"Cosmogenic" neutrinos and UHECR models

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The Multimessenger Sky at Extreme Energies: From Sources to Fundamental Physics
IFPU, Trieste, September 7-11 2026

Outline

- Basic UHECR models to explain measurements, and how they are currently surpassed
  - with basic analyses involving cosmogenic neutrino models
- State-of-the-art of UHECR models
  - and expectations for cosmogenic neutrinos, depending on UHECR parameters (focus on UHECR proton fraction);
  - refinements of UHECR scenarios allowed by current UHECR measurements
- Example of multimessenger study, exploiting the potential of UHE measurements
- Completing the picture for UHE neutrinos (?)
  - Focus on link between UHECR scenario below the ankle and associated neutrinos -> **from confinement regions and/or cosmogenic**
- Summary

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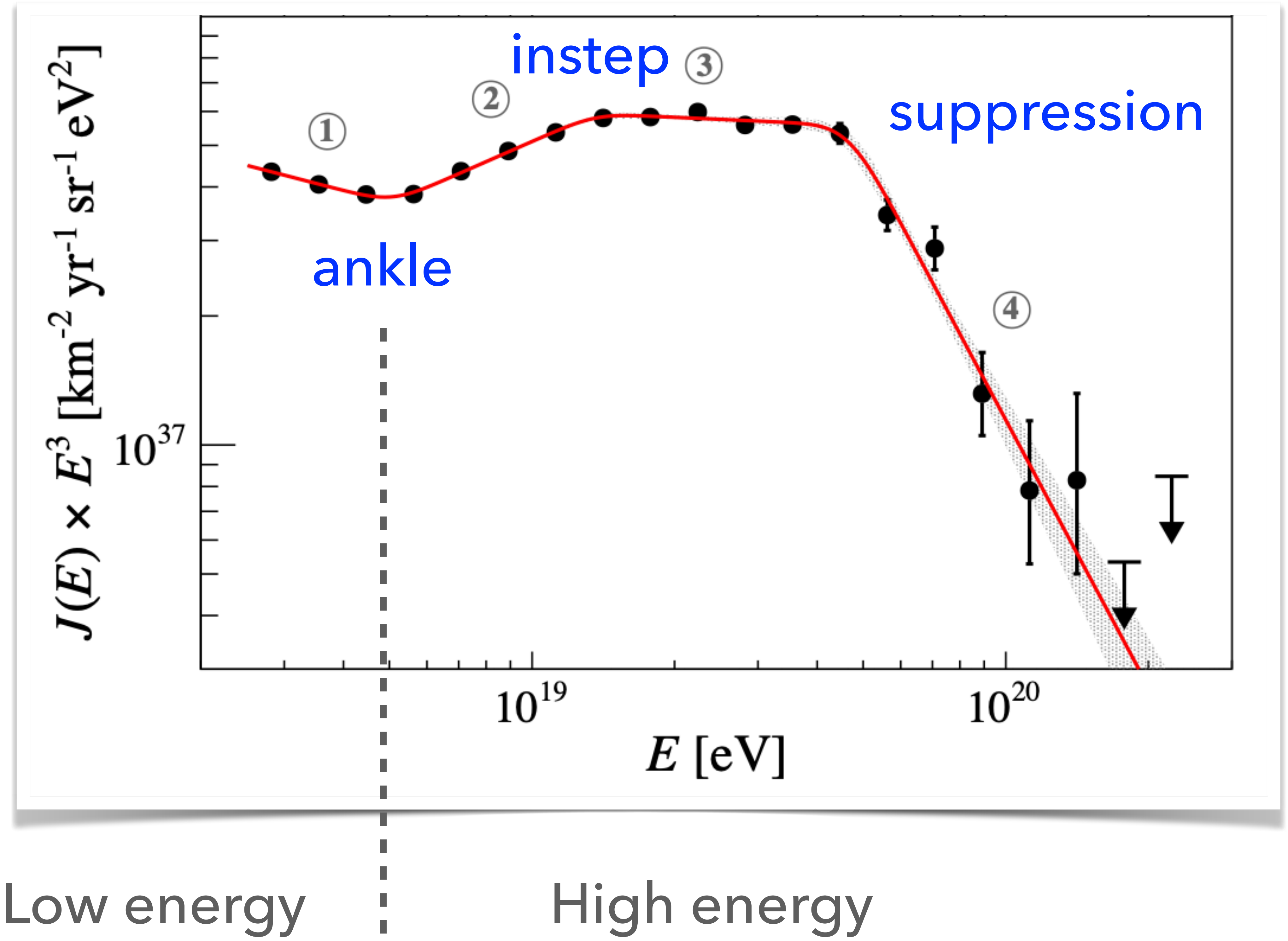
The Auger Collab. Phys.Rev.Lett. 125 (2020)

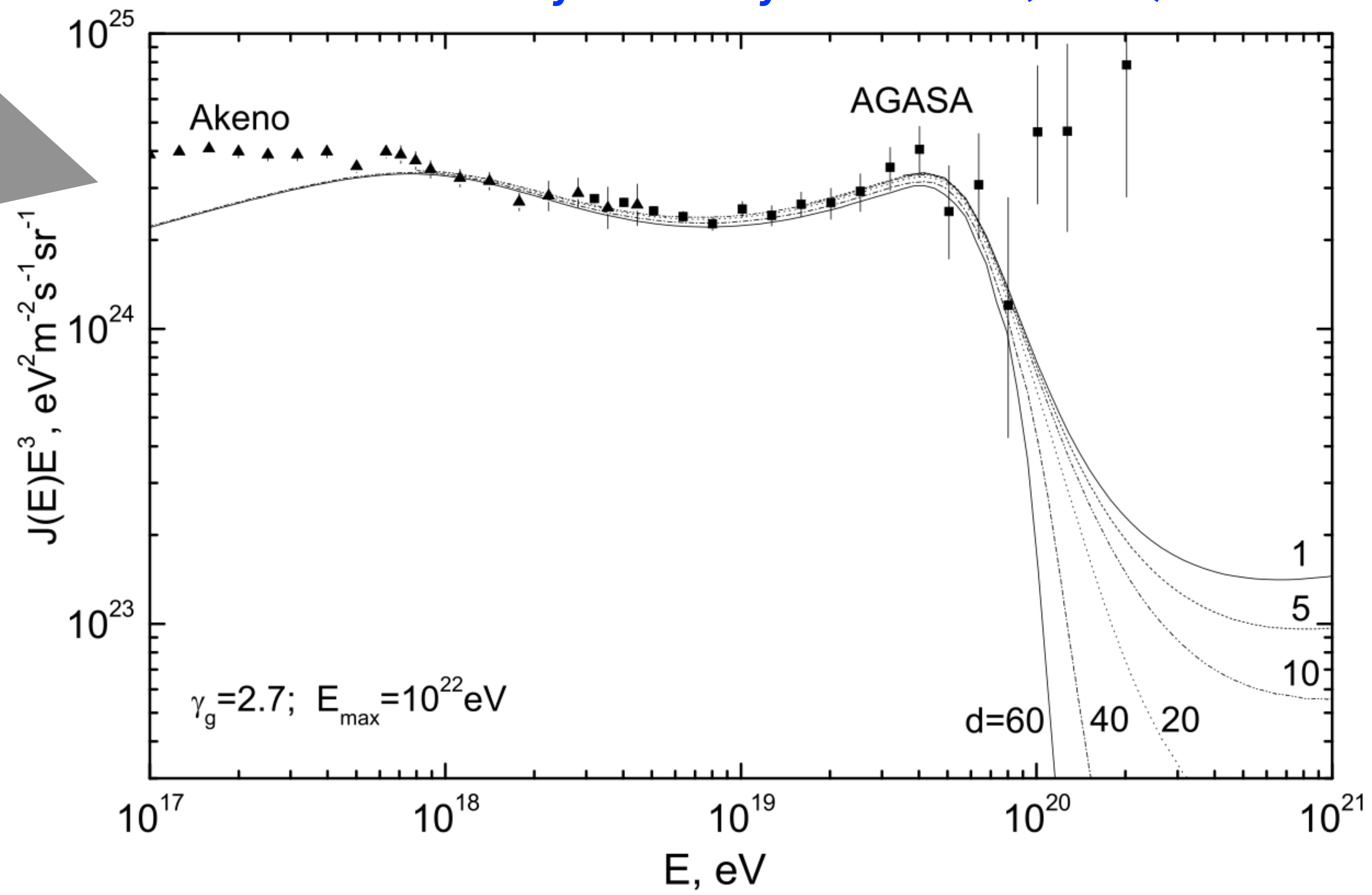


Basic UHECR scenario

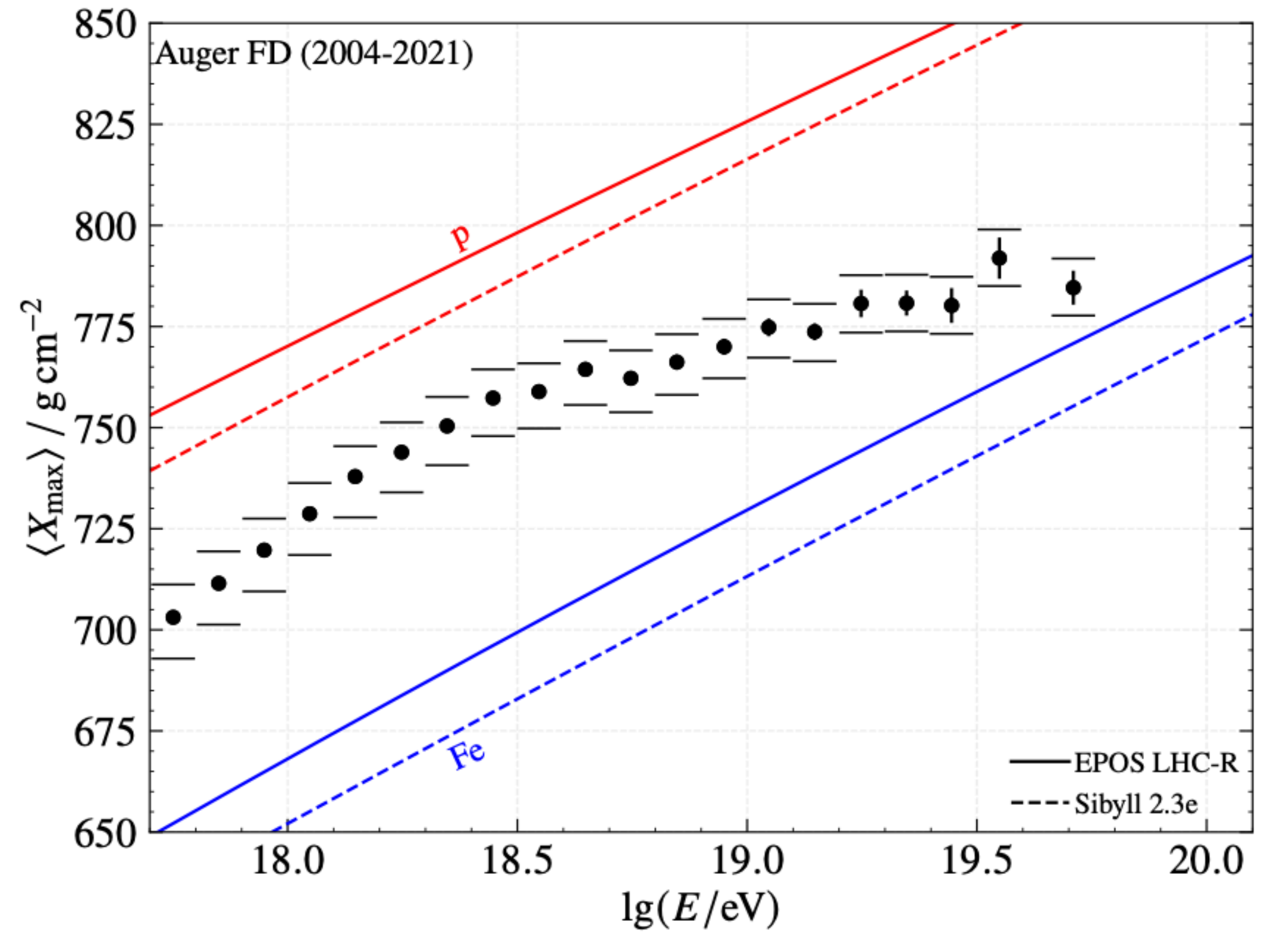
Basic models do not explain UHECR measurements

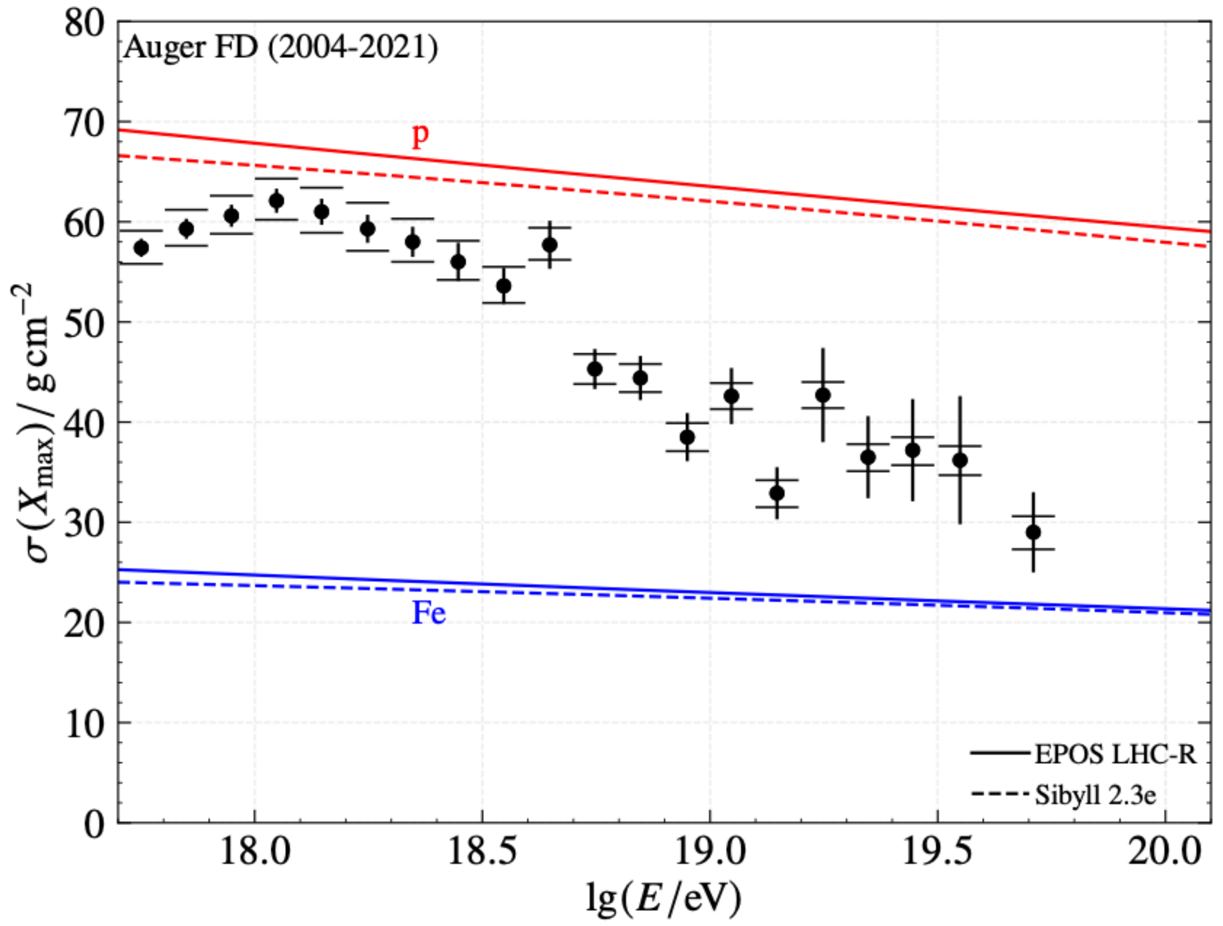
- State-of-the-art of interpretation of UHECR measurements
  - Basic interpretation of UHECR data (as **pure-proton composition scenario, dip model**) is challenged, thanks to
    - mass composition measurements
    - shape of UHECR flux
    - upper limits on cosmogenic particles

Berezinsky et al. Phys.Rev.D 74 (2006)



The Auger Collab. *Phys.Rev.D* 114 (2026)





- Mean Xmax shows a break at $10^{18.4}$ eV -> model-independent signal that mass composition is changing as a function of energy
- Decrease of Xmax fluctuations with energy indicates a transition toward a heavier and less diverse mass composition

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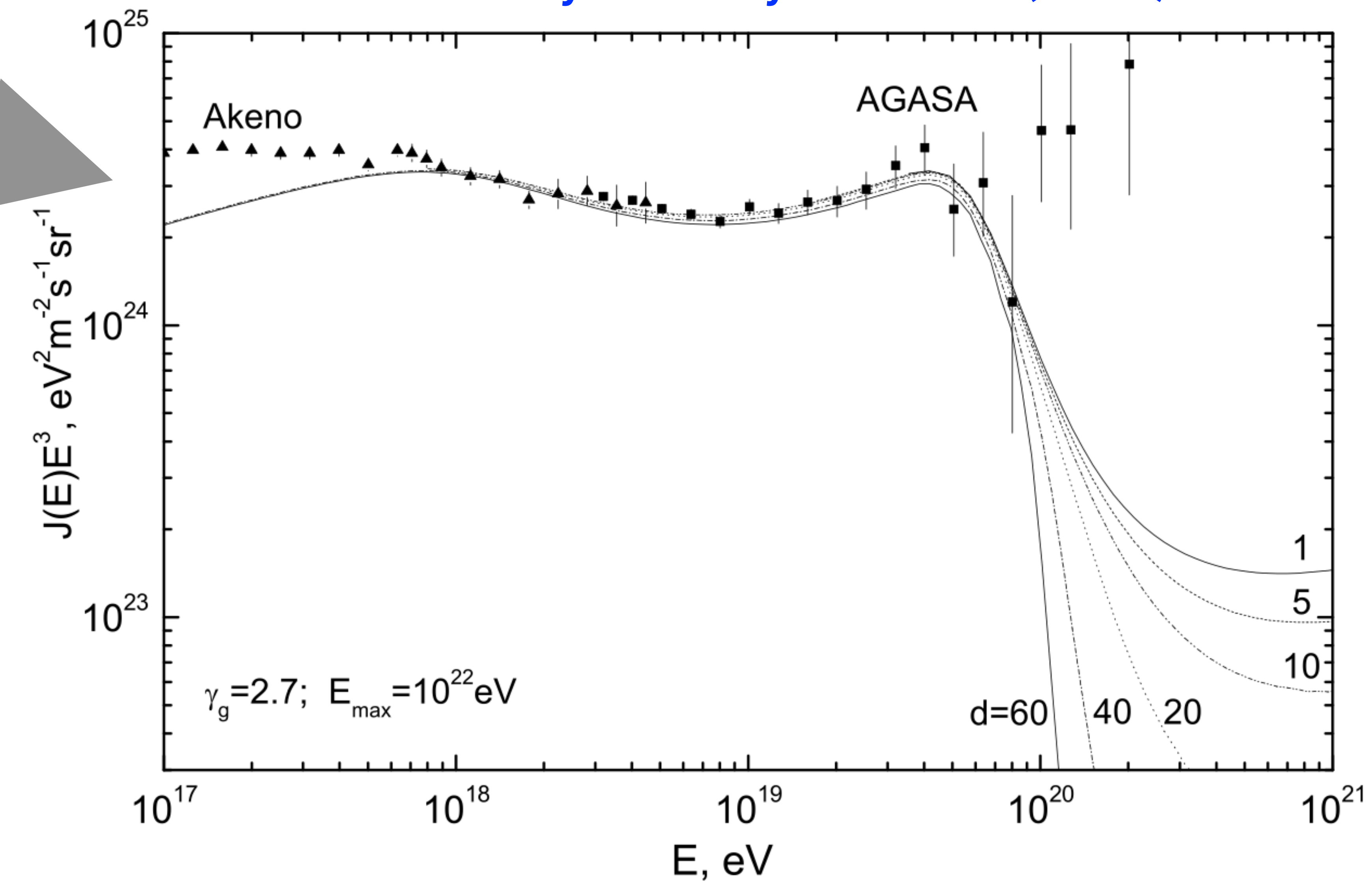

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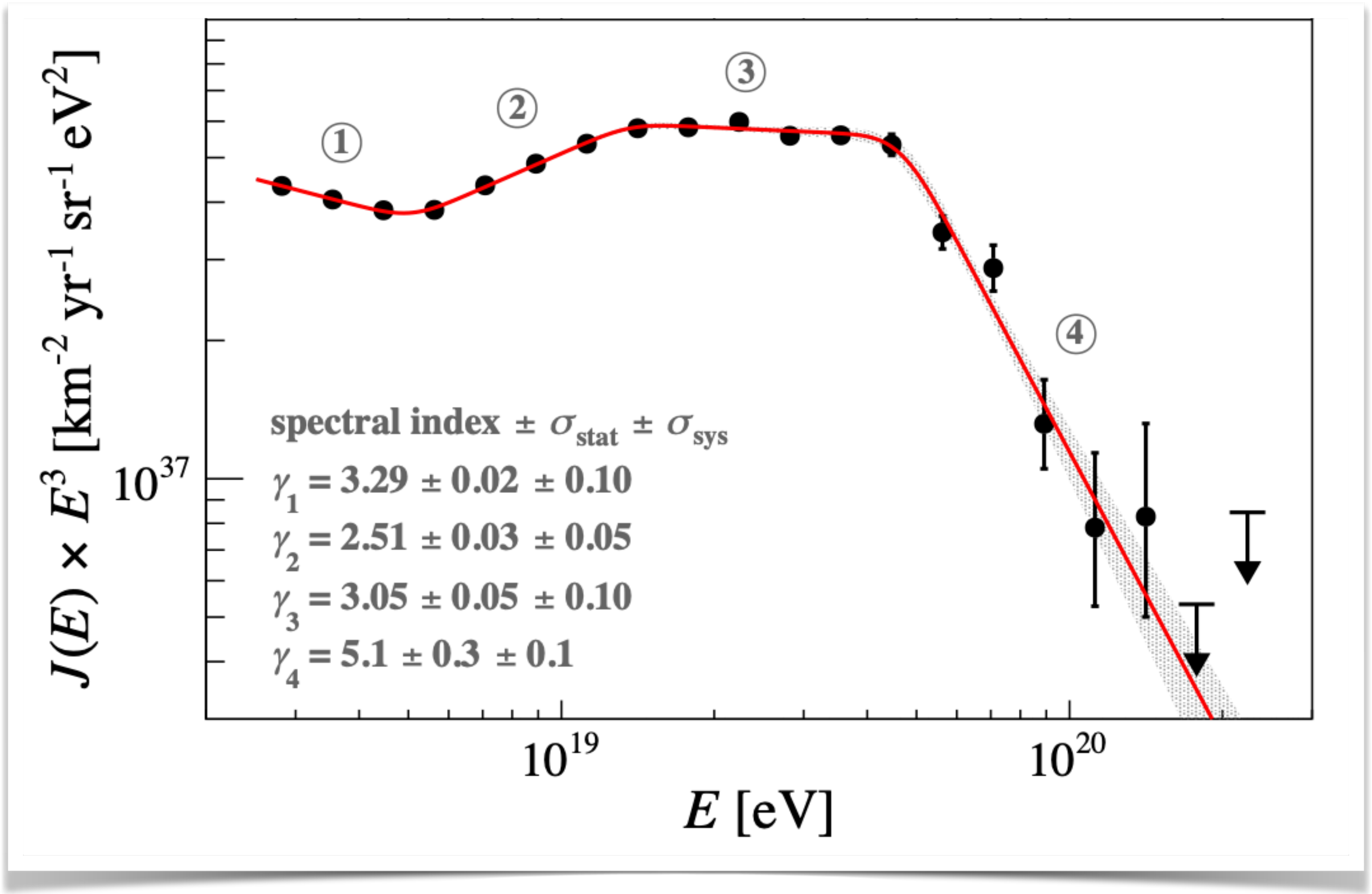

- Instep (feature at 13 EeV, see The Auger Collab. Phys.Rev.Lett. 125 (2020)) not predicted by dip model
- Absence of declination dependence of spectrum, see The Auger Collab. PRL 135 (2025)

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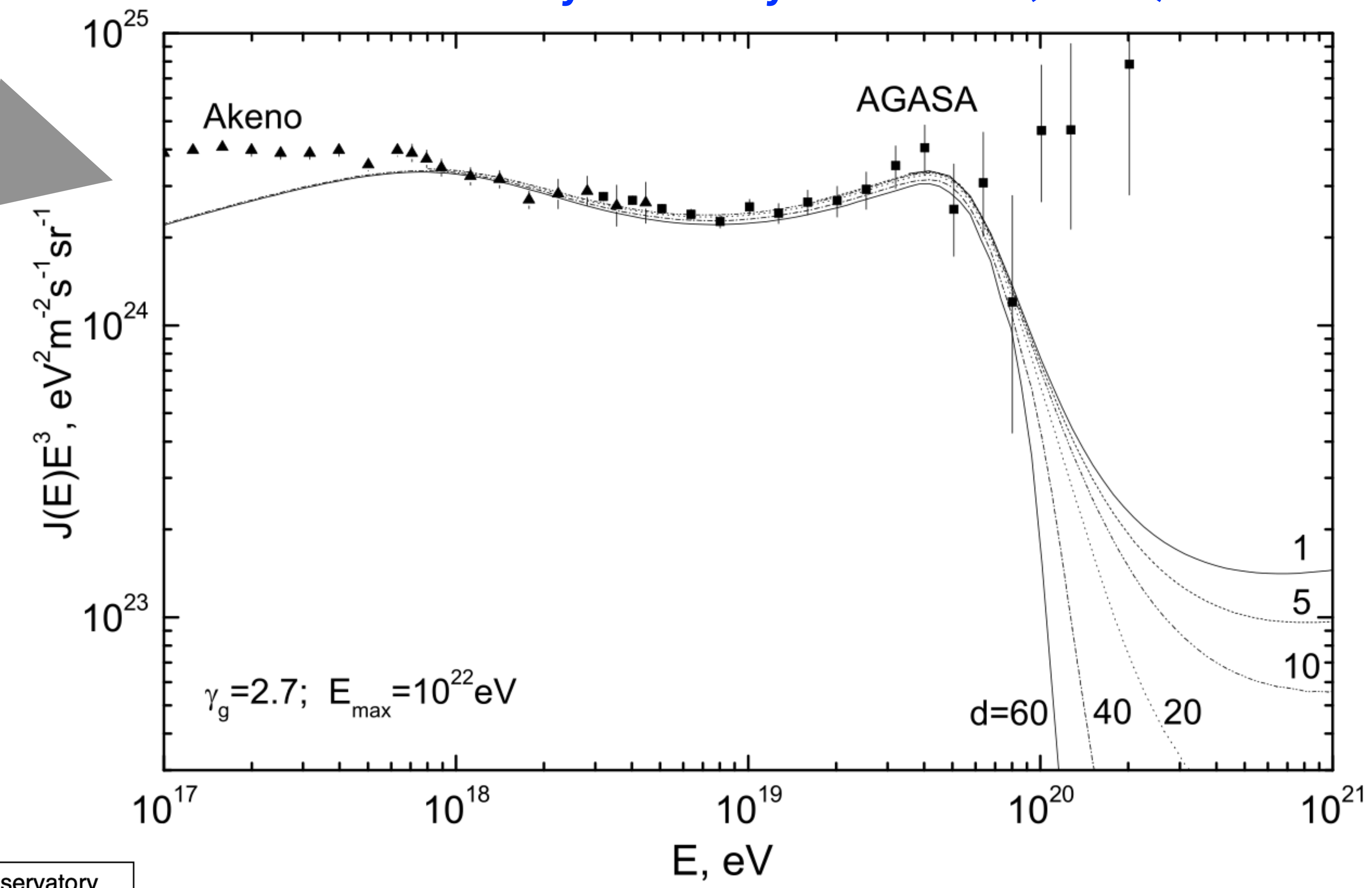
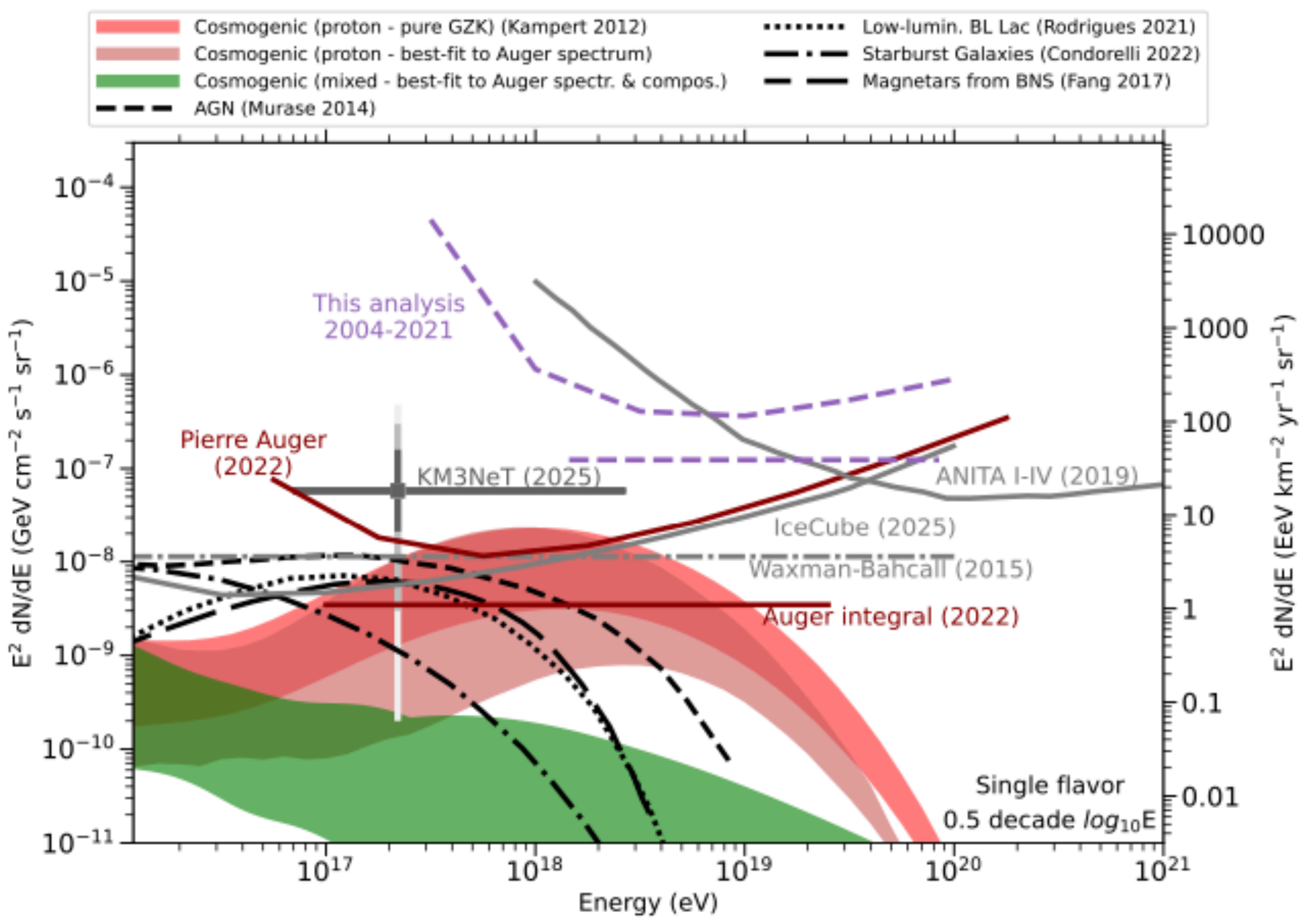
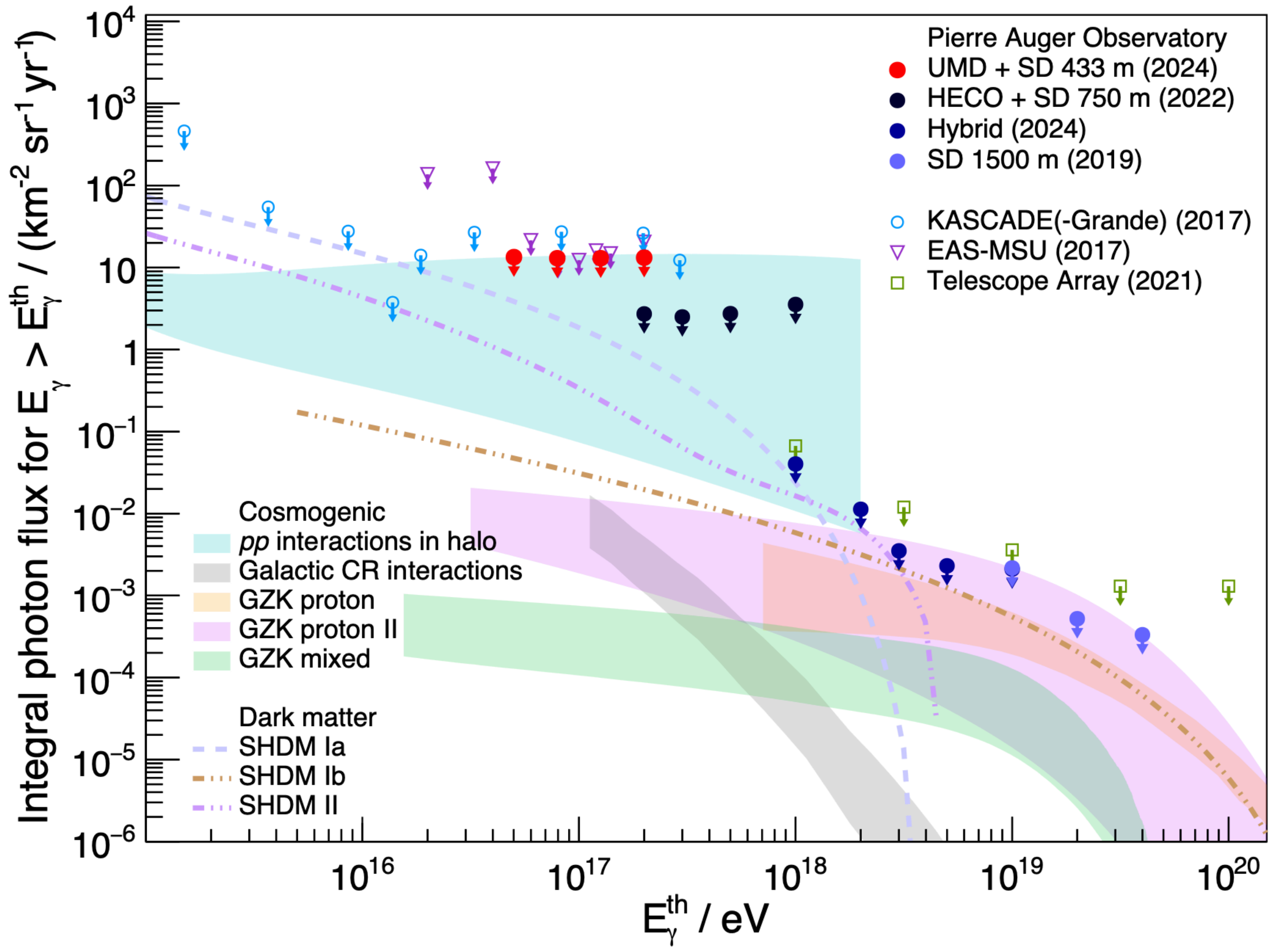




The Auger Collab. ICRC 2025



The Auger Collab. *JCAP* 05 (2025) 061

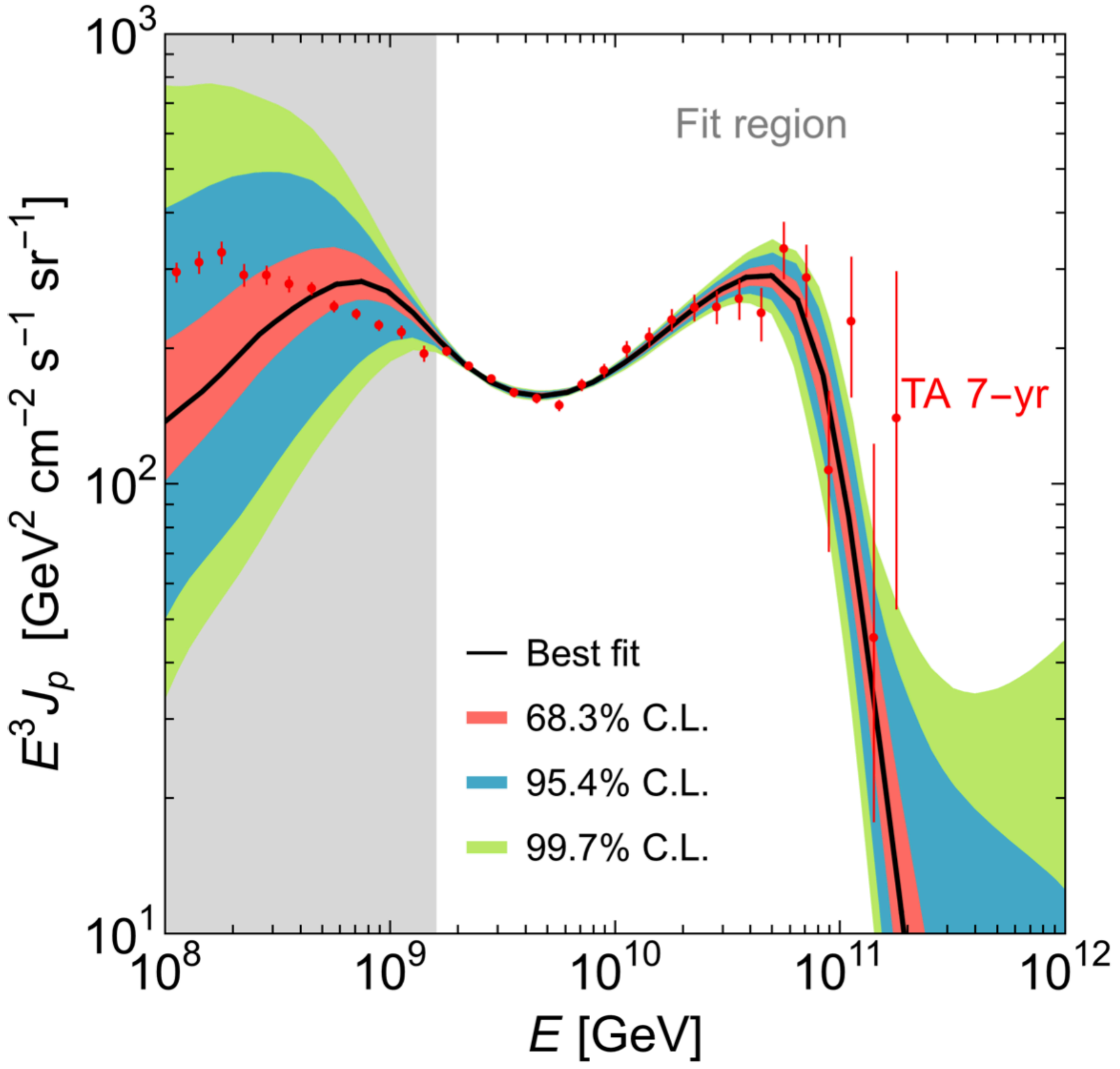
- Cosmogenic particles expected in the decay chain of mesons, originated in interactions of UHECRs with background photons
  - Threshold for pion production depends on Lorentz factor -> UHECR mass composition affect fluxes of secondary particles

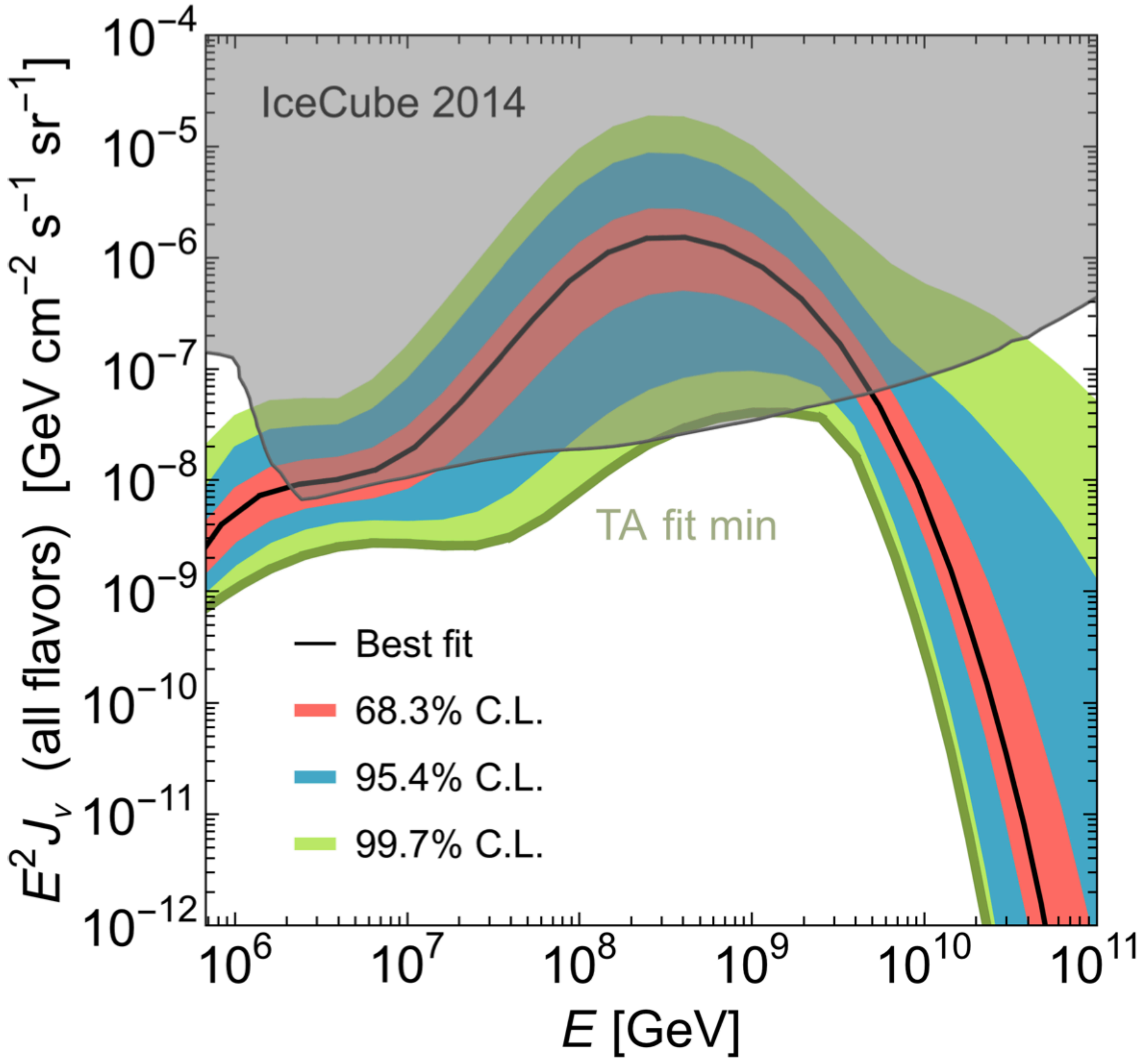
What information can we get from non-observation of neutrinos?

