# Ultra-high energy cosmic rays:

## Insights from the maximum rigidity distribution and the possible role of ultra-fast outflows in active galactic nuclei

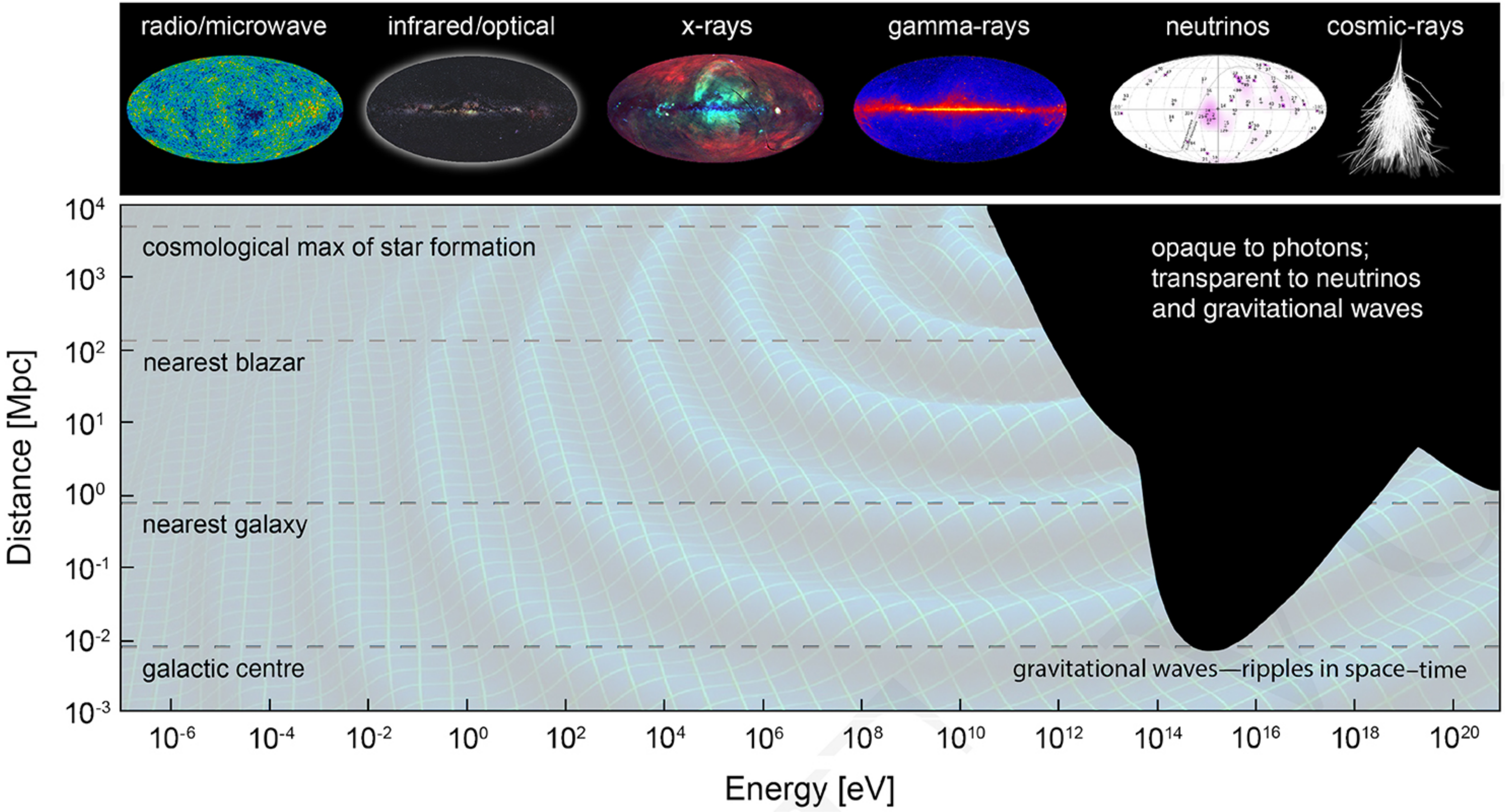
D. Ehlert, FO, M. Unger, PRD 107 (2023) 10

D. Ehlert, FO, E. Peretti, to appear in MNRAS

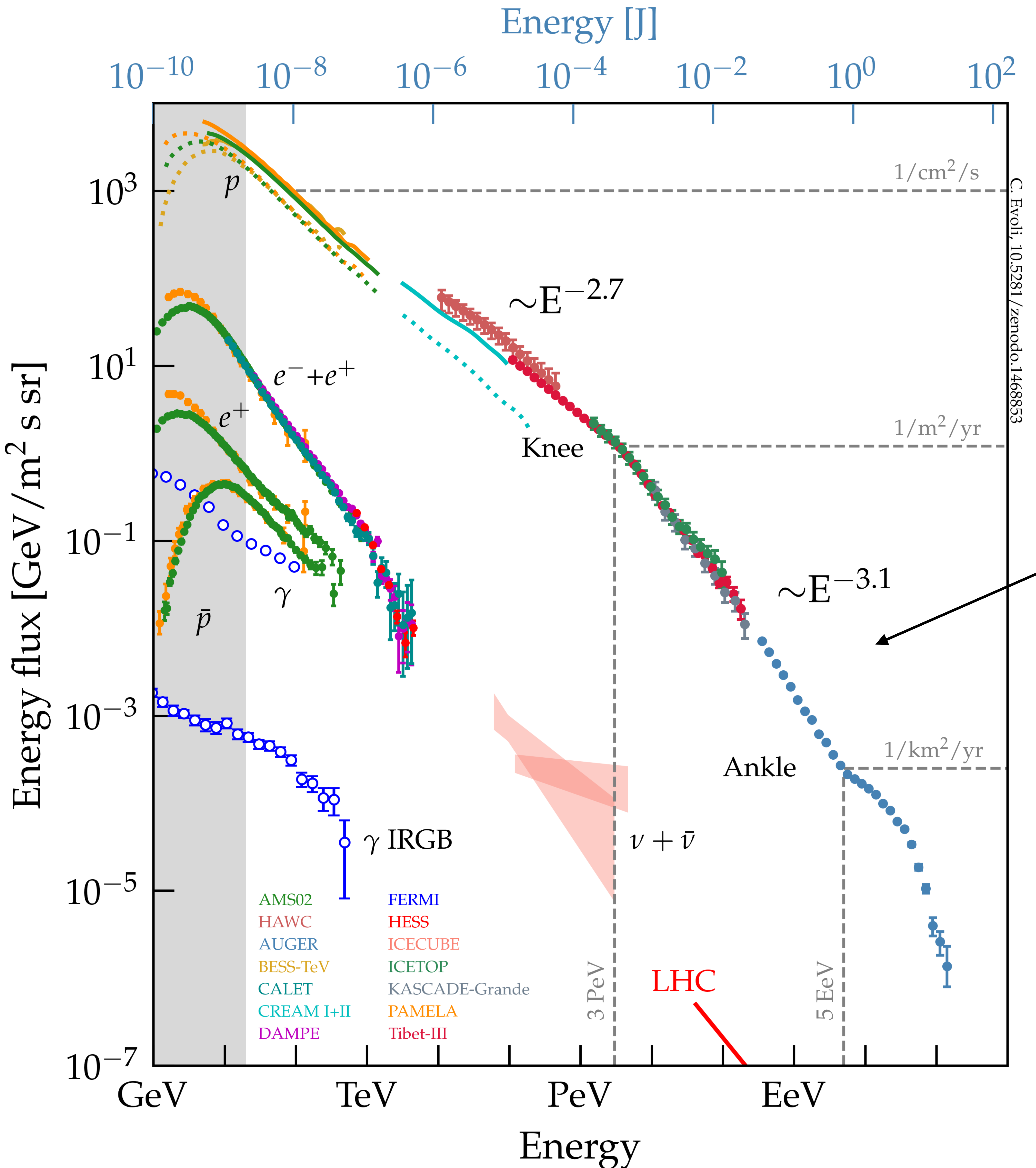
F. Oikonomou, APC Theory Seminar, Dec 3rd 2024

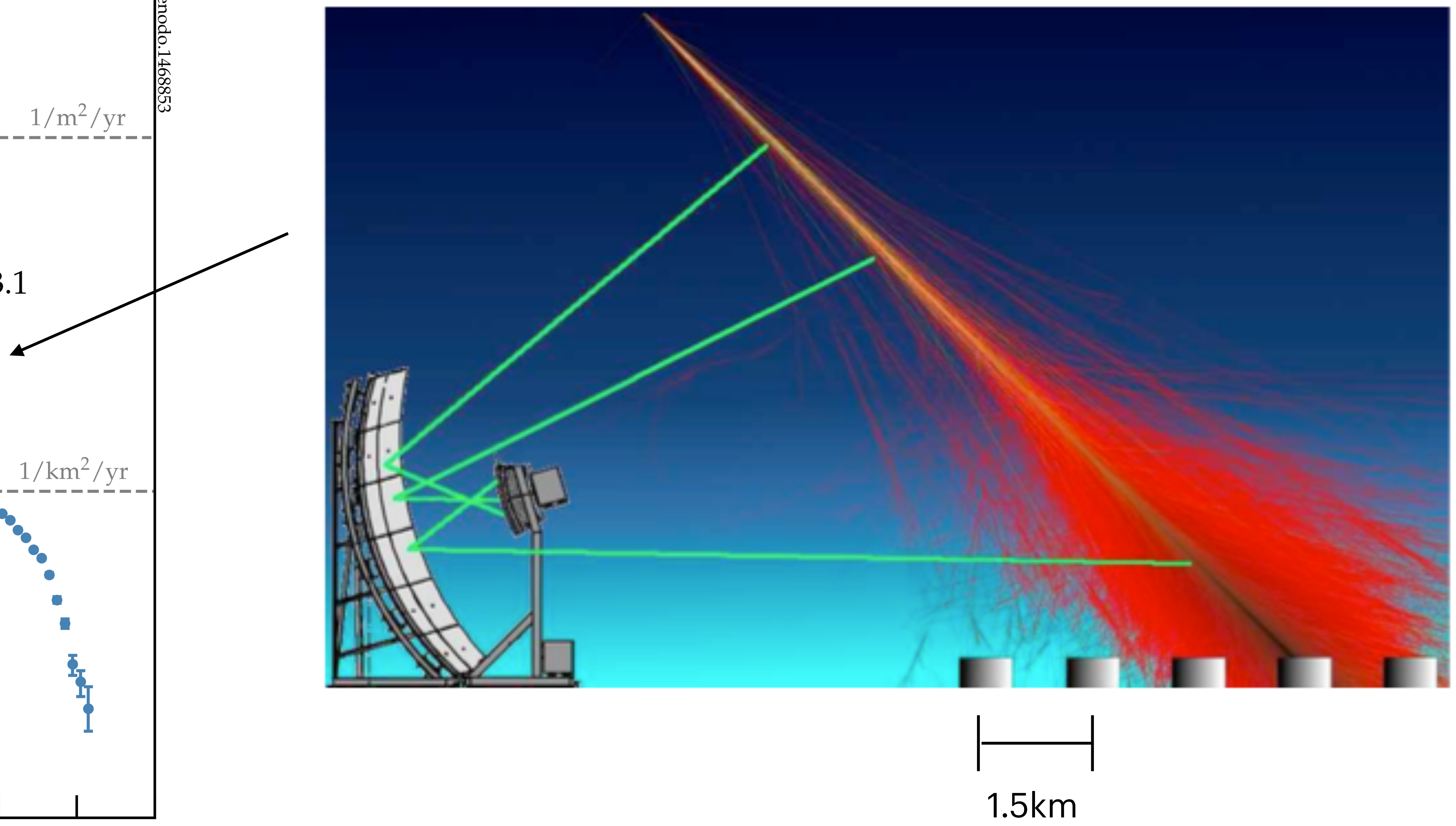
NTNU
Norwegian University of Science and Technology

