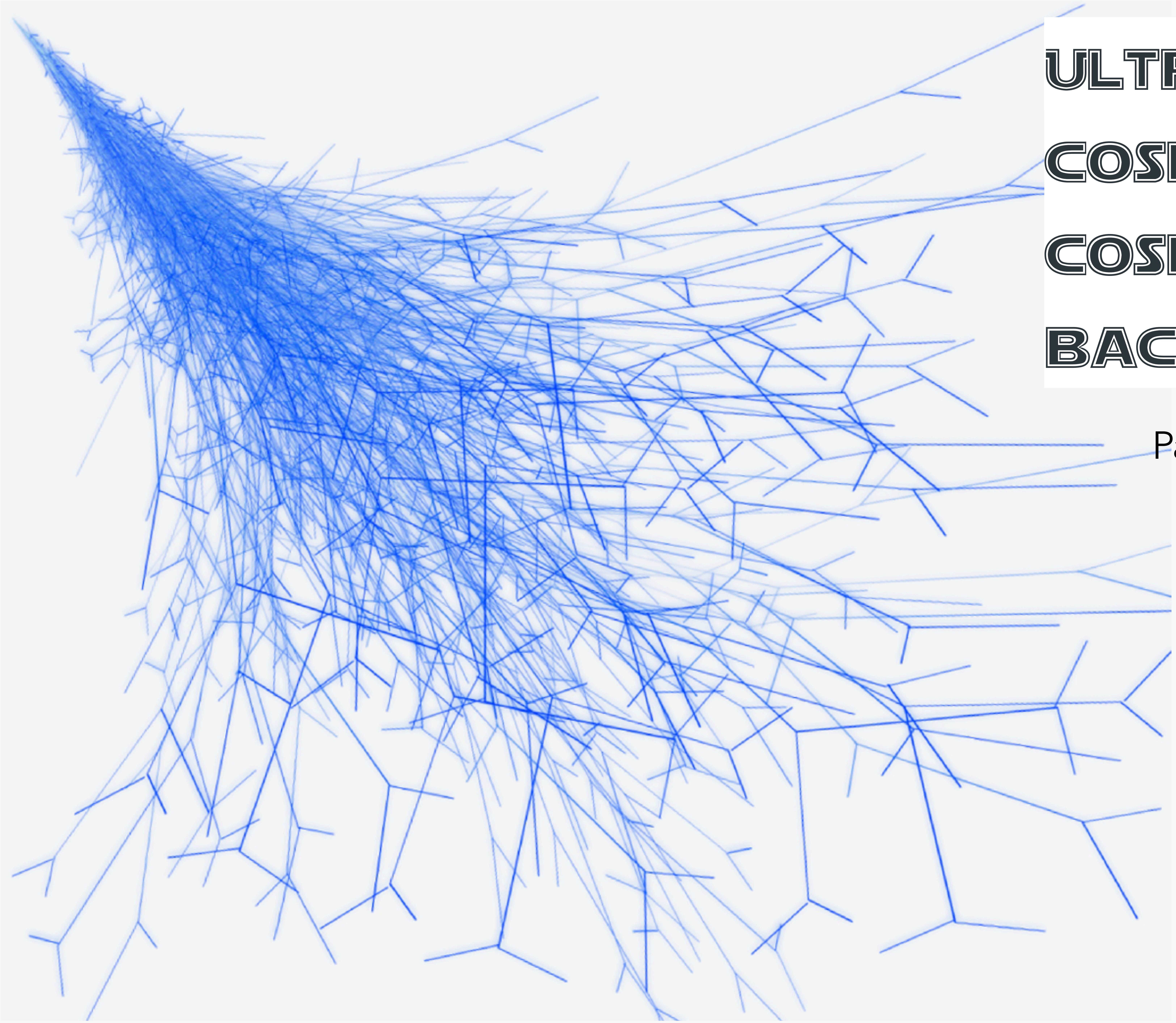
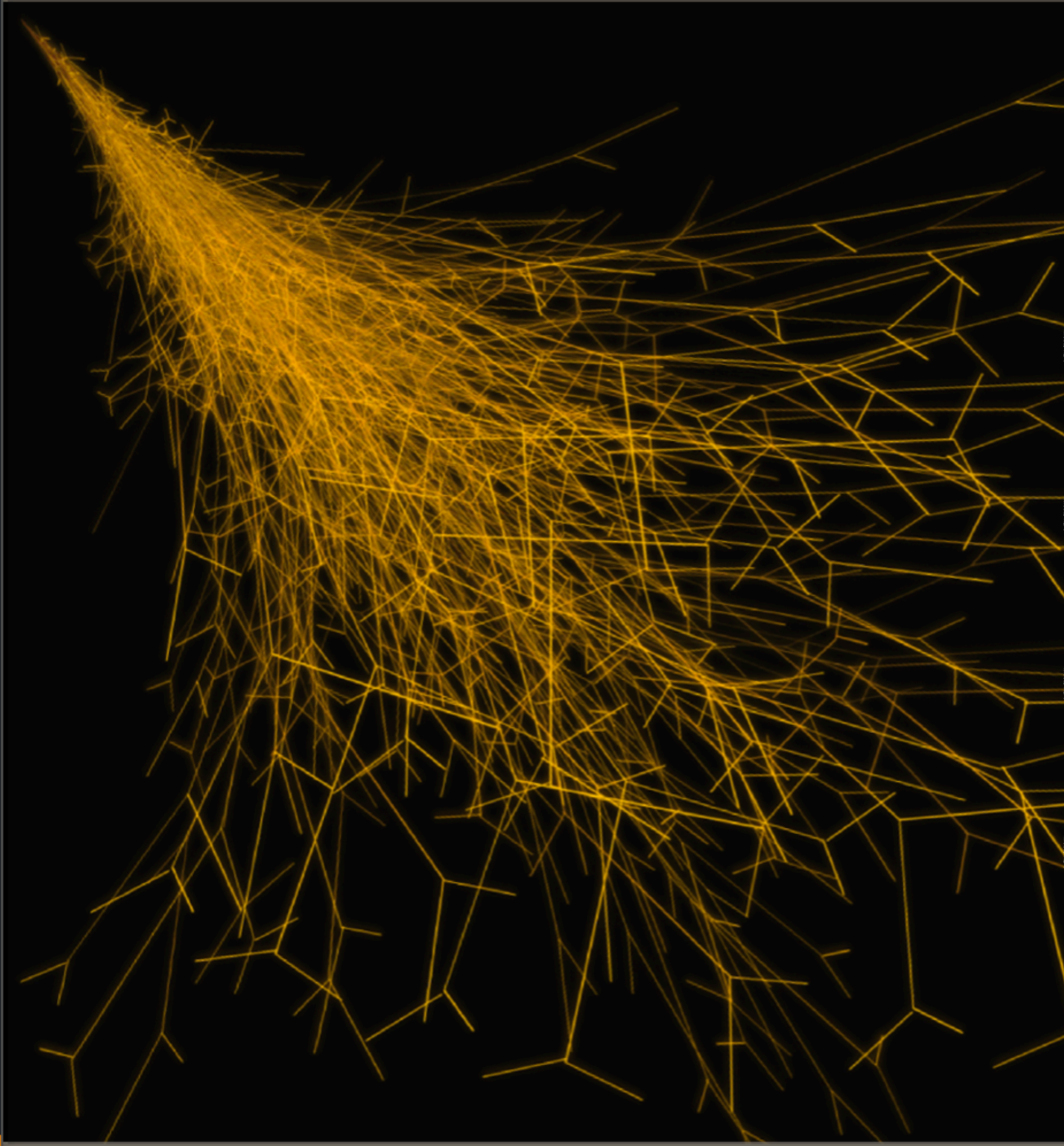


ULTRA-HIGH-ENERGY COSMIC RAYS AND THE COSMIC INFRARED BACKGROUND

Paris Saclay Astroparticle Symposium, 15/11/2024

Antonio Condorelli

APC/CNRS
condorelli@apc.in2p3.fr



Outline

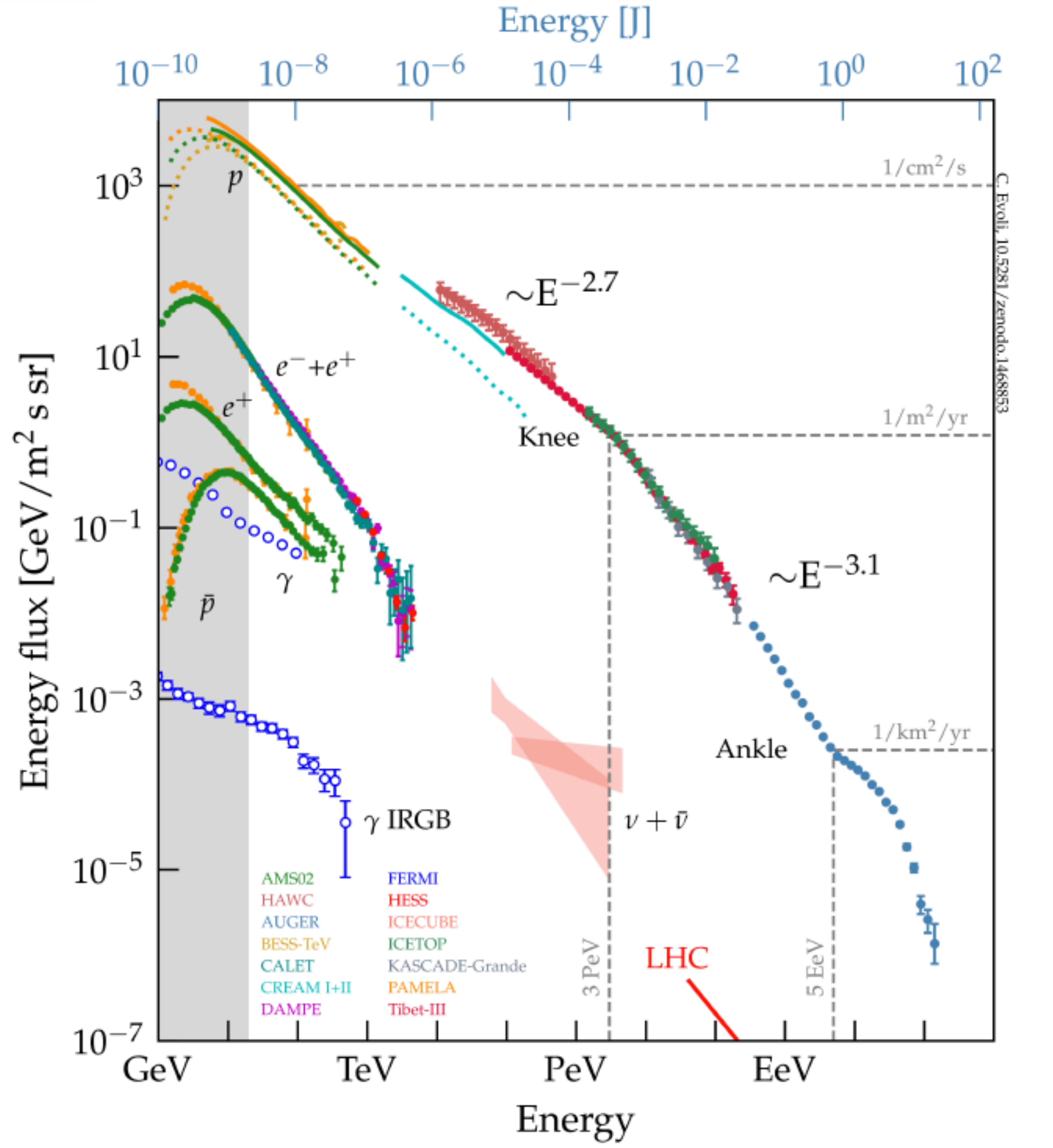
- UHECR observables: spectrum, mass composition;
- Astrophysical interpretation of UHECR data & Extragalactic propagation;
- Impact of EBL on UHECR astrophysical scenario
- Conclusions and future perspectives.

The cosmic ray spectrum

Cosmic rays (CR): charged particles from the Universe.

CR spectrum spans over several order of magnitude in energy and flux;

- Several detection techniques are needed;
- Power law: it reflects acceleration mechanism;
- Features can be addressed to propagation and/ or re-acceleration processes.

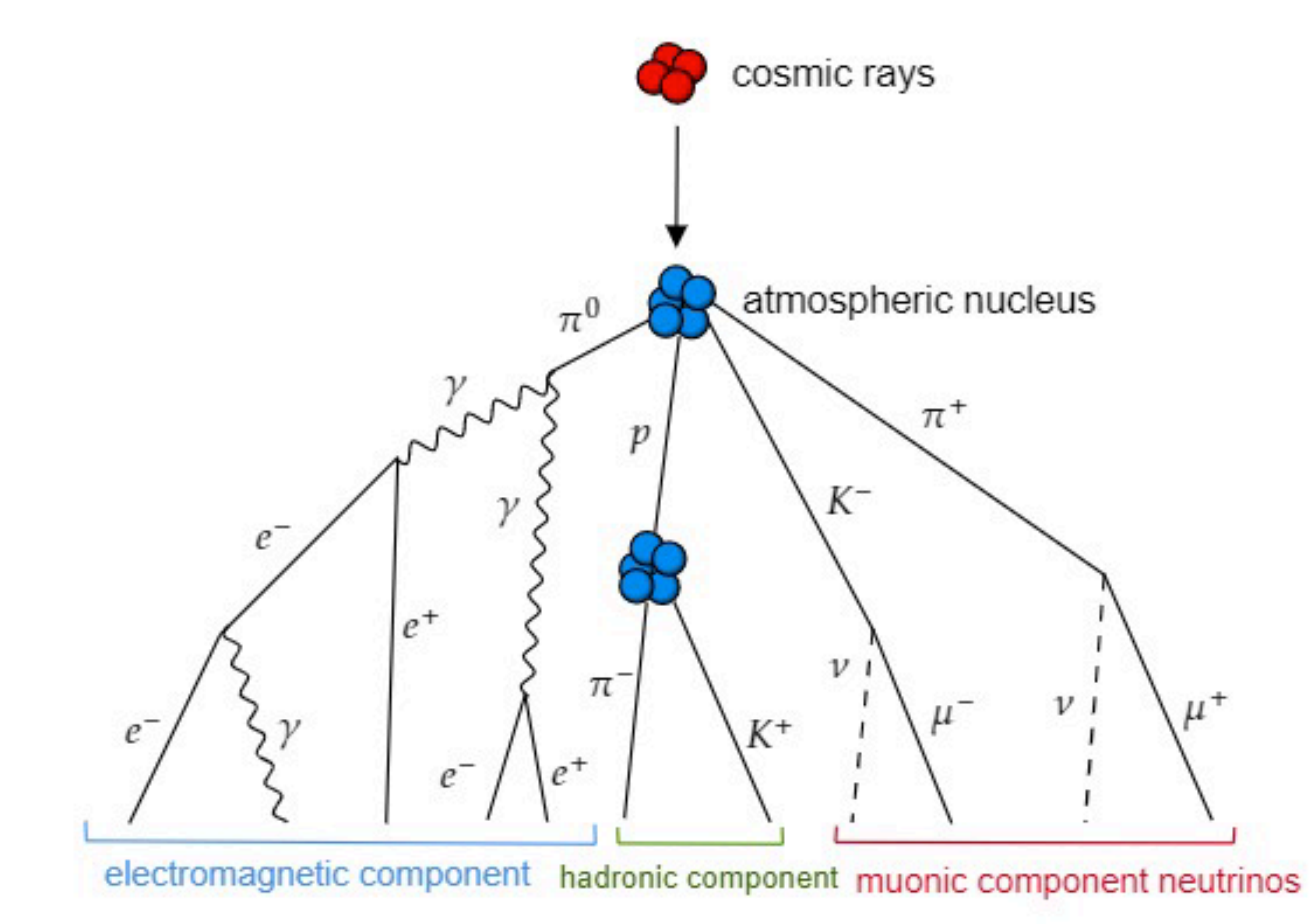


Indirect detection: Extensive Air Shower (EAS)

The collision of cosmic rays with the atmospheric molecules produces a cascade of particles, called Extensive Air Shower (EAS).

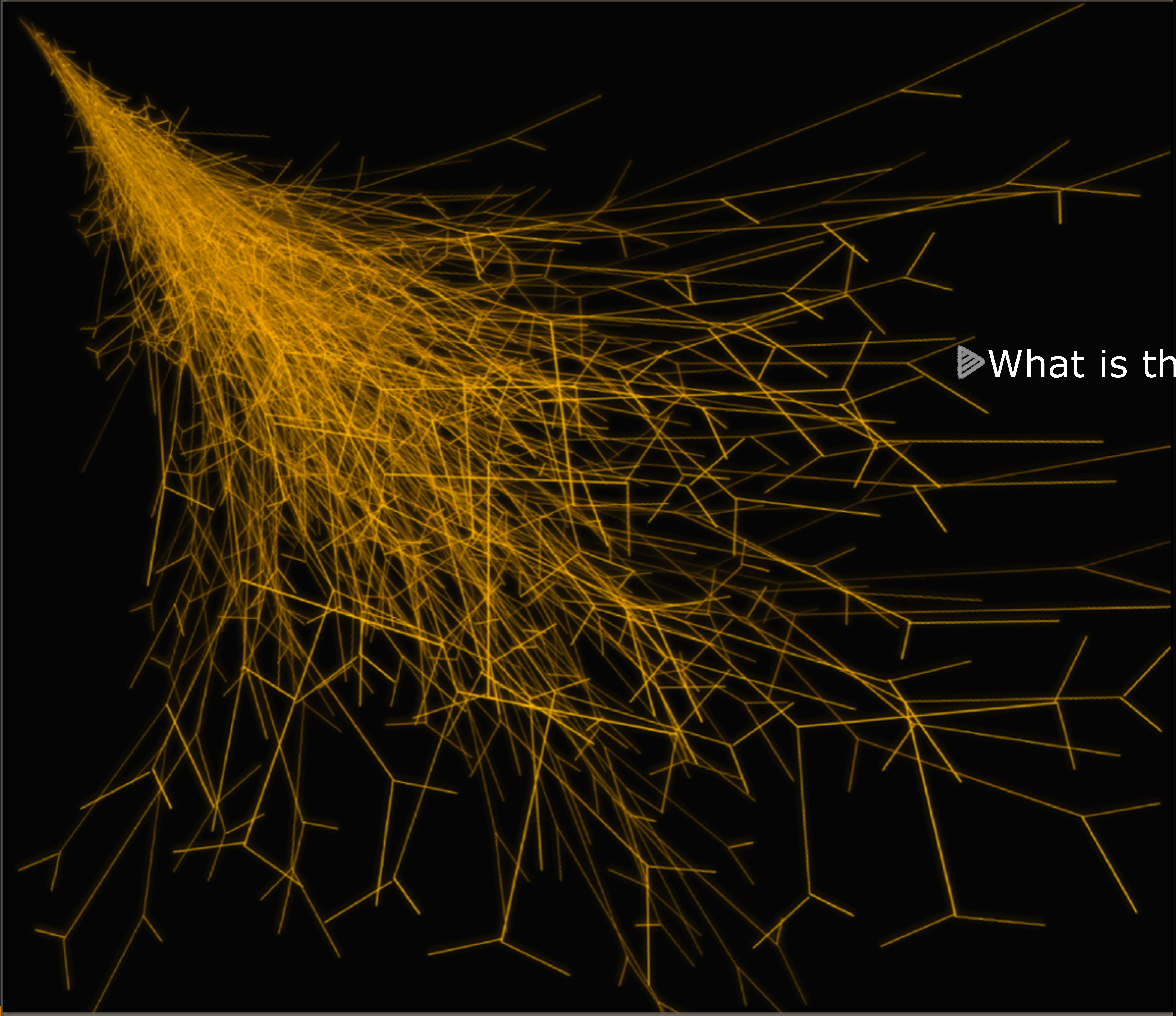
The particles of an EAS initiated by a proton or a nucleus can be roughly divided into three components:

- Hadronic (mostly pions)
- Electromagnetic (e^+, e^-, γ)
- Penetrant (muons and neutrinos)



A key information to infer about properties of the primary particle is the depth of the shower maximum

