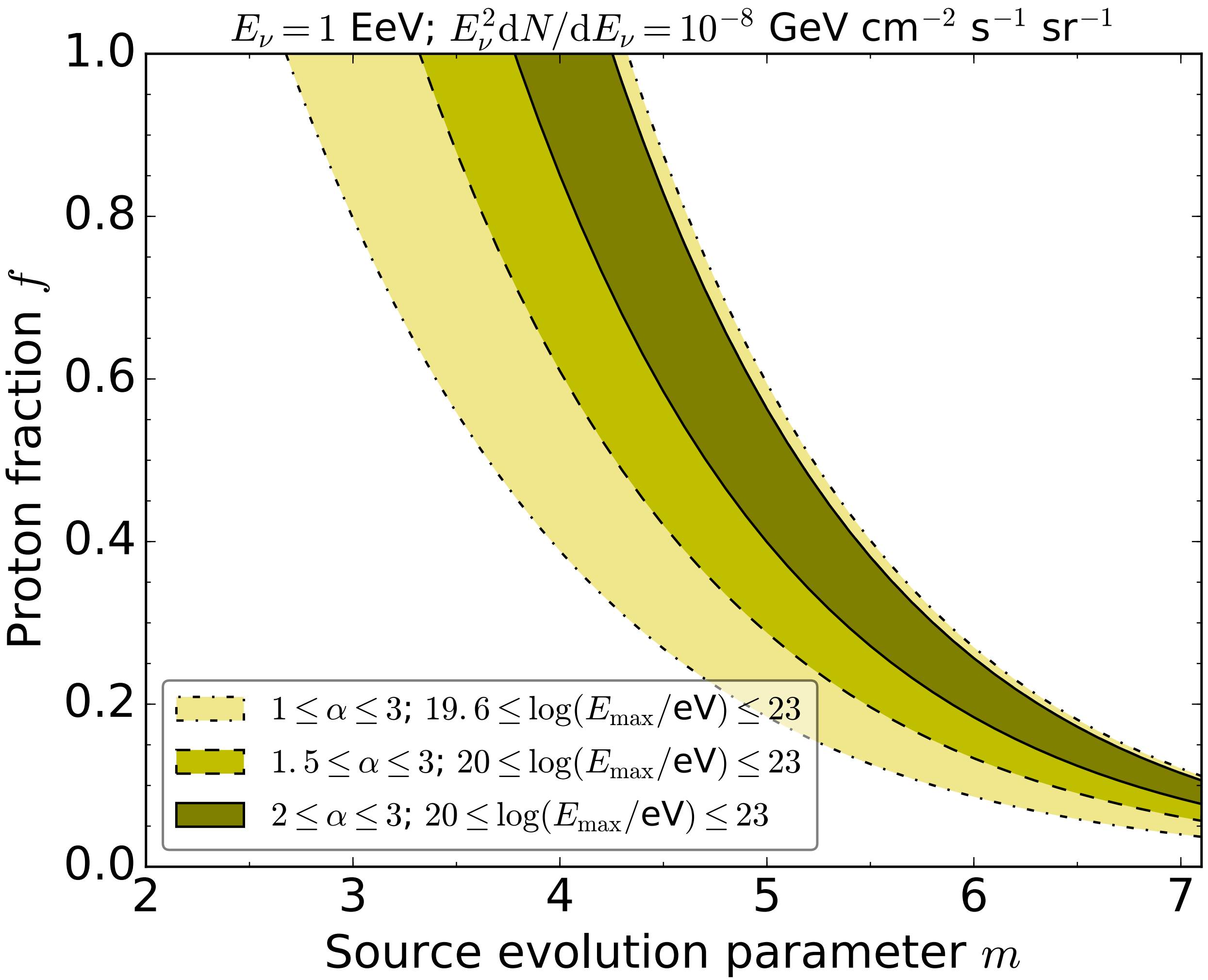




Current sensitivity

- 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

Current sensitivity

