UHECR emission models

and multimessenger perspectives

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Advances in Modeling High-Energy Astrophysical Sources:
Insights from recent multimessenger discoveries
Sexten 2025

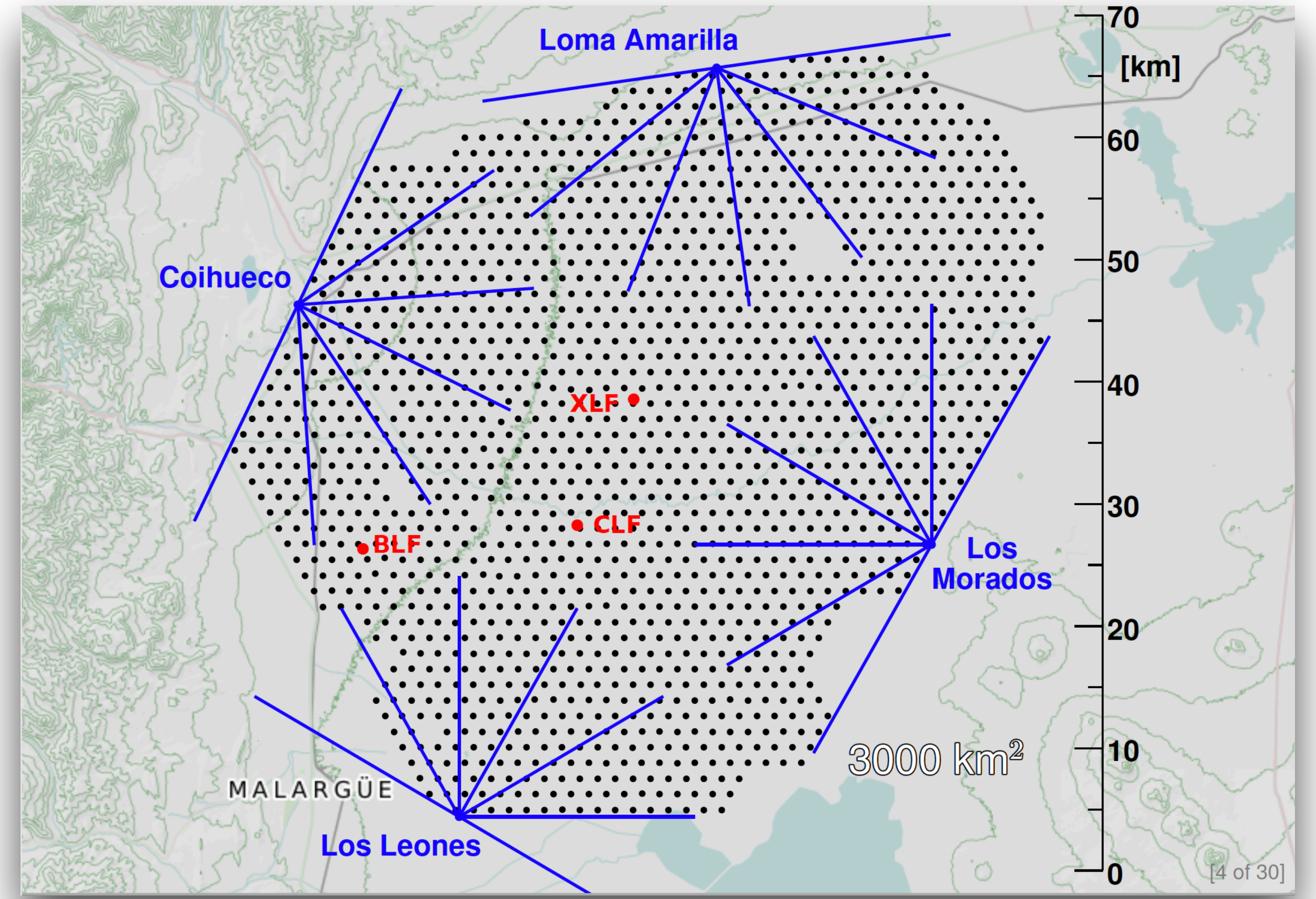
Outline

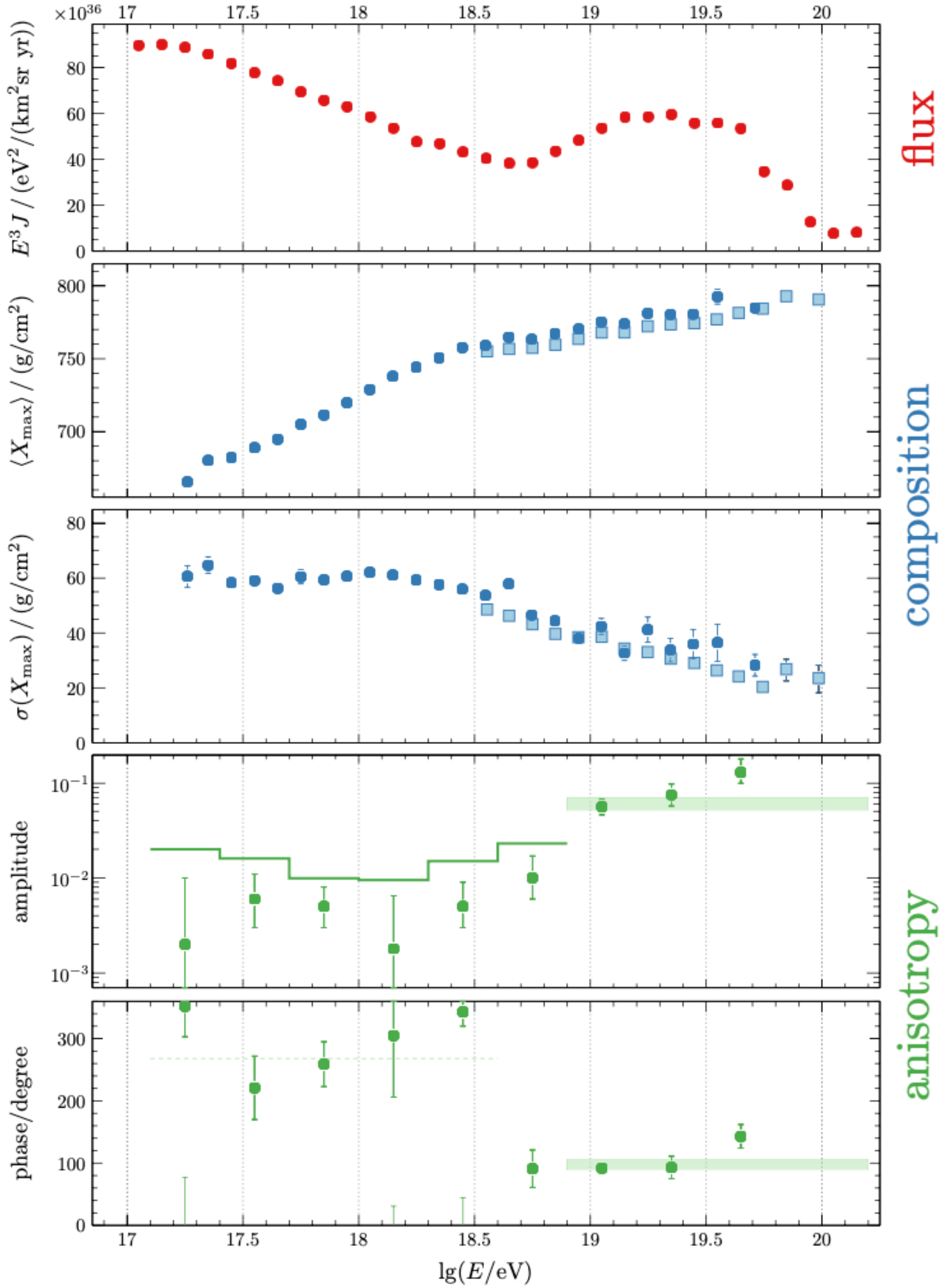
- State-of-the-art of UHECR measurements
- The **UHECR astrophysical picture** emerging from data
- Requirements from measurements and **how to model a UHECR source**
    - Example of modelling of spectral shape and mass composition
    - Sources emitting nuclei
- **What do we learn about UHECRs from other messengers**
- Summary
    - How **multimessenger approaches** could complete the UHECR picture

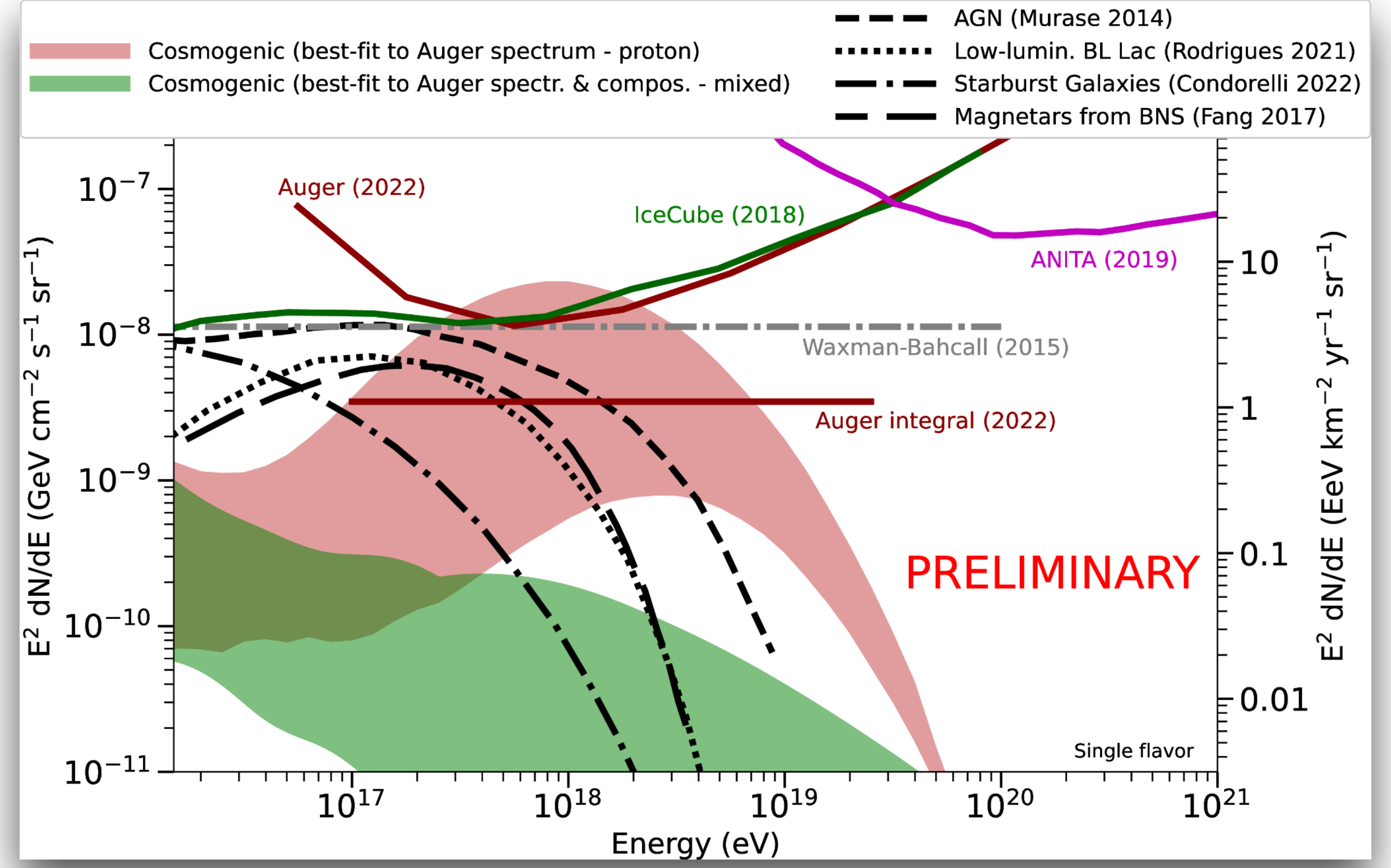
- Disclaimer: this talk discusses measurement-informed models :)

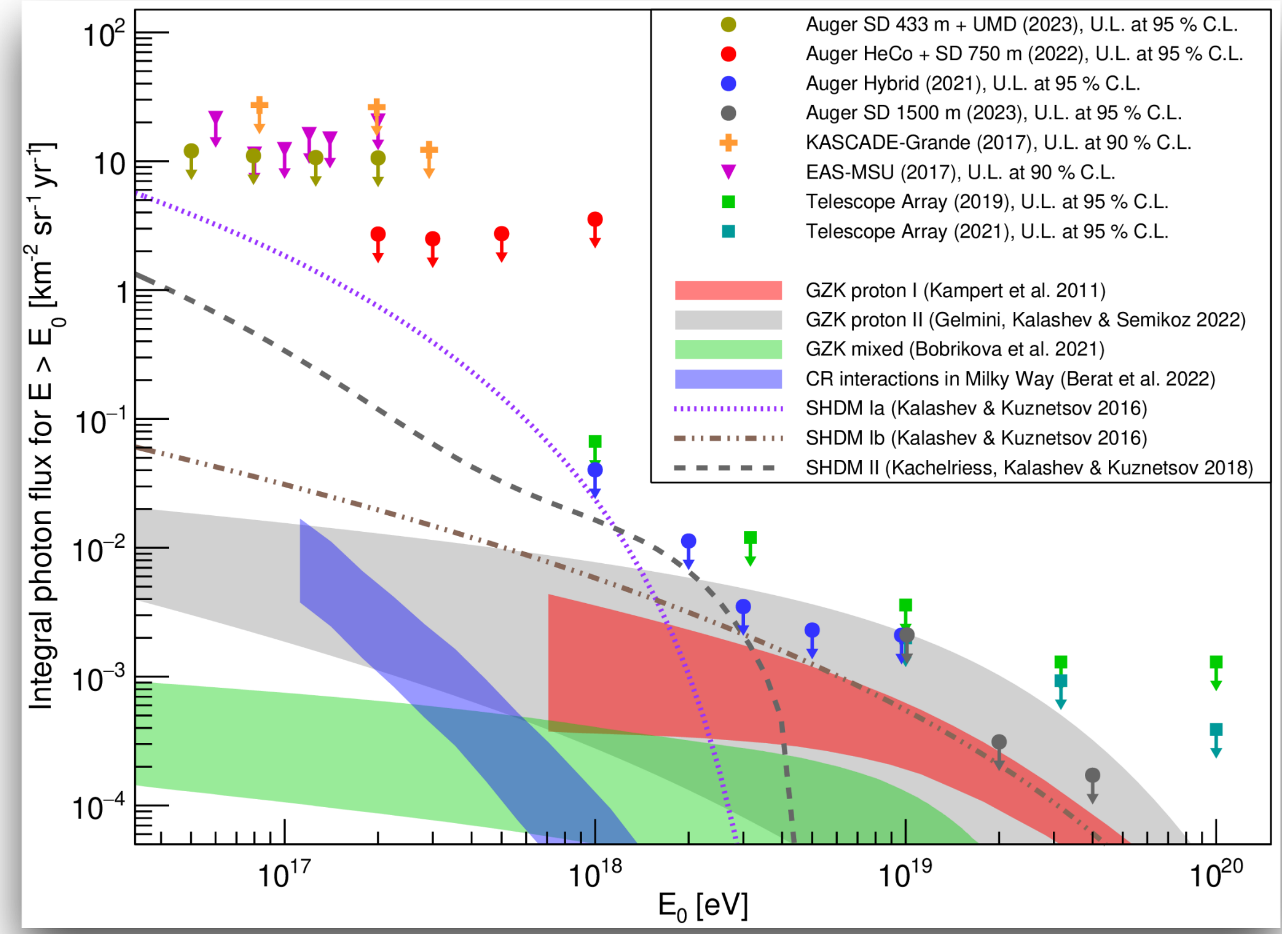
State-of-the-art of the latest UHECR measurements

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









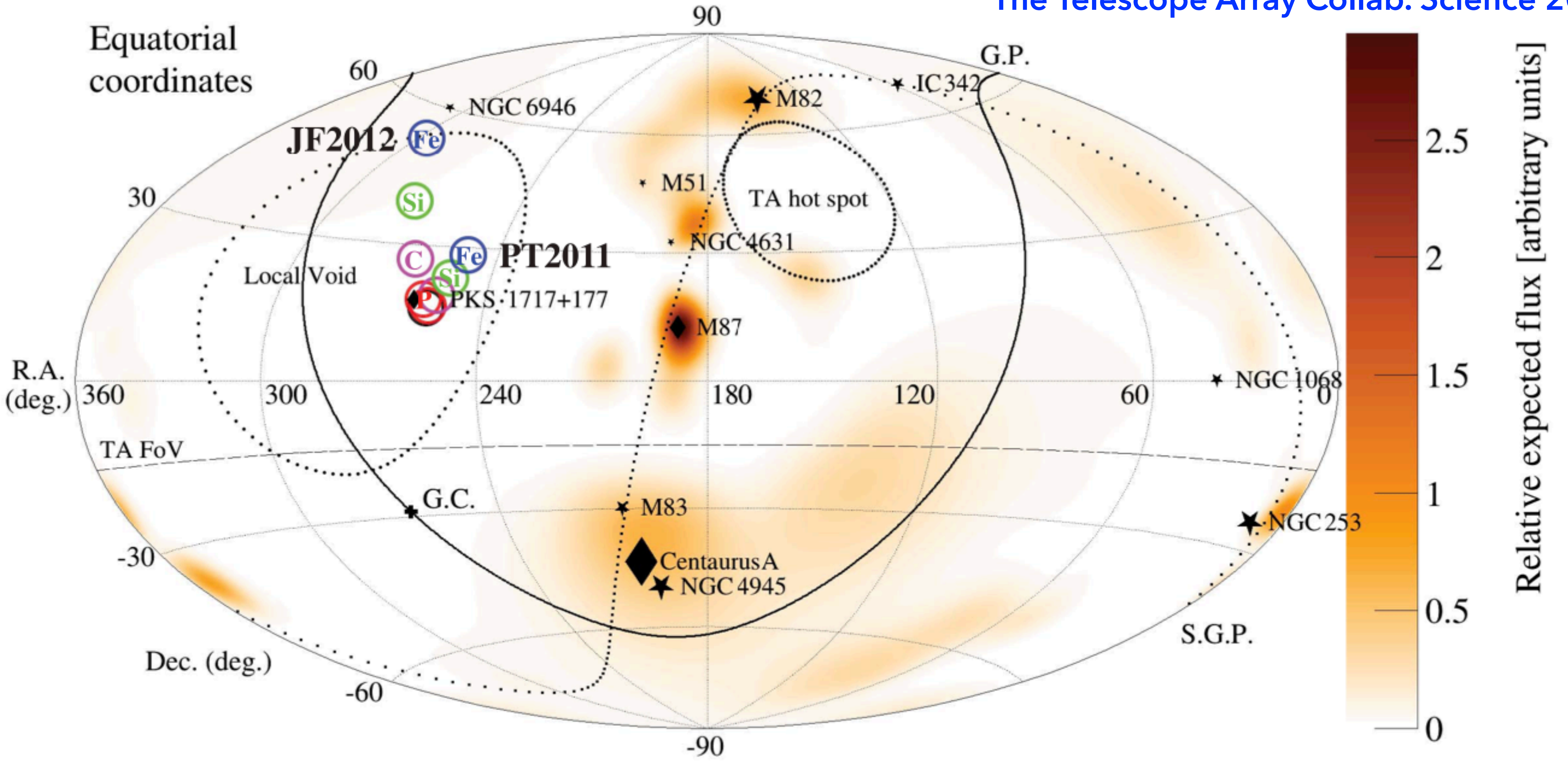
- Many results about **fundamental interactions** and **non-standard physics**!

The Pierre Auger Collab. ICRC23

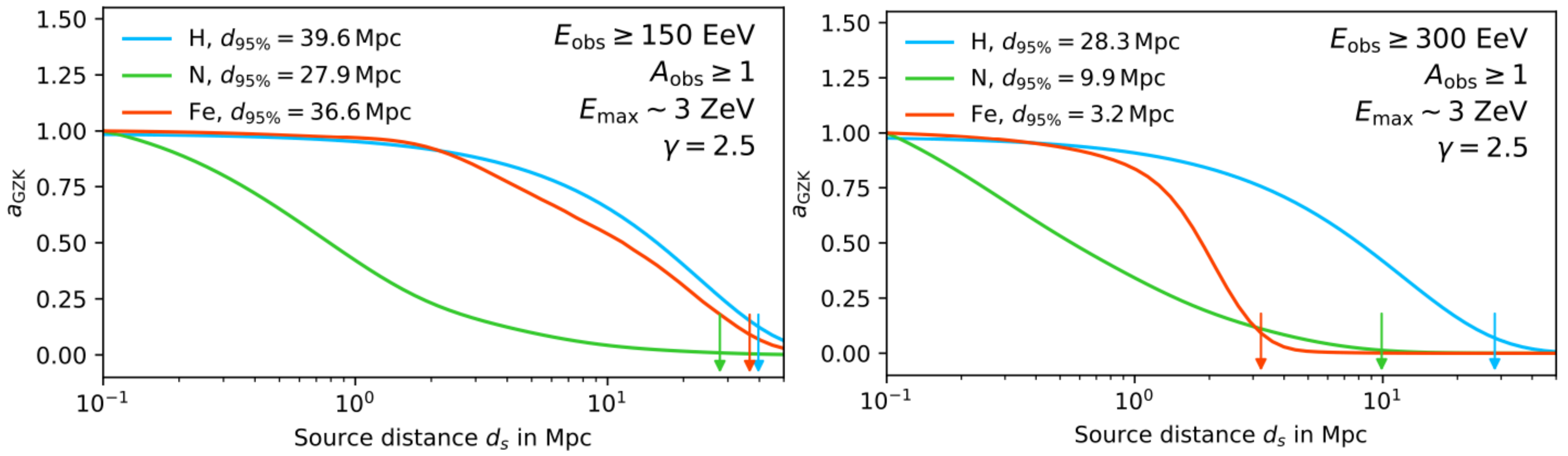
The extremely energetic cosmic ray observed by **Telescope Array**

The Telescope Array Collab. Science 2023

- 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!



Globus et al, ApJ 2023



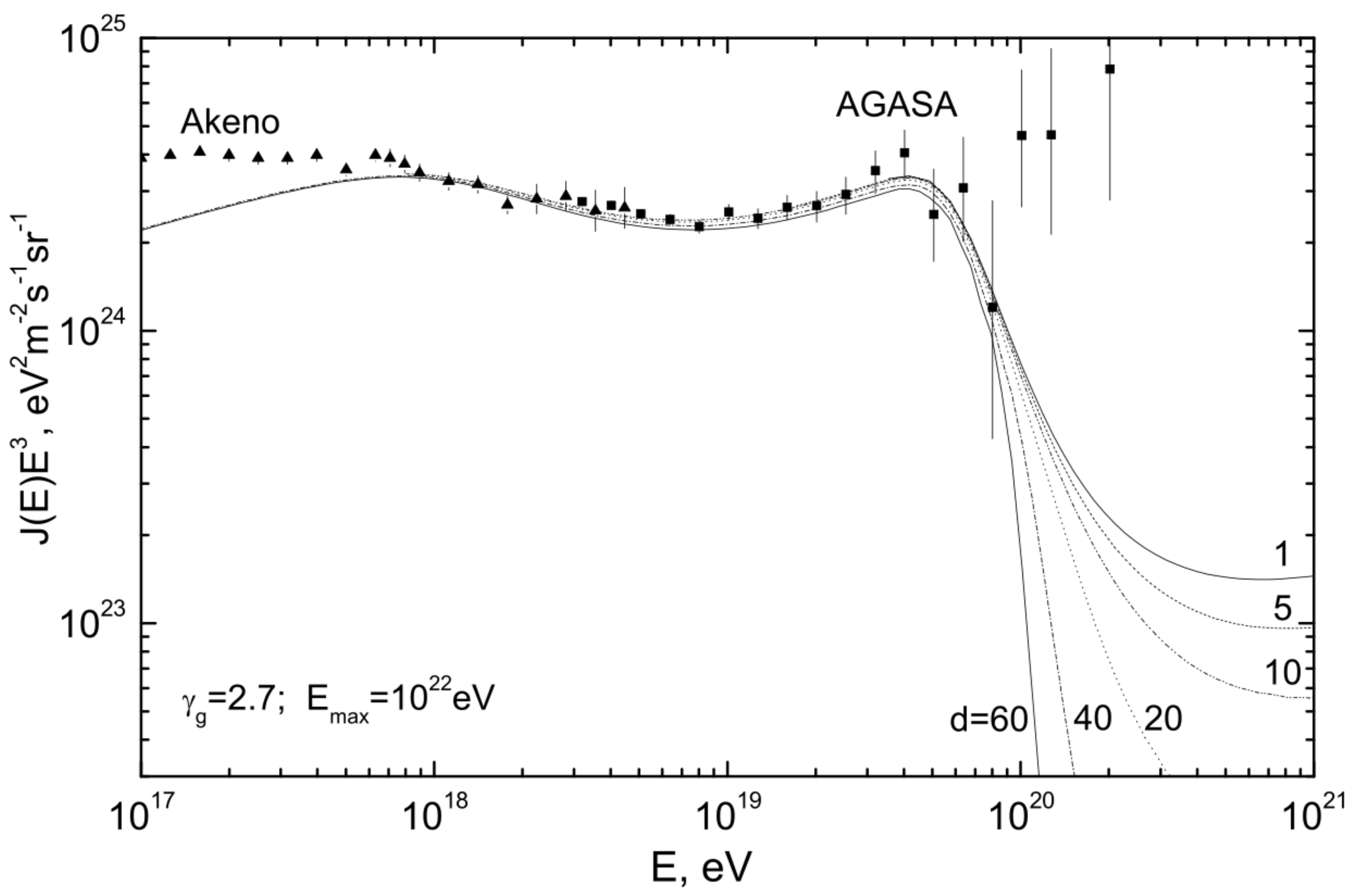
- Maximum source distance for this energy: 8-50 Mpc (the range reflects the uncertainty in the energy assignment); see Unger & Farrar ApJL 2023
  - Radio galaxies satisfying the luminosity criteria are not present in the localisation volume; no starburst galaxies within the source direction
  - **Transient event in an otherwise undistinguished galaxy?**
  - **Ultra-heavy nucleus?**