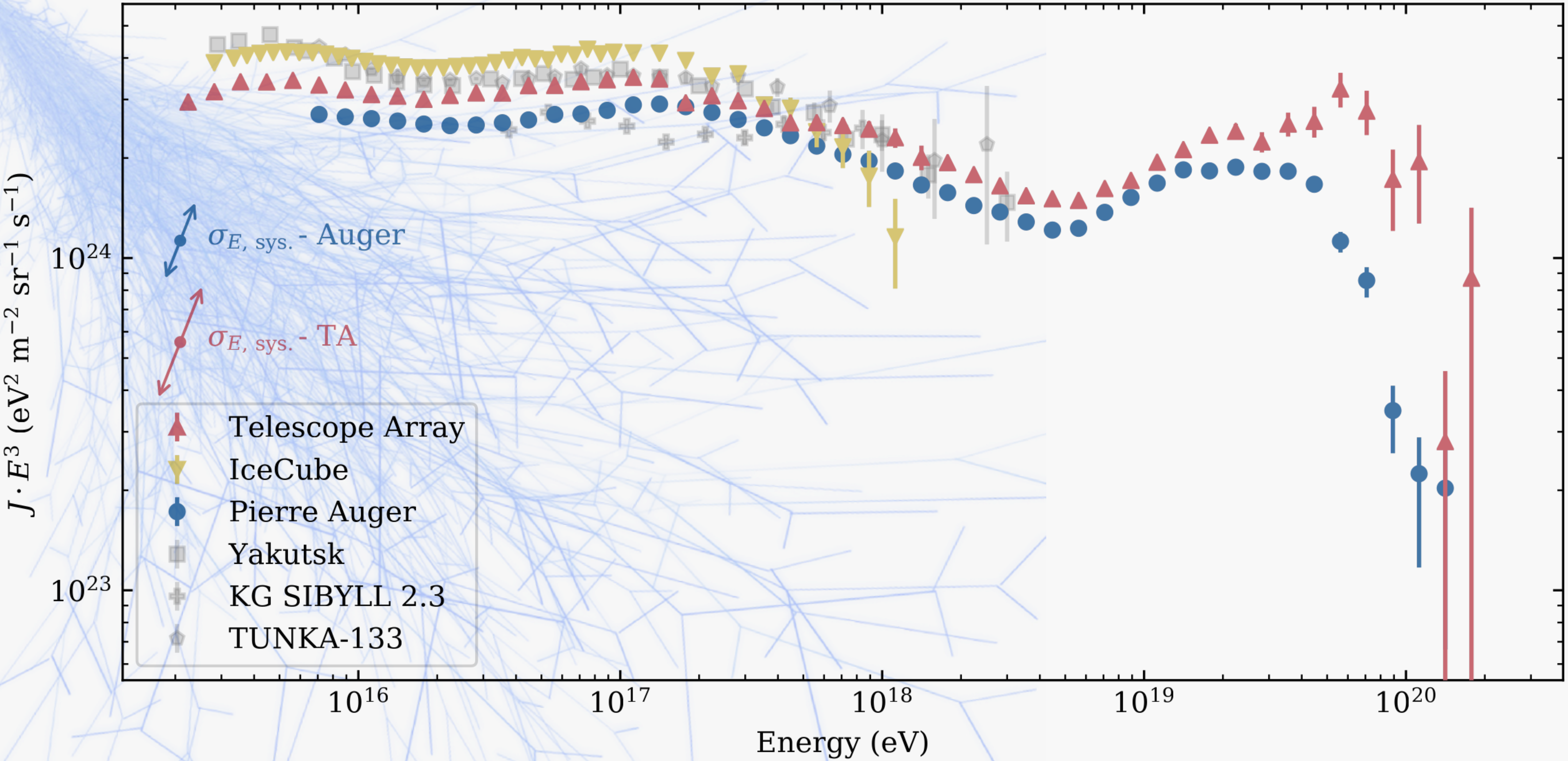
$$X_{max} \propto lg(E/A)$$



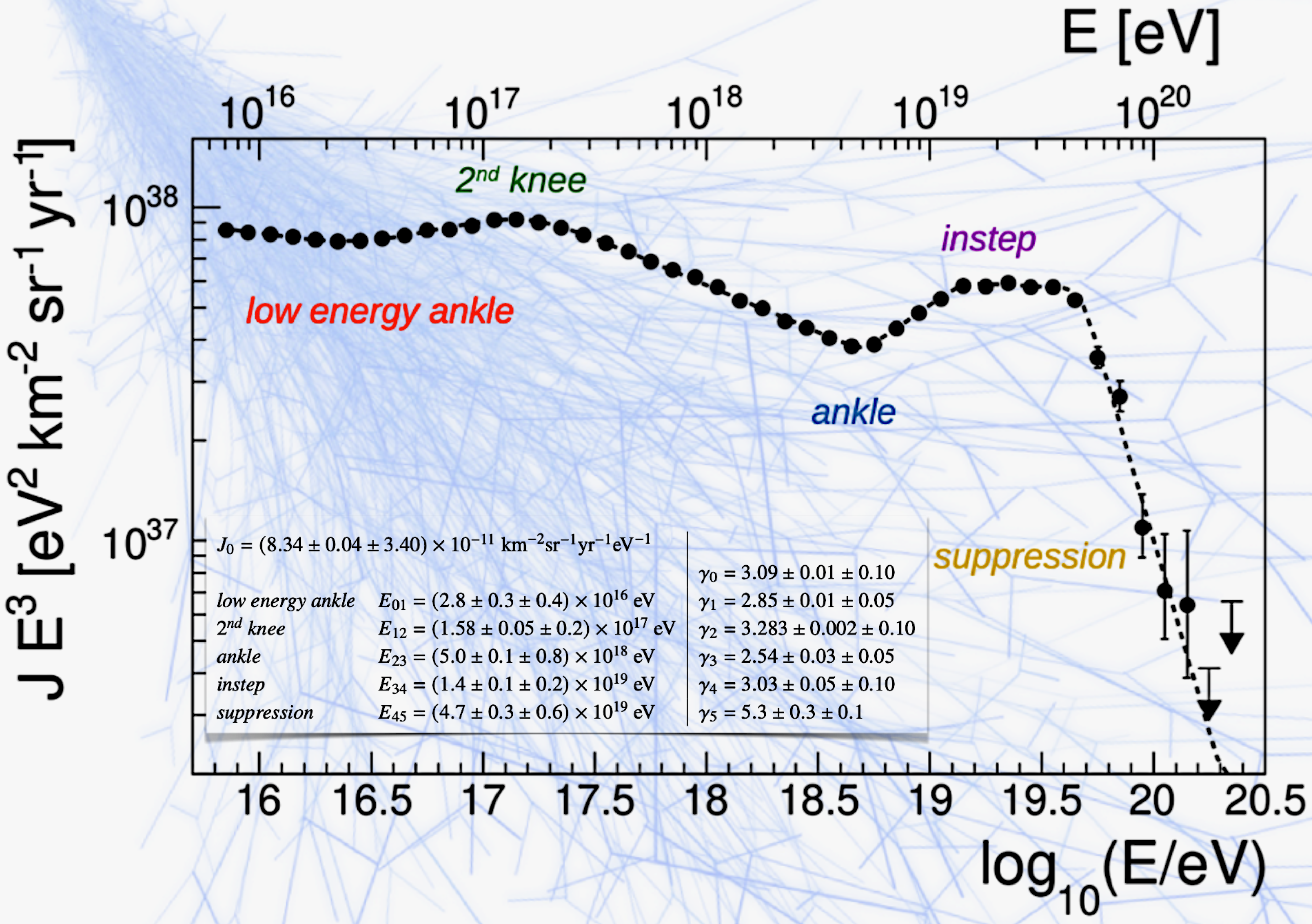
Now, in 2024

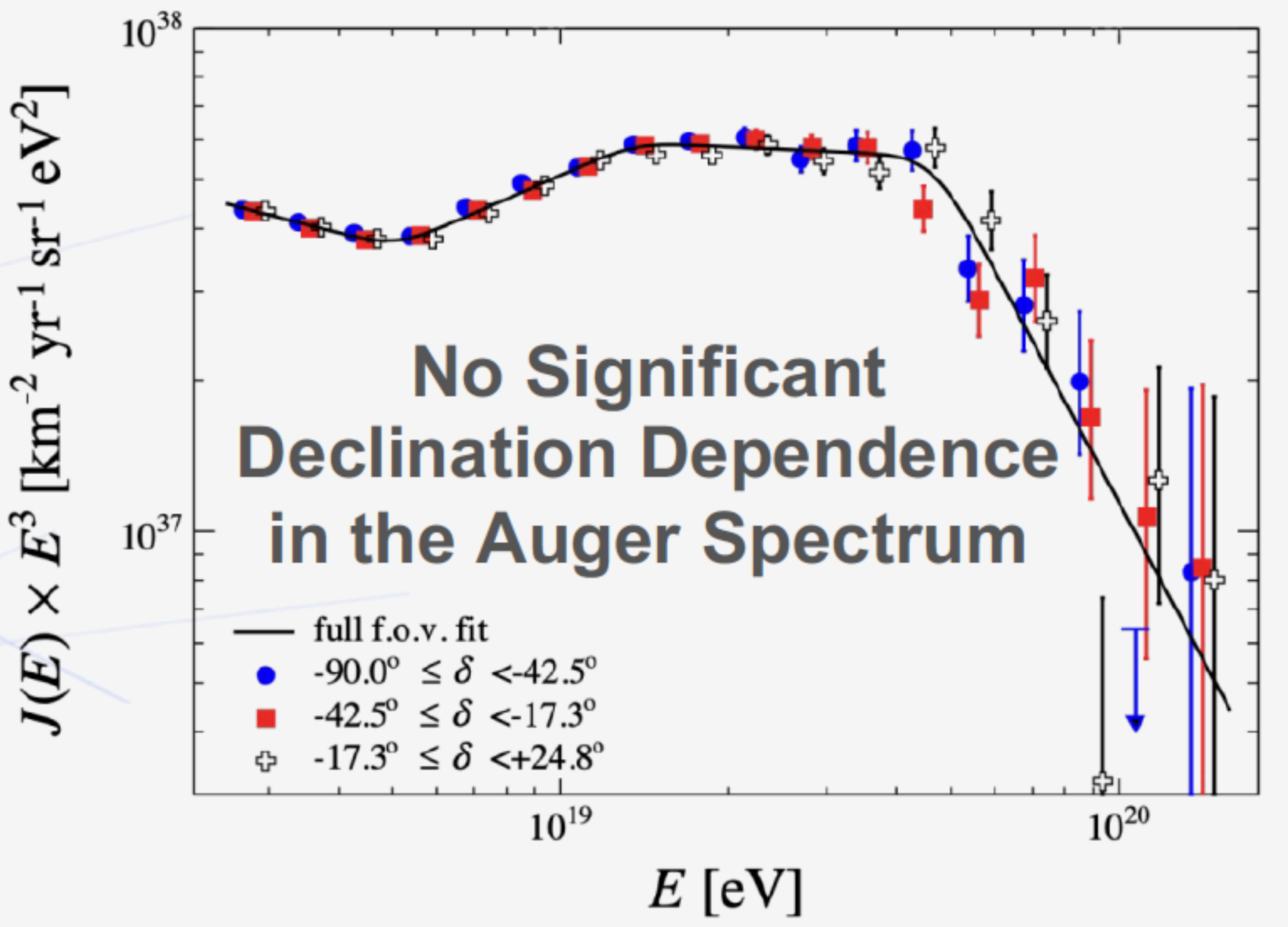
- What is the status of the art **today**?

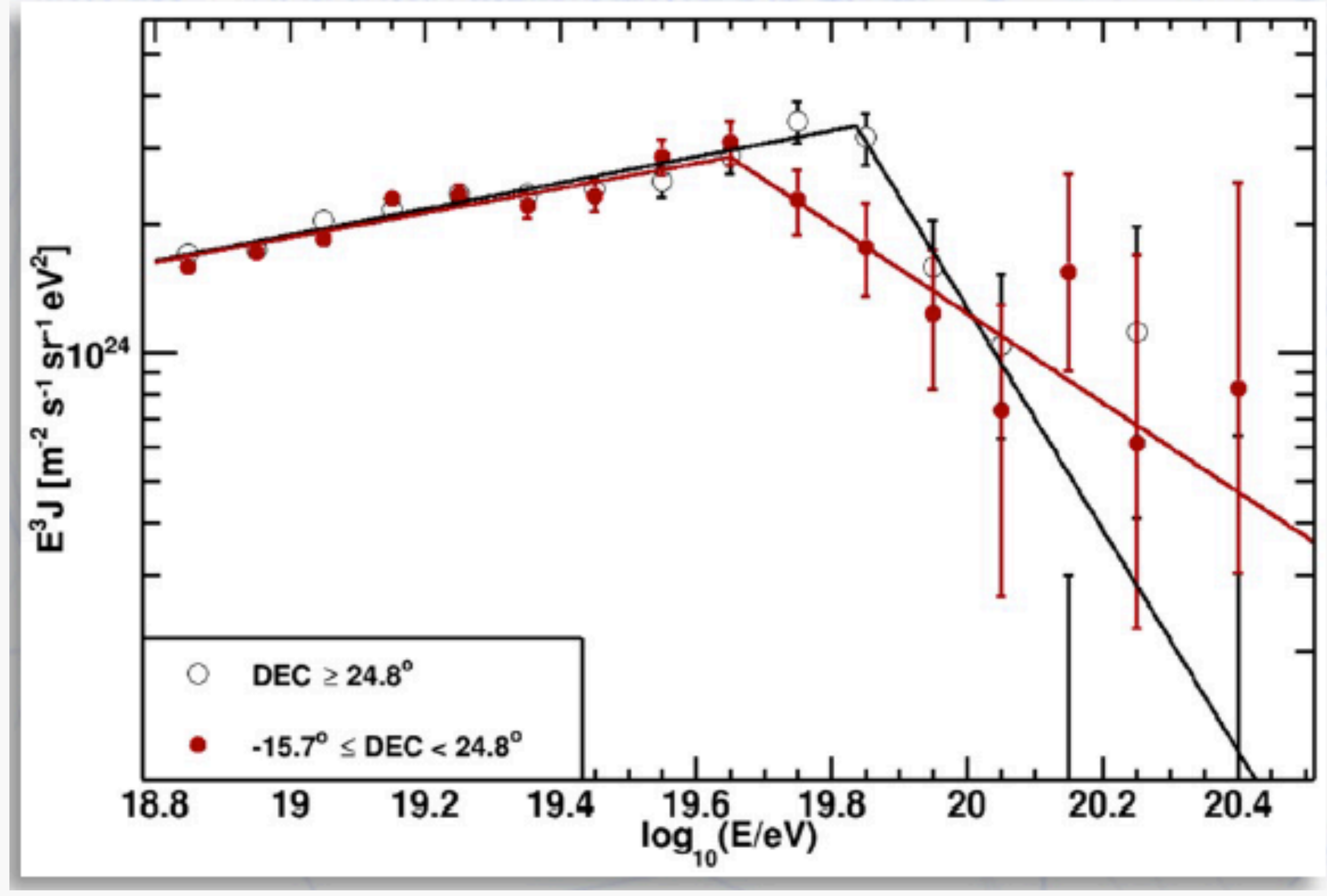
Current UHECR Picture: Energy Spectrum



Current UHECR Picture: Energy Spectrum

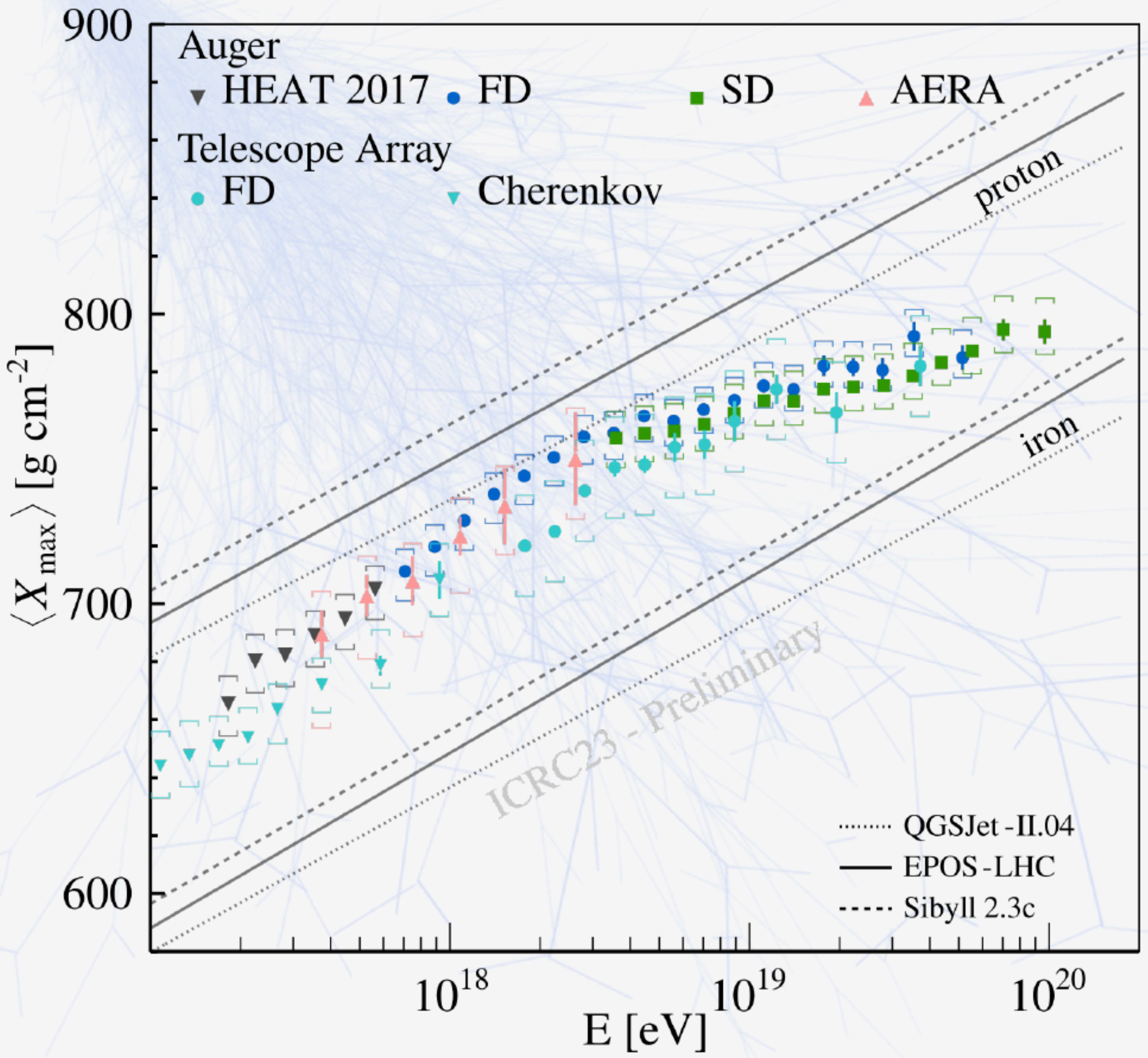


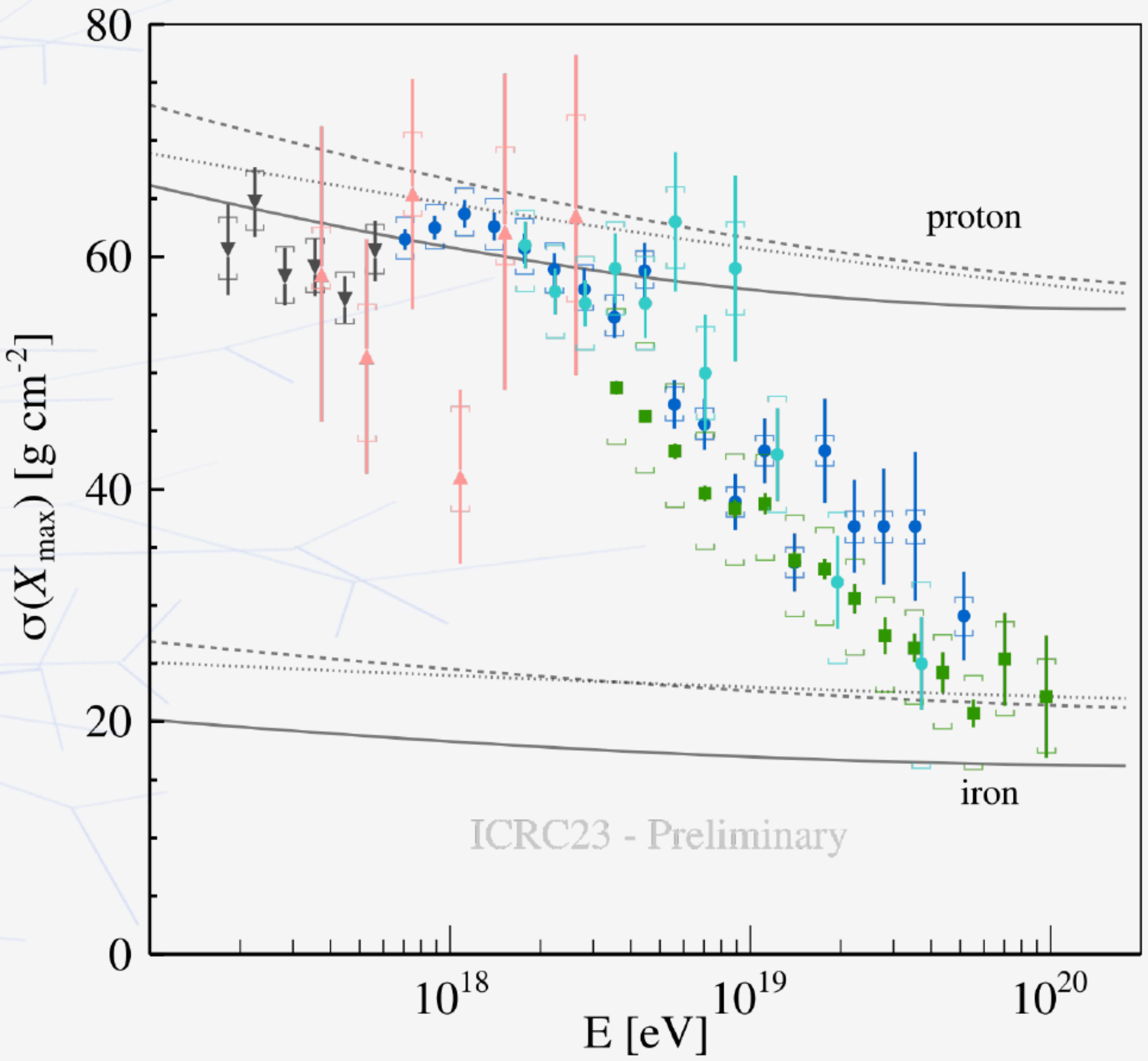




Differences in fluorescence yield, invisible energy, etc…
Possible astrophysical explanation?

Current UHECR Picture: Mass composition





Auger and TA measurements are in agreement!
Crosscheck –> Bring Auger best fit mass fractions into TA detector simulations and then compare –> still in agreement.