# High-energy messengers of the non-thermal Universe



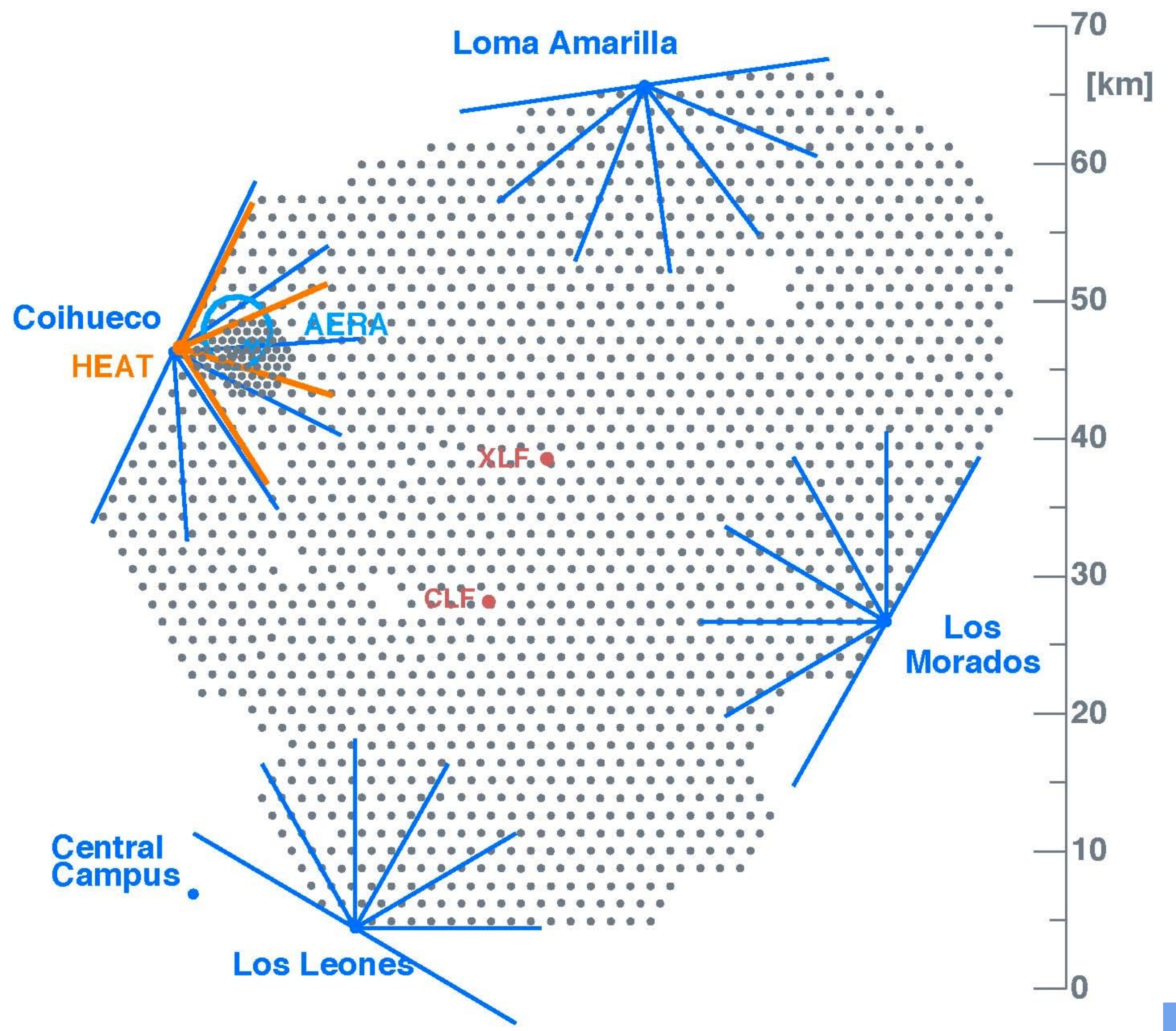
# Ultra-high-energy cosmic rays



# Ultra-high-energy cosmic ray Observatories

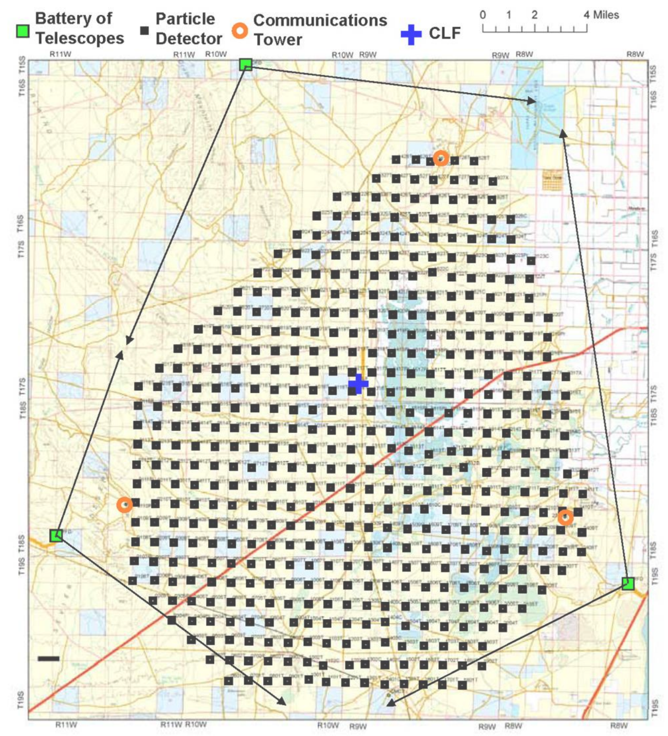
3000 km² in Mendoza (2004-)



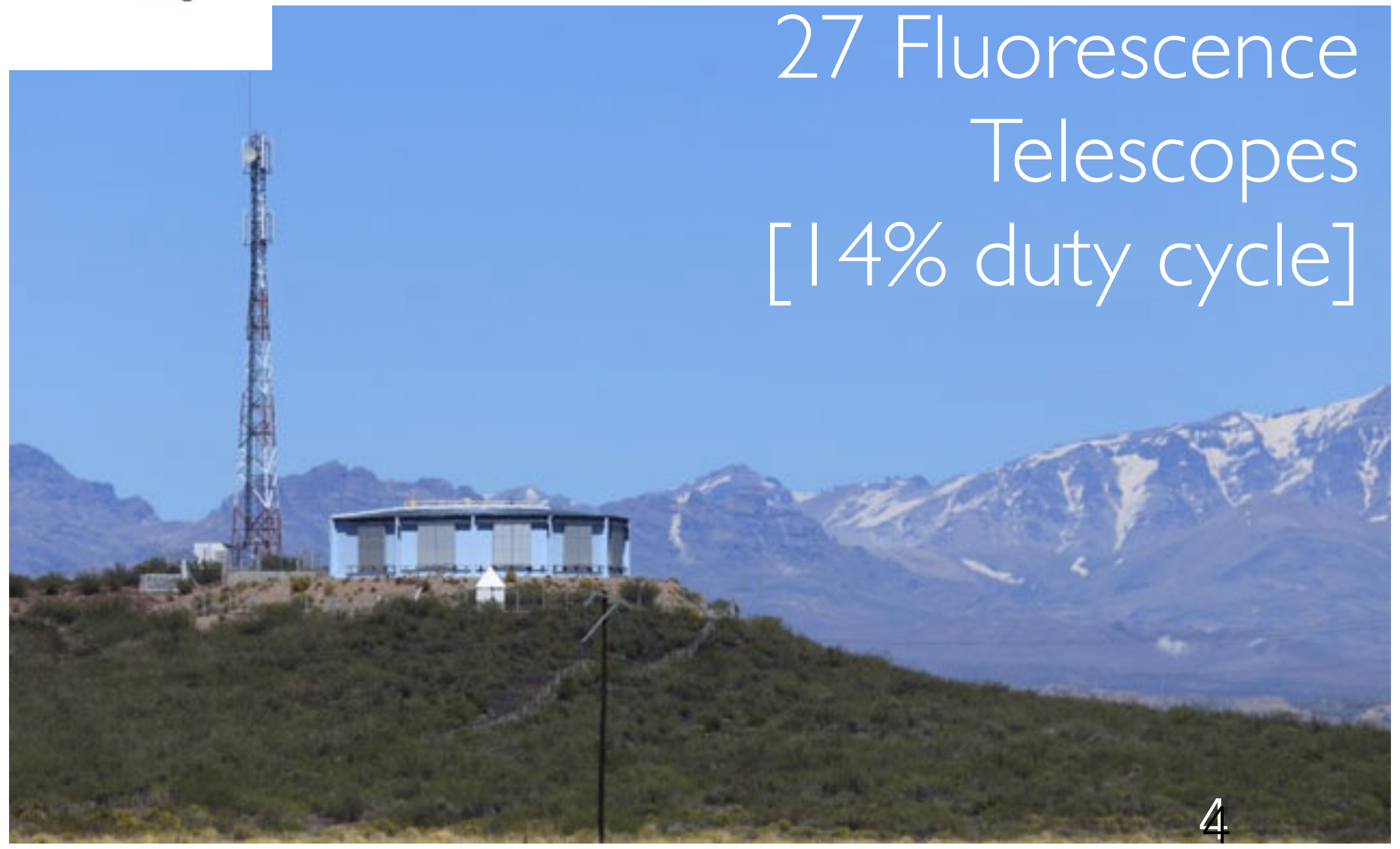

PIERRE AUGER OBSERVATORY

680 km² in Utah (2007-)