- Single-flavour neutrino flux at ~1 EeV
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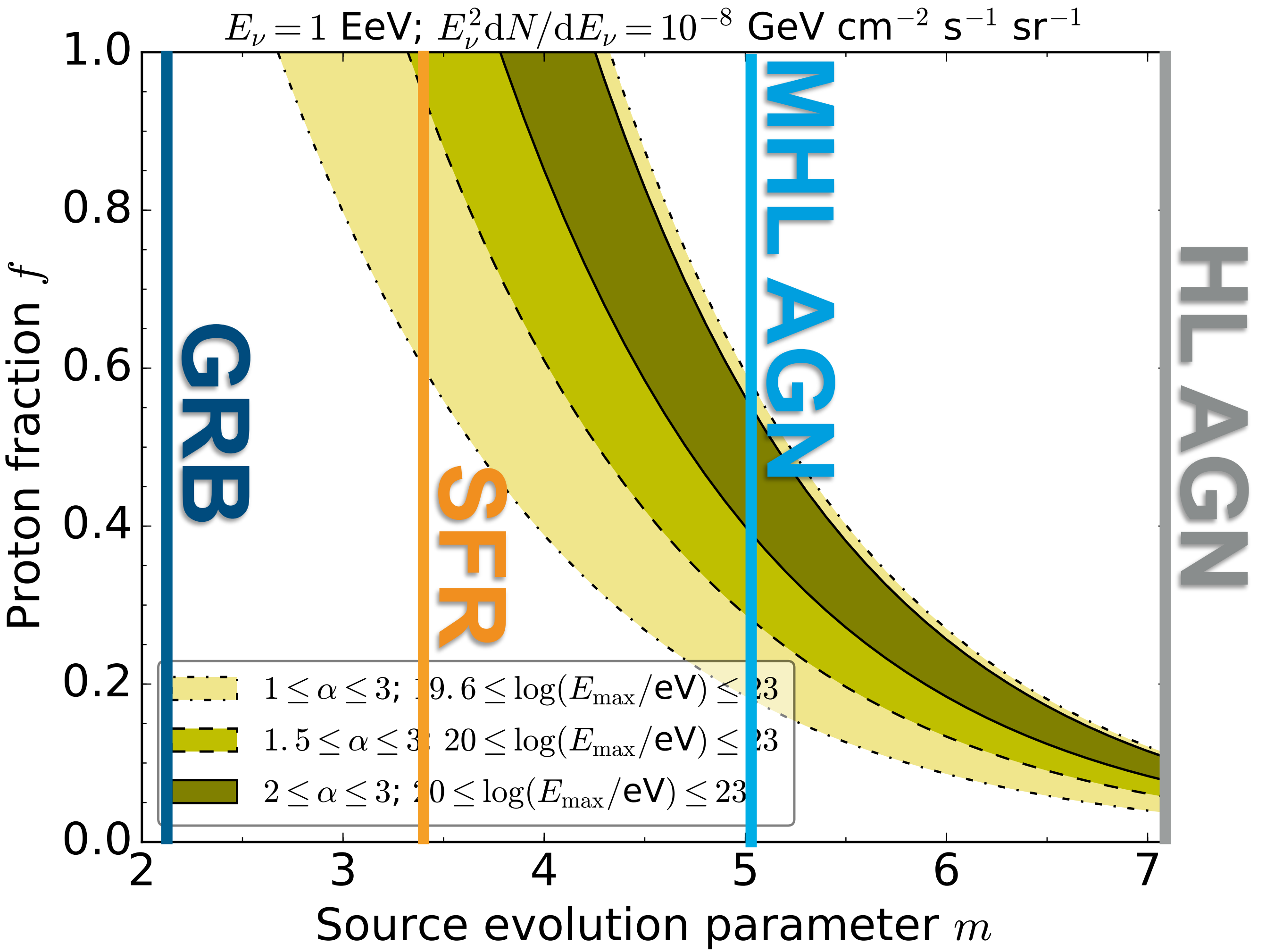