(A. Yushkov for Auger/TA
Pos ICRC2023 249, PRD in preparation)

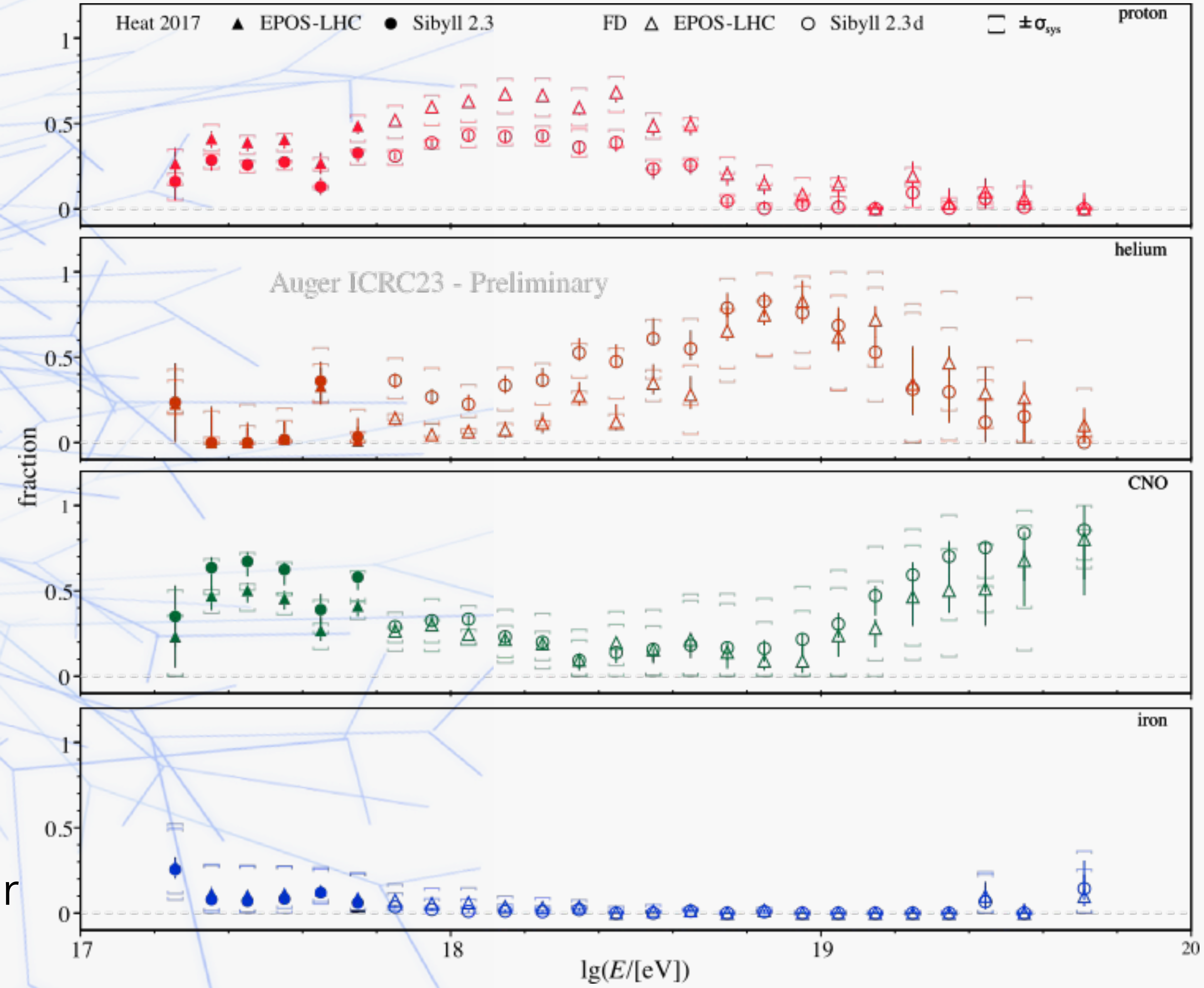
Current UHECR Picture: Mass composition

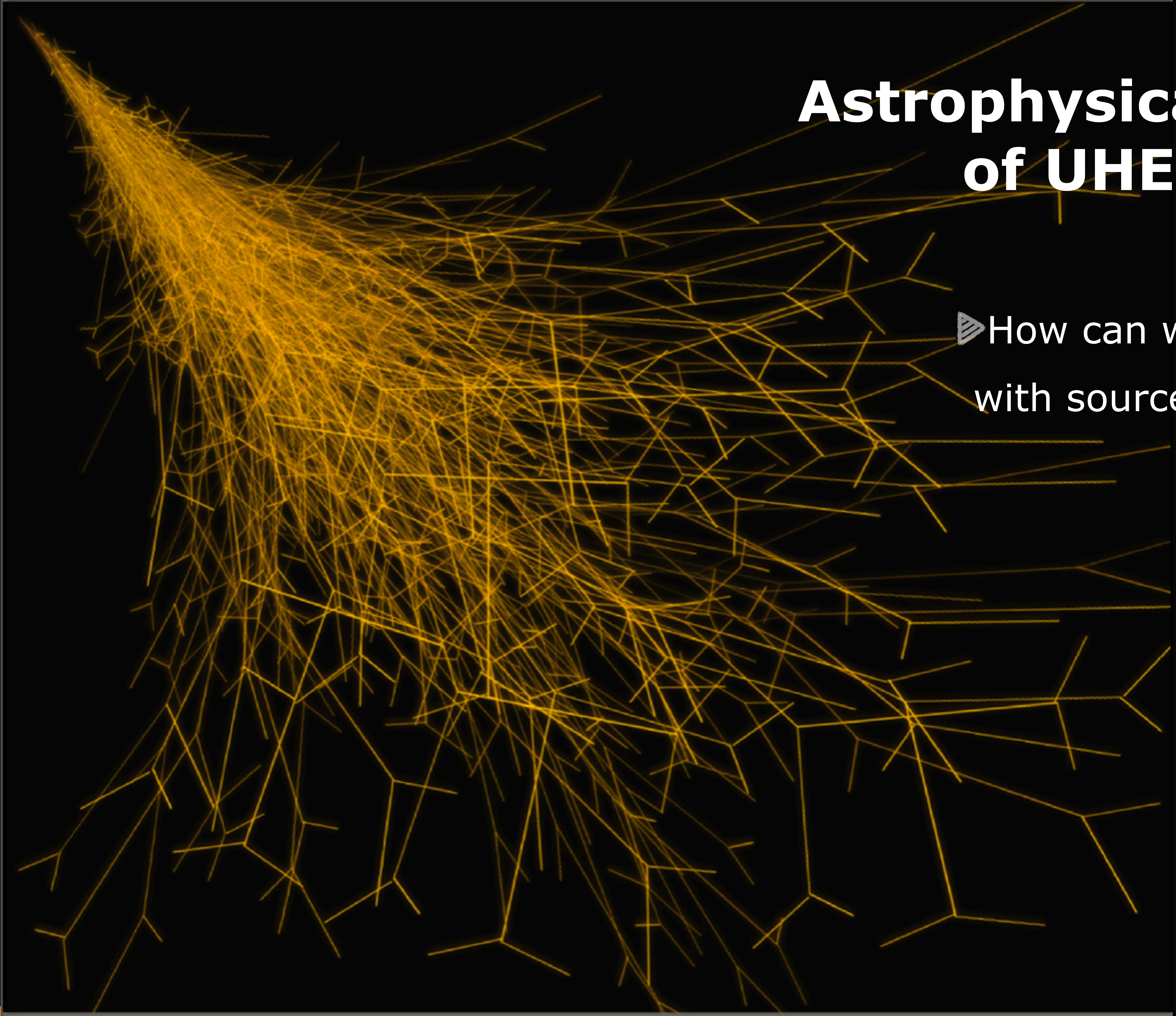
Protons: as expected from InA, peak around 2-3 EeV.
→ Only form a weak majority at this energy, but dominate the flux nowhere.

Helium: peaks at ~ 8 EeV
→ roughly ~ 4 times higher energy than protons

CNO: fraction continues to climb up to ~ 50 EeV
and may continue beyond

Iron: fitted fraction compatible with zero over nearly the full energy range
→ small fraction allowed at low/high energy





Astrophysical interpretation of UHECR sources

- How can we connect features at Earth with source parameters?

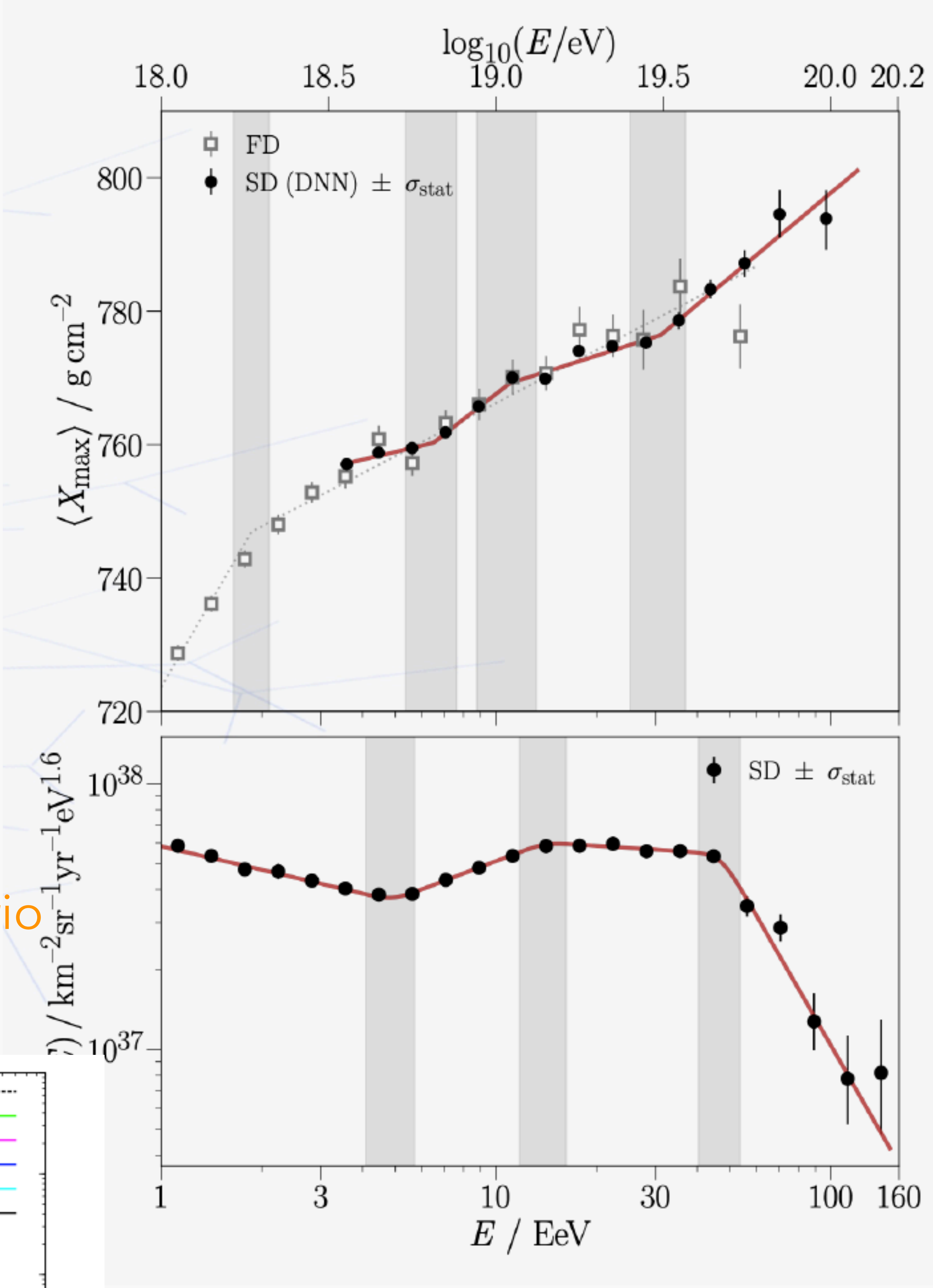
Astrophysical interpretation of UHECR measurements

Features in spectrum and composition do not coincide –> why?

It is possible to link features in the UHECRs to astrophysical processes?

Several possible explanations:

- Transition model;
- Pure proton scenario;
- Mixed composition scenario;

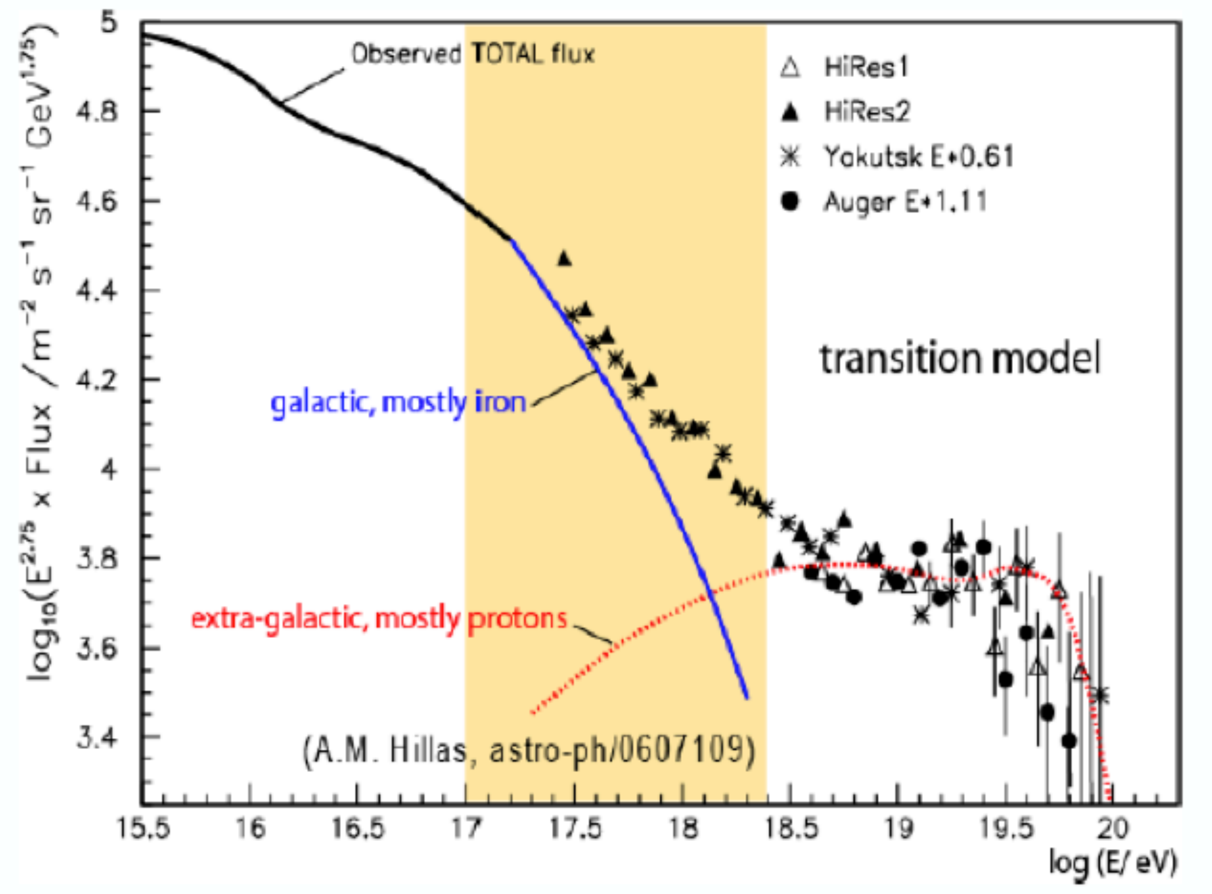


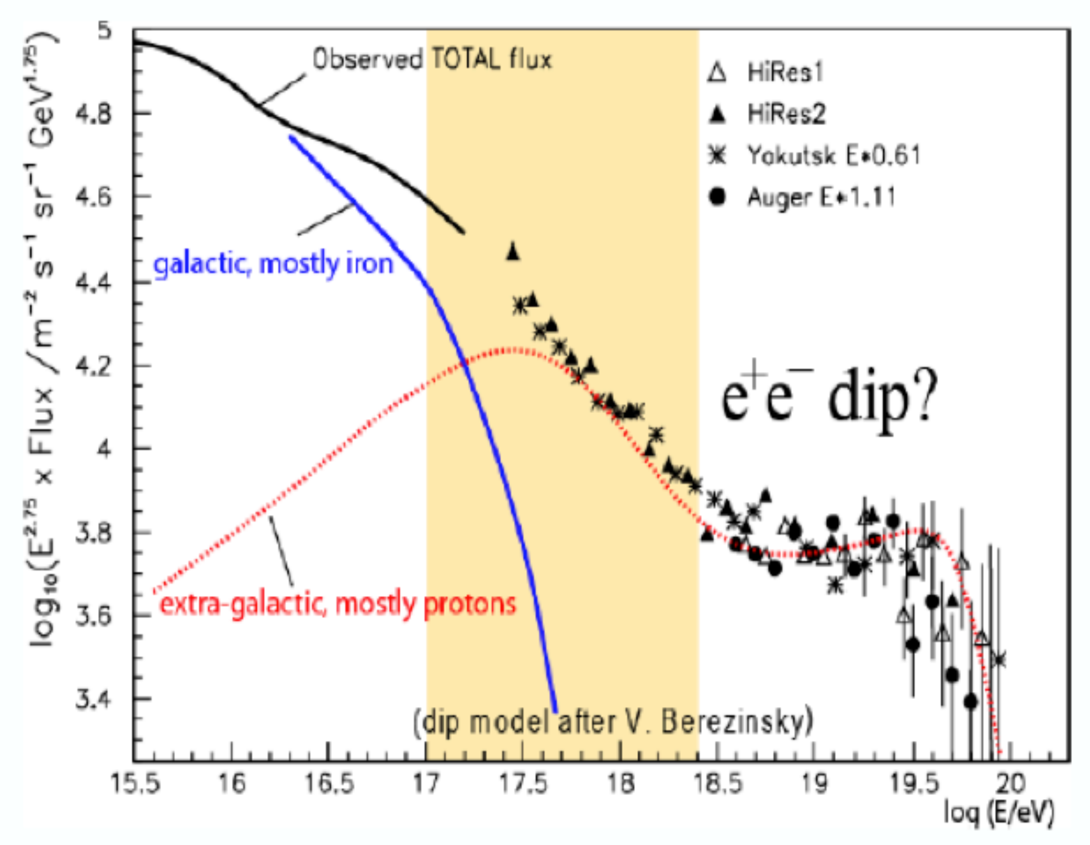
How to disentangle this?

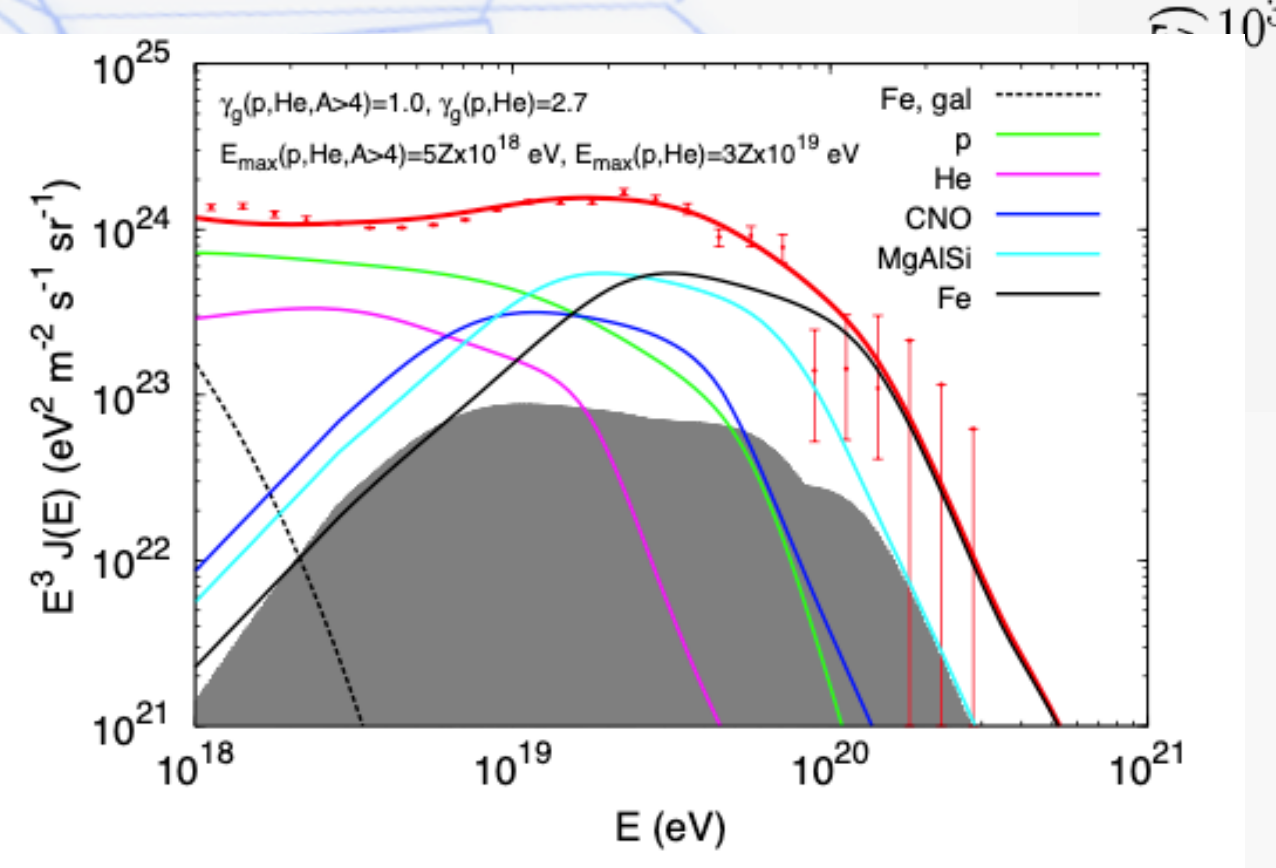
Transition model

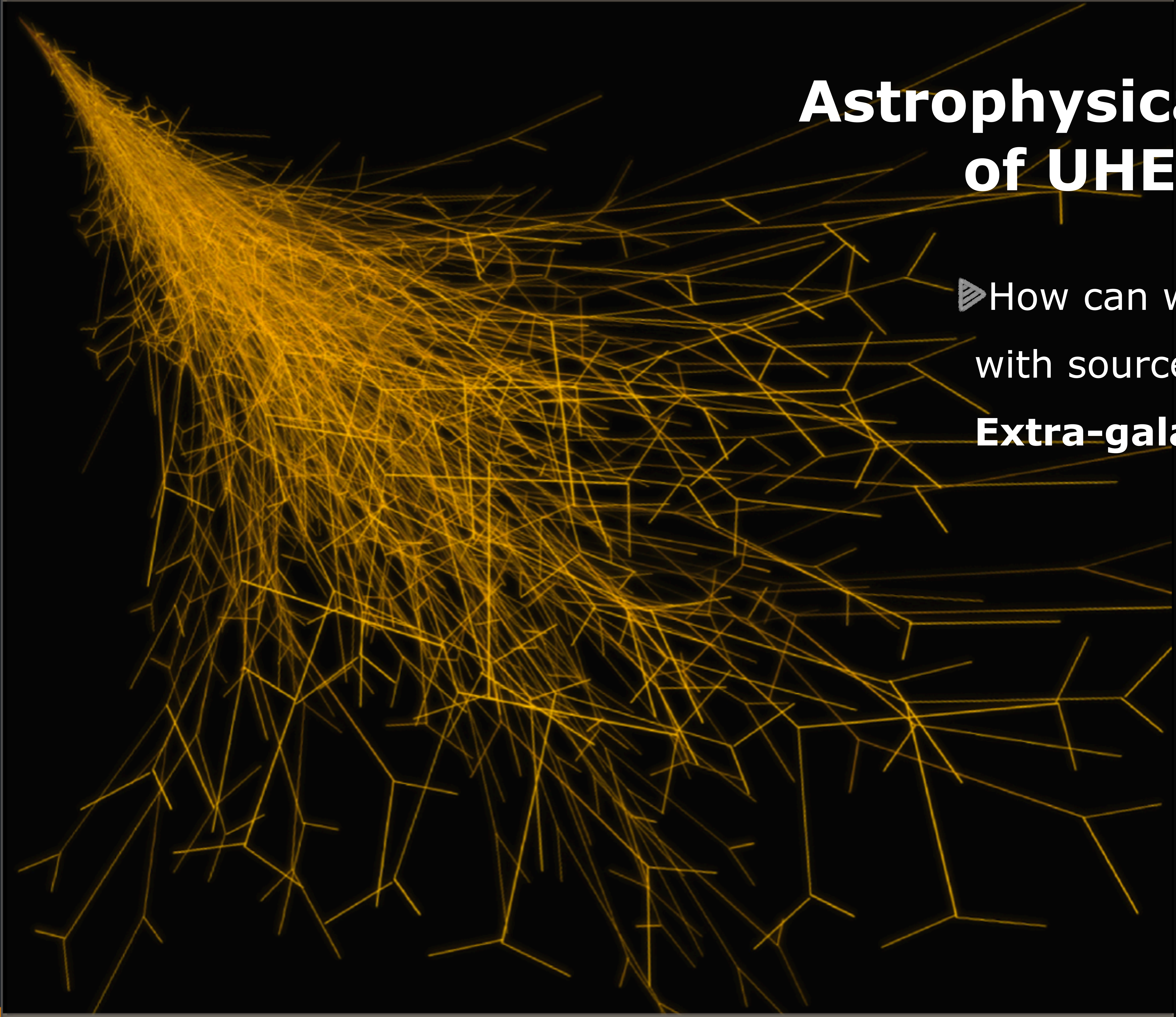
Pure proton scenario

Mixed composition scenario









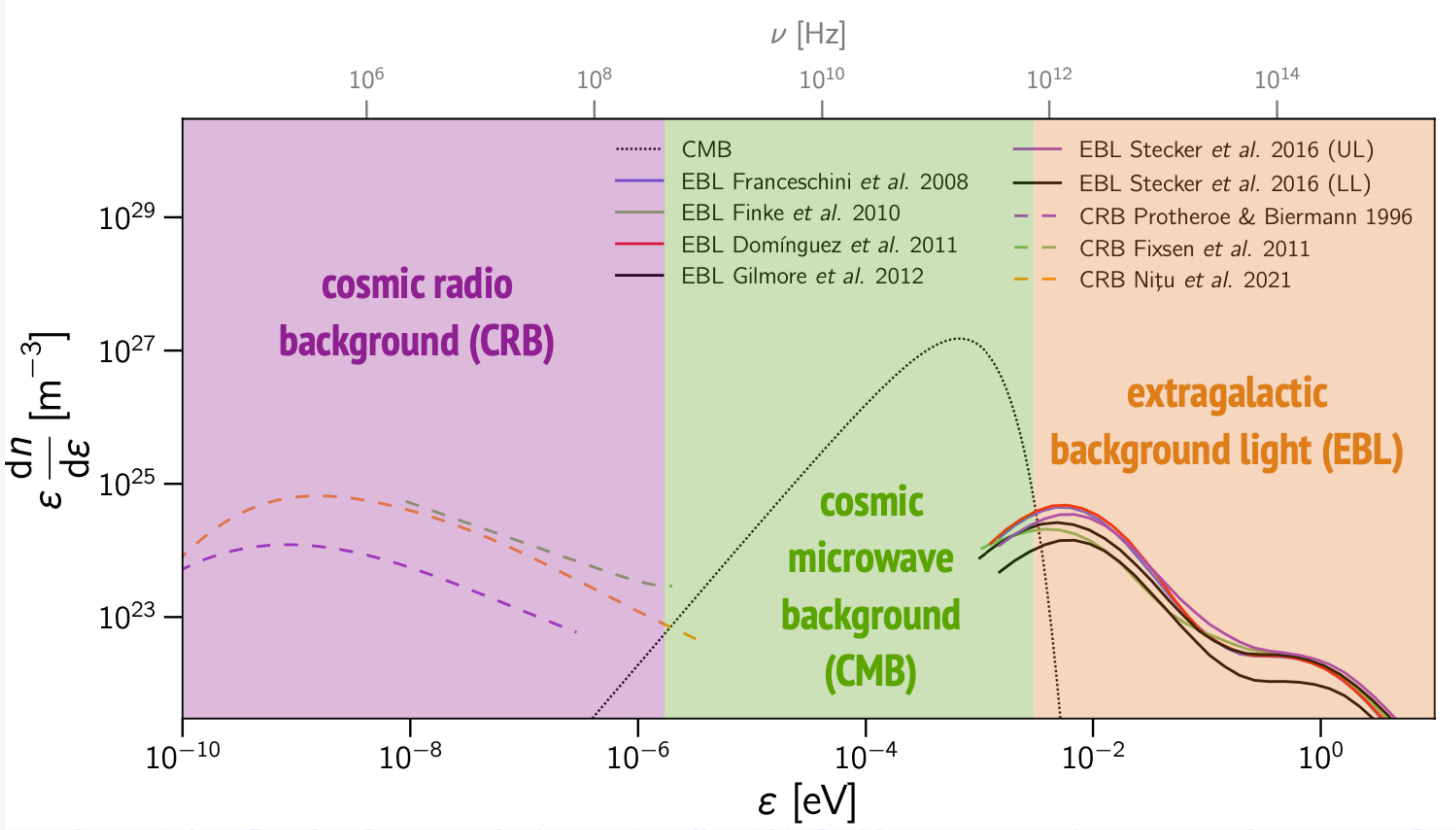
Astrophysical interpretation of UHECR sources

- How can we connect features at Earth with source parameters?