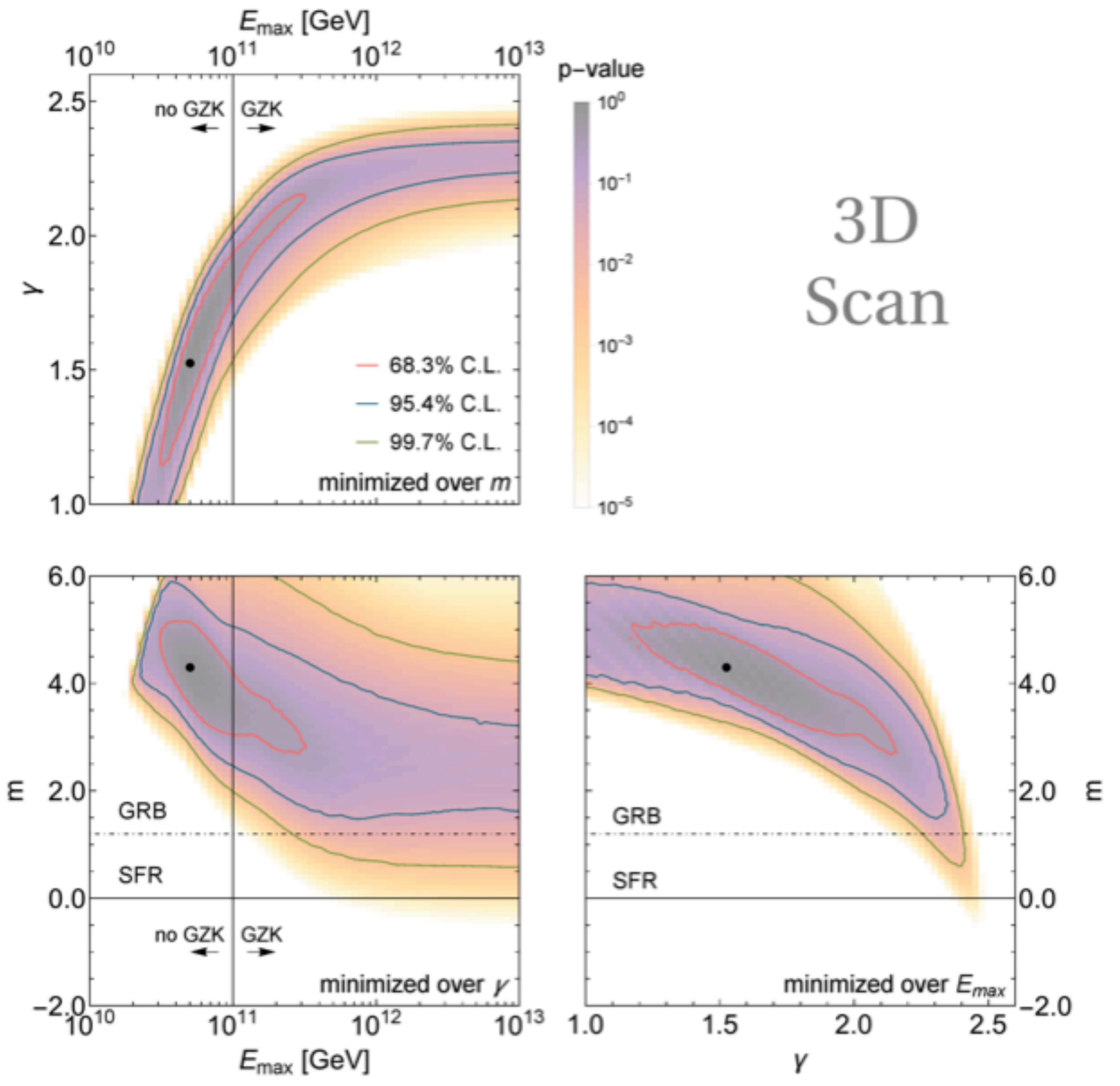
$$Q_p(E,z) \propto (1+z)^m E^{-\gamma} \exp(-E/E_{\max})$$

100% UHECR protons

- Constraints on
  - UHECR (proton) spectral parameters, from fit of UHECR spectrum
  - source evolution, from non-observation of cosmogenic neutrinos
- See also: The Auger Collab. JCAP 2019; van Vliet+ PRD 2019; Muzio+ PRD 2023







Heinze, DB, Bustamante & Winter Astrophys.J. 825 (2016)

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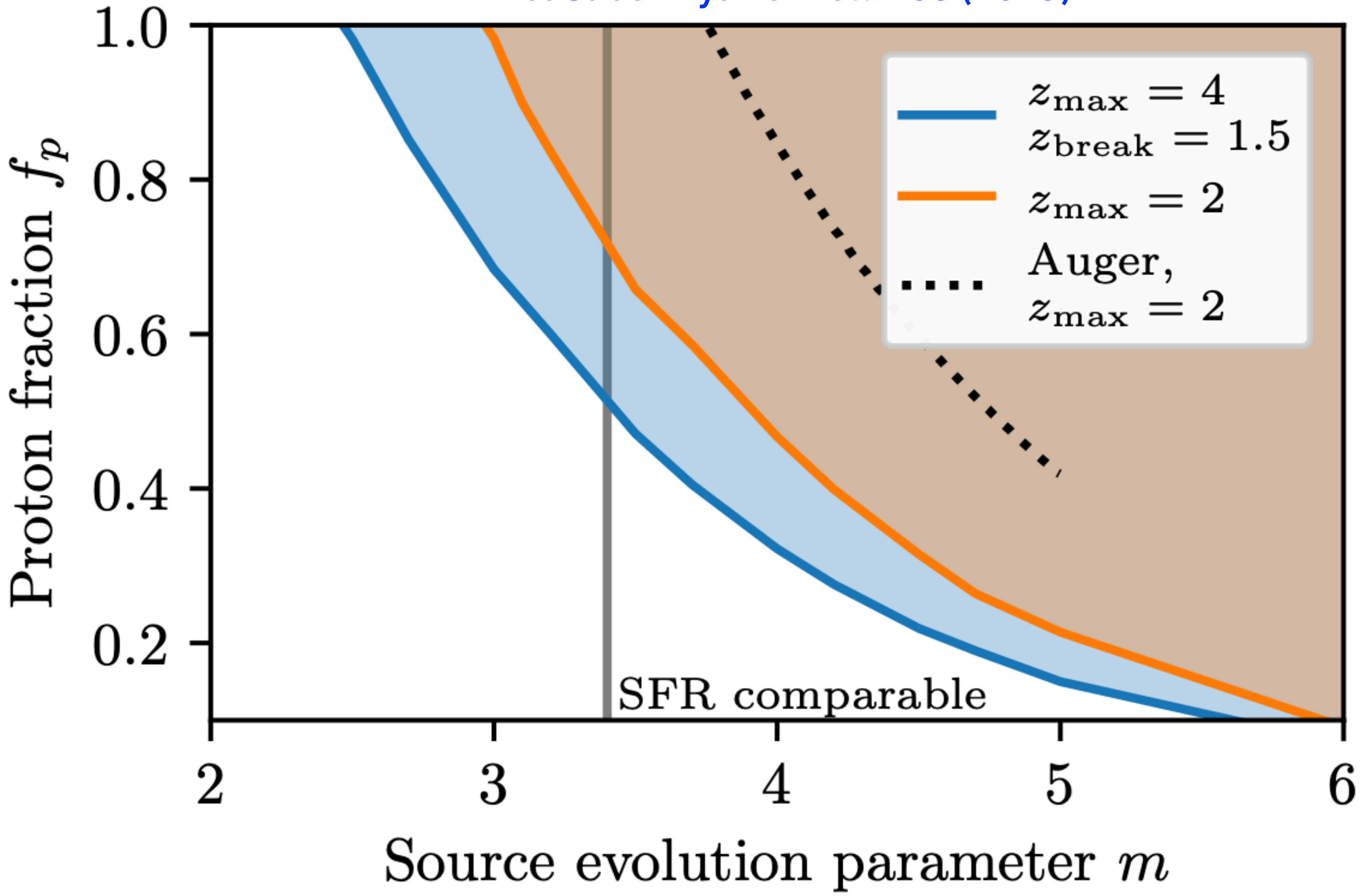
$$Q_p(E,z) \propto (1+z)^m E^{-\gamma} \exp(-E/E_{\max})$$

Varying proton contribution to UHECRs

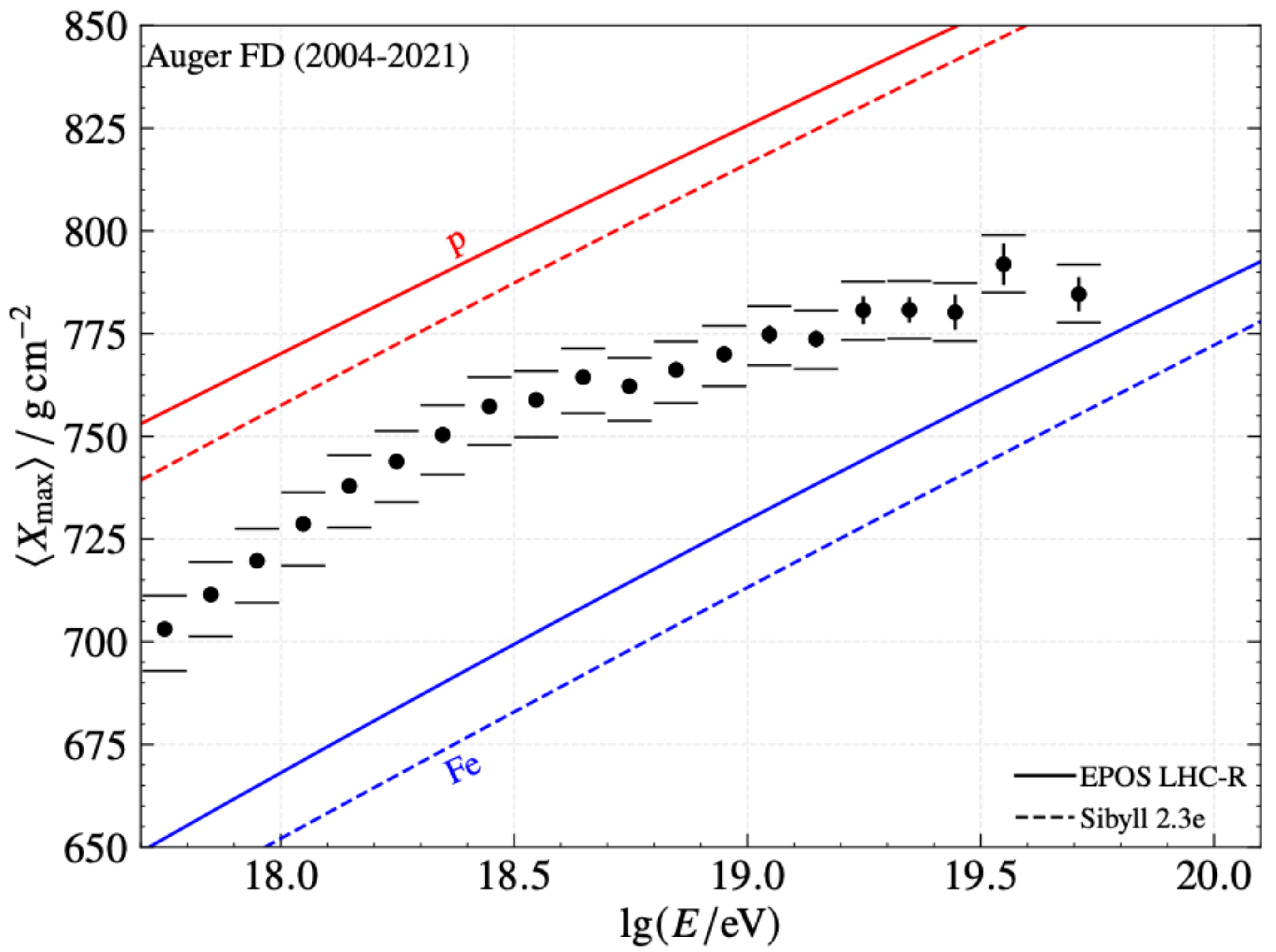
- Constraints on
  - **UHECR proton fraction**, and
  - source evolution, from UHECR spectrum and non-observation of cosmogenic neutrinos
- See also: The Auger Collab. JCAP 2019; van Vliet+ PRD 2019; Muzio+ PRD 2023

IceCube Phys.Rev.Lett. 135 (2025)



Evidence for **non pure-proton composition**

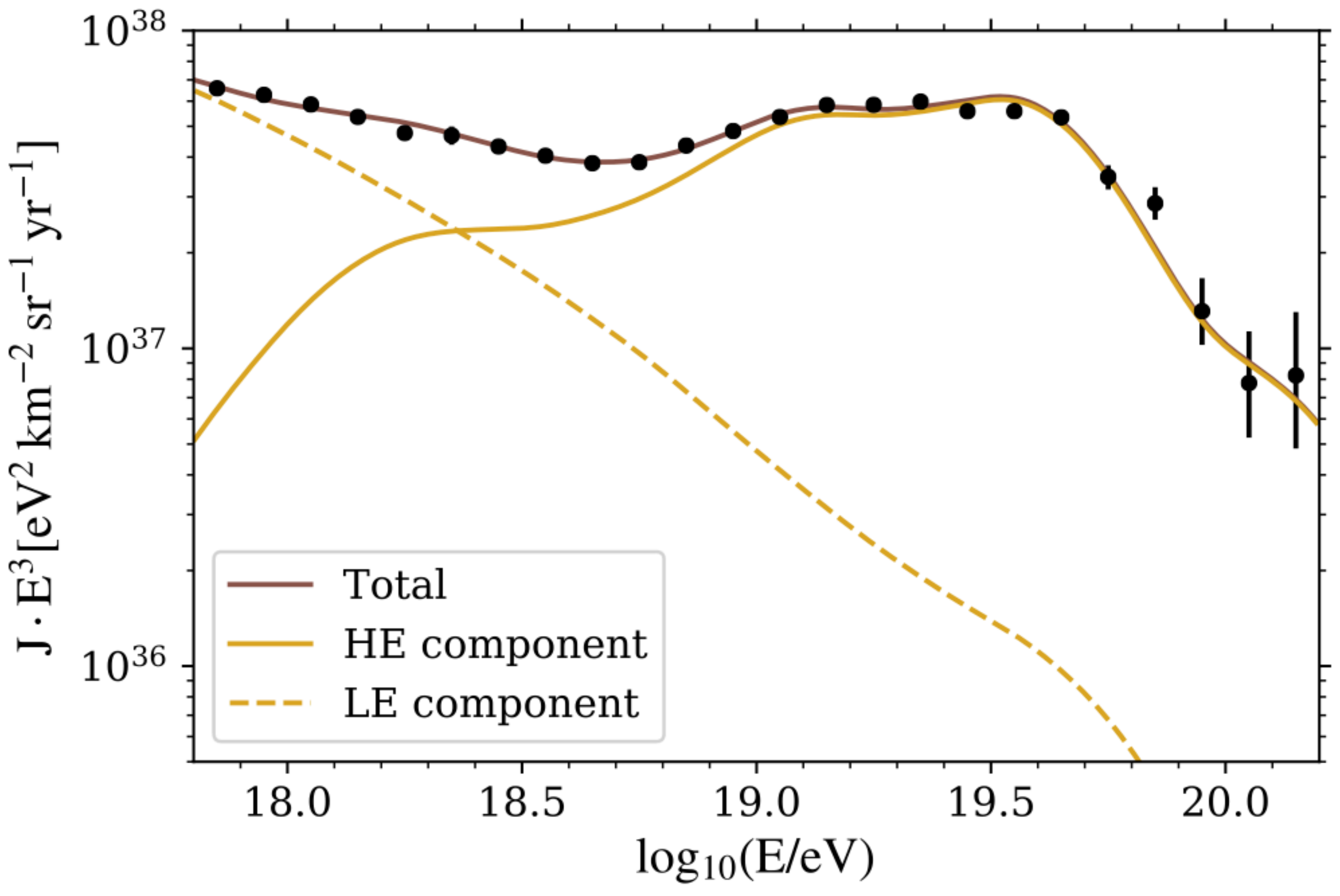
The Auger Collab. *Phys.Rev.D* 114 (2026)



- Proton fraction of UHECRs above 30 EeV constrained to be < 70 % (at 90% CL) if the cosmological evolution of the sources is comparable to or stronger than the star formation rate

State-of-the art of UHECR scenarios

State-of-the-art: astrophysical scenarios for UHECRs



State-of-the-art interpretation of astrophysical scenarios for UHECRs predicts two components contributing below and above the ankle:

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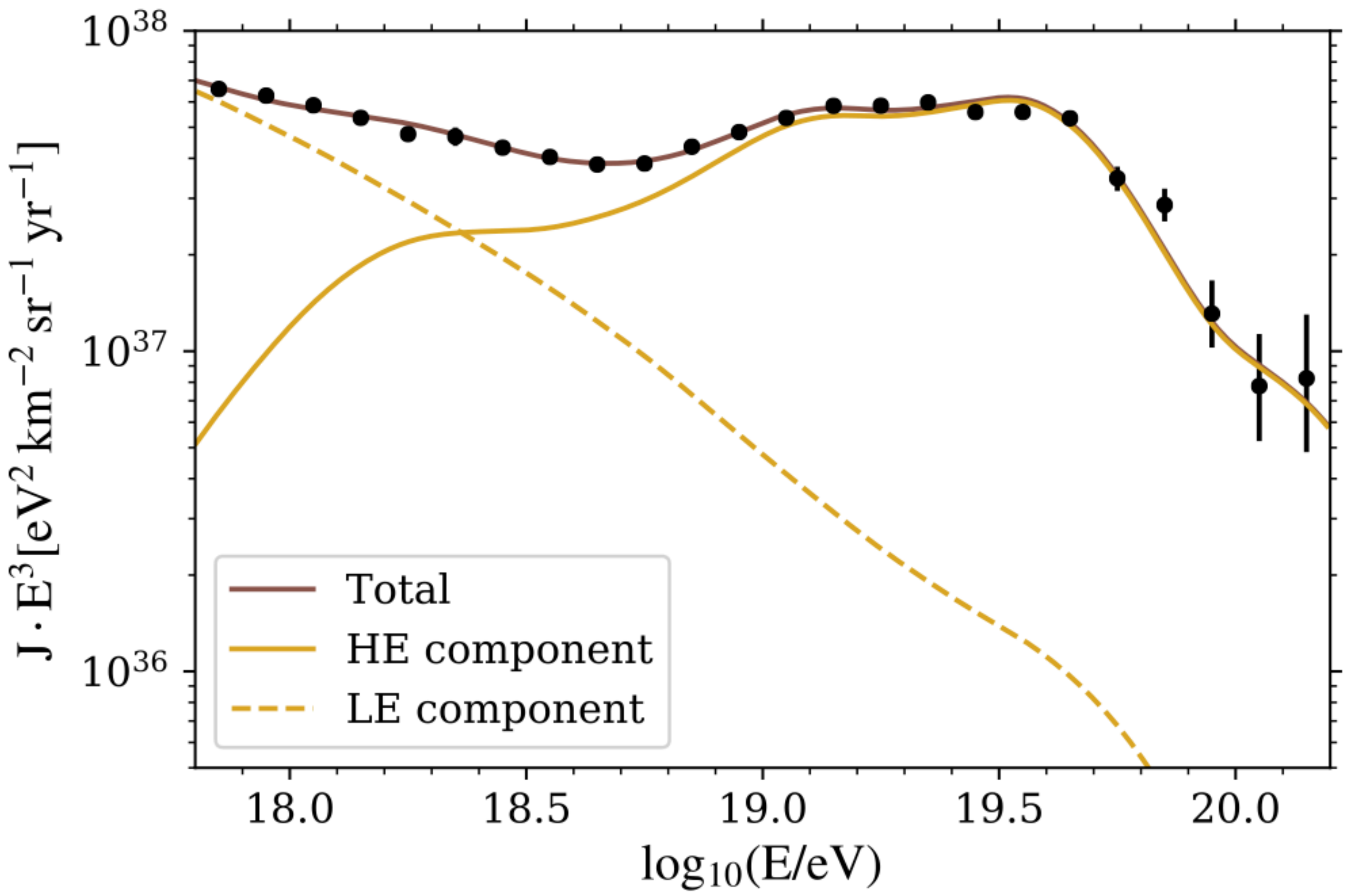

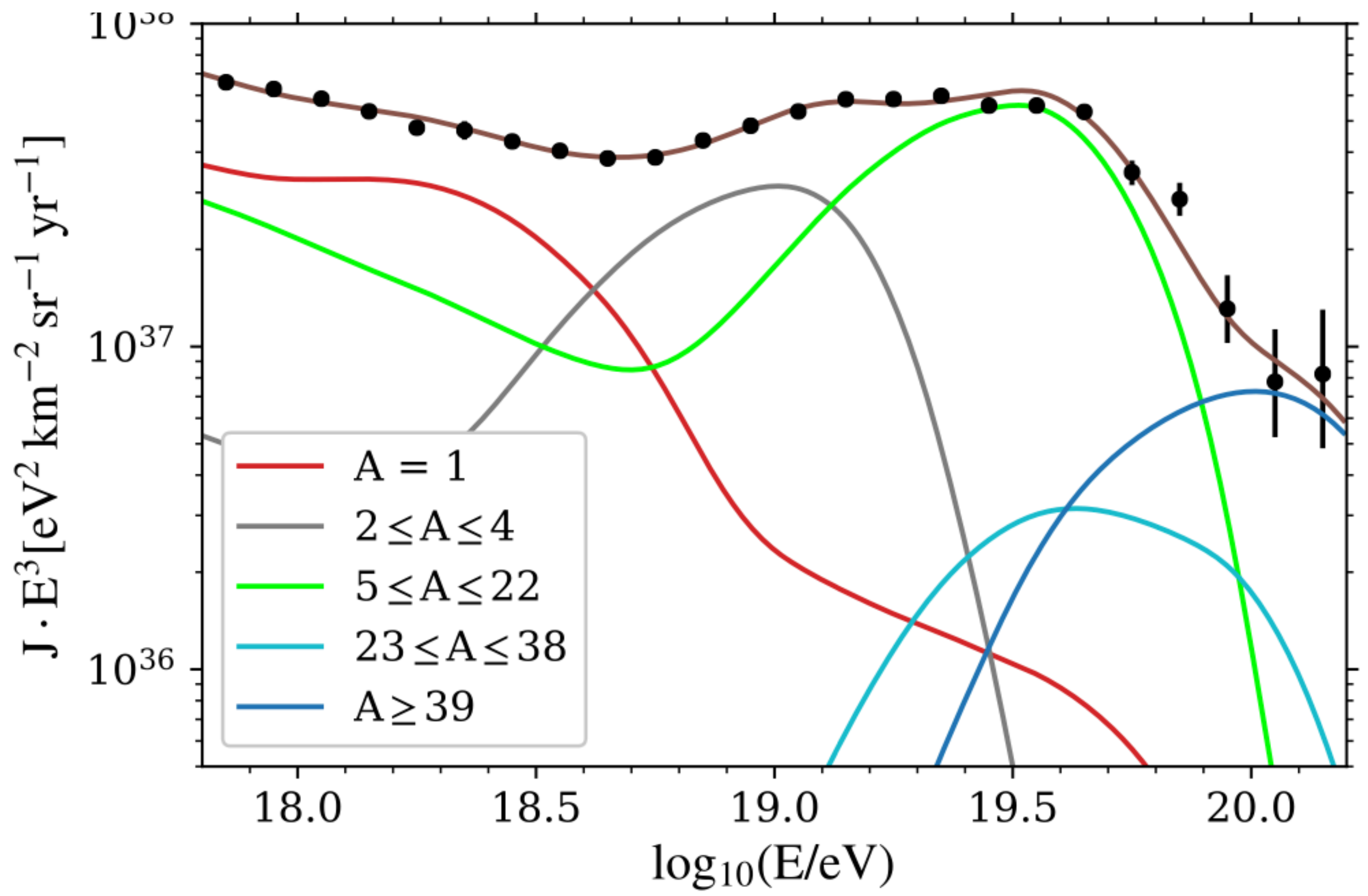

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- Different populations of sources contributing at low energy (LE, below the ankle) and high energy (HE, above the ankle)
- One population of sources, with softer spectrum of LE protons
  - End of additional (Galactic?) spectrum needed to adjust mass composition and spectral shape at the ankle

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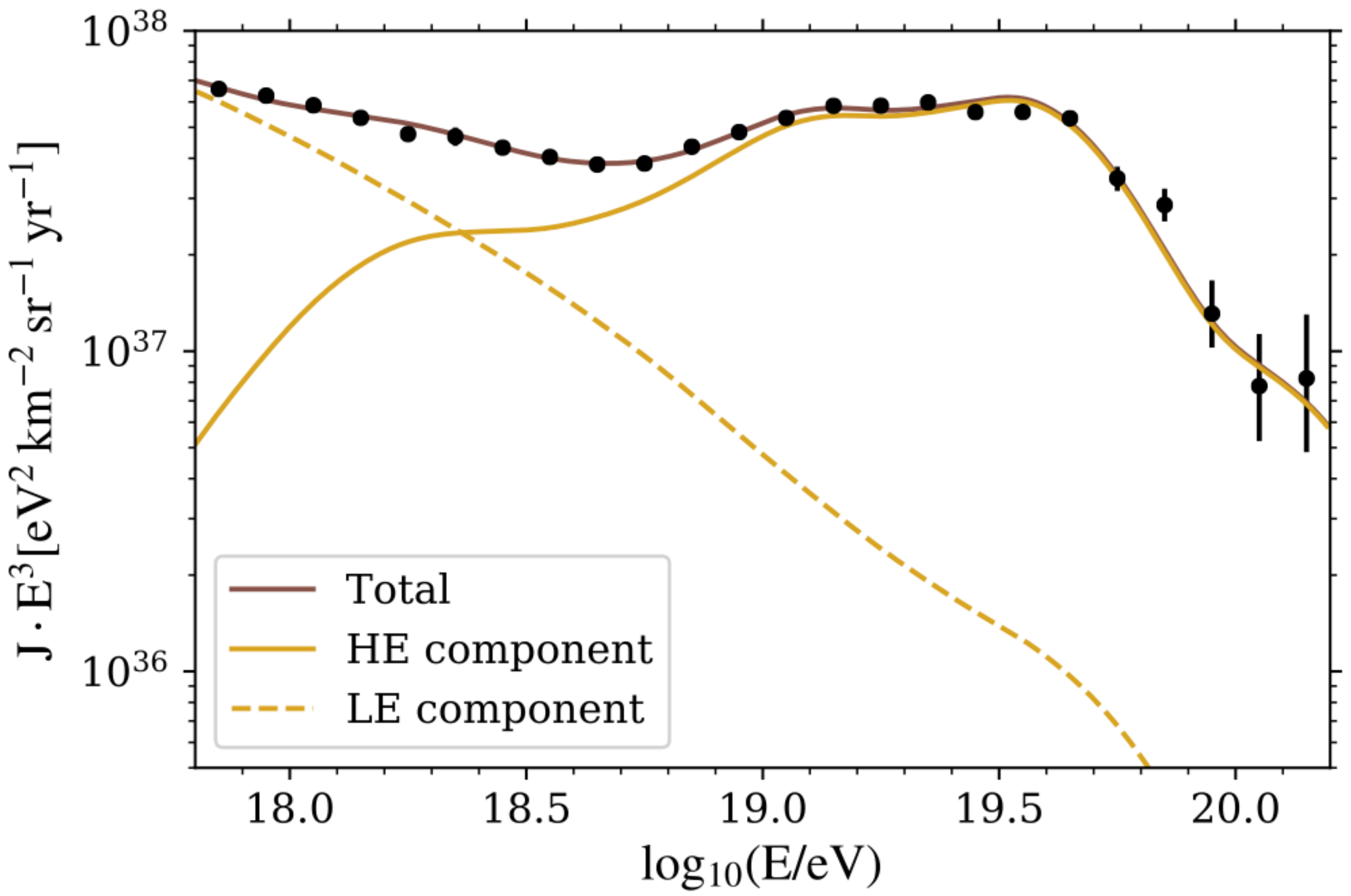

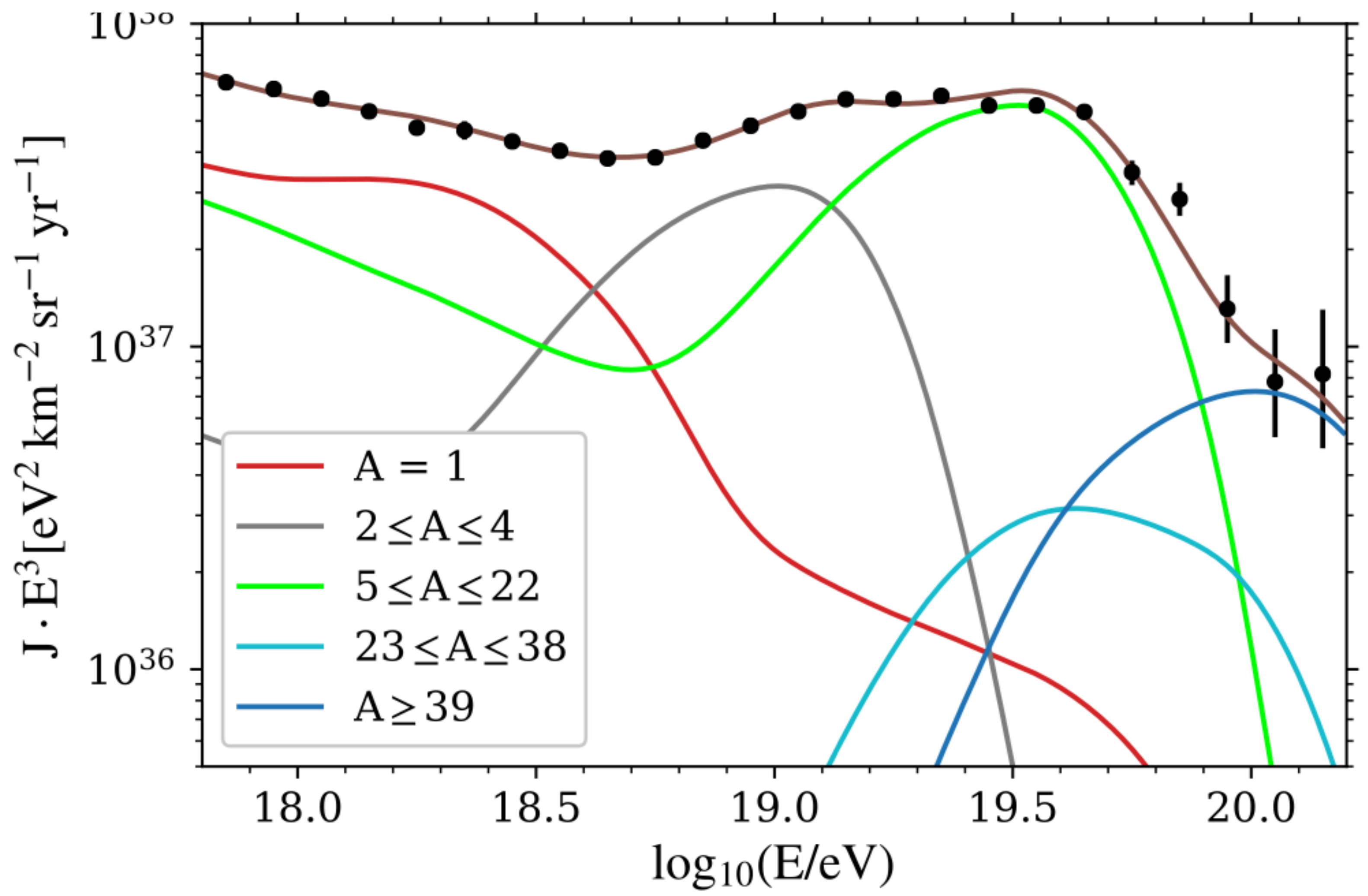

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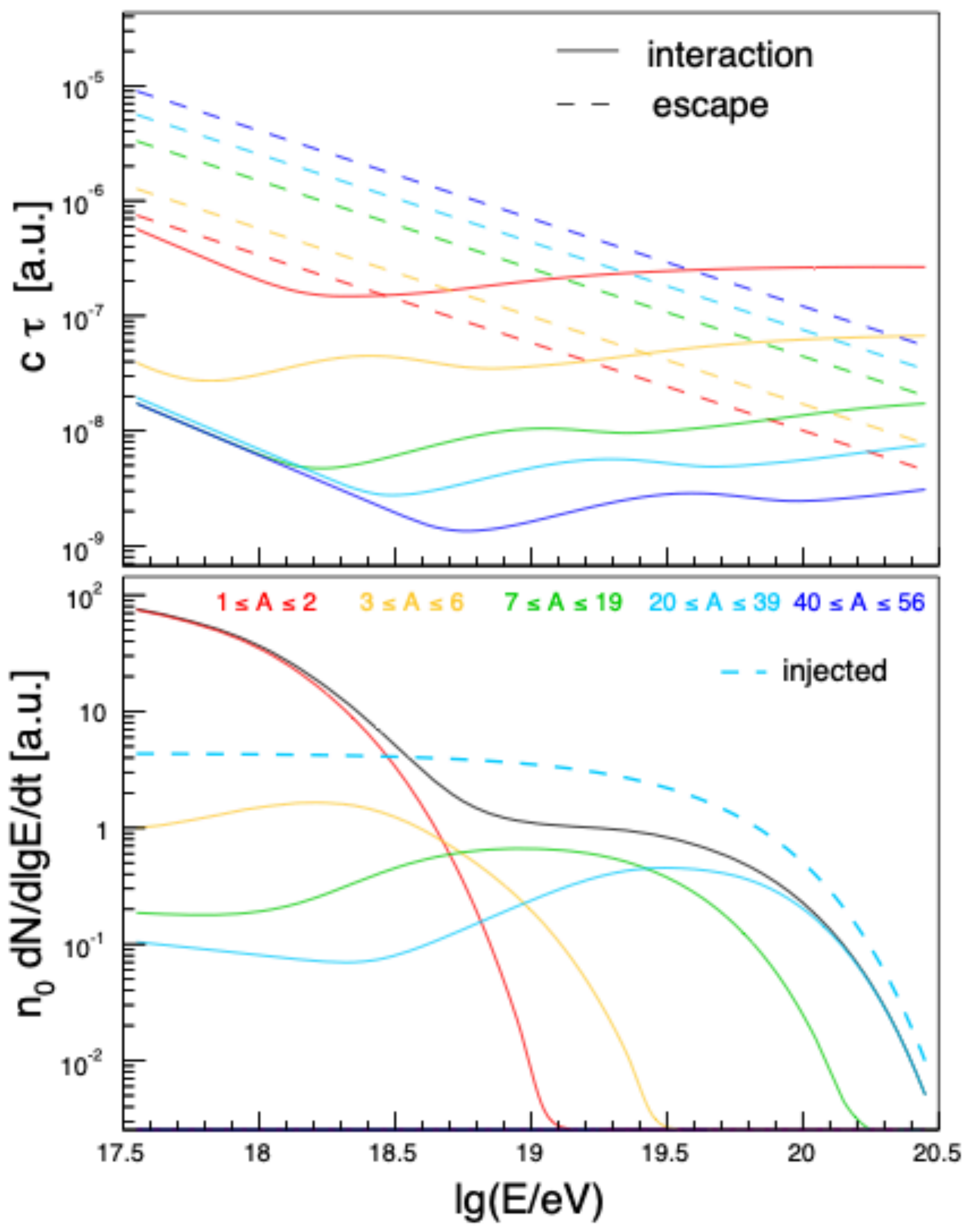

