Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

DSFC
Dipartimento
di Scienze Fisiche
e Chimiche

UNIVERSITÀ
DEGLI STUDI
DELL'AQUILA

# What does the **multimessenger era** disclose to us about UHECR sources?

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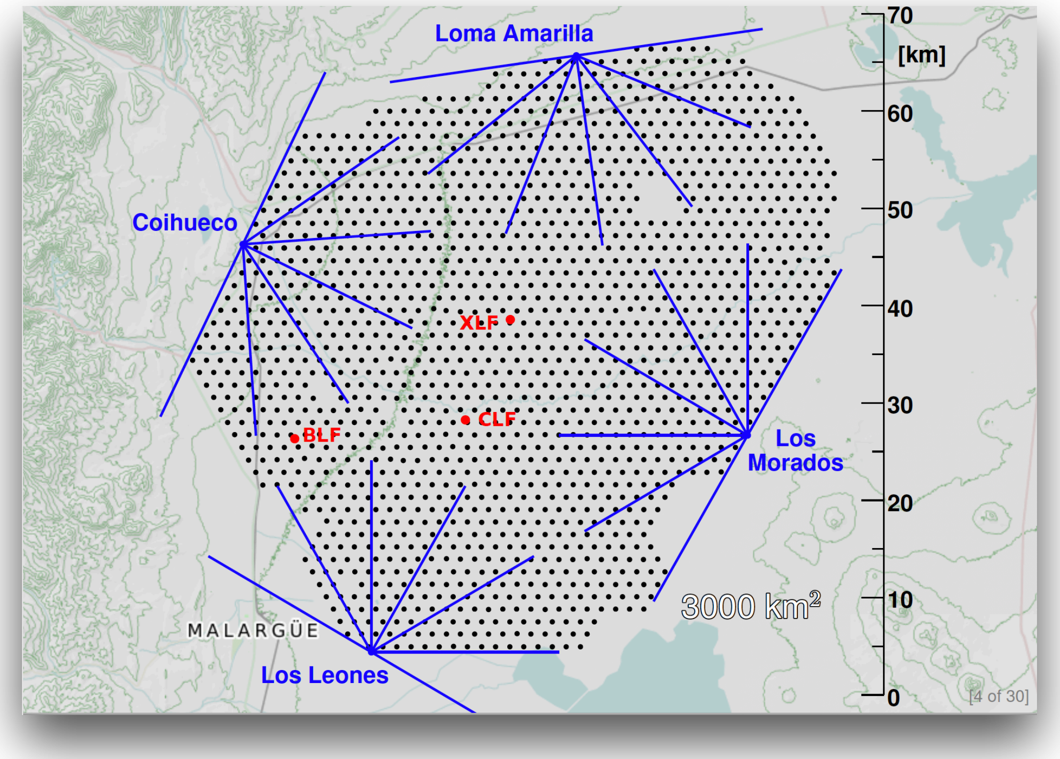
The New Era of Multi-Messenger Astroparticle Physics
February 19-23, 2024, Trieste

# State-of-the-art of the latest UHECR measurements

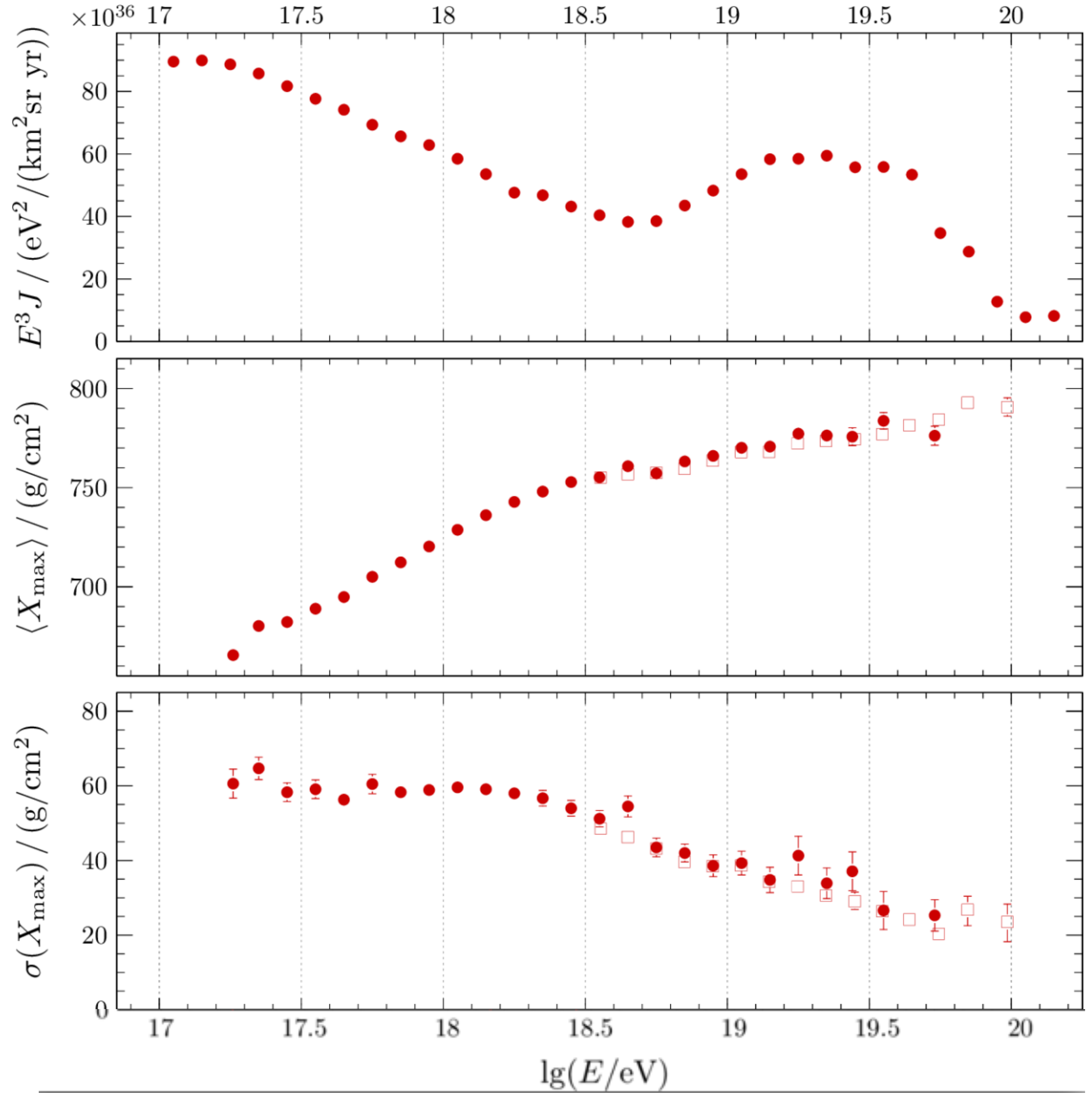


- The picture emerging from data is exciting!

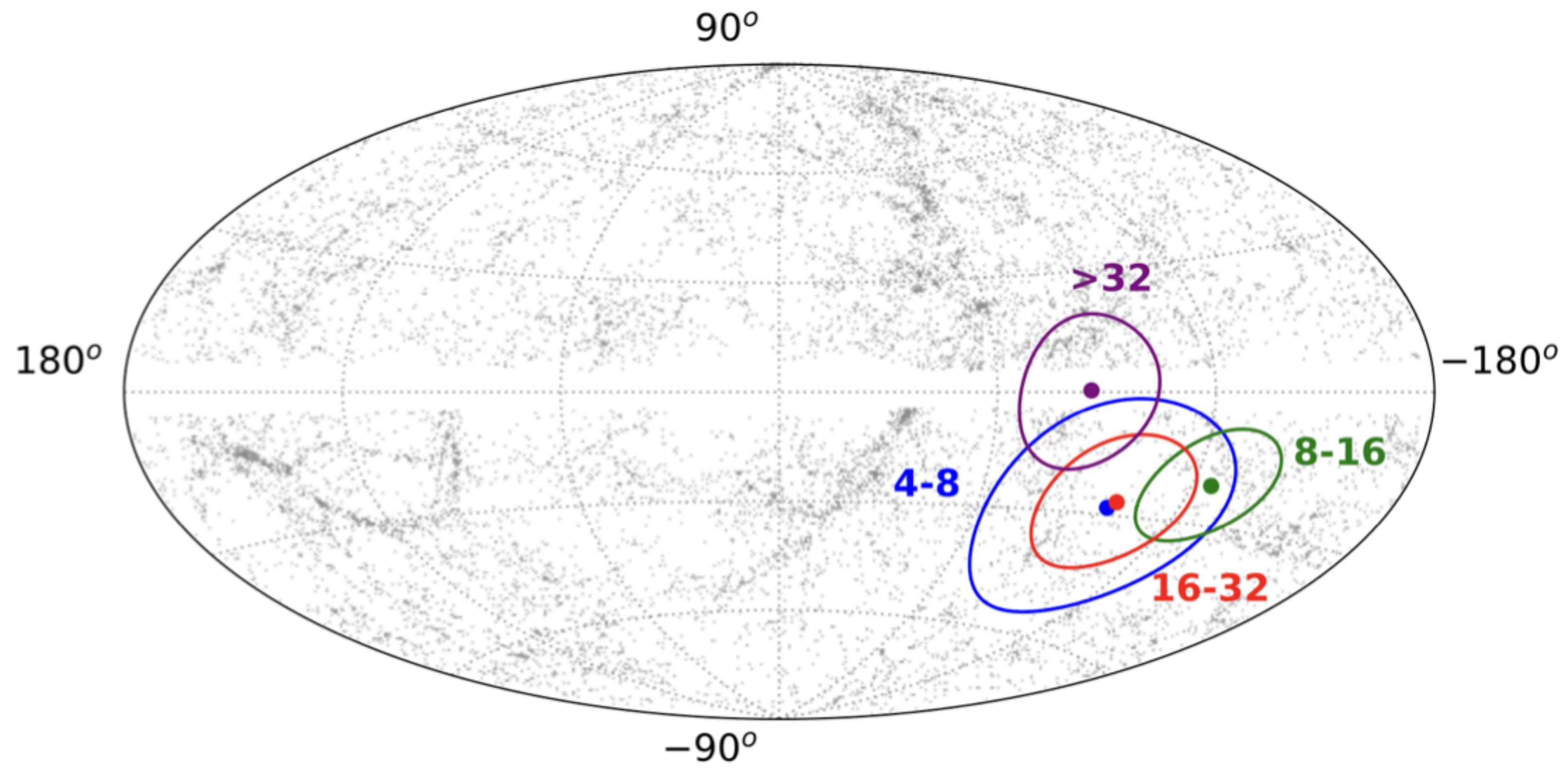
- Features in the energy spectrum
- Changes in mass composition
- Extragalactic origin from anisotropy signal
- Coherent results with non-observation of cosmogenic particles

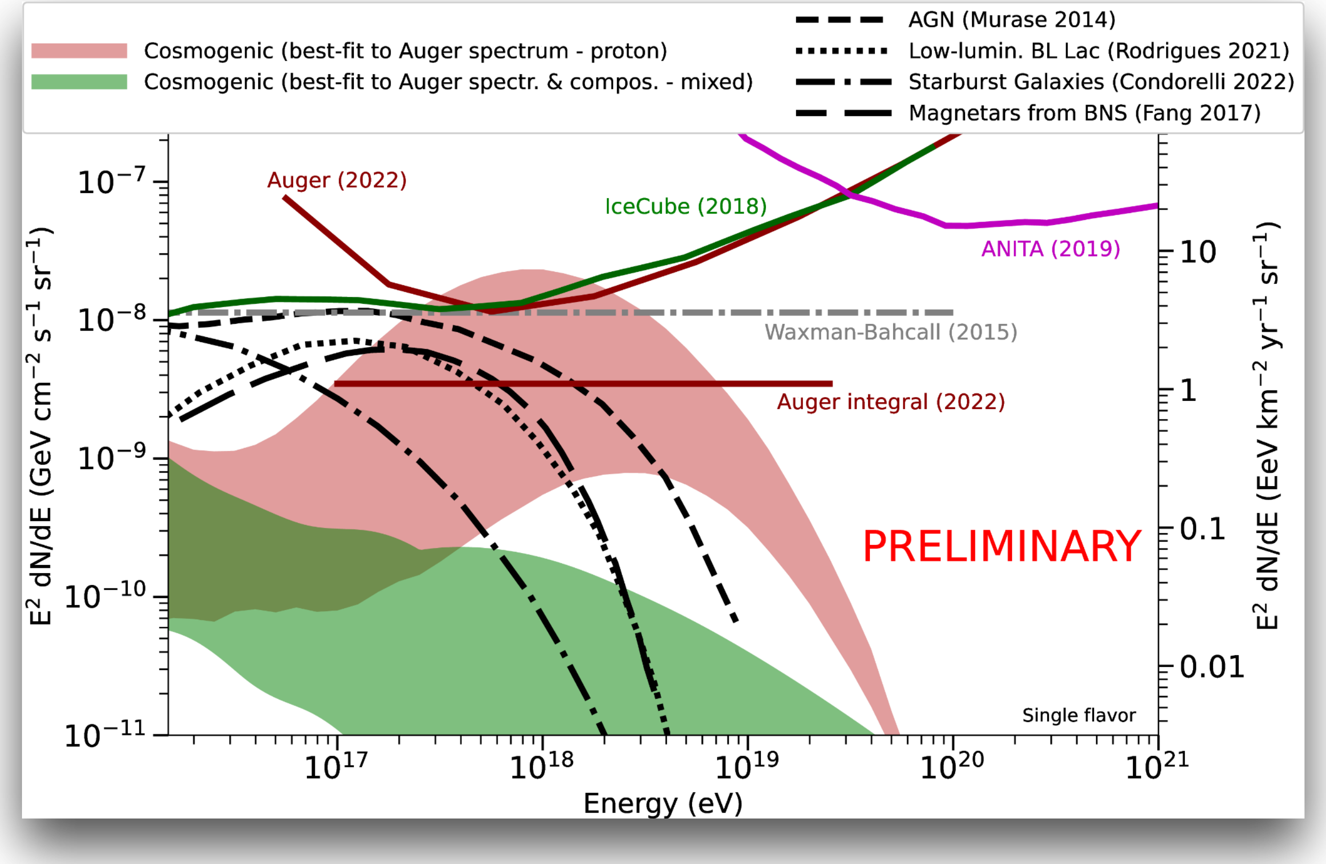
Energy spectrum

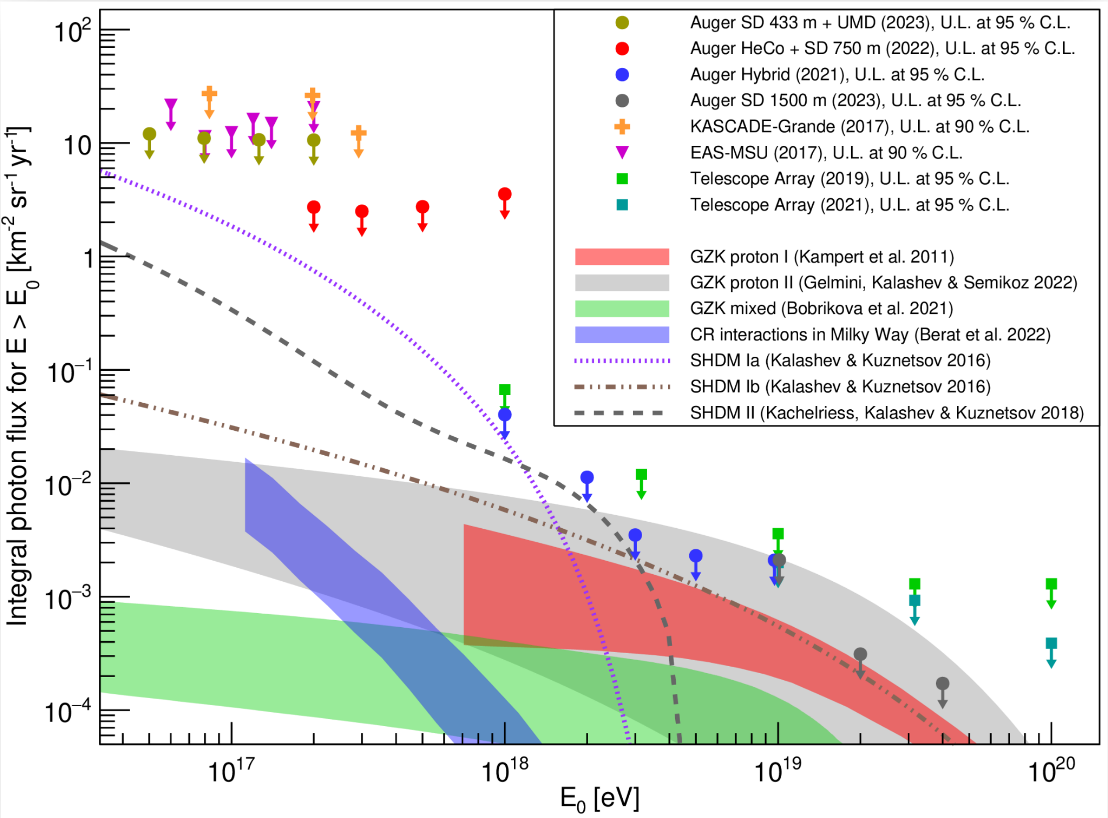
Mass composition



Anisotropy





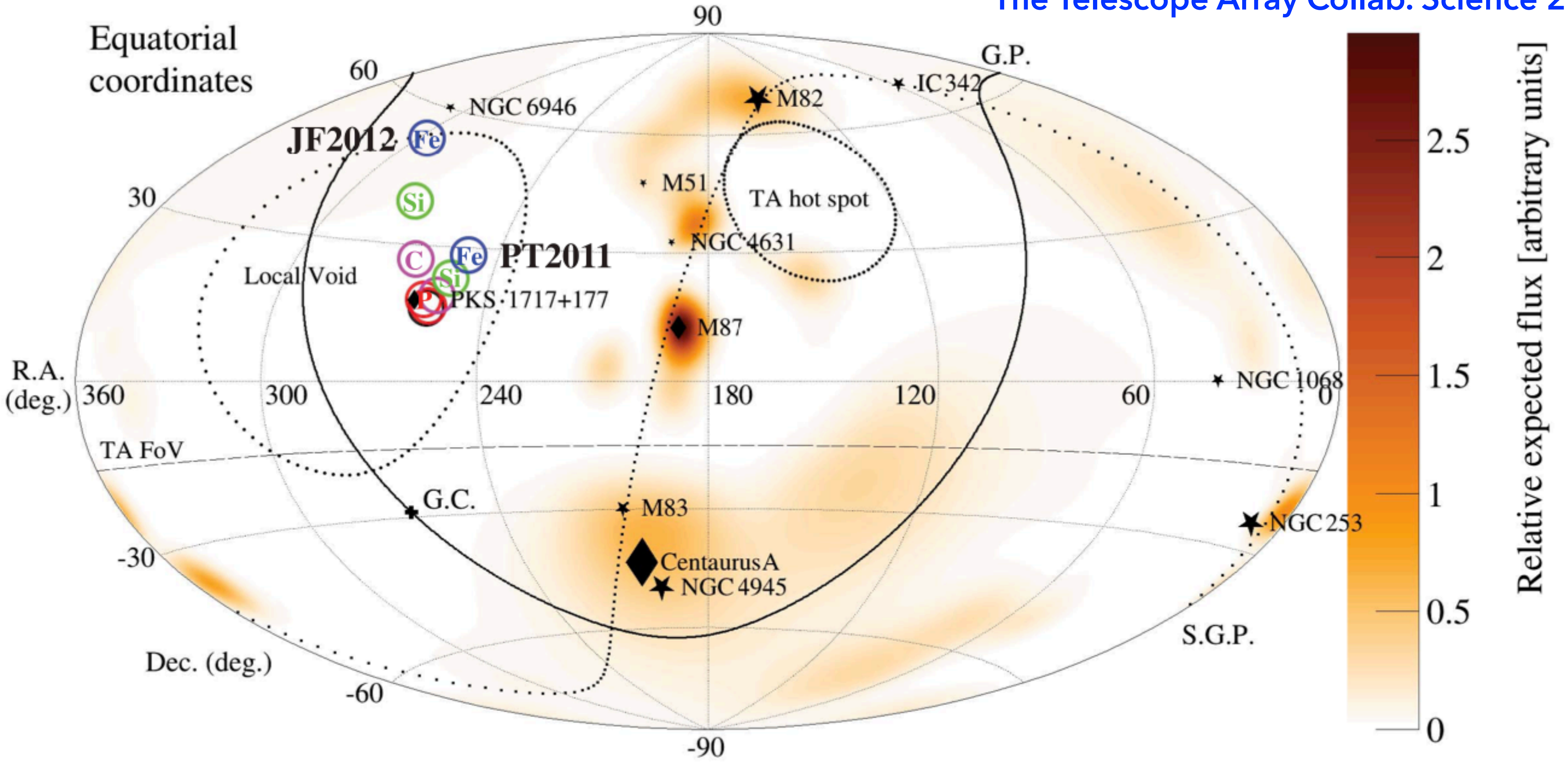


**The Pierre Auger Collab. ICRC23**

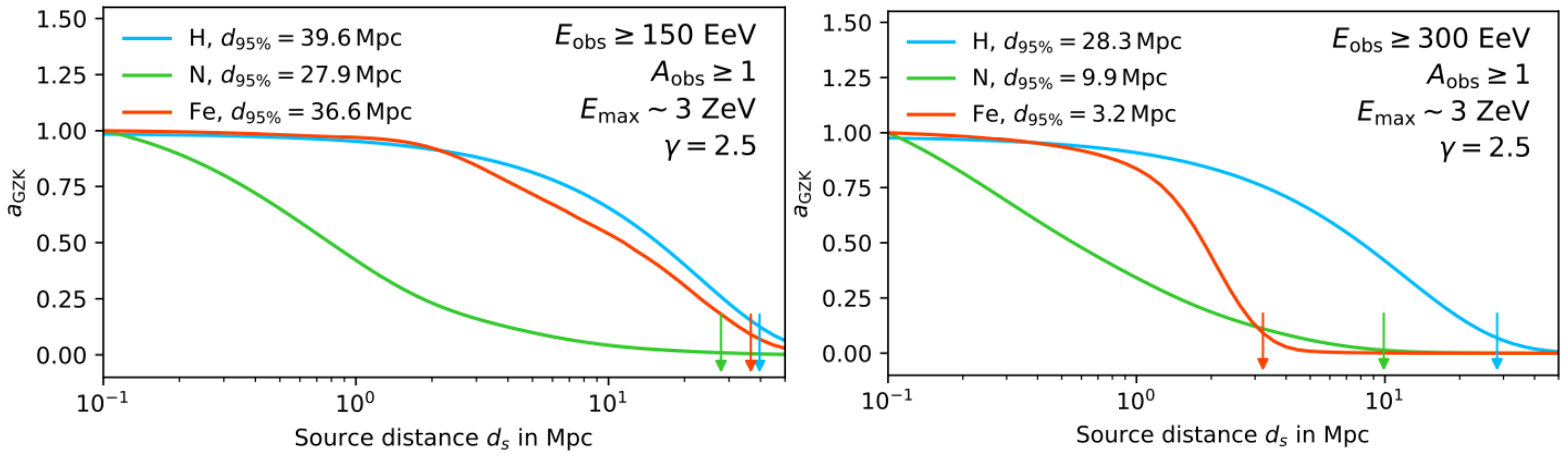
# The extremely energetic cosmic ray observed by **Telescope Array**

- May 27th, 2021, estimated energy: 244 EeV
- Back-tracked directions assuming two models of the Milky Way regular magnetic field, for four primaries
- The closest object to the proton backtracked direction in gamma rays is the active galaxy PKS 1717+177
  - Distance of 600 Mpc -> too large!

The Telescope Array Collab. Science 2023



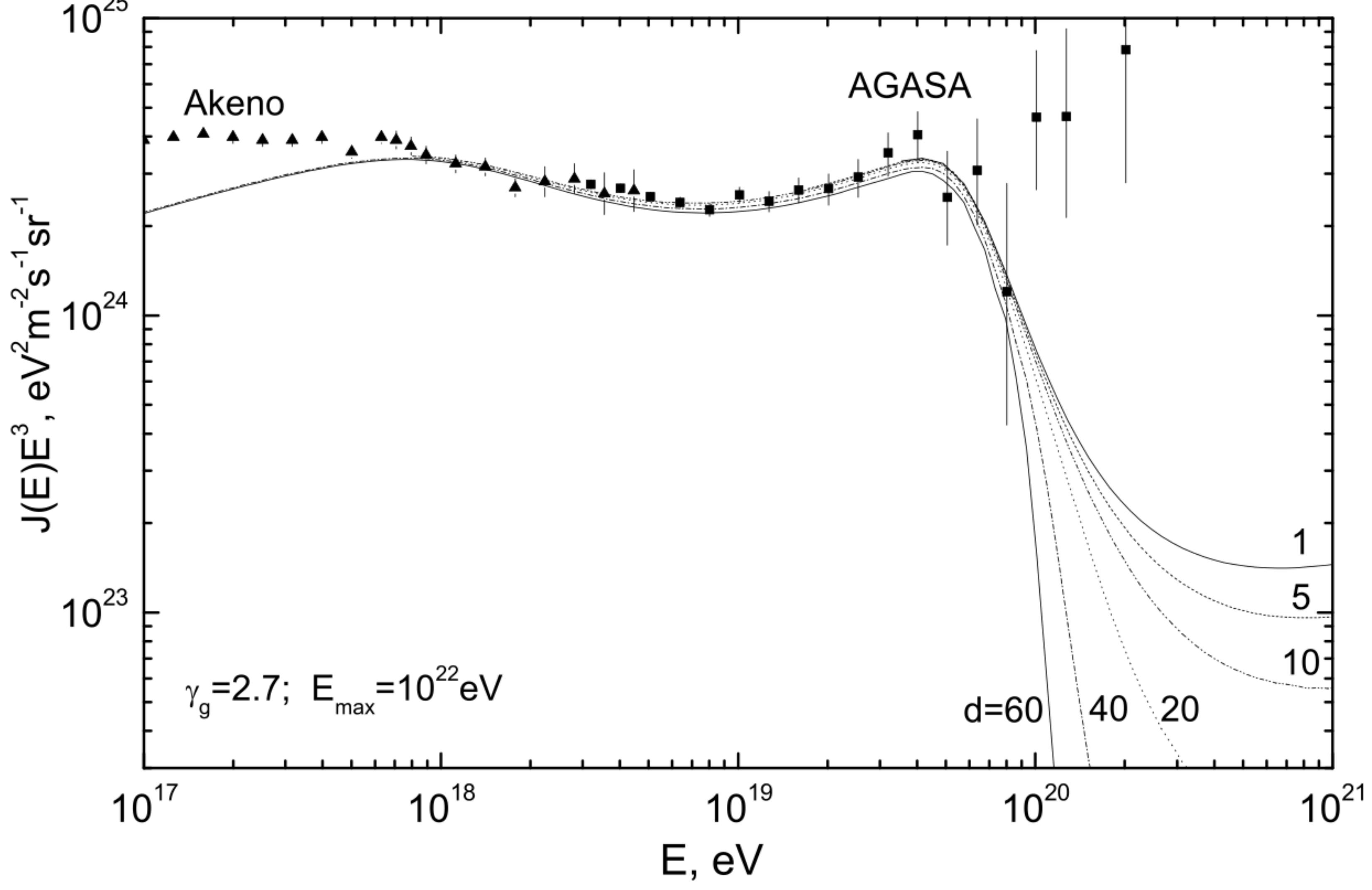
Globus et al, ApJ 2023



- Maximum source distance for this energy: 8-50 Mpc (the range reflects the uncertainty in the energy assignment); see Unger & Farrar ApJL 2023
  - "Detecting an event in this energy range is natural – even expected – given accumulated exposure of TA, based on extrapolating the spectrum already reported by TA"
  - Radio galaxies satisfying the luminosity criteria are not present in the localisation volume; no starburst galaxies within the source direction
  - Transient event in an otherwise undistinguished galaxy?

# My main take-home messages in this talk

- Nowadays **we can describe UHECR data (energy spectrum and mass composition) in terms of a basic and well accepted astrophysical scenario**; this basic scenario is less basic than the **dip model**
    - Understanding the information coming from the interpretation of the mass composition observables (and not only the energy spectrum) is crucial
    - In addition, experimental findings in the last 20 years, as well as the modelling capacity, push the basic model towards **refinements**



Berezinsky et al. PRD2006

- The UHECR astrophysical picture is usually derived from the study of **diffuse fluxes**
    - A **multimessenger approach** can be pursued
        - Example: cosmogenic neutrinos might uncover some characteristics of UHECR sources

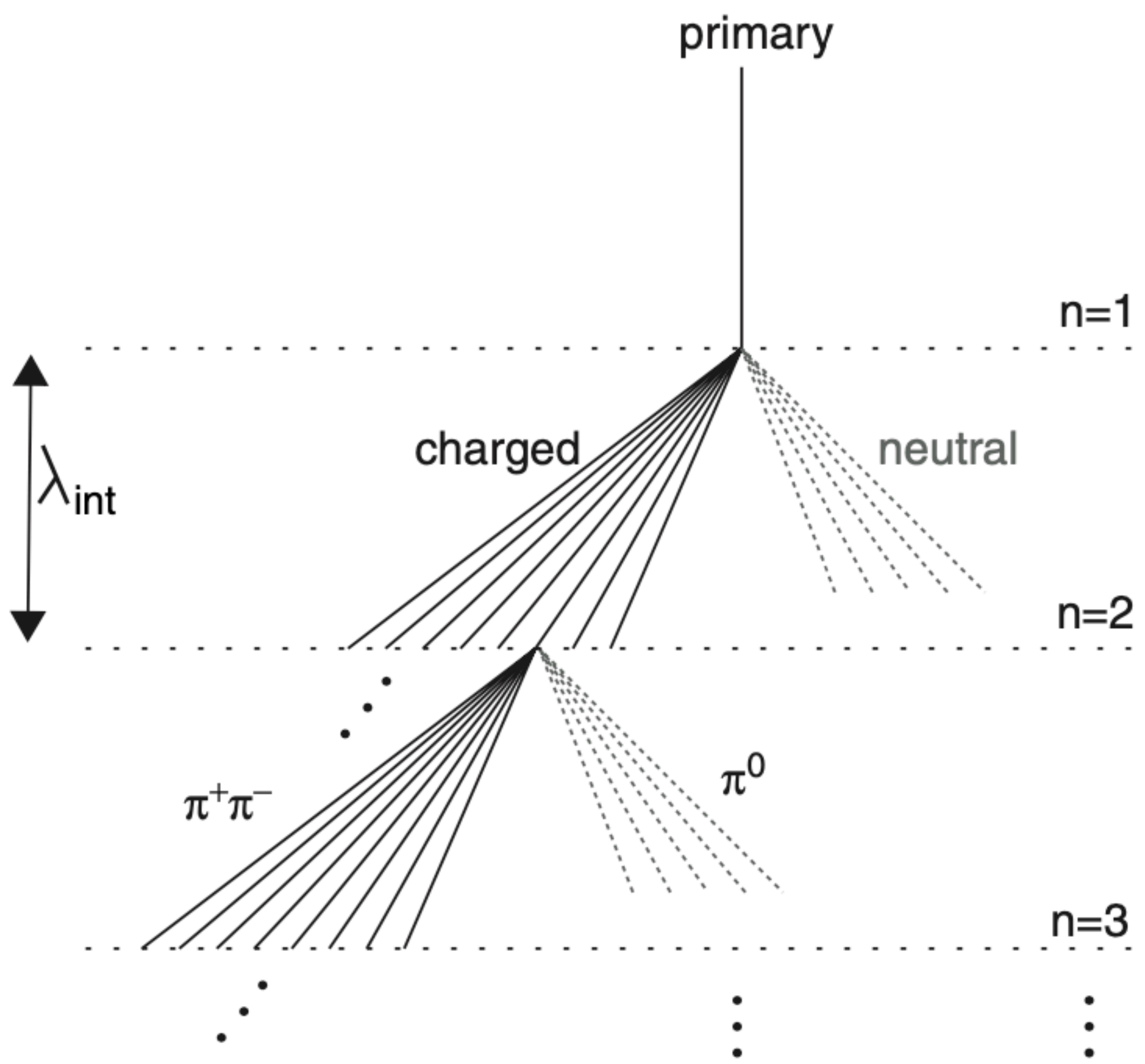
- Astrophysical neutrinos can reveal acceleration sites for cosmic rays
    - No indications for UHE up to now
    - Experimental findings and modelling show new insights

}

Focus on neutrinos

# BELIEVES FROM THE PAST AND CURRENT EVIDENCES

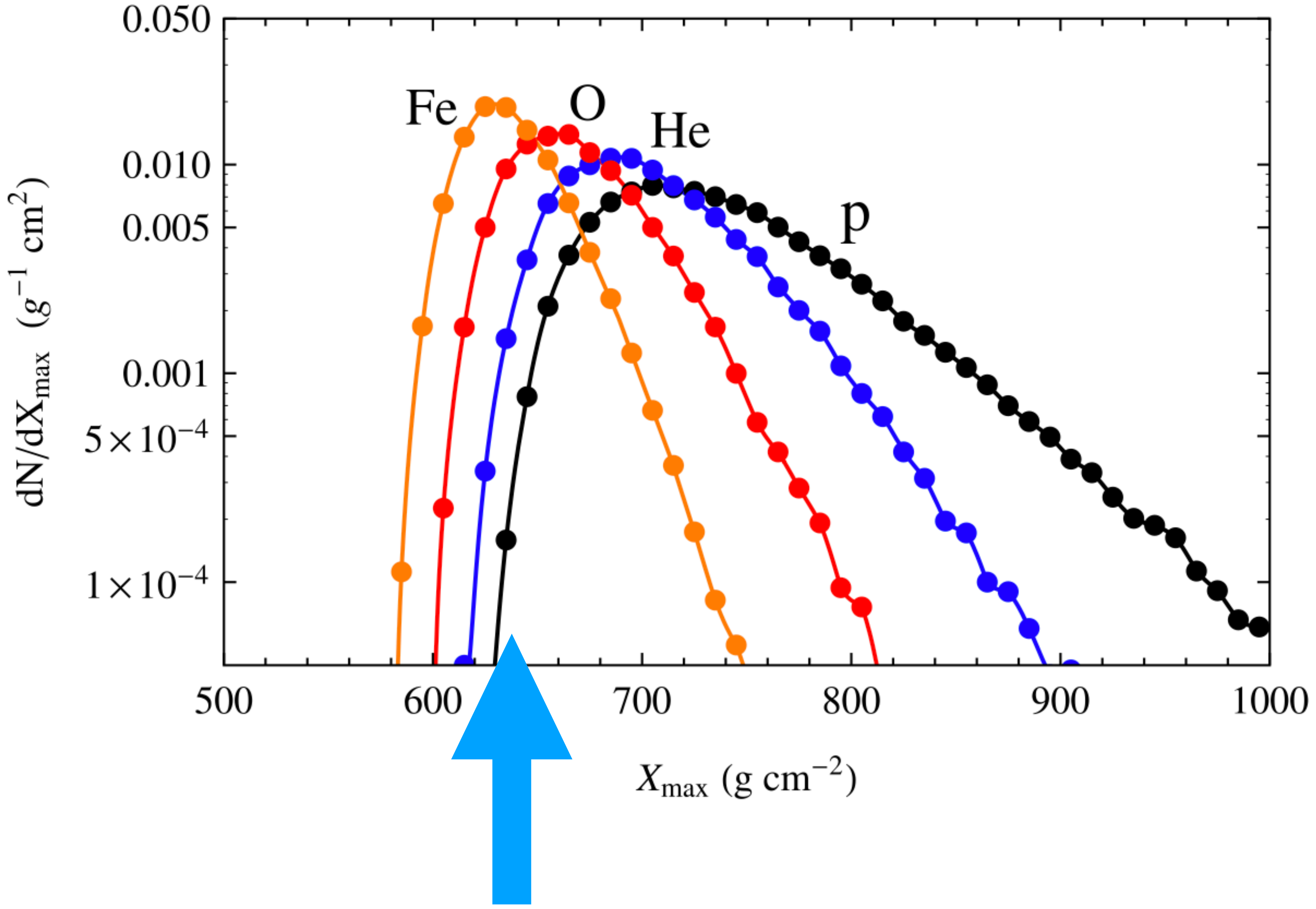
## ONE EXAMPLE: THE **UHECR MASS COMPOSITION**



$$X_{max} \propto \ln(E_0/E_c)$$

$${}^{A}X, E_0 \leftrightarrow A \times n, E_0/A$$

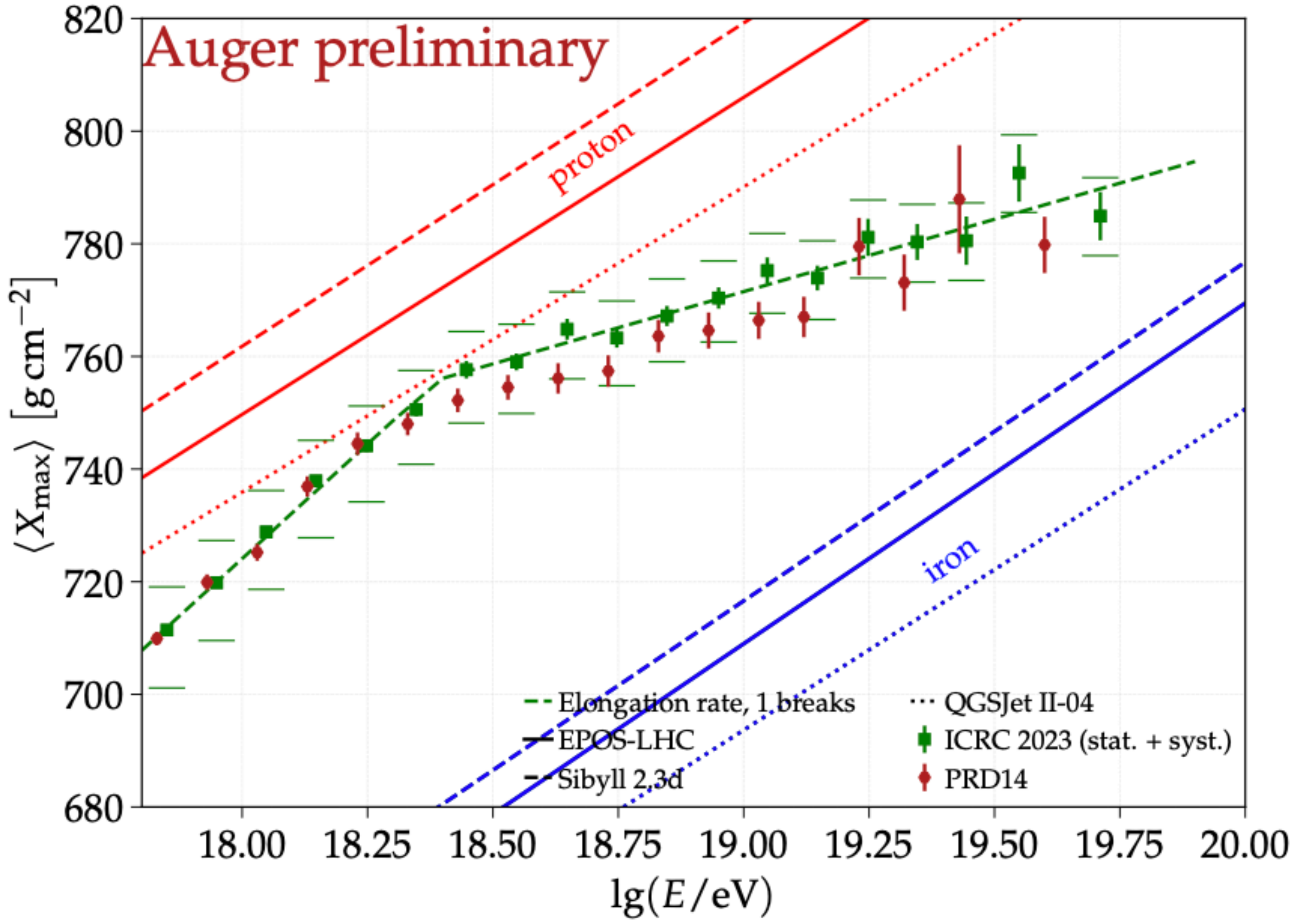
$$X^A_{max} \propto X_{max}(E_0/A)$$



Evidences:

- First momentum: elongation rate is not constant

The Pierre Auger Collab. ICRC23



$$D = \frac{d\langle X_{max}\rangle}{d\ln E}$$

# BELIEVES FROM THE PAST AND CURRENT EVIDENCES

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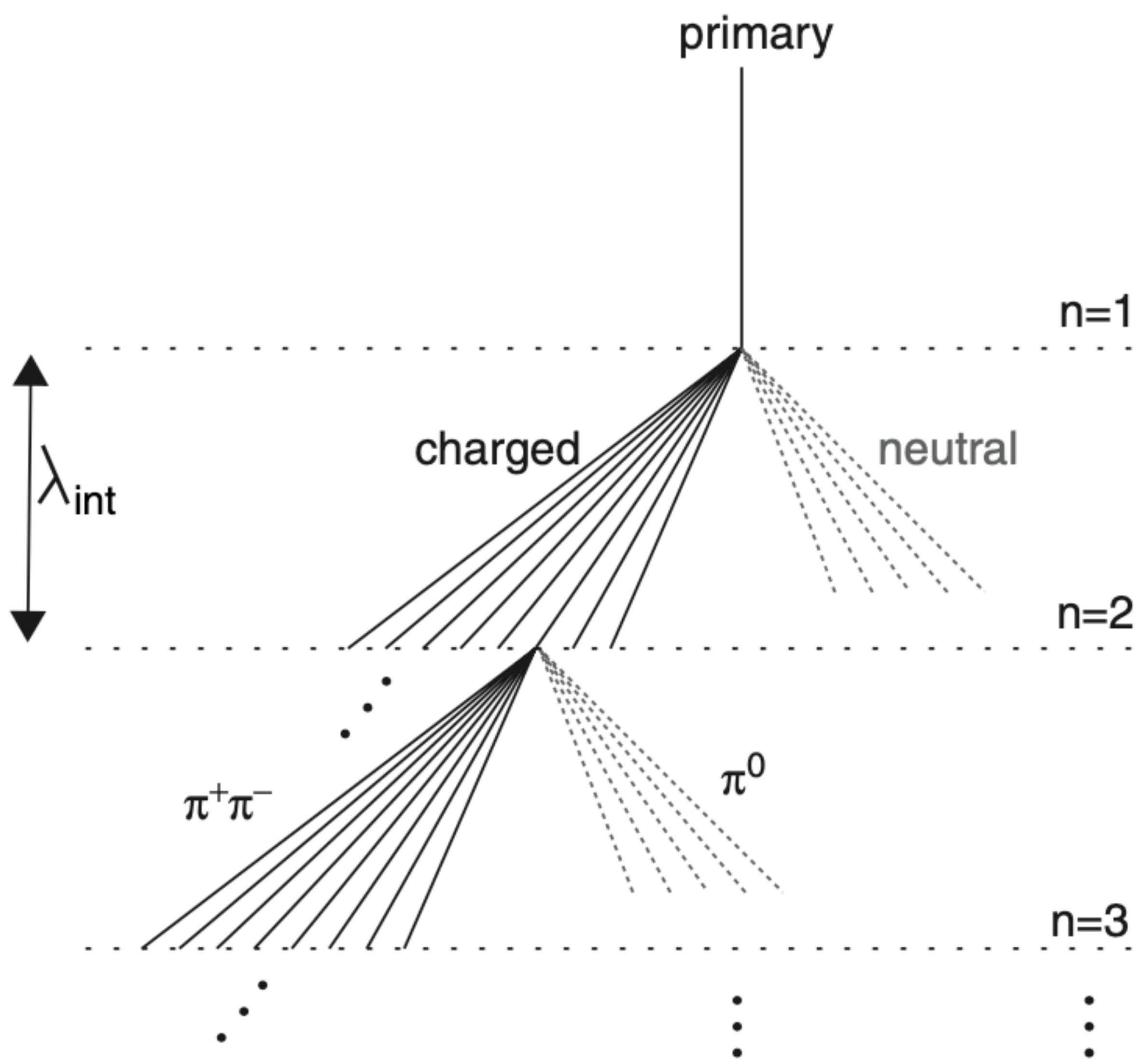

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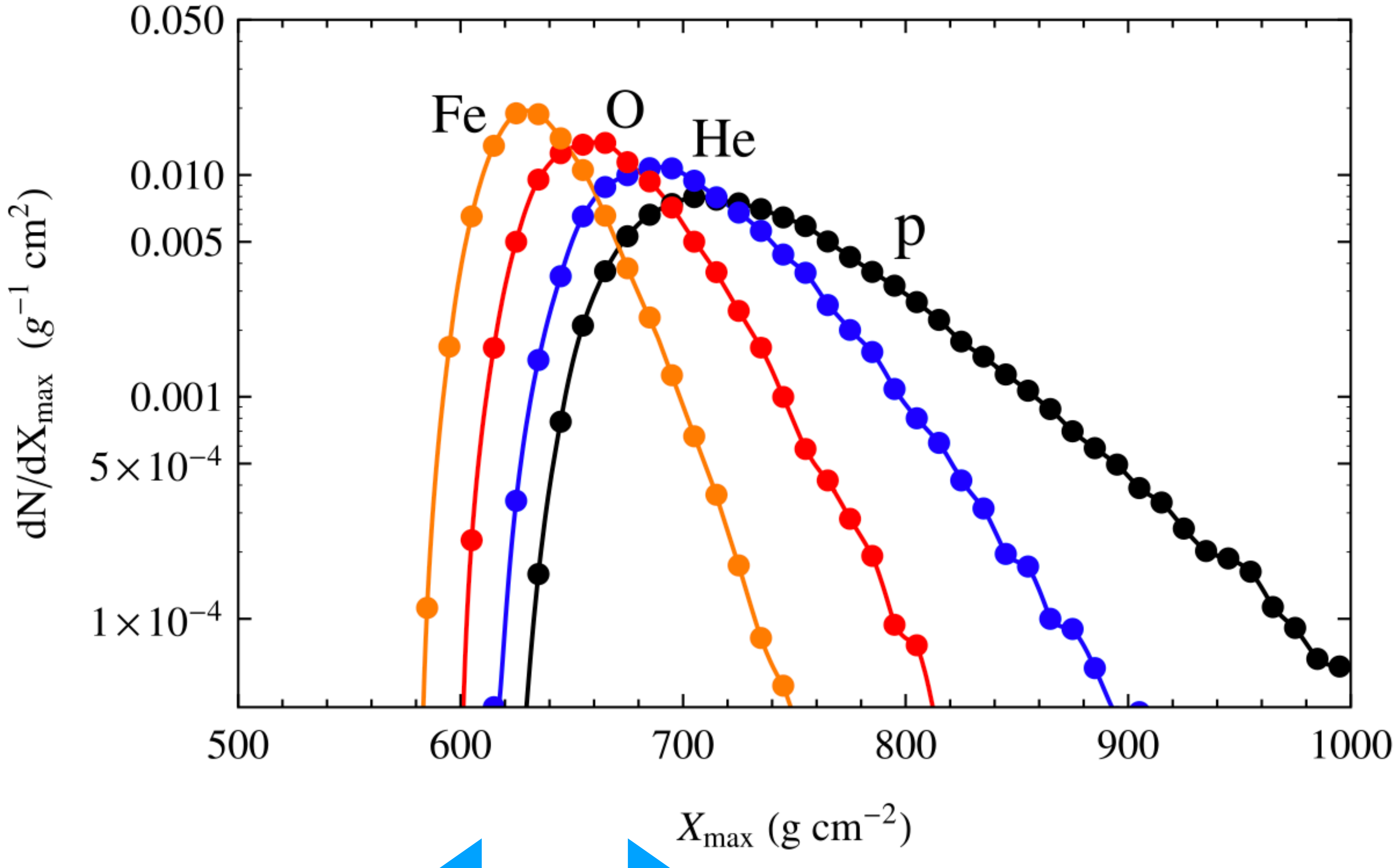

Evidences:

- First momentum: elongation rate is not constant
- Second momentum: fluctuations decrease

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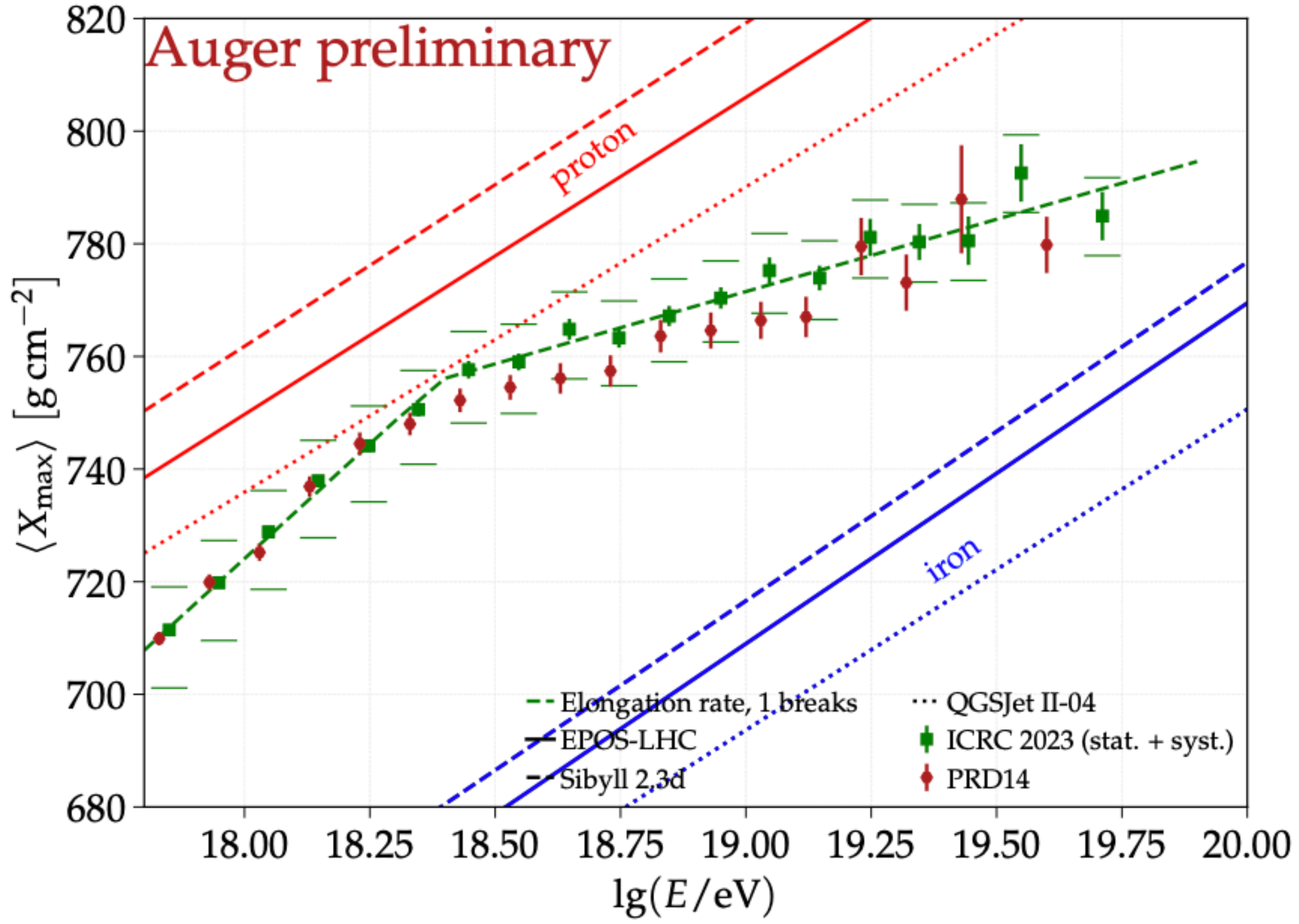
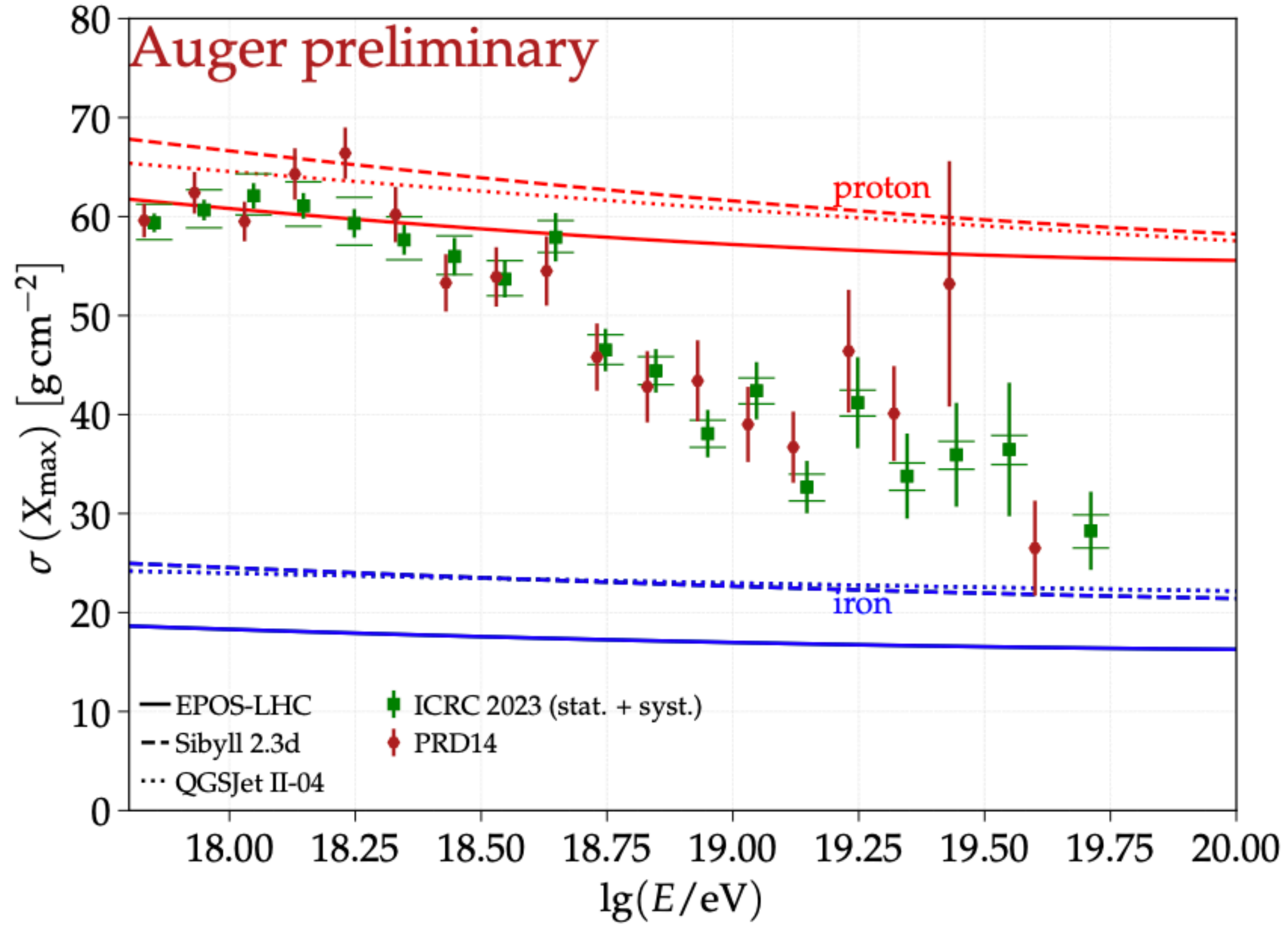




- See A. Watson EPJ Web Conf. 2023 for a historical overview about composition measurements

# LEARNING FROM THE MASS COMPOSITION

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

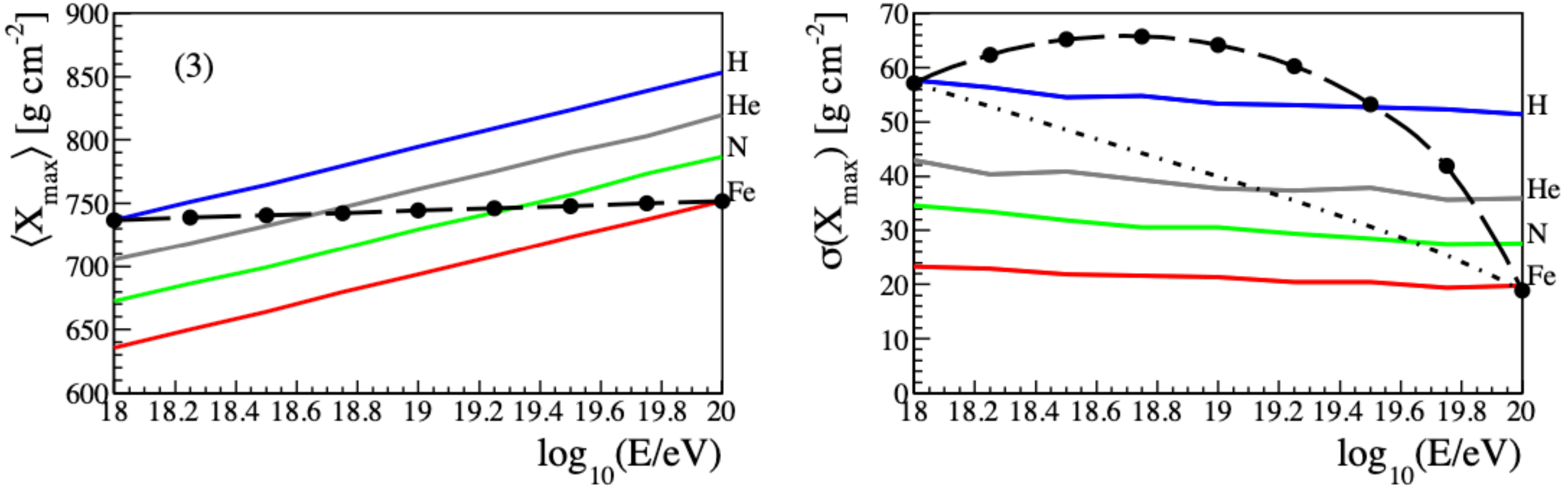
$$\boxed{\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f^2 \, \sigma^2(\ln A)}$$

Focusing on the second moment: 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

- 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:

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

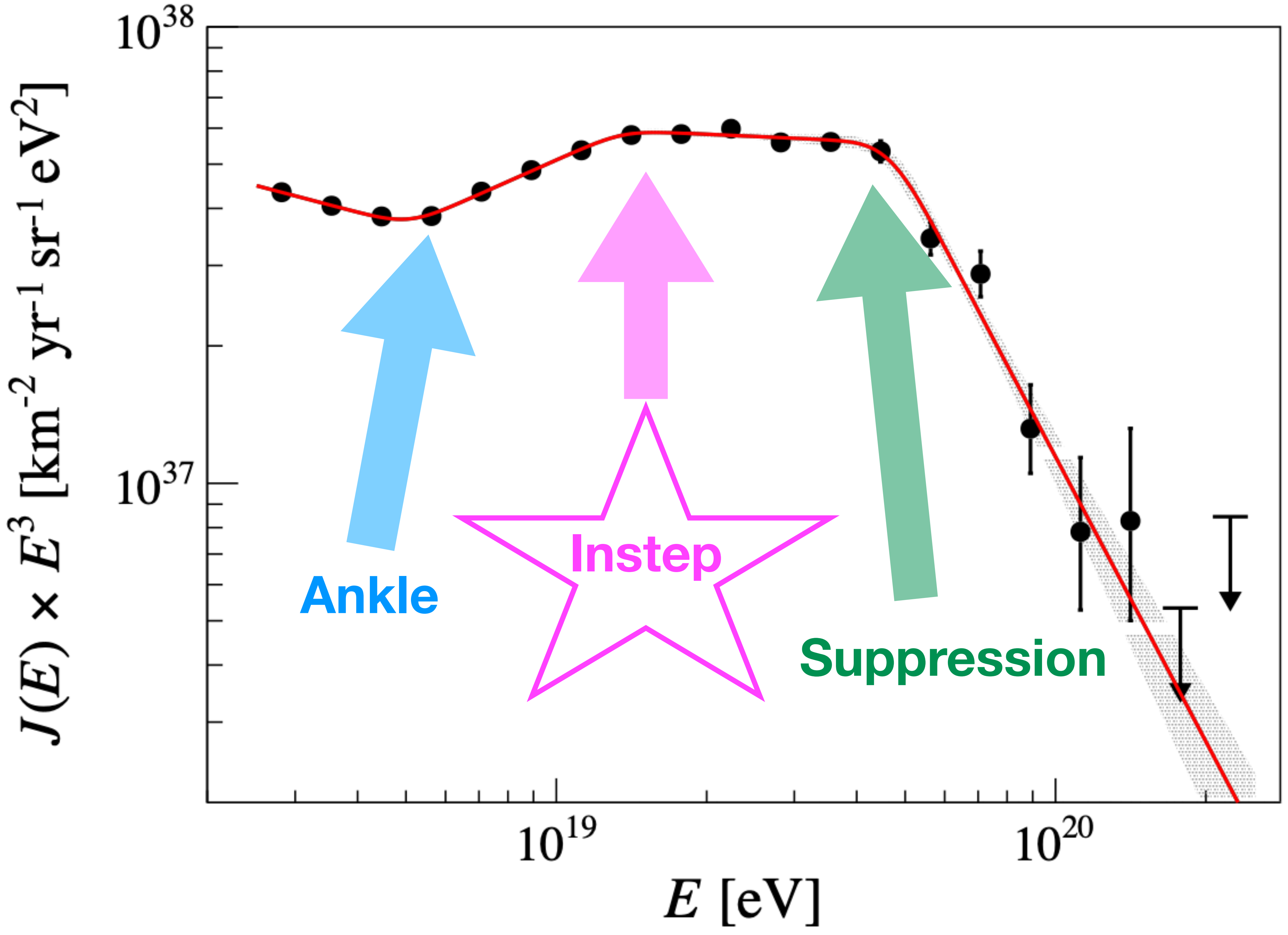
$$f\sigma_1^2 + (1-f)\sigma_2^2 + f(1-f)(\Delta(\langle X_{max} \rangle))^2$$

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

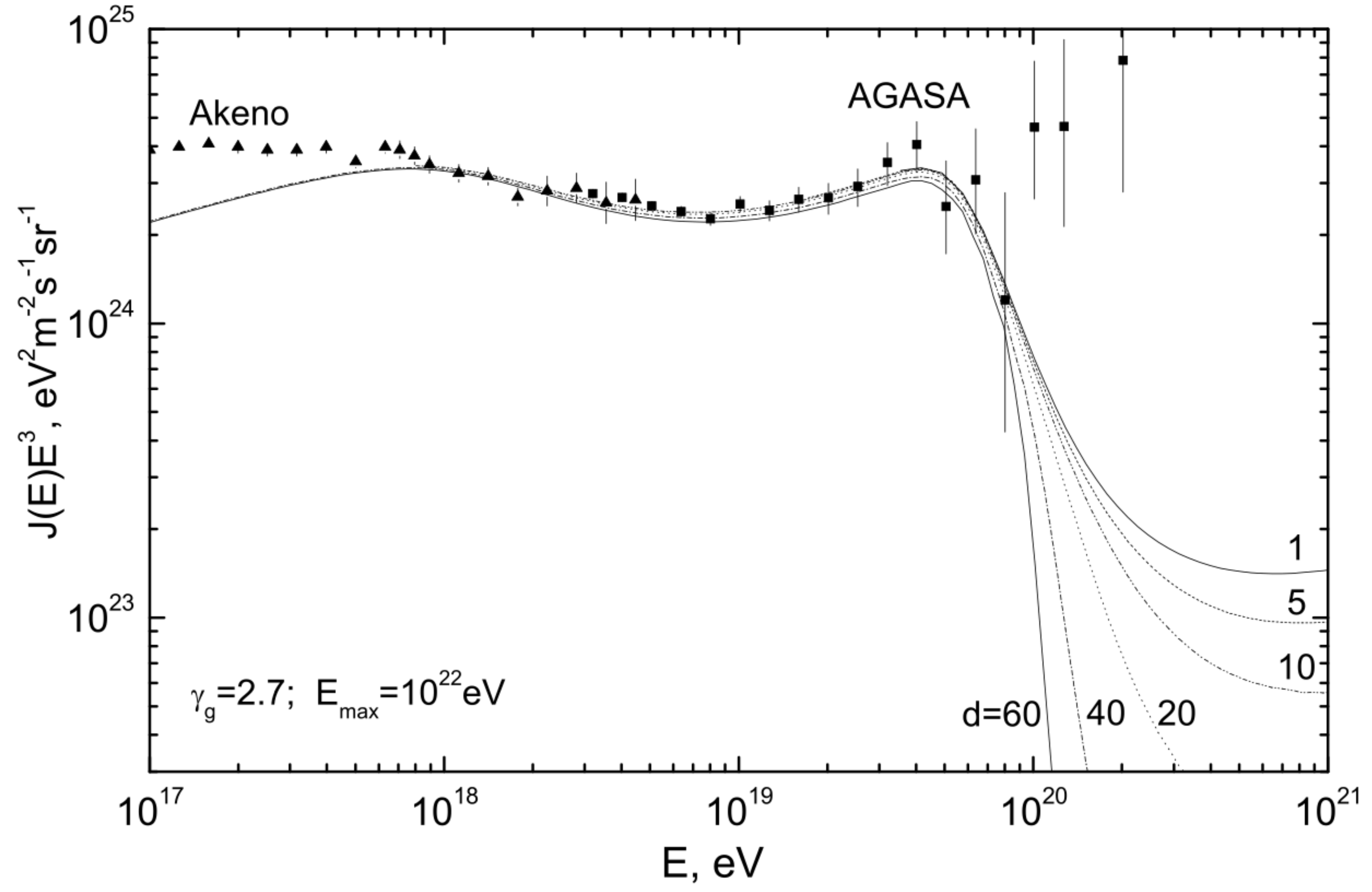
# ASTROPHYSICAL INTERPRETATION(S)

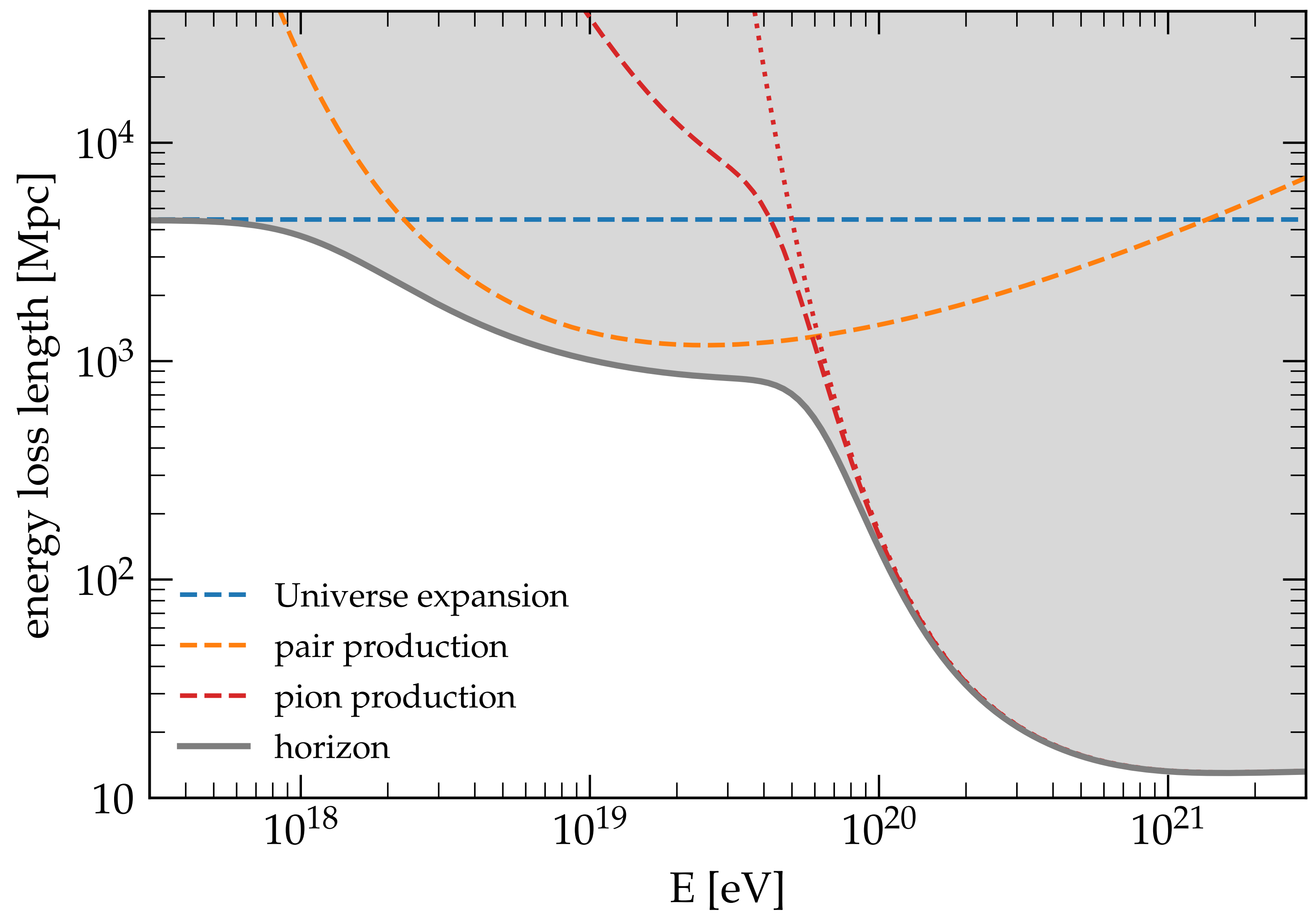
- Dip model: UHECR spectrum features can be explained with energy losses of protons travelling through the extragalactic space
  - Suppression of the flux due to photo-pion production (**GZK effect**)