Extra-galactic Propagation


Source
Universe
Earth
p
ν

UHECR interactions



Extra-galactic photon fields:

$\varepsilon_{CMB} \simeq$ 0.1 meV

$\varepsilon_{IR} \simeq$ 10 meV

$\varepsilon_{OPT} \simeq$ 1 eV

Background photons can trigger interactions with the very high energy cosmic rays !

UHECR interactions

Reference frame of the photon field

$$E_{CR} \sim 1\,\mathrm{EeV}, \quad \epsilon \sim 1\,\mathrm{meV}$$

Lorentz boost

Reference frame of the CR

$$E'_{CR} \sim m_p$$

$$\epsilon' \sim \Gamma\epsilon(1-\cos\theta) < 2\Gamma\epsilon$$

Because of the Lorentz boost a low energy photon appears as a high energy gamma ray

Interaction rate

$$\tau^{-1}(\Gamma) = \frac{c}{2\Gamma^2}\int_{\epsilon'_{\rm th}}^{\infty} \epsilon'\sigma(\epsilon')\int_{\epsilon'/2\Gamma}^{\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} d\epsilon\, d\epsilon'$$

Primed quantities in the reference frame of the CR, unprimed quantities in the reference frame of the photon field

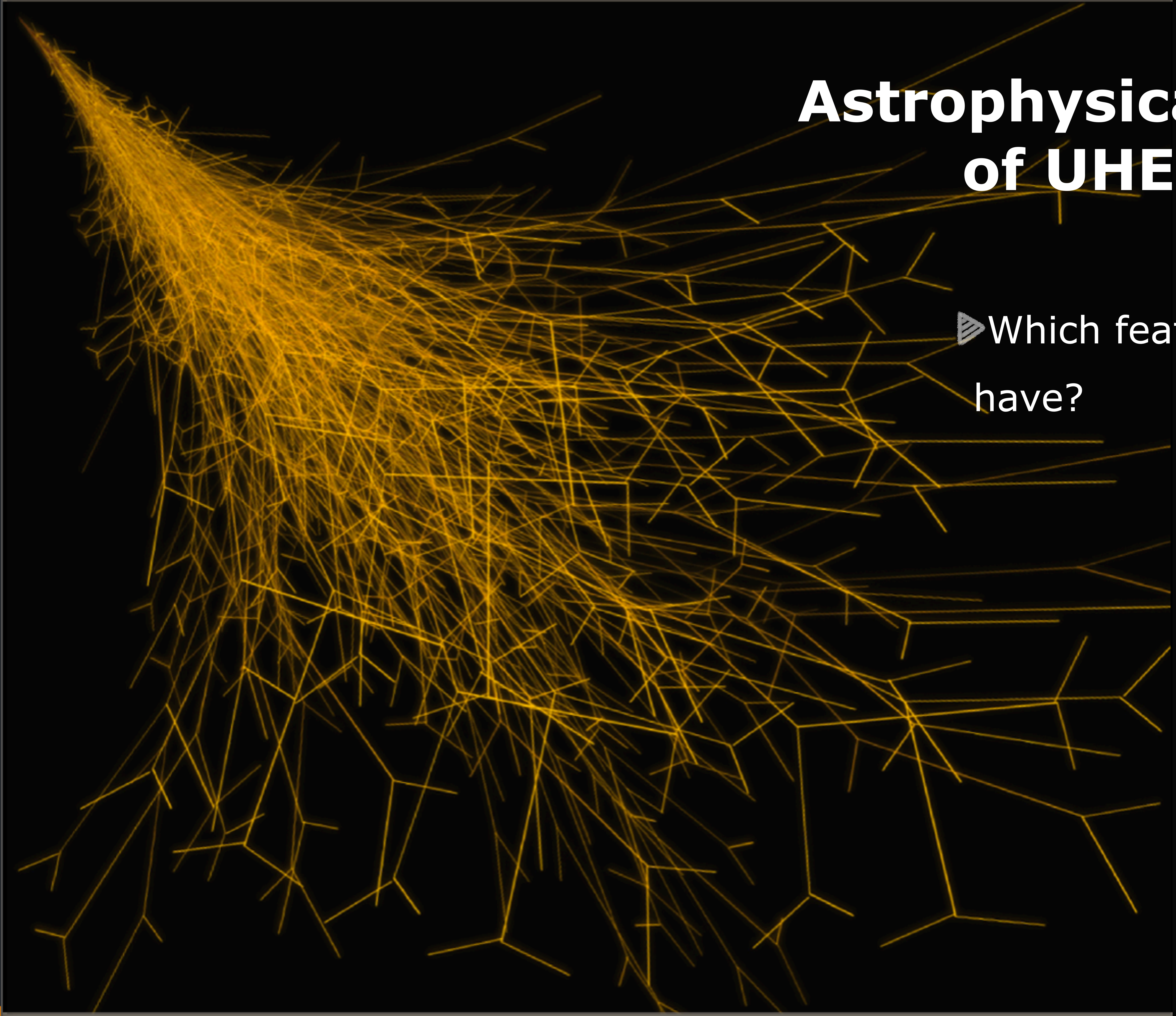
UHECR propagation codes

Propagation simulated using:
SimProp v2r4 [arXiv:1705.03729v4], a simple and fast Monte Carlo code using many (reasonable) approximations;
CRPropa 3.2 (JCAP 09 (2022) 035), a more detailed simulation with almost all known relevant processes.
See JCAP 10 (2015) 063 [arXiv:1508.01824] for comparisons between these codes.

Photon backgrounds:
CMB cosmic microwave background (very well known spectrum, T = 2.725 K black body)
EBL extragalactic background light

Processes:
- Adiabatic energy loss due to the expansion of the Universe (well known rate, RW metric)
- Pair photoproduction (very well known cross sections, Bethe–Heitler formula)
- Photodisintegration (unknown partial cross sections for certain channels, models needed)
- Pion photoproduction (reasonably well known cross sections, accelerator measurements)

Astrophysical interpretation of UHECR sources



- Which features UHECR sources should have?

Astrophysical interpretation of UHECR data

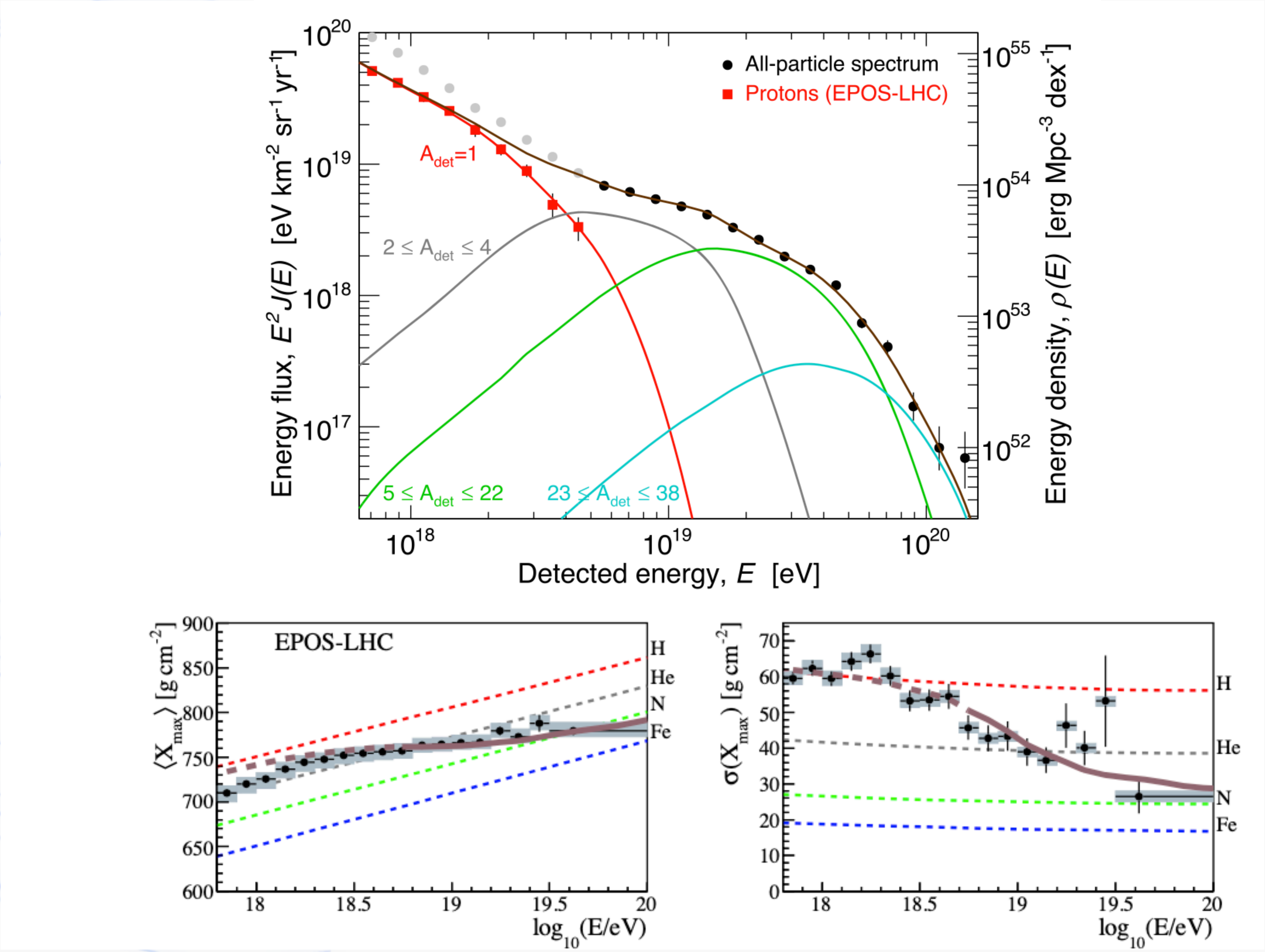
Minimal cosmological model, by assuming identical and point-like sources as standard candles emitting with a power law and rigidity cutoff;

$$\frac{dN}{dE} \propto f_A \left(\frac{E}{10^{18} eV} \right)^{-\gamma} \times f_{cut}(E, Z_A R_{cut}) \times \boxed{(1+z)^m}$$

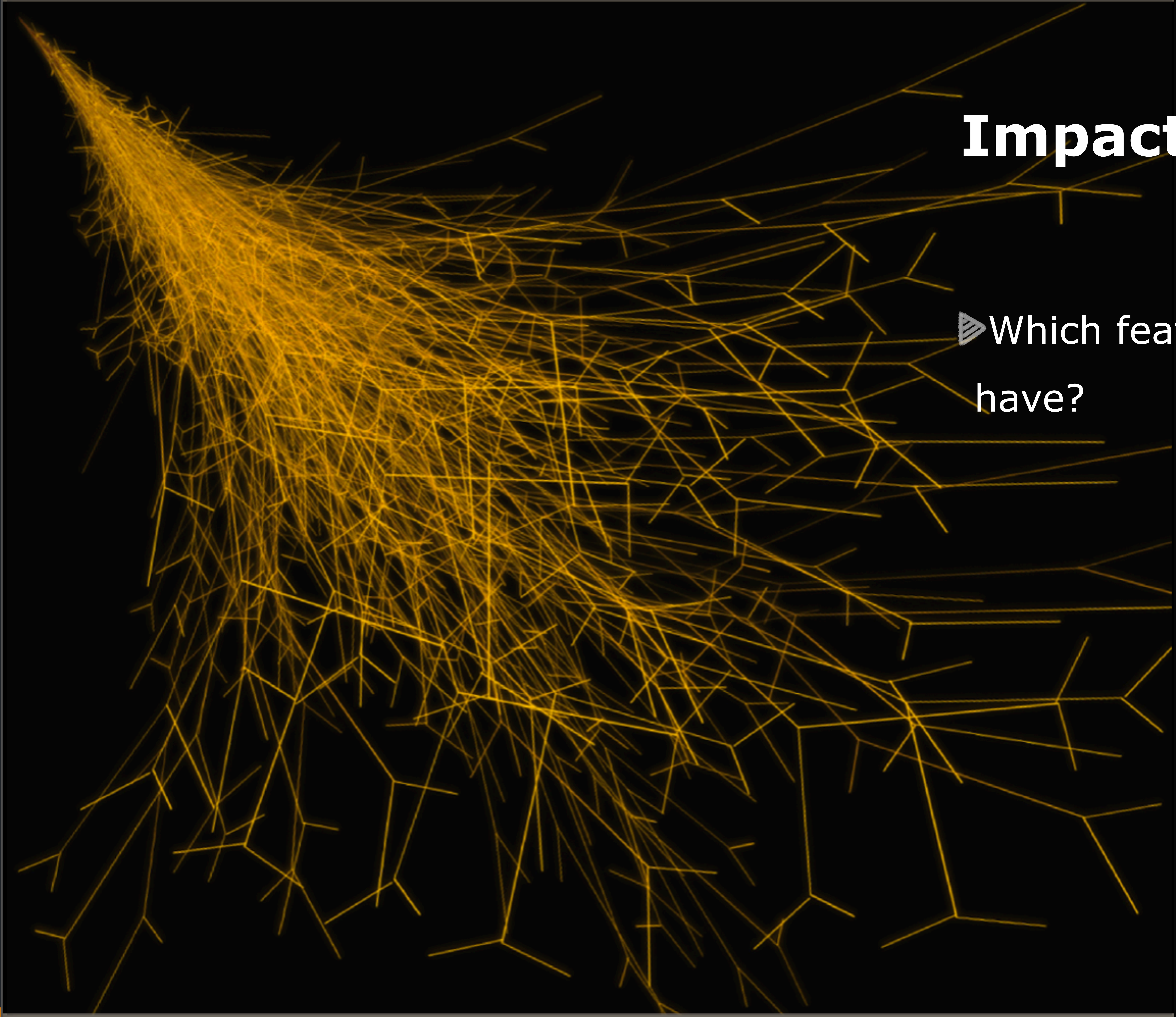
Astrophysical interpretation of UHECR data

Minimal cosmological model, by assuming identical and point-like sources as standard candles emitting with a power law and rigidity cutoff;

- Nuclei are accelerated at the sources.
- A hard injection spectrum at the sources is required.
- Suppression due to photo-interactions and by limiting acceleration at the sources, while the ankle feature is not easy to accommodate.



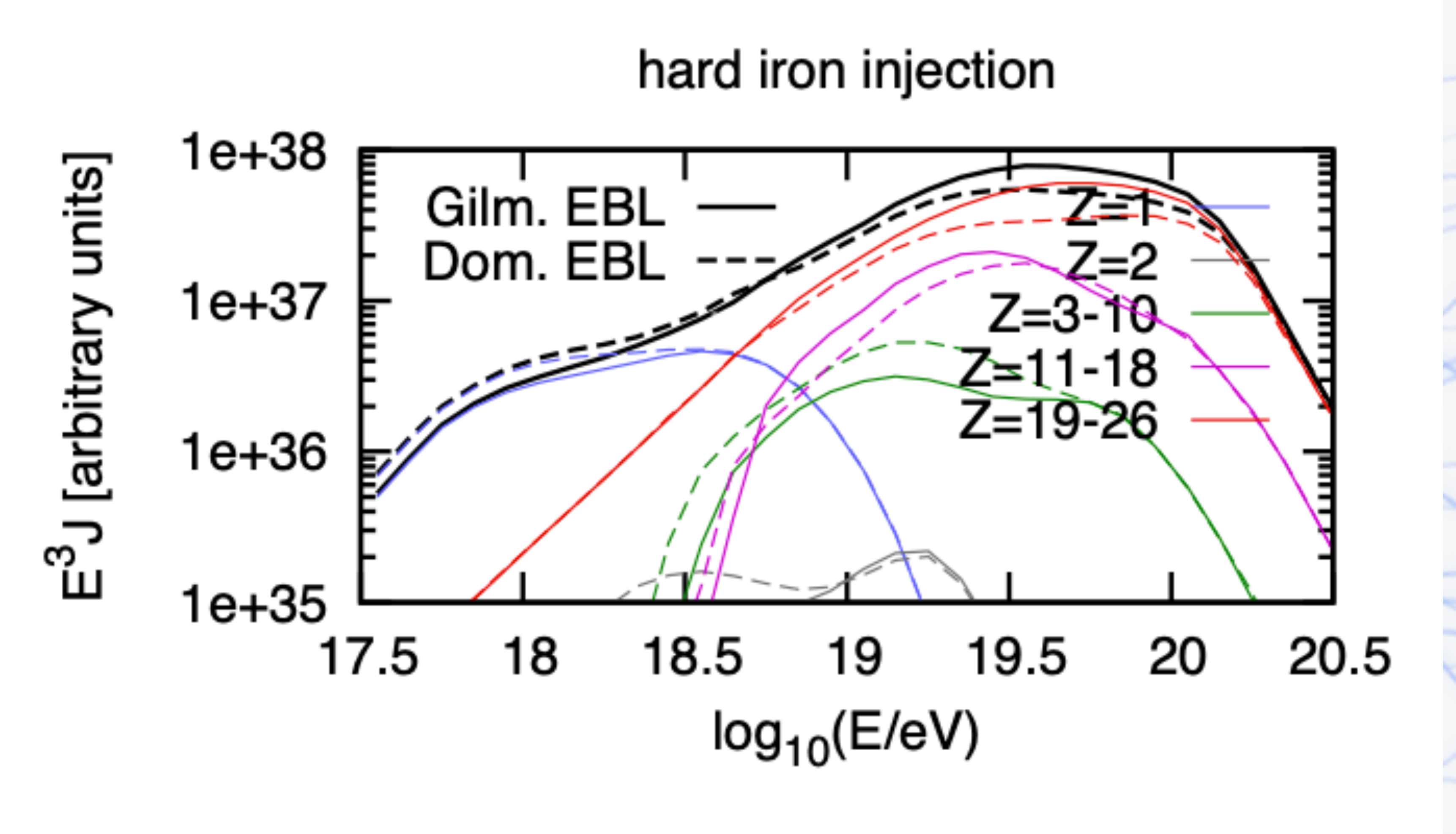
Q. Luce et al., 2022 *ApJ* **936** 62

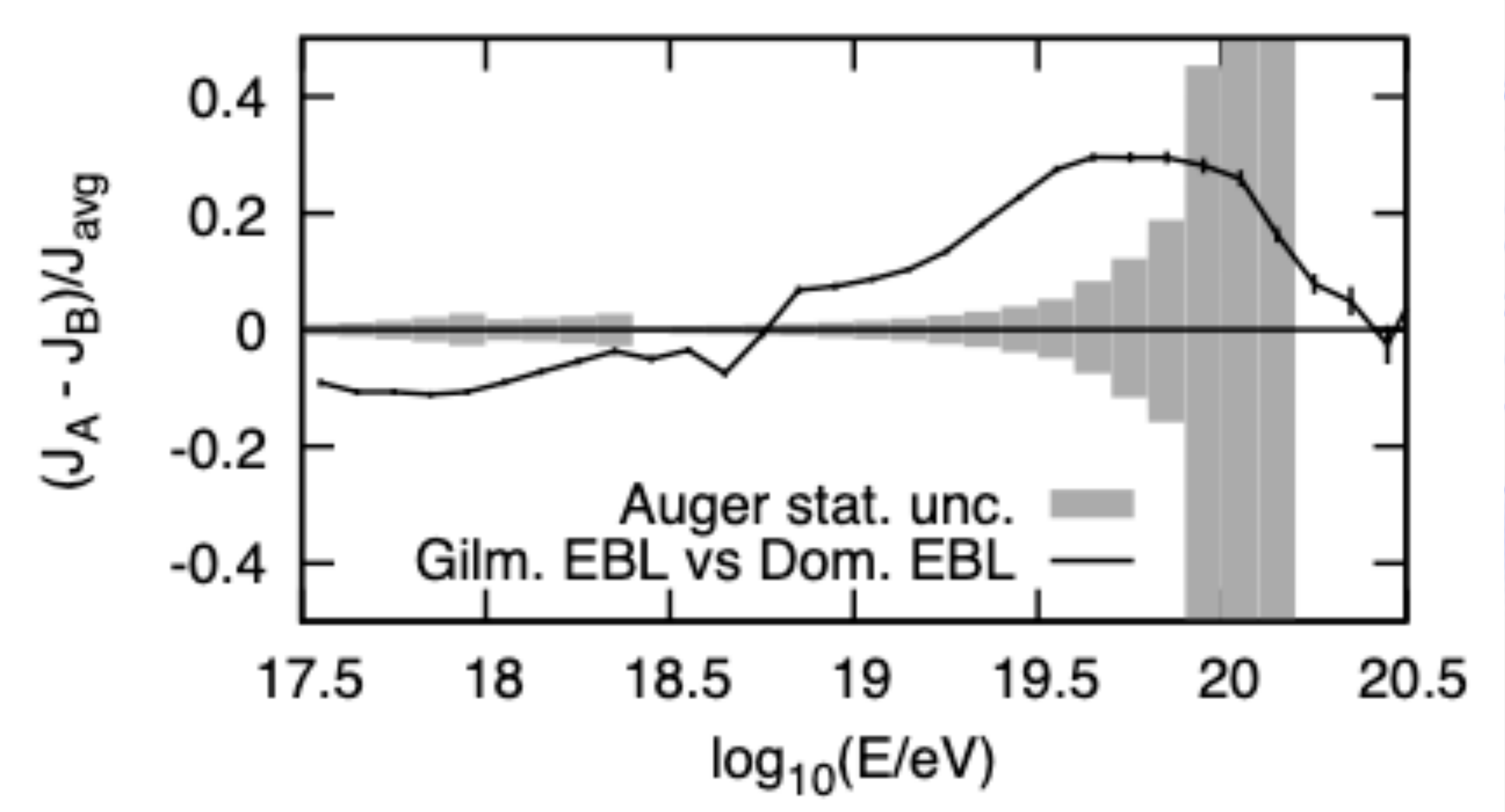


Impact of the EBL

- Which features UHECR sources should have?