Unger, Farrar & Anchordoqui PRD 2015

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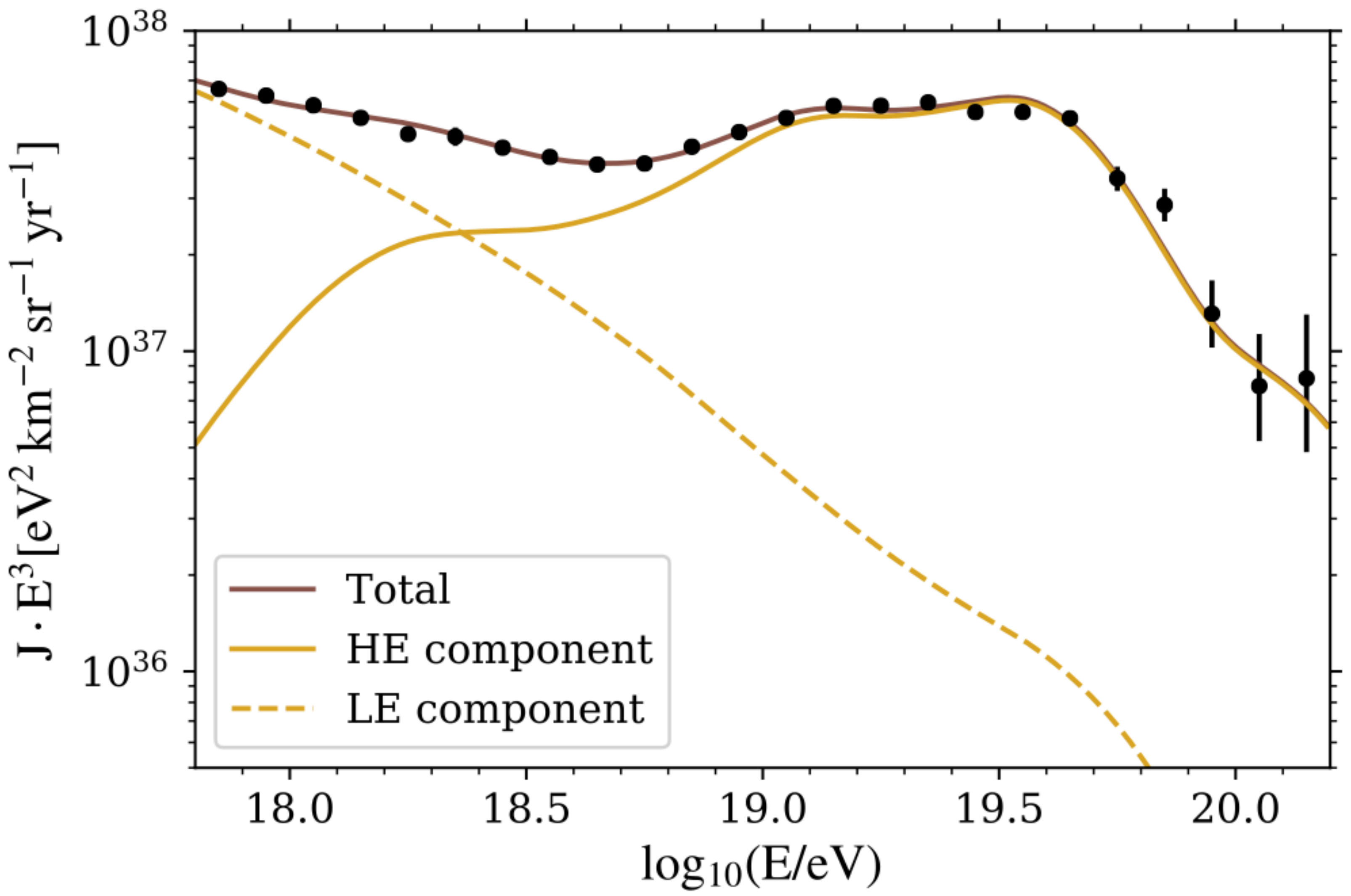

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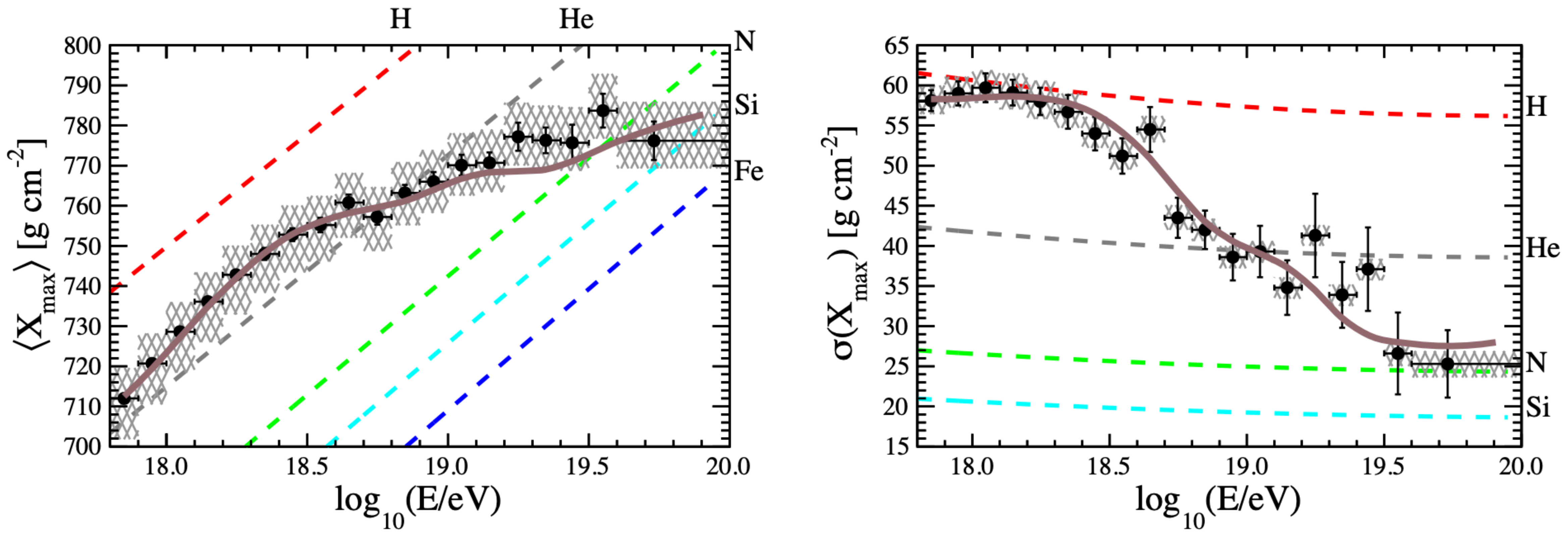
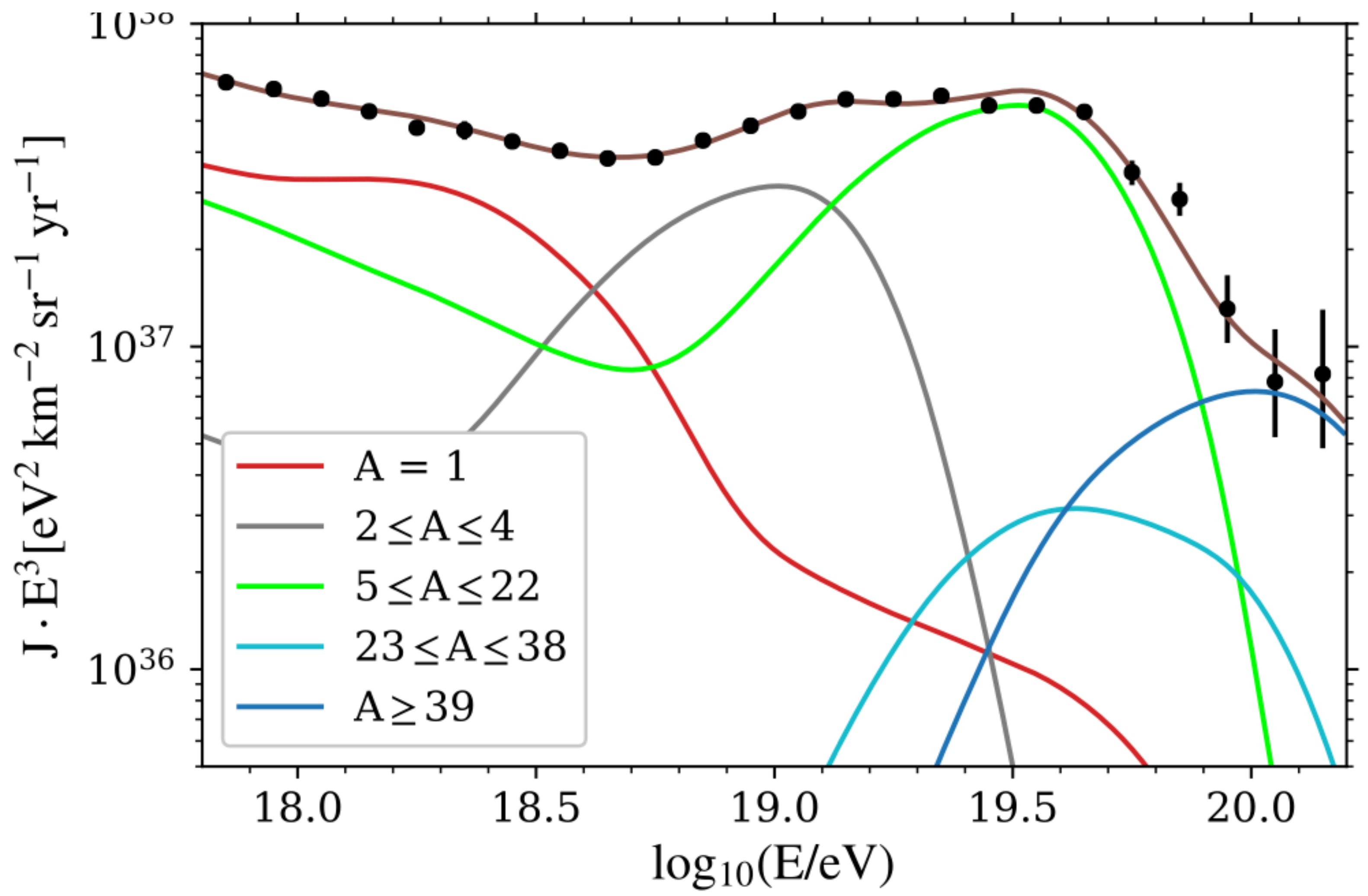
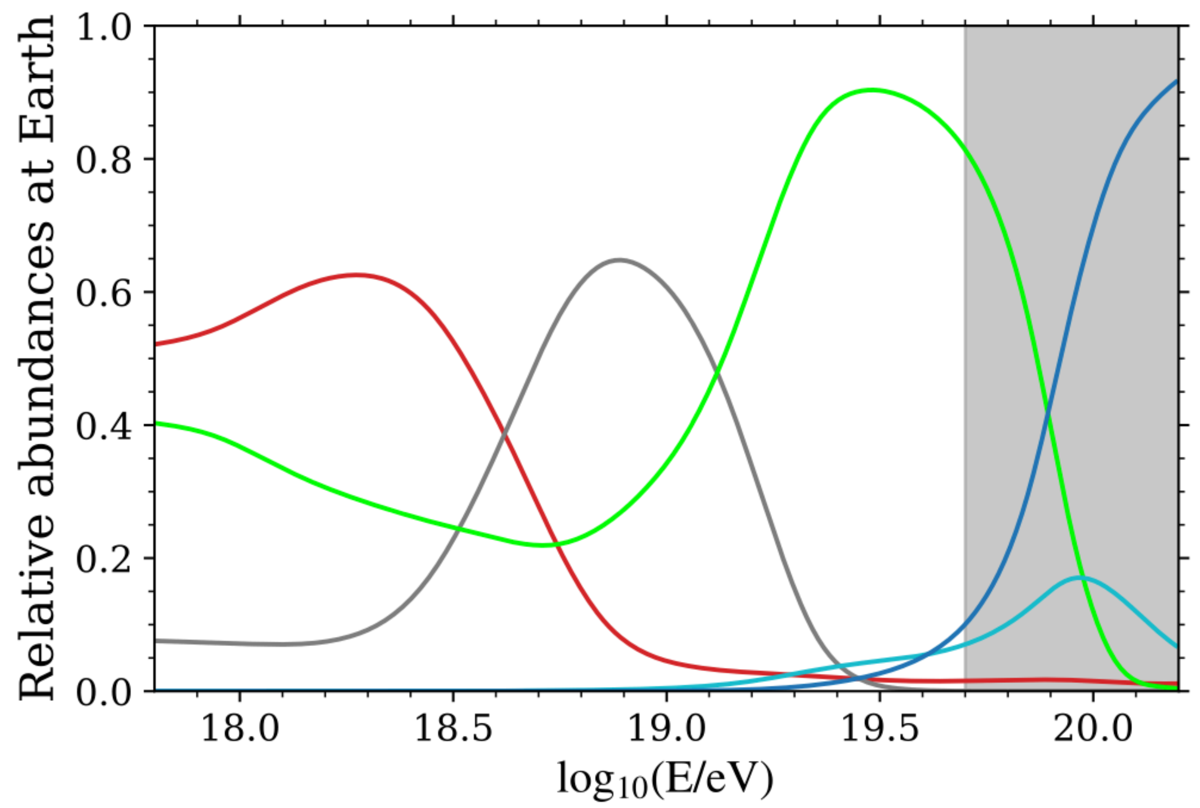




- Independently of the scenario, decreasing fluctuations of Xmax can be found corresponding to **limited mixing of spectra of different nuclear species at HE**, meaning
  - HE: hard spectra + low rigidity cutoff
  - LE: soft spectra + less constrainable rigidity



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State-of-the-art: astrophysical scenarios for UHECRs

EG components (at the escape)	LE	HE
$\mathcal{L}_0/(10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}})$ *	11.35 ± 0.15	5.07 ± 0.06
γ	3.52 ± 0.03	-1.99 ± 0.11
$\log_{10}(R_{\mathrm{cut}}/\mathrm{V})$	>19.4	18.15 ± 0.01
I_{H} (%)	48.7 ± 0.3	0.0 ± 0.0
I_{He} (%)	7.3 ± 0.4	23.6 ± 1.6
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D_J (N_J)	56.6 (24)	
$D_{X_{\max}}$ ($N_{X_{\max}}$)	516.5 (329)	
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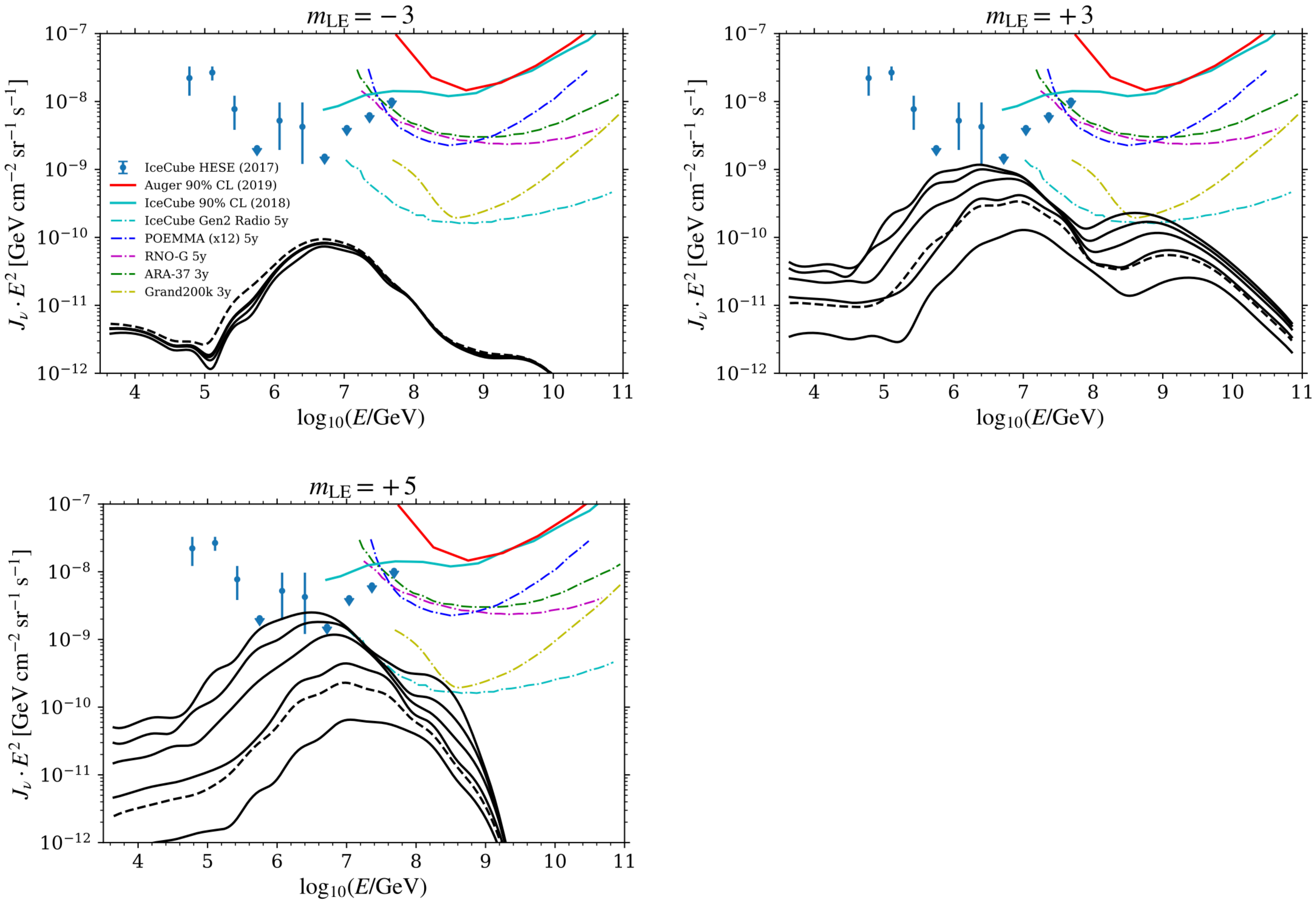
The Pierre Auger Collab. JCAP 2023

State-of-the-art: astrophysical scenarios for UHECRs

and expectations for cosmogenic neutrinos



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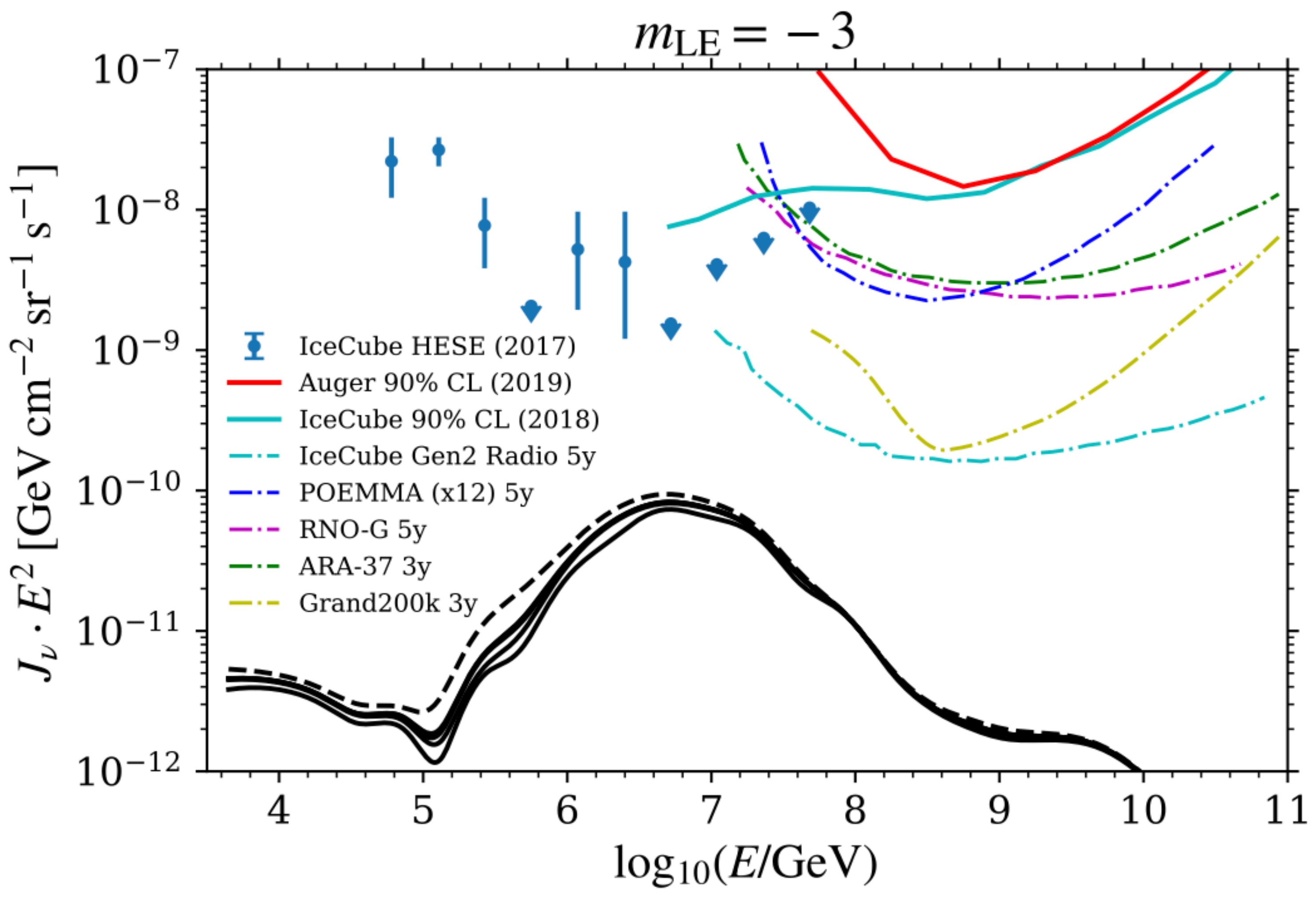

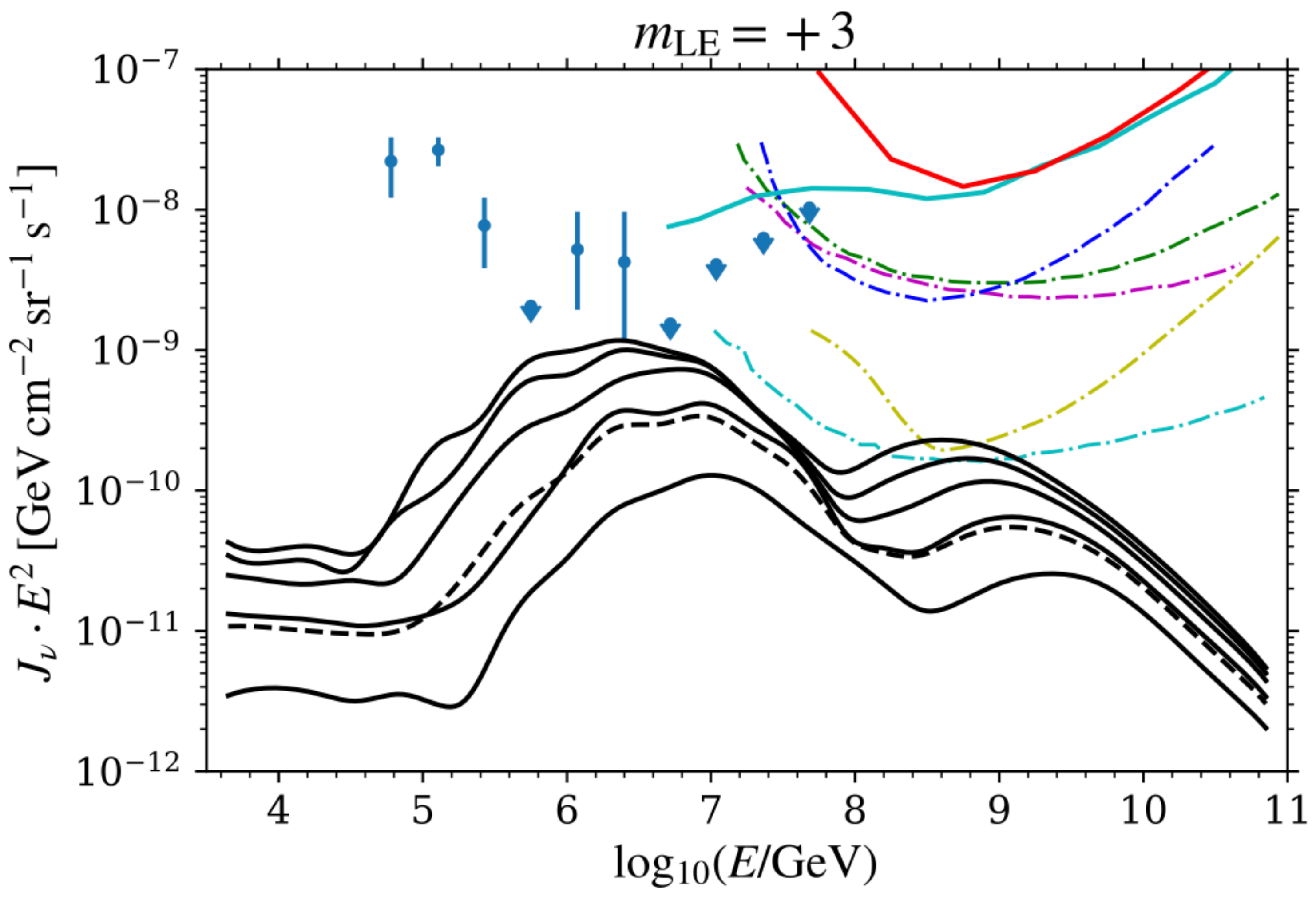

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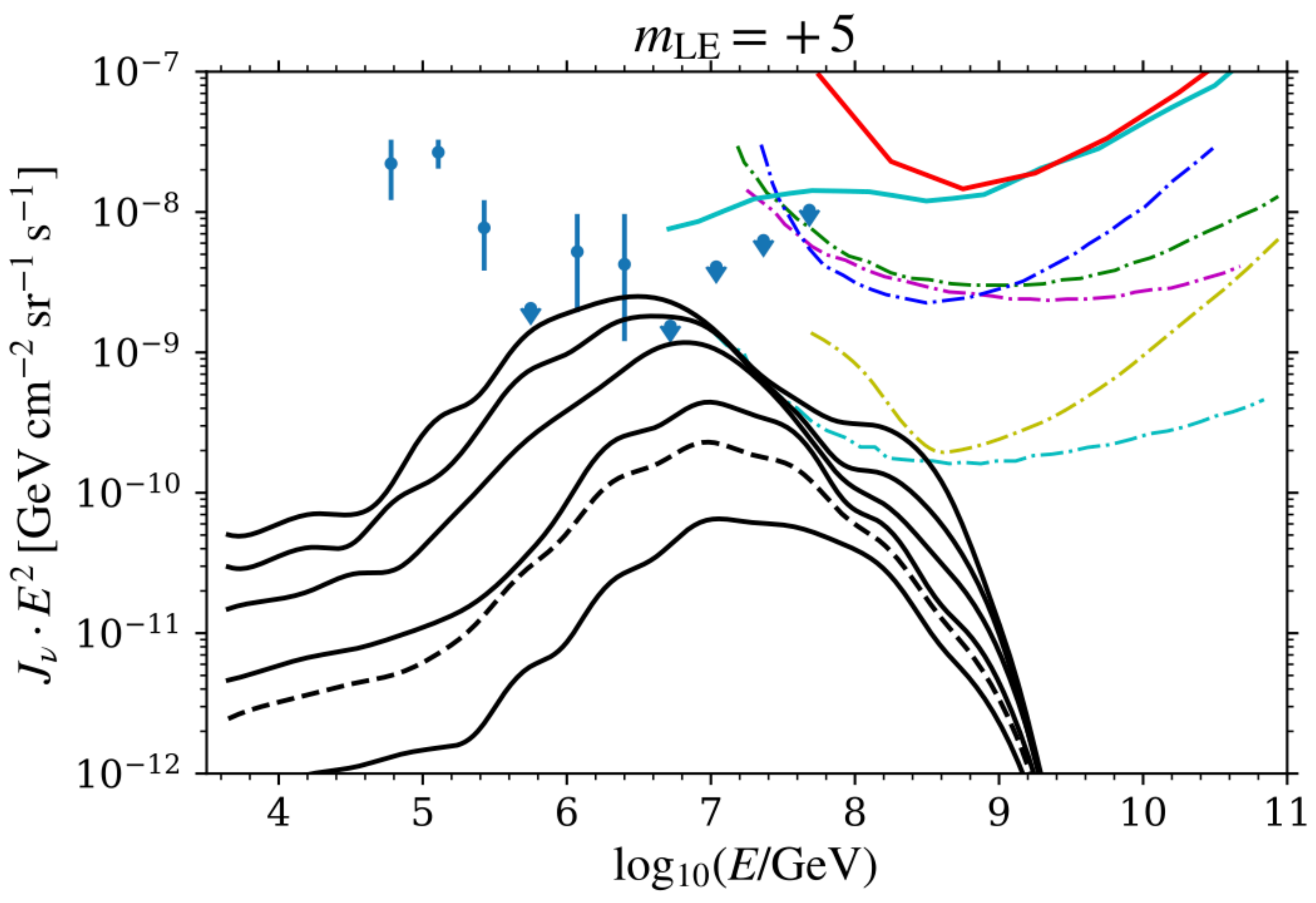
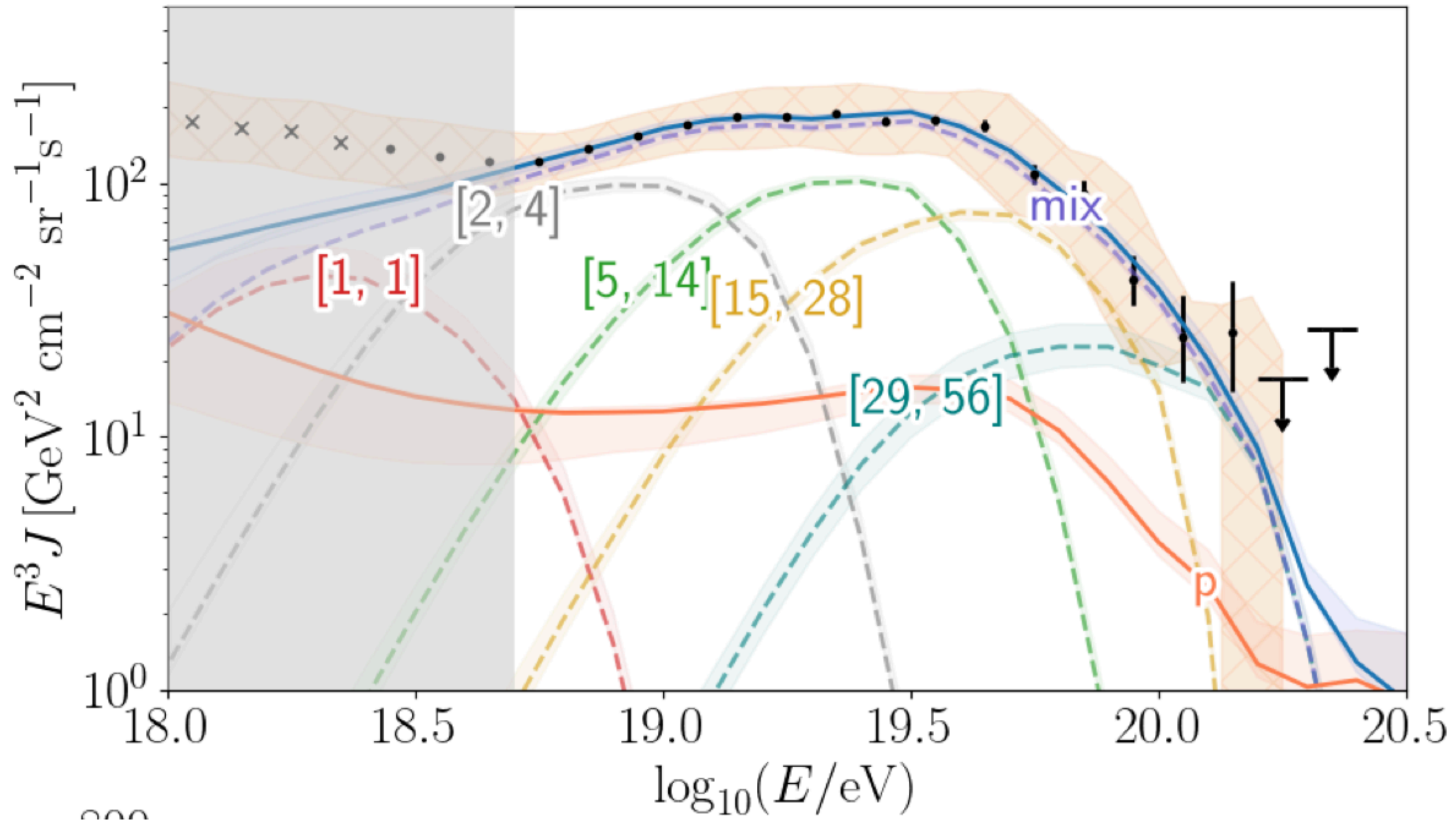


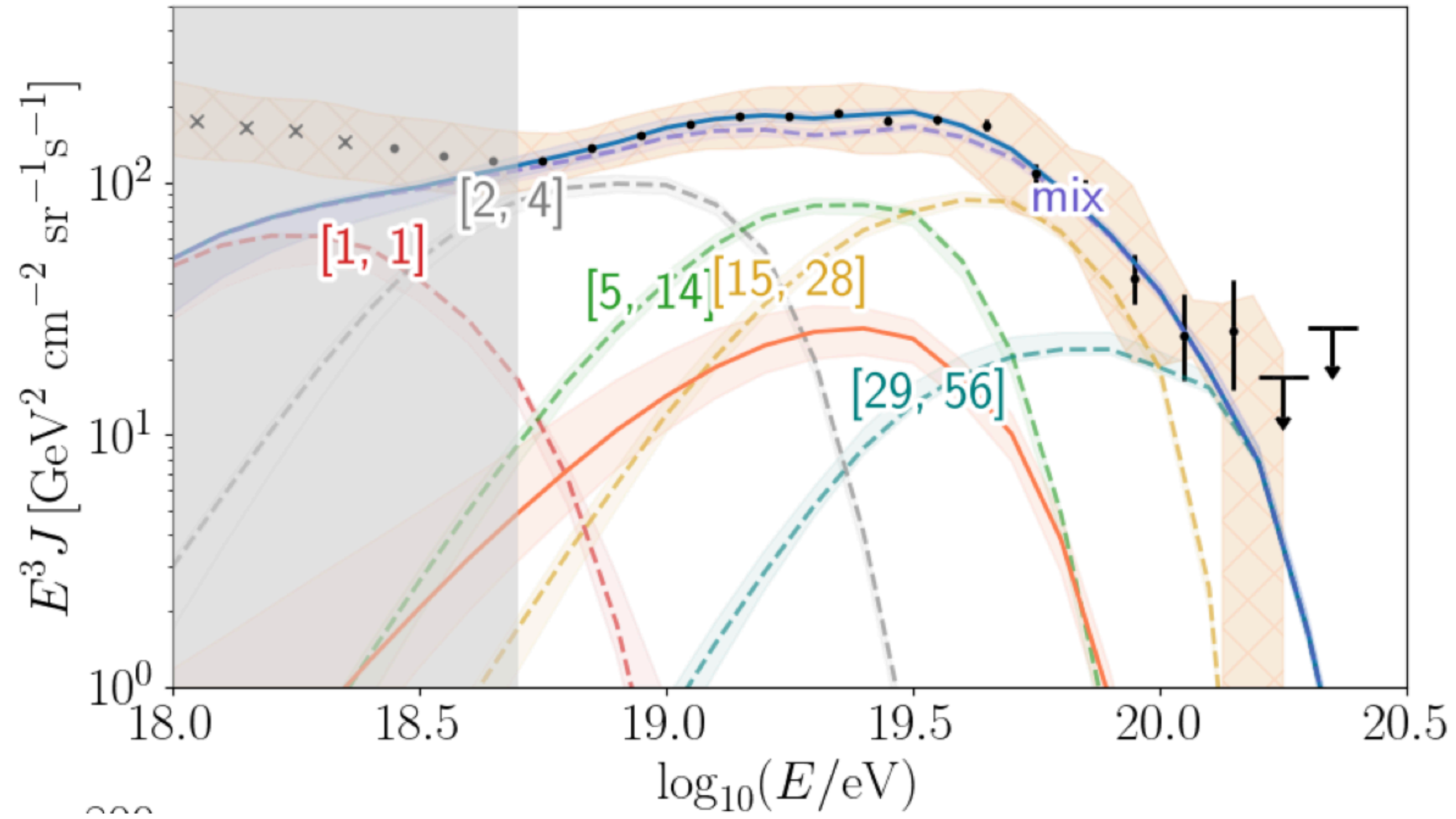
- Due to low value of maximum rigidity of the HE population and to the mass composition, the associated cosmogenic neutrinos are expected to peak between 10^{15} -10^{17} eV
- Due to the uncertainty on the maximum rigidity of the LE population and to the mass composition (and to source evolution), the associated cosmogenic neutrinos can be expected at larger energies with respect to the HE population
- Is an **additional proton component** allowed by data? How does it modify the expected cosmogenic fluxes?

