On astrophysical solution(s) to ultra-high-energy cosmic rays

Denise Boncioli

Università degli Studi dell'Aquila, Dipartimento di Scienze Fisiche e Chimiche
INFN-LNGS

denise.boncioli@univaq.it

Conference in memory of Veniamin Sergeyevich Berezinsky
October 1-3, 2024, GSSI, L'Aquila

On astrophysical solution to ultra high energy cosmic rays

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INFN, Laboratori Nazionali del Gran Sasso, I-67010 Assergi (AQ), Italy
and Institute for Nuclear Research of the RAS, Moscow, Russia

Askhat Gazizov
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Nezavisimosti Ave. 68, 220062 Minsk, Belarus

Svetlana Grigorieva
Institute for Nuclear Research of the RAS,
60th October Revolution prospect 7A, Moscow, Russia

We argue that an astrophysical solution to the ultra high energy cosmic ray (UHECR) problem is viable. The detailed study of UHECR energy spectra is performed. The spectral features of extragalactic protons interacting with Cosmic Microwave Background (CMB) are calculated in model-independent way. Using the power-law generation spectrum $\propto E^{-\gamma_g}$ as the only assumption, we analyze four features of the proton spectrum: the GZK cutoff, dip, bump and the second dip. We

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My main take-home messages in this talk

- Astrophysical **solutions** are viable
- We now have a global and consistent picture, thanks to
  - Improvements in the energy spectrum
  - Other observables than spectrum
  - Indications from other messengers

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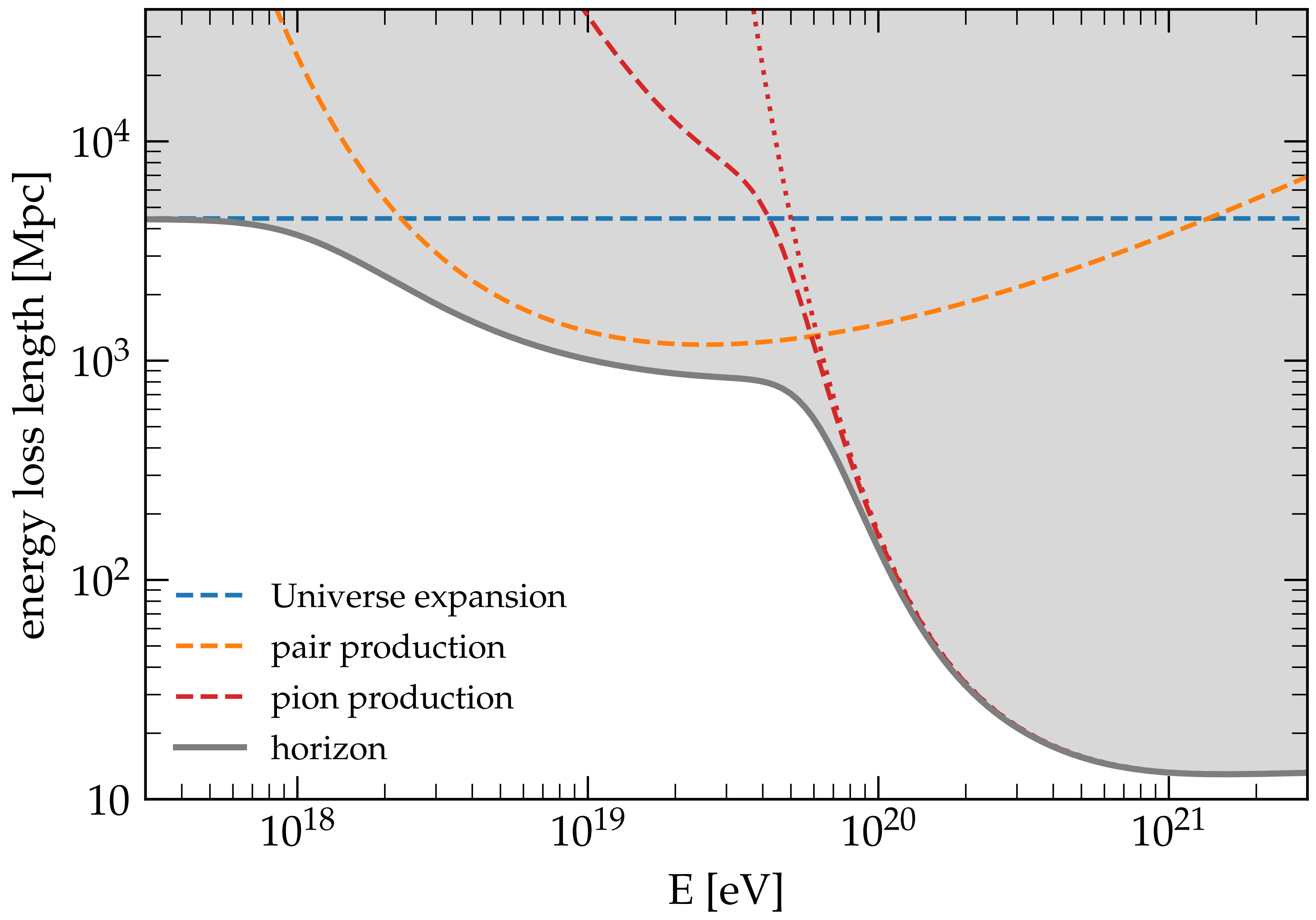
- I will have a **data-driven approach** in this talk
  - I will start from the most recent UHECR measurements and show how they guide the phenomenological understanding of the UHECR picture

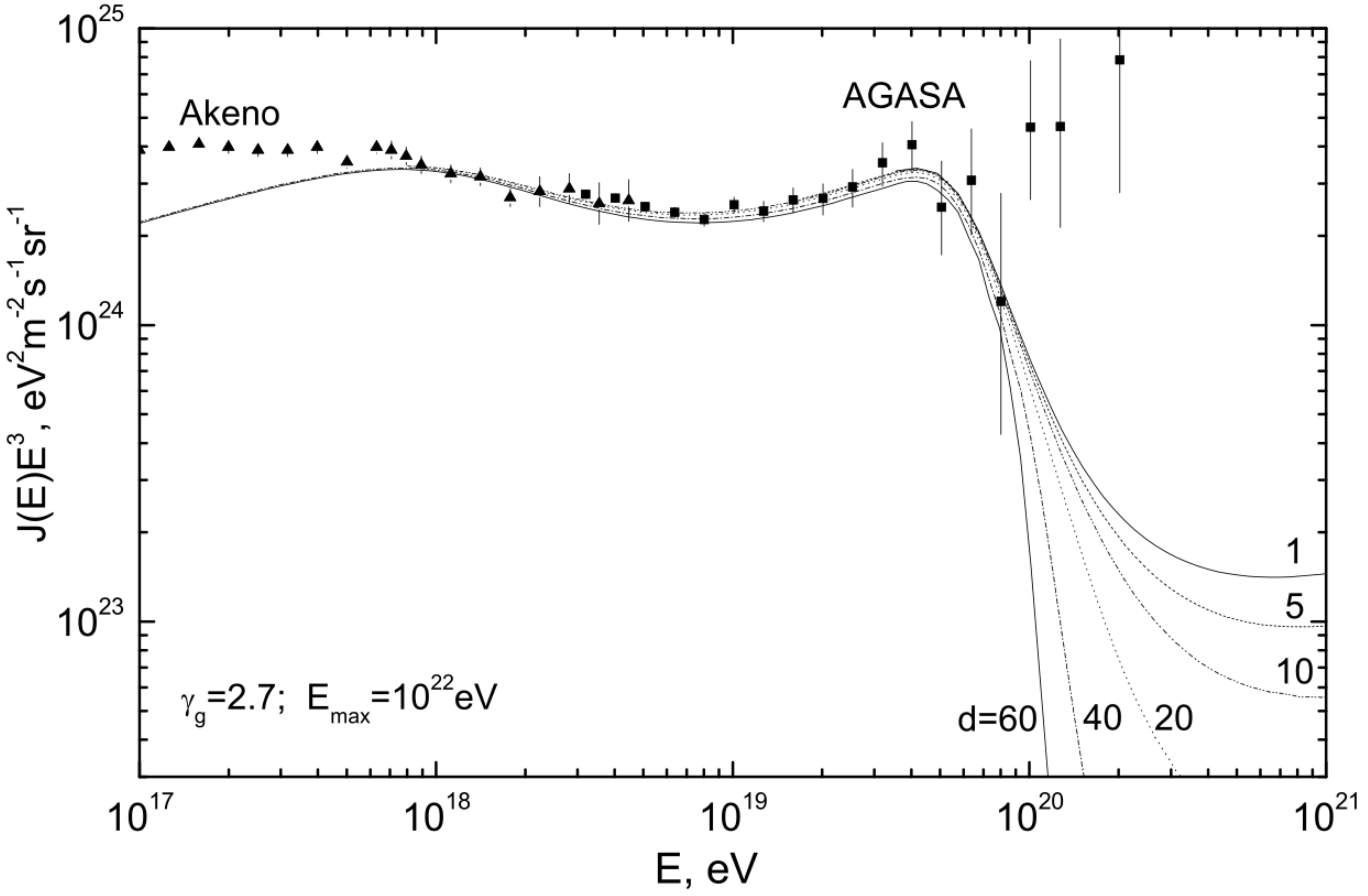
THE **UHECR ASTROPHYSICAL PICTURE** FROM THE STUDY OF DIFFUSE FLUXES

THE **DIP MODEL**

C. Evoli, work in progress for SimProp-Sirente

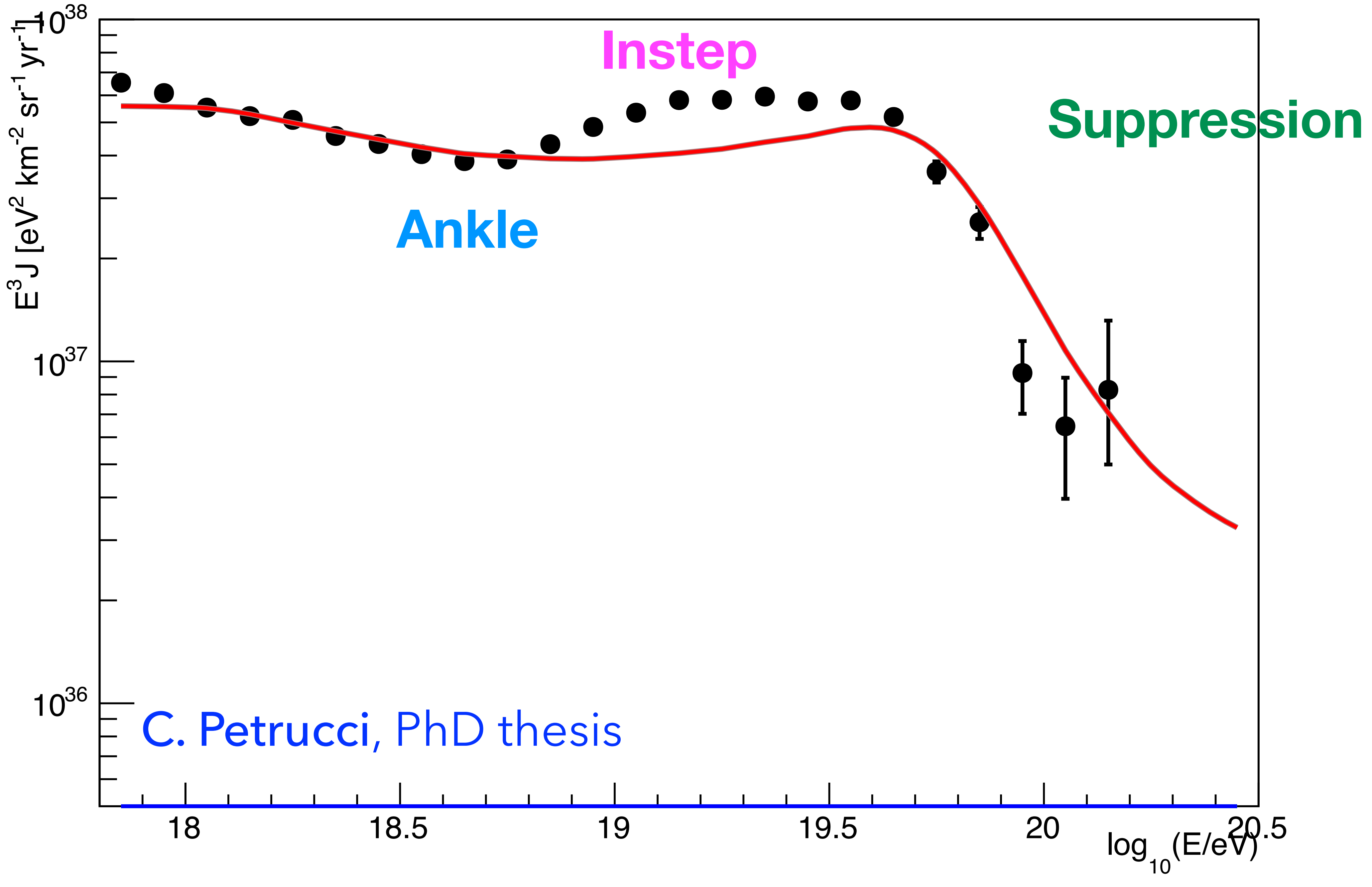


Berezinsky et al. PRD2006



- Dip model: the UHECR spectrum features can be explained with energy losses of protons travelling through the extragalactic space

THE **DIP MODEL** AND THE LATEST UHECR SPECTRUM MEASUREMENTS



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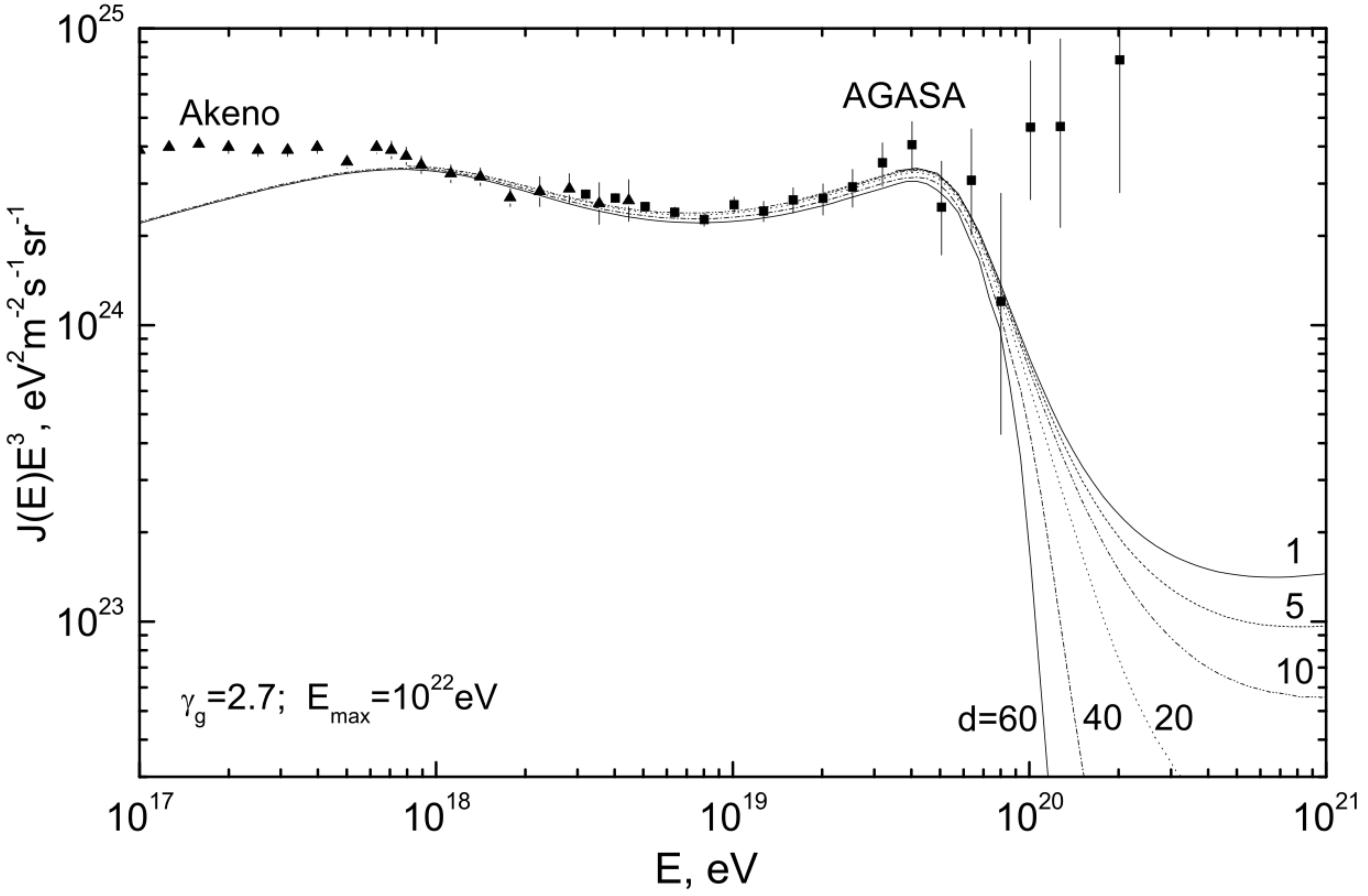

- Pure-proton scenario
- Same spectral parameters as in Berezinsky et al. PRD 2006

$$\gamma = 2.70; \quad E_{\rm cut} = 10^{22.0}\ \text{eV}; \quad m = 0$$

$$\chi^2/dof = 1594.3/24$$

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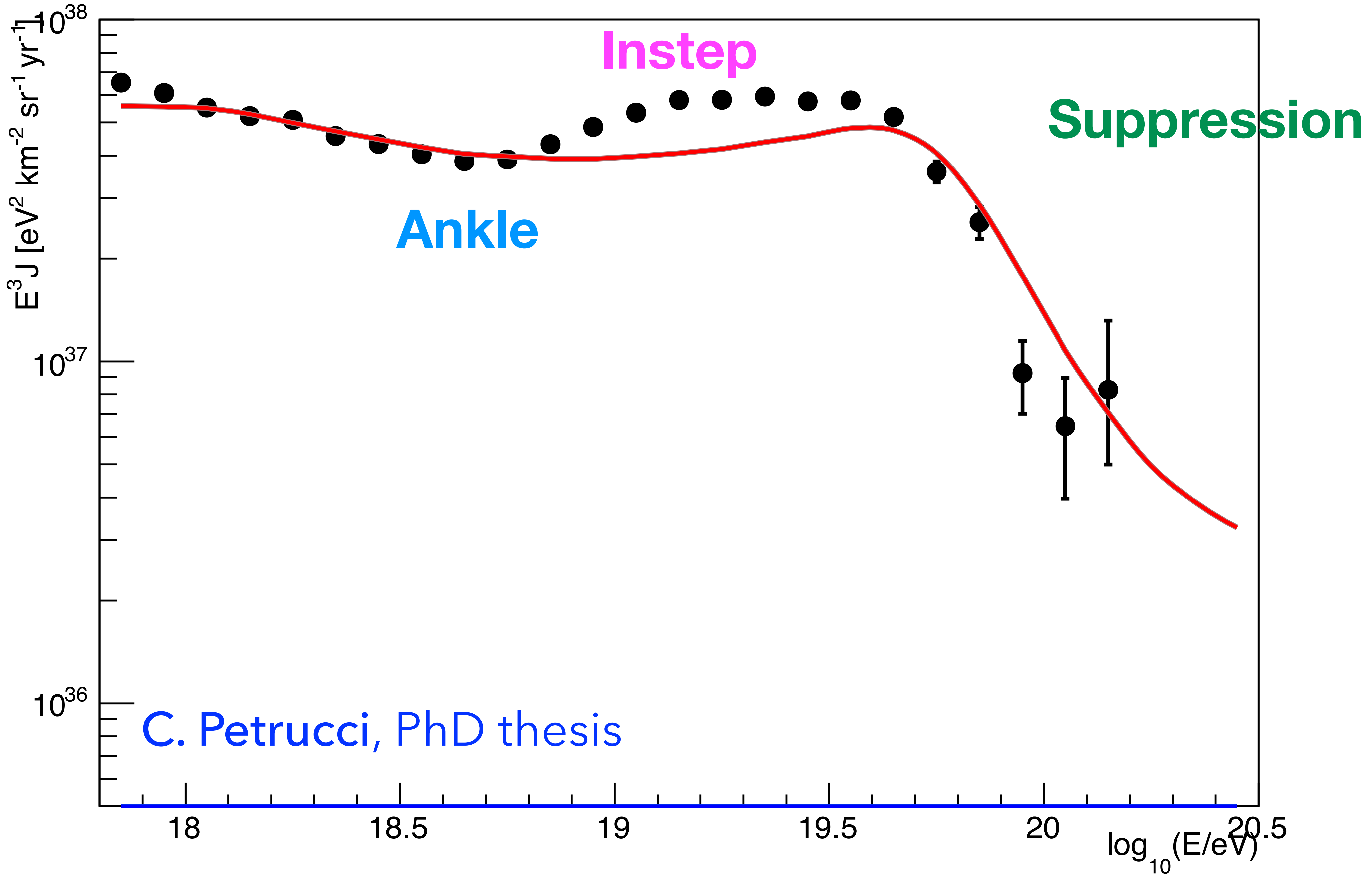

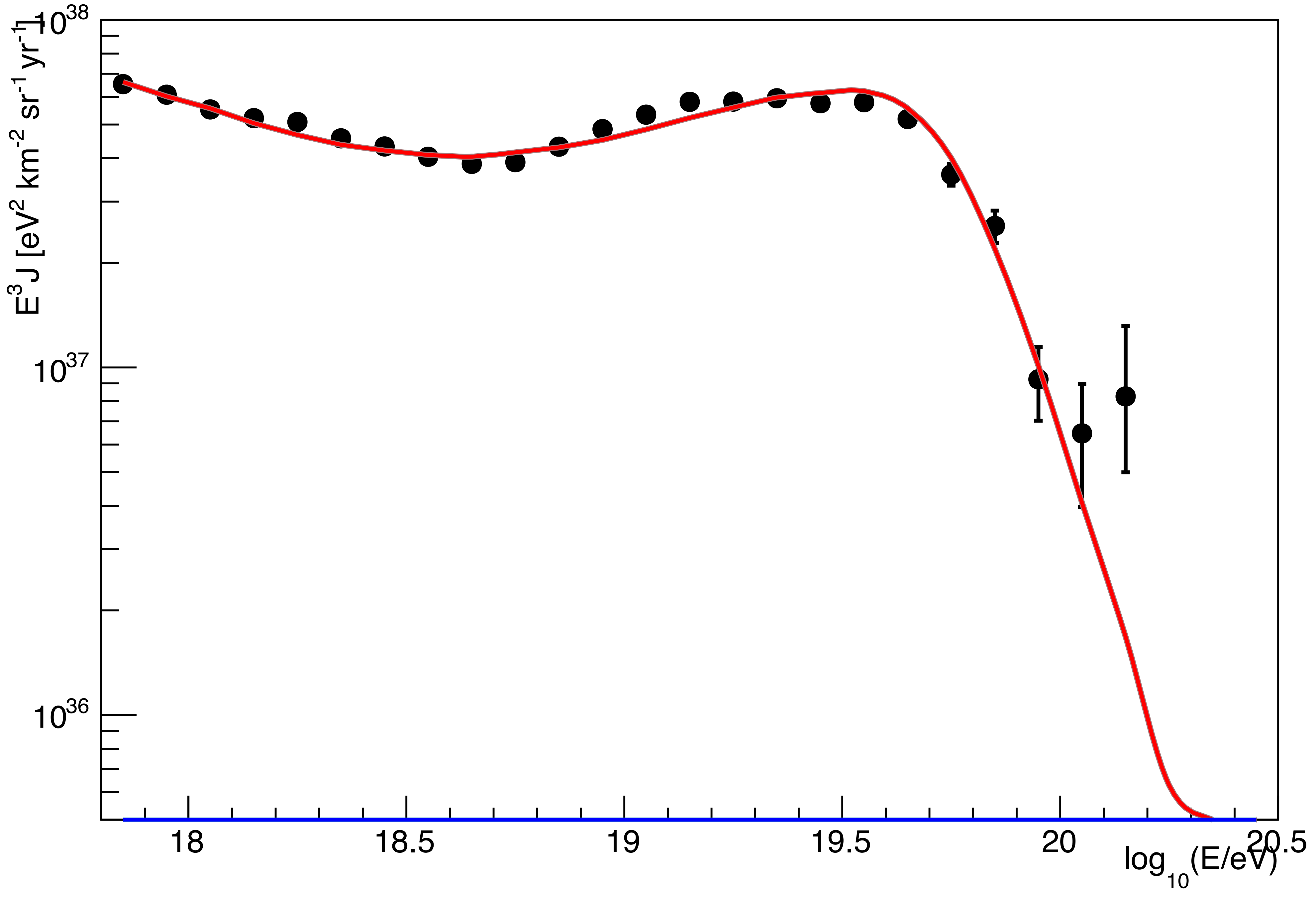

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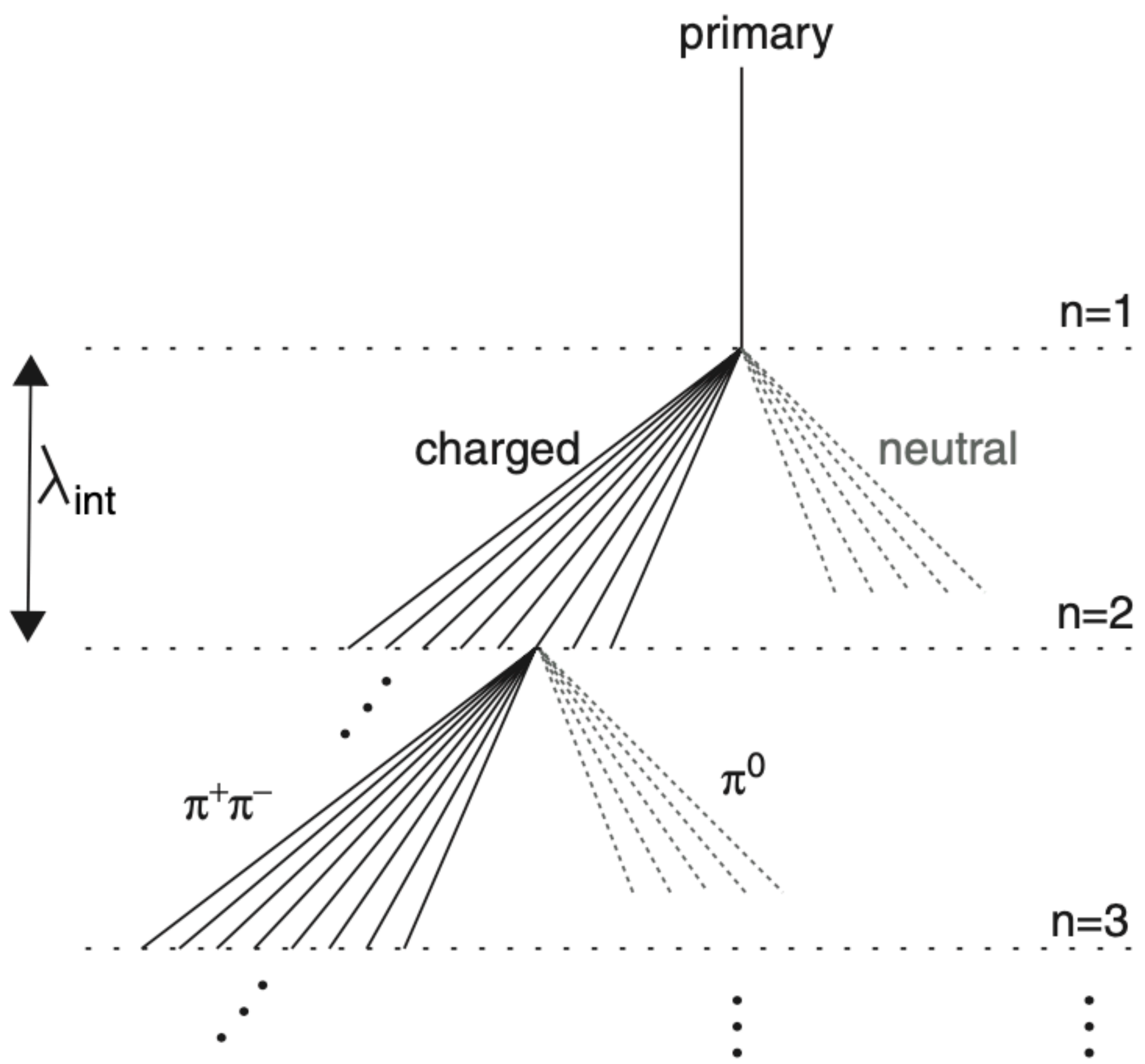
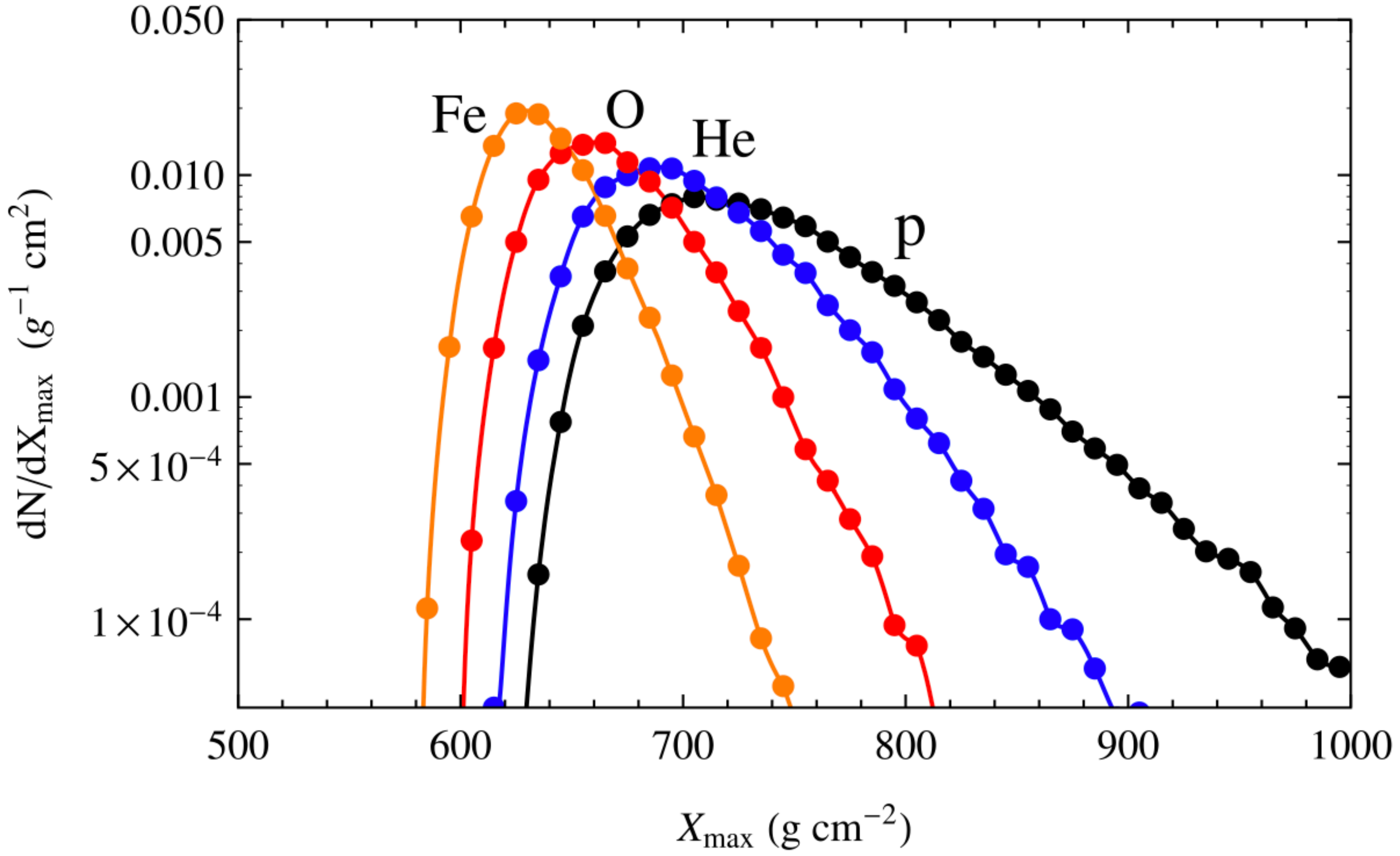
$\gamma = 2.25; \quad E_{\rm cut} = 10^{19.75}$ eV; $\quad m = 5$

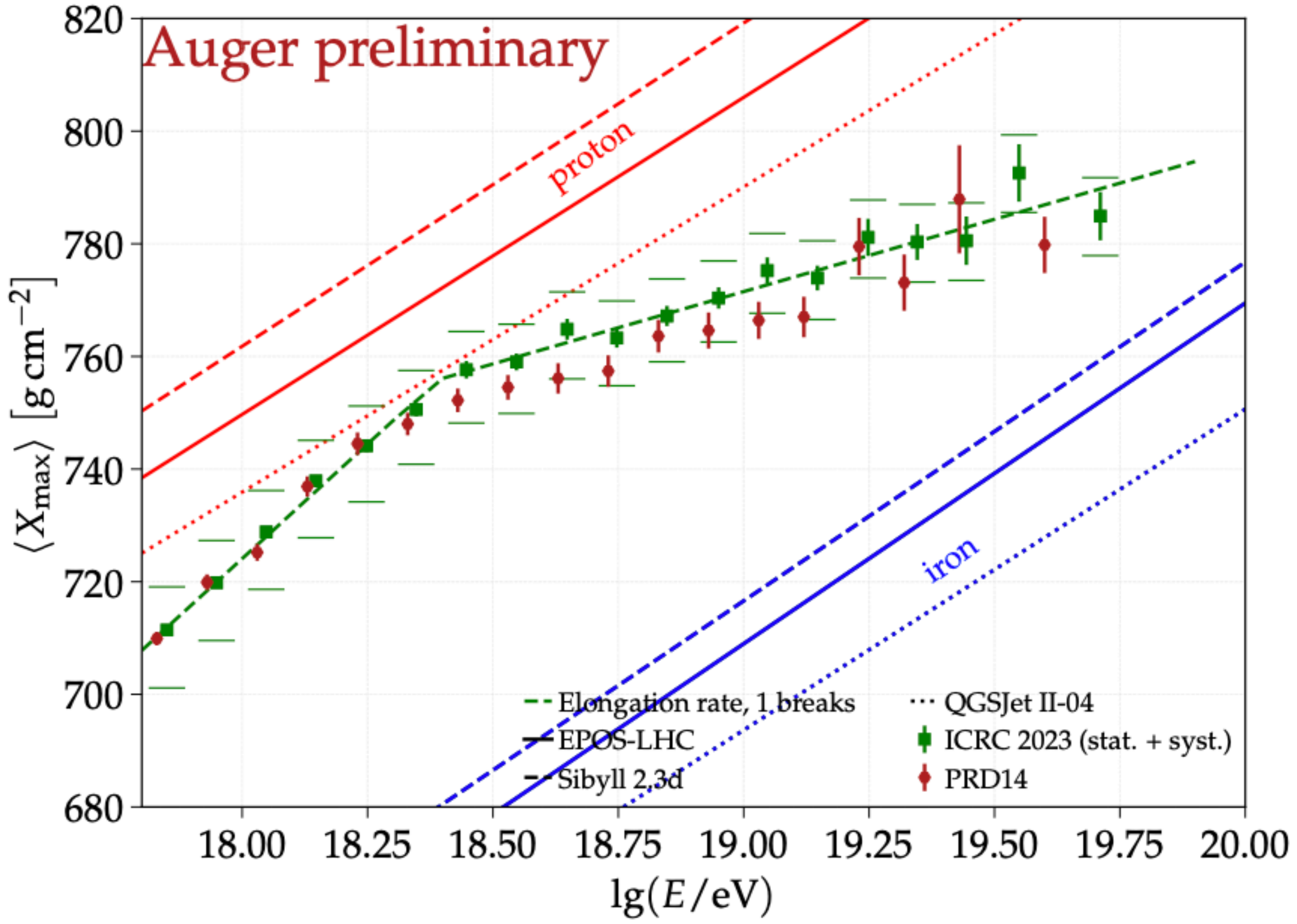
$\chi^2/dof = 483.5/24$

THE **MASS COMPOSITION MEASUREMENTS**



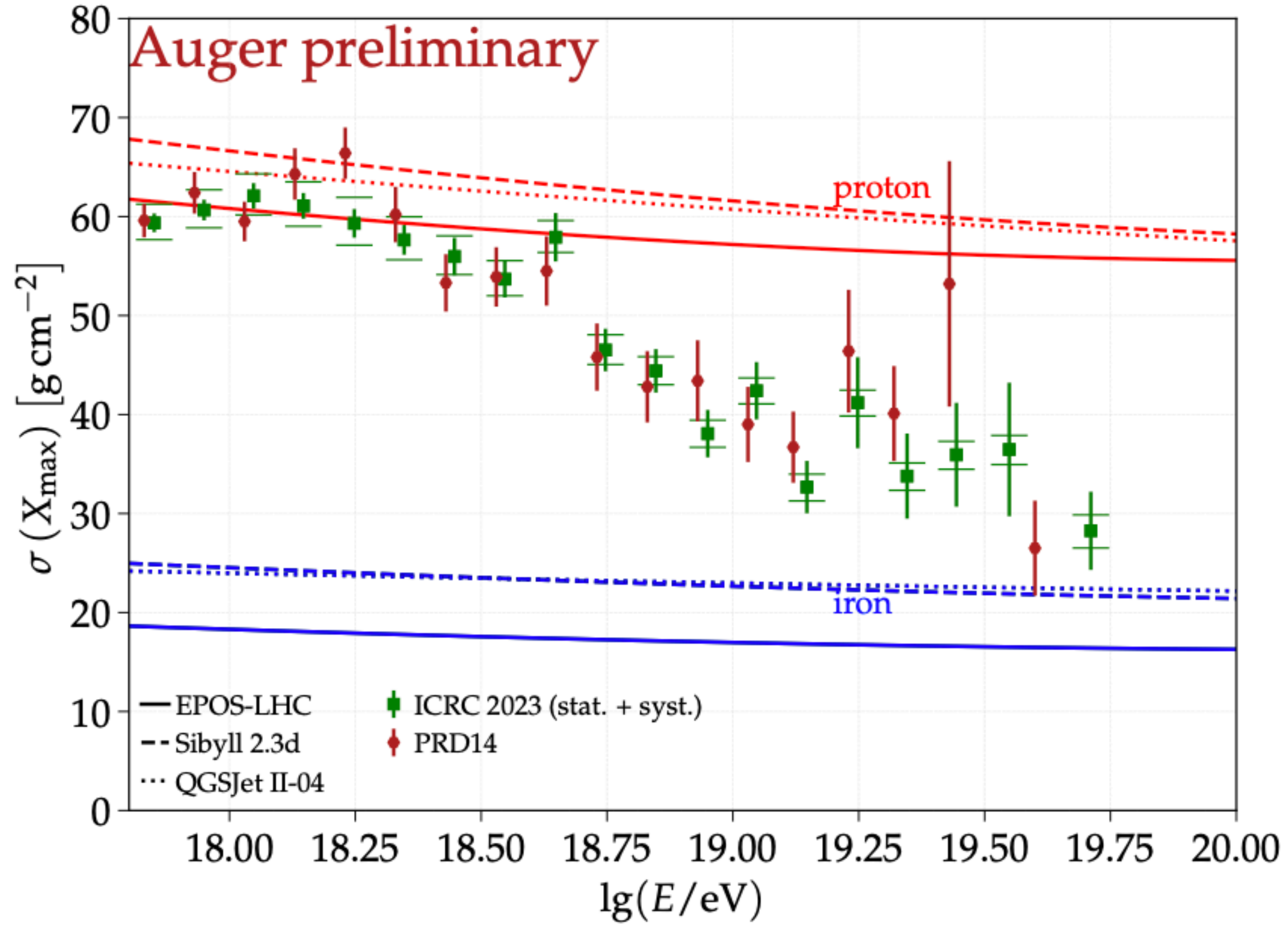


The Pierre Auger Collab. ICRC23



Evidences:

- First momentum: elongation rate is not constant
  -> see also The Auger Collab arxiv:2406.06315 and arxiv:2406.06319
- Second momentum: fluctuations decrease



- See A. Watson EPJ Web Conf. 2023 for a historical overview about composition measurements

WHAT DO WE LEARN FROM THE MASS COMPOSITION OBSERVABLES?