**The Pierre Auger Collab. PRD2020**



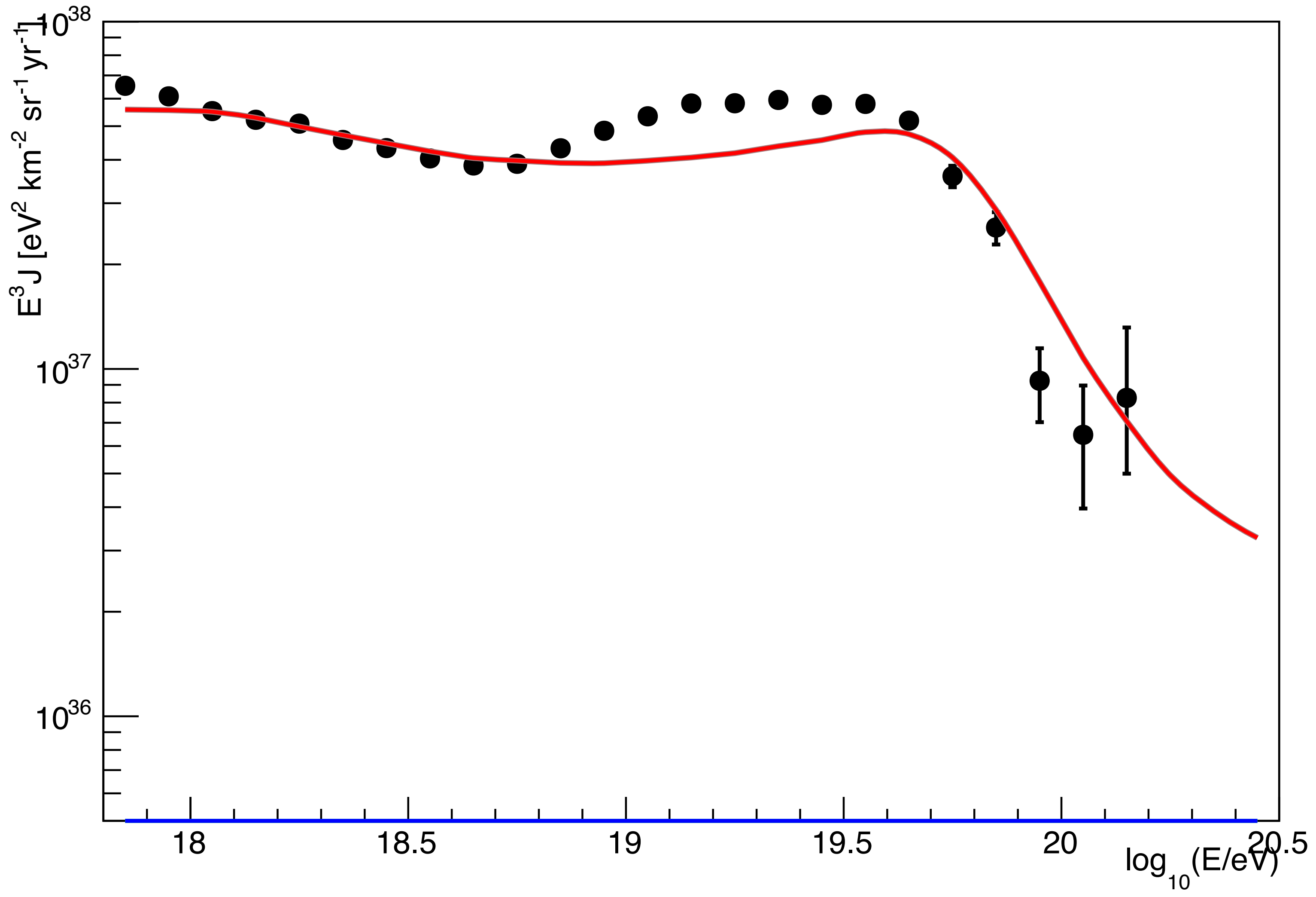
**Berezinsky et al. PRD2006**



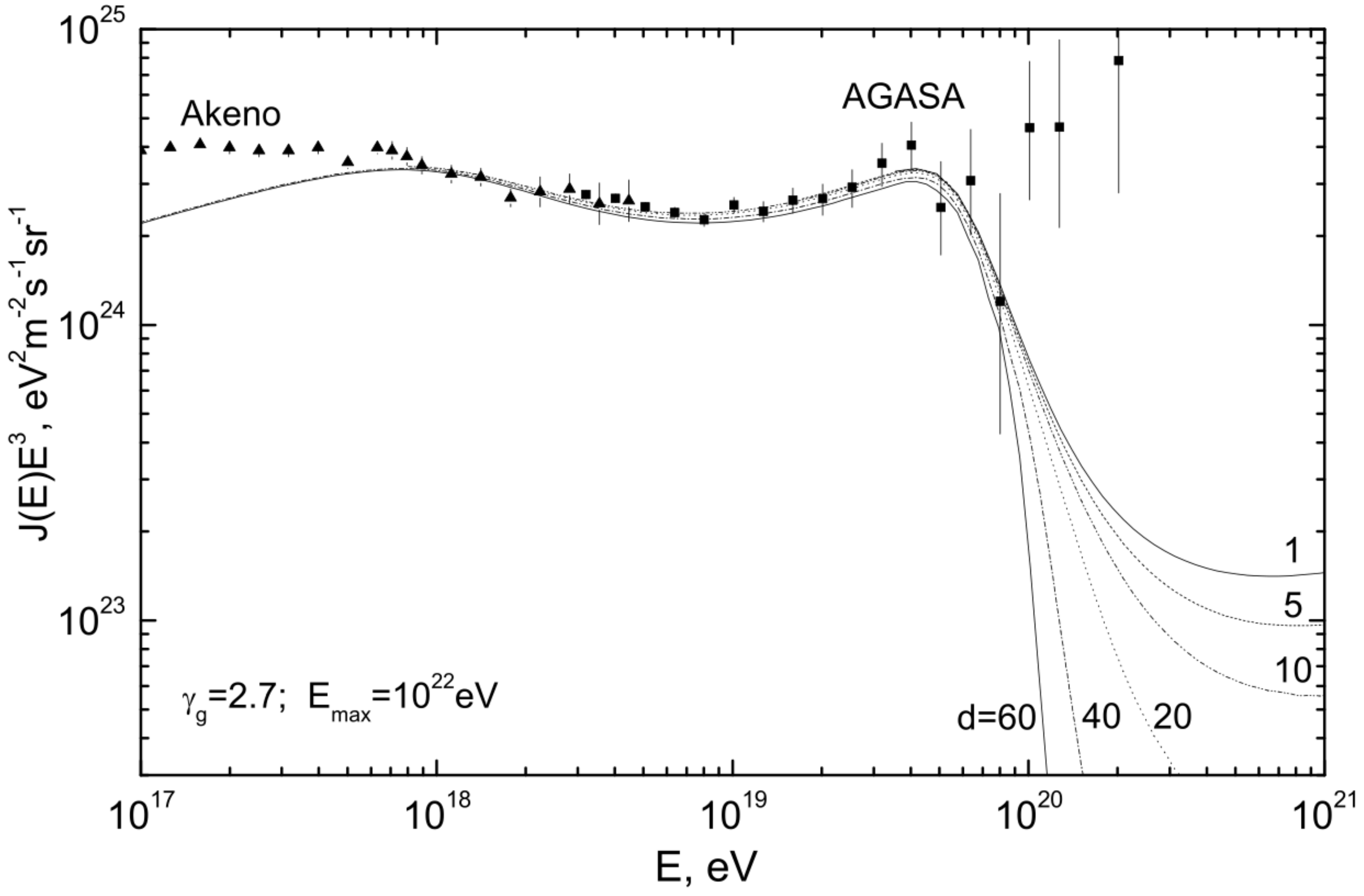


# ASTROPHYSICAL INTERPRETATION(S)

- Pure-proton scenario
- Same spectral parameters as in Berezinsky et al. PRD 2006
- Latest UHECR spectrum data
  - No good fit with pure protons at source, due to:
    - Sharpness of ankle feature, and presence of new feature (instep)
    - Heavier nuclear species needed

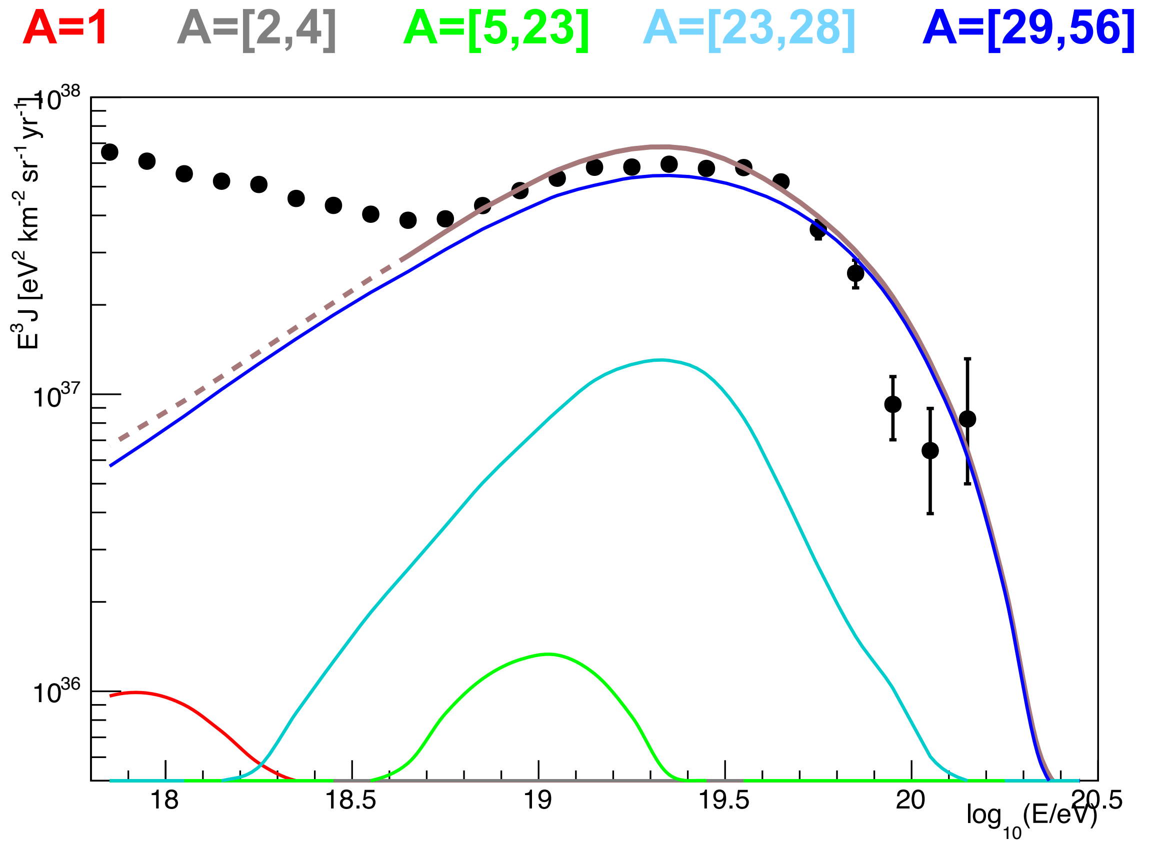


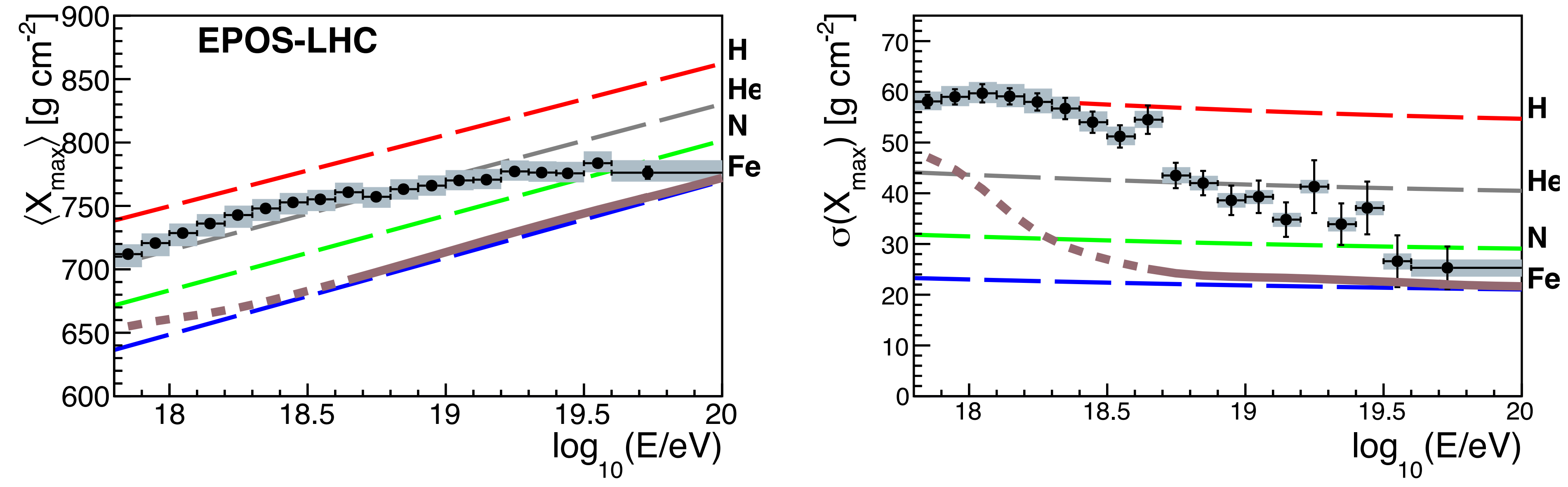
**Berezinsky et al. PRD2006**



$$Q_A(E) \propto f_A\, E^{-\gamma} f_{\mathrm{cut}}(E, Z_A R_{\mathrm{cut}})$$

- Exercise:
  - consider Iron at sources
  - Reproduce energy spectrum & composition, above the ankle

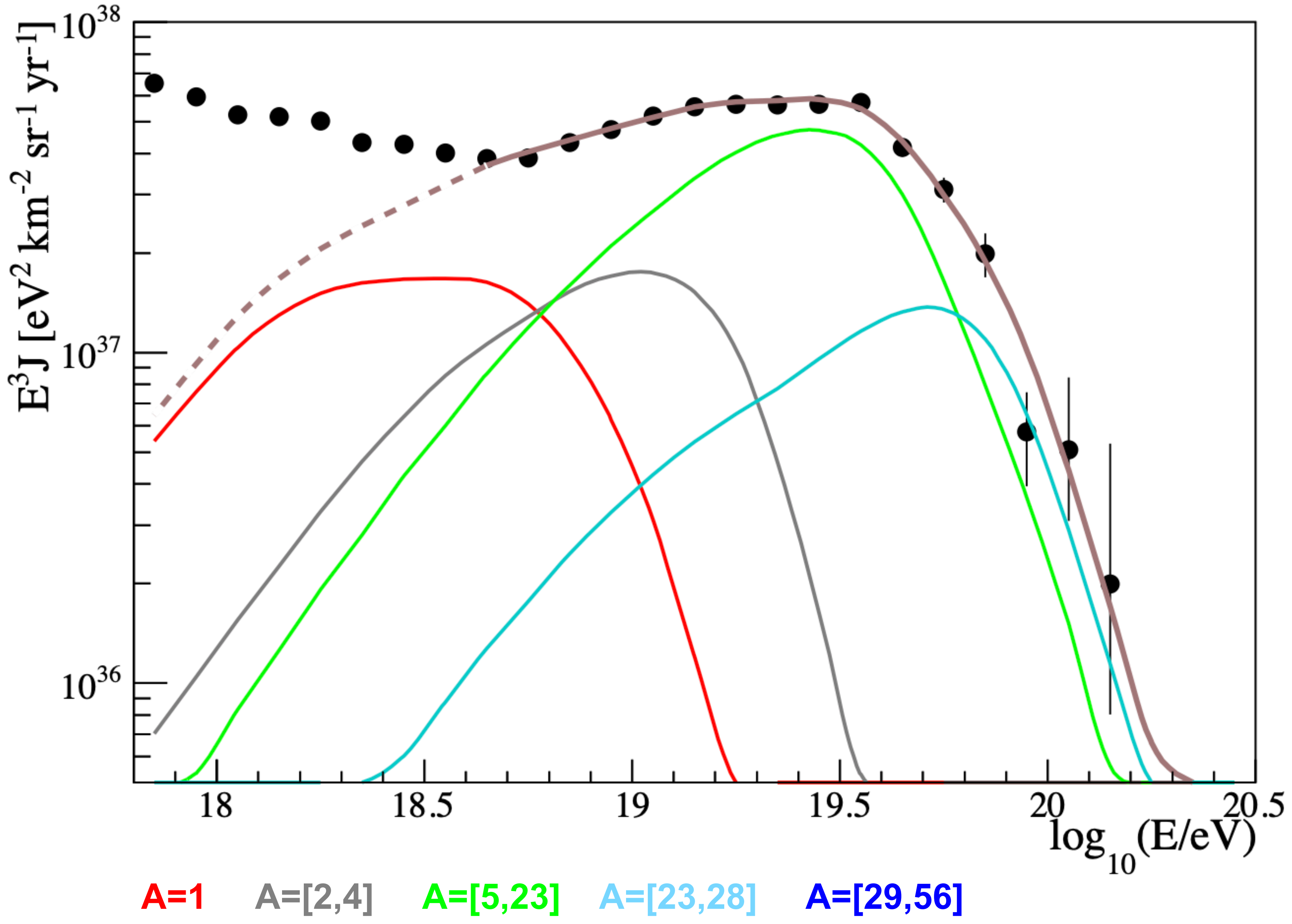




- Different nuclear species must be considered at the sources !

# ASTROPHYSICAL INTERPRETATION(S)

The Pierre Auger Collab. JCAP 2017

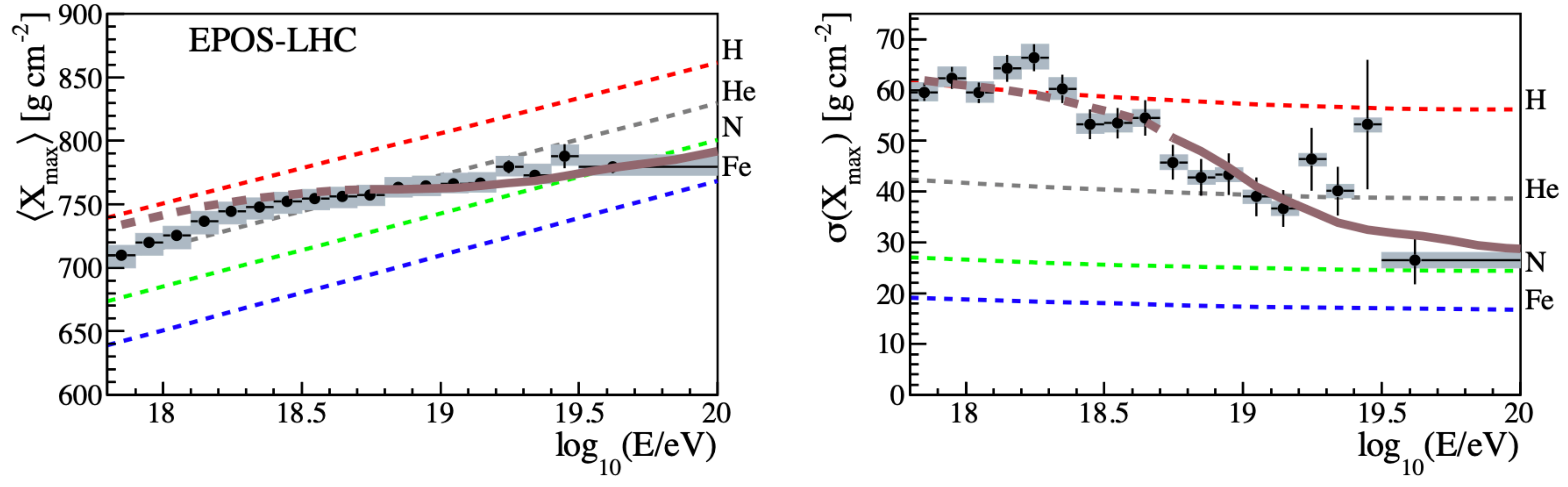


Basic scenario (energies above the ankle):

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

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

- **SimProp**, Aloisio, **DB**, di Matteo, Grillo, Petrera & Salamida, JCAP 2017
- **CRPropa**, R. Alves Batista et al, JCAP 2022

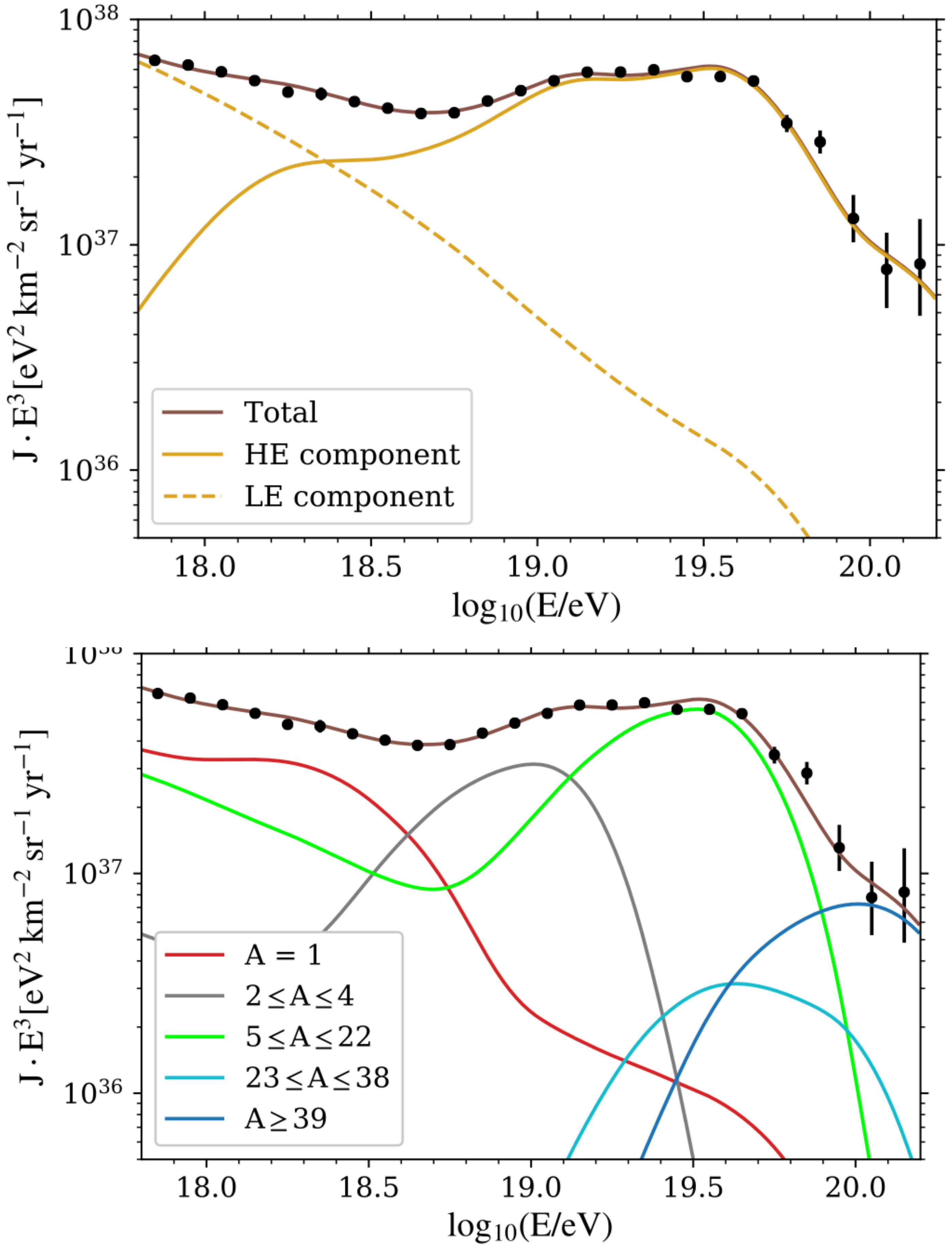


- UHECR source population contributing **above the ankle**:
  - Hard spectral index
  - Low rigidity cutoff
  - Intermediate nuclear species
- What happens **below the ankle**?

- See also Heinze, Fedynitch, **DB** & Winter ApJ 2019; Alves Batista et al, JCAP 2019 for similar results

# ASTROPHYSICAL INTERPRETATION(S)

Different populations of sources contributing at LE and HE



Aloisio et al, JCAP 2014; Mollerach & Roulet PRD 2020; Das et al, Eur.Phys.J. 2021; **The Pierre Auger Collab. JCAP 2023**

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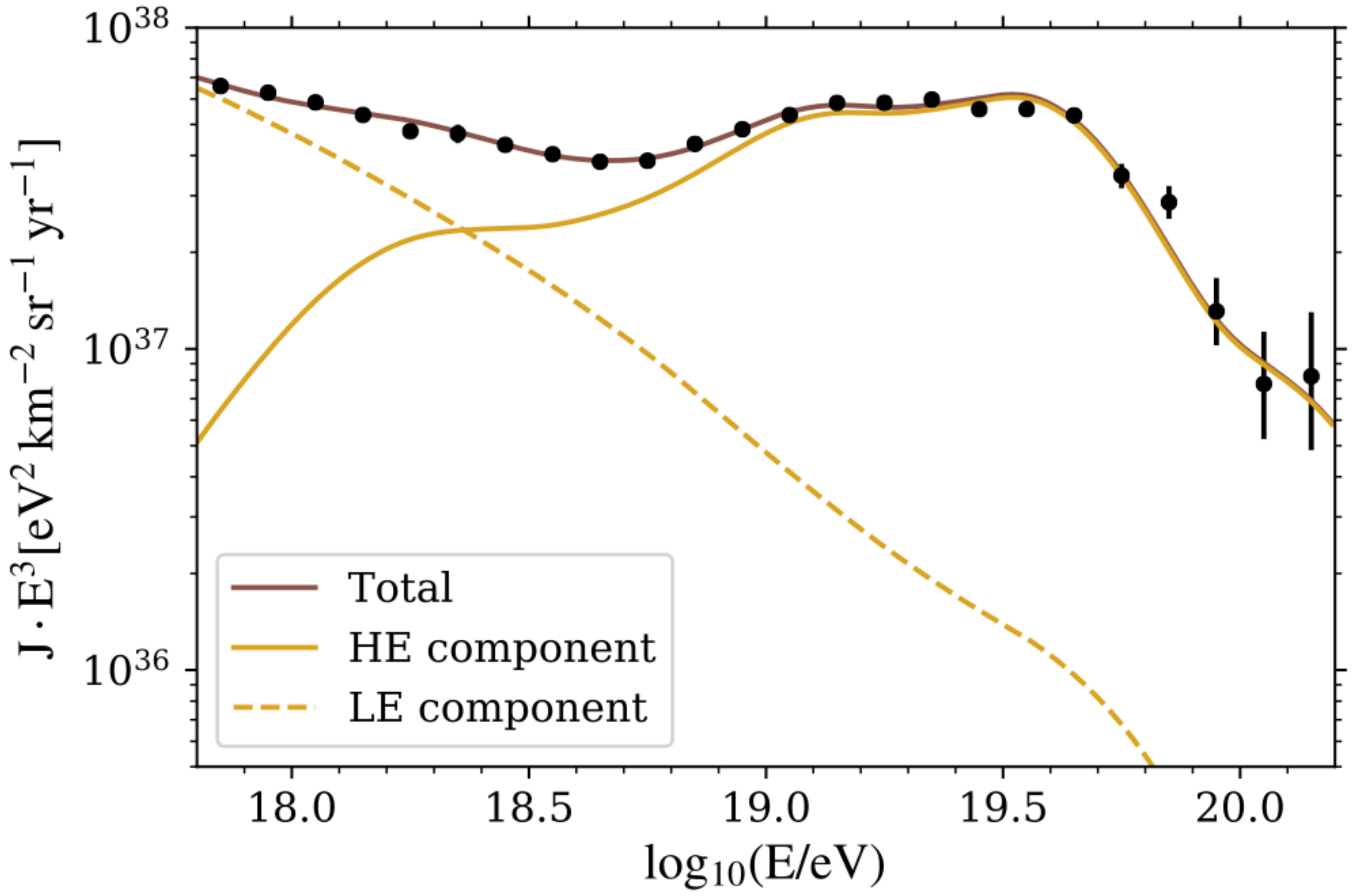

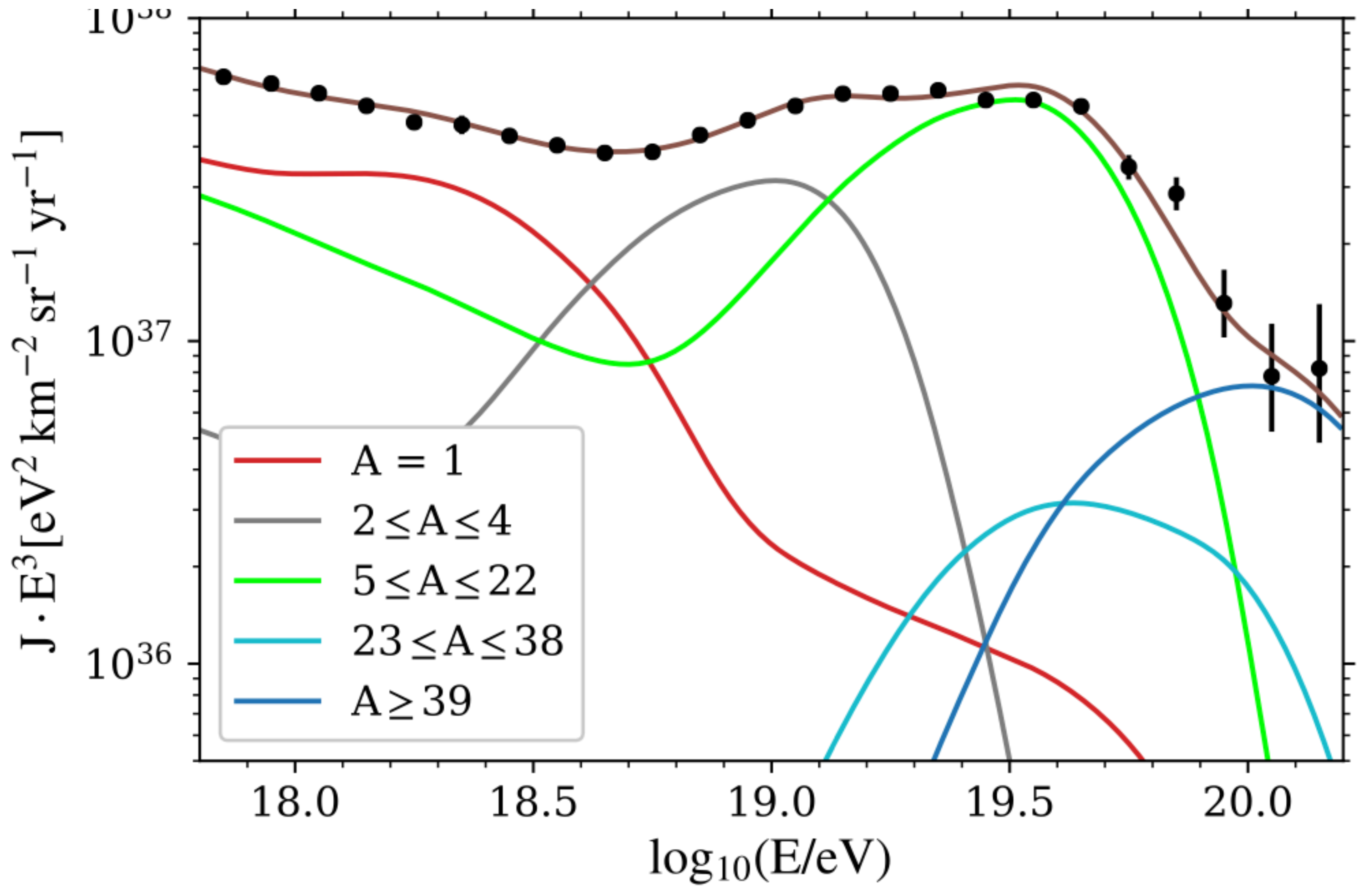

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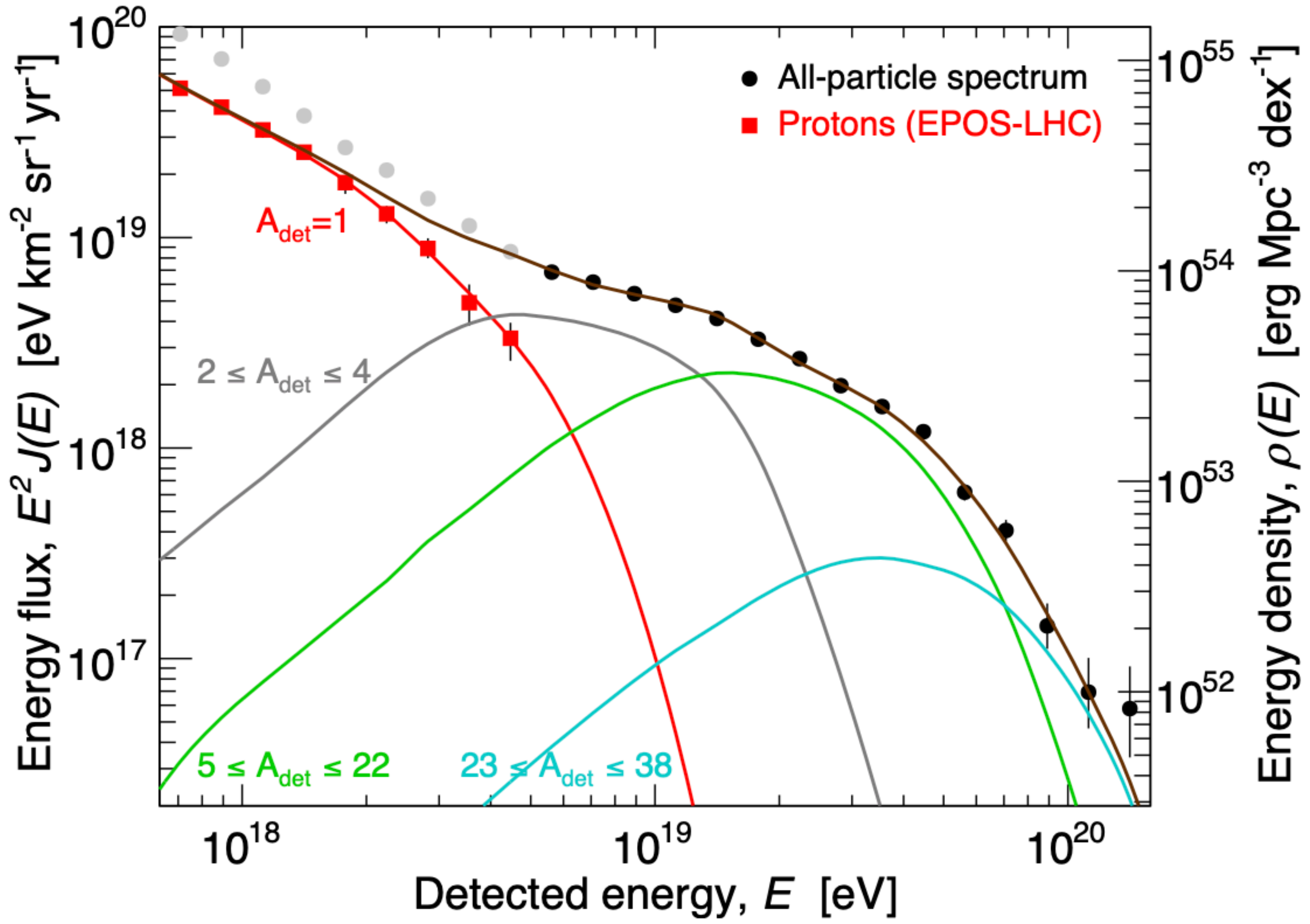
One population of sources, softer spectrum of protons due to in-source interactions



Contribution from heavier particles below the ankle needed to account for

- mixed composition
- missing flux

**Luce et al, ApJ 2022**

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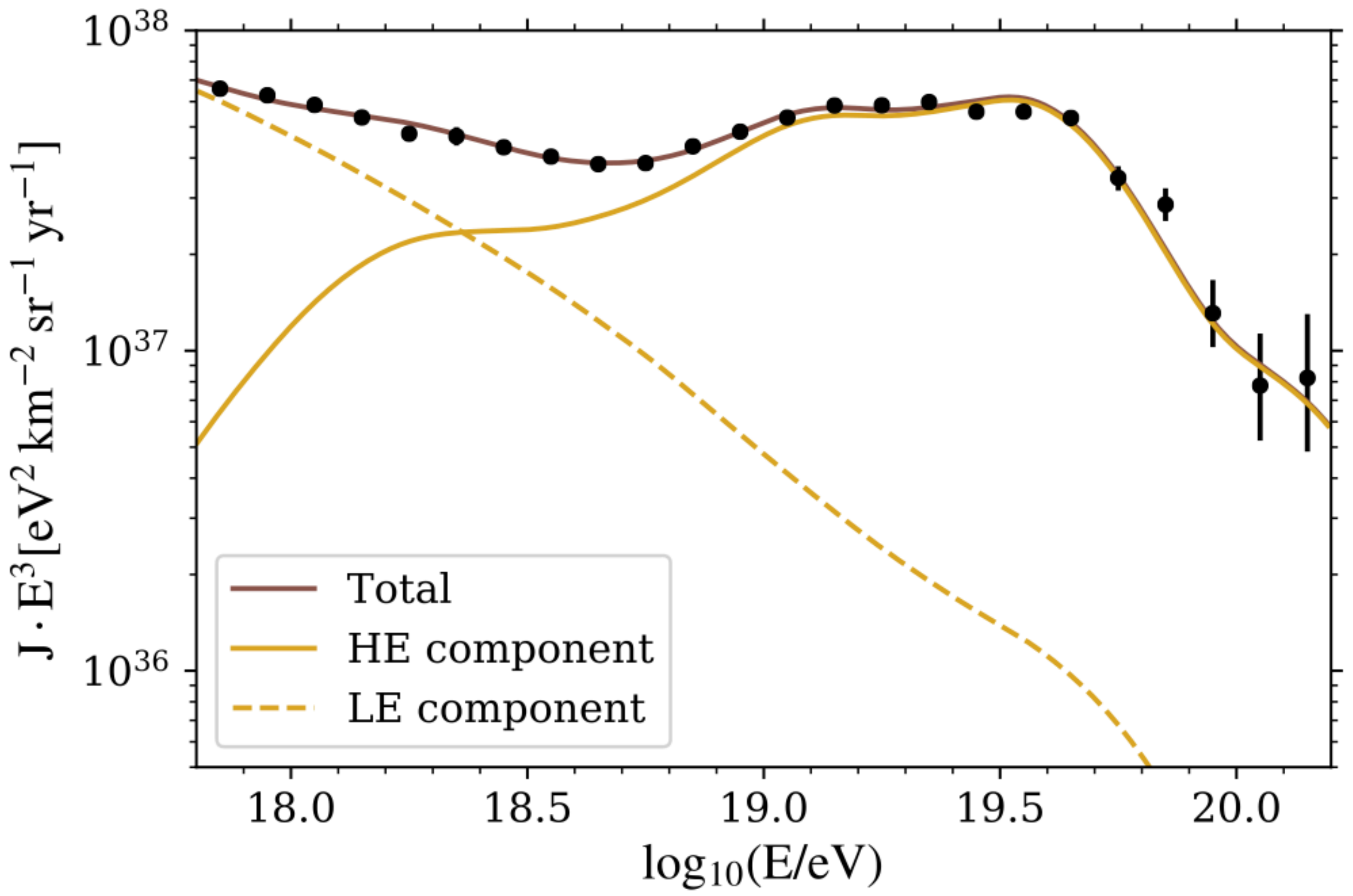

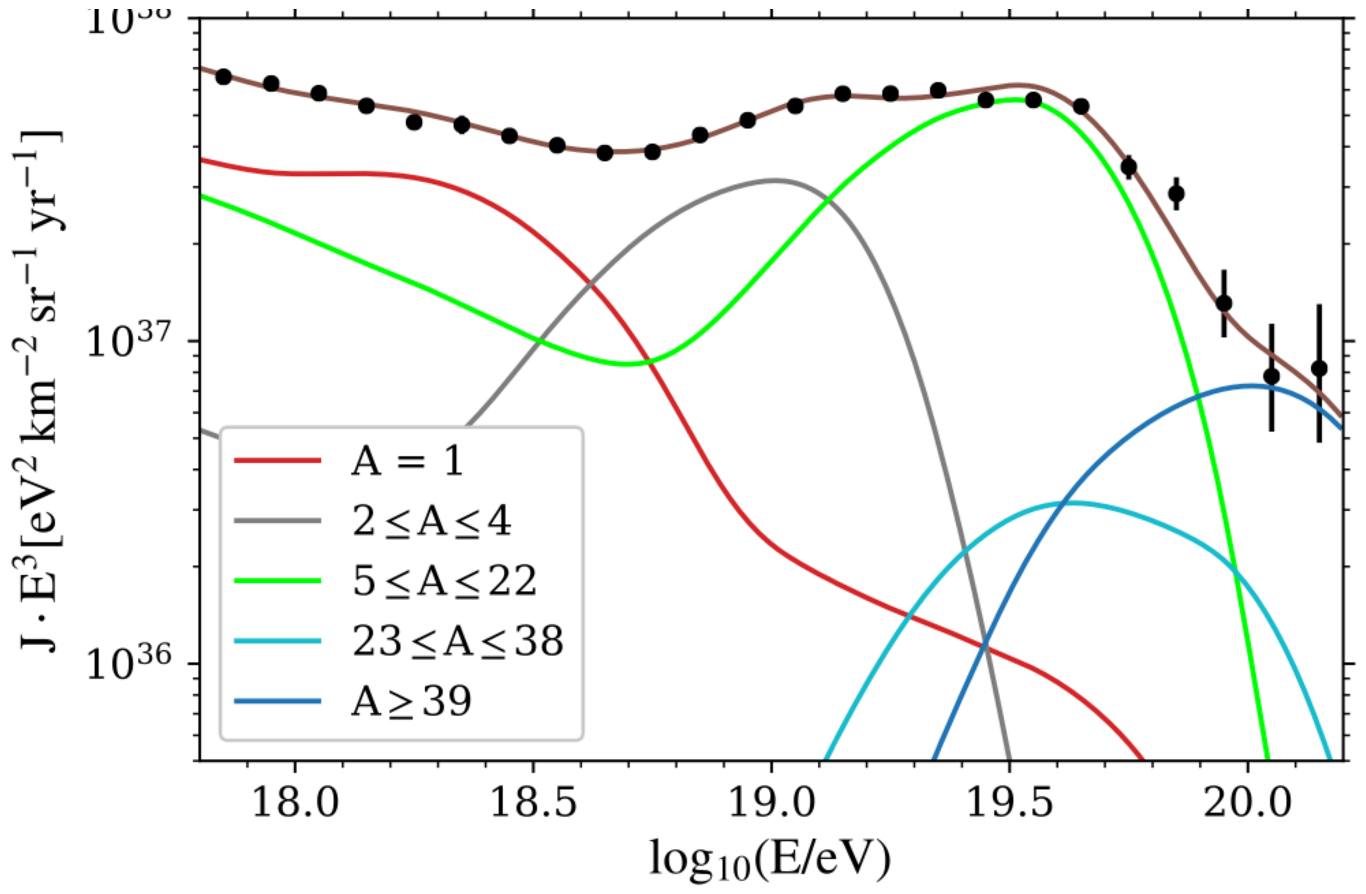

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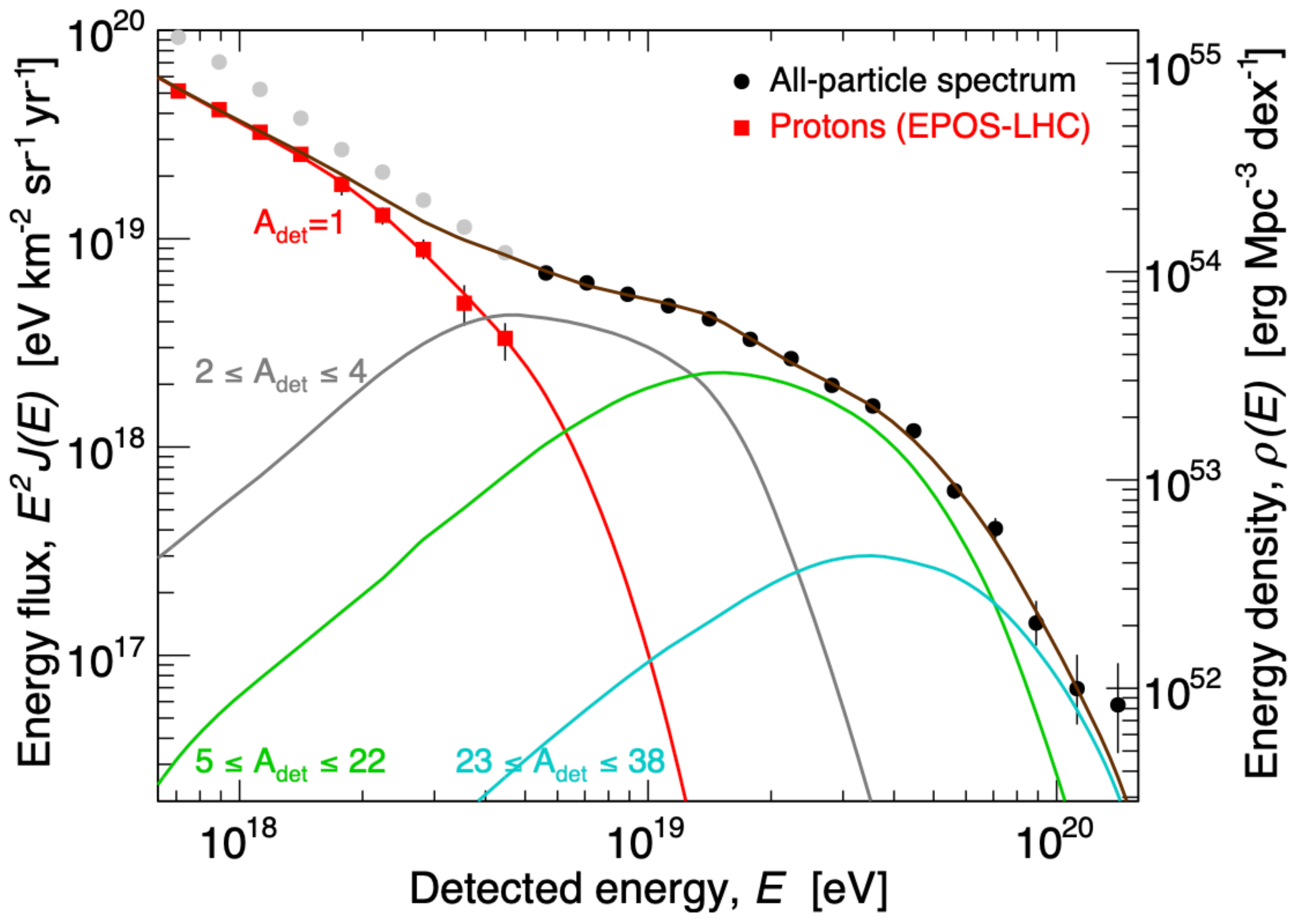

Contribution from <u>heavier particles below the ankle</u> needed to account for

- mixed composition
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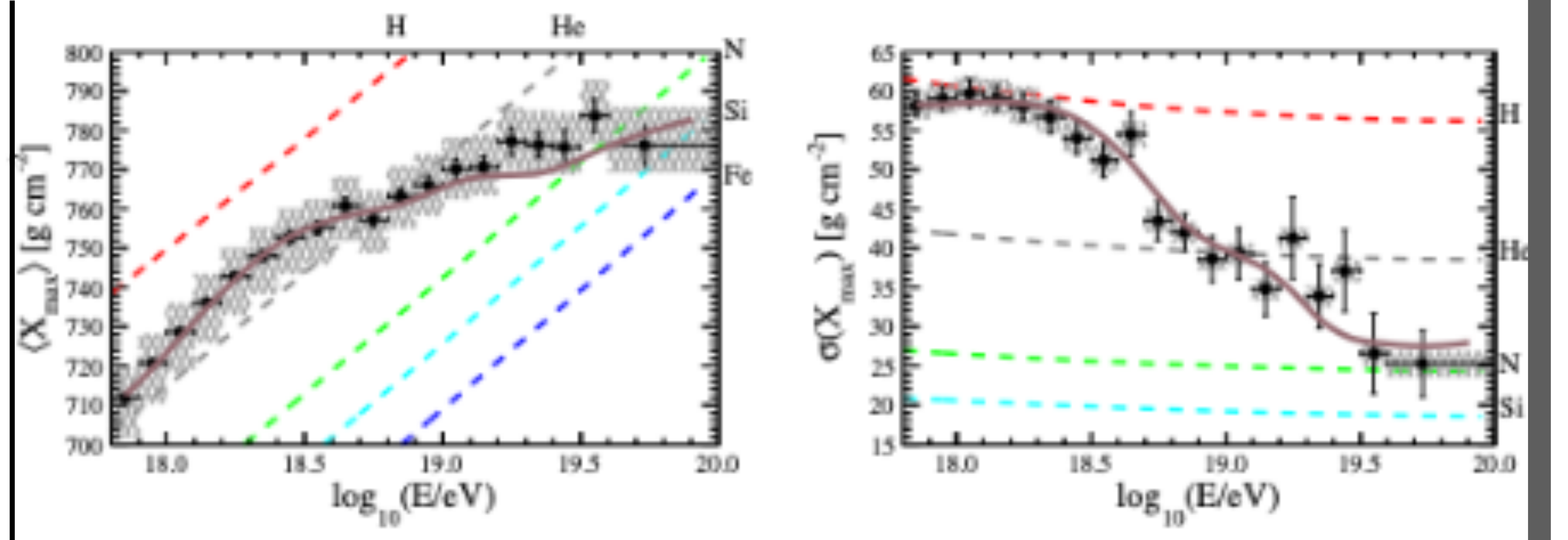
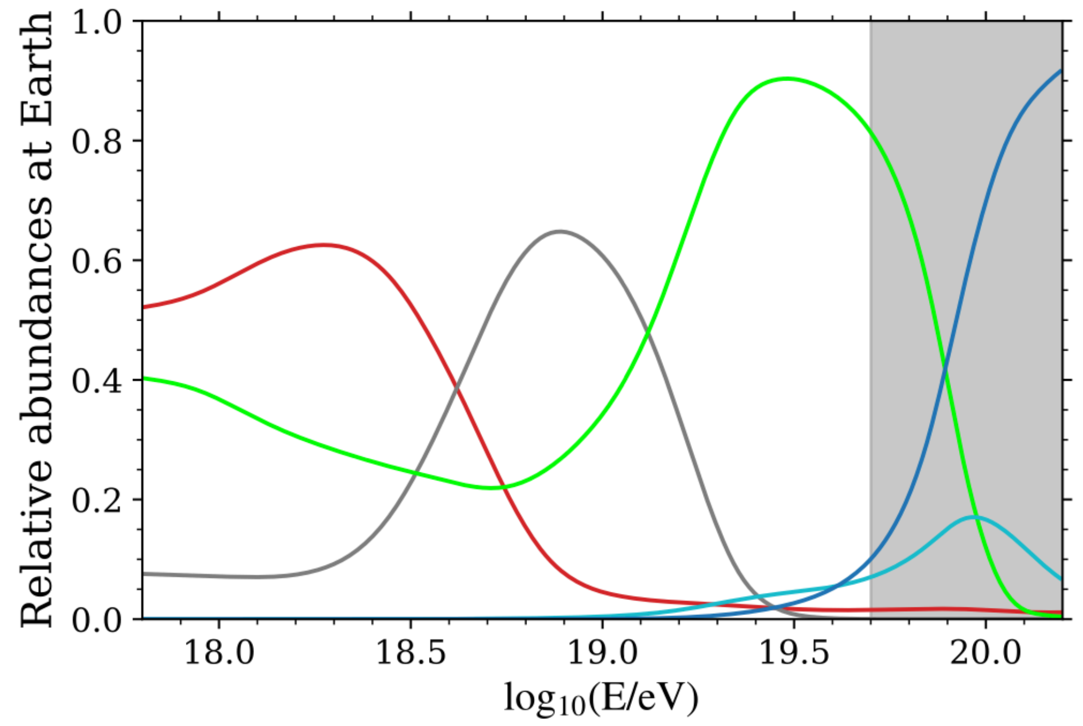
**Luce et al, ApJ 2022**

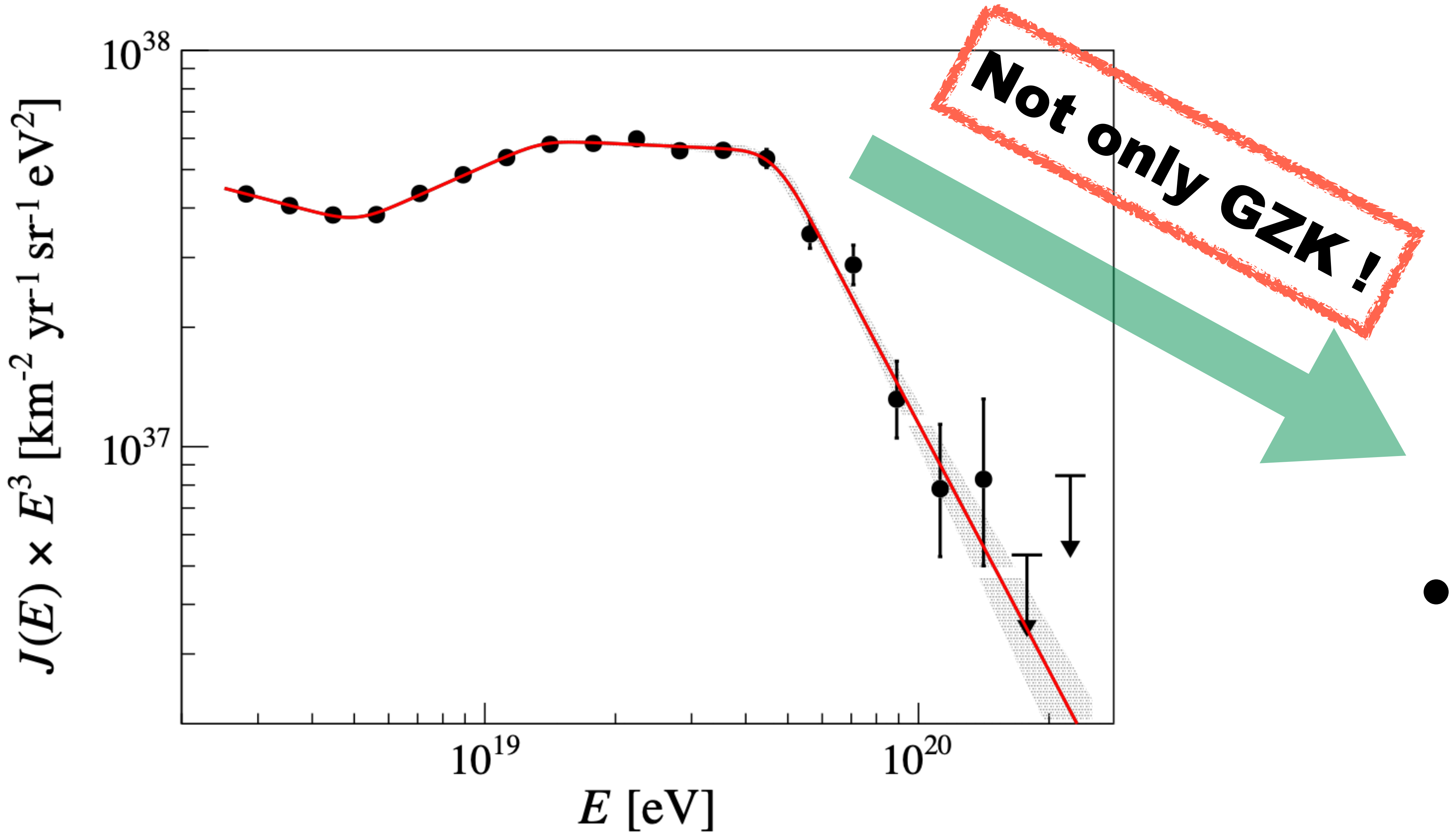


- Independently of the scenario, decreasing fluctuations of Xmax can be found corresponding to **limited mixing of spectra of different nuclear species at HE**, meaning
  - HE: hard spectra + low rigidity cutoff
  - LE: soft spectra + less constrainable rigidity



# 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**,

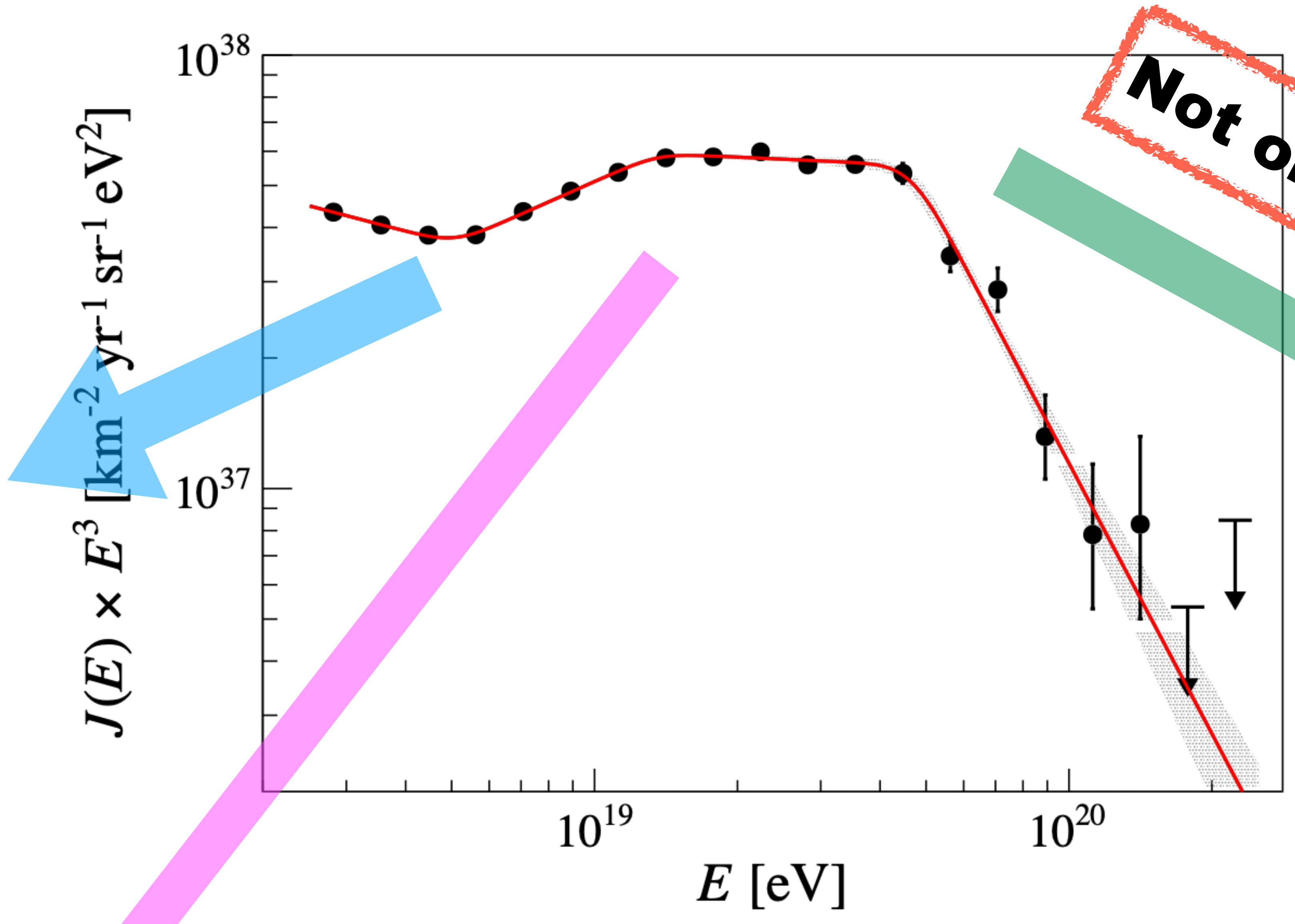
- Propagation effect
- Indication of source power

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

The Pierre Auger Collab. JCAP 2023

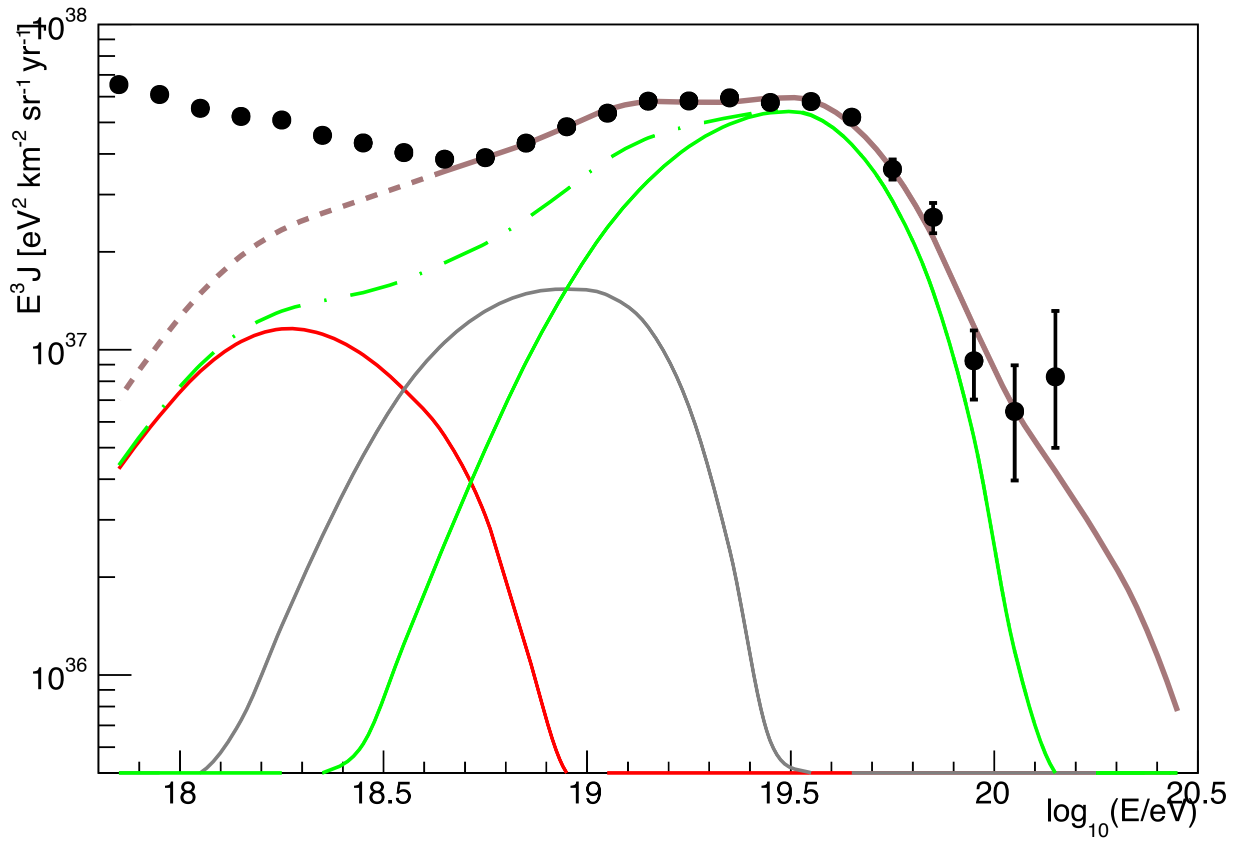
**Ankle**: interplay between (soft) LE and (hard) HE components

- Different populations of UHECR sources
- In-source interactions



Not only GZK !