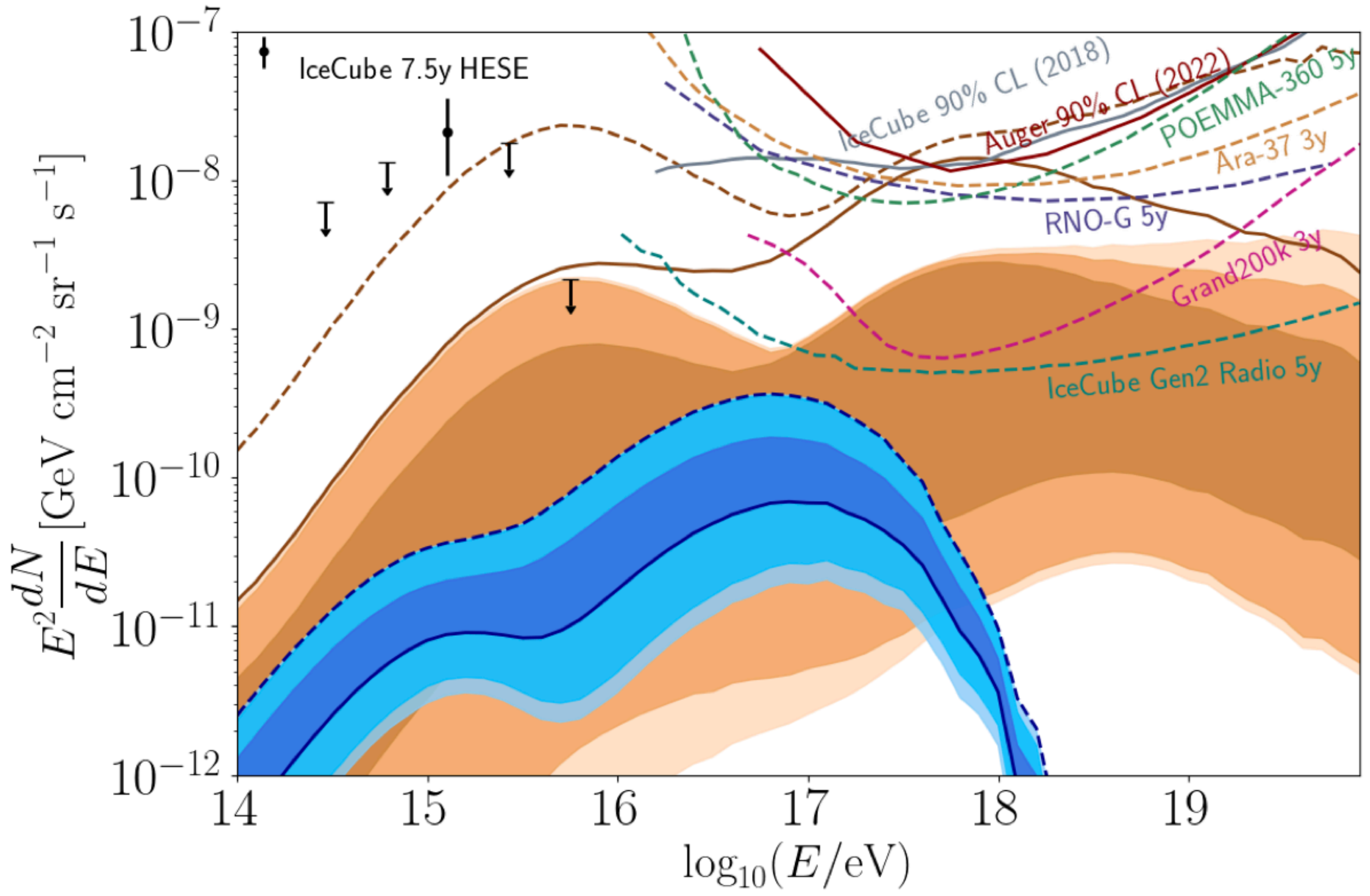
The Pierre Auger Collab. JCAP 2023

State-of-the-art: astrophysical scenarios for UHECRs

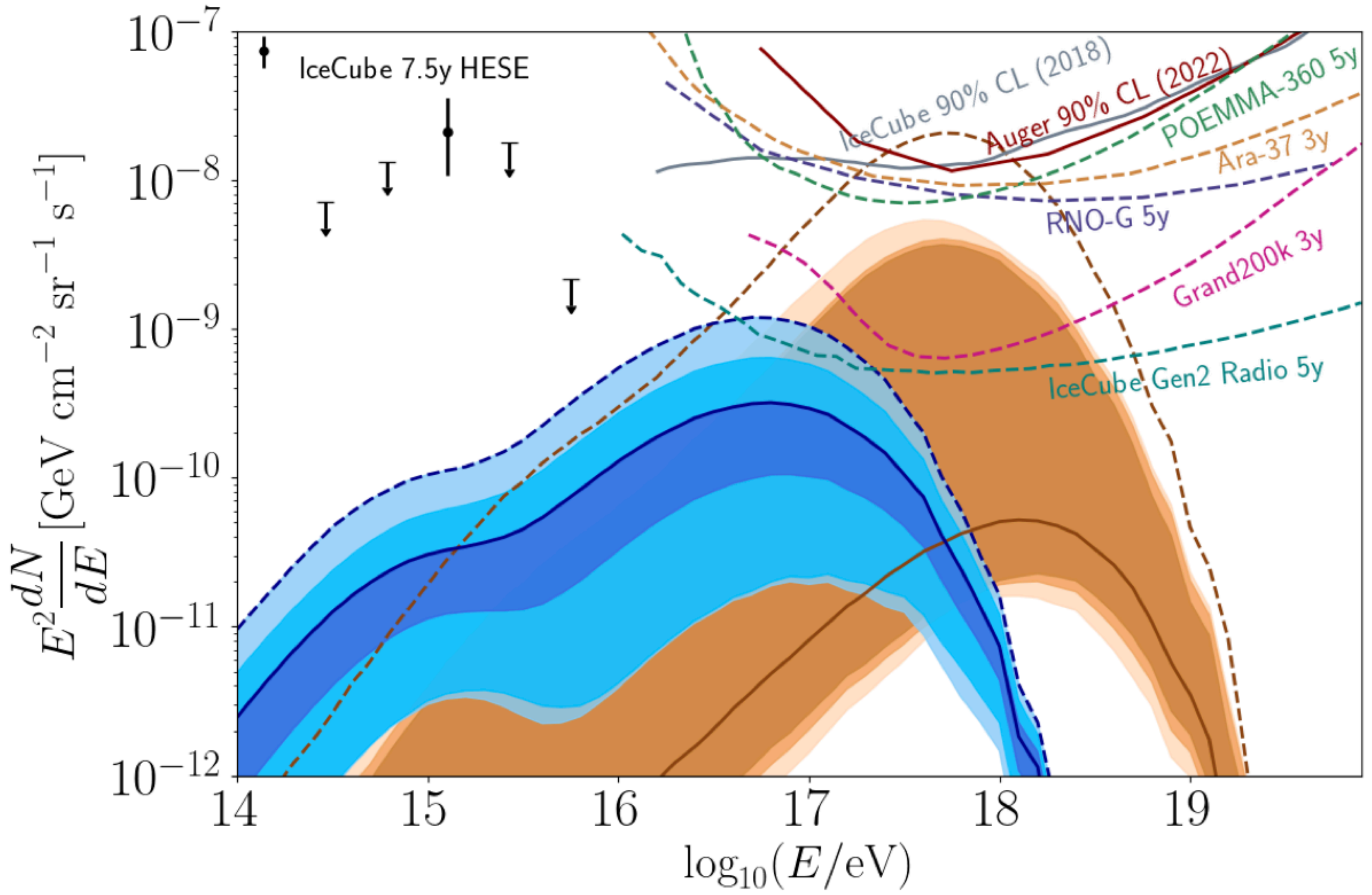
and additional proton component







- Brown contours -> from the UHECR fit
- Blue contours -> from the UHECR fit + penalty from multimessenger



Ehlert et al. JCAP 2024

State-of-the-art: astrophysical scenarios for UHECRs
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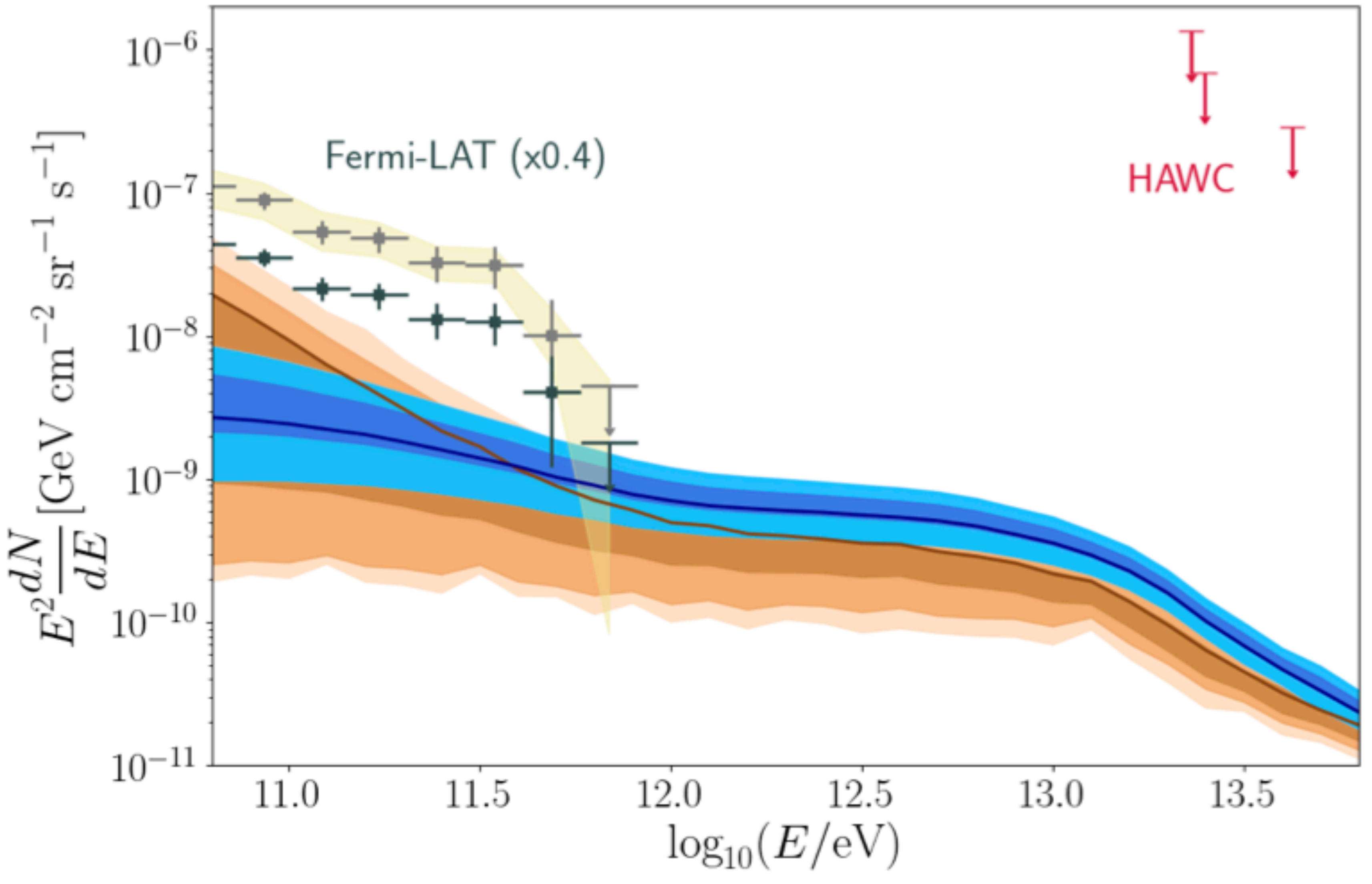
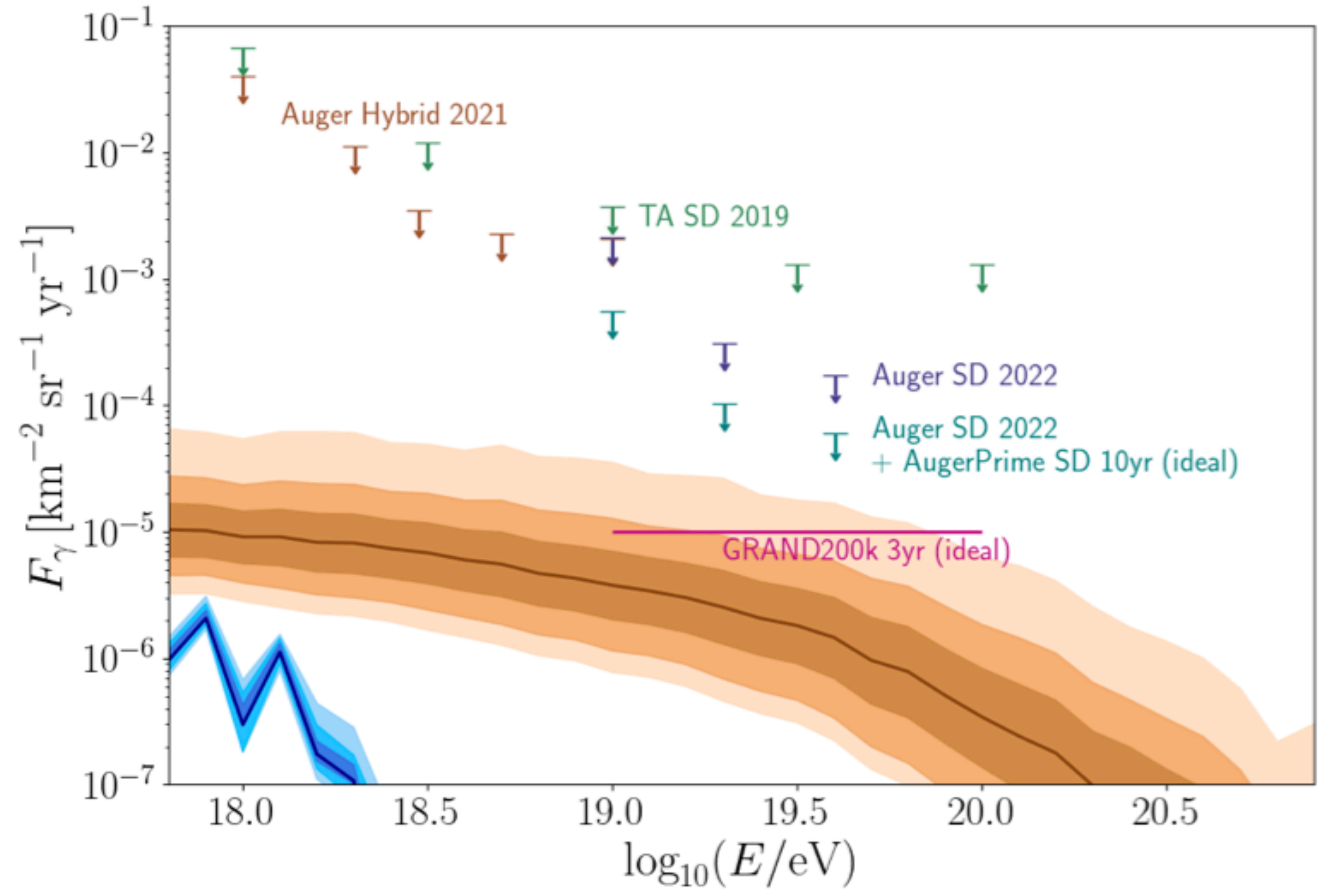
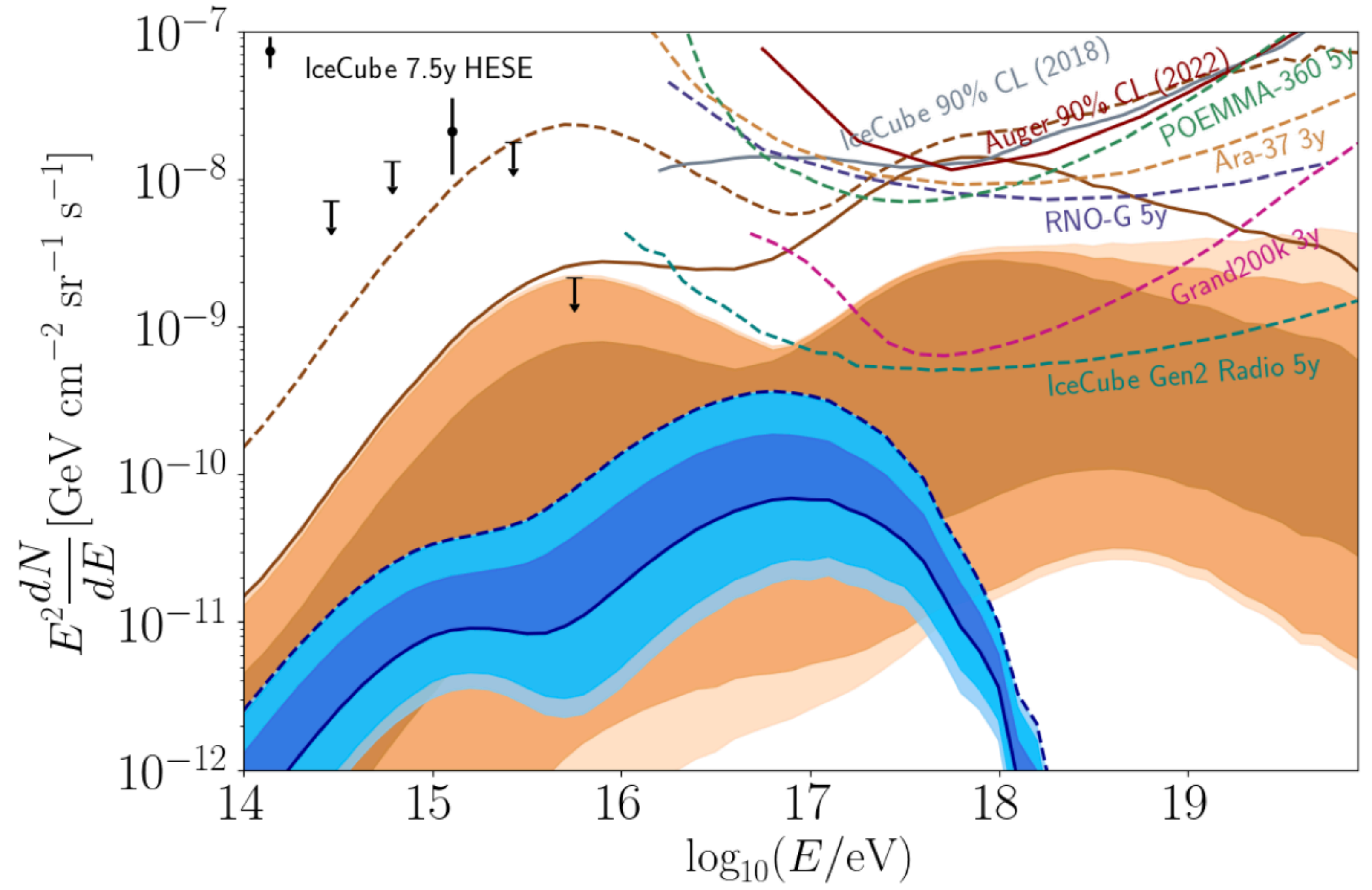




- Predicted cosmogenic gamma-ray signal for the in the GeV–TeV (left) and EeV (right) energy range



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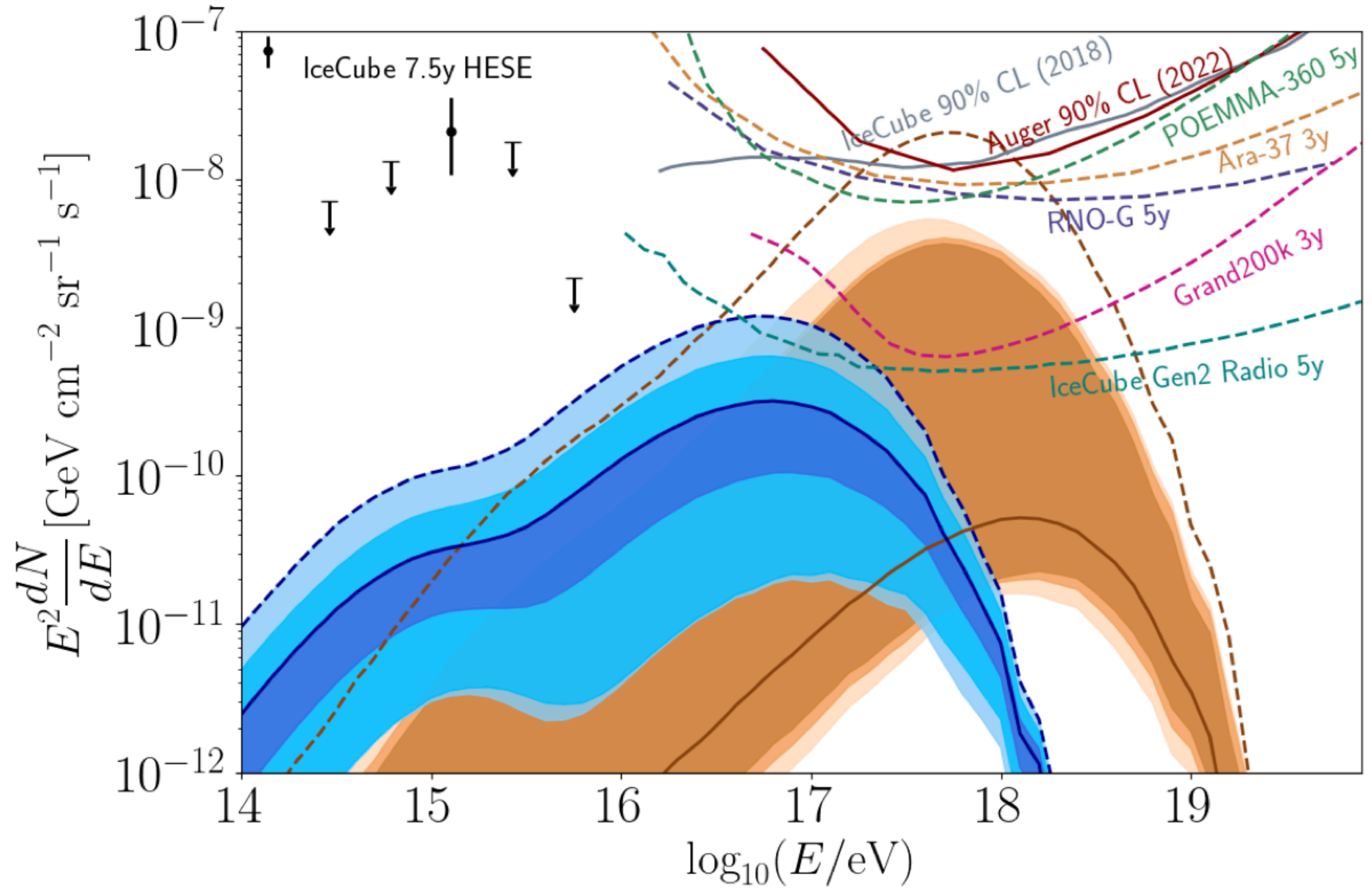


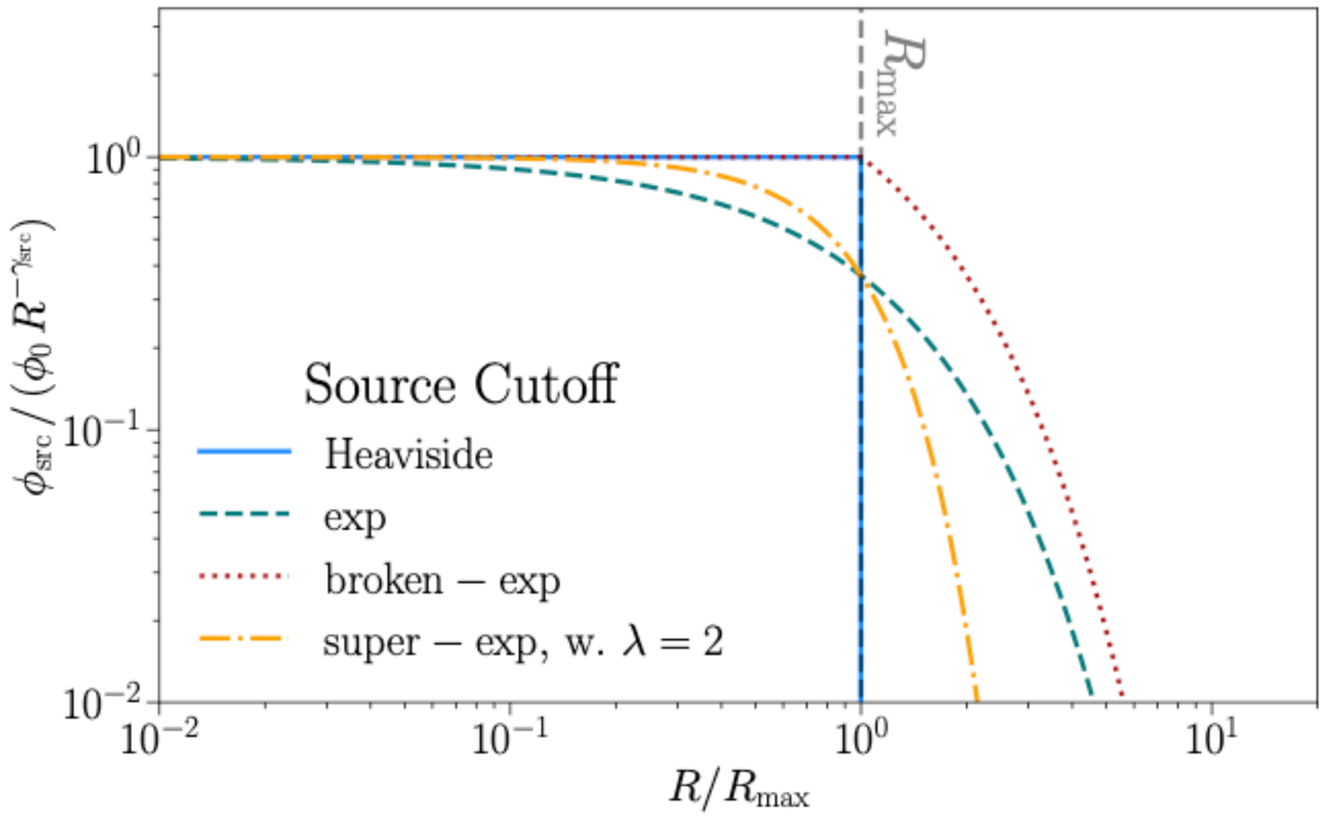
Ehlert et al. JCAP 2024

Some insights in UHECR models

- Relax the assumption of identical maximum energy at the sources
  - Because of different candidate sources of UHECRs: maximum rigidity can be connected to **Lorentz factor of relativistic jets**, to the observed **source luminosity**, etc…

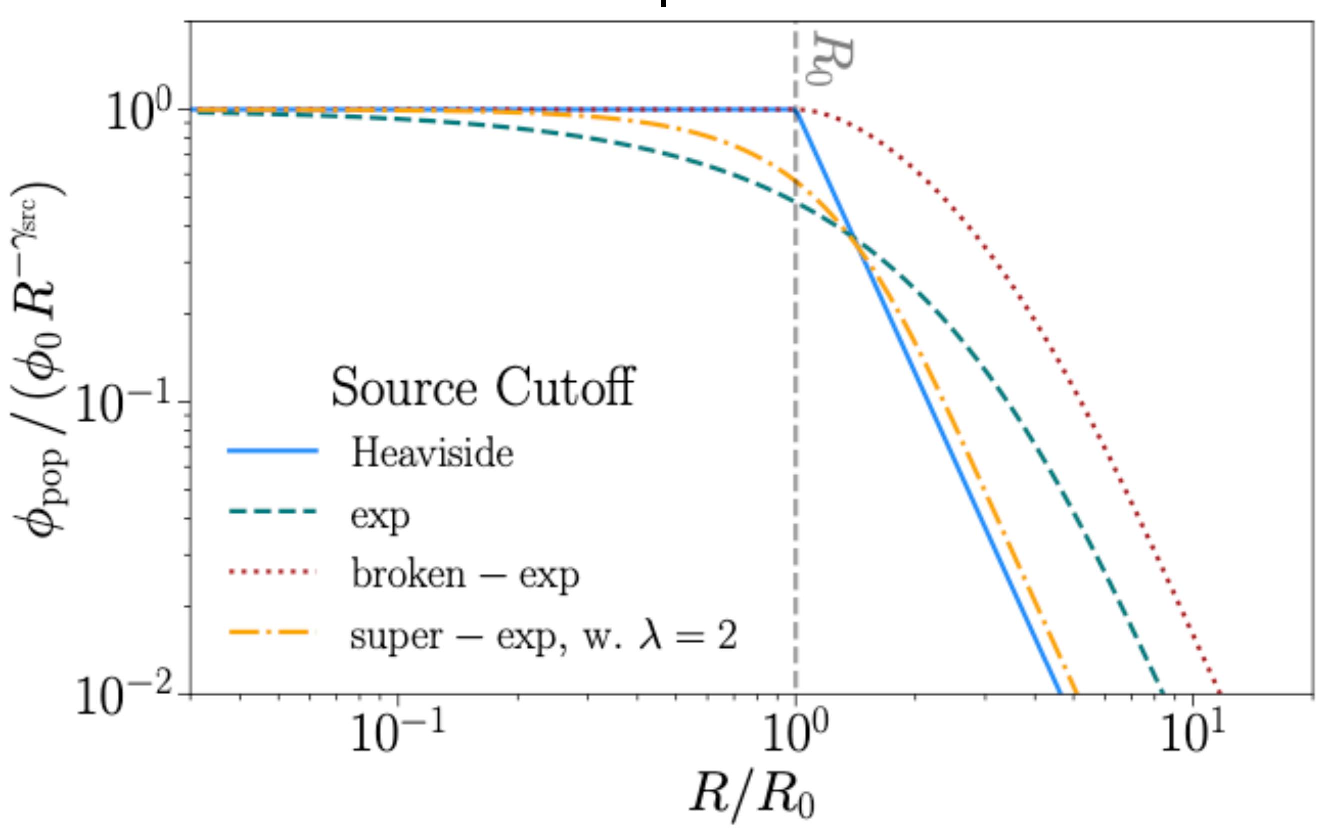
Ehlert+ PRD 2023; Mollerach & Roulet PRD 2020; Kachelriess & Semikoz PLB 2006

Source



$$\frac{dN}{dR} \propto R^{-\gamma_{src}}$$

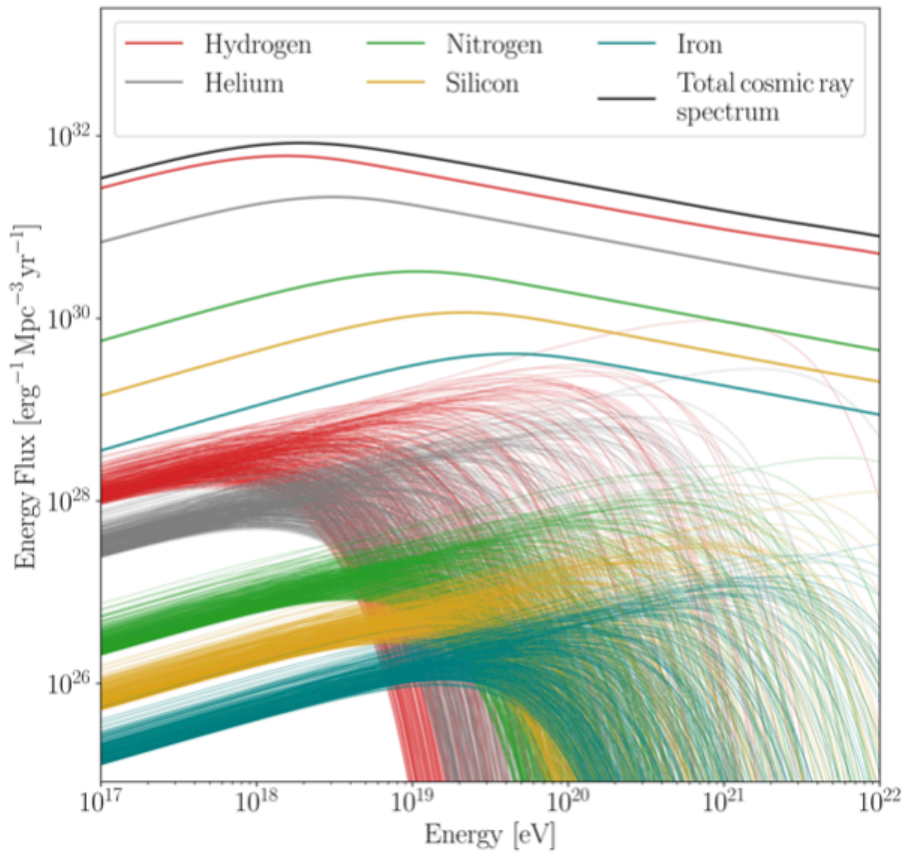
Population



$$\frac{dN}{dR_{max}} \propto R_{max}^{-\beta_{pop}}$$

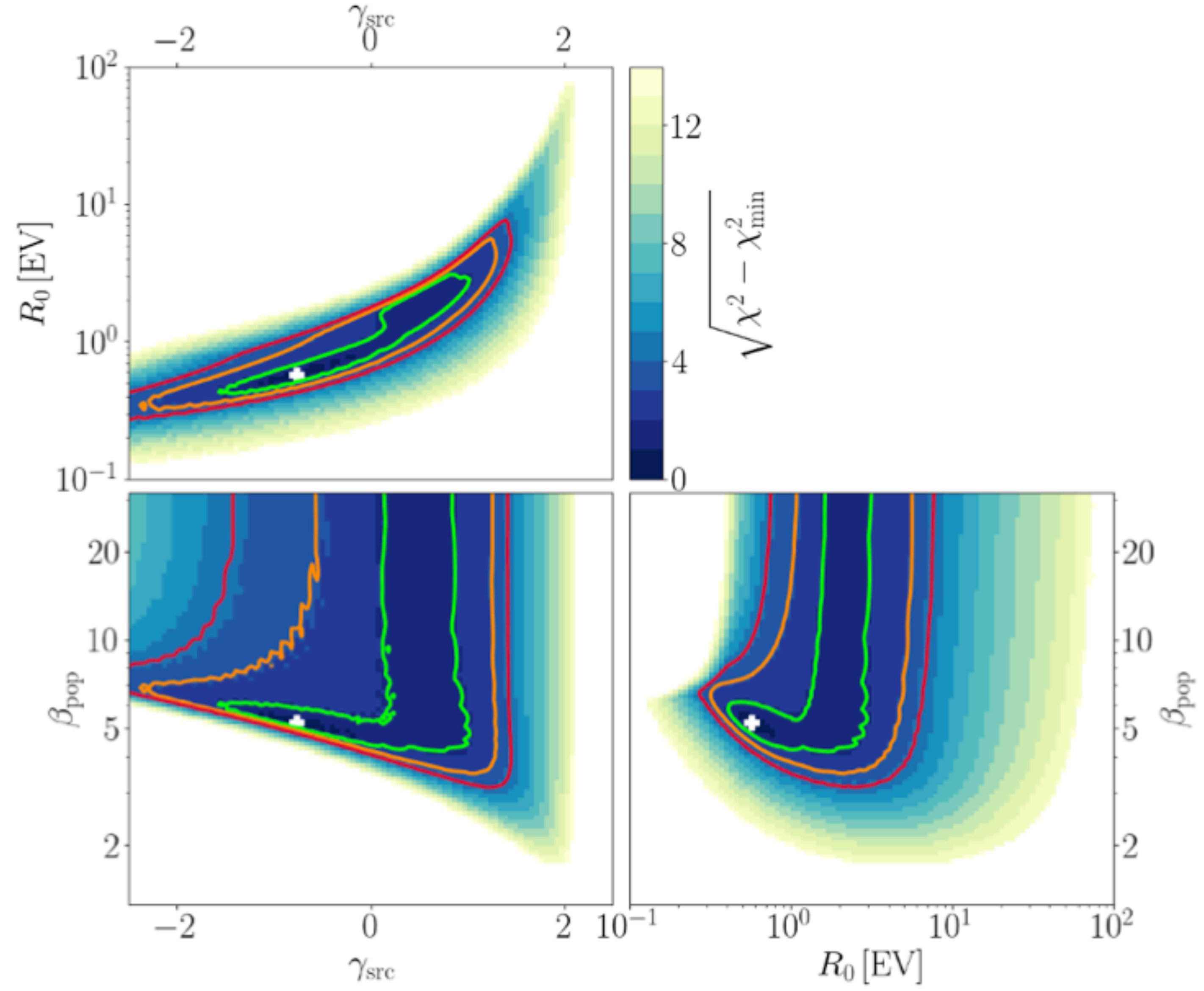
$$\phi_{pop} \propto R^{-\gamma_{src}} \text{ if } R < R_0$$