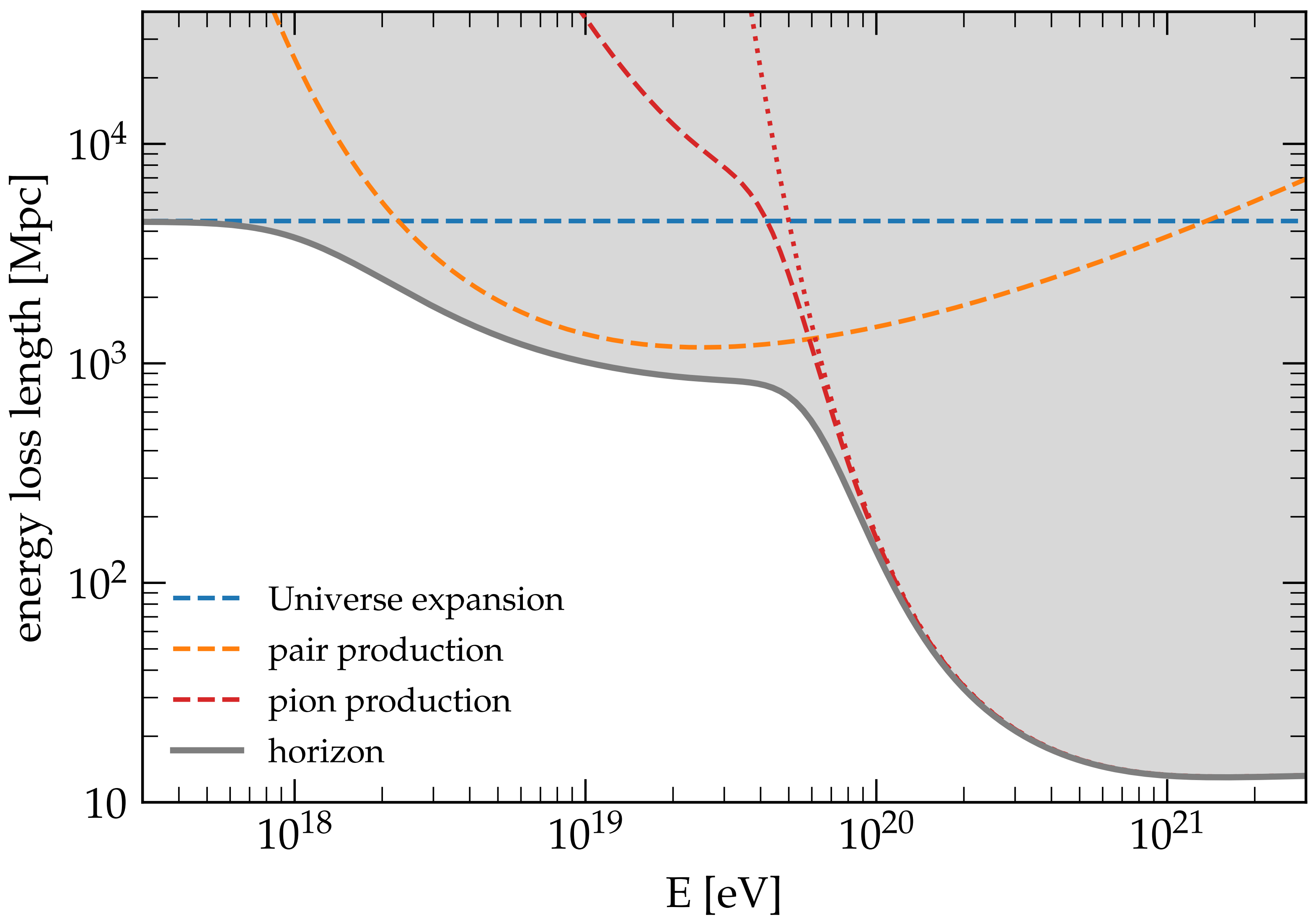
THE UHECR ASTROPHYSICAL PICTURE FROM THE STUDY OF DIFFUSE FLUXES

UHECRs are not protons…

- **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**)

Berezinsky et al. PRD2006

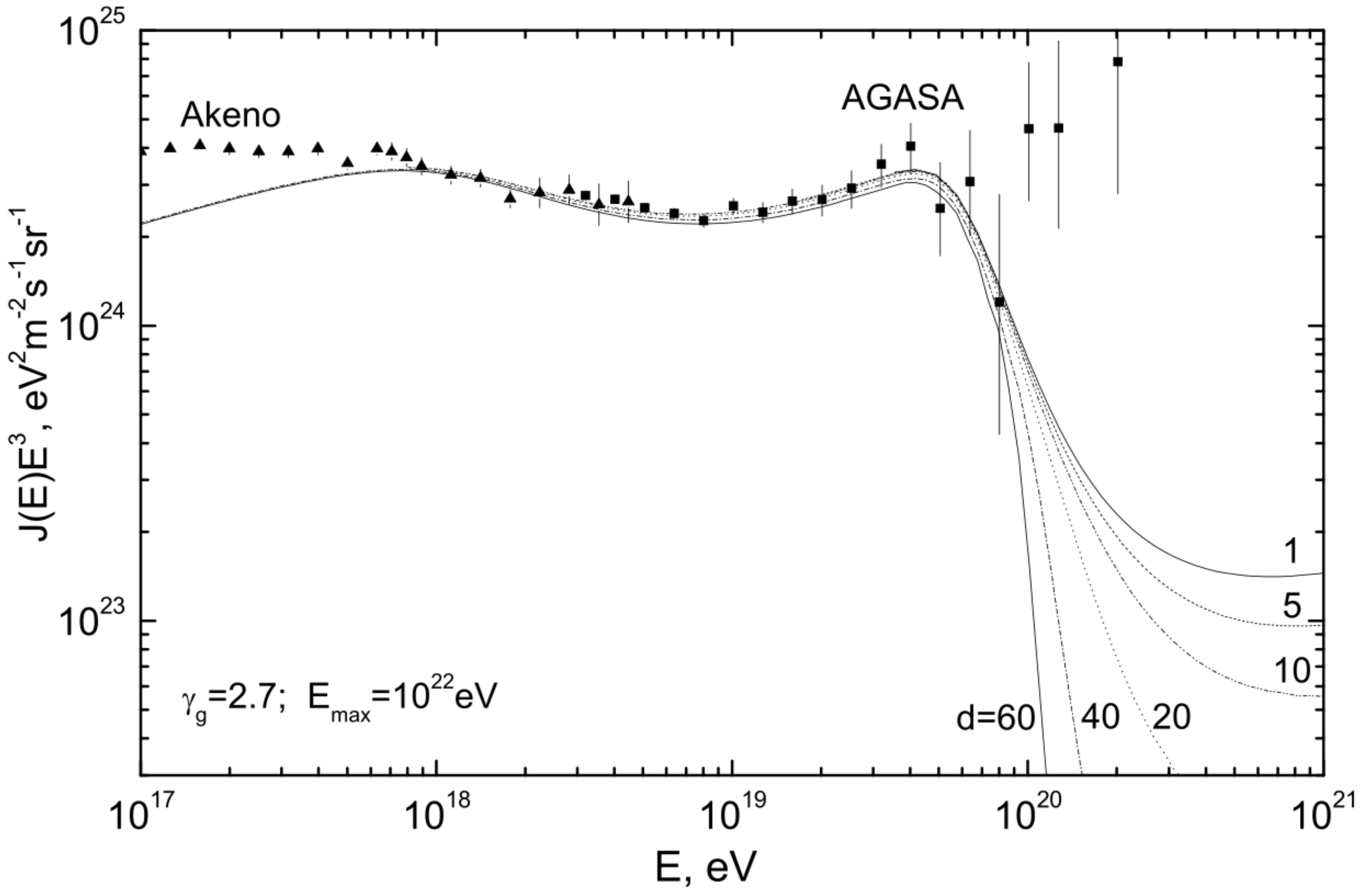


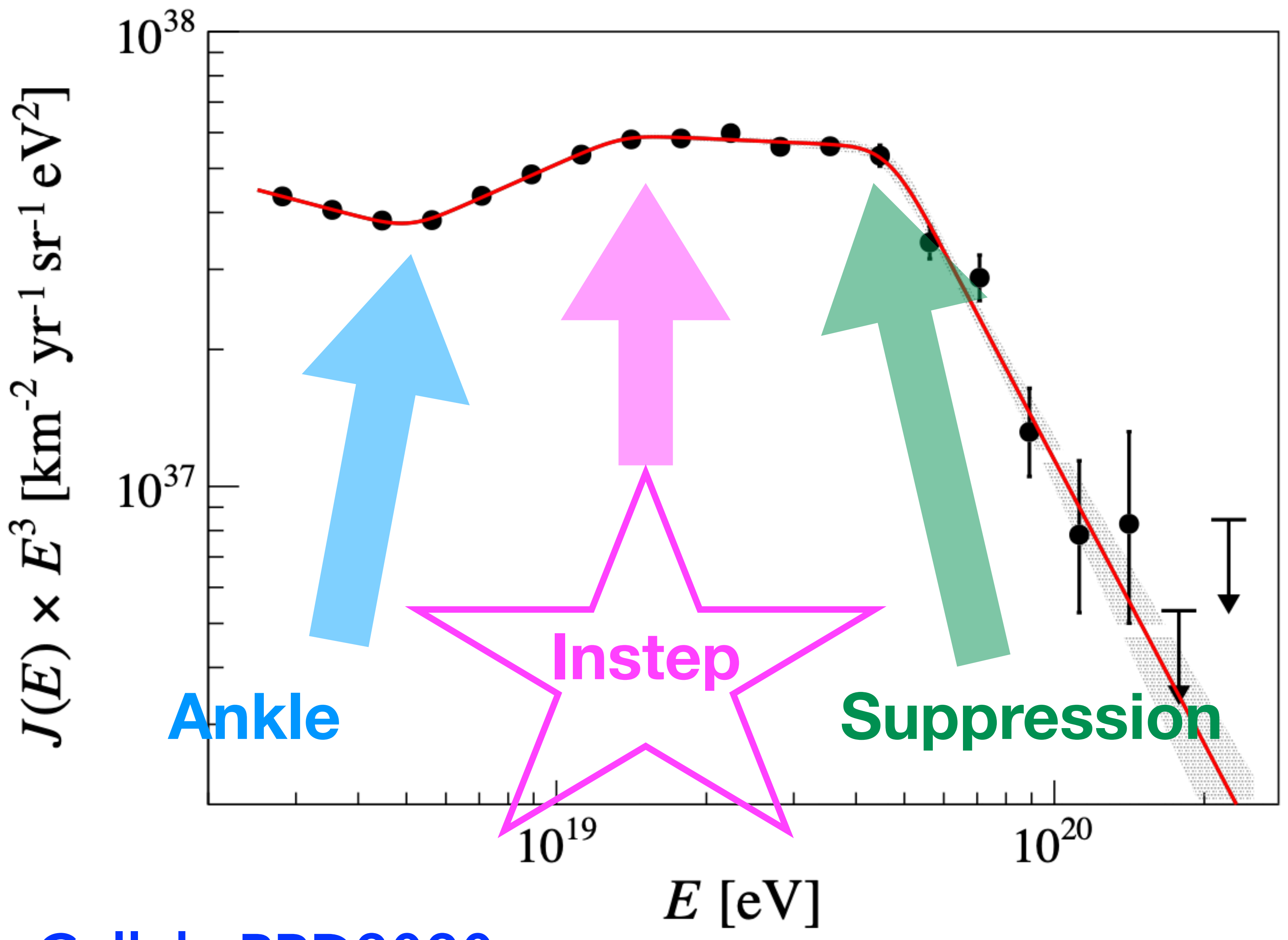


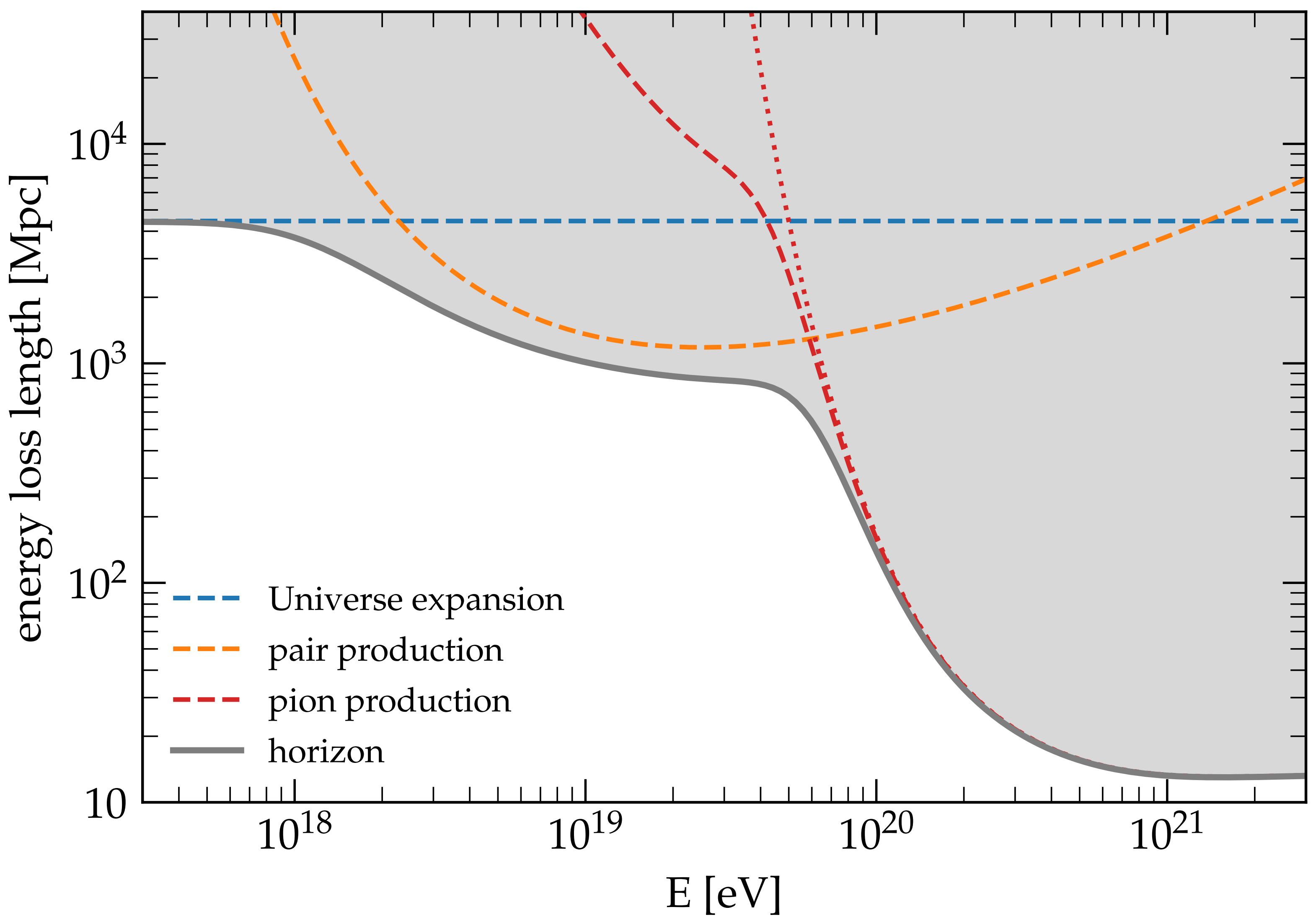
UHECRs are not protons…

- **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 current measured spectrum is not well reproduced within the dip model
  - New feature: instep
  - Suppression at lower energy than what expected from pure GZK
  - Ankle too pronounced
- And… the mass composition is “heavy"!

Berezinsky et al. PRD2006

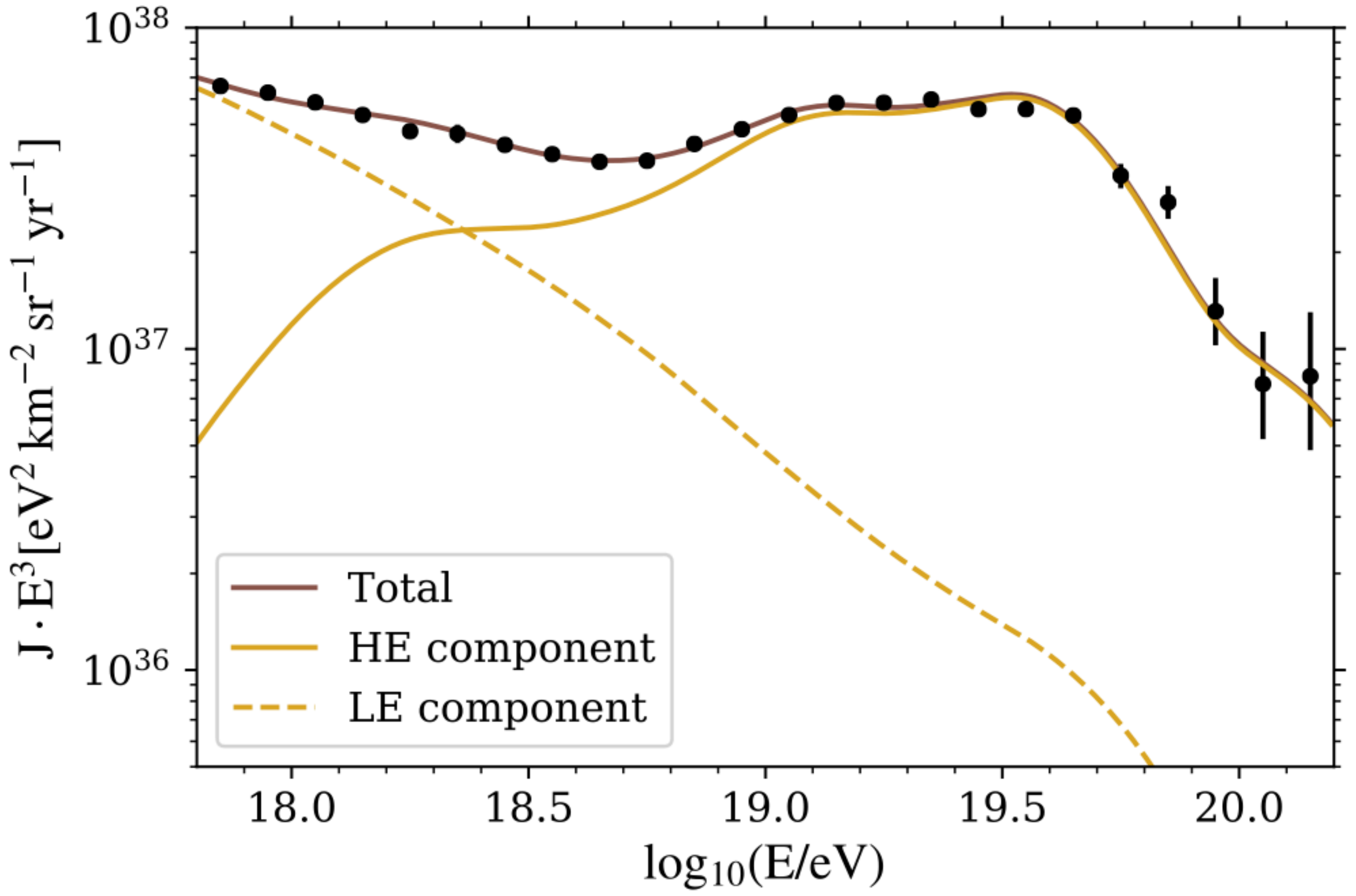


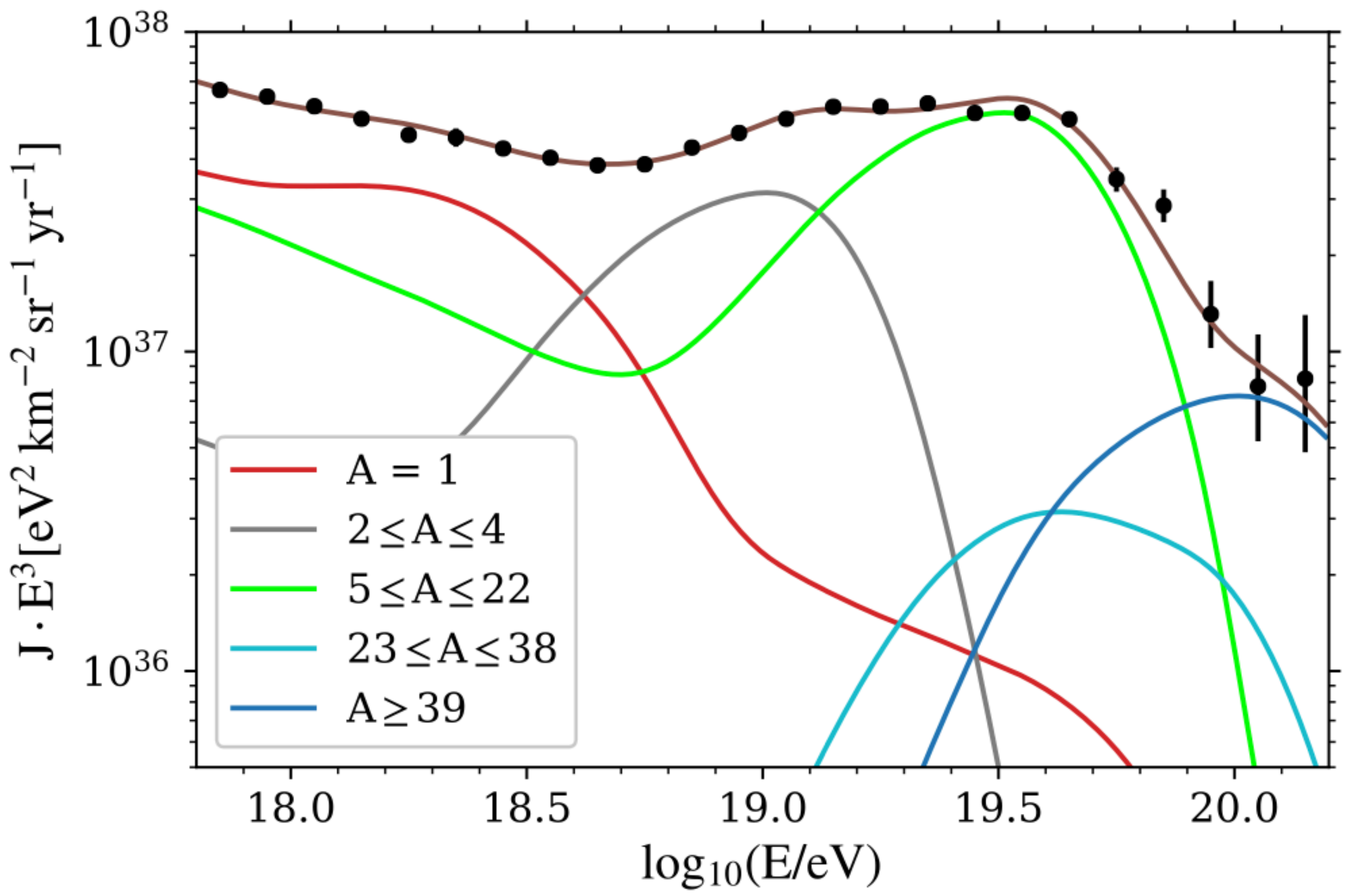


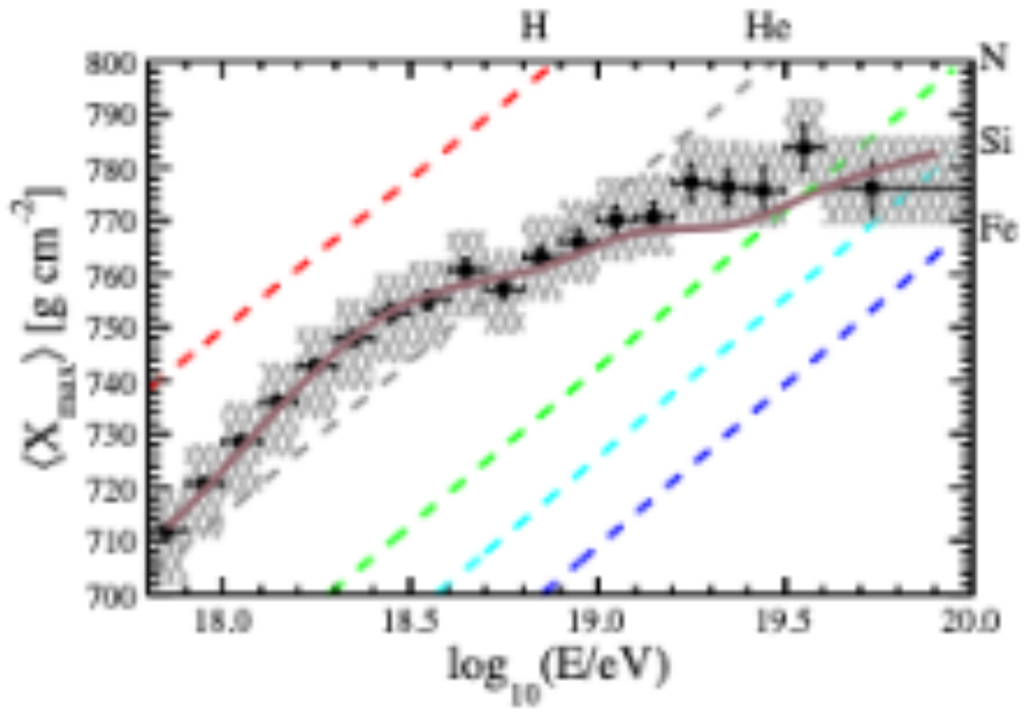


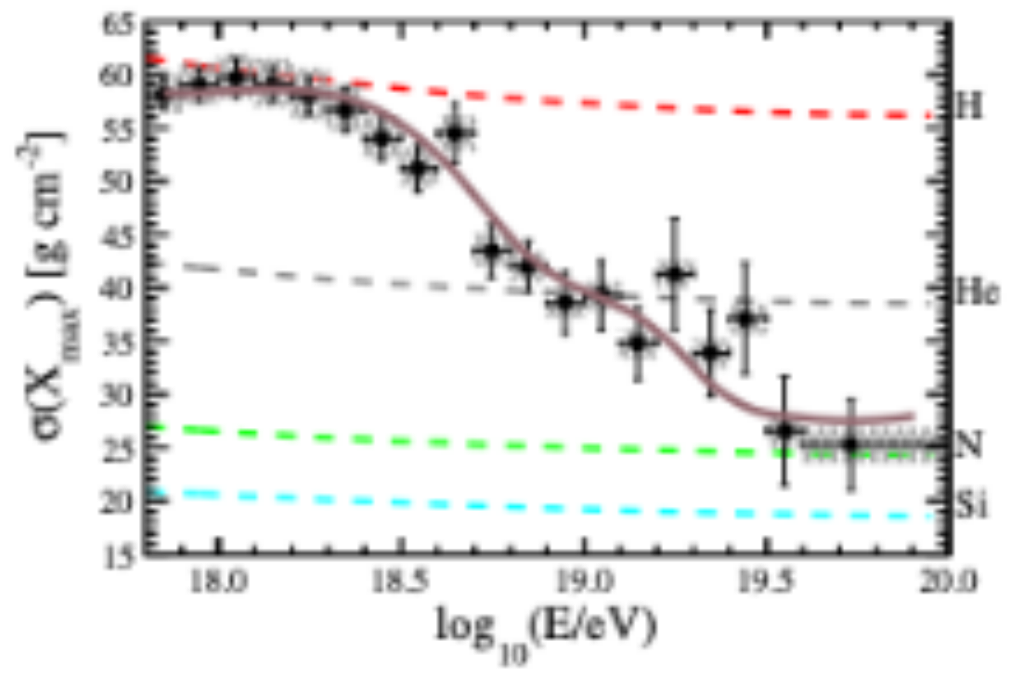
The Pierre Auger Collab. PRD2020

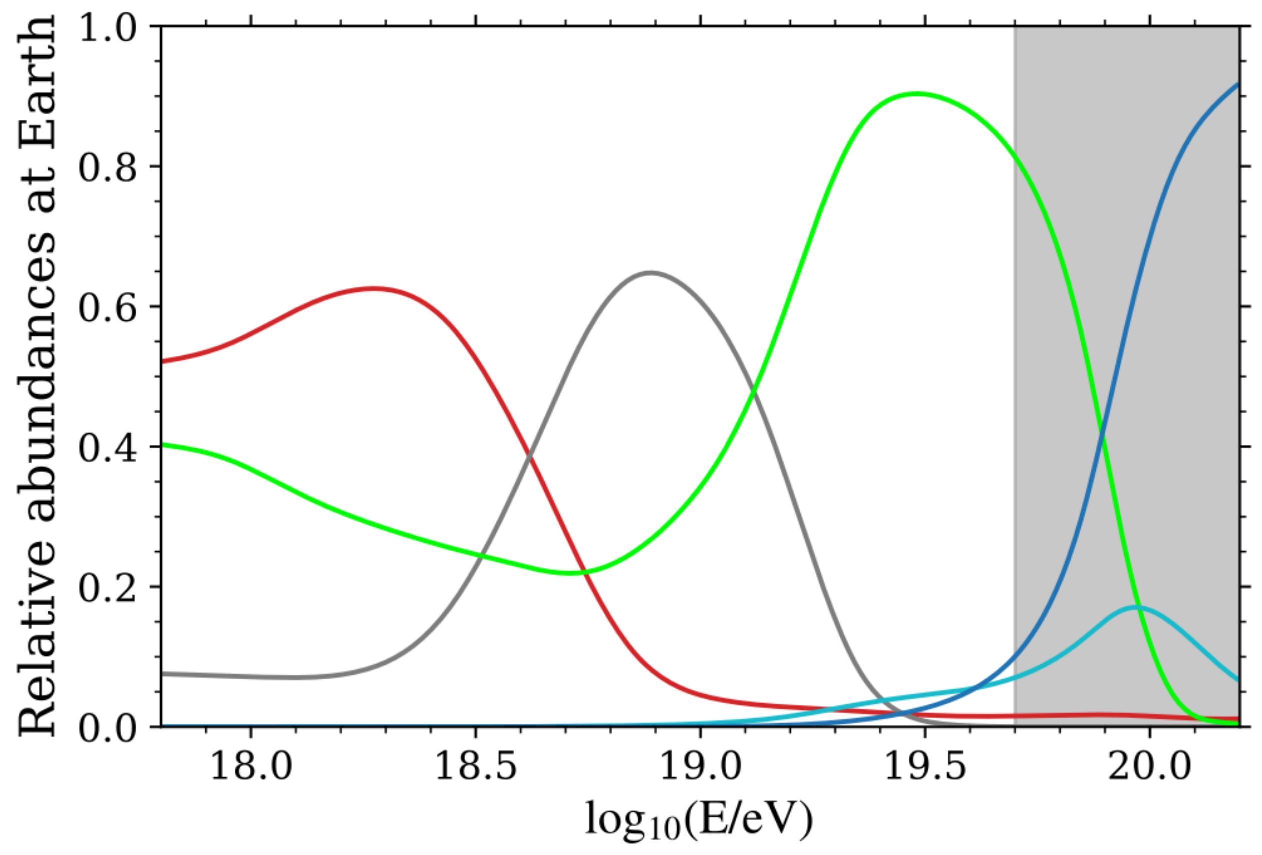
State-of-the-art: astrophysical scenarios