TELESCOPE ARRAY PROJECT

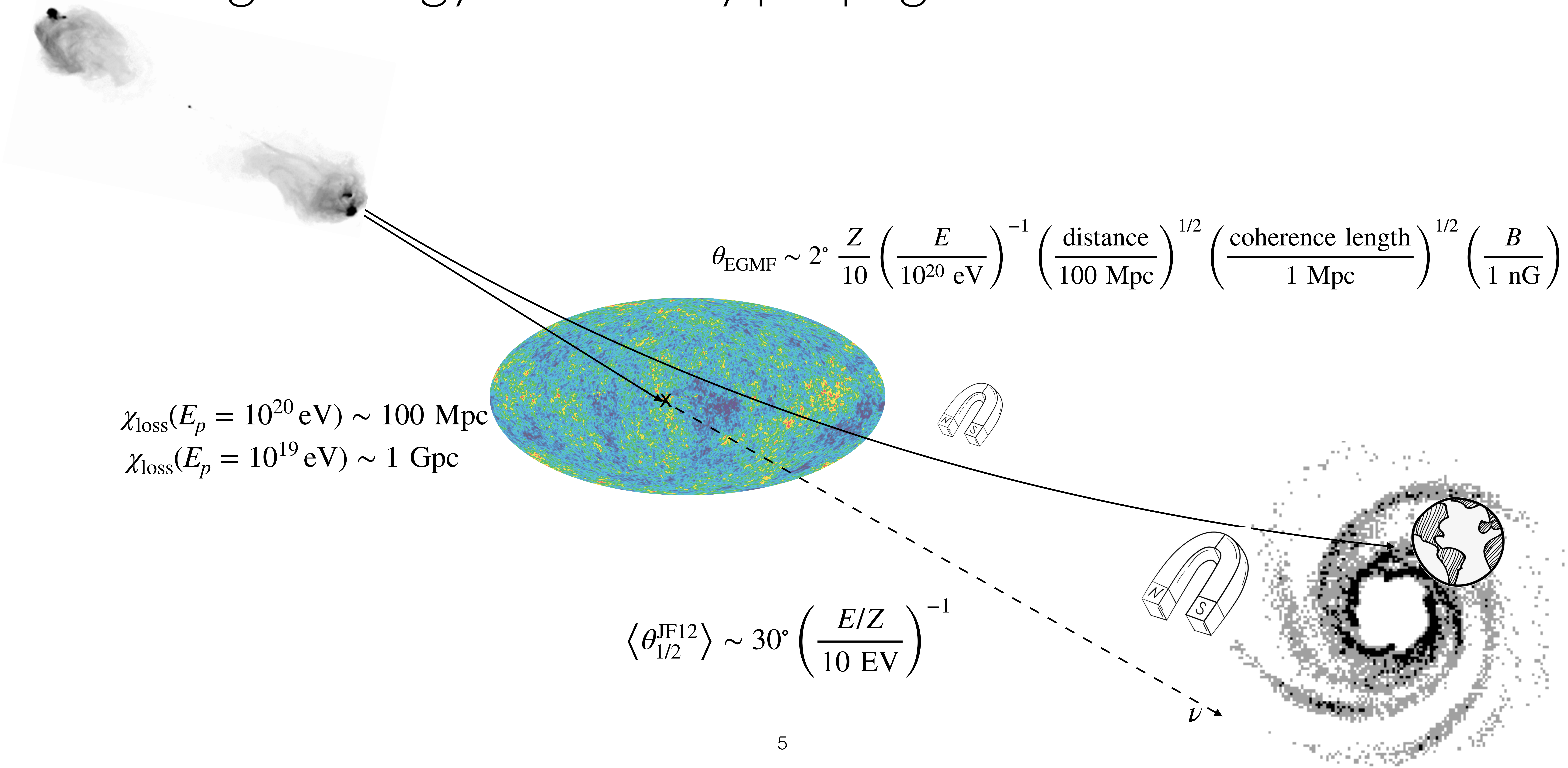



>100 scientists from USA, Japan, Korea, Russia, Belgium



# Ultra-high-energy cosmic ray propagation



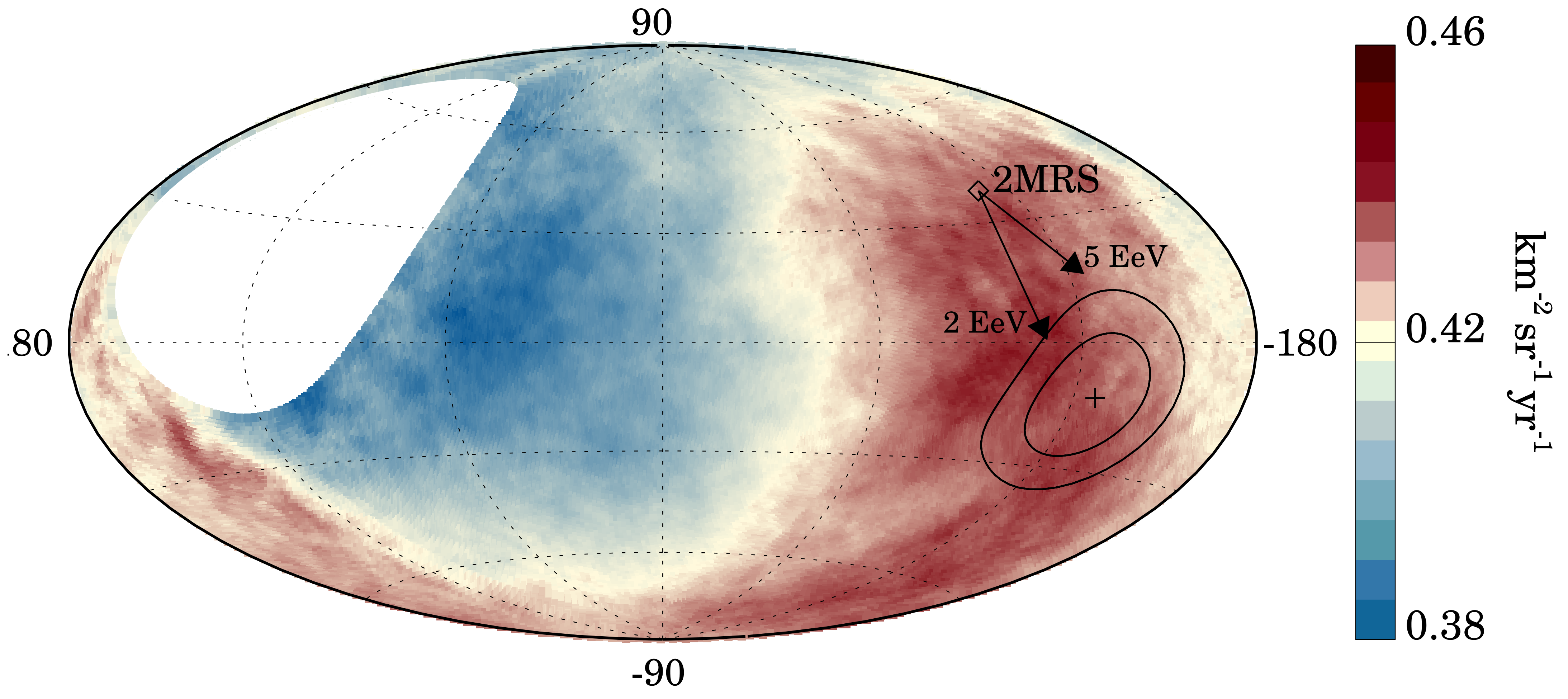

$$\theta_{\rm EGMF} \sim 2^\circ \, \frac{Z}{10} \left(\frac{E}{10^{20}\ {\rm eV}}\right)^{-1} \left(\frac{\rm distance}{100\ {\rm Mpc}}\right)^{1/2} \left(\frac{\rm coherence\ length}{1\ {\rm Mpc}}\right)^{1/2} \left(\frac{B}{1\ {\rm nG}}\right)$$

$$\chi_{\rm loss}(E_p = 10^{20}\,{\rm eV}) \sim 100\ {\rm Mpc}$$

$$\chi_{\rm loss}(E_p = 10^{19}\,{\rm eV}) \sim 1\ {\rm Gpc}$$

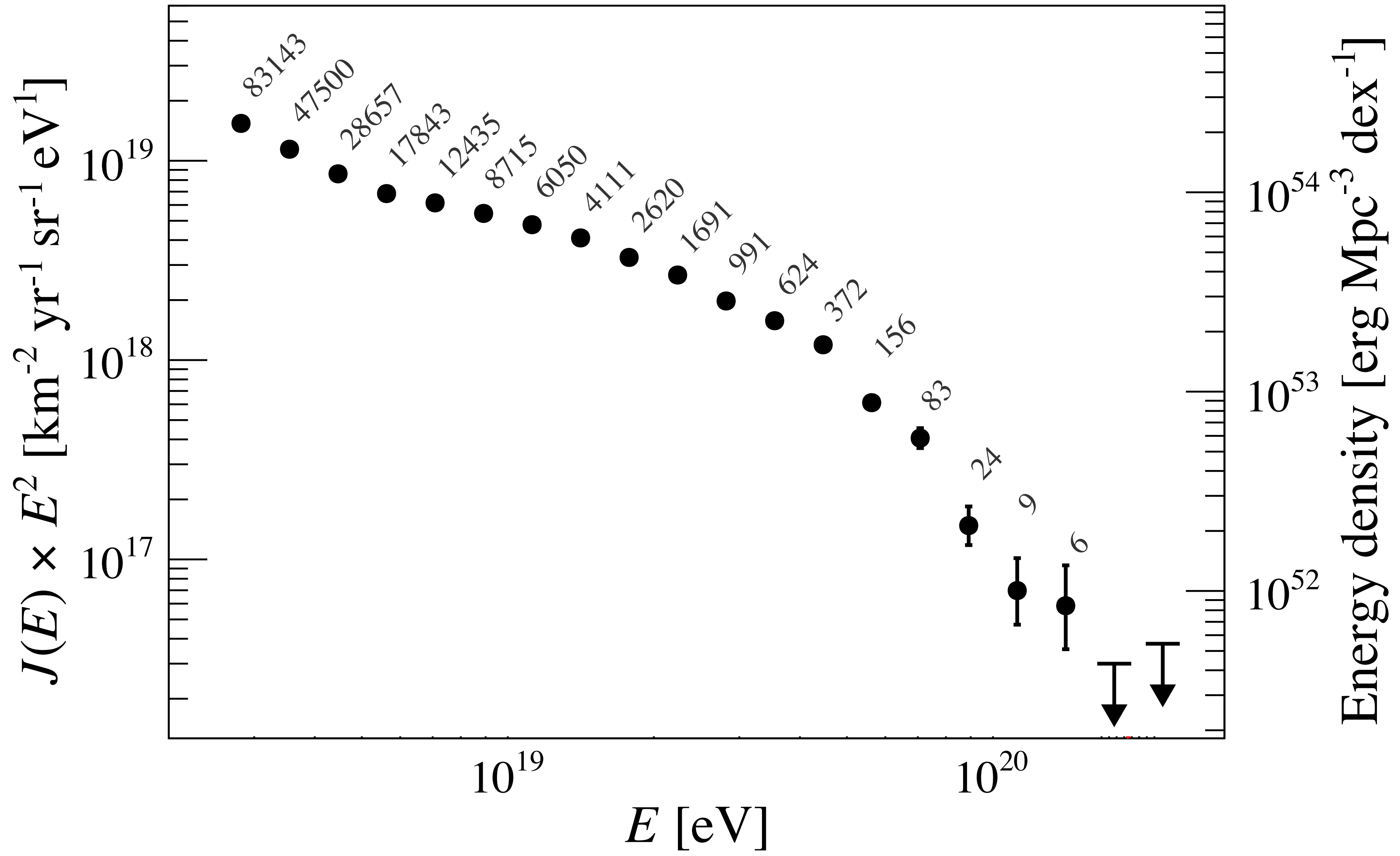
$$\left\langle \theta_{1/2}^{\rm JF12} \right\rangle \sim 30^\circ \left(\frac{E/Z}{10\ {\rm EV}}\right)^{-1}$$