$\langle X_{max} \rangle = \langle X_{max} \rangle_p + f \langle \ln A \rangle$

$\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f^2 \sigma^2(\ln A)$

Focusing on the second momentum: it contains

- the shower-to-shower fluctuations (first term) AND
- the dispersion of the masses as they hit the Earth atmosphere:
  - spread of nuclear masses at the sources
  - modifications that occur during their propagation to the Earth

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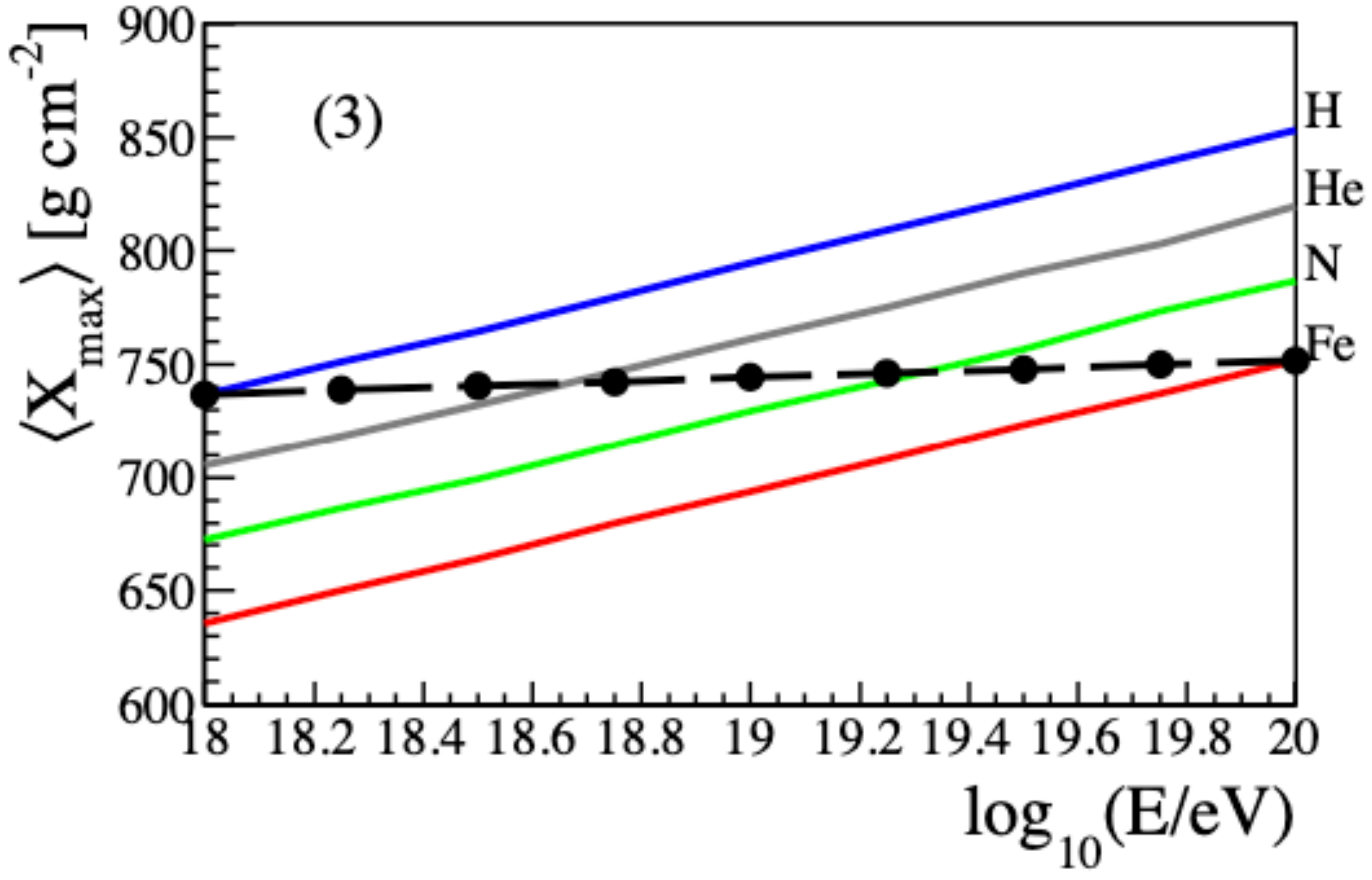
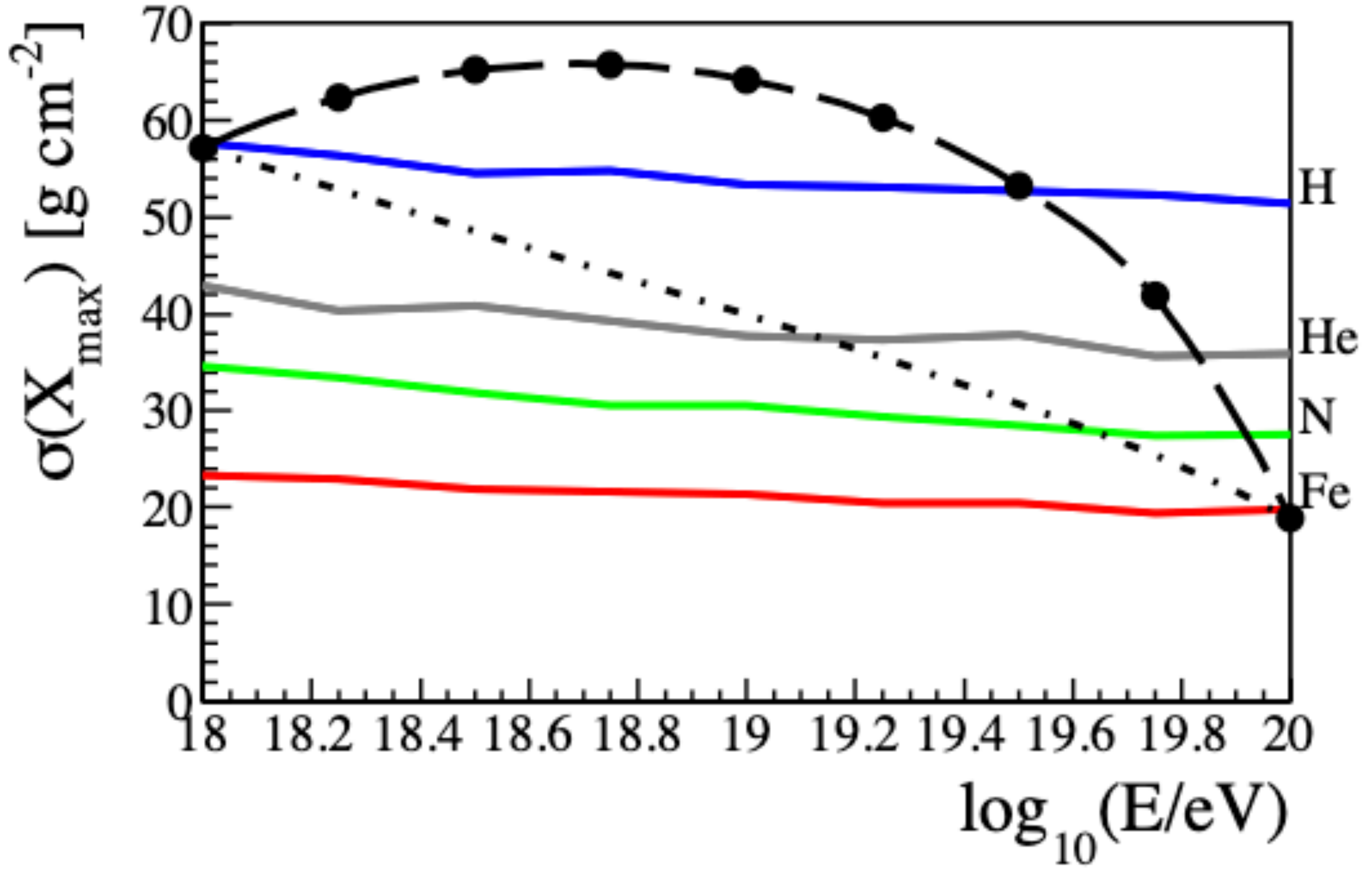
- Example for two components: H and Fe masses, fraction of H decreasing linearly with energy

The Pierre Auger Collab. JCAP 2013





- Dispersion of the masses in the case of two components:

$$\sigma^2(X_{max}) =$$

$$f\sigma_1^2 + (1-f)\sigma_2^2 + f(1-f)(\Delta(\langle X_{max} \rangle))^2$$

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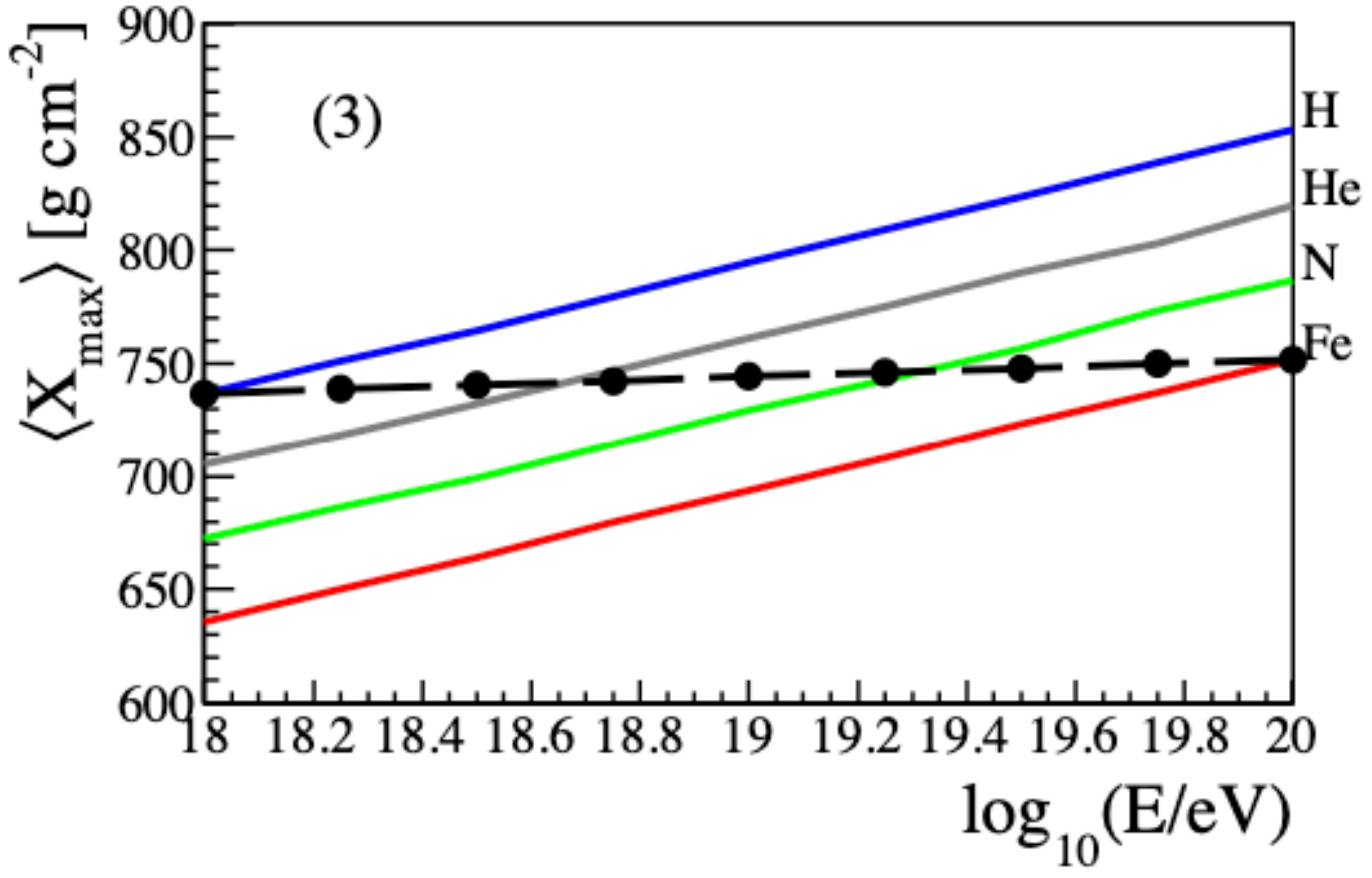
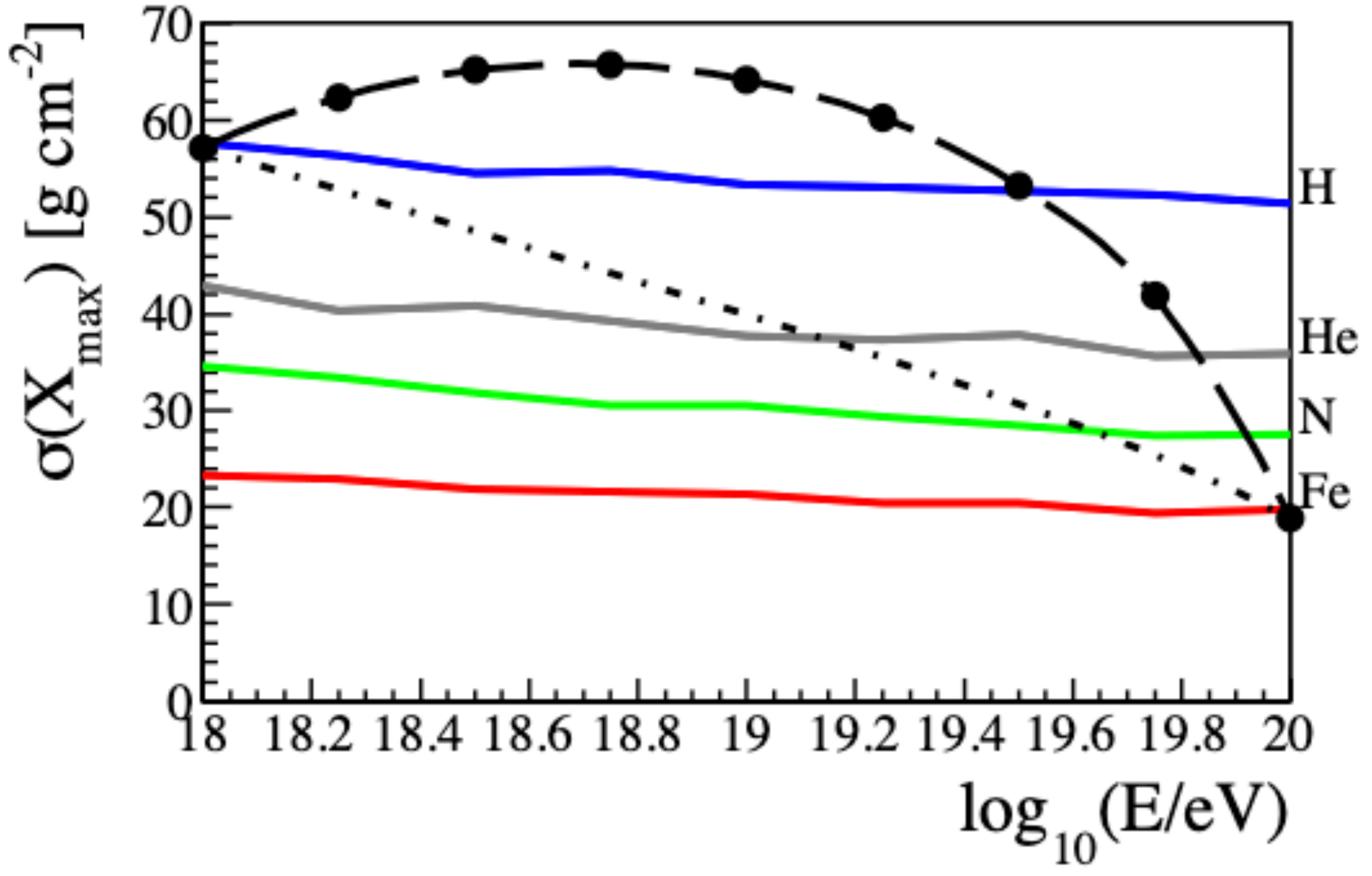
Requirements from the mass composition measurements, in terms of astrophysical scenarios:

- Average mass increasingly heavy after the ankle
- Minimal superposition of different nuclear species

The Pierre Auger Collab. JCAP 2013





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ASTROPHYSICAL INTERPRETATION(S)

Basic scenario (energies above the ankle):

- identical sources
- power-law spectra at escape, with rigidity dependence $Q_A(E) \propto f_A\, E^{-\gamma} f_{\rm cut}(E, Z_A R_{\rm cut})$

Extragalactic propagation taken into account; results presented in this talk are mainly obtained with:

- **CRPropa**, R. Alves Batista et al, JCAP 2022
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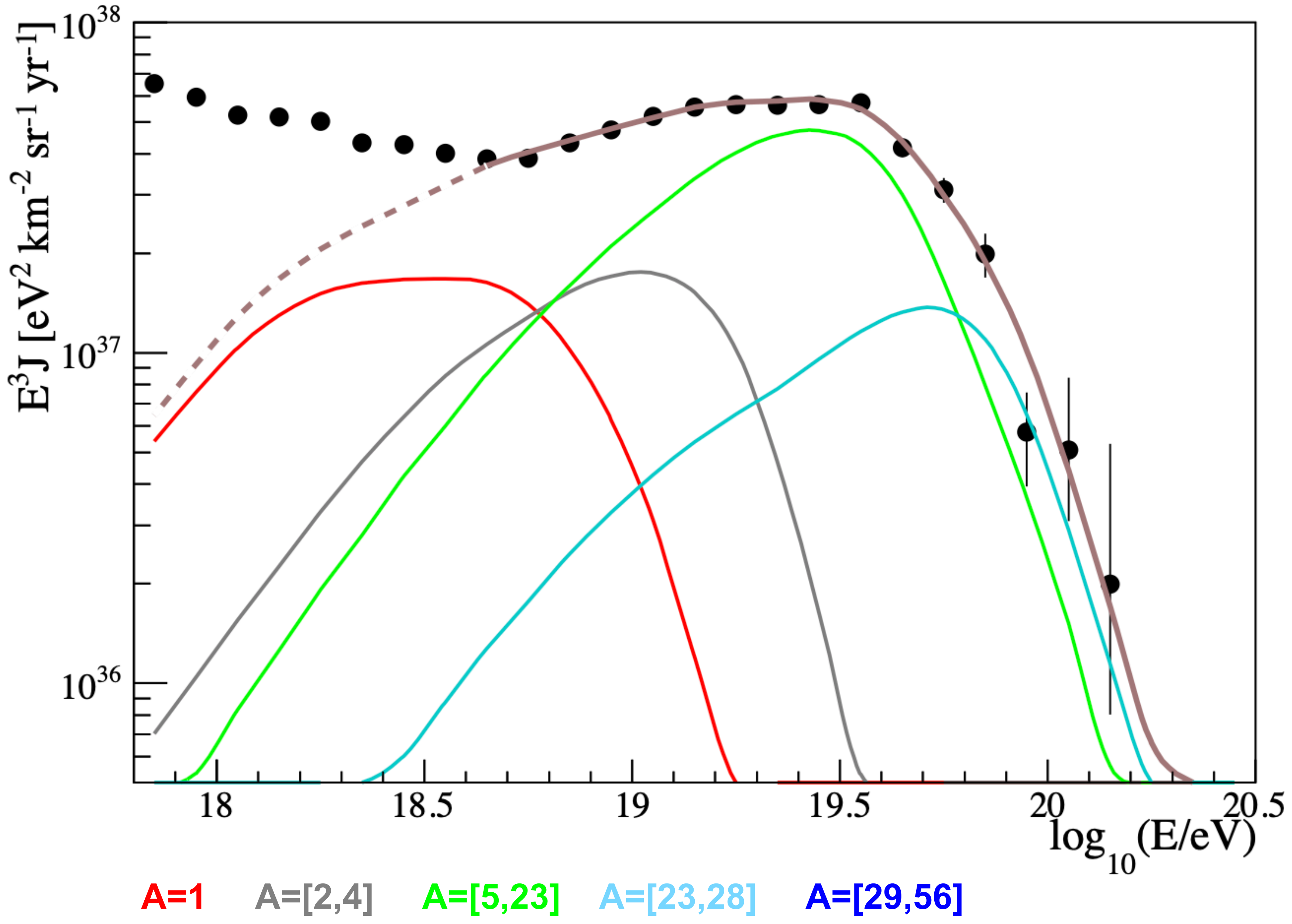
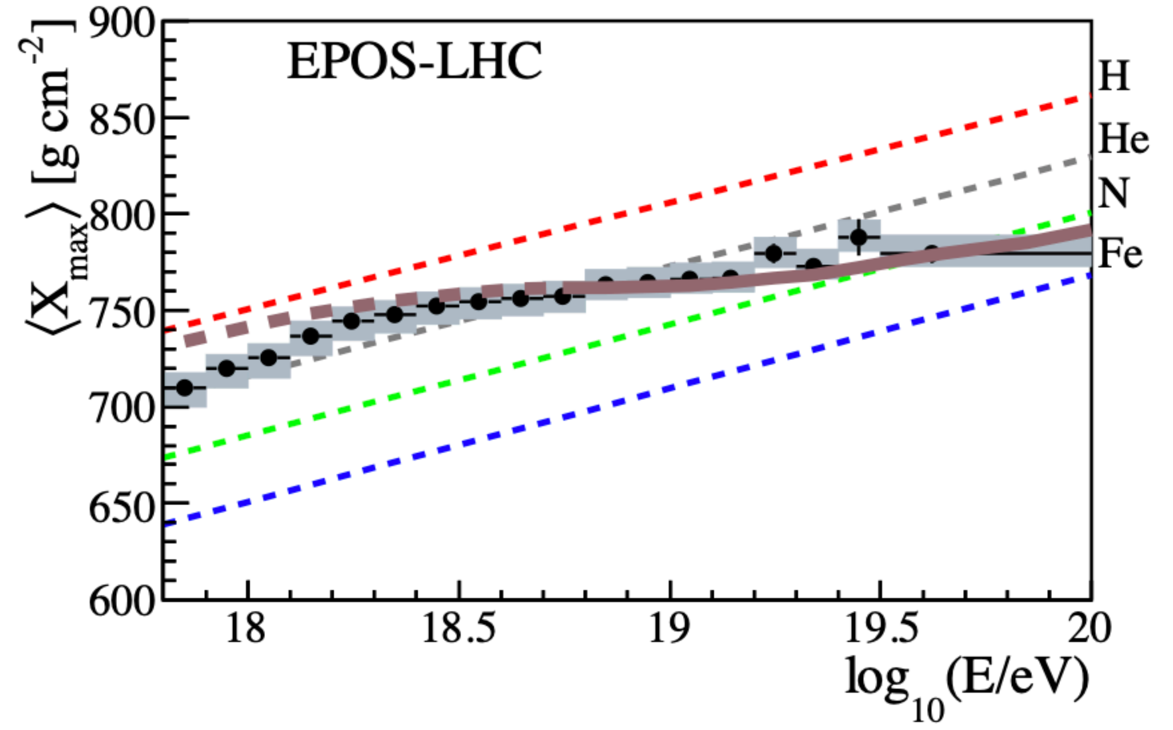
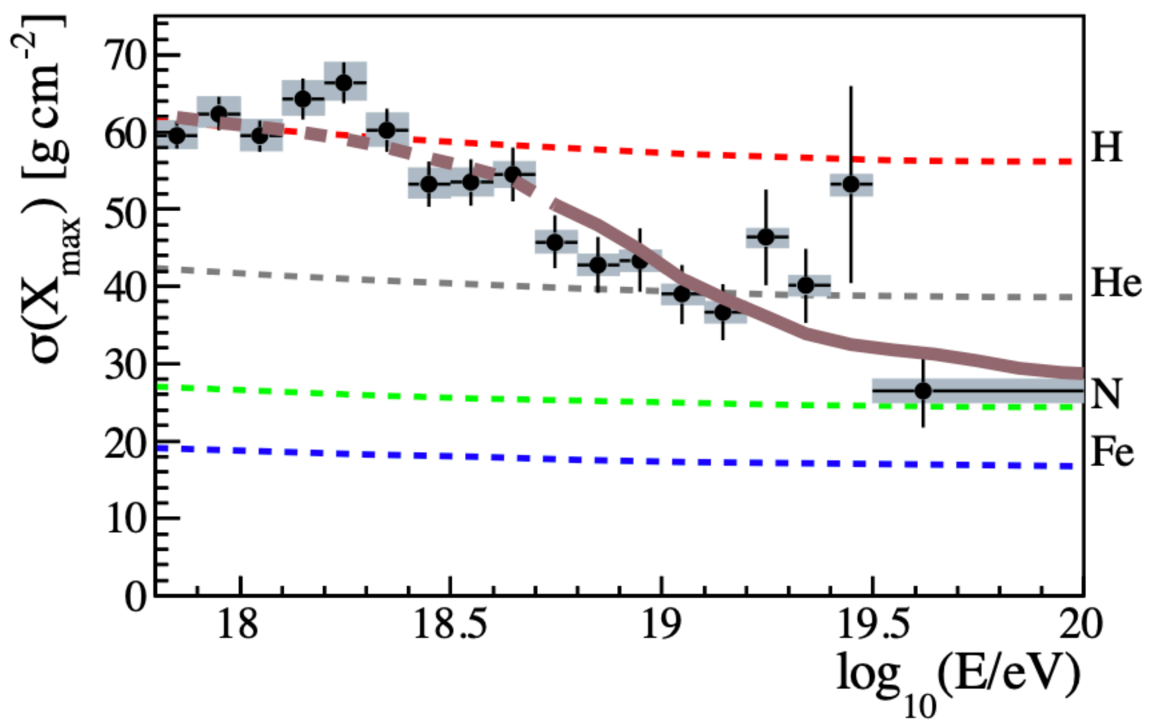
The Pierre Auger Collab. JCAP 2017







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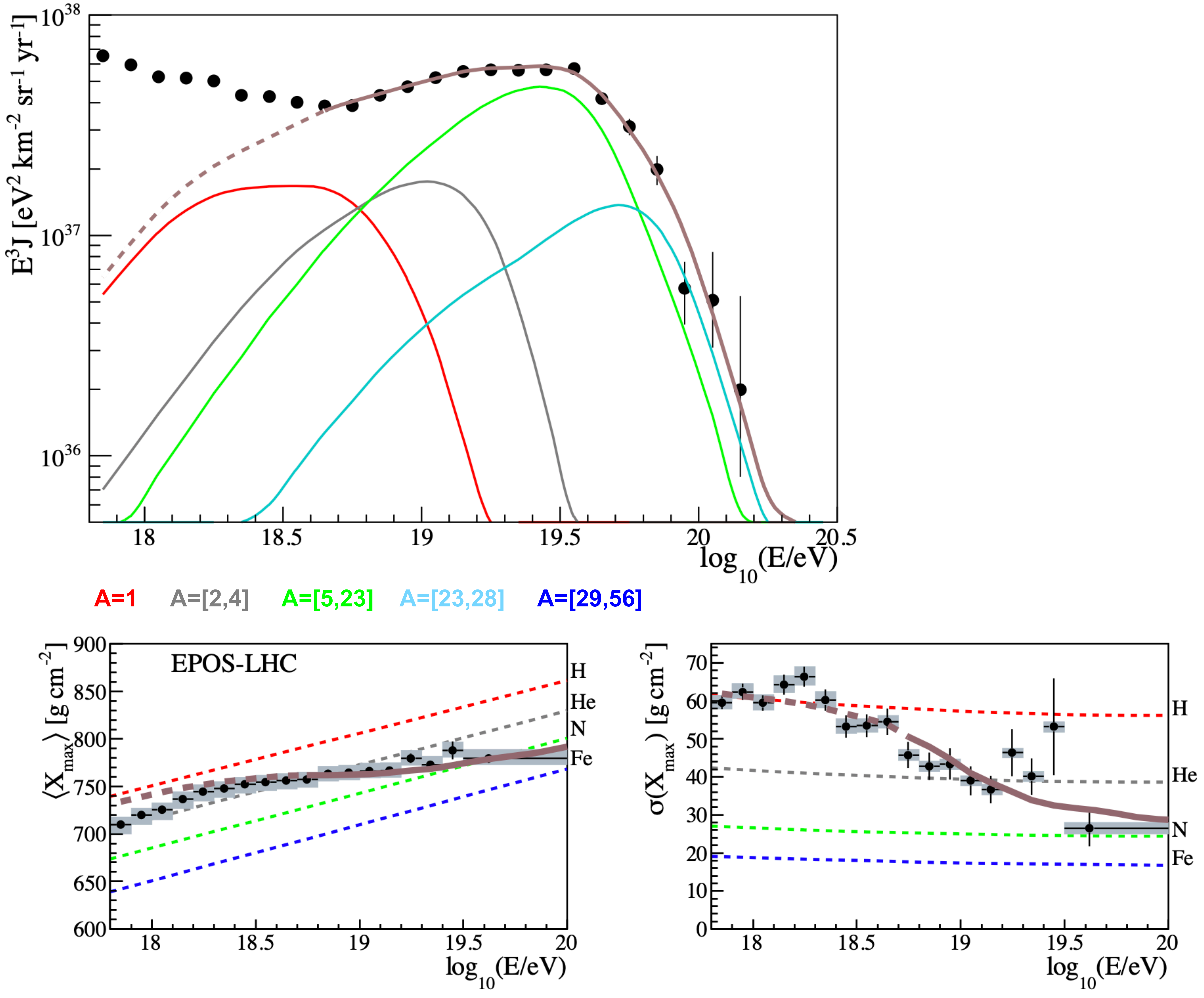

(SPG – EPOS-LHC)	best fit
$\mathcal{L}_0$ $[10^{44}$ erg Mpc^{-3} yr$^{-1}]$	4.99
γ	$0.96^{+0.08}_{-0.13}$
$\log_{10}(R_{\rm cut}/\rm V)$	$18.68^{+0.02}_{-0.04}$
$f_{\rm H}(\%)$	0.0
$f_{\rm He}(\%)$	67.3
$f_{\rm N}(\%)$	28.1
$f_{\rm Si}(\%)$	4.6
$f_{\rm Fe}(\%)$	0.0
D/n	174.4/119

- UHECR source population contributing **above the ankle**:
  - Hard spectral index
  - Low rigidity cutoff
  - Intermediate nuclear species

A ***disappointing model*** overall… (see Aloisio, Berezinsky & Gazizov, Astropart. Phys. 2011)

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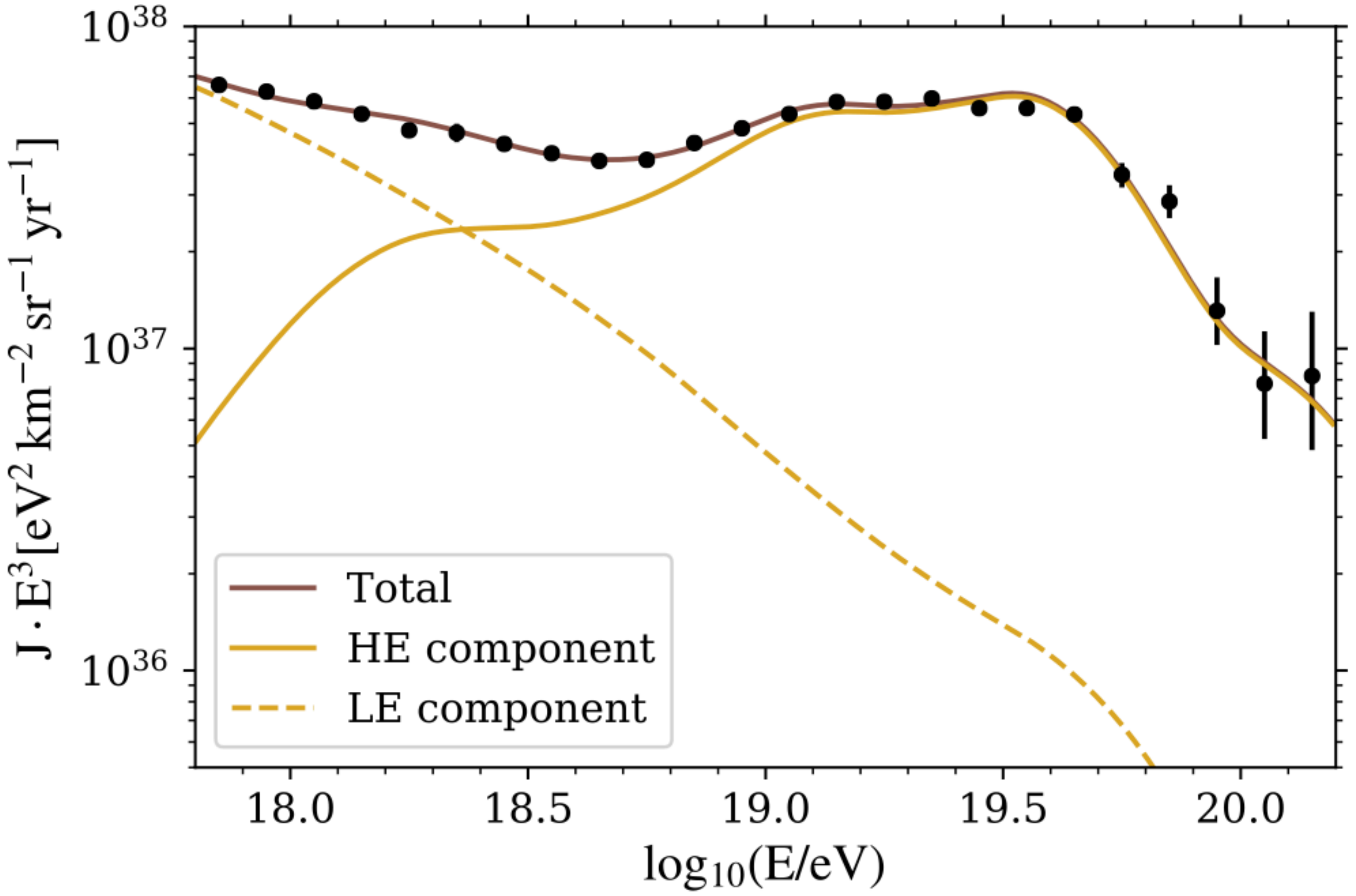

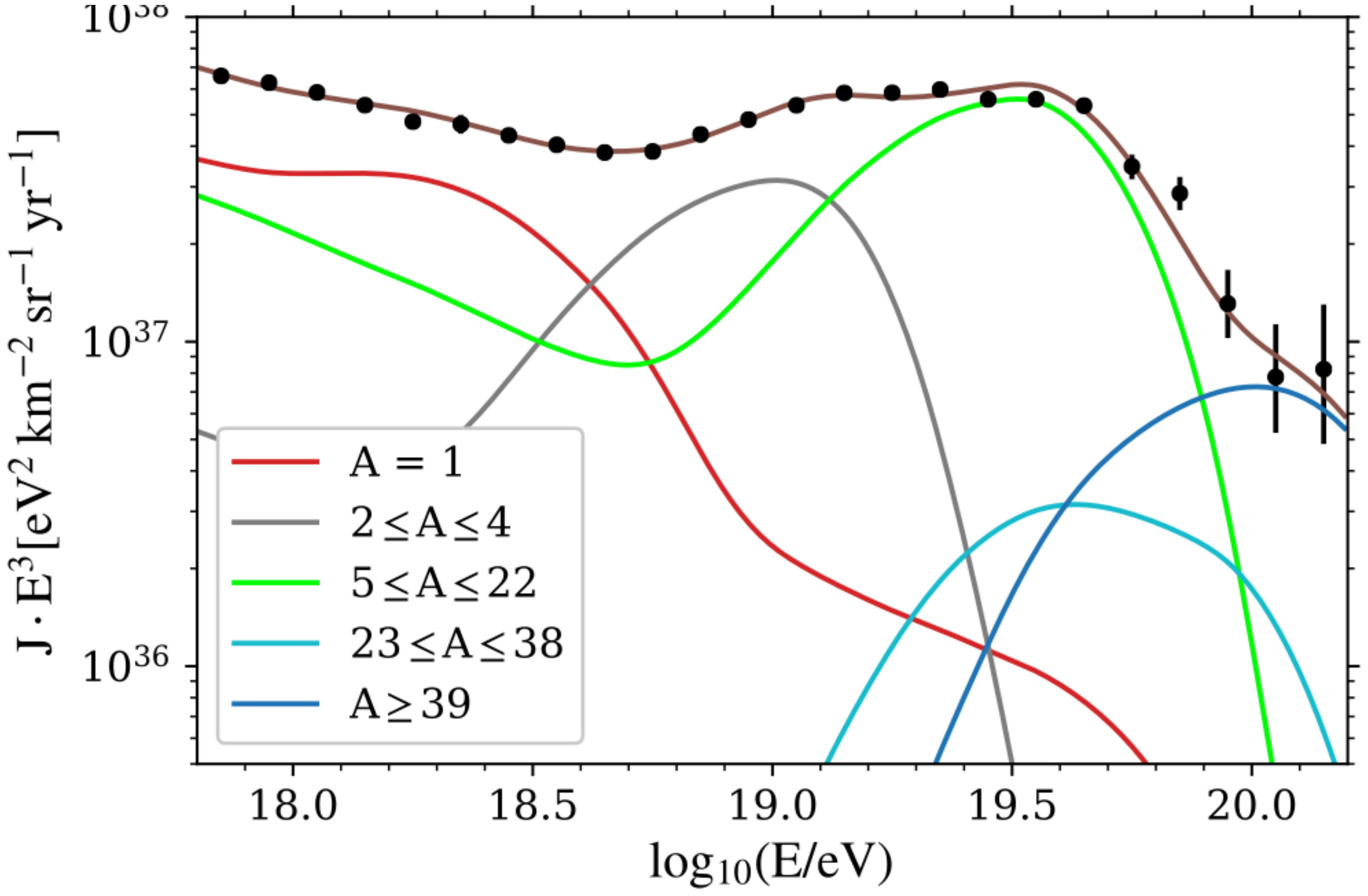

Towards energy below the ankle -> two components are needed to fit the data

- Different populations of sources contributing at LE and HE
- One population of sources, softer spectrum of protons due to in-source interactions
  - Contribution from heavier particles below the ankle needed to account for
    - mixed composition
    - missing flux

Aloisio, Berezinsky & Blasi JCAP 2014; Mollerach & Roulet PRD 2020; Das et al, Eur.Phys.J. 2021; Luce et al, ApJ 2022;**The Auger Collab. JCAP 2023**

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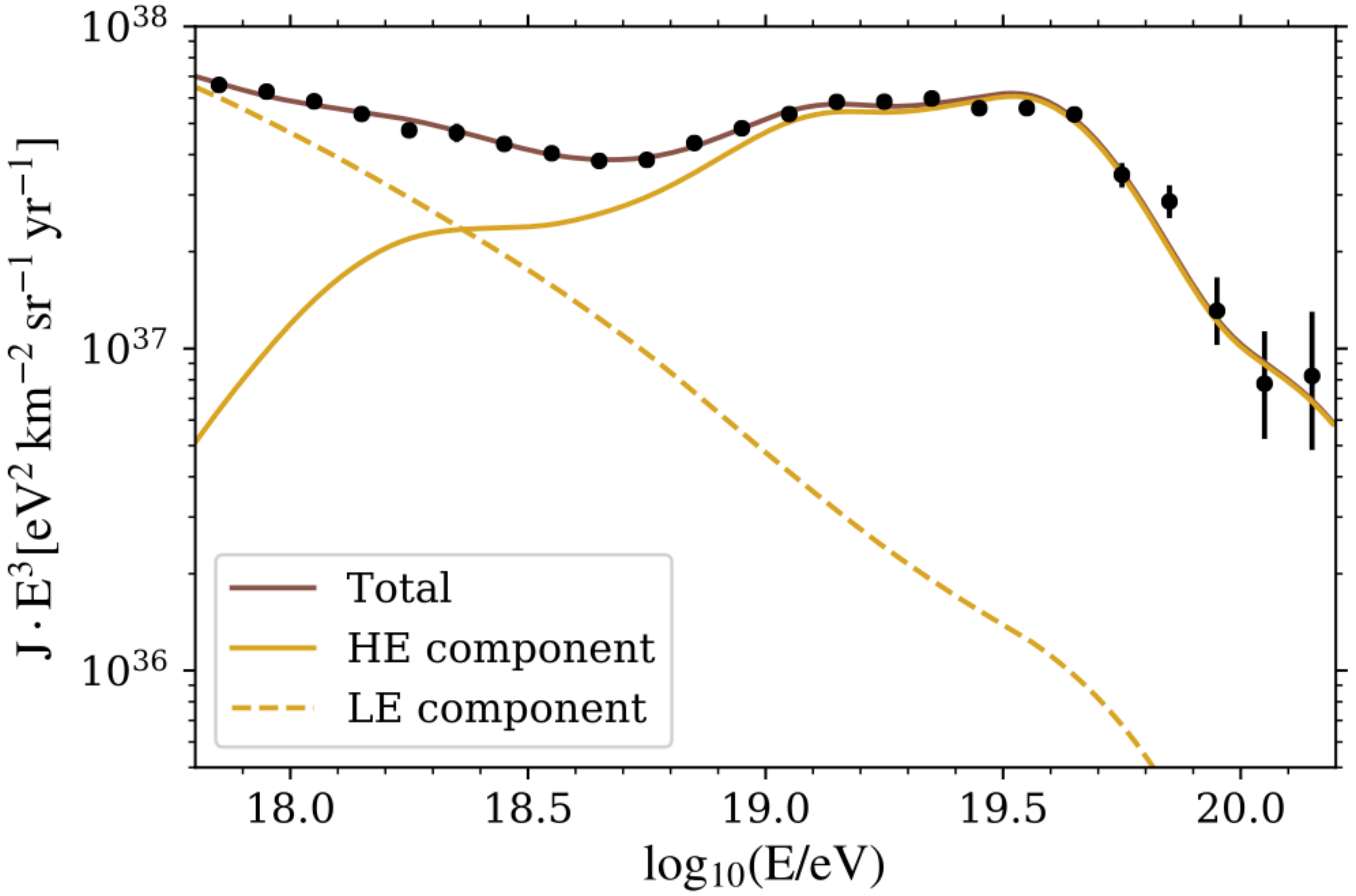