Different contributions needed at LE and HE:

- Different populations of sources Aloisio et al, JCAP 2014; Mollerach & Roulet PRD 2020; Das et al, Eur.Phys.J. 2021; **The Pierre Auger Collab. JCAP 2023**
- One population of sources (softer spectrum of protons due to in-source interactions) Unger et al. PRD 2015

Contribution from heavier particles below the ankle needed to account for mixed composition

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

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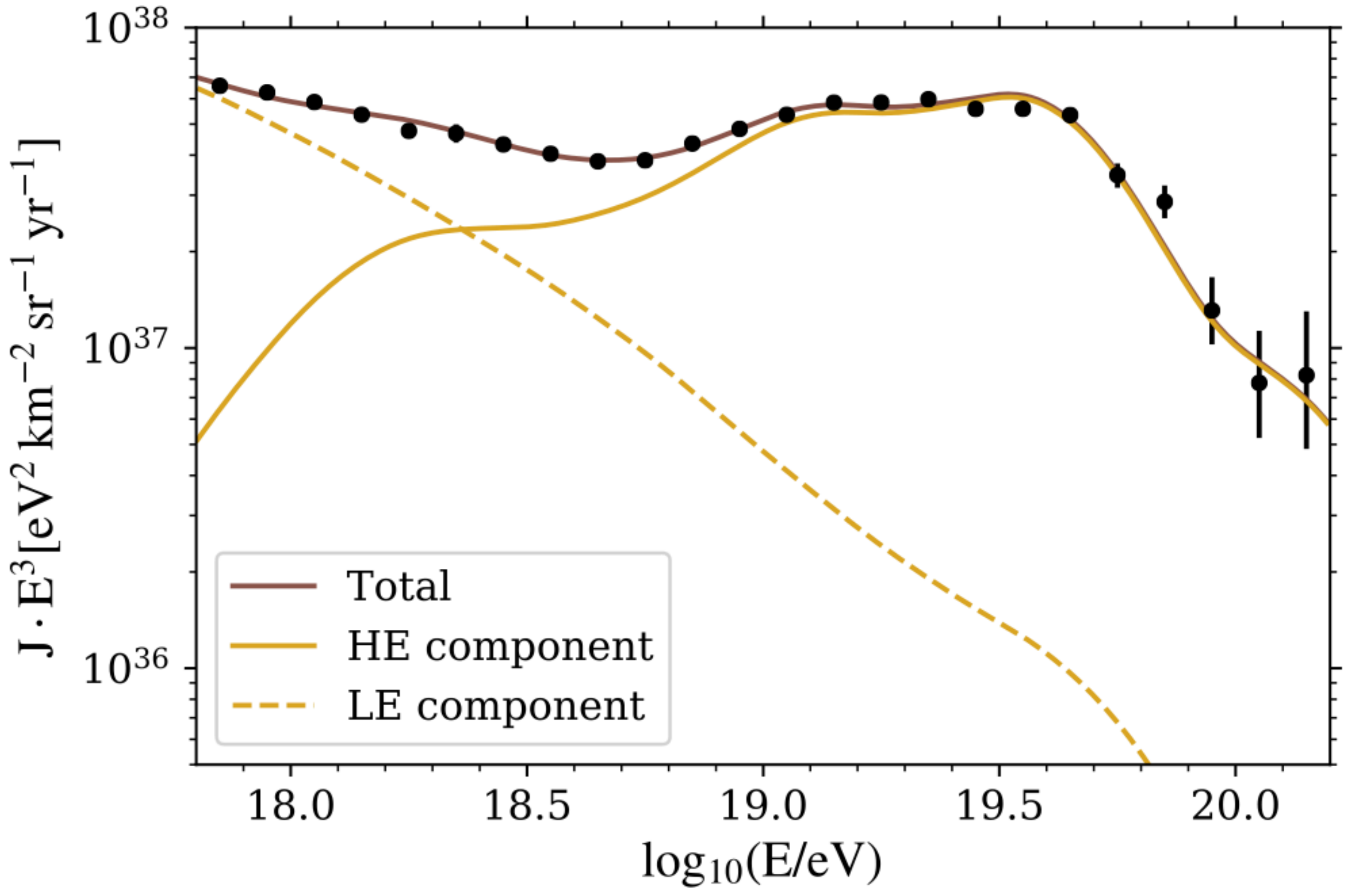

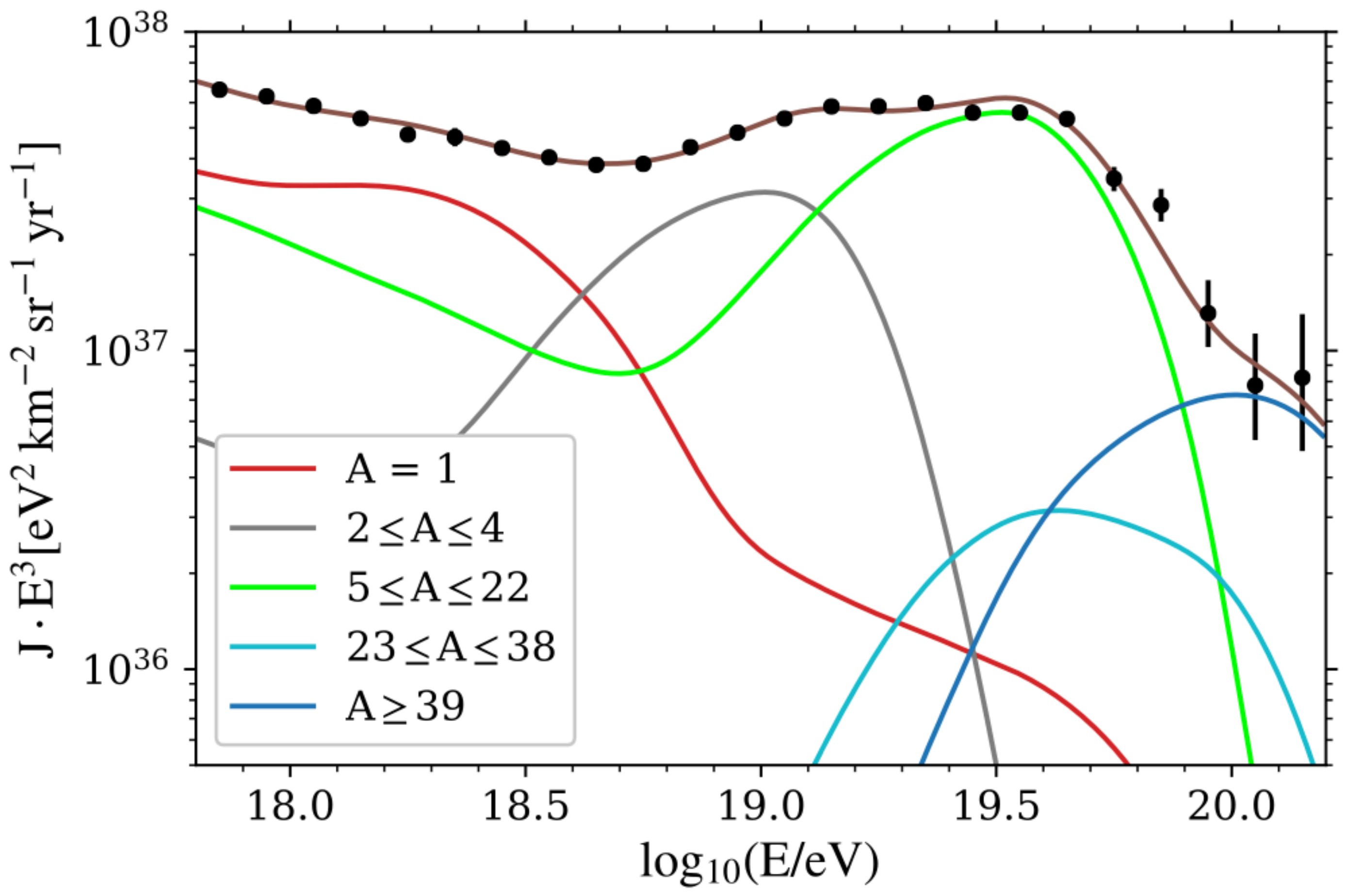

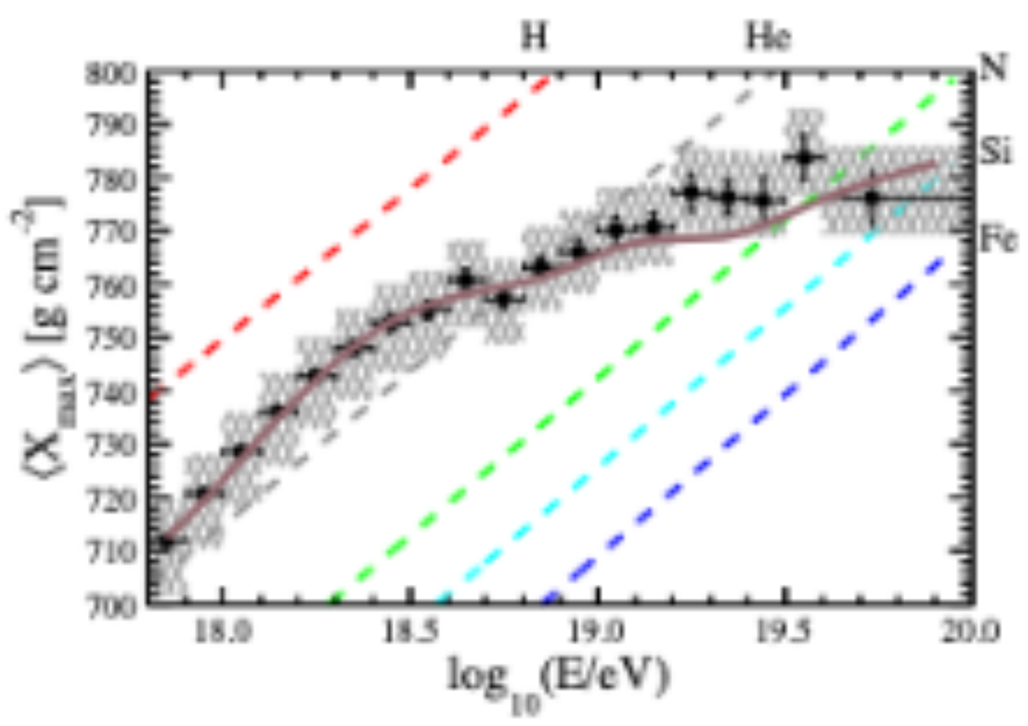

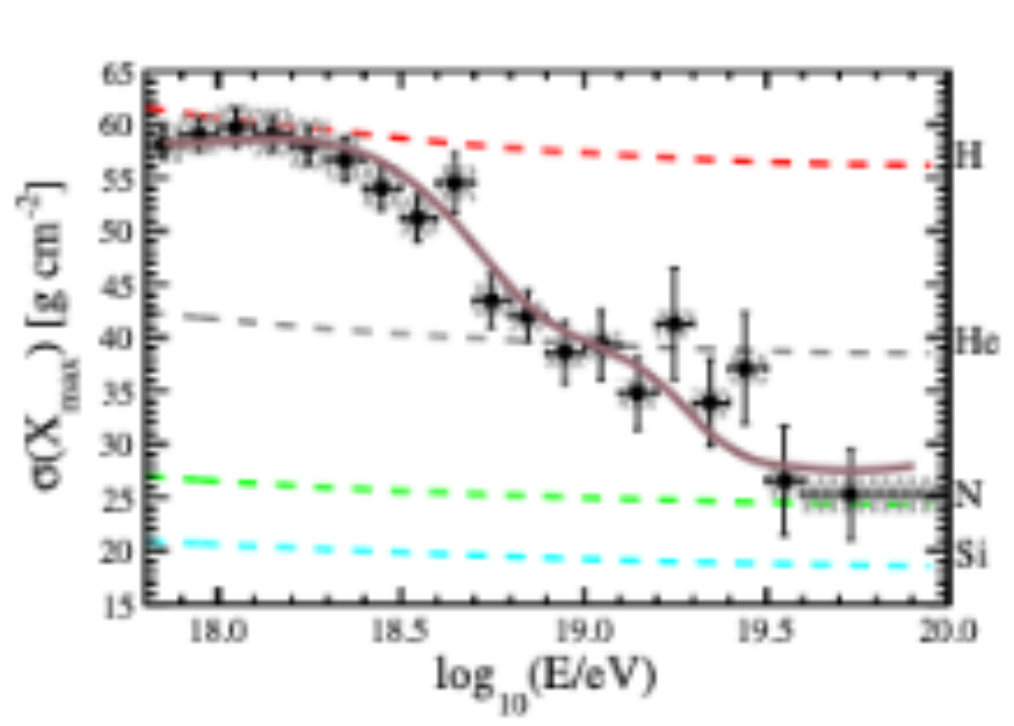

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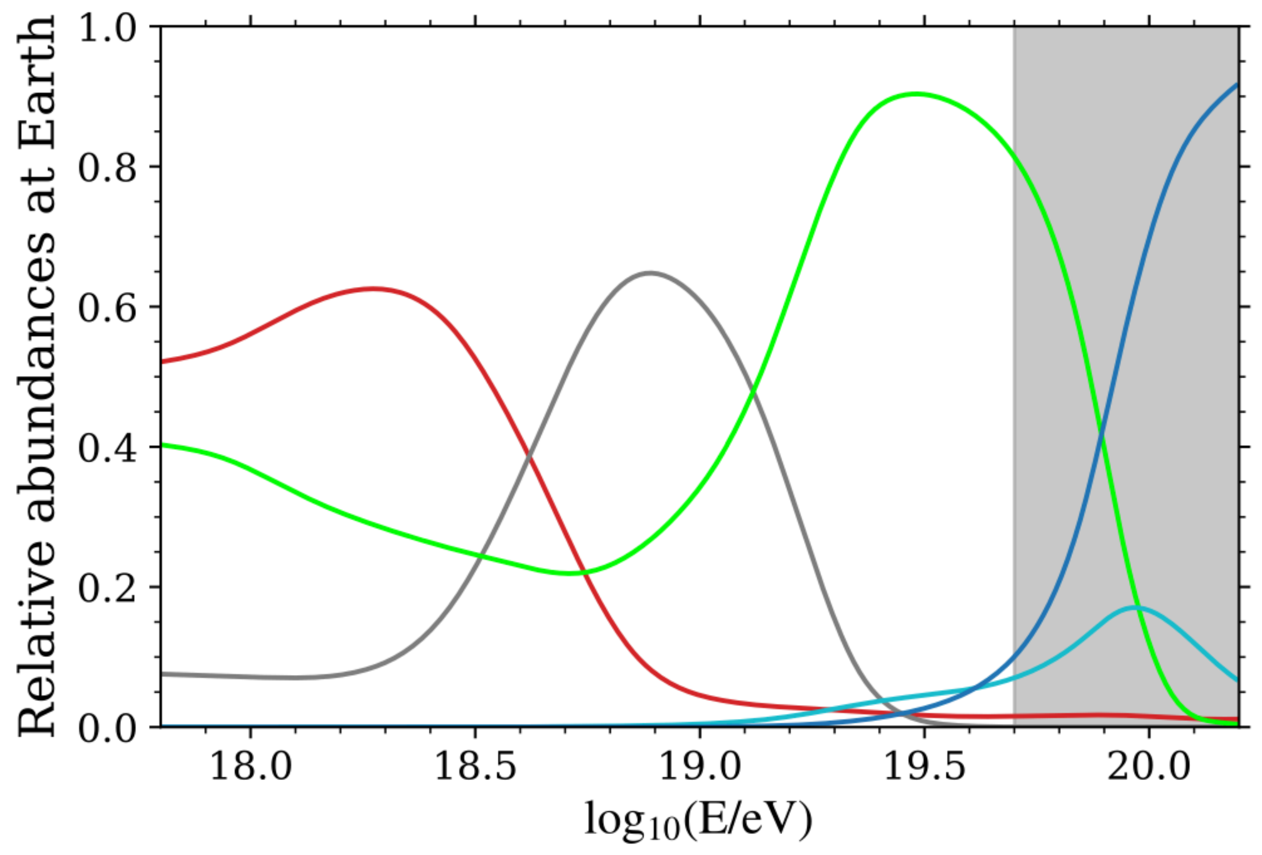

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  - HE: hard spectra + low rigidity cutoff
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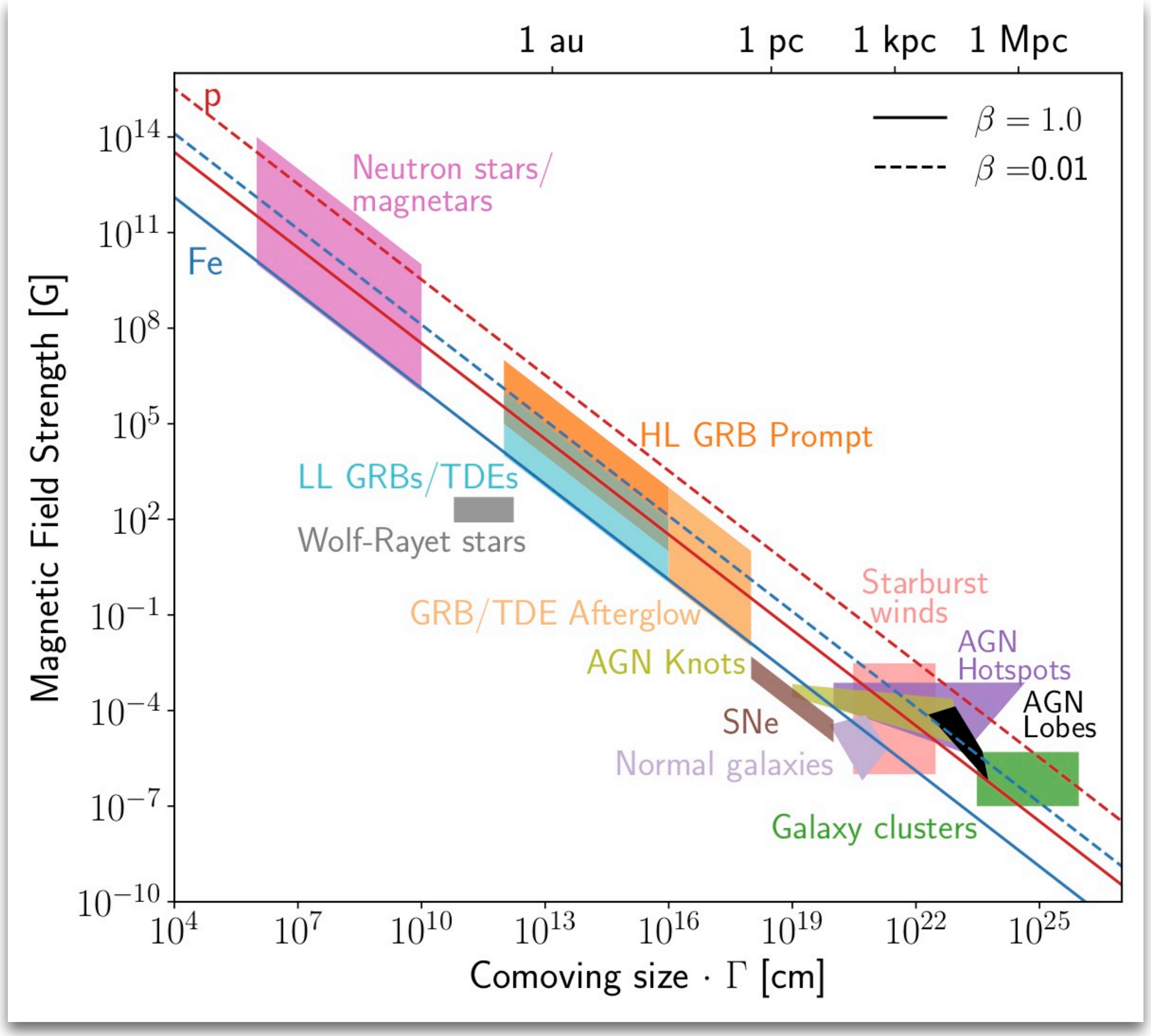
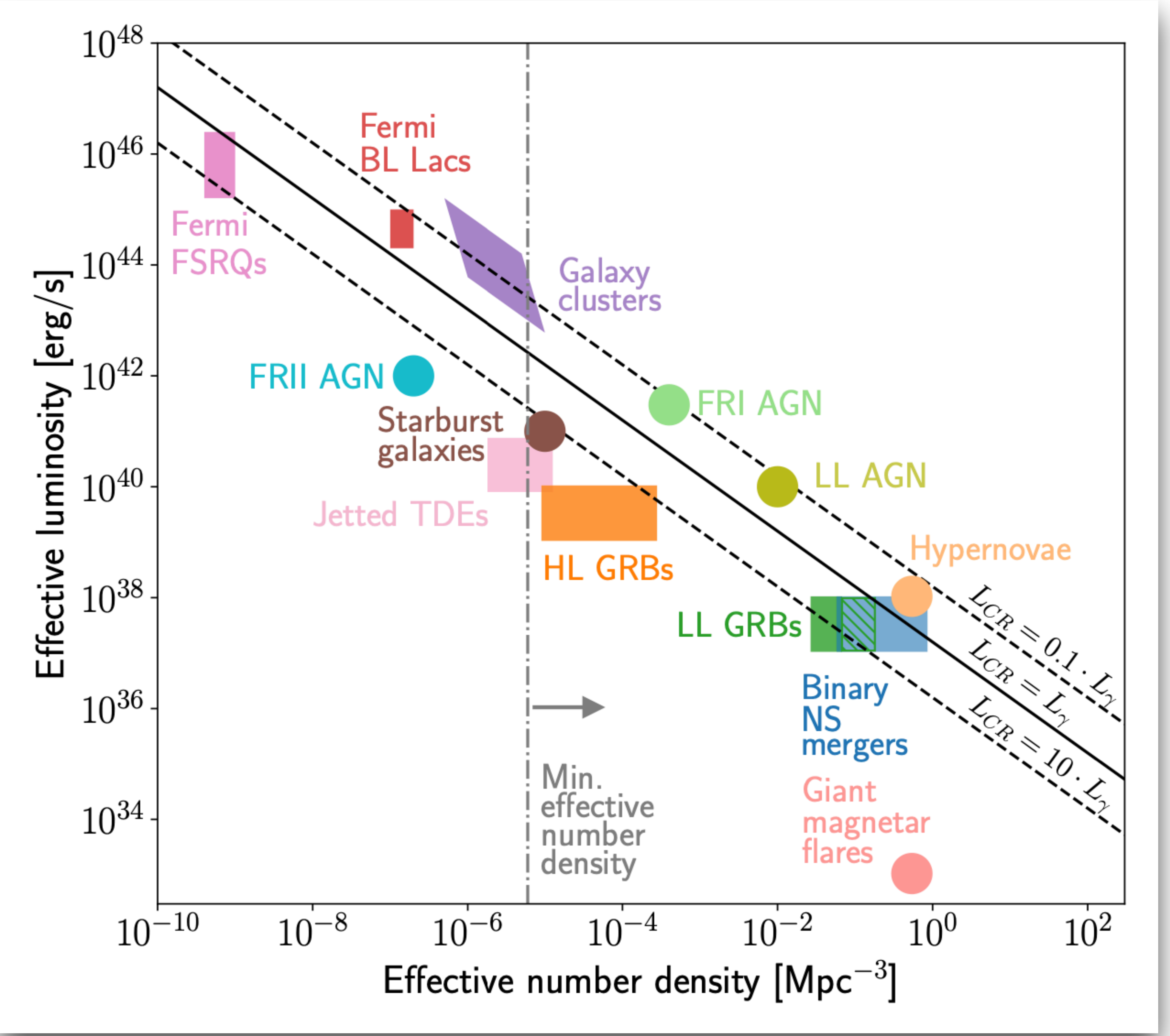
In terms of interpretation the **suppression**,

- Propagation effect
- Indication of source power

Not pure GZK !