# Observables

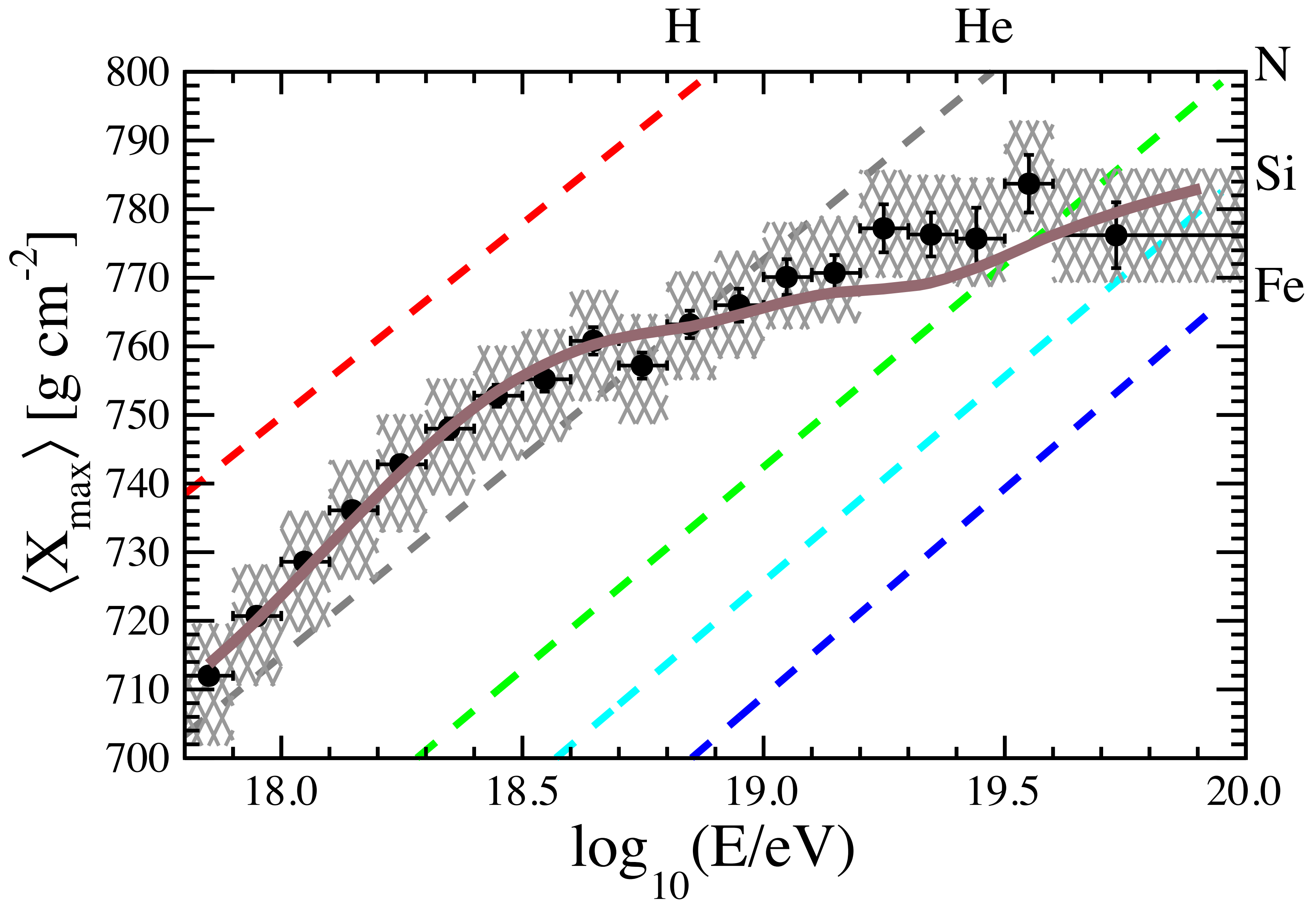


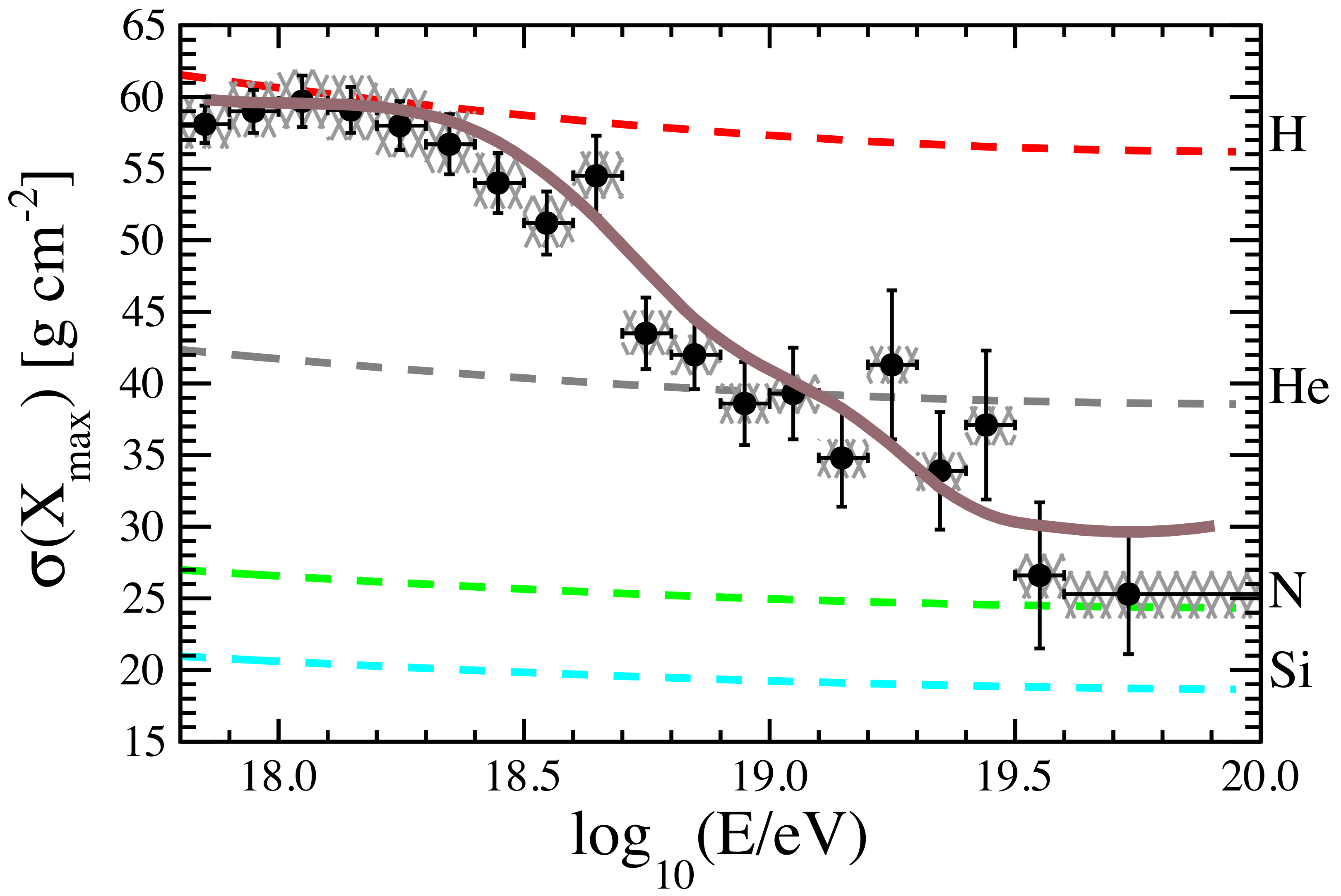

## Arrival Directions

## Diffuse all-particle spectrum



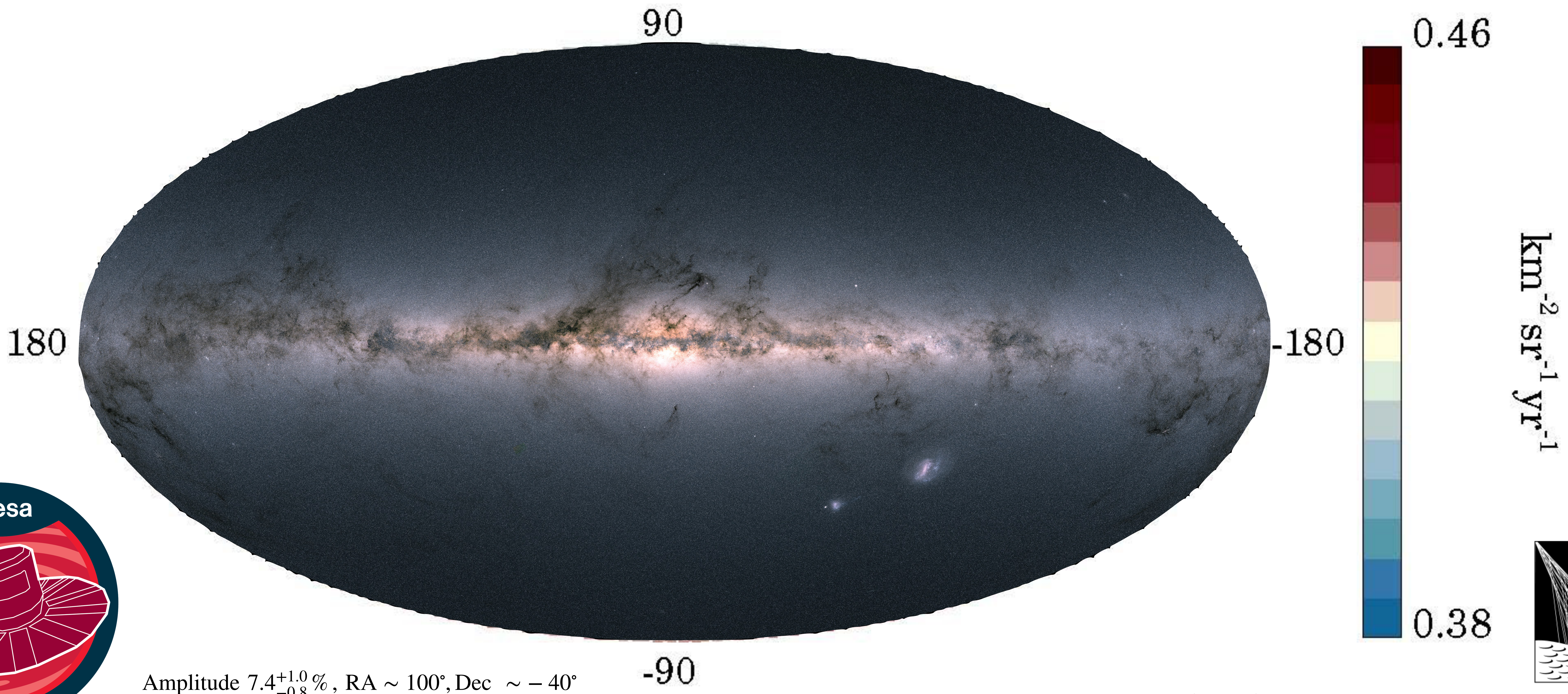

**Composition:**
Increasingly heavy with increasing energy



# Arrival directions above 8 x $10^{18}$ eV

*Auger Coll. 2017 Science 357 6357, (update 2024 ApJ)*




Amplitude $7.4^{+1.0}_{-0.8}\,\%$ , RA ~ 100°, Dec ~ − 40°

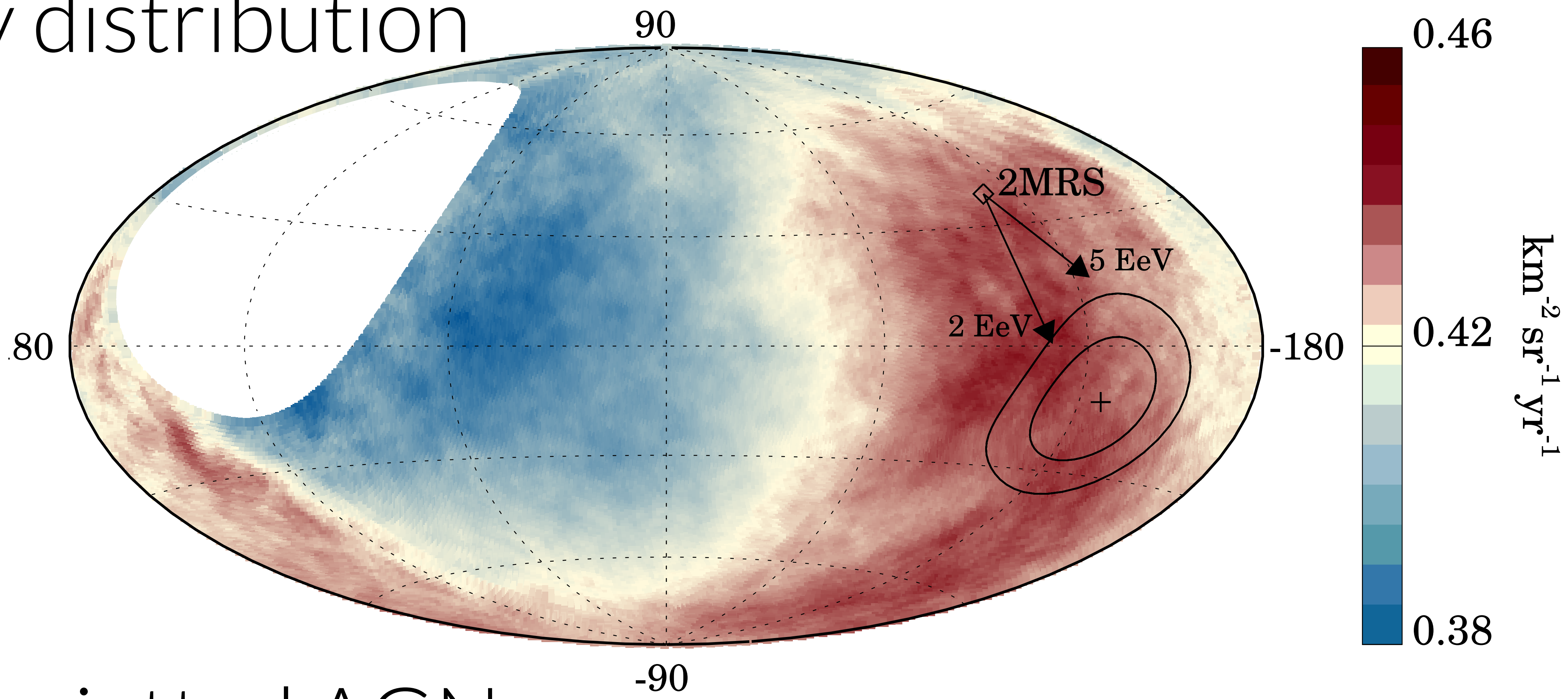
50,000 UHECRs with energy $\geq 8 \times 10^{18}$ eV