**Instep**: interplay between the flux contributions of the He and CNO components injected at the source with their distinct cut-off energies, shaped by photodisintegration during the propagation



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In terms of interpretation the **suppression**,

- Propagation effect
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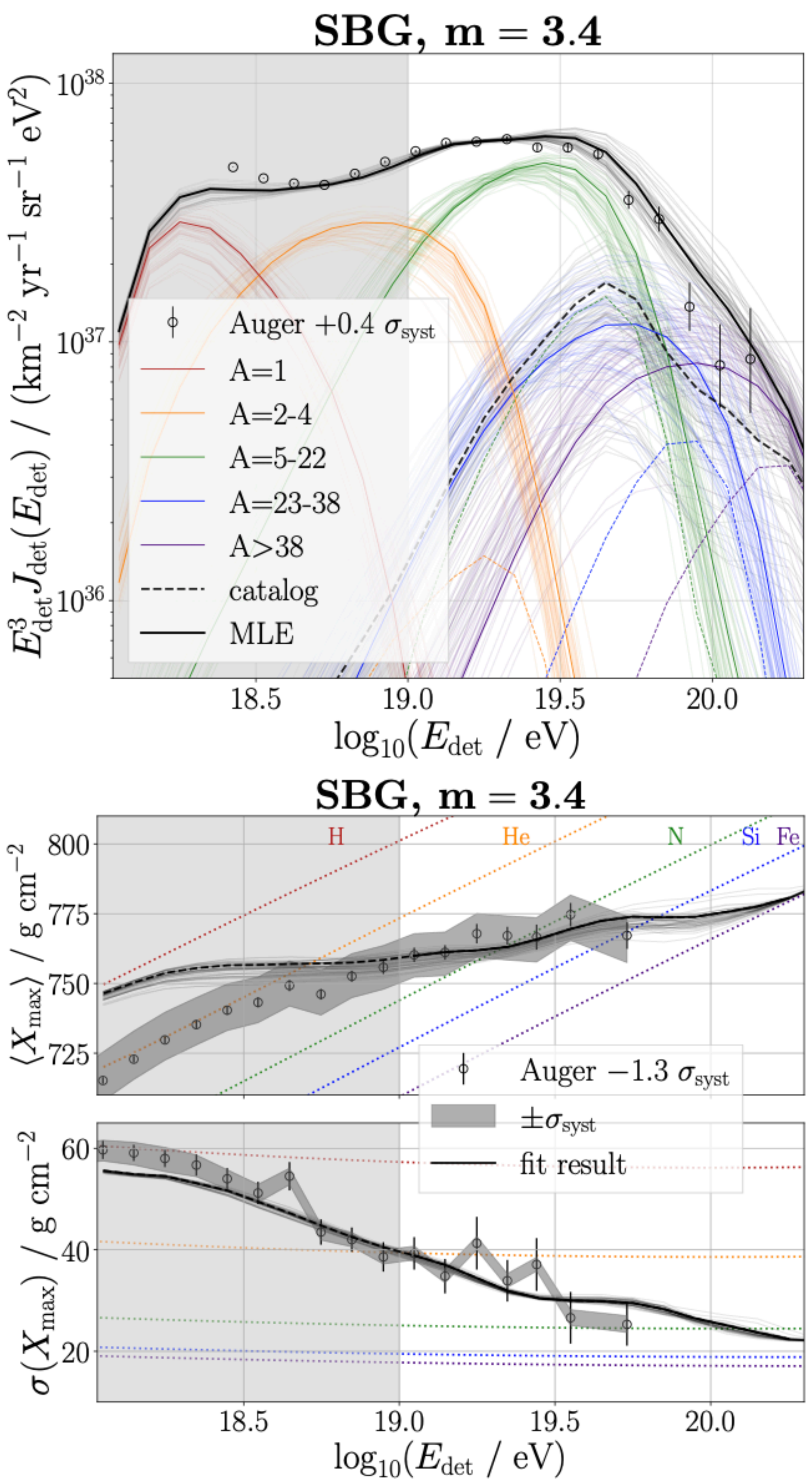
# REFINING THE BASIC PICTURE

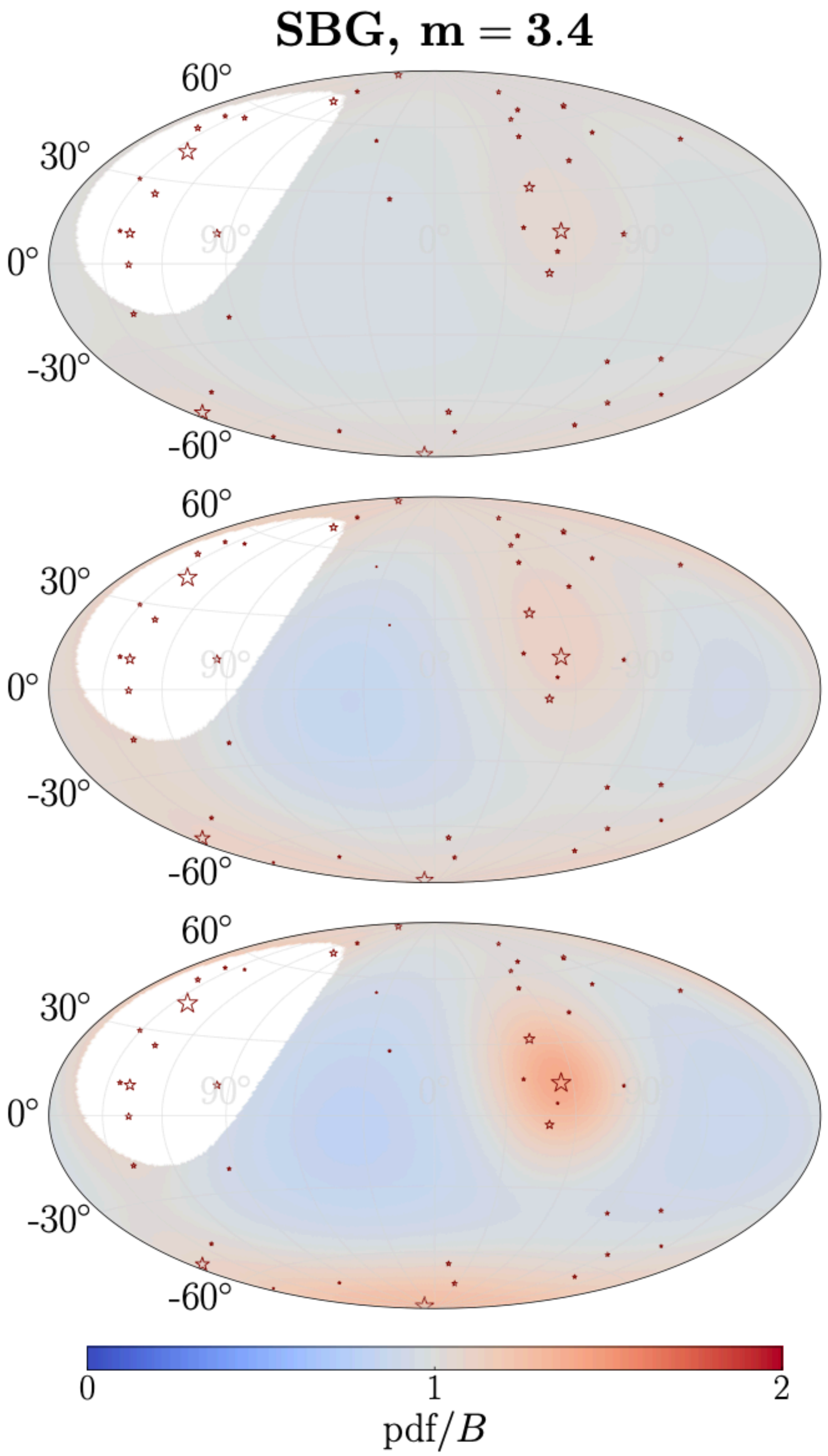
- Investigating the source distribution
- Including the effects of the propagation in magnetic fields
- Taking into account the (possible) transient nature of UHECR sources
- Investigating the UHECR spectrum shape at the escape from UHECR sources
  - Relaxing the assumption of identical sources
  - Investigating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

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

## HOW TO REFINE THE BASIC PICTURE

# REFINING THE BASIC PICTURE





- 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
- See also Eichmann et al. JCAP 2022

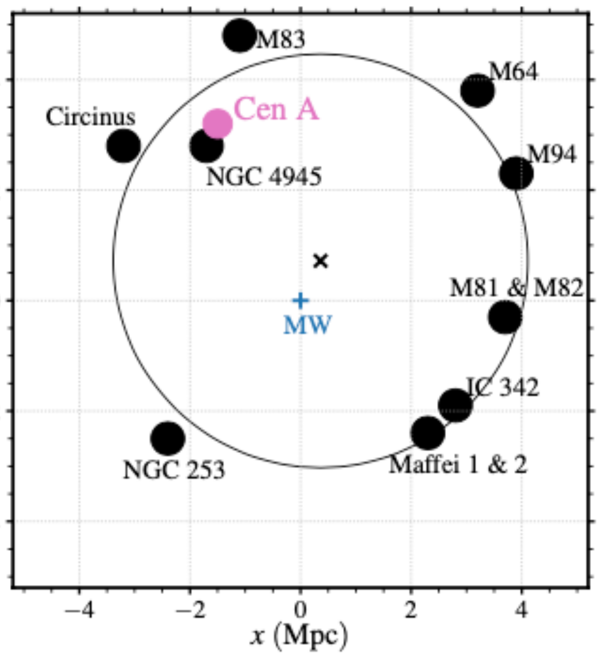
**The Pierre Auger Collab. JCAP 2024**

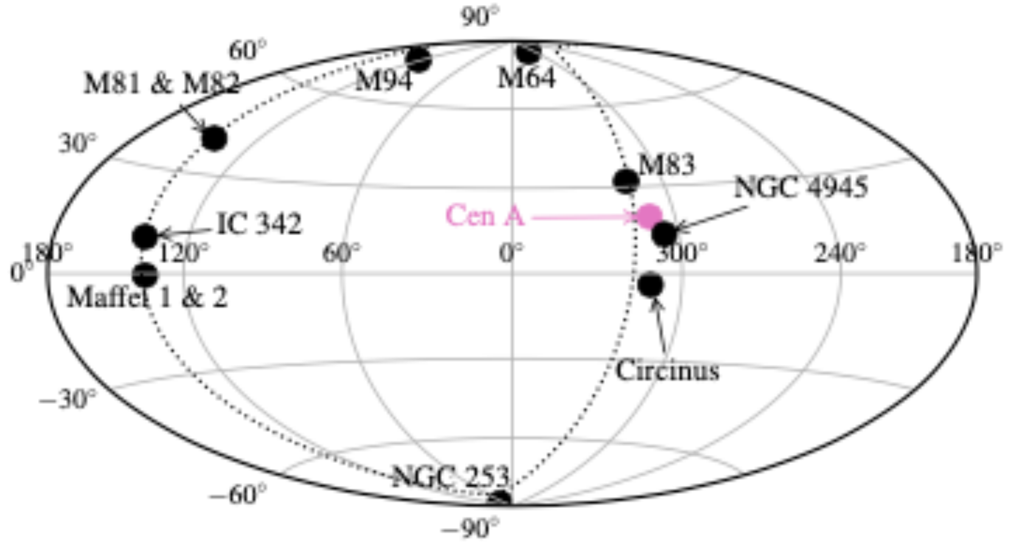
# REFINING THE BASIC PICTURE

Investigating the source distribution

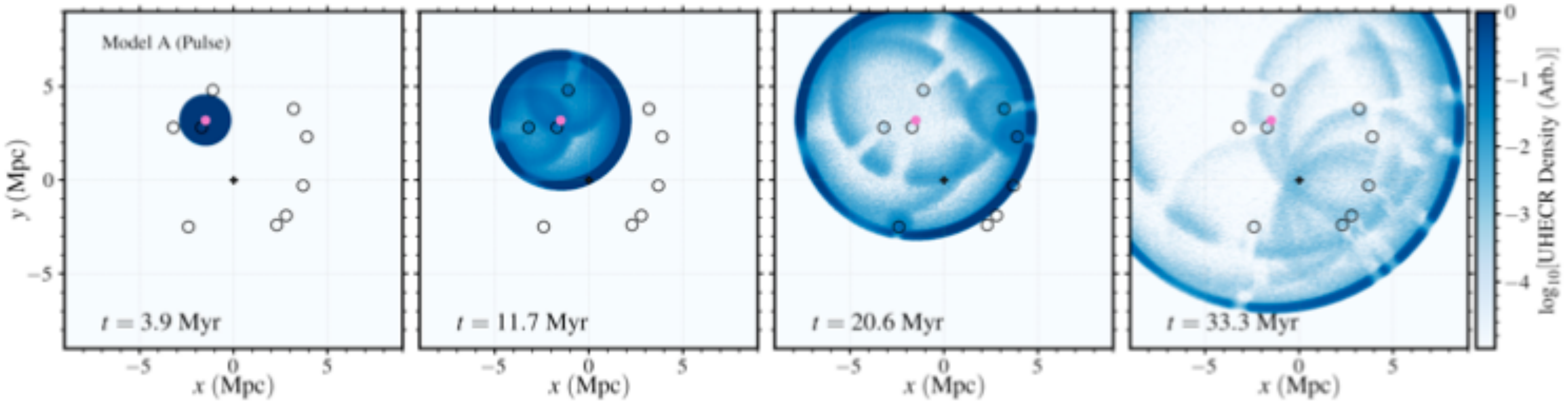
- Correlation with SBGs established
  - Can the correlation of UHECR with local structure be ascribed to the deflection of UHECRs, initially released by Cen A, on nearby galaxy systems?

Bell & Matthews MNRAS 2022;
**Taylor et al MNRAS 2023**



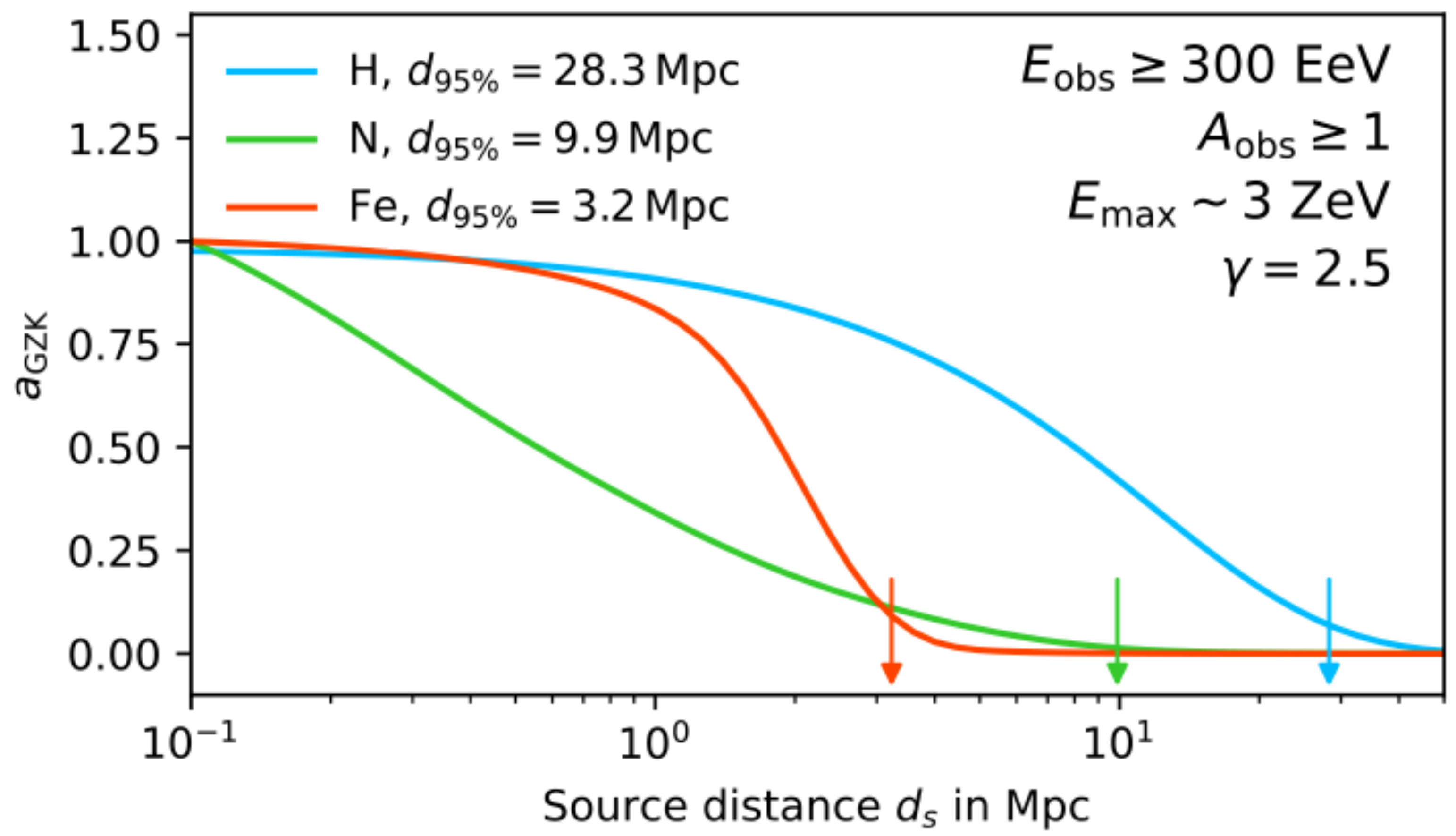


Council of Giants

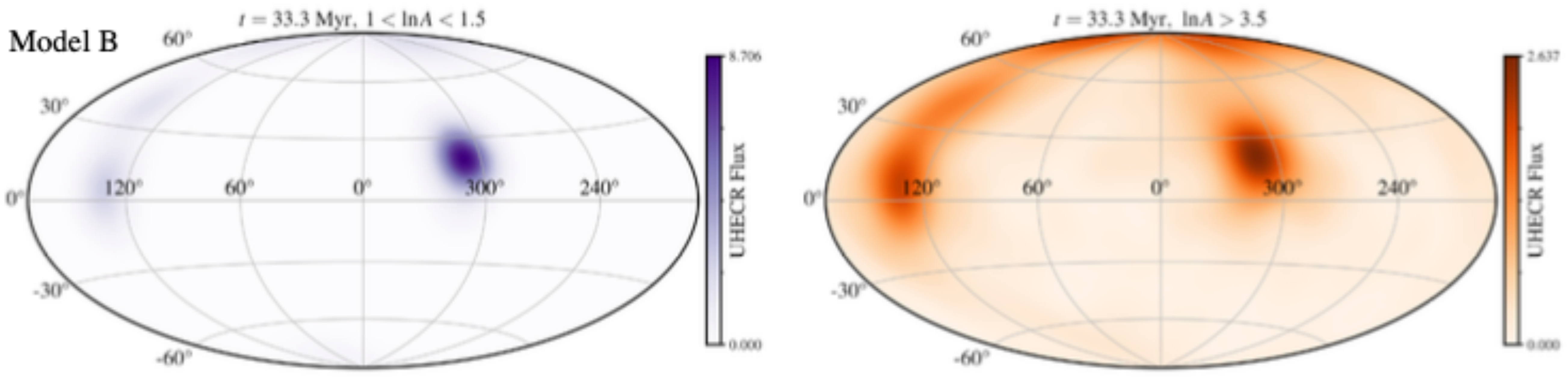


After the release from CenA, particles are scattered by magnetic fields around galactic structures

Local particle density depends on release models



**Globus et al, ApJ 2023**

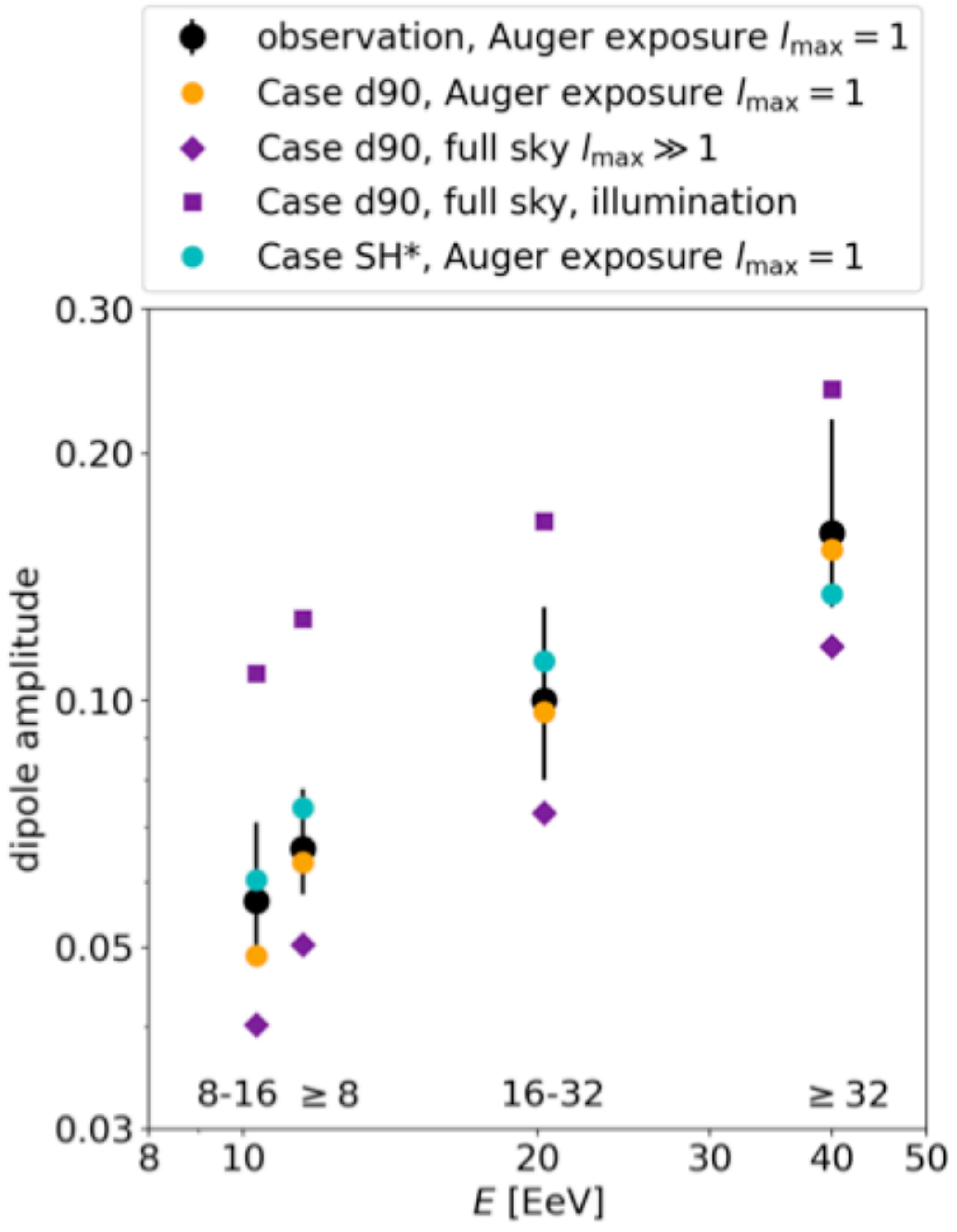


- UHECR nuclei provide a signature of the propagation scenario

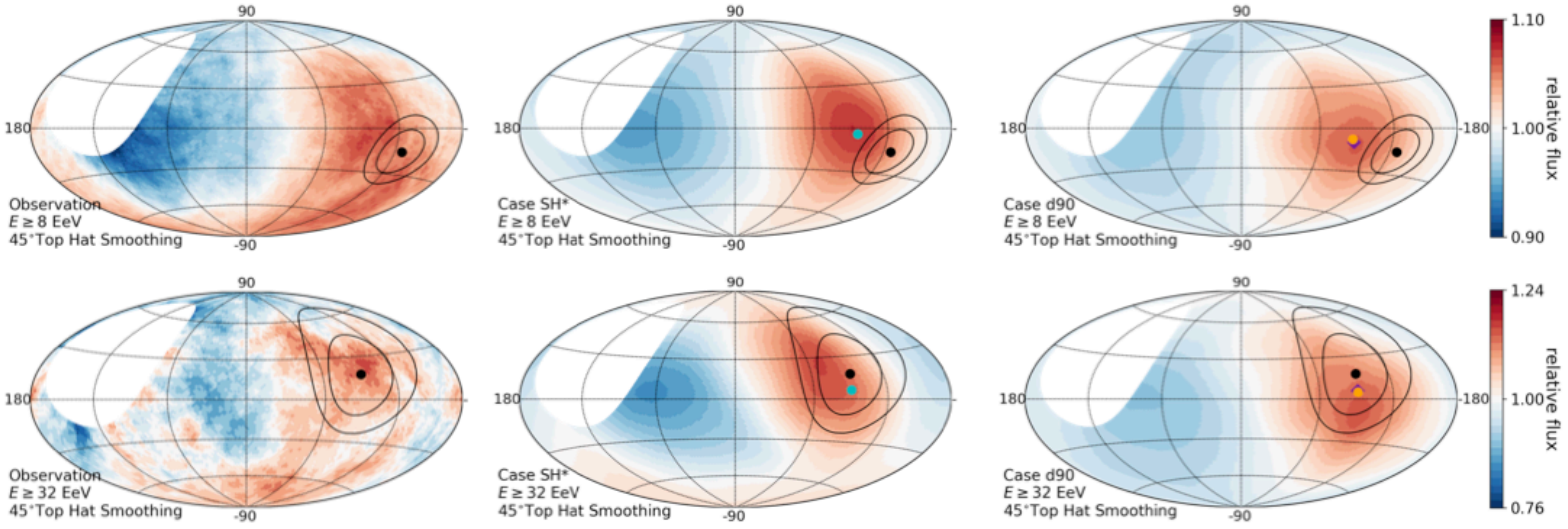
# REFINING THE BASIC PICTURE

## Including magnetic field effects

- Hypothesis: the UHECR source distribution follows the large-scale structure
- Dipole anisotropy and its evolution can be explained as a signature of the local LSS, if the diffusion in the extragalactic magnetic fields and the deflections by Galactic magnetic field (ordered + turbulent component) are taken into account: Jansson&Farrar2012 model



Ding et al ApJL 2021



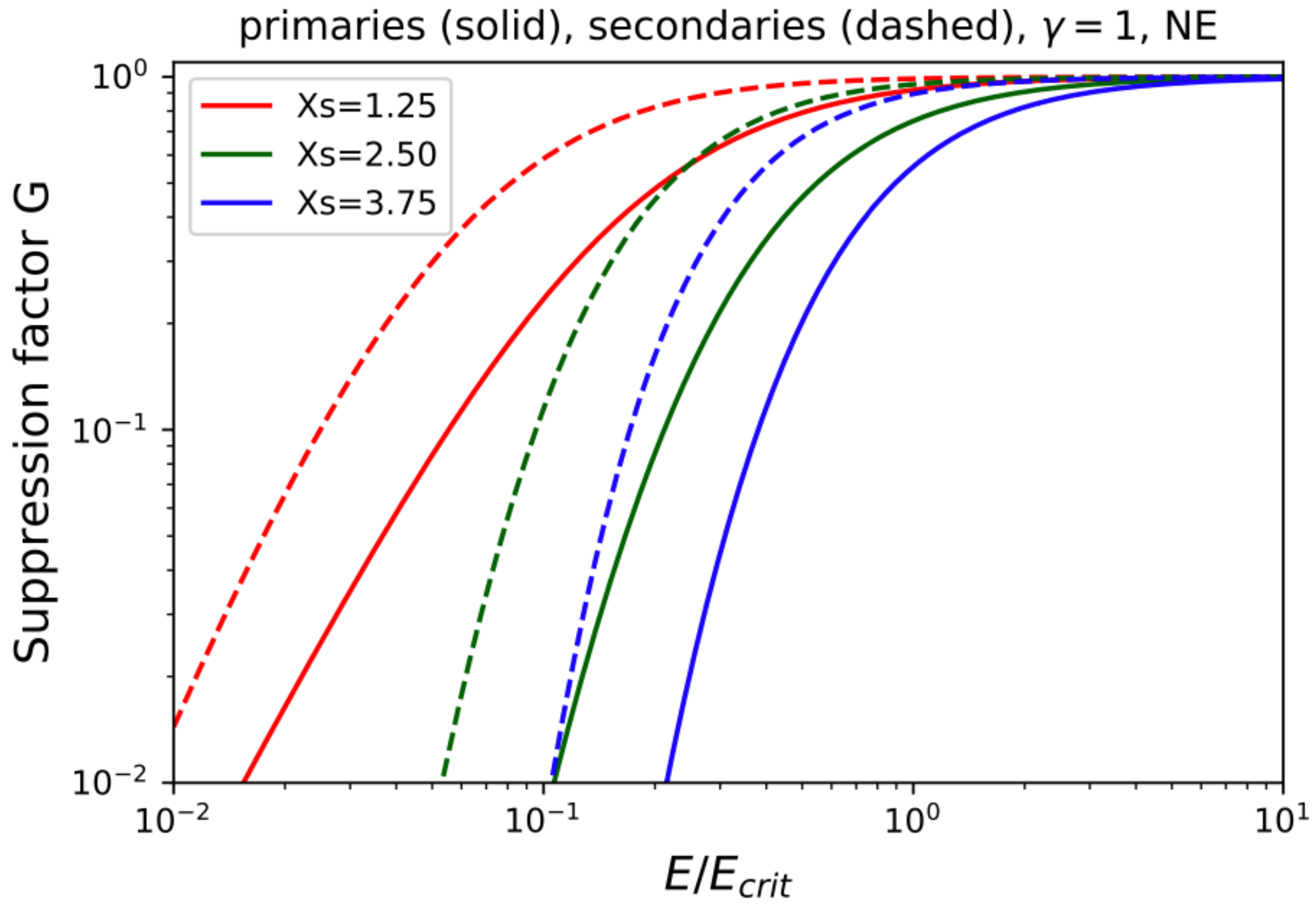
- **Composition affects anisotropy**:
  - GMF deflections are rigidity dependent and increase as rigidity drops

# REFINING THE BASIC PICTURE

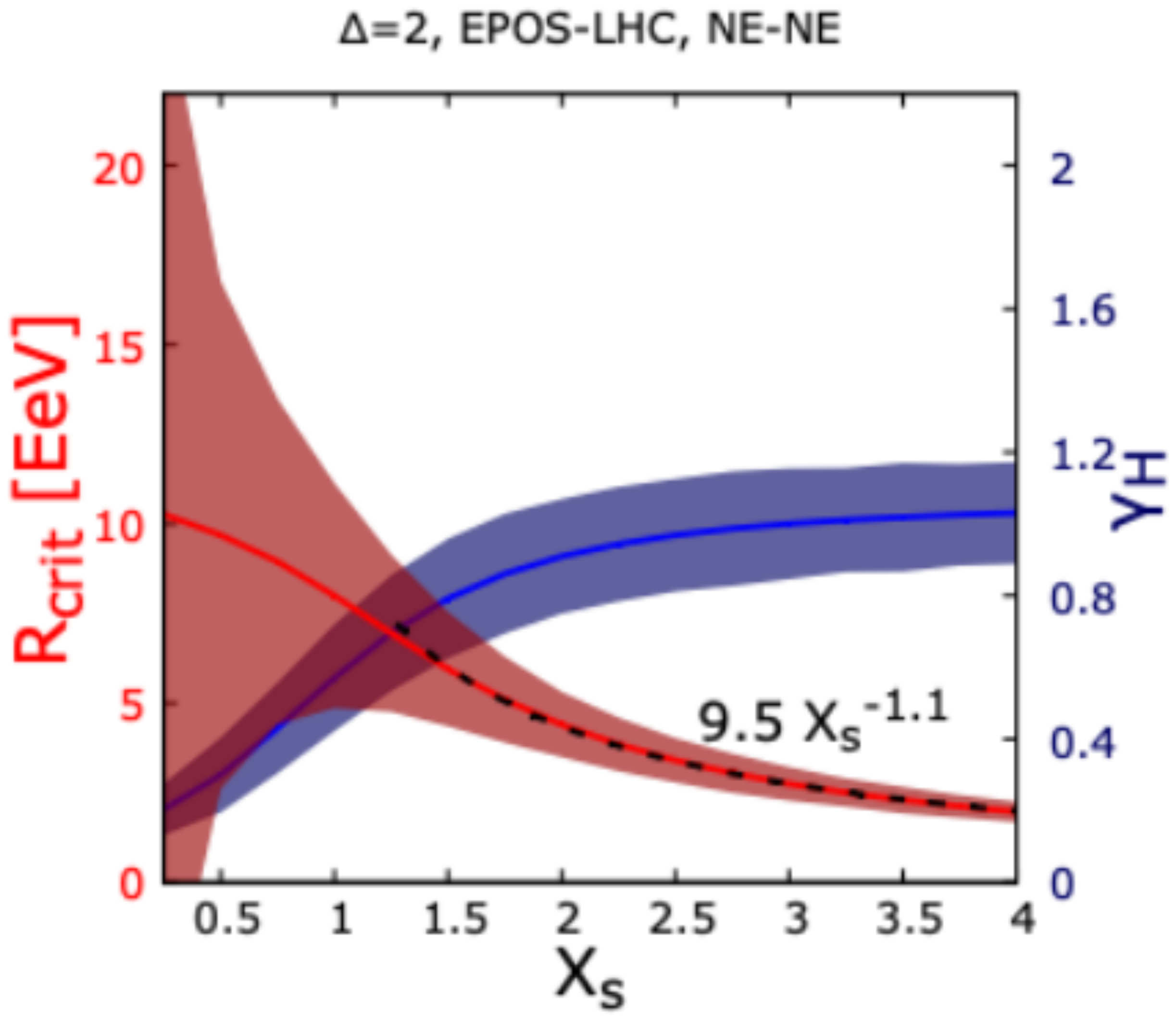
## Including magnetic field effects

- At **energies below the ankle**:
  - EGMF reduce the flux of low-rigidity particles that reach the Earth
    - increase of B -> soft spectrum at sources

$$r_L(E_{\rm crit}) = L_{\rm coh},\ \ R_{\rm crit} = \frac{E_{\rm crit}}{Z} = 0.9\frac{B_{\rm rms}}{\rm nG}\frac{L_{\rm coh}}{\rm Mpc}\,{\rm EeV} \qquad X_s = \frac{d_s}{25\,{\rm Mpc}}\sqrt{\frac{\rm Mpc}{L_{\rm coh}}}$$

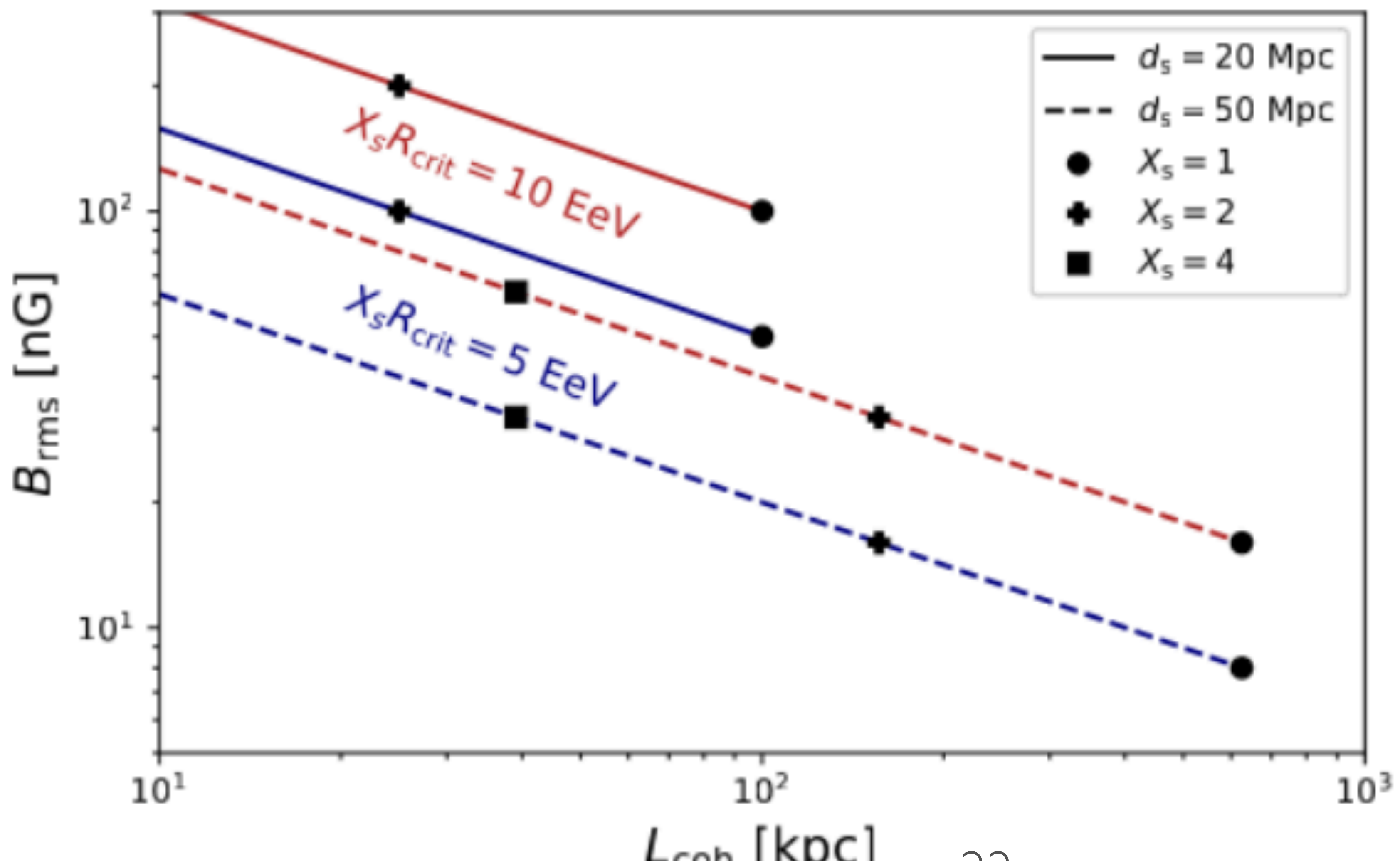


- **Magnetic fields affect the spectrum and composition:**
  - Softer spectra are allowed at the source if magnetic fields are considered -> acceleration theories can be reconciled with UHECR interpretations
  - Large inter-source distance and strong magnetic fields required between Earth and the closest source



**The Pierre Auger Collab, ICRC2023**

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



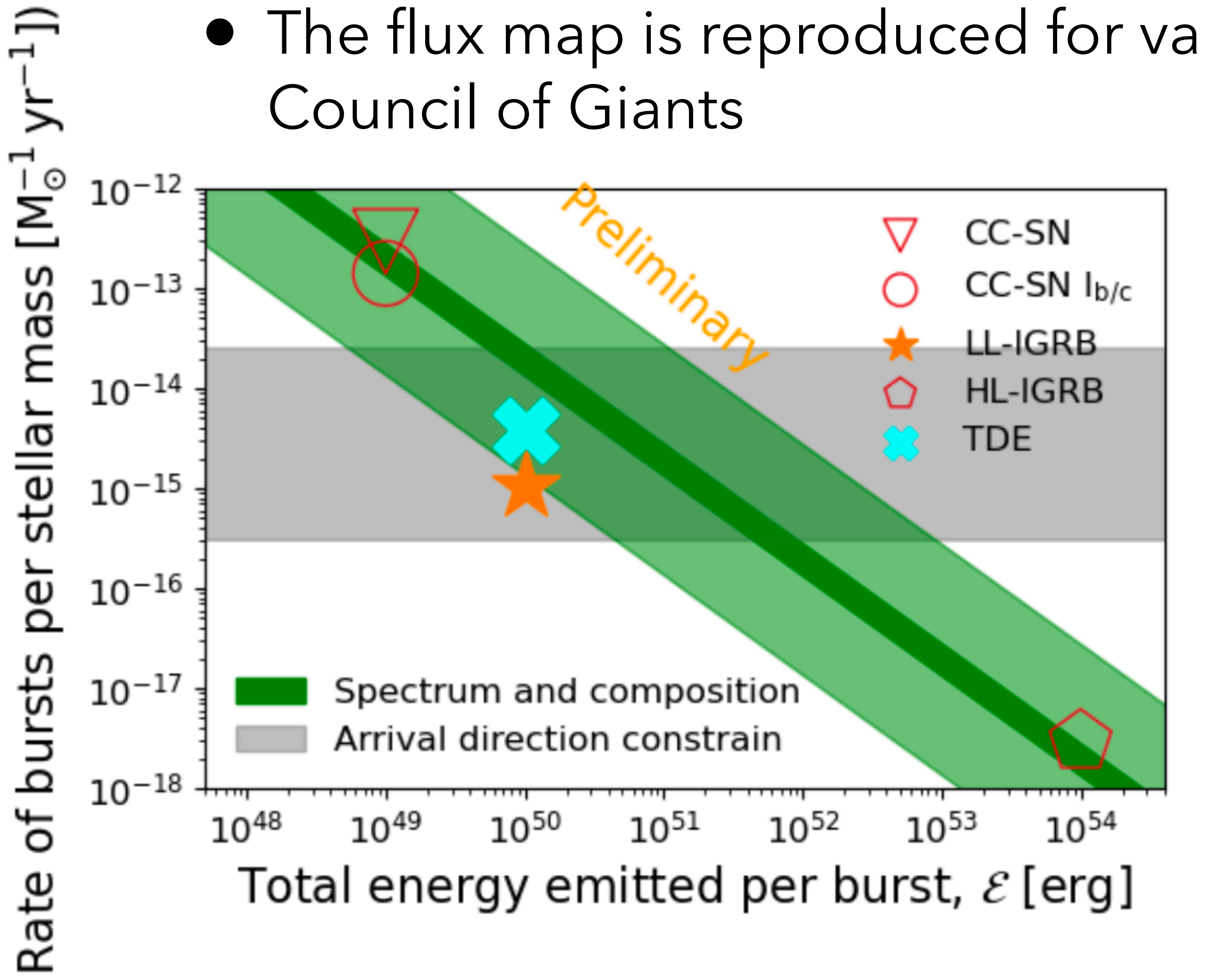
# REFINING THE BASIC PICTURE

## Persistent versus transient sources

- **Emission rate =** the ejection rate of UHECRs **x** the number of particles per energy unit (shape of injection spectrum)
- **Transient scenario**: sources are visible for a finite time, which depends also on the magnetic field on the line of sight (**the magnetic field imprints deflections and delays in the UHECR propagation**)
- Average number of bursts contributing to the spectrum

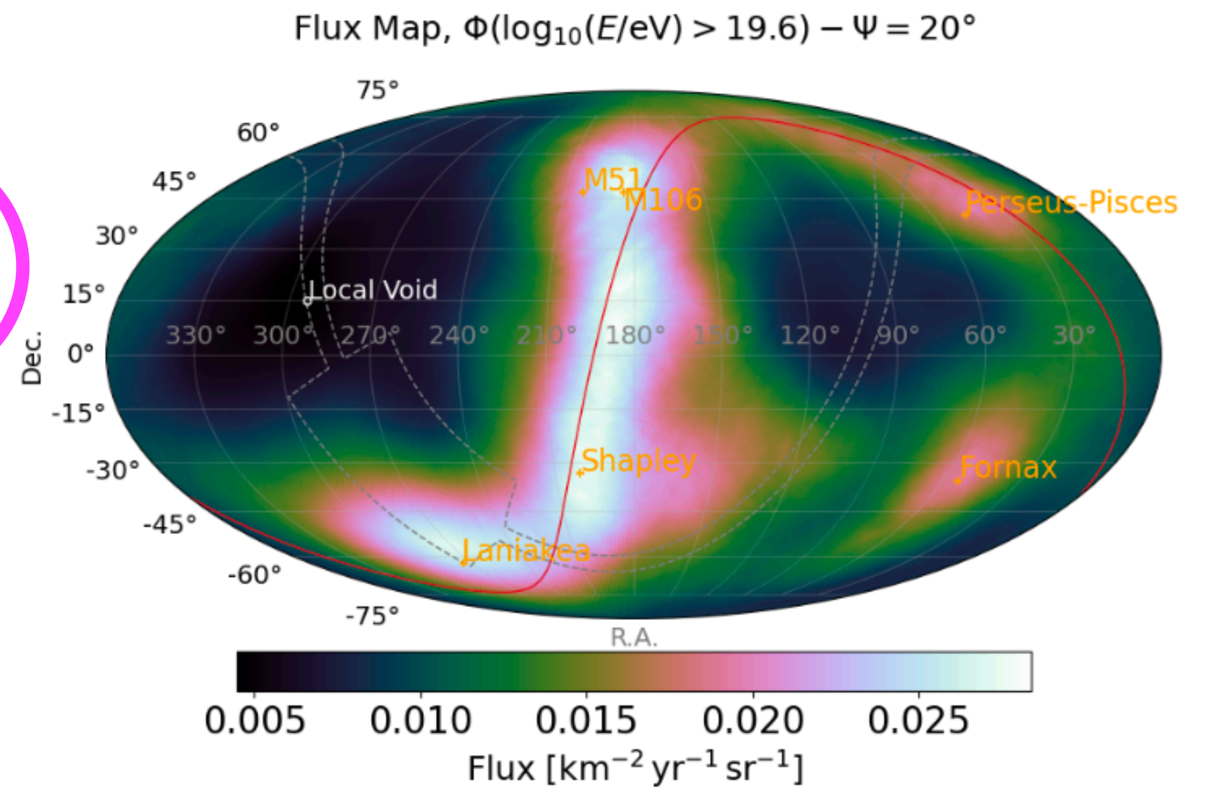
$$\lambda = \dot{k} M \Delta t$$

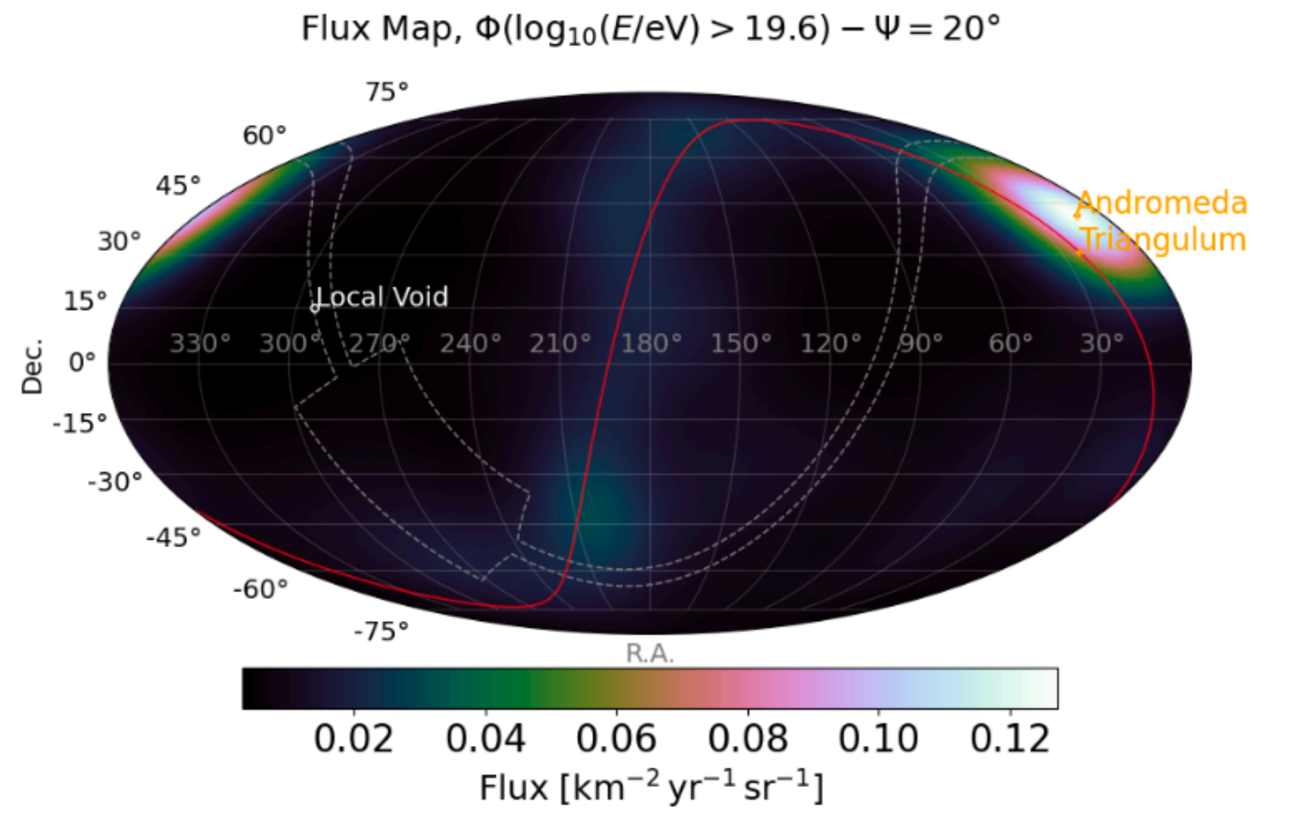
  - Scan over k
    - Low k -> closeby sources are filtered out, sources above 10 Mpc contribute
    - Large k -> the resulting rate of bursts is large enough to indicate contributions from extremely close sources, particularly Andromeda. Increasing the value of k would even allow the Milky Way to dominate the total intensity
    - The flux map is reproduced for values of k which allows the contribution from the Council of Giants



- The constraint from the arrival directions (horizontal band) has to be merged with the one from the energy (diagonal band), to match the observed UHECR spectrum

- See also Globus et al. ApJ 2023





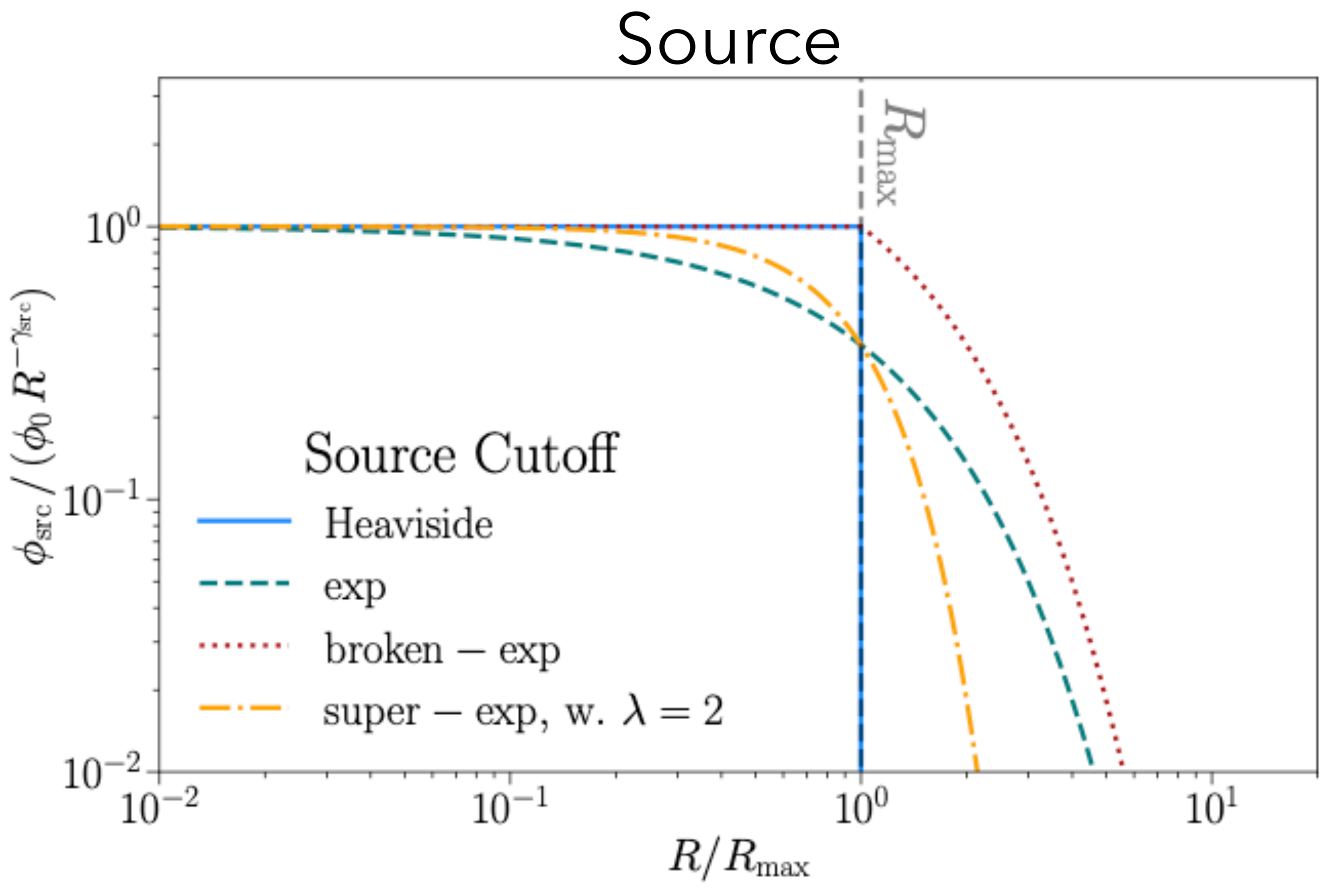
Condorelli et al. ICRC2023

# REFINING THE BASIC PICTURE

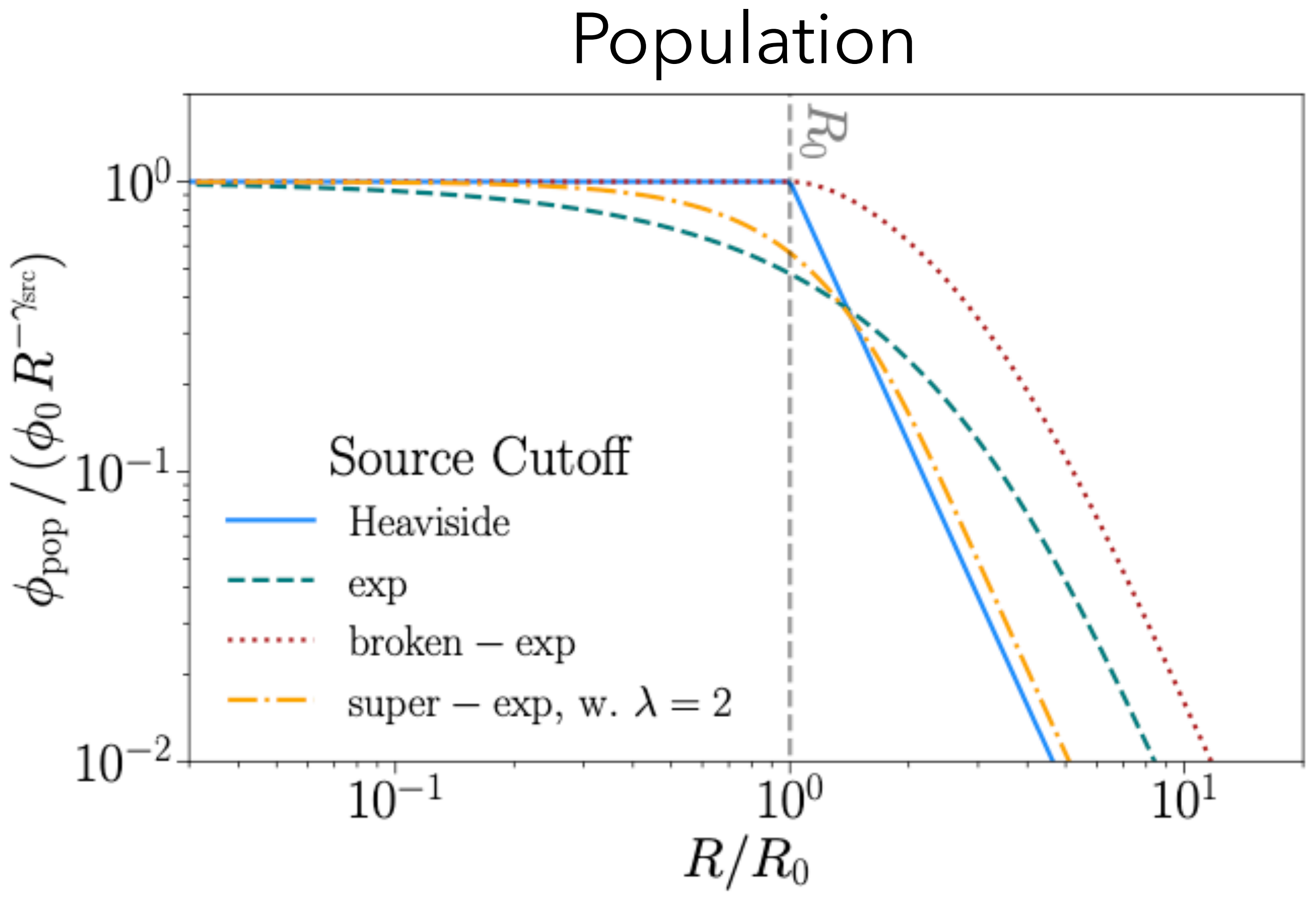
## Testing the assumption of identical sources

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



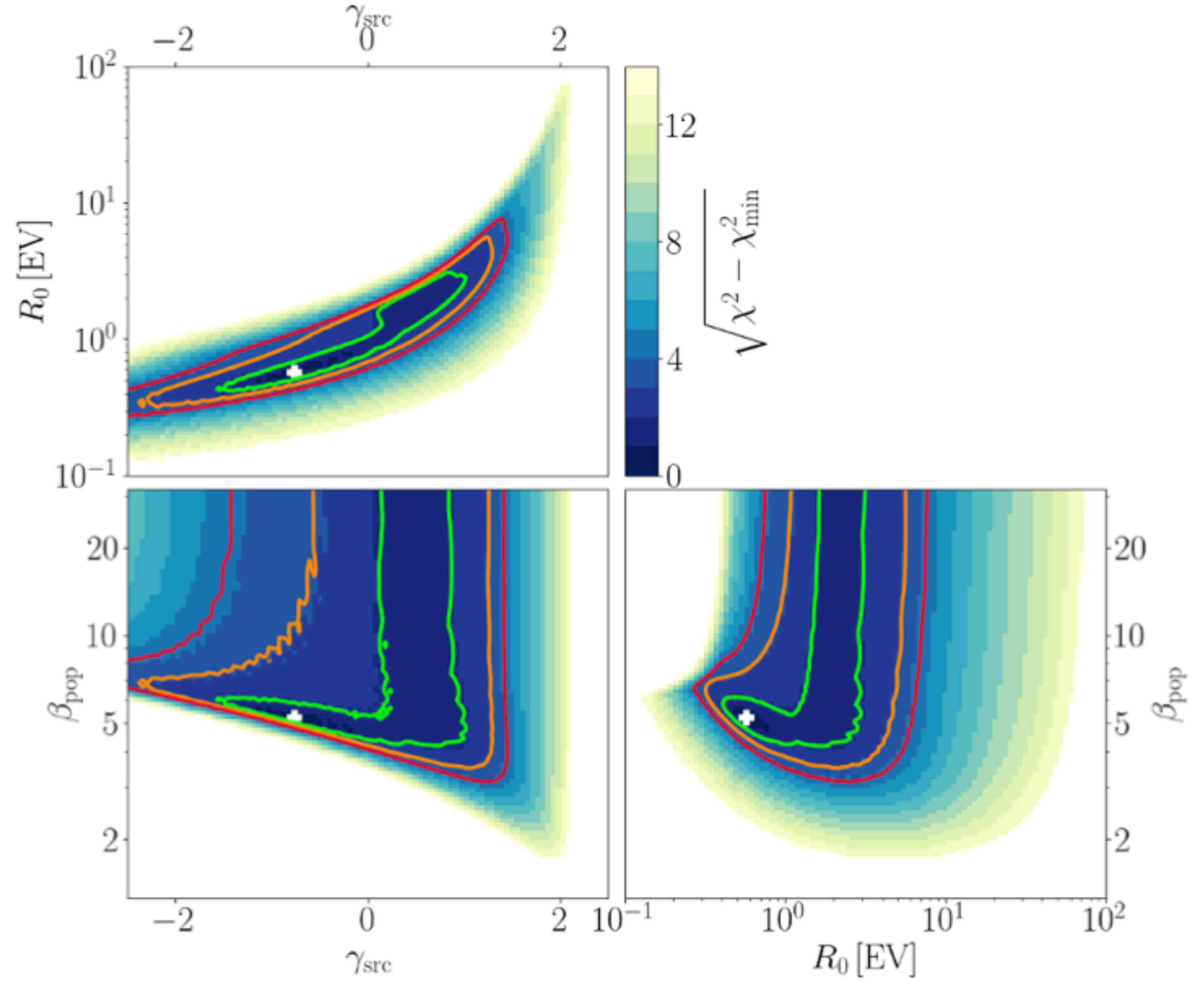
$$\frac{dN}{dR} \propto R^{-\gamma_{\rm src}}$$

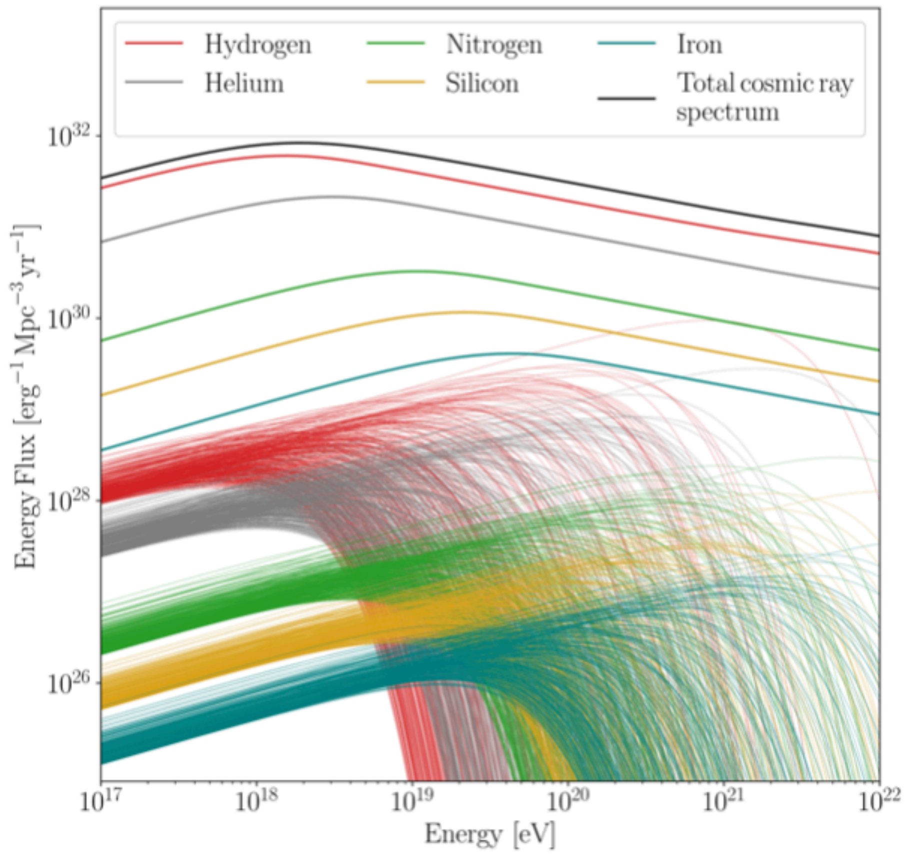


$$\frac{dN}{dR_{\rm max}} \propto R_{\rm max}^{-\beta_{\rm pop}}$$

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

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





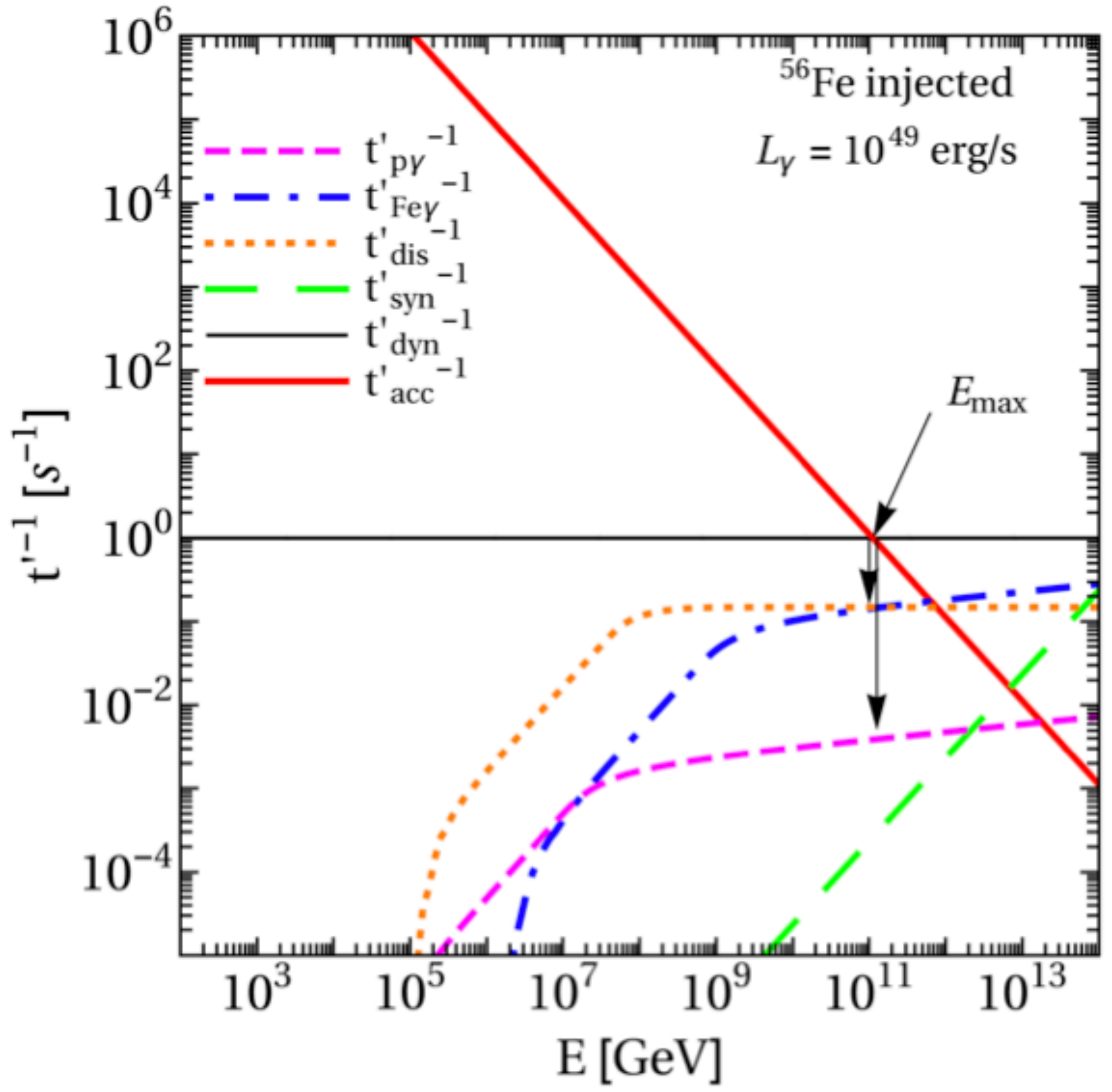
Plot from talk by F. Oikonomou @ICRC23

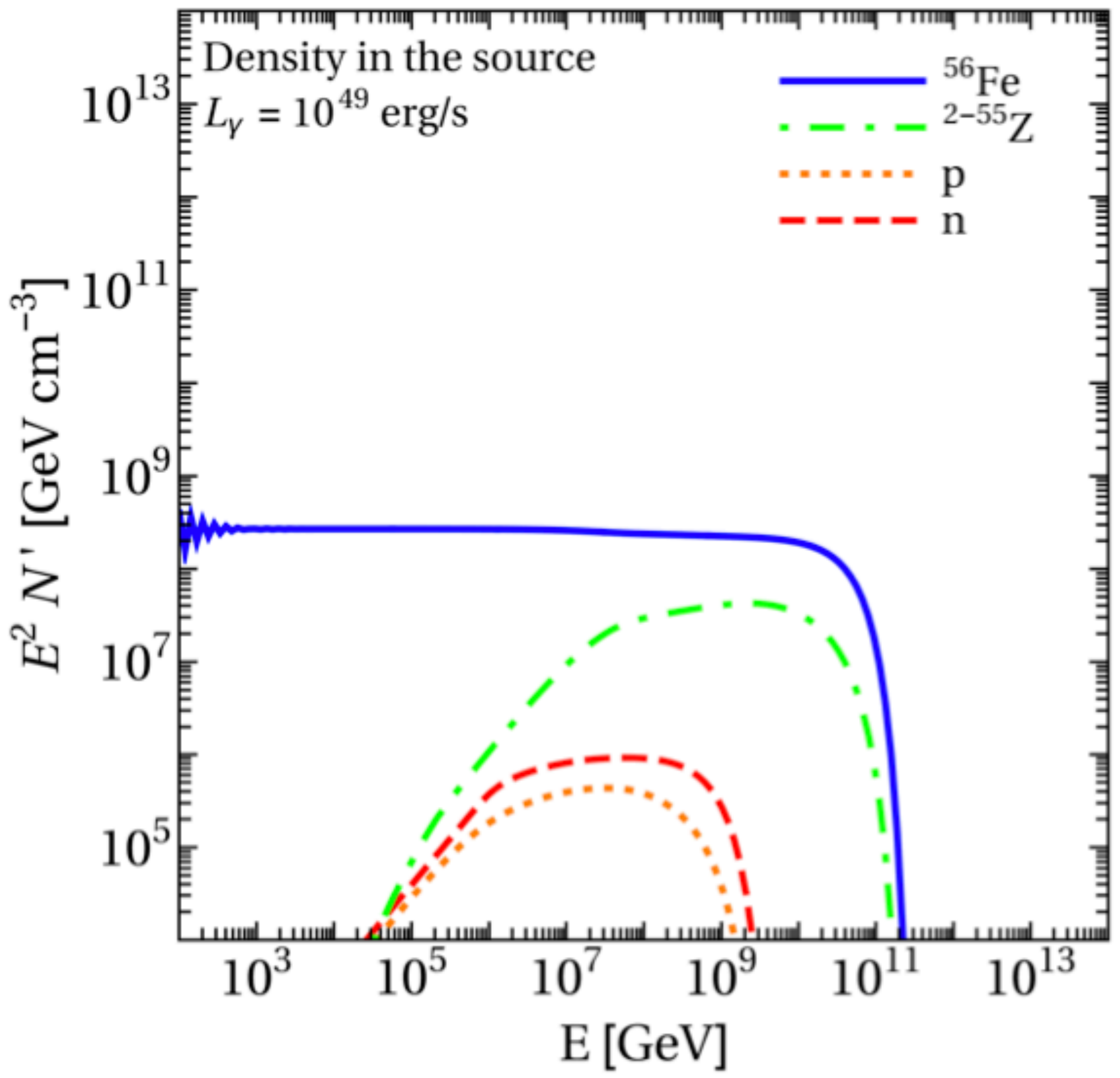
- To minimize the superposition of nuclear species, the population spectrum must be steep after the cutoff
- Combined with the finding on the source spectrum, **data favour the hypothesis of identical sources**
- Examples rated already (for GRB variability) in Globus et al MNRAS 2015; Heinze, Biehl,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