Requirements about maximum energy and emissivity





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

Summary of the requirements from measurements

- Some pieces of information collected from measurements -> requirements for UHECR source characteristics

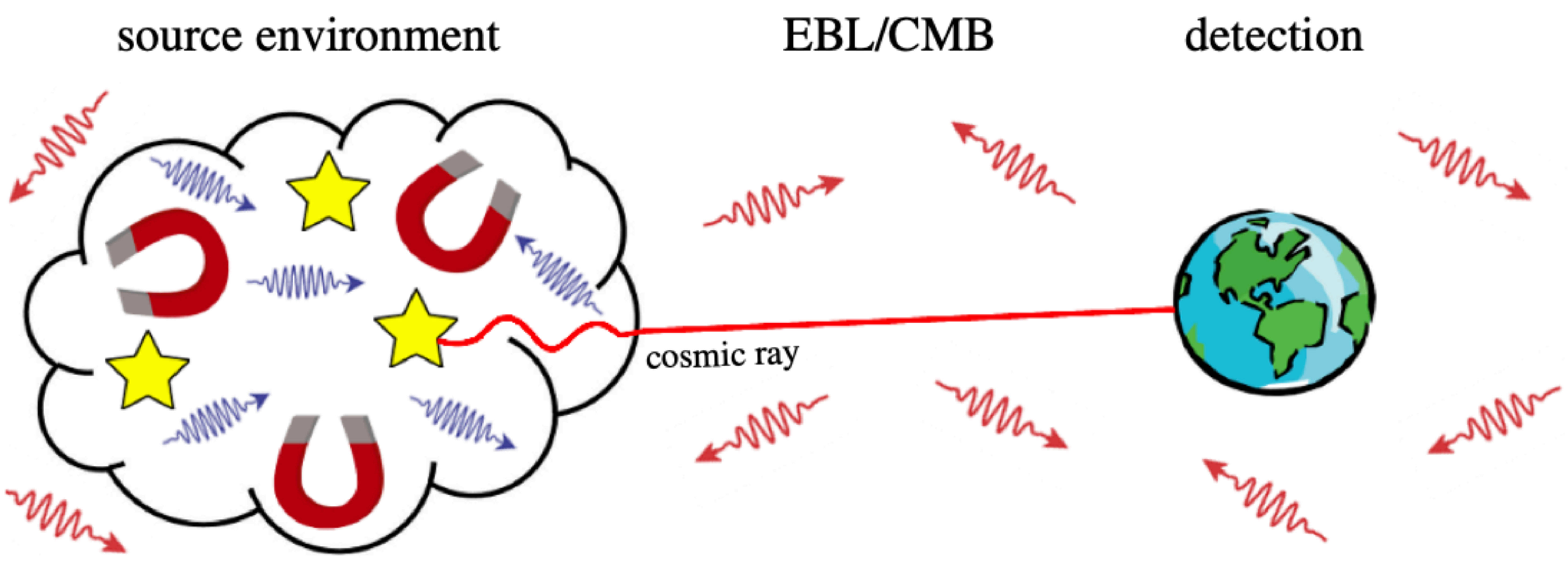
  - Hillas condition & emissivity requirements
  - Pure mass composition discarded by mass composition (and spectrum) data
    - Not pure GZK responsible for flux suppression
  - Different spectral shapes predicted for HE and LE components
    - In-source interactions, escape effects? Different populations? Magnetic effects (see The Auger Collab. JCAP 2024) ?
  - Peters cycle at the sources (but also Lorentz-factor ordering of of the spectra at the emission is quite ok, see for instance Muzio et al. PRD 2024) and Lorentz-factor ordering at Earth
  - Almost identical spectral shape at the emission from sources, see Ehlert et al. PRD 2023
  - Absence of declination dependence of the spectrum features, see The Auger Collab. arXiv:2506.11688
  - Narrow range of rigidity at Earth

→ Some of these requirements are discussed in the next slides…

- Many results on arrival directions, see The Auger Collab. ApJ 2022
  - At E > 8 EeV indications of extragalactic origin from the dipole direction
  - Hints of correlation with starburst galaxy sample
  - Overdensity in the Centaurus region

ABOUT THE SPECTRAL SHAPE (AND MASS COMPOSITION) AT THE ESCAPE FROM A UHECR SOURCE

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



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

Unger et al, PRD 2015

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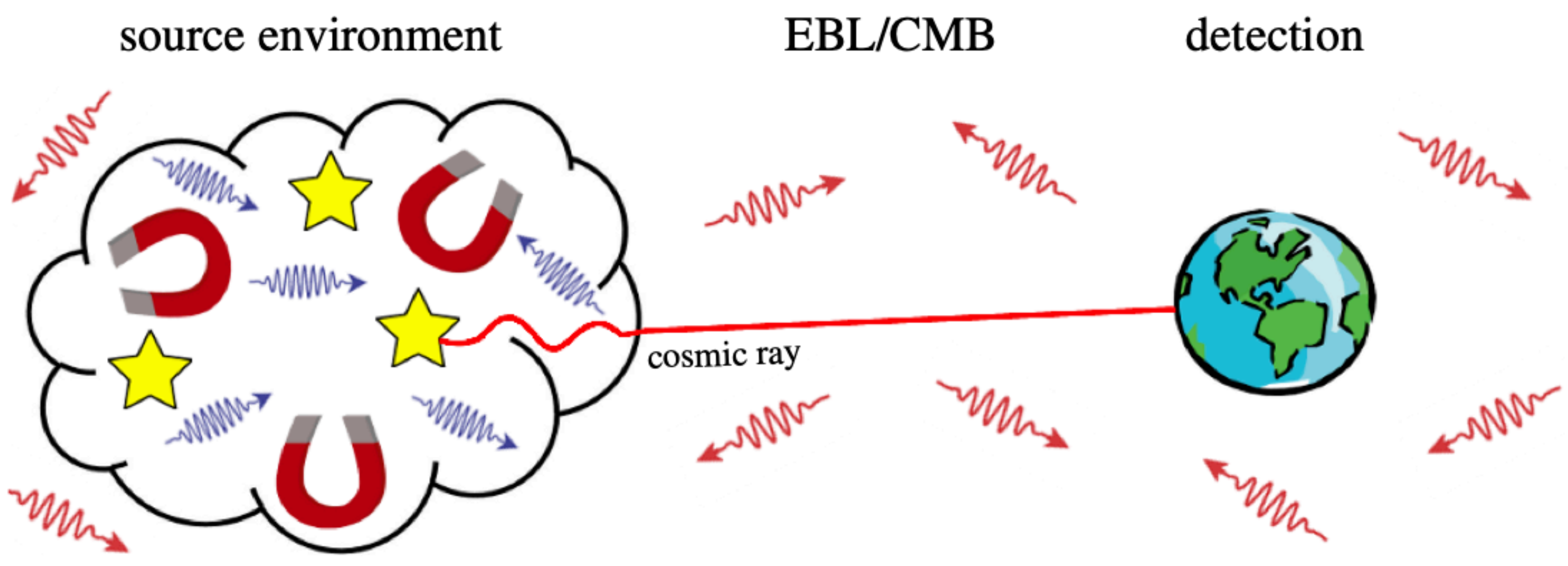

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$$\tau = (\tau_{\rm esc}^{-1} + \tau_{\rm int}^{-1})^{-1}$$

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

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

Particles escaping without interacting

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

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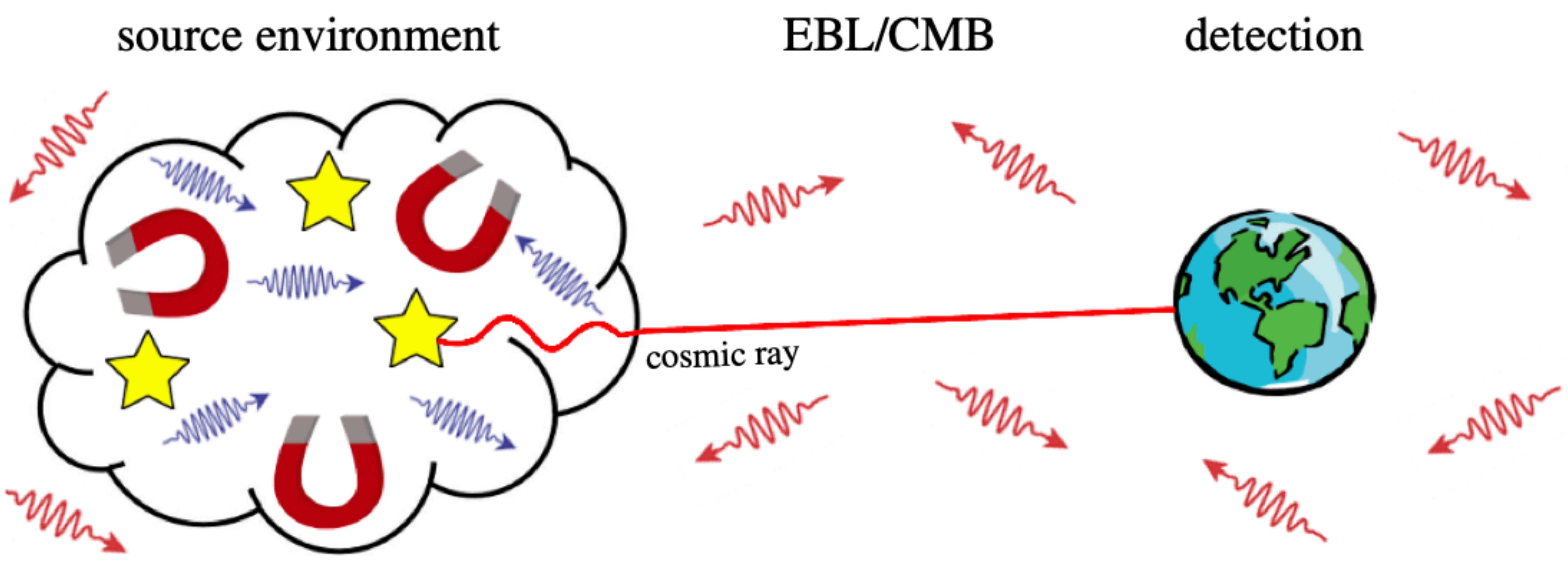

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$$\eta_{int} = 1 - \eta_{esc}$$

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

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

Only the ratio between escape and interaction is relevant

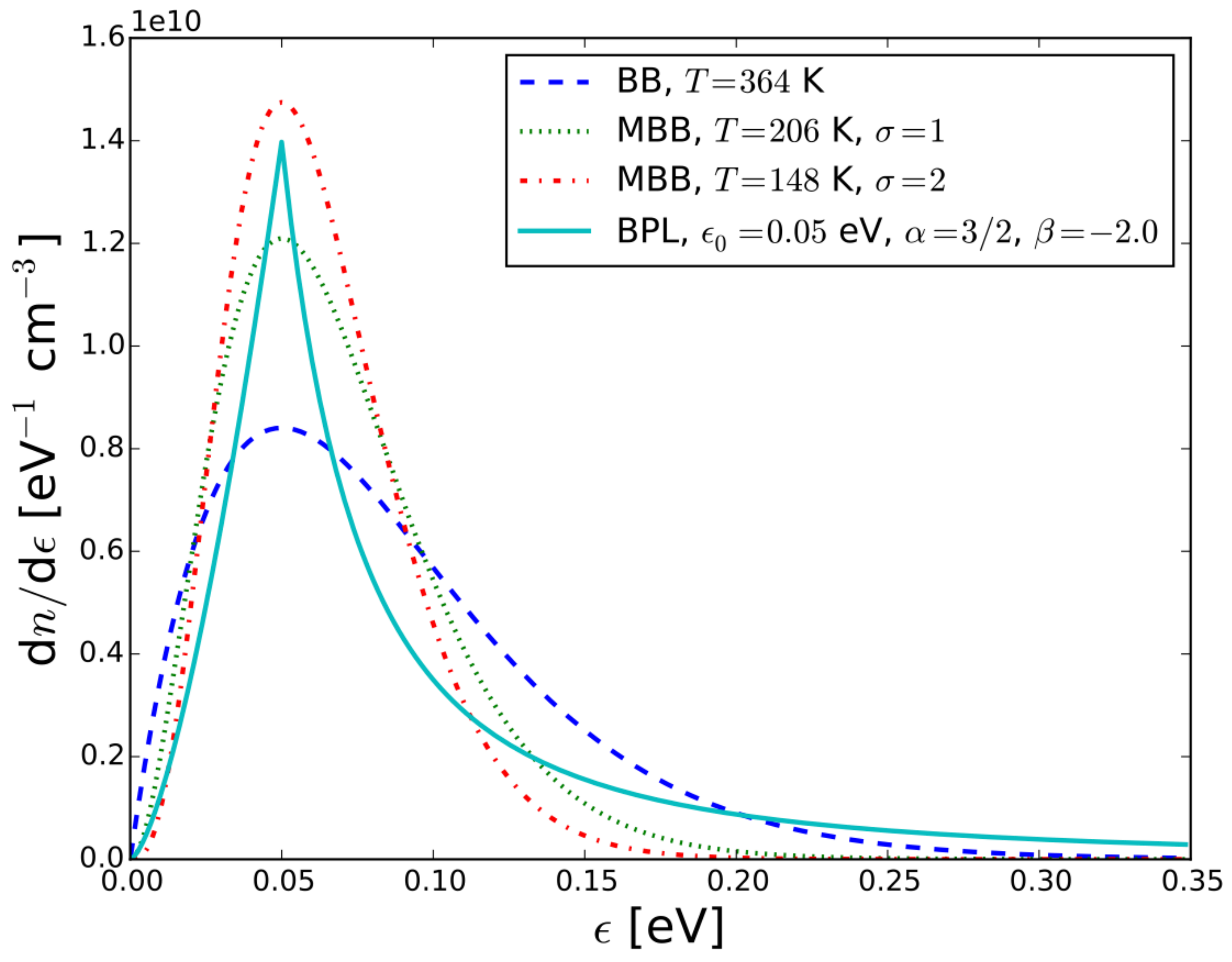
$\delta > \zeta$ — Low-pass filter

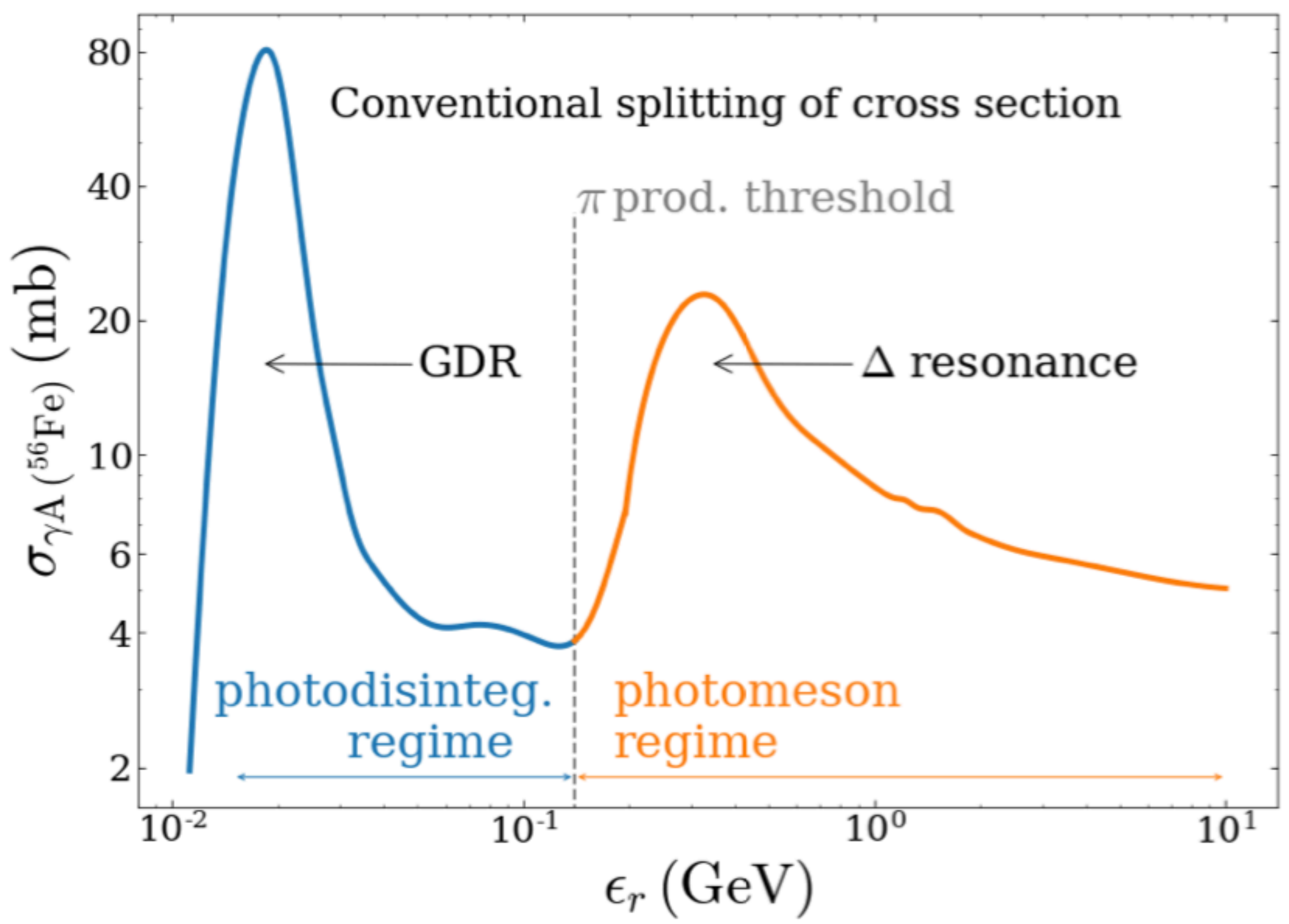
$\delta < \zeta$ — High-pass filter

Unger et al, PRD 2015

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

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





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

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

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

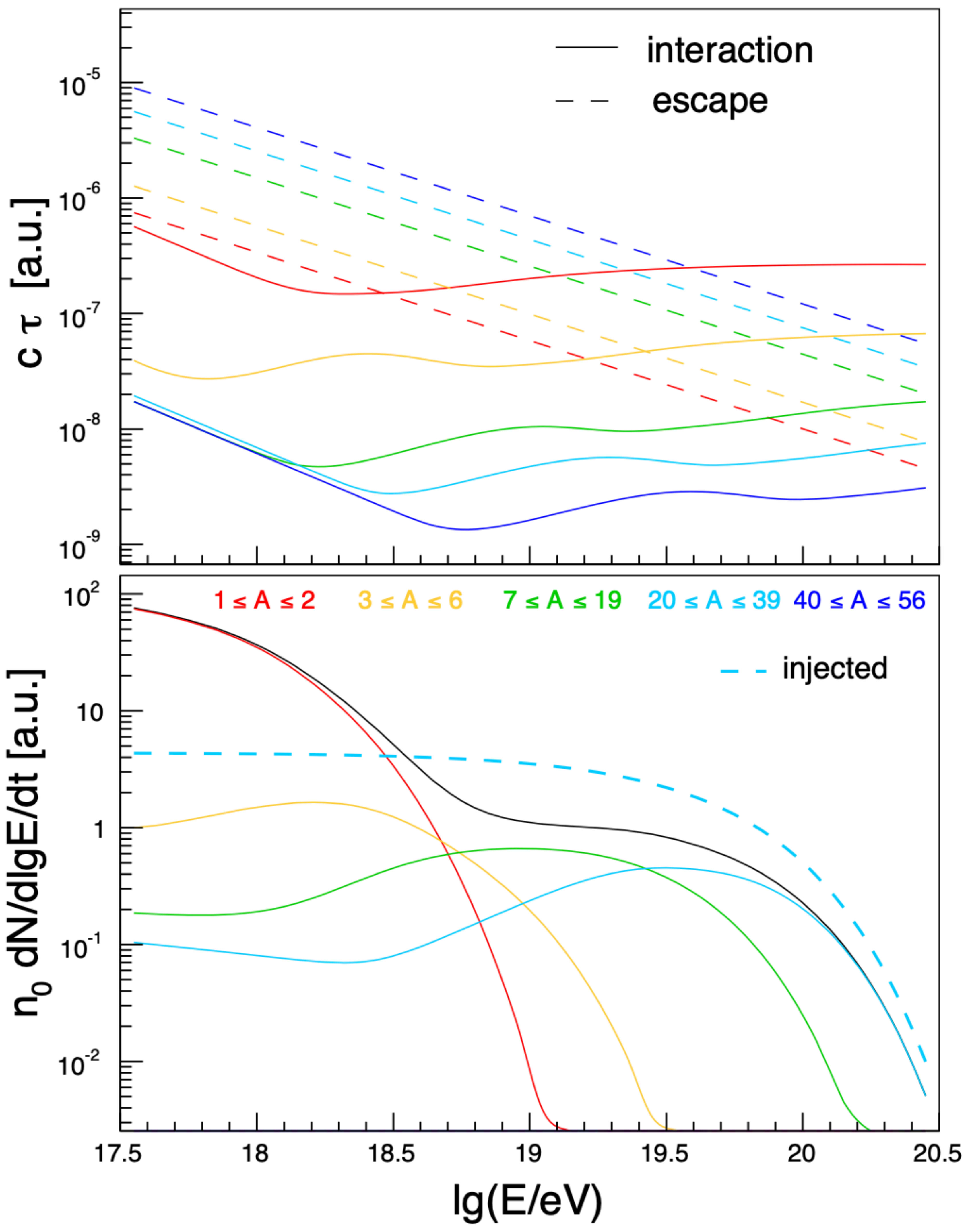
- Low CR energy -> high energy of the photon (above the peak) needed to reach the resonance energy -> steep spectrum -> time decreases
- High CR energy -> low energy of the photon (below the peak) needed -> time increases

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

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

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

Unger et al, PRD 2015



Source-propagation model

$$\frac{\partial N_i(E)}{\partial t} = \frac{\partial}{\partial E}(-b(E)N_i(E)) - \frac{N_i(E)}{t_{\rm esc}} + Q_{ji}(E)$$

$b(E) = E/t_{\rm loss}$

$Q_i(E)$ Injection of CRs (accelerated spectrum)

$Q_{j\to i}(E)$ Production of secondary cosmic rays

Coupled system of equations, arising because:

$Q_{ji} = Q_i(E) + Q_{j\to i}(E)$

$$Q(E,z) = Q_0 \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{E_{\rm max}}\right) f(z)$$

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

- Accelerated spectrum Q in the source
  - Interactions and escape in the source environment
- Spectrum at the escape -> injection in the extragalactic space
  - Interactions in the extragalactic space
- Spectrum at detection
- Secondary messengers can be computed (from source and from extragalactic propagation)

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Multimessenger connections:

$L_{\rm CR} = \int Q_{\rm CR}(E) E\, dE \approx \eta\, L_\gamma$ $L_\nu \approx f_\pi L_{\rm CR} \approx f_\pi \eta\, L_\gamma$

η baryonic loading, unknown

Corresponding quantities for transient sources can be also described

Source-propagation model

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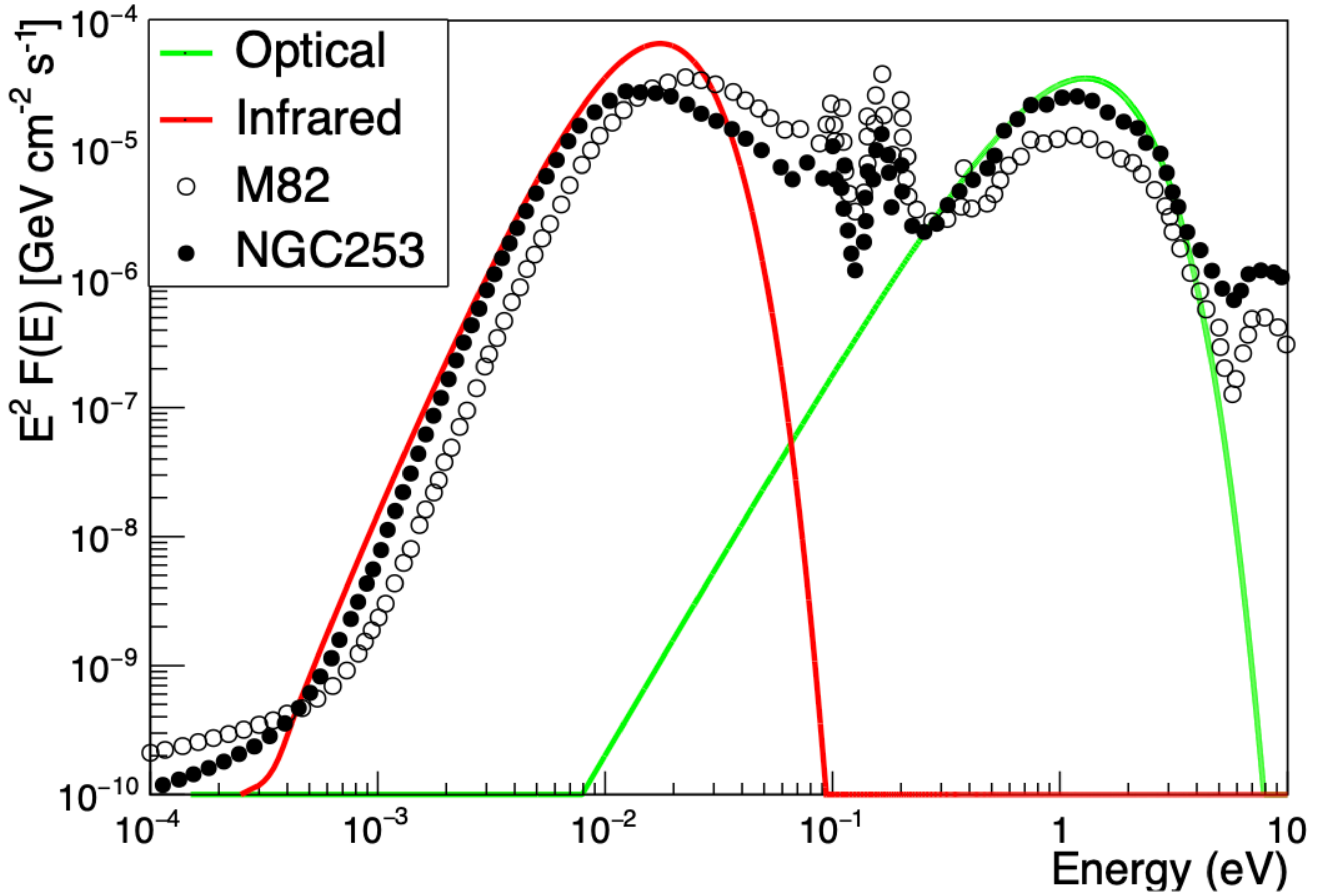
- **Cosmic Ray Injection**
    - Mass of primary particles
    - Maximum energy of CR spectra
    - Slope of CR spectra
    - Source evolution
    - Maximum distance of sources

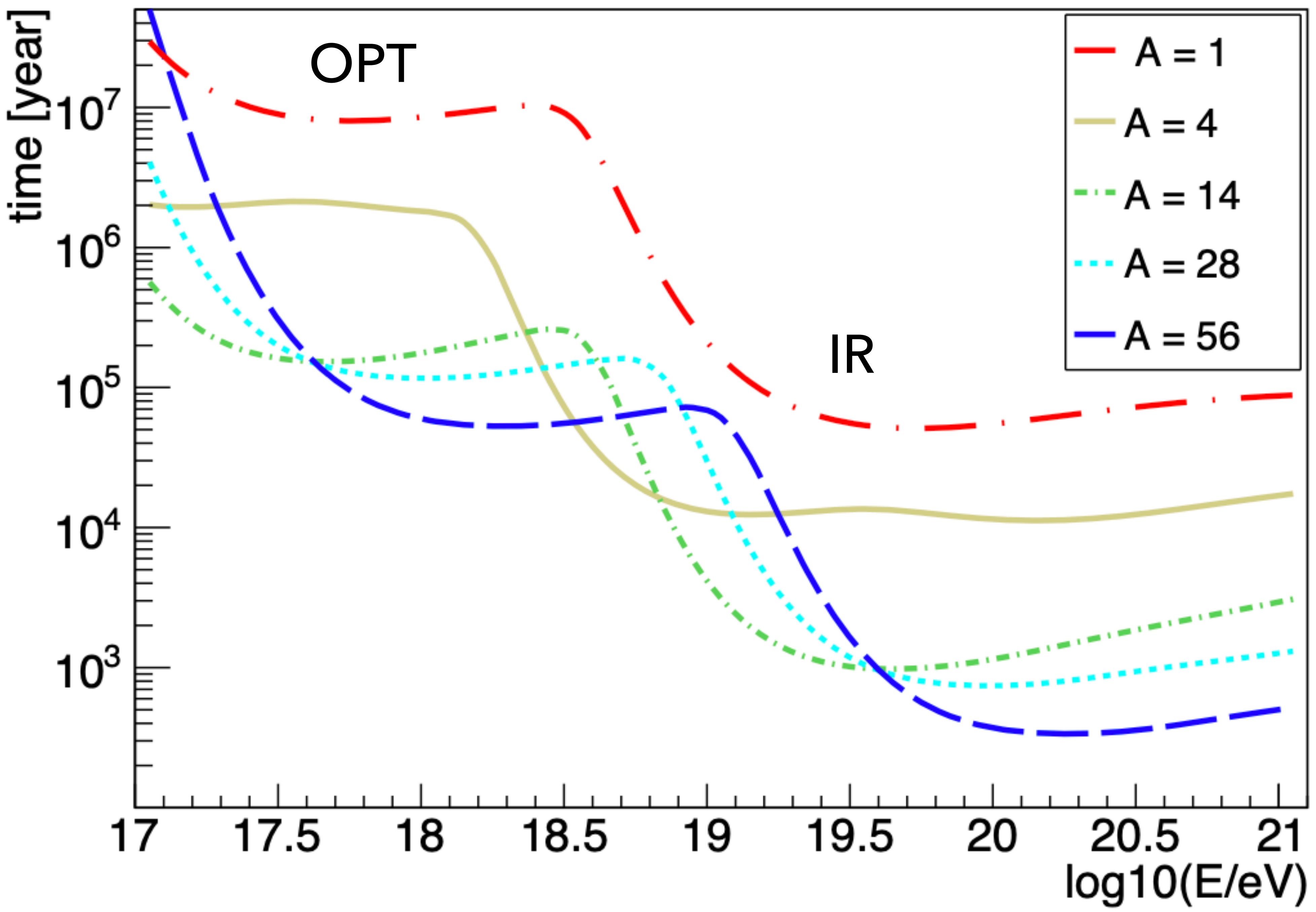
Not possible to be constrained only with UHECRs! Multimessenger approach needed; see for example:

- Heinze, **DB**, Bustamante & Winter, ApJ 2016
- Alves Batista, de Almeida, Lago & Kotera, JCAP 2019
- Heinze, Fedynitch, **DB** & Winter, ApJ 2019
- van Vliet, Alves Batista & Hoerandel, PRD 2019
- The Auger Collab. JCAP 2023; update in ICRC2023
- IceCube Collab. arxiv:2502.01963

Application to Starburst galaxies

- **Example** from Condorelli, DB, Peretti & Petrera PRD 2023: CR interactions in starburst galaxies





Characteristic time for photo-meson production and photodisintegration

- **Radiation field (or matter density)**:
  - Intensity -> increase interaction rate
  - Min and max energy -> define range of interaction rate
  - Power law, energy break (if broken power law) or energy peak (if black-body radiation) -> change shape and/or shift interaction rate
  - Size -> interplay with escape/diffusion

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

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

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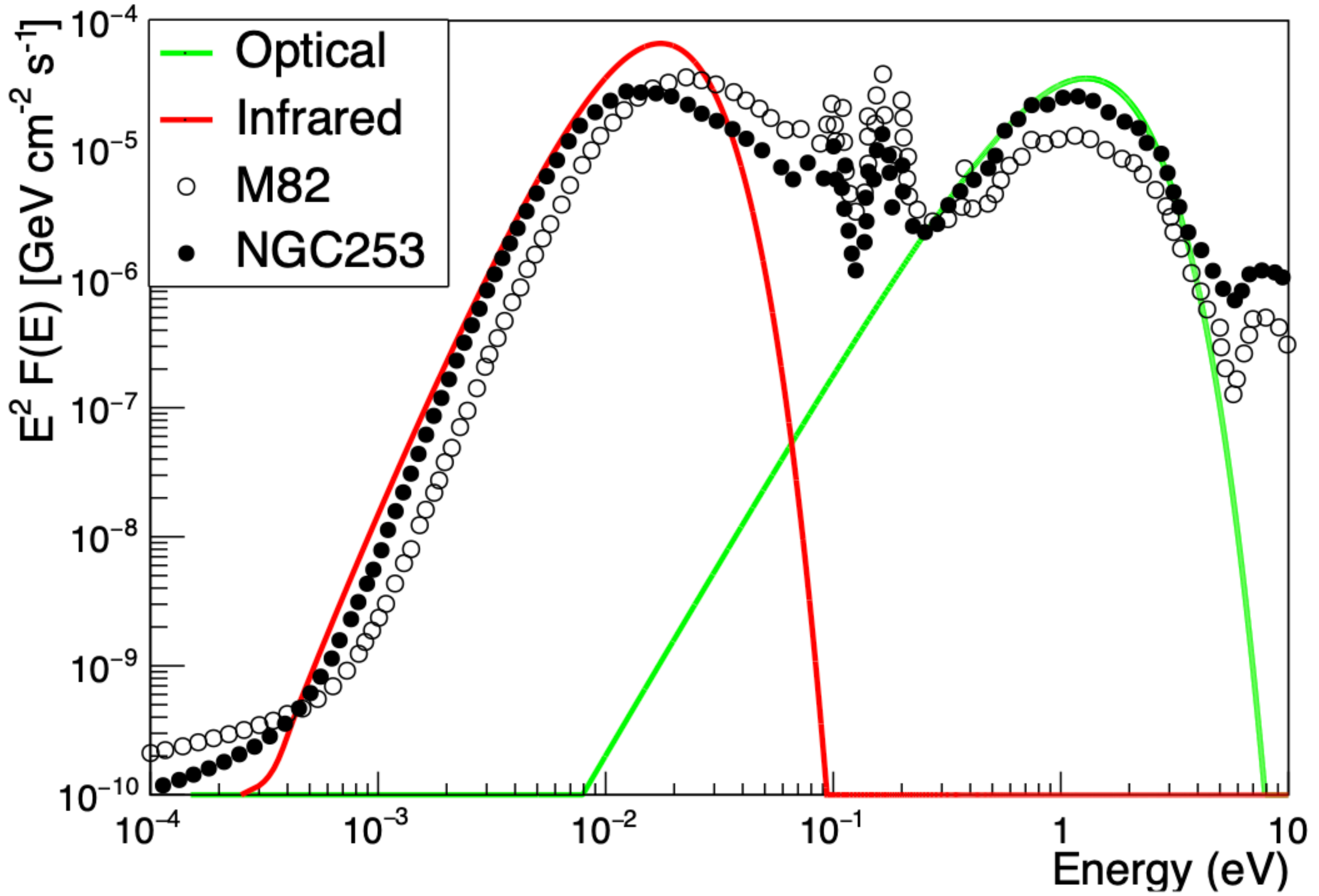

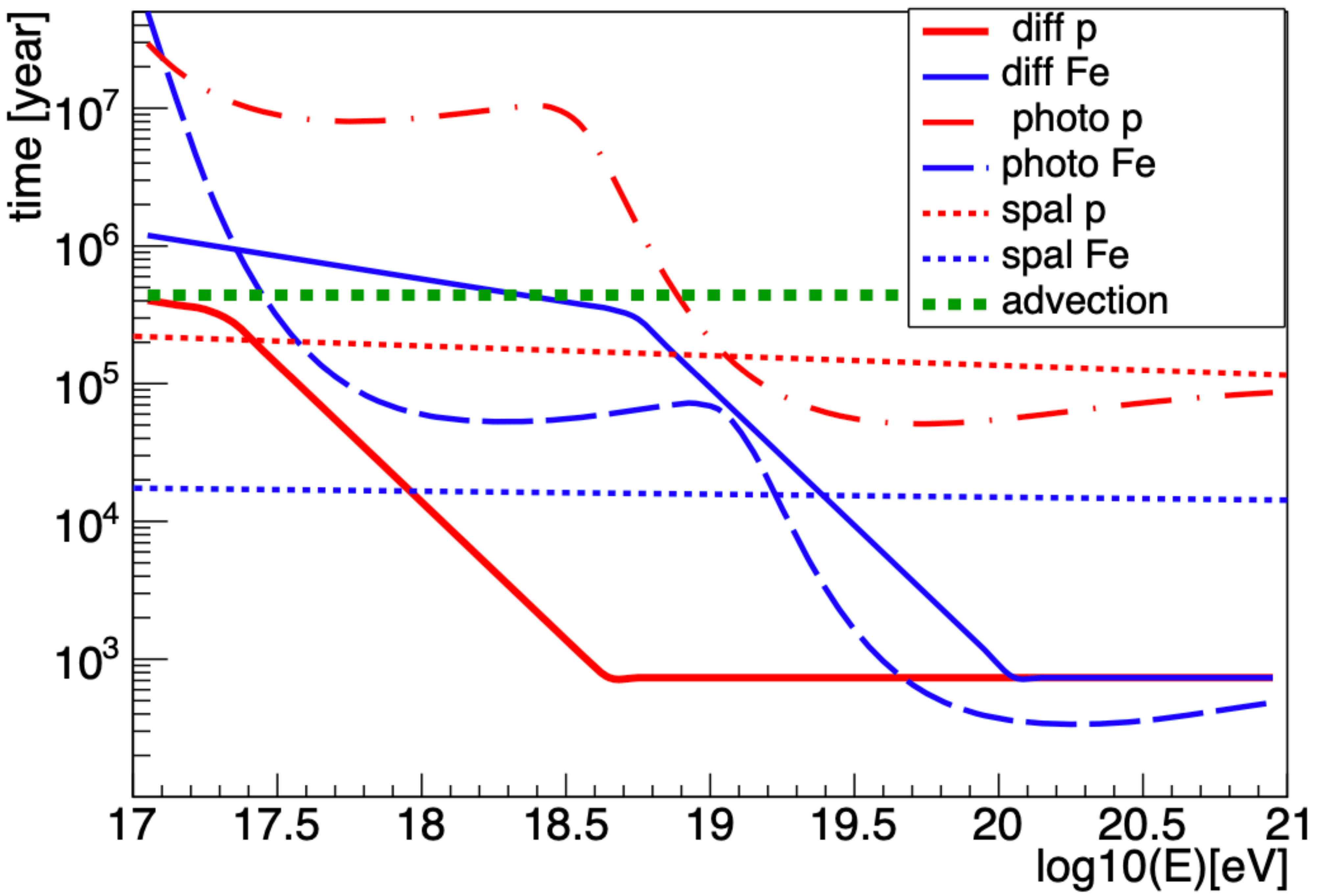

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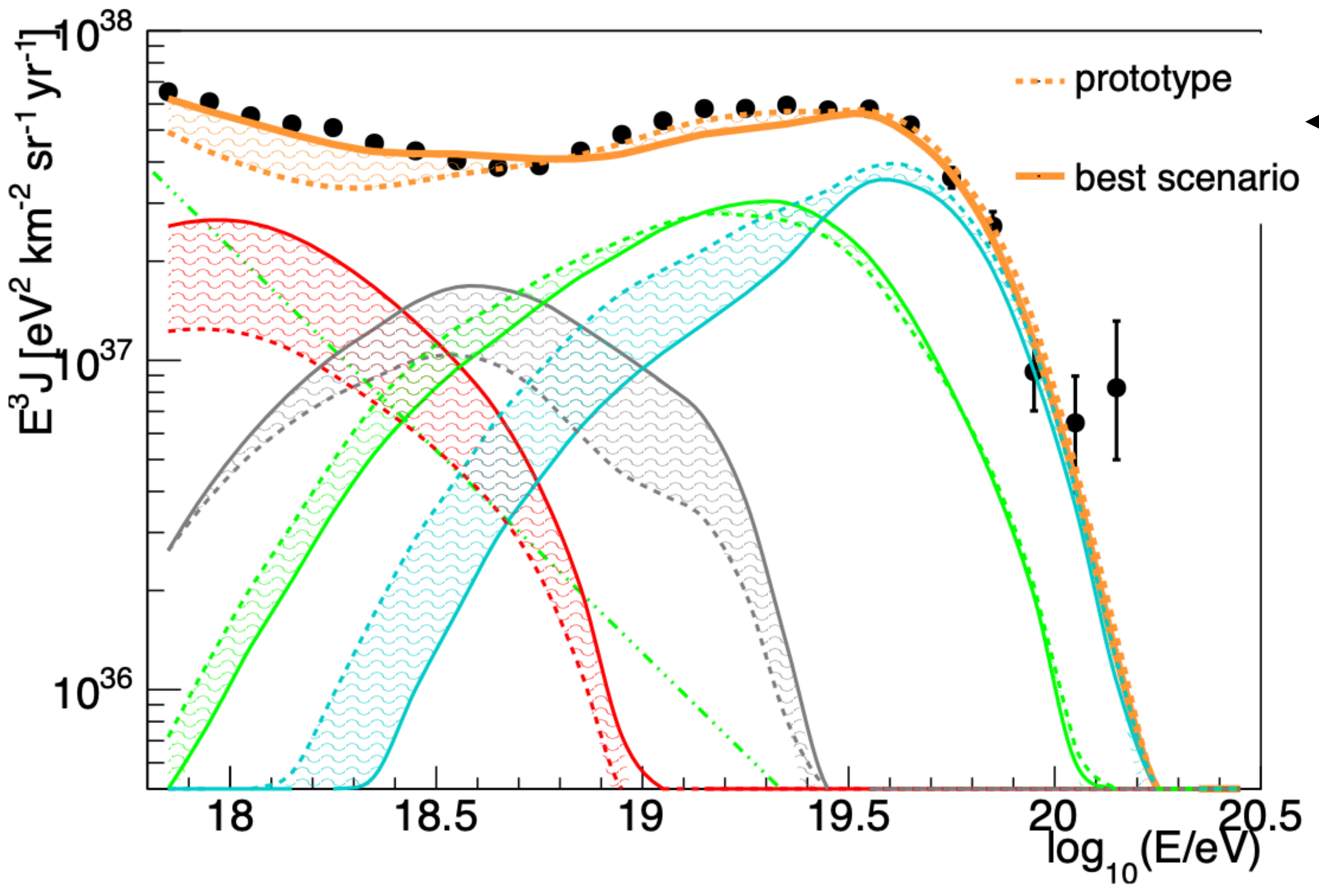
Characteristic time for diffusion compared to spallation and photonuclear interactions

$$t_{\rm adv} = \frac{R}{v_W} \qquad t_{\rm D} = \frac{R^2}{D(E)} \qquad t_{\rm esc} = \min[t_{\rm adv}, t_{\rm D}]$$

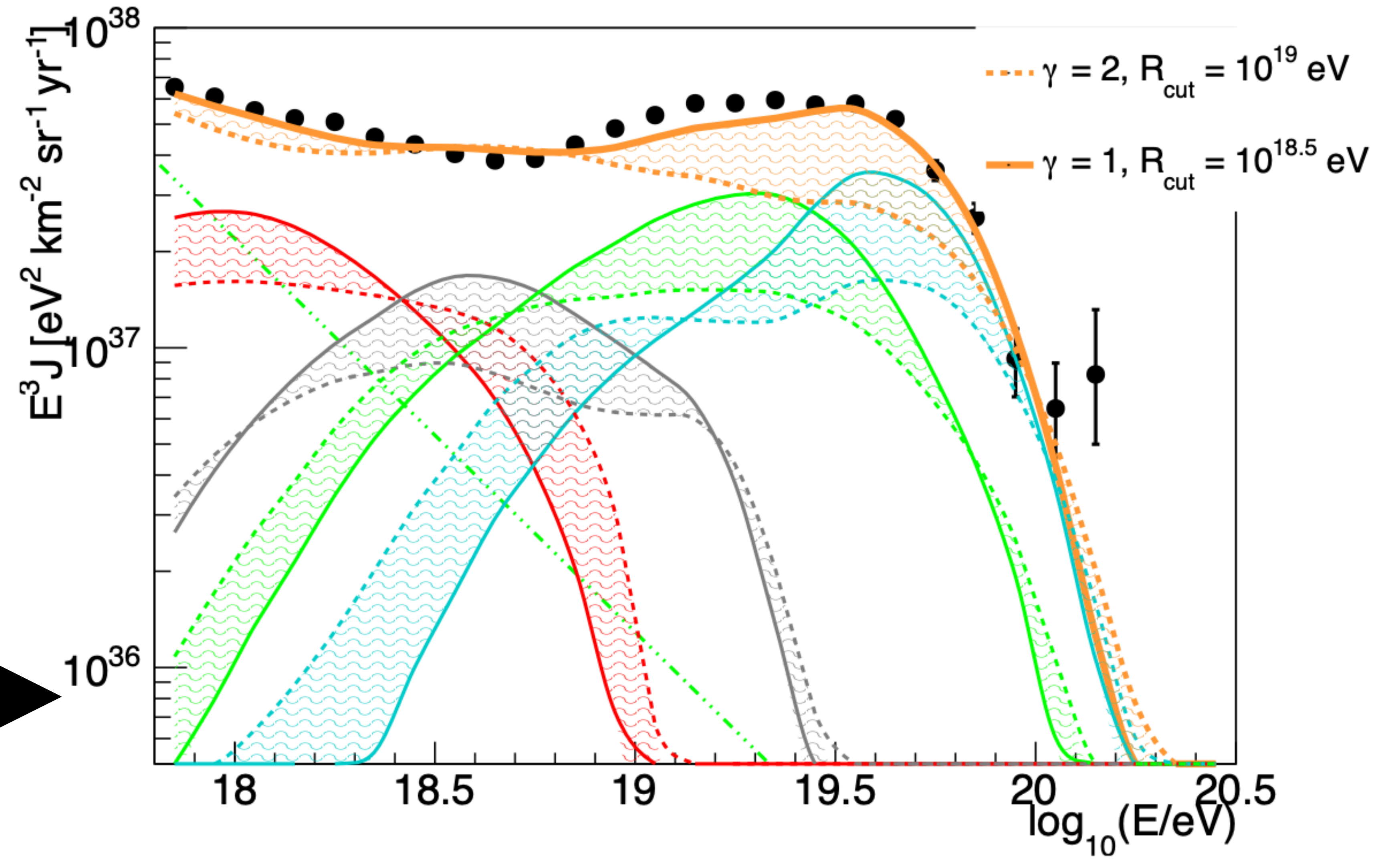
Maximum energy is not just defined by acceleration!

Application to Starburst galaxies



Effect of increased interaction efficiency

Effect of change of CR spectrum



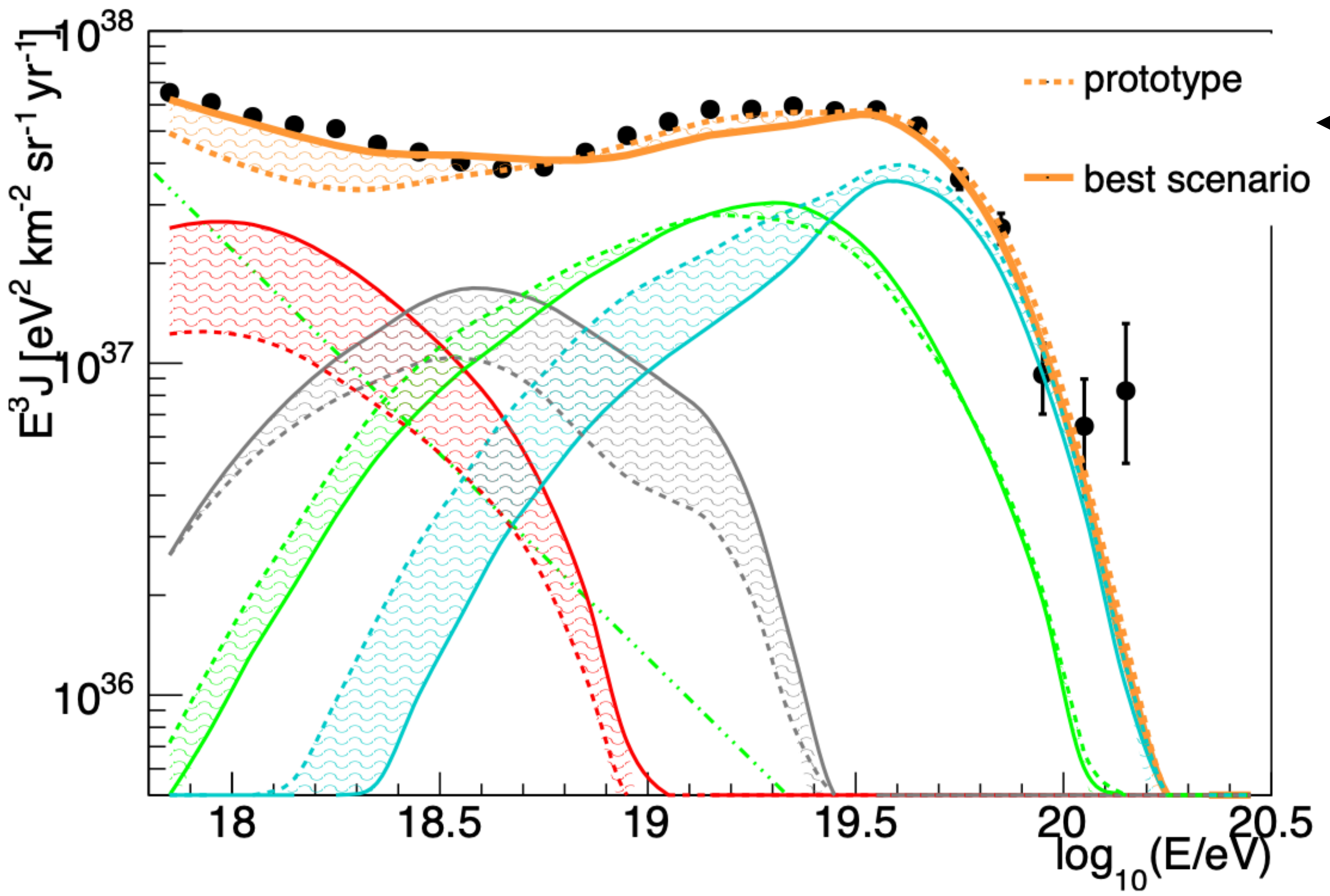
Condorelli, DB, Peretti & Petrera PRD 2023

- Denser photon field
  - heavier nuclei interact more efficiently
  - Lighter nuclei are more abundant

- Harder spectrum at acceleration
  - Larger number of particles at high energy with respect to low energy

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

Application to Starburst galaxies + neutrinos



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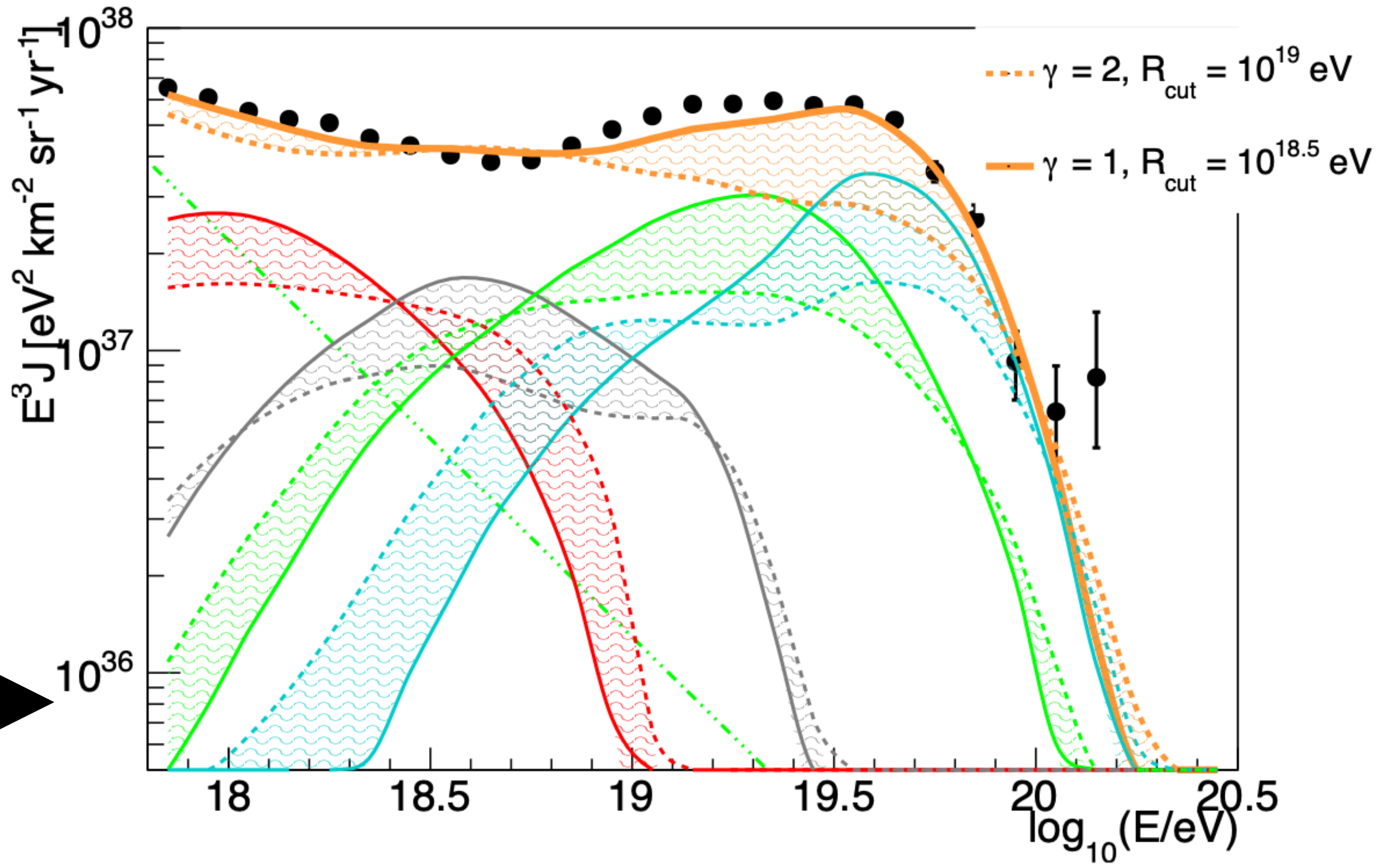
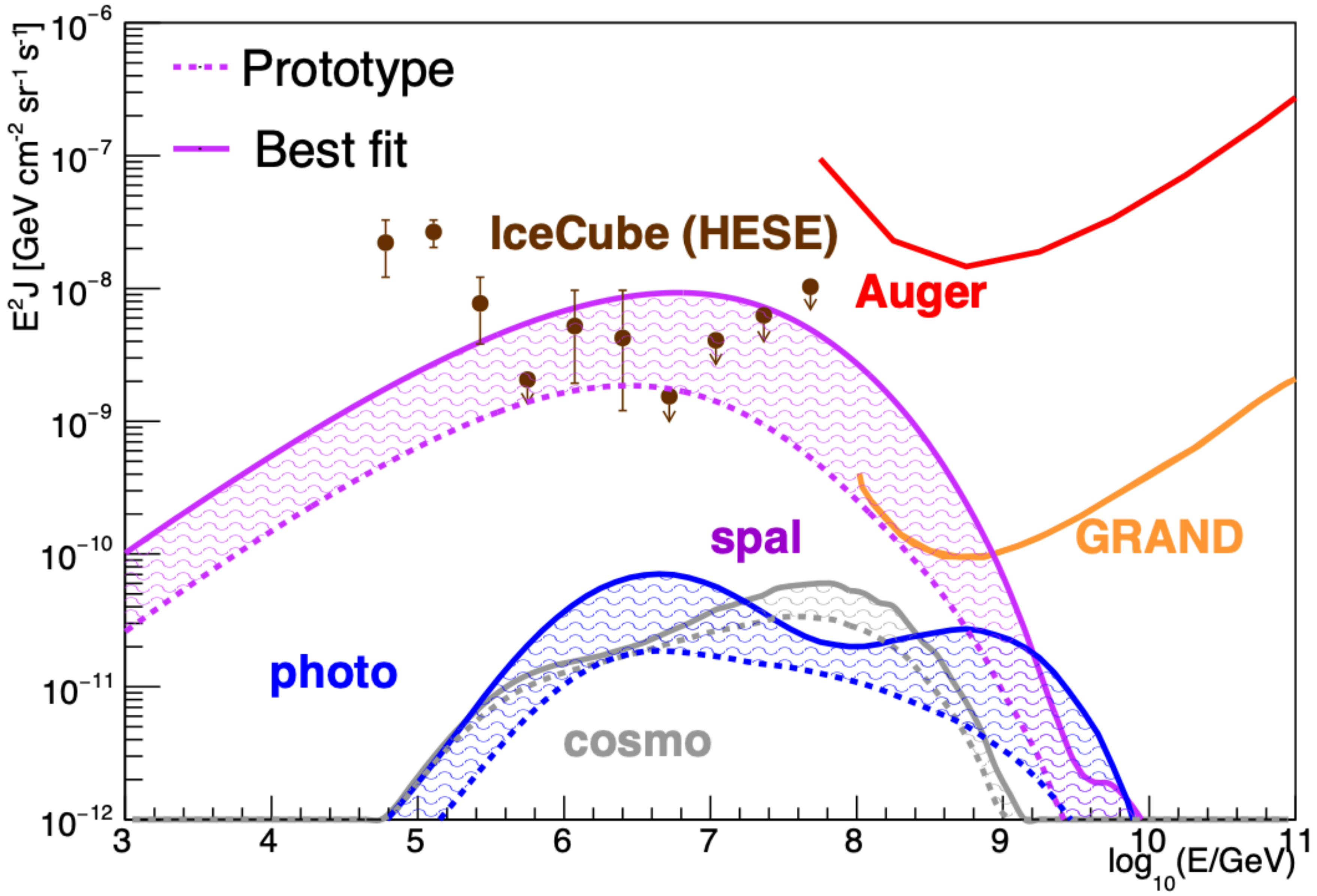