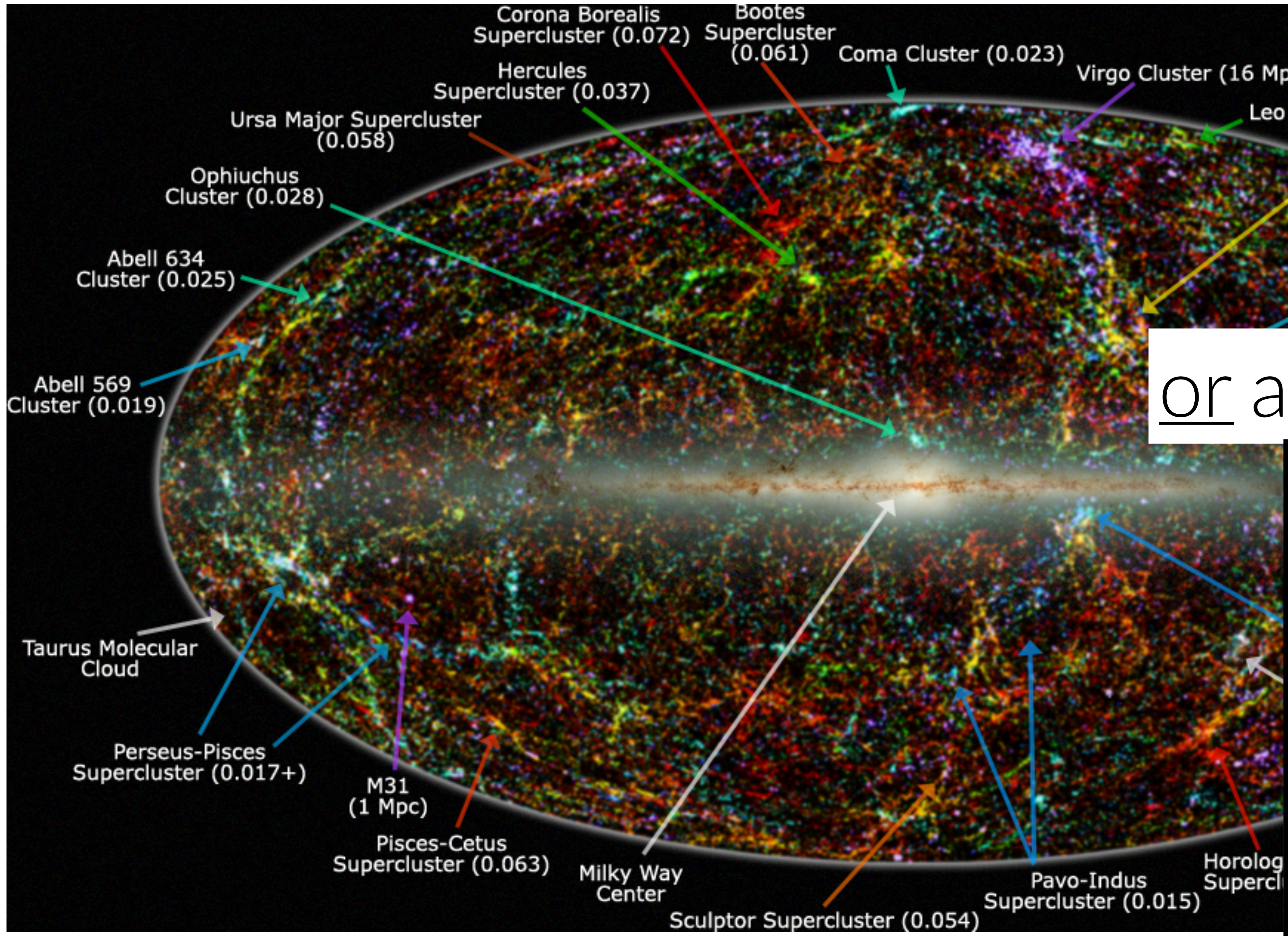
p-val: $2.6\times10^{-8}$ (6.8σ)

# Arrival directions above 8 x 10$^{18}$ eV

*Ding, Globus, Farrar, ApJL 913 (2021) 1*
*Allard, Aublin, Baret, Parizot, A&A (2022)*
*Bister, Farrar, ApJ 966 (2024) 1, 71*

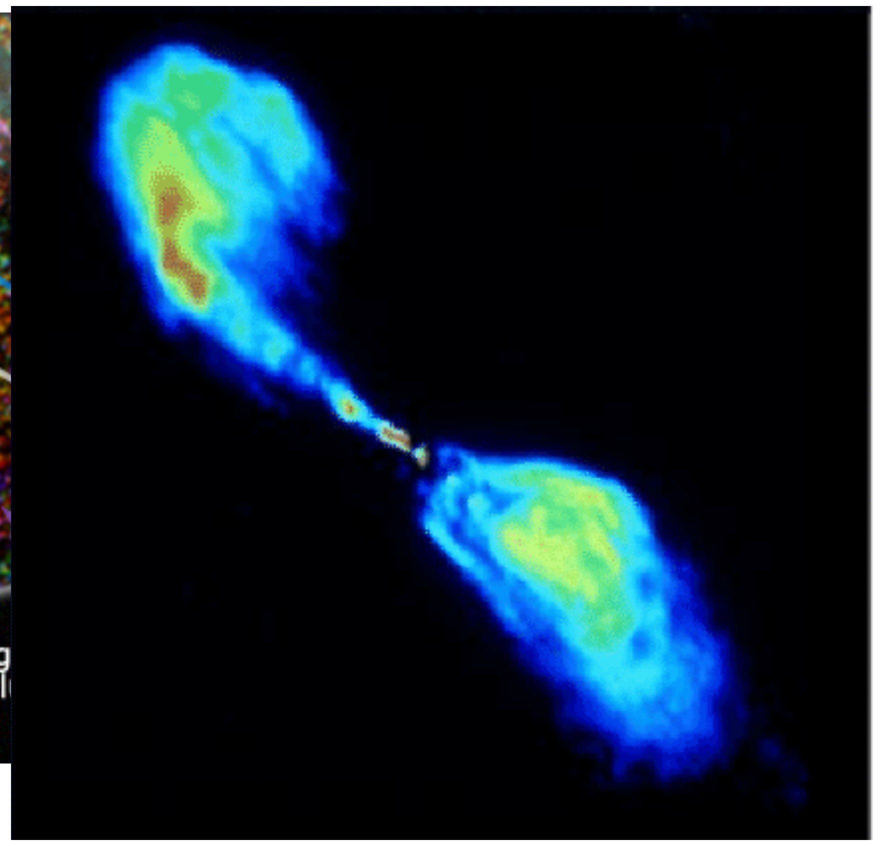
Consistent with dipole of galaxy distribution

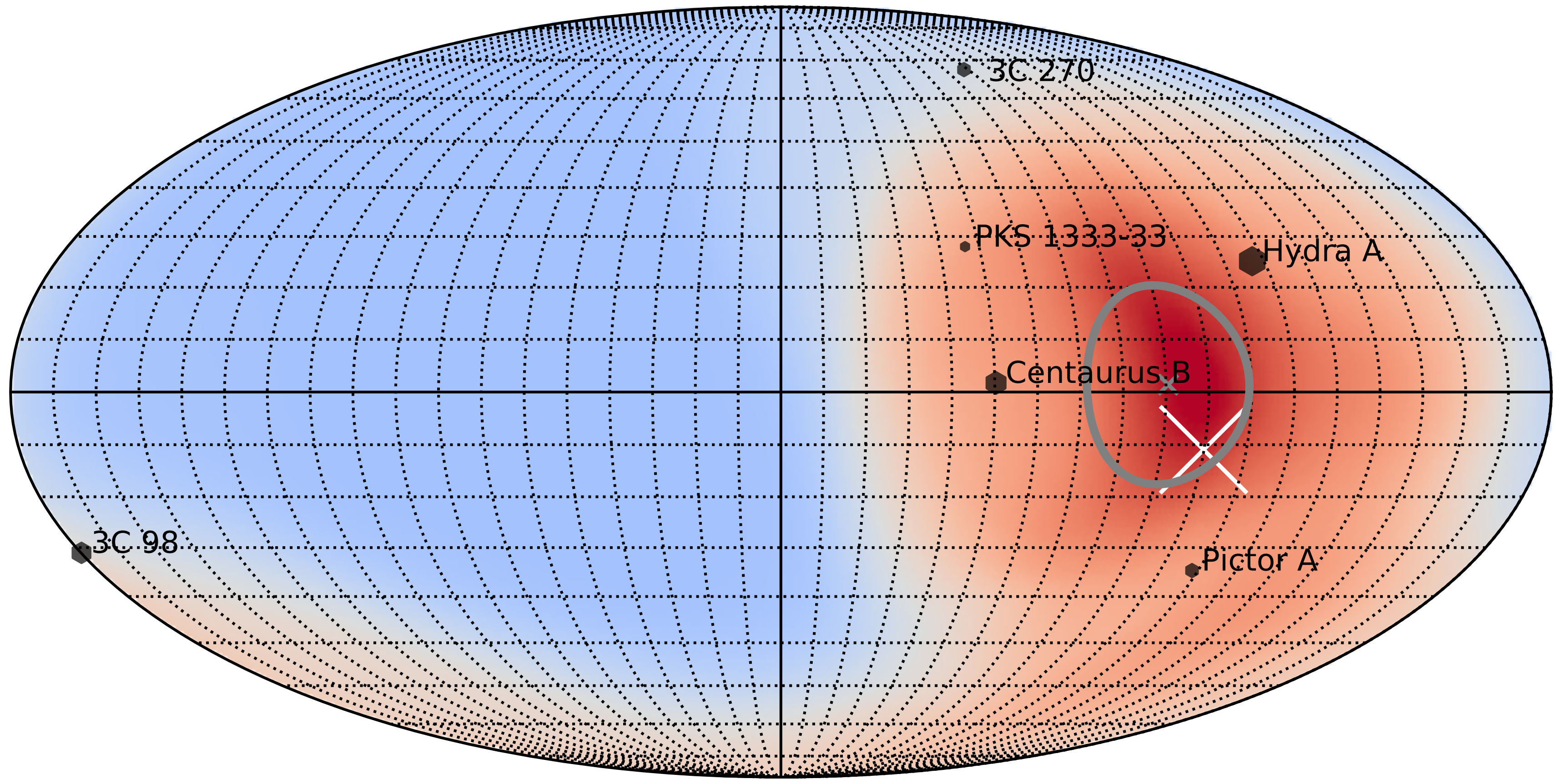



<u>or</u> a handful of nearby jetted AGN..