# The benefits from source-propagation models

Performing in-source interactions

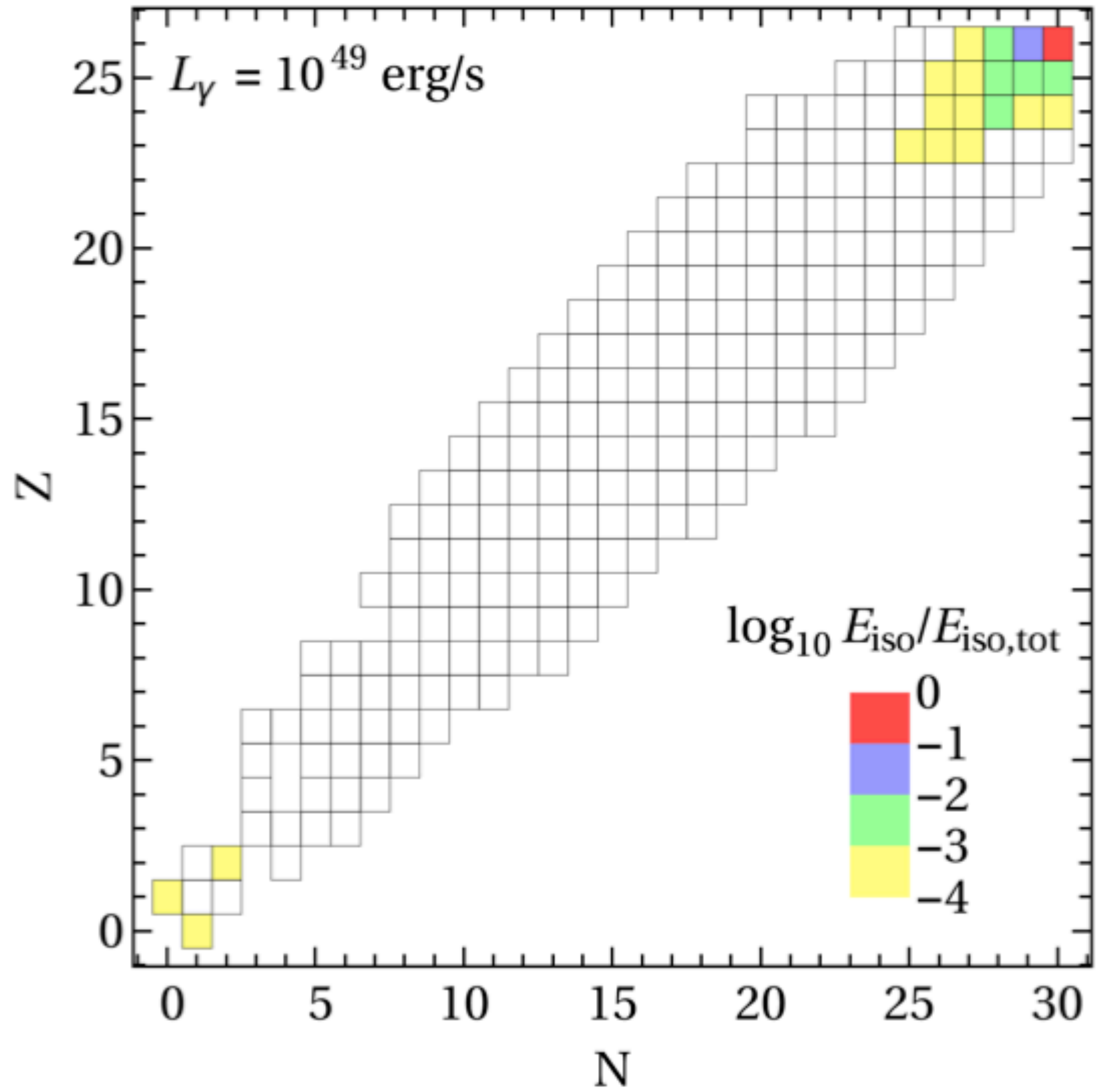
Interaction rates in the source environment (case of GRB)

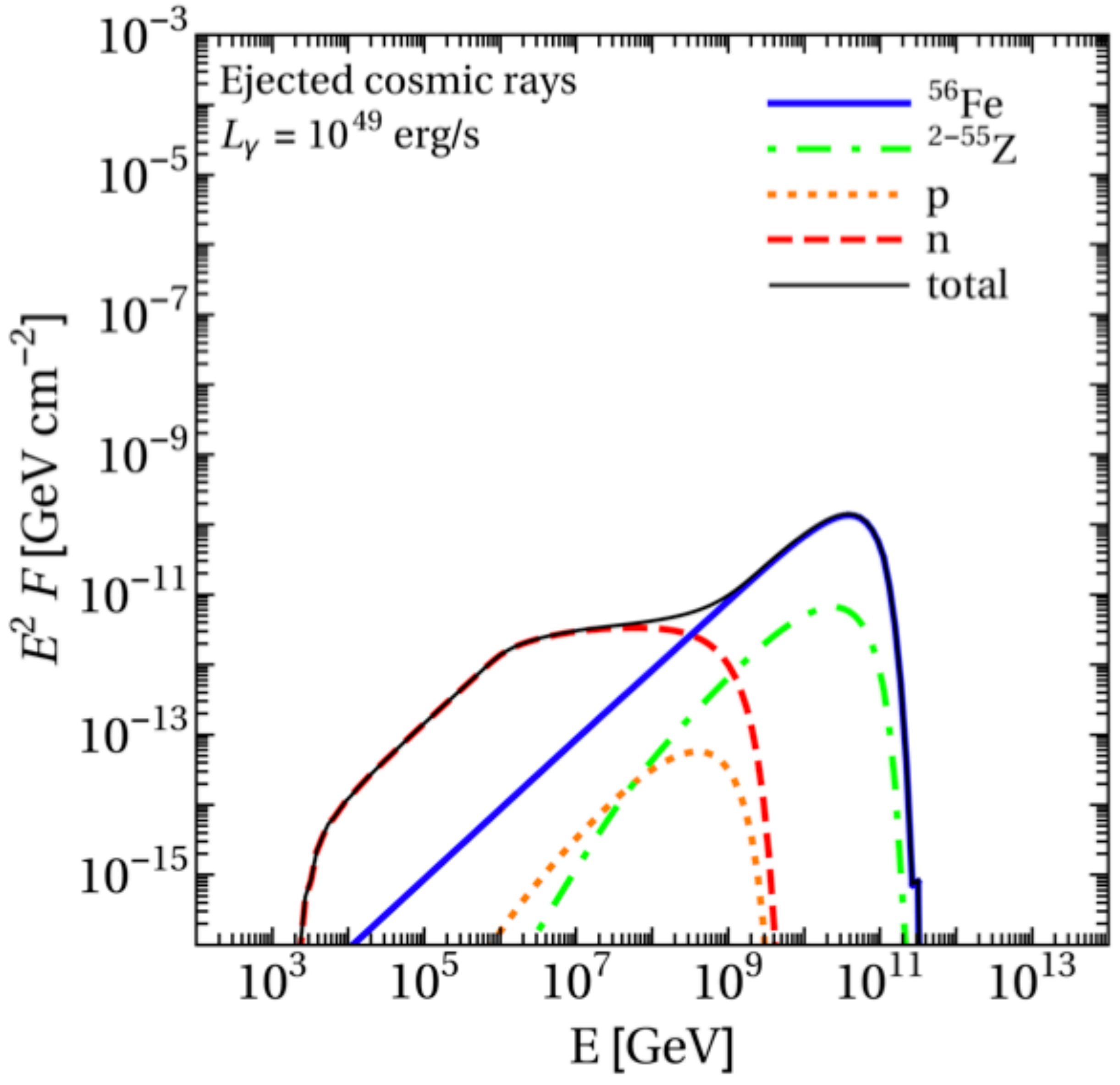


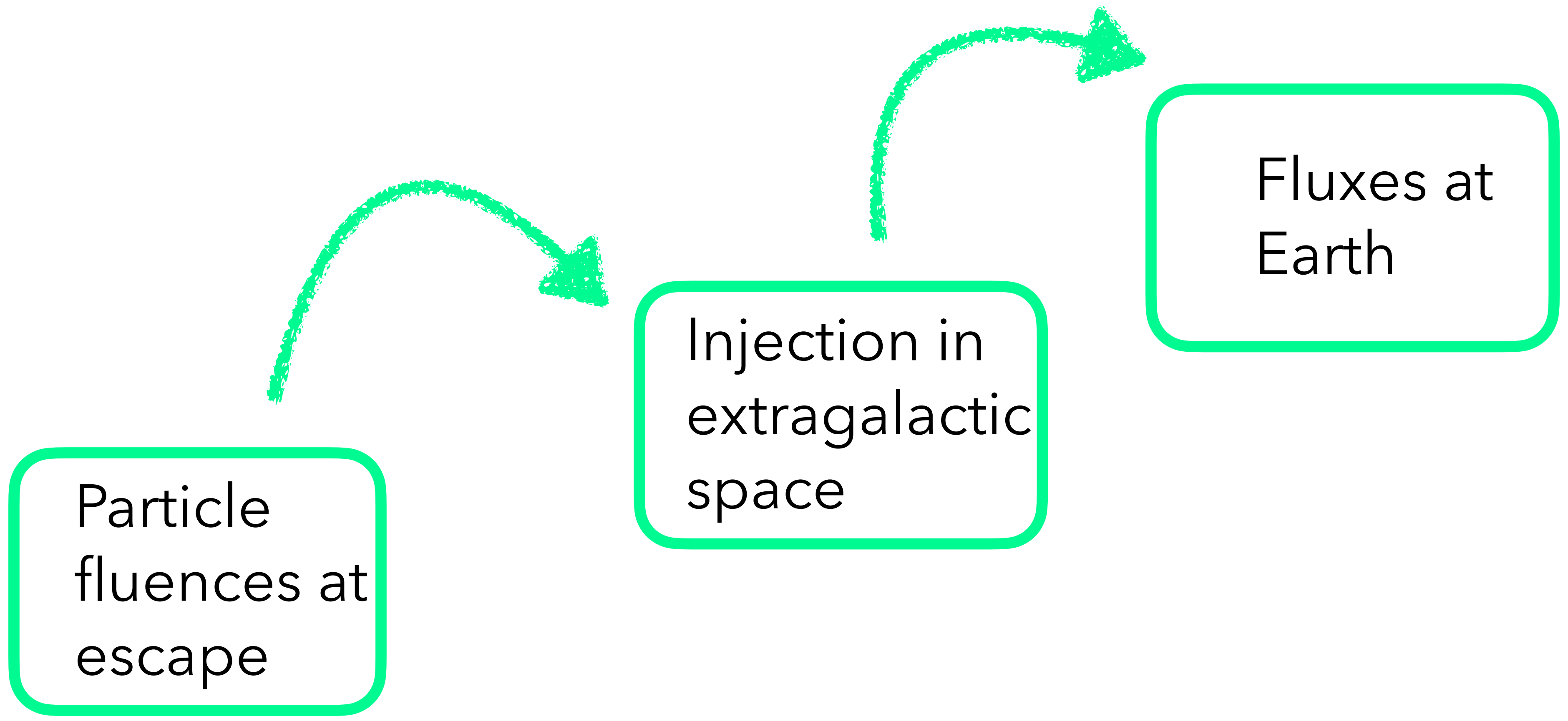


Particle densities in the source

Nuclear cascade






Particle fluences at escape

Injection in extragalactic space

Fluxes at Earth

- Test of UHECR spectra at escape; for different nuclear species:
  - Maximum energy: **Peters cycle** valid only if interactions are not efficient in the source environment (see also **Muzio et al PRD 2023**)
  - Slope: affected by escape mechanisms (see also **Baerwald et al ApJ 2013**)
    - Can motivate the ankle feature
- **Connect UHECRs to messengers produced in the same source environment and to the source characteristics**

Biehl, **DB** et al Astron. Astrophys. 2018

# The benefits from source-propagation models

- *Giacinti, Kachelriess, Kalashev, Neronov & Semikoz, PRD 2015*
- *Baerwald, Bustamante & Winter, ApJ 2015*
- *Globus, Allard, Mochkovitch & Parizot, MNRAS 2015*
- *Globus, Allard & Parizot, PRD 2015*
- *Unger, Farrar & Anchordoqui, PRD 2015*
- *Biehl, **DB**, Fedynitch & Winter, A&A 2018*
- *Biehl, **DB**, Lunardini & Winter, Sci.Rep. 2018*
- *Fang & Murase, Nature Phys. 2018*
- *Supanitsky Cobos & Echtegoyen, PRD 2018*
- *Zhang, Murase, Kimura, Horiuchi & Meszaros, PRD 2018*
- ***DB**, Biehl & Winter, ApJ 2019*
- *Muzio, Unger & Farrar, PRD 2019*
- *Zhang & Murase, PRD 2019*
- *Heinze, Biehl, Fedynitch, **DB**, Rudolph & Winter, MNRAS 2020*
  - Investigates the mixed composition at acceleration
- *Rodrigues, Heinze, Palladino, van Vliet & Winter, PRL 2021*
  - Shows different contributions from subgroups of blazars to UHECRs and neutrinos
- *Muzio, Unger & Farrar, PRD 2022*
- *Condorelli, **DB**, Peretti & Petrera, PRD 2023*
  - Includes the treatment of hadronic and photo-hadronic interactions in the nucleus of starburst galaxies

Some works developing **source-propagation models**, including **multimessenger approaches;**

**Summary conclusion: opposite conditions for emission of UHECRs and high-energy neutrinos**

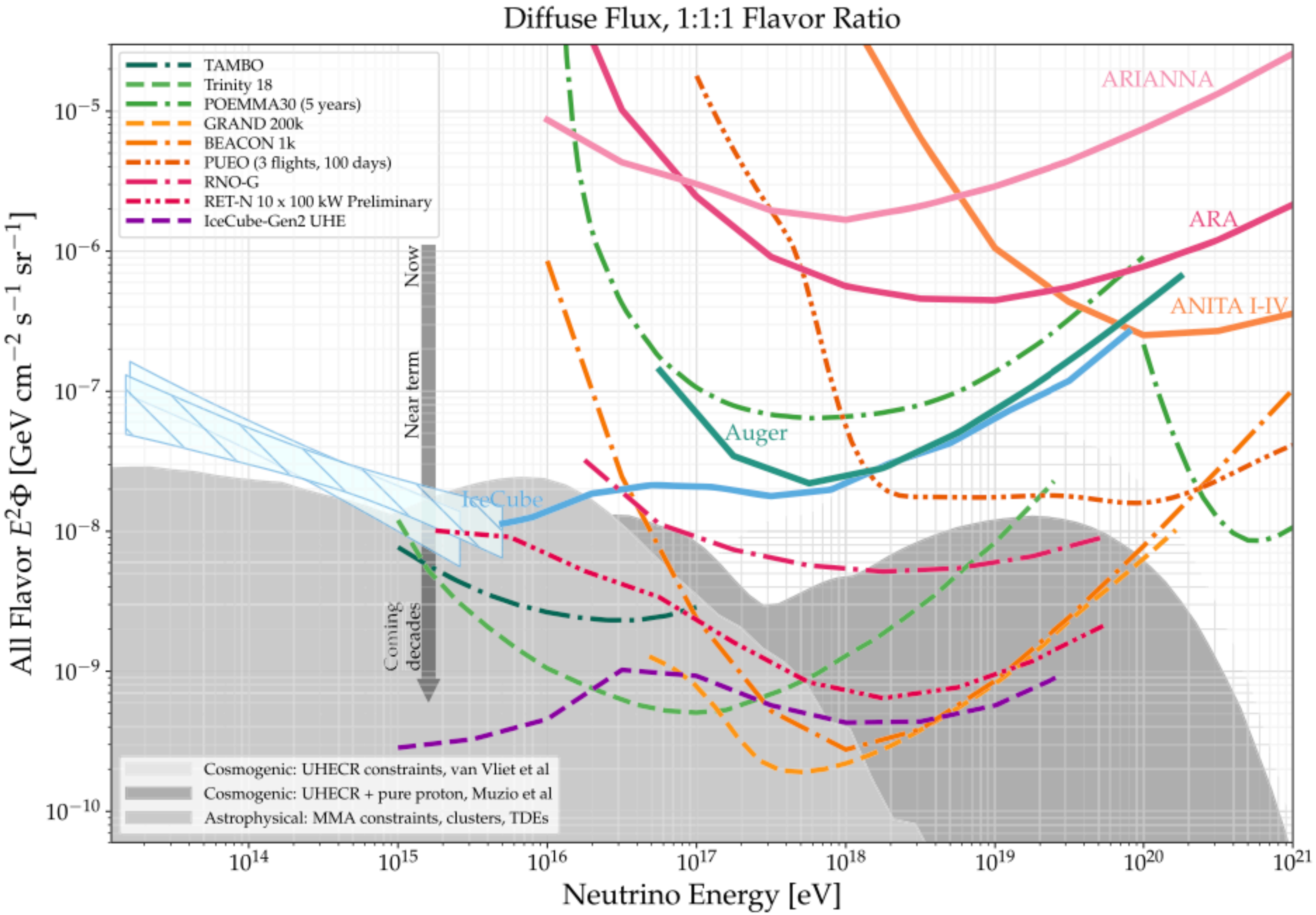
# MULTIMESSENGER ASPECTS

## Focus on neutrinos

# State-of-the-art

## Measured diffuse flux

- Measurement of **astrophysical neutrino flux** with energy spectrum consistent with a single power law spectrum with best-fit index 2.87
- Upper limit for **cosmogenic neutrino flux** and expected sensitivities from future experiments



IceCube ICRC2023; Ackermann et al. JHEA 2022

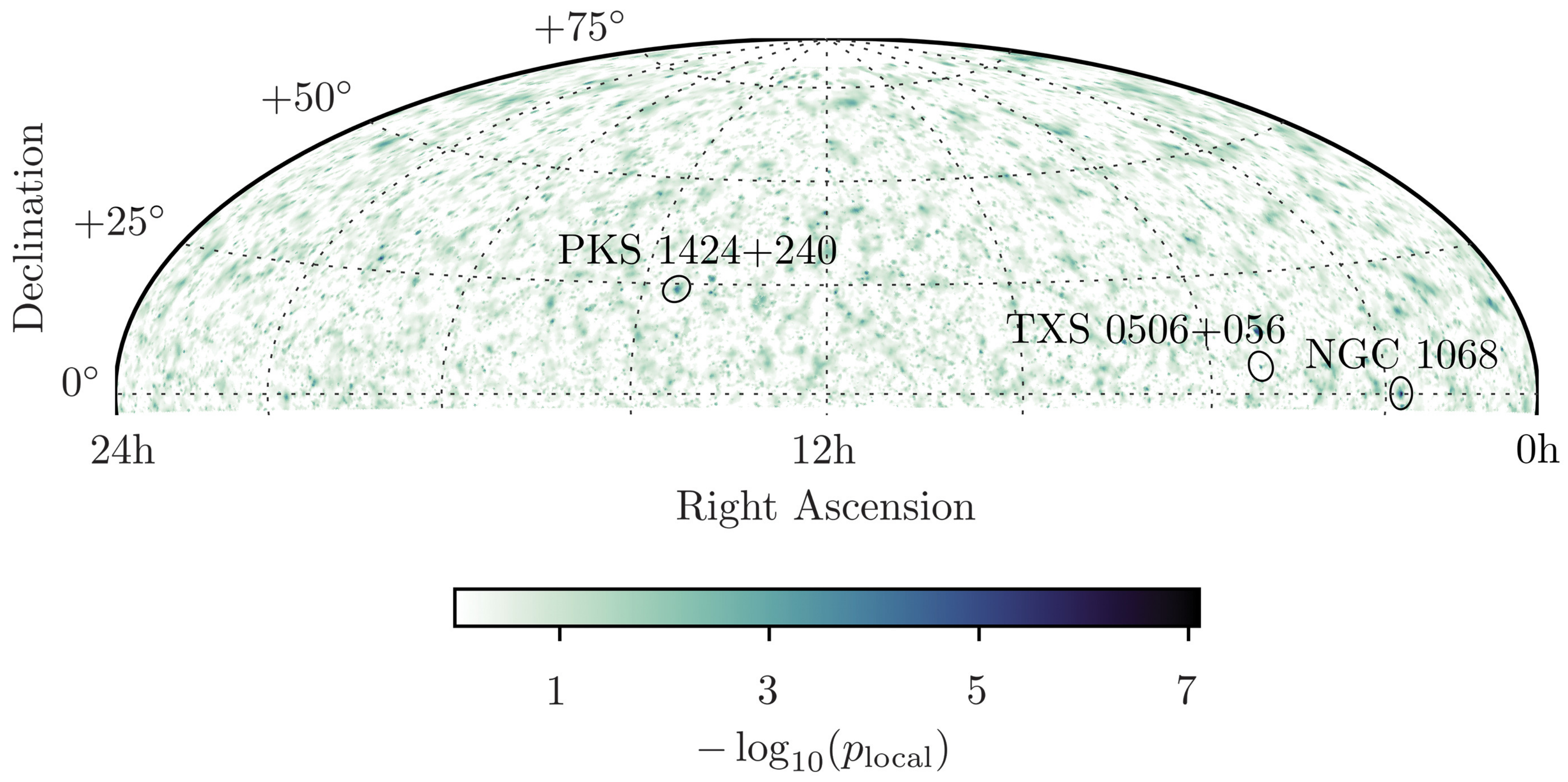
# State-of-the-art

## Findings from multimessenger alerts

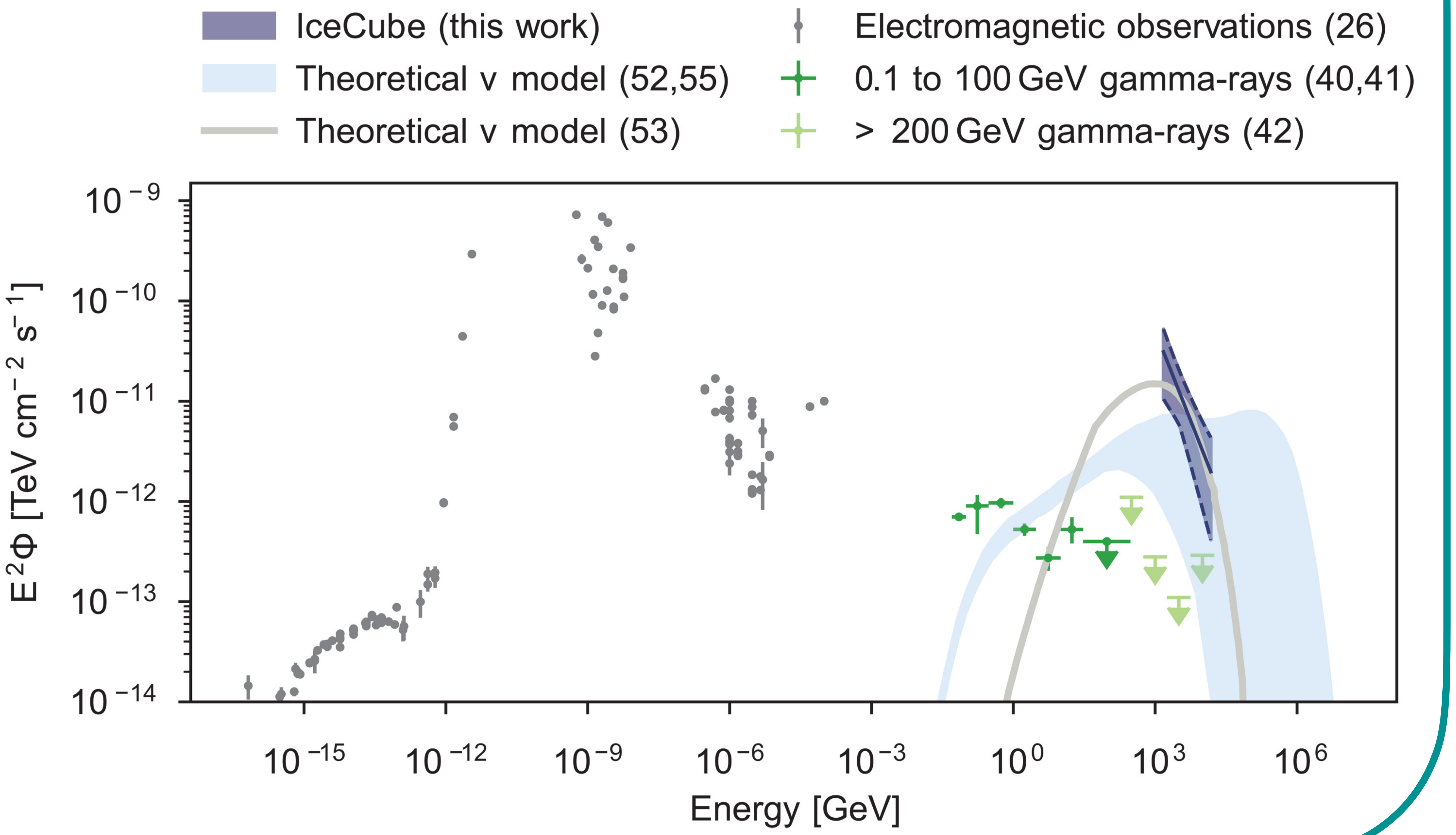
- The detection of a single HE neutrino is promptly communicated to the astronomical community so that targeted observations can be collected to identify, for instance, an EM counterpart

### Neutrinos from **blazars**

- 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



IceCube, Science 2022



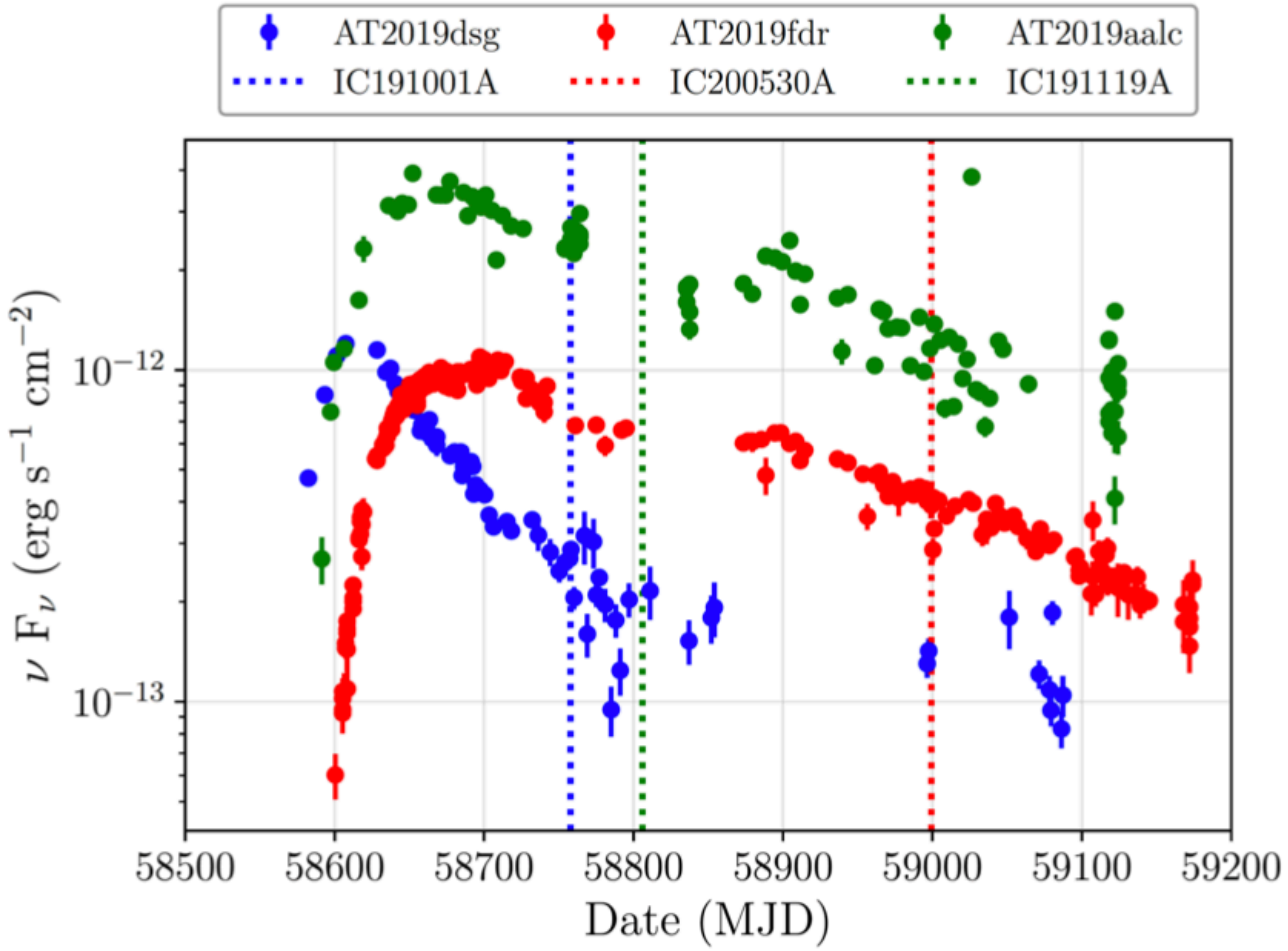
- Nov. 2022: IceCube Neutrino Observatory published an archival search for neutrinos, finding 79 events associated to **NGC1068**

# State-of-the-art

## Findings from multimessenger alerts

- The detection of a single HE neutrino is promptly communicated to the astronomical community so that targeted observations can be collected to identify, for instance, an EM counterpart

Neutrinos from **tidal disruption events**



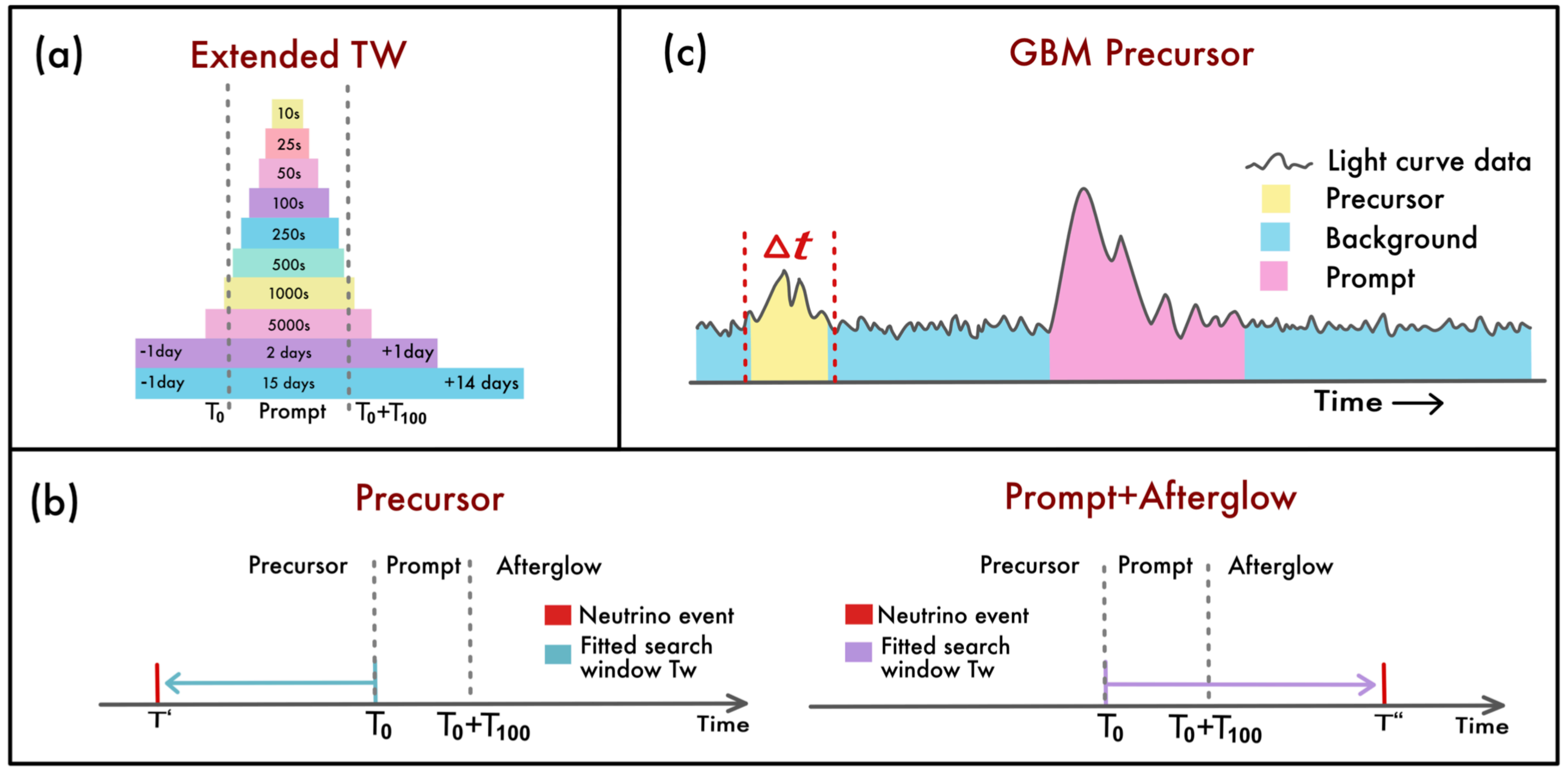
**Simeon Reusch @ ECRS 2022**

- Zwicky Transient Facility identified AT2019dsg (Stein et al. Nature Astron. 2021) and AT2019fdr (Reusch et al. PRL 2021) as optical counterparts of two IceCube neutrinos
- TDEs can be accompanied by an echo due to reprocessing of BB and X-ray radiation into the IR by surrounding dust -> identification of a third TDE, AT2019aalc, as counterpart of another IceCube neutrino event (van Veltzen et al. MNRAS 2021)

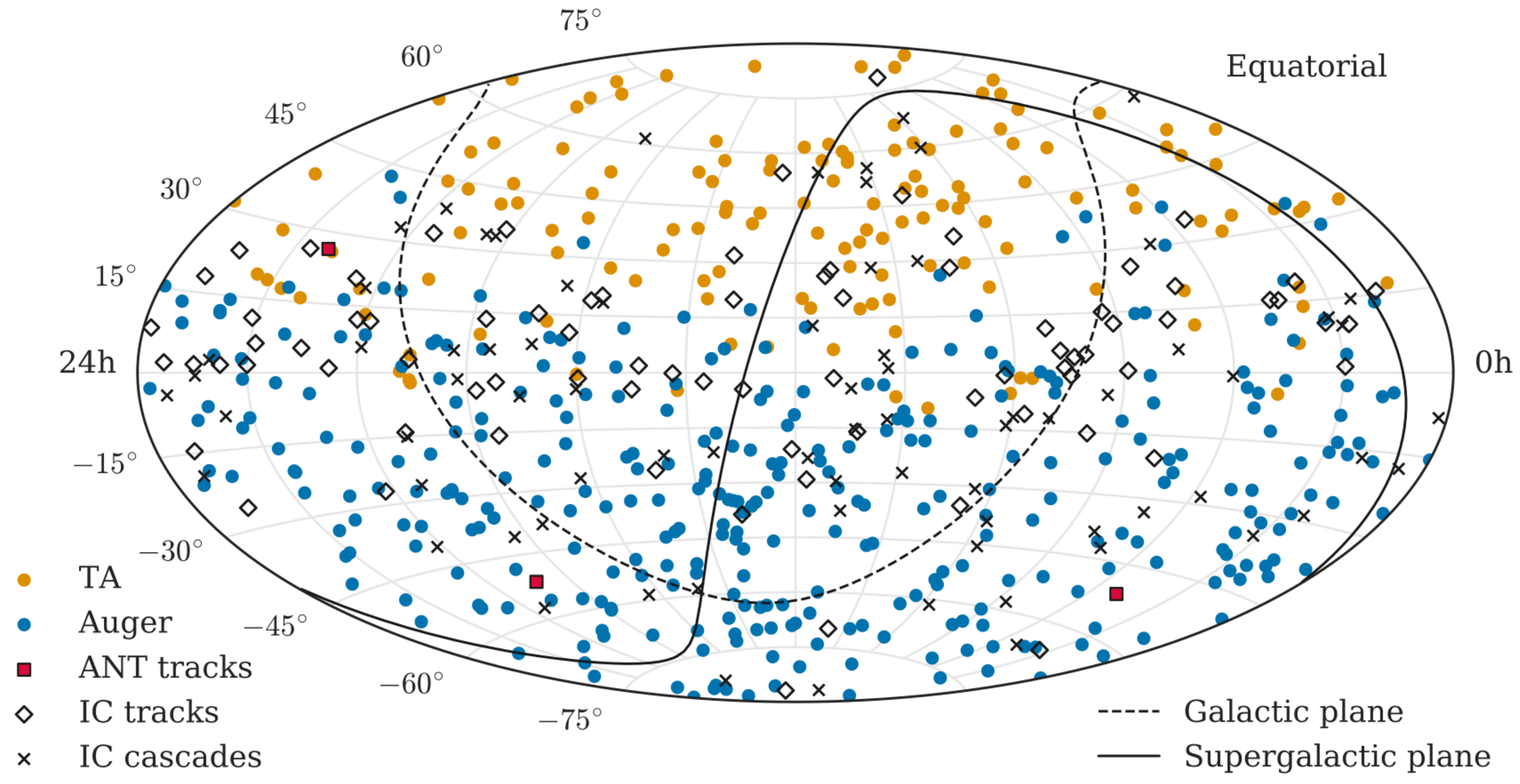
# State-of-the-art

## Directional and time-dependent searches

- Searches for cross-correlation with gamma-ray sources AMON Team ApJ 2020
- Searches for correlation of high-energy neutrino arrival directions with known high-energy gamma-ray sources (blazars, ultra-luminous infrared sources, radio galaxies) IceCube Coll. ApJ 2022
- Time-domain searches performed for neutrino emission from blazars, gamma-ray bursts, fast radio bursts, tidal disruption events, supernovae IceCube Coll. ApJ 2015, IceCube Coll. ApJ 2015, IceCube Coll. ApJ 2015, Fermi-LAT, ASAS-SN and IceCube Coll. ApJ 2019, IceCube Coll. ApJ 2020, Stein et al. Nature Astron. 2021
- Searches for coincidences with gravitational wave events (IceCube Coll. ApJL 2020) and cosmic rays (IceCube, TA, Auger and Antares Coll. ApJ 2022)



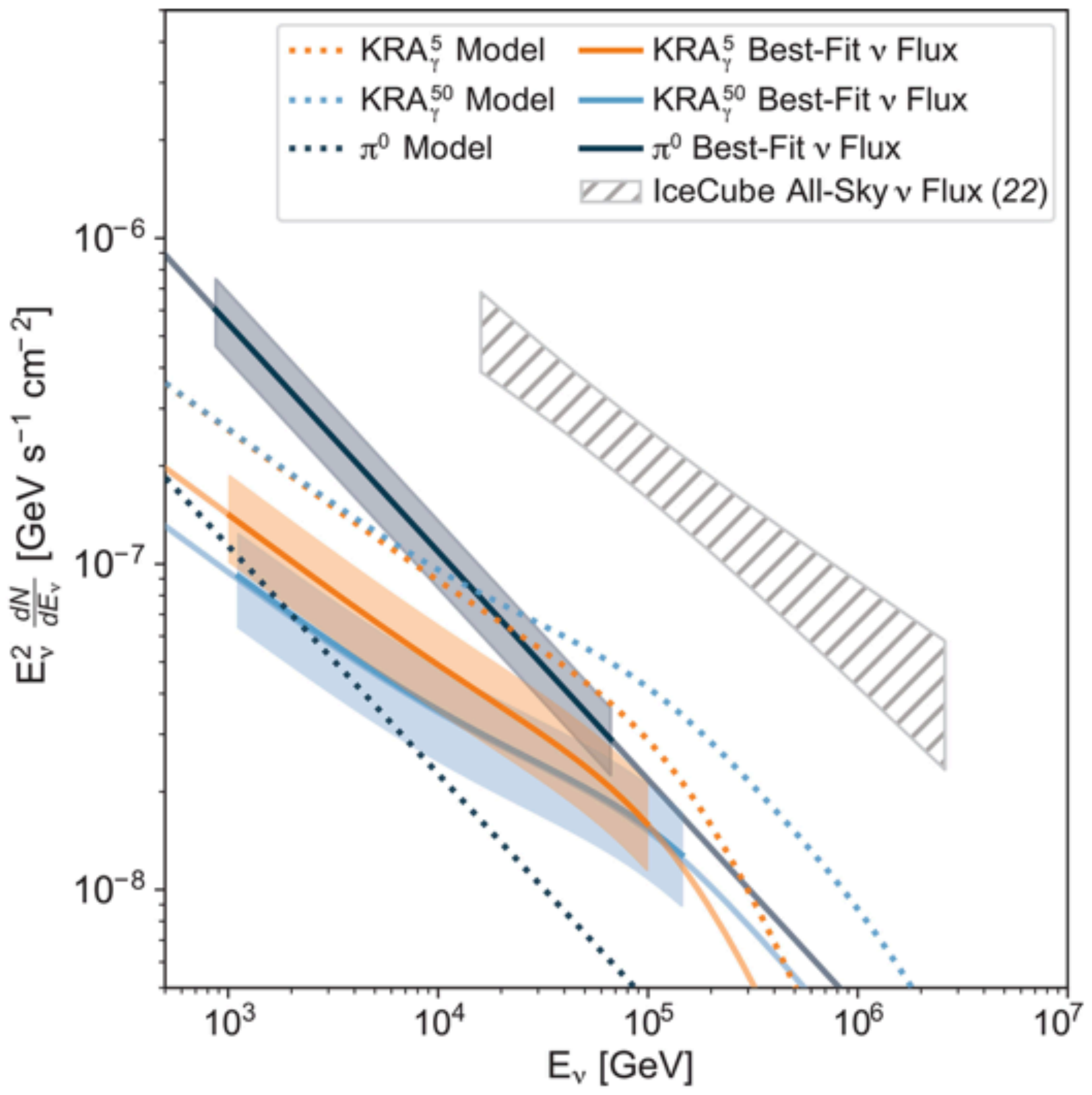
- Detail of a time-dependent search



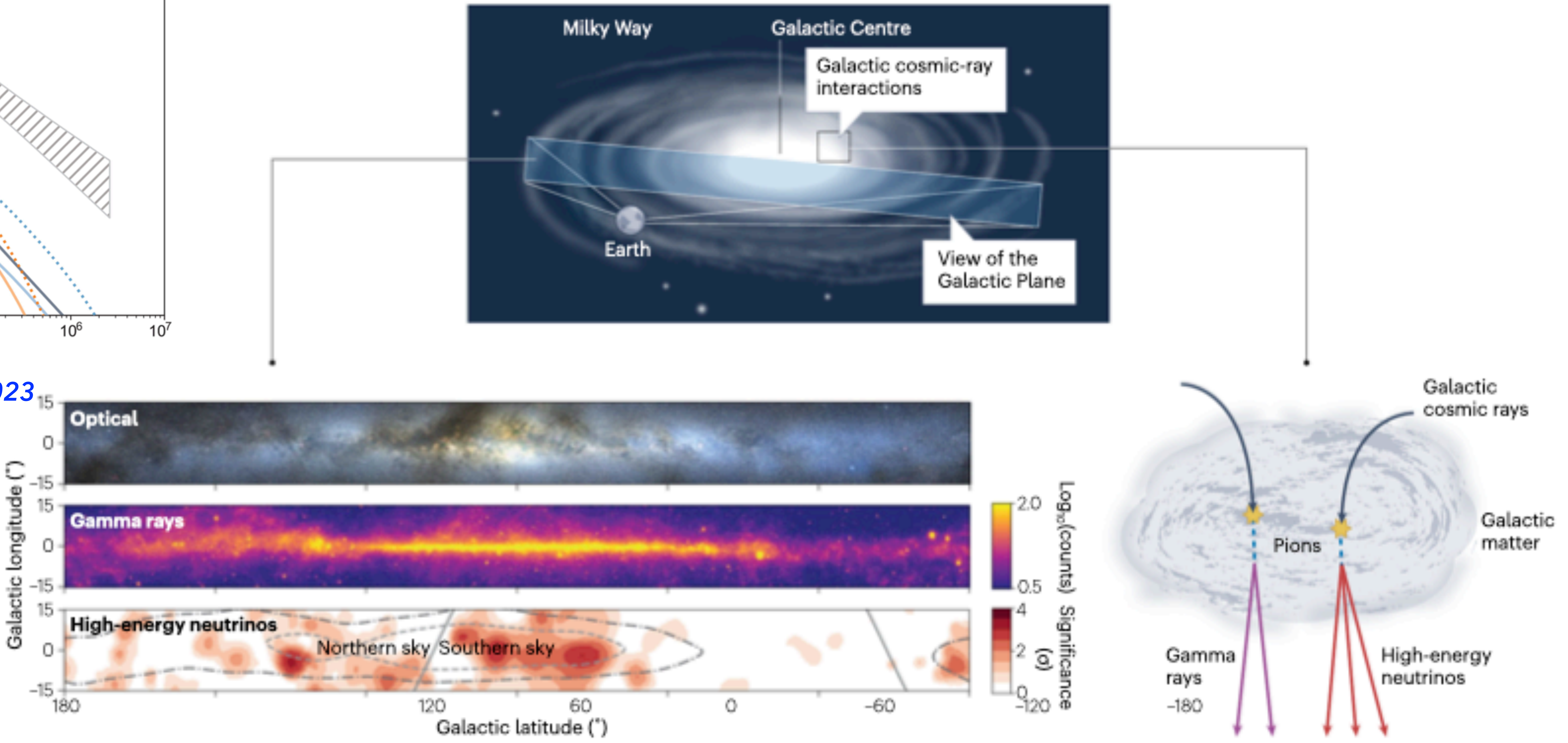
- Example of a directional search

# State-of-the-art

## Neutrinos from the Milky Way



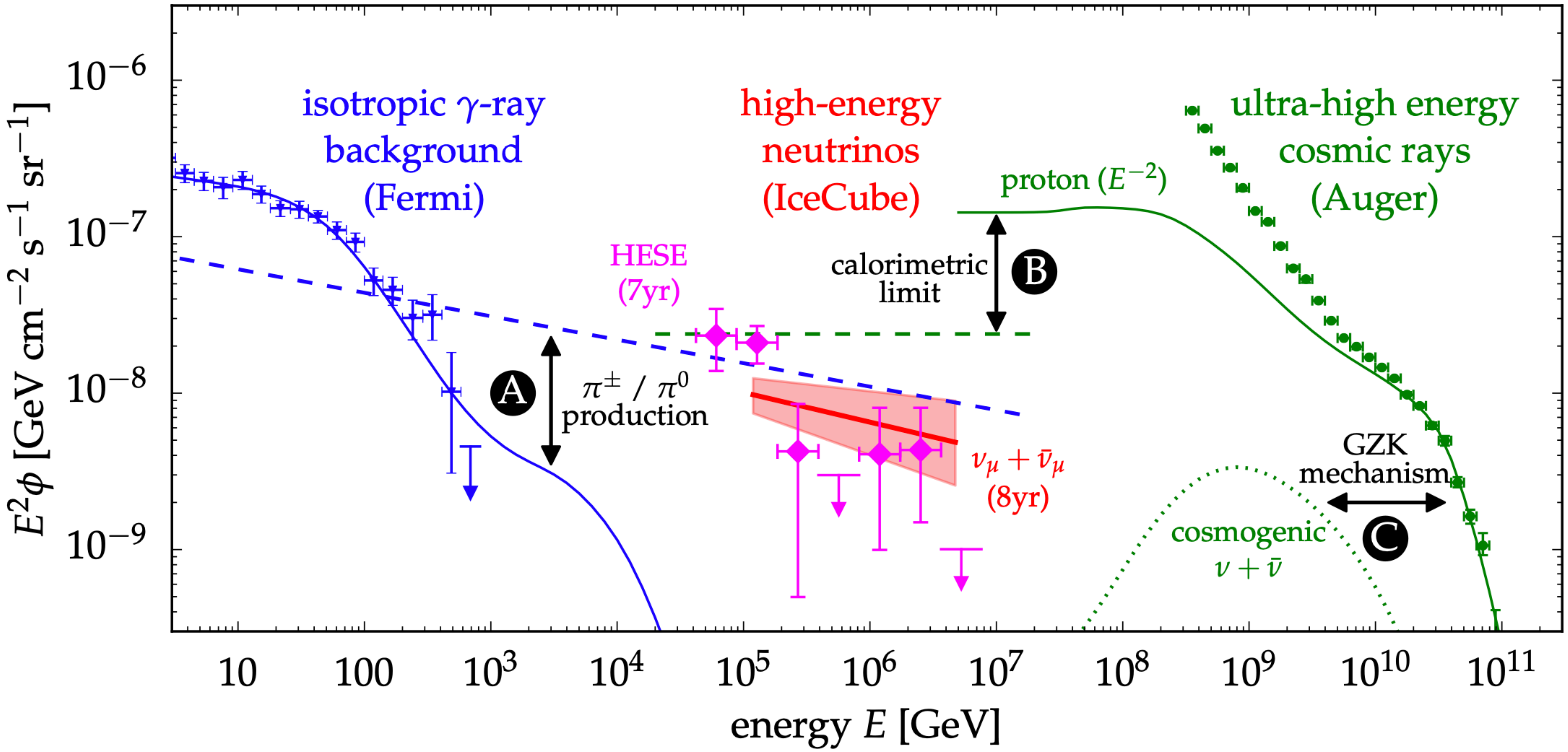
**IceCube Coll.** ***Science 2023***



**Bustamante, Nature Reviews 2023**

# State-of-the-art

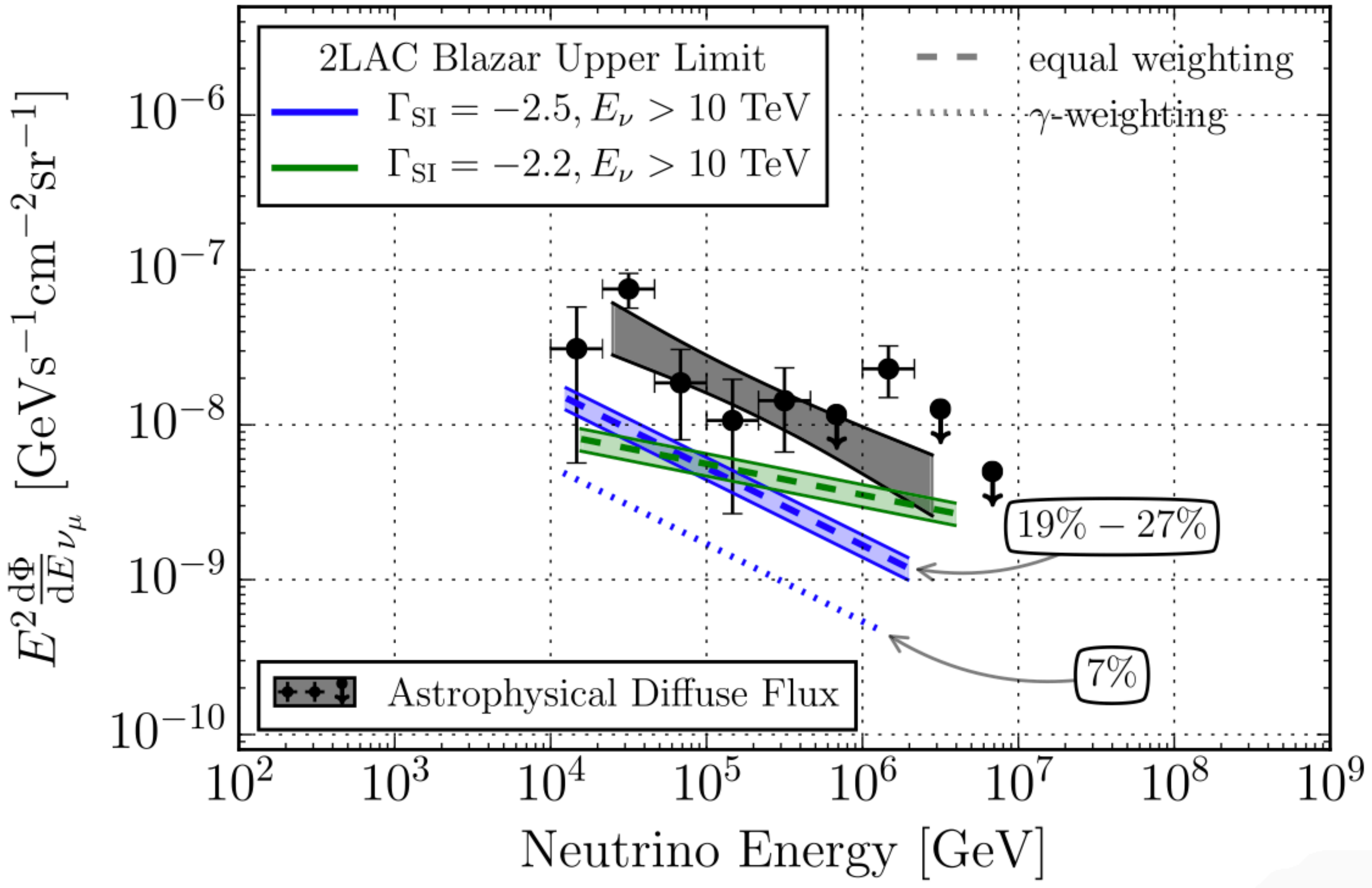
# The **multimessenger** picture

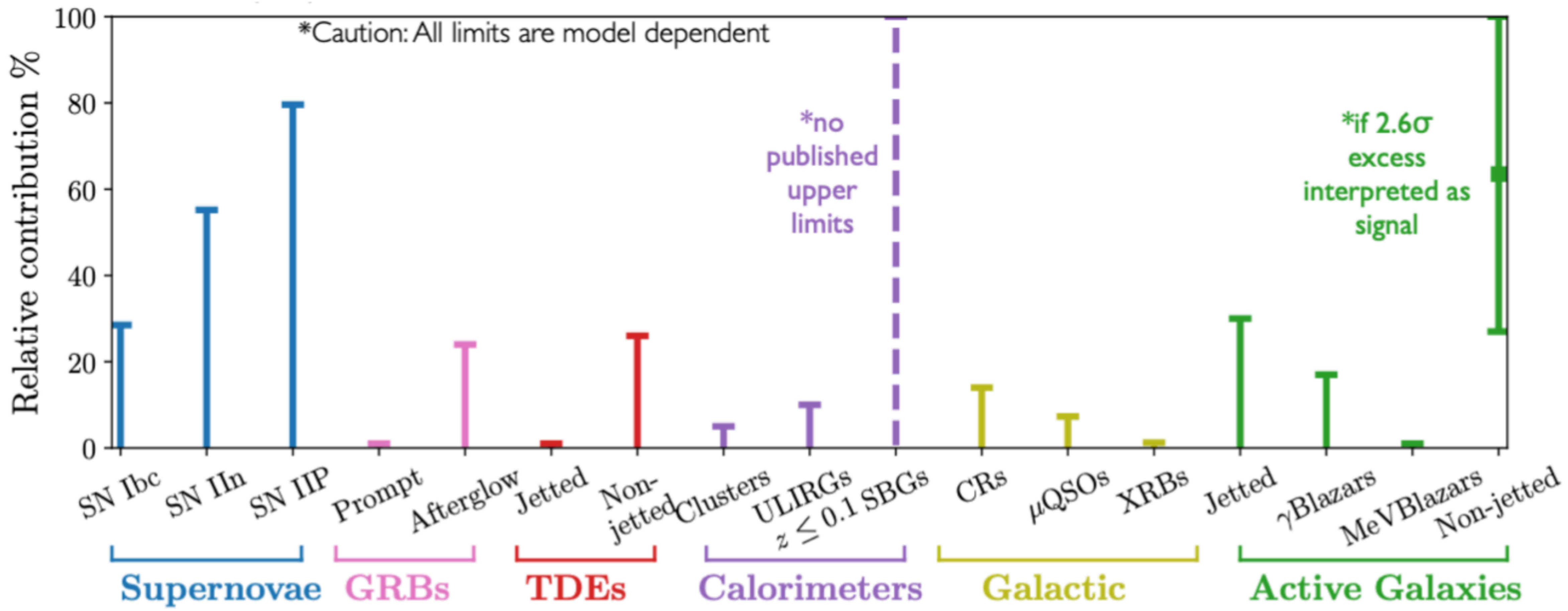


**Ahlers, EPJ Web Conf 2016**

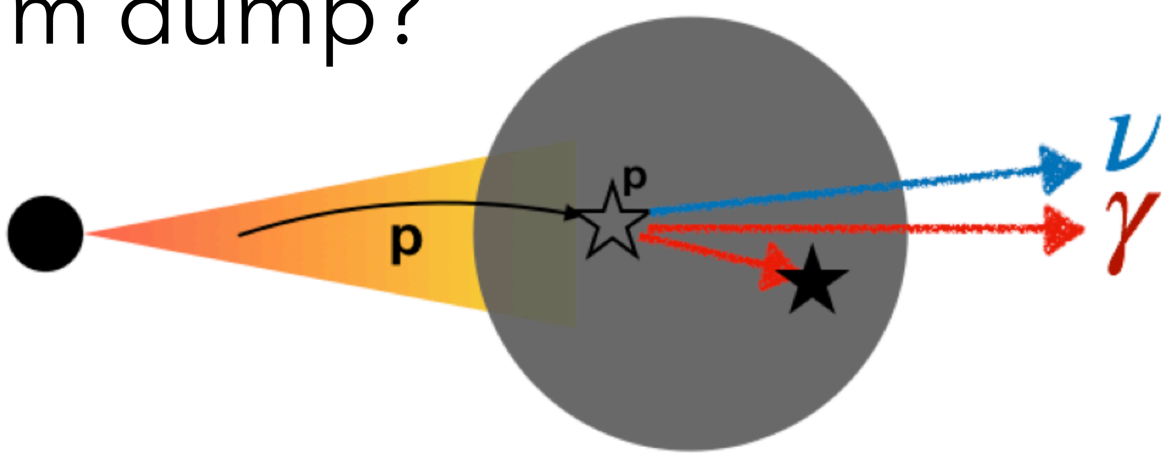
# State-of-the-art

- **The neutrino-blazar and neutrino-TDE associations are not sufficient for establishing a clear connection between neutrino and astrophysical sources**
- A wide range of candidate neutrino-source classes has been investigated and found no evidence for neutrinos originating from such sources; constraints from:
  - Blazars (from Fermi catalog): < 10% of diffuse flux IceCube ApJ 2017
  - Non-blazars: indirect constraints from Fermi-LAT observations
    - Hints towards neutrino sources that are gamma-ray opaque, Murase et al PRL 2016: dense gas cloud near the cosmic-ray source acting as a beam dump? Vereecken & de Vries arxiv:2004.03435



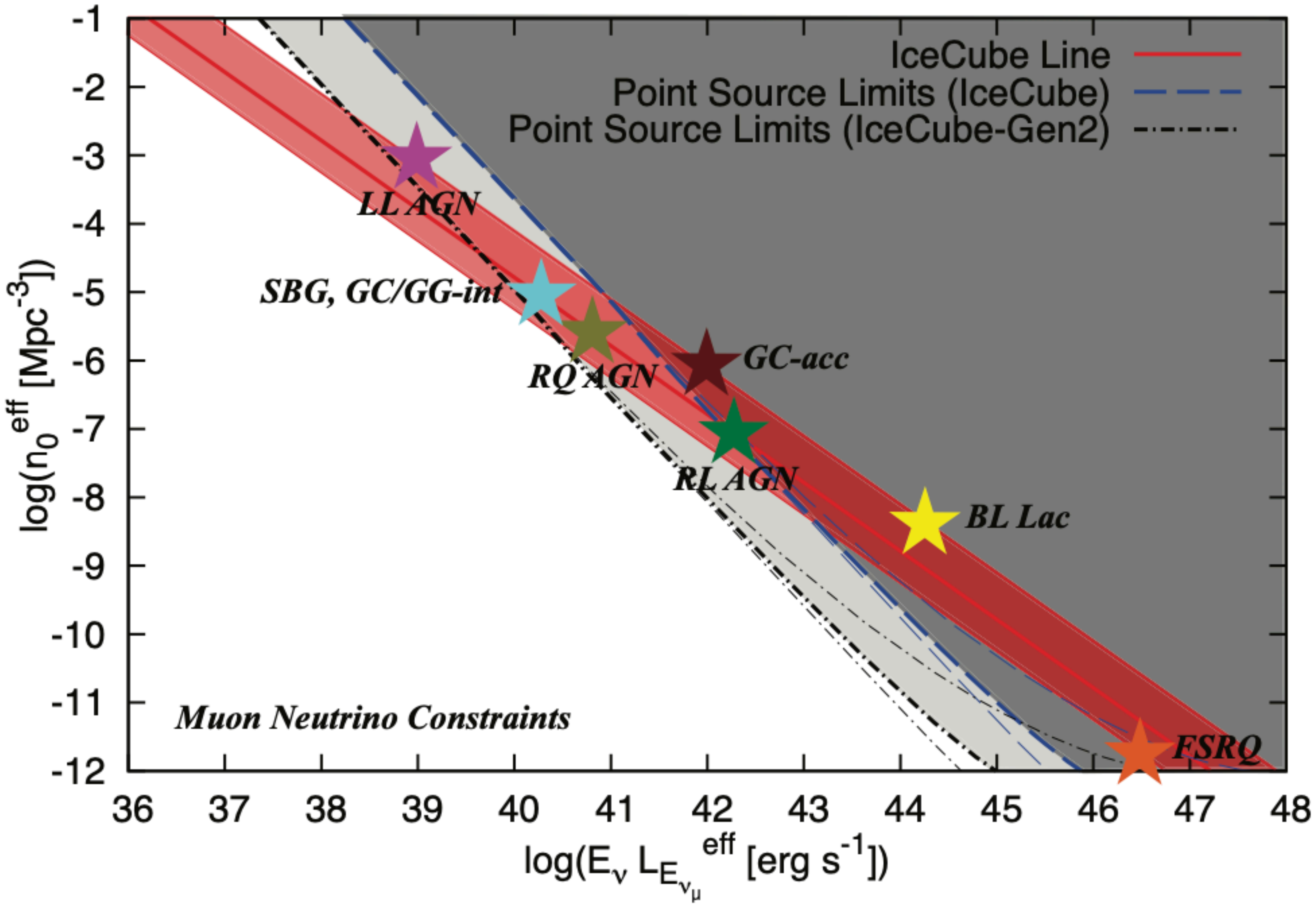


Oikonomou, ICRC2021



# State-of-the-art

- By measuring the diffuse flux, the density of sources multiplied by the luminosity can be constrained, as done in Murase & Waxmann PRD 2016; similar study in Palladino et al. MNRAS 2020



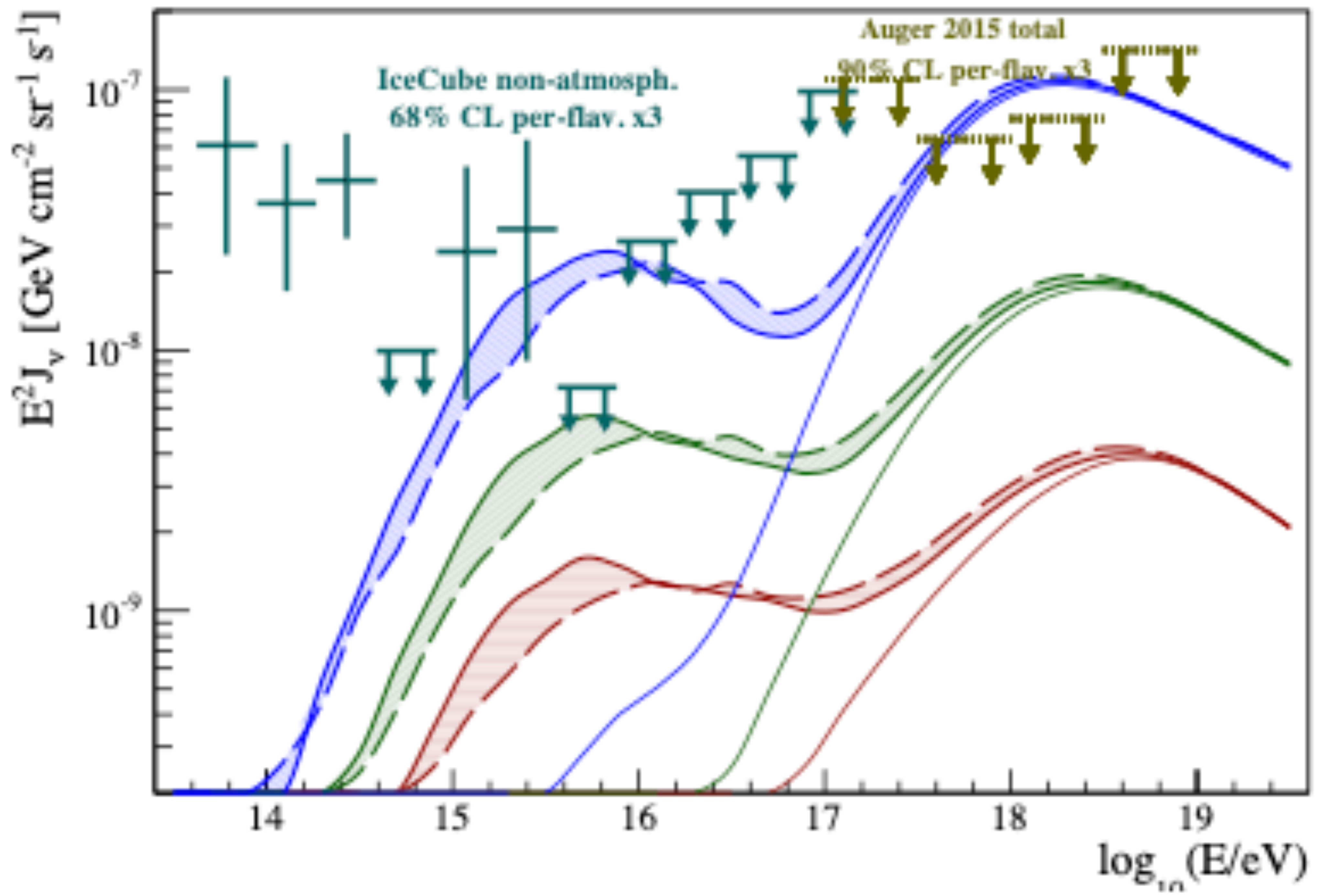
Open questions

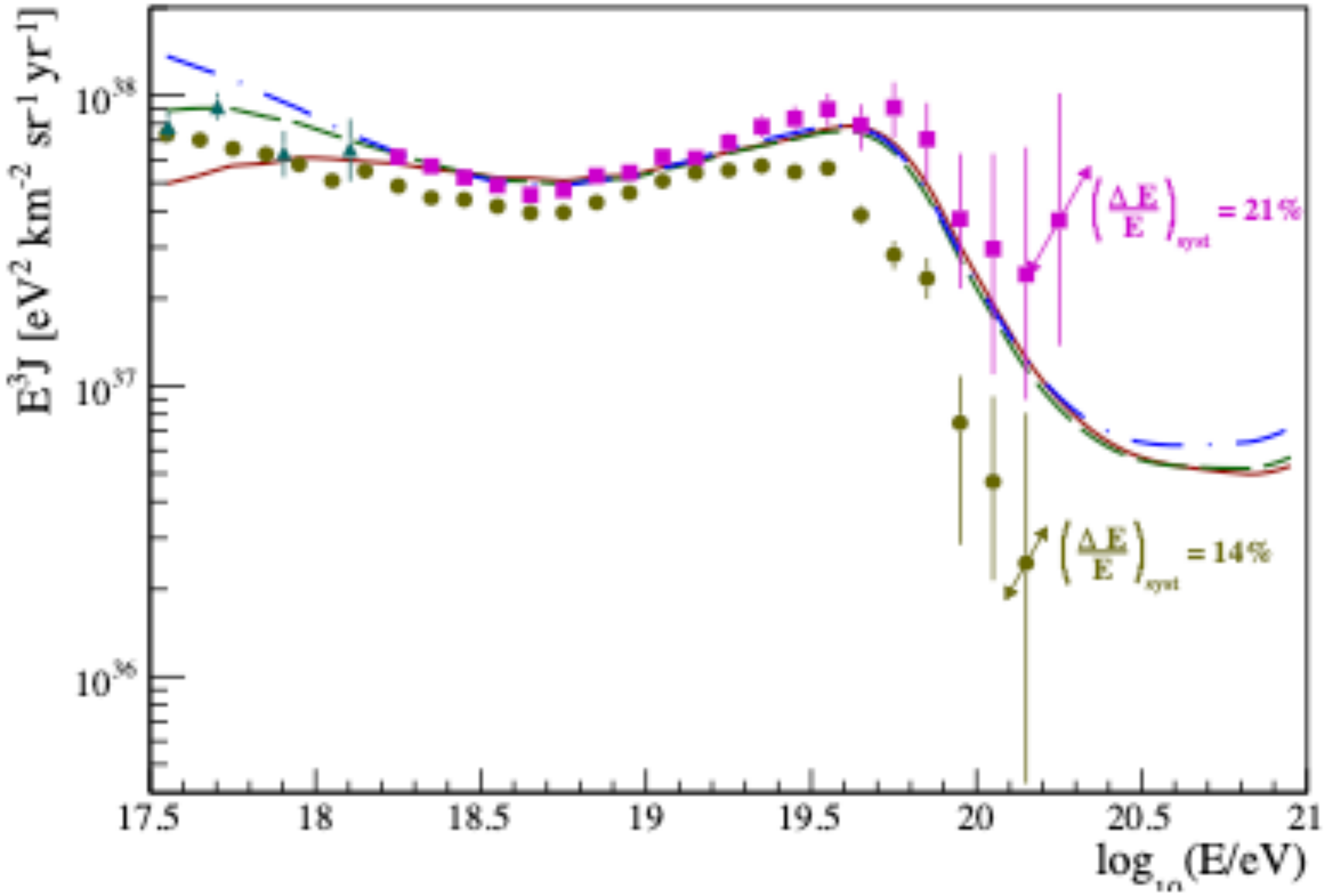
- Which source class(es) power the astrophysical neutrino flux?
- What is the cosmogenic neutrino flux expected at Earth?
- How can we investigate the mechanisms at work in the possible sources and in the extragalactic space?
- **Is there any advantage from a multi messenger approach, towards the understanding of UHECR characteristics?**