Effect of change of CR spectrum

Condorelli, DB, Peretti & Petrera PRD 2023



Neutrinos computed from in-source interactions and extragalactic propagation

The importance of a **multimessenger approach, within a source-model scenario**:

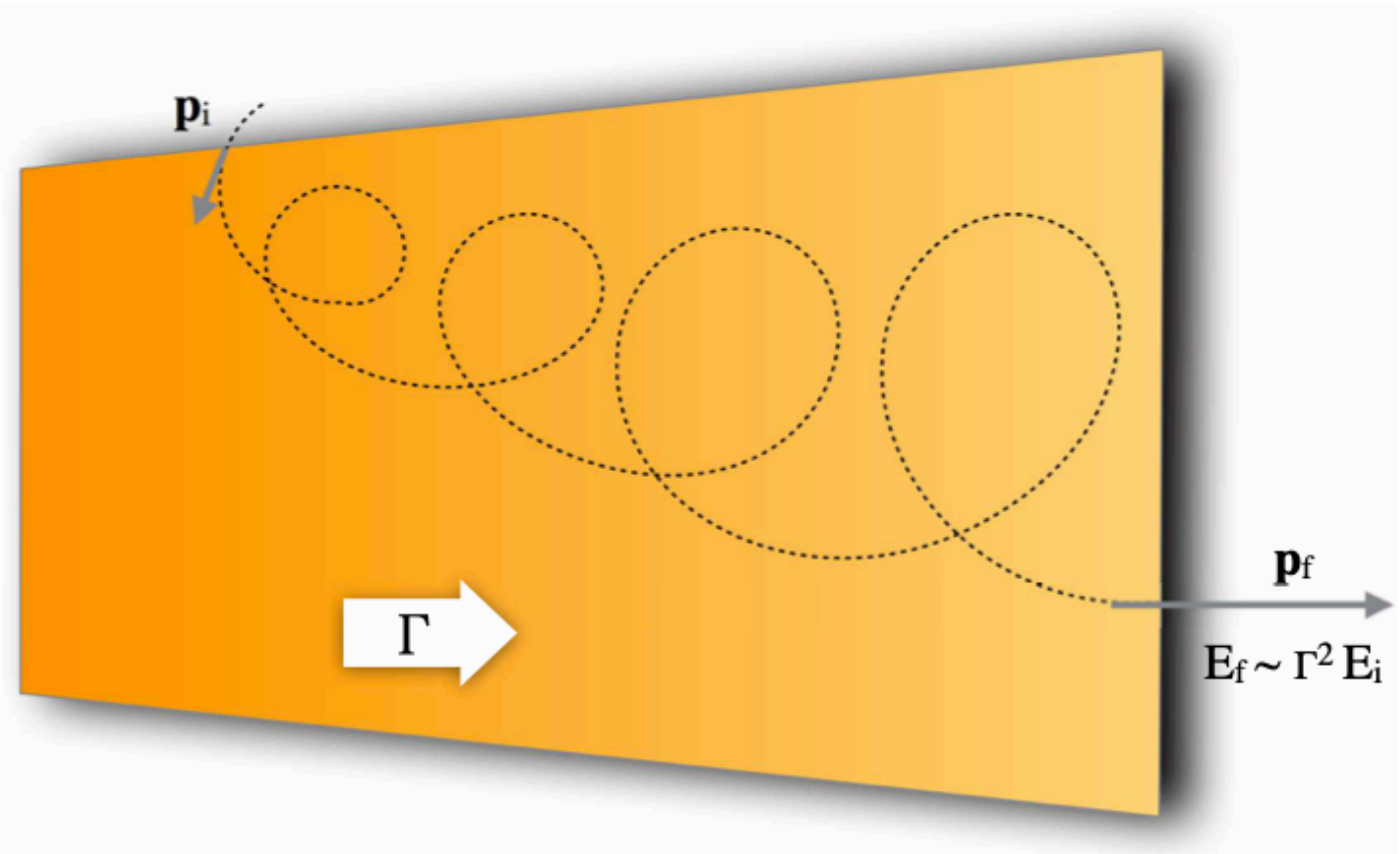
- The cosmogenic neutrinos cannot reach the measurement level
- The contribution of in-source interactions can be investigated
  - the intensity of the photon field can be related to the neutrino flux, as well as the <u>sub-ankle nucleons</u>
  - The interactions responsible for the neutrino flux can be distinguished

ABOUT THE NUCLEAR SPECIES

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

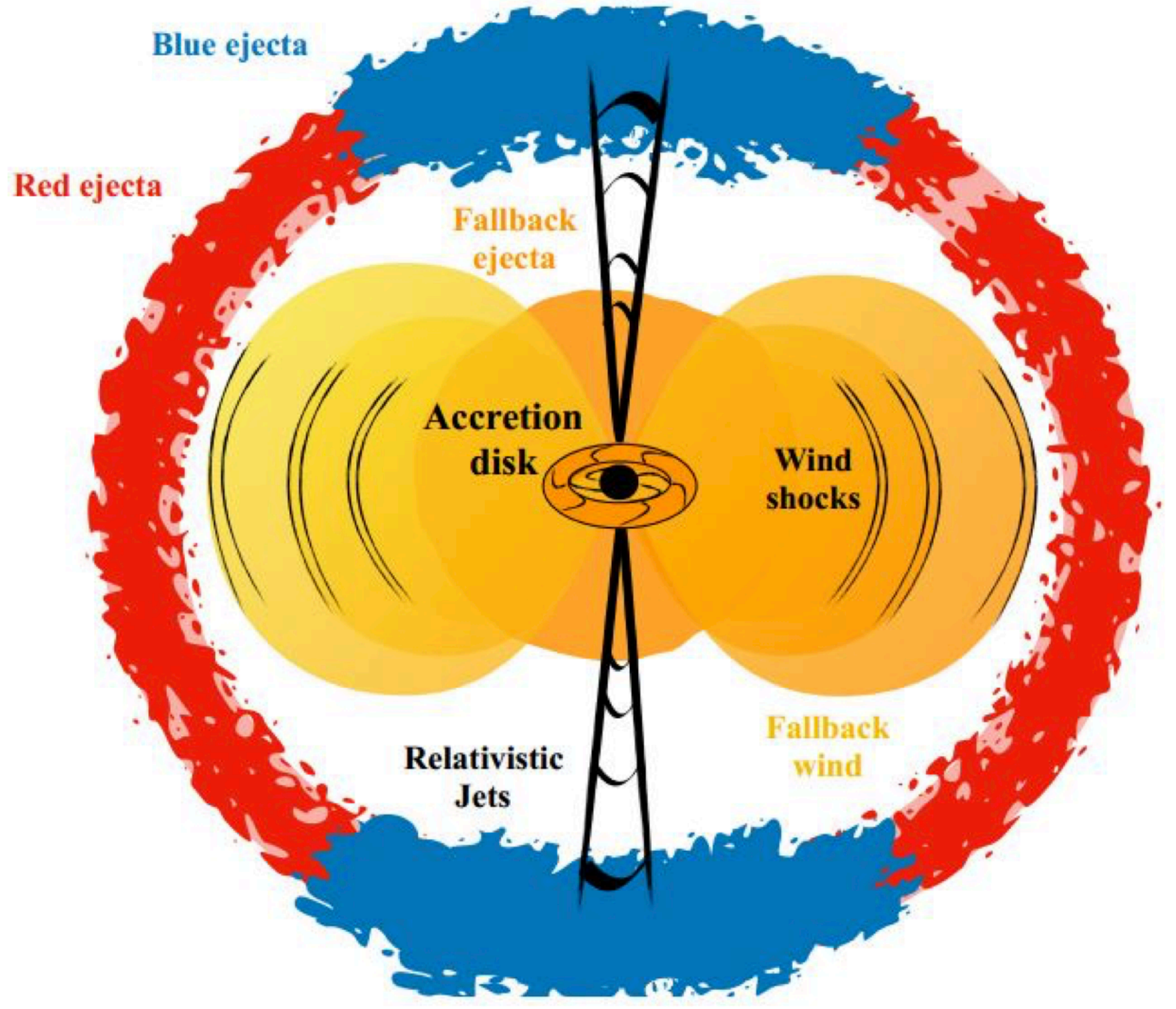


- Seed galactic CRs with energies of 10^{17} eV that penetrate the jet sideways receive a "one-shot" boost of a factor of Γ^2 in energy (**Caprioli ApJL 2015**)
- Chemical composition of Galactic-like CRs?

Binary-neutron-star mergers

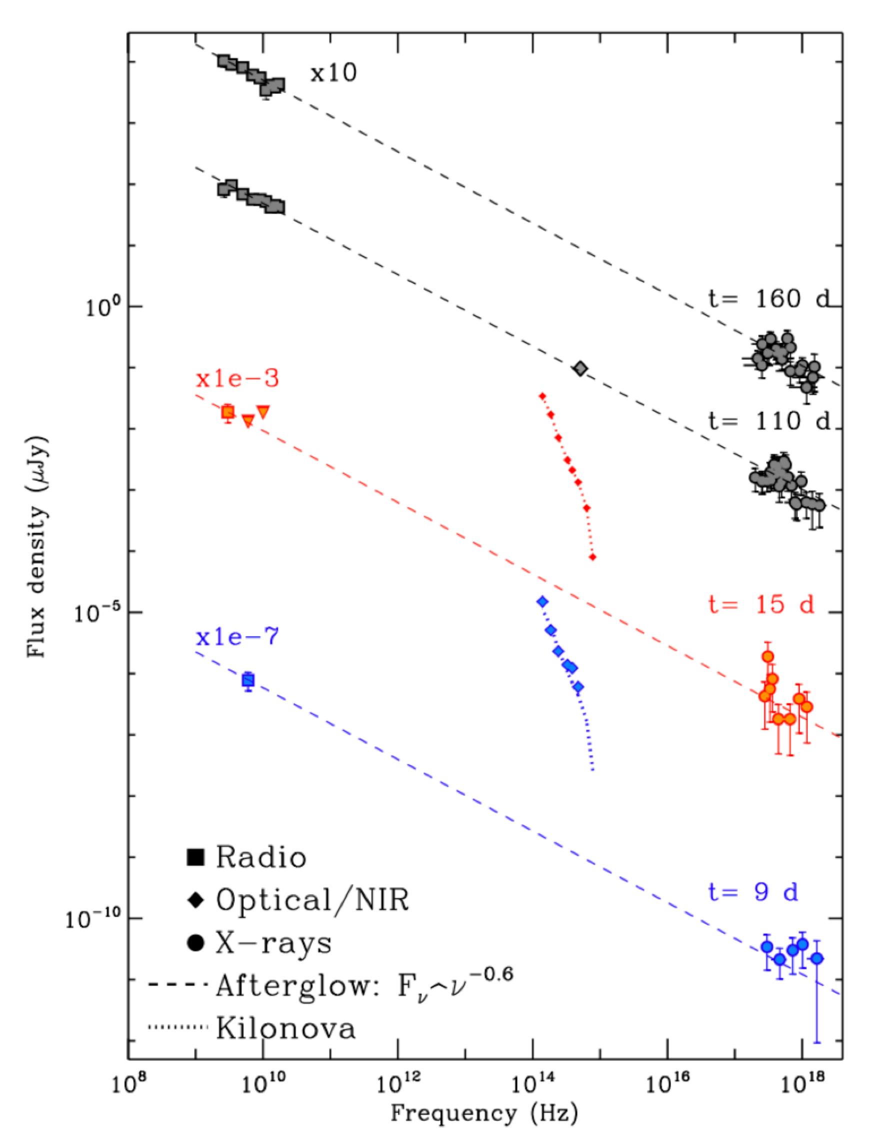
- Acceleration site in BNS merger: short gamma-ray burst generated thanks to the formation of the black hole with relativistic jet powered by accreting material (see Blasi et al ApJL 2000; Arons ApJ 2003; Kotera et al JCAP 2015 for discussion about survival of nuclei)

- **Alternative** acceleration site in the BNS: a fraction of the ejected material can fall back to the central compact object produced after the merger. This fallback outflow encounters the earlier ejected mass shell producing a shock wave where particles can be accelerated (see Rodrigues, Biehl, DB & Taylor Astropart. Phys. 2019 for discussion on the characteristics of magnetic field and Decoene et al. JCAP 2020; Rossoni, **DB** & Sigl JCAP 2025 for the source model)
    - Thermal photon field -> due to the nuclear decay of the unstable species synthesized in the ejecta by the merger
    - Non-thermal photon field: synchrotron emission
    - Modelling inspired by the electromagnetic counterpart of GW170817

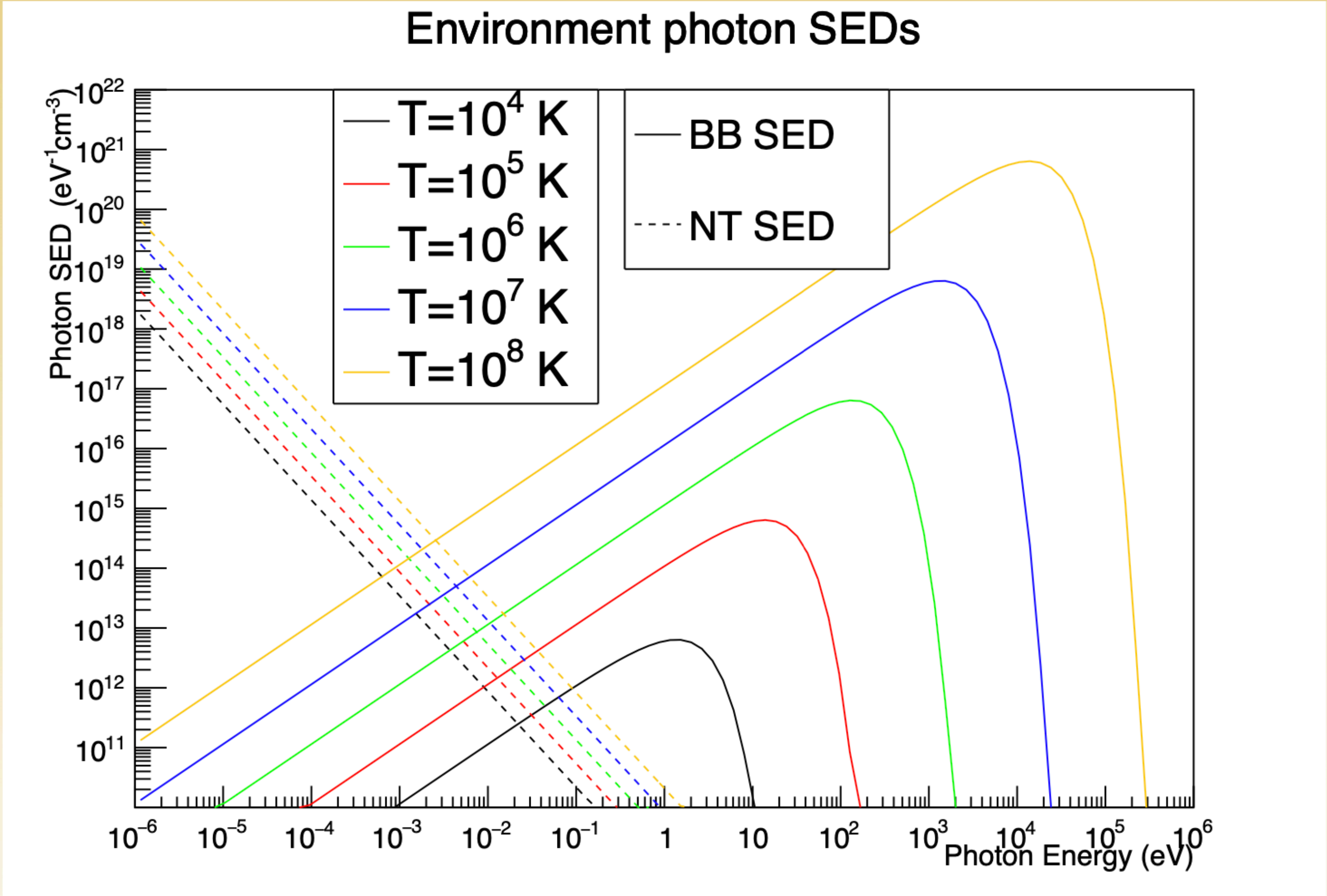


Additional info about UHECR production (see Farrar PRL 2025):

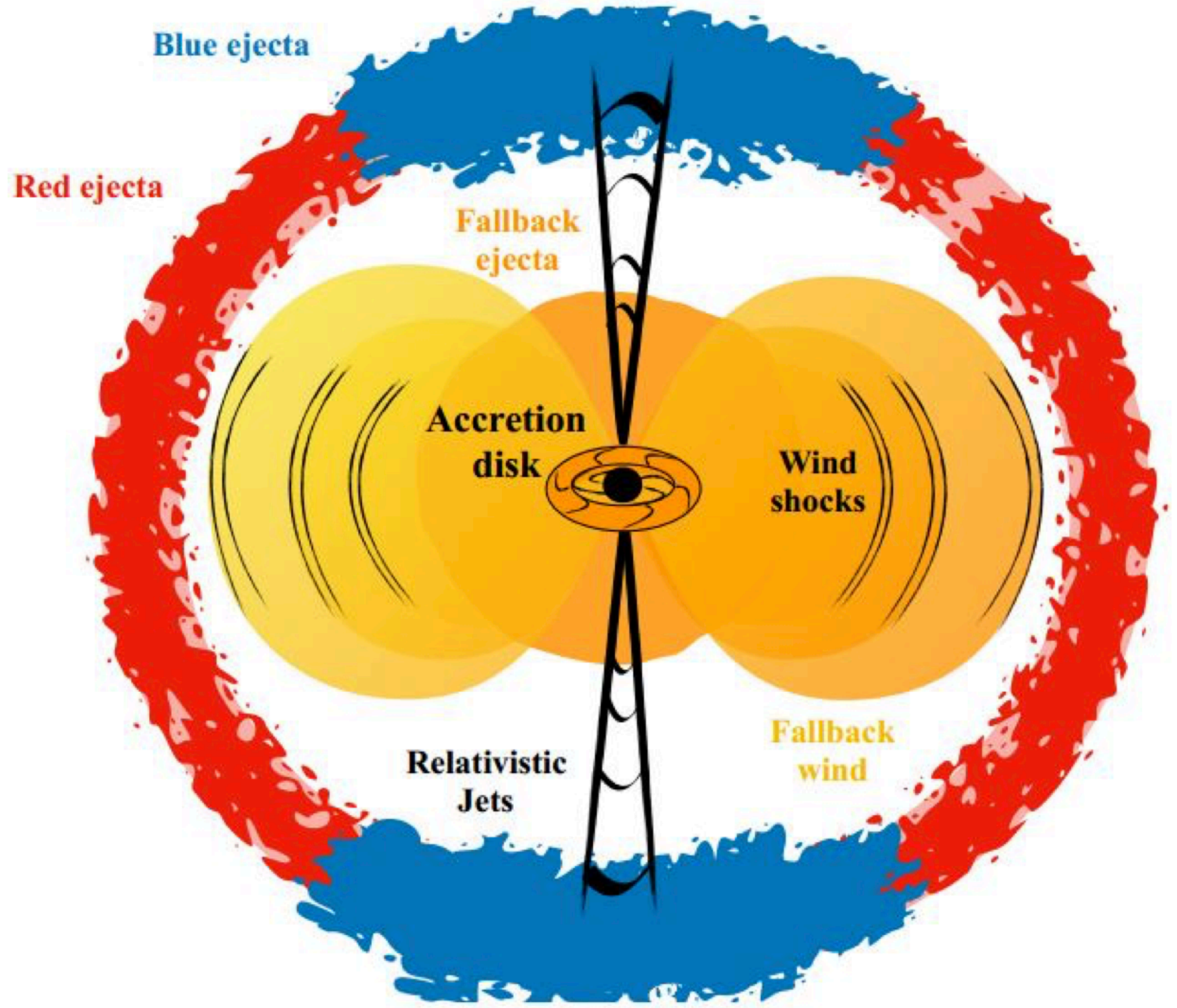
- the merger of two neutron stars with 1.35 solar mass creates a pair of powerful back-to-back jets satisfying the Hillas criterion and Poynting luminosity requirement
- jets of BNS mergers are generated by a gravitationally-driven dynamo and thus are nearly identical due to the narrow range of BNS masses -> narrow rigidity for emitted UHECRs
- **The Amaterasu event could be explained with non-exotic scenarios, for a ultra-heavy nucleus**



R. Margutti et al 2018 ApJL 856 L18



Binary-neutron-star mergers



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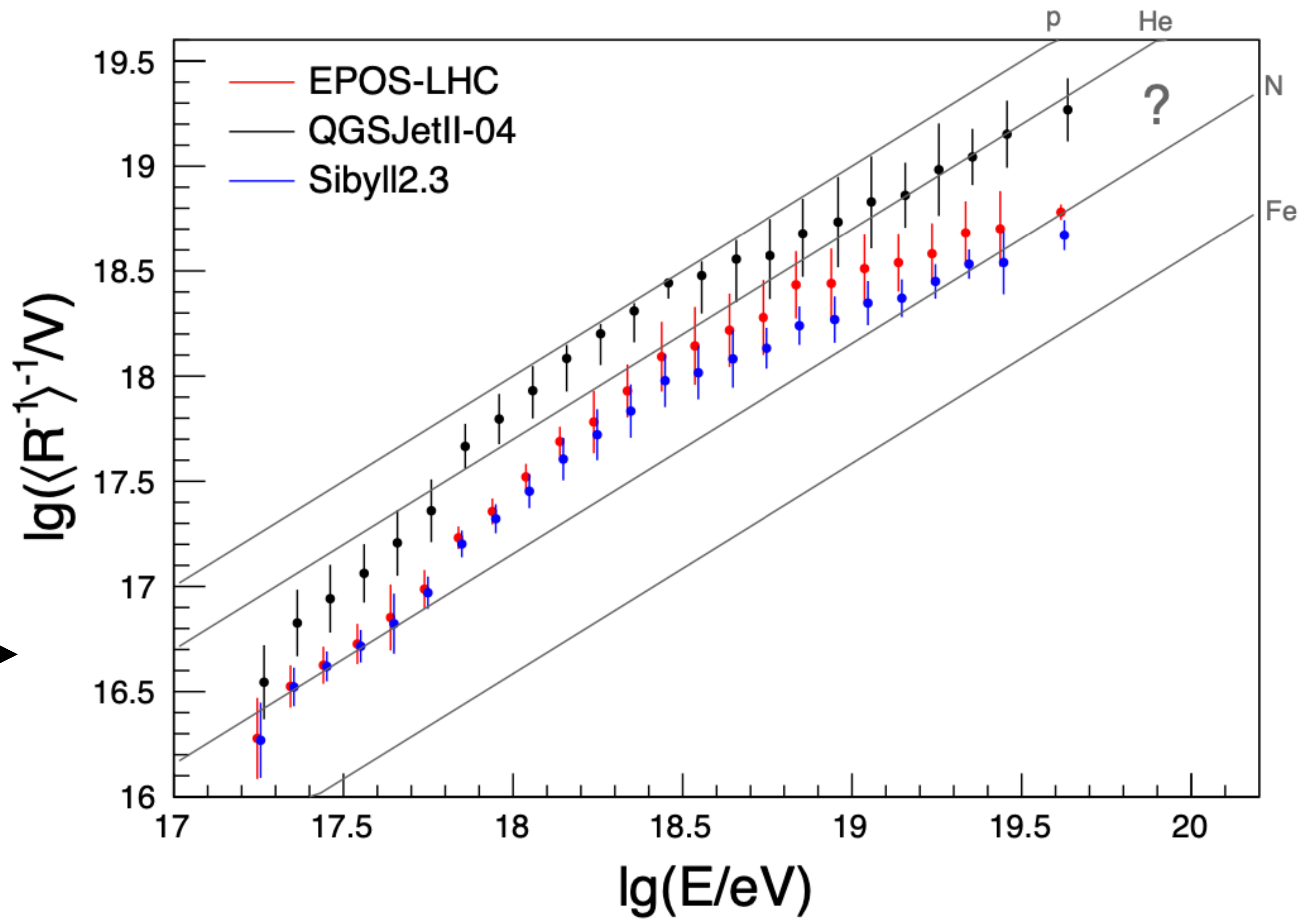


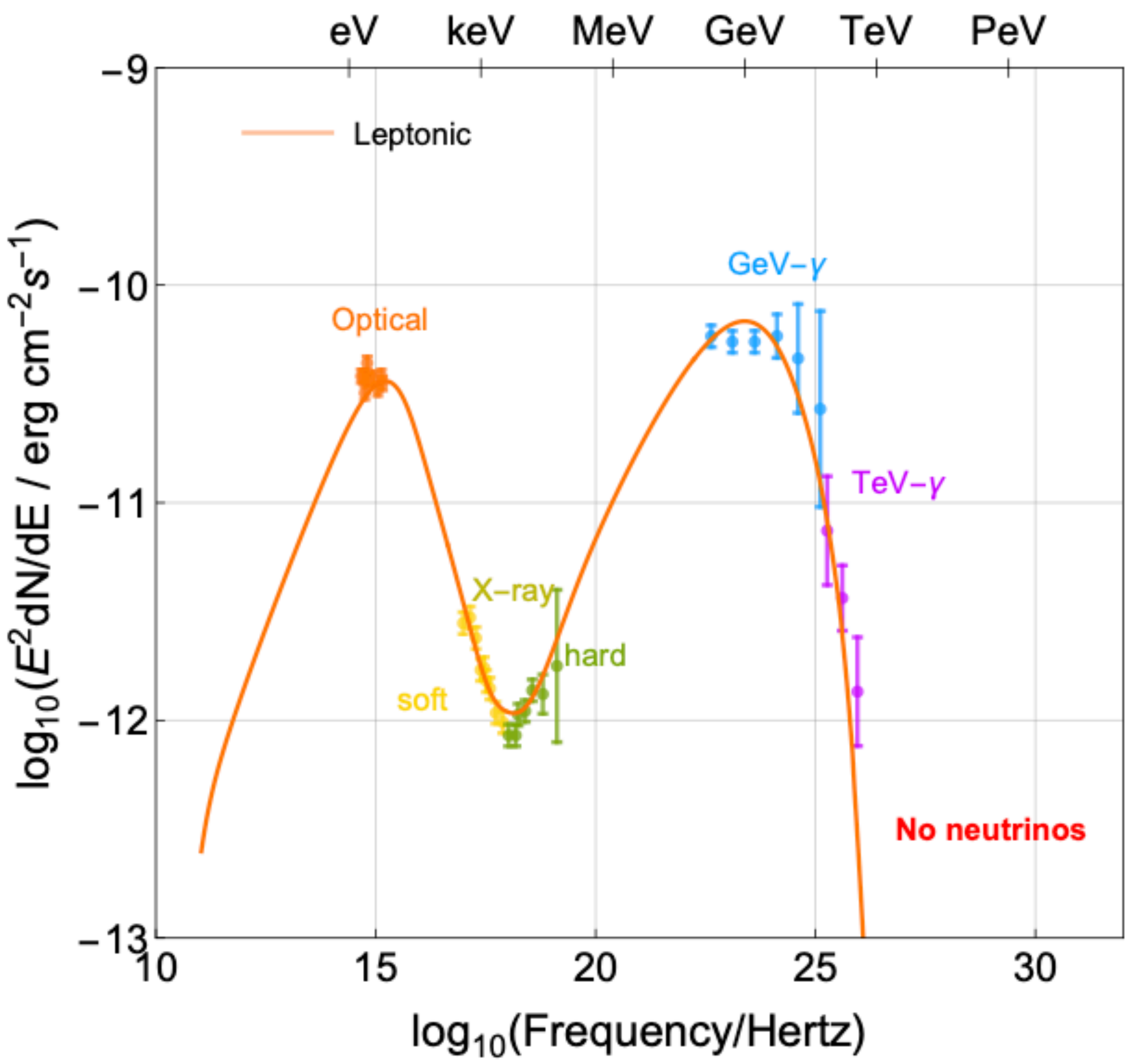
Alves Batista et al, Front.Astron.Space Sci. 2019