Astrophysical interpretation of UHECR data





Q. Luce et al., 2022 *ApJ* **936** 62

Uncertainties on EBL –> Systematics in this type of study! See e.g. JCAP04(2017)038 or JCAP05(2023)024

Over the last 10 years several new measurements (especially on the IR range) & models.

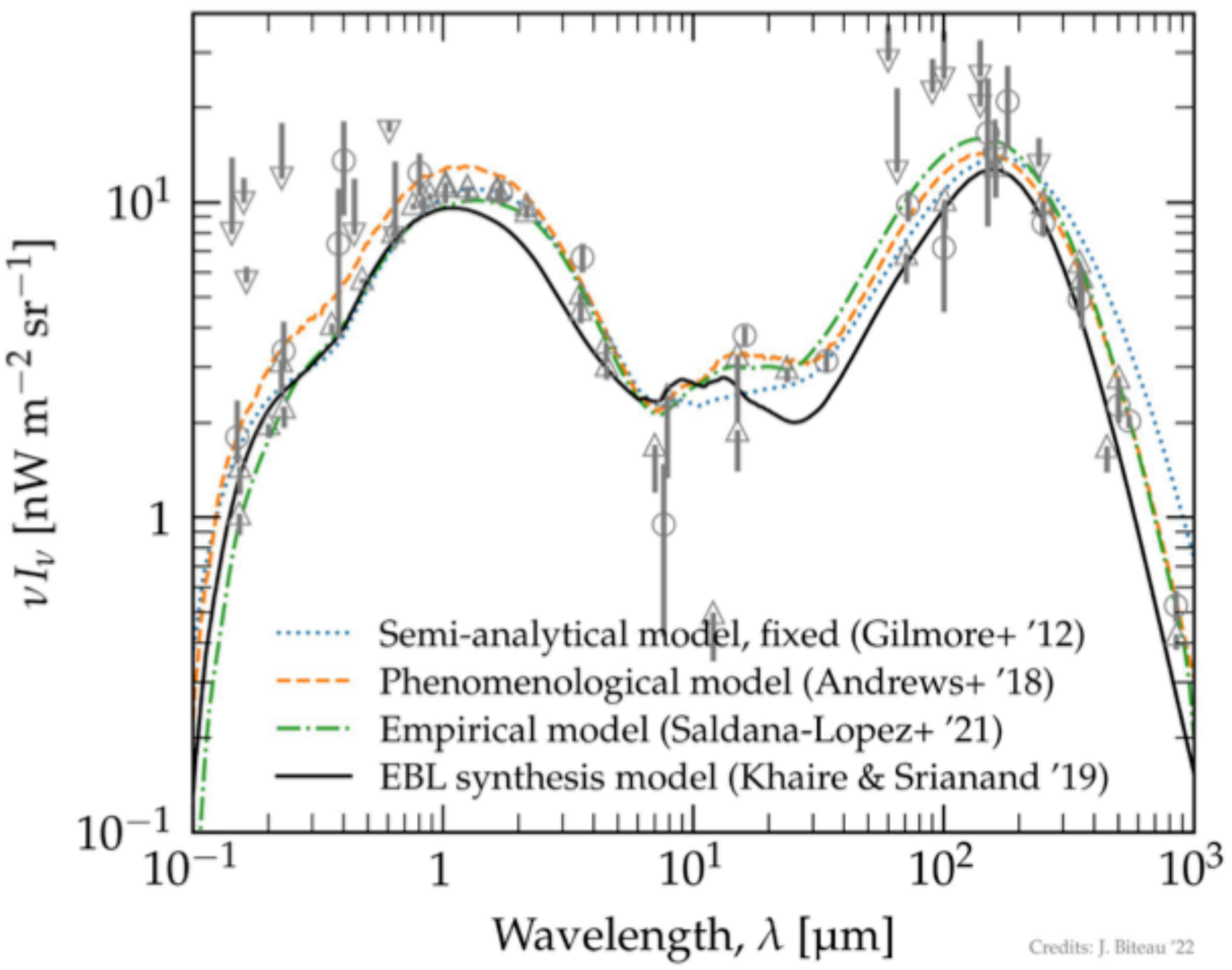
How this impacts UHECR propagation?

Astrophysical interpretation of UHECR data

Three main categories of models:

- **Empirical models**
  from observed luminosity functions
  of galactic populations,
  extrapolate them to high-z
- **Phenomenological models**
  from initial mass function
  (distribution of stellar mass at 0 age),
  cosmic star formation history and
  stellar population synthesis models
- **Semi-analytical models**
  from cosmological simulations with
  simplified equations wrt N-body sims,
  including sub-grid recipes for baryonic feedback

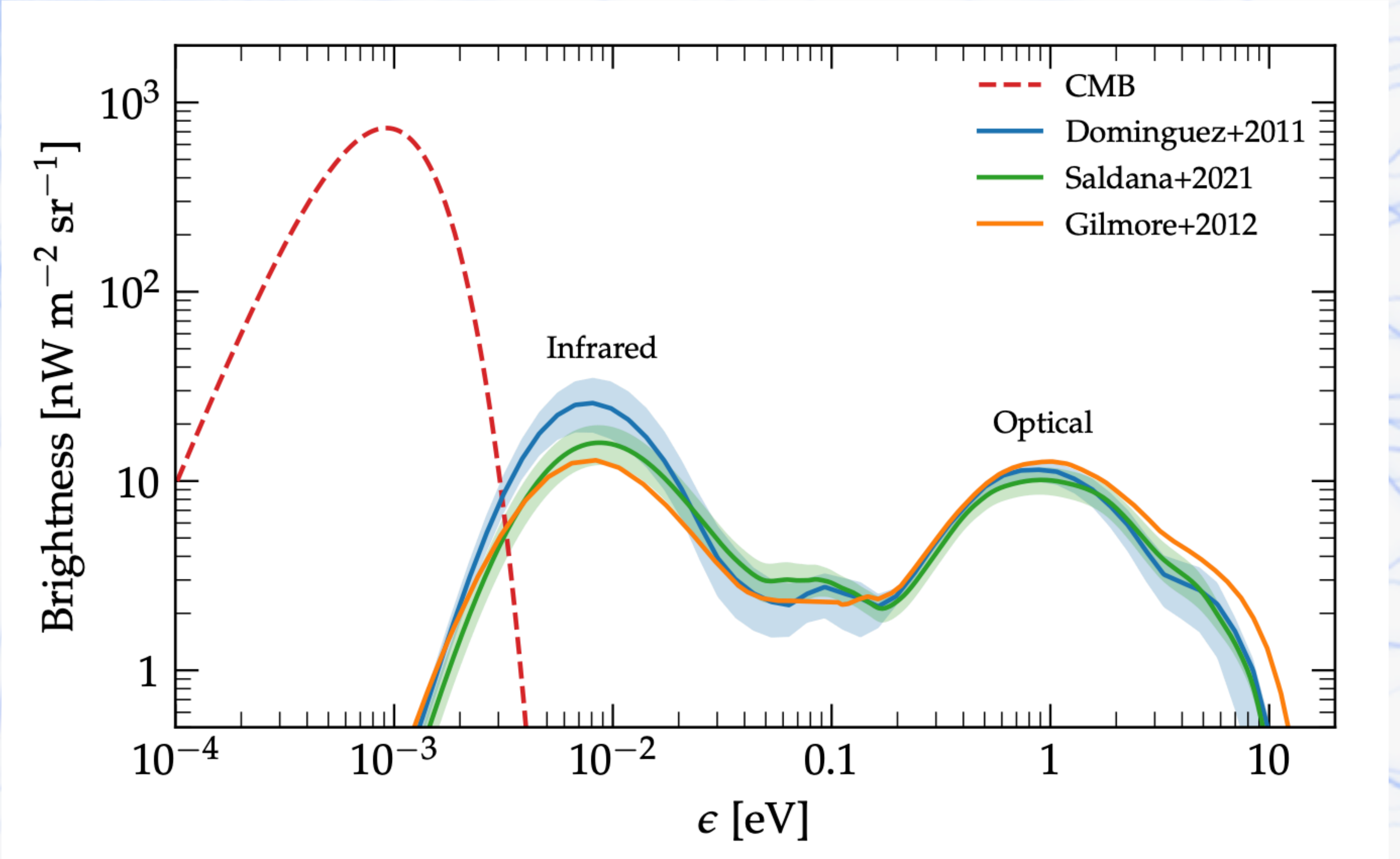
All models aim at matching observations,
in particular galaxy counts (**unknowns = 0**)

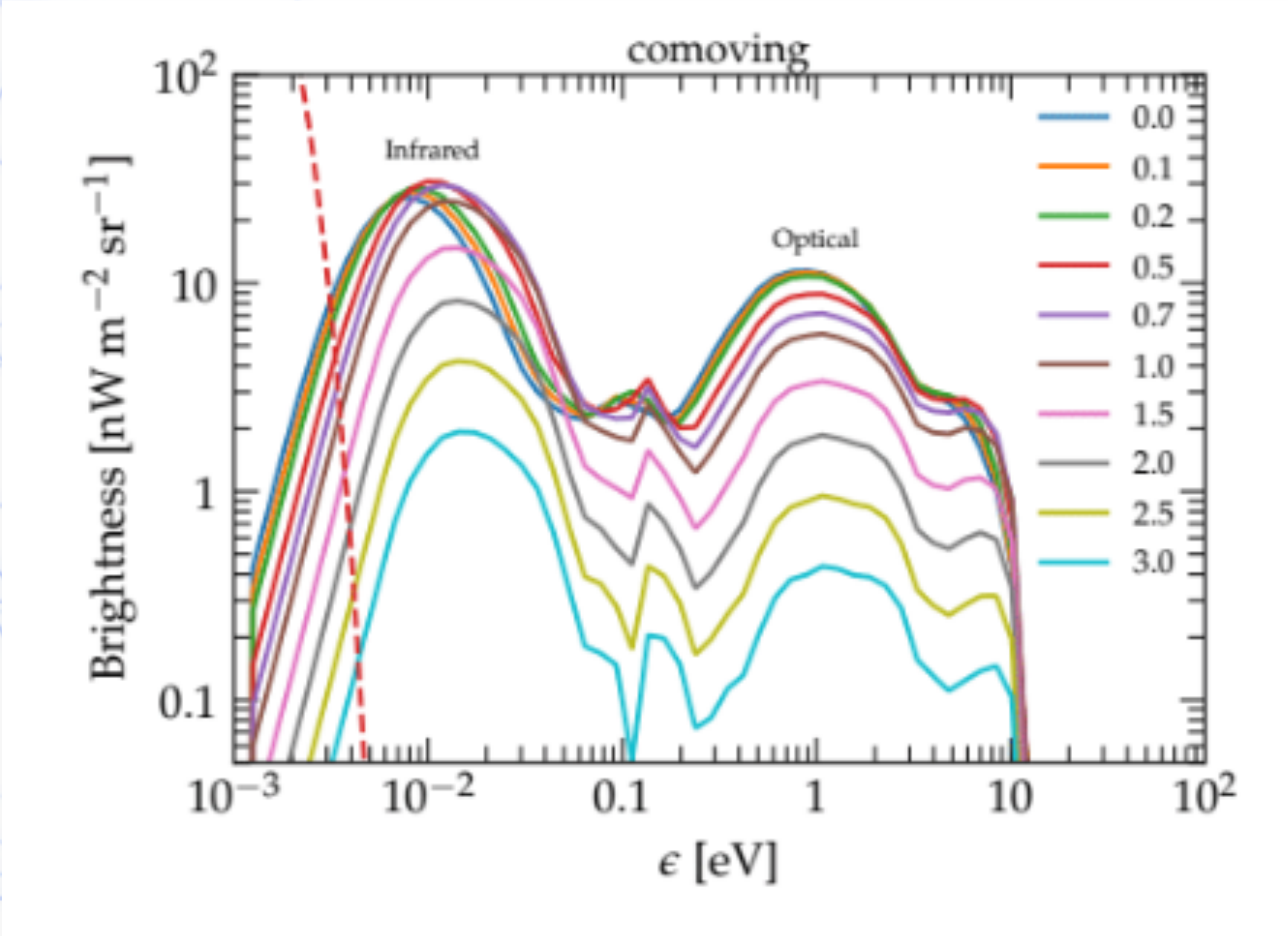


J. Biteau, Paris Saclay Astroparticle Symposium 2022

Astrophysical interpretation of UHECR data

- Starting from raw data: Saldana https://arxiv.org/pdf/2012.03035.pdf or Andrews https://core.ac.uk/reader/143472900





$$\frac{1}{\tau} = \frac{1}{2\Gamma^2}\int_{\epsilon'_{\mathrm{min}}}^{2\Gamma\epsilon}\int_{\epsilon=0}^{+\infty}\frac{n_\gamma(\epsilon)}{\epsilon^2}\,\mathrm{d}\epsilon\,\sigma(\epsilon')\epsilon'\,\mathrm{d}\epsilon'\,,$$

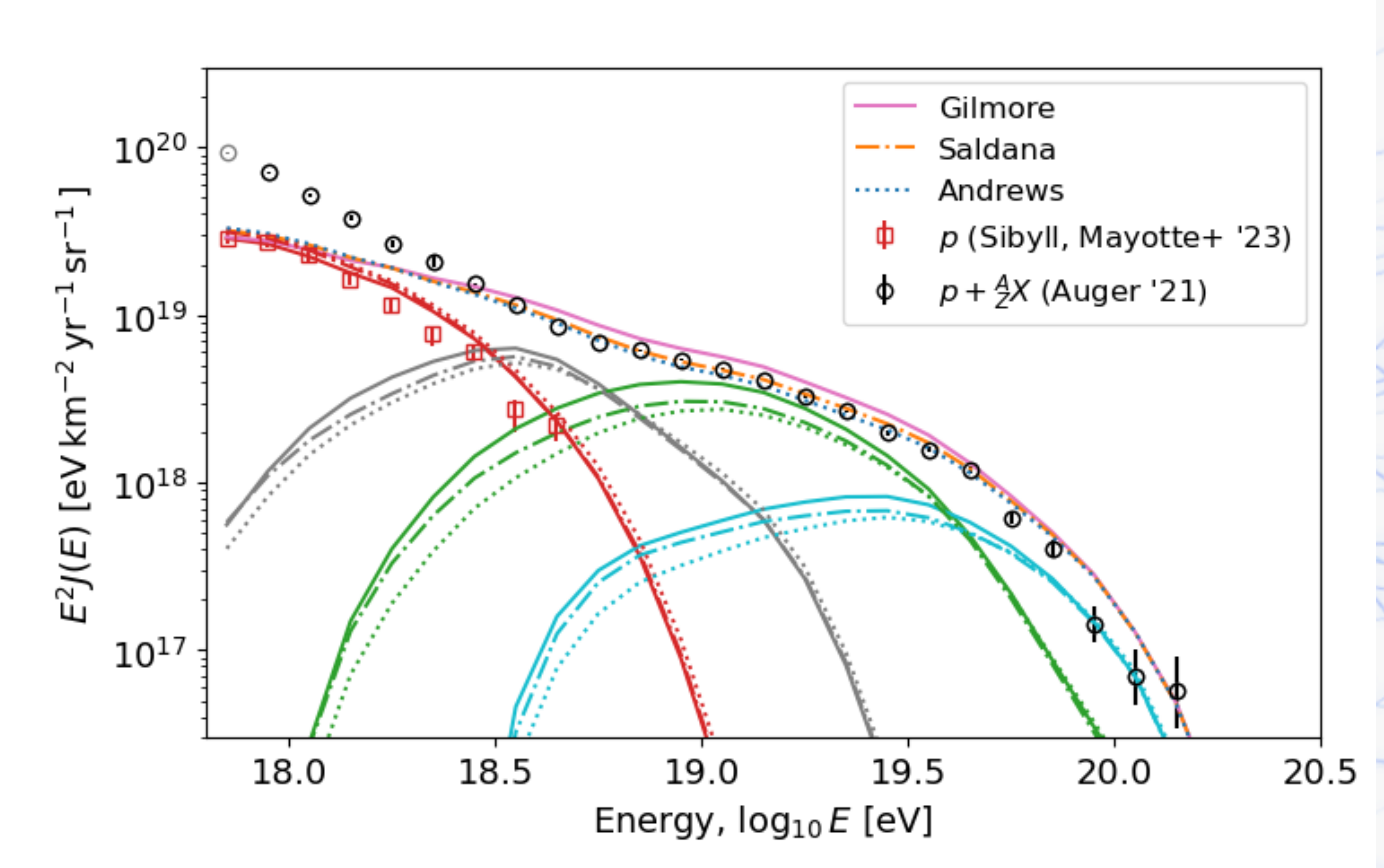
$$I(\epsilon) = \int_{\epsilon}^{+\infty}\frac{n_\gamma(\varepsilon)}{2\varepsilon^2}d\varepsilon,$$

- Converting photon field in energy density and plug it in the propagation code;
- Crosscheck with existing models (Gilmore and Dominguez);
- Propagation tensor production with new EBL models.

Astrophysical interpretation of UHECR data

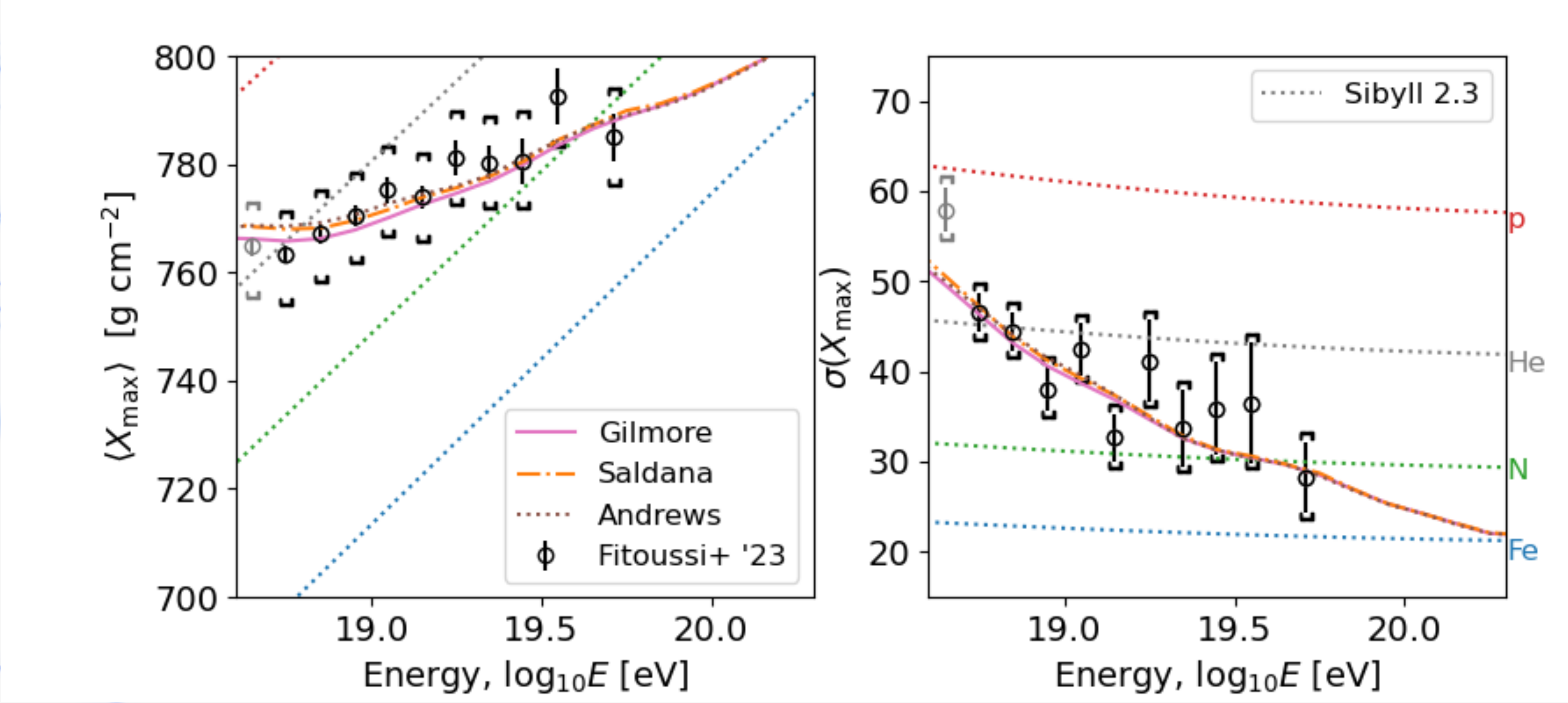
Model	Andrews	Gilmore	Saldana
log(Rcut/V)	18.25 ± 0.02	18.26 ± 0.02	18.28 ± 0.02
gamma p	2.67 ± 0.65	3.27 ± 0.85	4.75 ± 0.29
gamma nucl	-0.51 ± 0.09	-0.55 ± 0.18	-0.19 ± 0.12
k x Etot above log(R/V) = 17.8	(4.74 ± 0.19) x 10^{46} erg per solar mass	(4.91 ± 0.35) x 10^{46} erg per solar mass	(4.76 ± 0.35) x 10^{46} erg per solar mass
H (%)	15.7 ± 3.6	18.8 ± 6.6	9.2 ± 8.0
He (%)	13.9 ± 1.7	18.1 ± 1.9	16.3 ± 2.5
N (%)	57.8 ± 2.9	40.7 ± 2.8	47.2 ± 3.4
Si (%)	7.7 ± 2.7	22.4 ± 1.4	27.2 ± 1.5
Fe (%)	5.0 ± 1.1	0 ± 0.0	0 ± 0.0
Spectrum deviance	41.29	24.99	26.72
Composition deviance	31.45	34.02	31.09