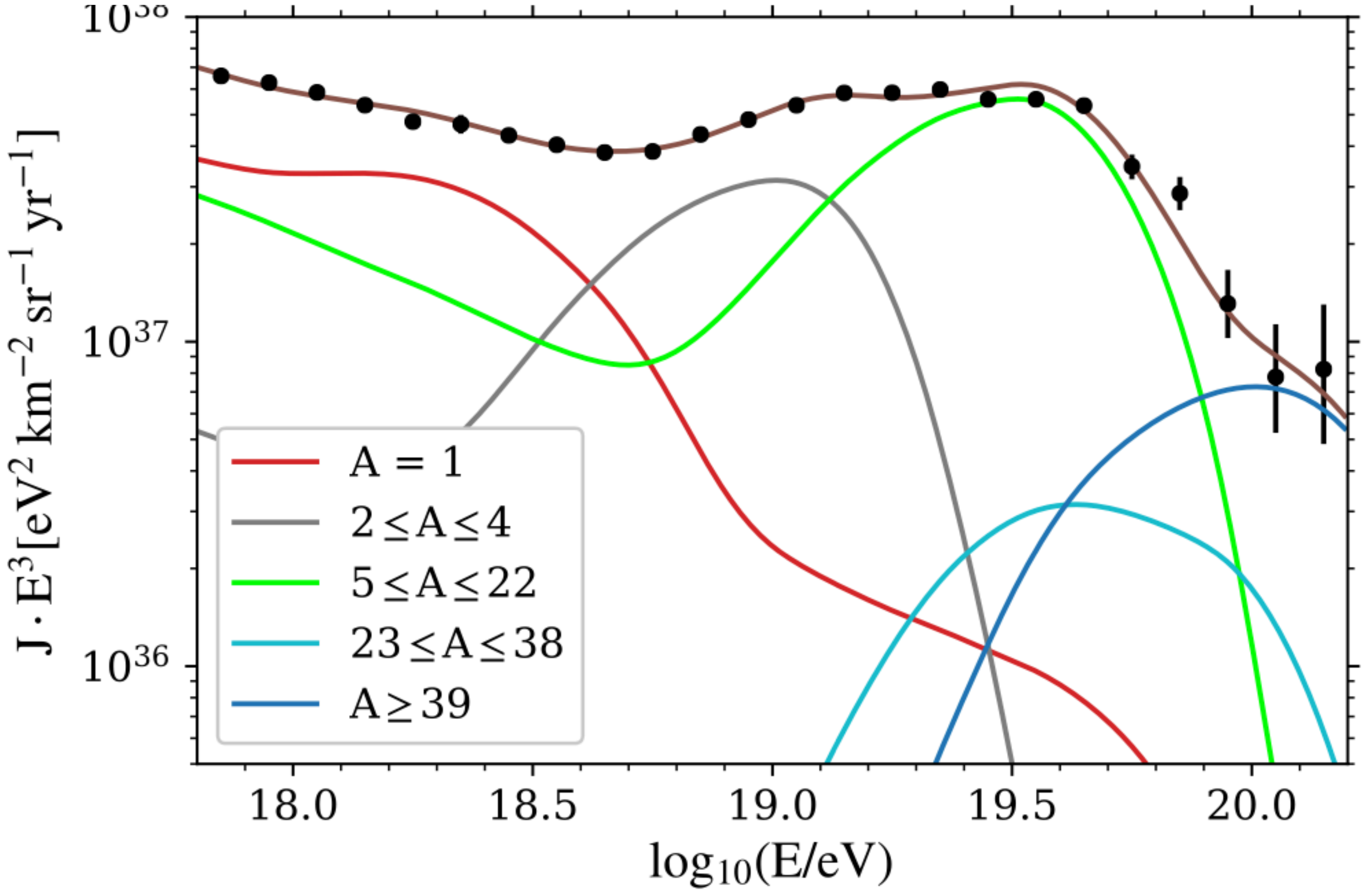

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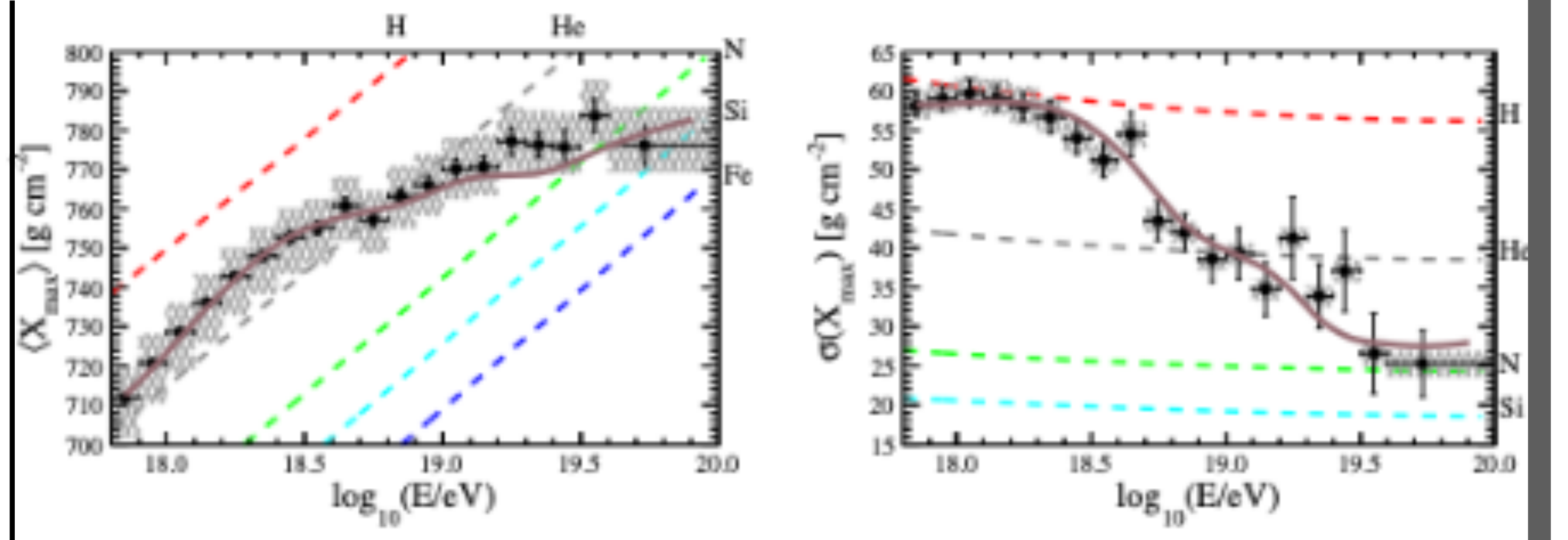
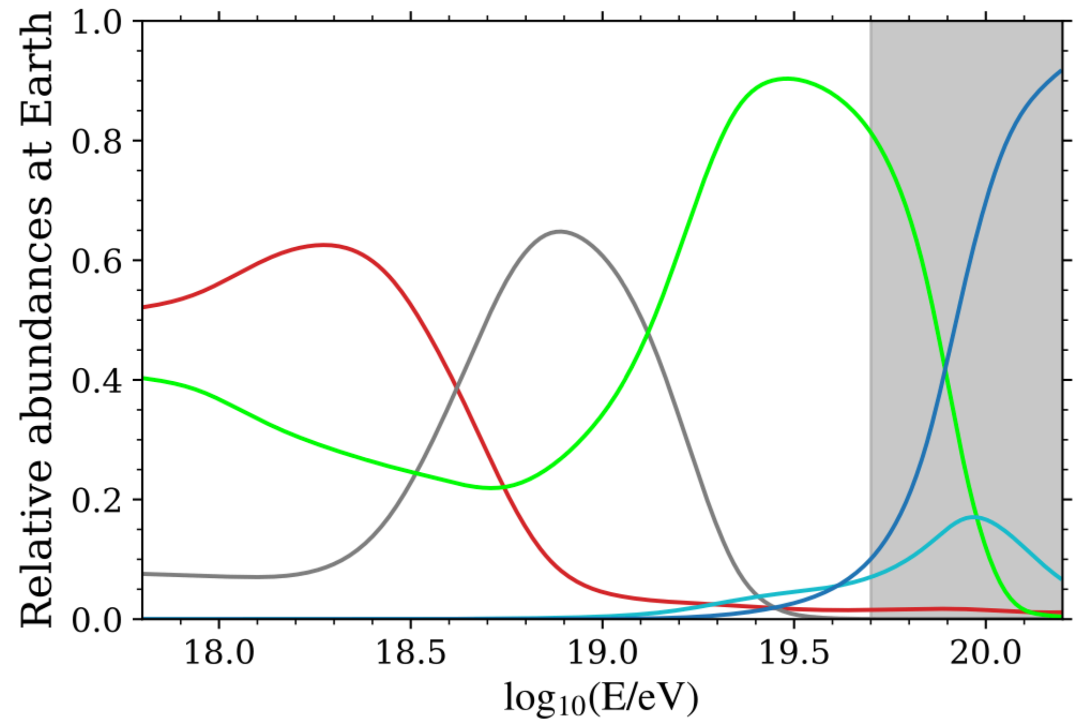
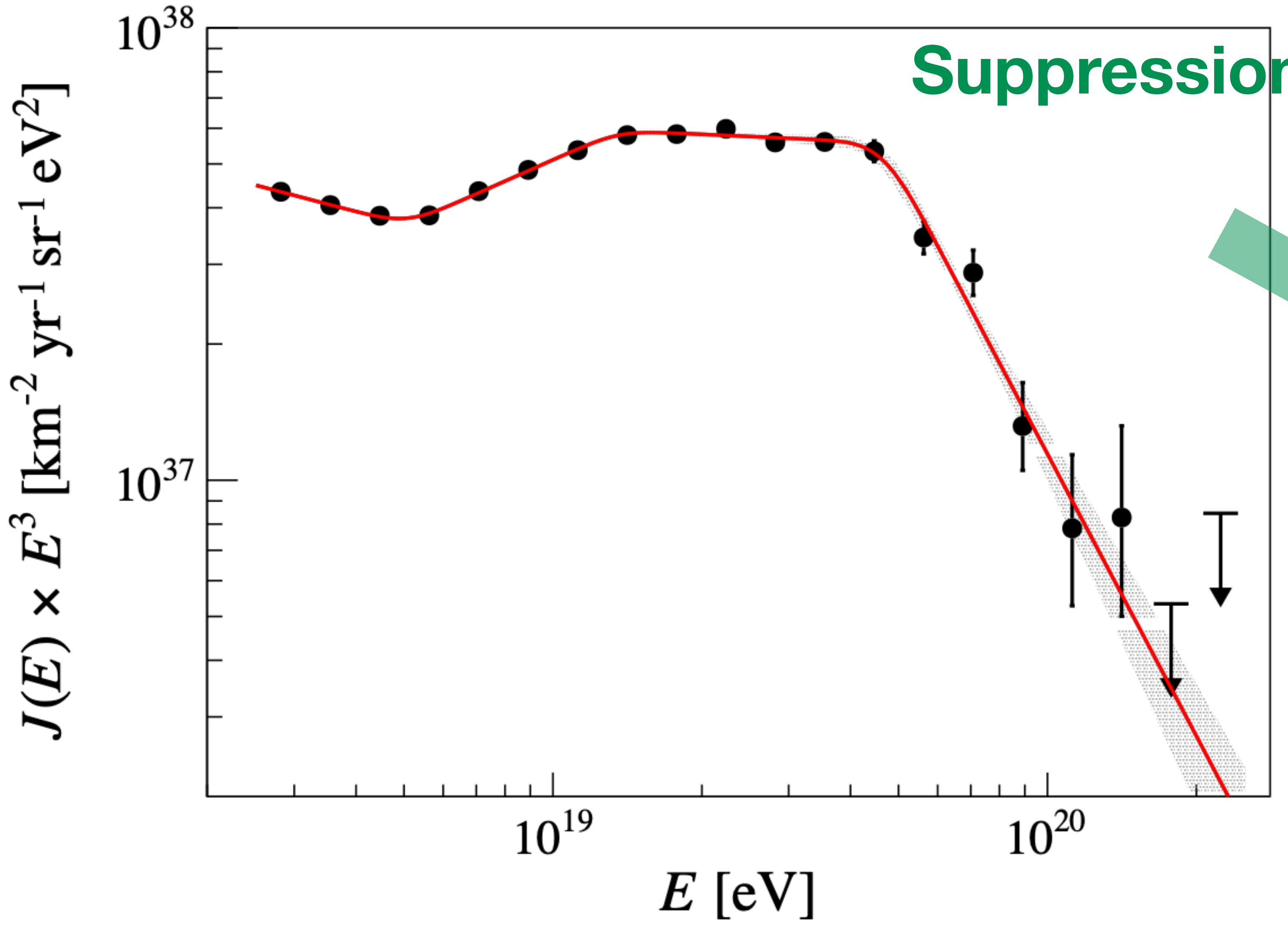


- Independently of the scenario, decreasing fluctuations of Xmax can be found corresponding to **limited mixing of spectra of different nuclear species at HE**, meaning
  - HE: hard spectra + low rigidity cutoff
  - LE: soft spectra + less constrainable rigidity



WHAT IS THE ORIGIN OF THE SPECTRUM (AND COMPOSITION) FEATURES ?

The Pierre Auger Collab. JCAP 2023



Not only GZK !

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In terms of interpretation, the **suppression is a combination of effects**

- Propagation effect
- Indication of source power

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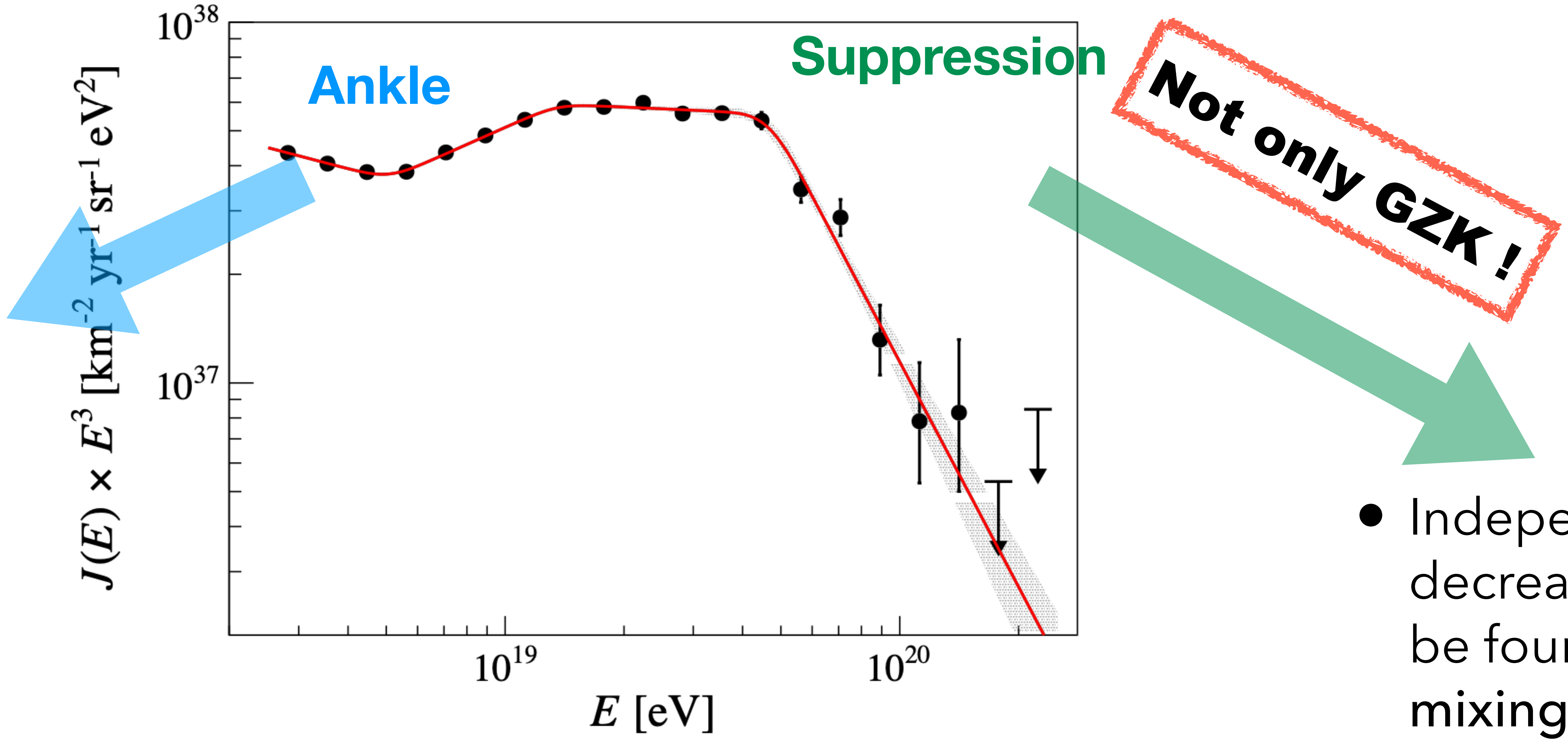

Ankle: interplay between (soft) LE and (hard) HE components

- Different populations of UHECR sources
- In-source interactions

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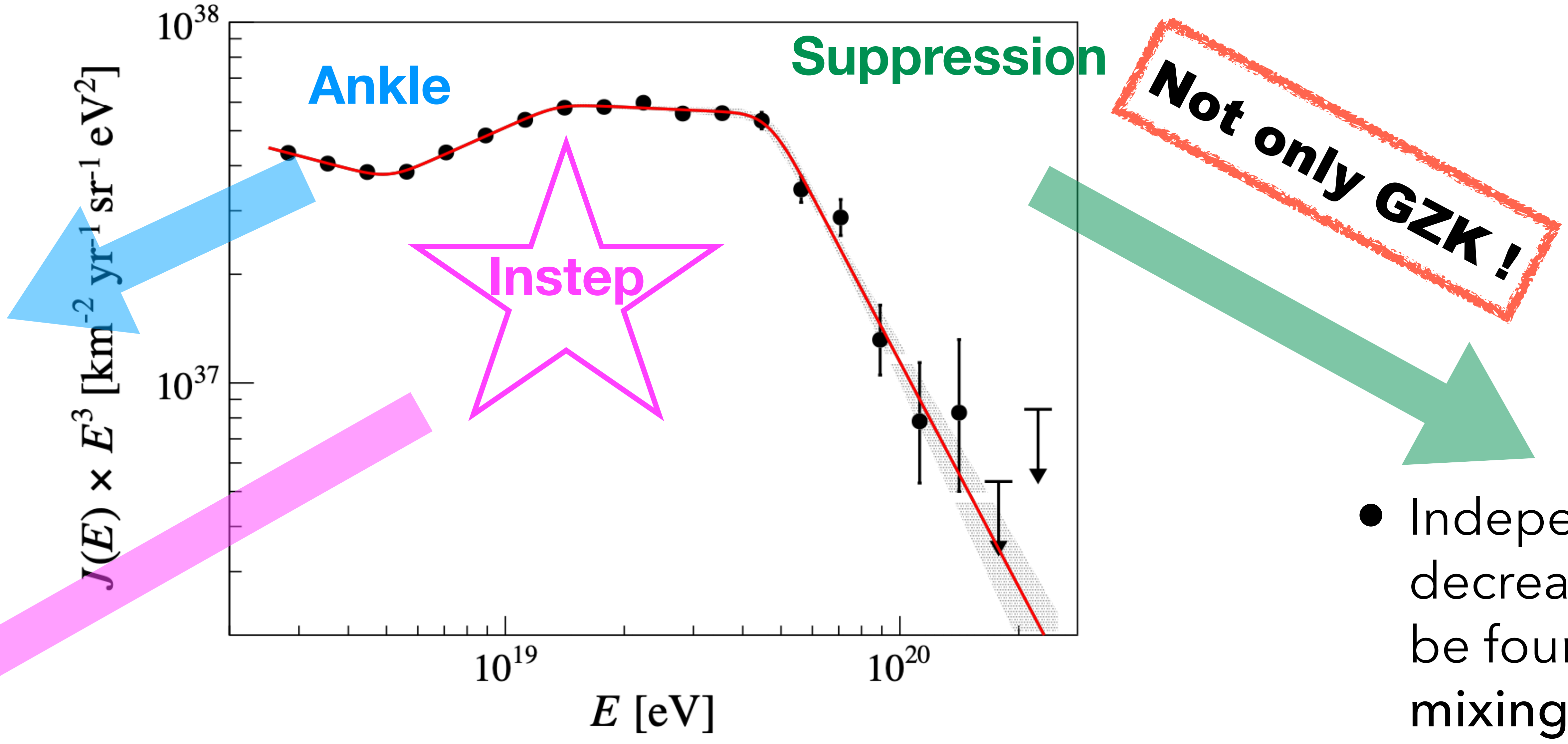

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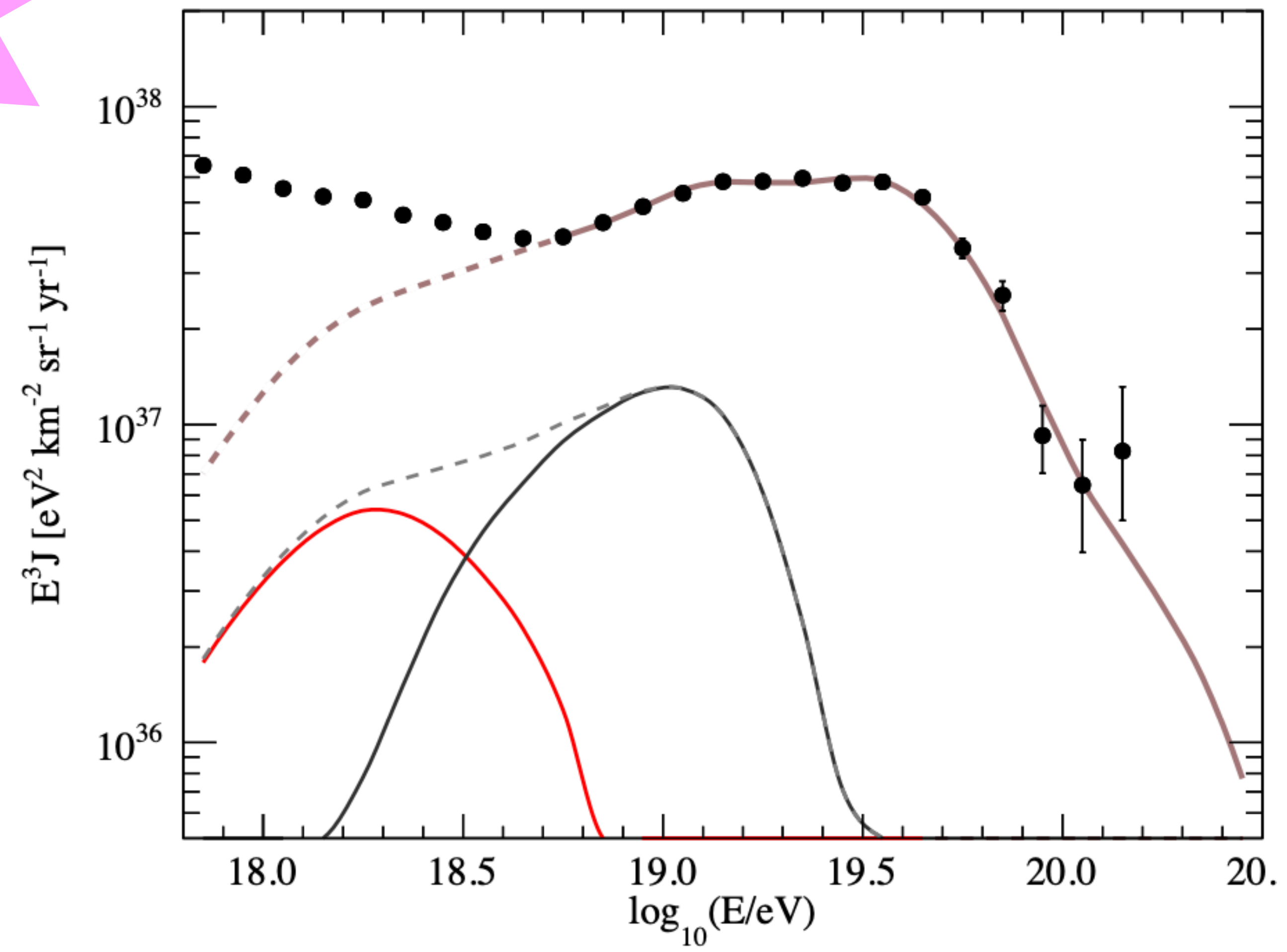
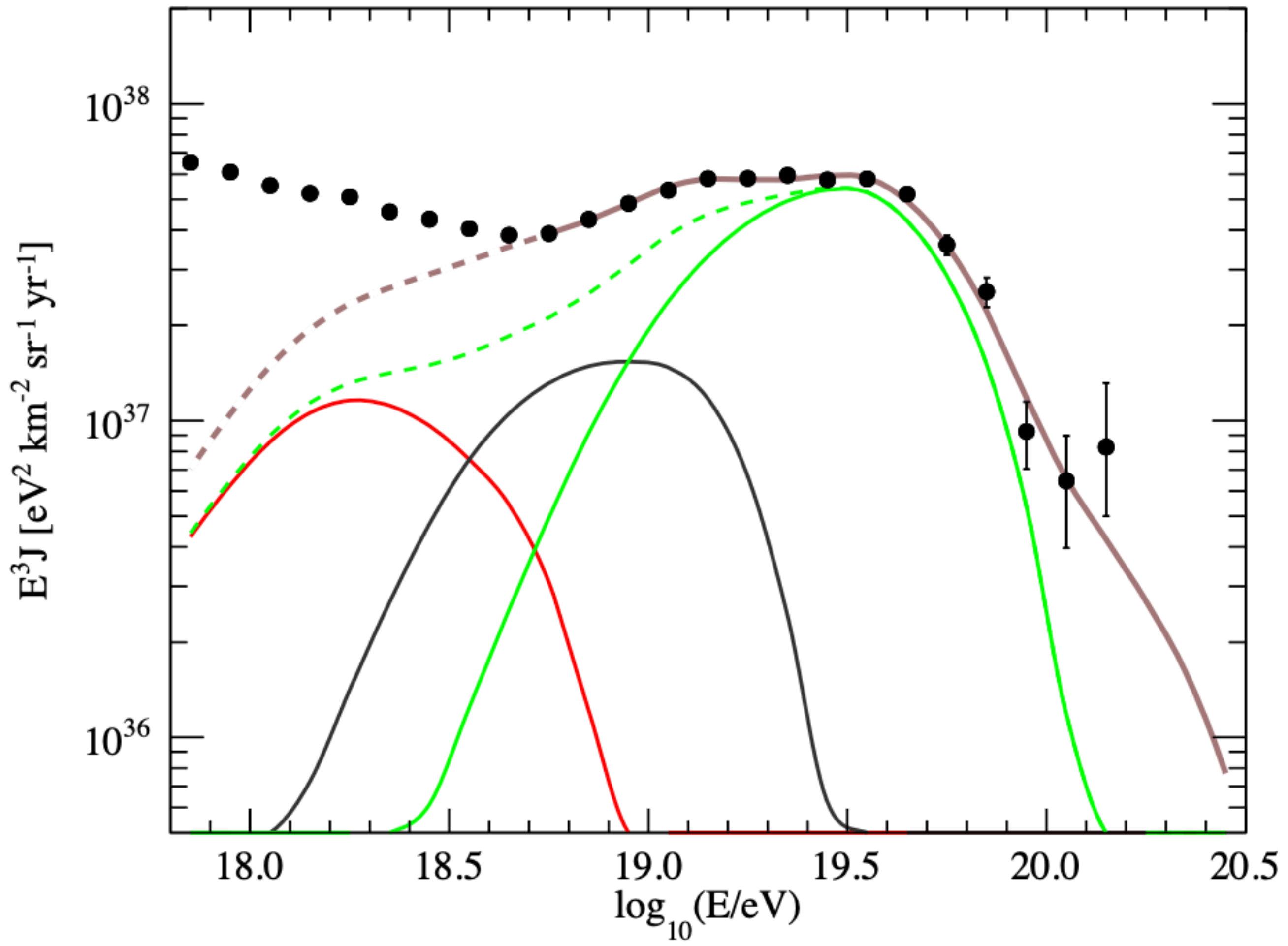
Instep: interplay between the flux contributions of the He and CNO components





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REFINING THE BASIC PICTURE

- **(Some of the) remaining open issues:**
  - How to accelerate particles to UHE?
  - Which sources are responsible for accelerating heavy nuclei?
  - How to get a harder spectrum at the escape for nuclei, and a softer one for protons?
  - What is the cosmological evolution of the sources?

- Investigating the source distribution
- Including the effects of the propagation in magnetic fields
- Taking into account the (possible) transient nature of UHECR sources
- Investigating the UHECR spectrum shape at the escape from UHECR sources
  - Relaxing the assumption of identical sources
  - Investigating the validity of the Peters cycle
- Including additional information from other messengers (produced in sources and/or in the extragalactic propagation)

UHECRS:
WHAT IS THE COSMOLOGICAL EVOLUTION OF THEIR SOURCES ?

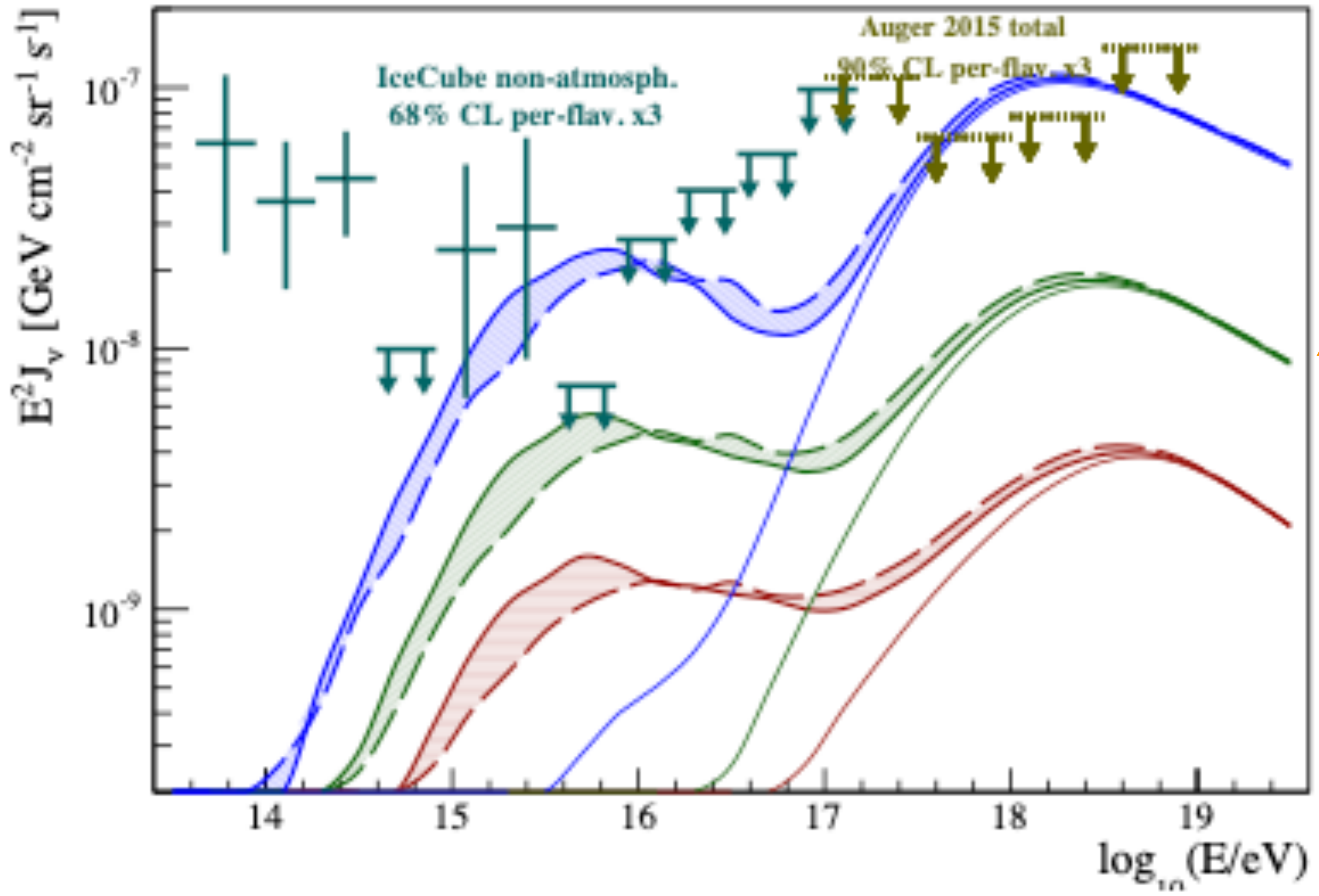
UHECR flux at Earth and the corresponding cosmogenic neutrinos

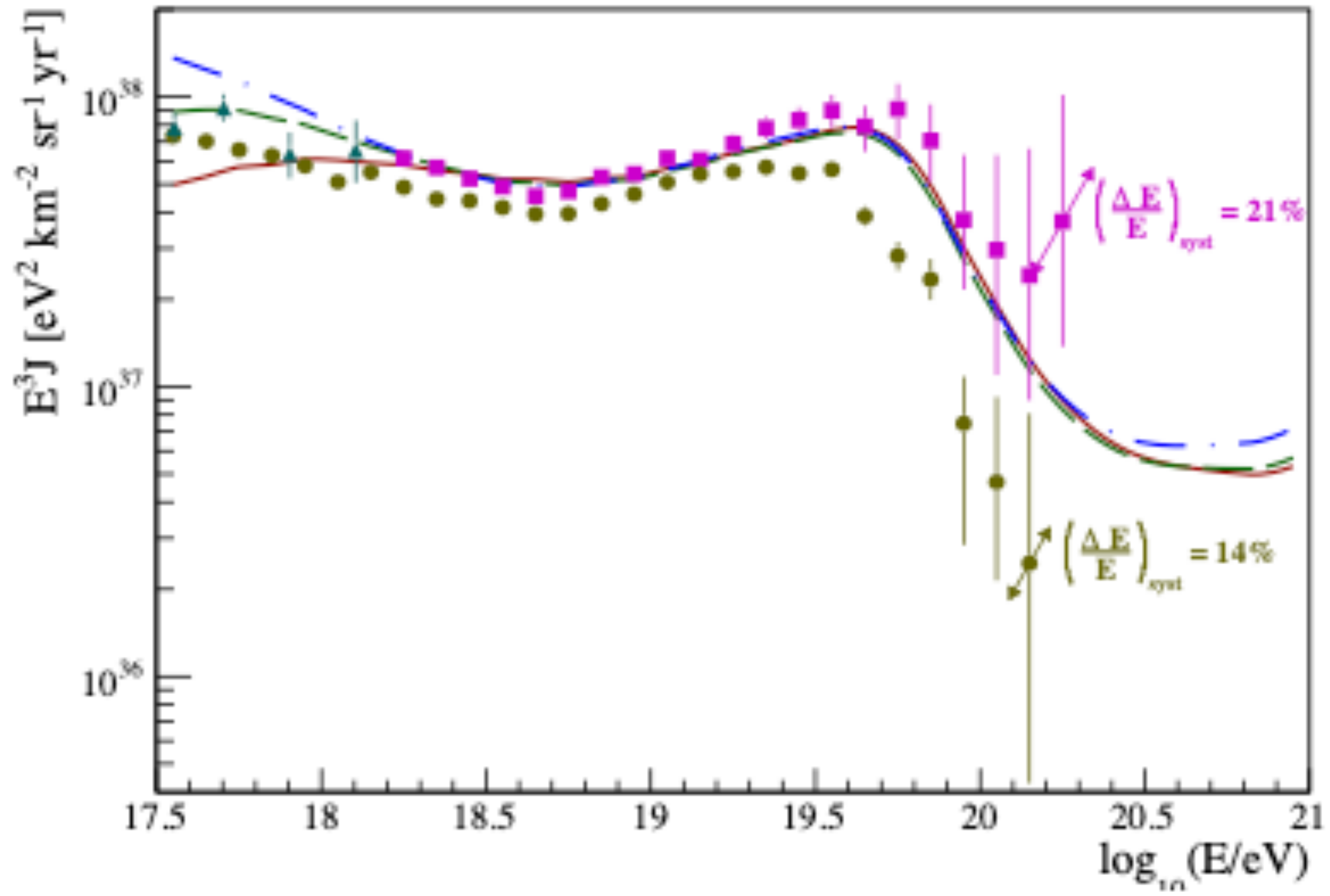
Berezinsky & Zatsepin, 1970

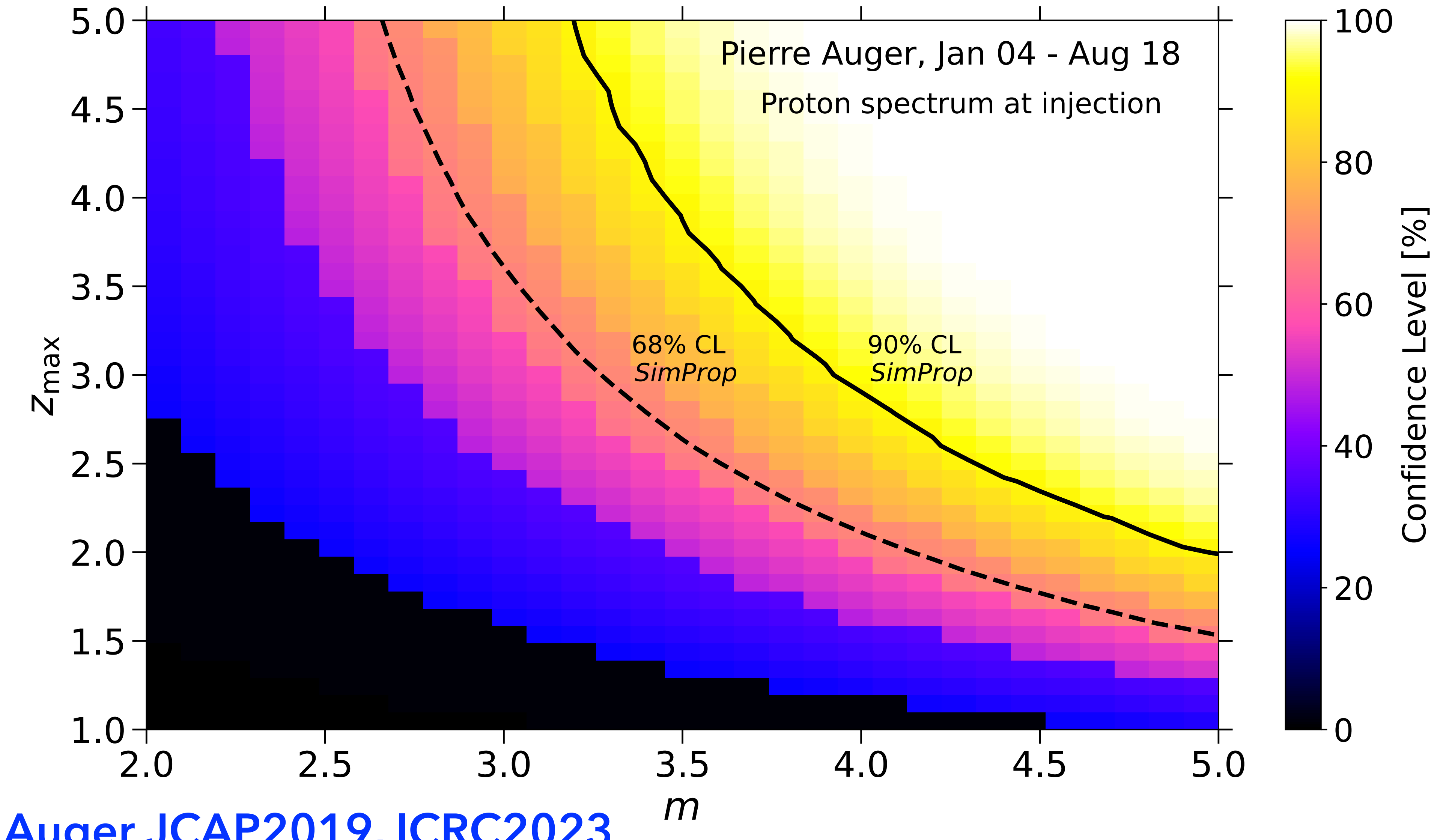
Aloisio, **DB**, di Matteo, Grillo, Petrera & Salamida, JCAP 2015

Effect of **cosmological evolution** of sources

$$(1+z)^m$$







Auger JCAP2019, ICRC2023

- On cosmic-ray spectra the effect is much less relevant than for neutrinos
- Parametric studies can constrain the **UHECR spectral parameters** and the **cosmological distribution of sources** (UHECR scenarios corresponding to neutrino fluxes higher than current limits can be excluded)
- **Unrealistic scenario: UHECRs are100% protons**
  - See also Heinze, **DB**, Bustamante & Winter ApJ 2016; van Vliet et al. PRD 2019; Muzio et al. PRD 2023; Ehlert et al. JCAP 2024