AvV, J. R. Hörandel and R. Alves Batista, PoS(ICRC2019)125

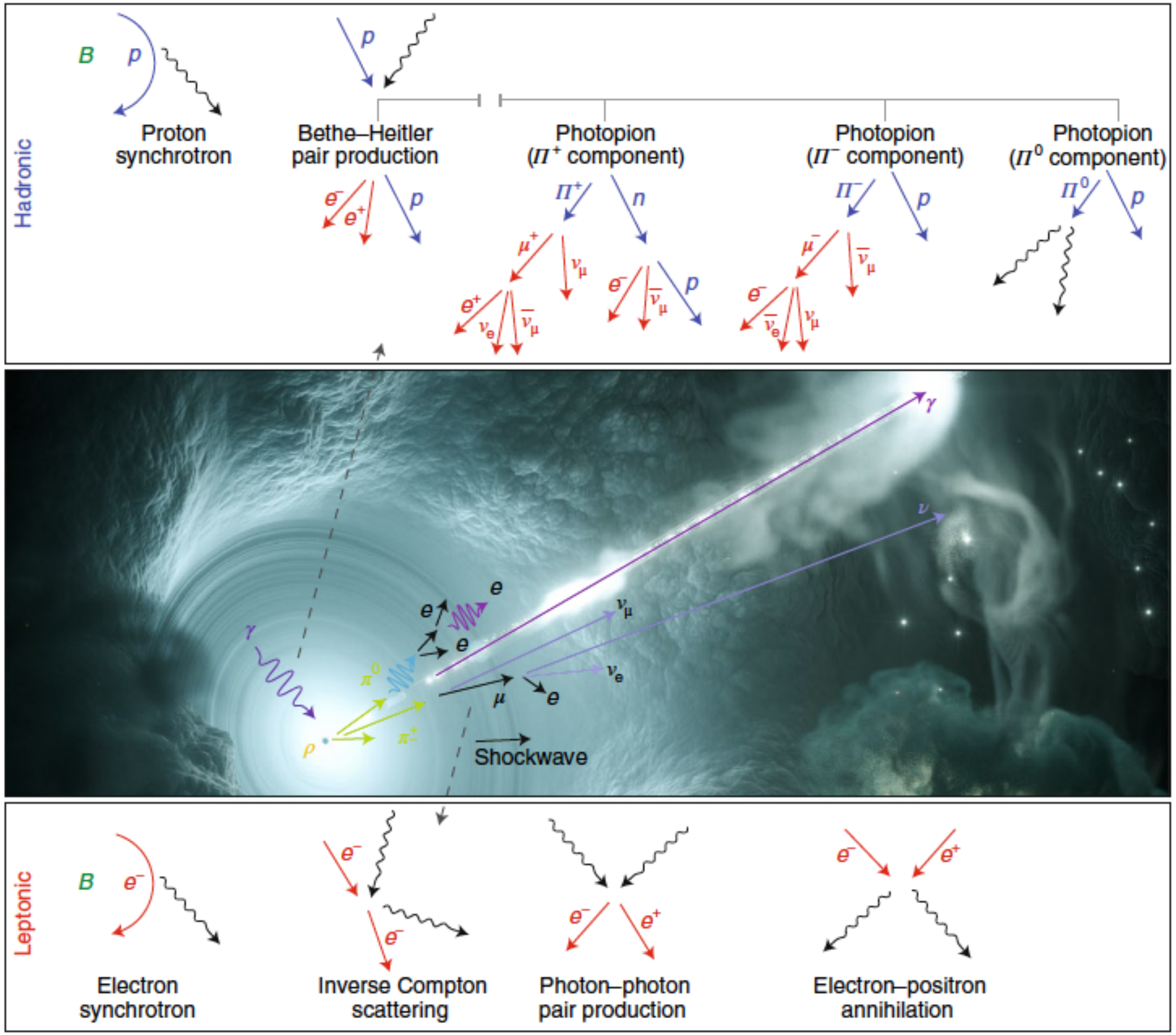
UHECR sources also produce high-energy neutrinos