WHAT CAN WE LEARN ABOUT UHECRS FROM OTHER MESSENGERS

Active Galactic Nuclei

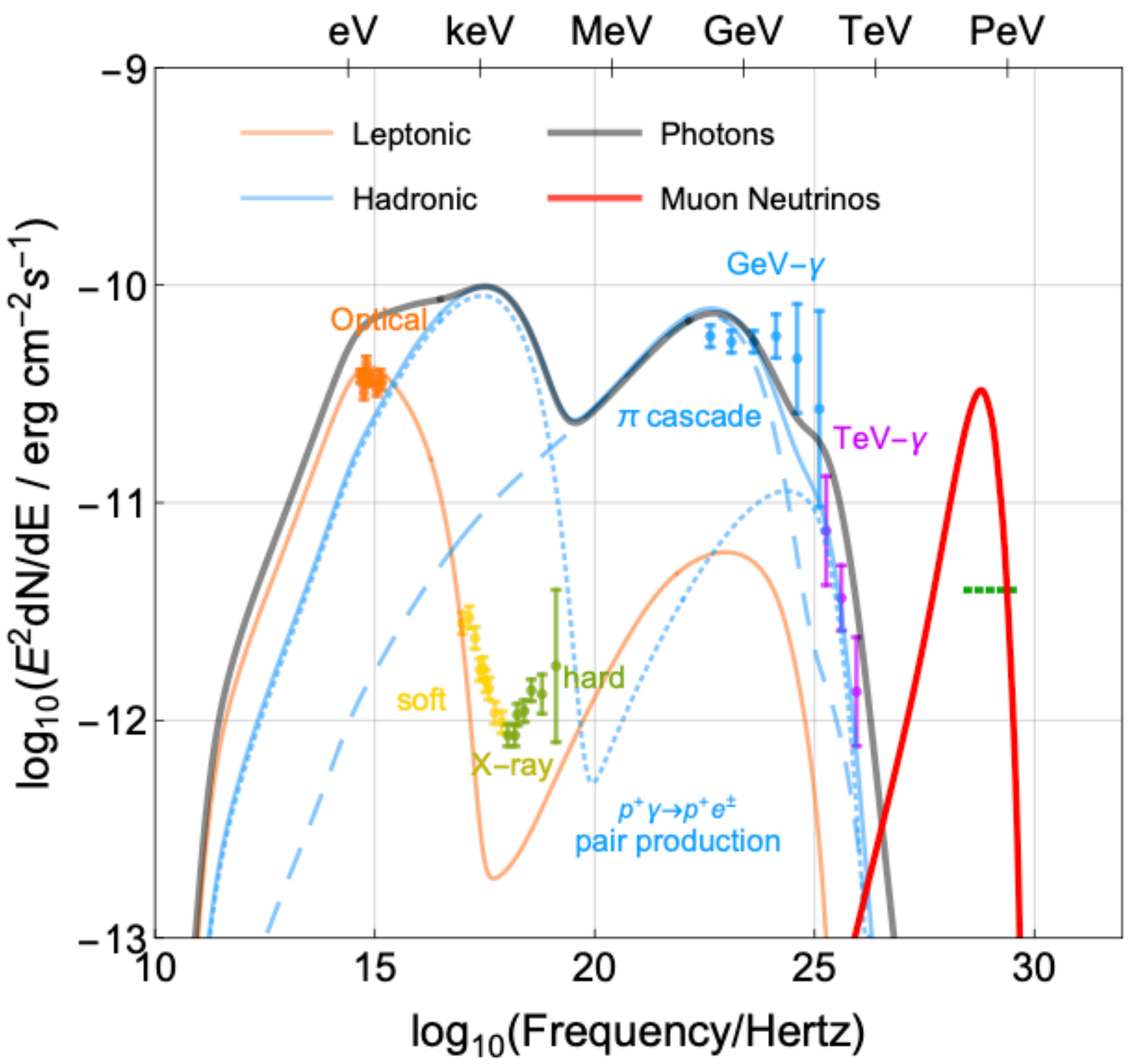
Modelling **TXS0506+056**

Gao et al, Nature Astron. 2019; Cerruti et al MNRAS2019



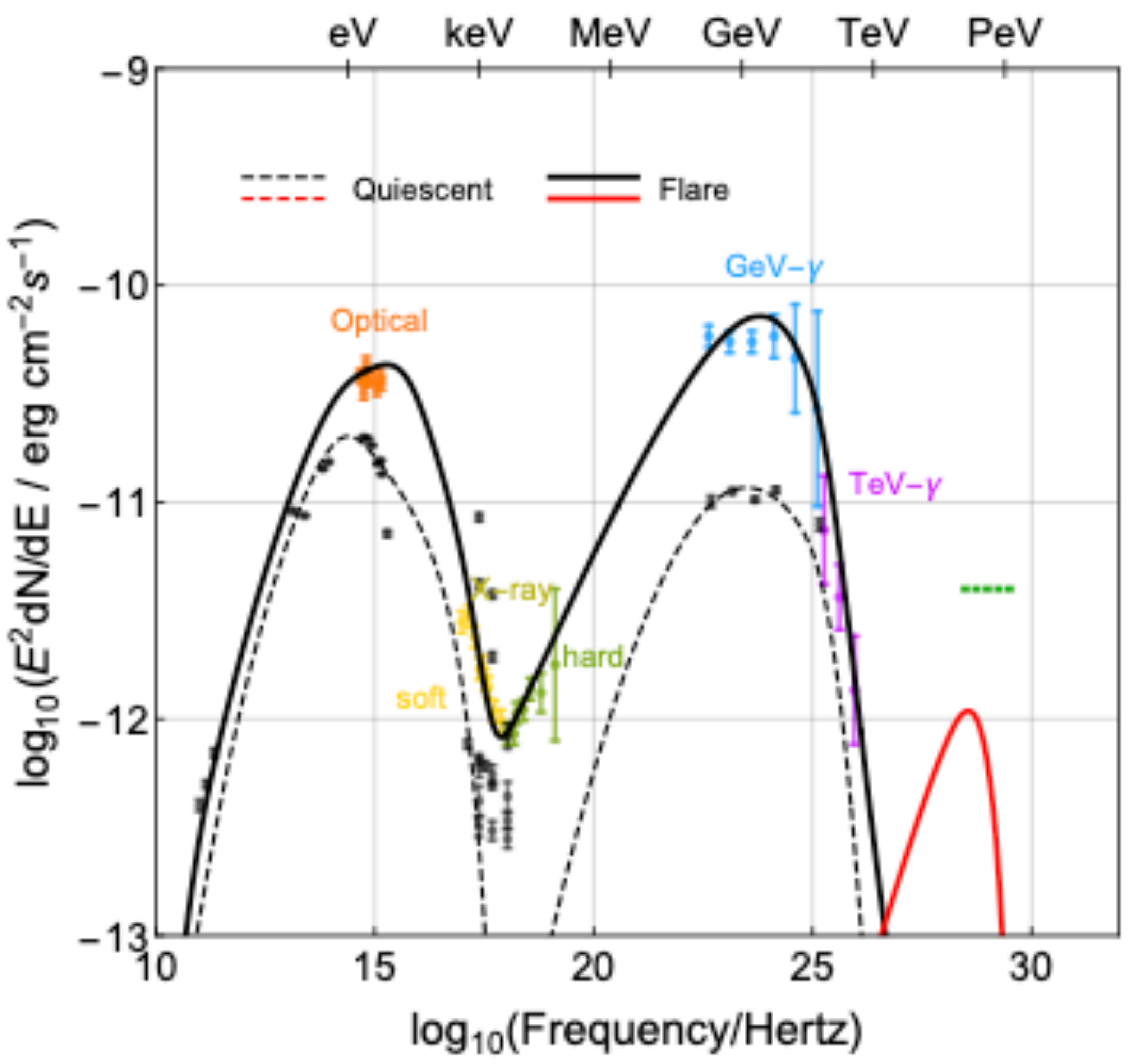
Pure leptonic model reproduces the SED of the source

- No neutrinos predicted



Hadronic model reproduces the second bump and the neutrino

- Overshoots the X-ray flux

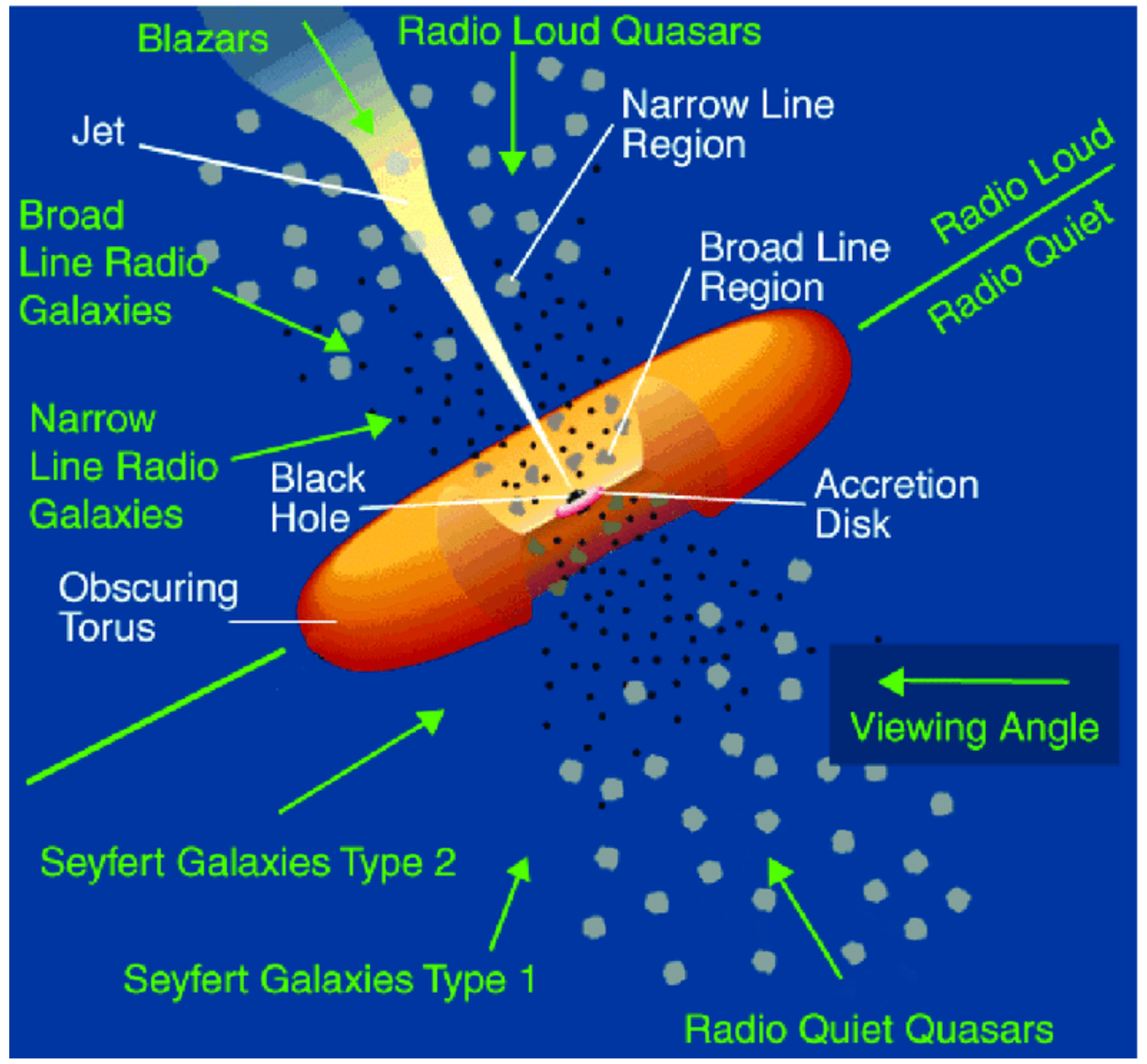


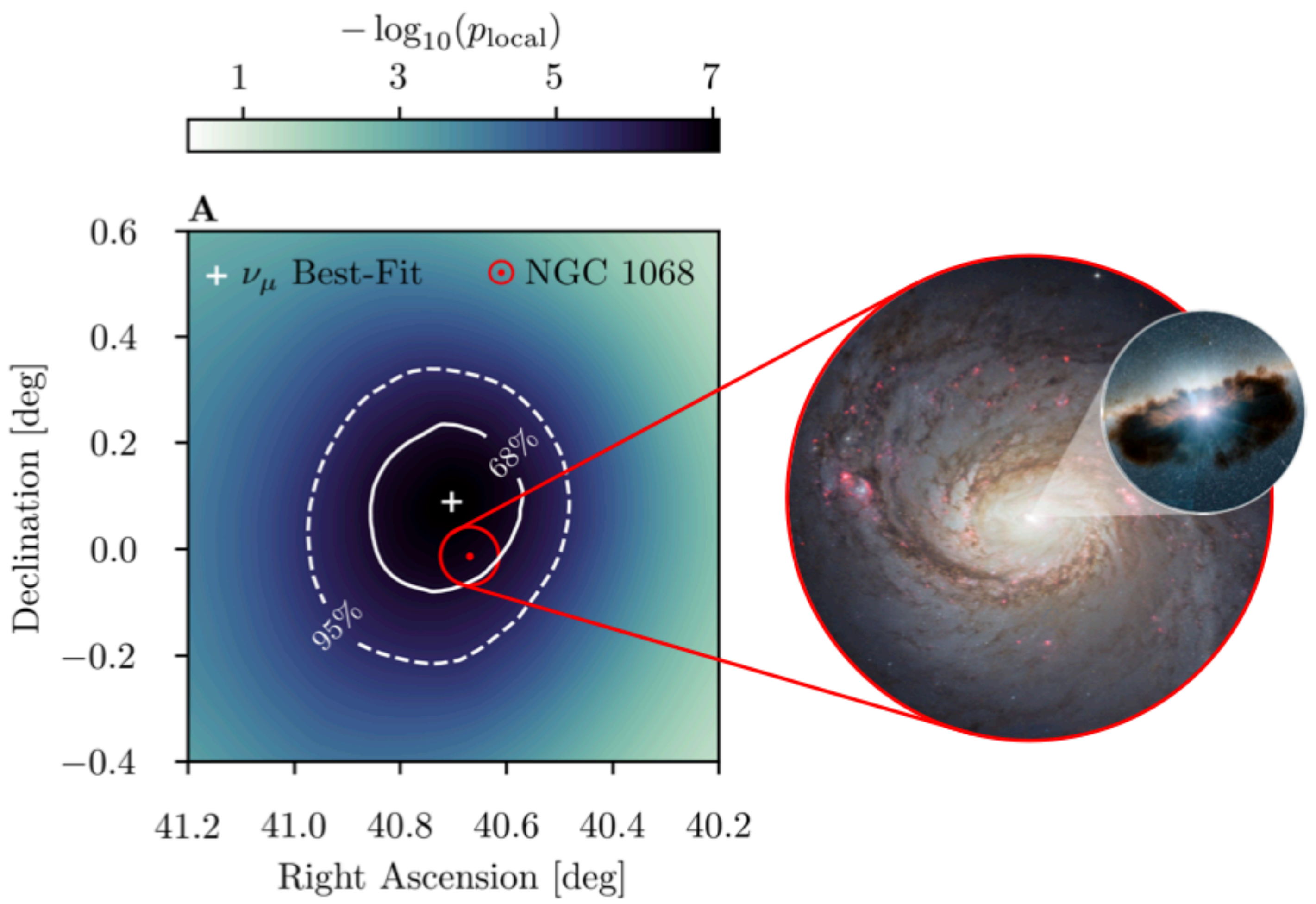
Lepto-hadronic model

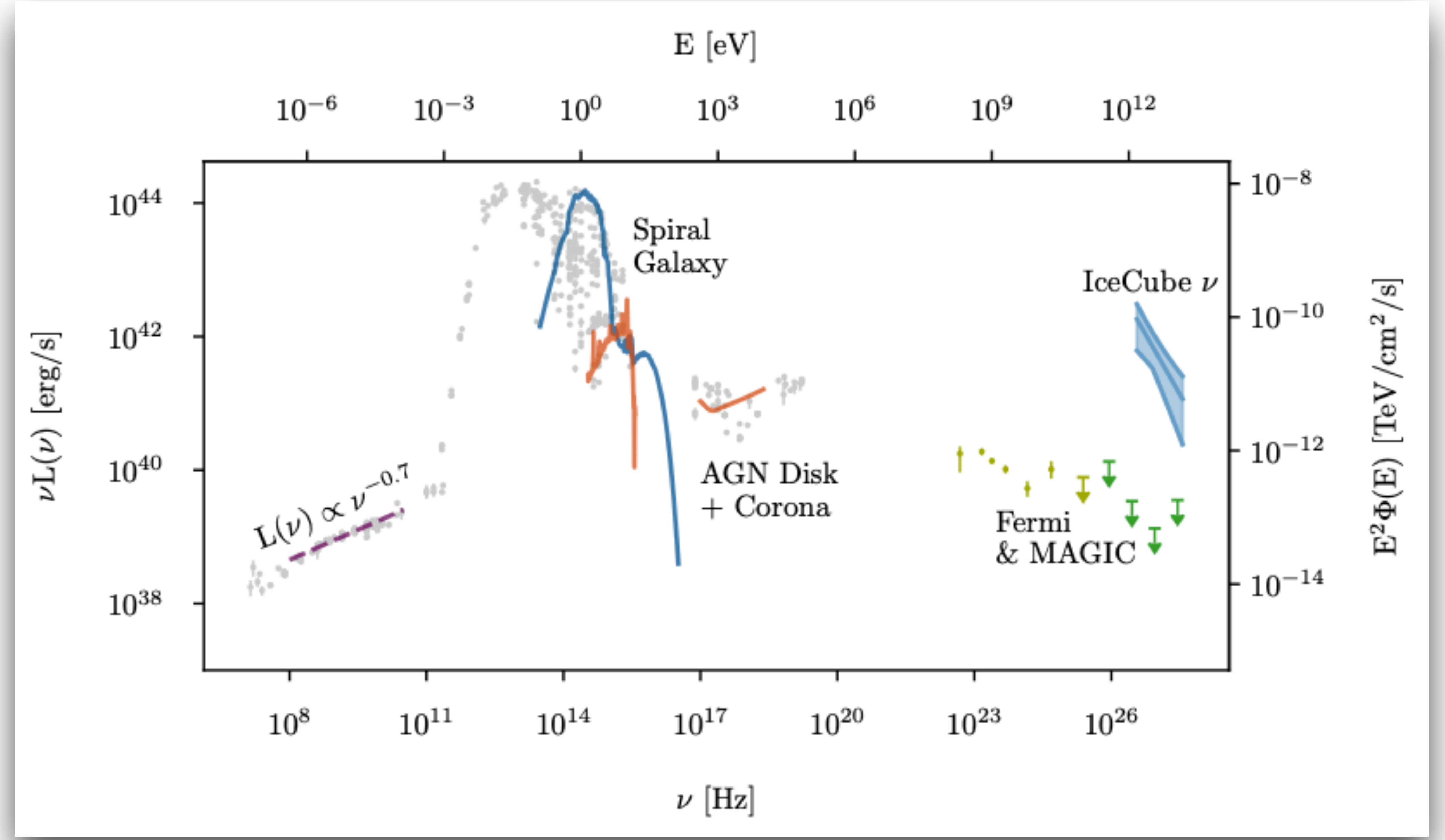
- In-source interactions modeling for the **blazar sequence**: see for instance Murase et al PRD 2014; Rodrigues, Fedynitch, Gao, **DB** & Winter ApJ 2018
- For the **modeling of the spectral energy distribution** of jetted active galactic nuclei see Cerruti et al. arxiv:2411.14218 (comparison of 5 hadronic codes in the market)

Active Galactic Nuclei

- 79 neutrino IceCube events associated to NGC1068: Seyfert II AGN
- Neutrino observations cannot distinguish the emission zone (as well as for the other associations)







- No intense gamma-ray flux
- X-ray emission associated to corona (very hot ($T \approx 10^9$ K) electrons inverse Compton scatter the UV photons from the accretion disc thereby producing X-ray photons), as also in Murase et al PRL2020

$L_{\rm radio}$ (1.4 GHz)	$L_{\rm FIR}$ (8 – 1000 μm)	$L_{\rm x}$ (2 – 10 keV)	L_γ (0.1 – 100 GeV)	L_ν (1.5 – 15 TeV)	$L_{\rm Edd}$
$10^{38.9}$	$10^{44.6\pm0.1}$	$10^{43.4\pm0.3}$	$10^{40.92\pm0.03}$	$10^{42.1\pm0.2}$	$10^{44.9\pm0.3}$ [a]

measured

$L_{\rm kin}$	$L_{\rm jet}$	$L_{\rm bol}$	$L_{\rm bol}/L_{\rm Edd}$
$10^{41.6\pm1.0}$	$10^{42.9\pm1.0}$	$10^{44.7\pm0.5}$	$10^{-0.3\pm0.6}$

derived

Component	Scale	L_γ (0.1 – 100 GeV)	L_ν (1.5 – 15 TeV)
Star formation	$>$ kpc	$\sim 10^{40.9}$	$\lesssim 10^{40.1}$
Jet	$\sim$ kpc	$< 10^{41.7}$ (M87-like)	$< 10^{40.9}$
Outflow (UFO)	$\sim$ pc	$< 10^{41.2}$	$< 10^{40.4}$
BH vicinity	~ 0.03 mpc ($\sim 50\ R_s$)	?	?
	Total	$\lesssim 10^{41.9}$	$\ll 10^{41.1}$
	Observed	$10^{40.92\pm0.03}$	$10^{42.1\pm0.2}$

derived, with some assumptions

Padovani et al, Nature Astron. 2024; A&A 2024

Active Galactic Nuclei

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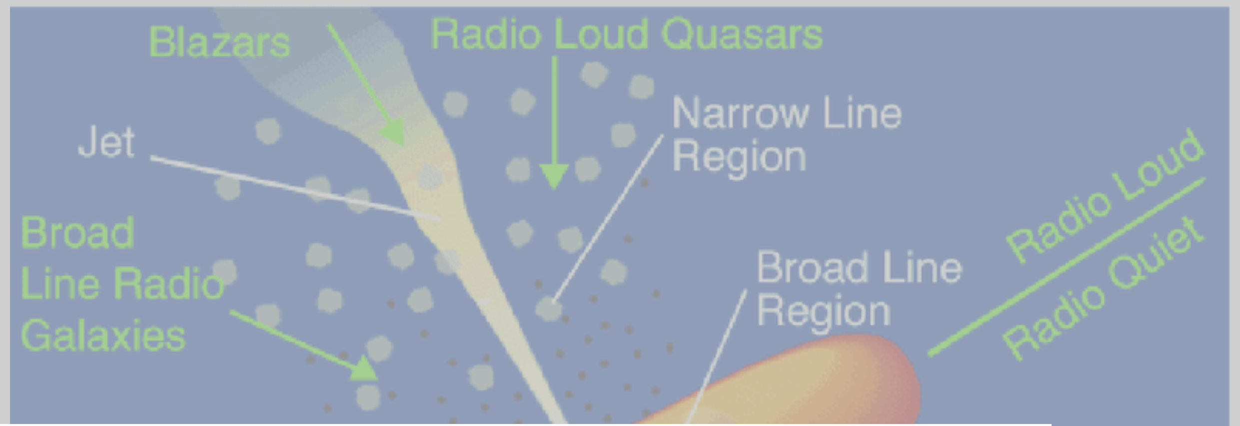