# COSMOGENIC NEUTRINOS

## Neutrinos trace the distribution of UHECR sources

# UHECR flux at Earth and the corresponding cosmogenic neutrinos





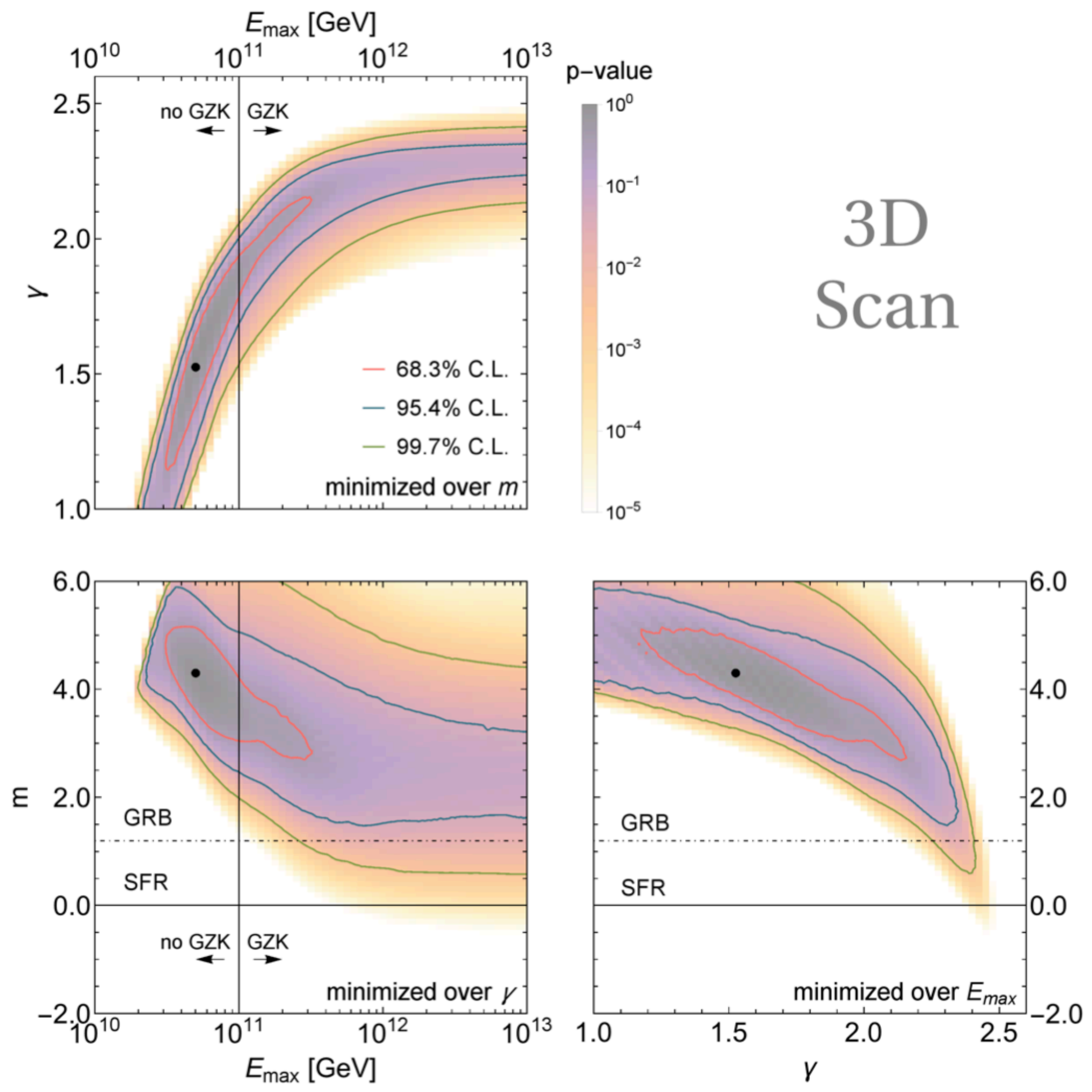
Effect of **cosmological evolution** of sources $(1+z)^m$

$$J(E) = \frac{c}{4\pi}\int dz \left|\frac{dt}{dz}\right| \tilde{Q}(E_g(E,z),z)\frac{dE_g}{dE}$$

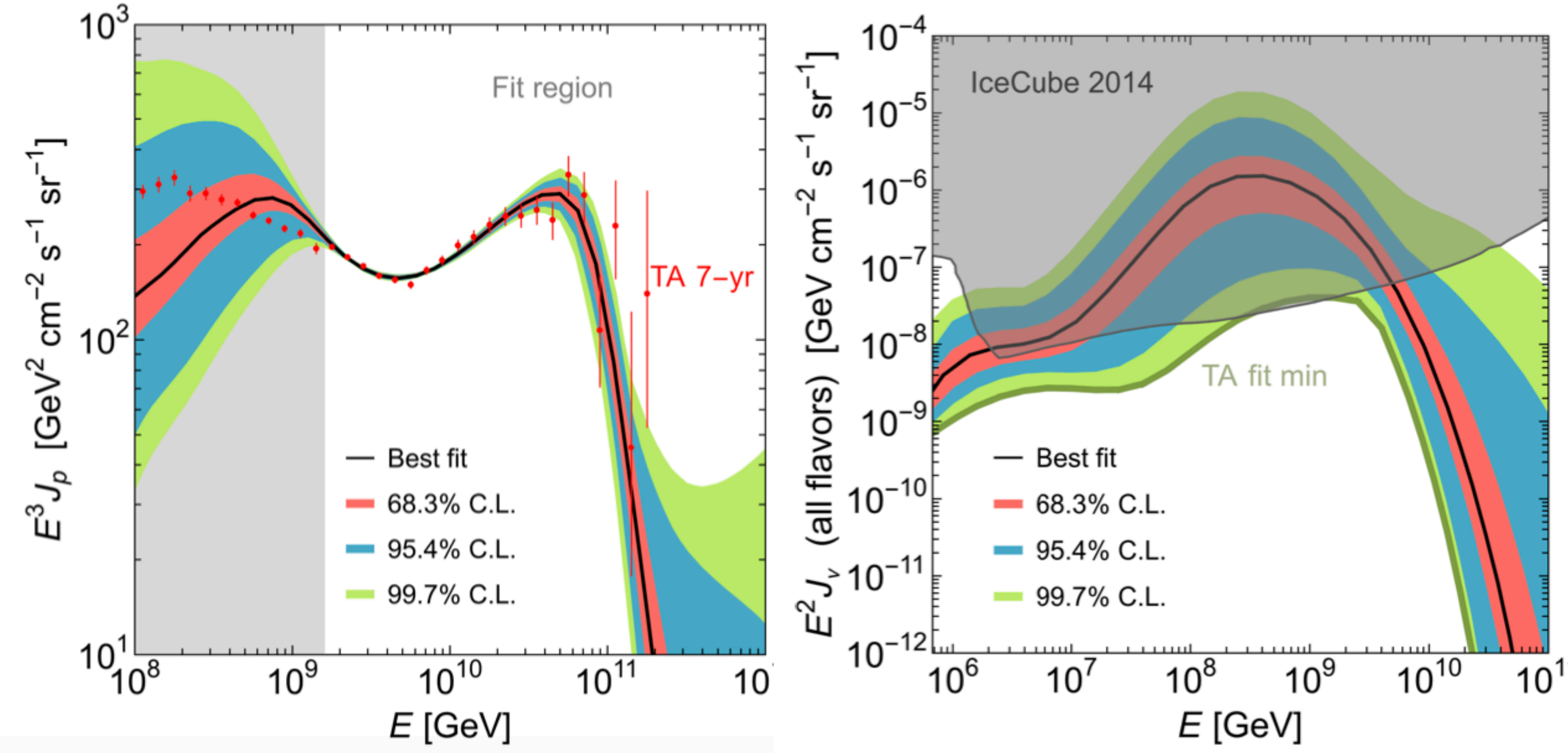
- On cosmic-ray spectra the effect is much less relevant than for neutrinos
- Cosmogenic neutrinos could improve the understanding of the **distribution of UHECR sources**

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

# UHECR flux at Earth and the corresponding cosmogenic neutrinos



3D Scan

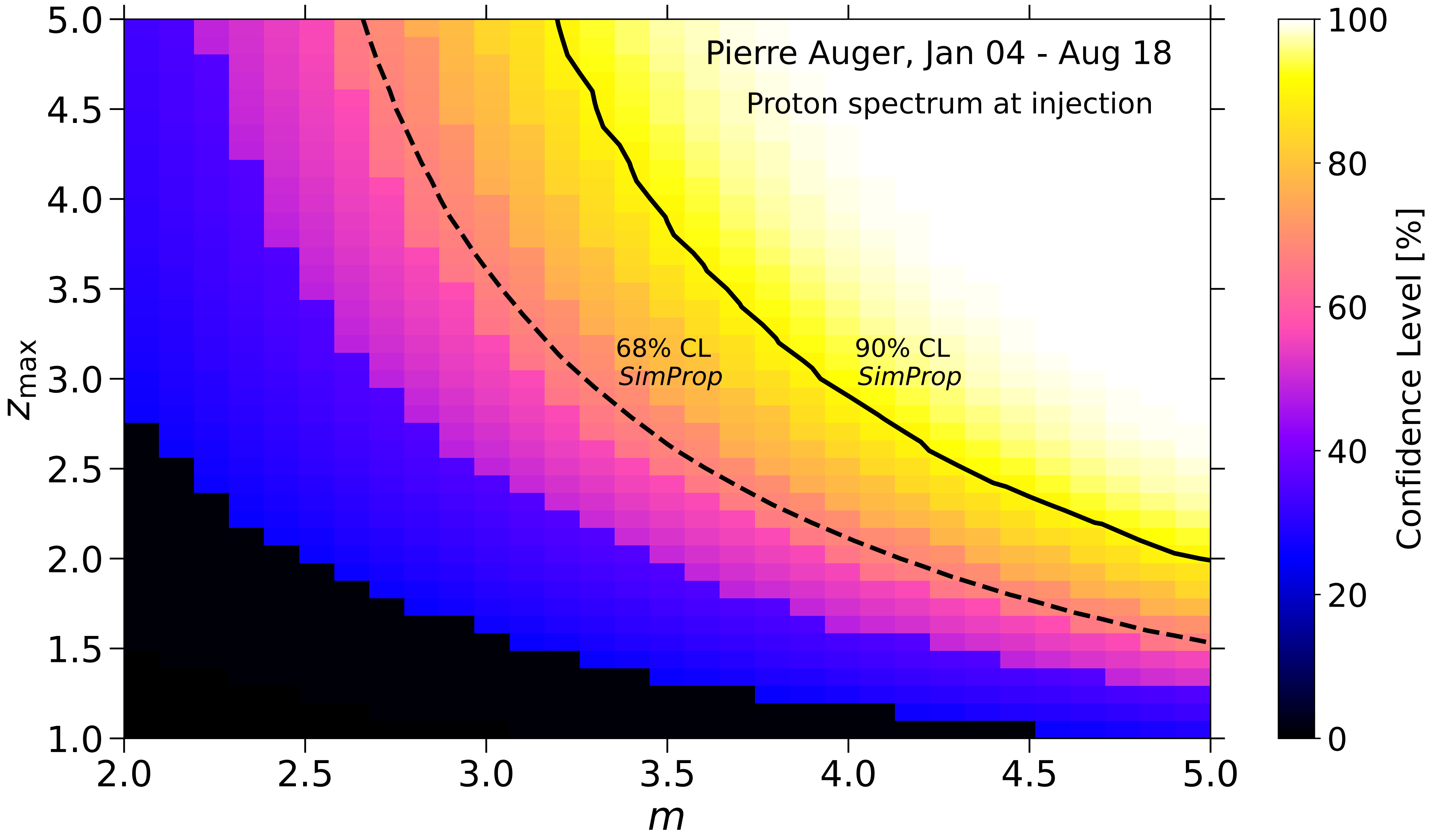


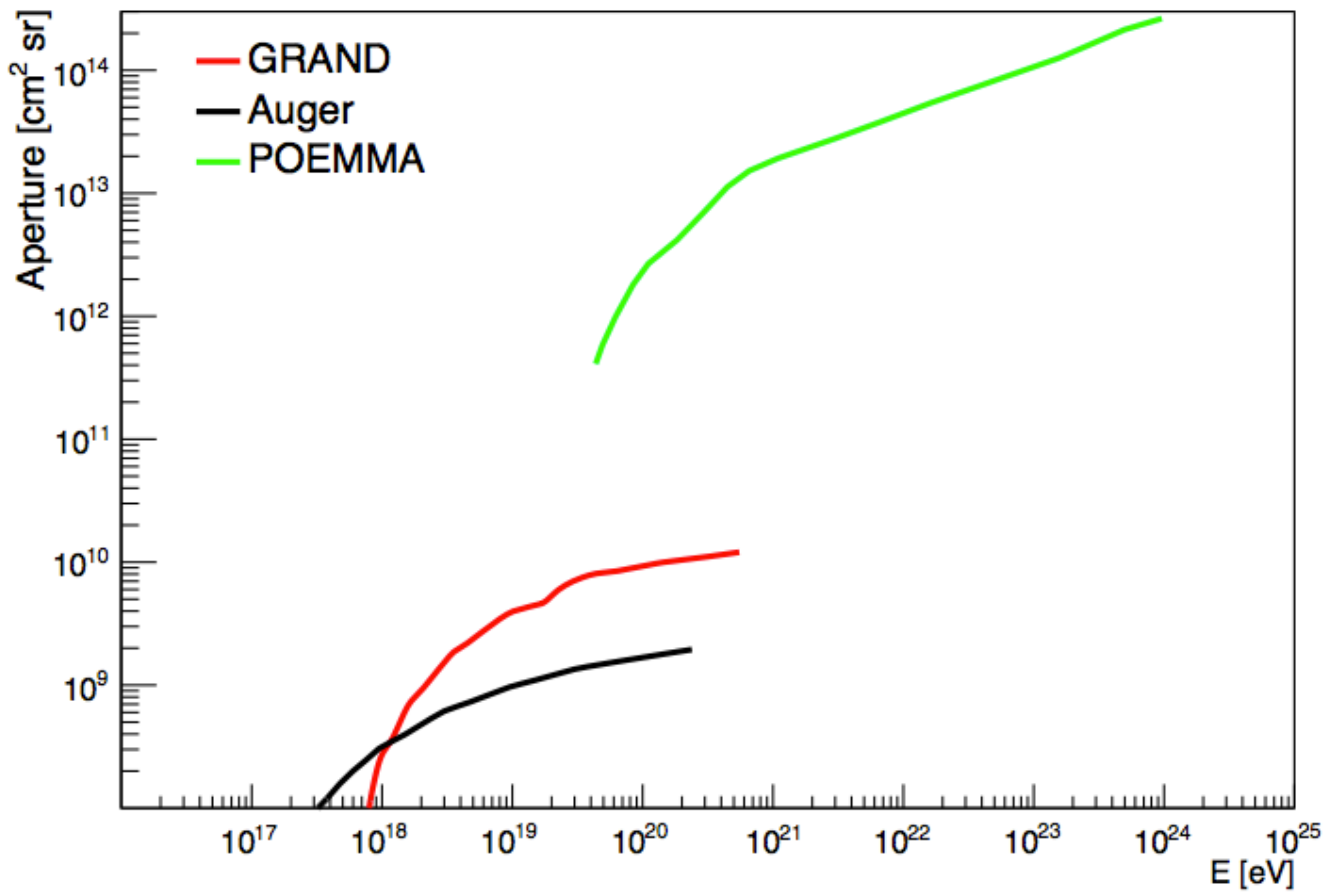
- Parametric studies can constrain the **UHECR spectral parameters** and the **cosmological distribution of sources** (UHECR scenarios corresponding to neutrino fluxes higher than current limits can be excluded)
- **Optimistic scenario: UHECRs are100% protons**
  - See also The Pierre Auger Collab. JCAP 2019; van Vliet et al. PRD 2019; Muzio et al. PRD 2023; Ehlert et al. 2304.07321 for UHECR-protons and neutrino connections

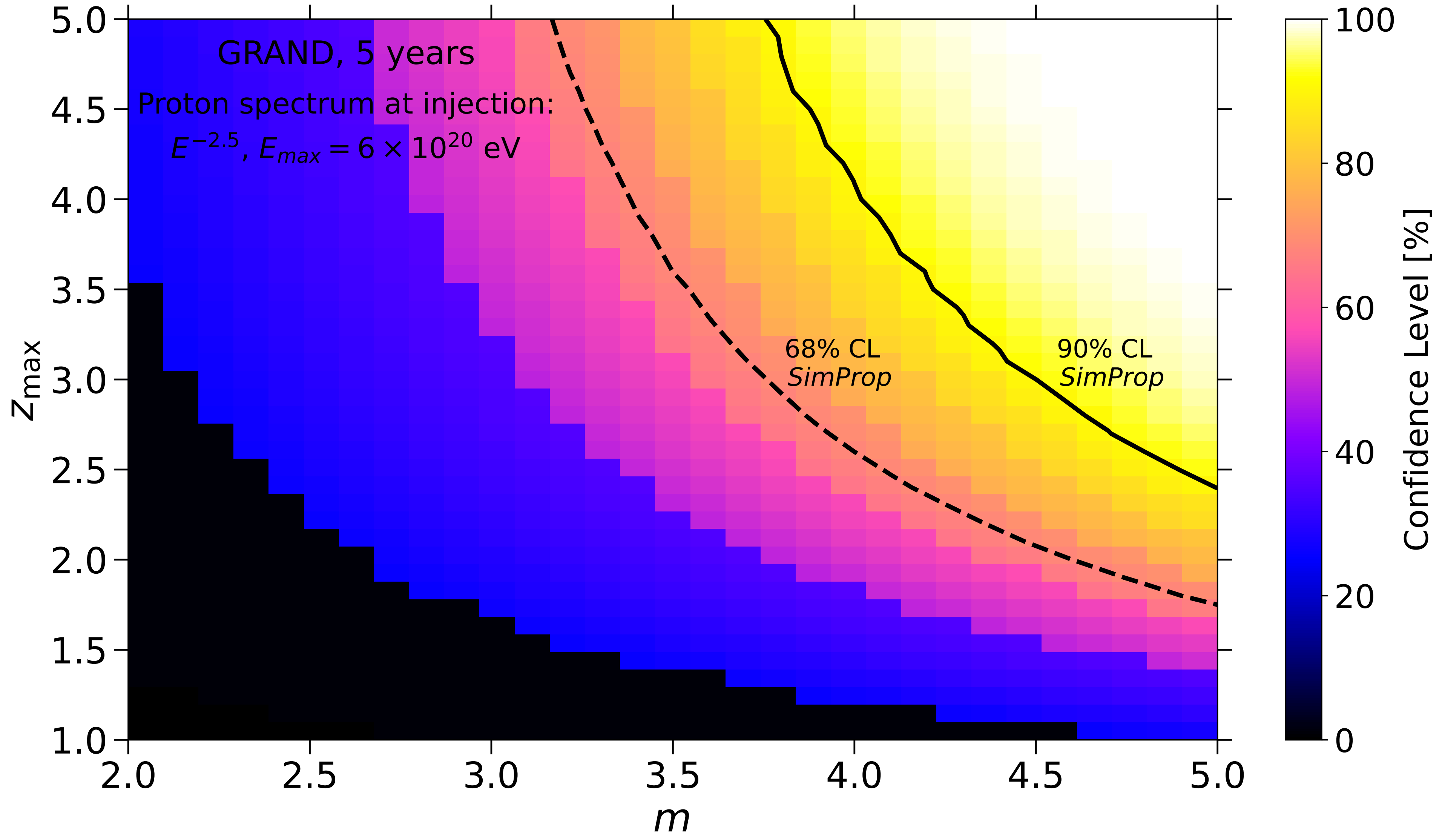
Pure proton composition for UHECRs

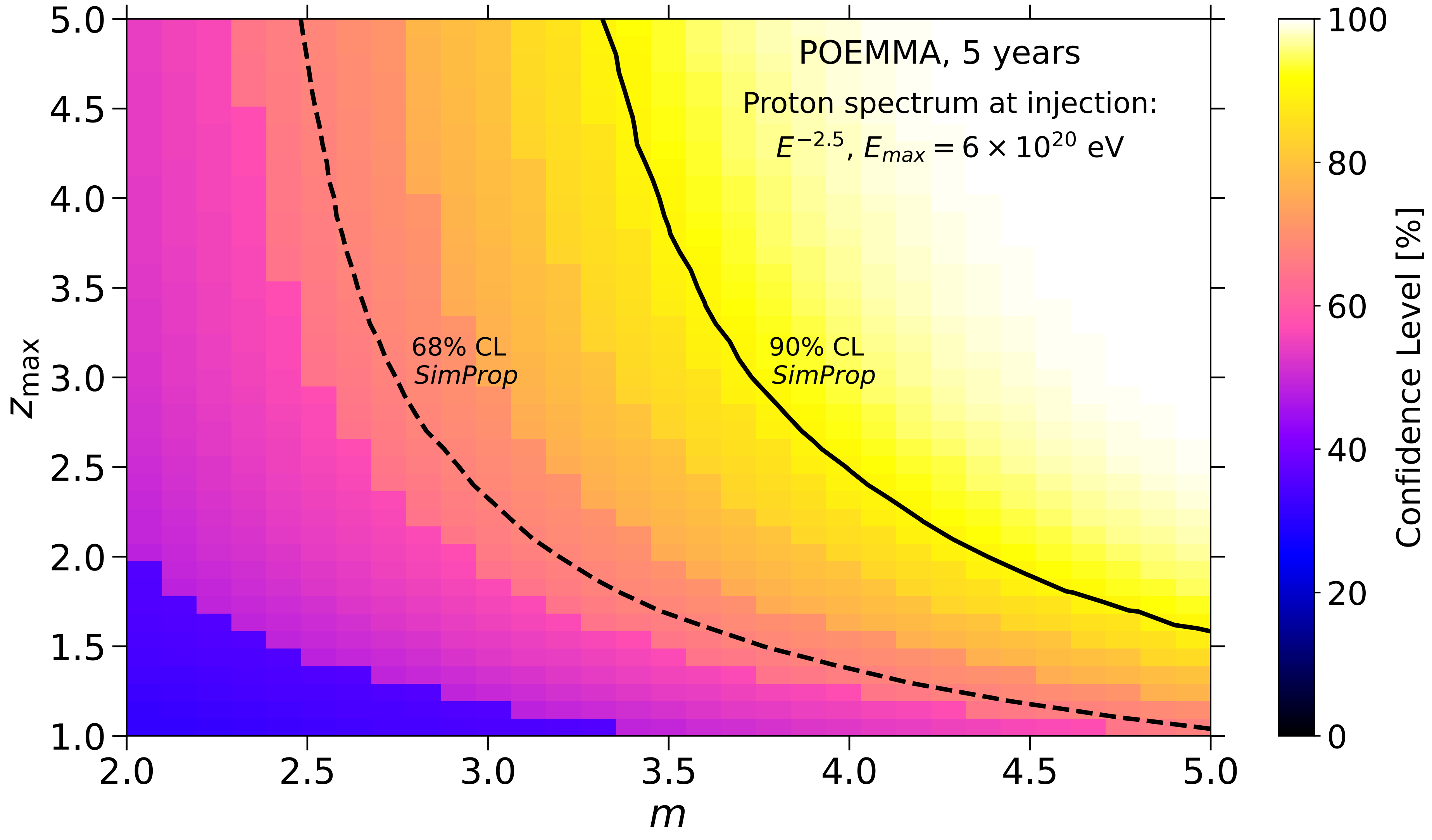
**Heinze, DB,** Bustamante & Winter, **ApJ 2016**

# Constraining power with future detectors





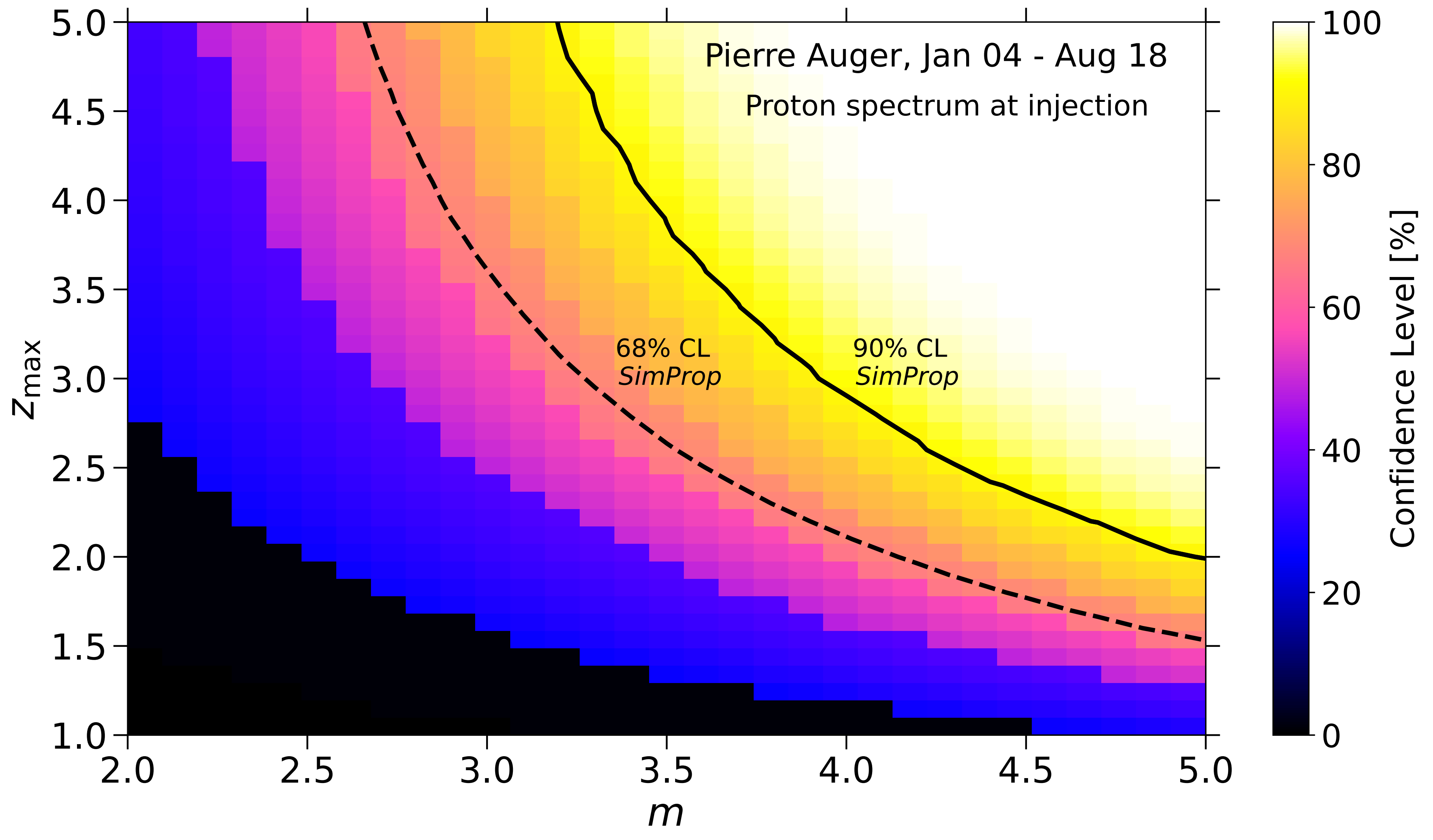


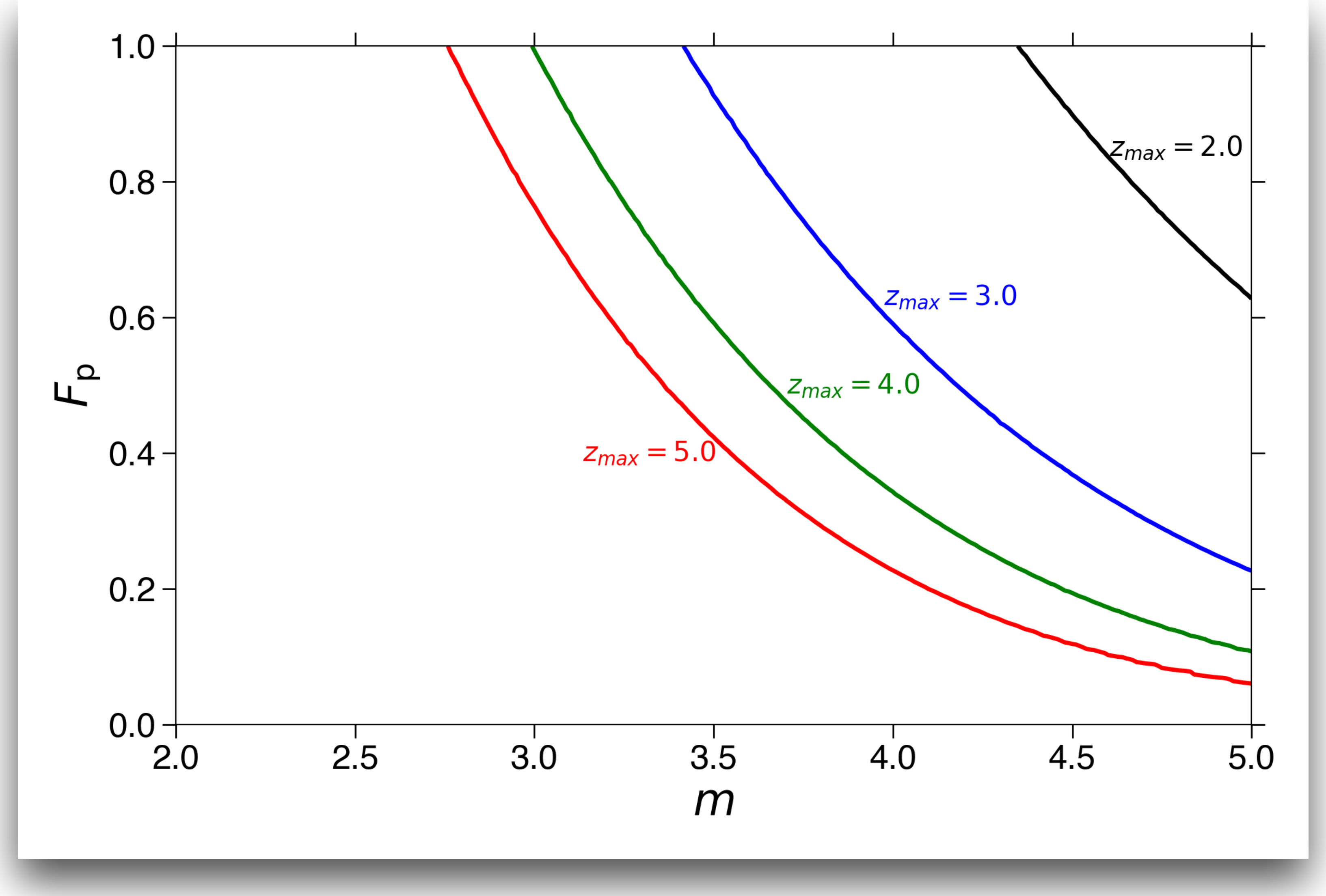


Pure proton composition for UHECRs

C. Petrucci, PhD thesis

# Constraining power depending on proton fraction





- See also The Pierre Auger Collab. JCAP 2019

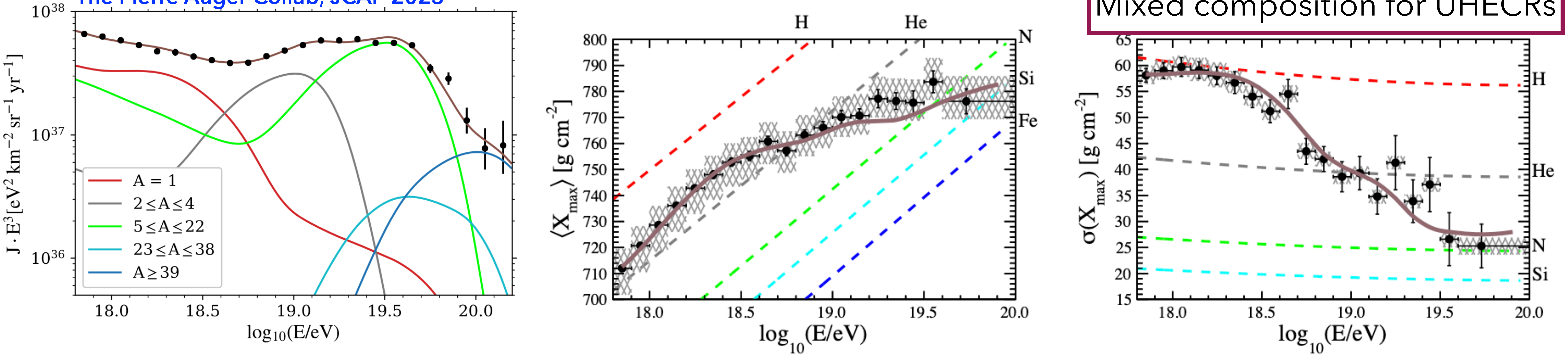
Pure proton composition for UHECRs

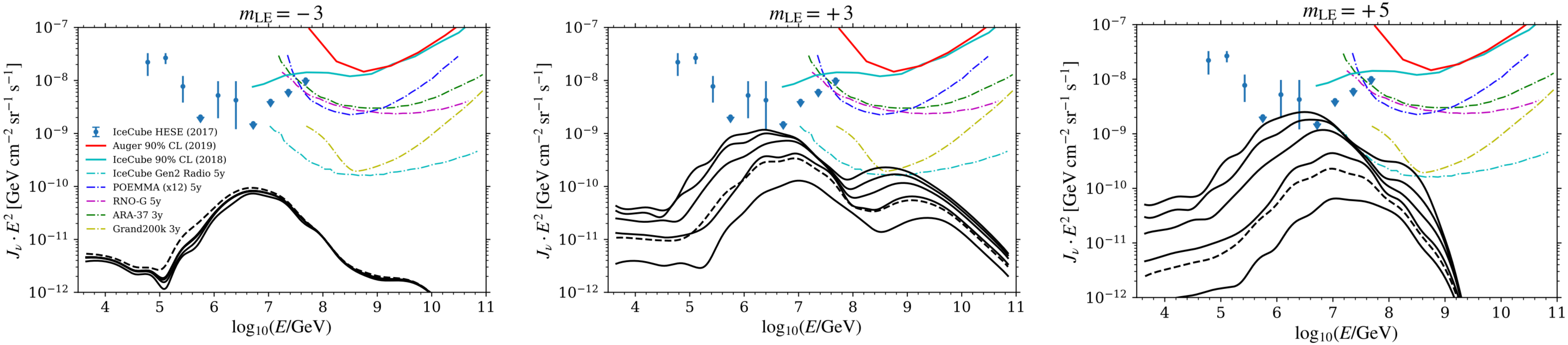
C. Petrucci, PhD thesis

# UHECR flux at Earth and the corresponding cosmogenic neutrinos

The Pierre Auger Collab, JCAP 2023

Mixed composition for UHECRs



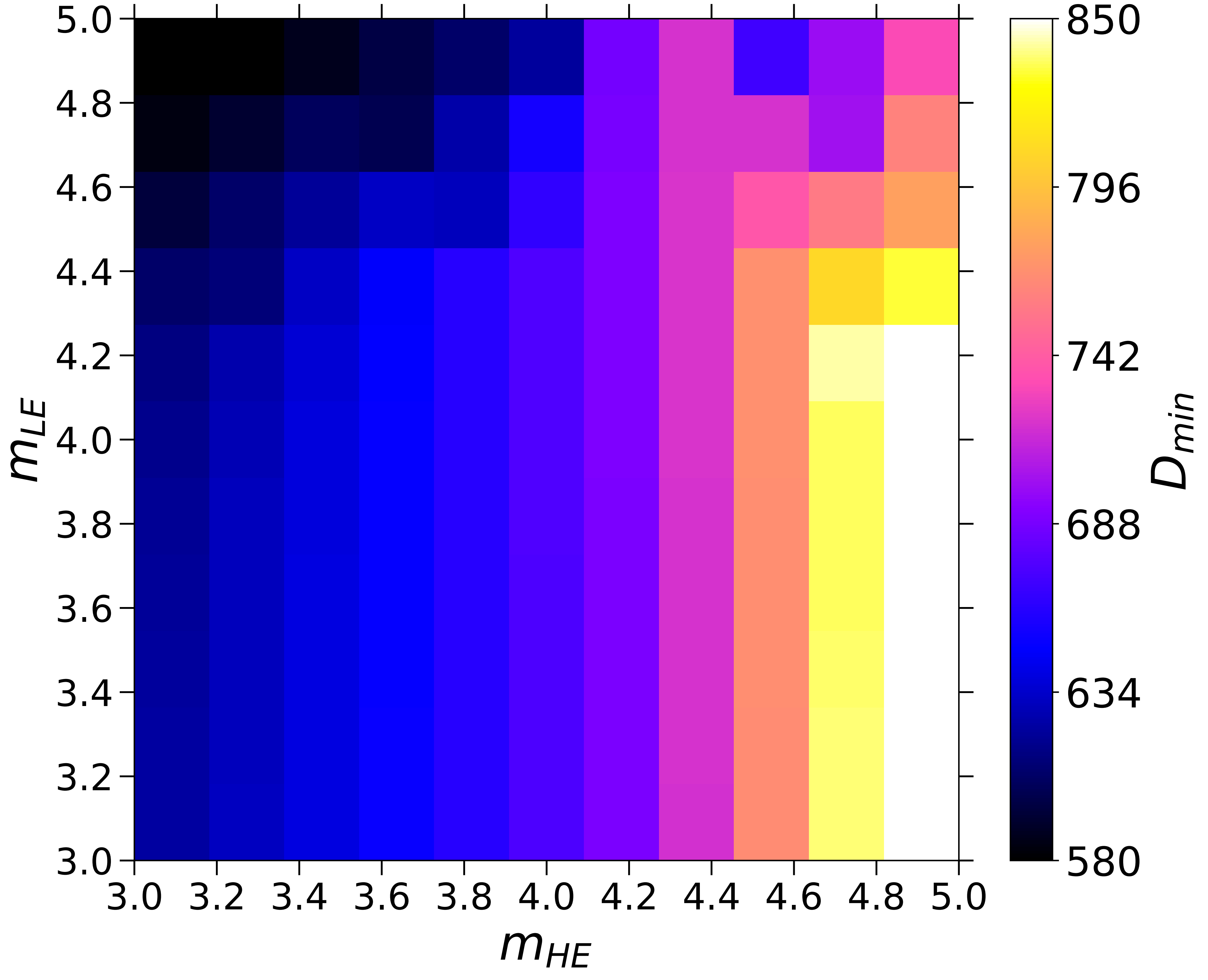


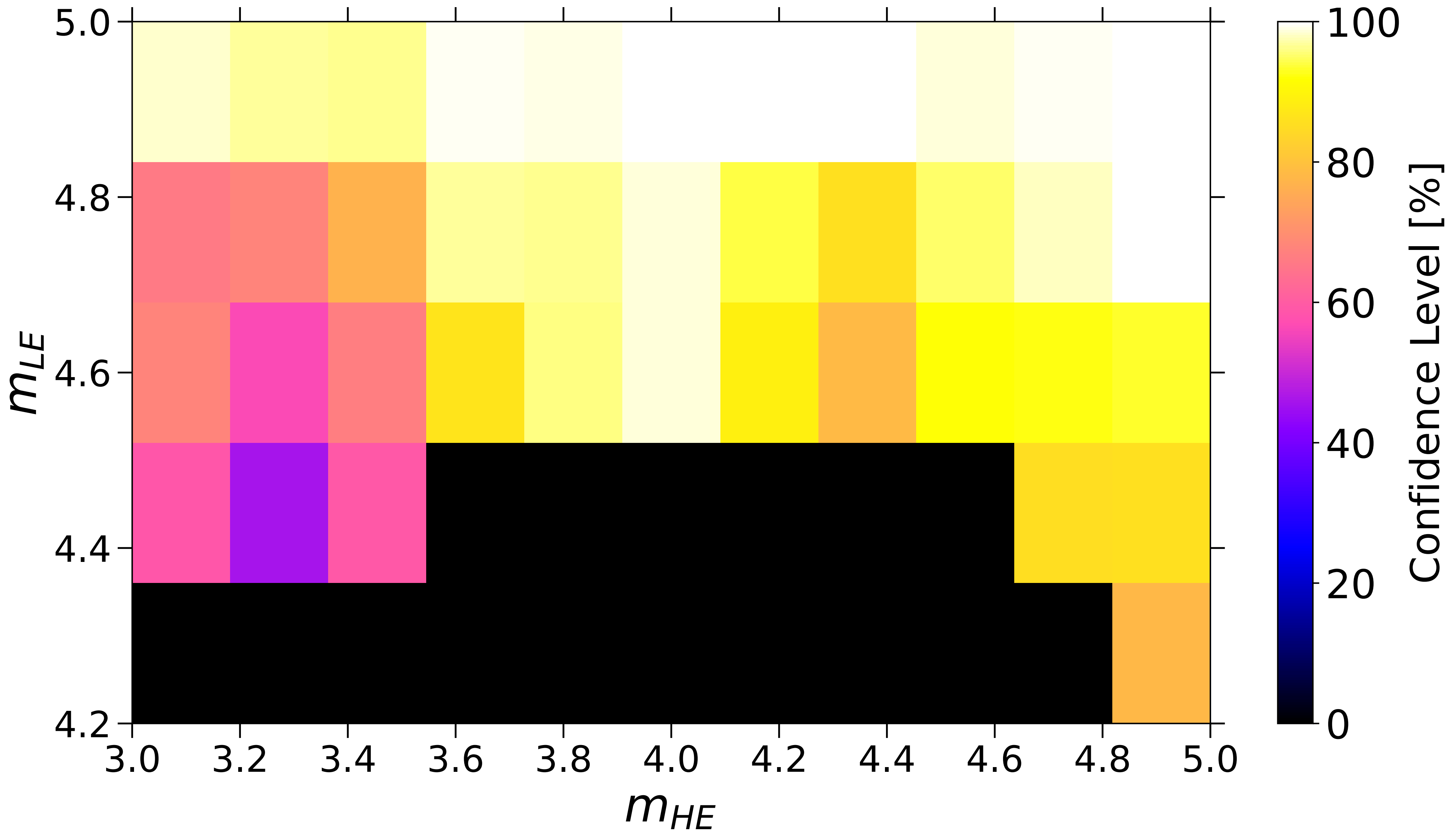
- Constraining the cosmological evolution of sources is more challenging if a realistic UHECR composition is taken into account!
    - See also Alves Batista et al. JCAP 2019; Heinze, **DB** et al ApJ 2019; The Pierre Auger Collab. ICRC2023

# UHECR flux at Earth and the corresponding cosmogenic neutrinos

The Pierre Auger Collab, JCAP 2023

Mixed composition for UHECRs



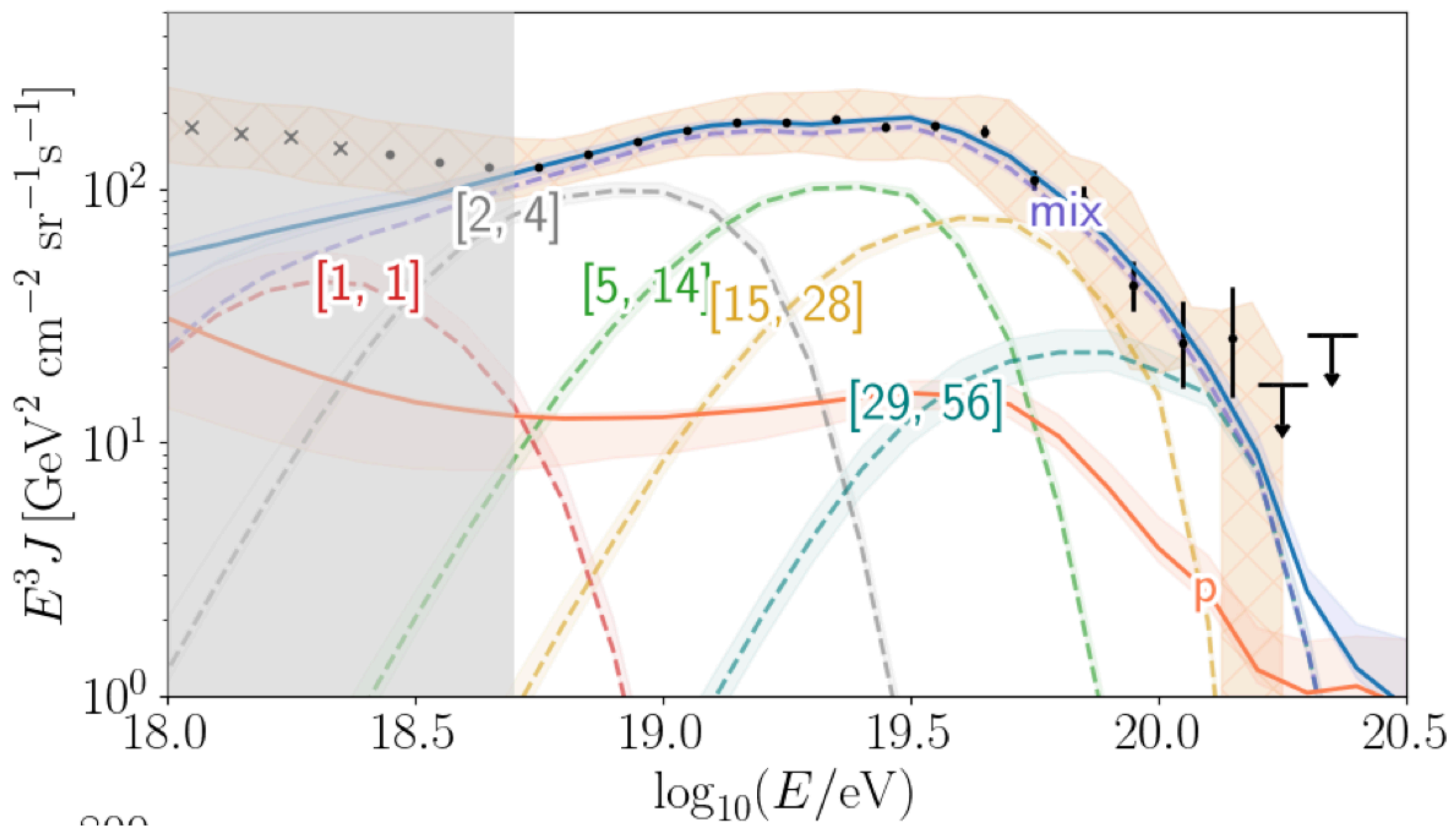


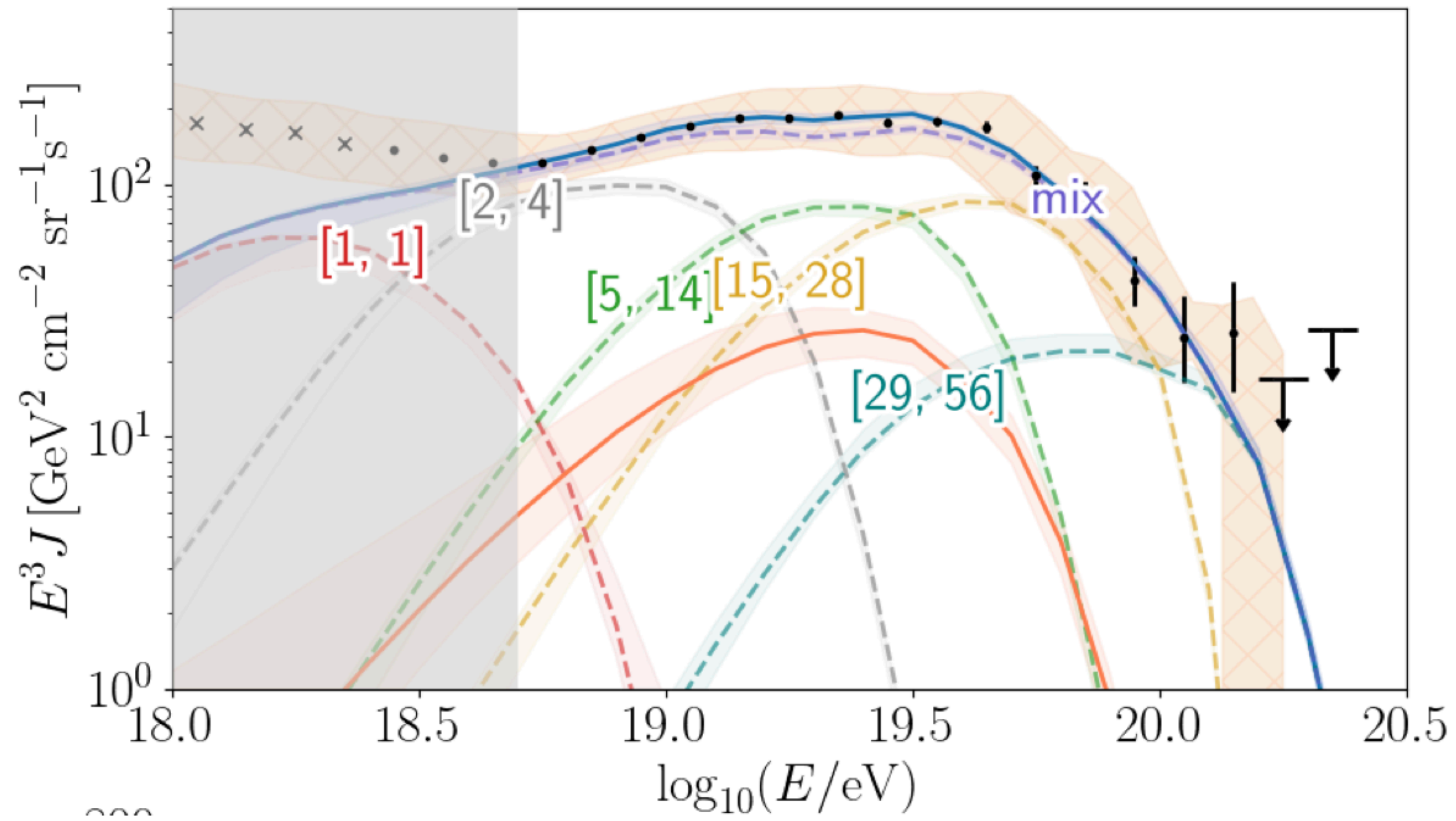
C. Petrucci, PhD thesis

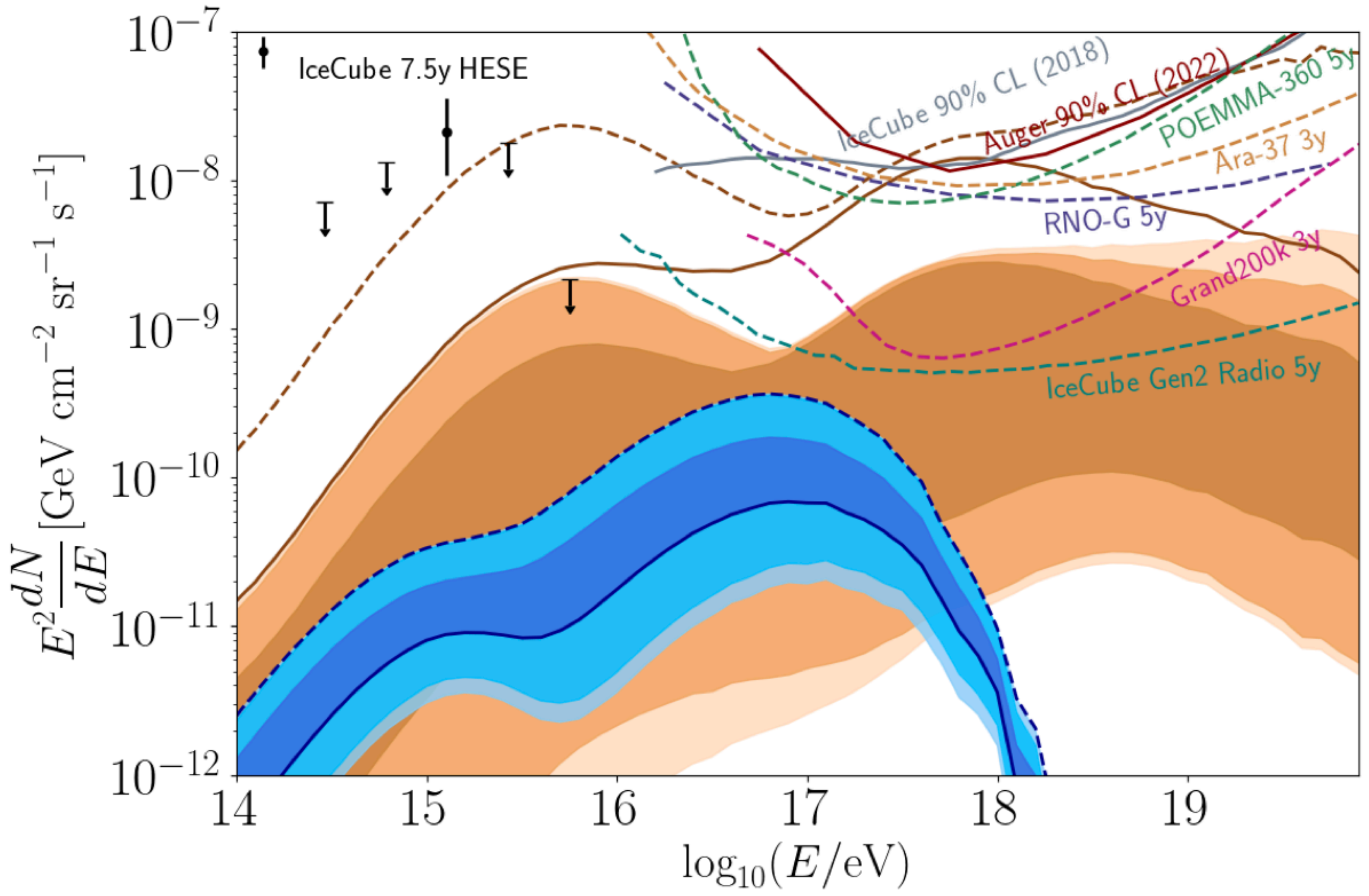
# UHECR flux at Earth and the corresponding cosmogenic neutrinos

Mixed composition for UHECRs

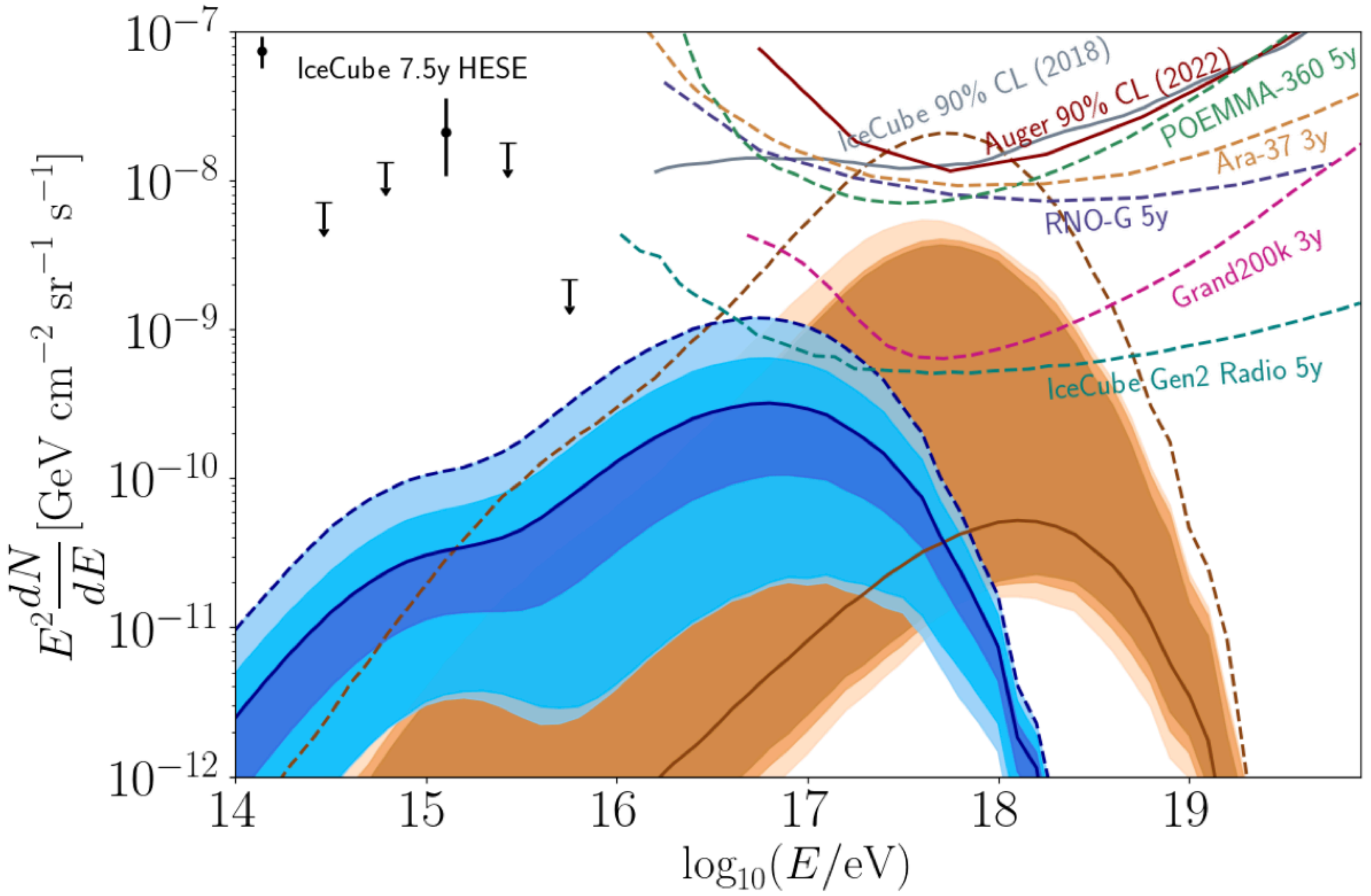
- Shaping the additional proton component







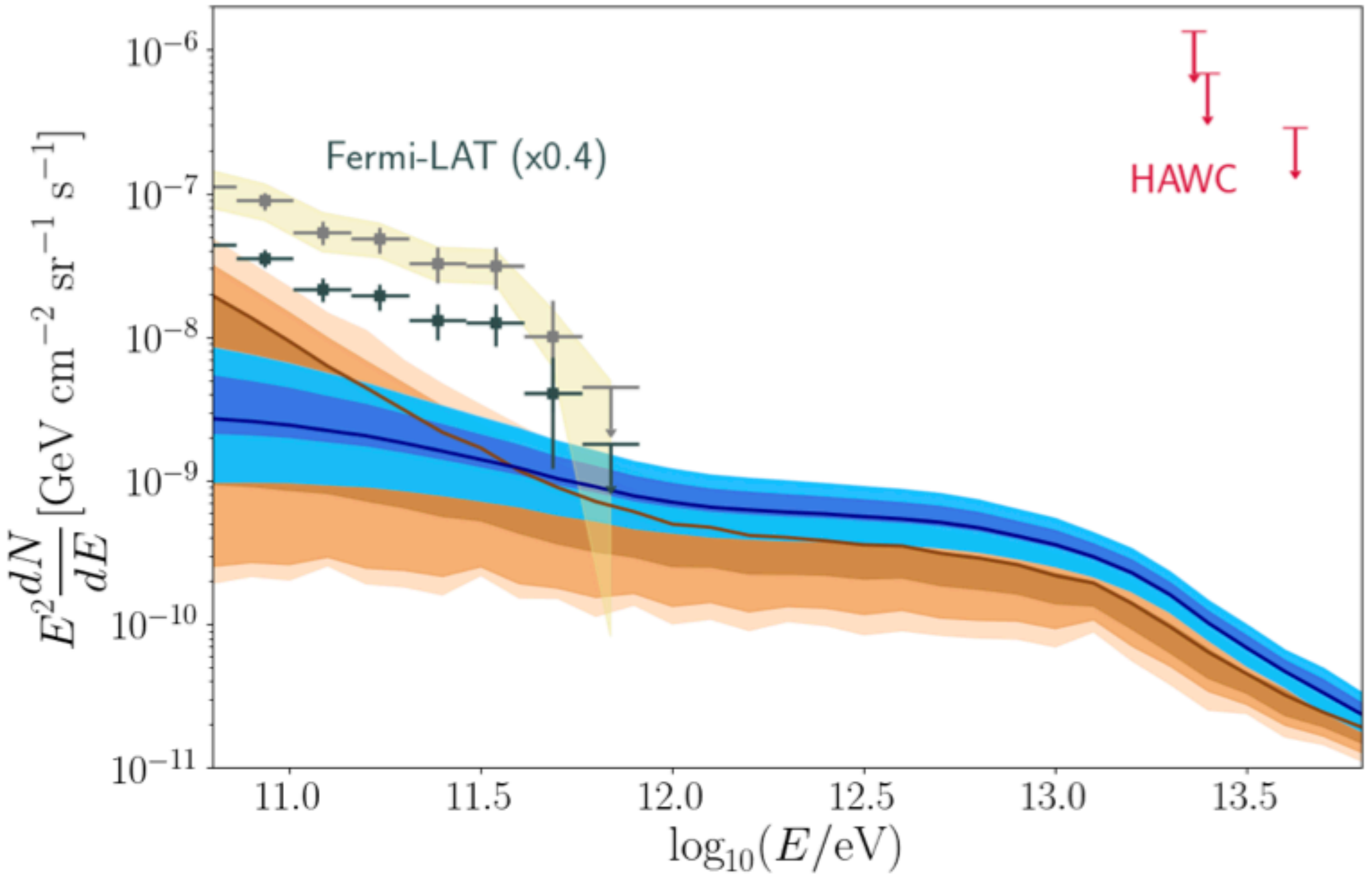
- Brown contours -> from the UHECR fit
- Blue contours -> from the UHECR fit + penalty from multimessenger



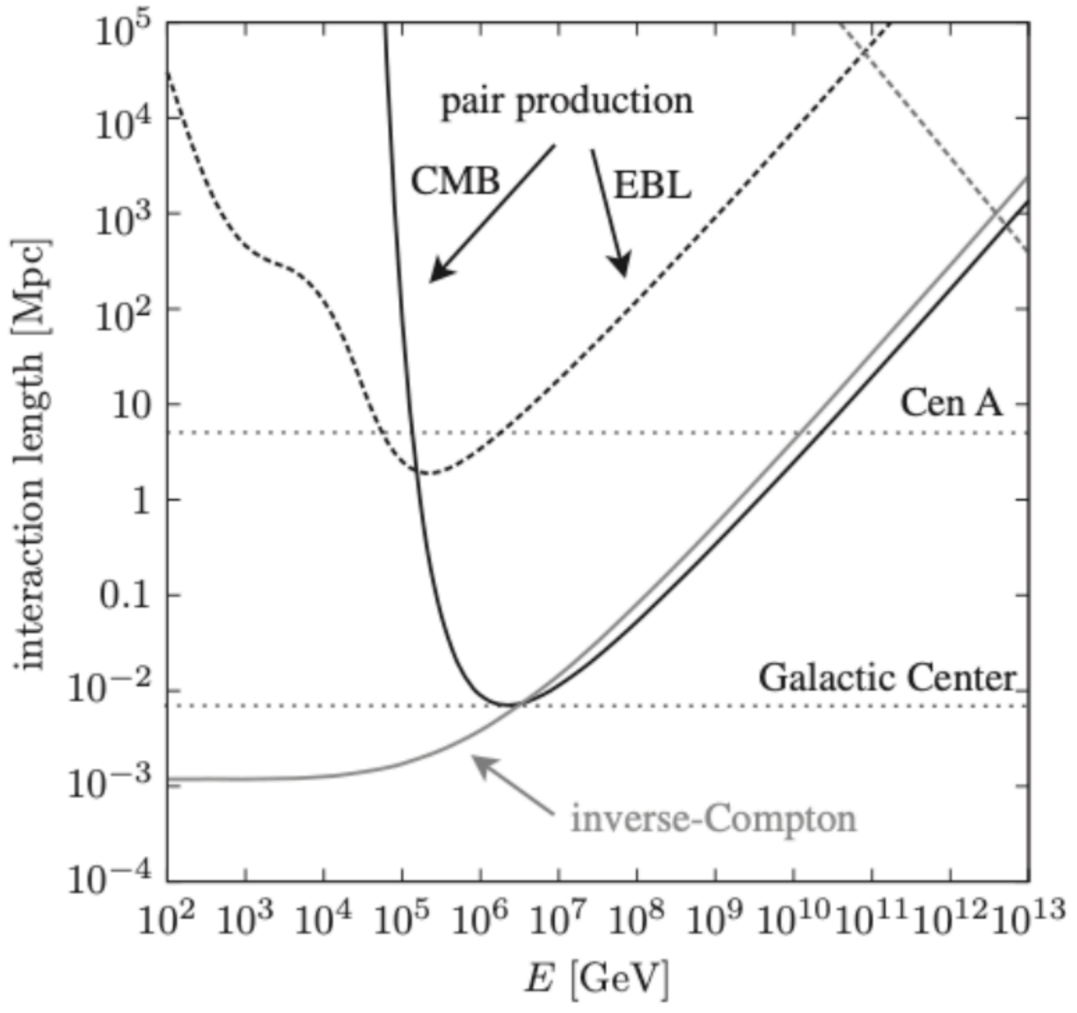
**Ehlert et al. JCAP 2024**

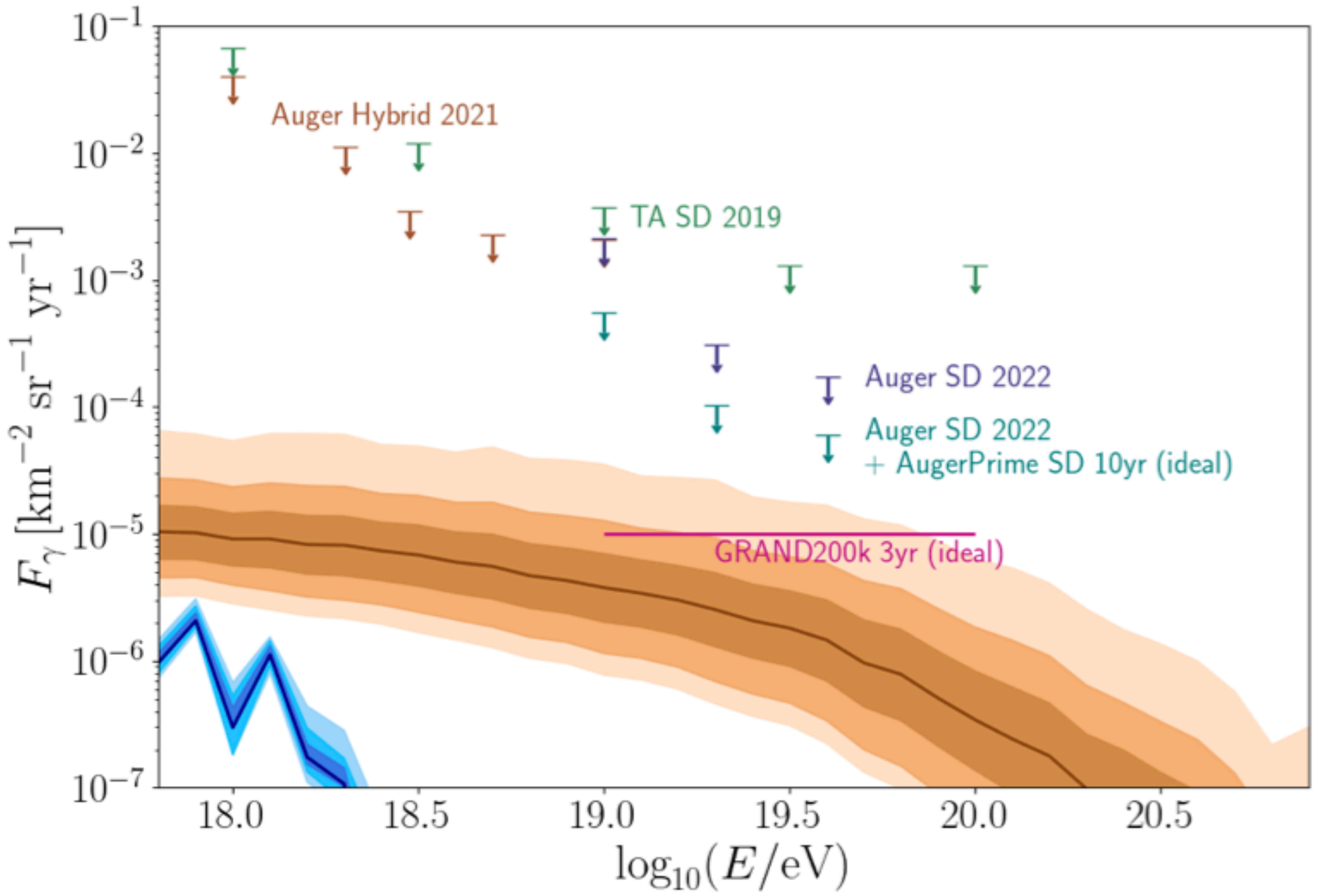
# UHECR flux at Earth and the corresponding cosmogenic neutrinos