- 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?**

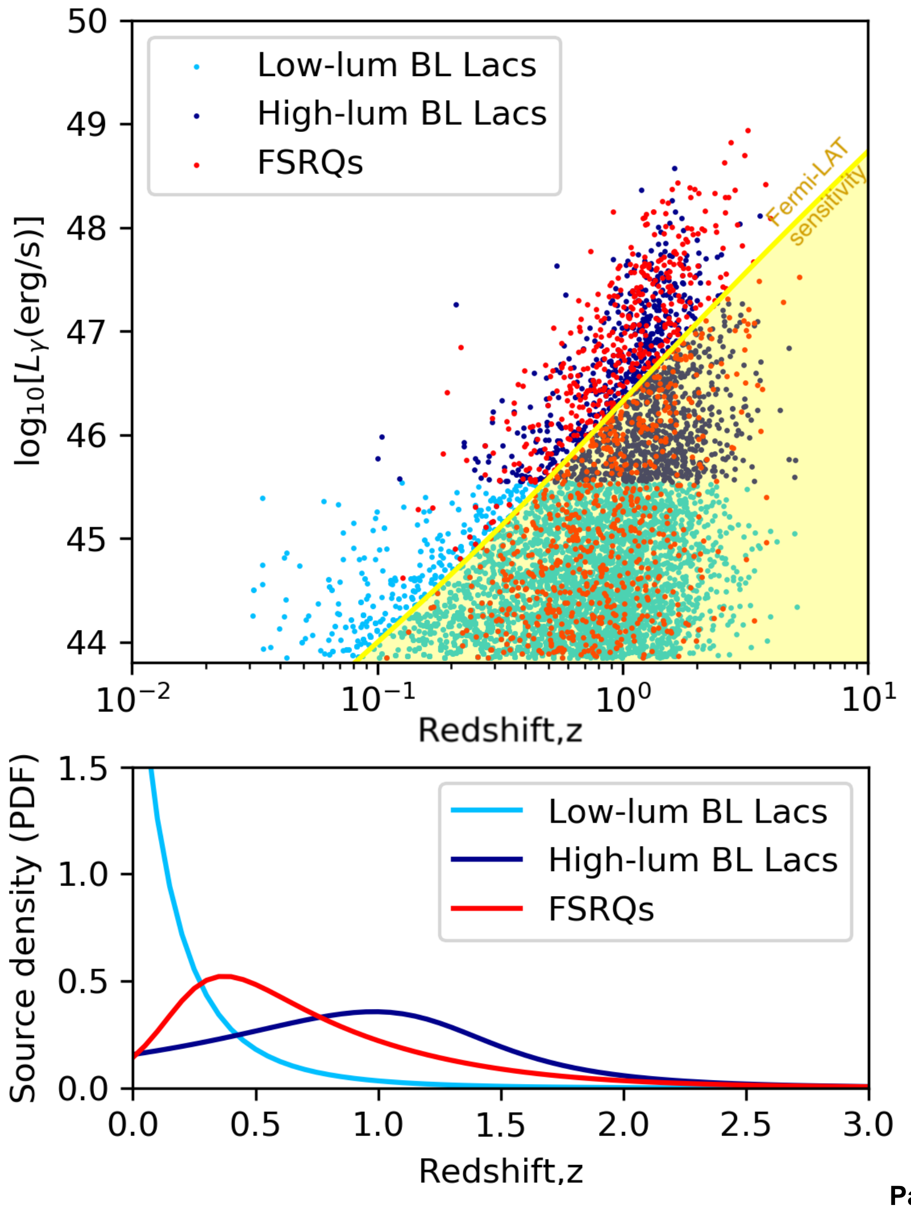
A. Palladino, AvV, W. Winter and A. Franckowiak, MNRAS 494 (2020) 4255