$$\phi_{pop} \propto R^{-\gamma_{src}-\beta_{pop}+1} \text{ if } R > R_0$$

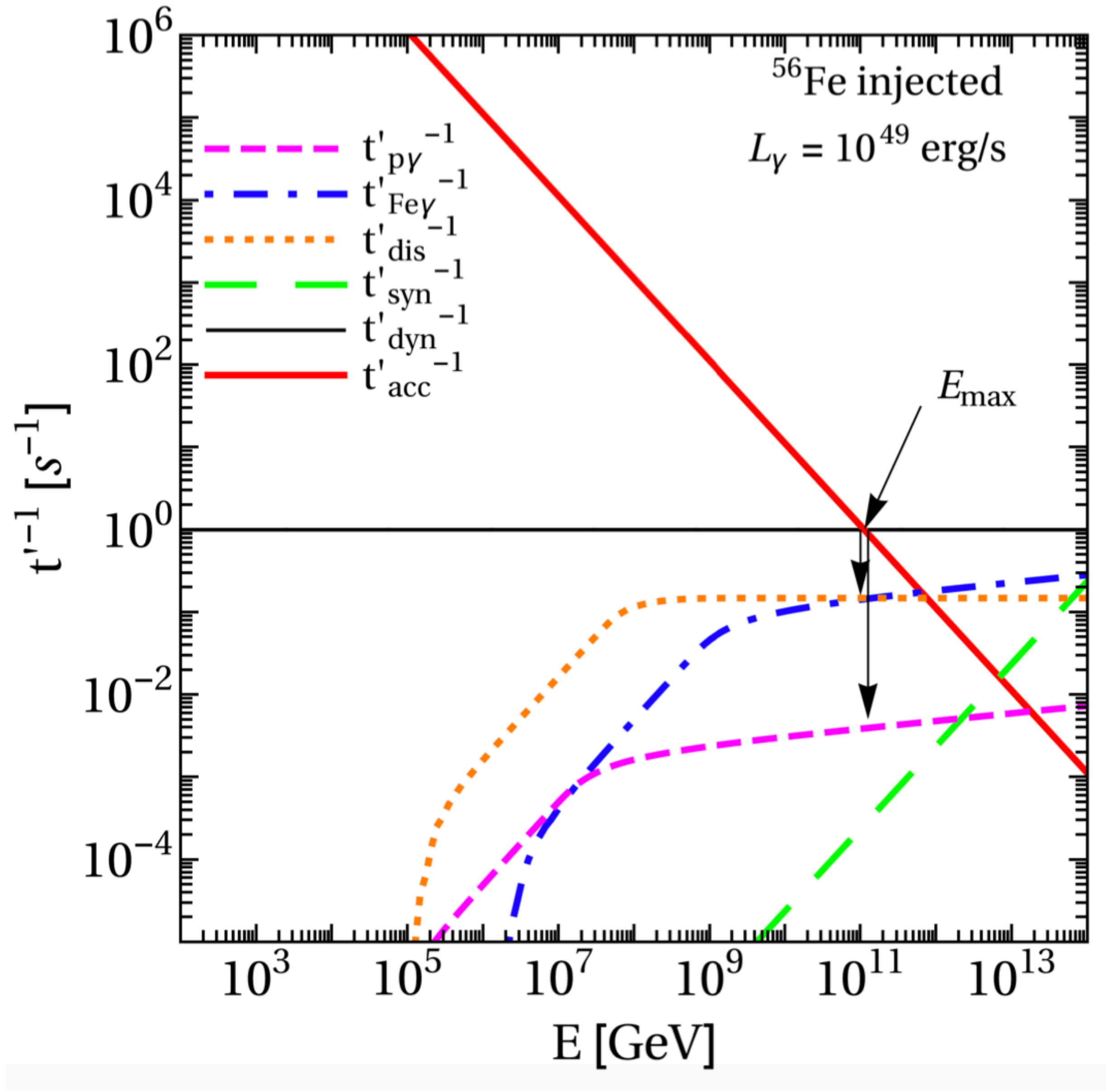


Plot from talk by F. Oikonomou @ICRC23

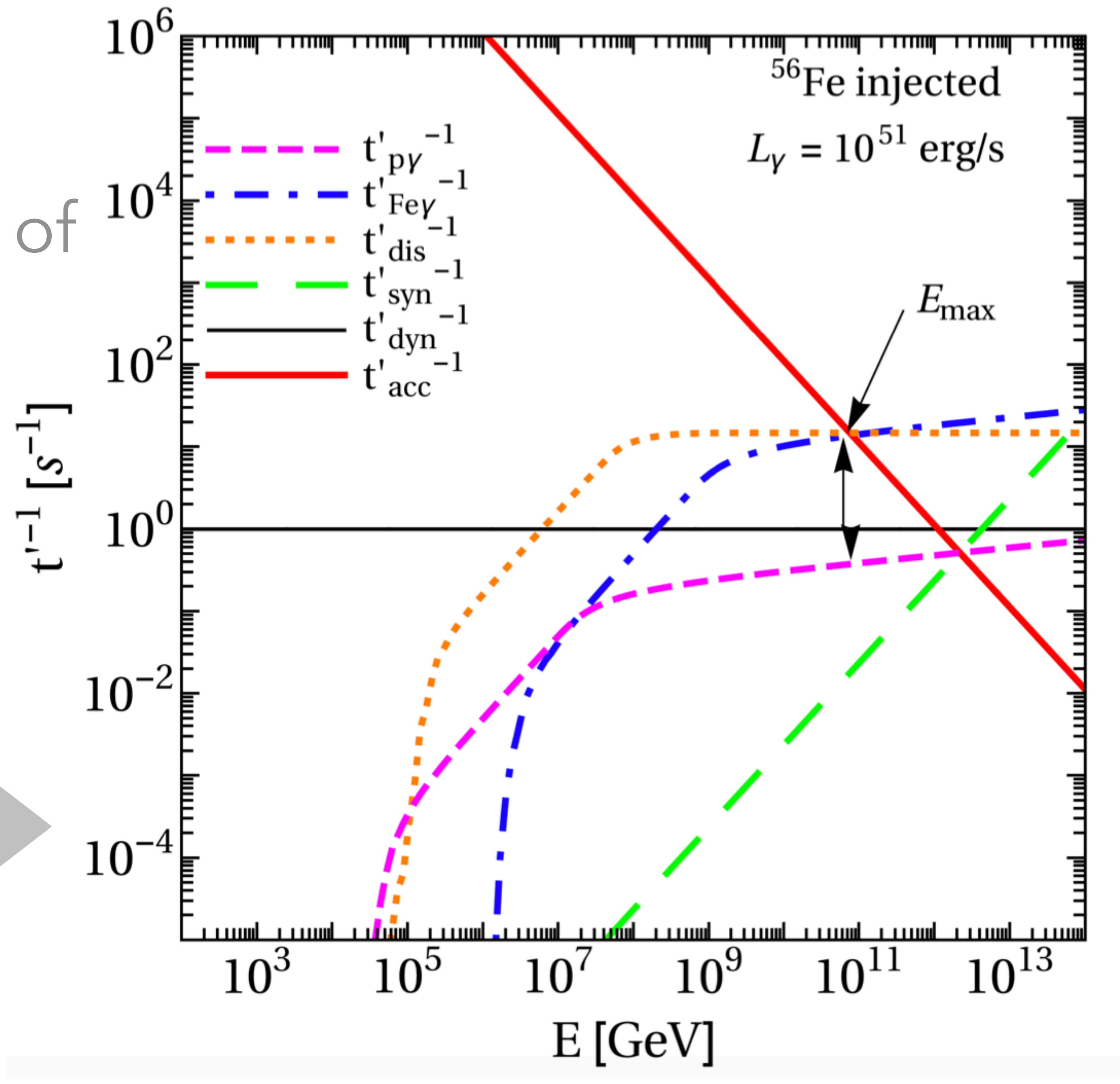
- To minimize the superposition of nuclear species, the population spectrum must be steep after the cutoff
- Combined with the finding on the source spectrum, **data favour the hypothesis of identical sources**
- Examples rated already (for GRB variability) in Globus et al MNRAS 2015; Heinze, Biehl, Fedynitch, DB, Rudolph & Winter MNRAS 2020

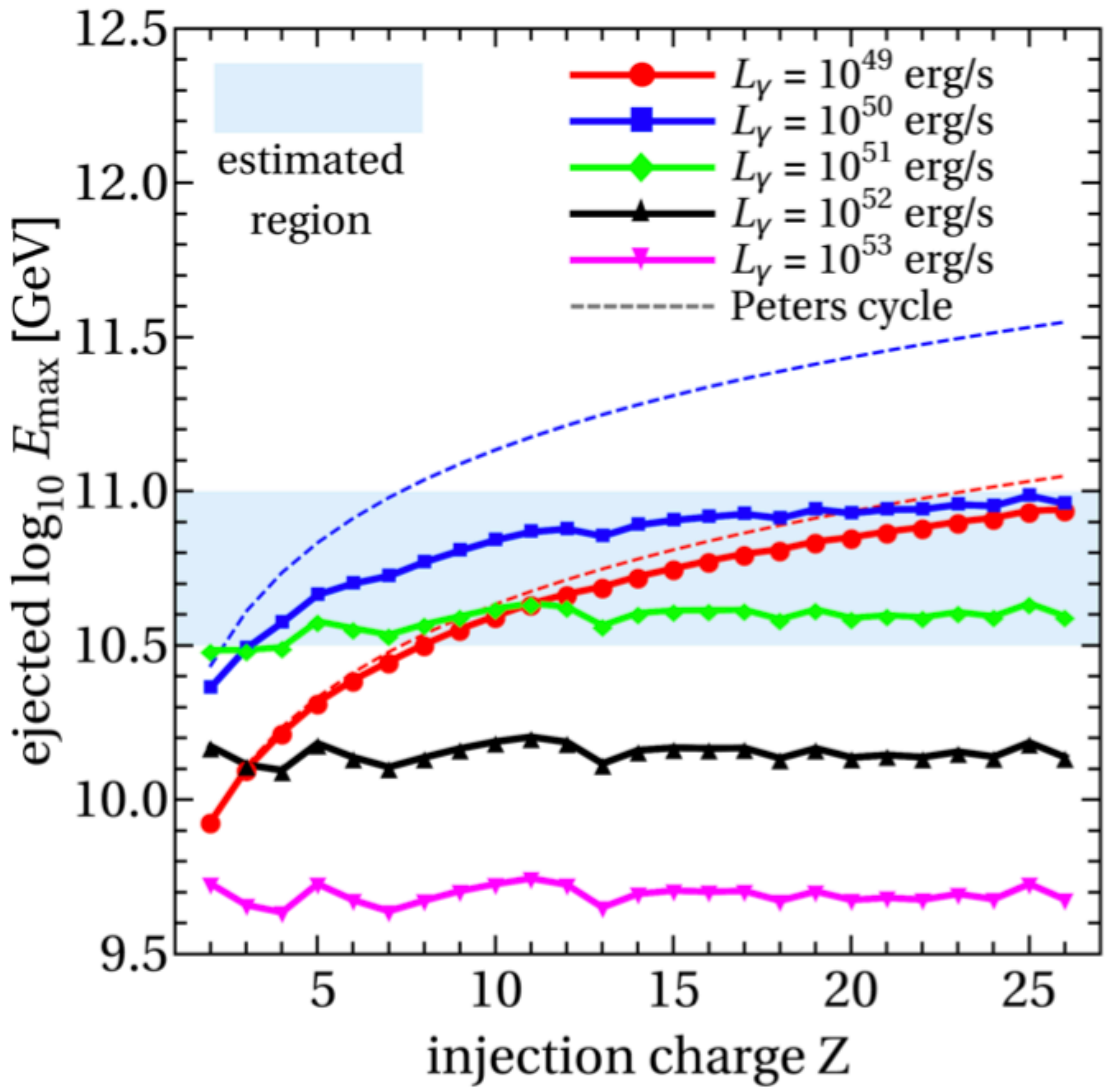


Some insights in UHECR models



Increase of photon density





- Example from study of UHECR nuclei interactions in GRB internal shock model
  - Maximum energy defined by acceleration -> rigidity dependence
  - Maximum energy defined by interactions -> Lorentz-factor dependence

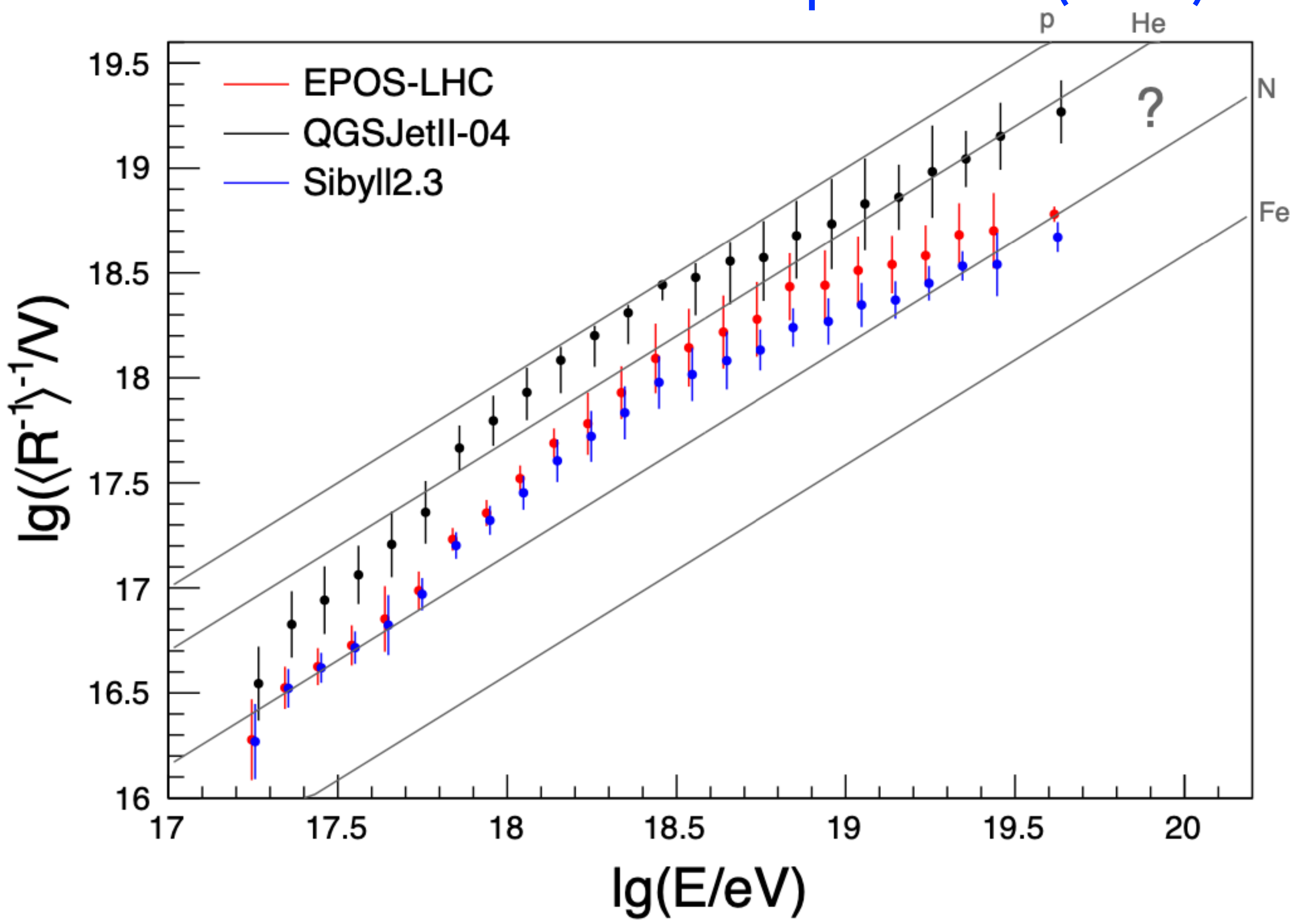
Biehl, DB, Fedynitch & Winter, Astron.Astrophys. 611 (2018)

- EeV neutrinos might be linked to scenarios excluding the Peters cycle (UHECR protons up to the highest energies), see Muzio, Anchordoqui & Unger Phys.Rev.D 109 (2024)

Some insights in UHECR models

- Which information is the (narrow) rigidity at the highest energies telling us?

Alves Batista+ Front.Astron.Space Sci. 6 (2019)

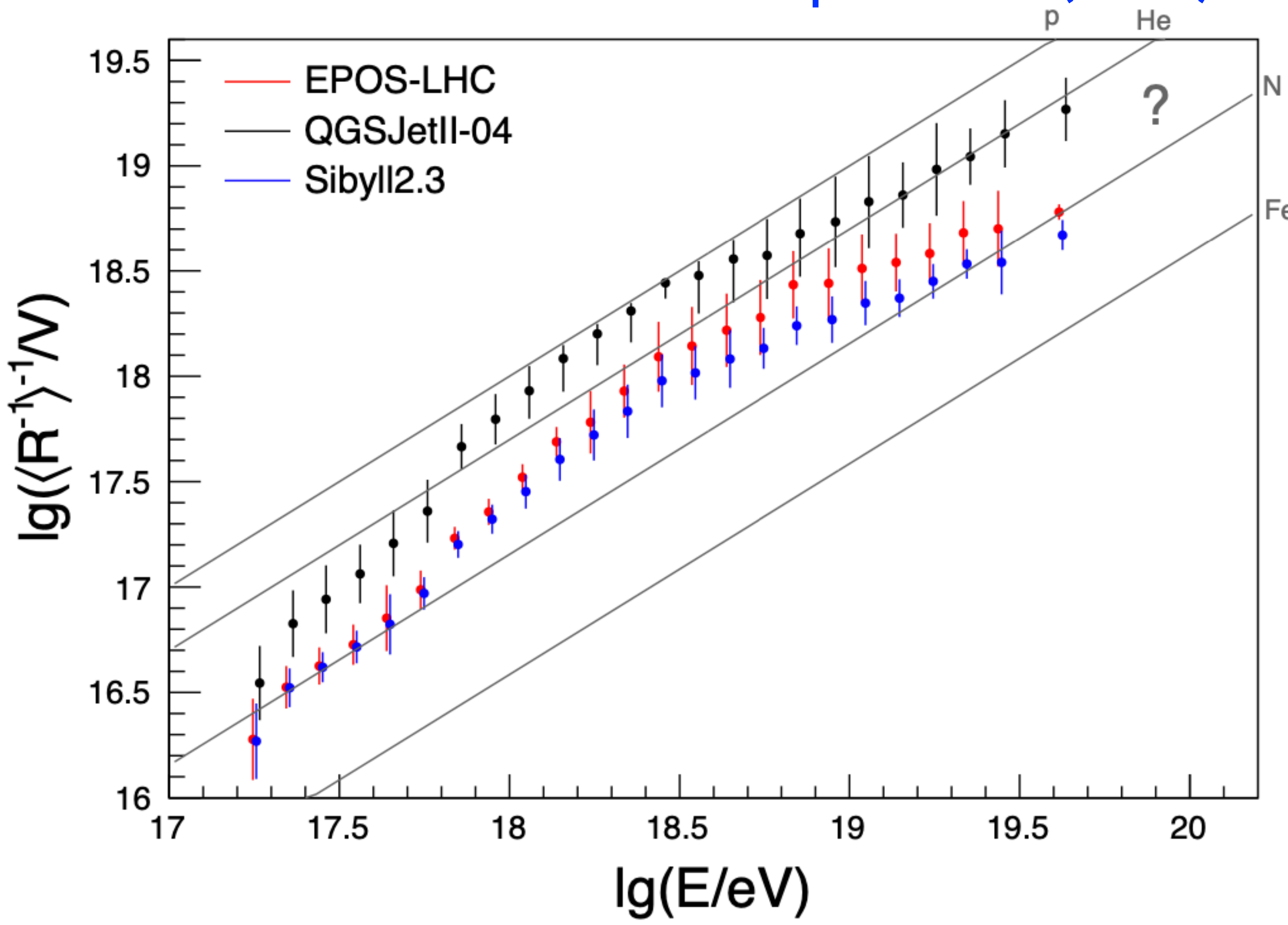


- A narrow range of rigidities -> UHECRs produced in jets from binary neutron star mergers (BNS masses constitute a very narrow range of total mass of binary neutron stars + the post-merger magnetic fields are produced by a dynamo whose energy source is gravitational), see Farrar Phys.Rev.Lett. 134 (2025), Astrophys.J.Lett. 994 (2025)
- Ultra-heavy nuclei could be produced because of r-processes, see Zhang+ Phys.Rev.Lett. 136 (2026); Esmaeili+ arXiv:2606.23812

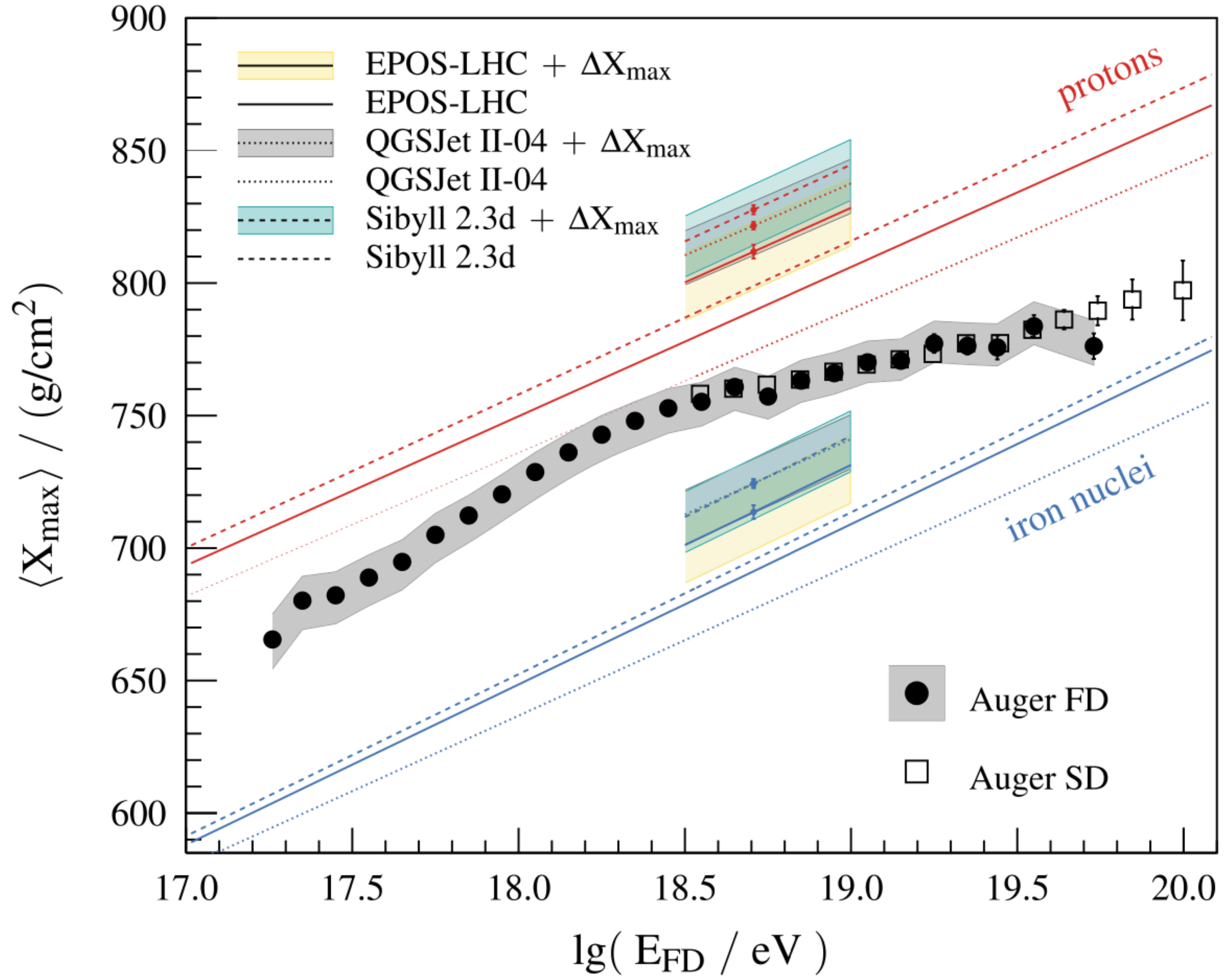
Some insights in UHECR models

- Which information is the (narrow) rigidity at the highest energies telling us?
- How heavy are the nuclear species contributing at the highest energies?

Alves Batista+ Front.Astron.Space Sci. 6 (2019)



The Auger Collab. PRD 109 (2024)



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- A fit of depth of maximum of air-shower profiles and ground-particle signals in WCDs at 1000 m from the shower shows that the best description of data is achieved when the hadronic interaction models are shifted to deeper Xmax values and larger hadronic signals at all zenith angles

Some insights in UHECR models

- Other (astro) results not discussed in this talk:
  - Arrival directions
  - Galactic and extragalactic magnetic fields
  - Transient vs persistent nature of UHECR sources
  - Acceleration

-> see discussion on Monday (M. Unger) and Auger talk by L. Perrone

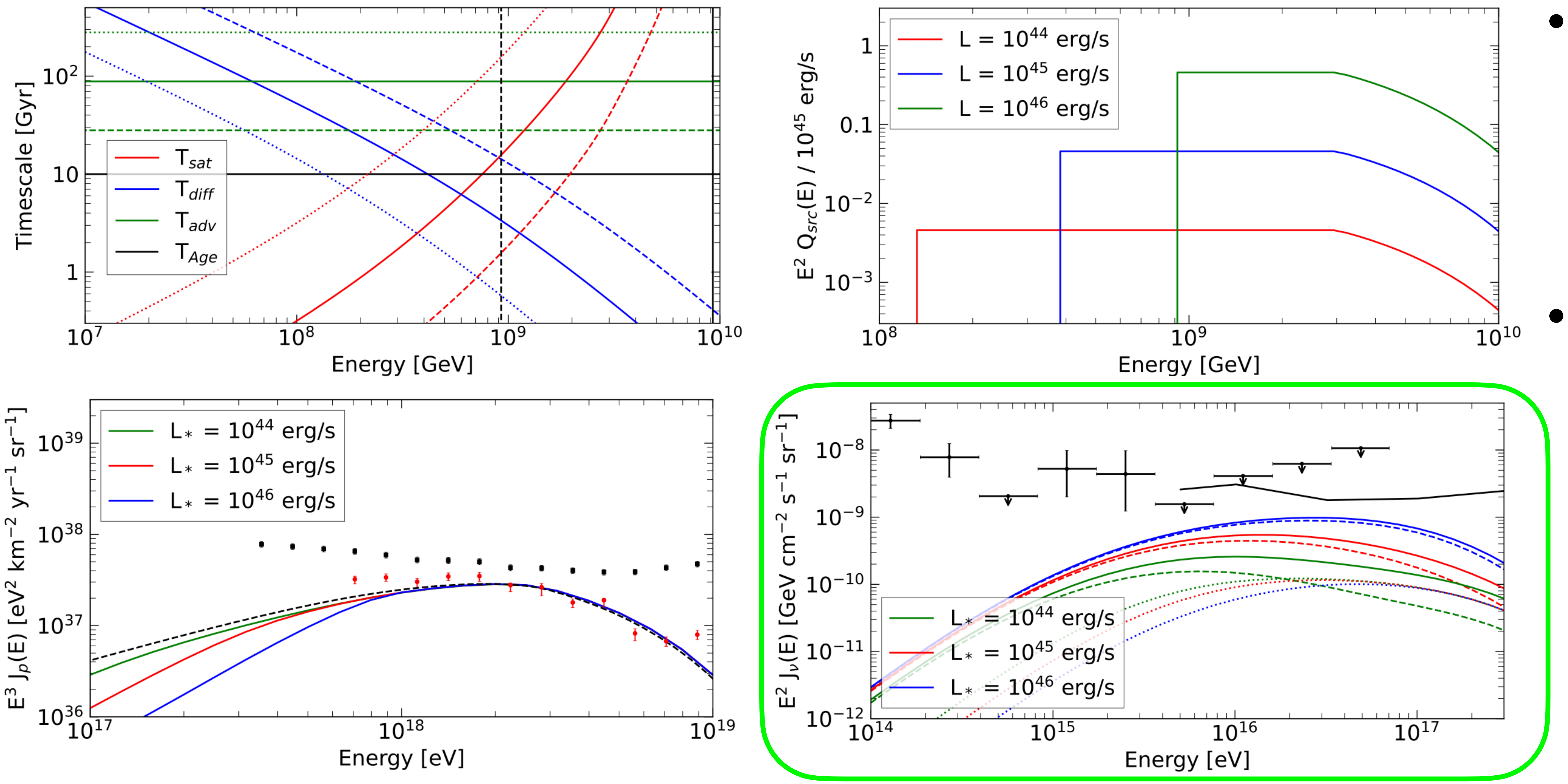
-> Tuesday talk by M. Lemoine

-> today's talks by L.Comisso, G. Farrar, F. Oikonomou, T. Bister

Some insights in UHECR models

- UHECR data require very hard spectral index at the escape from sources. It could be motivated by
  - Propagation in **extragalactic magnetic fields**, see The Auger Collab. JCAP 07 (2024)
  - Interplay of in-source interactions and confinement, see Unger, Farrar & Anchordoqui, Phys.Rev.D 92 (2015)
    - Example for confinement: scattering of UHECRs on self-generated magnetic perturbations near sources in **galaxy clusters** (CRs may be accelerated either by shocks in the intracluster medium or by individual galaxies)

Cermenati, Aloisio, Blasi & Evoli, Astron.Astrophys. 707 (2026) A19



- The larger the luminosity,
  - the harder the proton spectrum at Earth
  - the larger the neutrino flux from the cluster environment -> it adds on top of the customary cosmogenic contribution
- See Cermenati, Aloisio & Evoli arXiv:2605:14869 for the corresponding analysis on UHECR nuclei

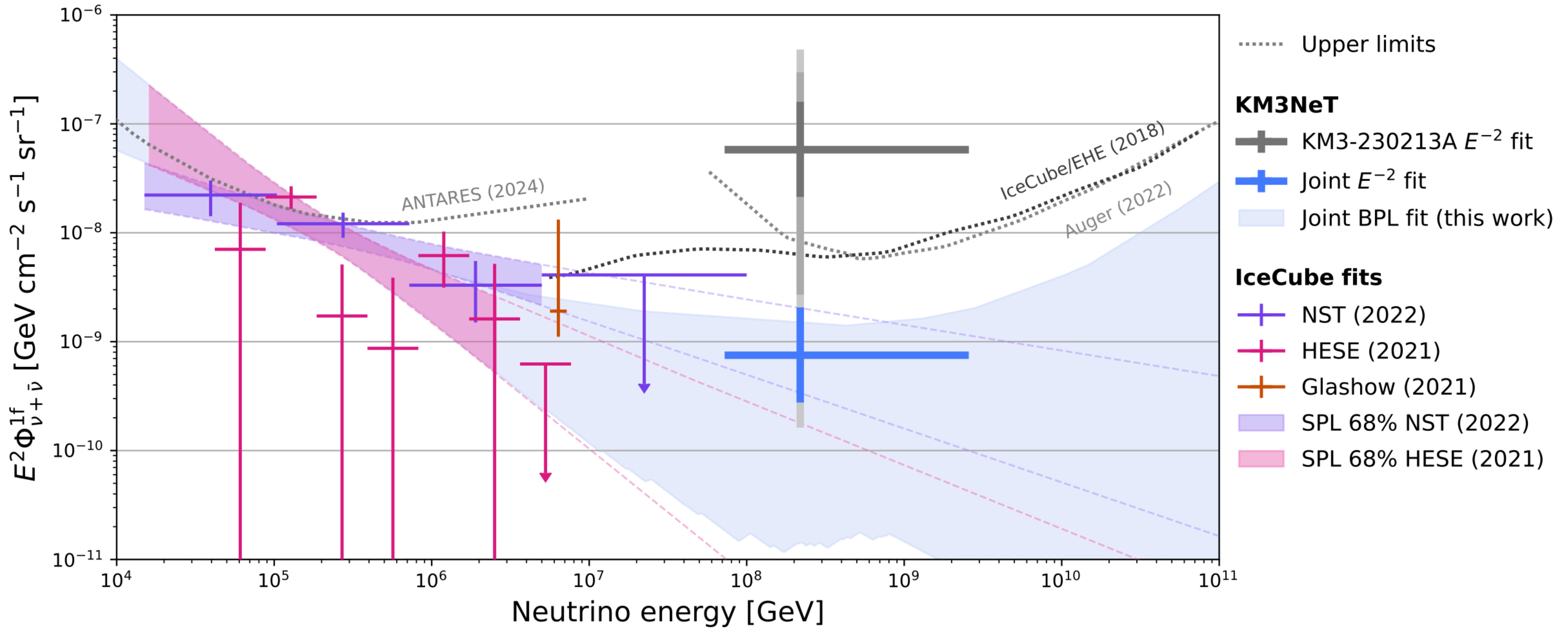
Enhancement in "cosmogenic" neutrinos

A complete multimessenger view with constraints from UHE neutrino events

Example: which UHECR population could be responsible of the KM3-230213A event?

Km3Net, PRX 2025

- Km3Net reported the measurement of a neutrino of E≈220 PeV, Km3Net Nature 2025
- The corresponding energy of a parent proton is about 4.4 EeV (close to the "ankle")



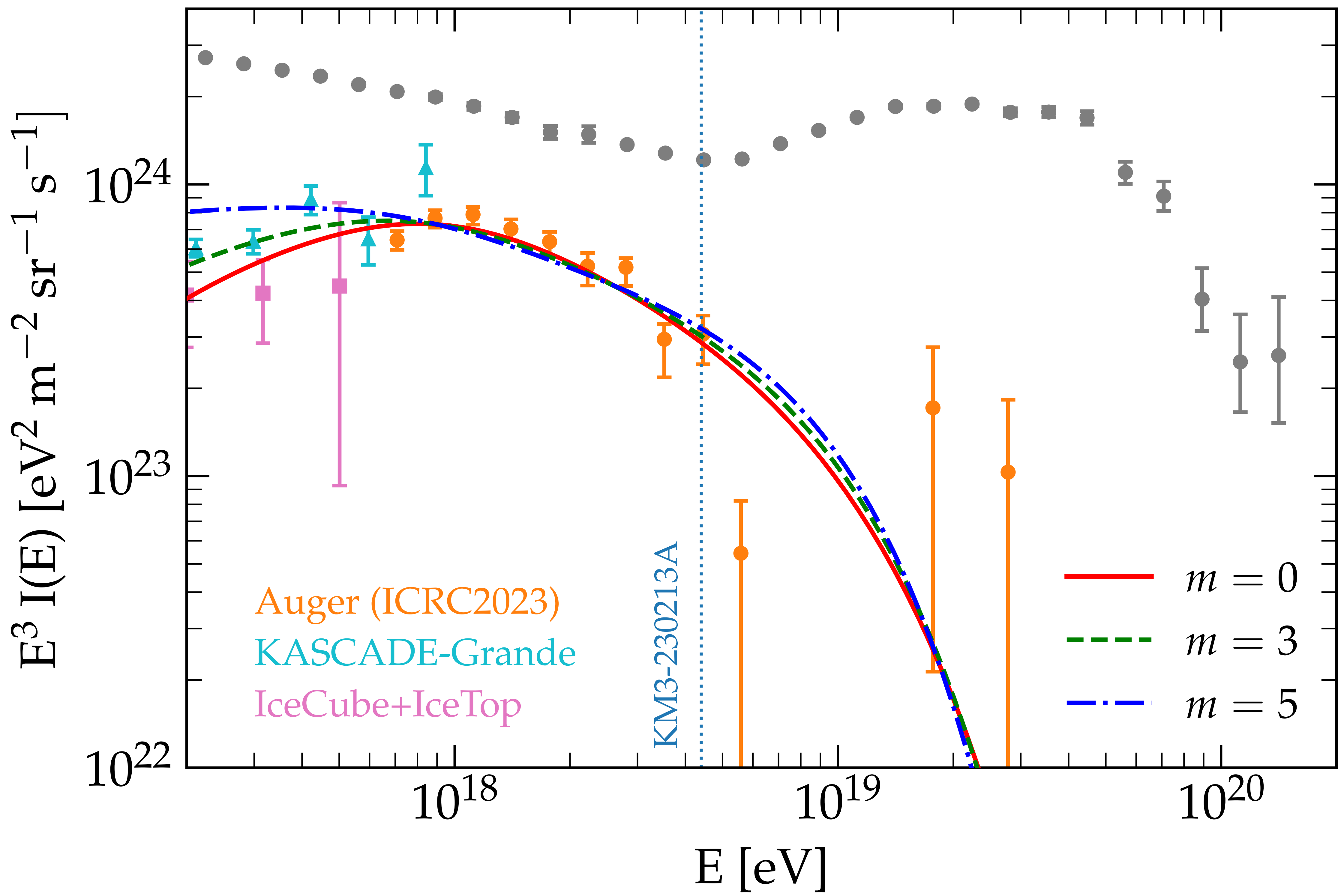
- **Test the hypothesis of cosmogenic origin of the km3Net event and of UHECR characteristics**
  - based on the implications it might have on diffuse gamma rays,
  - considering UHECR protons allowed by measurements or upper limits, with contributions from:
    - a population of sources contributing below the ankle
    - a population of sources contributing above the ankle

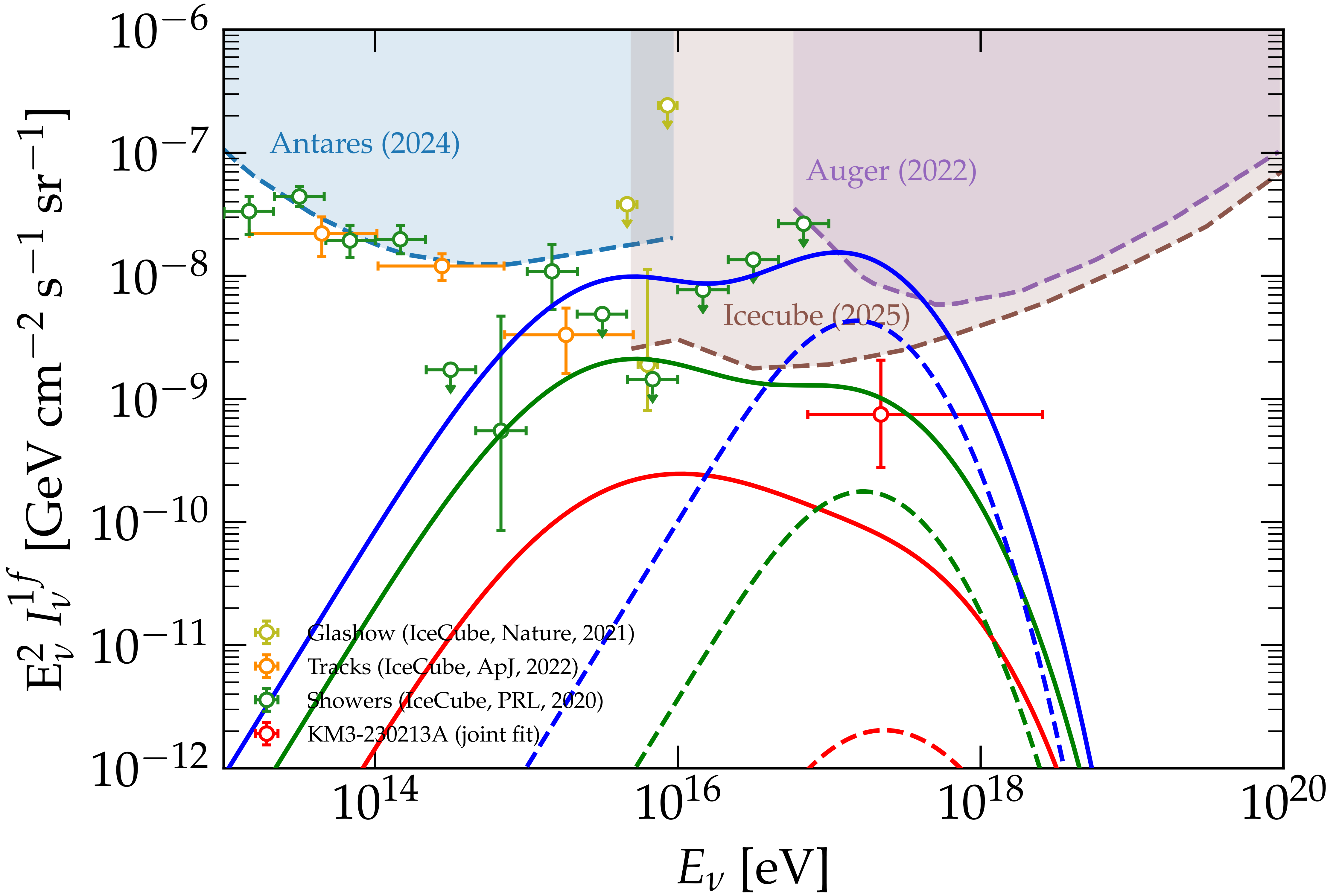
- Similar studies in: Muzio+ PRD 2023; Ehlert+ JCAP 2024; Km3Net ApJL 2025; Kuznetsov+ JETP Lett. 2026, Alhebsi+ ApJ 2026; Allard+ arXiv:2608.16540