UHECR flux at Earth and the corresponding cosmogenic neutrinos

Berezinsky & Zatsepin, 1970

Effect of **cosmological evolution** of sources

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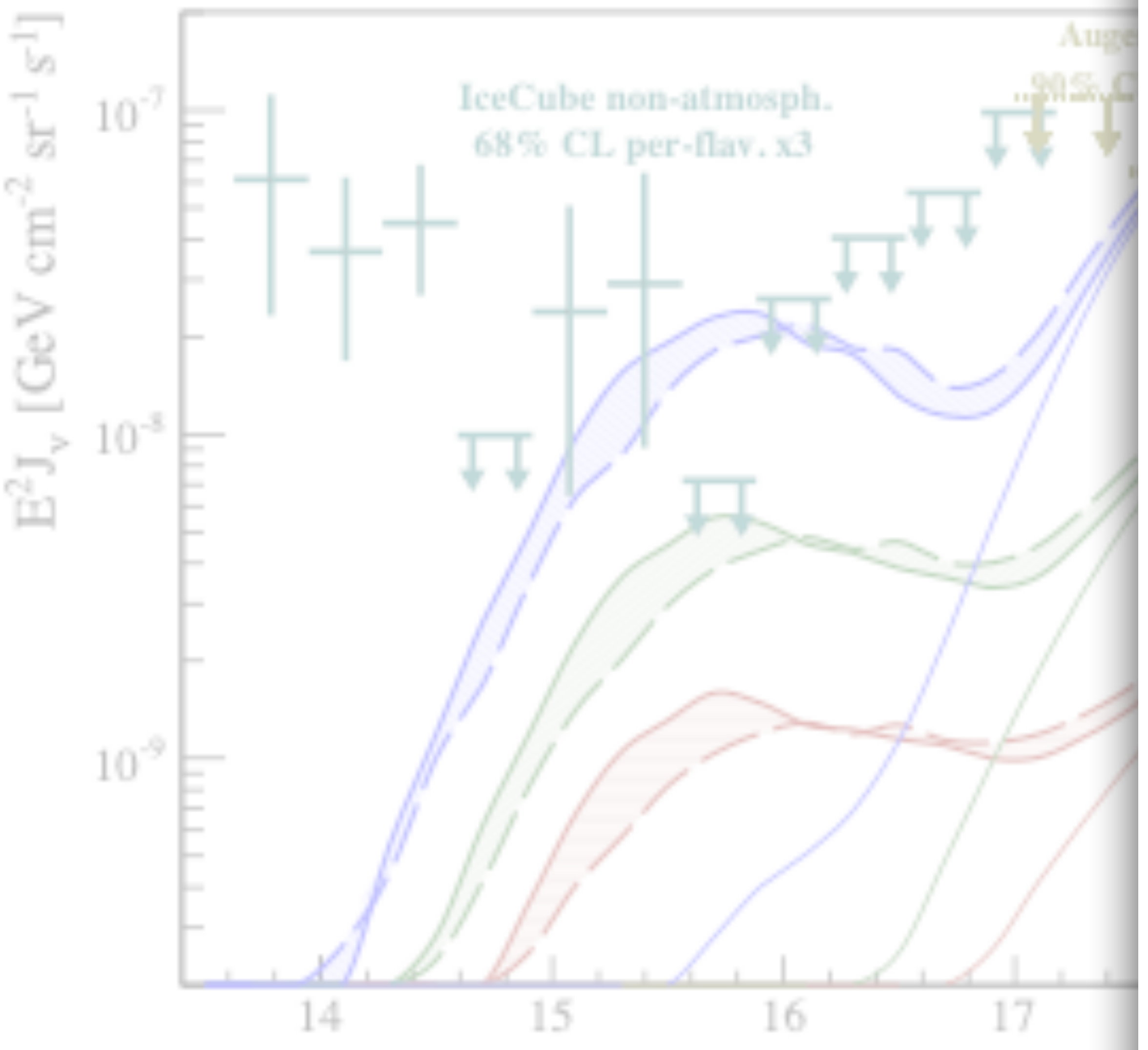

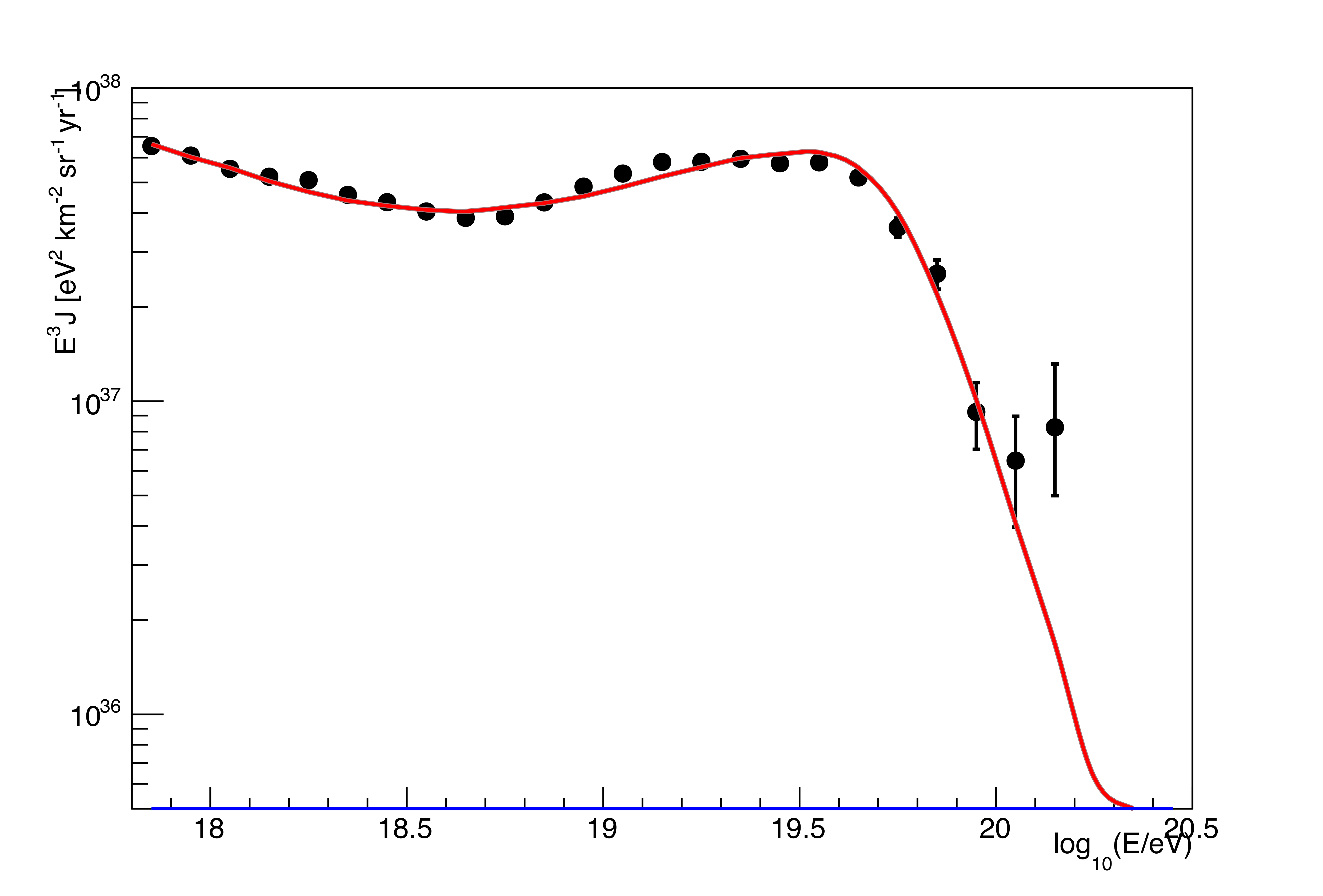

The best fit (in the pure-proton scenario) is excluded by the non-observations of cosmogenic neutrinos!

On … trinos

Para … nd

the …

corr …

excl …

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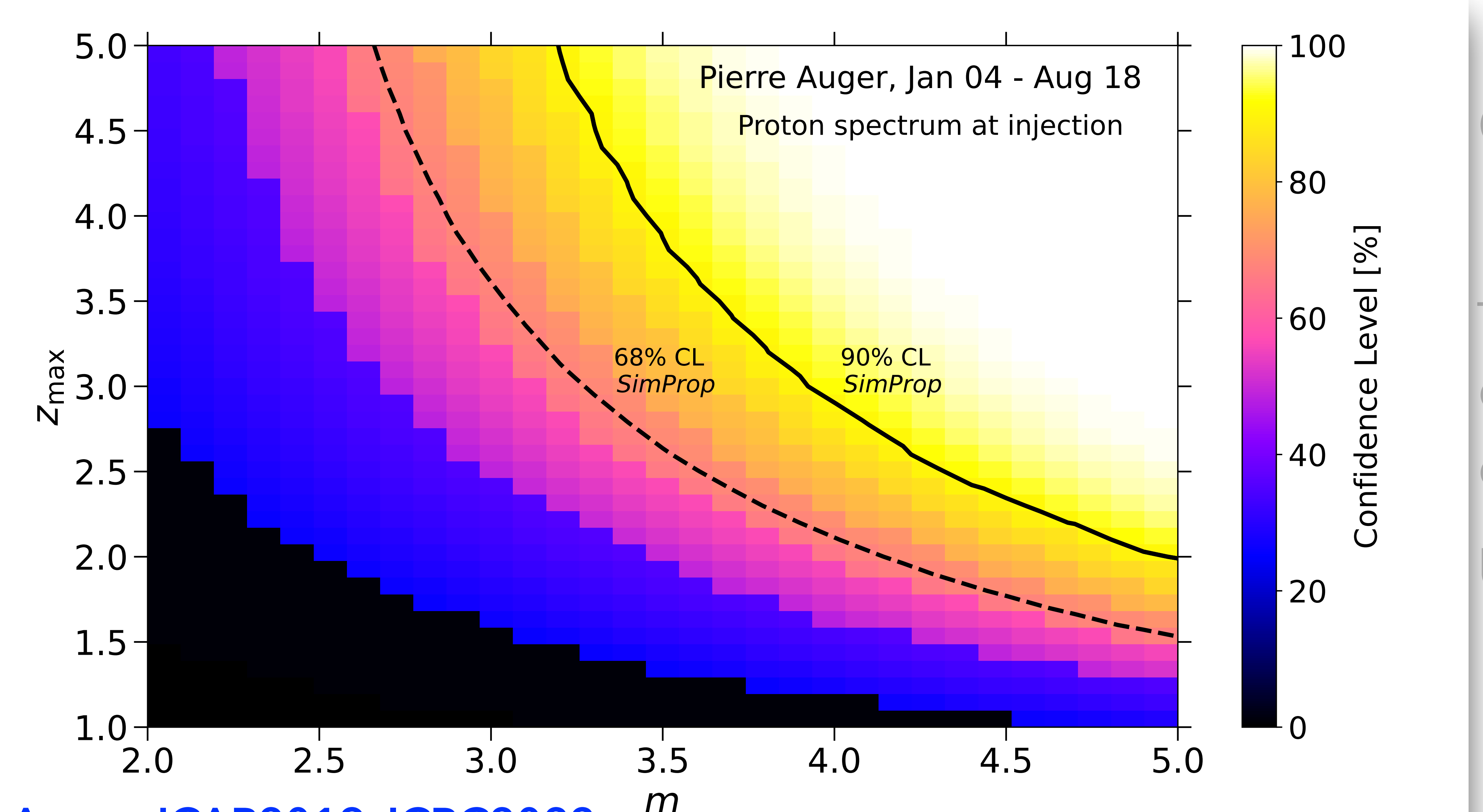
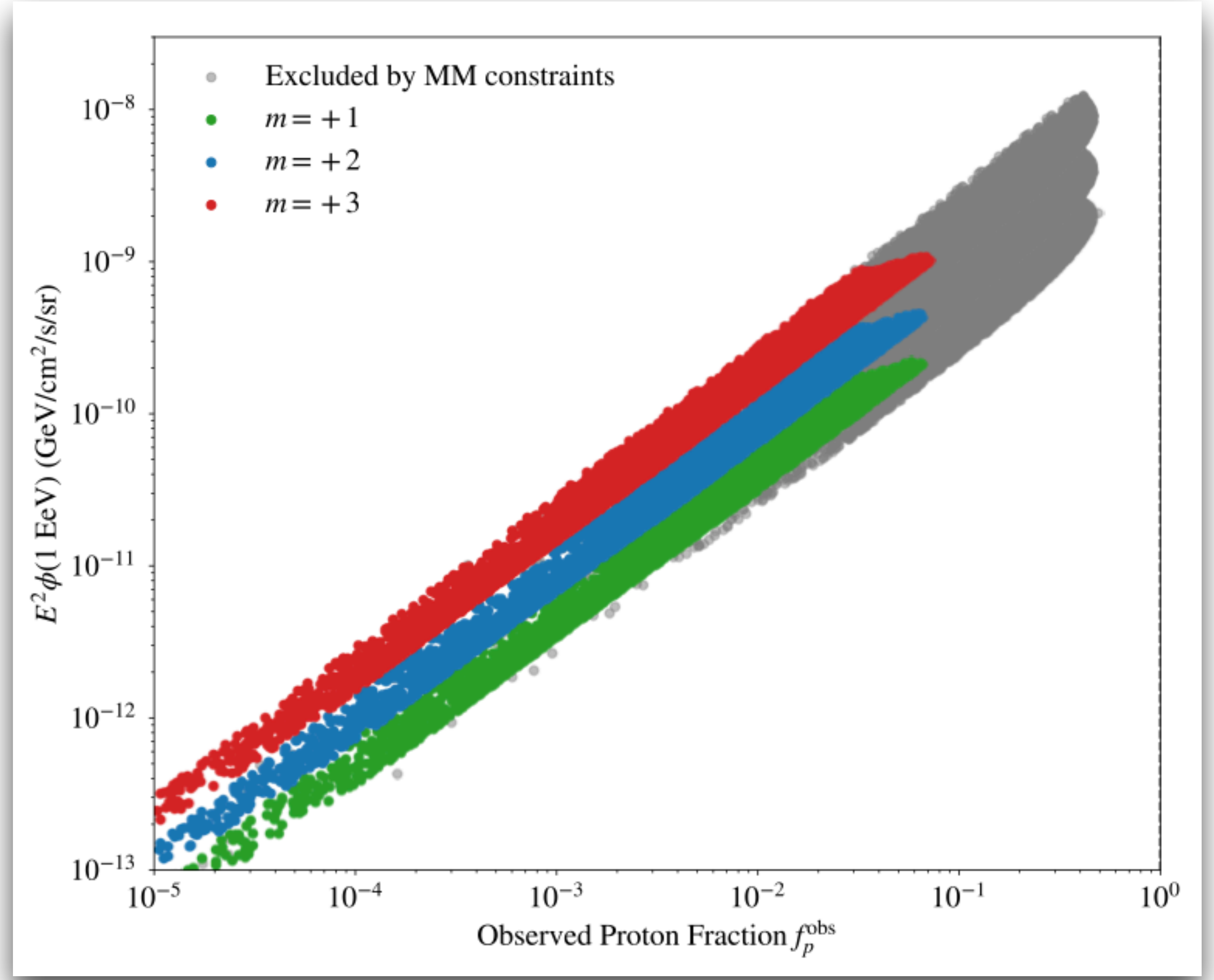


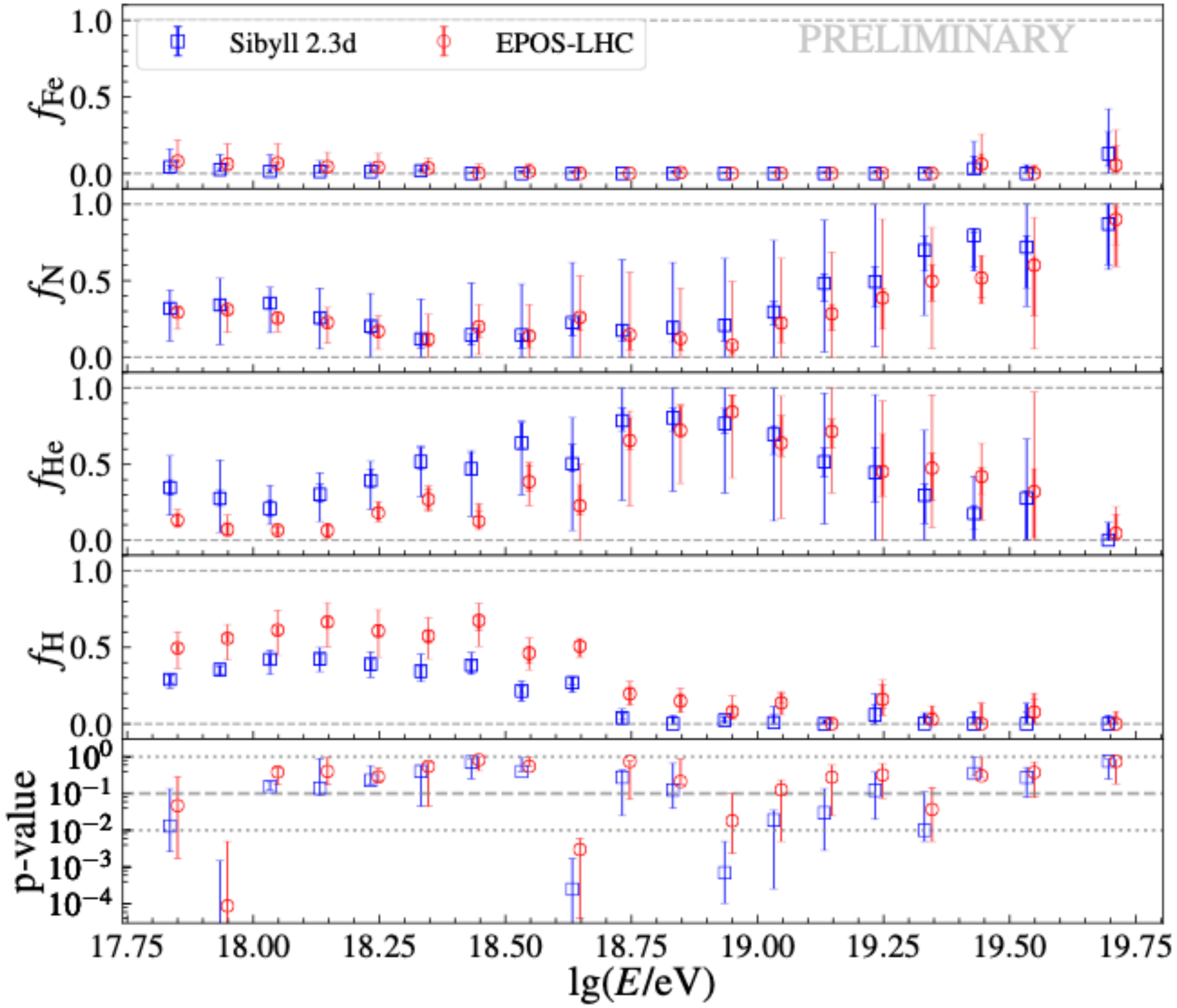
Auger JCAP2019, ICRC2023

Constraining power of proton fraction in UHECRs with cosmogenic neutrinos

Muzio et al PRD 2023



The Auger Collab. ICRC2023



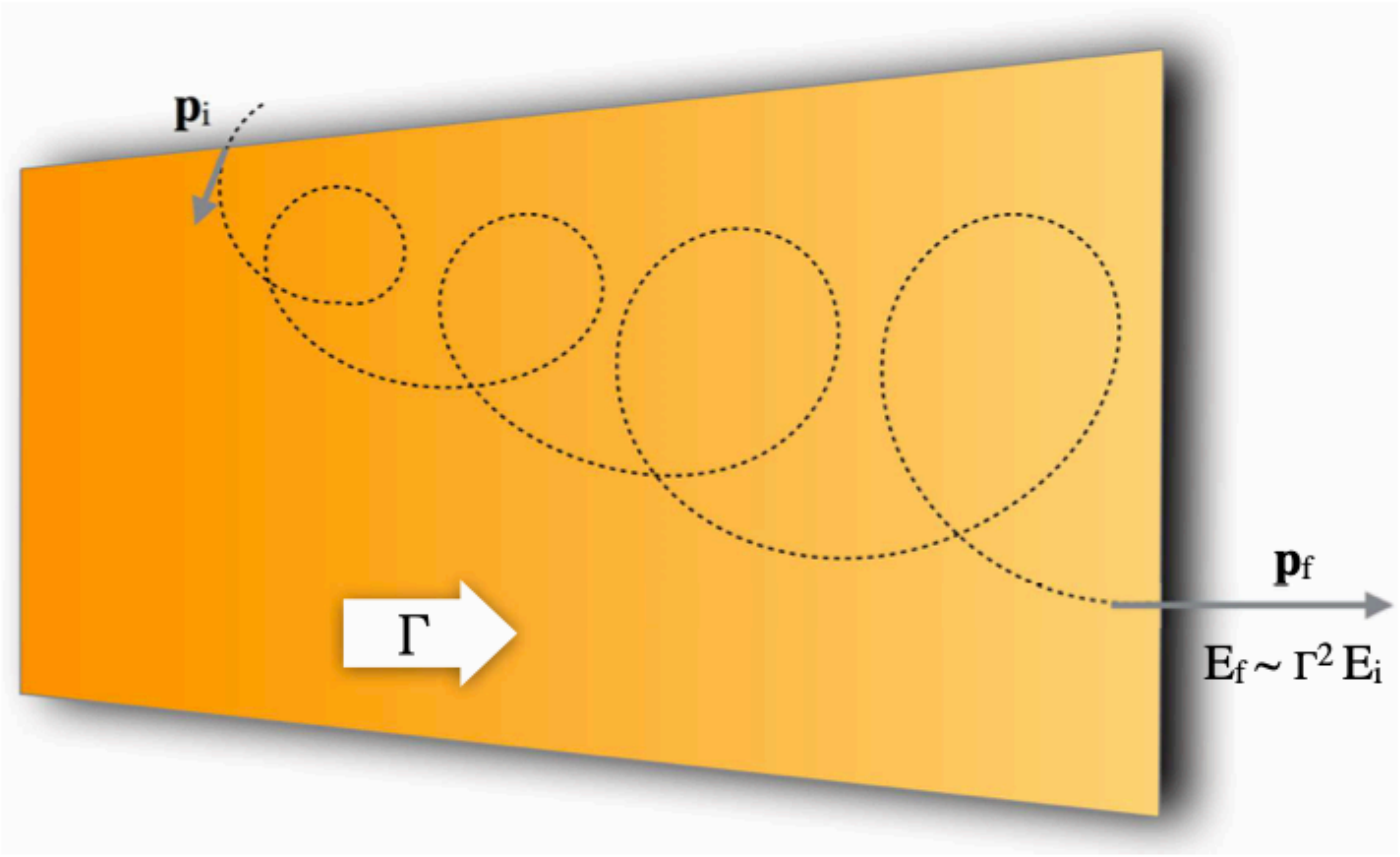
- Determining the UHECR proton fraction at the highest energies is crucial for understanding the detected UHECR mass composition, but also indirectly to better constrain the UHECR characteristics
  - One of the key science cases of AugerPrime

UHECR NUCLEI:
HOW TO REACH ULTRA-HIGH-ENERGIES?
WHERE CAN WE FIND NUCLEI?

Example: starburst galaxies

- High level of star formation and supernova explosions -> collective wind -> acceleration
- Acceleration to UHE might be possible (**Anchordoqui PRD 2018**), but high gas density and turbulence -> calorimetric behaviour (secondary particles, see for instance **Peretti et al MNRAS 2018**)
- Signal of correlation of SBGs with the highest energy CR events (**The Auger Collab ApJL 2018**)

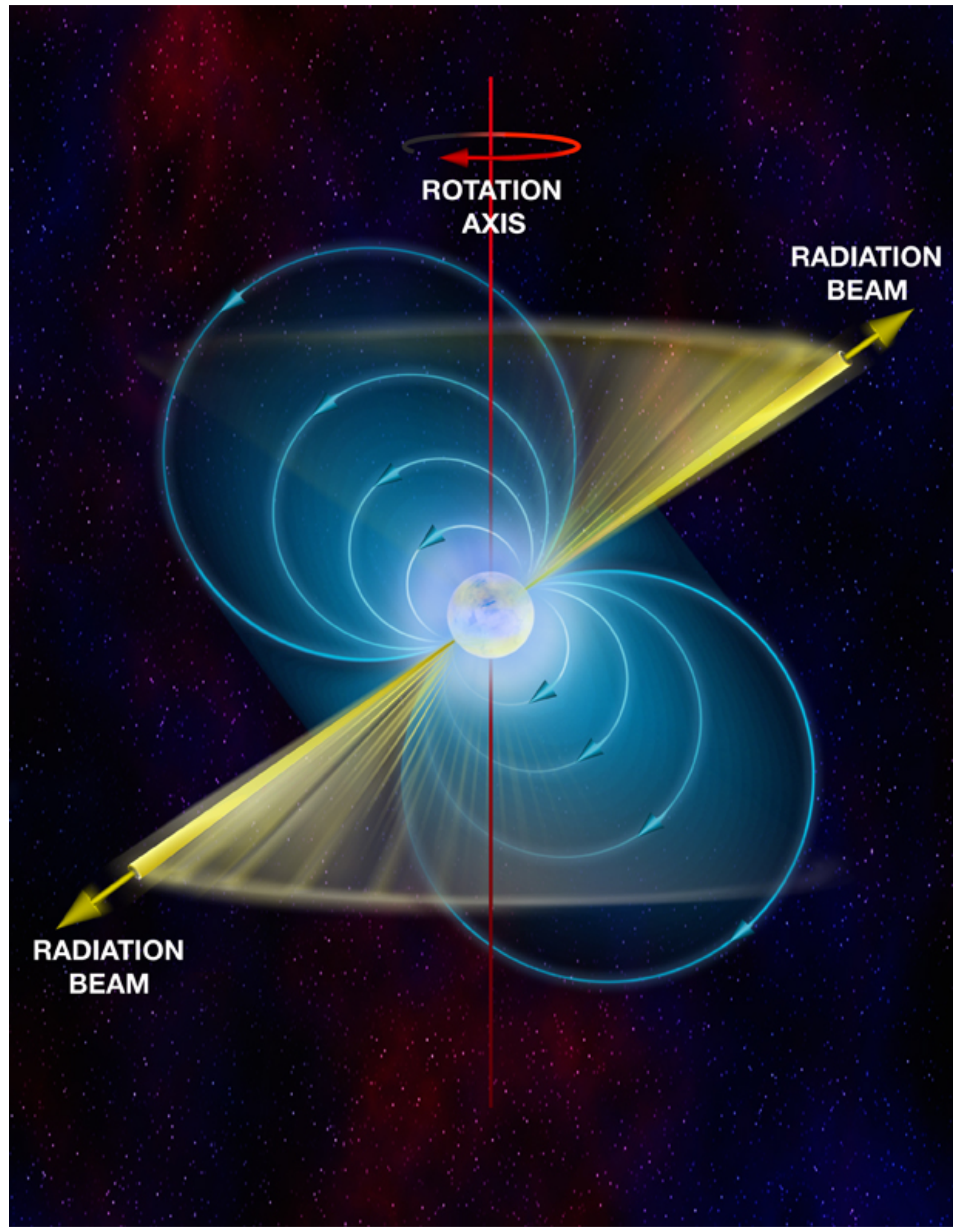
Example: AGN jets



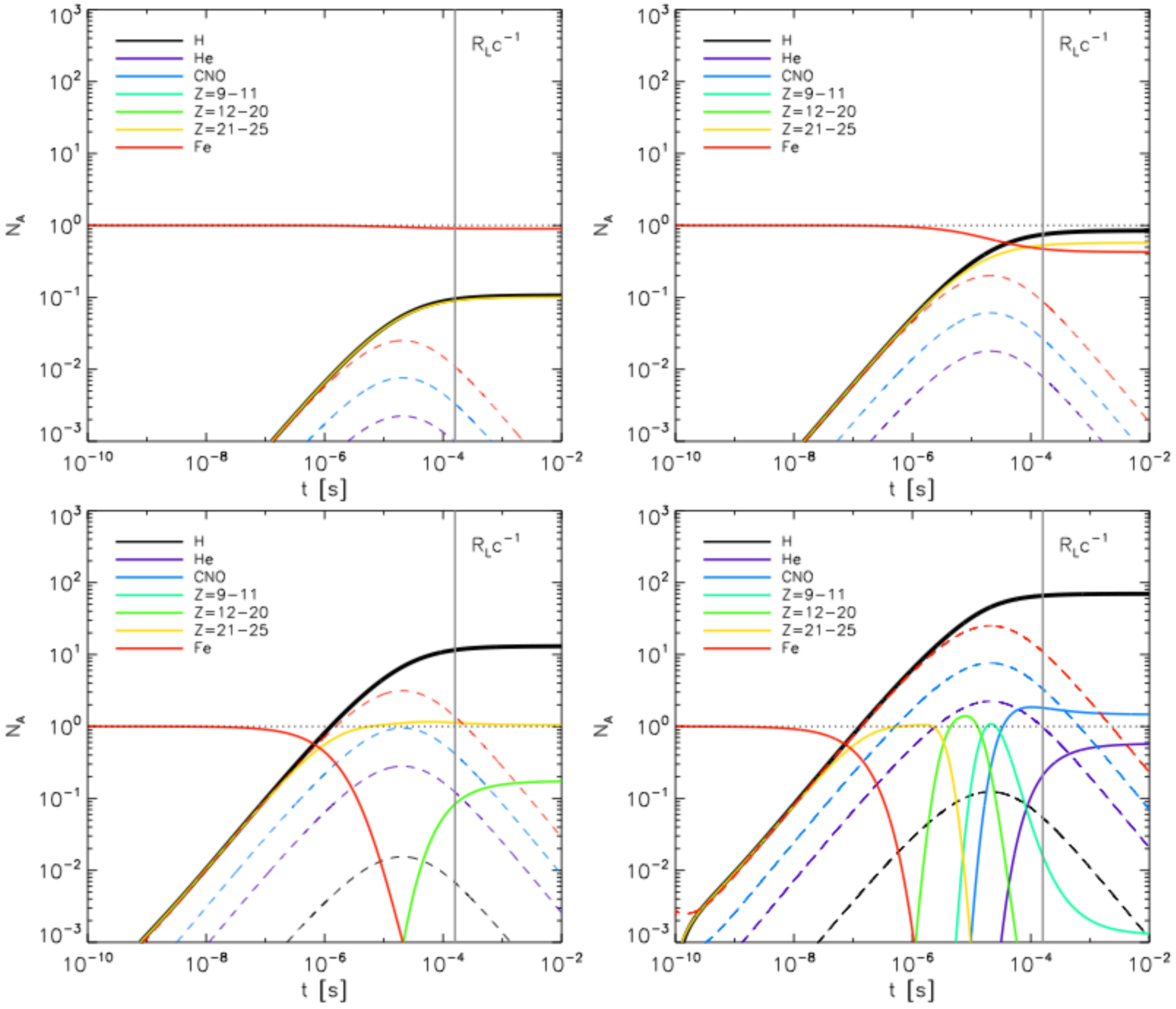
- Seed galactic CRs with energies of 10^{17} eV that penetrate the jet sideways receive a "one-shot" boost of a factor of Γ^2 in energy (**Caprioli ApJL 2015**)
- Chemical composition of Galactic-like CRs?

Example: young fast-rotating pulsars

Blasi et al ApJL 2000; Kotera et al JCAP 2015

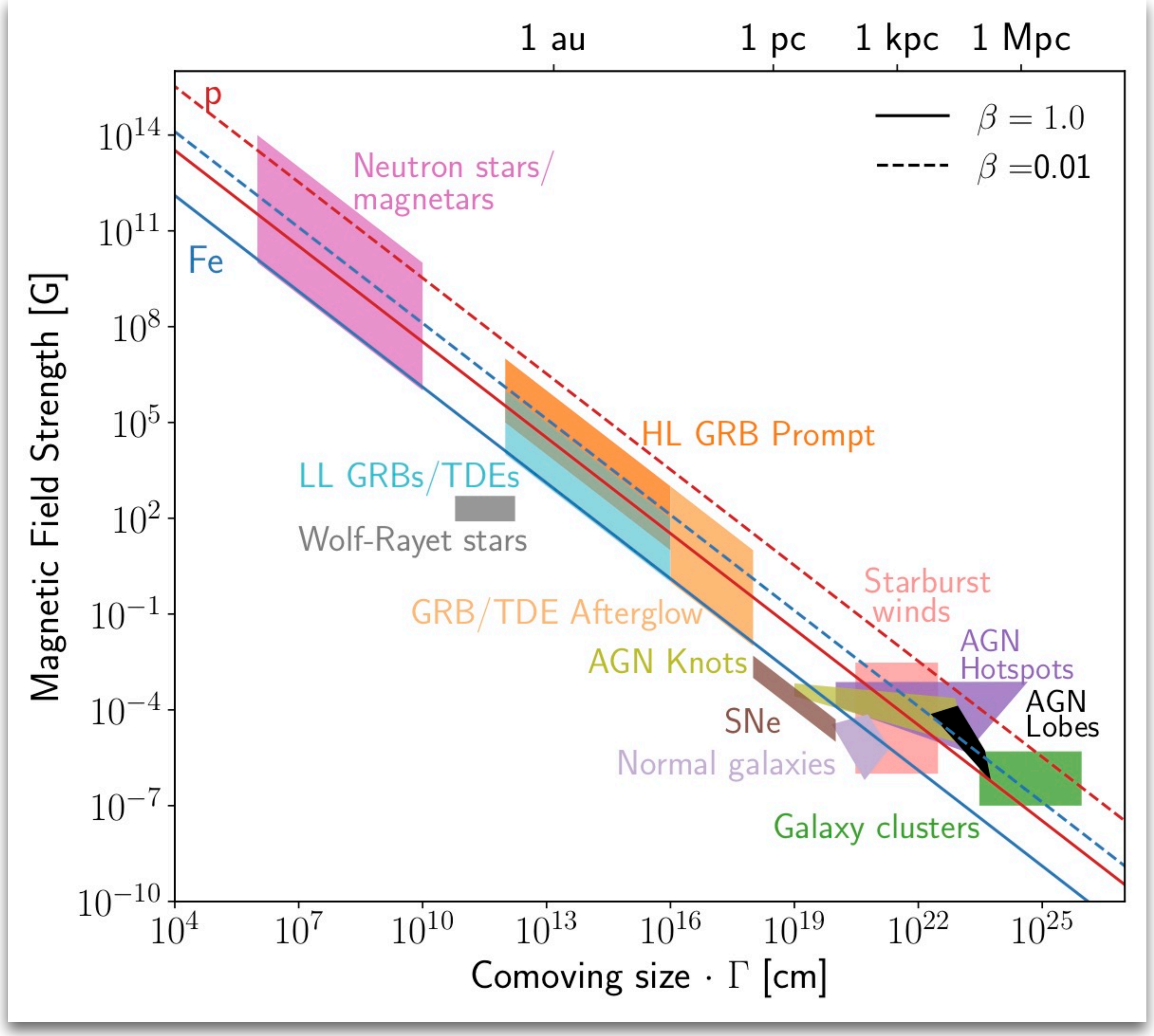


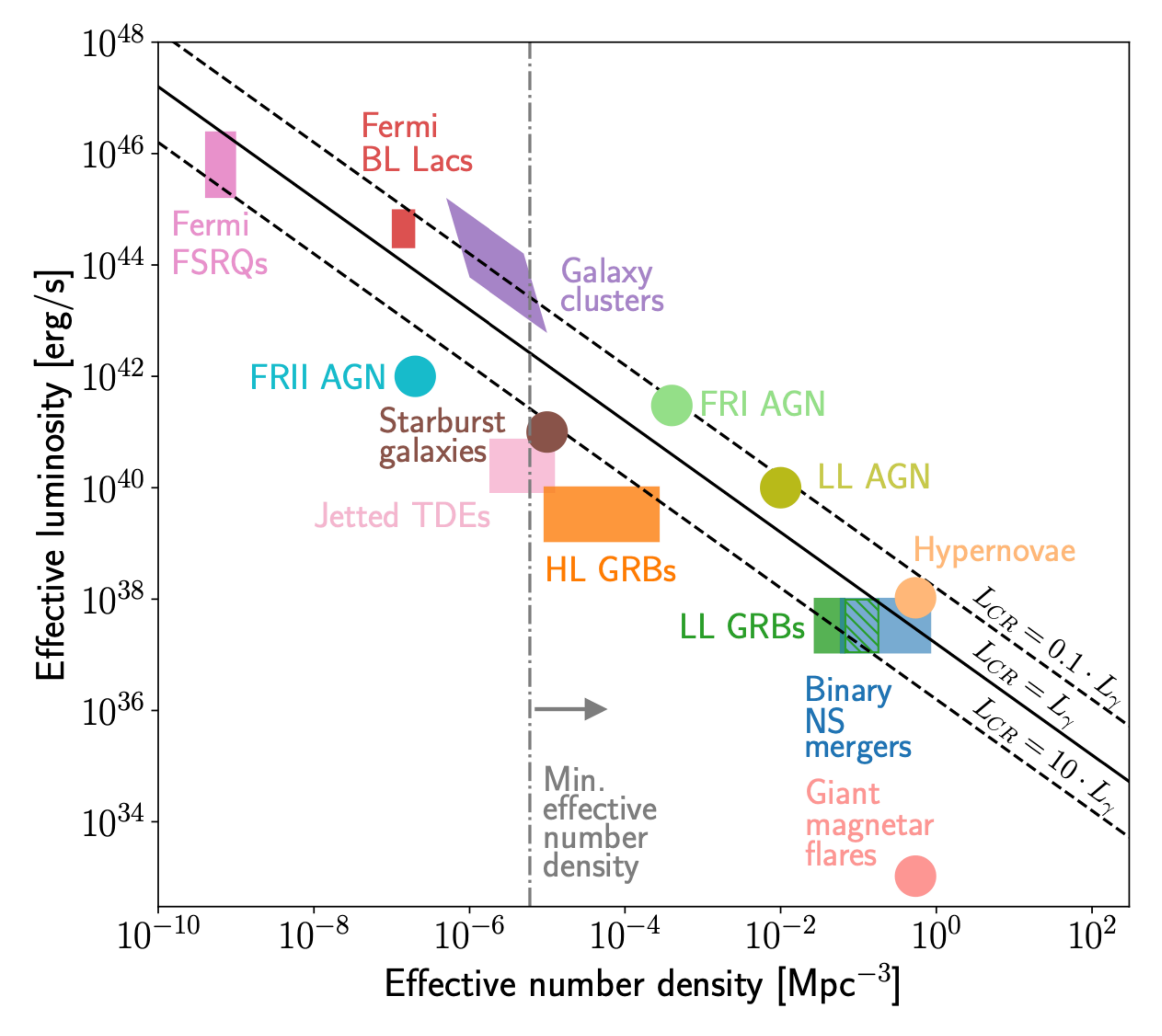
- Fast spinning very young pulsars could accelerate iron nuclei (extracting them from the iron-rich surface)
- Iron nuclei interact with the thermal photons coming from the hot surface of the star



- The nuclei that reach the light cylinder region eventually end up in the wind of electron-positrons propagating outwards
- A mixed composition appears at the escape, depending on the temperature of the photon field
- Some studies about binary-neutron-star mergers in Decoene et al JCAP2020; Rossoni, **DB** & Sigl arxiv:2407.19957

UHE maximum energy is necessary but not sufficient…





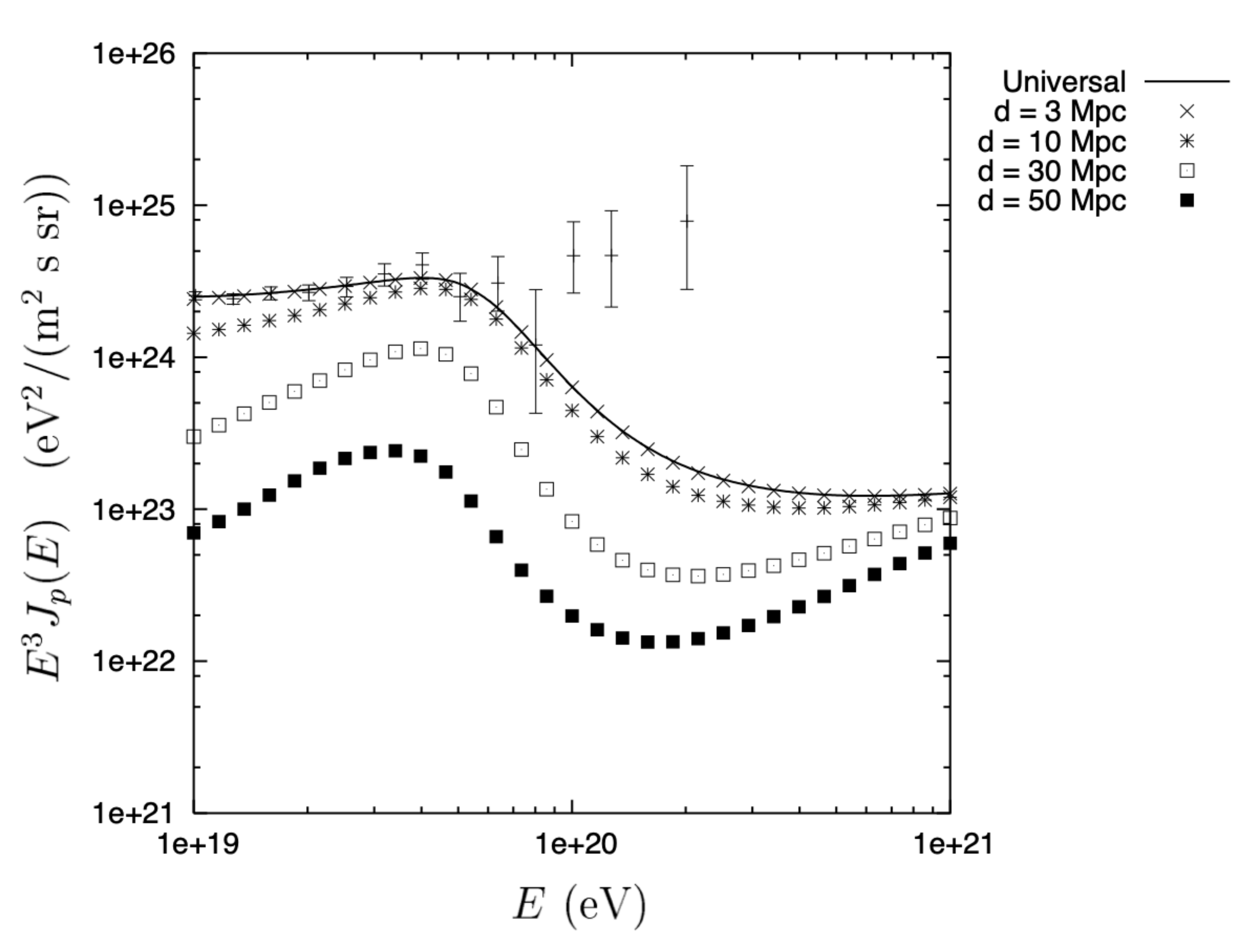
Alves Batista et al, Front.Astron.Space Sci. 2019

HOW IS THE SPECTRUM AT THE ESCAPE FROM ACCELERATORS SHAPED ?