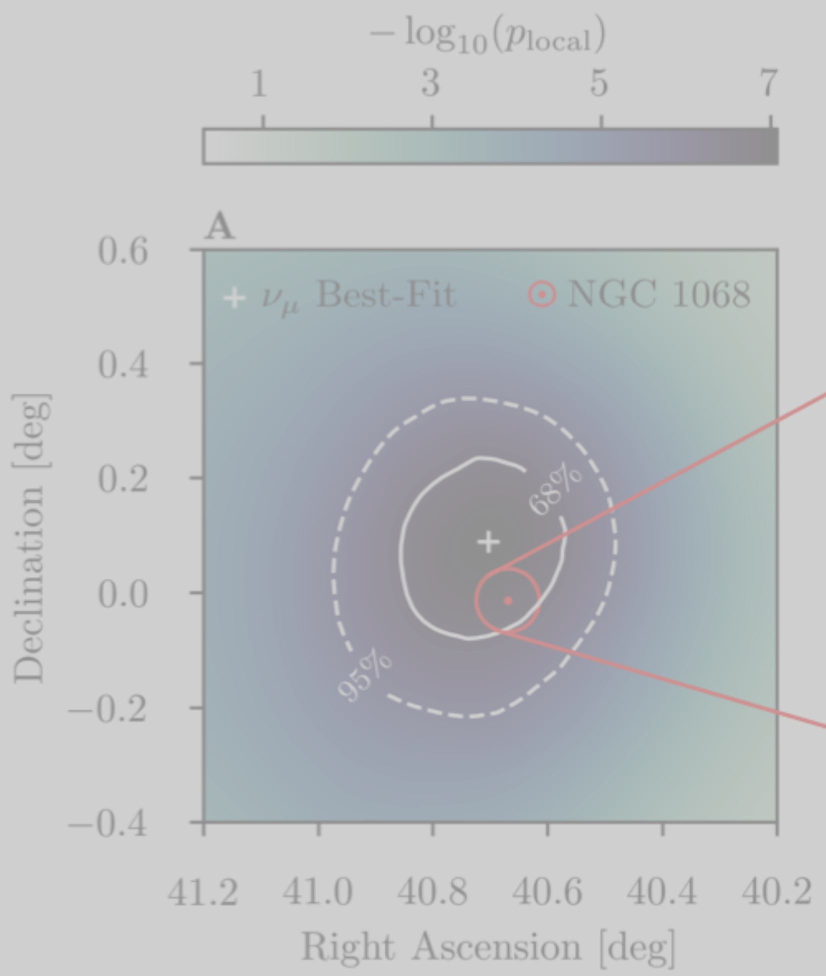

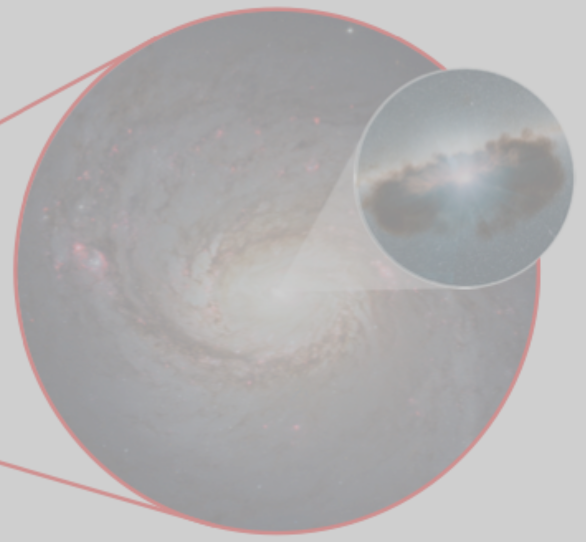

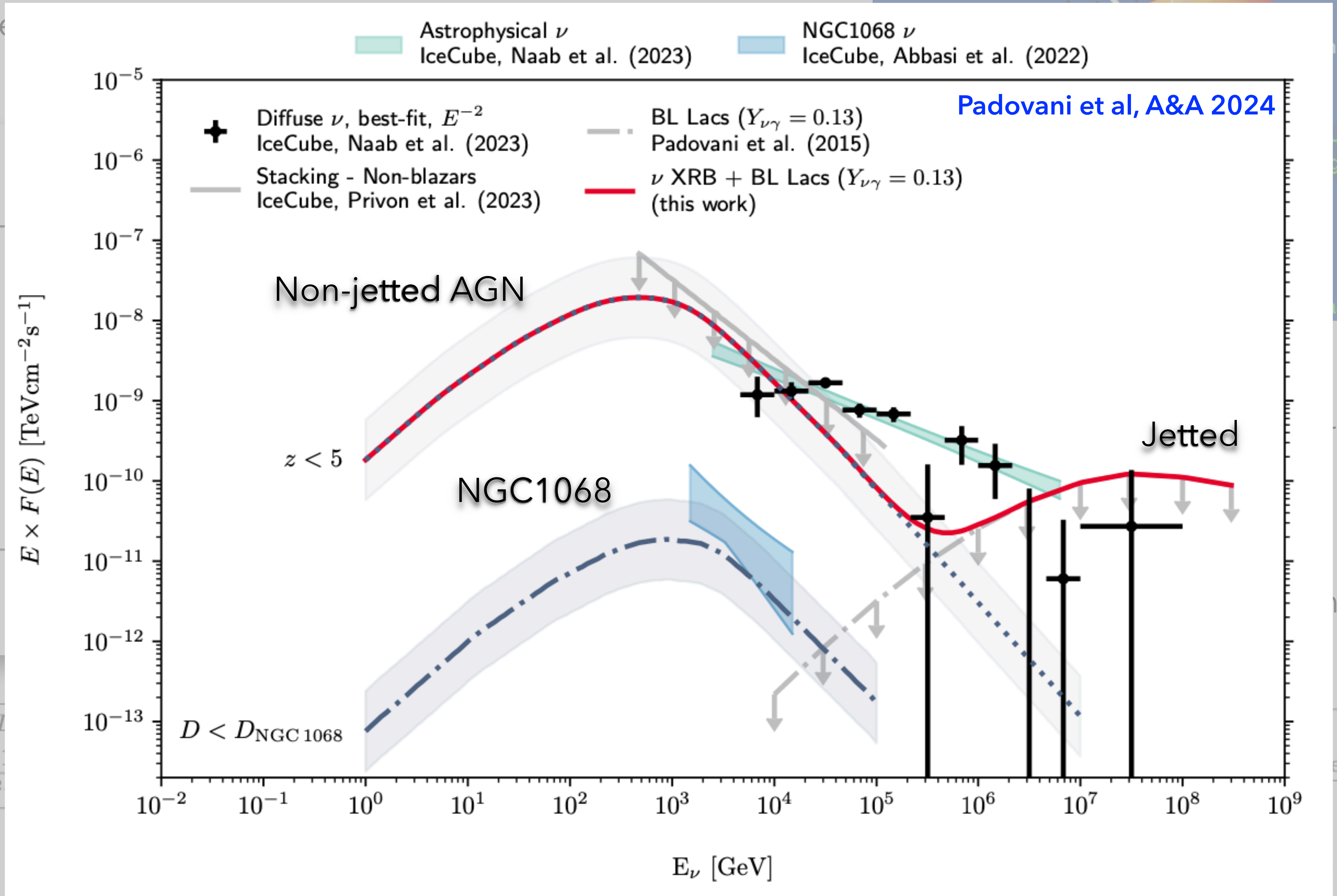

L_{radio} (1.4 GHz)	L_{FIR} (8 – 1000 μm)	L_x (2 – 10 keV)	L_γ (0.1 – 100 GeV)	(1.5 –
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derived

rona

ns),

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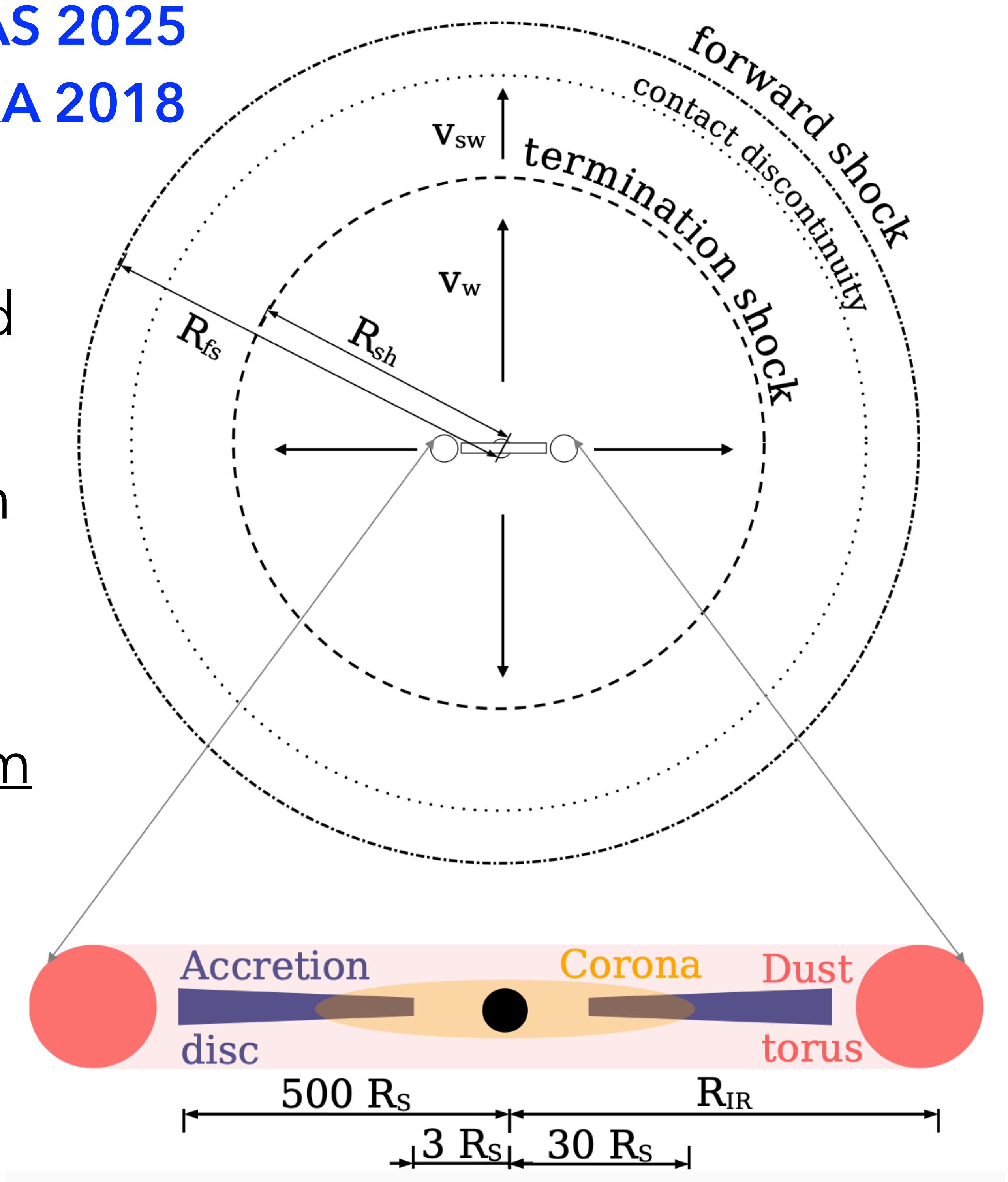
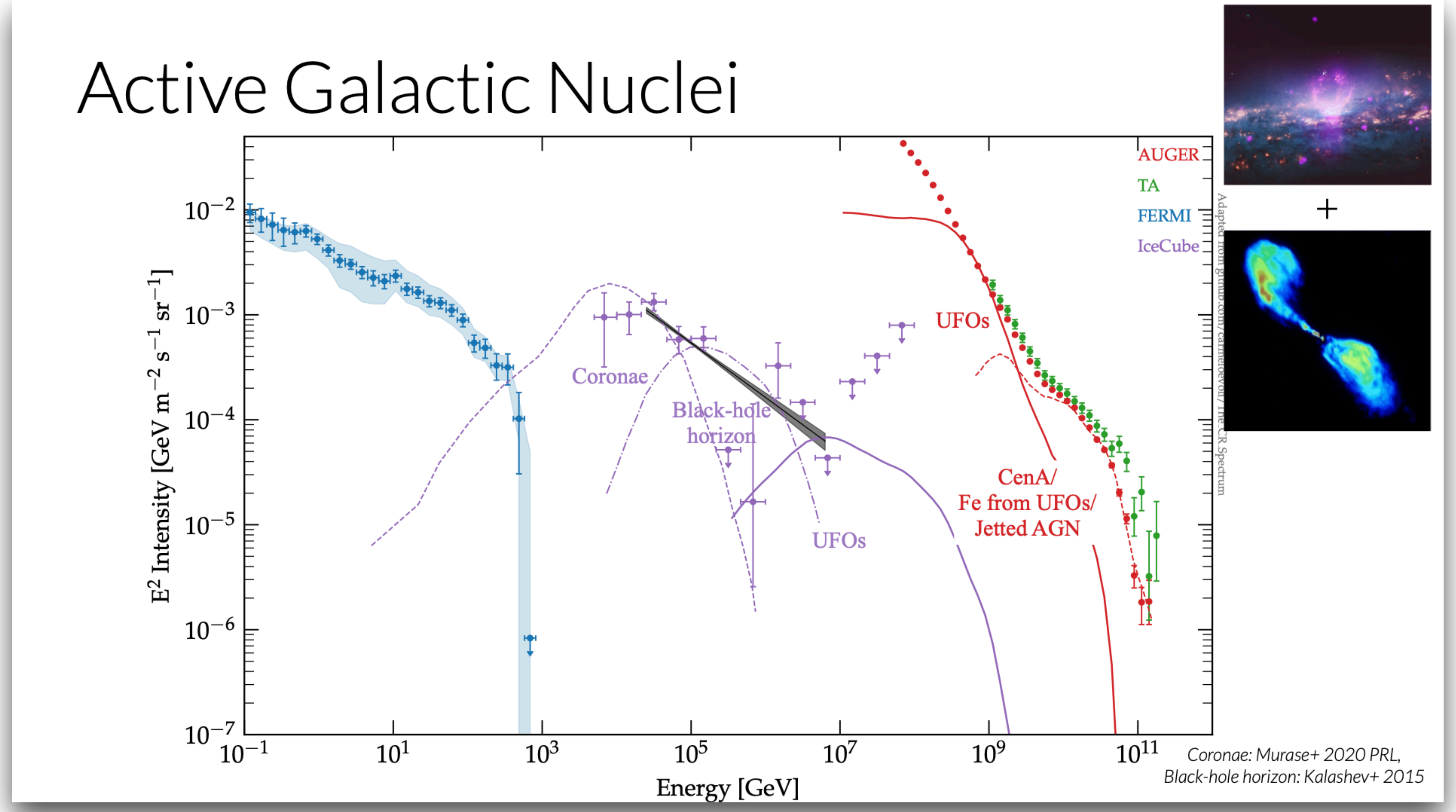
Active Galactic Nuclei

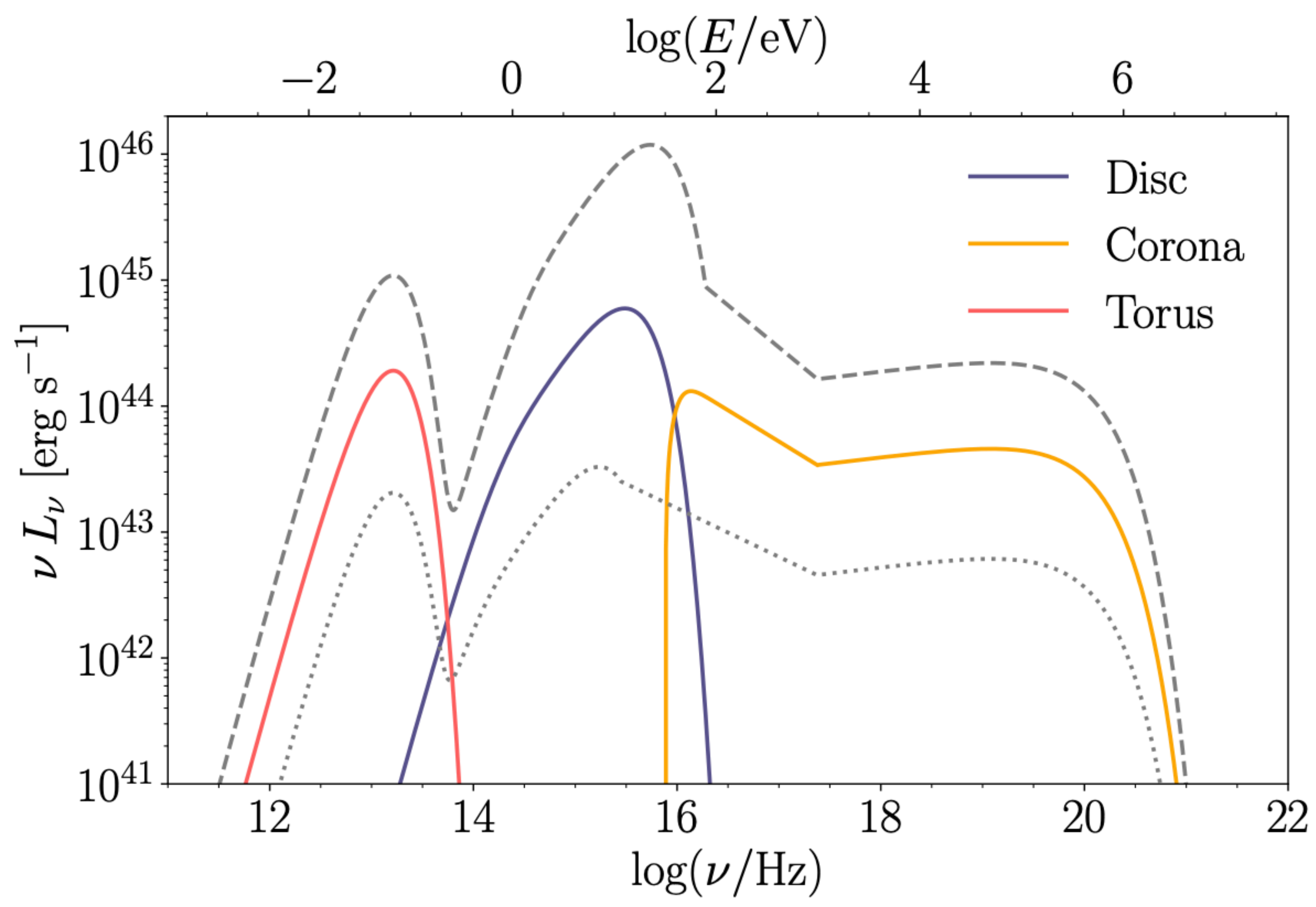
Ehlert et al. MNRAS 2025
Lamastra et al. A&A 2018

- AGN not only accrete matter to sustain their activity, but show also **large-scale outflows/winds (ultra-fast outflow, UFO)** of matter driven by the central BH, which are both less collimated (wide-angle) and slower than relativistic jets
- Velocities ranging from ~ 10^2 km s^{-1}, typical of warm absorbers, up to semi-relativistic speeds ~ 10^5 km s^{-1} for ultra fast outflows, and are observed at different spatial scales (sub-pc to kpc) and ionization states
- <u>The hot corona could contribute to low-energy neutrinos, while at higher energy the contribution from UFOs could emerge (as in the sub-ankle region for UHECRs)</u>





F. Oikonomou
@ UHECR2024



SUMMARY

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 can build source-propagation model and refine the basic scenario suggested by measurements
- 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
    - Main expectation from UHECR observatory upgrades -> **improve the understanding of the mass composition, crucial for UHECR and several multimessenger aspects**

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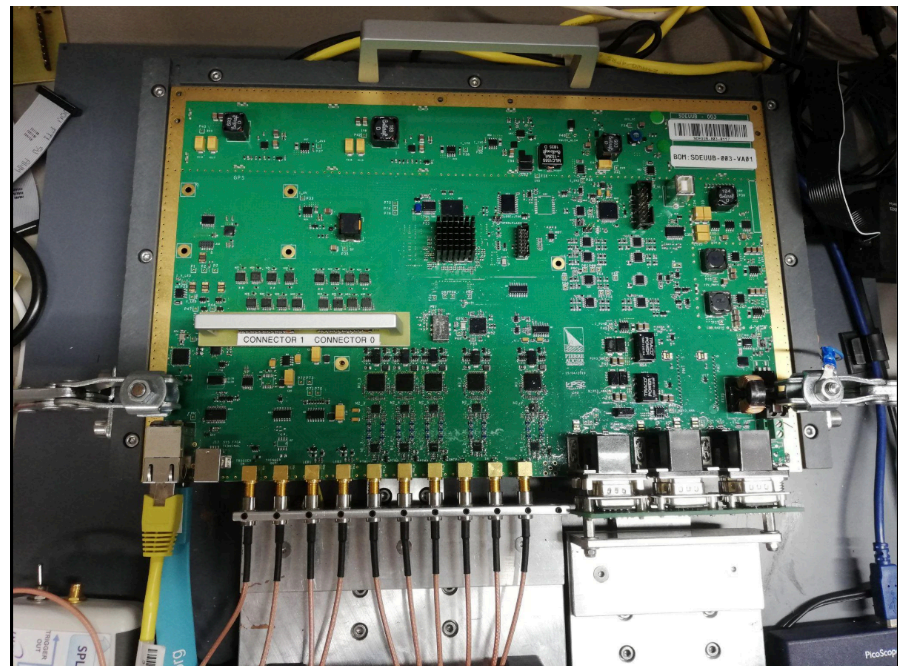
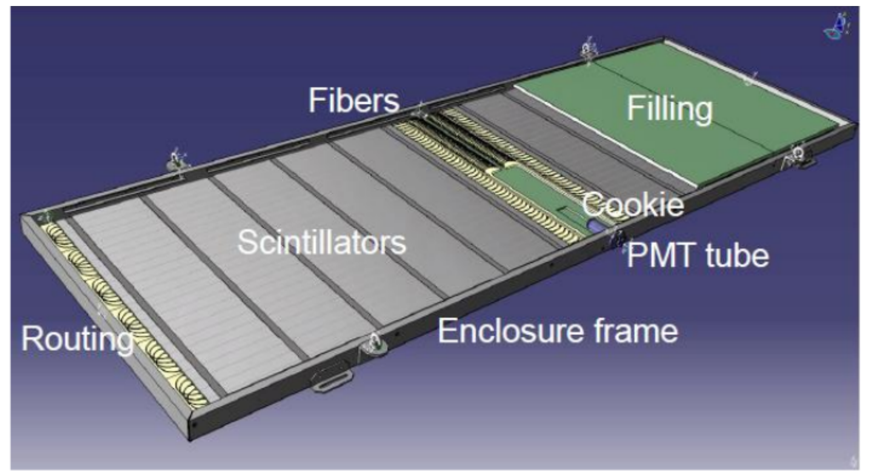
Towards multi-hybrid observations of extensive air showers with **AugerPrime!**

Radio upgrade

New electronics



Scintillators



Underground muon detectors

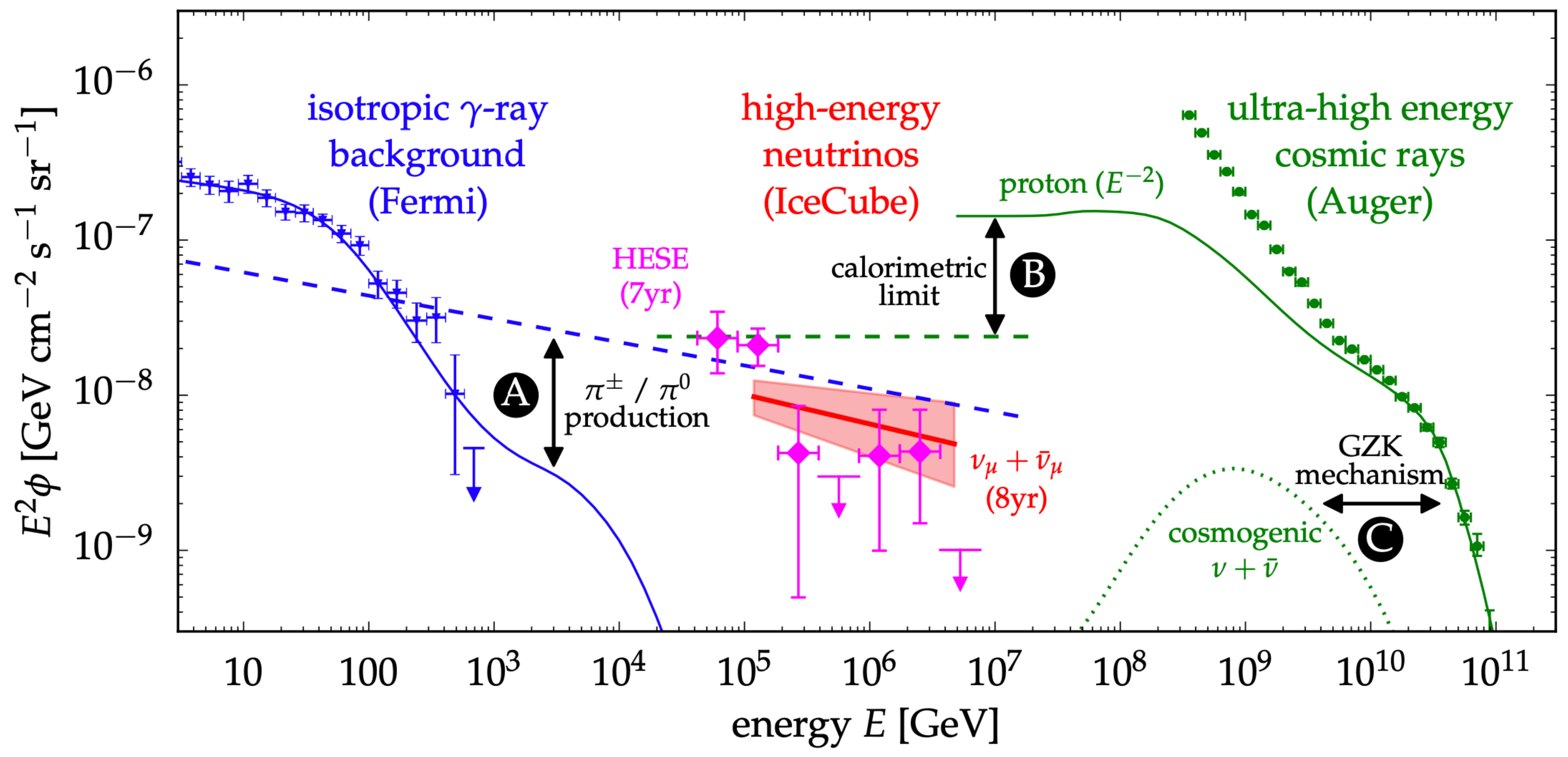
High-dynamic range PMTs

Summary with a multimessenger perspective

- Common origin of different messengers

CR-neutrino-photon connection to be explored beyond simplistic scenario of similar intensity in different messengers

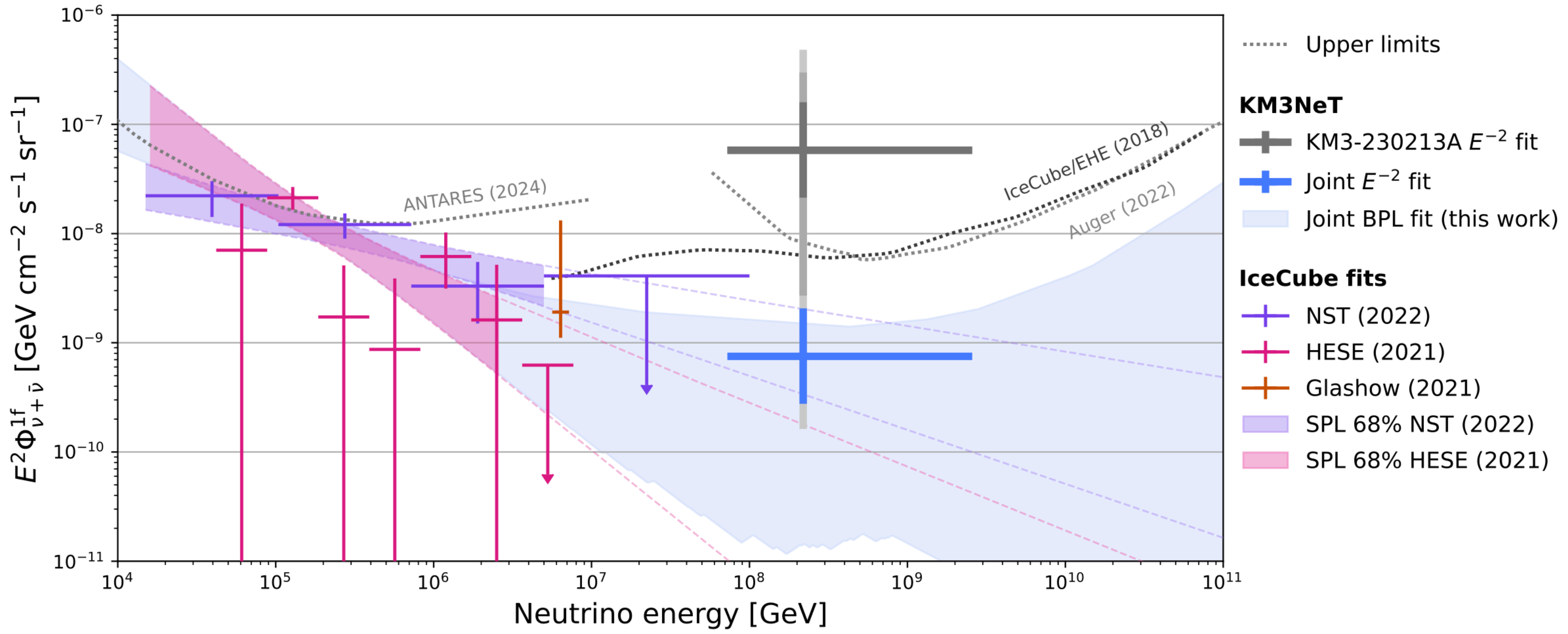
Ahlers EPJ Web Conf 2019



- What about the allowed fraction of protons in UHECRs?
  - Emerging evidence, from source-propagation models, that UHE neutrinos (from sources) are linked to sub-ankle protons

- Cosmogenic vs astrophysical neutrinos
  - Neutrino energy -> maximum rigidity of the CR particle
    - Cosmogenic neutrino -> maximum rigidity of the CR at the escape
    - Astrophysical neutrino -> maximum rigidity of the CR in the source (if the calorimetric condition is satisfied, no direct correspondence of neutrino-CR flux)
  - Neutrino intensity -> spectral index, CR nuclear species, spectral index and maximum energy

KM3NeT Collab. arxiv:2502.08173



corresponding energy of a proton: ankle energy