UHECR protons below the ankle -> implications on neutrino flux

$Q_p(E,z) \propto (1+z)^m E^{-\gamma} \exp(-E/E_{max})$

Cermenati, Ambrosone, Aloisio, DB & Evoli arXiv:2507.11993

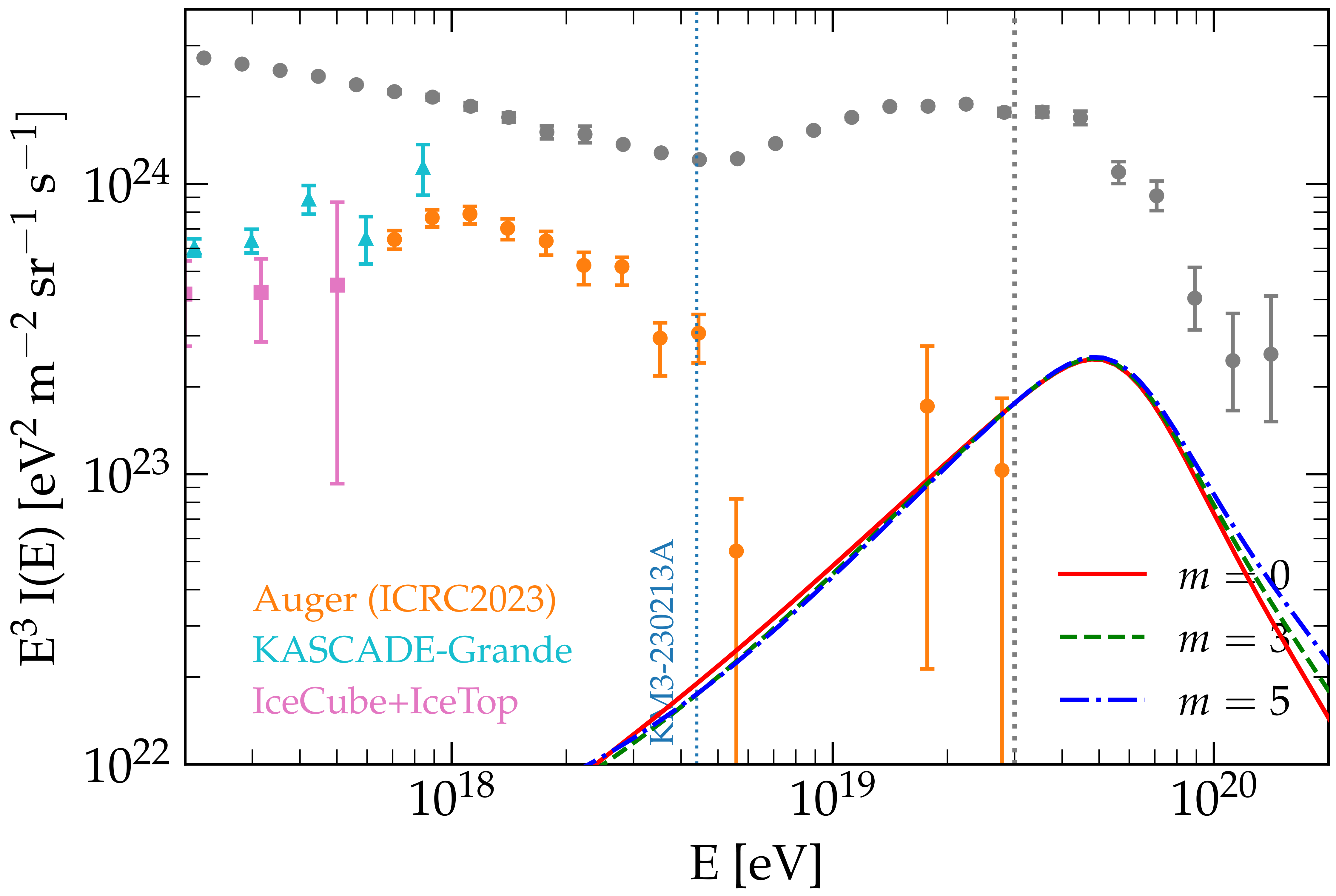




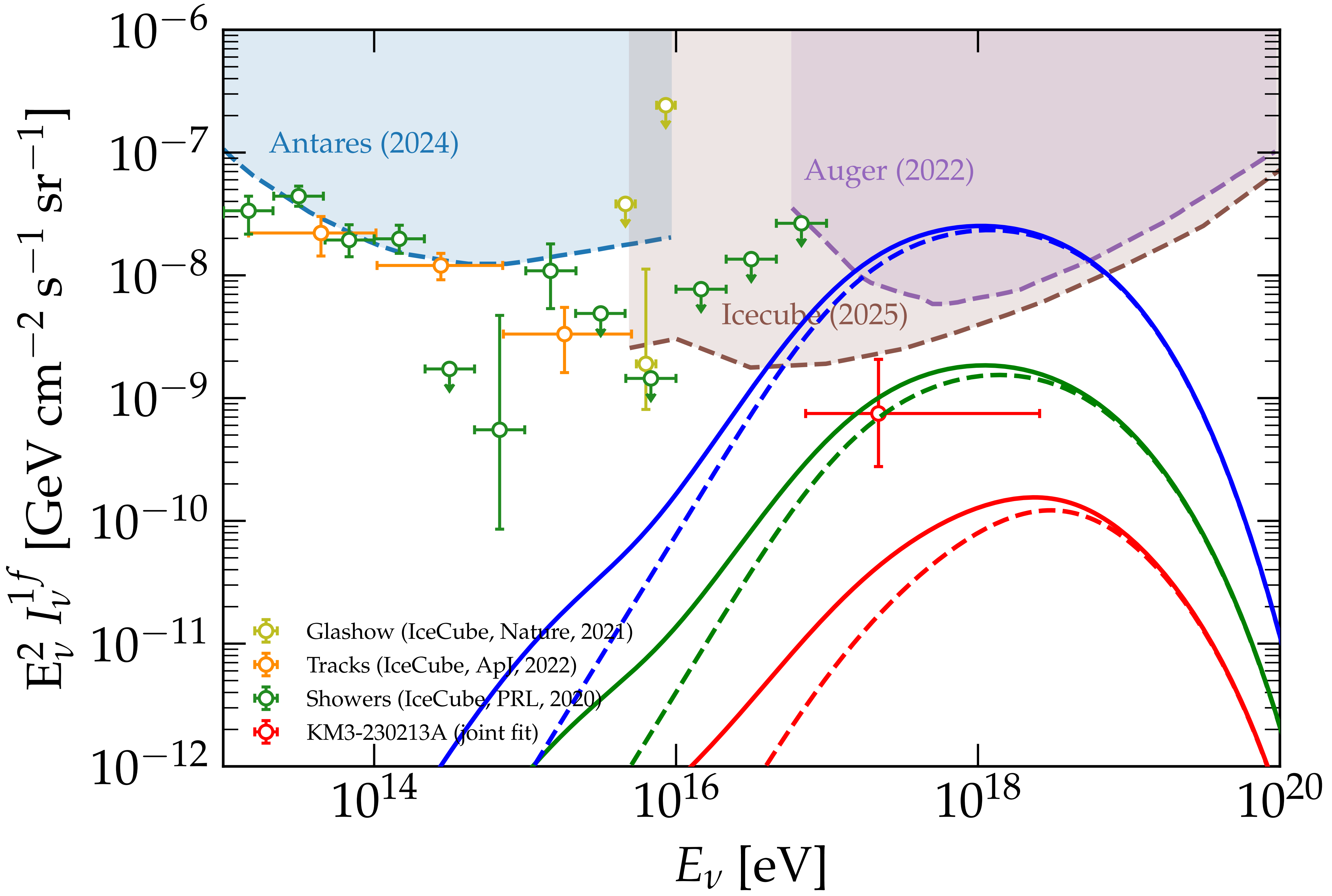
- Source emissivity of LE population normalised to match the proton spectrum obtained from the proton fraction (as from Auger ICRC 2023, multiplied by the all-particle spectrum from Auger ICRC 2023)
- Various combinations of source parameters (spectral index, maximum energy, source evolution) are used (results being in agreement with what found for instance in Heinze, DB, Bustamante & Winter ApJ 2016)
- Because of the softness of the spectral index and the limited maximum energy of the proton population, the neutrino flux is mostly due to proton interactions off EBL
- Source evolution m=3 of the LE population can account for the Km3Net neutrino flux

UHECR protons above the ankle -> implications on neutrino flux

$Q_p(E,z) \propto (1+z)^m E^{-\gamma} \exp(-E/E_{max})$



Cermenati, Ambrosone, Aloisio, DB & Evoli arXiv:2507.11993



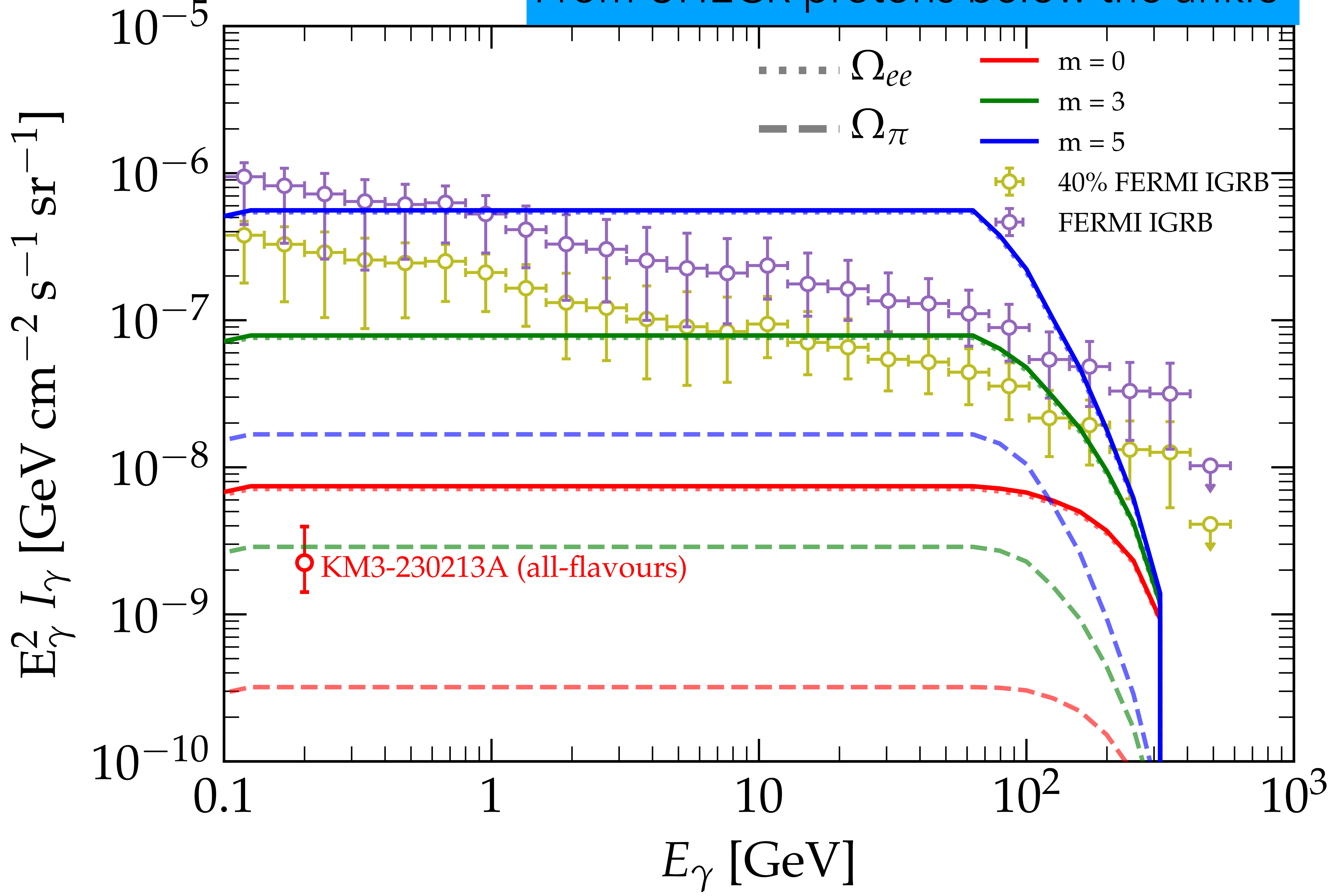
- Source emissivity of HE population normalised to match 10% of the all-particle spectrum at approximately 3×10^{19} eV

- Because of the hardness of the spectral index and the larger maximum energy of the proton population, the neutrino flux is mostly due to proton interactions off CMB
- Source evolution m=3 of the LE population can account for the Km3Net neutrino flux

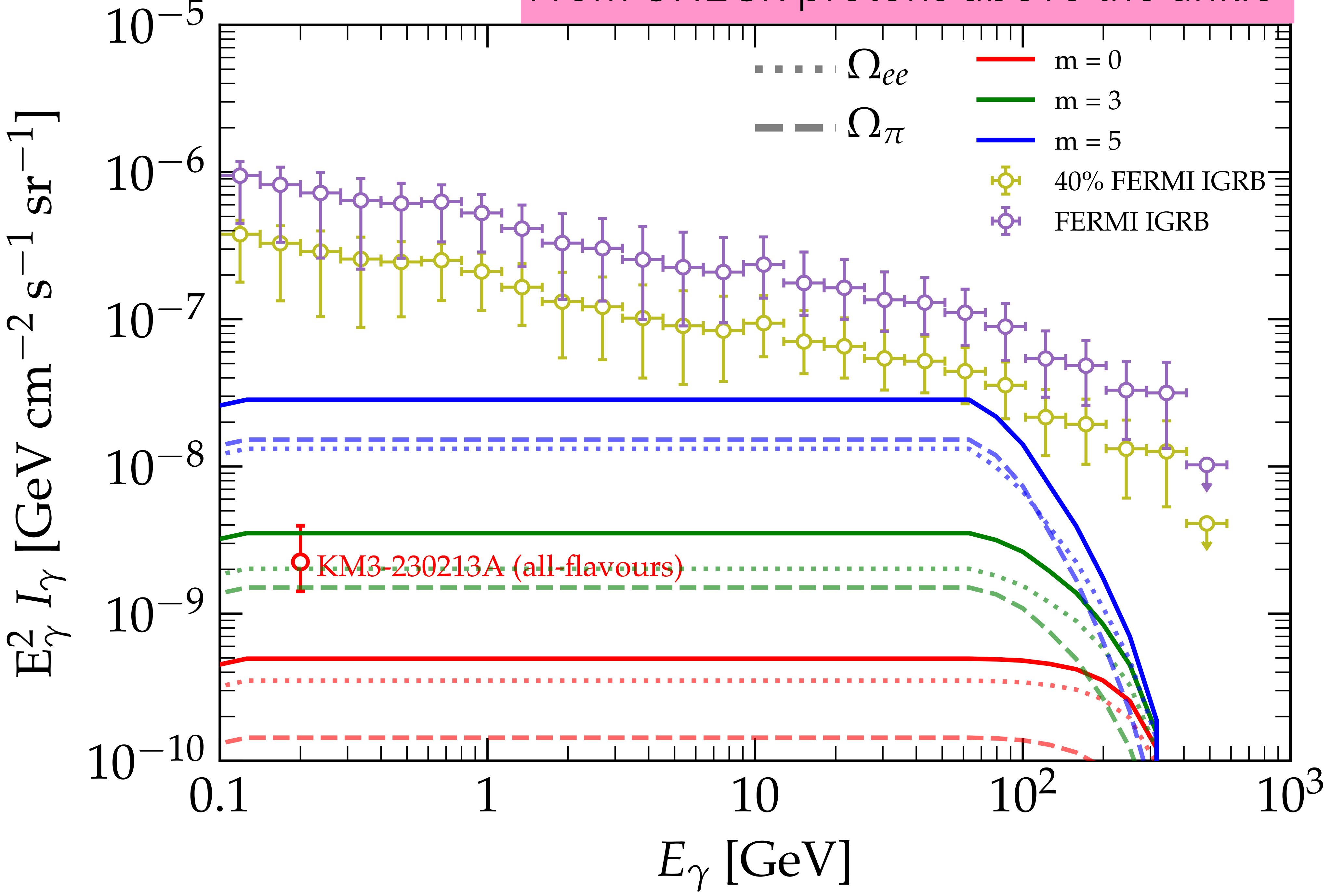
Diffuse gamma rays

Cermenati, Ambrosone, Aloisio, DB & Evoli arXiv:2507.11993

From UHECR protons below the ankle



From UHECR protons above the ankle



- Separate contributions of photo-pion and pair production processes are shown, obtained as in Berezinsky & Kalashev PRD 2016

- The contribution from pair production is dominant, due to the softness of the spectral index of the LE proton population
- Strong source evolutions are disfavoured by Fermi data

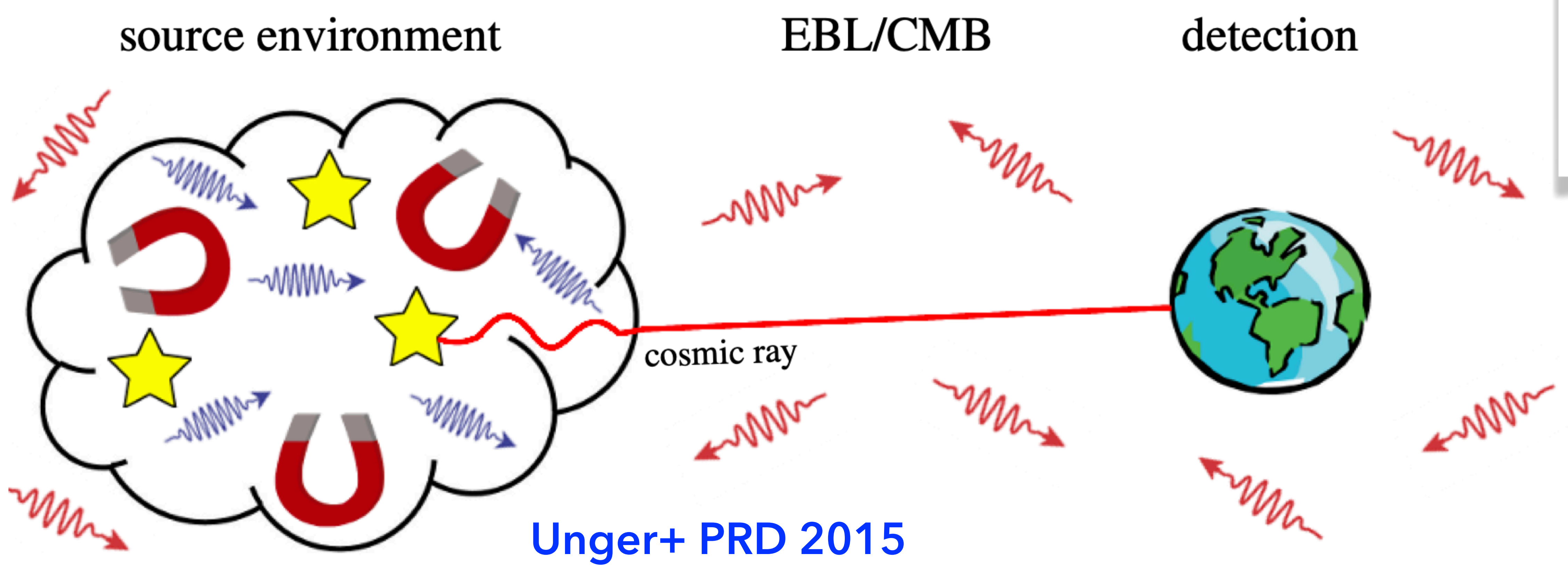
- The variations among different contributions are smaller, due to the hardness of the spectral index of the HE proton population
- Even strong source evolution is allowed

Diffuse gamma rays break the degeneracy of the LE vs HE population

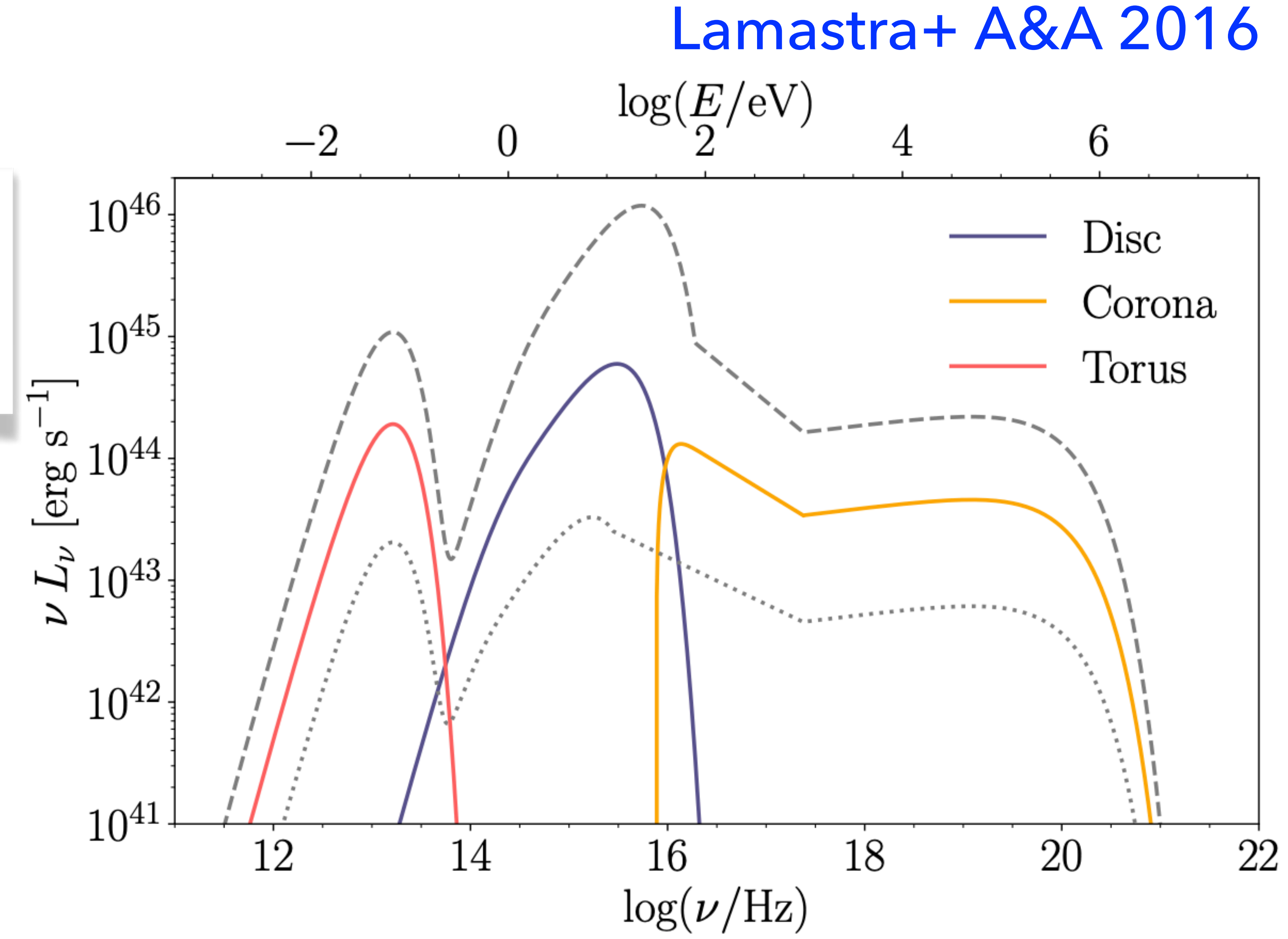
A complete picture for neutrinos…

and the association to UHECR protons

A complete picture for neutrinos (1)



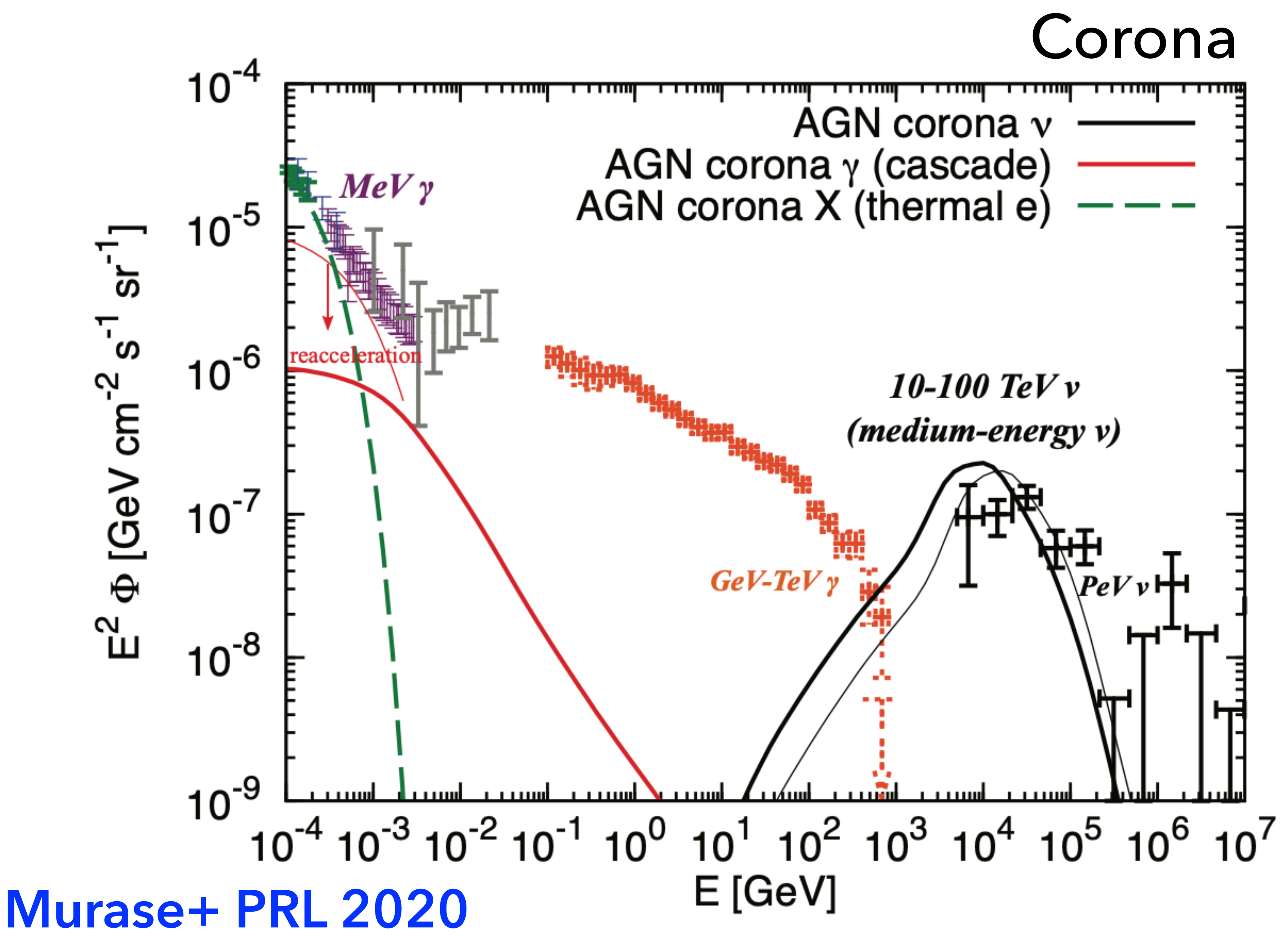
Example for **source neutrinos** from AGN

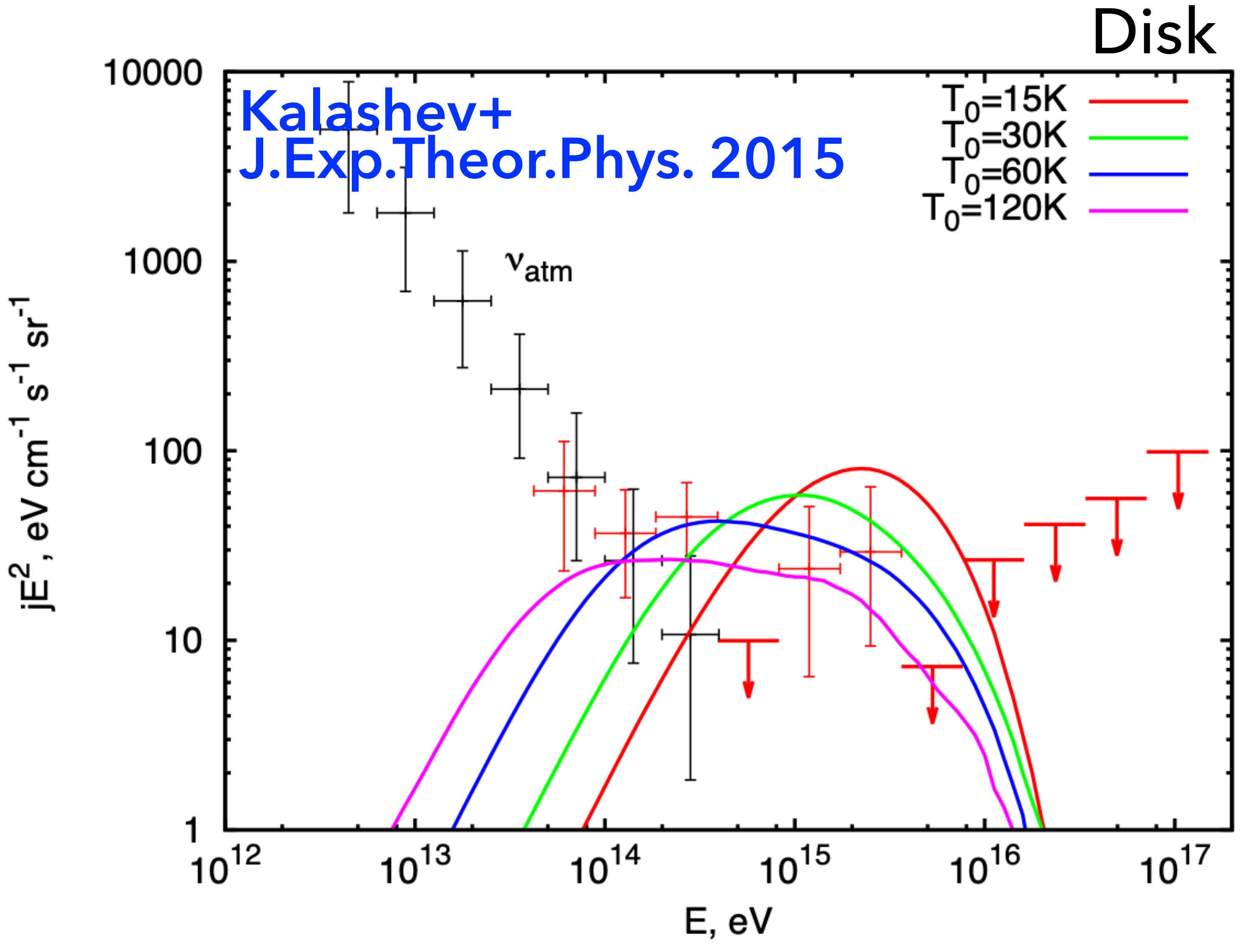


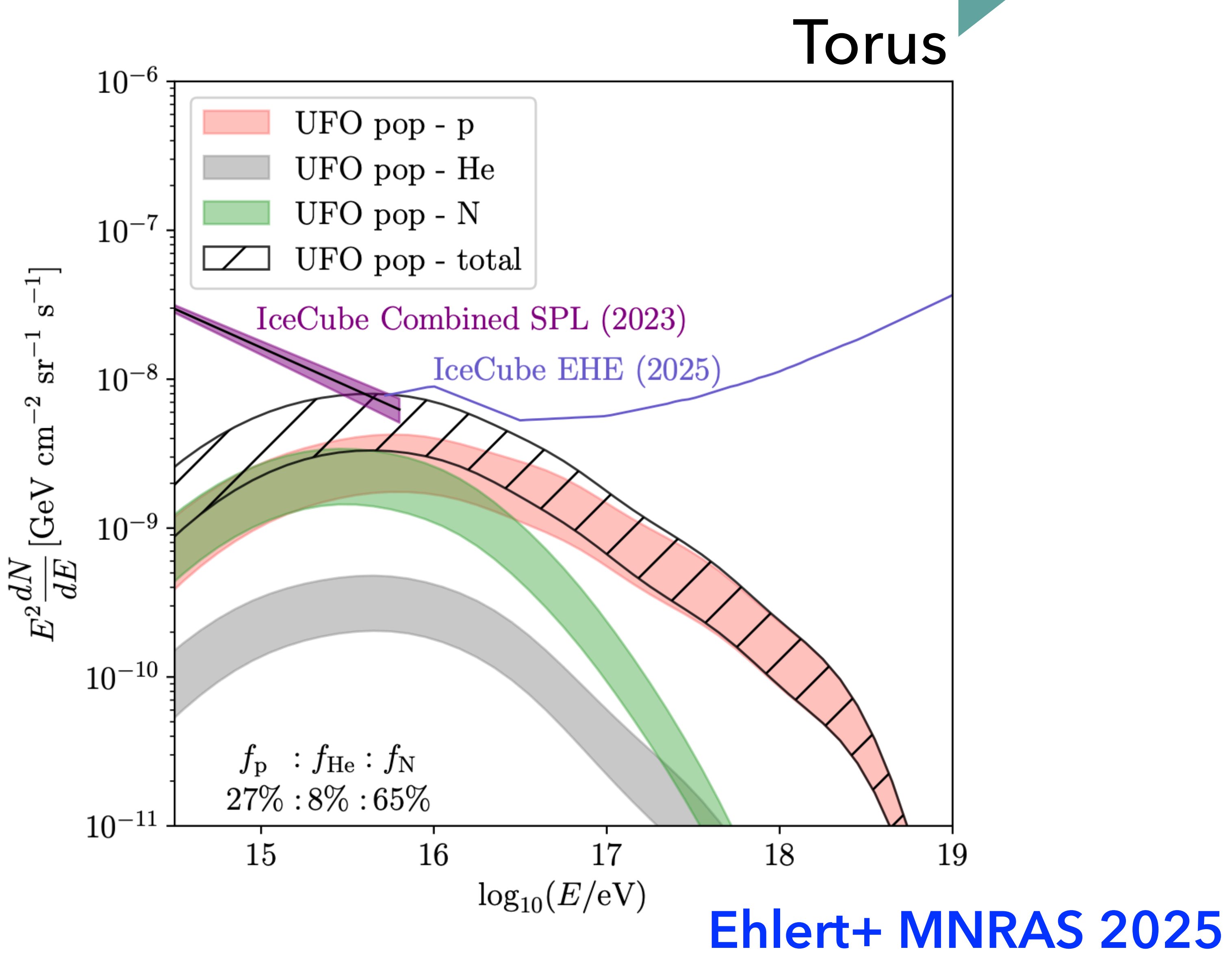
Energy range of the photon field

Location of the photon field with respect to the black hole

Energy range of the corresponding neutrino flux







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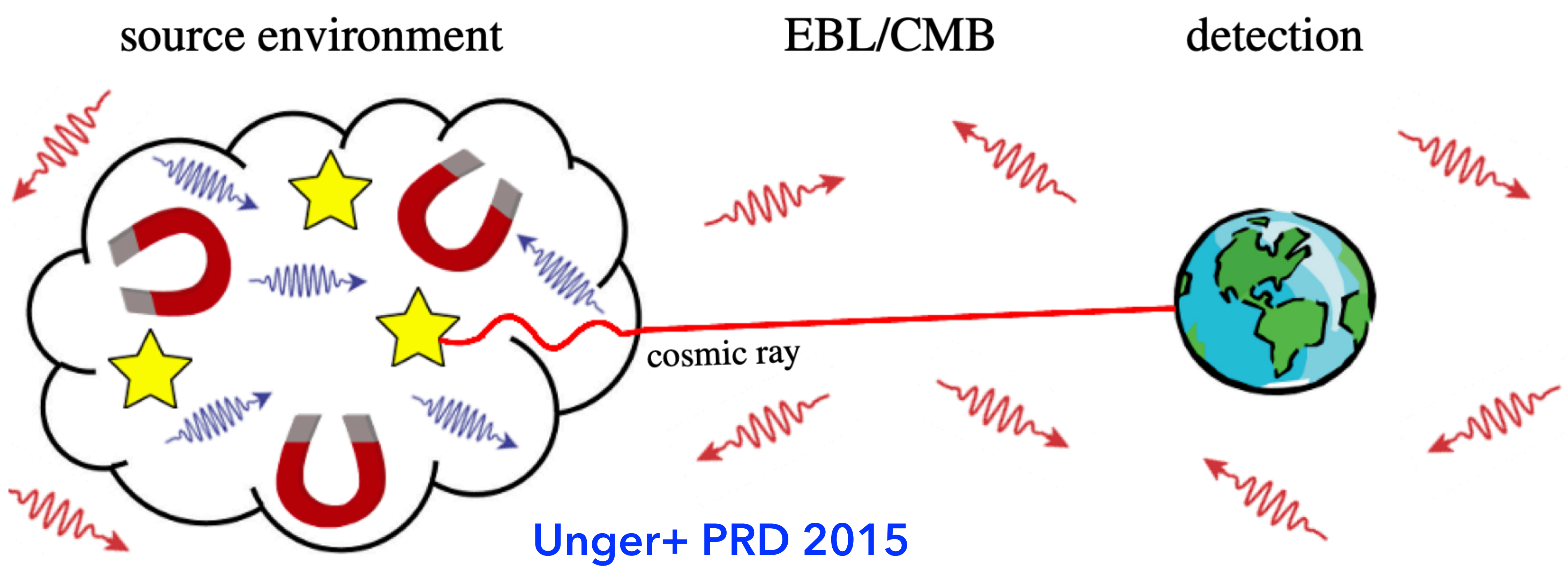
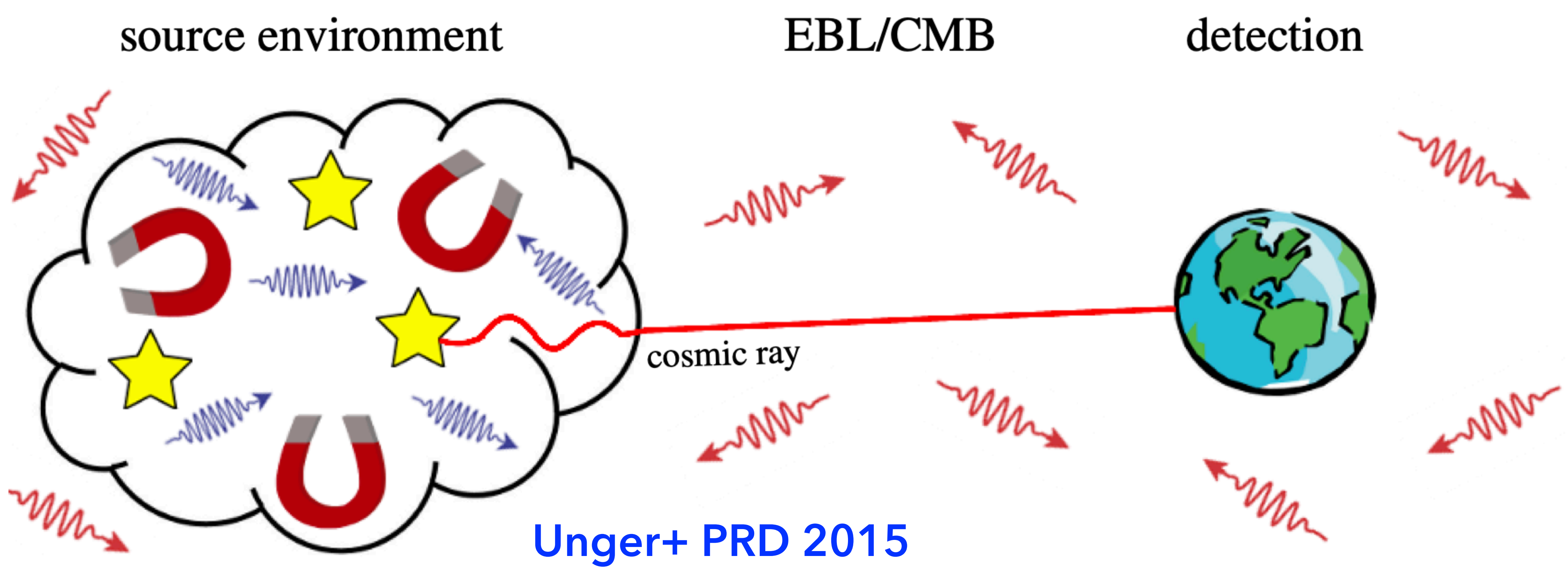