HOW IS THE SPECTRUM AT THE ESCAPE FROM ACCELERATORS SHAPED ?

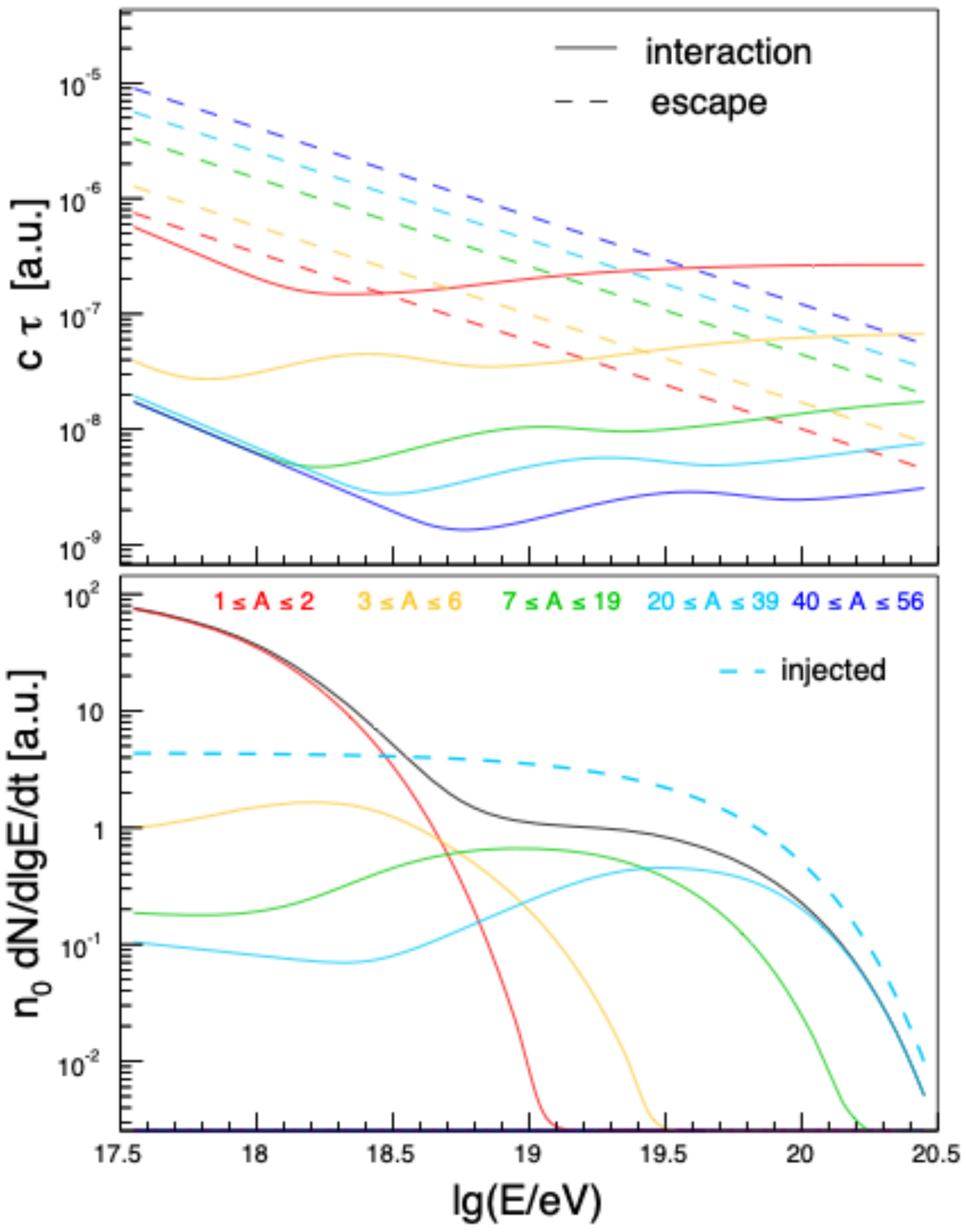
Propagation in magnetic fields might also re-shape the flux after the escape from accelerators, depending on the separation between the sources

Propagation theorem



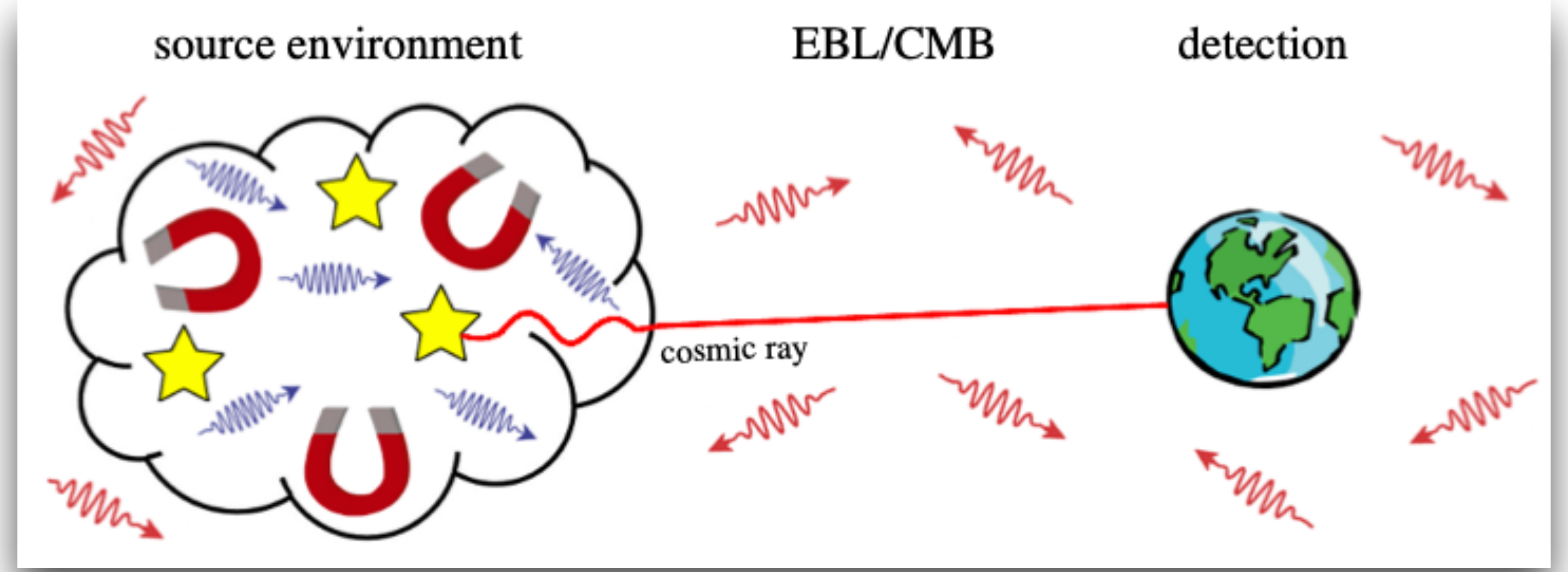
-> See Aloisio & Berezinsky ApJ 2004, ApJ 2005, and applications to mixed composition and Auger data in The Auger Collab. JCAP 2024

Requirements for the spectral shape at the escape from sources

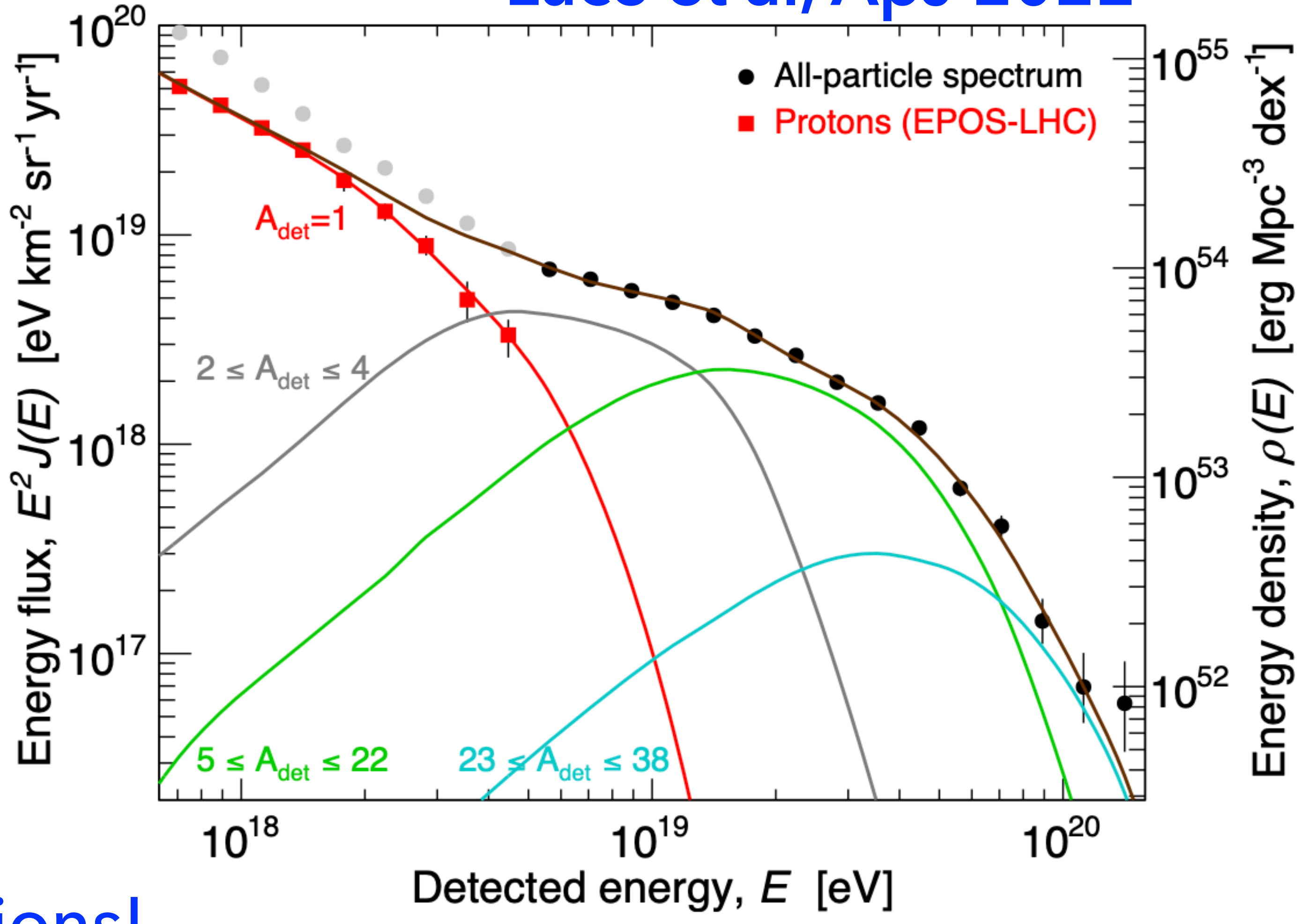


Unger et al. PRD 2015

- Escape time decreasing with energy (due to diffusion in turbulent magnetic fields outside the accelerator) -> the lower the energy, the more time the nuclei have to interact before escaping
  - <u>hardening of the spectrum of nuclei</u>, and
  - <u>lightening of the composition</u> of nuclei escaping the region surrounding the source.



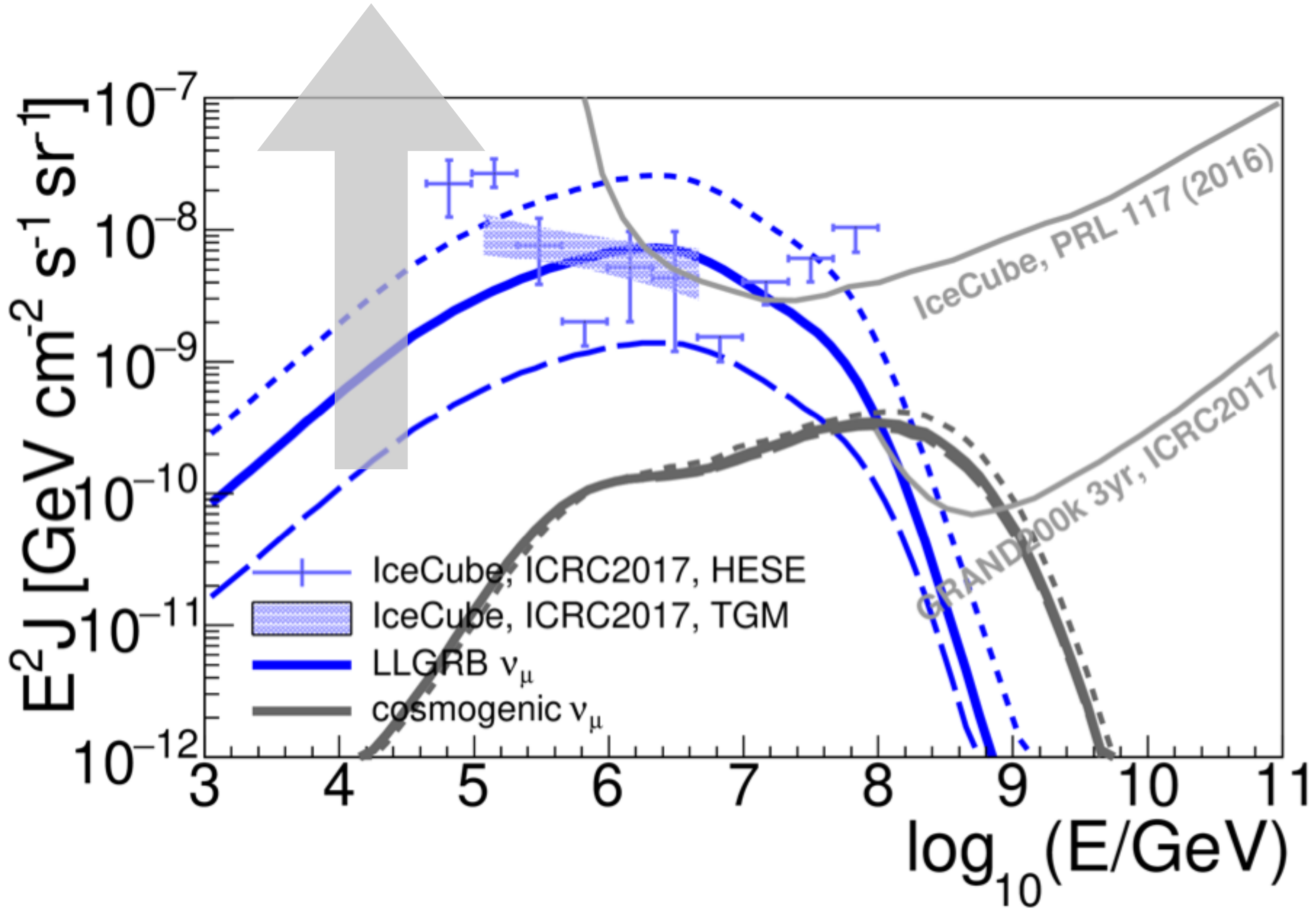
Luce et al, ApJ 2022



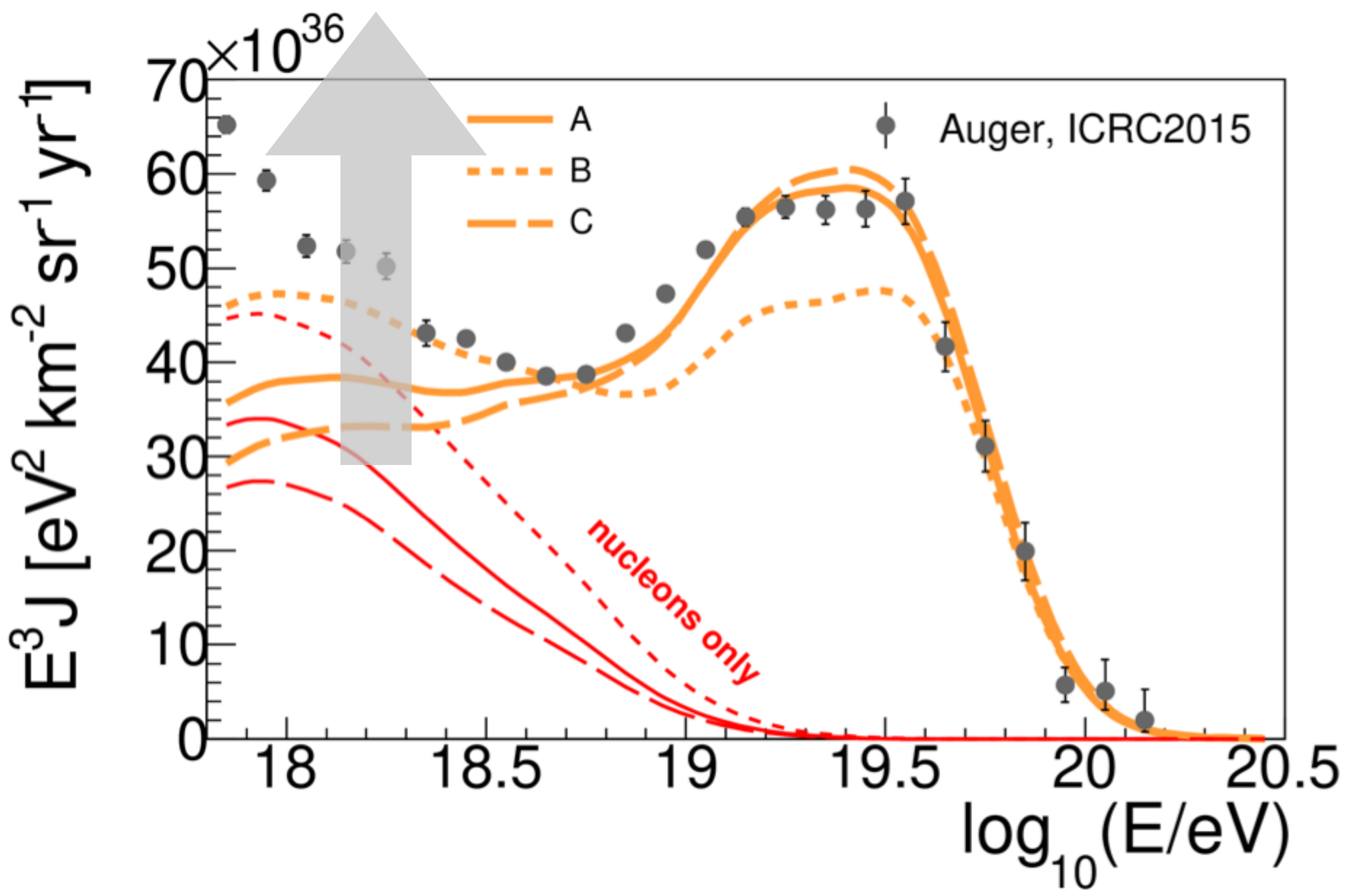
- **The ankle could be shaped by in-source interactions!**
- Many studies in the last 10 years on similar topics, involving several types of candidate sources, and performing **source-propagation models**. Some examples are:
  - **GRBs** (Globus et al PRD 2015; Biehl, **DB**, Fedynitch & Winter, A&A 2018); **LL-GRBs** (Zhang, Murase, Kimura, Horiuchi & Meszaros, PRD 2018; **DB**, Biehl & Winter, ApJ 2019)
  - **Starburst galaxies** (Condorelli, **DB**, Peretti & Petrera, PRD 2023)
  - **TDEs** (Zhang, Murase, Oikonomou & Li, PRD 2017; Biehl, **DB**, Lunardini & Winter, Sci.Rep. 2018)

Requirements for the spectral shape at the escape from sources → Consequences for neutrinos

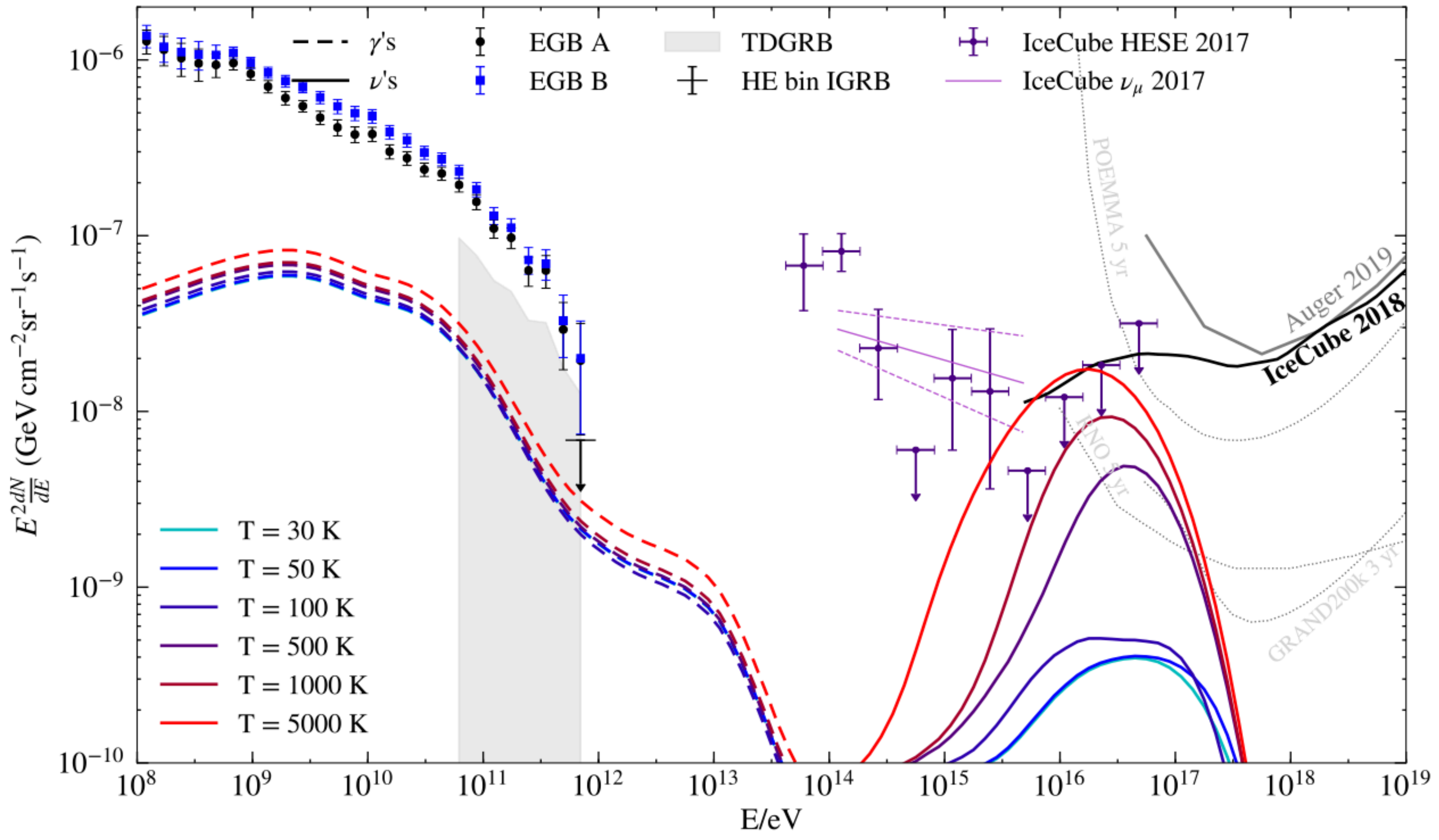
Increase of photon density



DB et al ApJ 2019



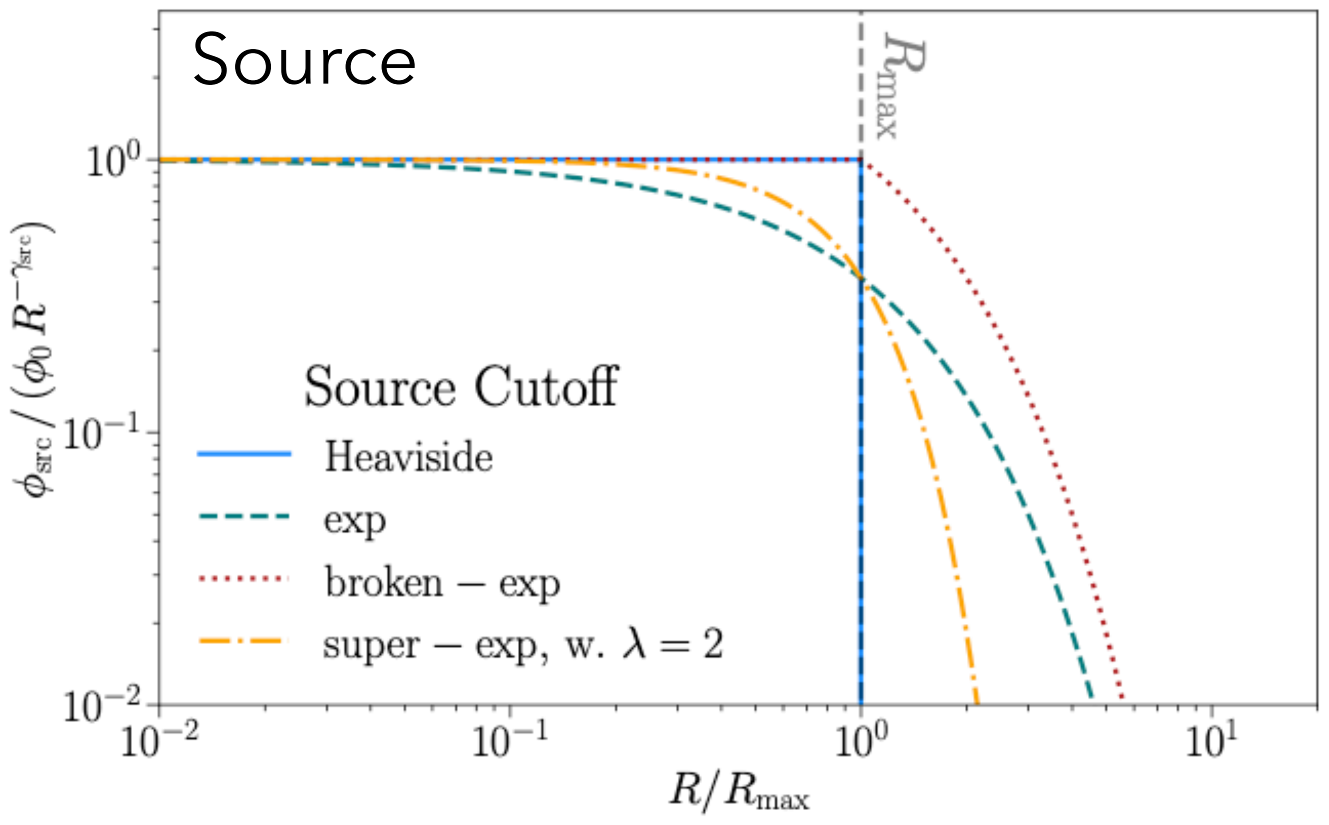
Muzio et al PRD 2019



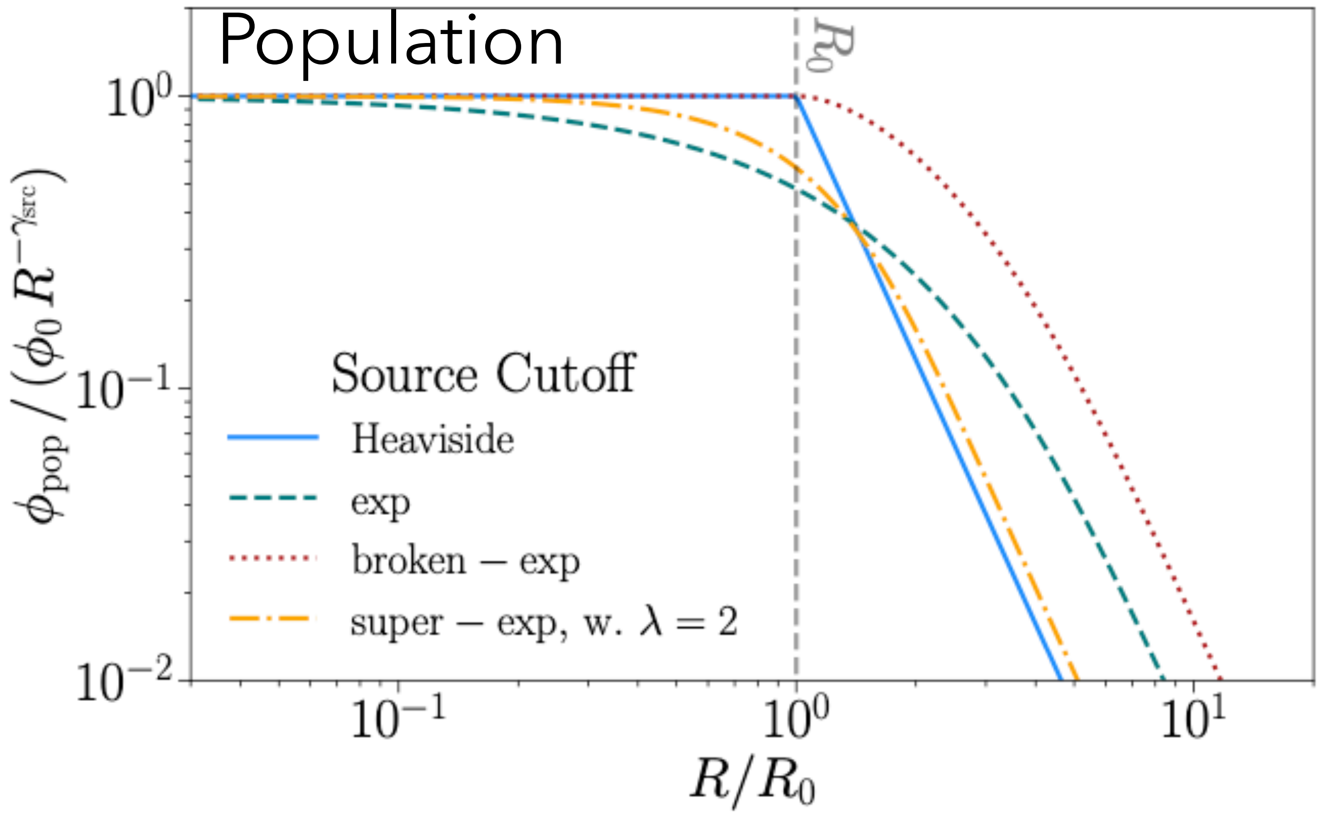
- **UHECRs - neutrinos connection**
  - Neutrinos produced in sources (**astrophysical**):
    - depend on efficiency of interactions in the source environment
    - are connected to **proton fraction below the ankle** (see also Muzio et al. PRD 2019; PRD 2022; PRD 2023)
  - Neutrinos produced in extragalactic propagation (**cosmogenic**):
    - are connected to **UHECR maximum energy at the escape from the source**
- **Gamma-ray - neutrino connection:** neutrinos play a special role in the study of dense source environments that are not probed by gamma rays (see Murase et al PRL 2016)

Are UHECR sources identical?

- 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…



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

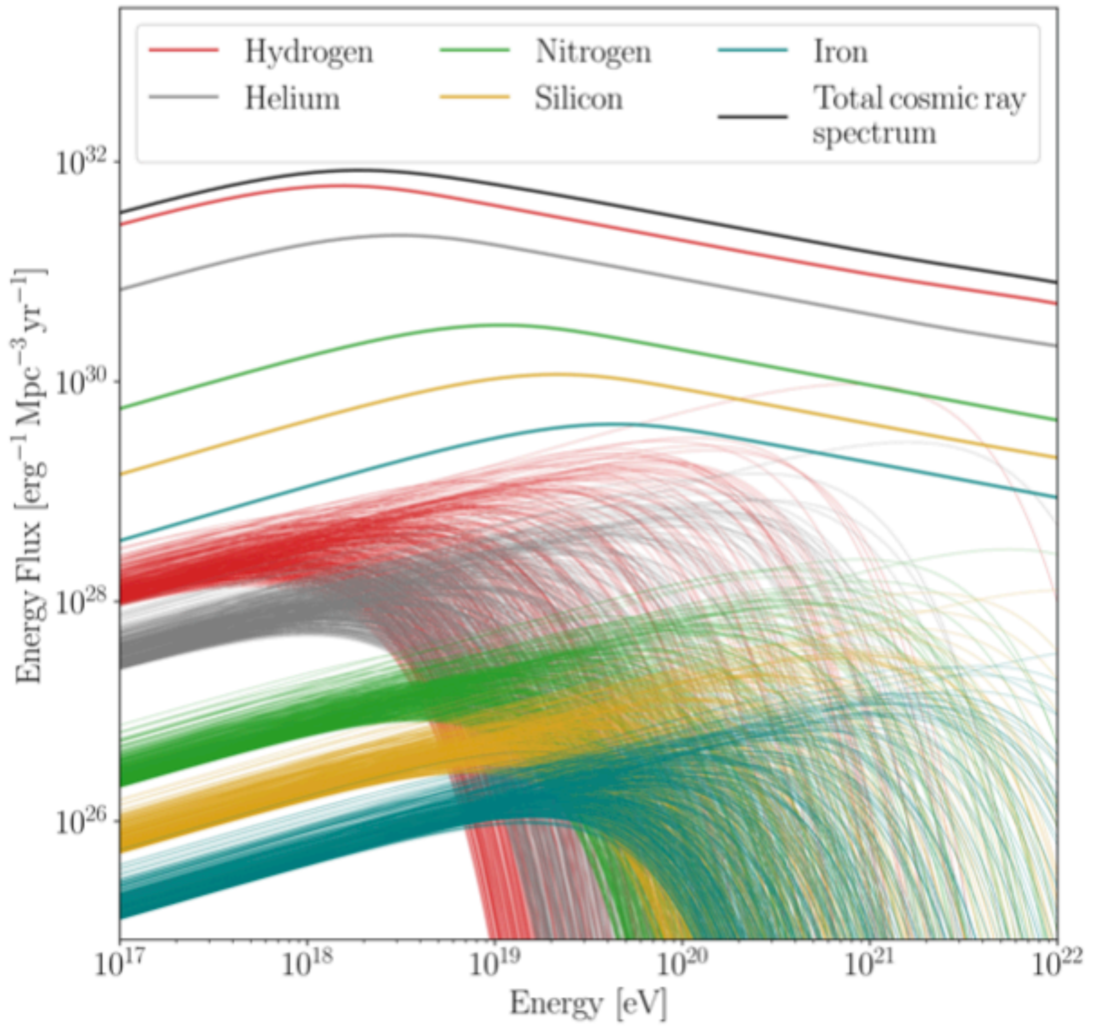


Ehlert et al PRD 2023; Mollerach & Roulet PRD 2020; Kachelriess & Semikoz PLB 2006

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

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

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



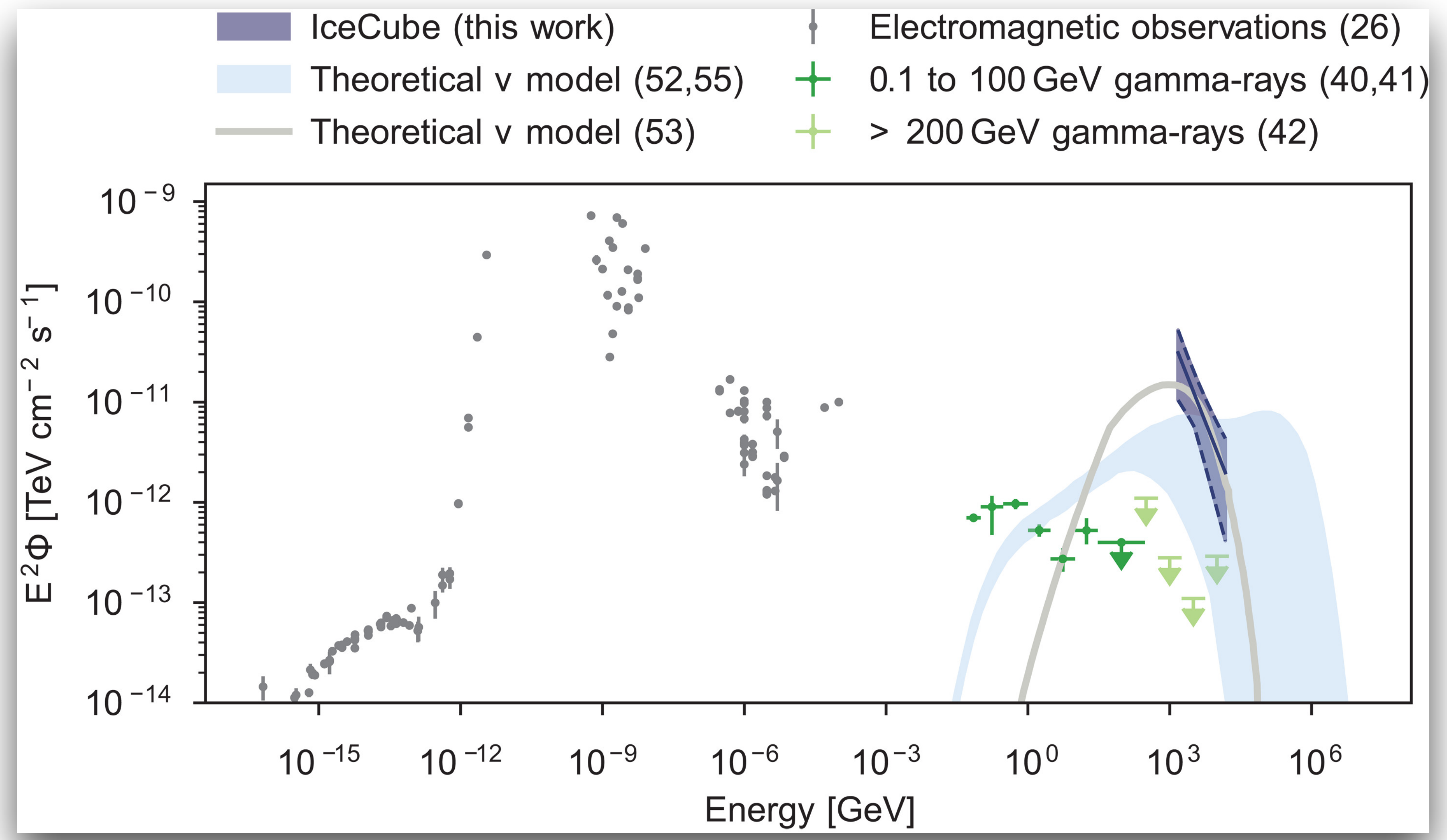
Plot from talk by F. Oikonomou @ICRC23

- 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

WHAT DO WE LEARN FROM THE STUDY OF SINGLE EVENTS?

Exciting times for multimessenger astrophysics!