Impact of EBL

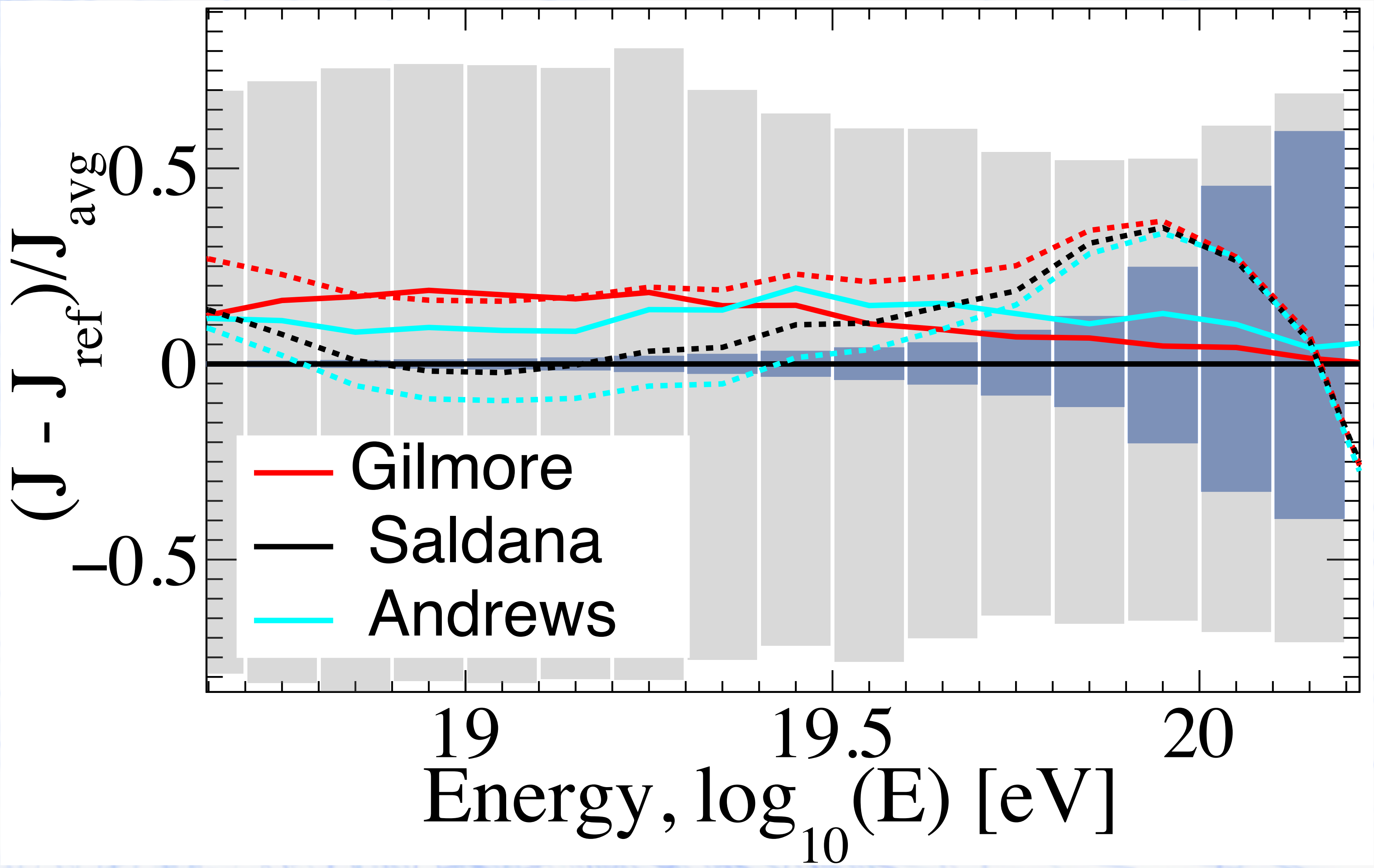


SimProp
CRPropa

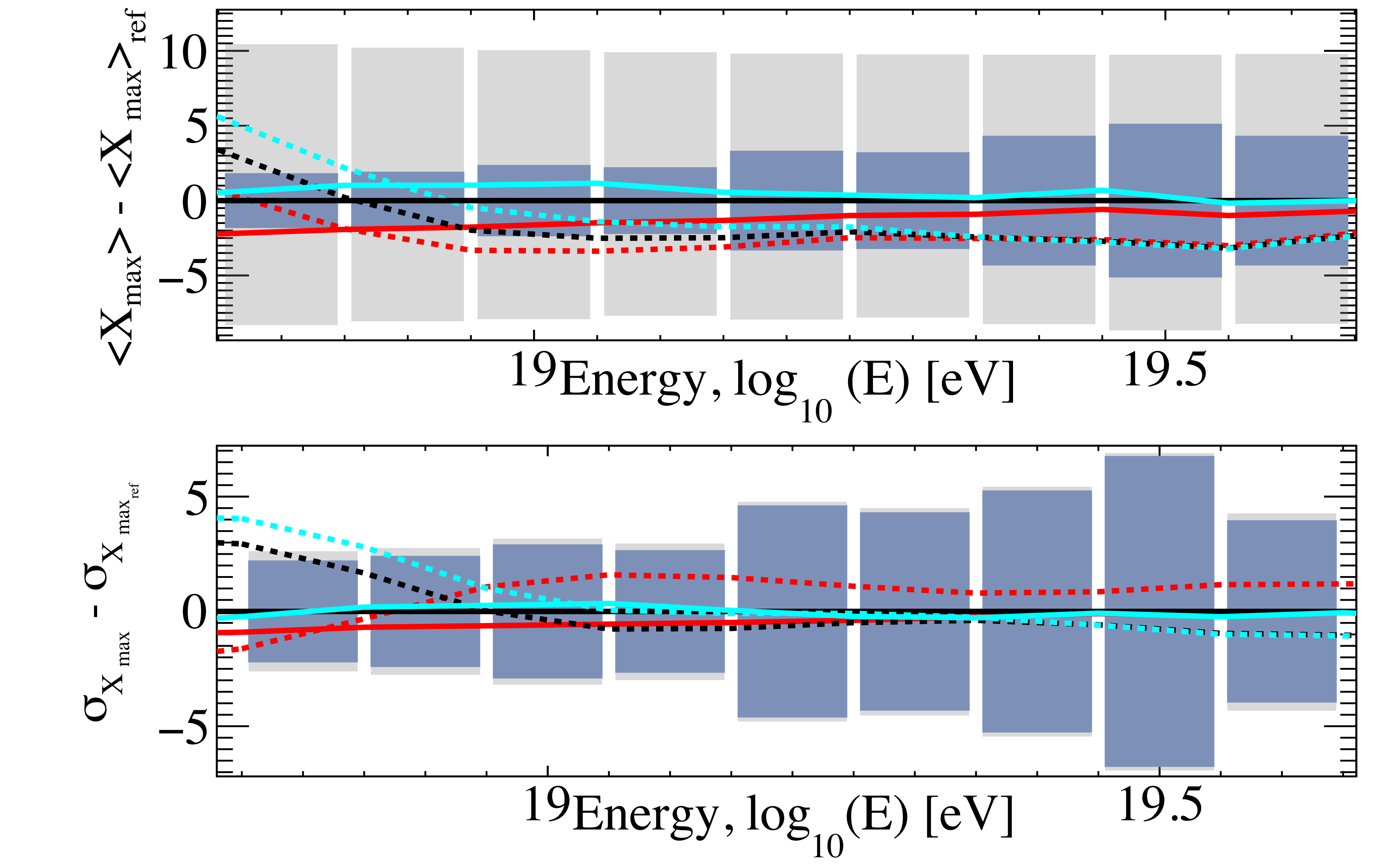
The uncertainties of the EBL do not constrain anymore our astrophysical scenario above the ankle.



Astrophysical interpretation of UHECR data



The uncertainties induced by the EBL modelling are smaller wrt statistical+systematic uncertainties of UHECR data



Conclusions and final remarks

- ✴Take-home message: the uncertainties of the EBL do not constrain anymore our astrophysical scenario above the ankle;
- ✴This result does not depend on the UHECR propagation code;
- ✴Latest EBL models already implemented in SimProp and public available soon;
- ✴Analogous work on gamma rays propagation and paper in preparation.

Conclusions and final remarks

anks for your attention!

UHECR interactions

Energy loss equation:

$$-\frac{1}{E}\frac{dE}{dt} = \frac{c}{2\Gamma^2}\int_{\epsilon'_{\rm th}}^{\infty} \epsilon' \nu(\epsilon')\sigma(\epsilon') \int_{\epsilon'/2\Gamma}^{\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} d\epsilon \, d\epsilon' = \beta(E)$$

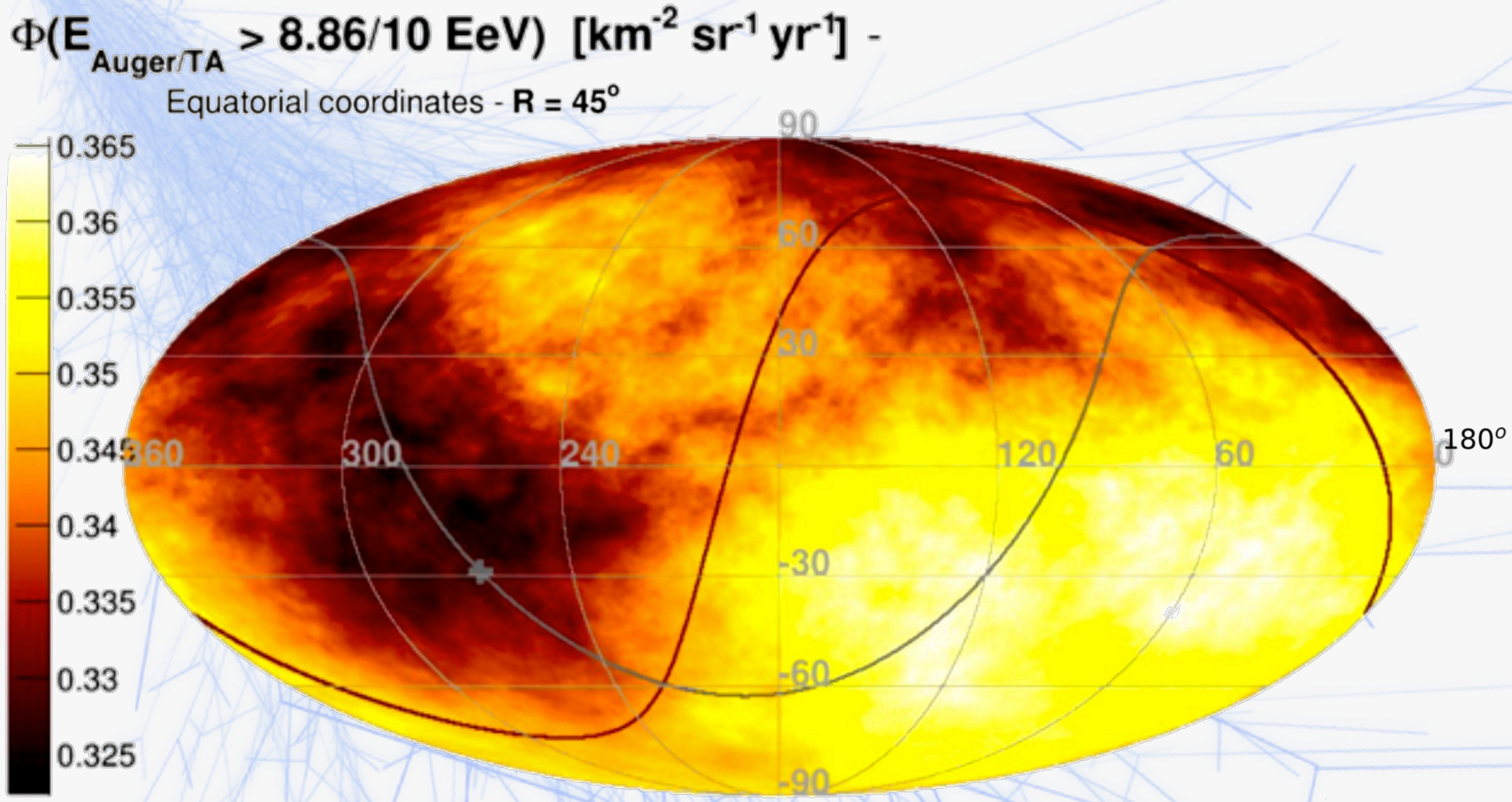
Adiabatic expansion:

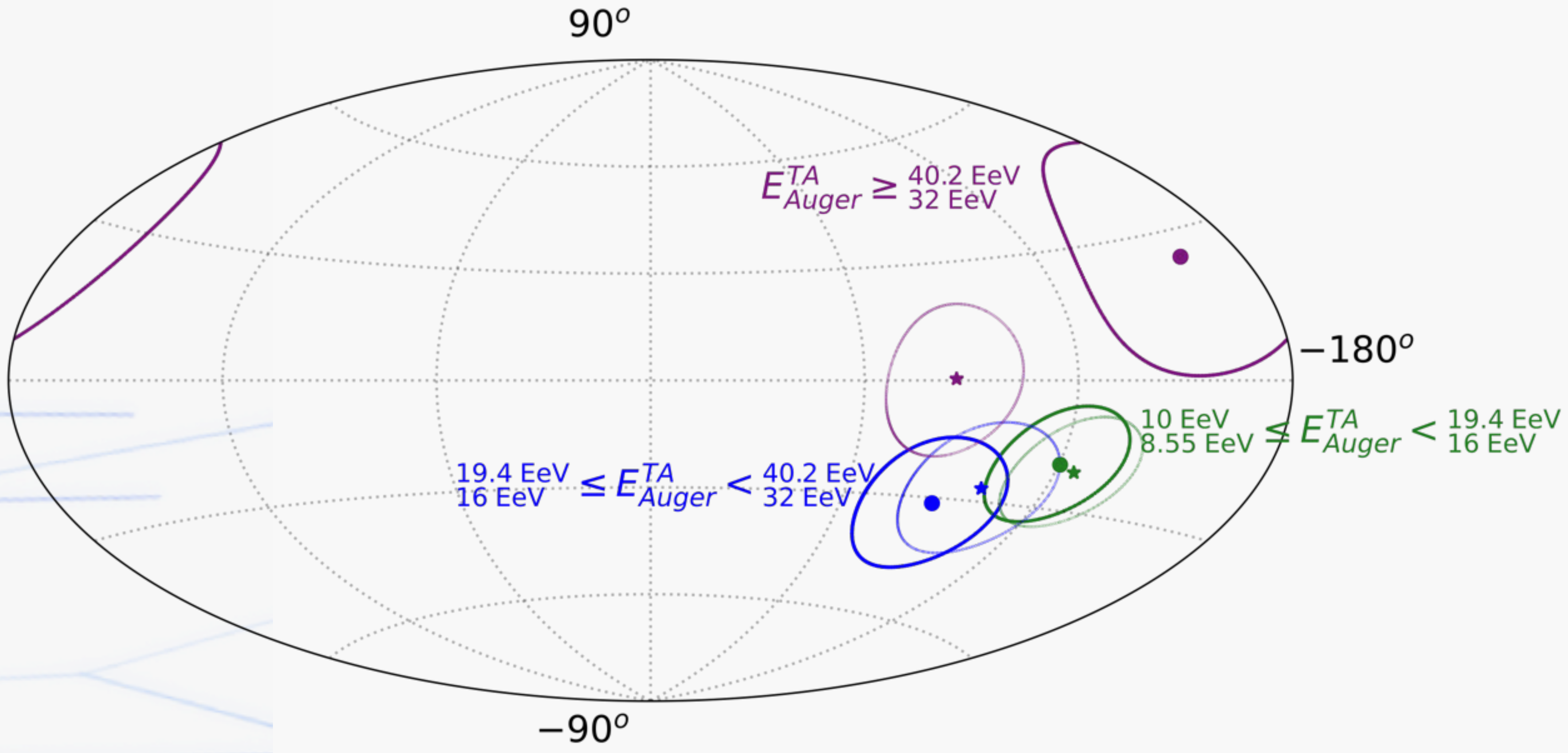
$$\frac{1}{E}\frac{dE}{dt} = \beta(E,t) + H(t), \quad \beta(E,t) = \sum_{\rm int} \beta_i(E,t)$$

Redshift evolution:

$$\left(\frac{dt}{dz}\right)^{-1} = -(1+z)H(z), \quad H(z) = H_0\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}$$

Current UHECR Picture: Arrival direction



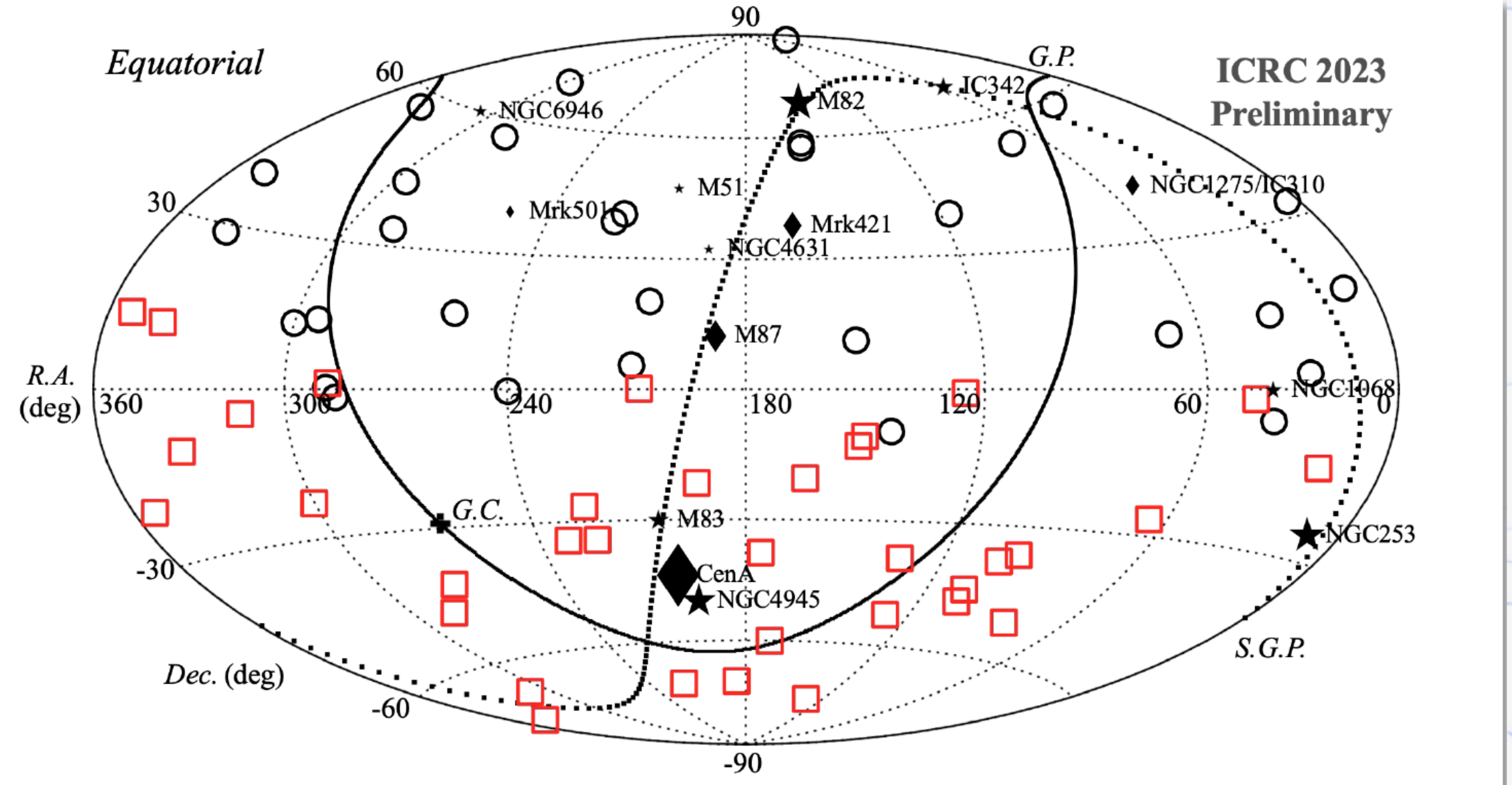


The above flux map is immediately interpretable

- ➢ equal sensitivity anywhere in the sky
- ➢ upper limits uniform over the sky
- ➢ no need for methods to re-weight individual exposures

Confirm the presence of a dipole pointing away from the GC

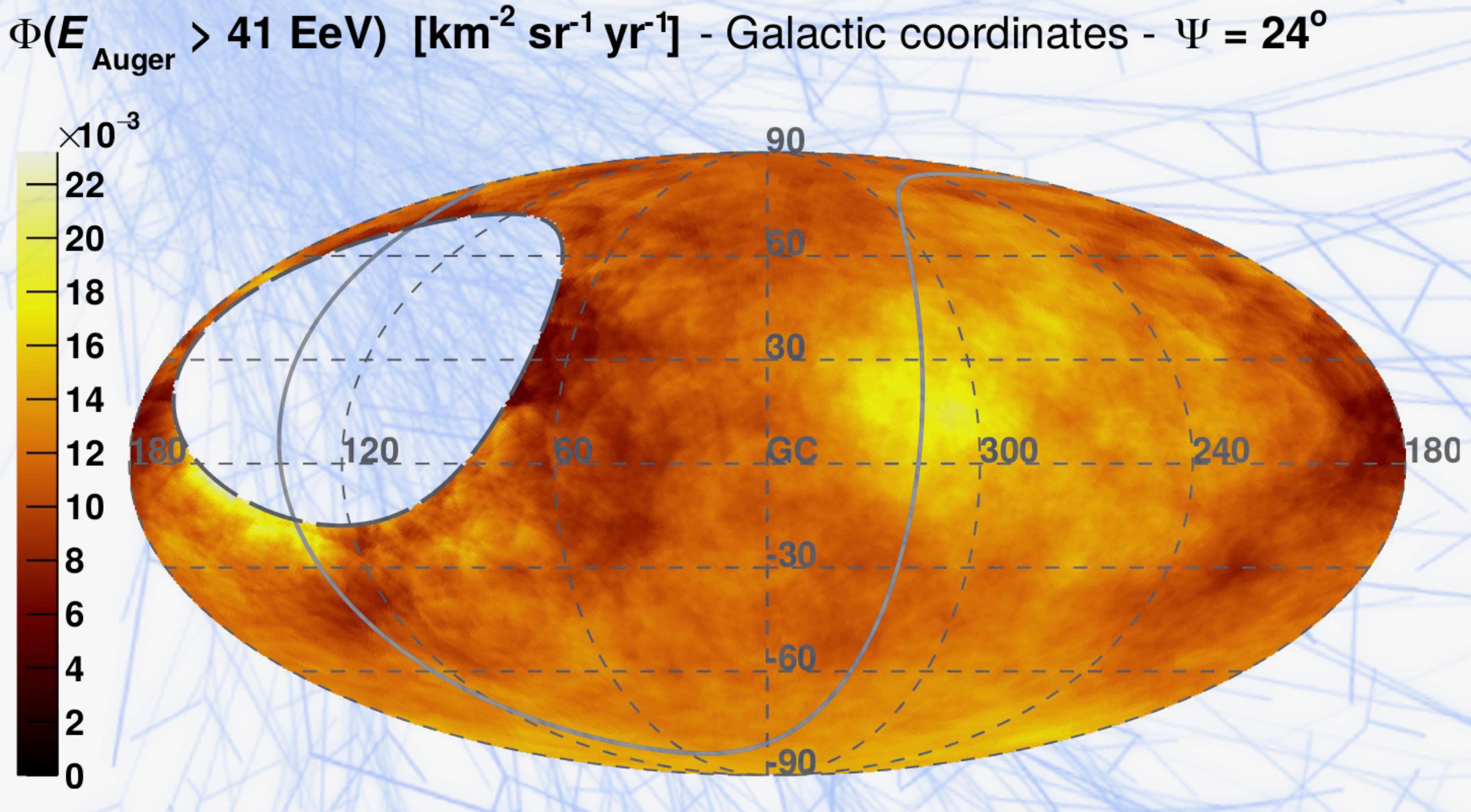
Current UHECR Picture: Arrival direction