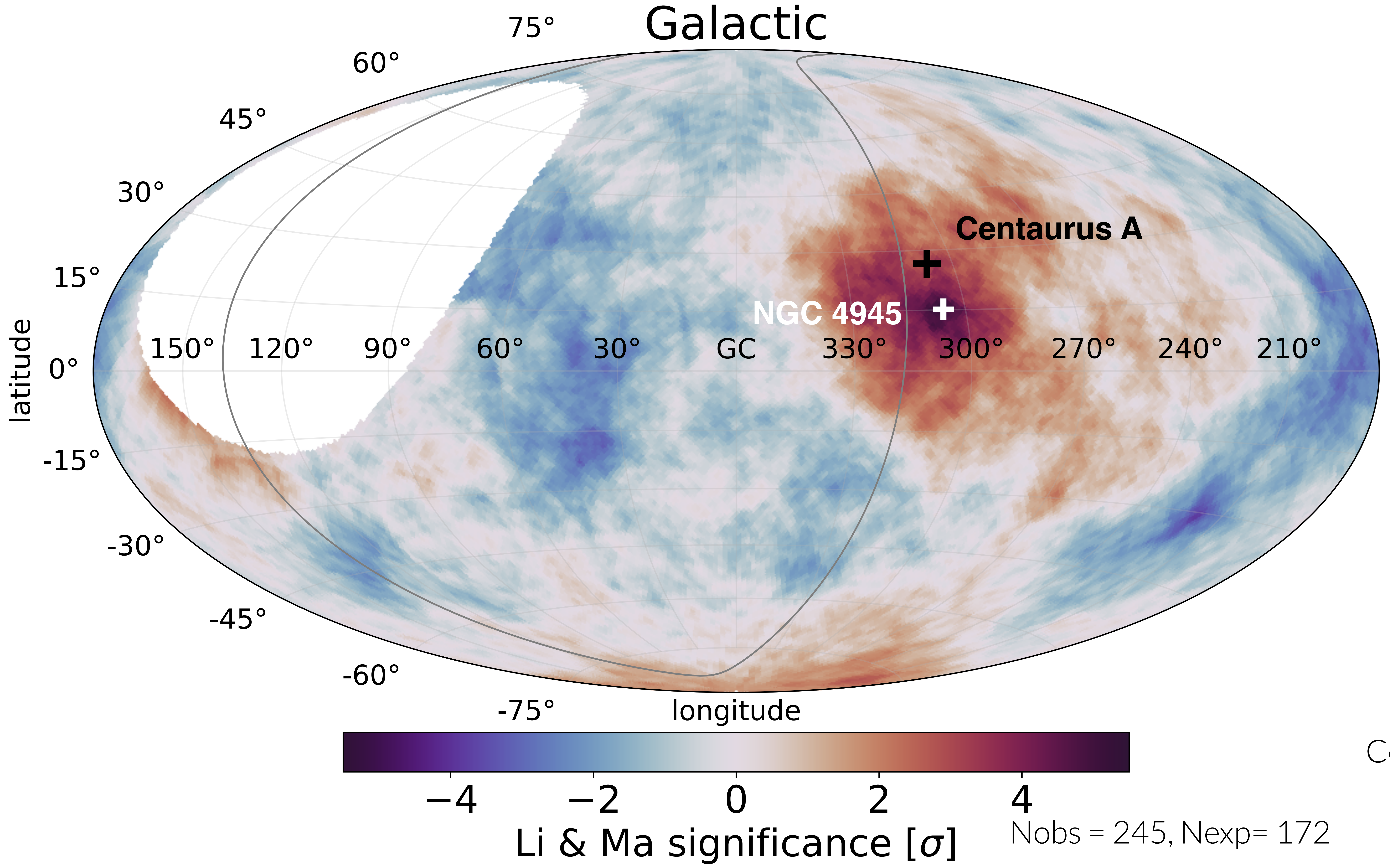
*Eichmann, Kachelriess, FO, JCAP07(2022)06*

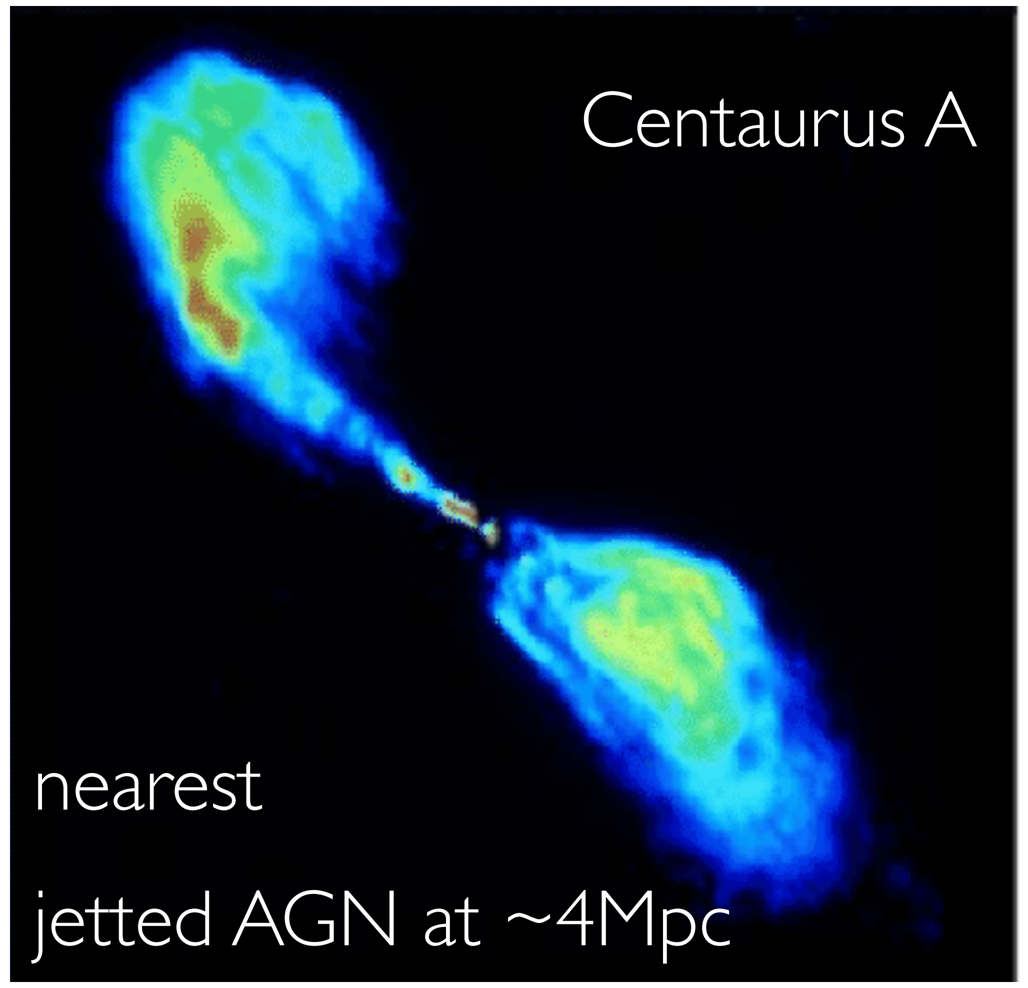


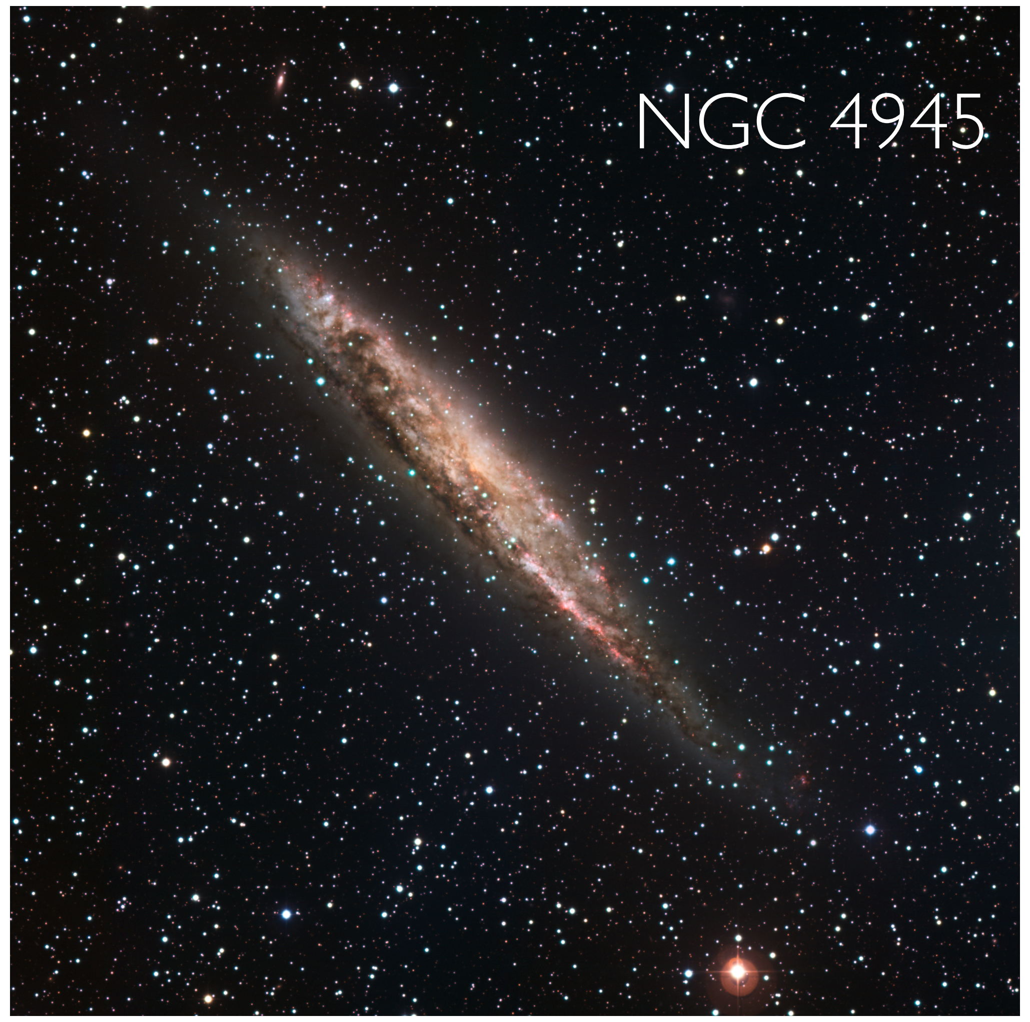



*or e.g. Cen A [+ M82] (Harari et al 2016, Mollerach et al 2019, Mollerach & Roulet 2022)*