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



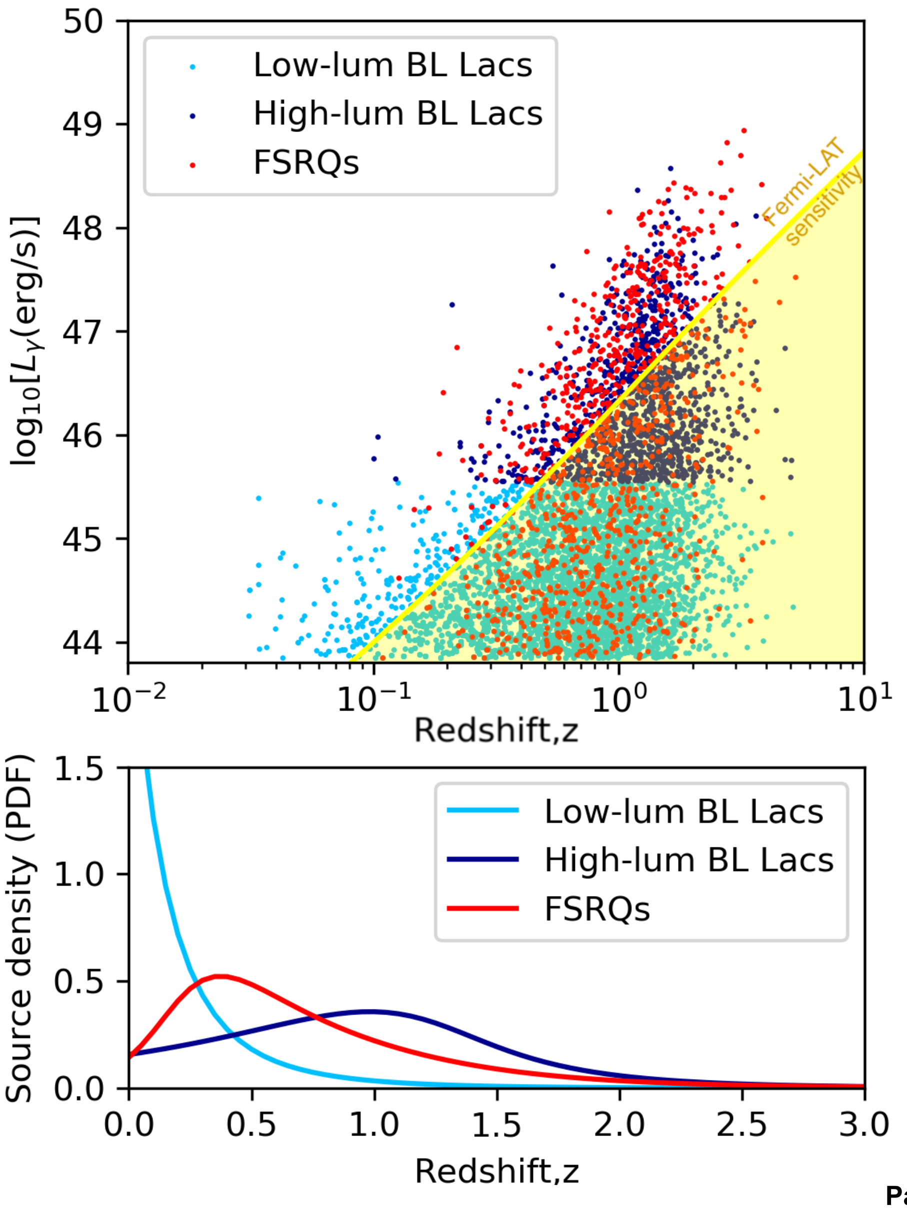
Simulation setup

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

- 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:

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

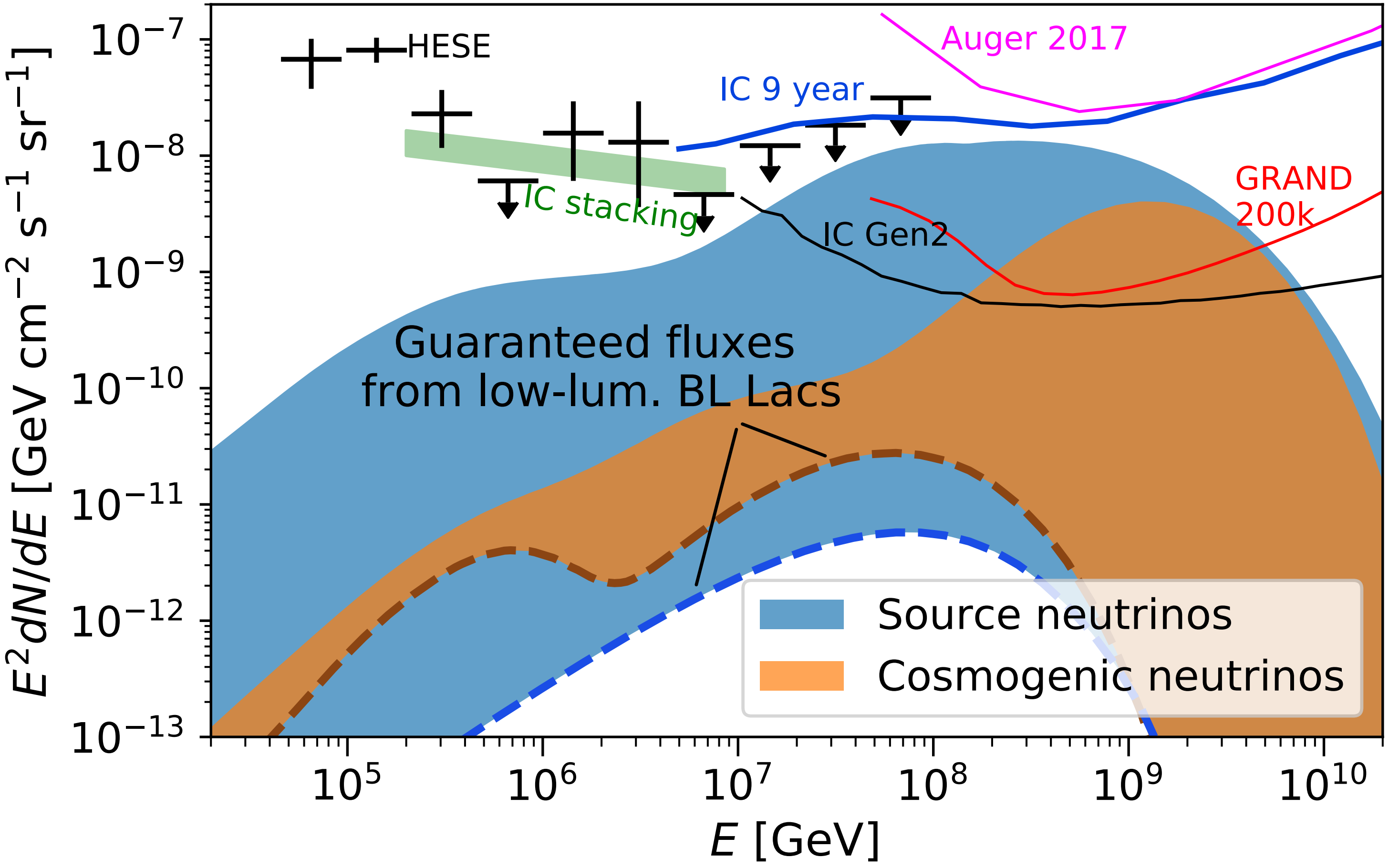
- AGN properties:
  - Baryonic loading (different for Low-lum. BL Lacs vs. FSRQs)
  - UHECR acceleration efficiency (the same for all sources)
  - Size of the radiation zone (fixed, r = 0.1 pc)
  - Escape mechanism (fixed, Bohm-like diffusion)