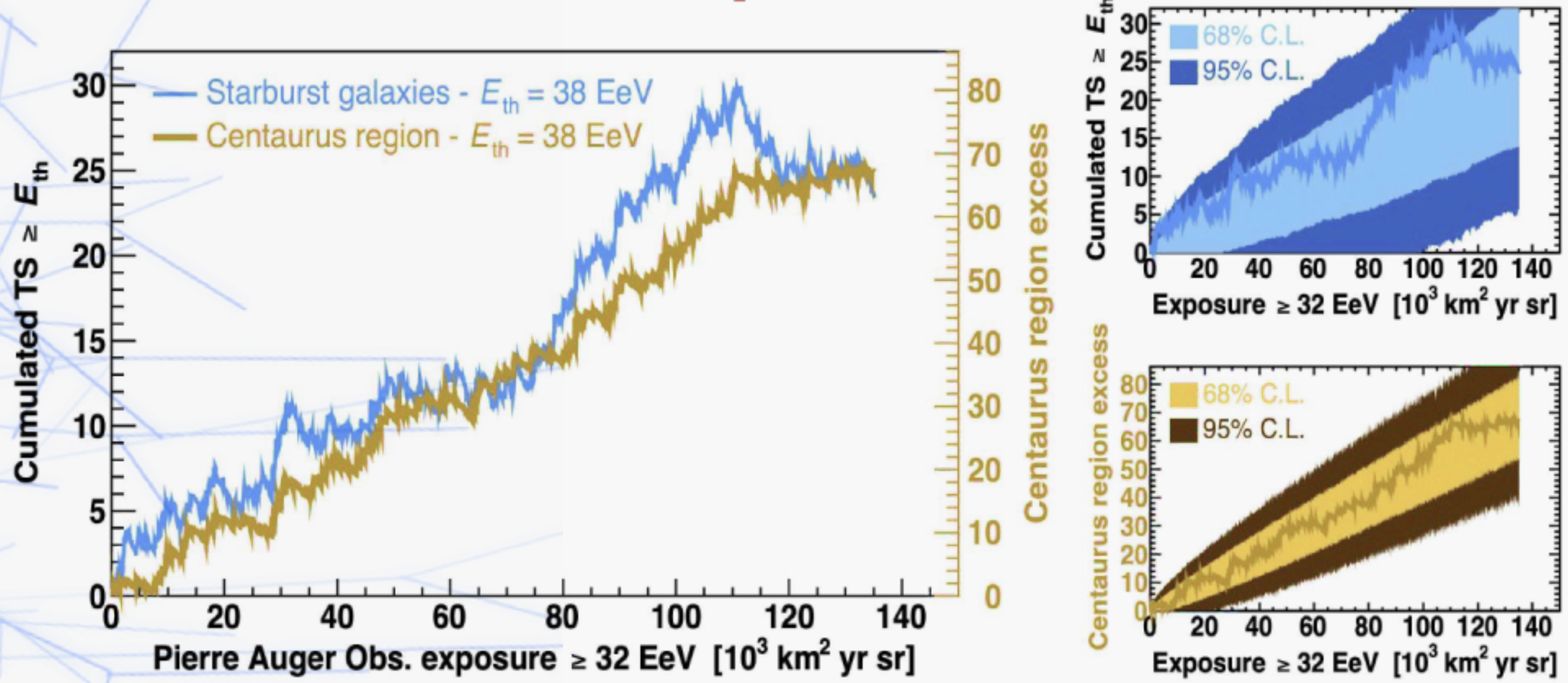
TA 15-years (ICRC2023 Preliminary), Auger 17-years (ApJ 935 170 (2022))

No Obvious Sources above 100 EeV in TA or Auger –>This level of isotropy strongly disfavours Protons at the highest energies event at extremely high EGMF strengths.

Narrowing down Source Candidates In Southern Sky



~90% isotropic distribution

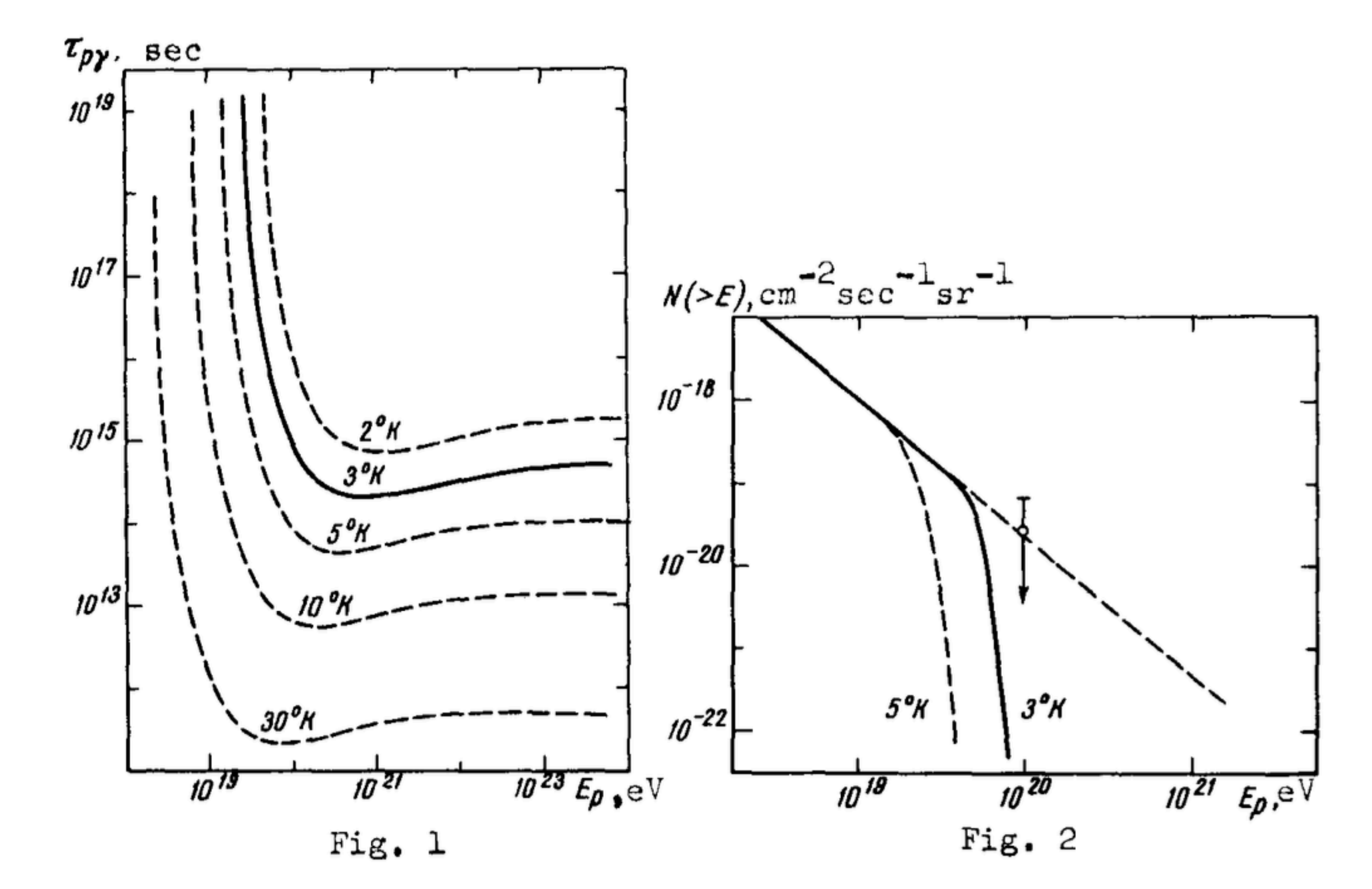


Correlation with catalogues of SBGs (3.8 σ) and AGN (3.5 σ)

➢Correlation mostly driven by CenA region

➢Still 90% of isotropic flux –> what does it mean in terms of astrophysical sources?

GZK effect



K. Greisen. Phys. Rev. Lett. 16 (1966)
G. T. Zatsepin and V. A. Kuzmin, JETP Lett. 4 (1966)

Pion production in photohadronic interactions with CMB photons

$$p + \gamma \rightarrow n + \pi^+$$

$$p + \gamma \rightarrow p + \pi^0$$

Proton energy:

$$E_p = \frac{(m_\pi + m_p)^2 - m_p^2}{2\epsilon(1 - \cos\theta)}$$

Threshold:

$$E_p^{\text{th}} = \frac{2m_\pi m_p + m_\pi^2}{4k_B T} \sim 7 \cdot 10^{19}\,\text{eV}$$

UHECR interactions

- **Pair production**

$$p + \gamma \rightarrow p + e^{+} + e^{-}$$

$$E_p^{\rm th} \sim 2.5 \cdot 10^{18}\,{\rm eV}$$

- **Photodisintegration**

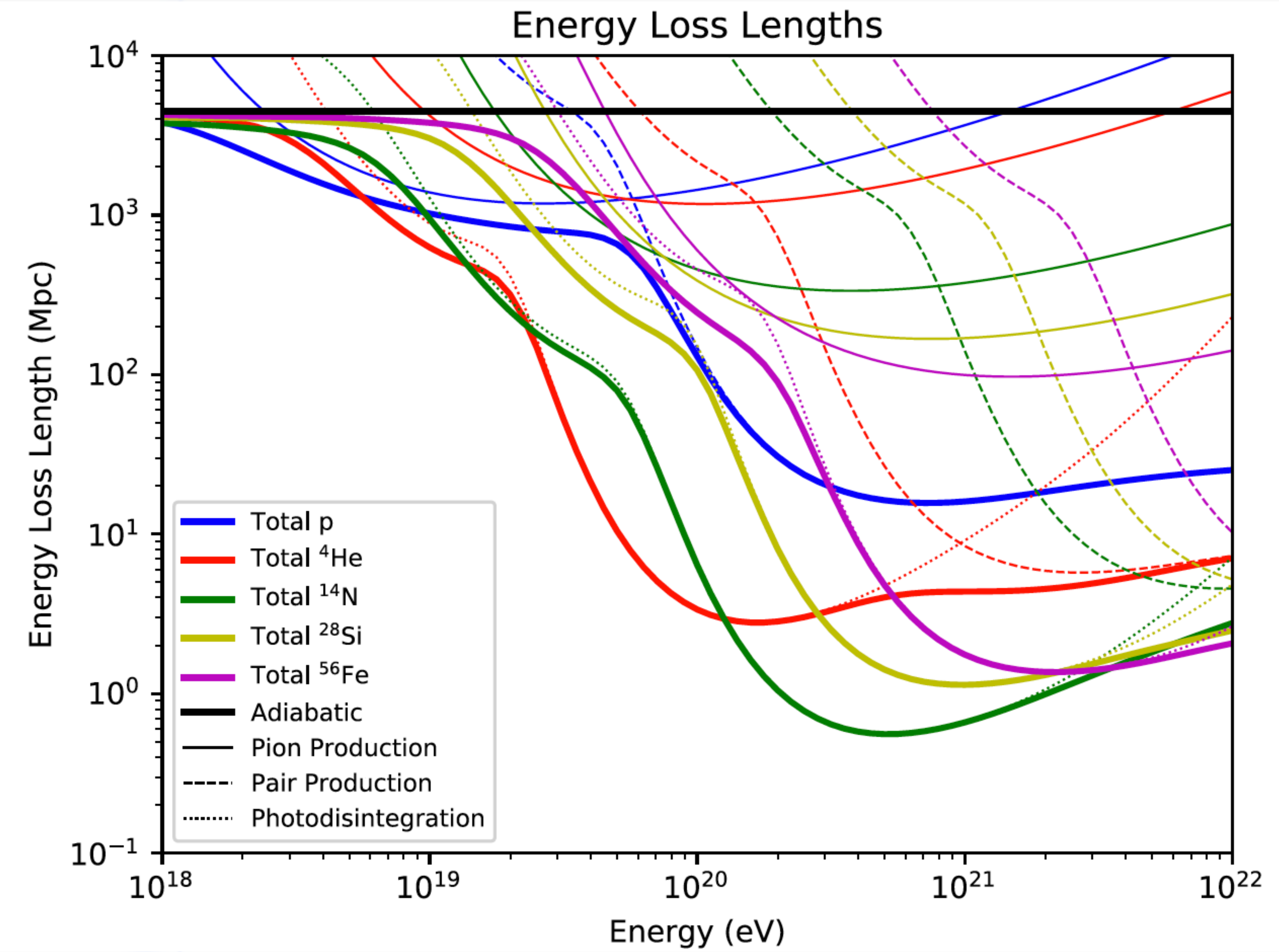
$$(A, Z) + \gamma \rightarrow (A - n, Z - m) + nN$$

- **Adiabatic**

$$-\frac{1}{E}\frac{dE}{dt} = H_0$$

- **Nuclear decay**

$$\tau = \Gamma \tau_0$$



UHECR interactions

UHECRs propagate over cosmological distances Background photon fields are not static, but evolve with redshift

Cosmological expansion:

$$n_\gamma(\epsilon, z) = (1+z)^2 n_\gamma\left(\frac{\epsilon}{1+z}\right) \quad \longrightarrow \quad \tau^{-1}(\Gamma, z) = (1+z)^3 \tau^{-1}((1+z)\Gamma)$$

Astrophysical feedback:

$$n_\gamma(\epsilon, z) = (1+z)^2 n_\gamma\left(\frac{\epsilon}{1+z}, z\right) \quad \longrightarrow \quad \text{Numerical integration}$$

Extra-galactic magnetic field

UHECRs are charged particles and they are deflected by magnetic fields.
The extra-galactic magnetic field is purely known in both strength and structure

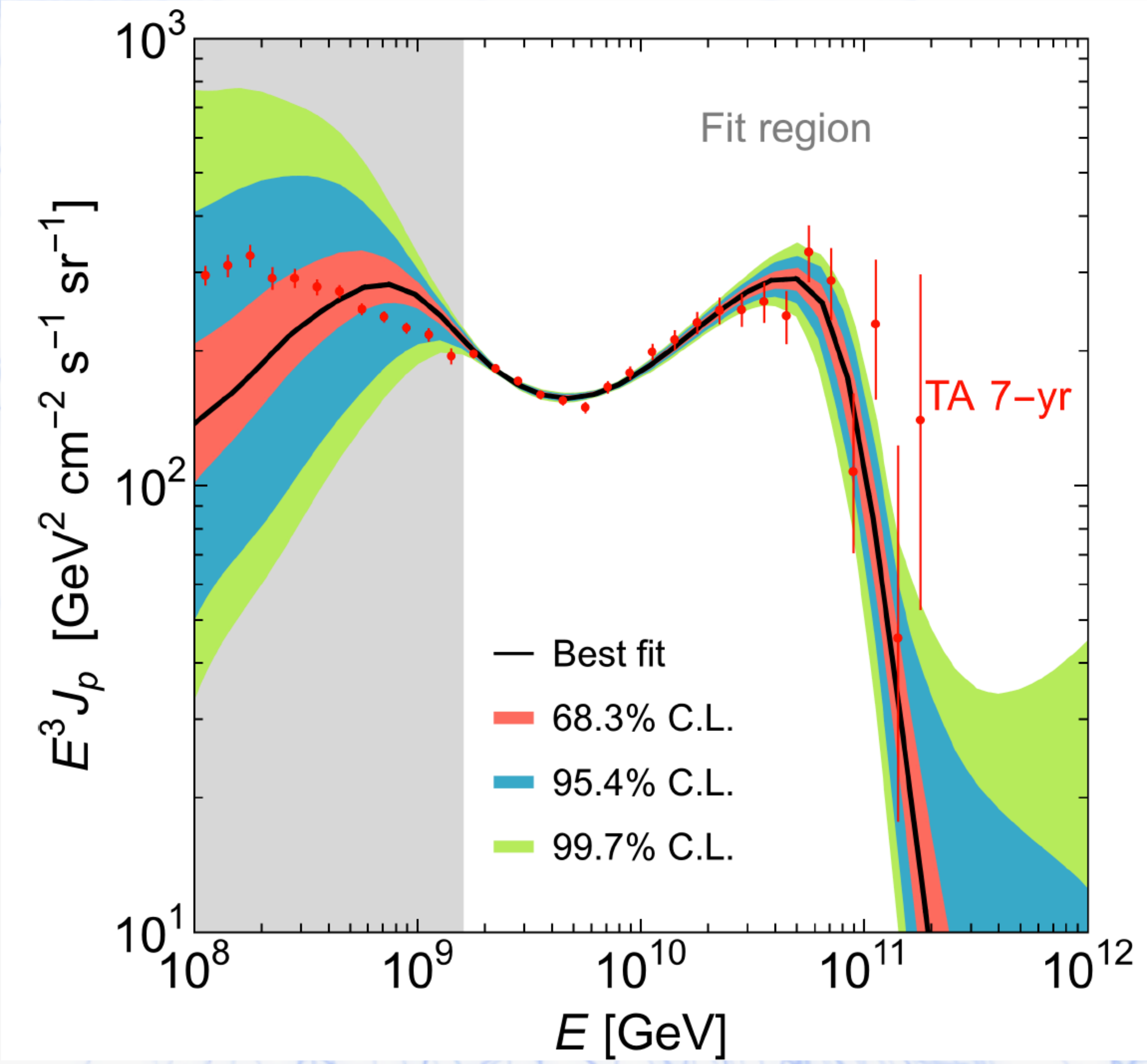
Statistically uniform field:

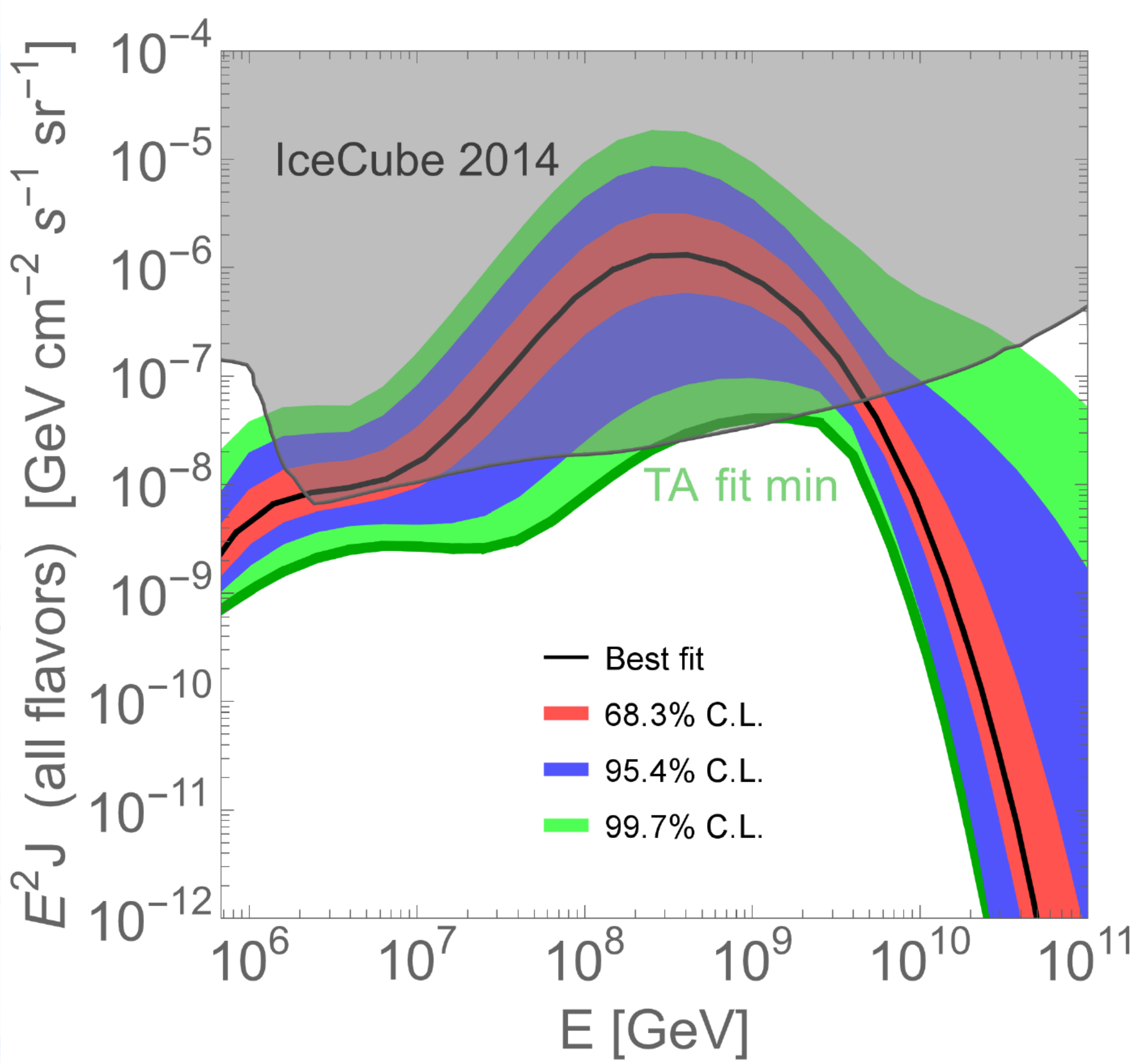
The magnetic field has the same statistical properties everywhere and it can be characterised by two parameters *Brms* , *λcoh*

Structured field:

The magnetic field has been obtained with constrained cosmological simulations of the evolution of the local Universe The strength and the structure of the field depend on the simulation parameters

Neutrino production

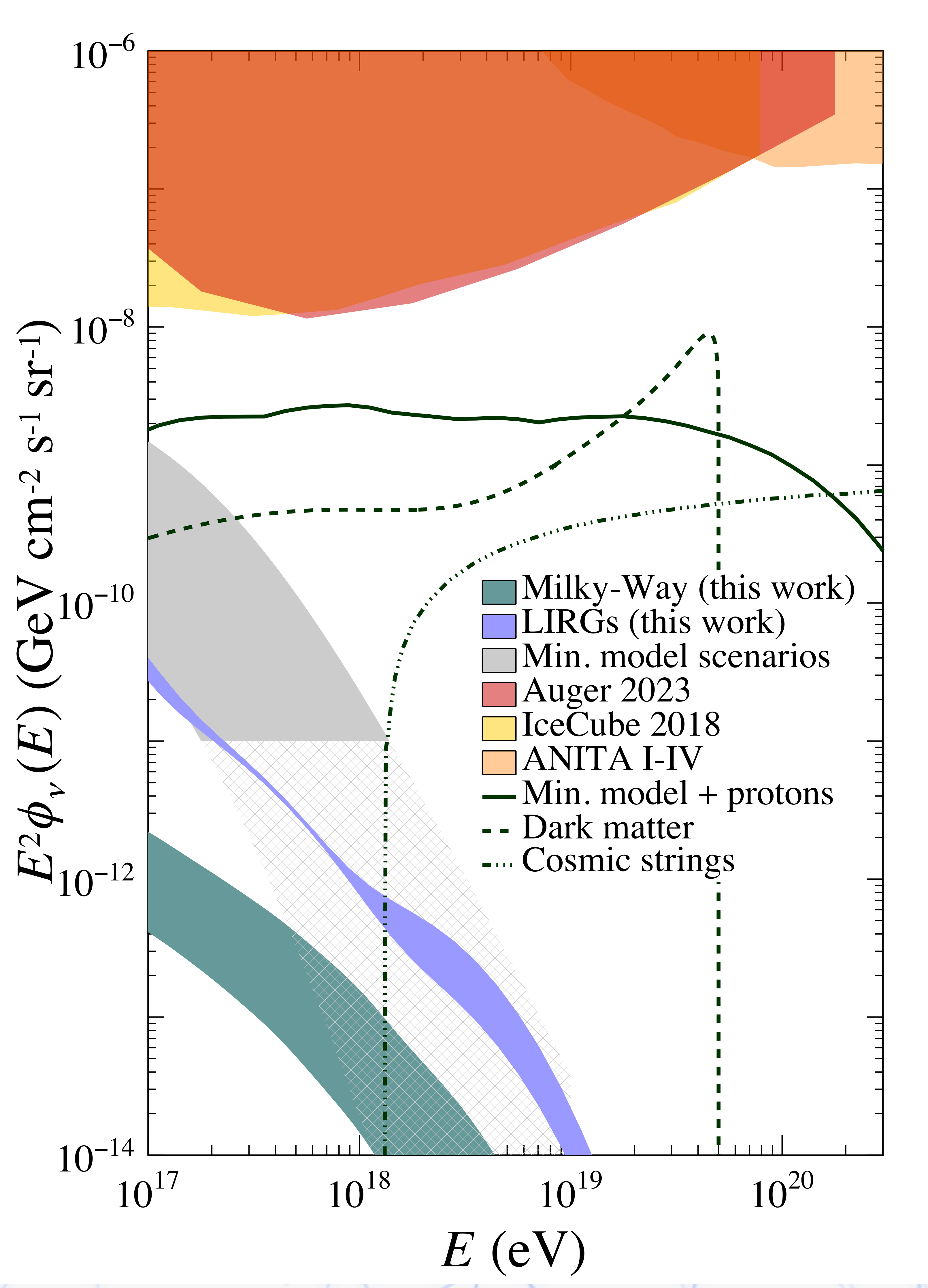




- Baseline interpretation: The proton contribution must be constrained by cosmogenic neutrino flux!