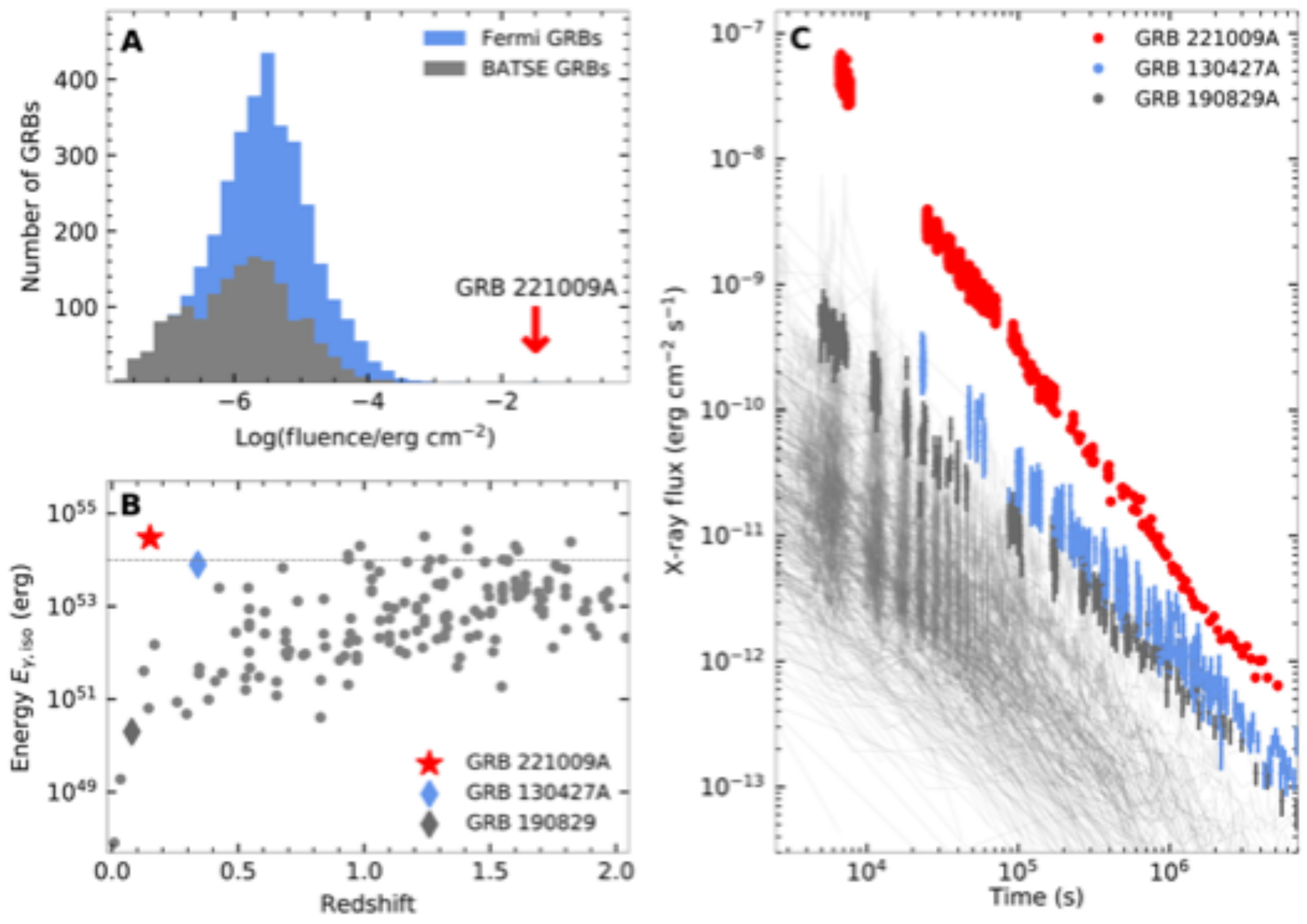
- Sep. 2017: IceCube Neutrino Observatory recorded a 300 TeV neutrino in directional coincidence with a blazar in a bright gamma-ray state, **TXS0506+056** (IceCube, Fermi, MAGIC ..., Science 2018)
- Nov. 2022: IceCube Neutrino Observatory published an archival search for neutrinos, finding 79 events associated to **NGC1068** (IceCube, Science 2022)



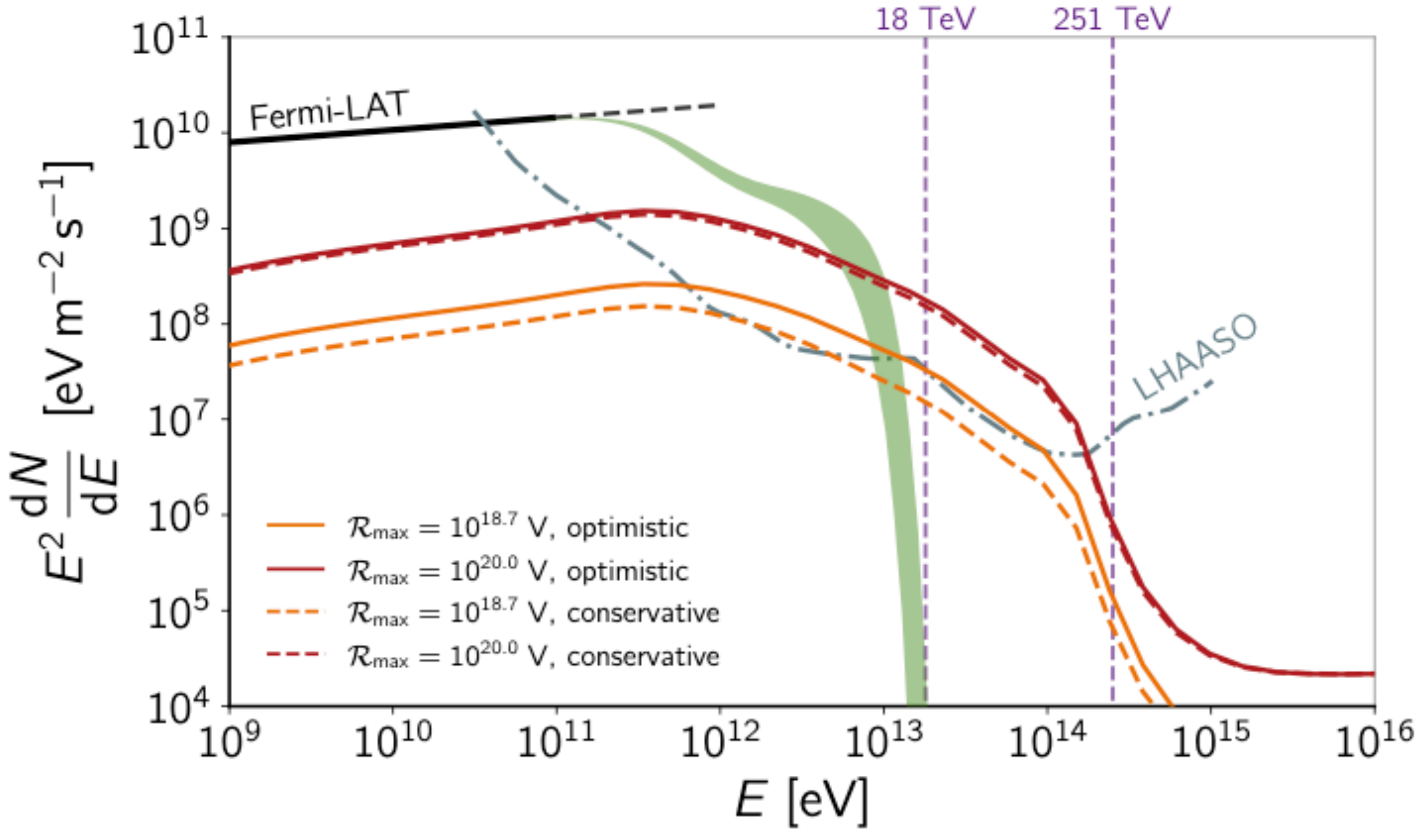
- Zwicky Transient Facility identified AT2019dsg (Stein et al. Nature Astron. 2021) and AT2019fdr (Reusch et al. PRL 2021) as tidal disruption events and optical counterparts of two IceCube neutrinos
- Identification of a third TDE, AT2019aalc, as counterpart of another IceCube neutrino event (van Veltzen et al. MNRAS 2021)

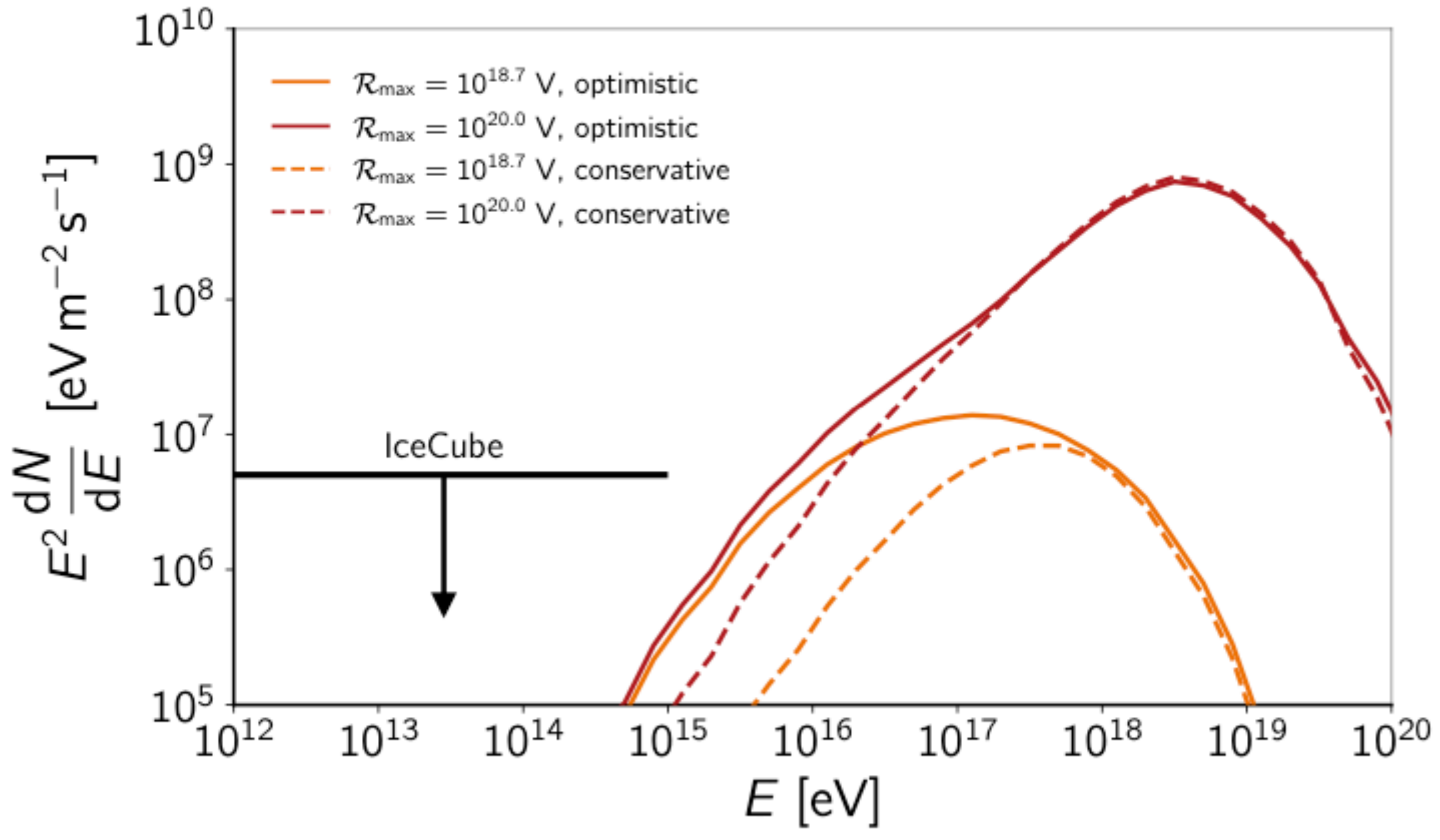
These events are not directly linked to ultra-high-energies !

What can we learn from GRB221009?



- Observed photons up to 18 TeV
- Based on the distance of the GRB, we do not expect *primary* photons from this GRB
  - If UHECR protons are accelerated in the GRB up to 1 EeV, *cosmogenic photons* can be expected (some conditions on EGMF and time window of observation are requested), as shown in Alves Batista, arxiv:2210.12855; Das & Razzaque Astron. & Astrop. 2023
- Other studies explore the proton synchrotron emission, as in Zhang et al. ApJ 2023
- Delayed UHECRs from Galactic magnetic fields? See He et al. arxiv:2401.11566

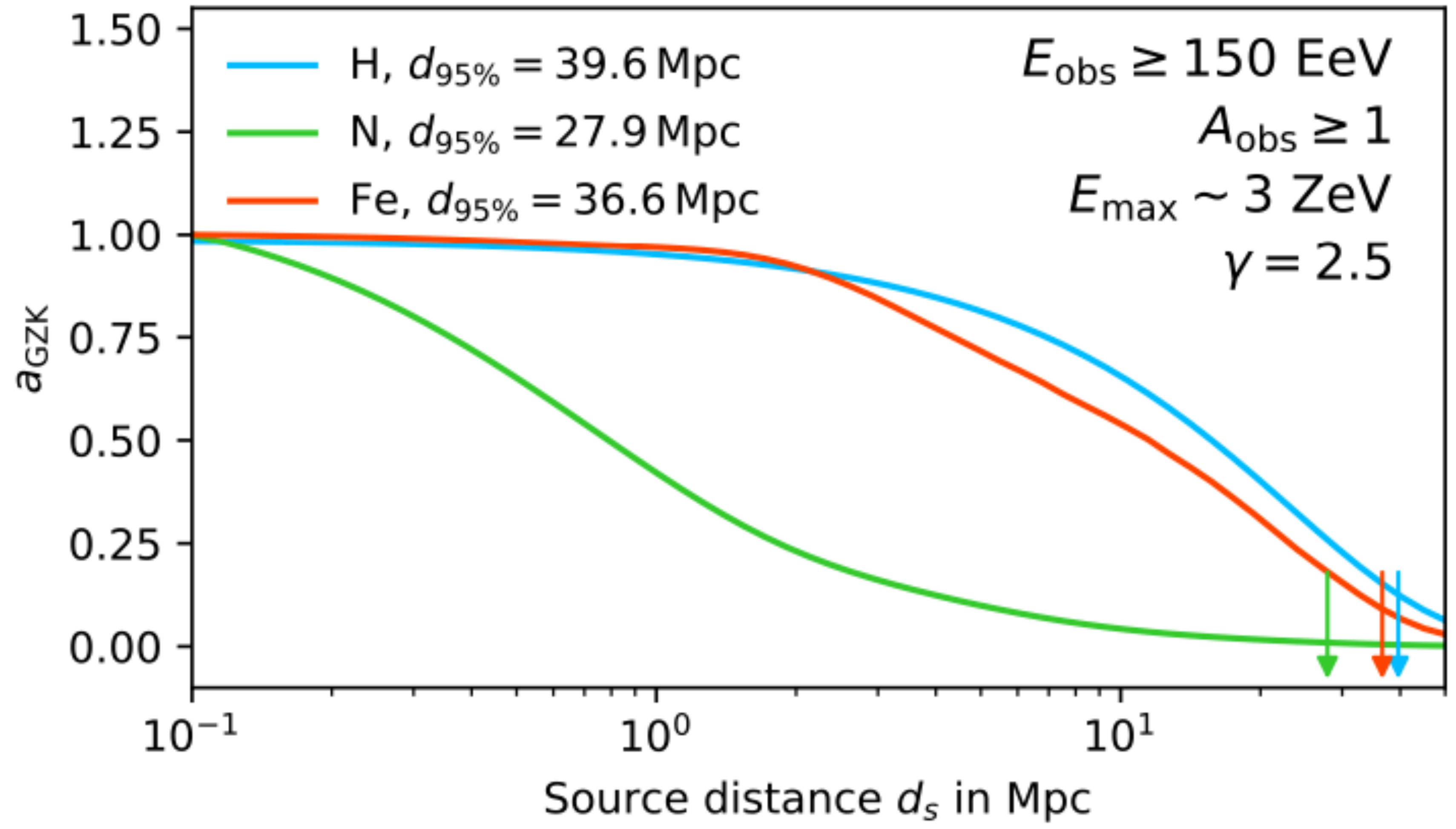


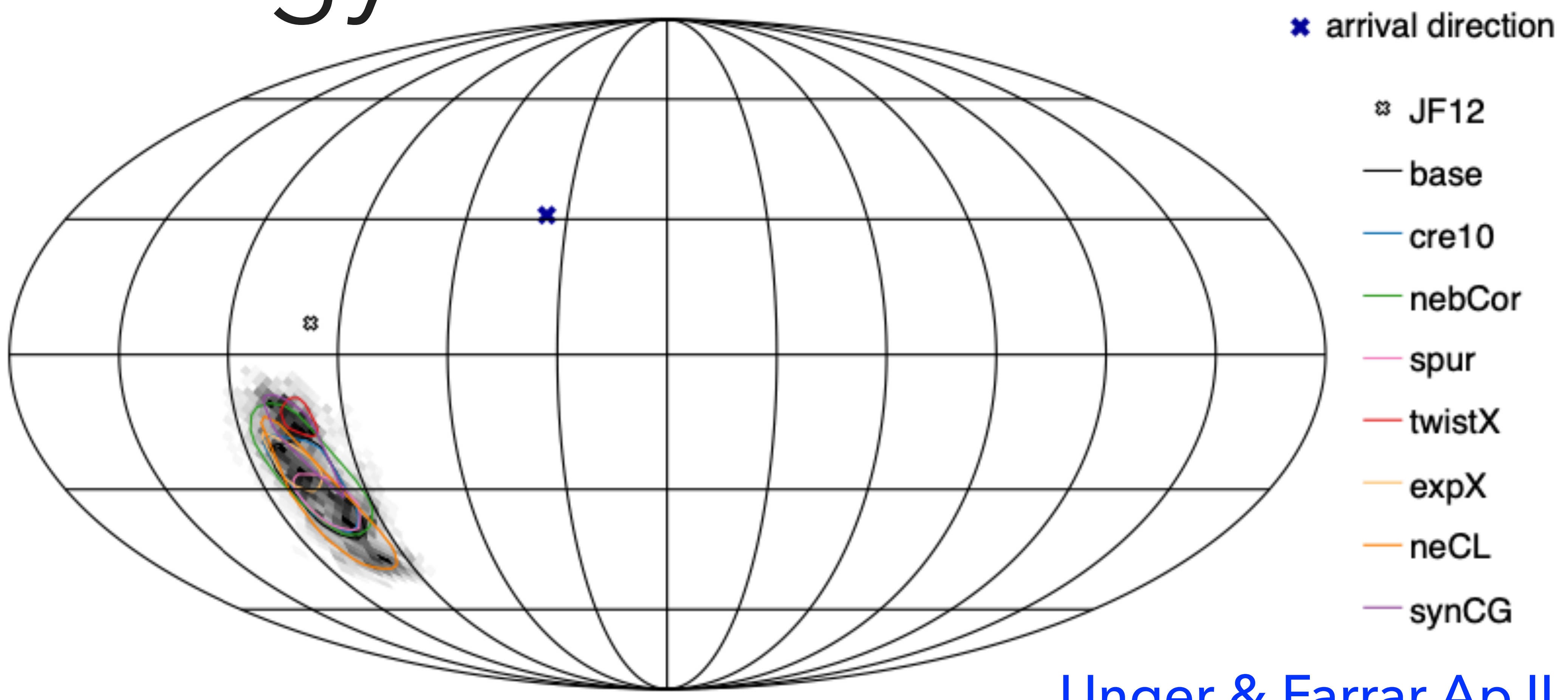


- **Probe of UHECR acceleration in GRBs?**
- See Waxman & Bahcall PRD 1999 for estimate of neutrino intensity from GRBs

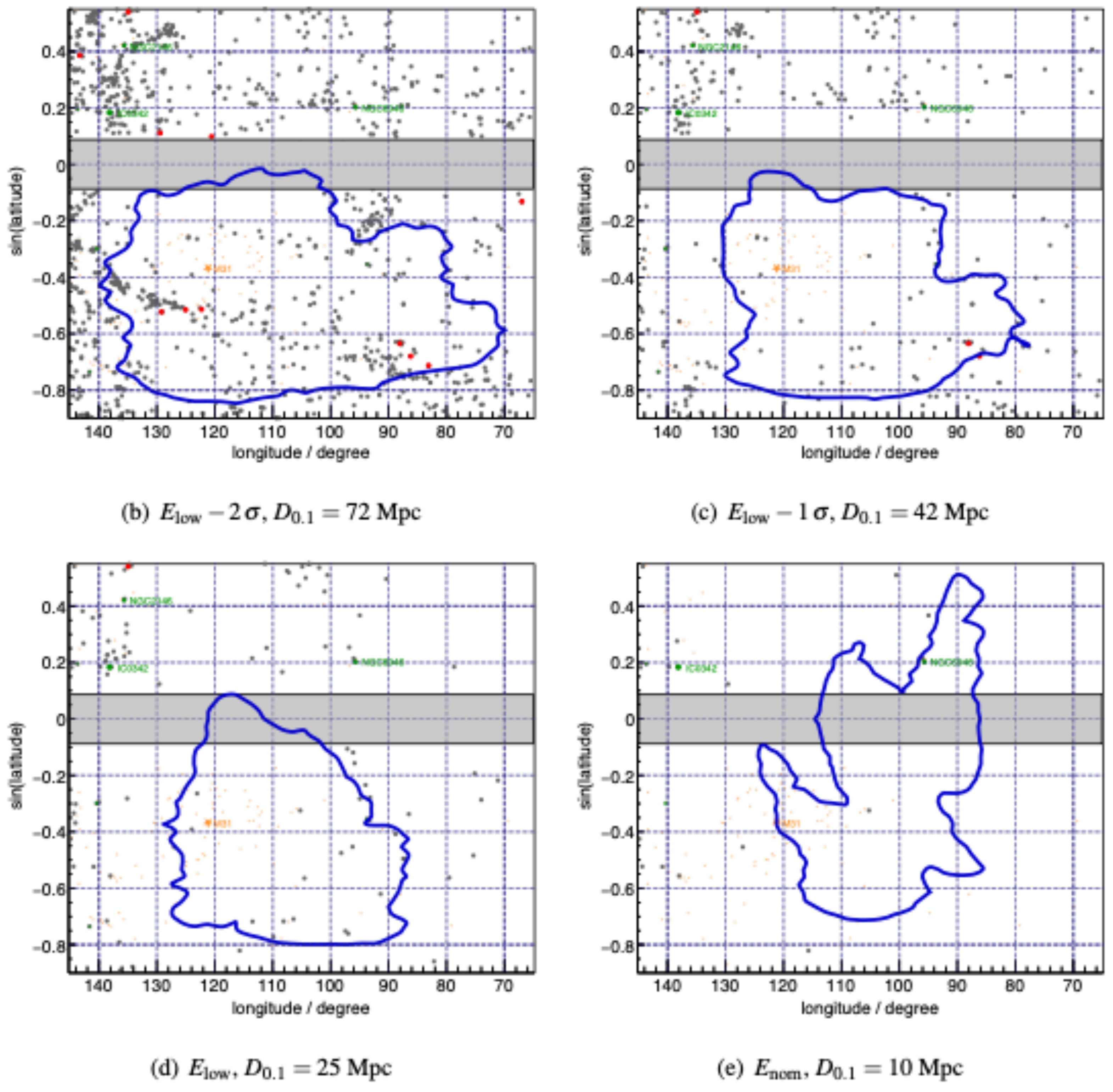
What can we learn from the highest energy CR events?

Globus et al ApJ 2023





Unger & Farrar ApJL 2024

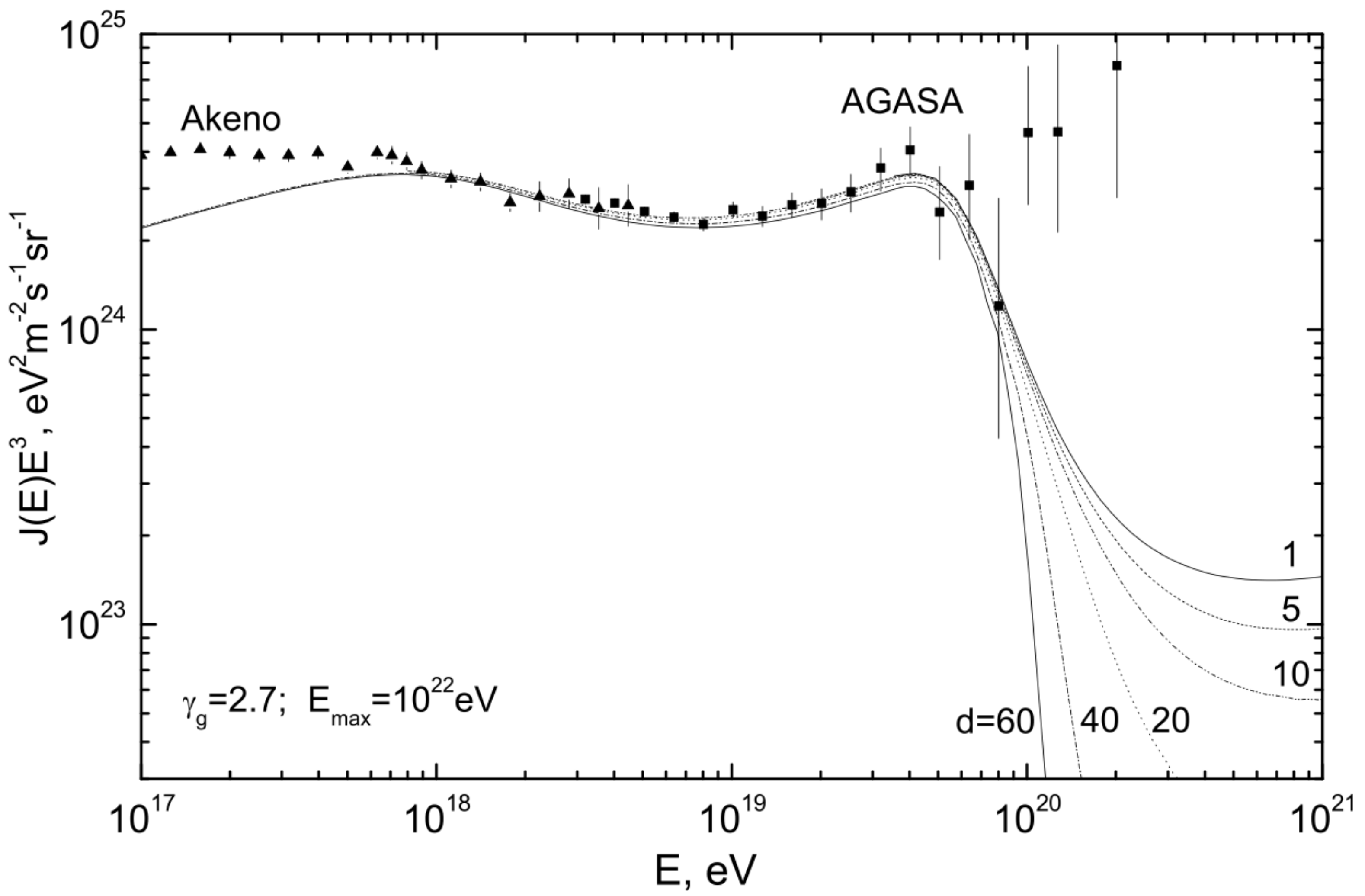


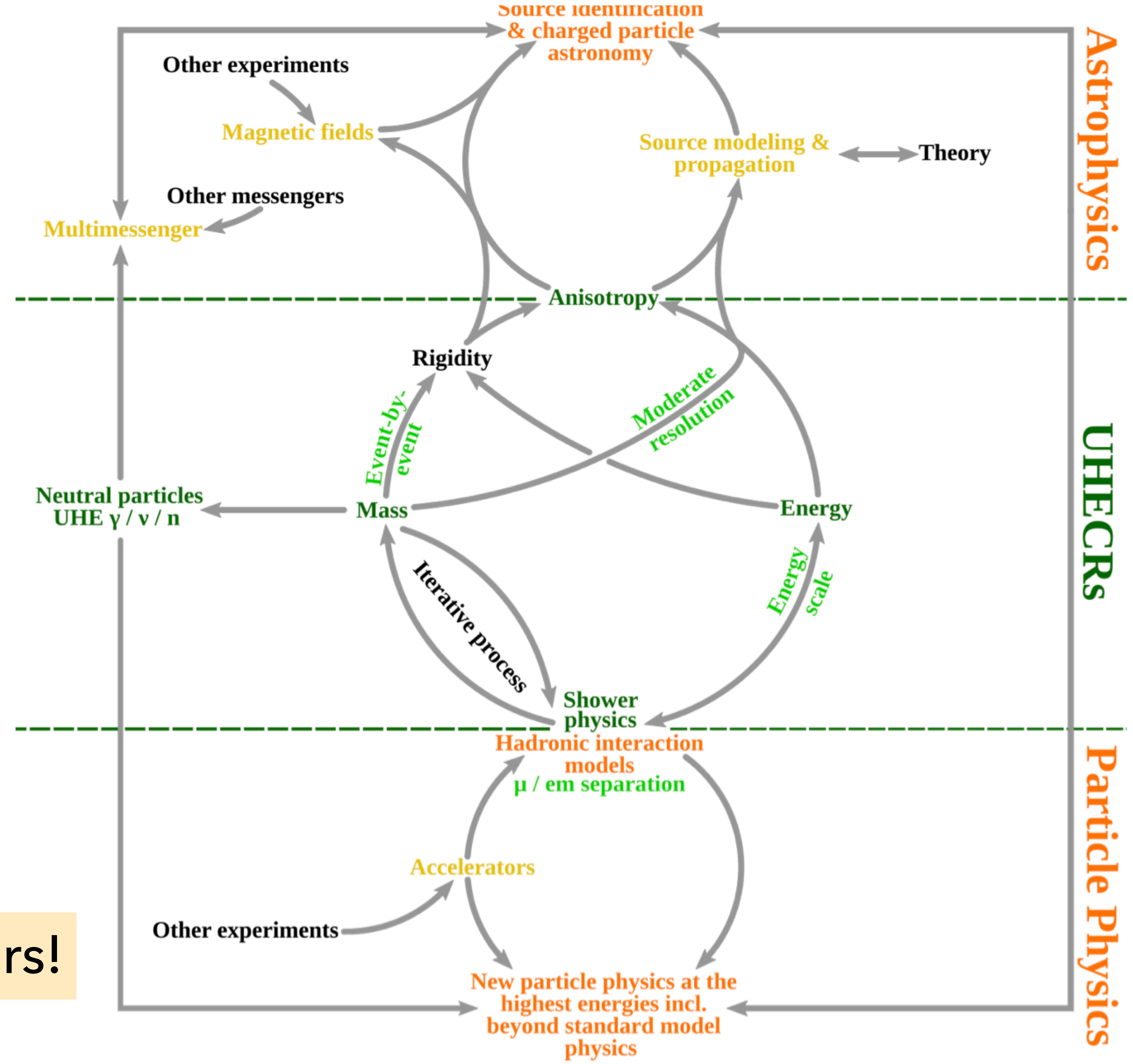
- Inspired by the Amaterasu event, Telescope Array Collab, Science 2023
- **How to gain insights about UHECR sources with extremely energetic events?**
  - By assuming a nuclear species for the event, it is possible to
    - Compute the maximum distance from which the CR is coming, taking into account the interactions in the extragalactic fields
    - Determine the area of the sky from which the CR is coming, taking into account the Galactic magnetic field models

-> the volume of the universe responsible for the CR event can be compared to source catalogues

SUMMARY

- Simple phenomenological models, based on current UHECR data, can provide a basic **description of UHECR data in terms of astrophysical scenarios**
  - This is consistent with what we can deduce from the current limits on other messengers
- We still miss a clear understanding of the **acceleration mechanisms** with which particles reach UHEs
- Thanks to **current (and future) experimental advancements**,
  - we can start refining the basic UHECR scenarios
    - for instance, we can investigate the origin of the measured spectrum features
  - we can predict the sensitivity to characteristics of the UHECR source scenario with upgraded techniques and exploiting the information from other messengers

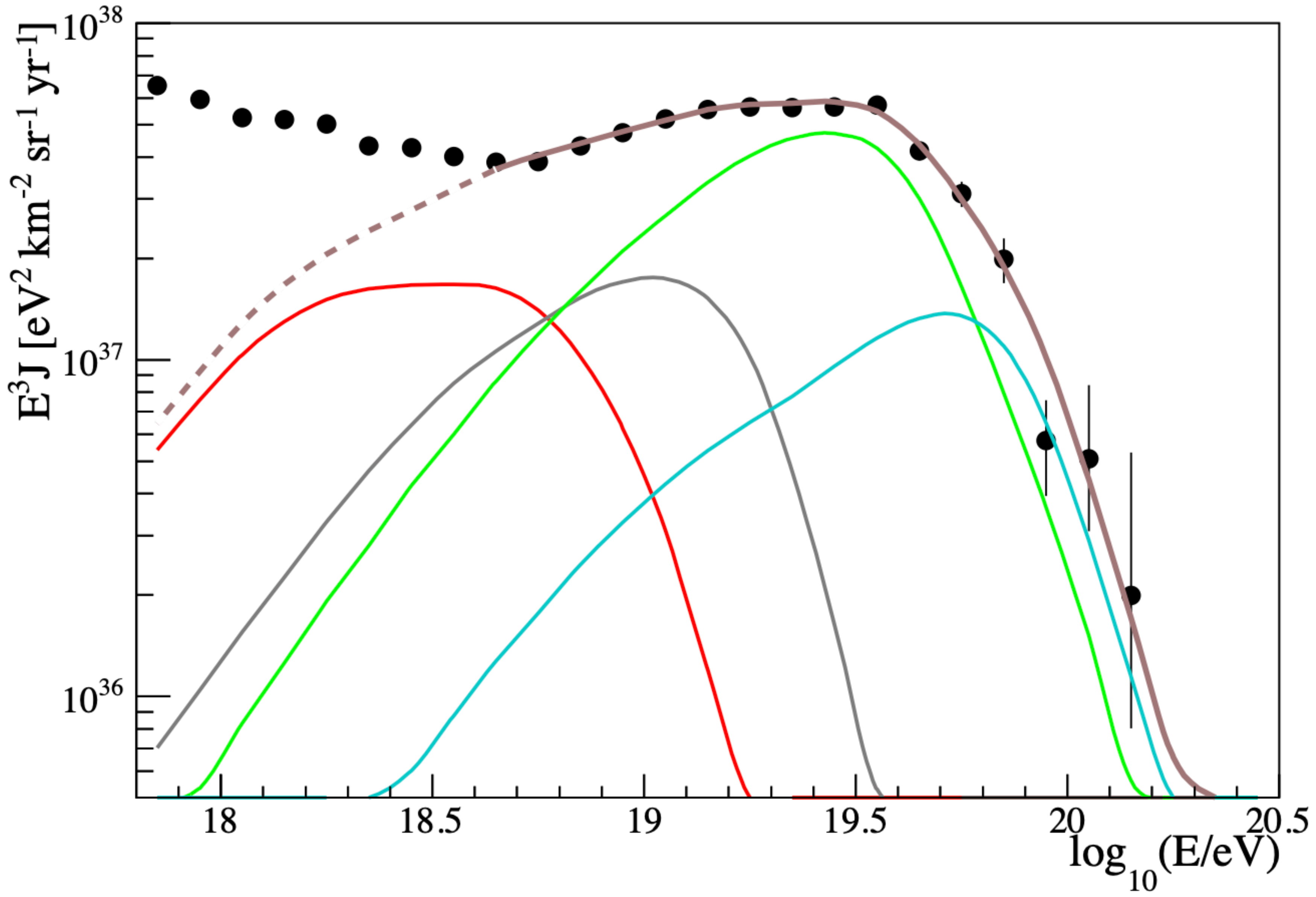




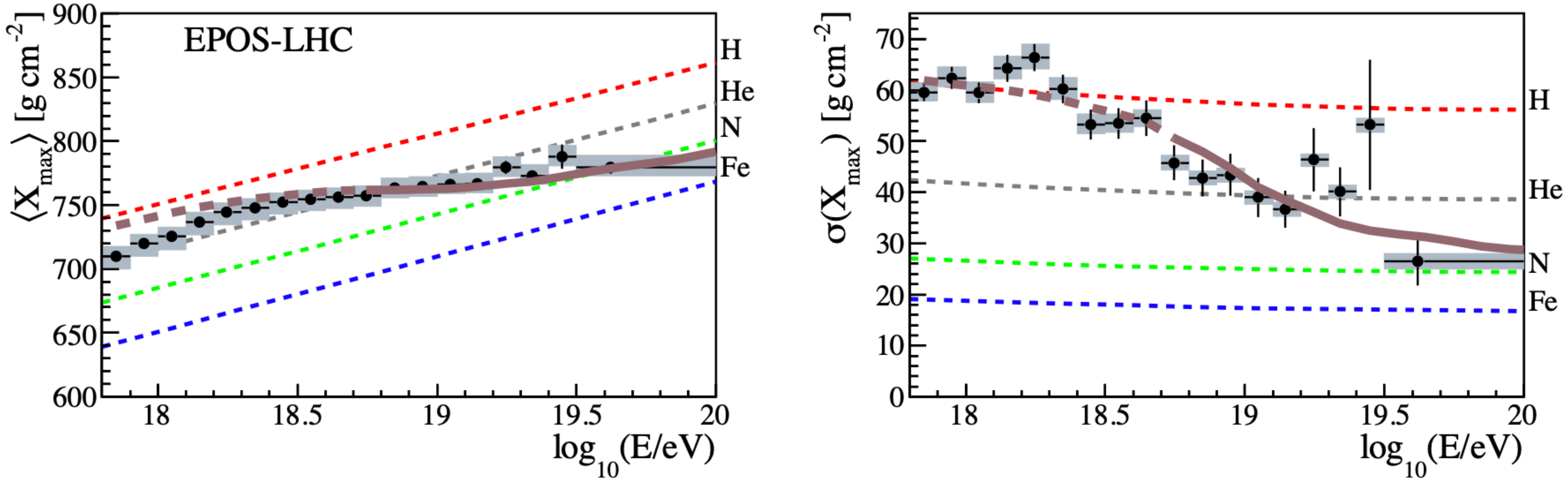
From astrophysical solution(s) to an exciting picture of astrophysical messengers!