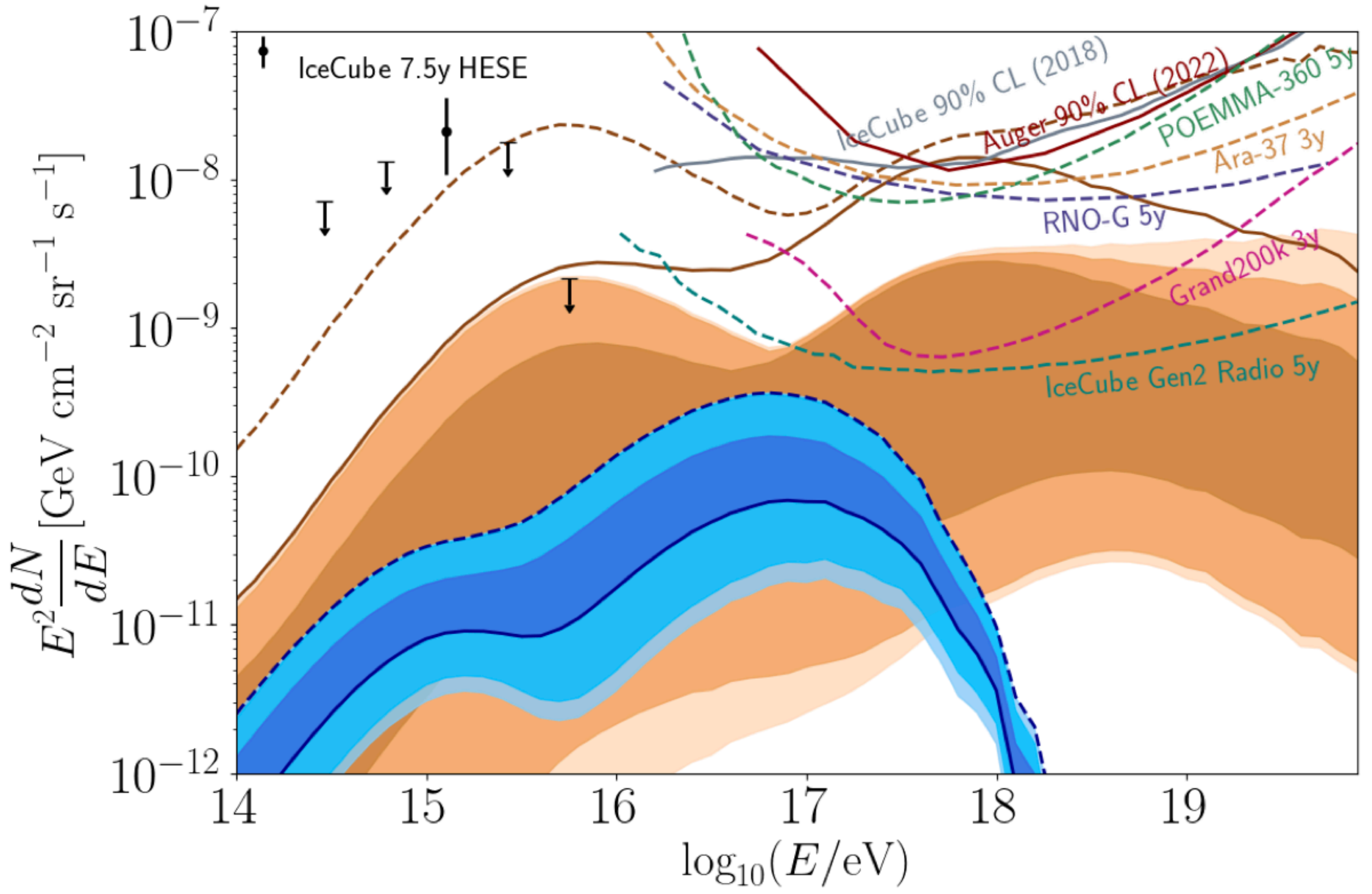
**Mixed composition for UHECRs**



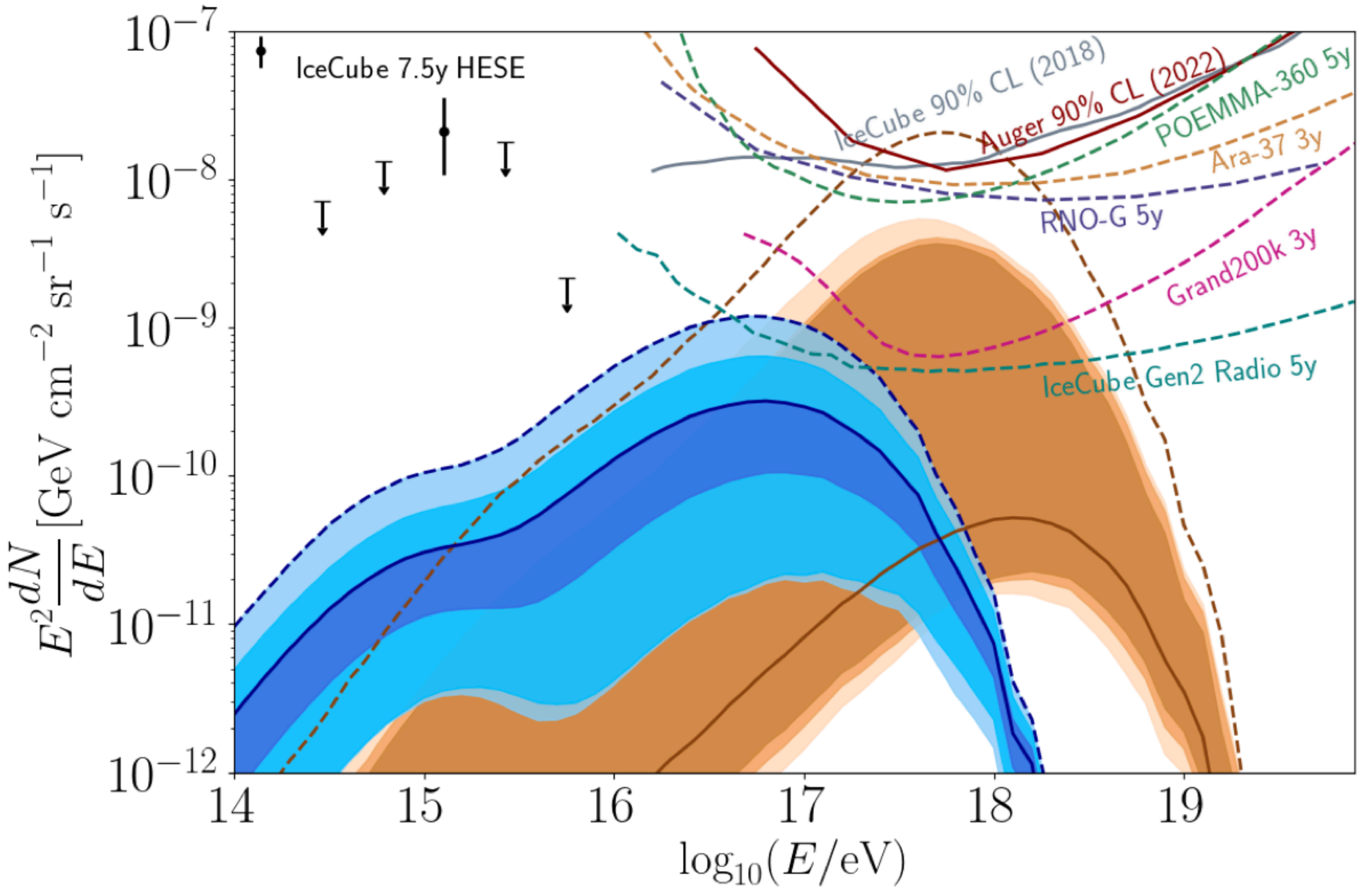
- Predicted cosmogenic gamma-ray signal for the in the GeV–TeV (left) and EeV (right) energy range







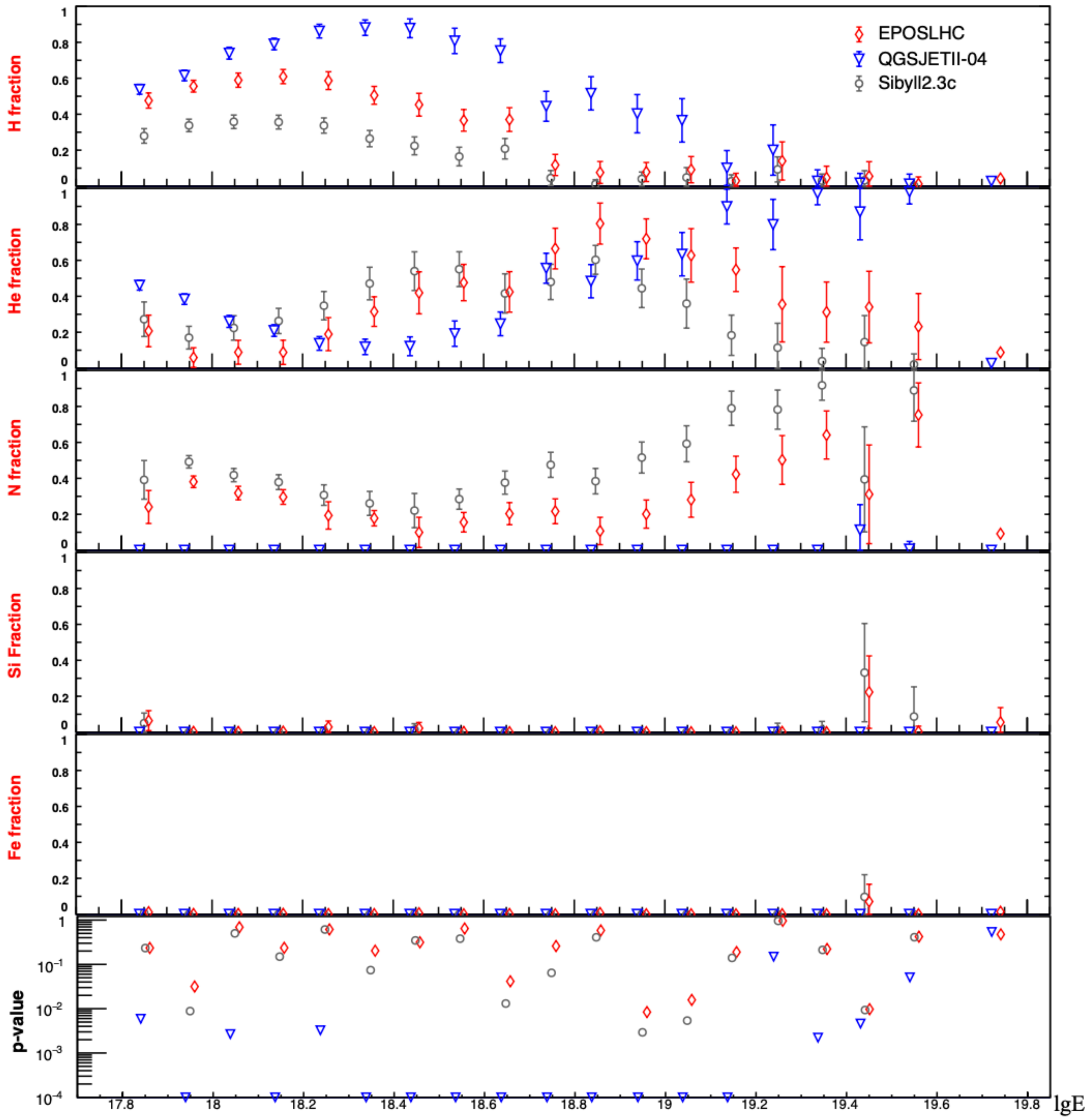
- Brown contours -> from the UHECR fit
- Blue contours -> from the UHECR fit + penalty from multimessenger



**Ehlert et al. JCAP 2024**

# What do we learn from UHECRs and cosmogenic neutrinos?

- Cosmogenic neutrinos are more sensitive to the distribution of UHECR sources in redshift than UHECR themselves, due to the UHECR horizon
- Cosmogenic neutrinos are produced in photo-meson productions -> UHECR mass composition influences the expected neutrino flux (as well as the UHECR spectral parameters)



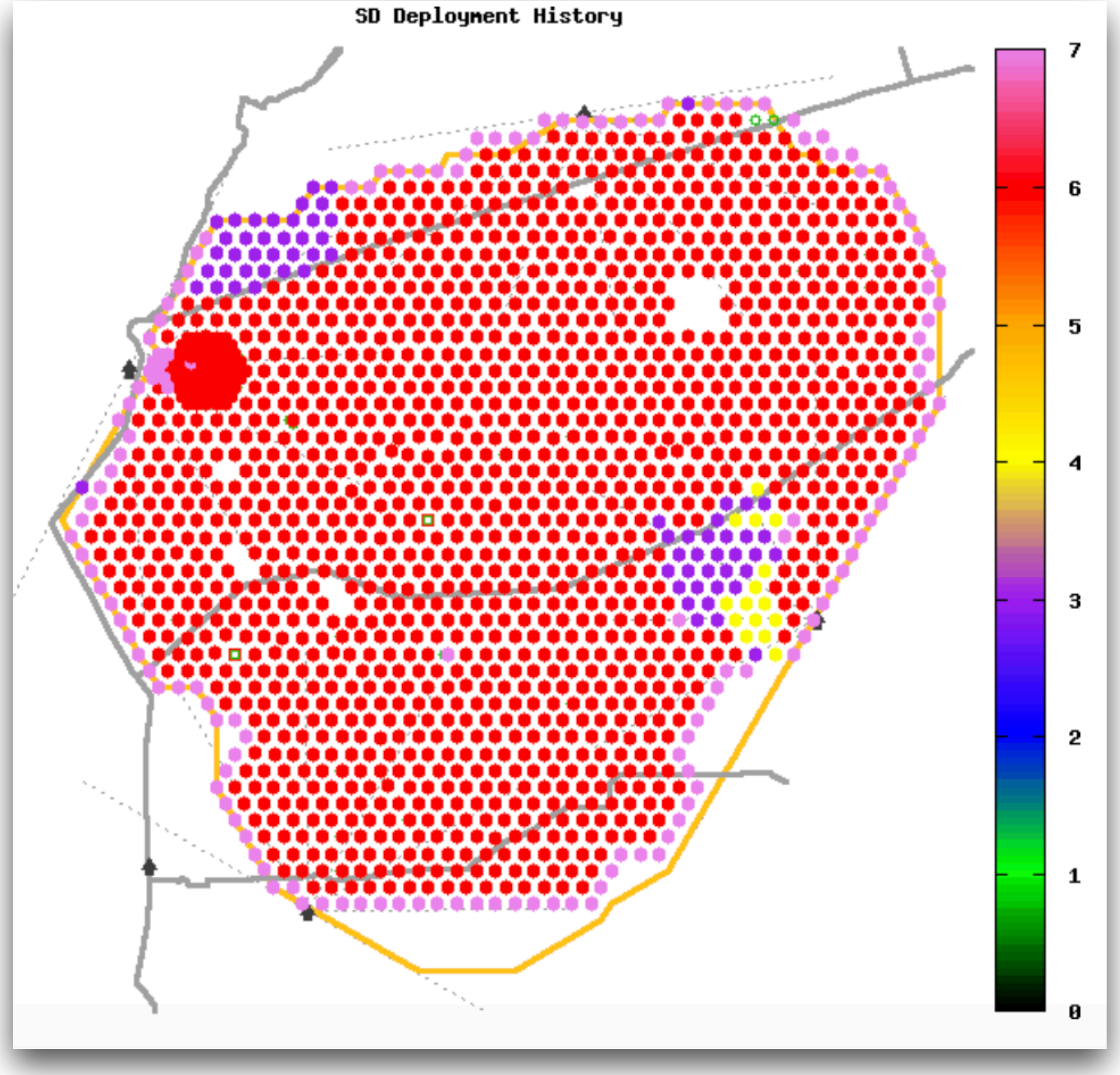
- **Determining the UHECR proton fraction at the highest energies is crucial for understanding the detected UHECR mass composition, but also indirectly to better constrain the UHECR characteristics**
  - Determination of heavy masses relevant for understanding of acceleration processes (re-acceleration?) and/or mas composition in acceleration sites
  - Indication of ordering of mass fractions in terms of increasing mass/charge (even without considering any astrophysical scenario -> the mass fraction fit is performed at each energy)

# One of the science cases of AugerPrime…

- **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**
    - **Upgrade of the Pierre Auger Observatory** (AugerPrime)

- Auger Phase 2 -> 10 years (foreseen)
    - Deployment and installation of scintillators on top of water Cerenkov detectors -> completed
        - <u>complementary response of the detectors to muon and electromagnetic part of the shower</u>

Plot from talk by F. Salamida @ICRC23



# ASTROPHYSICAL NEUTRINOS

## Neutrinos are the smoking-gun signature for hadronic acceleration

# Particle acceleration

- Observing neutrinos from a source would reveal that **hadronic processes are at work**
- Example: observed neutrino with energy $10^{15}$ eV -> produced at the source by a proton of $2\times10^{16}$ eV -> in order to trigger the photo-pion production, in the source I need:
  - IR or optical photons
  - High-energy protons

$$\varepsilon' \approx \varepsilon\Gamma$$

- Acceleration of particles -> repeated interactions of a particle with the magnetic structures embedded in a shock may lead to energy gain and to (power-law) universal spectra; Fermi and DSA acceleration, for a review see Matthews et al. New Astron. Rev. 2020; Caprioli, Varenna Lecture notes arxiv:2307.00284

  - Astrophysical jets are ideal sites for acceleration
  - Other evidences from recent observations

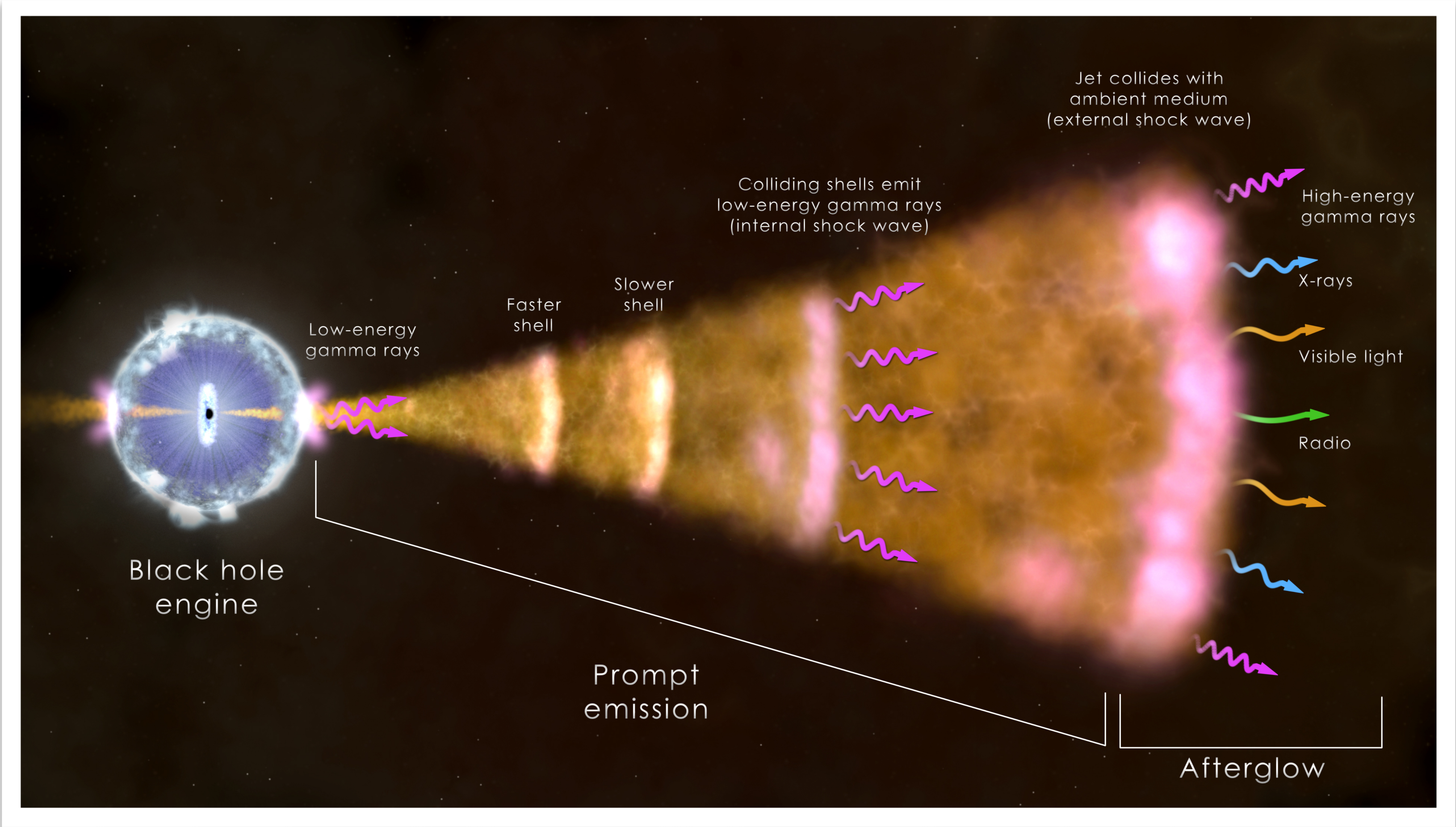
$\Big\}$ Can be tested thanks to observations of astrophysical neutrinos

# Gamma Ray Bursts

- Internal shock model (one zone)
  - **Geometry** → all collisions happen at the same radius, R (connected to the Lorentz factor and to the variability time)
  - **Luminosity**

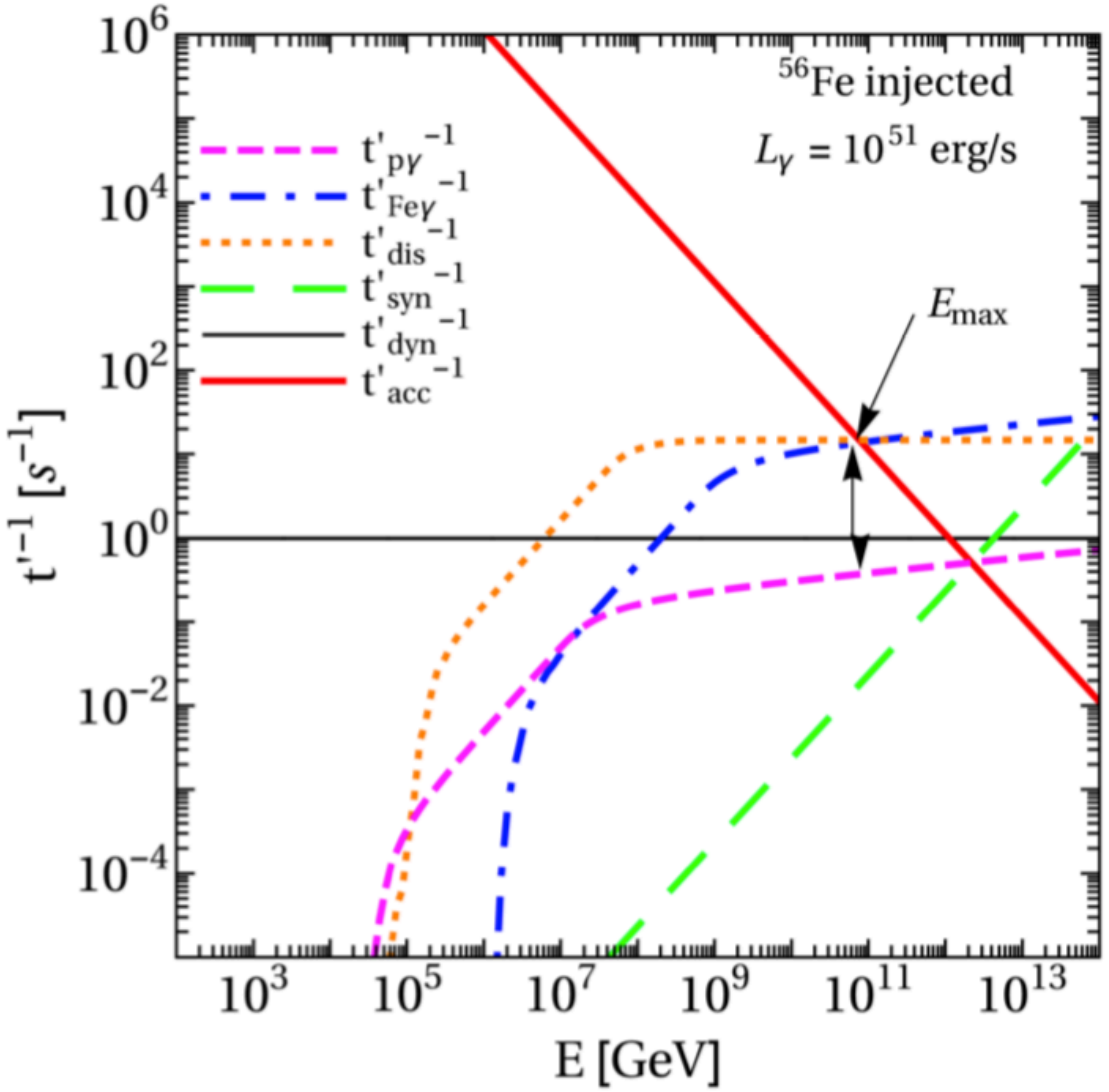
- **Ingredients for modelling the CR and neutrino emission**
  - Photon fields
  - Cross section of relevant interactions

- Energy to power UHECR flux and efficiently produce neutrinos, see for example Murase & Fukugita, PRD 2019
- Nuclear composition, see for example Zhang et al, PRD 2018; Woosley et al, RevModPhys 2002

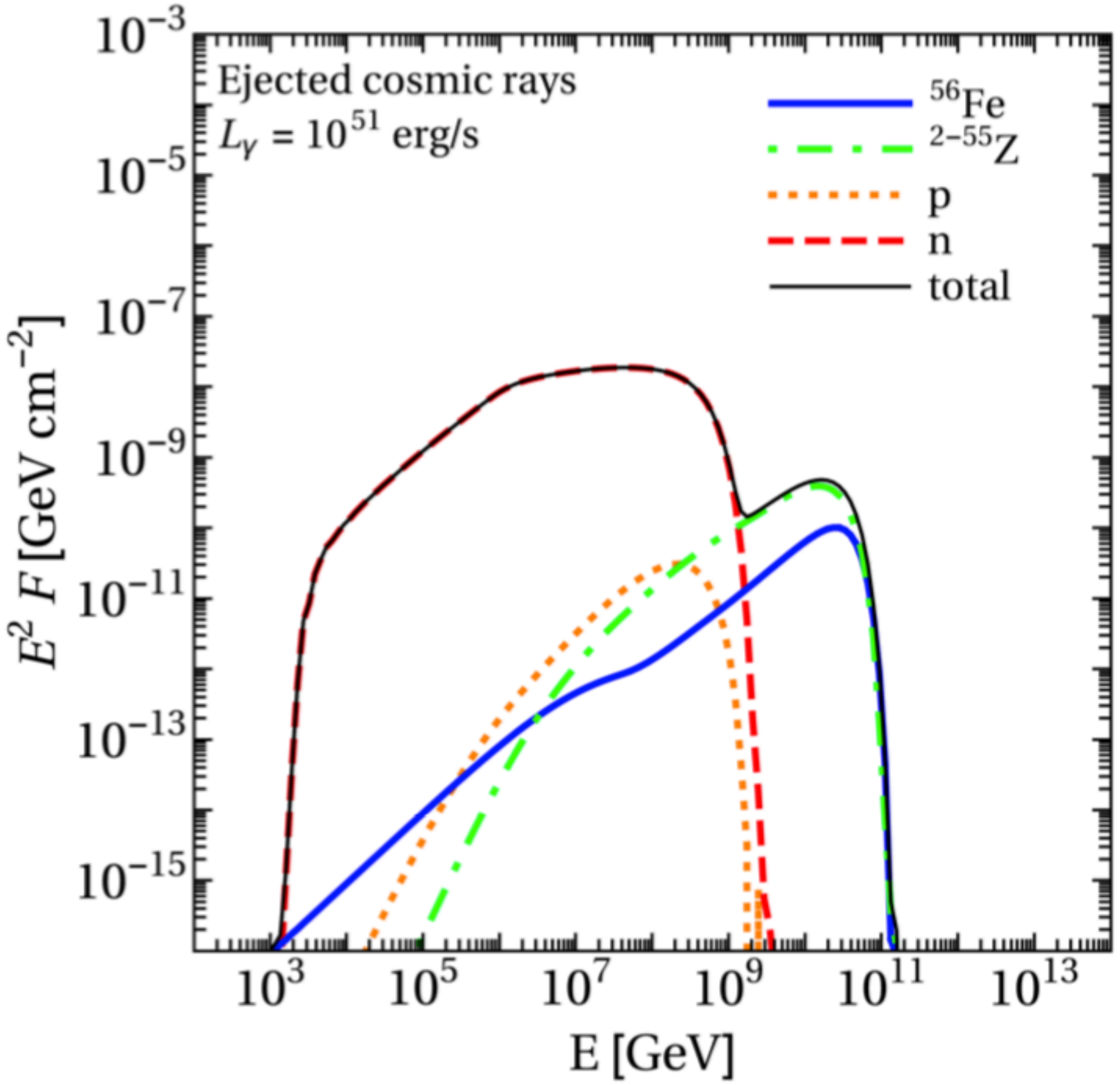


# Gamma Ray Bursts

# CR interactions and escape



- CR interactions in GRB photon field:
  - Determination of max energy of cosmic rays that can escape the source: balance of acceleration rate and losses
  - Density of primary CRs in the source is depleted, while secondary nuclei (and nucleons) increase
  - Here also the **photo-disintegration of nuclei** is taken into account

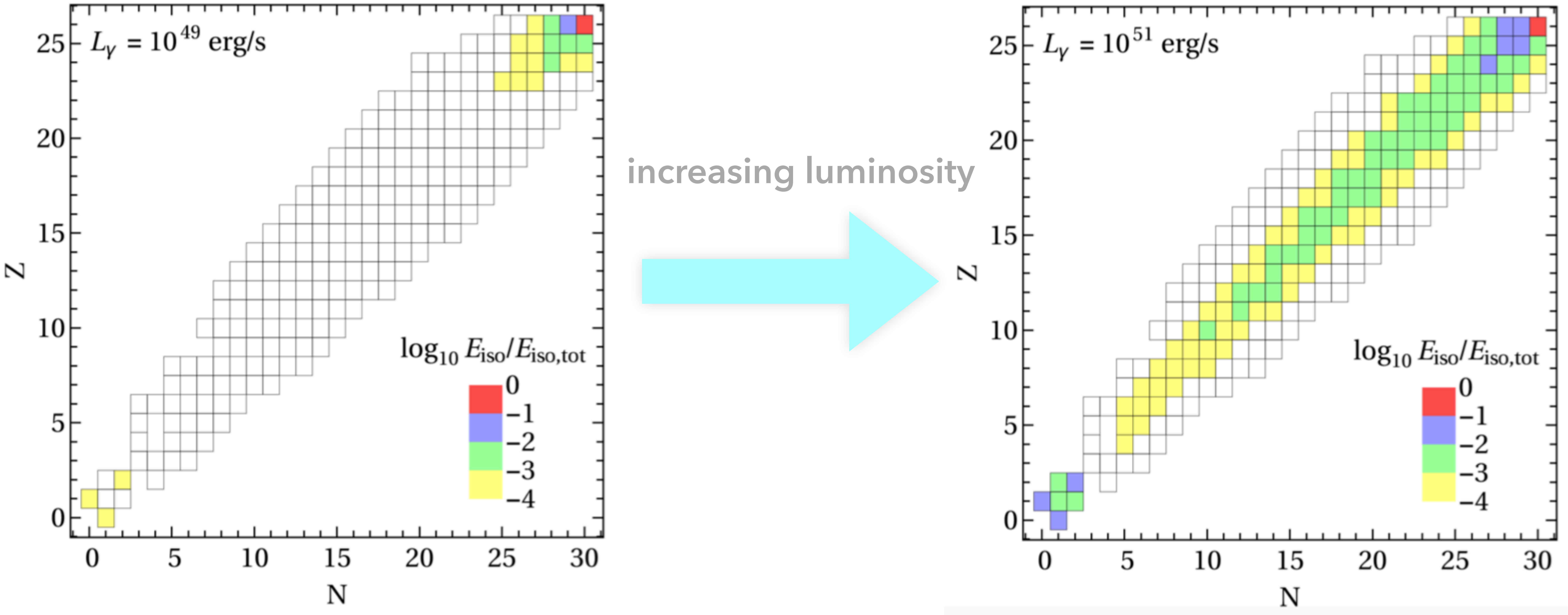


- CR escape (see also Baerwald et al ApJ 2013; Globus et al MNRAS 2015):
  - Neutral particles escape freely
  - Charged particles escape easily only at high energy -> **hardening of the spectrum**

Biehl, **DB**, Fedynitch, Winter, A&A 2018

# Gamma Ray Bursts

## CR interactions and nuclear cascade



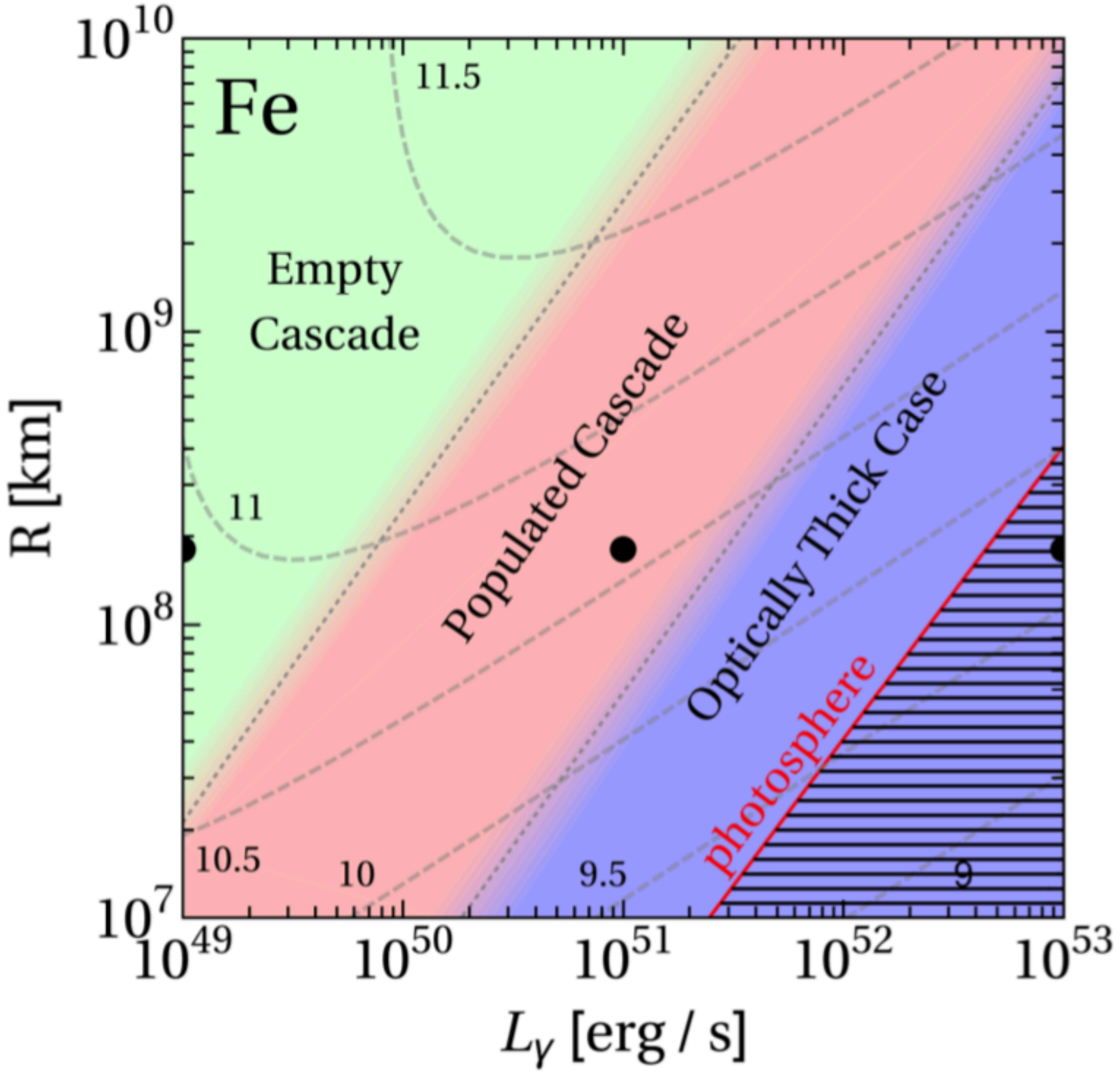
- Development of nuclear cascade strongly dependent on the radiation density in the shell
- Increase of luminosity implies increase of production of secondary nuclei and small fragments along the chain (helium, protons, neutrons)

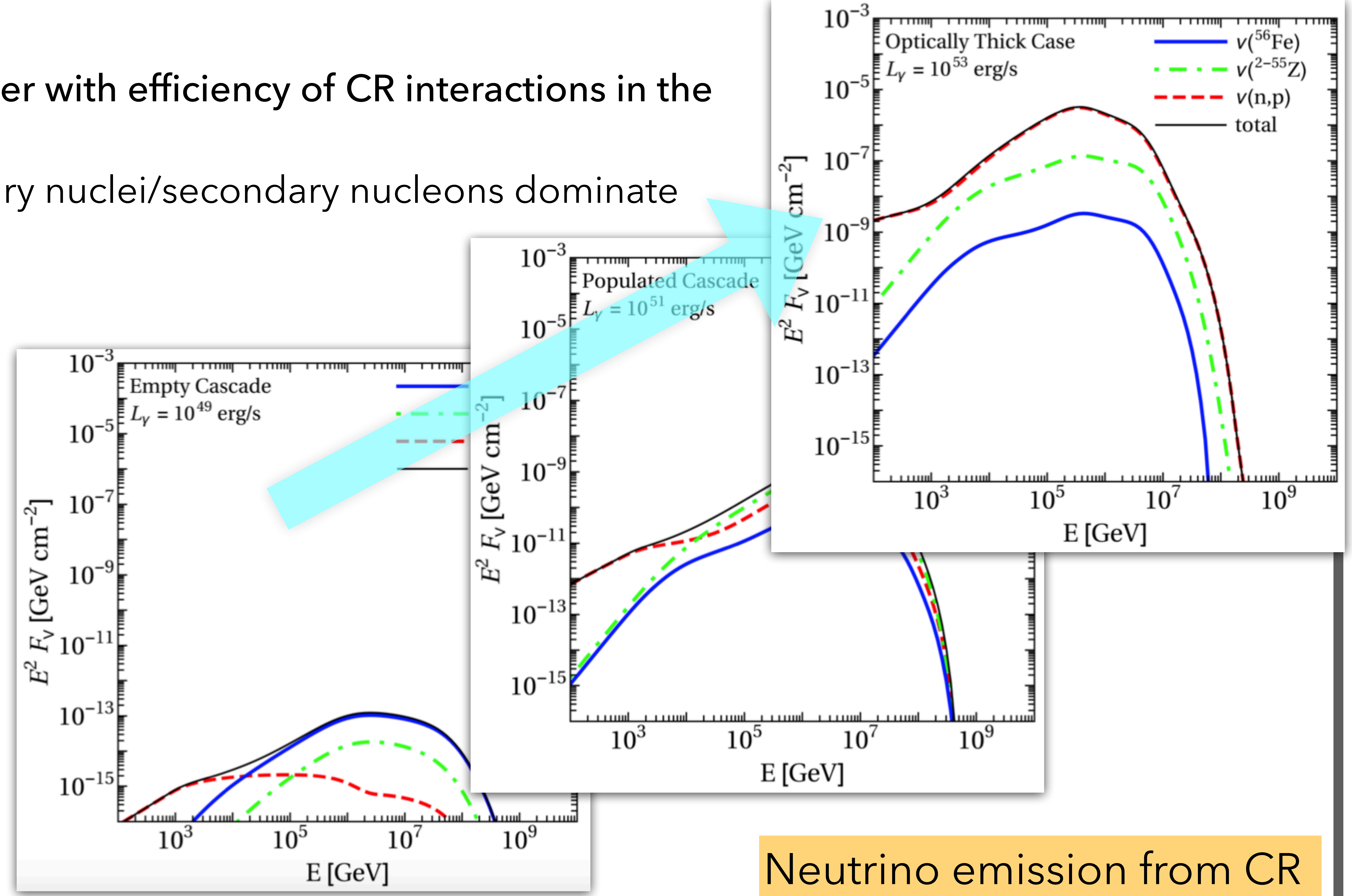
Biehl, **DB**, Fedynitch, Winter, A&A 2018

# Gamma Ray Bursts

## CR interactions and neutrinos

- Increase of neutrino production together with efficiency of CR interactions in the source
- Neutrinos from primary nuclei/secondary nuclei/secondary nucleons dominate the neutrino flux in different regimes





- More refined internal model in Heinze, Biehl, Fedynitch, **DB**, Rudolph & Winter MNRAS 2020

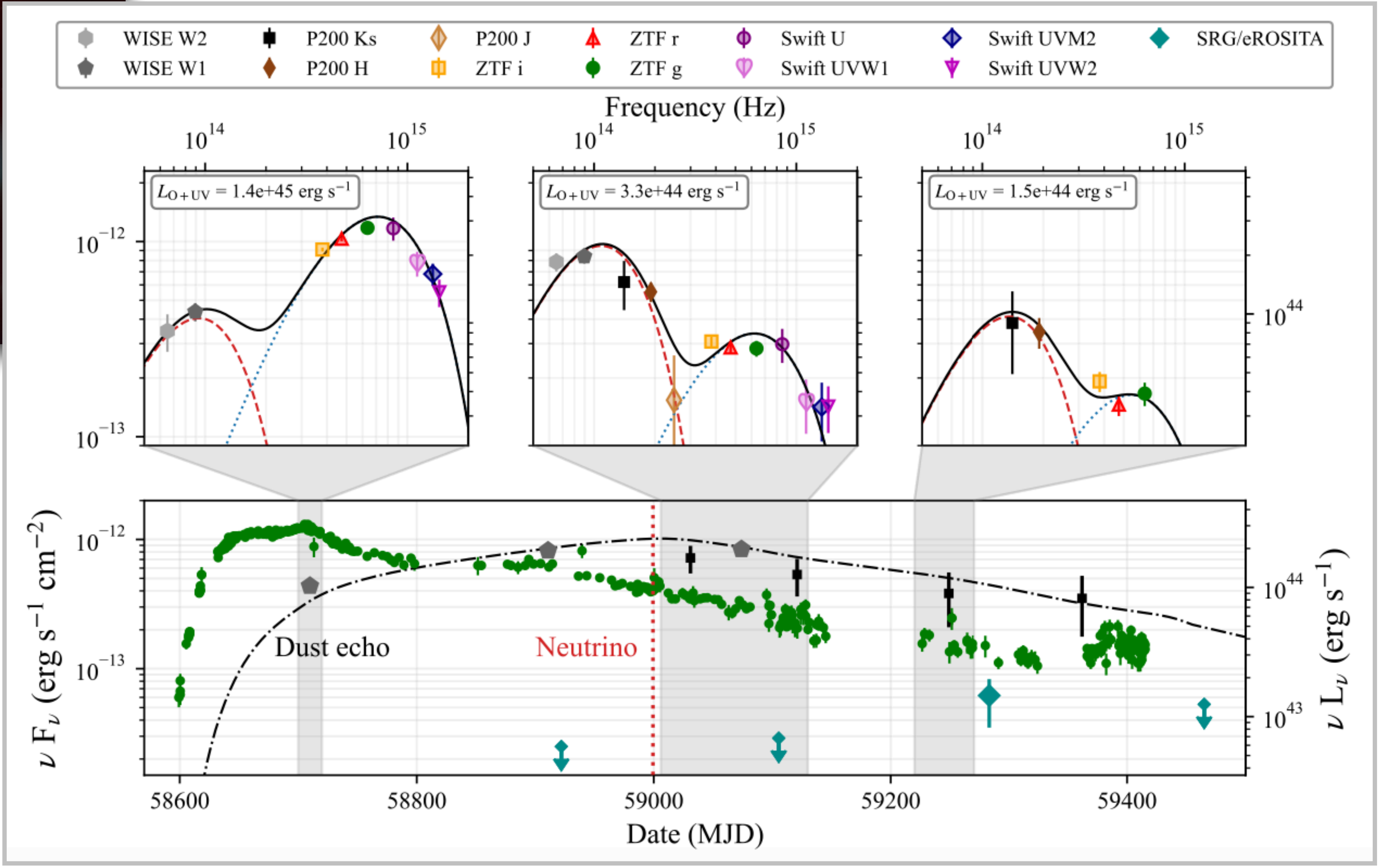
Neutrino emission from CR interactions in the **GRB jet**

Biehl, **DB**, Fedynitch, Winter, A&A 2018

# Tidal disruption events

- Stars are torn apart by a SMBH → part of the debris is accreted → a jet can form
    - Investigated as sources of UHECRs (Farrar & Piran, arxiv:1411.0704) and high-energy neutrinos (Wang et al, PRD 2011) -> acceleration in the jet
- Nuclear species: depends on the type of disrupted star
- Rate of events: negative evolution with redshift → consequences for cosmogenic neutrinos

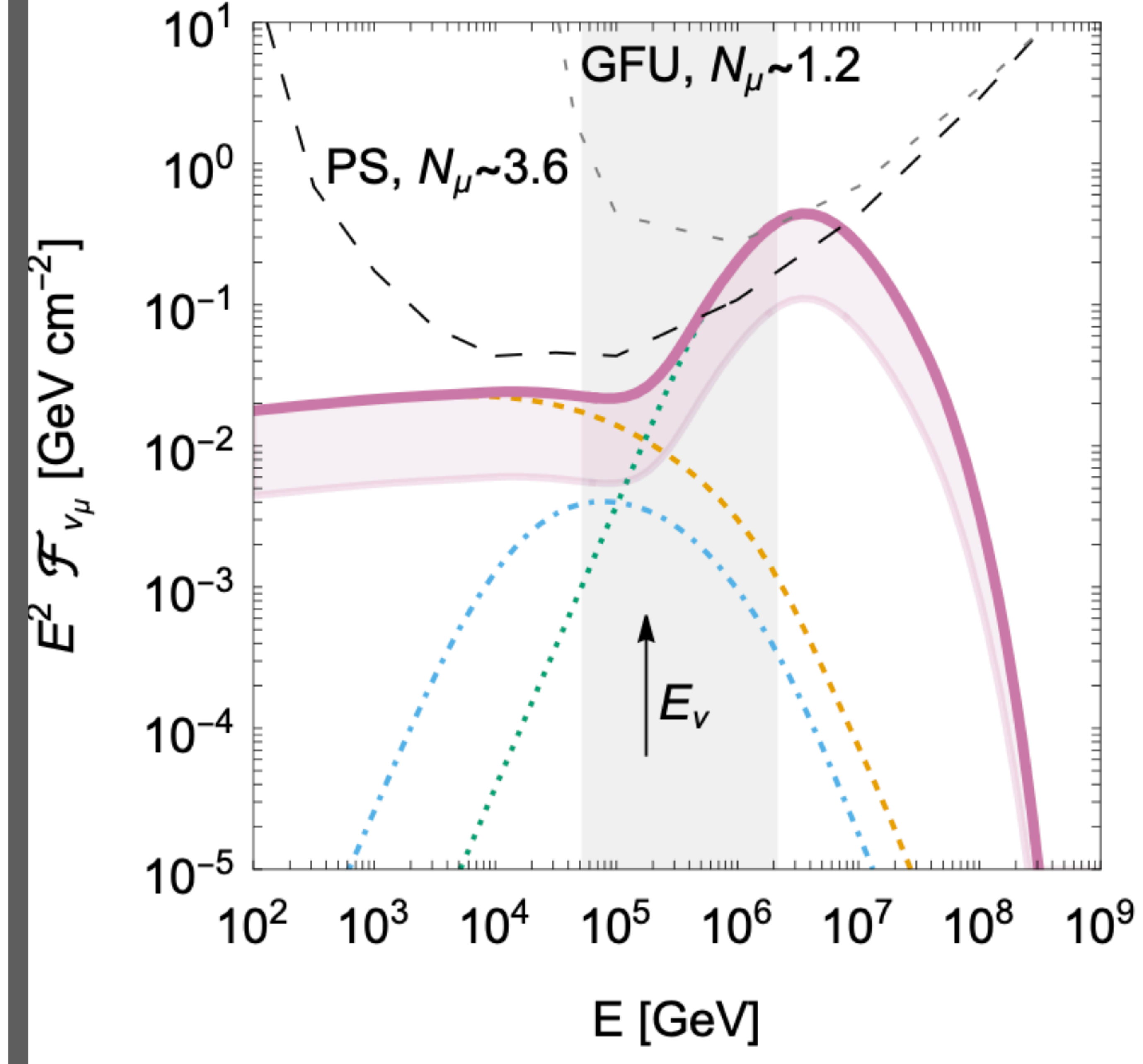
# Tidal disruption events

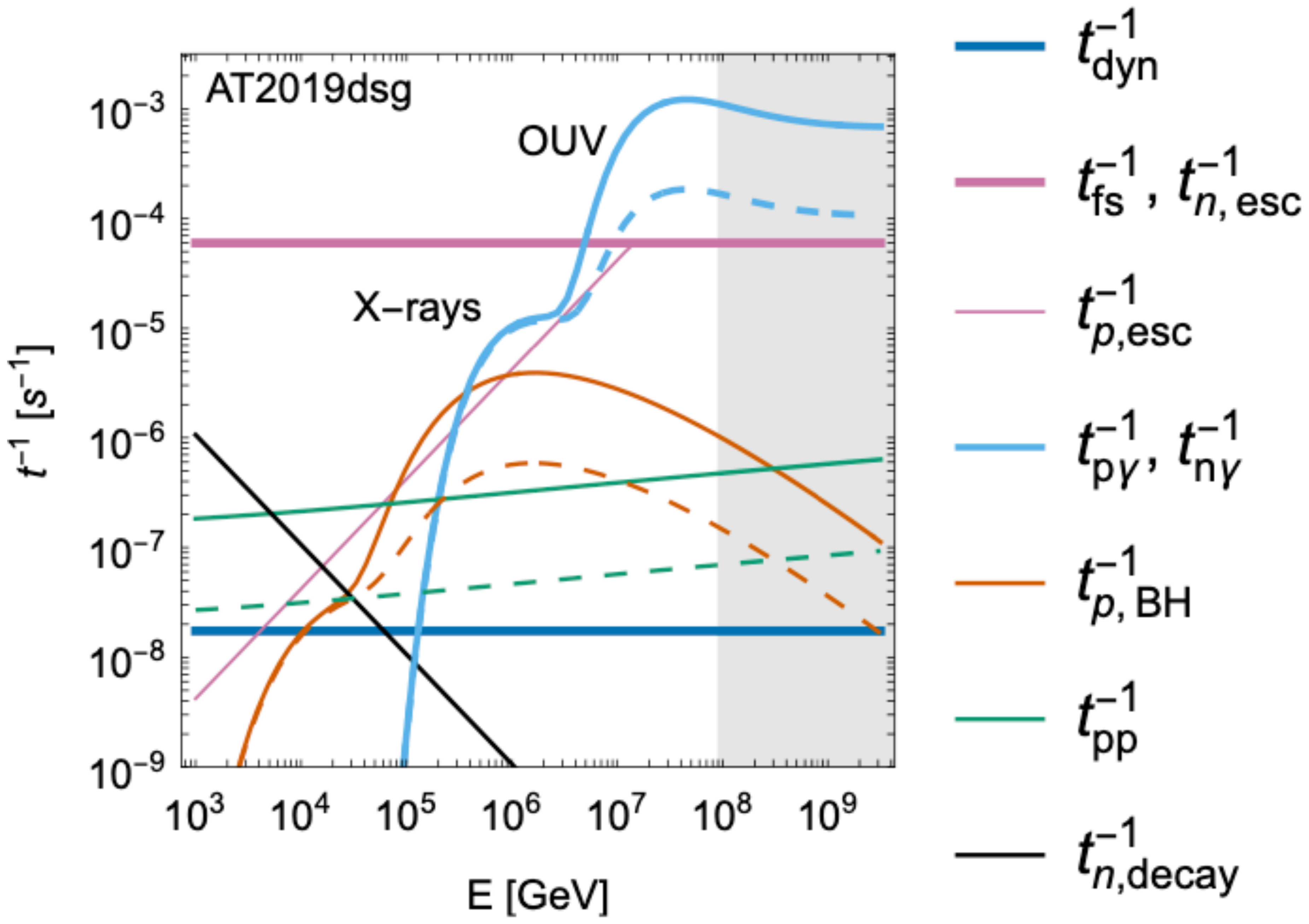


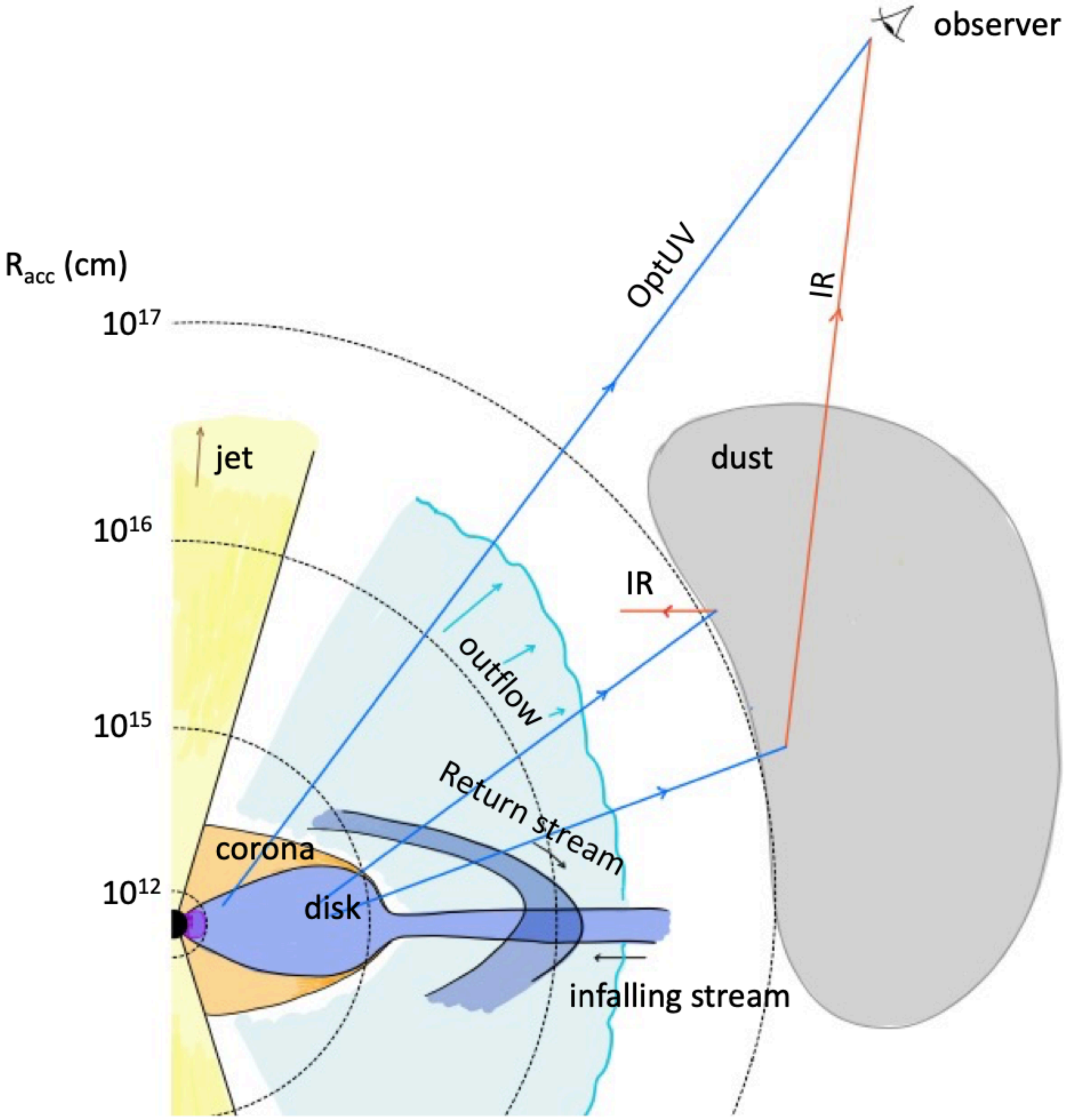
- Three associations of IceCube neutrinos with TDEs in 2019
- Last association, **AT2019aalc**, shows neutrino emission in coincidence with peak of dust echo emission
  - is the dust echo itself (IR) is the target for cosmic ray interactions?

Reusch et al, PRL 2022

# Tidal disruption events







- Interaction rates at the time of the peak (solid lines) and at the time of the neutrino emission (dashed)
- Neutrino emission depends on the relevant photon field (or matter) (shown as pp: dashed orange, X-rays: blue dashed-dotted, OUV: green dotted), **which is modelled as a function of the time**

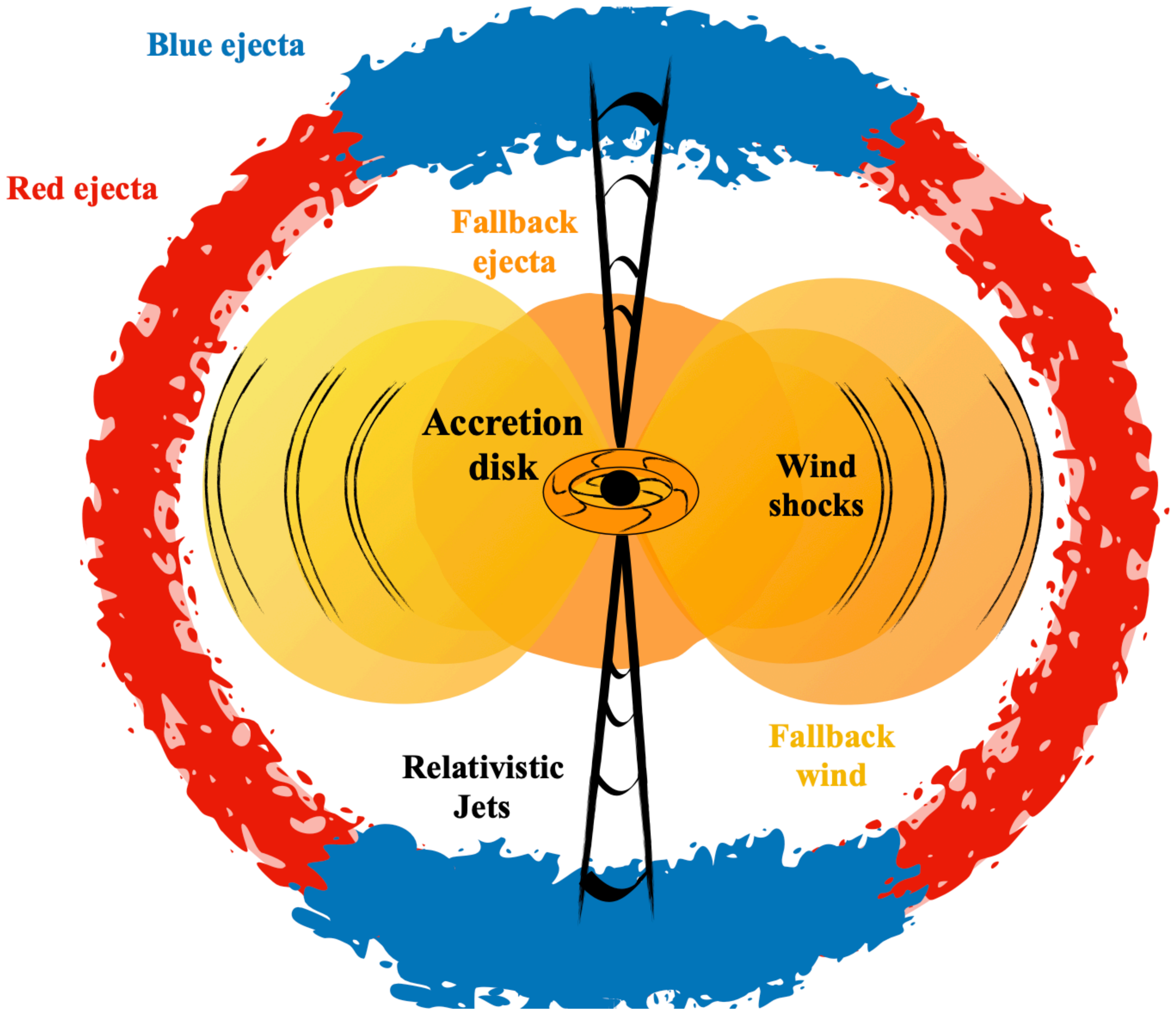
Neutrino emission from CR interactions in the **non-jetted region**

- see also Biehl, **DB**, Lunardini & Winter Sci.Rep. 2018 for diffuse fluxes and connection to UHECRs

Lunardini & Winter, PRD 2017; Winter & Lunardini, Nature Astron. 2021; Winter & Lunardini, ApJ 2023; Yuan et al arxiv:2401.09320

# Binary neutron star mergers

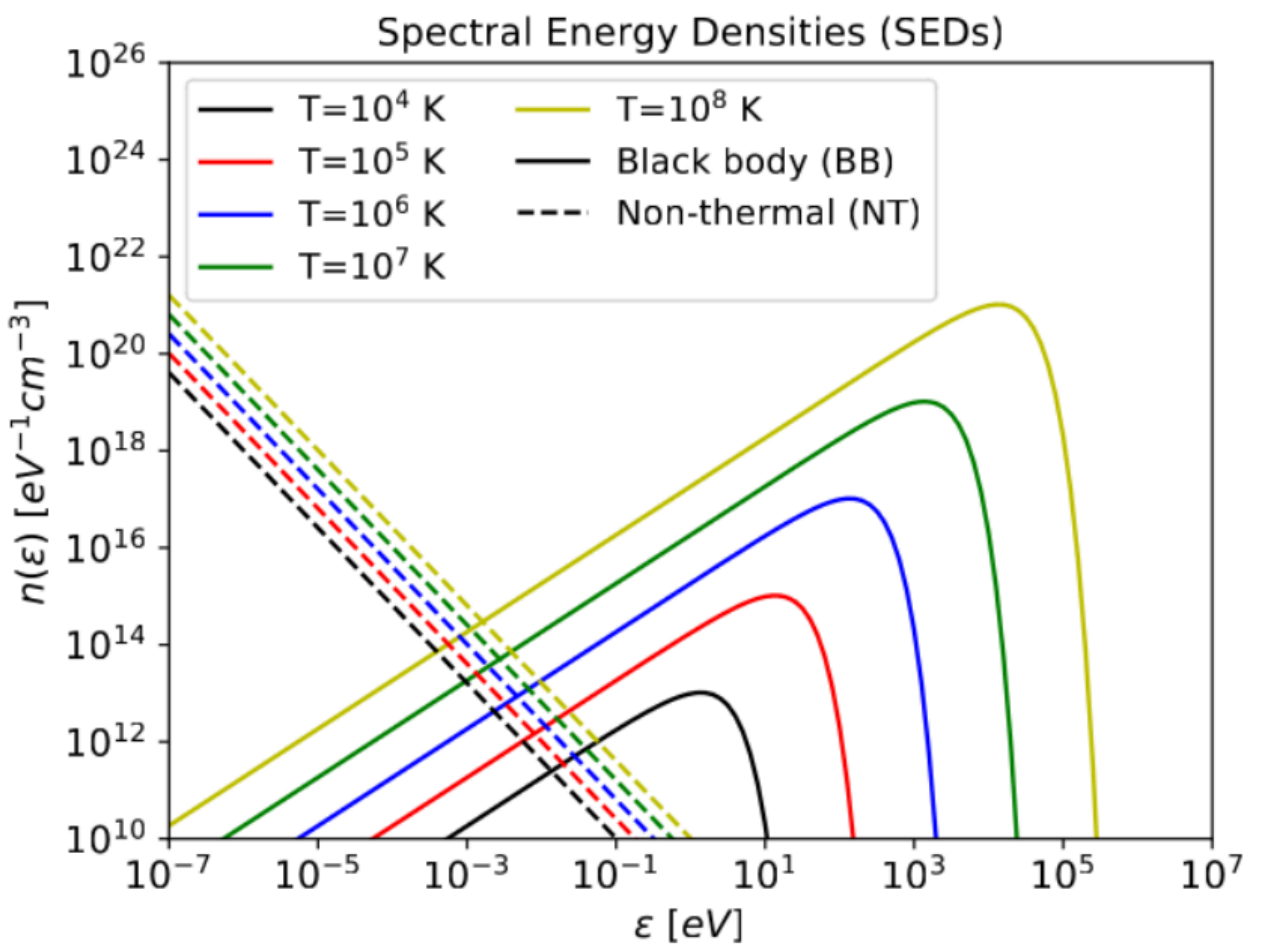
**Neutrino emission from CR interactions in the non-jetted region**

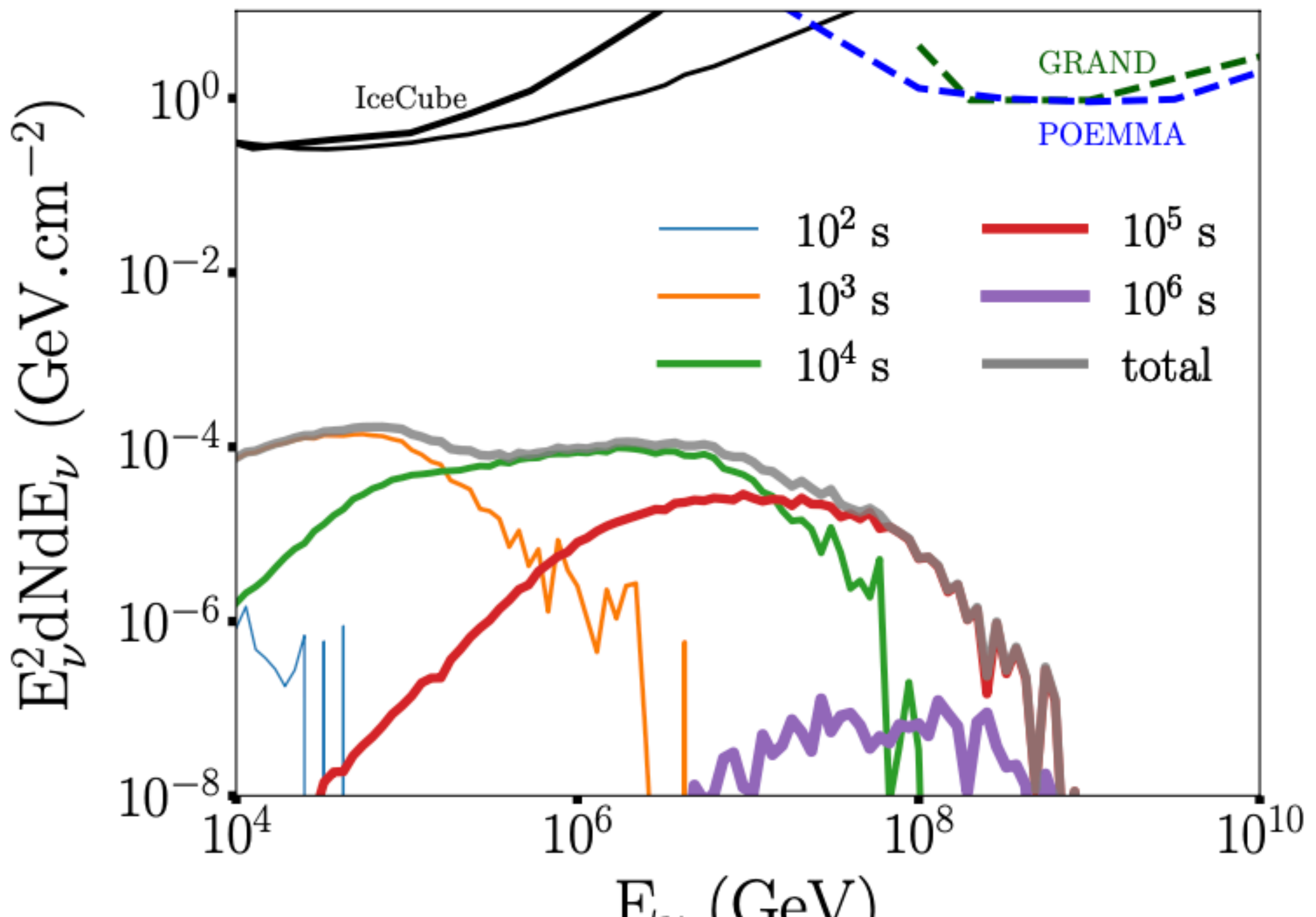


- At late times after the merger, a small fraction of the ejecta remains marginally bound to the black hole, falling back to it over a range of timescale from seconds to days or longer; **assumption (as done in Decoene et al JCAP 2020)**: such an interaction results in efficient cosmic-ray acceleration in the nebula behind the shell