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

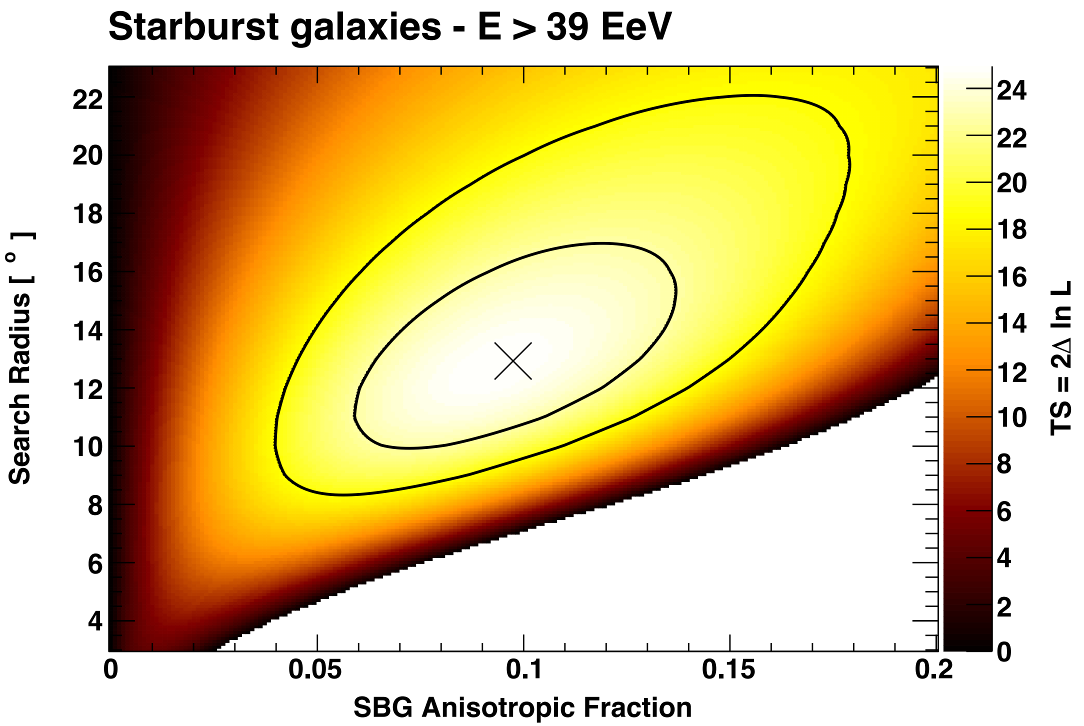
X. Rodrigues, J. Heinze, A. Palladino, AvV and W. Winter, PRL 126 (2021) 191101