Heinze, Boncioli, Bustamante, Winter, Astrophysical Journal 825 (2016) 122

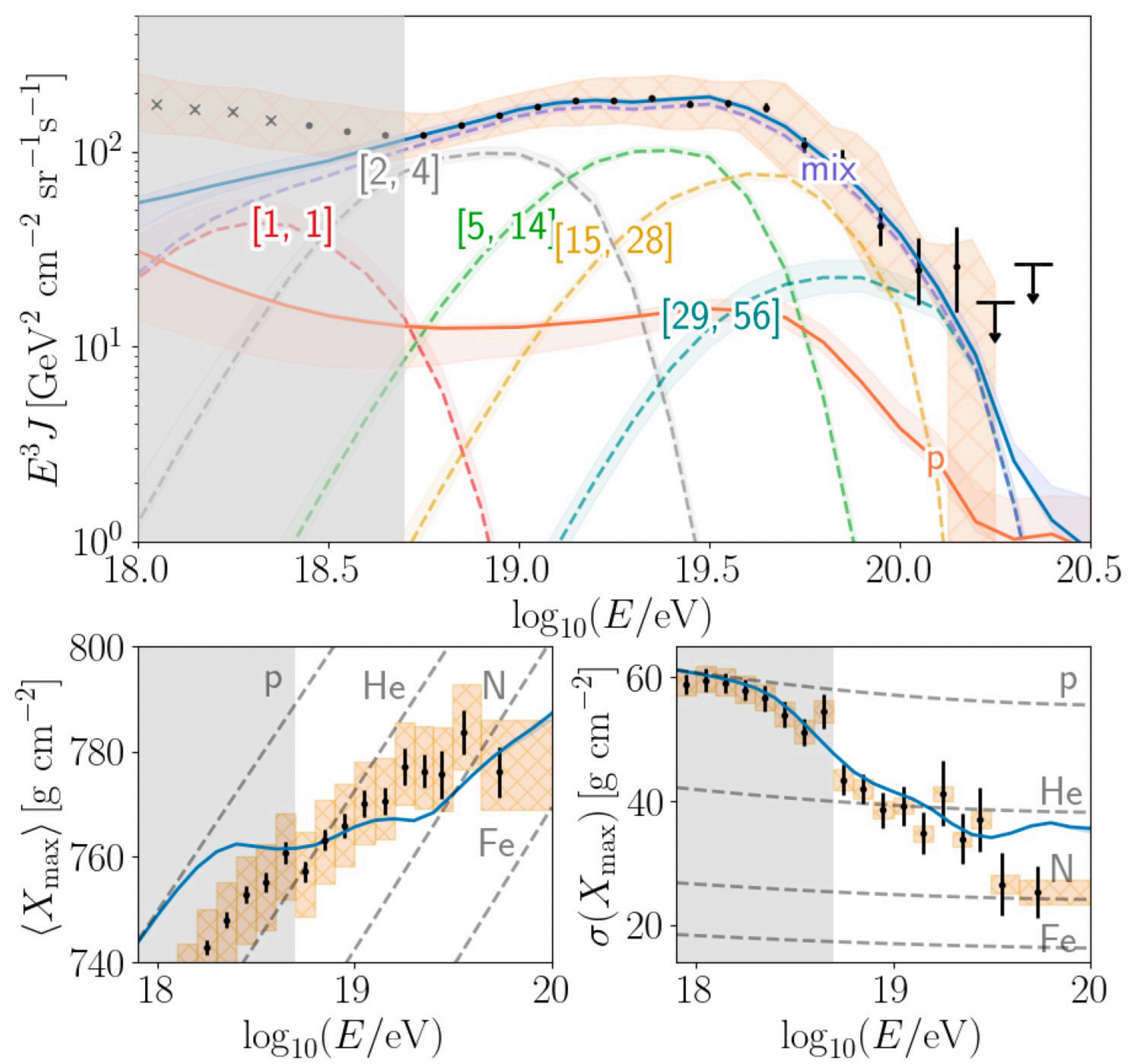
UHECR interactions

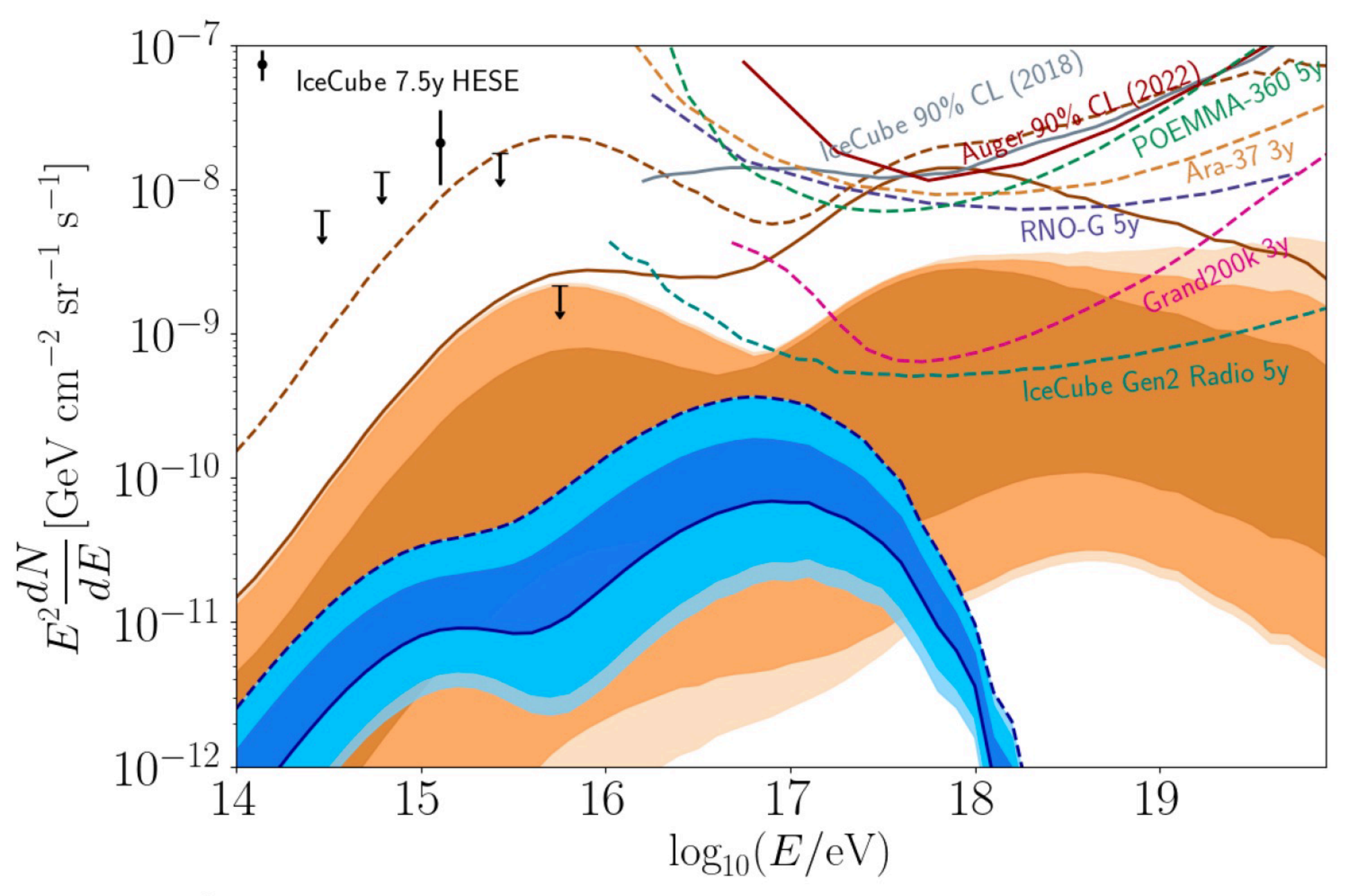


A. Condorelli et al., ApJ (2024)

- What is the minimal neutrino flux associated to the UHECR flux?
- Galactic contribution: computing the interaction of UHECRs within our Galaxy;
- Extra-galactic contribution: assuming a generic source as standard candle for UHECR acceleration and computing neutrino in source environment and in extra-galactic propagation.
- Take-home message: the neutrino flux associated to the minimal model is very low, room for detecting UHE protons and/or dark matter decay.

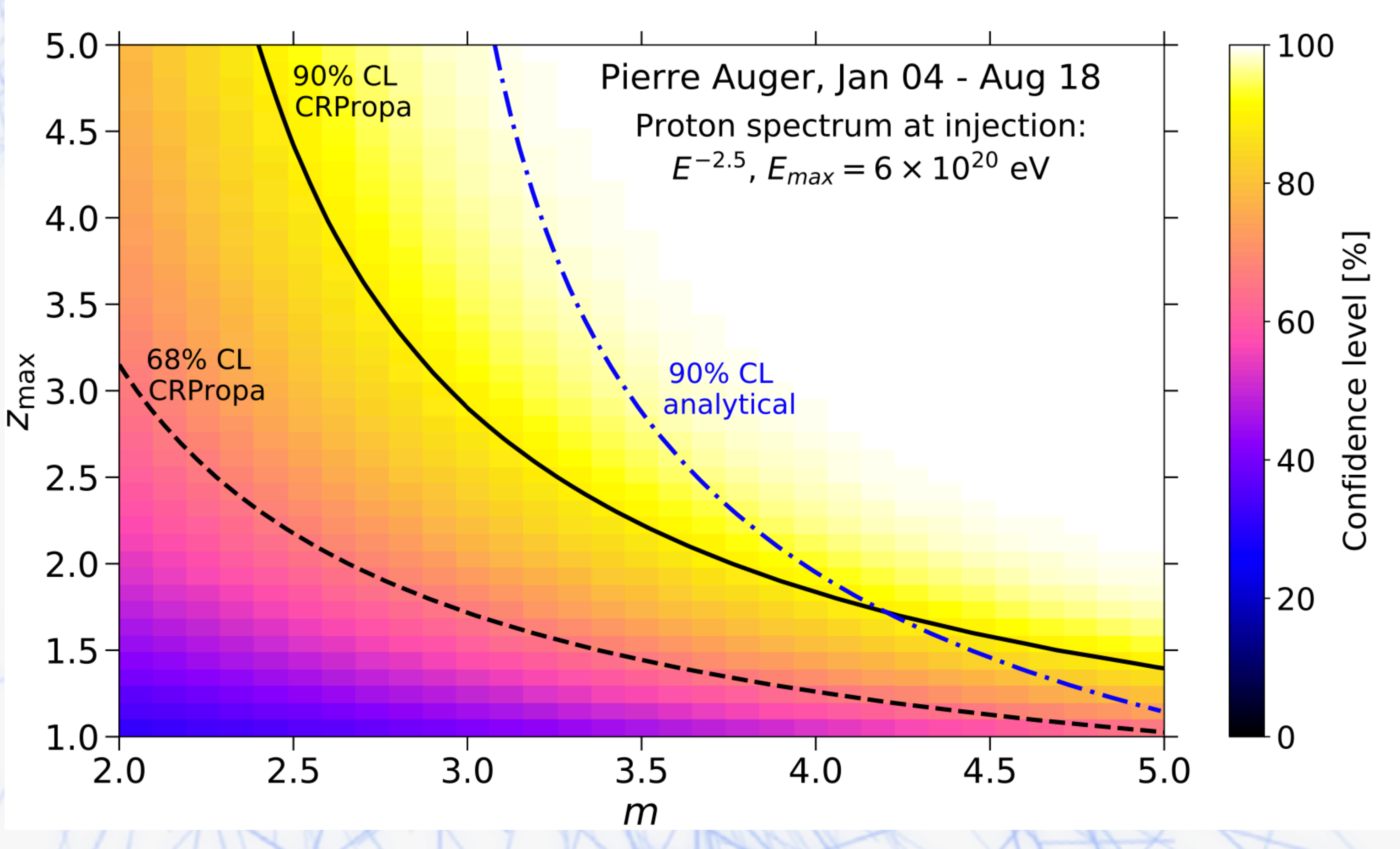
UHECR interactions

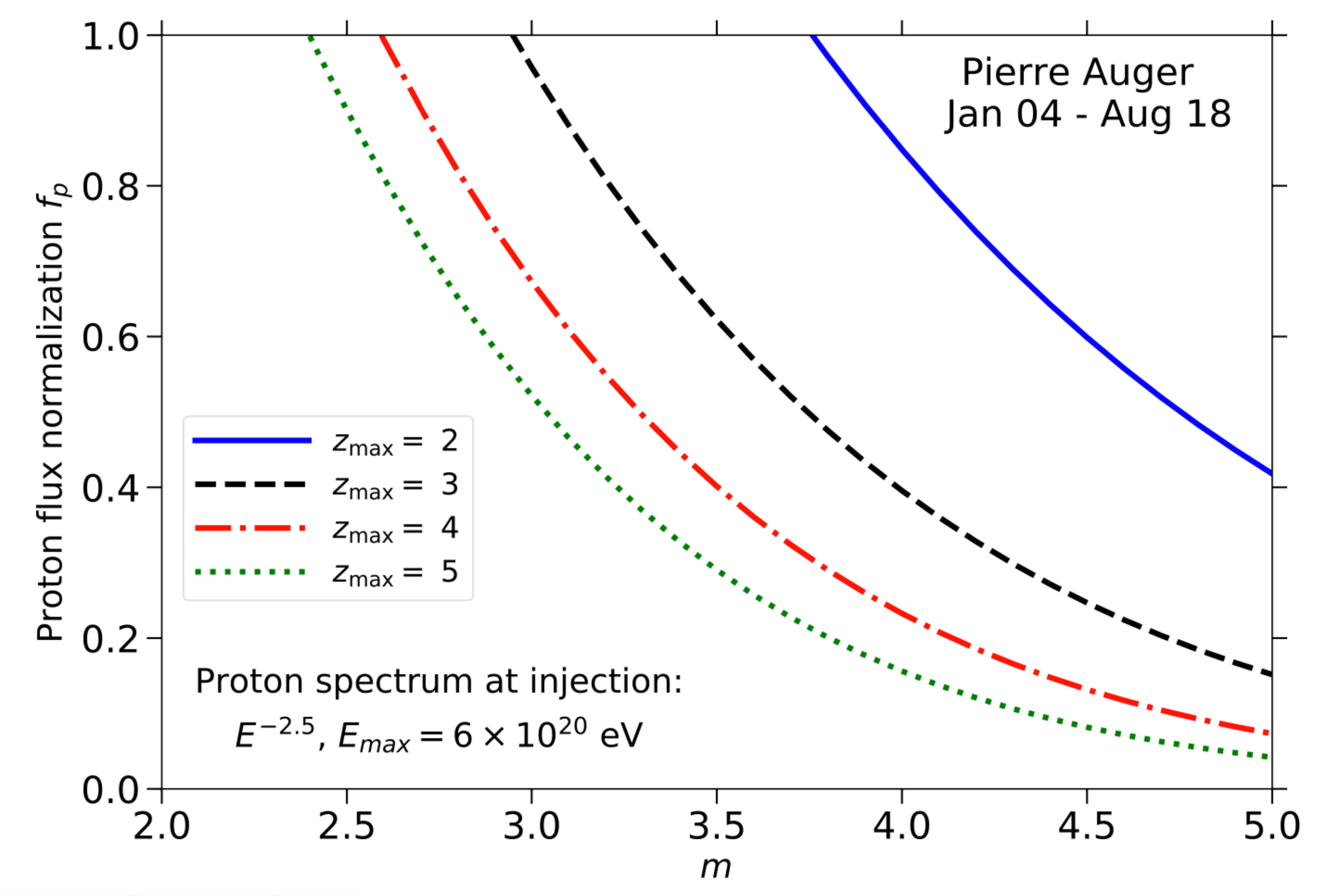




Ehlert, van Vliet, Oikonomou, Winter, JCAP 02 (2024) 022;

UHECR interactions



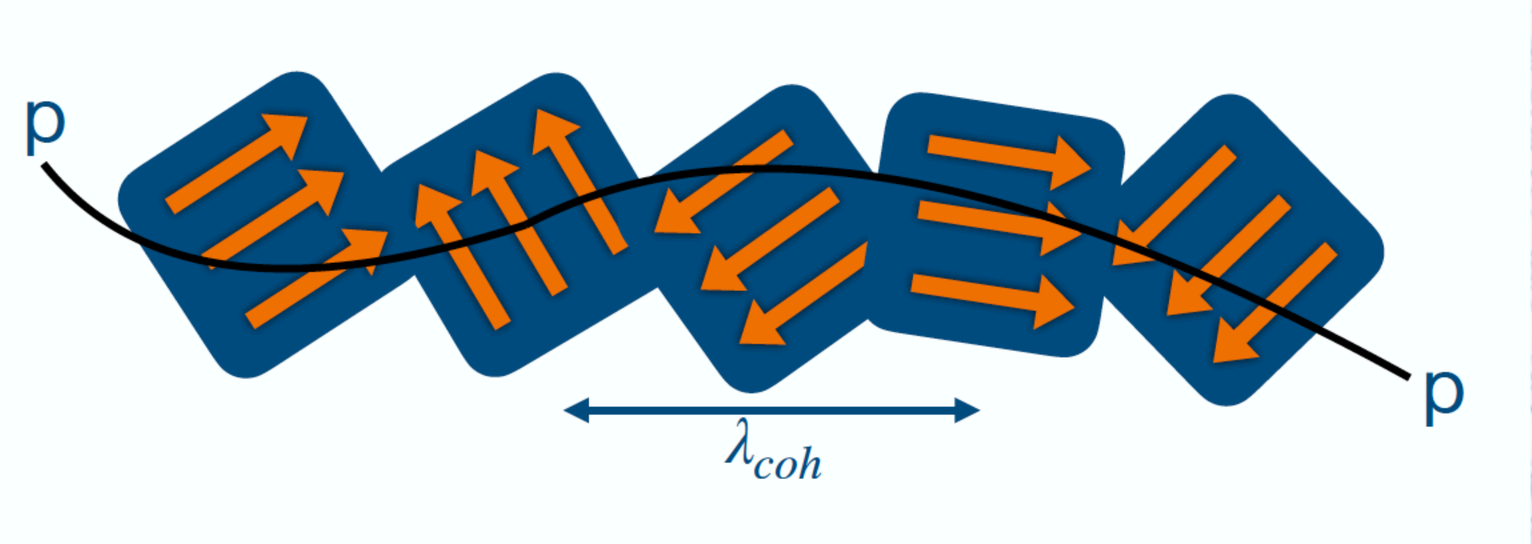


Energy spectrum, mass composition and neutrinos can constrain **source evolution** and **proton fraction**!

A. Condorelli, The Pierre Auger Collaboration, Winter, JCAP 10 (2019) 022

Extra-galactic magnetic field

UHECRs are charged particles and they are deflected by magnetic fields.
The extra-galactic magnetic field is purely known in both strength and structure



The average deflection angle can be obtained by modelling the magnetic field as a series of regions with the same magnetic field strength, but different orientation

Larmor radius

$$r_L(E) = \frac{E}{q\ B} \sim 100 \left(\frac{E/Z}{10^{20}\,eV}\right)\left(\frac{1\,\mu G}{B}\right)\,kpc$$

Deflection angle

$$\alpha_{\lambda_{coh}} \sim \frac{\lambda_{coh}}{r_L}$$

Total deflection angle

$$\langle \alpha^2 \rangle \sim \frac{d}{\lambda_{coh}}\alpha^2_{\lambda_{coh}} = \frac{d\lambda_{coh}}{r_L^2} = d\lambda_{coh}\left(\frac{eB}{E/Z}\right)^2$$

$$\theta \sim 0.8^\circ Z \left(\frac{E}{10^{20}\,eV}\right)^{-1}\left(\frac{d}{10\,Mpc}\right)^{1/2}\left(\frac{\lambda_{coh}}{1\,Mpc}\right)^{1/2}\left(\frac{B}{1\,nG}\right)$$