**Decoene et al. JCAP 2020; Rossoni, DB & Sigl, in prep.**

- Explored in Decoene et al JCAP 2020; Rossoni, DB & Sigl ICRC2021
  - Non-thermal emission (synchrotron -> limits on B can be computed) + thermal emission (Due to the nuclear decay of the unstable species synthesized in the ejecta by the merger)

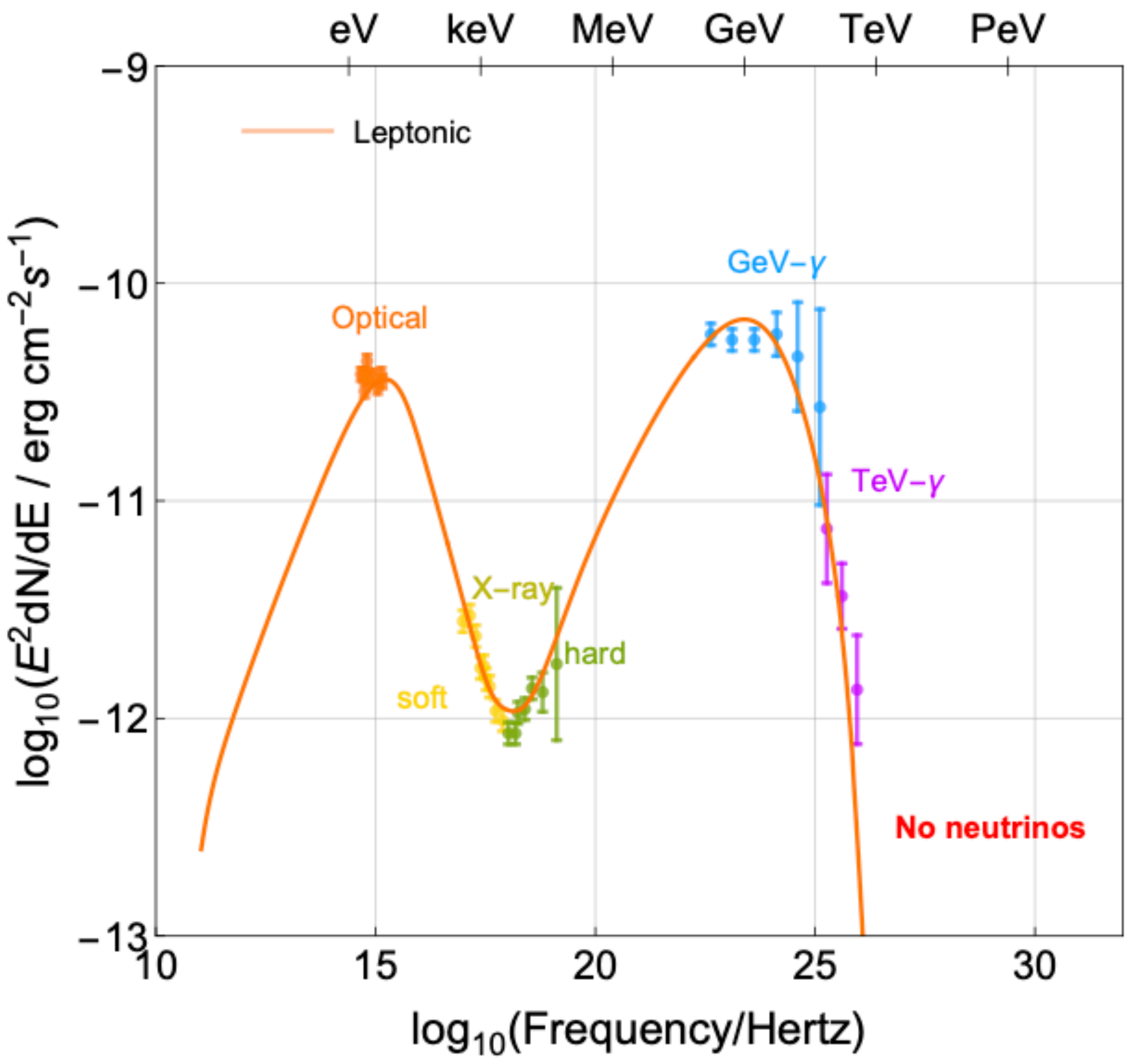




- As for the other examples where disrupted stars are involved, the nuclear species involved strongly depend on **the type of the star and/or the base of the jet**

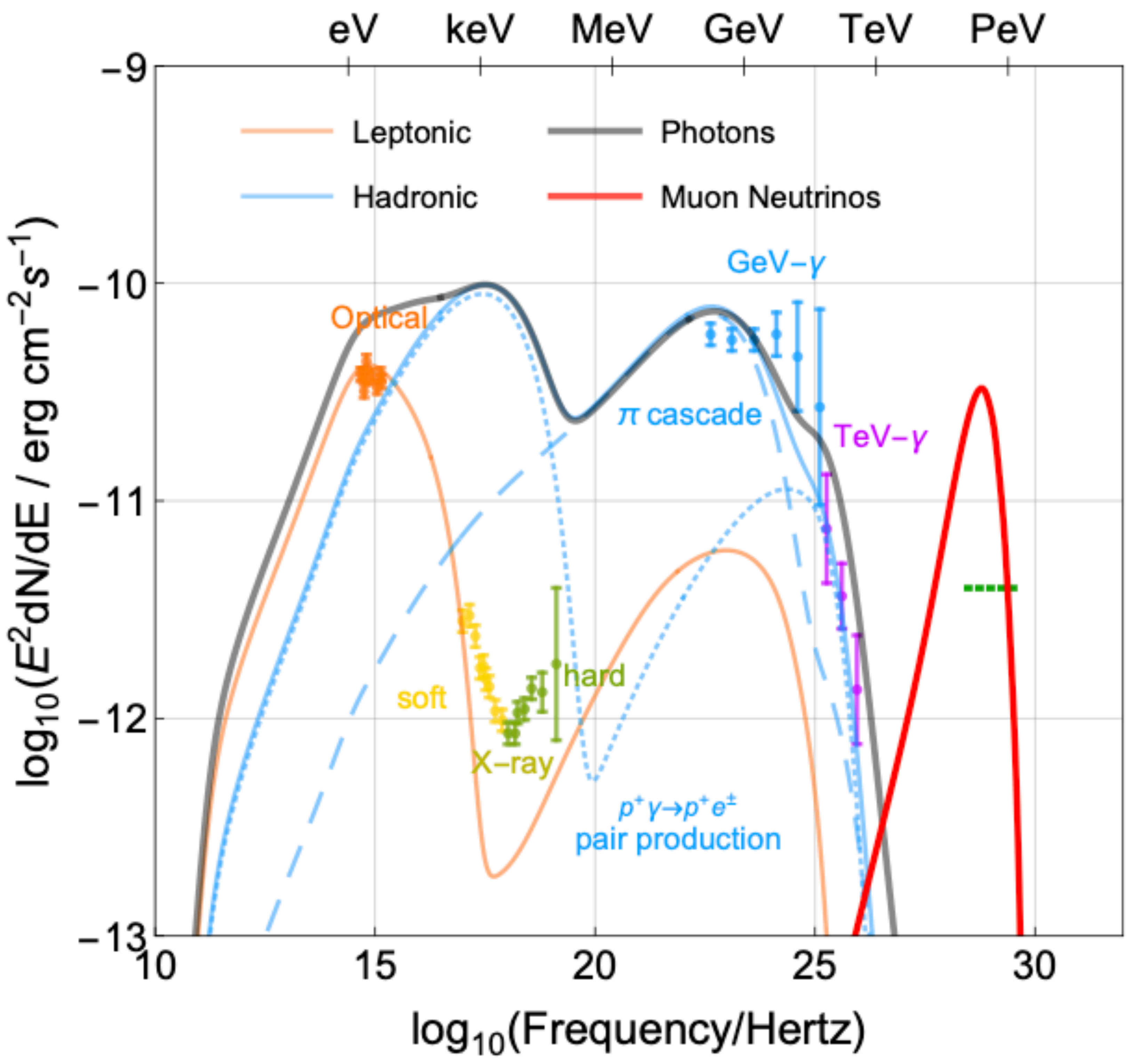
# Active Galactic Nuclei

Modelling of the spectral energy density of **TXS0506+056**



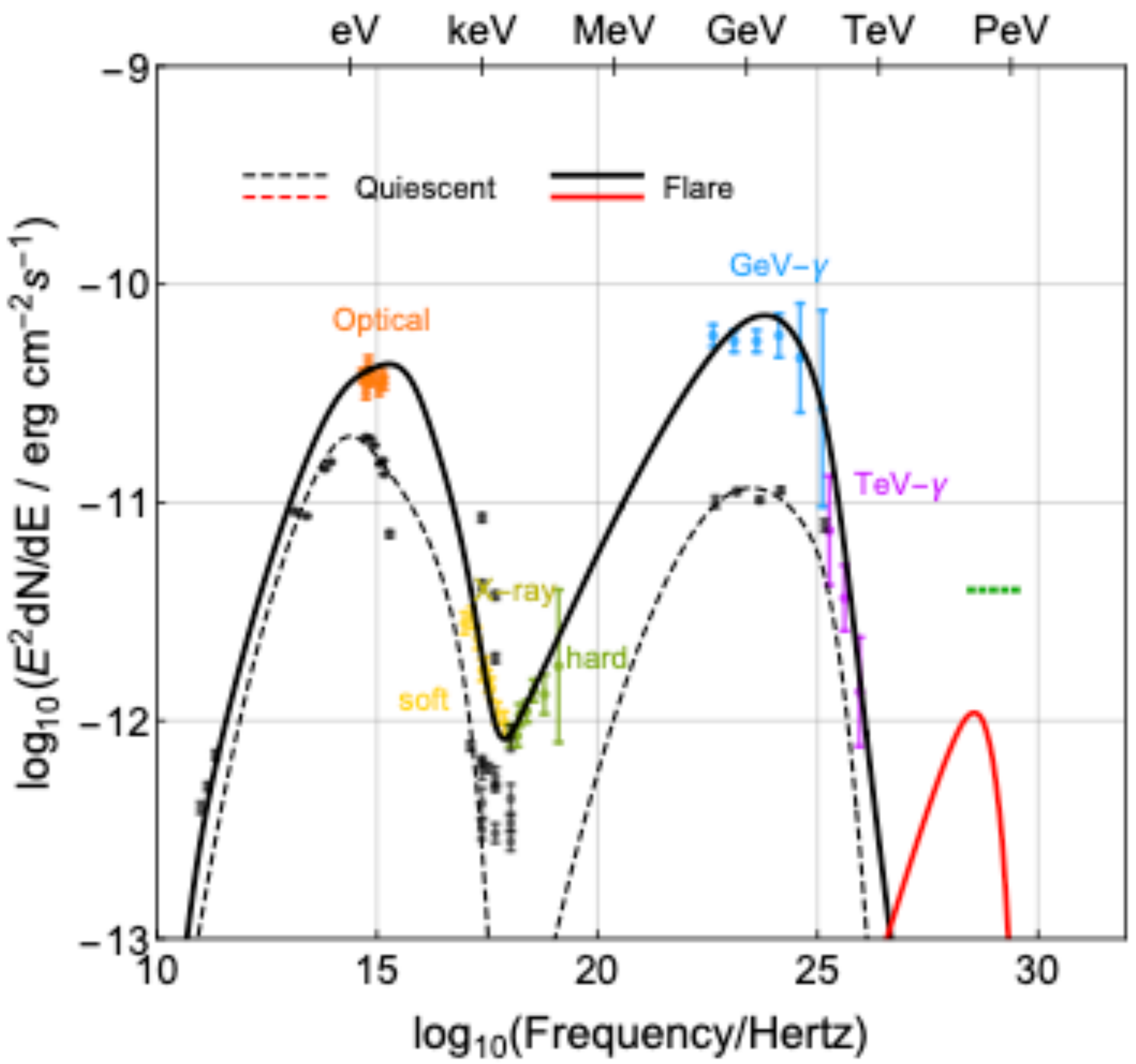
Pure leptonic model reproduces the SED of the source

- No neutrinos predicted



Hadronic model reproduces the second bump and the neutrino

- Overshoots the X-ray flux



Lepto-hadronic model

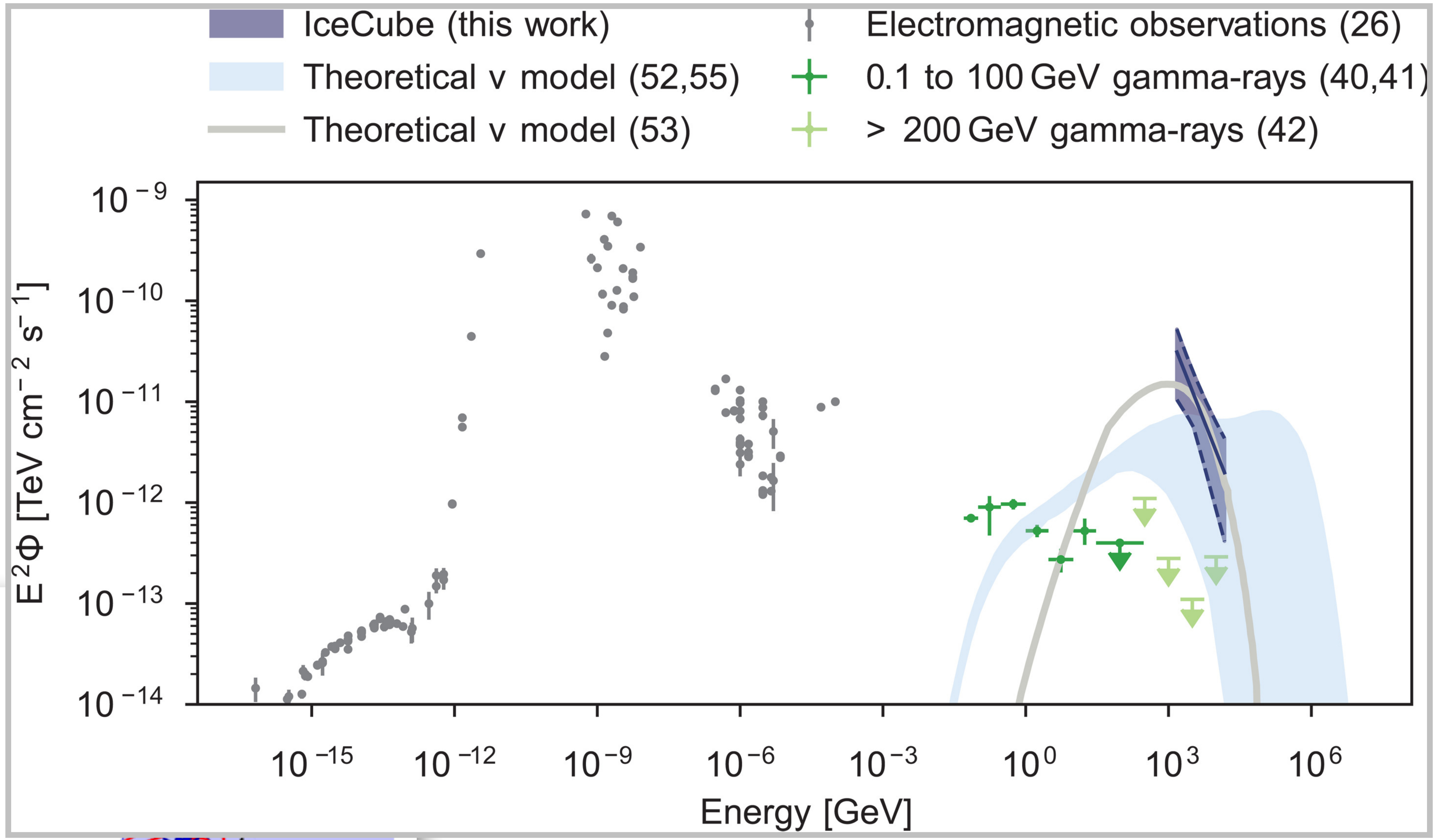
Gao et al, Nature Astron. 2019

Neutrino emission from **lepto-hadronic** model

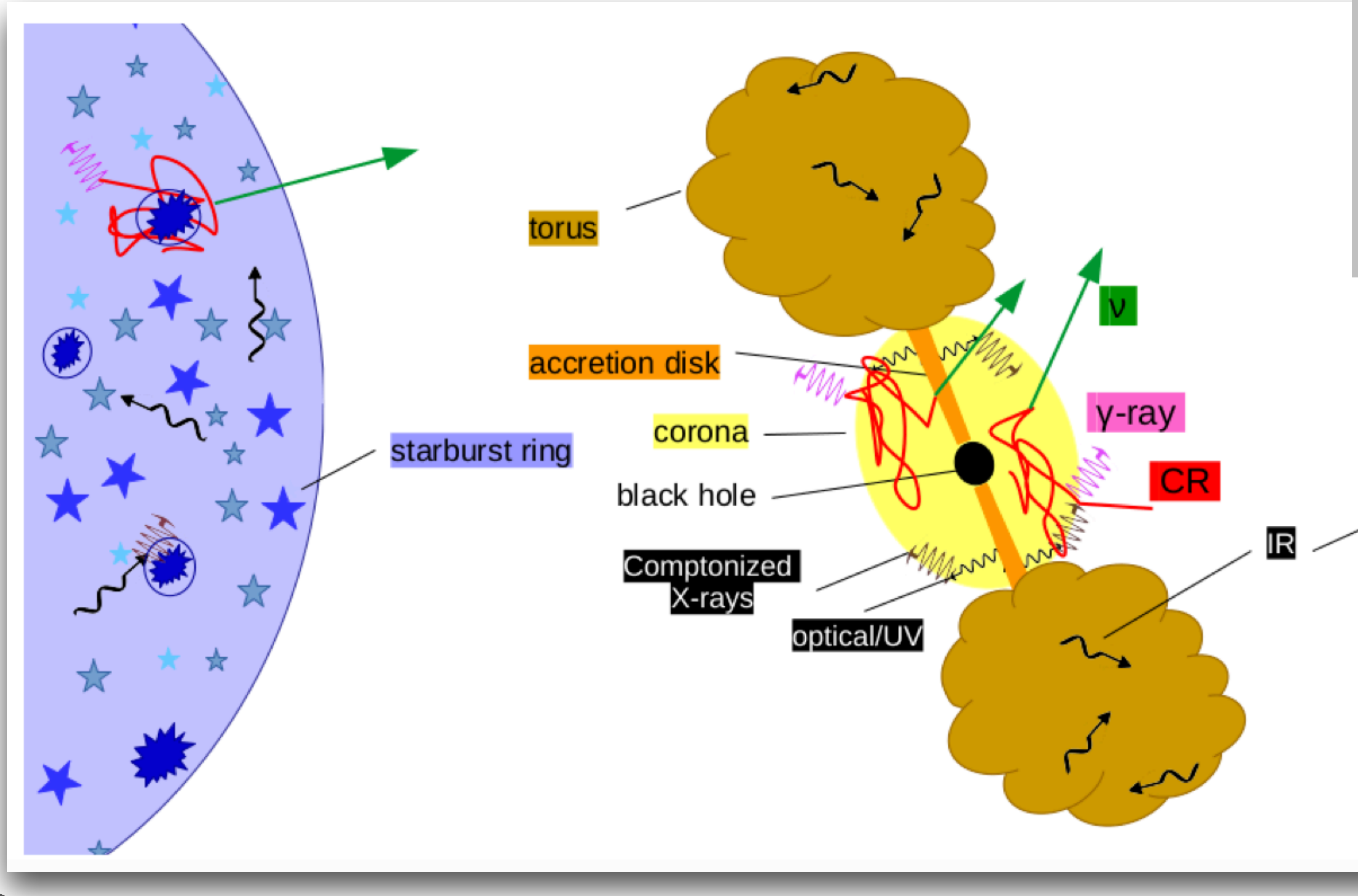
# Active Galactic Nuclei

IceCube, Science 2022

- 79 neutrino IceCube events associated to NGC1068: obscured AGN (Seyfert2)
- Gamma-ray flux smaller than neutrino flux
- **IceCube cannot distinguish the emission zone (as well as for the other associations)**

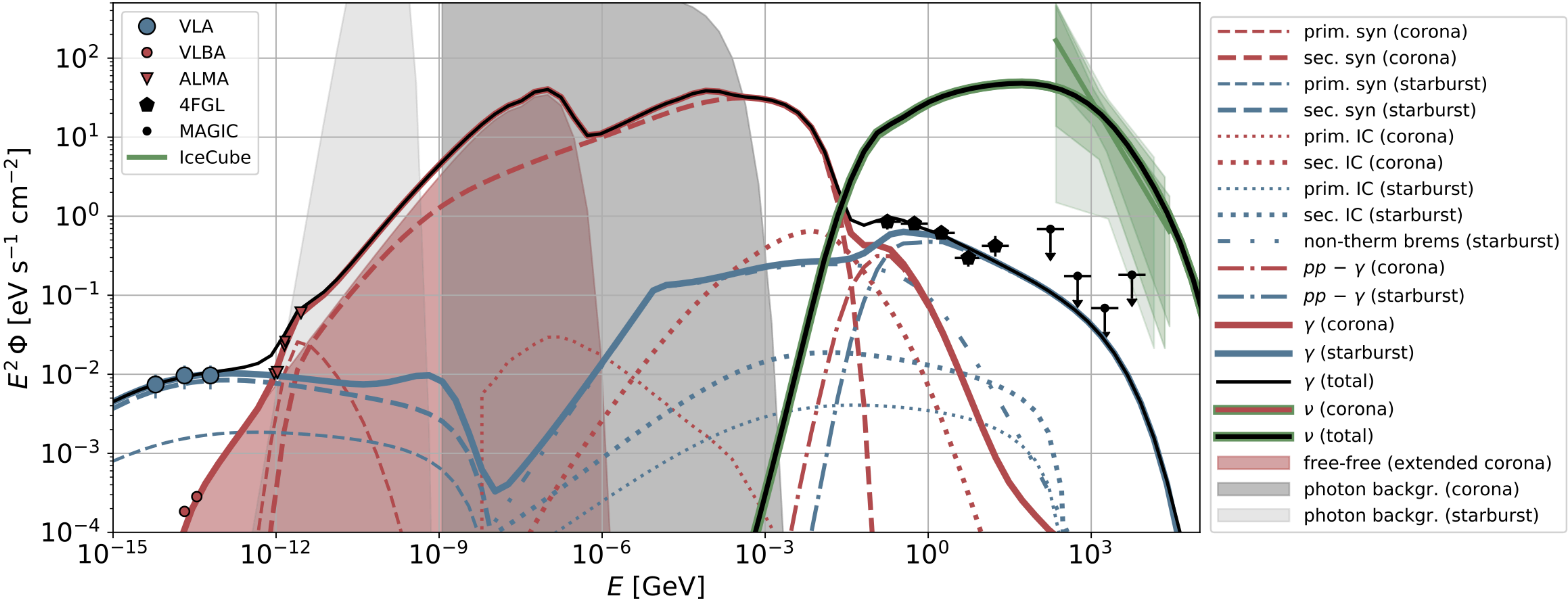


Eichmann et al, ApJ 2022



# Active Galactic Nuclei

- Is the neutrino emission really coming from the jet?
  - From one-zone model to two zones (one zone is not sufficient), see for instance Eichmann et al ApJ 2022 (neutrinos from corona + gamma-rays from starburst region) or Inoue et al 2022 (neutrinos from failed outflow + gamma rays from external shock)



One-zone model is not sufficient to explain gamma-ray and neutrinos

Eichmann et al, ApJ 2022

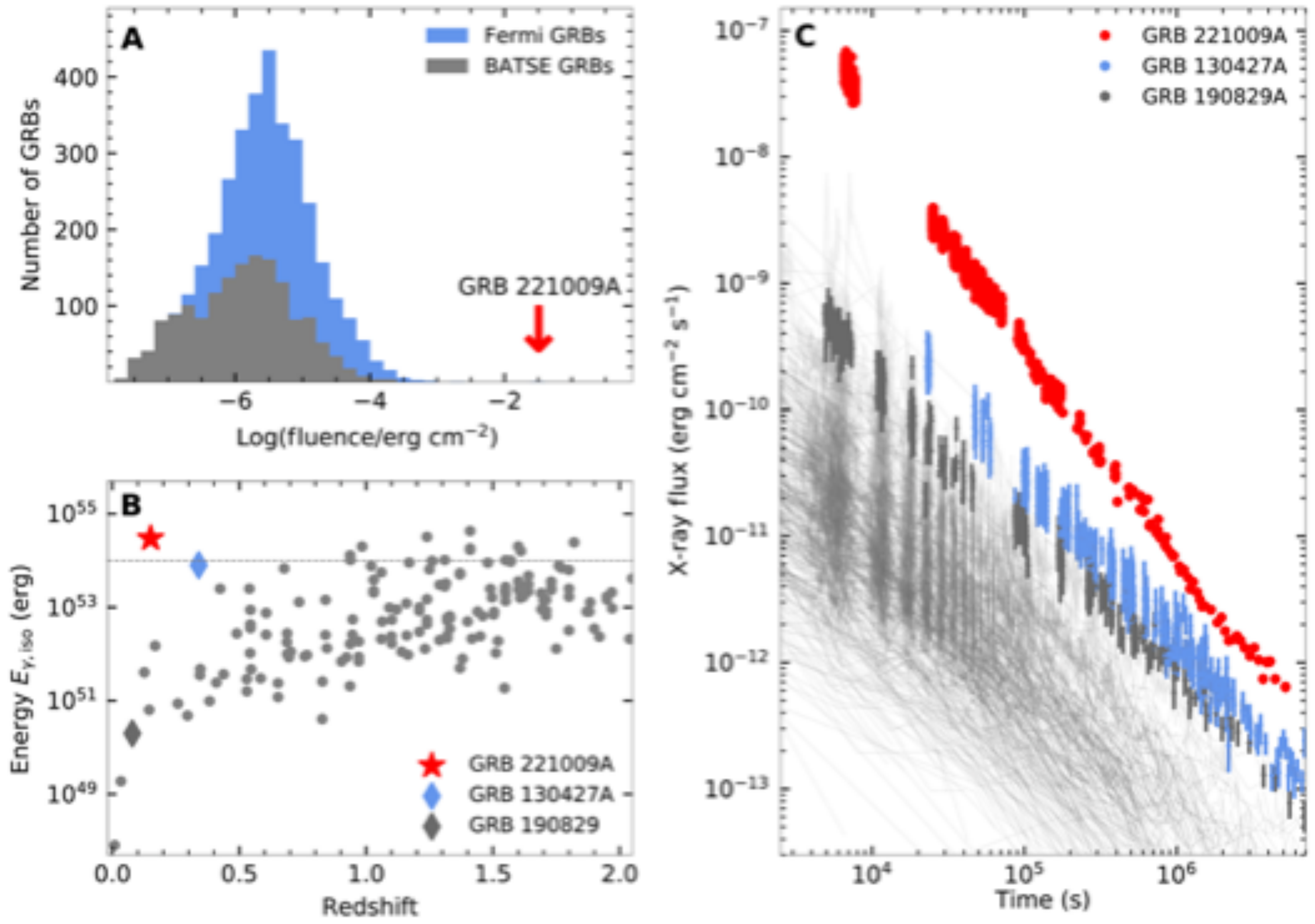
# What do we learn from astrophysical neutrinos?

- A wide range of candidate neutrino-source classes has been investigated and
  - found no evidence for neutrinos originating from several source classes; possibility to constrain the contribution from blazars and non-blazars
  - **Blazar and TDE associations with neutrinos:**
    - **not sufficient to account for the diffuse neutrino flux;**
    - several hints from modelling of possible sources:
      - Neutrino emission from **jets** (such as jets in GRBs) energetically motivated, but no evidence of association -> are we looking at the correct GRB phase?
      - Neutrino emission from **non-jetted regions** (such as in some TDE or blazar models) possible
        - One-zone models start to be challenged
        - Neutrino production sites could be gamma-ray opaque
      - **Modelling of source sites must be performed in time and energy**

Associating photon- and neutrino-signals is not trivial as expected!

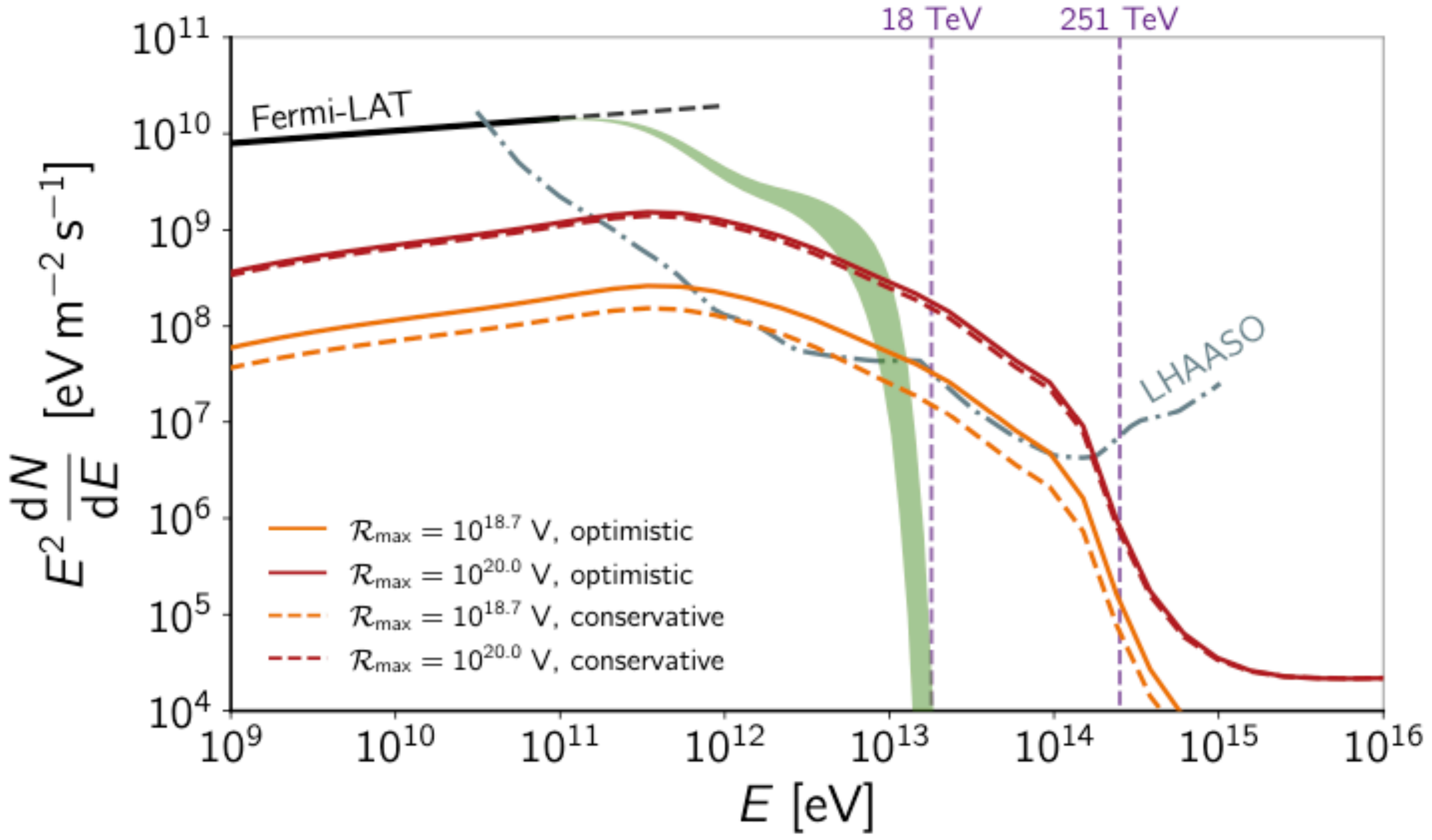
# Any help to understand UHECRs?

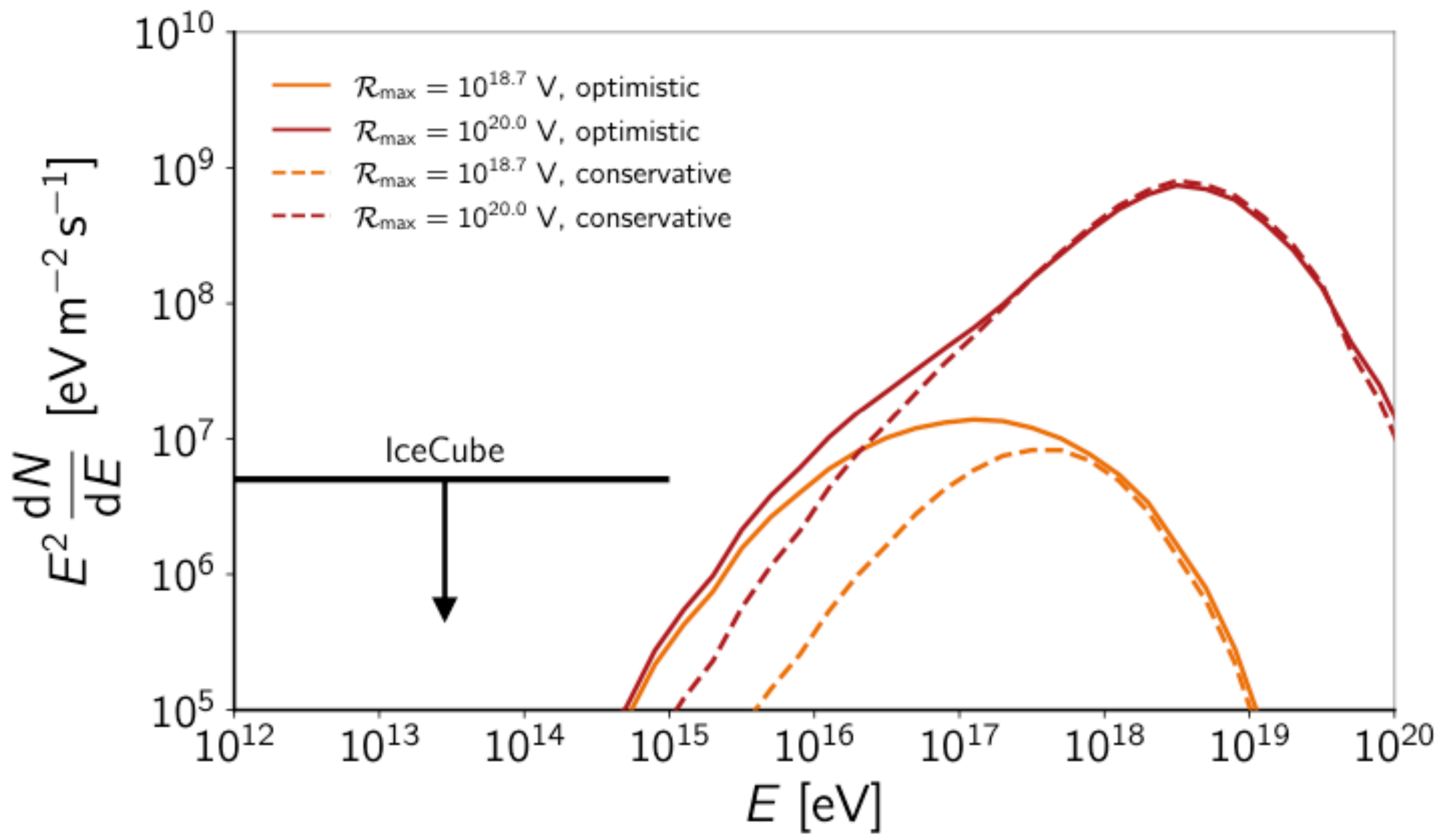
From the TDE and blazar associations with neutrinos: **PeV protons** are necessary in the sources…



However, thanks to the observation of **GRB221009A**…

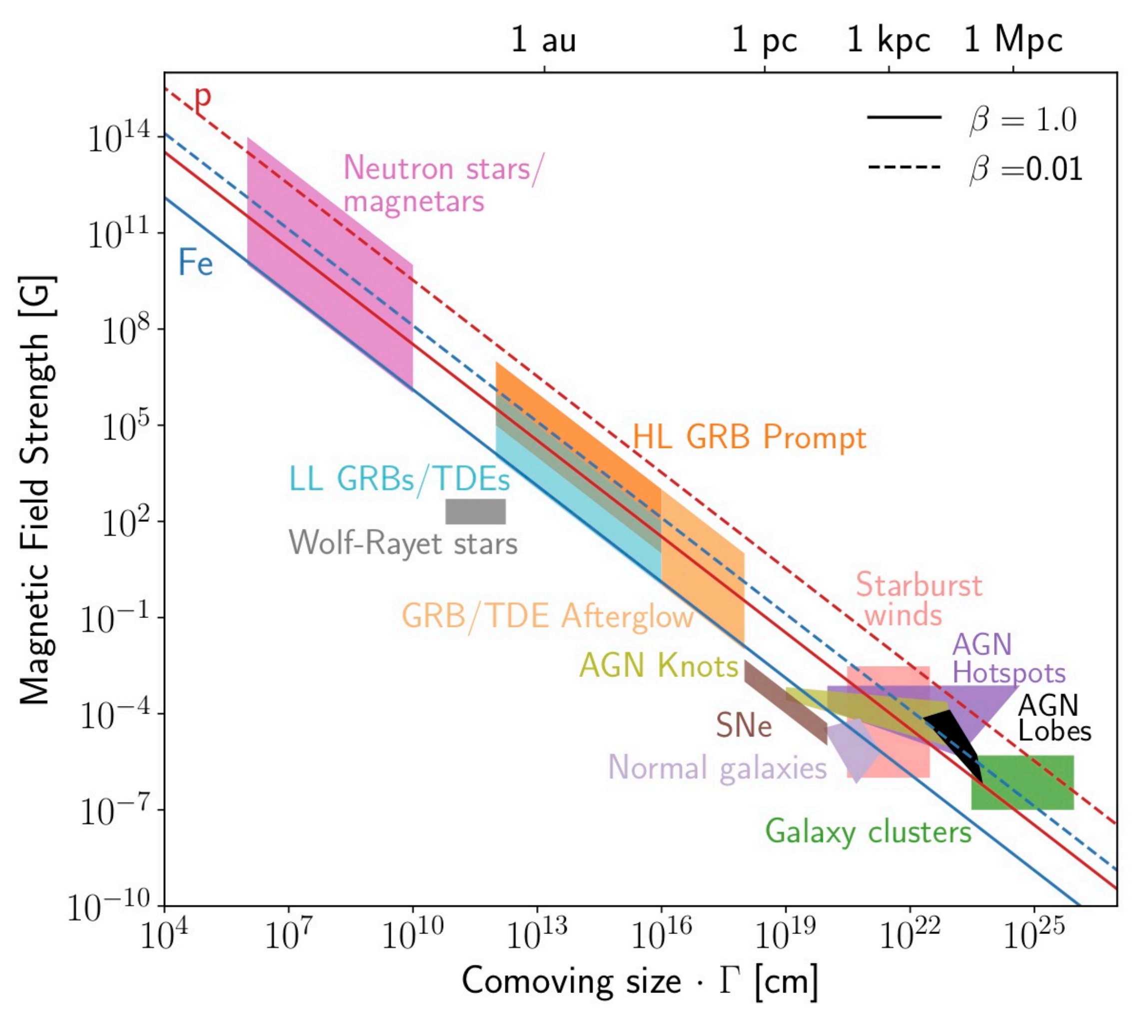
- Observed photons up to 18 TeV
- Based on the distance of the GRB, we do not expect *primary* photons from this GRB
  - If UHECR protons are accelerated in the GRB up to 1 EeV, *cosmogenic photons* can be expected (some conditions on EGMF and time window of observation are requested), as shown in Alves 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





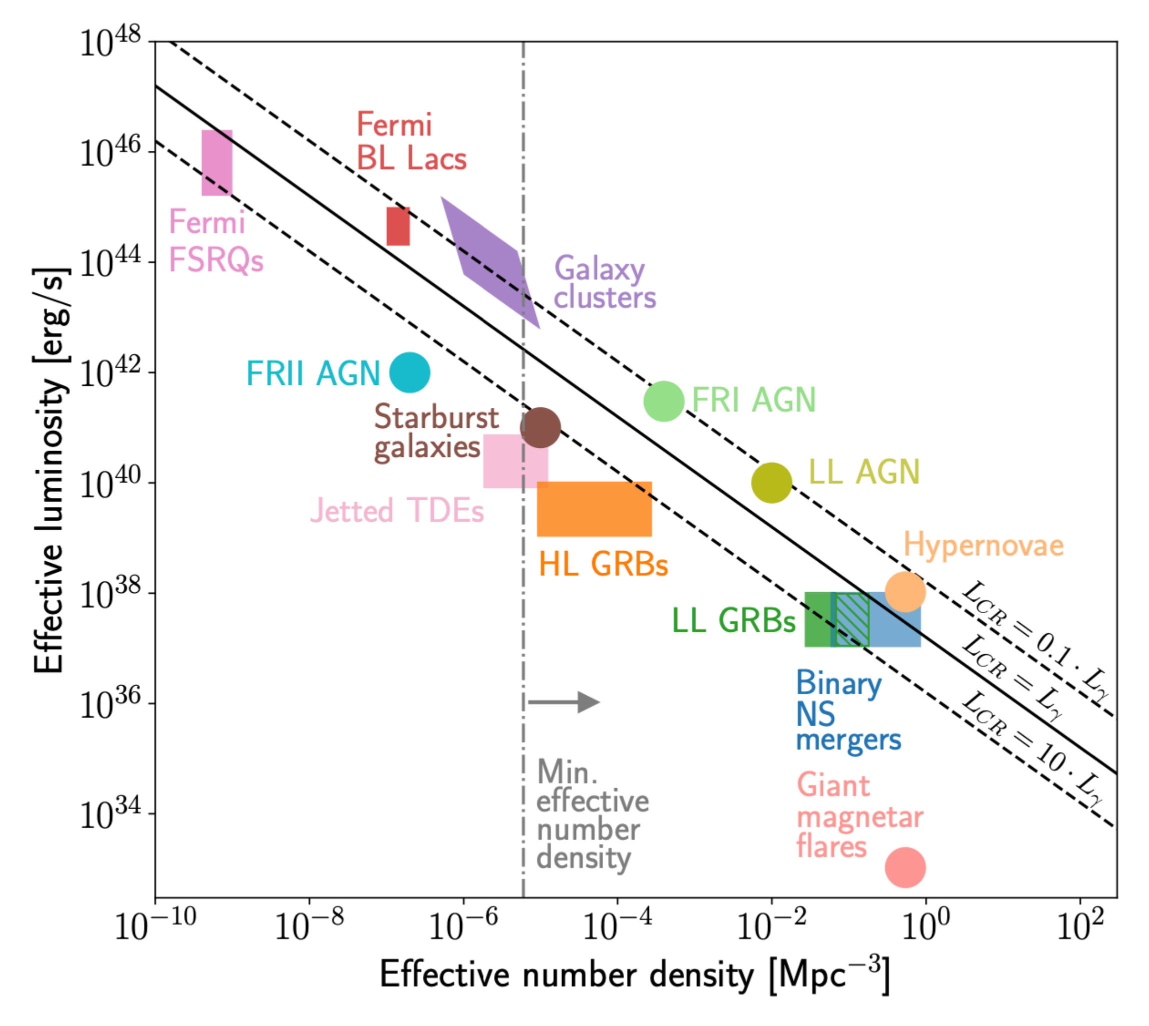
- **Probe of UHECR acceleration in GRBs?**
- See Waxman & Bahcall PRD 1999 for estimate of neutrino intensity from GRBs

# Do GRBs pass the requirements for being UHECR (and neutrino) sources?



- Maximum energy of protons in the GRB might be ok!

- How can we test if GRBs can power the UHECR flux?



$$\varepsilon_{\rm CR} = L_{\rm CR} n =$$

$$10^{44}\ \mathrm{erg\ Mpc^{-3}\ yr^{-1}}$$

$$\varepsilon_{\rm CR} = E_{\rm CR} \dot{n}$$

**emissivity**, computed from fit of UHECR spectrum and composition

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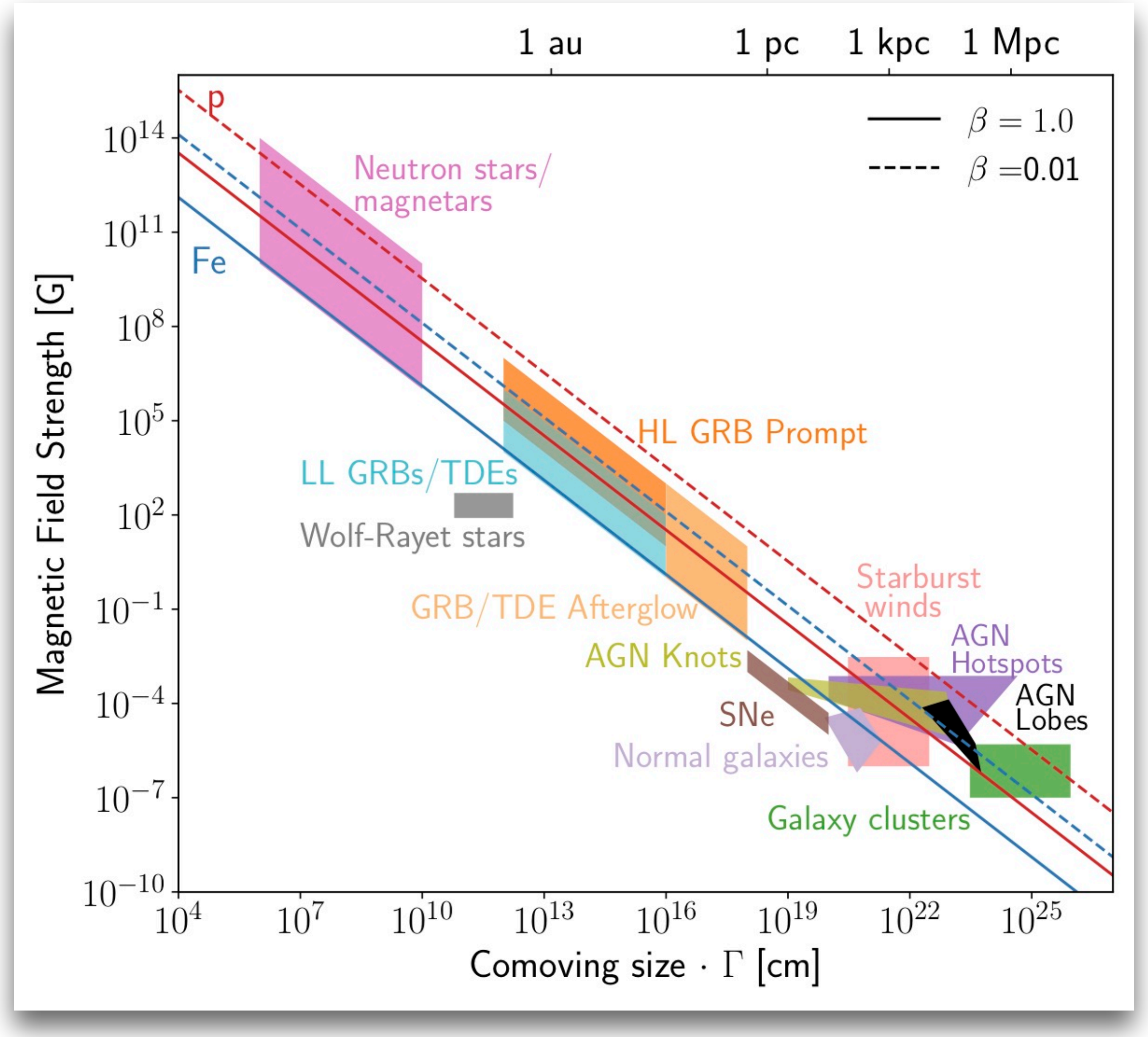

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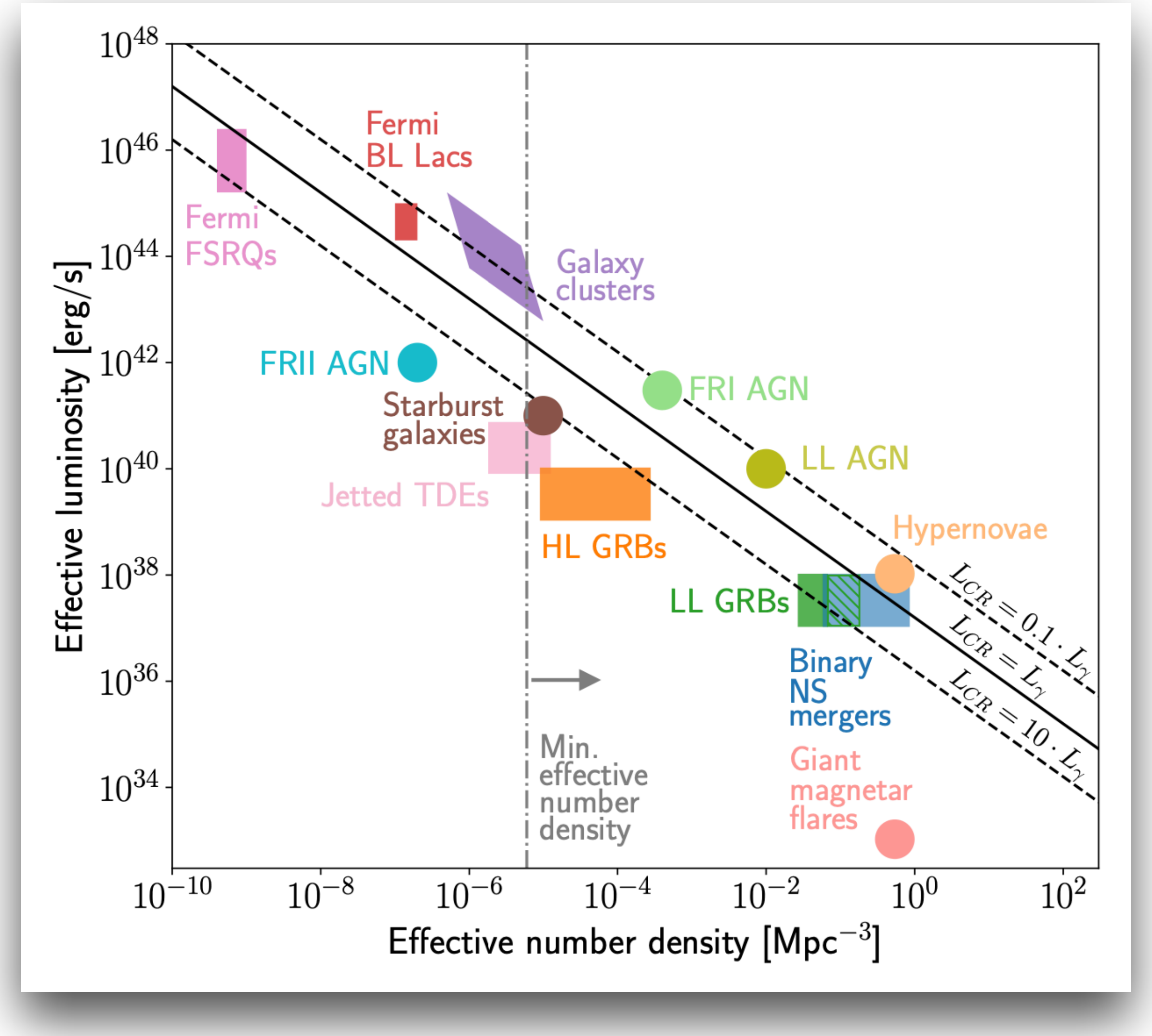

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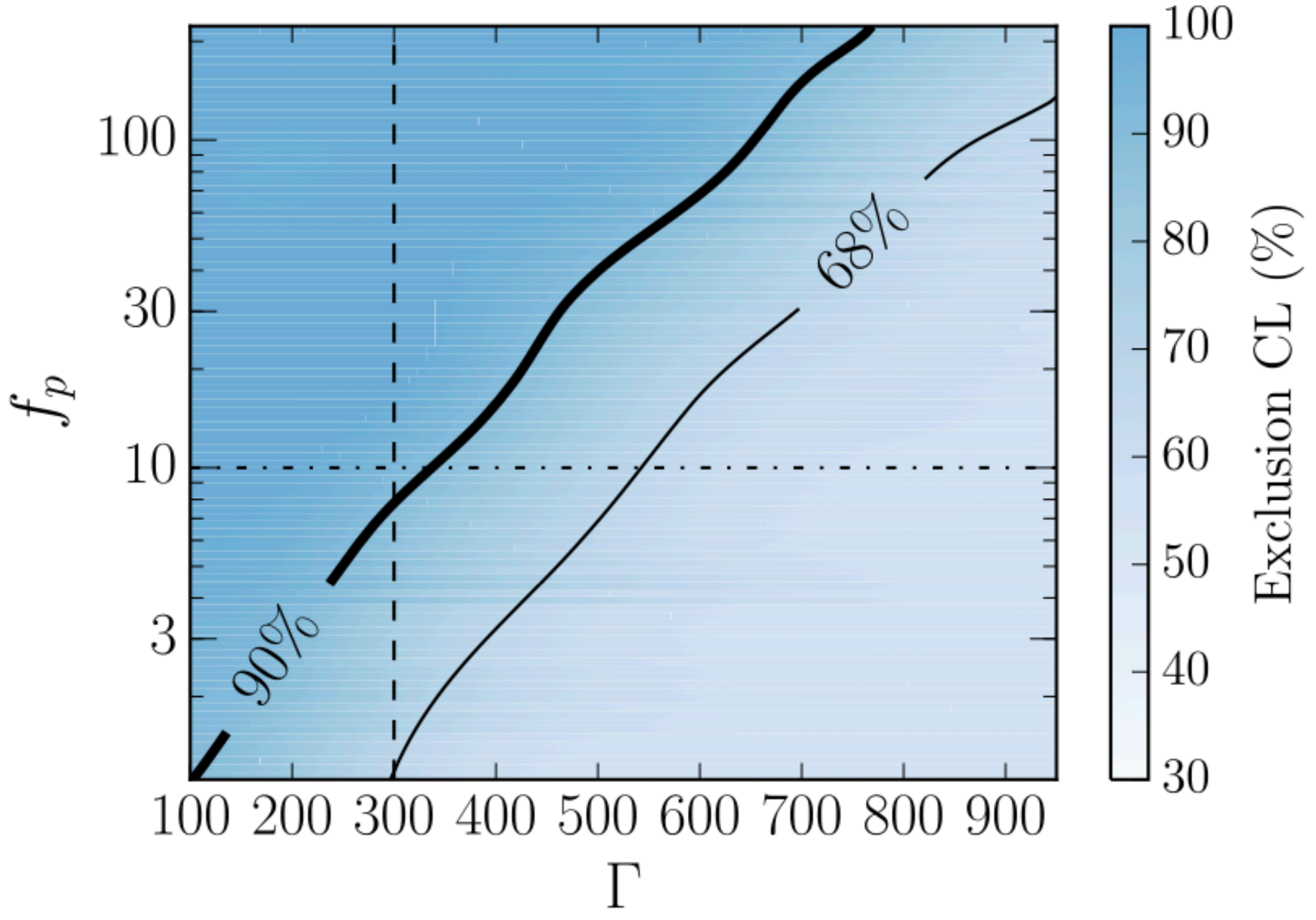
**emissivity**, computed from fit of UHECR spectrum and composition

$$L_{\rm CR} = \int Q_{\rm CR}(E)E\,dE \approx f_p L_\gamma$$

$$L_\nu \approx f_\pi L_{\rm CR} \approx f_\pi f_p L_\gamma$$

$f_p$ baryonic loading, unknown

IceCube, ApJ 2016



- The baryonic loading (and other parameters describing the GRB model) can be constrained with neutrinos

- The combination of experimental analyses and theoretical modelling of different messengers is crucial!

- As for the photon-neutrino connection, what is OK for neutrino production in terms of characteristics of the source environment, might be not optimal for CR emission…

# SUMMARY

# Summary

What does the **multimessenger era** disclose to us about UHECR sources?

## Cosmogenic neutrinos

- Cosmogenic neutrinos are sensitive to the distribution of UHECR sources in redshift
- Cosmogenic neutrinos depend on the characteristics of the UHECRs at the escape from their sources
- **More sensitive detectors needed in the future!**

## Astrophysical neutrinos

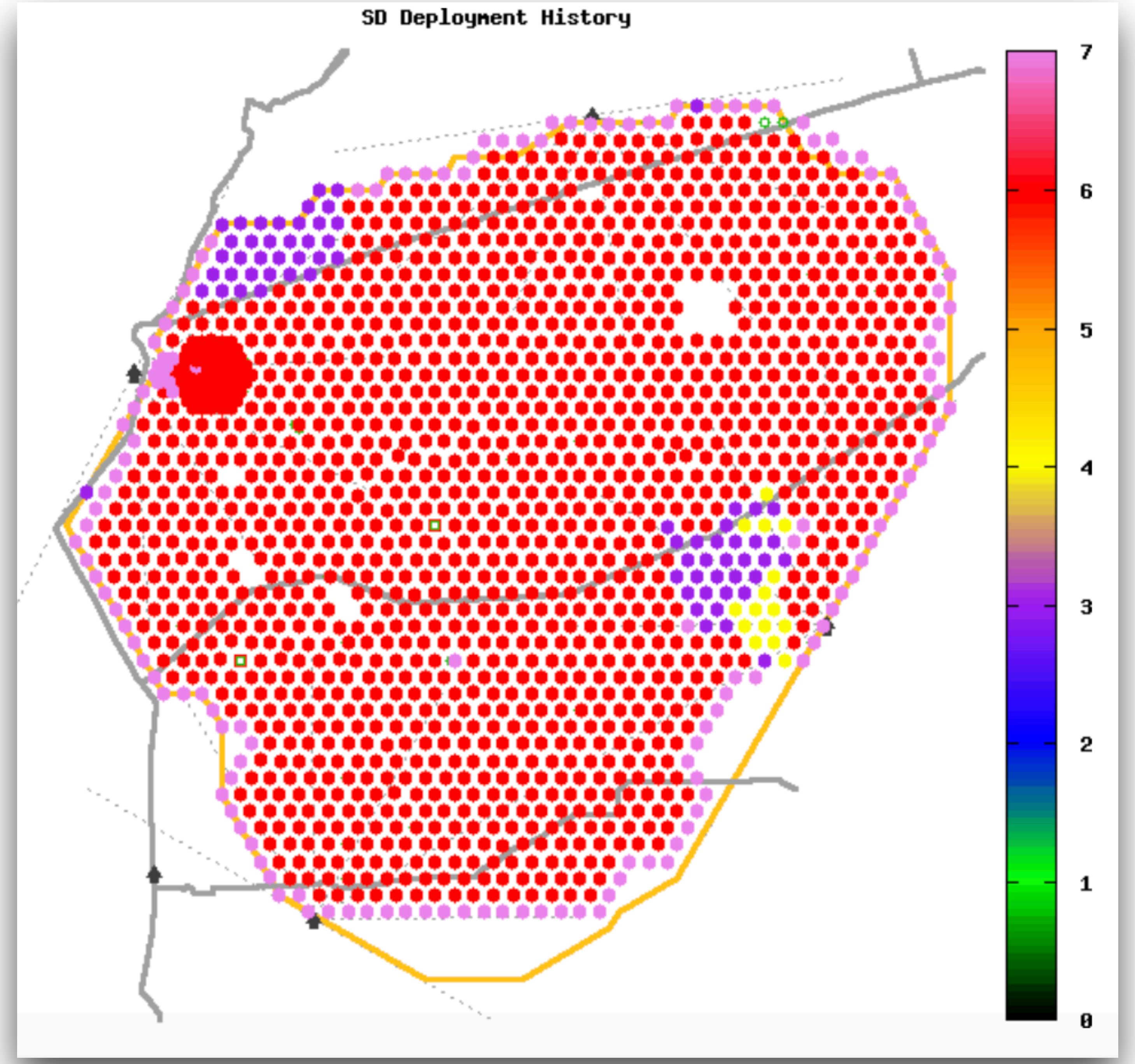
- The neutrino-blazar and neutrino-TDE associations are not sufficient for establishing a clear connection between neutrino and astrophysical sources
- Acceleration of cosmic rays in jets regions might be disfavoured in some cases
- One-zone models start to be challenged
- **Multi-wavelength and multimessenger observations + connections between observatories needed**
- **Modeling of source environment is crucial!**

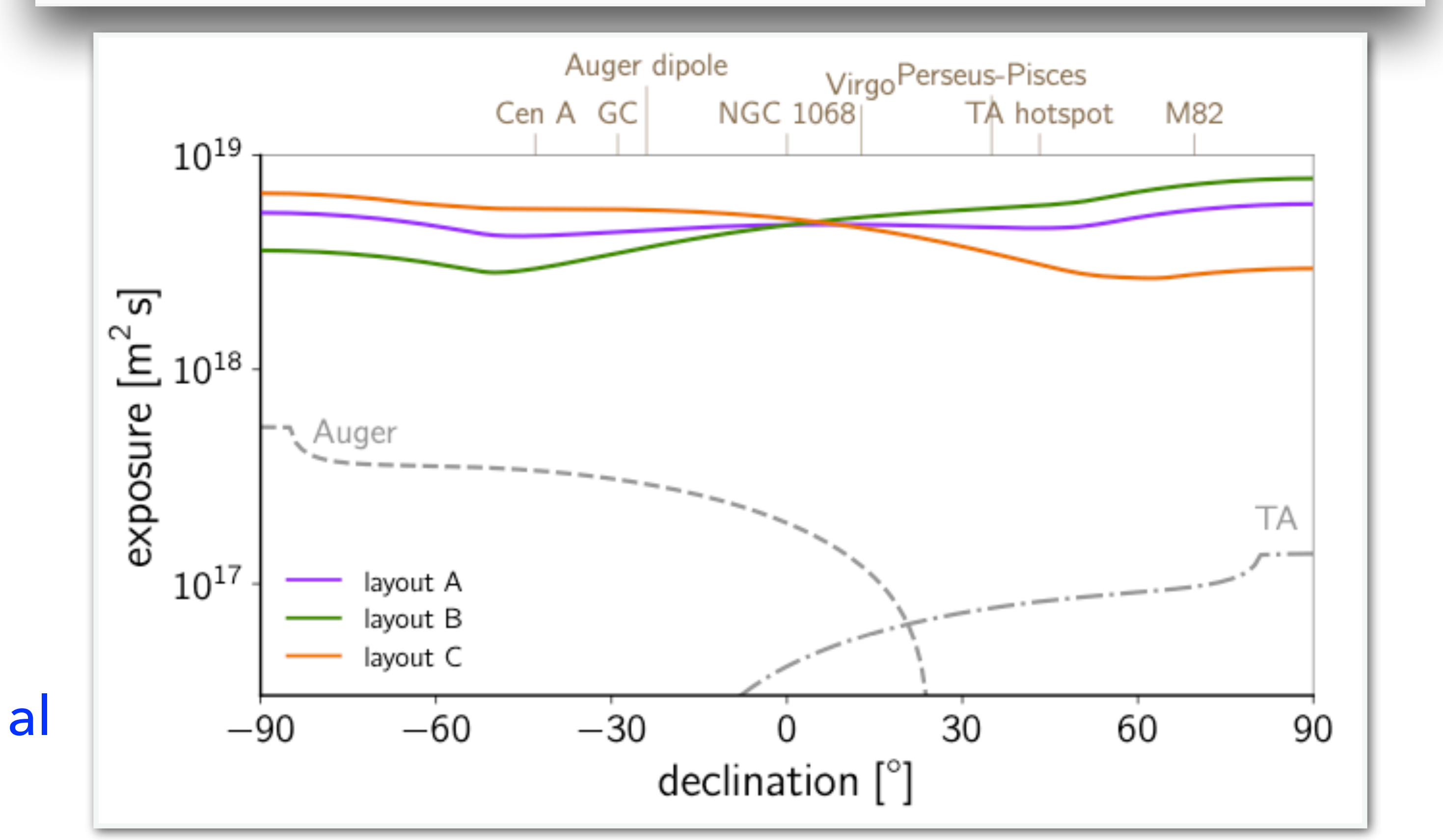
# UHECRS: PRESENT AND FUTURE

- Upgrade of the Pierre Auger Observatory is expected to push forward the understanding of several issues:
  - **Mass composition at the highest energies**
    - discrimination among astrophysical scenarios depends on composition
    - selection of pure protonic events at the highest energies would allow to exclude quasi-isotropic background due to nuclei
  - Improvement on muon content of the shower and **particle physics** in general
  - **Physics beyond standard model?**

- Auger Phase 1 -> 15 years with full SD
- Auger Phase 2 -> 10 years (foreseen)
  - Deployment and installation of scintillators on top of water Cerenkov detectors -> completed
    - complementary response of the detectors to muon and electromagnetic part of the shower

Plot from talk by F. Salamida @ICRC23





R. Alves Batista et al ICRC23

- Next-generation experiments are foreseen to deepen the multimessenger approaches
  - POEMMA, GRAND, GCOS

# UHECRS: PRESENT AND FUTURE

- Upgrade of the Pierre Auger Observatory is expected to push forward the understanding of several issues:
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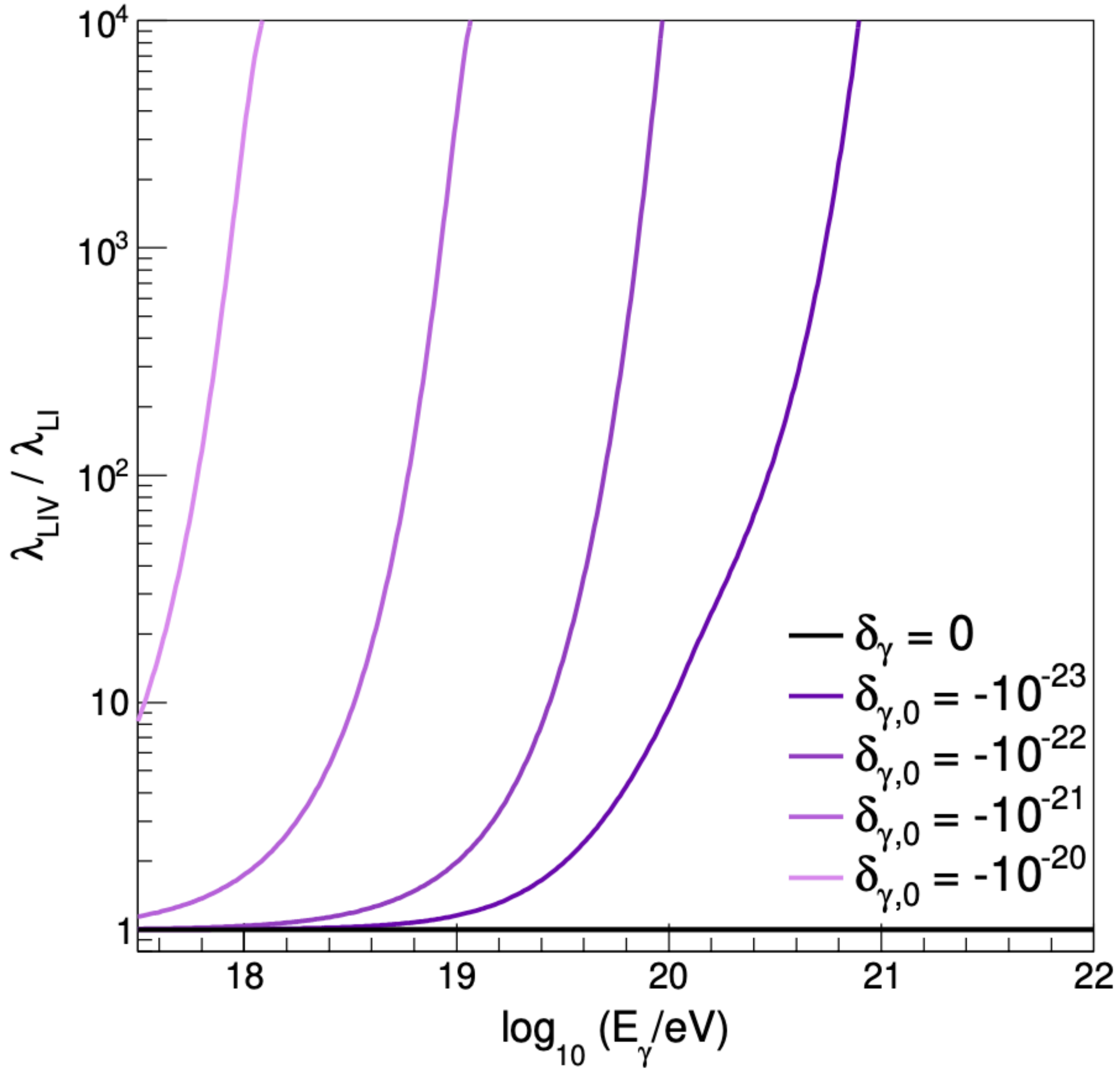
  - Improvement on muon content of the shower and **particle physics** in general
  - **Physics beyond standard model?**