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

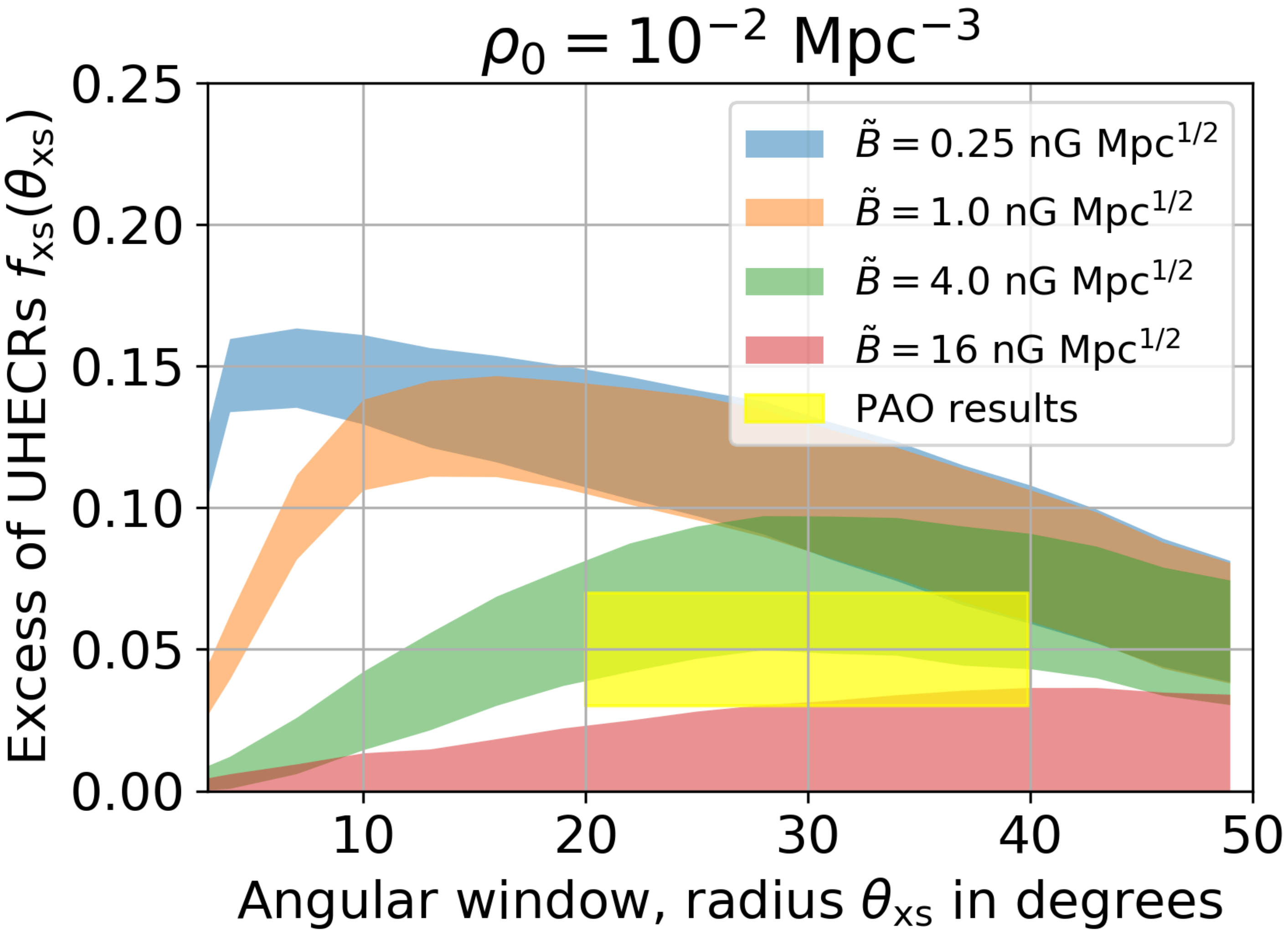


Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	15^{+5}_{-4}°	11^{+5}_{-4}%	29.5	4.5 σ
γ-AGNs	39 EeV	14^{+6}_{-4}°	6^{+4}_{-3}%	17.8	3.1 σ
Swift-Bat	38 EeV	15^{+6}_{-4}°	8^{+4}_{-3}%	22.2	3.7 σ
2MRS	40 EeV	15^{+7}_{-4}°	19^{+10}_{-7}%	22.0	3.7 σ