# Arrival directions above 4 x $10^{19}$ eV




Nobs = 245, Nexp= 172

post-trial significance: 2.0σ

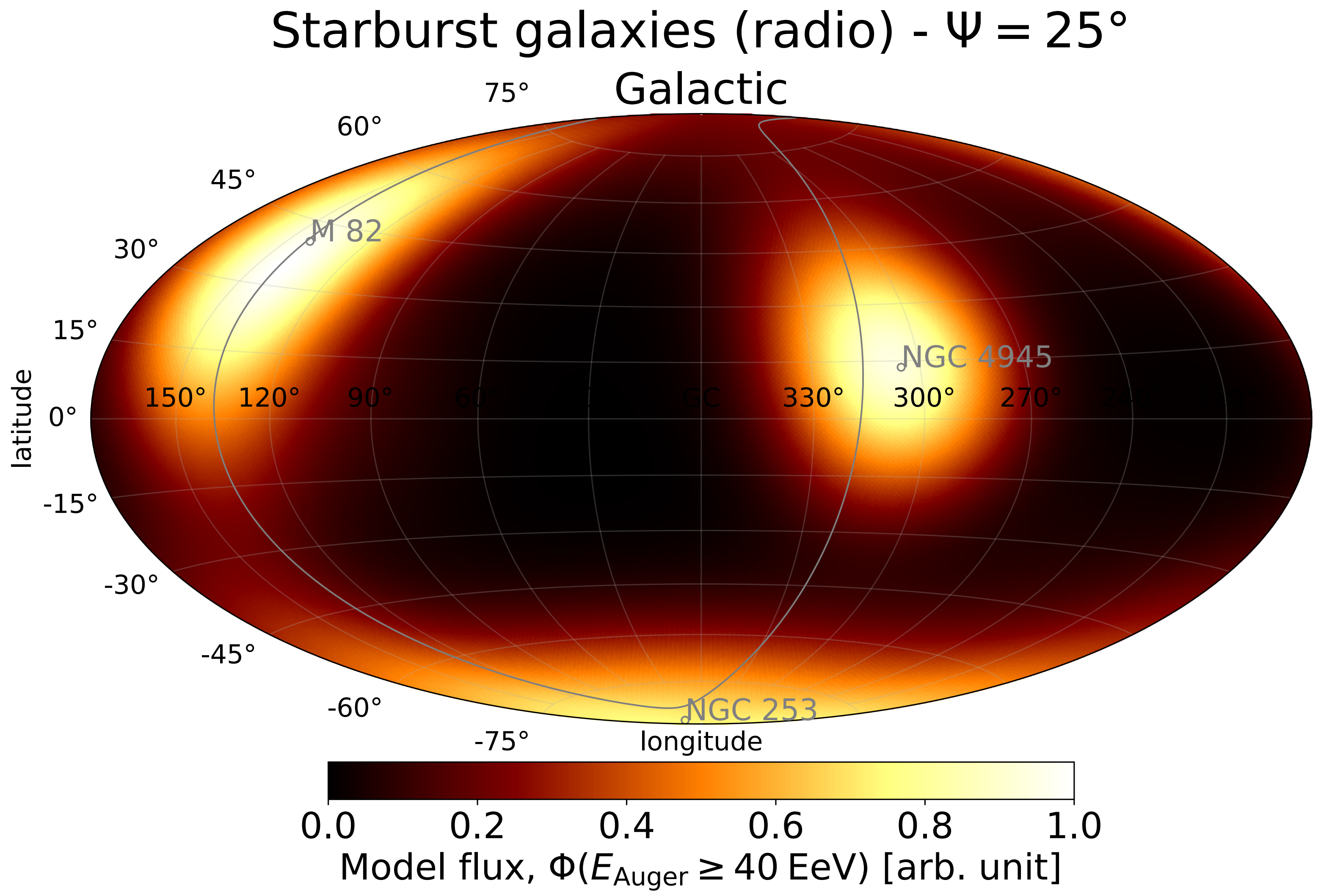
Centaurus A: Nobs = 237, Nexp=169

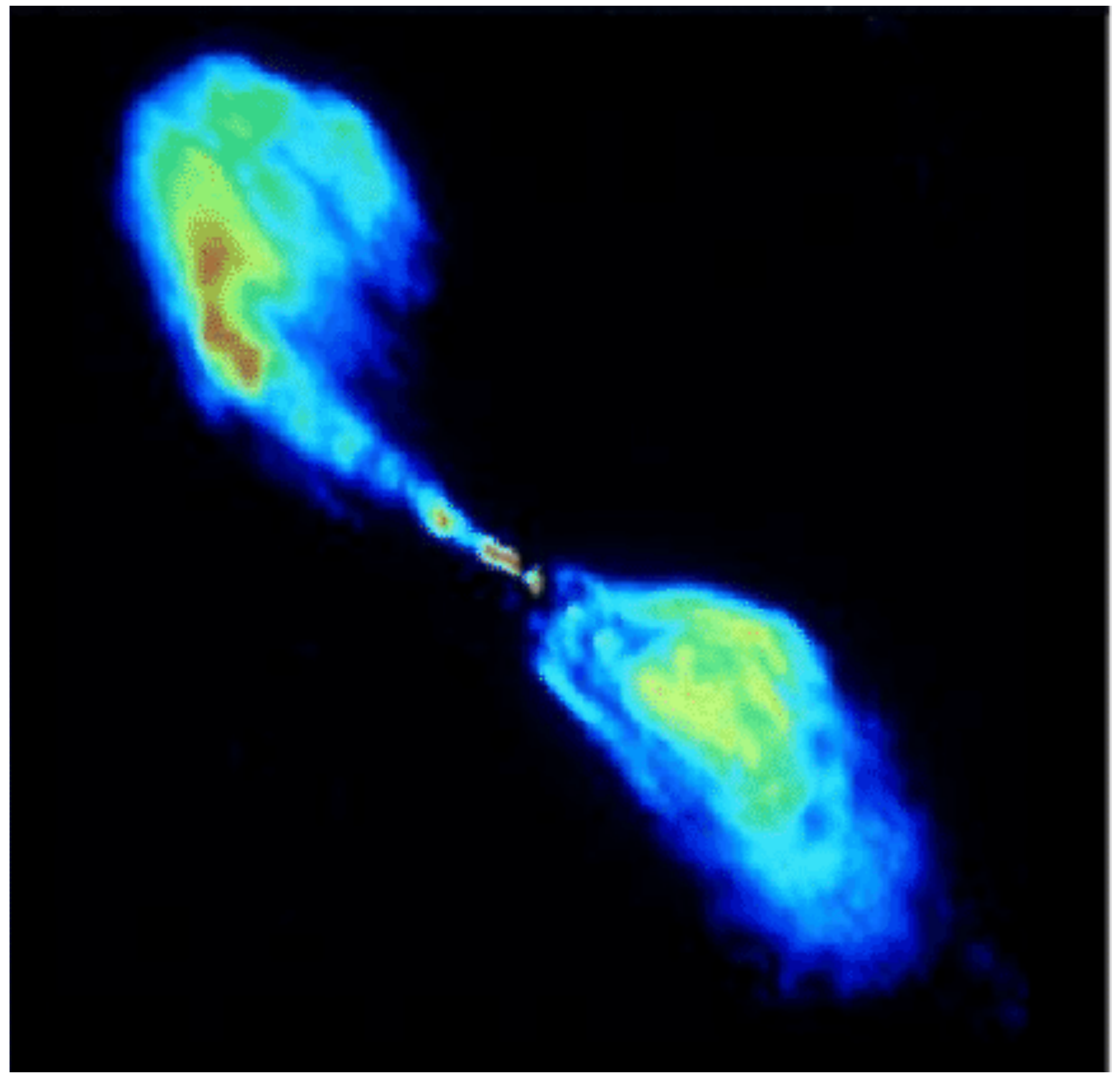
angular radius: 27deg

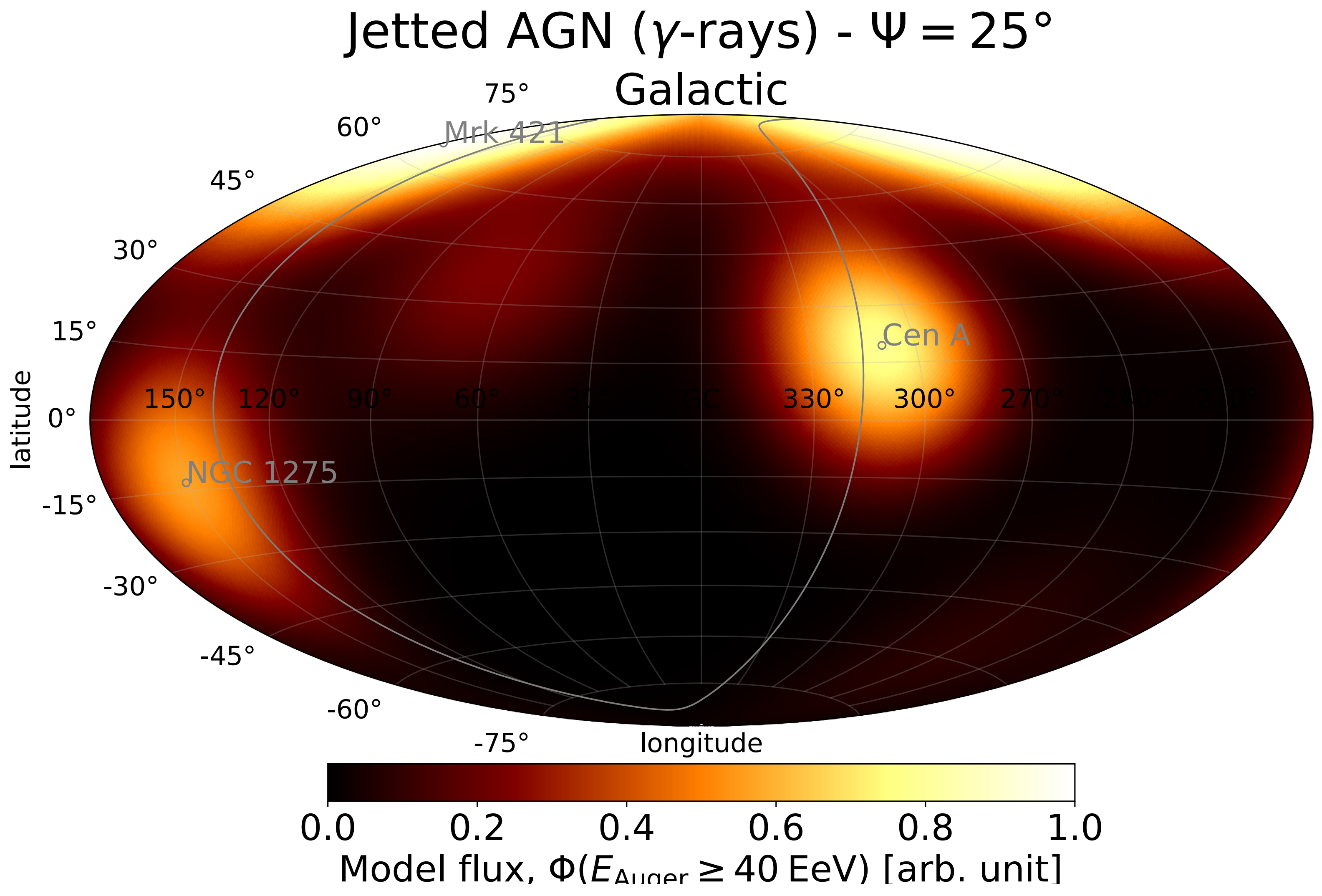
post-trial significance: 4.0σ

*Auger Coll, ApJL, 853, L29, 2018, Auger Coll 2022, ApJ 935 (2022) 2, 170*

# Arrival directions above 4 x $10^{19}$ eV






Starburst galaxies (radio flux weights)

E ≥38 EeV, Flux fraction $9^{+7}_{-4}$ %

3.8σ post-trial

* NGC 4945 is the most significant source (~20%)

Jetted AGN (γ-ray flux weights)

E ≥38 EeV, Flux fraction $6 \pm 3$ %

3.3σ post-trial

Swift-BAT AGN (X-ray flux weights)

E ≥38 EeV, Flux fraction $7^{+4}_{-3}$ %

3.5σ post-trial

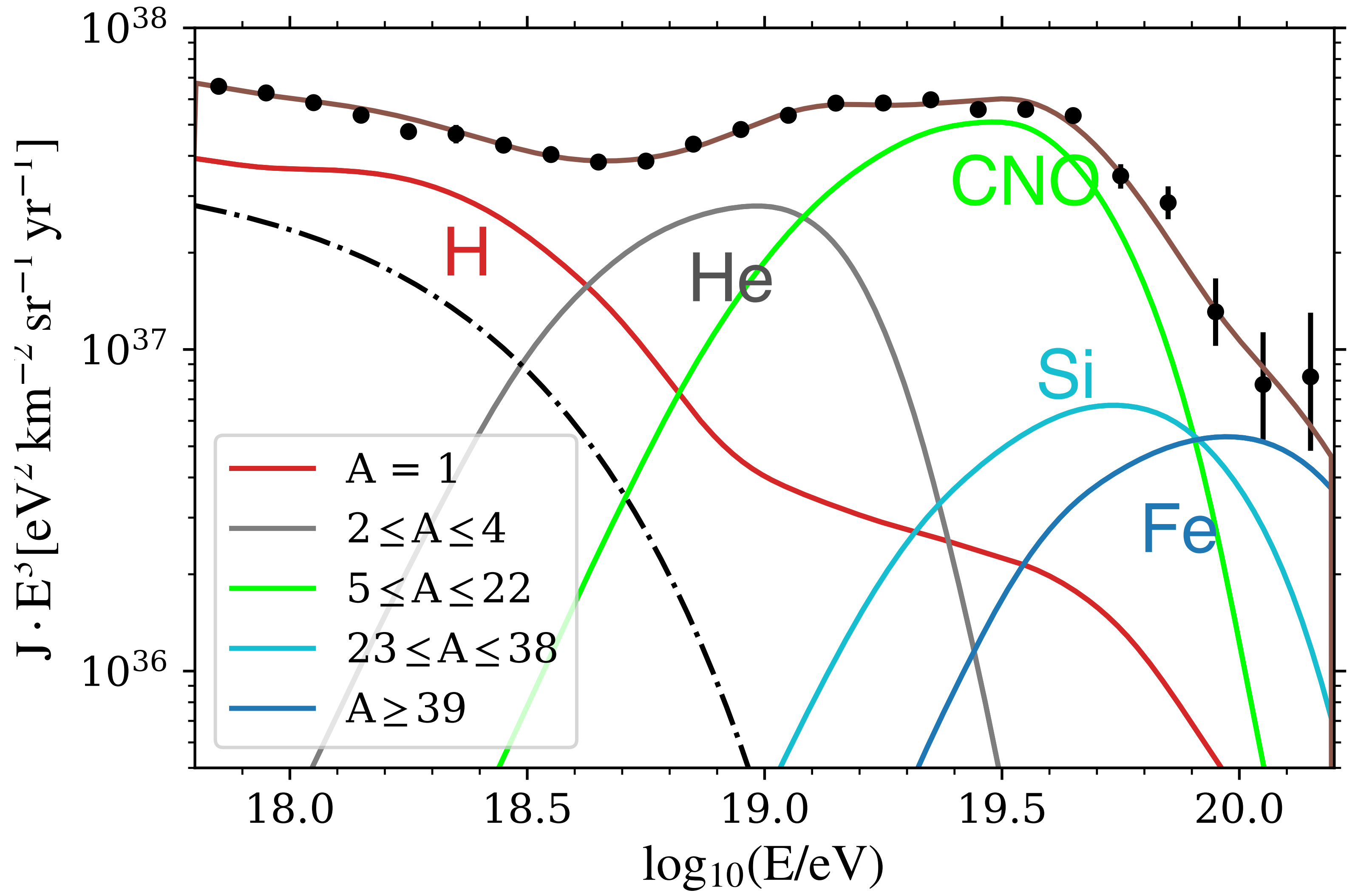
2MRS galaxies (IR flux weights)