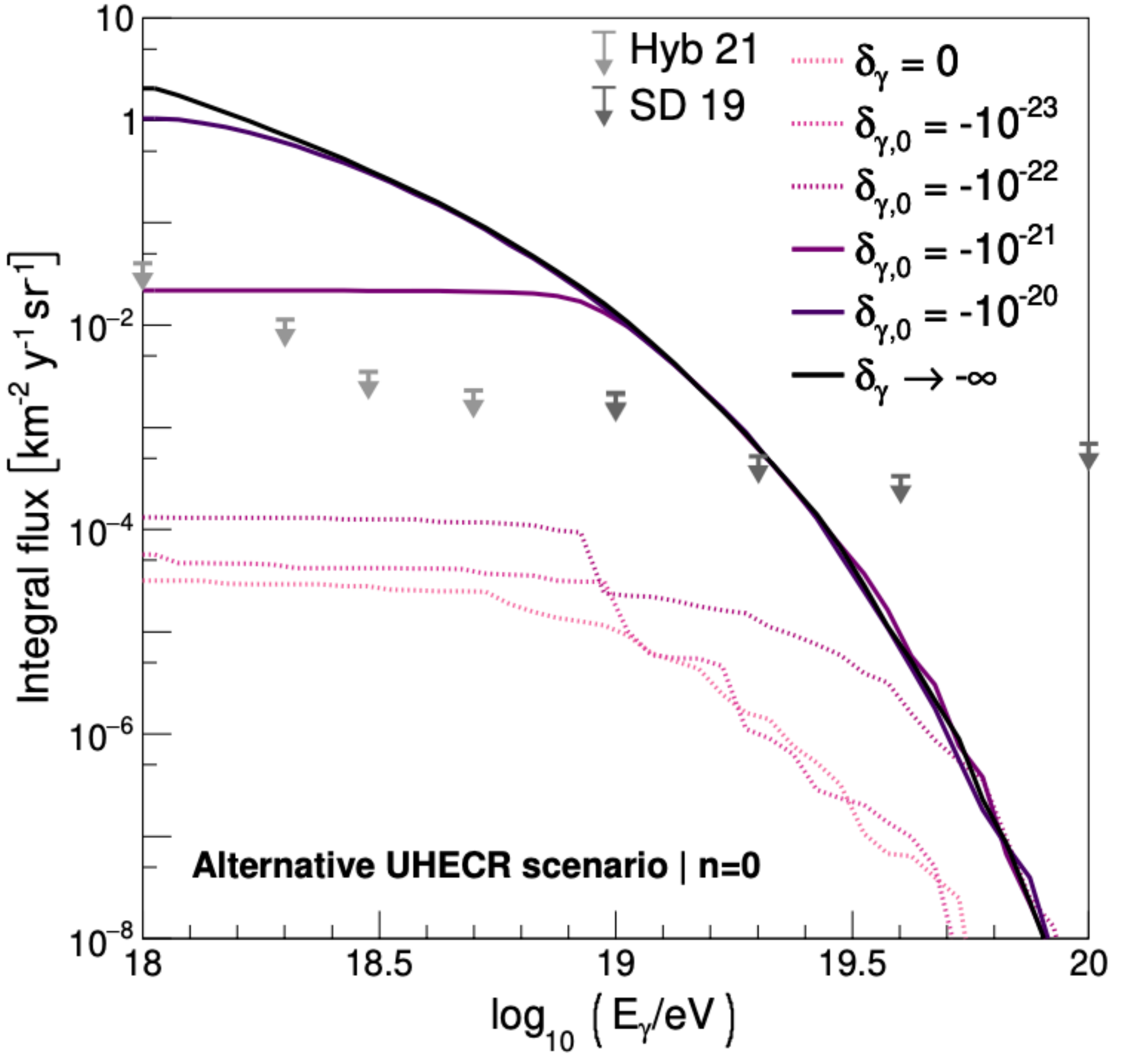
- UHECR data start to be sensitive to finer details with respect to basic astrophysical scenarios !
- For a comprehensive description of UHECR data and understanding of UHECR characteristics, improvements in modelling are needed:
  - UHE acceleration
  - GMF and EGMF modelling
  - In-source interactions (including connections to modelling of spectral energy density of  candidate sources)
  - Multimessenger connections

# UHECRS: **NOT ONLY** STANDARD PHYSICS

- LIV effects on cosmogenic photons

$$E_i^2 - p_i^2 = m_i^2 + \sum_{n=0}^{N} \delta_{i,n} E_i^{2+n}\,, \qquad \delta_{i,n} = \frac{\eta_{i,n}}{M_{\rm Pl}^n}\,,$$



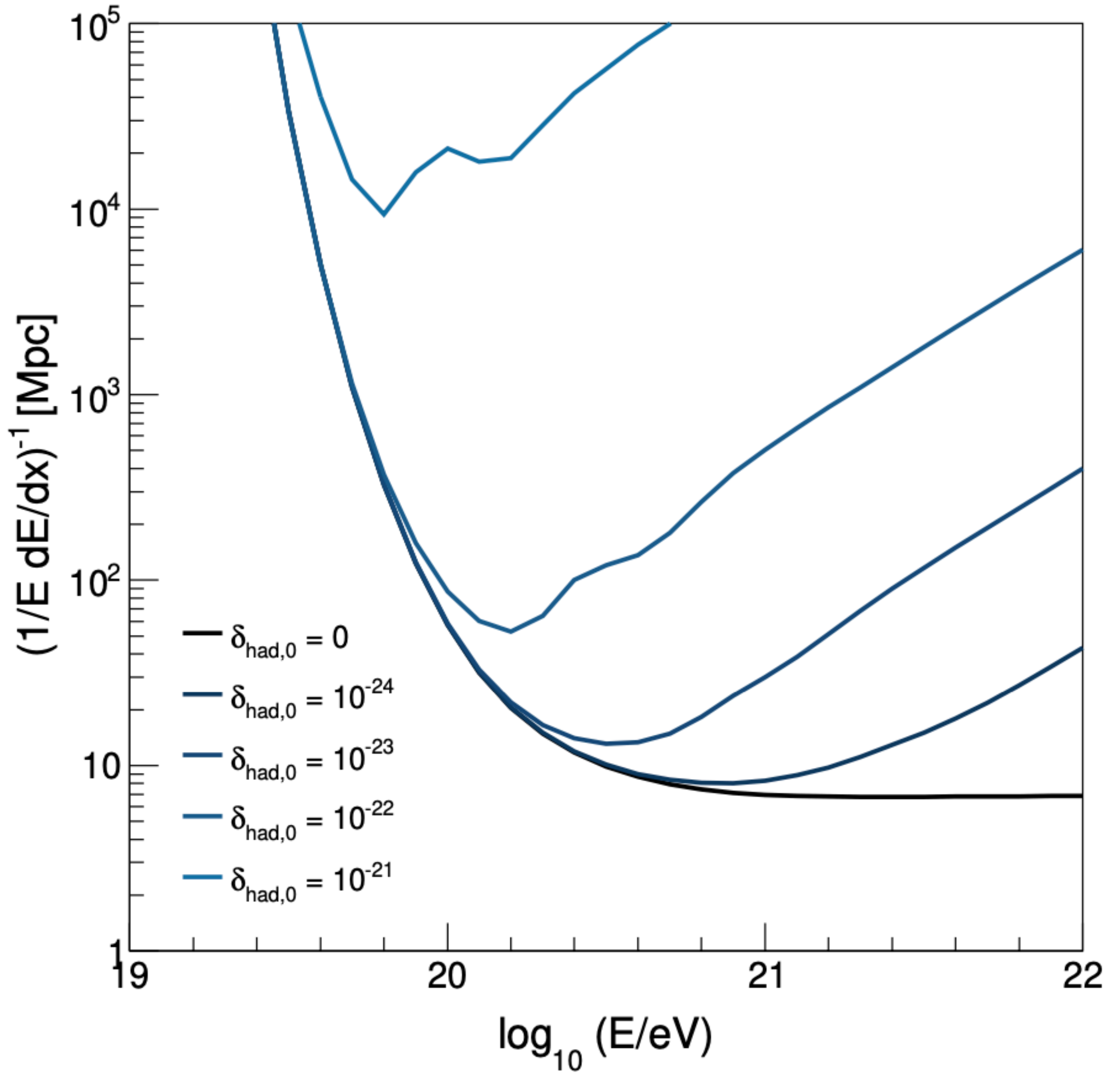


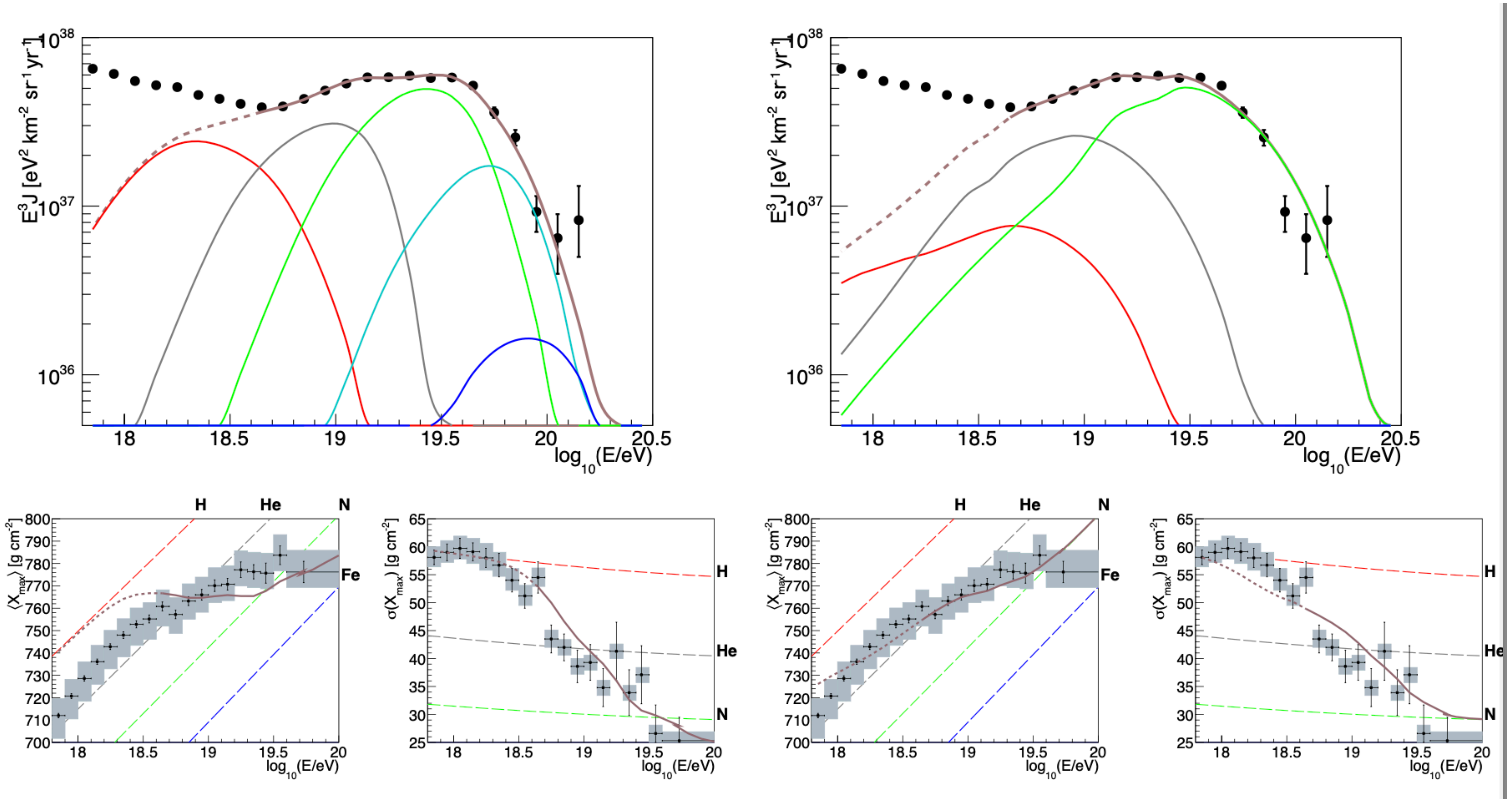
The Pierre Auger Collab. JCAP 2022

# UHECRS: **NOT ONLY** STANDARD PHYSICS

- LIV effects on UHECR protons and nuclei

$$\delta_{\text{had},0} R_{\text{cut}}^2 Z^2 = \delta_{\text{had},n} R_{\text{cut}}^{(n+2)} Z^{n+2} \implies \delta_{\text{had},n} = \delta_{\text{had},0} R_{\text{cut}}^{-n} Z^{-n} \quad ,$$

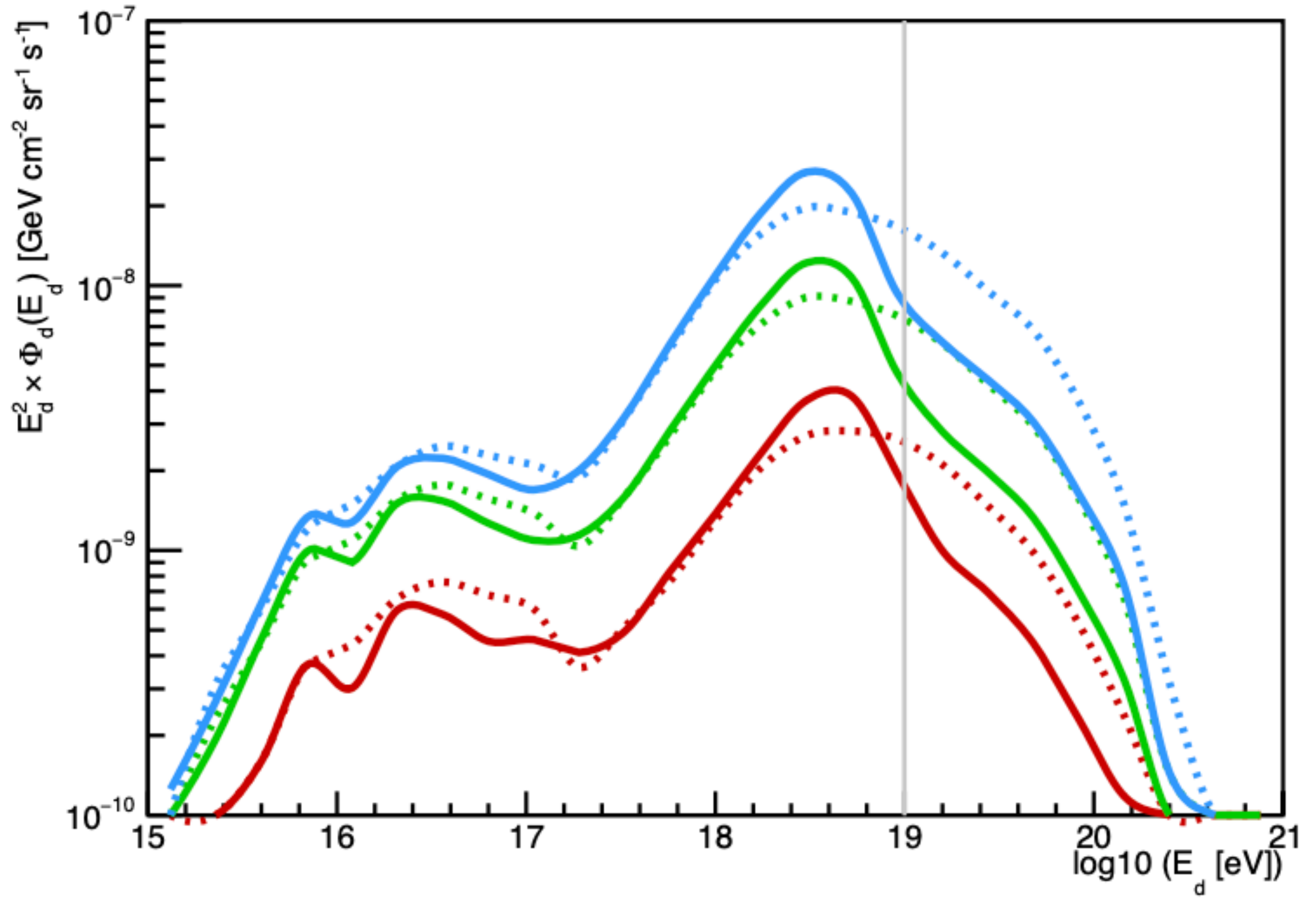


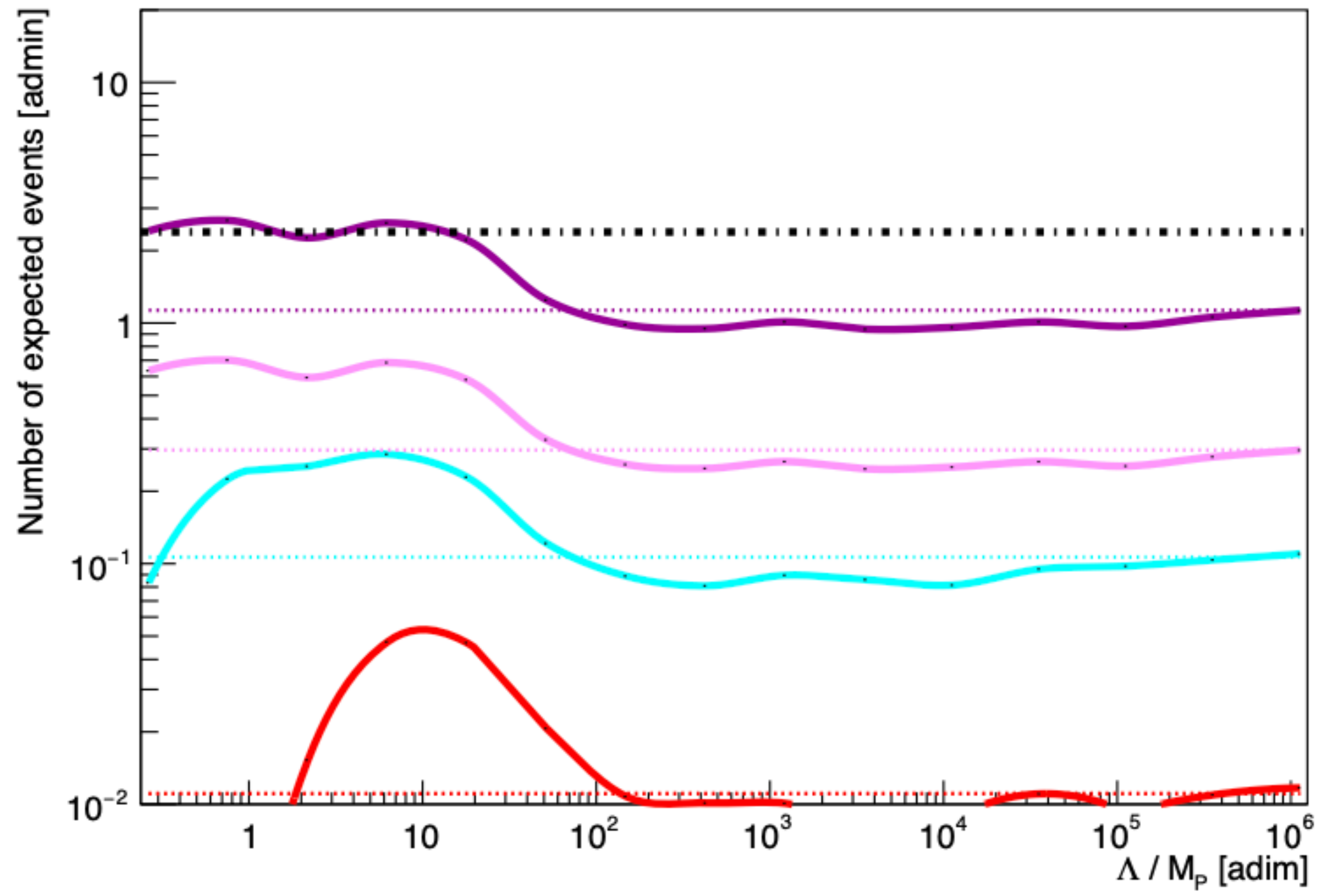


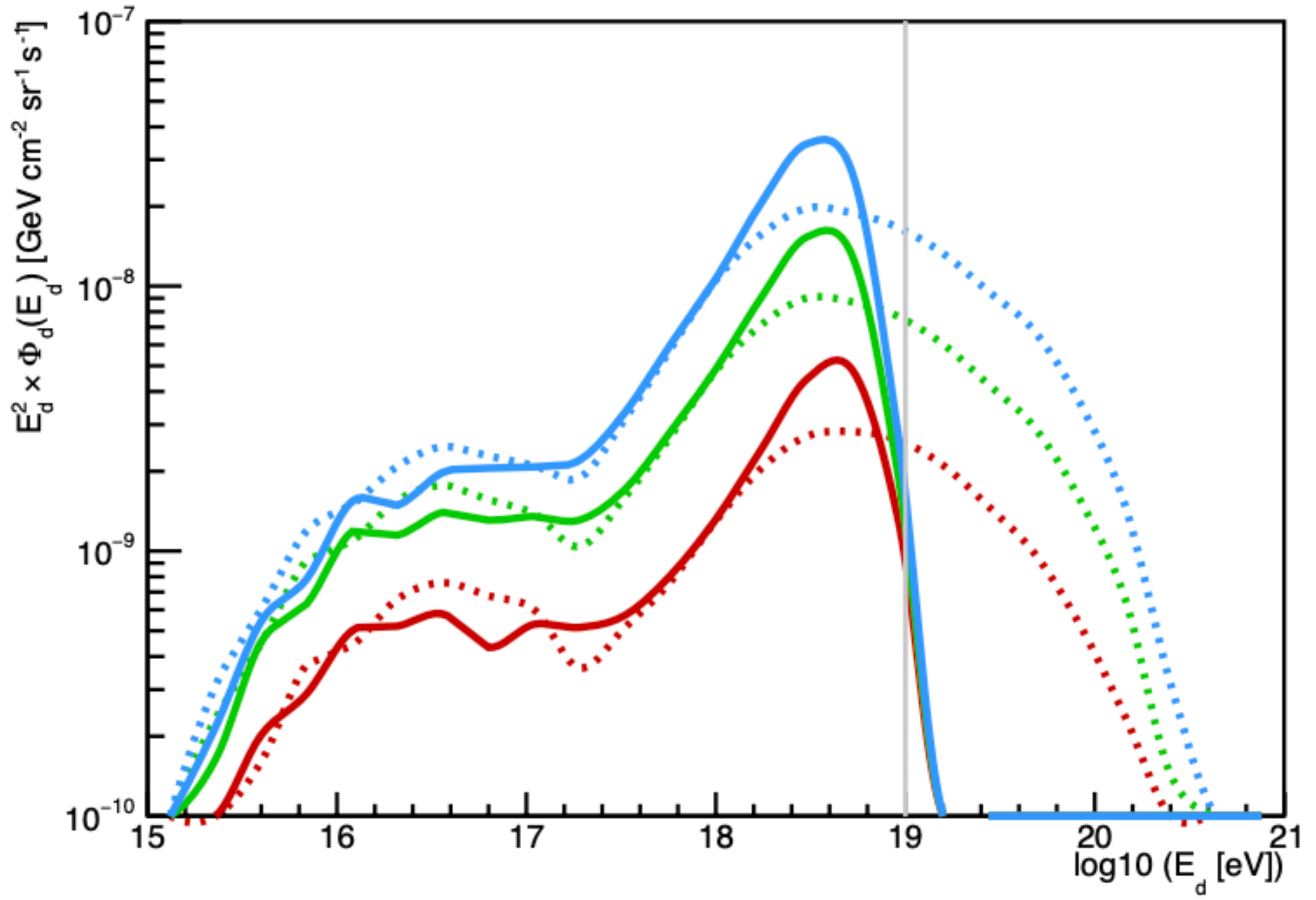
The Pierre Auger Collab. JCAP 2022

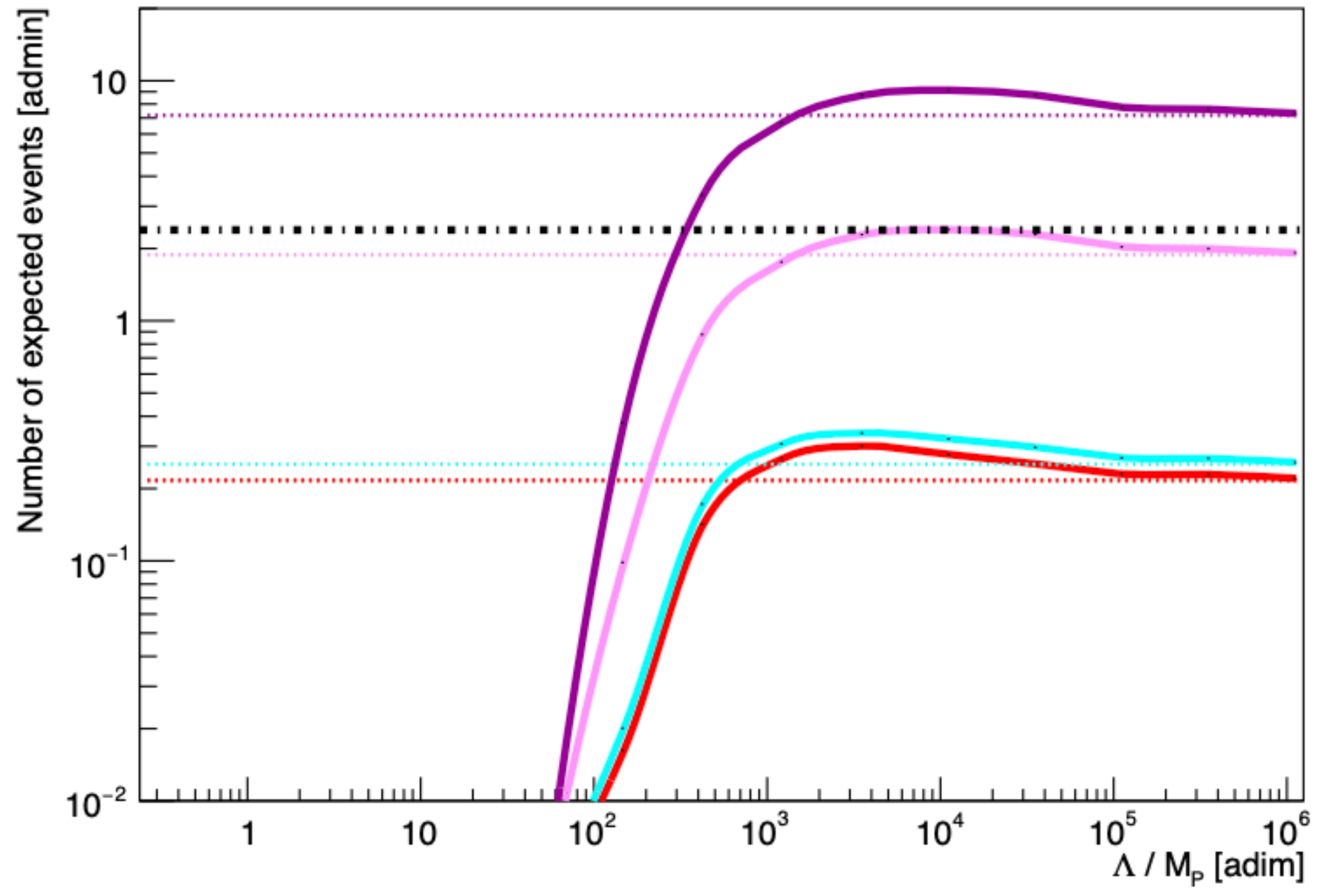
# UHECRS: **NOT ONLY** STANDARD PHYSICS

- LIV effects on cosmogenic neutrinos: neutrinos and/or anti-neutrinos acquire superluminal velocities and subsequently become unstable



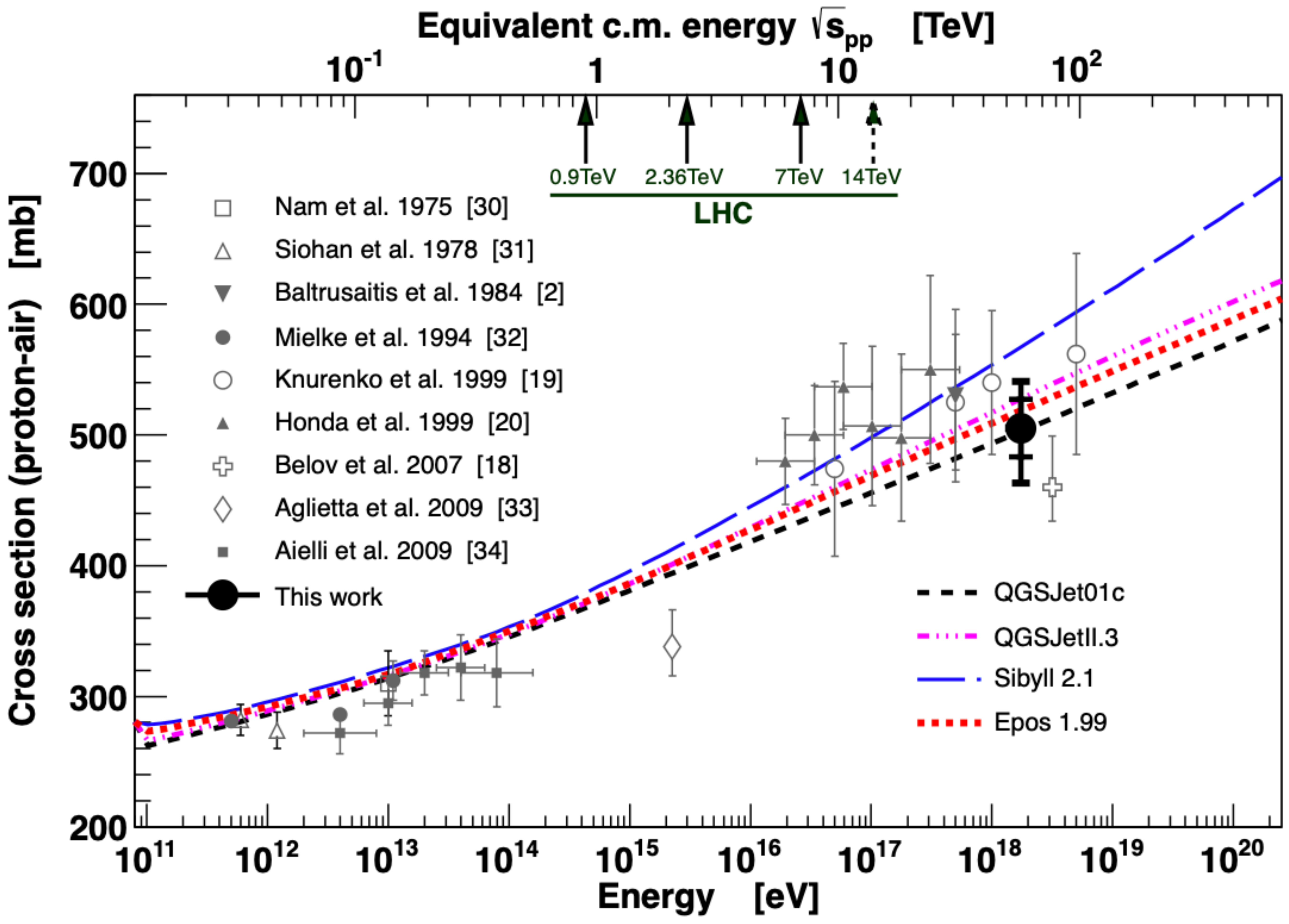






Reyes, DB, Carmona, Cortes ICRC2023

# UHECRS: **NOT ONLY** ASTROPARTICLE PHYSICS

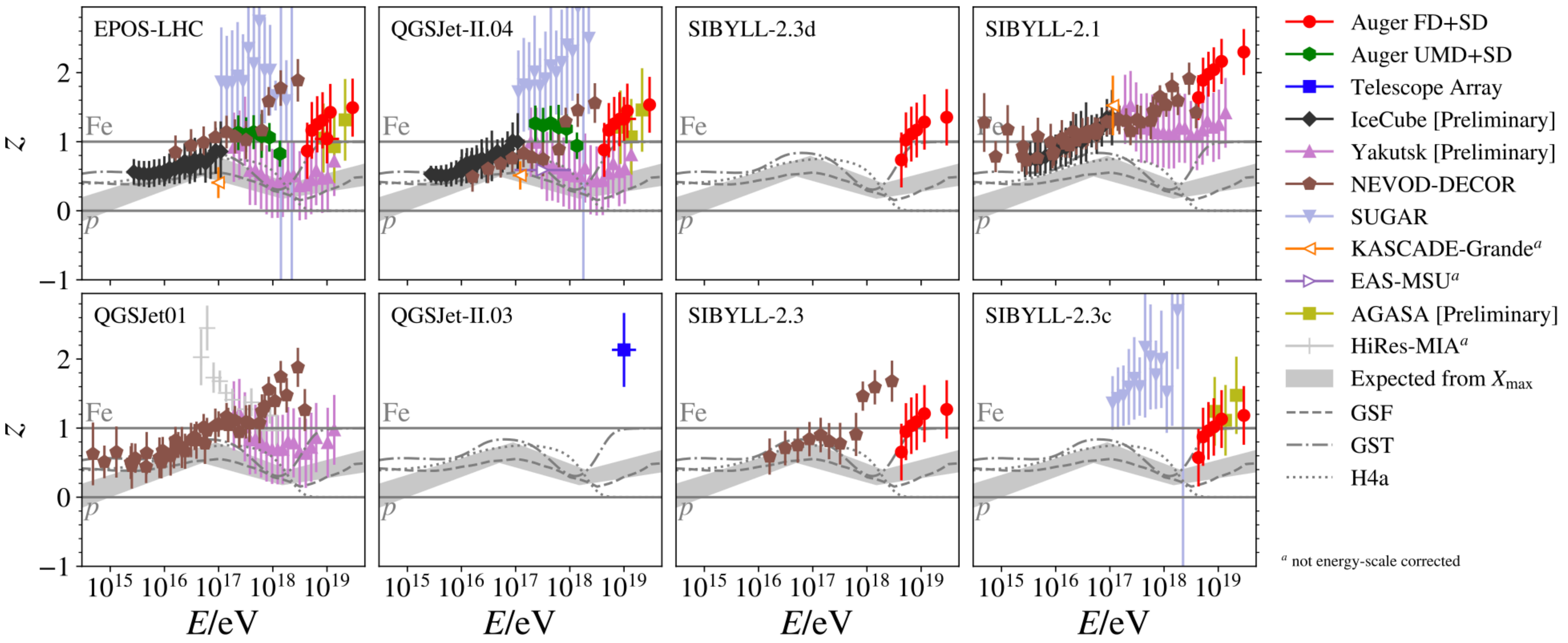


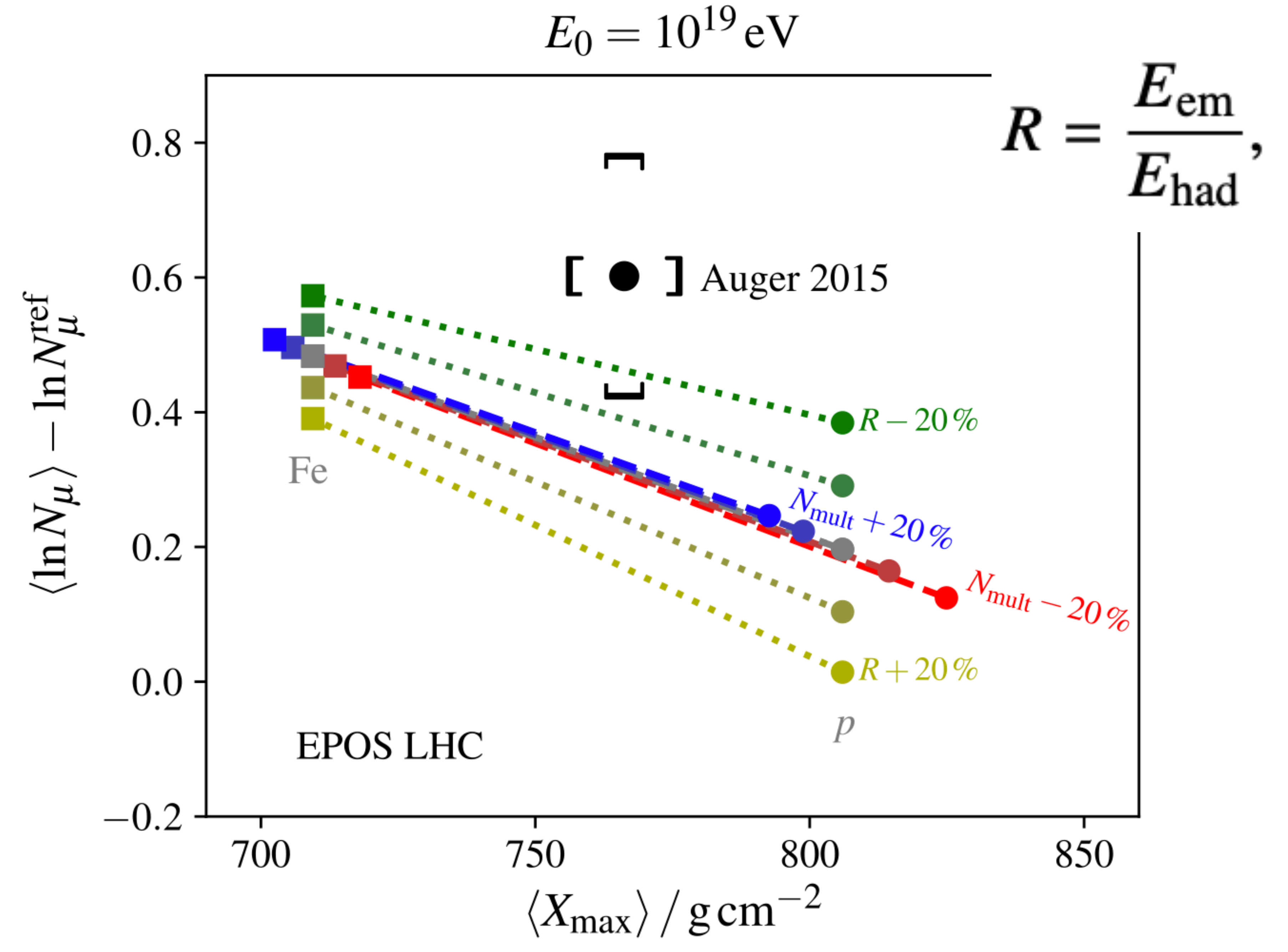
The Pierre Auger Collab. PRL 2012

- p-air cross section from very penetrating showers
- Conversion in pp cross section through Glauber calculations

# UHECRS: **NOT ONLY** ASTROPARTICLE PHYSICS

Albrecht et al. ICRC21





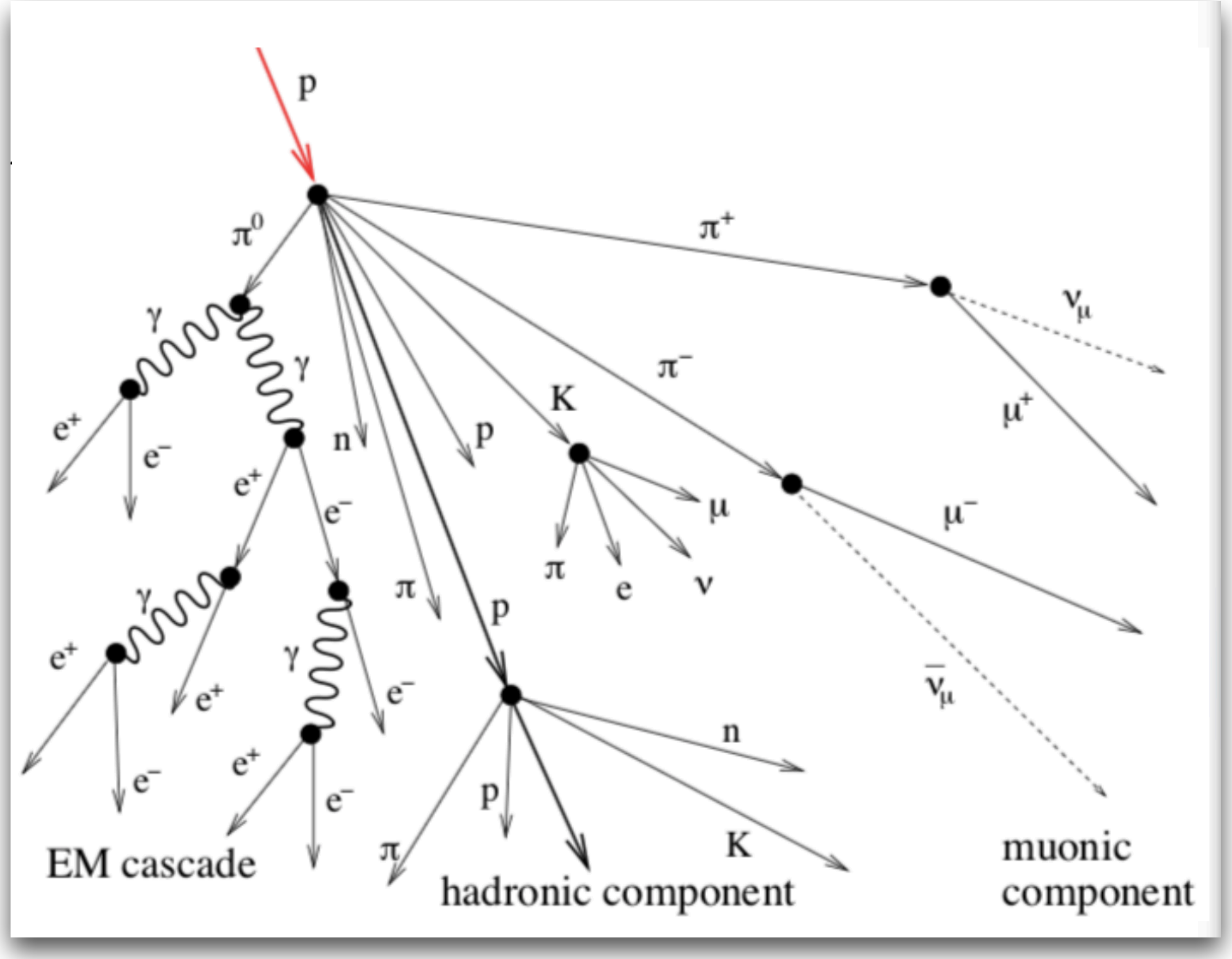
$$R = \frac{E_{em}}{E_{had}},$$

$$z = \frac{\ln N_\mu - \ln N_{\mu,p}}{\ln N_{\mu,\mathrm{Fe}} - \ln N_{\mu,p}},$$

- Air-shower simulations with state-of-the-art QCD models show a significant **muon deficit** with respect to measurements starting at TeV scale in center-of-mass frame

- Ratio of energy in electromagnetic vs muonic component influenced by:
  - cross section
  - elasticity
  - multiplicity
  - fraction of neutral mesons
- Fluctuations of number of muons are less affected (see Cazon et al PRL 2018; The Pierre Auger Colla. PRL 2019)

# LIV IN EXTENSIVE AIR SHOWERS

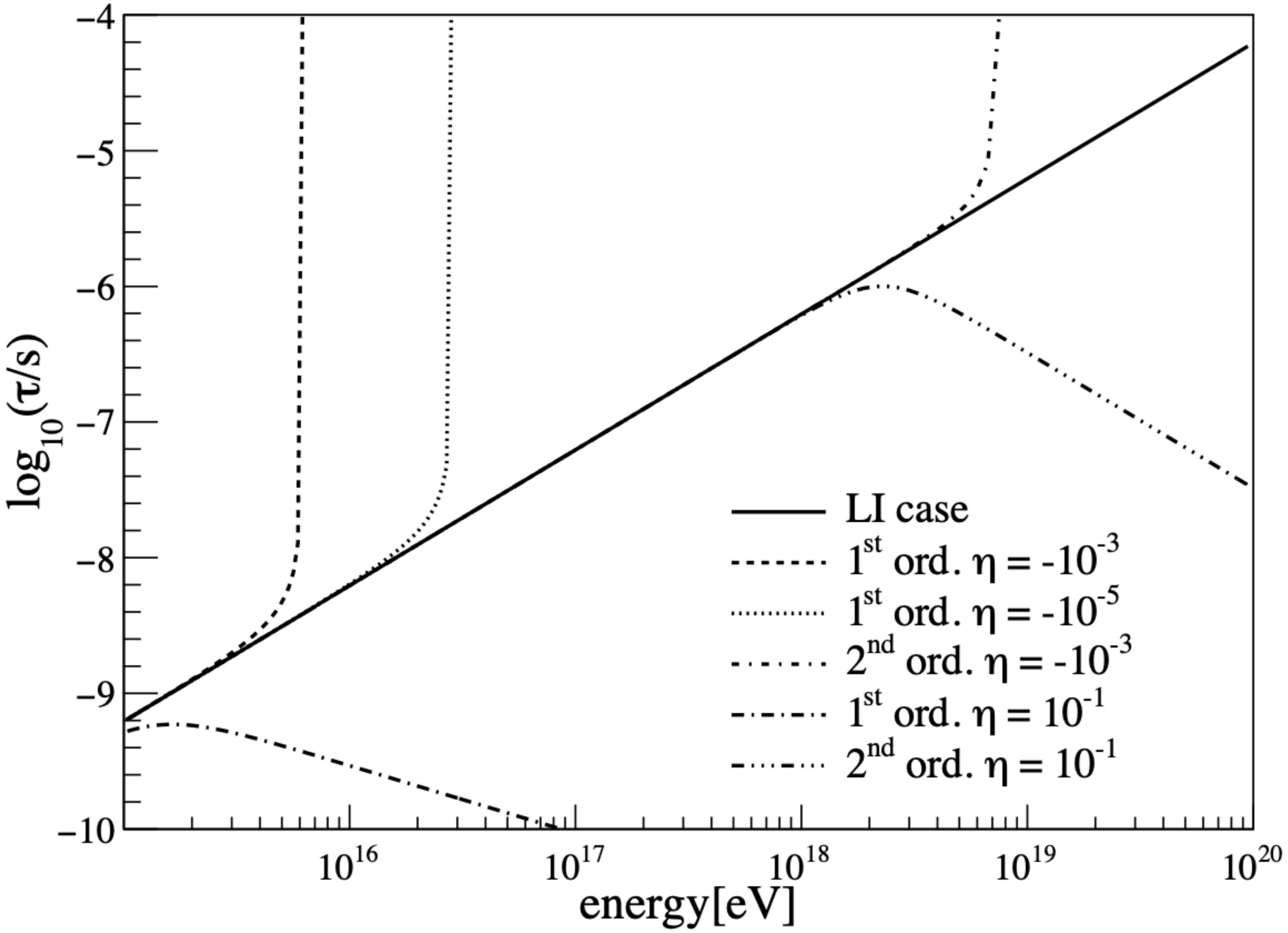


- Heavy primary CRs with respect to light primary CRs with same energy
  - EAS develops earlier in atmosphere (smaller Xmax)
  - Position of Xmax fluctuates less
  - Contain more muons
  - Number of muons fluctuates less
- LIV can affect kinematics
  - Example:
    - Pions do not decay -> neutral pions interact
    - More muons are produced
    - Electromagnetic vs muonic component of the shower are affected

# MODIFICATIONS TO EAS DEVELOPMENT

C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021

$$E_i^2 - p_i^2 = m_i^2 + \sum \eta_{i,n} \frac{E_i^{2+n}}{M_{Pl}^n}$$



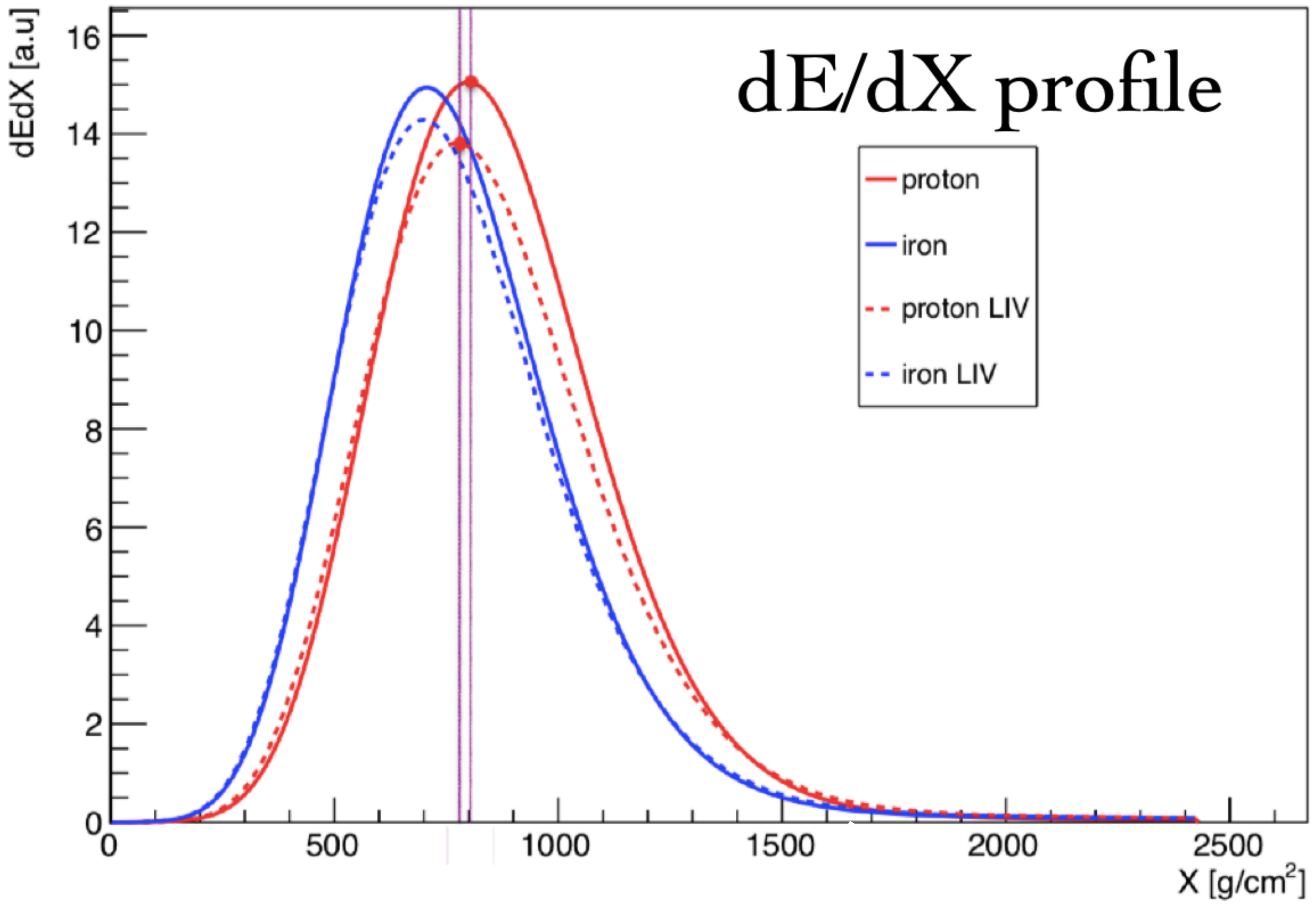
$$\Gamma = \frac{E}{m_{\mathrm{LIV}}} \qquad \tau = \Gamma \tau_0$$

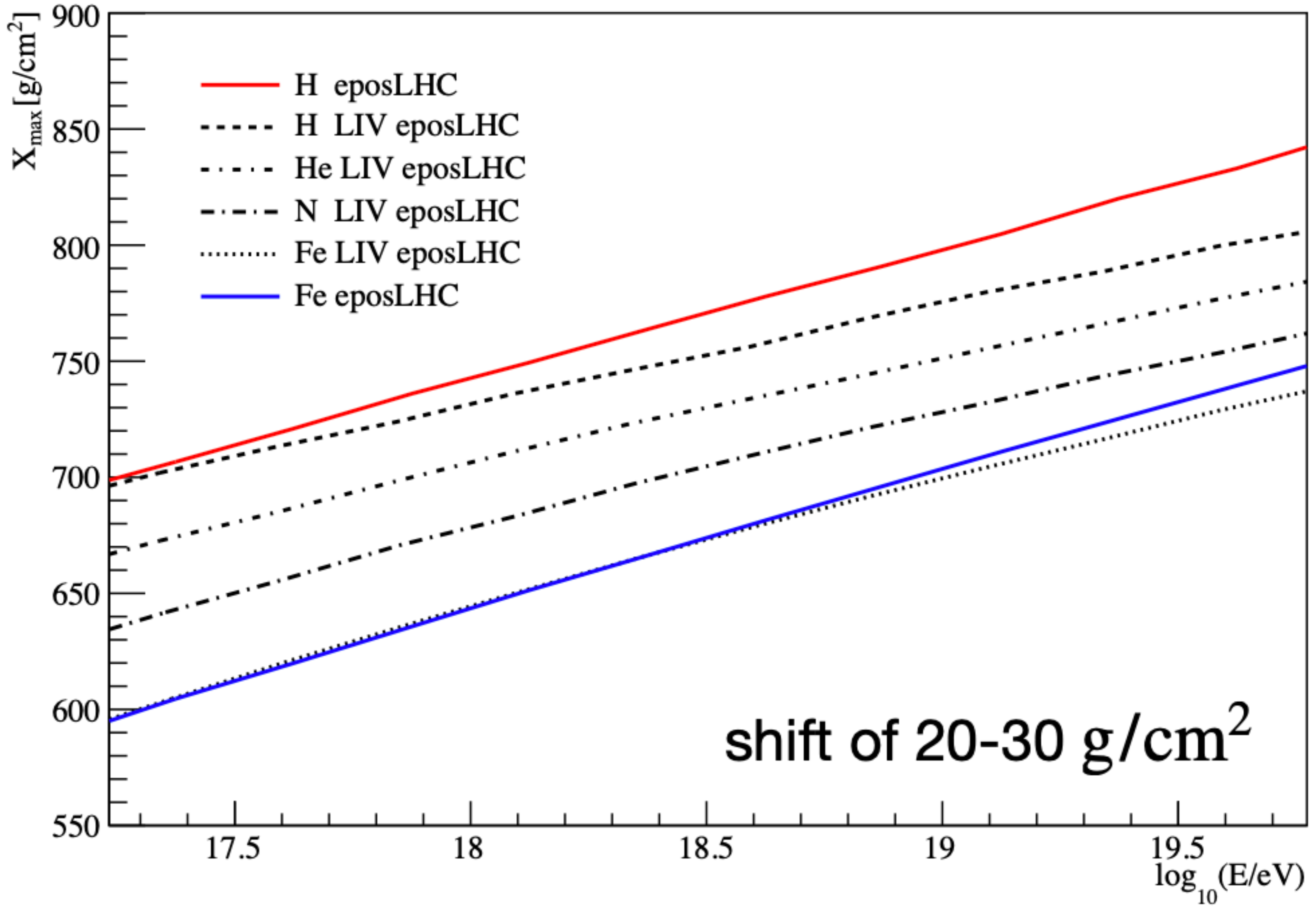
1. Positive eta: negligible effects
2. Negative eta: forbidden neutral pion decay if…

$$m_\pi^2 + \eta_\pi^{(n)} \frac{E_\pi^{2+n}}{M_{Pl}^n} < 0$$

# MODIFICATIONS TO MASS OBSERVABLES

C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021

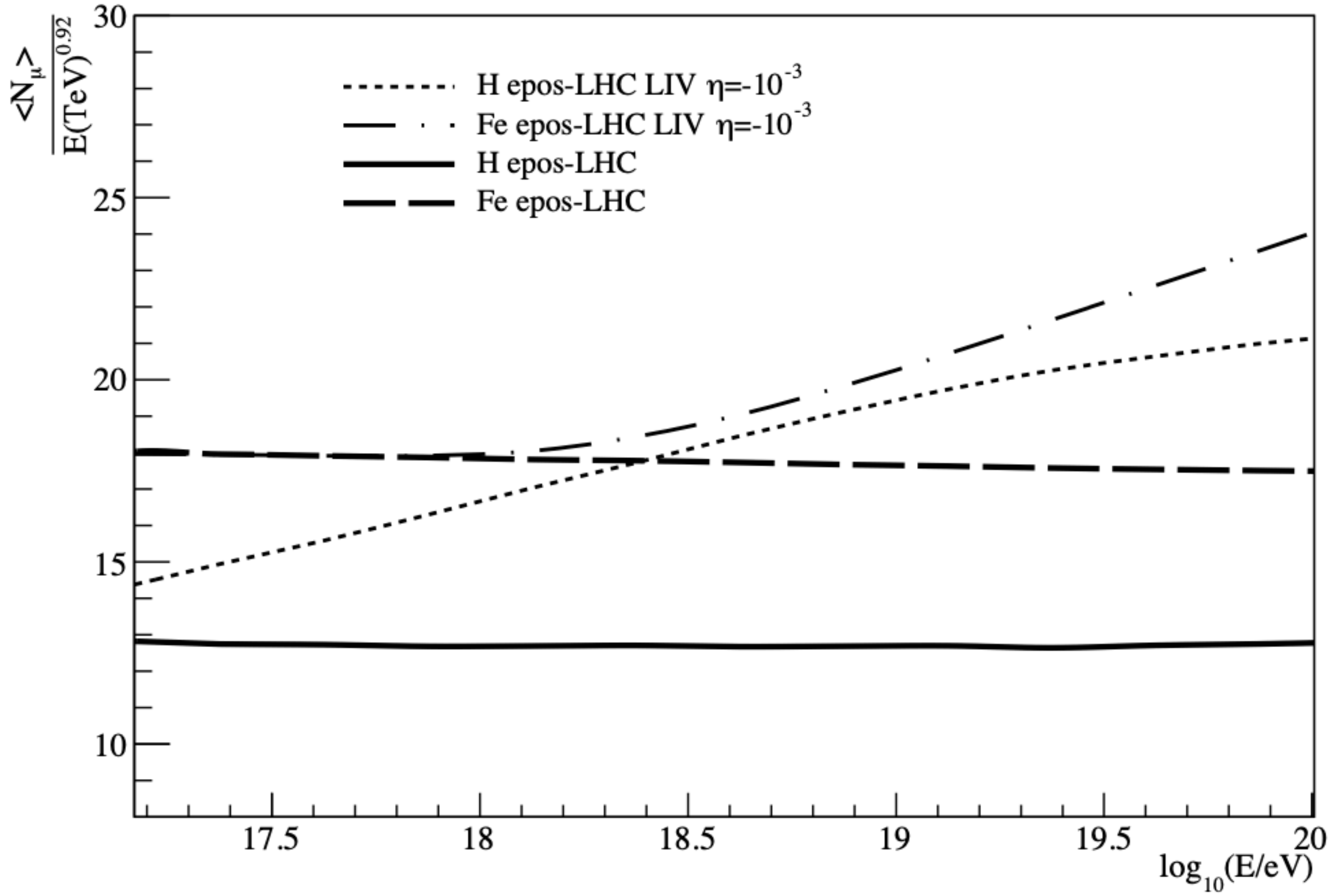


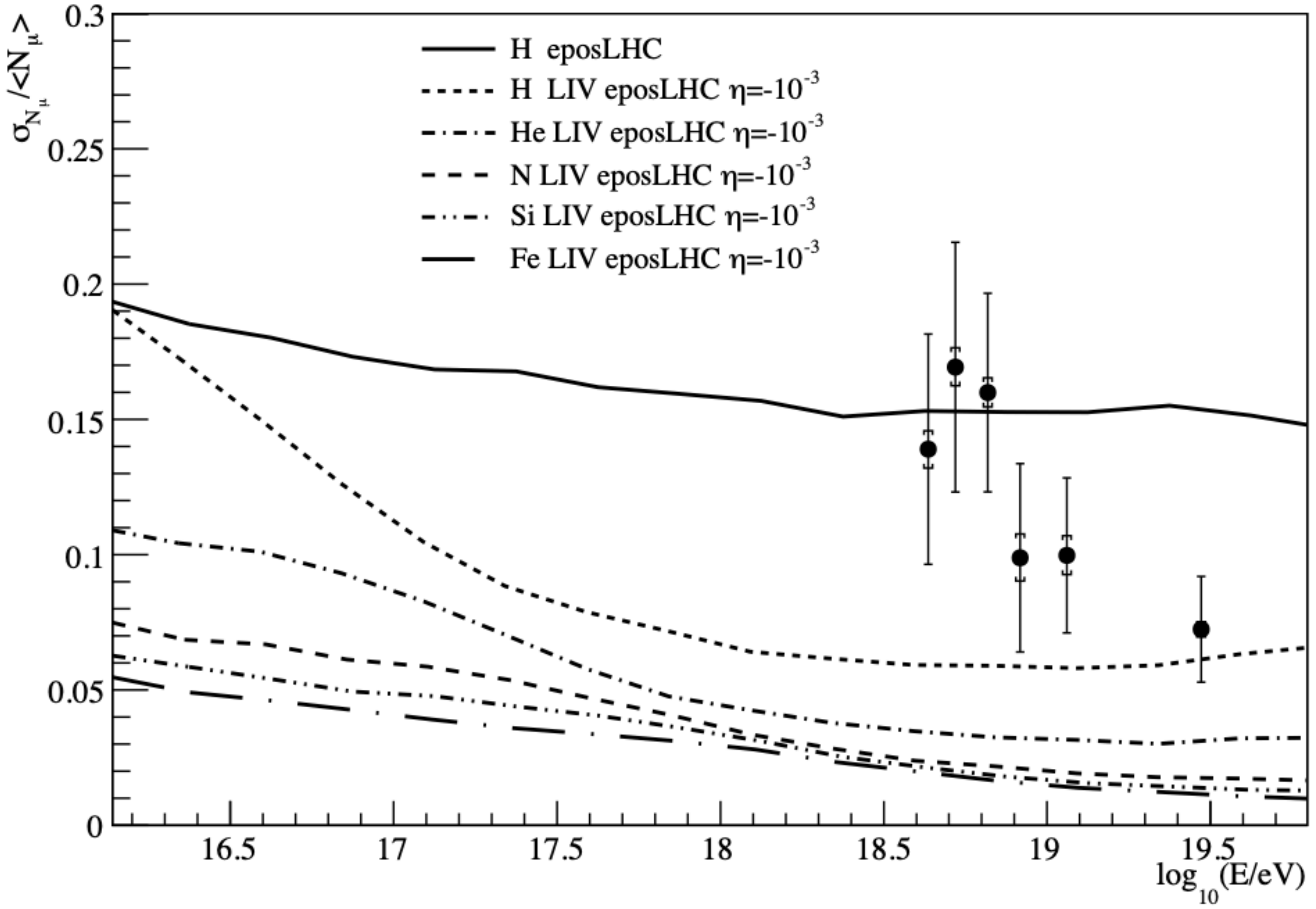


- If neutral pion does not decay, it can interact
  - Calorimetric energy is smaller than in the LI case
  - Predictions for Xmax decrease with energy with respect to the LI case

# MODIFICATIONS TO MASS OBSERVABLES

C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021





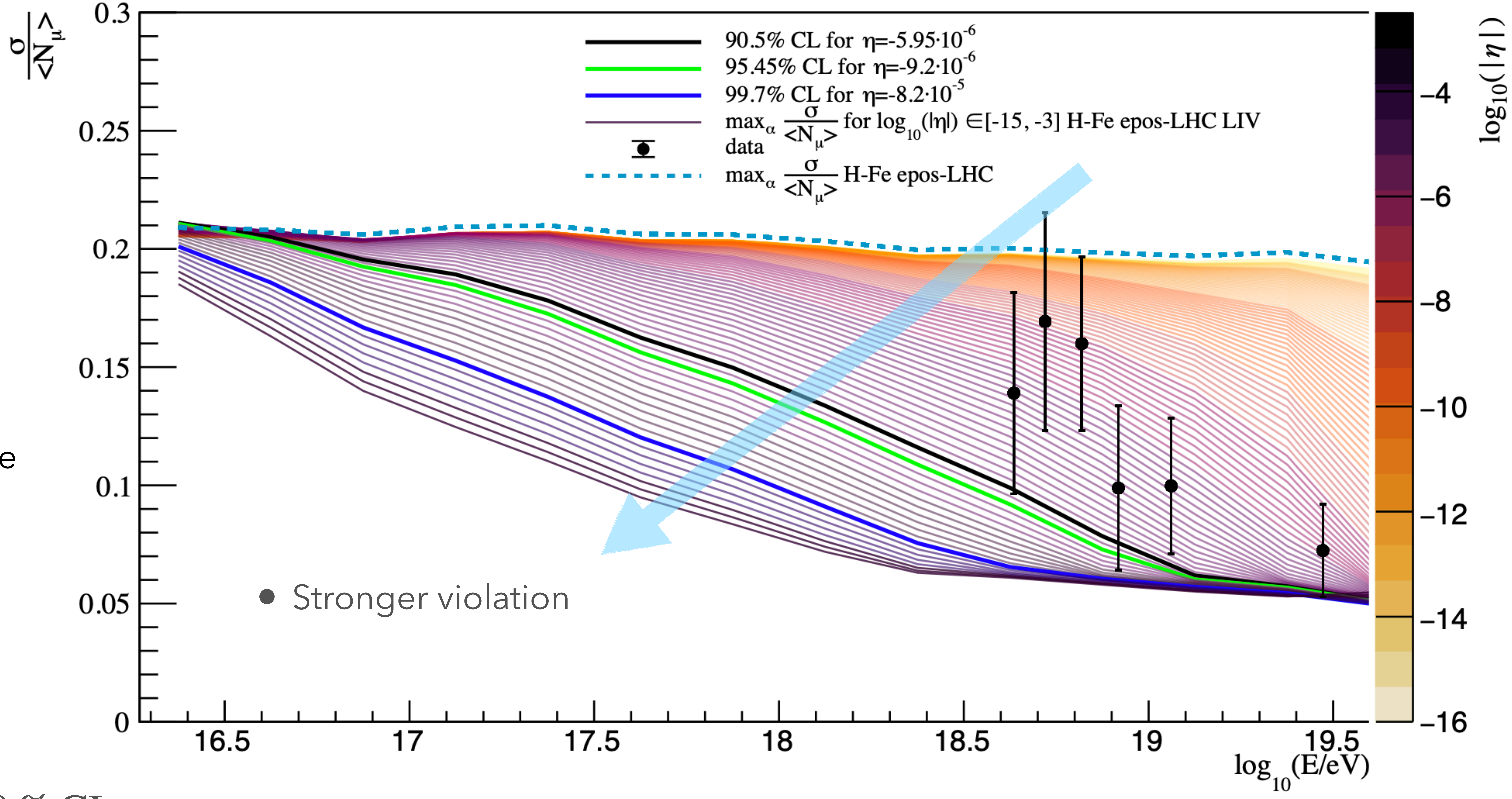
- LI case:
  - number of muons larger (and less fluctuations) in showers initiated by heavy nuclear species with respect to protons
- LIV case:
  - Fluctuations decrease with respect to the LI case

- Focus on fluctuations in the number of muons
  - **Decrease** if (pure) mass becomes heavier
  - **Increase/decrease** depending on the mass mixing
  - **Decrease** if LIV strength increases

# CONSTRAINTS FROM MUON FLUCTUATIONS

C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021

- Procedure:
  - Combine masses as a function of energy and LIV strength in order to have the largest fluctuation for each LIV parameter
  - Compare the data to the predictions corresponding to LIV parameters



- Stronger violation

$$\eta^{(1)} > -5.95 \cdot 10^{-6},\ 90\,\%\,\mathrm{CL}$$