Compare with Auger results

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS (2021) stab3495

- 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

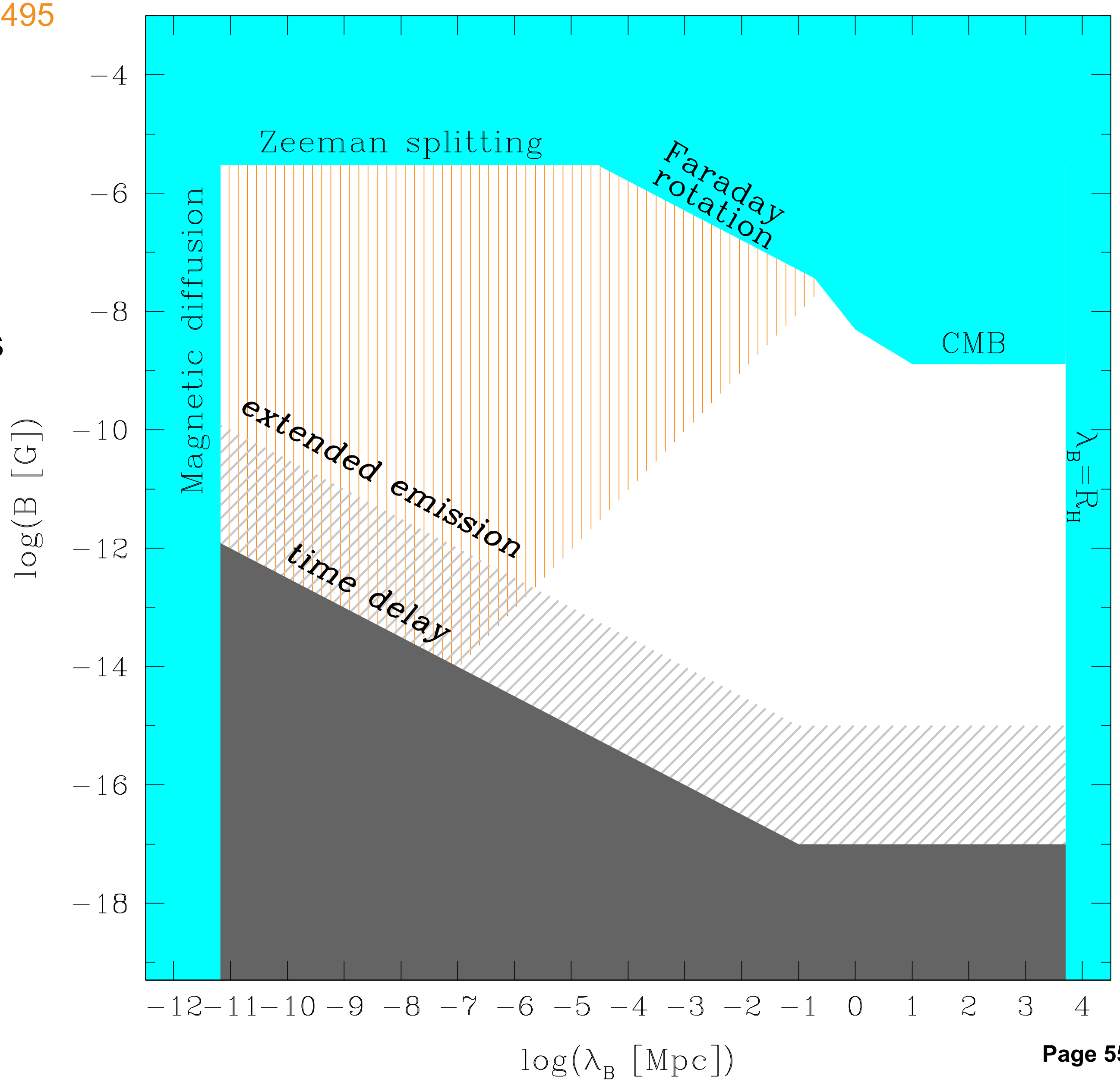


EGMF limits

AvV, A. Palladino, A. Taylor and W. Winter, MNRAS (2021) stab3495

- 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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