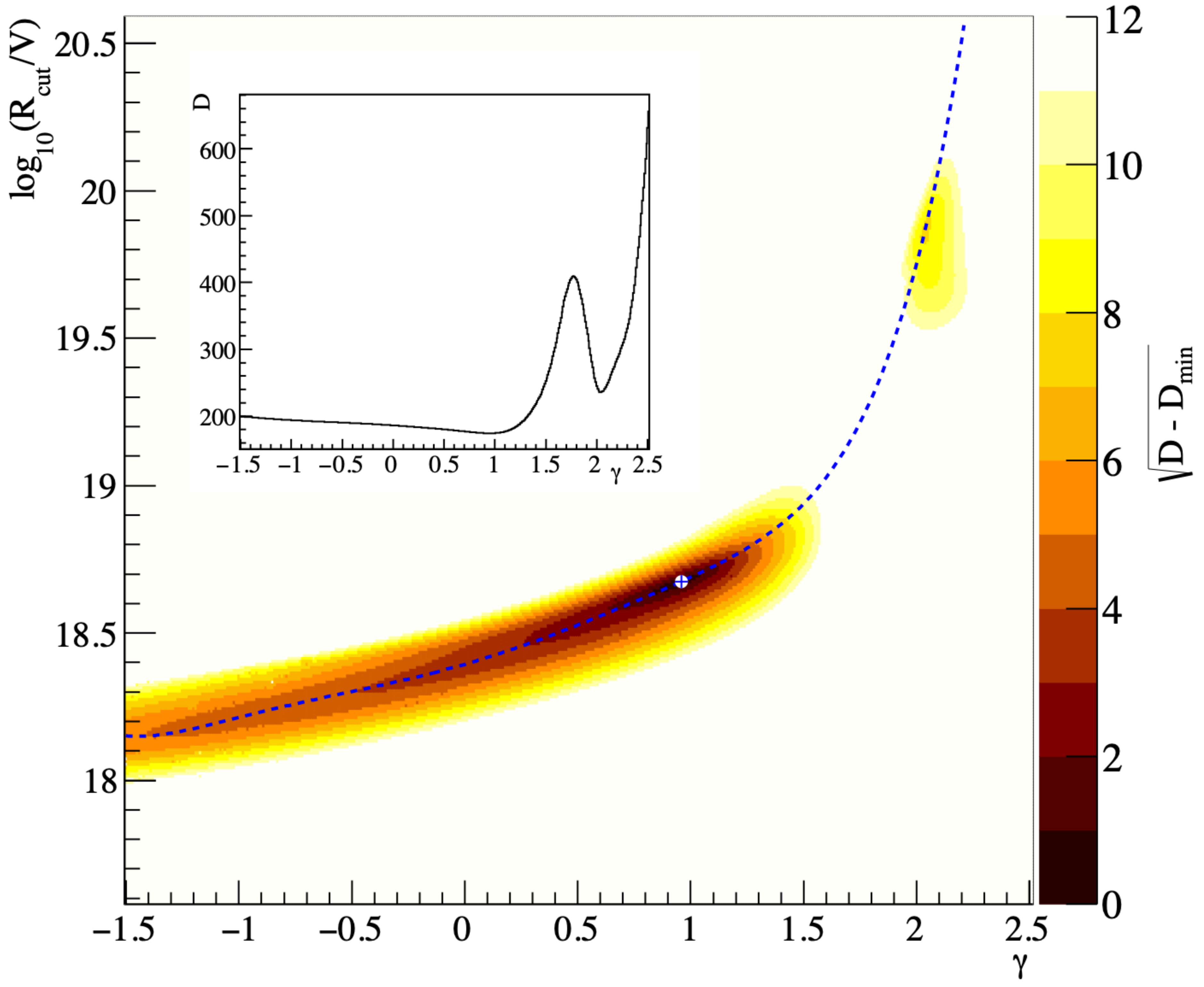
BACKUP SLIDES

Details of the fit of spectrum and composition above the ankle



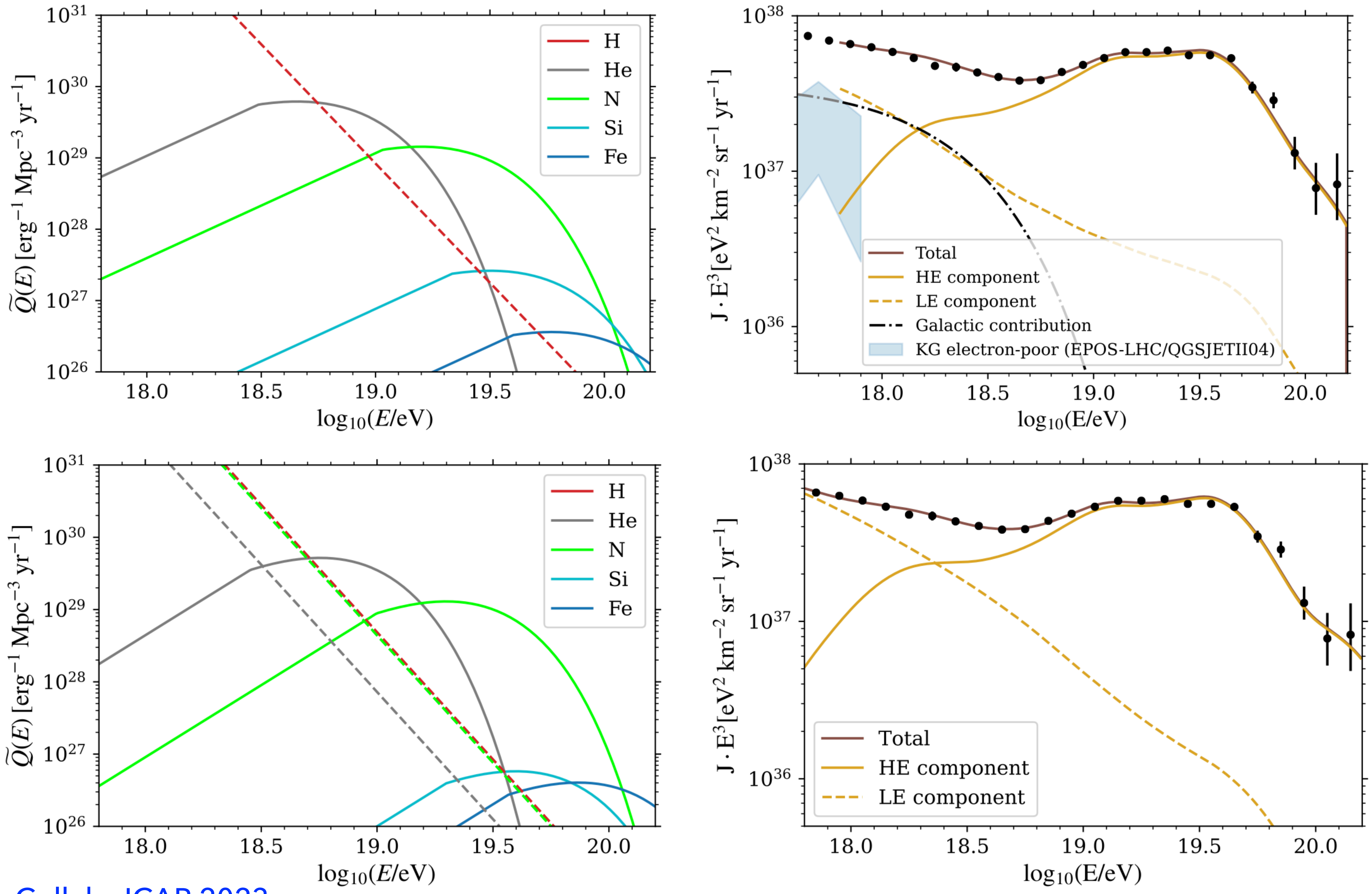
(SPG – EPOS-LHC)	best fit
$\mathcal{L}_0$ [10^{44} erg Mpc^{-3} yr^{-1}]	4.99
γ	$0.96^{+0.08}_{-0.13}$
$\log_{10}(R_{cut}/V)$	$18.68^{+0.02}_{-0.04}$
$f_H(\%)$	0.0
$f_{He}(\%)$	67.3
$f_N(\%)$	28.1
$f_{Si}(\%)$	4.6
$f_{Fe}(\%)$	0.0
D/n	174.4/119





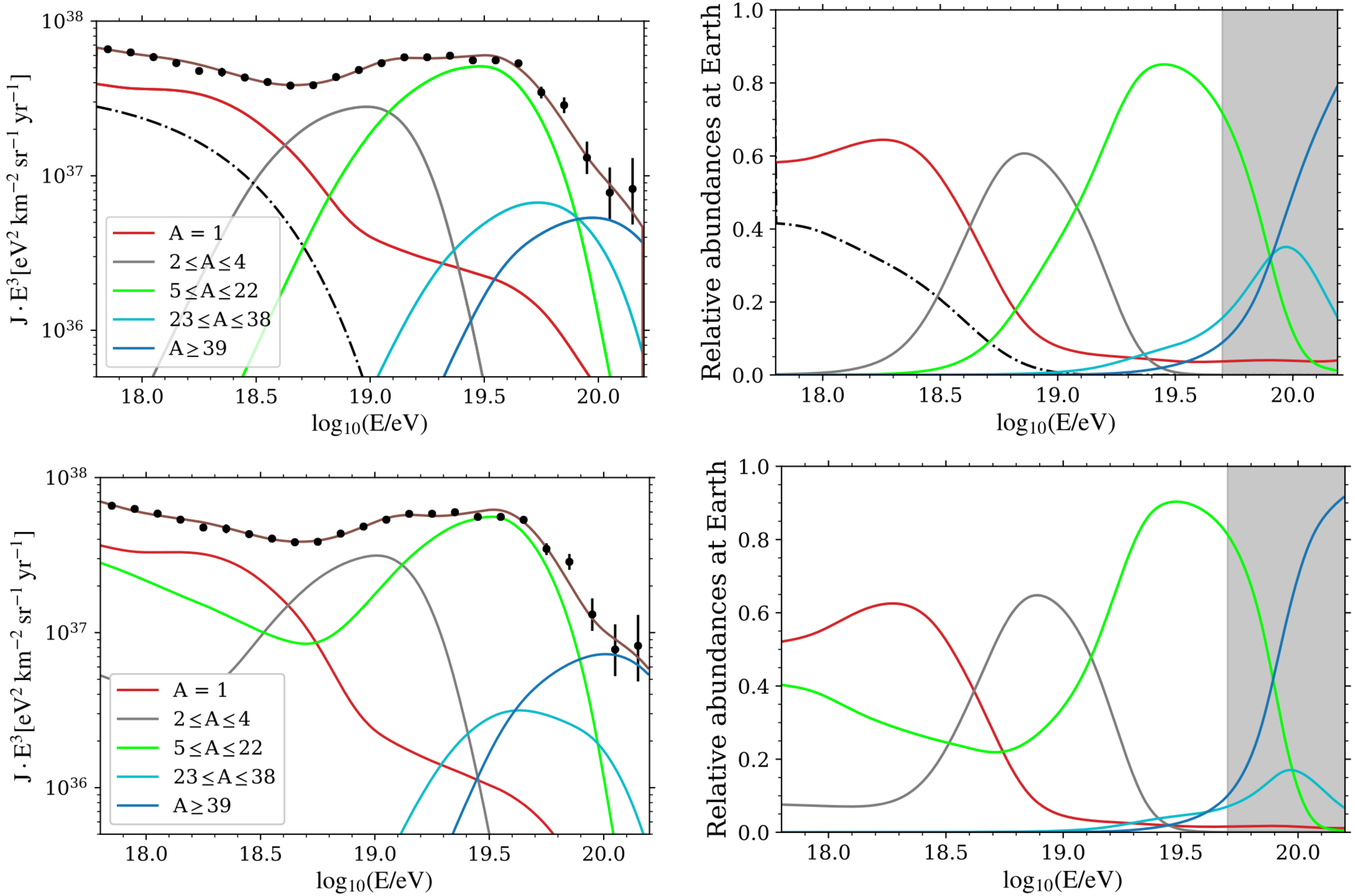
The Pierre Auger Collab. JCAP 2017

Details of the fit of spectrum and composition above and across the ankle



The Pierre Auger Collab. JCAP 2023

Details of the fit of spectrum and composition above and across the ankle



The Pierre Auger Collab. JCAP 2023

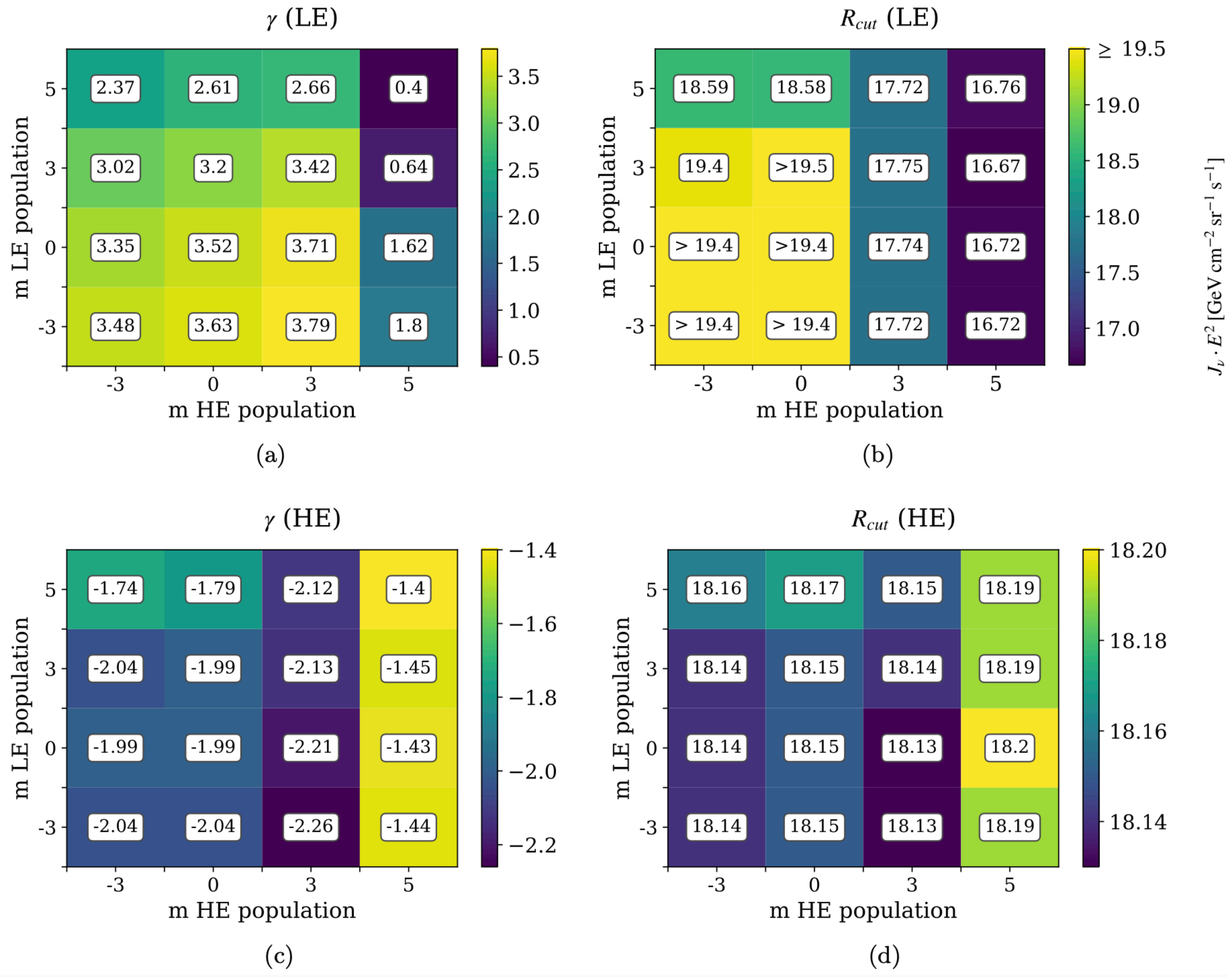
Details of the fit of spectrum and composition above and across the ankle

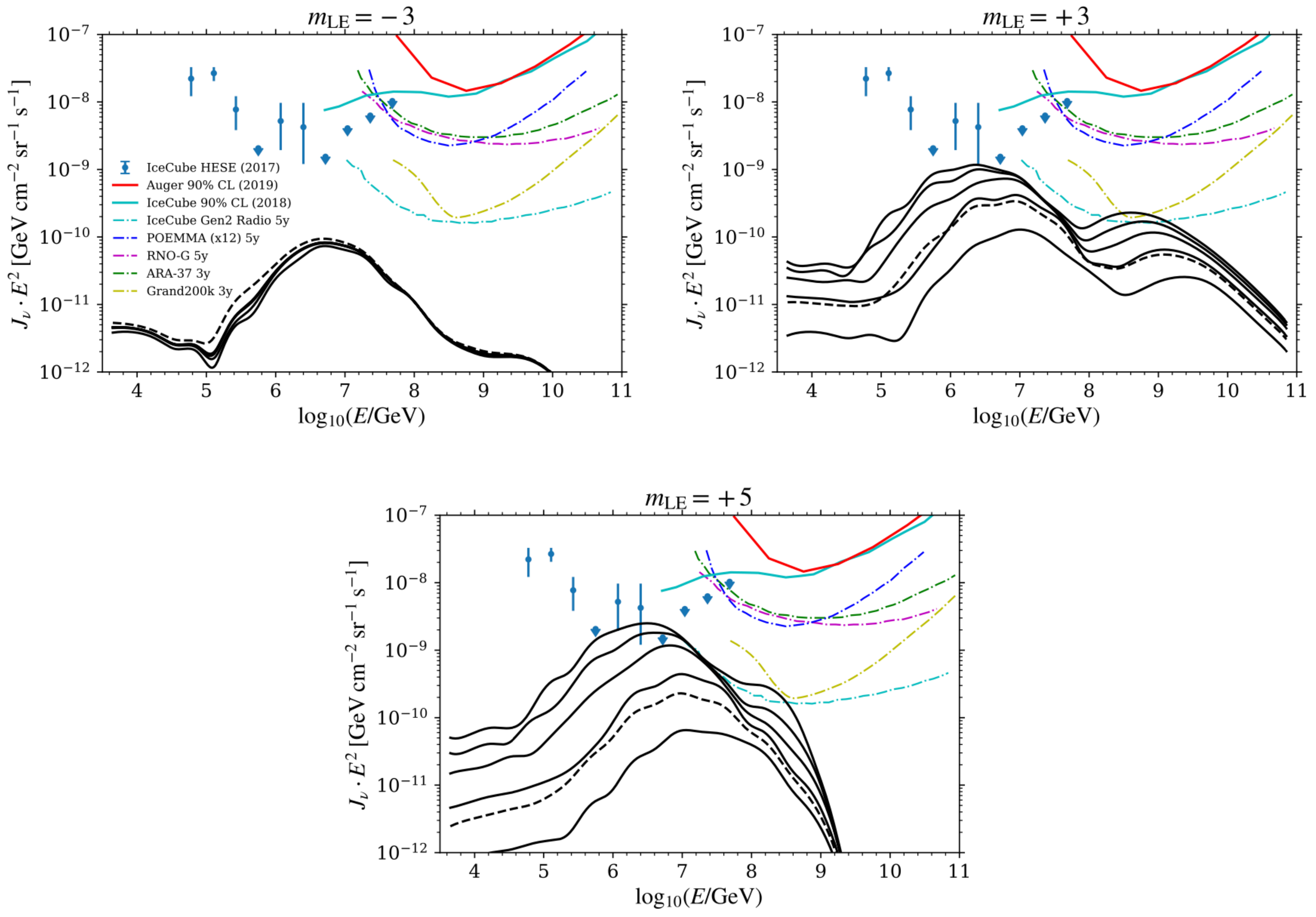
	SCENARIO 1		SCENARIO 2	
Galactic contribution (at Earth)	pure N		—	
$J_0^{\rm Gal}/({\rm eV^{-1}\,km^{-2}\,sr^{-1}\,yr^{-1}})$	$(1.06 \pm 0.04)\times10^{-13}$		—	
$\log_{10}(R_{\rm cut}^{\rm Gal}/{\rm V})$	17.48 ± 0.02		—	
EG components (at the escape)	LE	HE	LE	HE
$\mathcal{L}_0/(10^{44}\,{\rm erg\,Mpc^{-3}\,yr^{-1}})$ *	6.54 ± 0.36	5.00 ± 0.35	11.35 ± 0.15	5.07 ± 0.06
γ	3.34 ± 0.07	-1.47 ± 0.13	3.52 ± 0.03	-1.99 ± 0.11
$\log_{10}(R_{\rm cut}/{\rm V})$	>19.3	18.19 ± 0.02	>19.4	18.15 ± 0.01
$I_{\rm H}$ (%)	100 (fixed)	0.0 ± 0.0	48.7 ± 0.3	0.0 ± 0.0
$I_{\rm He}$ (%)	—	24.5 ± 3.0	7.3 ± 0.4	23.6 ± 1.6
$I_{\rm N}$ (%)	—	68.1 ± 5.0	44.0 ± 0.4	72.1 ± 3.3
$I_{\rm Si}$ (%)	—	4.9 ± 3.9	0.0 ± 0.0	1.3 ± 1.3
$I_{\rm Fe}$ (%)	—	2.5 ± 0.2	0.0 ± 0.0	3.1 ± 1.3
D_J (N_J)	48.6 (24)		56.6 (24)	
$D_{X_{\rm max}}$ ($N_{X_{\rm max}}$)	537.4 (329)		516.5 (329)	
D (N)	586.0 (353)		573.1 (353)	

* from $E_{\rm min} = 10^{17.8}$ eV.

The Pierre Auger Collab. JCAP 2023

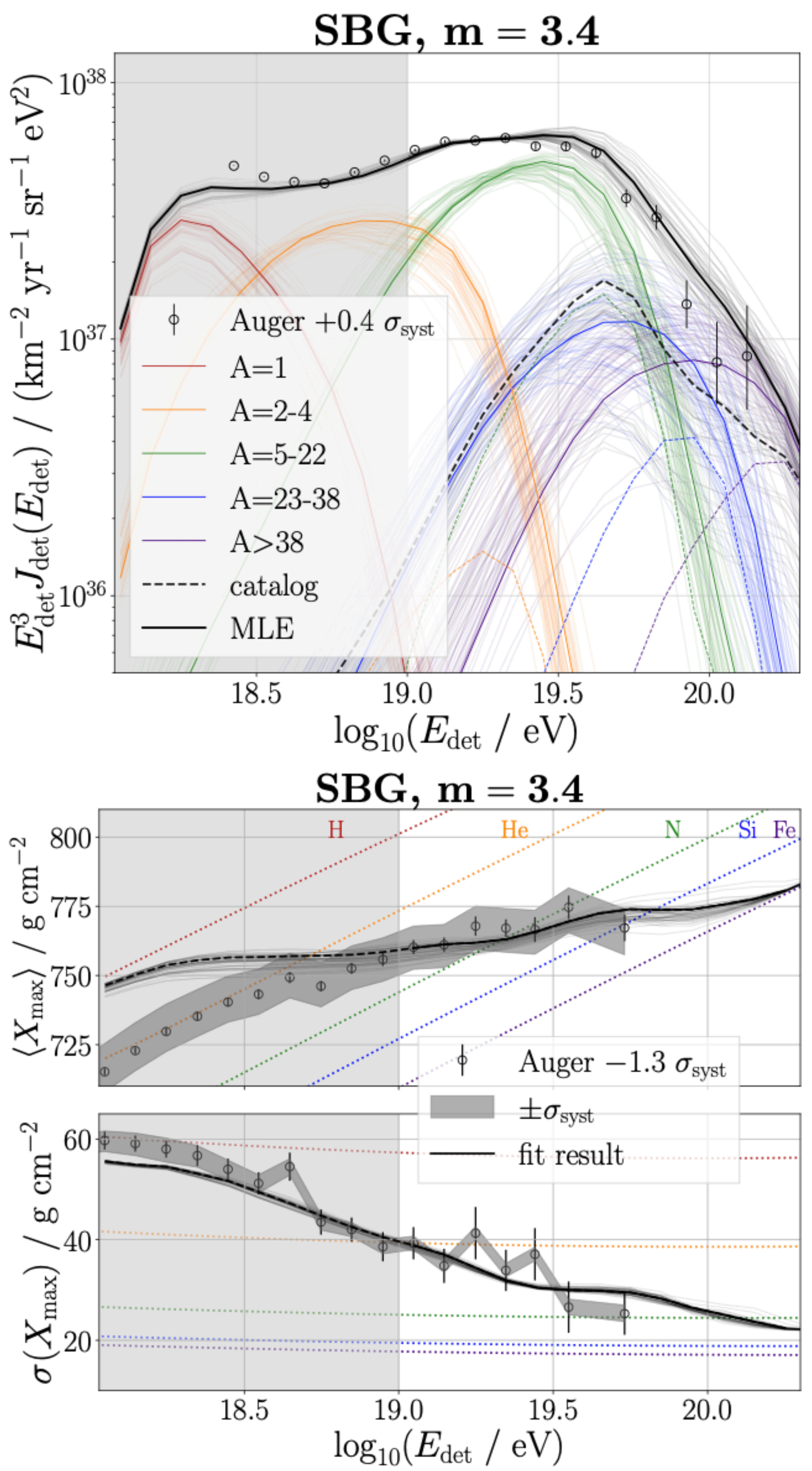
Details of the fit of spectrum and composition above and across the ankle

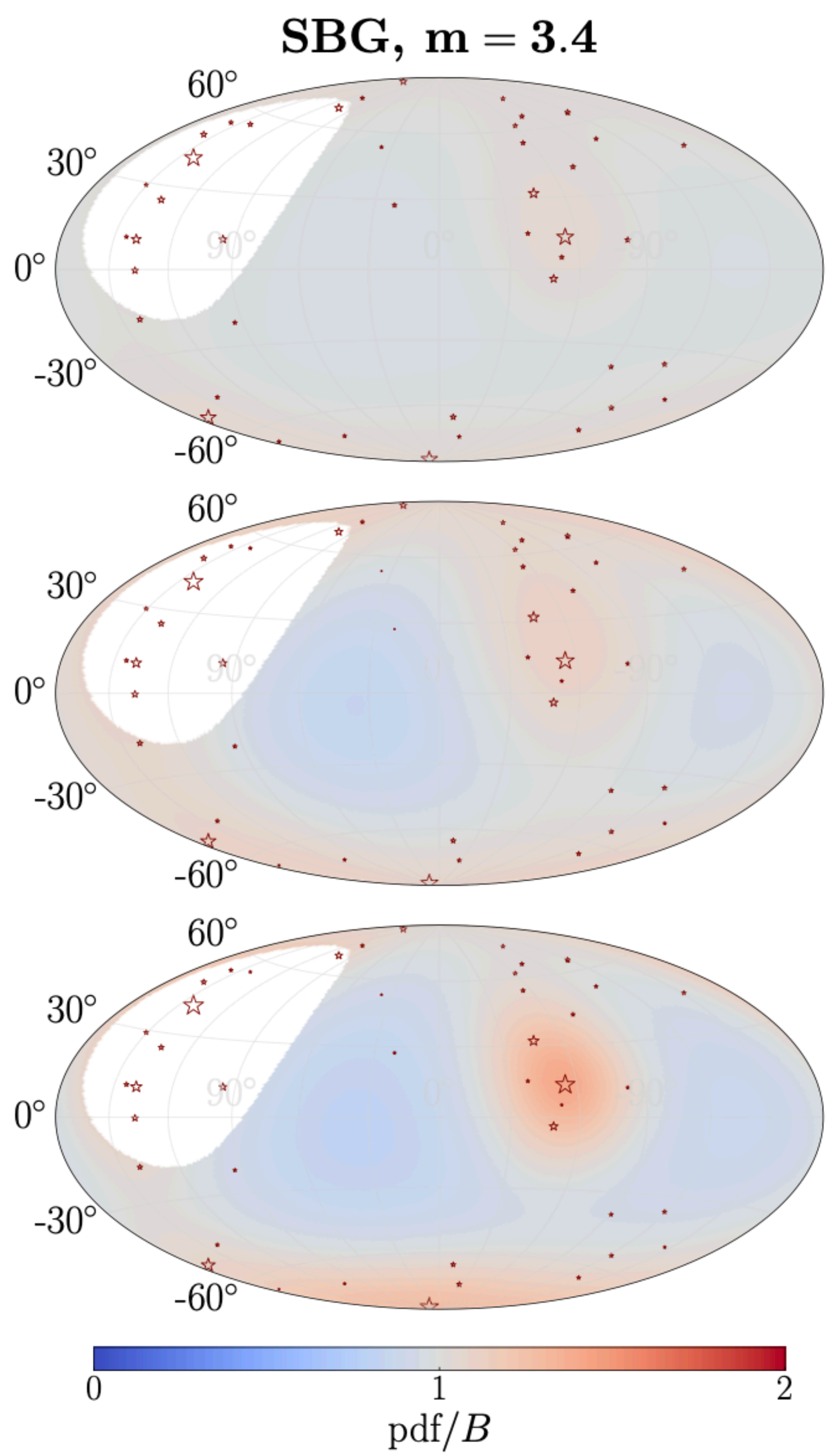




The Pierre Auger Collab. JCAP 2023

Details of the fit of spectrum, composition and arrival directions

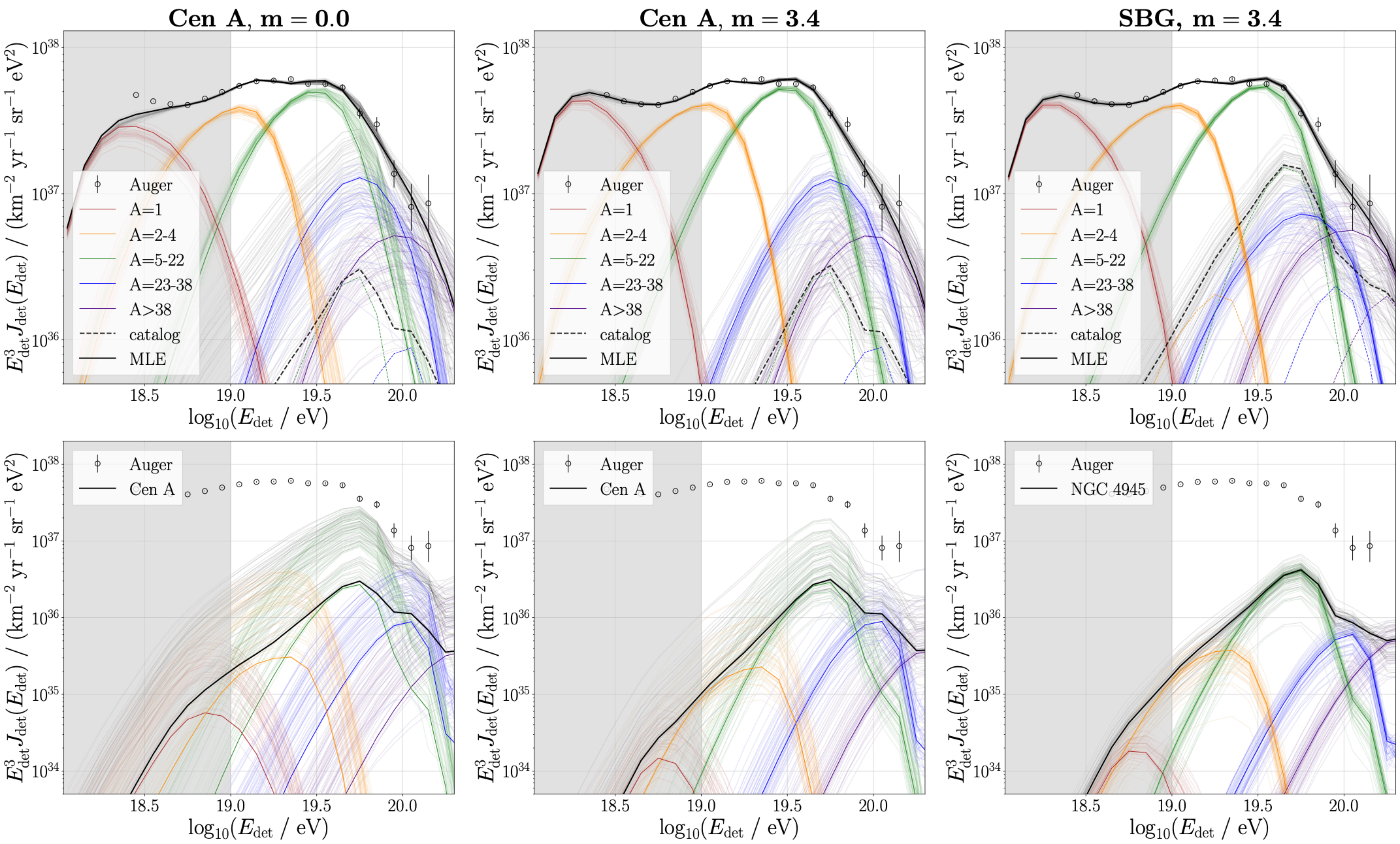




- Signal fraction and uncertainty in arrival direction included in the analysis
- Best improvement with respect to spectrum + composition fit found for **starburst sources**
- gamma-AGN sources disfavoured

The Pierre Auger Collab. JCAP 2024

Details of the fit of spectrum, composition and arrival directions



The Pierre Auger Collab. JCAP 2024

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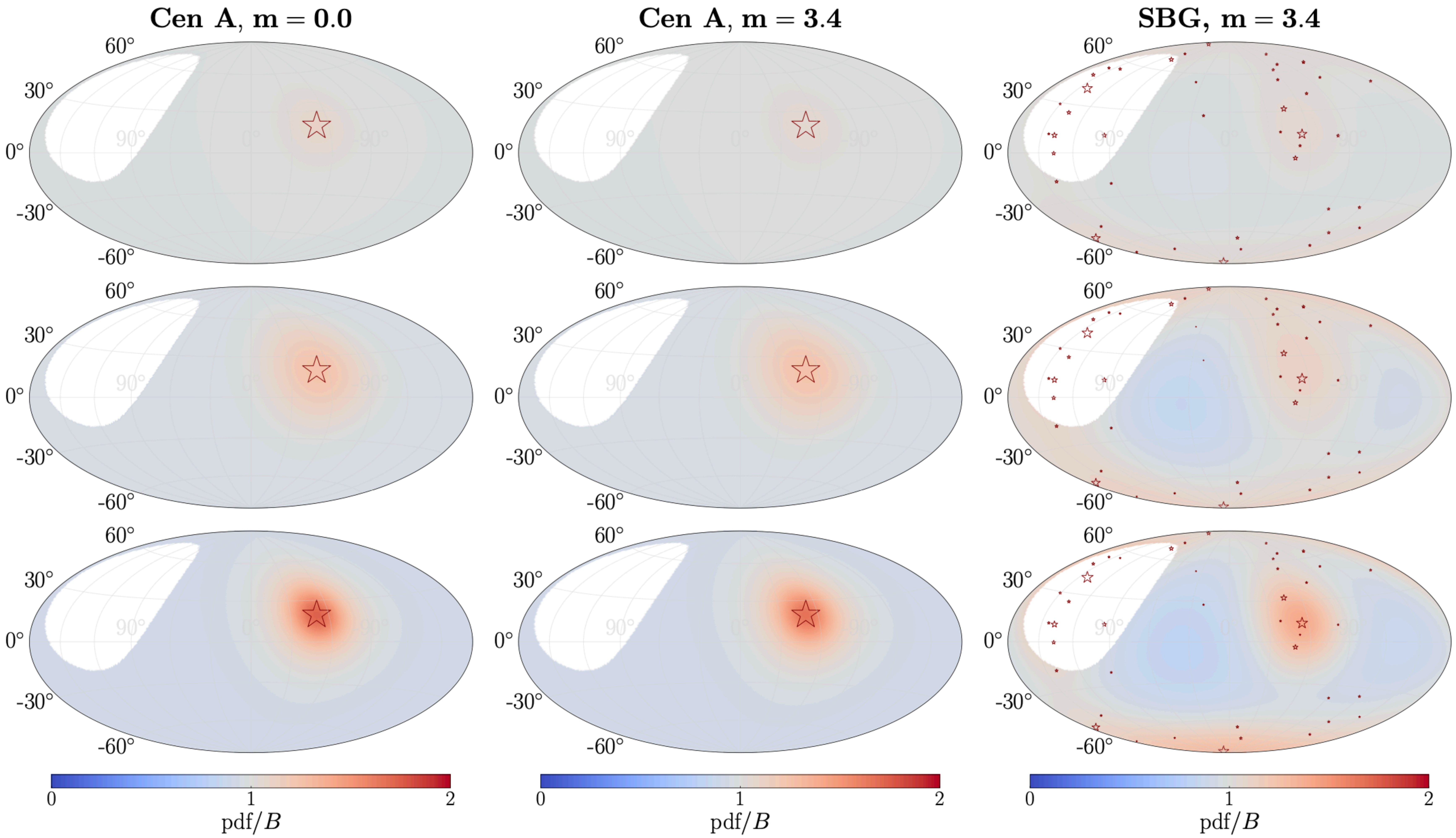

The Pierre Auger Collab. JCAP 2024

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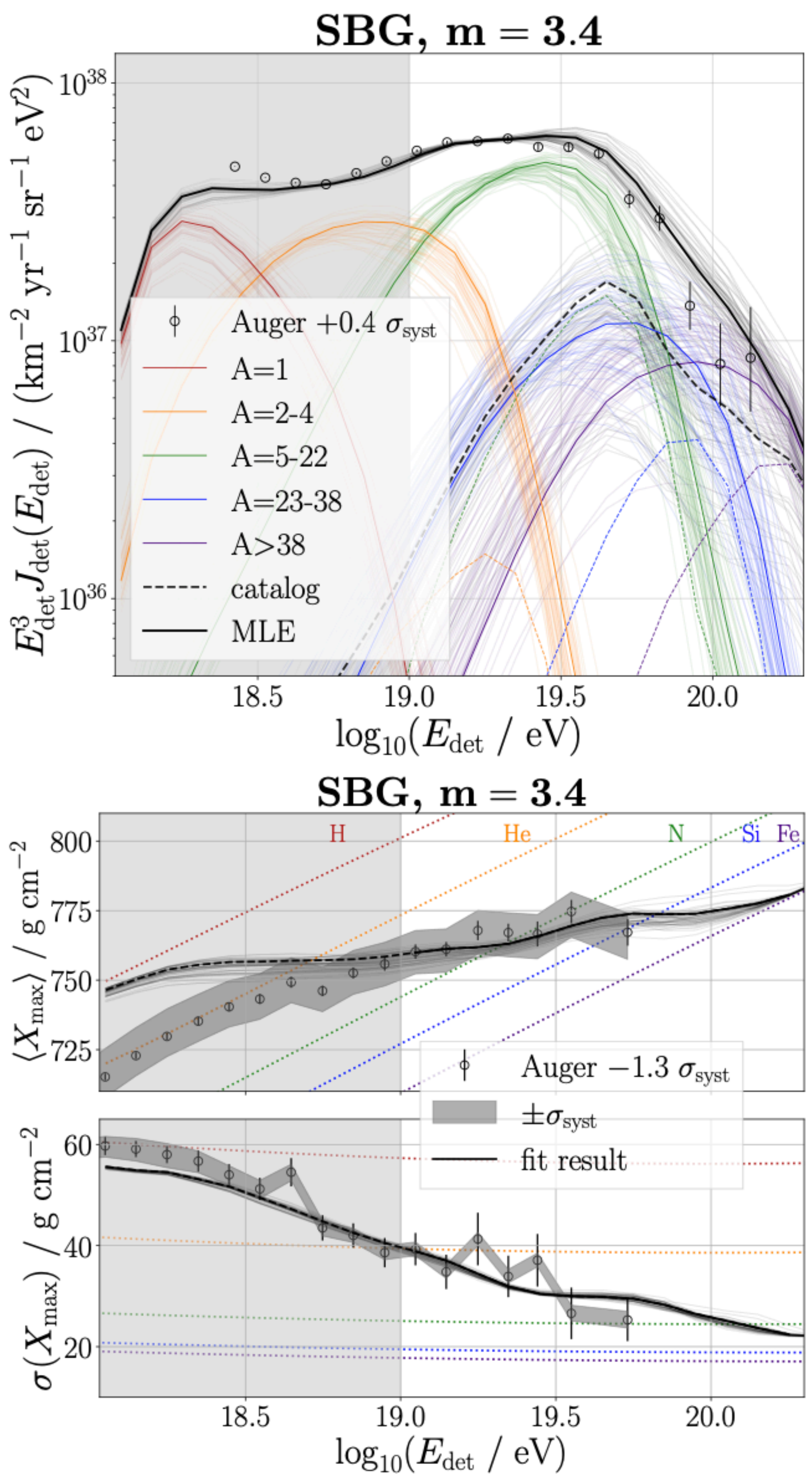


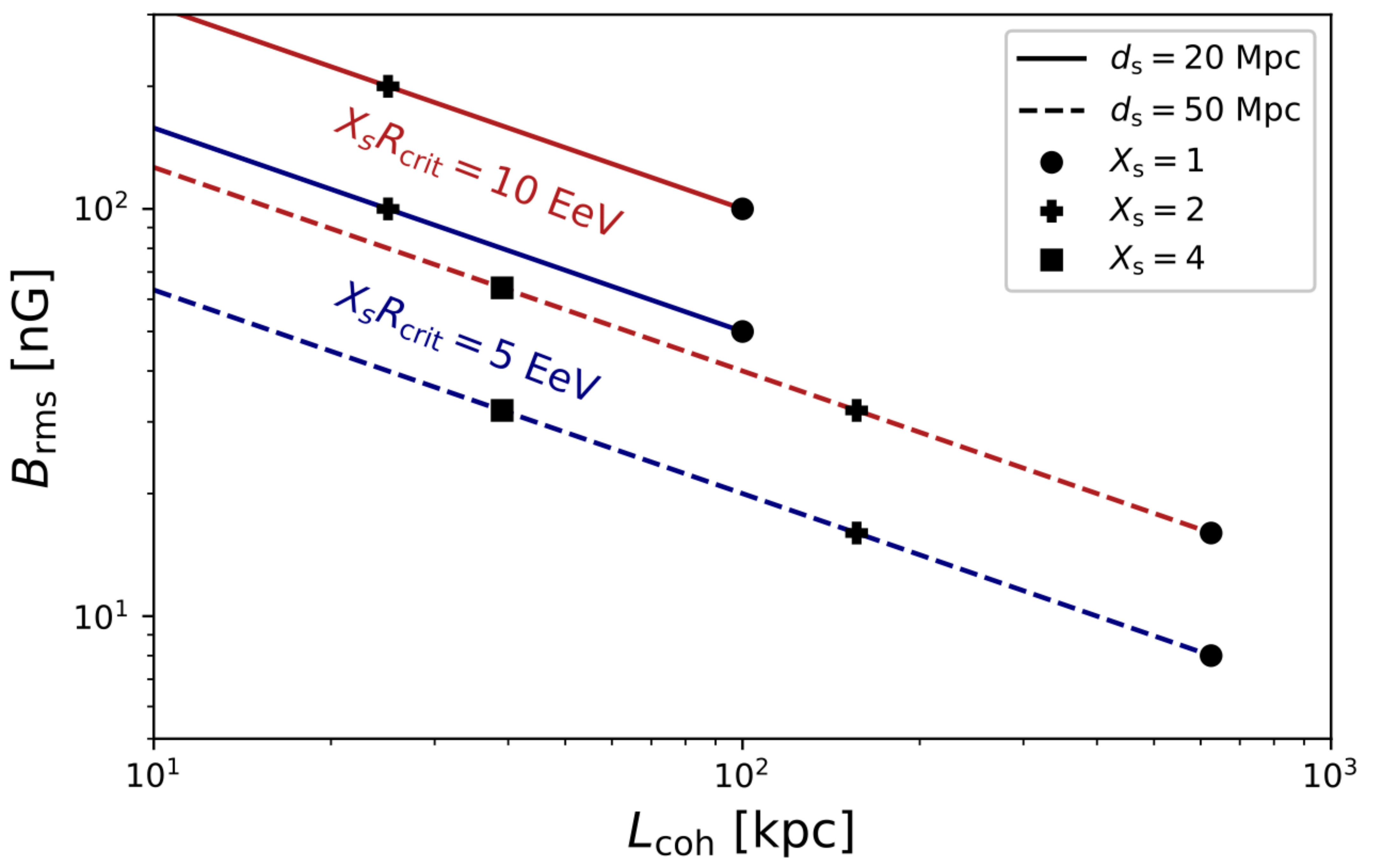
	Cen A, $m = 0$ (flat)		**Cen A, $m = 3.4$** (SFR)		**SBG, $m = 3.4$** (SFR)	
	posterior	MLE	posterior	MLE	posterior	MLE
γ	$-1.67^{+0.48}_{-0.47}$	-2.21	$-3.09^{+0.23}_{-0.24}$	-3.05	$-2.77^{+0.27}_{-0.29}$	-2.67
$\log_{10}(R_{cut}/V)$	$18.23^{+0.04}_{-0.06}$	18.19	$18.10^{+0.02}_{-0.02}$	18.11	$18.13^{+0.02}_{-0.02}$	18.13
f_0	$0.16^{+0.06}_{-0.14}$	0.028	$0.05^{+0.01}_{-0.03}$	0.028	$0.17^{+0.06}_{-0.08}$	0.19
$\delta_0/°$	$56.5^{+29.4}_{-12.8}$	16.5	$27.6^{+2.7}_{-16.3}$	16.8	$22.2^{+5.3}_{-4.0}$	24.3
I_H	$5.9^{+2.5}_{-1.7} \times 10^{-2}$	7.1×10^{-2}	$8.3^{+2.0}_{-8.3} \times 10^{-3}$	1.6×10^{-5}	$6.4^{+1.3}_{-6.4} \times 10^{-3}$	4.3×10^{-5}
I_{He}	$2.3^{+0.3}_{-0.5} \times 10^{-1}$	1.9×10^{-1}	$1.3^{+0.2}_{-0.2} \times 10^{-1}$	1.4×10^{-1}	$1.7^{+0.3}_{-0.4} \times 10^{-1}$	1.8×10^{-1}
I_N	$6.3^{+0.3}_{-0.3} \times 10^{-1}$	6.2×10^{-1}	$7.4^{+0.3}_{-0.3} \times 10^{-1}$	7.3×10^{-1}	$7.4^{+0.3}_{-0.3} \times 10^{-1}$	7.4×10^{-1}
I_{Si}	$6.5^{+3.6}_{-3.3} \times 10^{-2}$	9.9×10^{-2}	$9.2^{+3.2}_{-2.3} \times 10^{-2}$	1.1×10^{-1}	$5.7^{+2.5}_{-3.1} \times 10^{-2}$	5.4×10^{-2}
I_{Fe}	$1.6^{+0.7}_{-1.0} \times 10^{-2}$	2.0×10^{-2}	$2.5^{+0.8}_{-0.9} \times 10^{-2}$	2.3×10^{-2}	$2.5^{+0.8}_{-0.9} \times 10^{-2}$	2.3×10^{-2}
$\log b$	-264.0 ± 0.2		-272.6 ± 0.2		-266.9 ± 0.1	
D_E ($N_J = 14$)		22.3		28.5		33.3
$D_{X_{max}}$ ($N_{X_{max}} = 74$)		124.9		130.6		126.2
D		147.2		159.1		159.5
$\log \mathcal{L}_{ADs}$		10.5		10.4		13.3
$\log \mathcal{L}$		−239.1		−245.1		−242.4