Neutrinos produced in **sources (astrophysical)**:

- Their intensity depends on efficiency of interactions in the source regions in which they are produced -> <u>injection of protons, production of protons (as due to disintegration) and their interaction/diffusion/escape</u>
- Their energy range depend on the proximity to the location of the photon field with respect to the central engine (example of AGN)

A complete picture for neutrinos (1 + 2)



Unger+ PRD 2015

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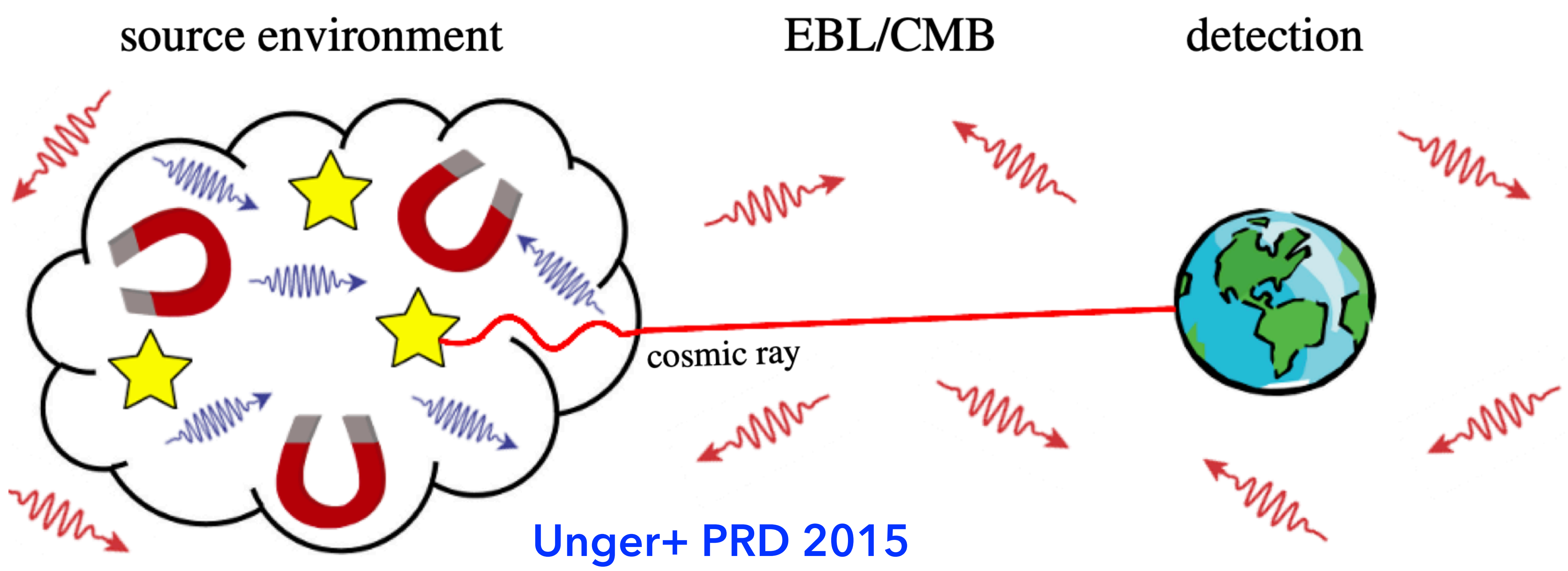
Neutrinos produced in **confinement regions**

- Their intensity depends on efficiency of interactions in the confinement regions -> <u>production of protons (as due to disintegration) and their interaction/diffusion/escape</u>
- They are connected to **UHECR maximum energy at the escape from the source (acceleration)**

A complete picture for neutrinos (1 + 2 + 3)



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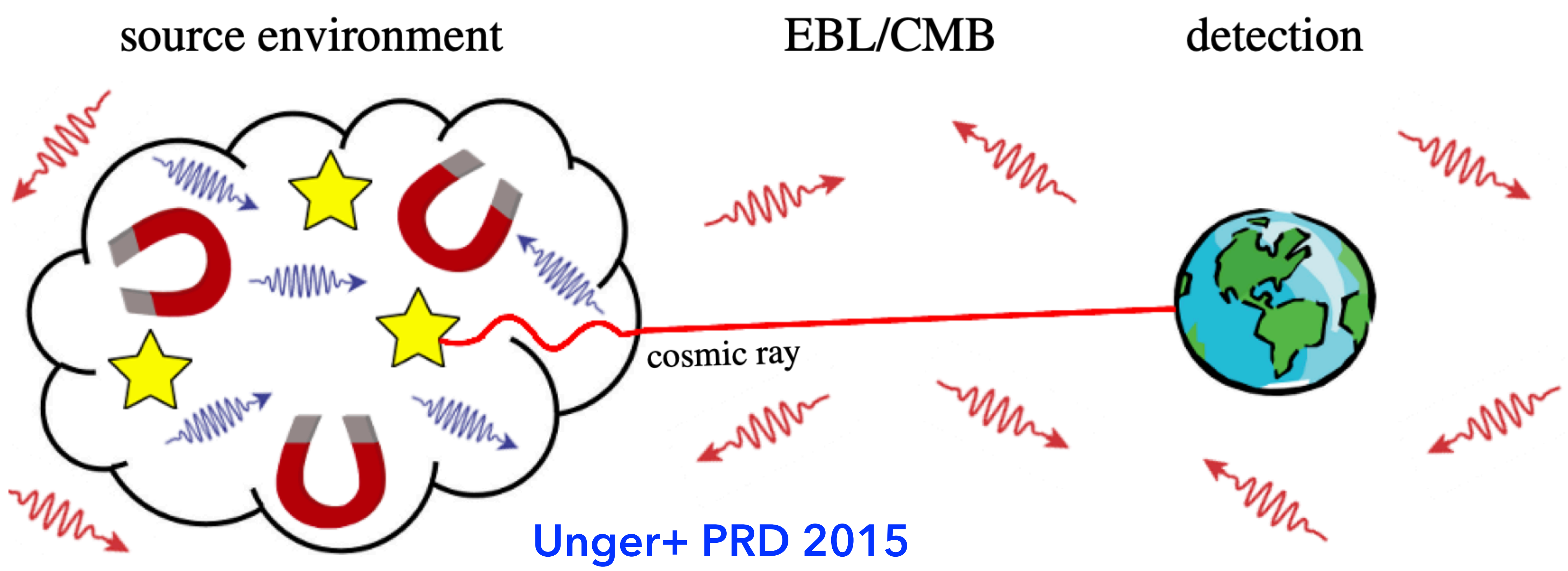
Neutrinos produced in **propagation (cosmogenic)**

- Their intensity depend on efficiency of interactions in the extragalactic space -> known uncertainties (source evolution, EBL models)
- They are connected to **UHECR maximum energy at the escape from the confinement region**

A complete picture for neutrinos (1 + 2 + 3)



Confinement and cosmogenic neutrinos are expected in the energy range of the exposure for UHE neutrinos in IceCube, Auger…

Neutrinos produced in **sources (astrophysical)**:

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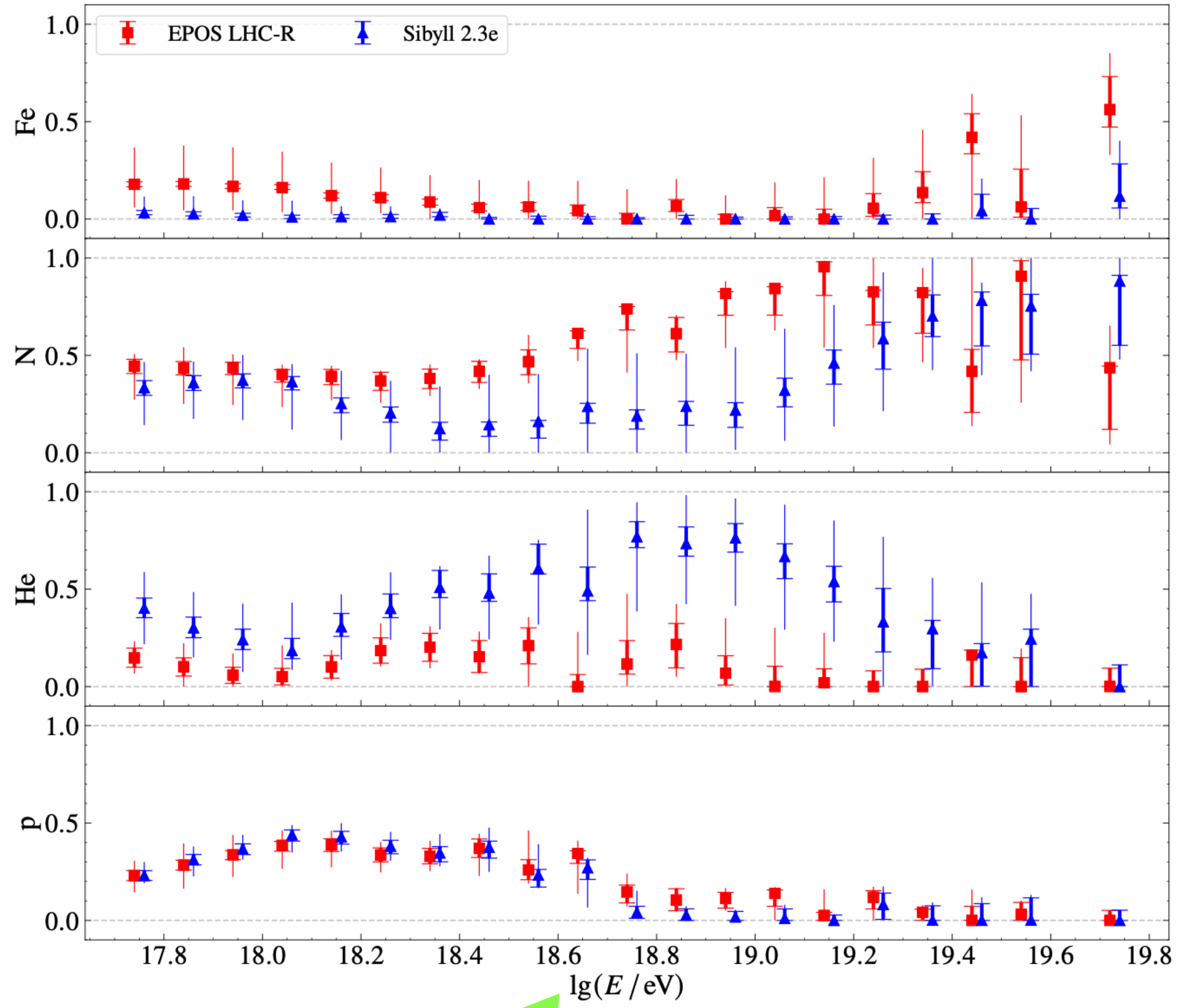
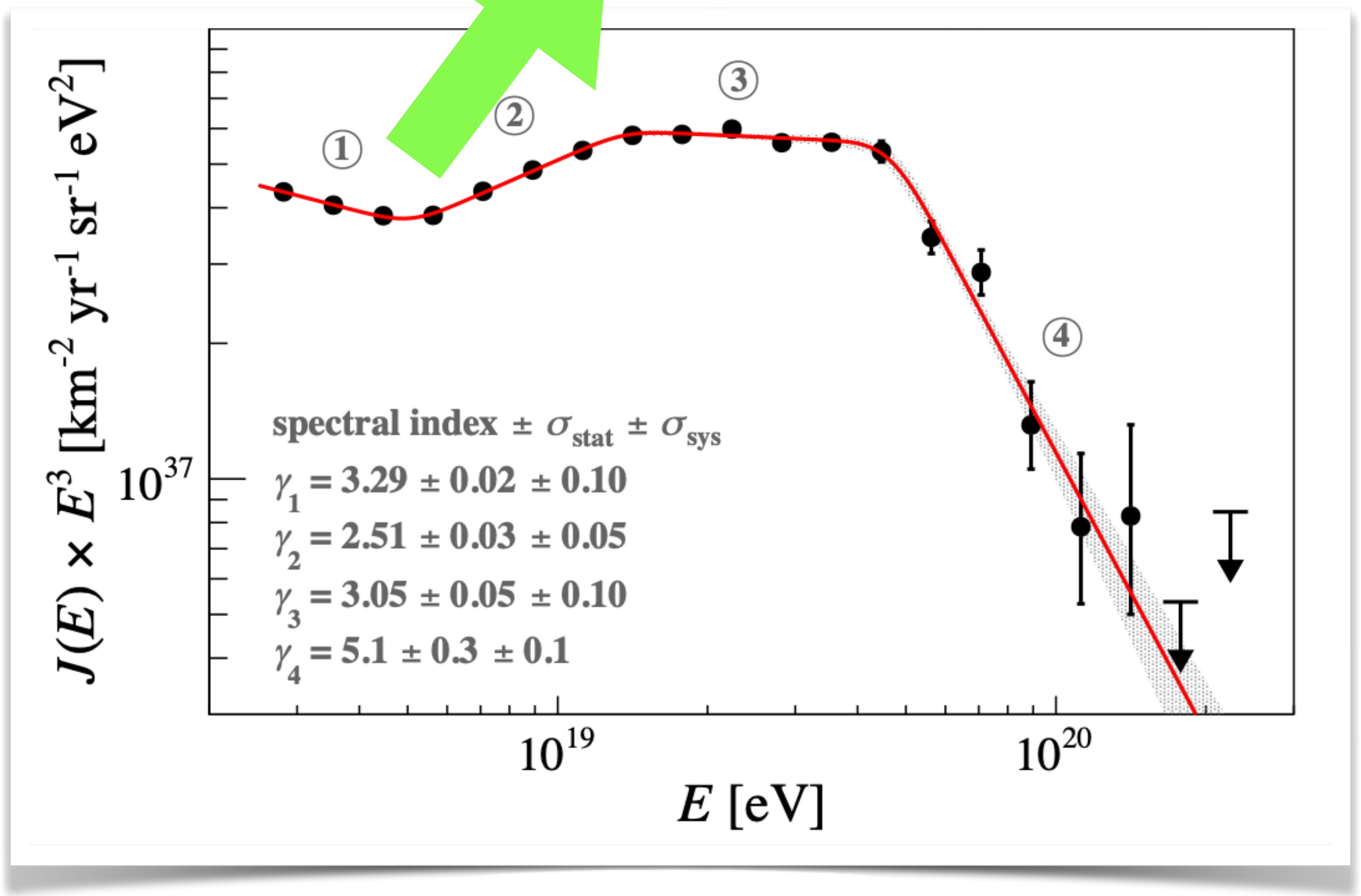
State-of-the-art: astrophysical scenarios for UHECRs

The Auger Collab. *Phys.Rev.D* 114 (2026)

-> the origin of UHECR protons and the associated neutrinos





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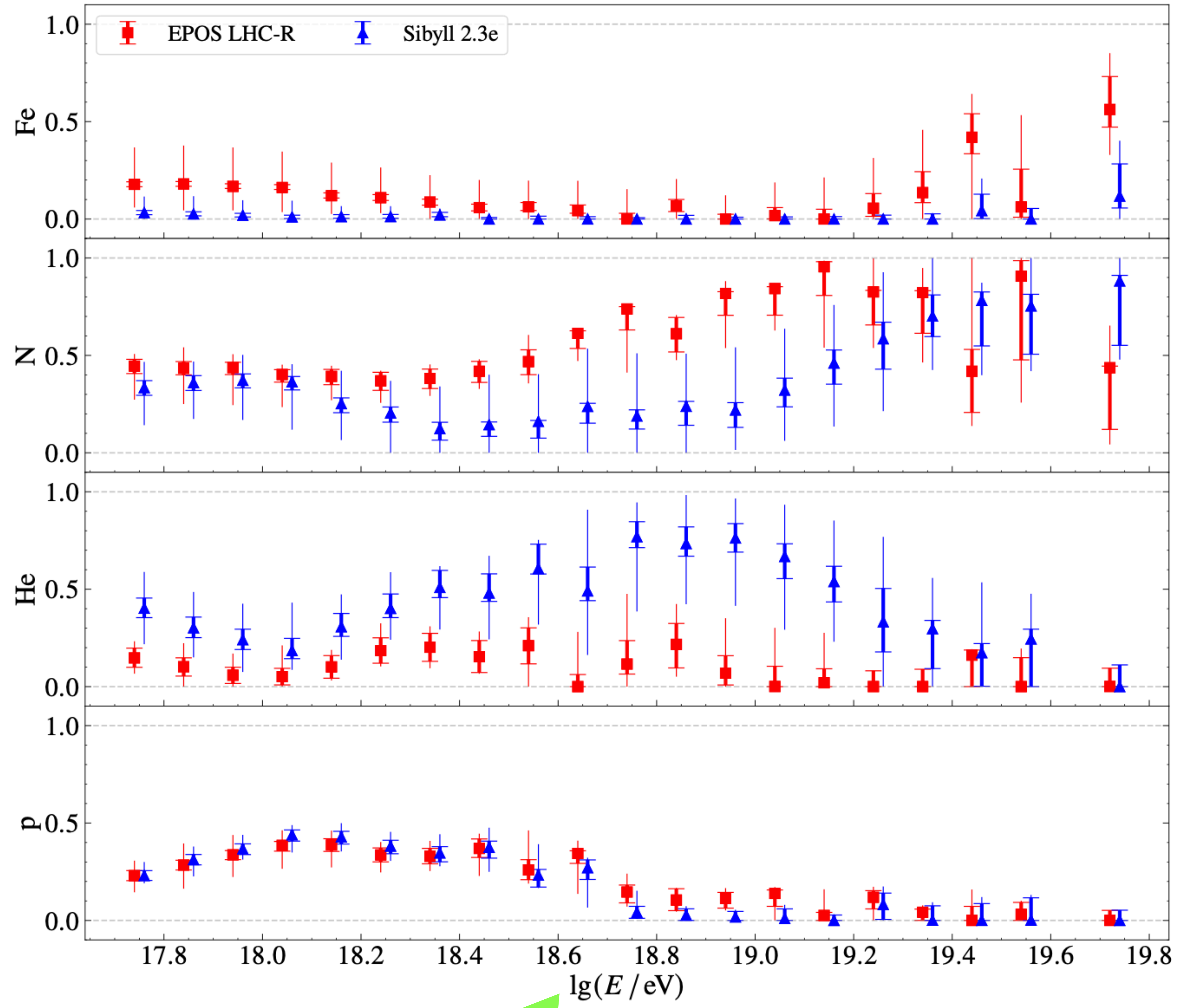
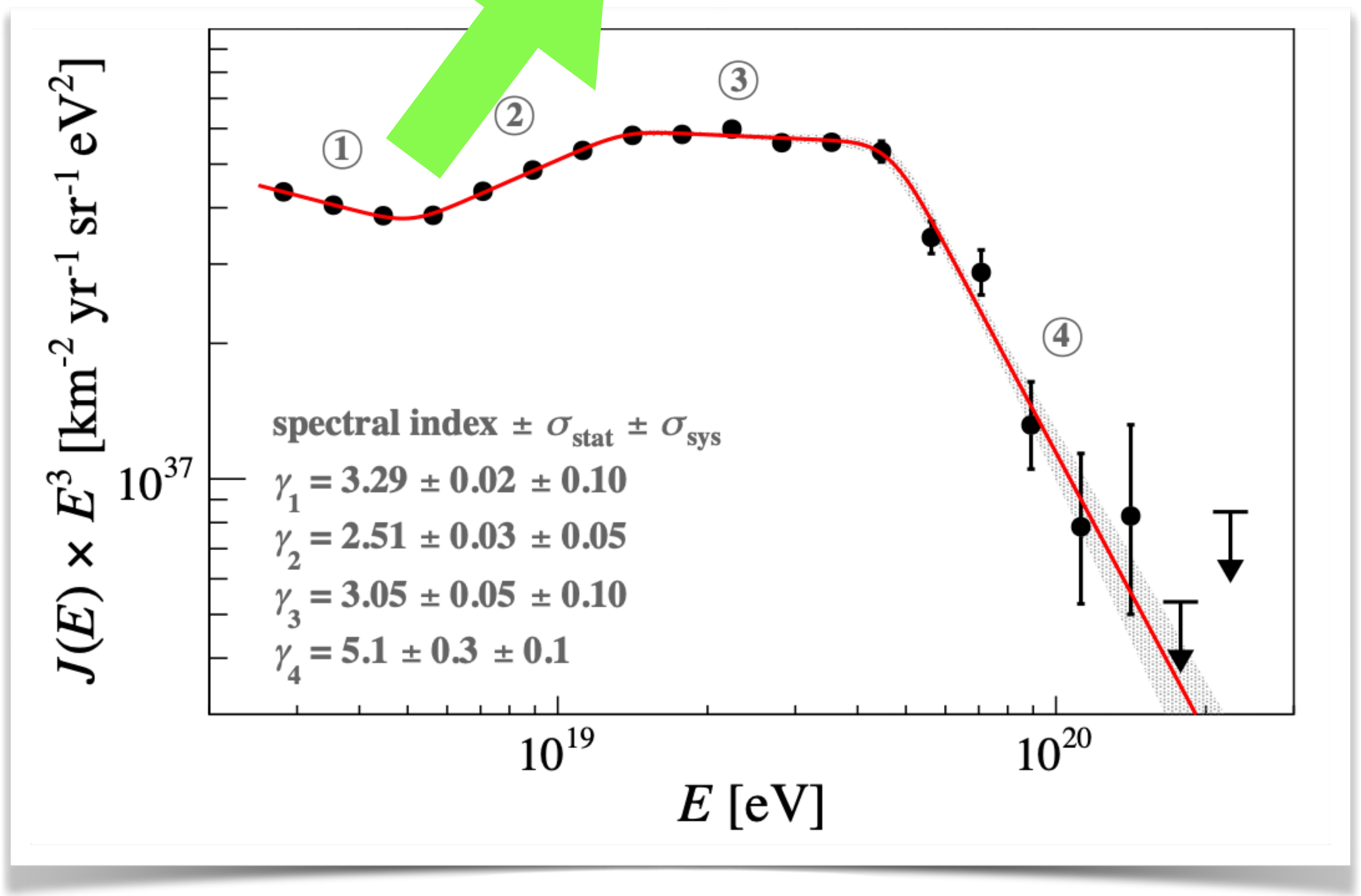


- Proton fraction below the ankle: if it is associated to
    - nucleons from confinement (one population of sources contributes to the UHECRs above 1 EeV), the associated neutrinos (confinement neutrinos) might outshine the cosmogenic neutrinos in the same energy range
    - another extragalactic population (two populations of sources contribute to UHECRs above 1 EeV -> extragalactic component B below the ankle?), the associated cosmogenic neutrinos might be expected up to the highest energies, due to the LE rigidity and the interplay with the LE source evolution



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The Auger Collab. *Phys.Rev.D* 114 (2026)

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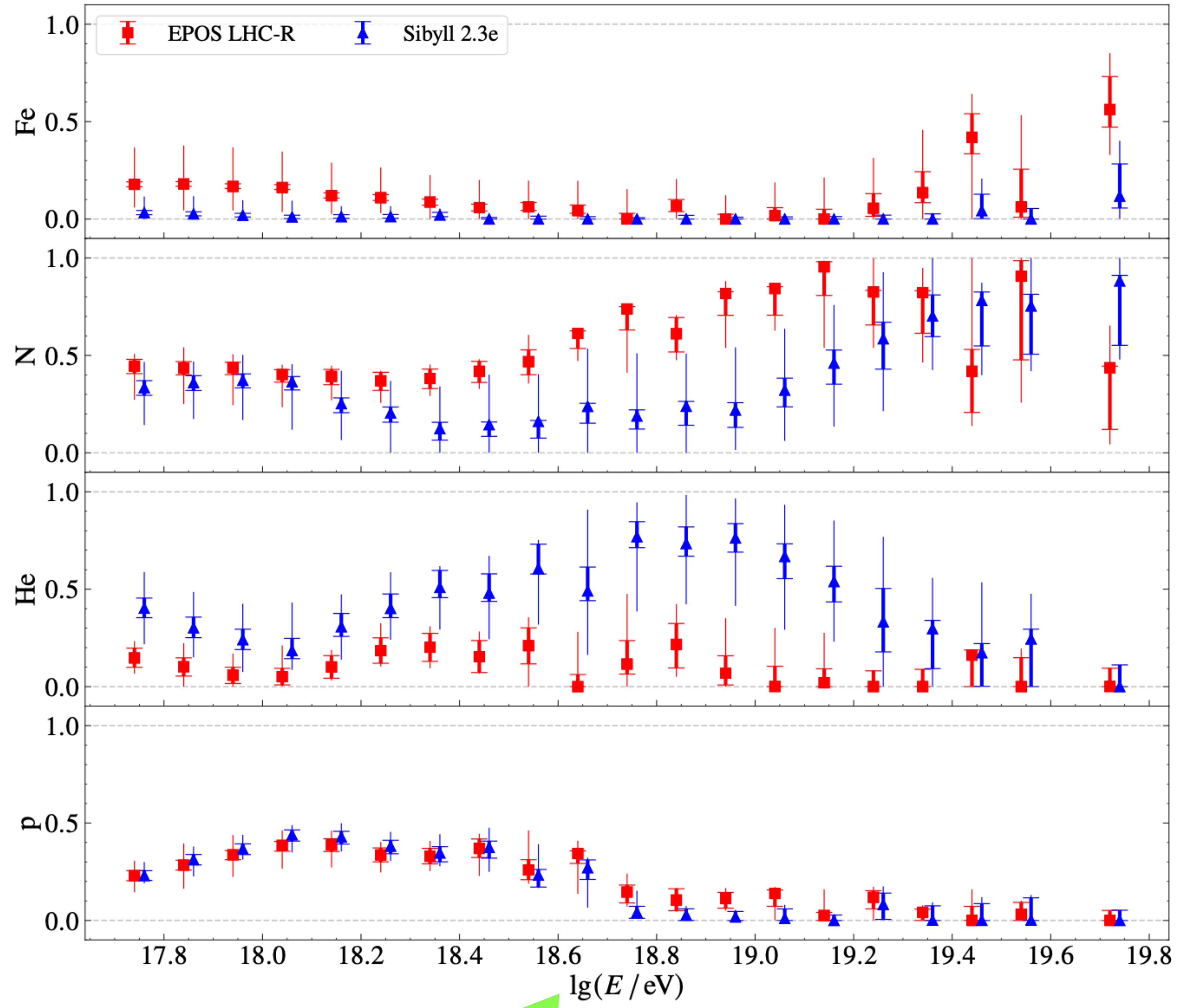

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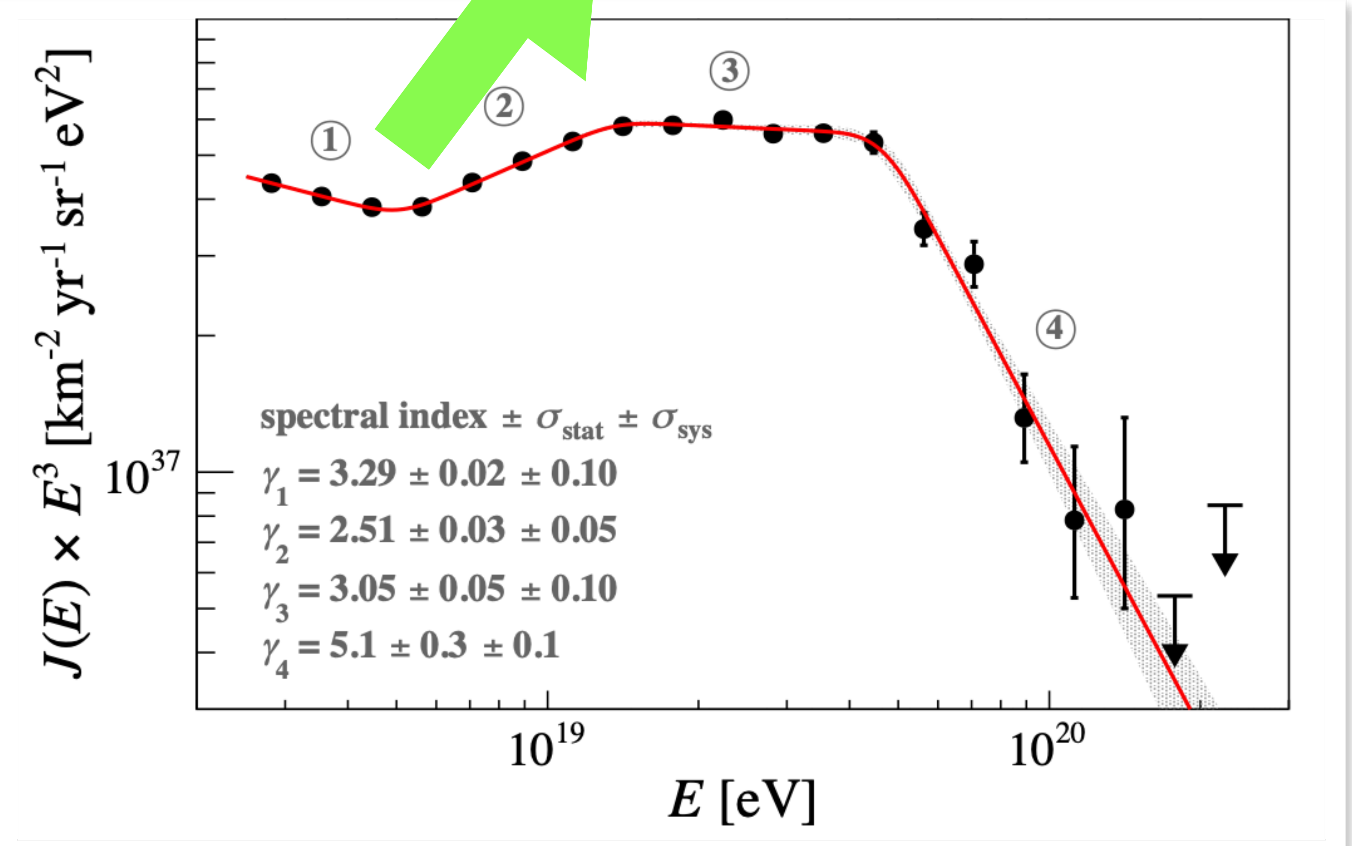
Max energy of protons linked to the one of nuclei above the ankle

Max energy of protons NOT linked to the one of nuclei above the ankle



State-of-the-art: astrophysical scenarios for UHECRs

The Auger Collab. *Phys.Rev.D* 114 (2026)

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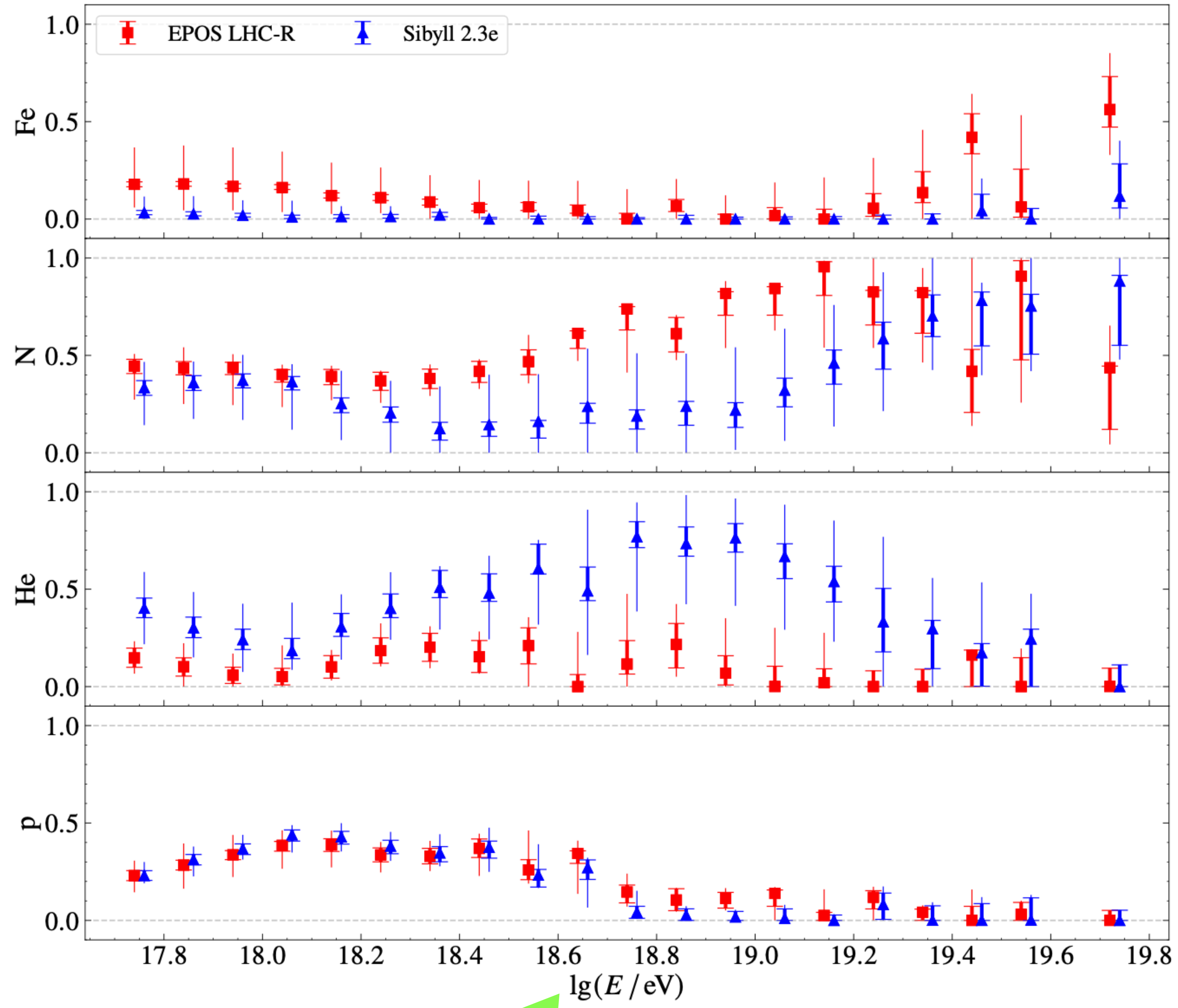

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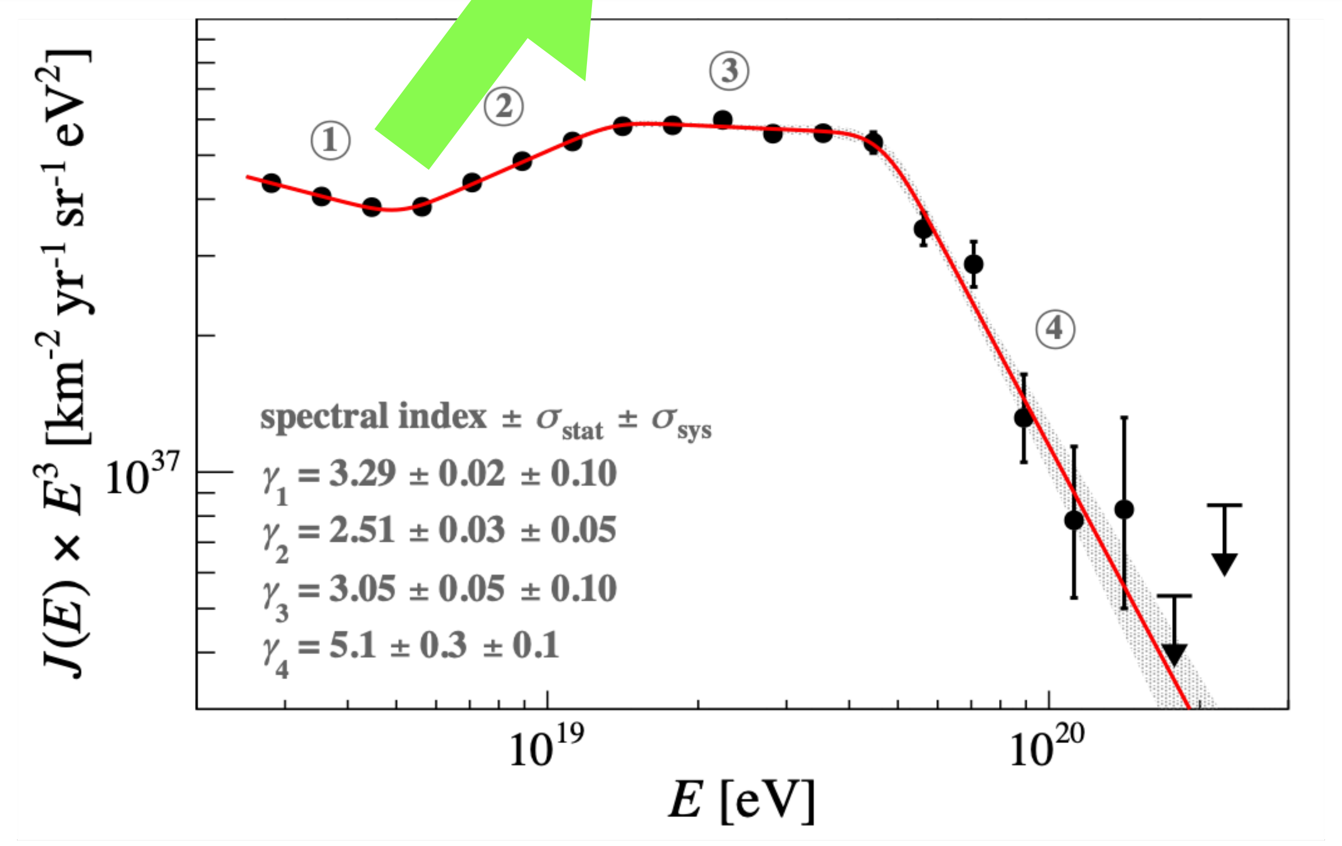