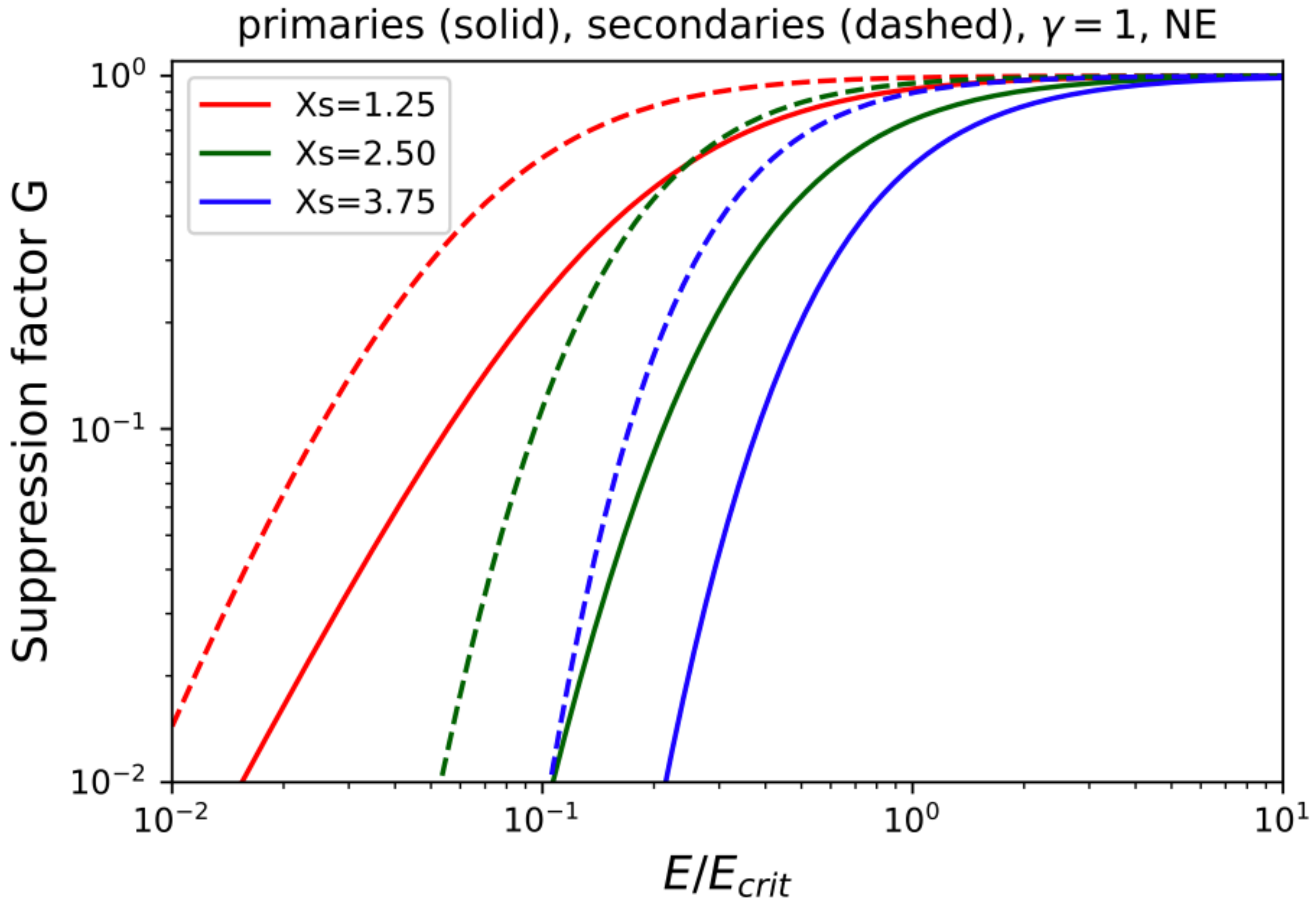
The Pierre Auger Collab. JCAP 2024

Effects of the magnetic horizon

- Extragalactic magnetic fields (EGMF) between Earth and closest sources modelled as turbulent and isotropic with average amplitude and coherence length
- Critical energy Ecrit such that: $r_L(E_{\rm crit}) = L_{\rm coh}, \quad R_{\rm crit} = \frac{E_{\rm crit}}{Z} = 0.9 \frac{B_{\rm rms}}{\rm nG} \frac{L_{\rm coh}}{\rm Mpc} {\rm EeV}$
- Uniform source density, intersource distance ds; Xs is the normalised distance $X_s = \frac{d_s}{25\,{\rm Mpc}} \sqrt{\frac{\rm Mpc}{L_{\rm coh}}}$
- **The magnetic horizon suppresses the flux at low energies**

$$X_s R_{\rm crit} \approx 10\,{\rm EeV} \frac{d_s}{40\,{\rm Mpc}} \frac{B_{\rm rms}}{100\,{\rm nG}} \sqrt{\frac{L_{\rm coh}}{25\,{\rm kpc}}}$$



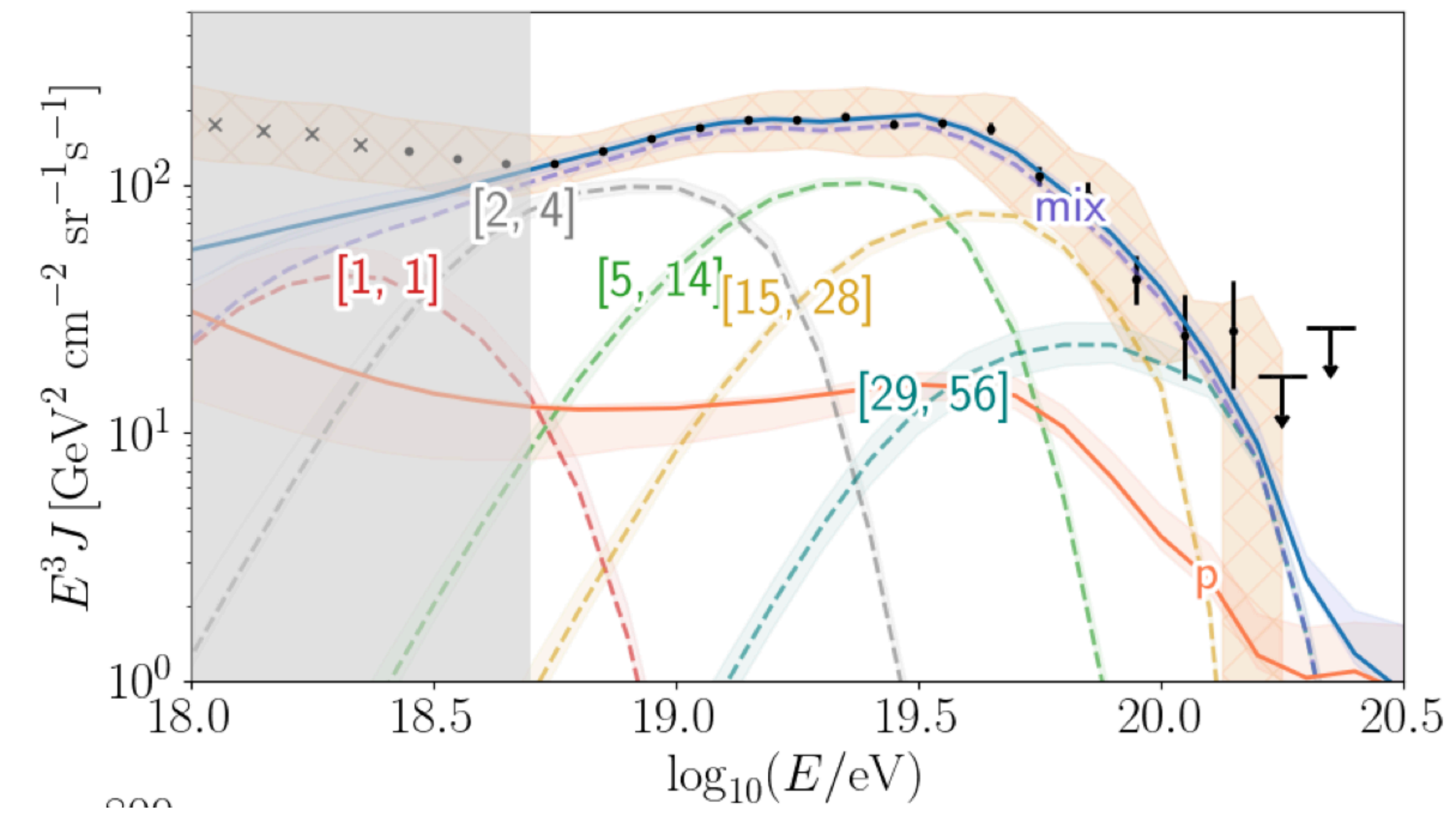


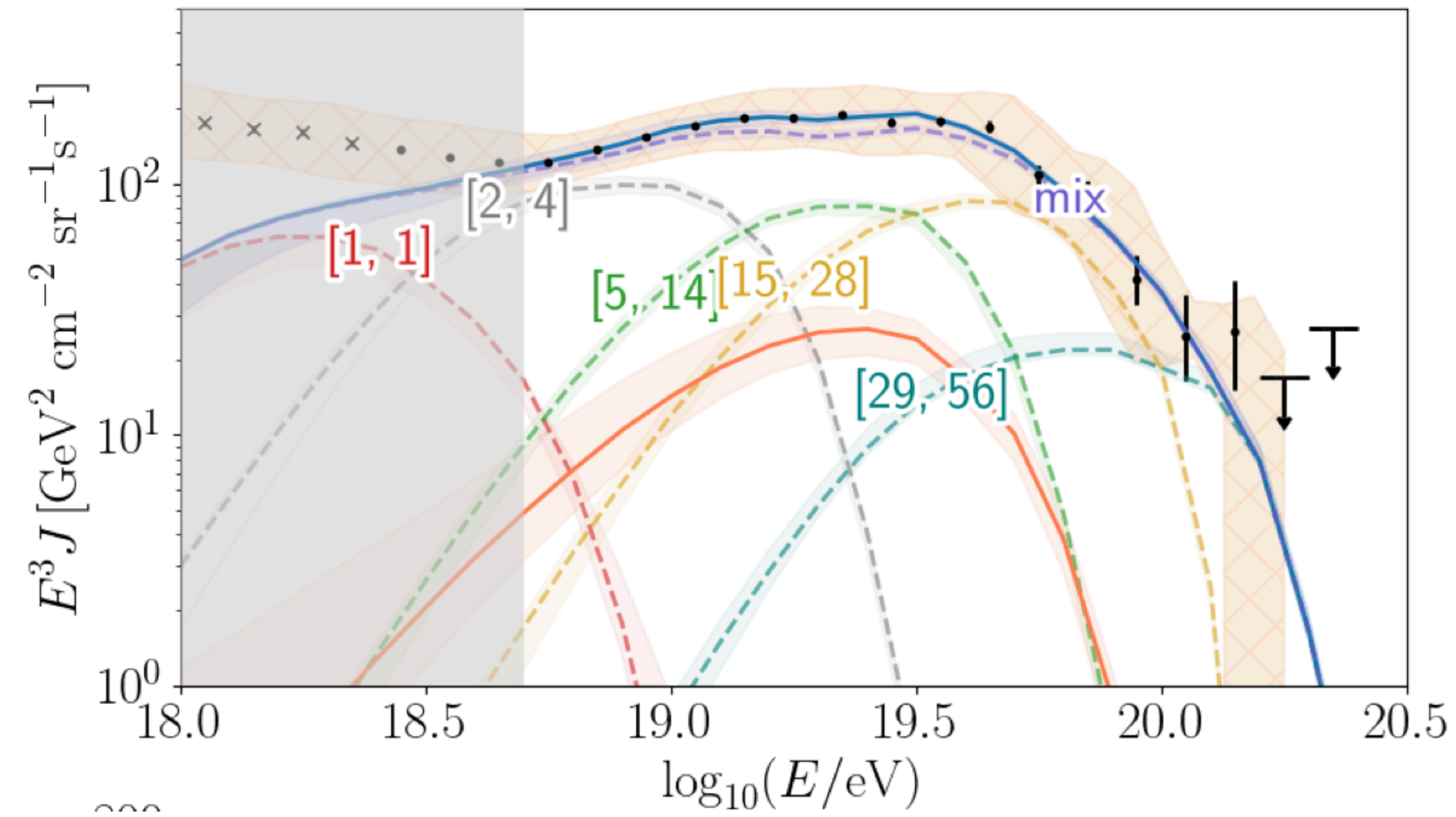
The Pierre Auger Collab. JCAP 2024; Gonzales et al PRD 2021

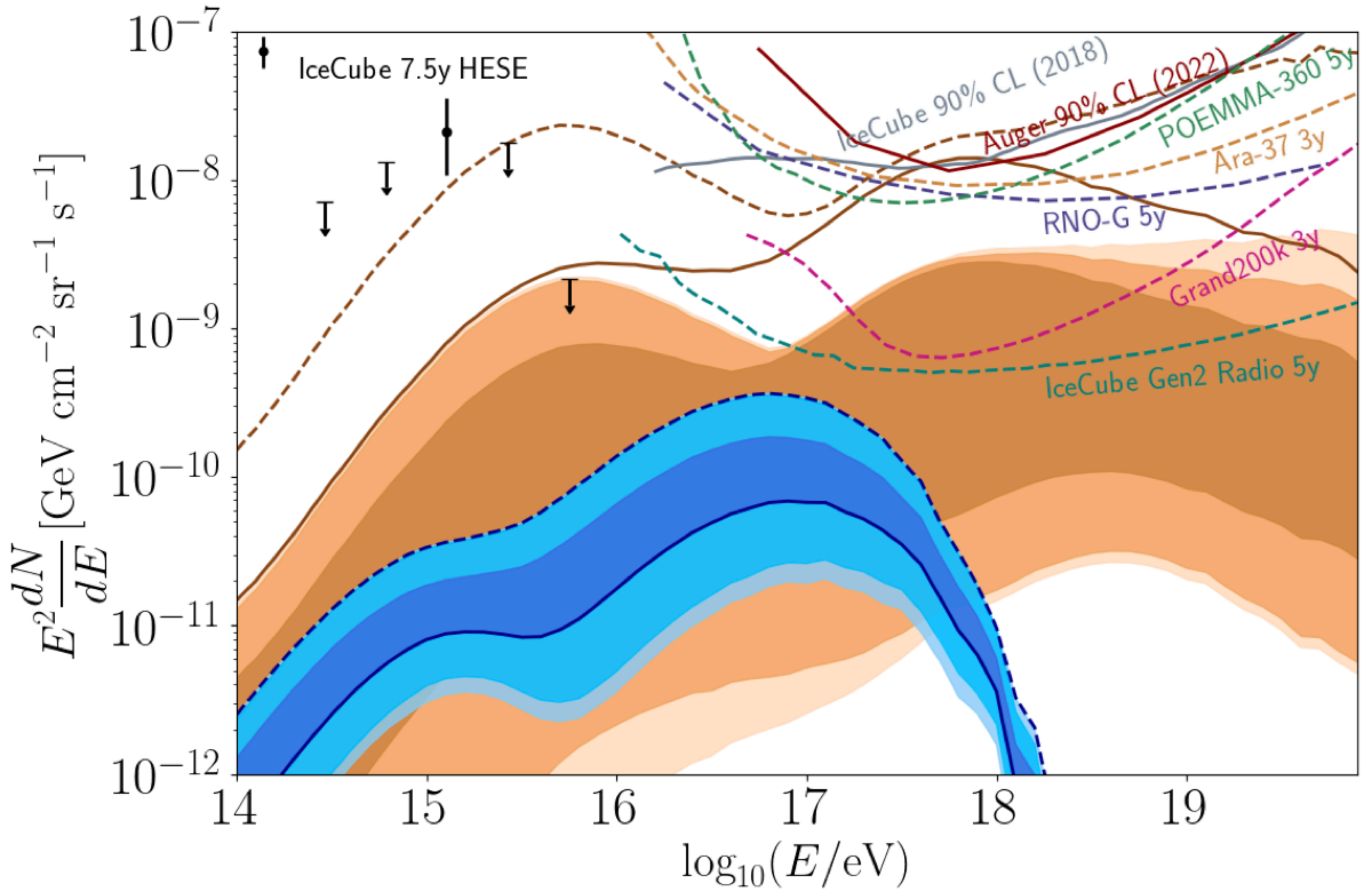
UHECR flux at Earth and the corresponding cosmogenic neutrinos

Mixed composition for UHECRs

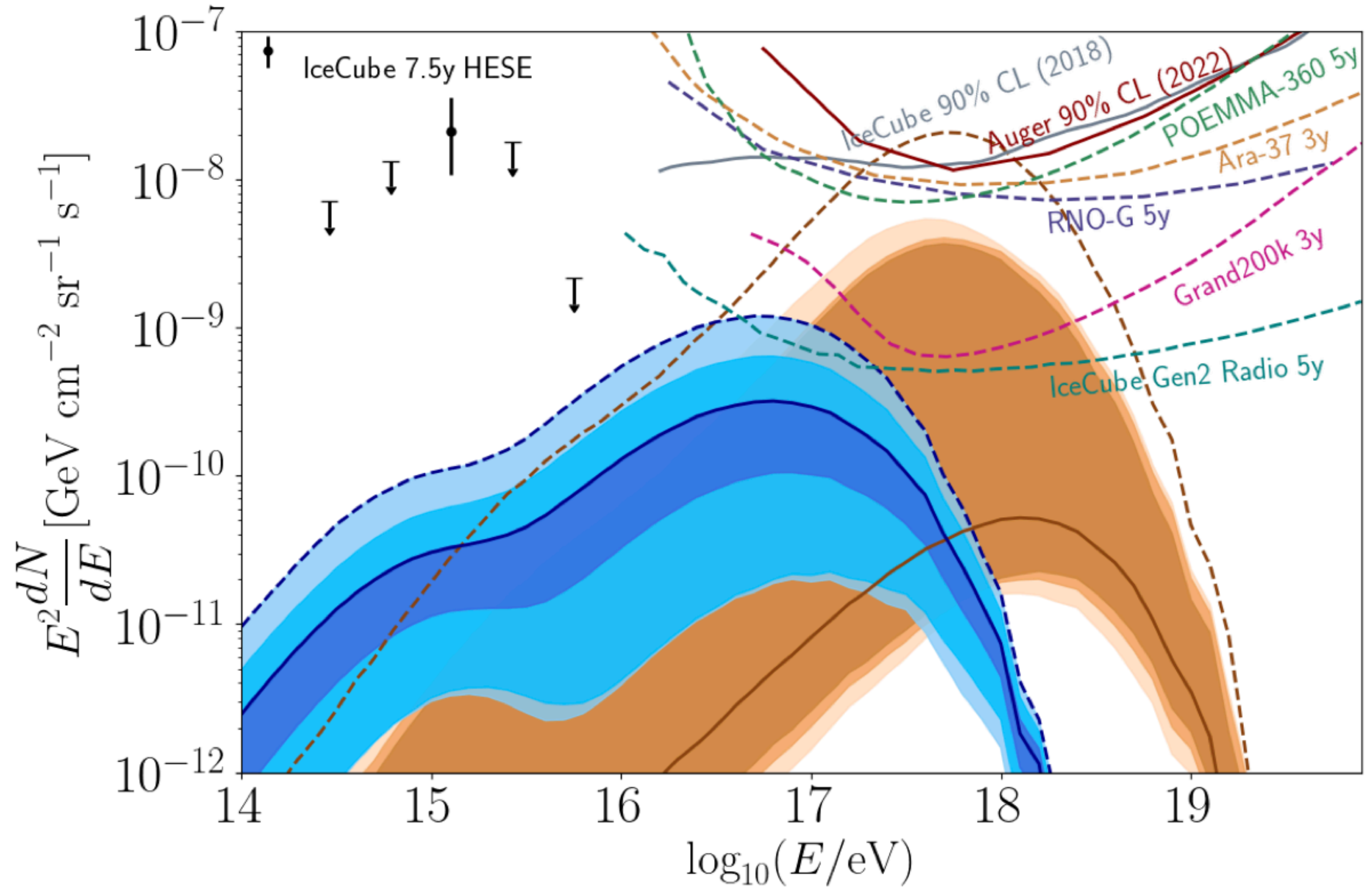
- Shaping the additional proton component







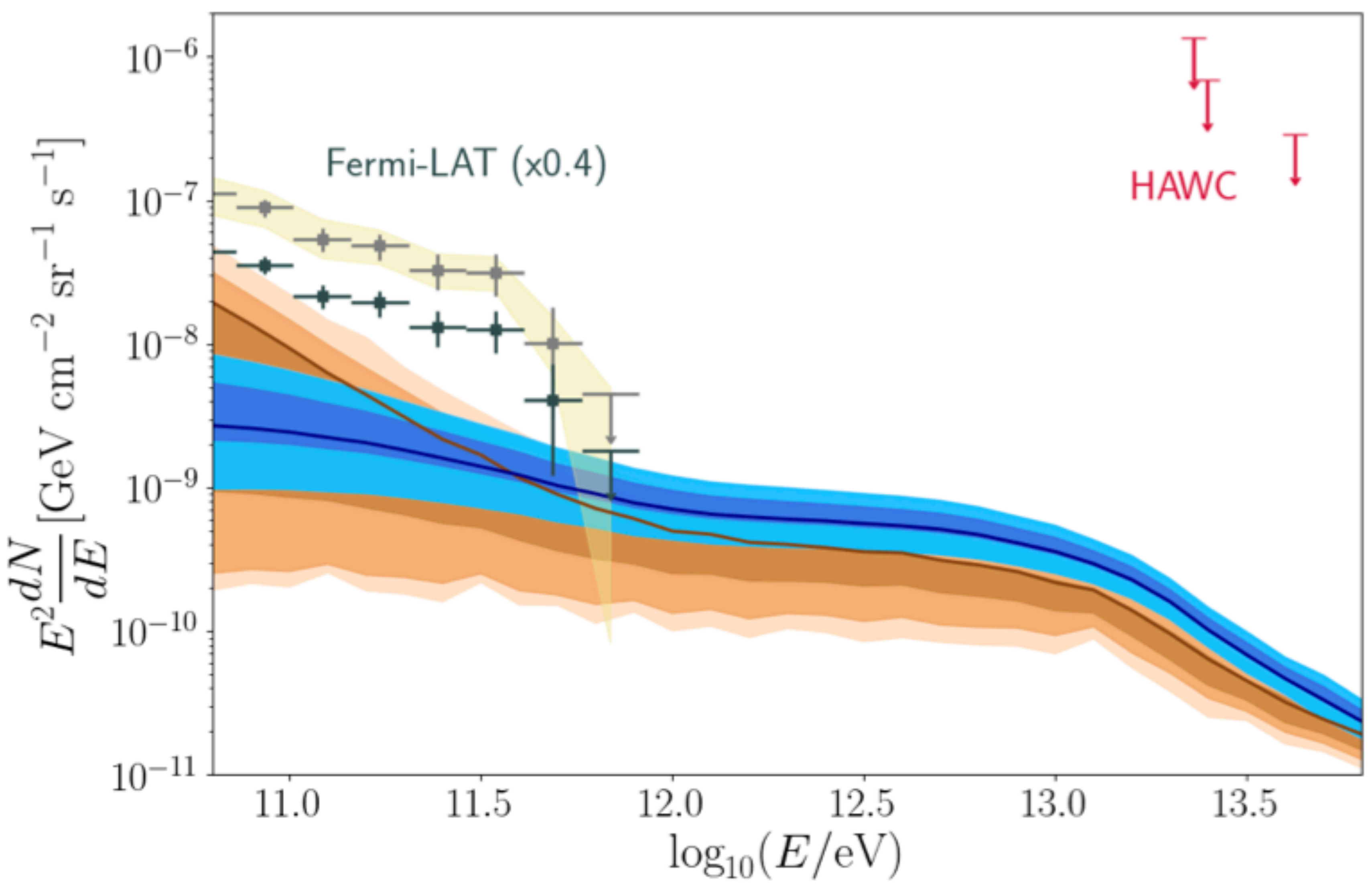
- Brown contours -> from the UHECR fit
- Blue contours -> from the UHECR fit + penalty from multimessenger



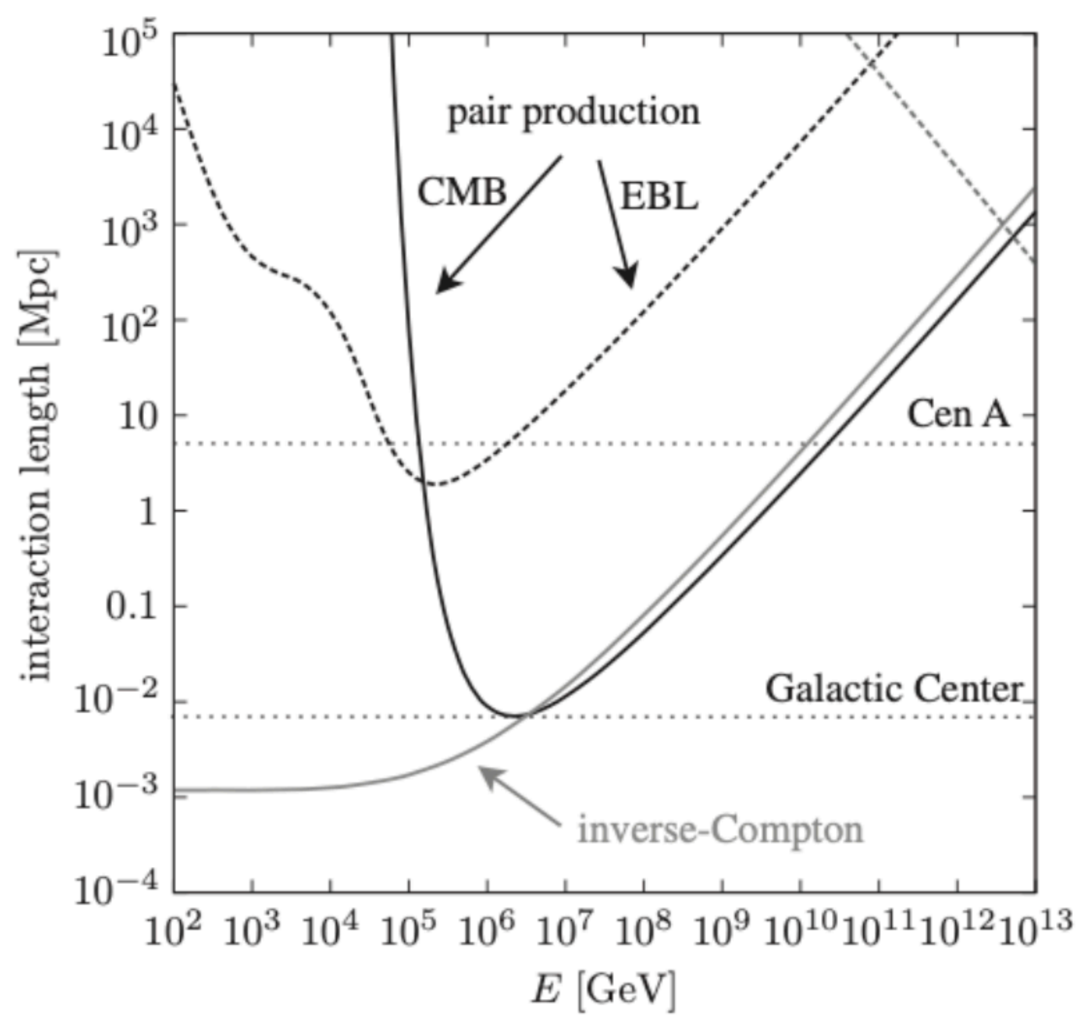
Ehlert et al. JCAP 2024

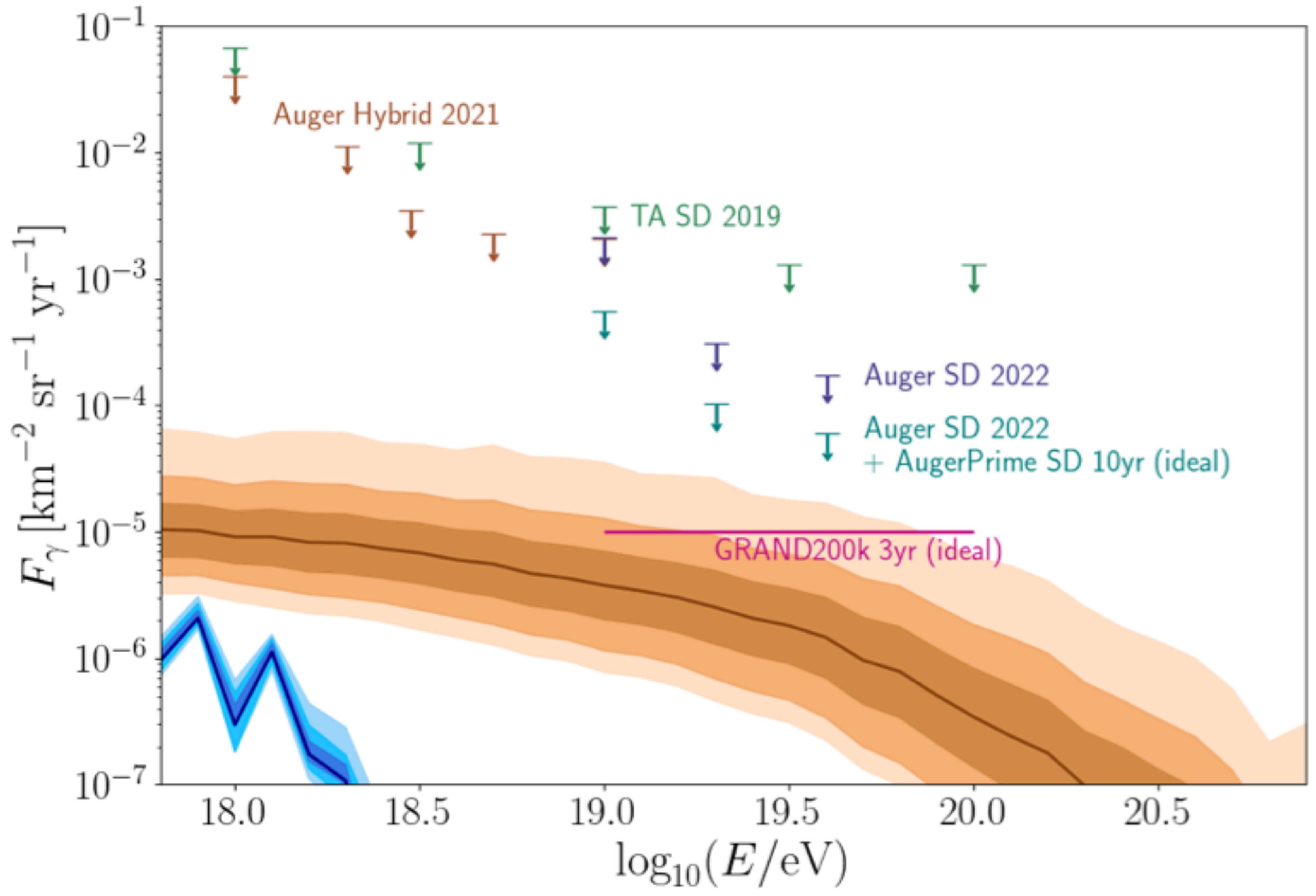
UHECR flux at Earth and the corresponding cosmogenic neutrinos

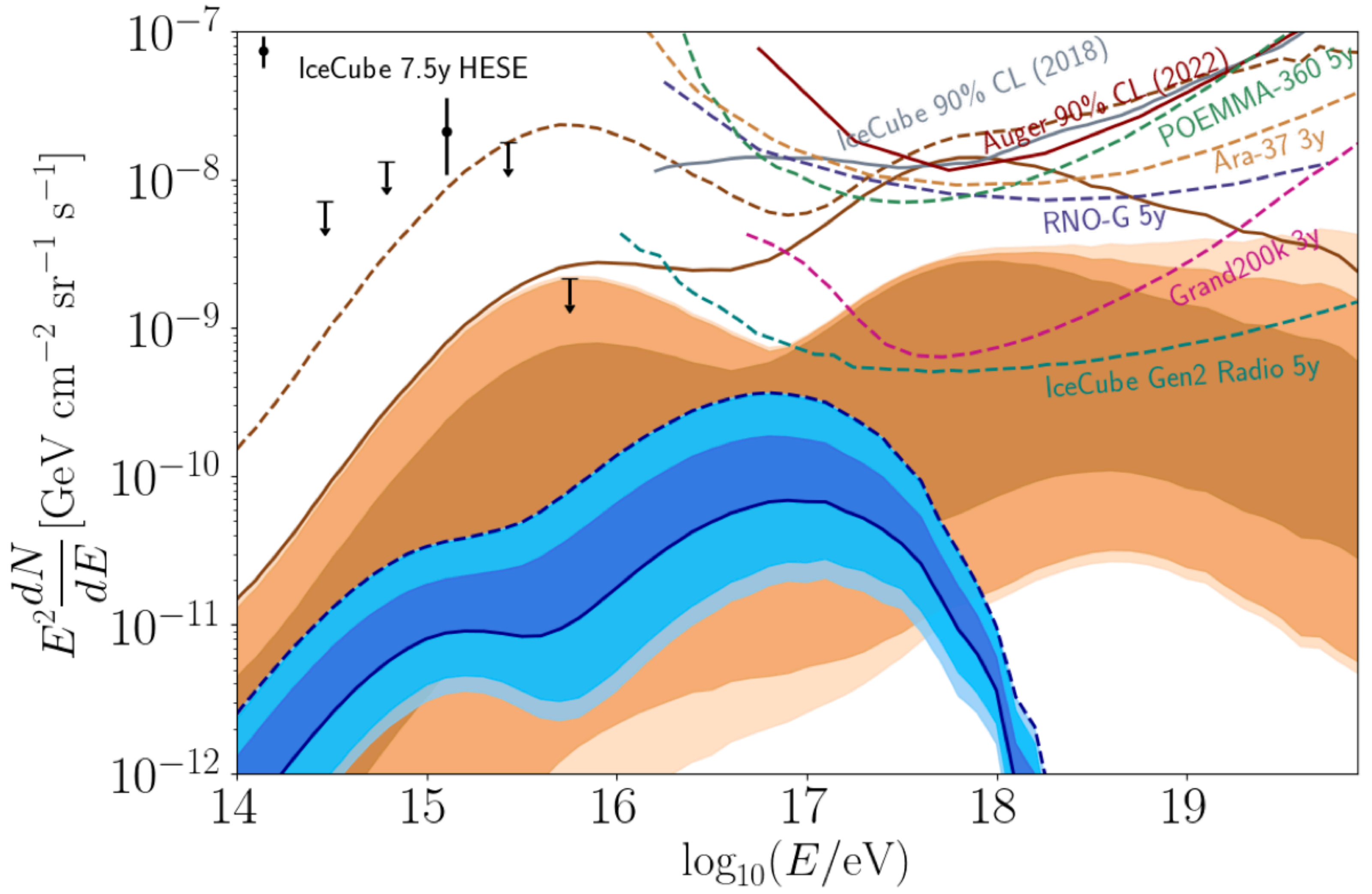
Mixed composition for UHECRs



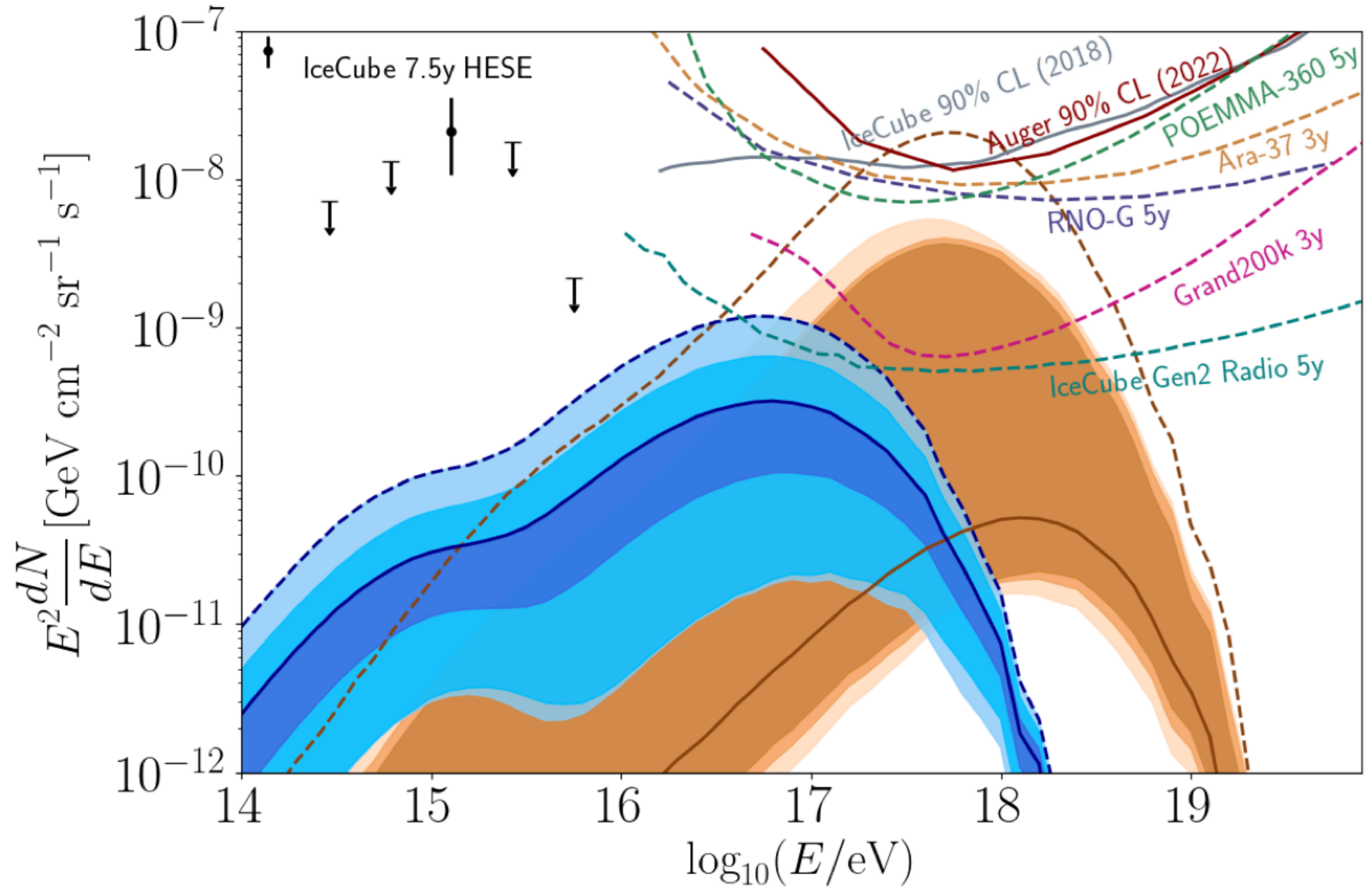
- Predicted cosmogenic gamma-ray signal in the GeV–TeV (left) and EeV (right) energy range







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



Ehlert et al. JCAP 2024