- **Proton fraction above the ankle and/or UHE neutrino events could help in discriminating among these scenarios**

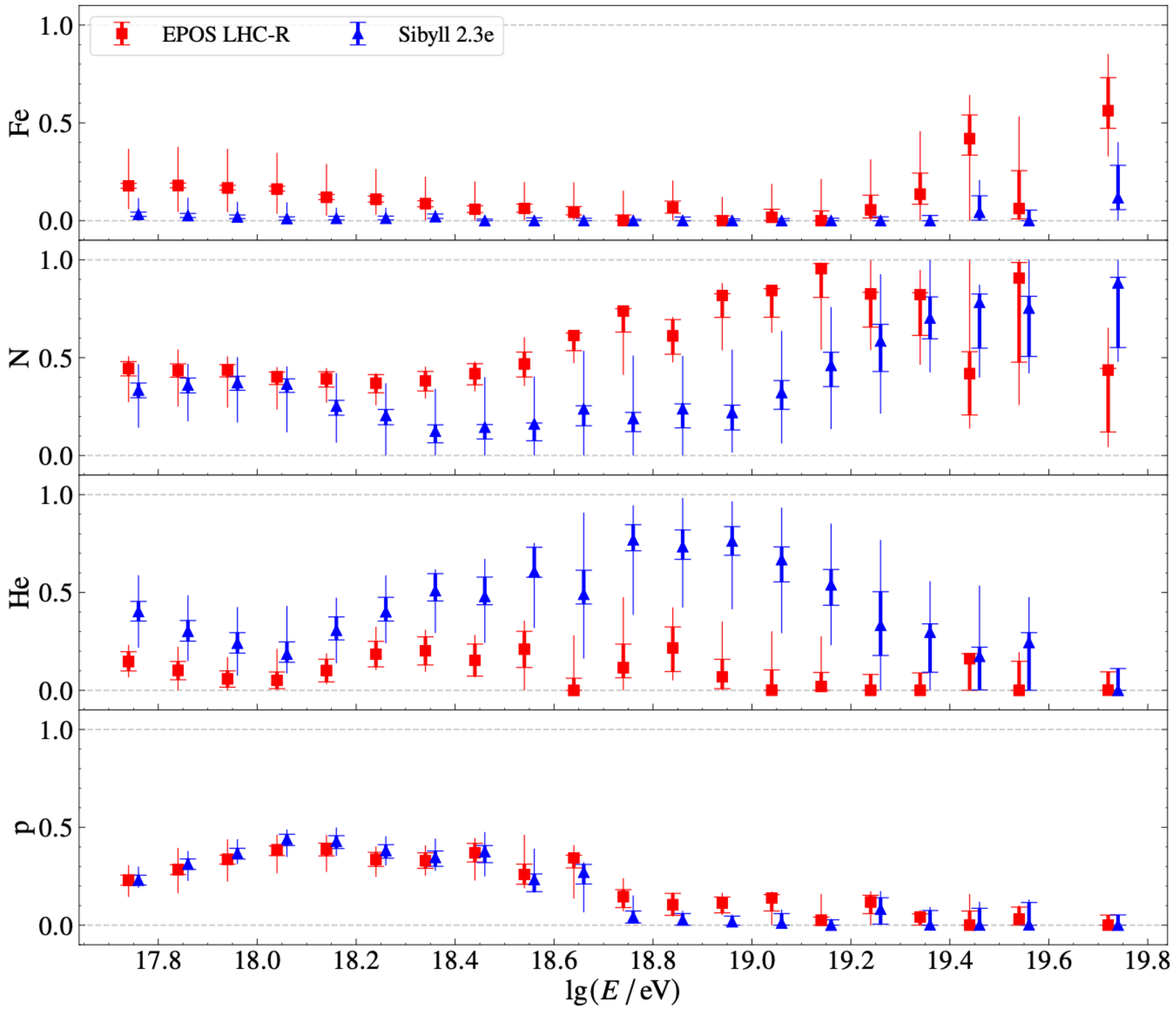
Summary

- **Confinement + Cosmogenic neutrinos** can be exploited
  - as an independent test of UHECR mass composition with respect to UHECR measurements, in addition to UHECR source evolution and spectral parameters at the escape from their sources
  - to investigate the characteristics of LE vs HE source populations (or in-source interactions) contributing to the UHECR flux

-> future prospects on detection of UHE particles will improve the discrimination power of multimessenger scenarios including UHECRs, moving forward from basic interpretation of UHECR data

-> investigating the mass composition of UHECRs is the key to move forward in UHECR astrophysics (and in particle and fundamental physics at the highest energies)

The Auger Collab. *Phys.Rev.D* 114 (2026)



Backup slides

Population parameters

Cermenati, Ambrosone, Aloisio, **DB**, Evoli arxiv:2507.11993

	m	γ	$E_{\max}\ [10^{18}\ \mathrm{eV}]$	$\mathbf{L}\ [10^{45}\ \frac{\mathrm{erg}}{\mathrm{Mpc^3 yr}}]$	$\Omega^{ee}_{\mathrm{tot}}\ [\frac{\mathrm{eV}}{\mathrm{cm^3}}]$	$\Omega^{\pi}_{\mathrm{tot}}\ [\frac{\mathrm{eV}}{\mathrm{cm^3}}]$
LE	0	2.5	6.0	2.68	2.90×10^{-9}	1.31×10^{-10}
	3	2.01	5.0	17.3	3.09×10^{-8}	1.17×10^{-9}
	5	1.4	4.0	0.24	2.22×10^{-7}	6.85×10^{-9}
HE	0	1.3	10^2	1.59×10^{-2}	1.47×10^{-10}	6.02×10^{-11}
	3	1.0	10^2	9.86×10^{-3}	8.46×10^{-10}	6.30×10^{-10}
	5	0.7	10^2	6.86×10^{-3}	5.52×10^{-9}	6.37×10^{-9}

$$Q_p(E,z) = Q_0 \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{E_{\max}}\right)(1+z)^m$$

$$Q_0 = \frac{L}{\int_{E_0}^{\infty} \left(\frac{E'}{E_0}\right)^{-\gamma} \exp\left(-\frac{E'}{E_{\max}}\right) E' dE'}$$

$$\omega^{\pi}_{\mathrm{casc}}(z) = \int dE\, E \left[Q^{\pi}_{e^-}(E,z) + Q^{\pi}_{e^+}(E,z) + Q^{\pi}_{\gamma}(E,z)\right]$$

$$\omega^{ee}_{\mathrm{casc}}(z) = \int dE_p\, E_p^2\, n_p(E_p,z)\, \beta(E_p,z)$$

Transport equations for messengers

Cermenati, Ambrosone, Aloisio, **DB**, Evoli arxiv:2507.11993

$$\frac{dn_p}{dz} + \frac{3n_p}{1+z} - \frac{\partial}{\partial E}\left[b_p(E,z)n_p(E,z)\right]\left|\frac{dt}{dz}\right| = Q_p(E,z)\left|\frac{dt}{dz}\right|$$

$$\frac{dn_\nu}{dz} + \frac{3n_\nu}{1+z} - \frac{\partial}{\partial E}\left[\frac{E}{1+z}\right]n_\nu(E,z) = Q^p_\nu(E,z)\left|\frac{dt}{dz}\right|$$

$$\frac{dn_{ee}}{dz} + \frac{3n_{ee}}{1+z} - \frac{\partial}{\partial E}\left[\frac{E}{1+z}\right]n_{ee}(E,z) + \frac{n_{ee}}{\tau_{\rm ICS}}\left|\frac{dt}{dz}\right| = \left[Q^p_{ee}(E,z) + Q^{\rm ICS}_{ee}(E,z) + Q^{\rm PP}_{ee}(E,z)\right]\left|\frac{dt}{dz}\right|$$

$$\frac{dn_\gamma}{dz} + \frac{3n_\gamma}{1+z} - \frac{\partial}{\partial E}\left[\frac{E}{1+z}\right]n_\gamma(E,z) + \frac{n_\gamma}{\tau_{\rm PP}}\left|\frac{dt}{dz}\right| = \left[Q^p_\gamma(E,z) + Q^{\rm ICS}_\gamma(E,z)\right]\left|\frac{dt}{dz}\right|$$

$$Q^\pi_i(E_i,z) = \int_{E_i}\frac{dE_p}{E_p}n_p(E_p,z)\int_{\epsilon_{th}(E_p)}d\epsilon\, n_b(\epsilon,z)\phi(E_i,E_p,z)$$

Injection rate of secondary particles from photopion production

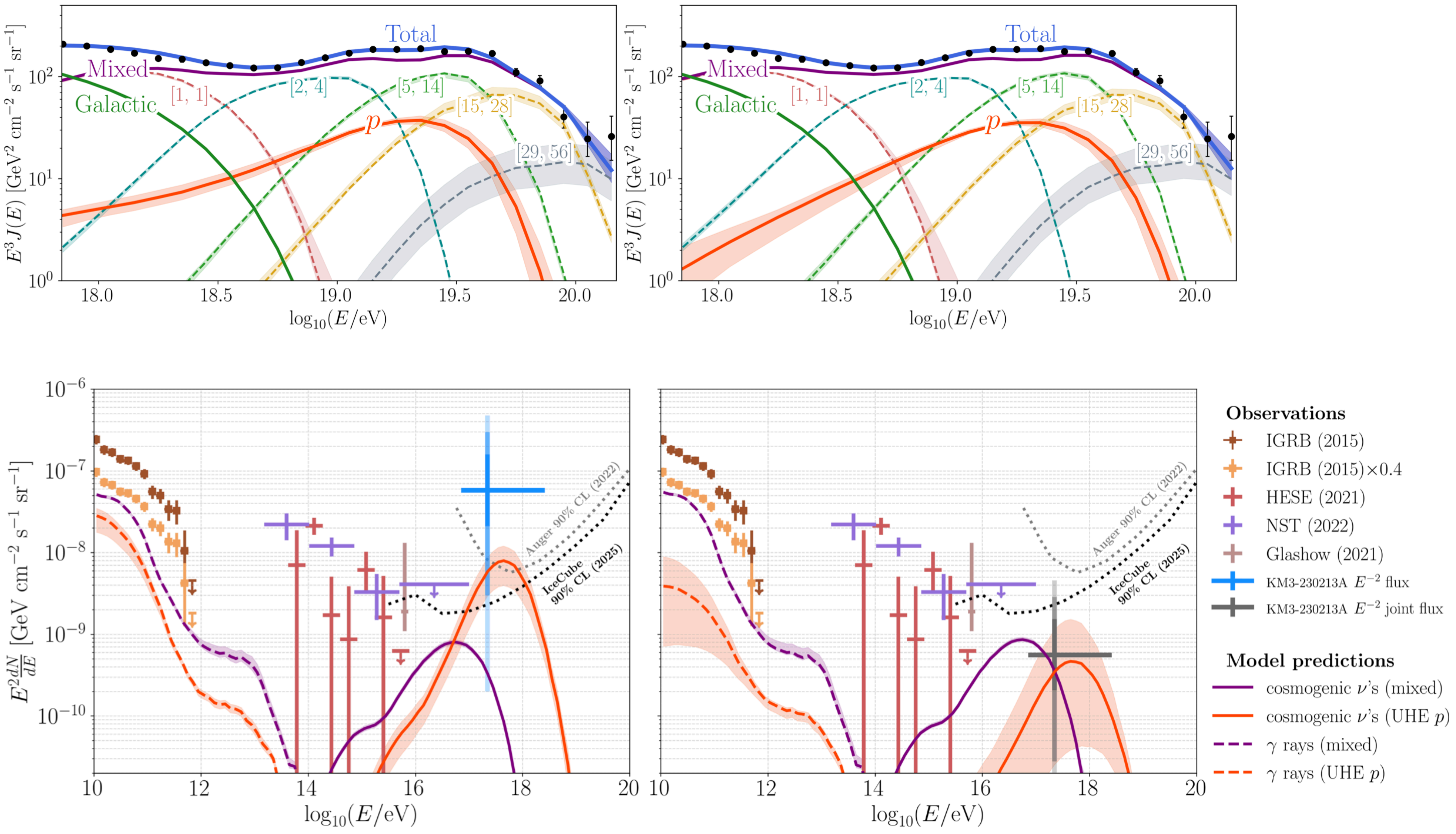
$$Q_\gamma(E,z) = \frac{\omega_{\rm casc}(z)}{\epsilon_X^2[2+\ln(\epsilon_C/\epsilon_X)]}\begin{cases}\left(E/\epsilon_X\right)^{-3/2} & \text{if } E \lesssim \epsilon_X\,, \\ \left(E/\epsilon_X\right)^{-2} & \text{if } E \gtrsim \epsilon_X\,,\end{cases}$$

Injection rate of cascade gamma rays

$$\omega^\pi_{\rm casc}(z) = \int dE\, E\left[Q^\pi_{e^-}(E,z) + Q^\pi_{e^+}(E,z) + Q^\pi_\gamma(E,z)\right]$$

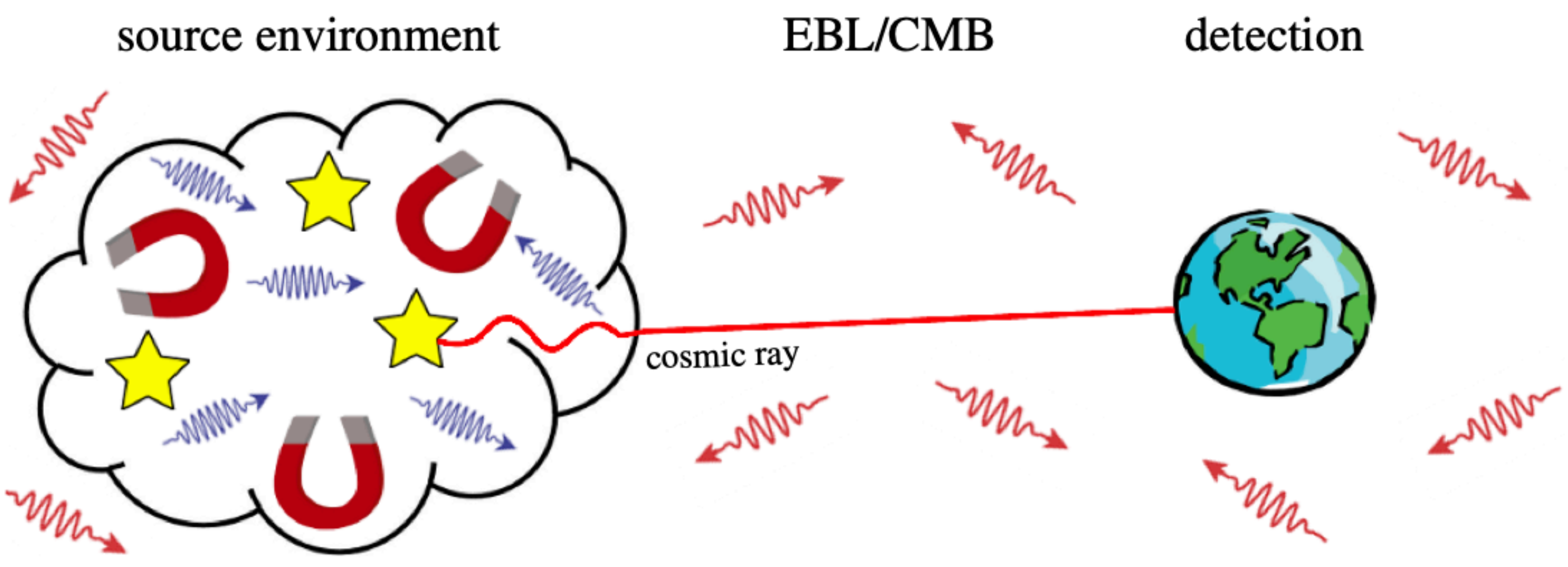
$$\omega^{ee}_{\rm casc}(z) = \int dE_p\, E_p^2\, n_p(E_p,z)\,\beta(E_p,z)$$

UHECR proton component and neutrinos



Alhebsi, van Vliet, Ehlert & Thoudam Astrophys.J. 1003 (2026)

A toy-model to investigate the spectral shape and mass composition at the escape of a source environment



- Accelerator within an environment where cosmic rays can be confined by magnetic fields and interact with radiation and matter fields
- A cosmic ray either
  - escapes without changing energy,
  - or interacts one or more times before escaping;
- Typical lengths are independent of position in the source environment and depend only on E, A, Z

$$\tau = (\tau_{\rm esc}^{-1} + \tau_{\rm int}^{-1})^{-1}$$

Number of particles of a certain species is decreasing exponentially with time

$$\eta_{\rm esc} = (1 + \tau_{\rm esc}/\tau_{\rm int})^{-1}$$

Particles escaping without interacting

$$\eta_{\rm int} = 1 - \eta_{\rm esc}$$

$$\tau_{\rm esc} = a(E/E_0)^{\delta} \qquad \tau_{\rm int} = b(E/E_0)^{\zeta}$$

$$\eta_{\rm esc} = (1 + R_0(E/E_0)^{\delta-\zeta})^{-1}$$

Only the ratio between escape and interaction is relevant

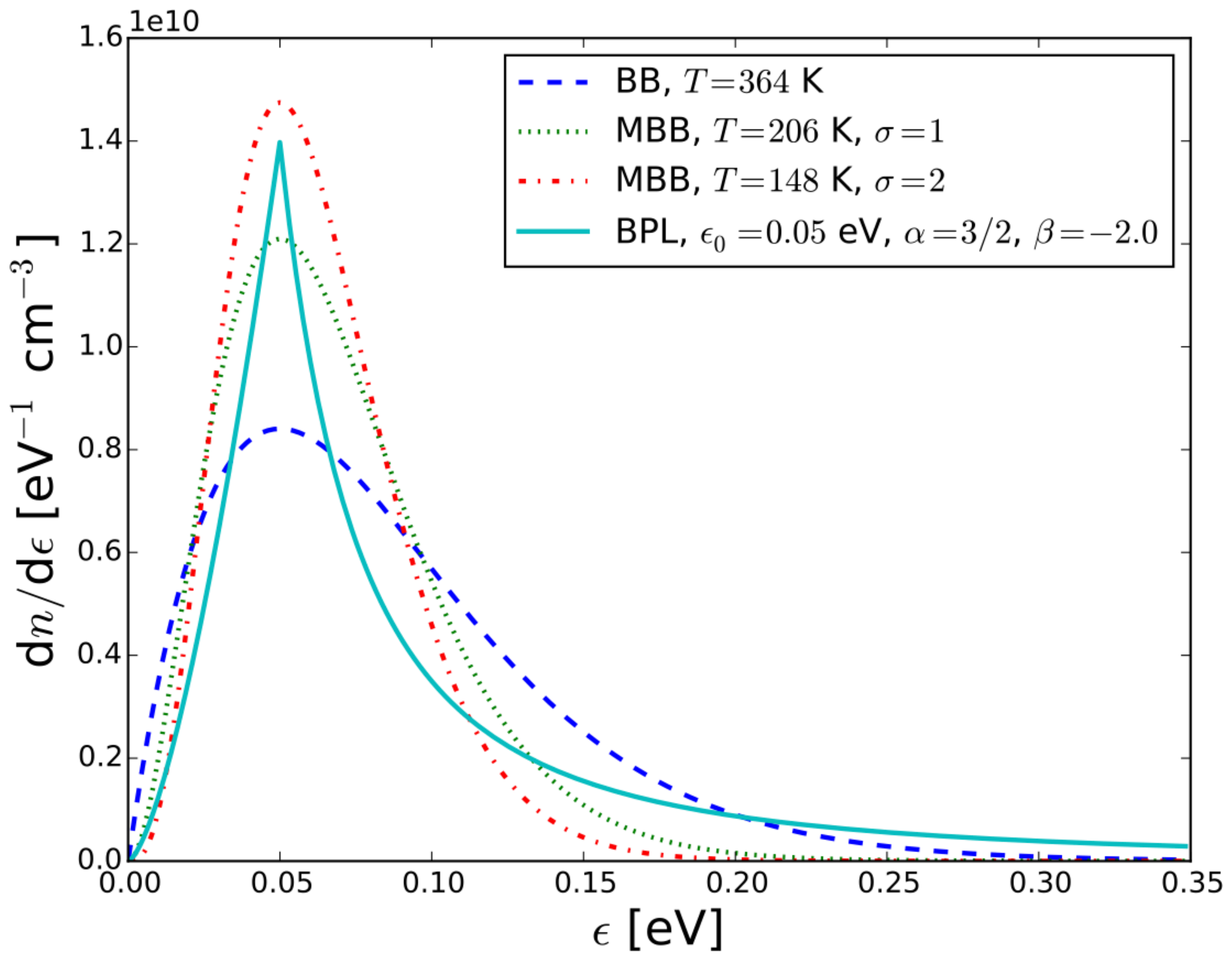
$\delta > \zeta$ — Low-pass filter

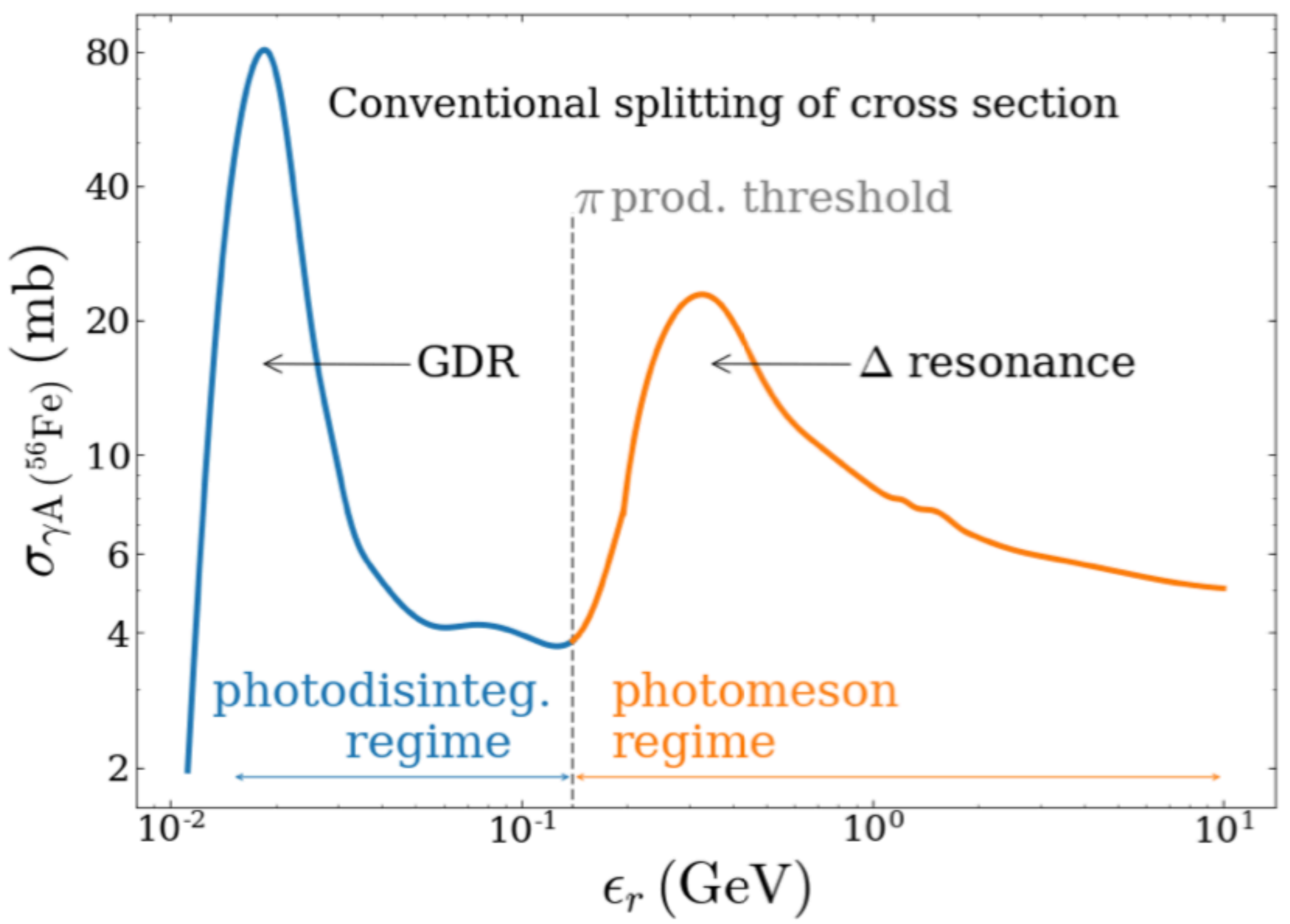
$\delta < \zeta$ — High-pass filter

Unger et al, PRD 2015

A toy-model to investigate the spectral shape and mass composition at the escape of a source environment

- Black body or power-law radiation field (peaked spectrum)
- Photopion production and/or photo-disintegration (resonances)





$$\frac{dN_{\rm int}}{dt} = \frac{c}{2\Gamma^2}\int_{\varepsilon'_{\rm th}}^{\infty} \sigma(\varepsilon')\varepsilon' \int_{\varepsilon'/2\Gamma}^{+\infty} \frac{n_\gamma(\varepsilon)}{\varepsilon^2} d\varepsilon d\varepsilon' \qquad \varepsilon' \approx \varepsilon\Gamma$$

A toy-model to investigate the spectral shape and mass composition at the escape of a source environment

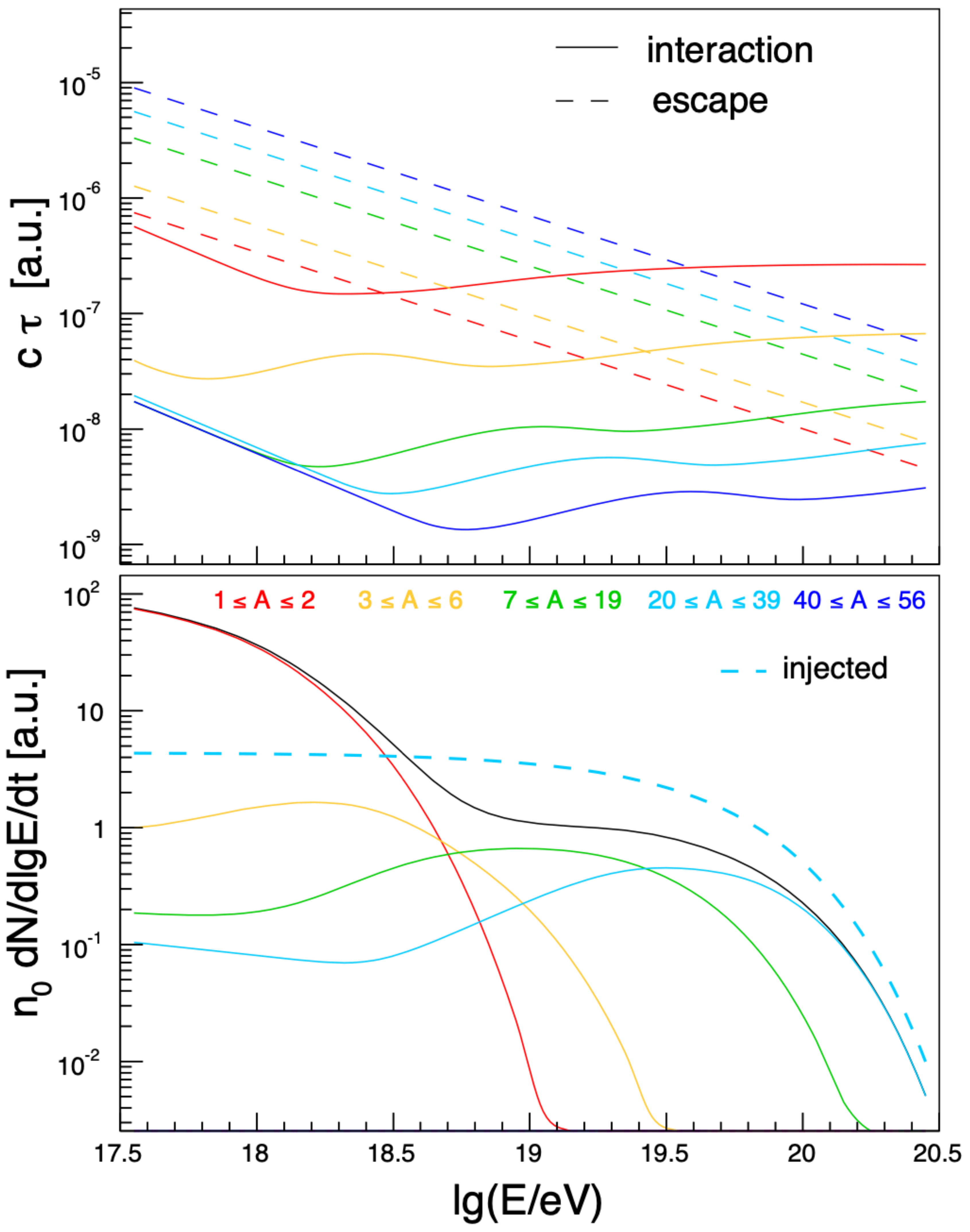
- Black body or power-law radiation field (peaked spectrum)
- Photopion production and/or photo-disintegration (resonances)

- Low CR energy -> high energy of the photon (above the peak) needed to reach the resonance energy -> steep spectrum -> time decreases
- High CR energy -> low energy of the photon (below the peak) needed -> time increases

- The lower the energy, the more time the nuclei have to interact before escaping
  - hardening of the spectrum and
  - lightening of the composition

$$\frac{dN_{\rm int}}{dt} = \frac{c}{2\Gamma^2}\int_{\varepsilon'_{\rm th}}^{\infty}\sigma(\varepsilon')\varepsilon'\int_{\varepsilon'/2\Gamma}^{+\infty}\frac{n_\gamma(\varepsilon)}{\varepsilon^2}d\varepsilon d\varepsilon' \qquad \varepsilon' \approx \varepsilon\Gamma$$

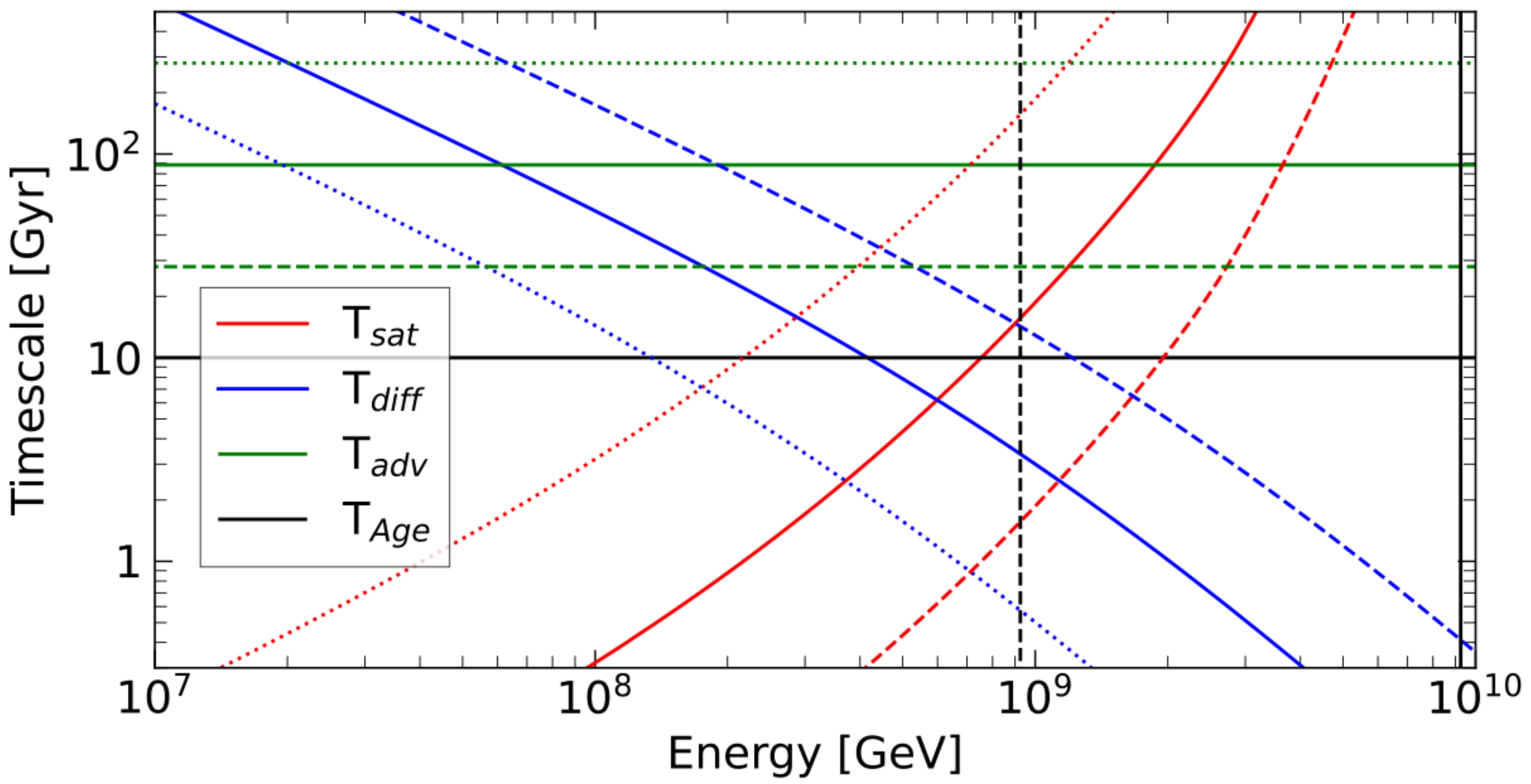
- The high-pass filter scenario leads naturally to an **ankle-like feature** separating the nucleonic fragments from the remaining nuclei

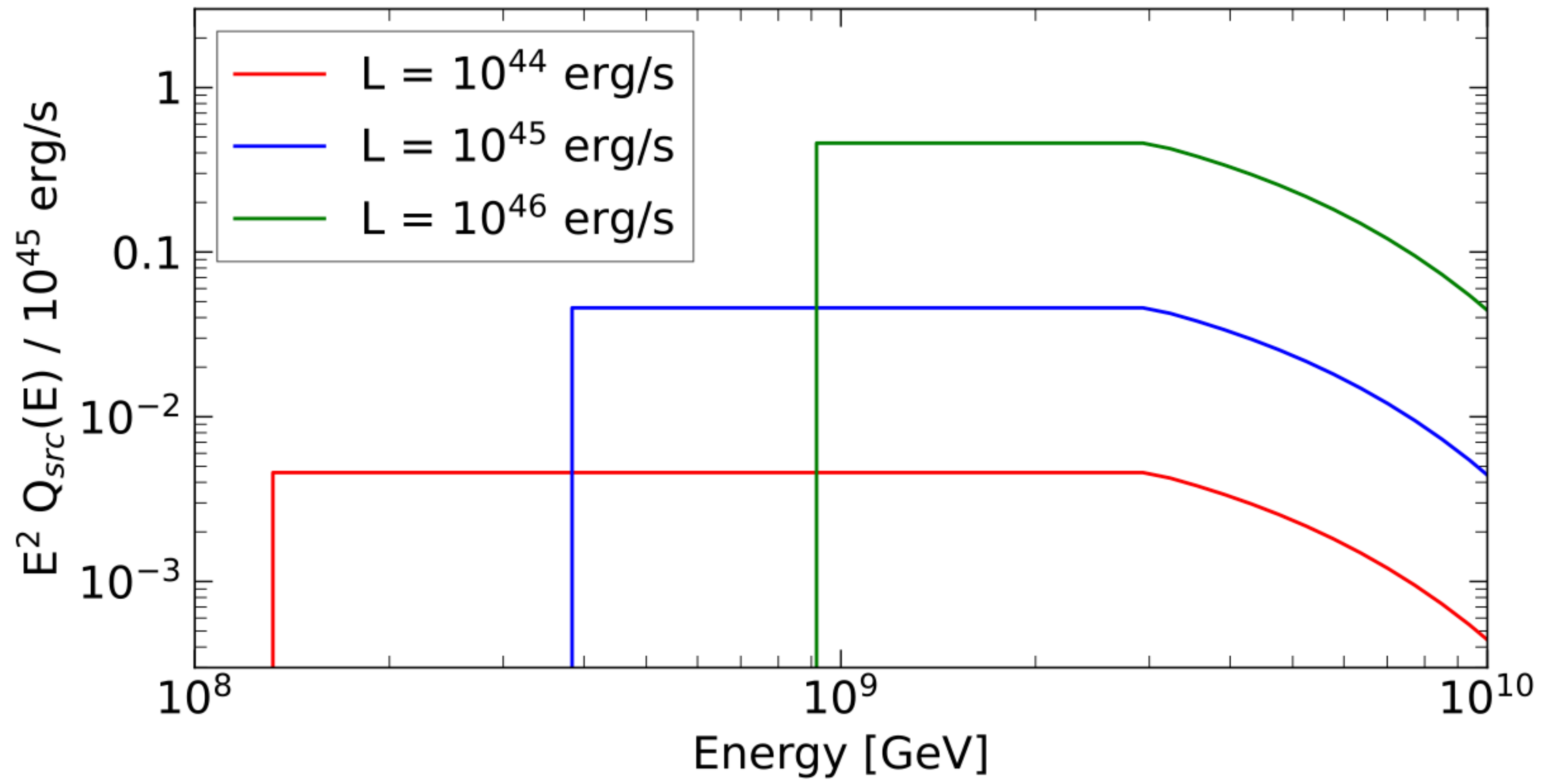


Unger et al, PRD 2015

Confinement in clusters of galaxies

Cermenati, Aloisio, Blasi & Evoli, Astron.Astrophys. 707 (2026) A19





- UHECRs escaping the source create a positive electric current density, which may excite a non-resonant streaming instability provided the energy density carried by the current is larger than the magnetic energy density in the pre-existing field
- Relevant timescales:
  - advection of the cosmic rays with the background plasma is considered
  - saturation time: timescale at which the instability saturates
  - escape time is defined as related to the diffuse time and the advection time
- Luminosity range:
  - the requirement that the instability is excited translates into a minimum source luminosity in the form of cosmic rays
  - the condition that the advection time exceeds the source age sets an upper limit on the source luminosity
- When the source luminosity is within this range, cosmic ray confinement near the source occurs if the diffusion time exceeds the source age -> cutoff