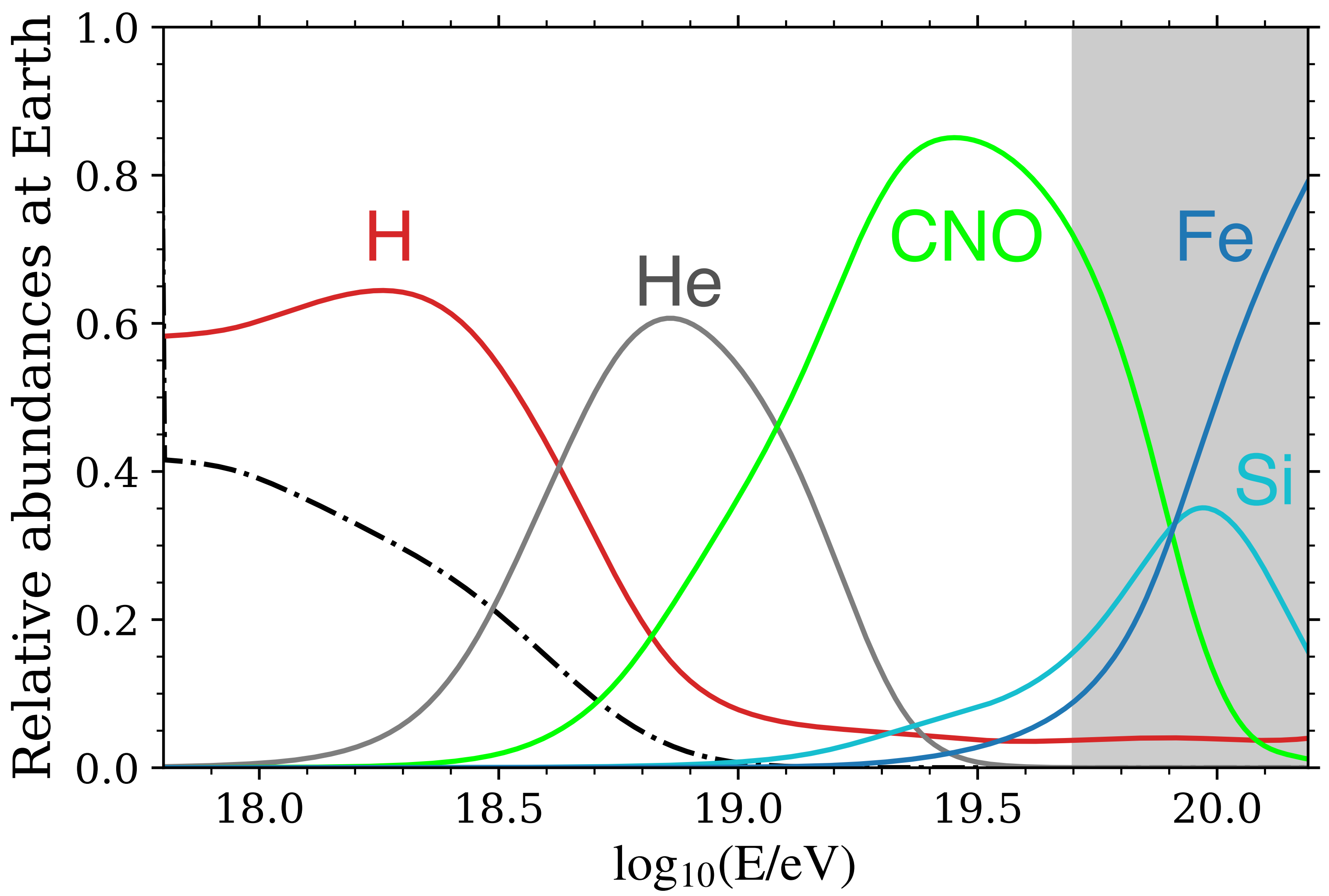
E ≥38 EeV, Flux fraction $14^{+8}_{-6}$ %

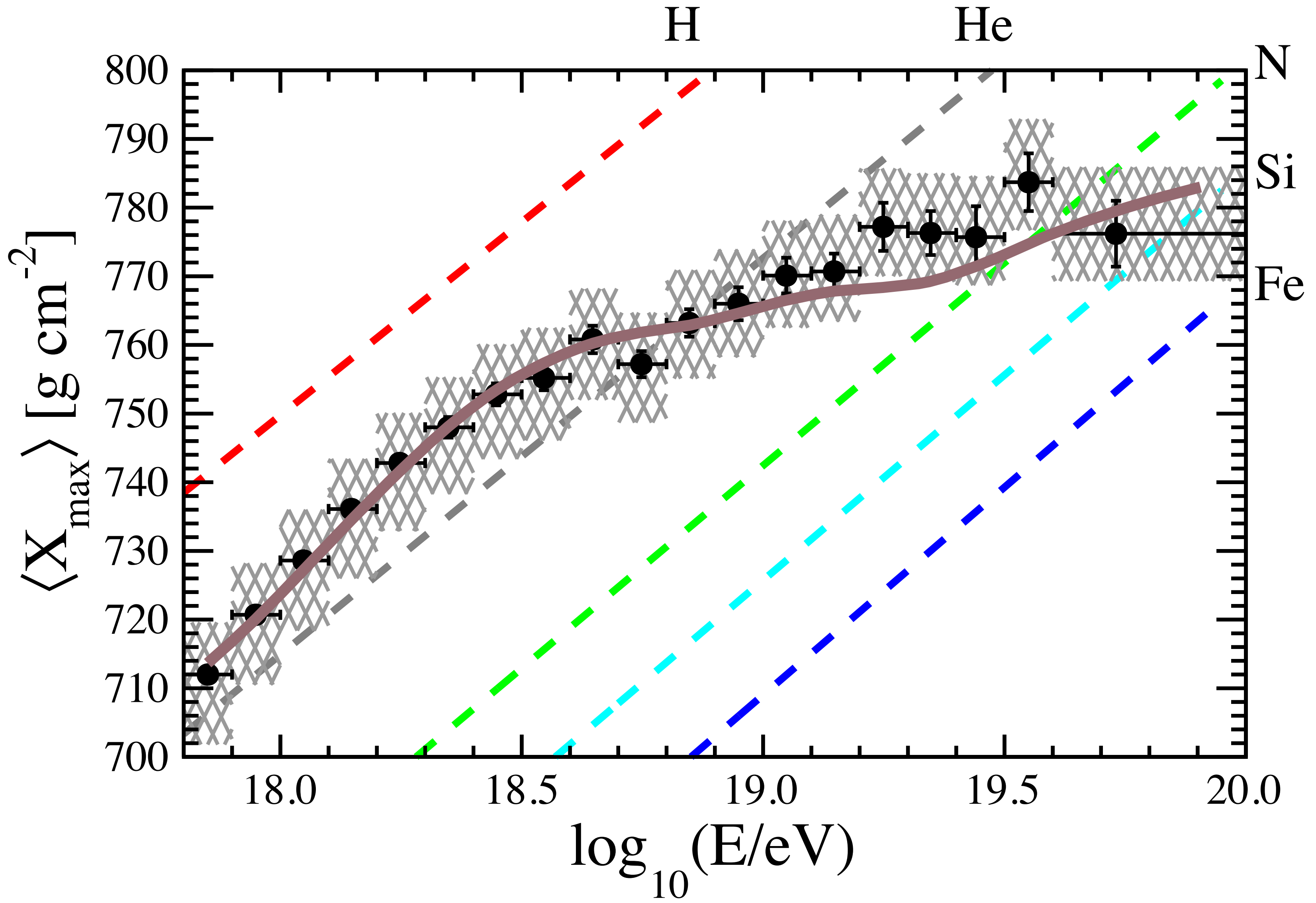
3.2σ post-trial

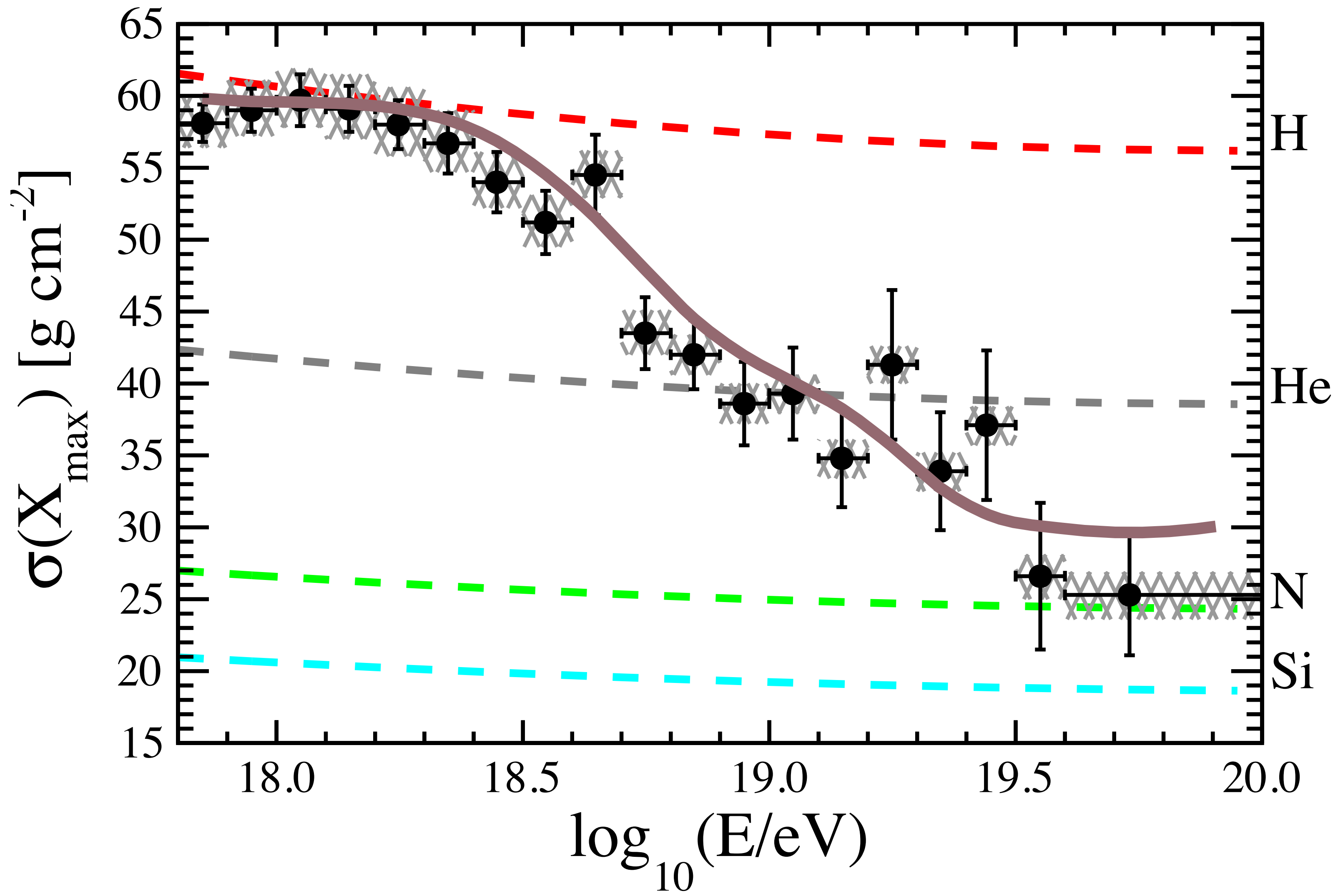
*[see Allard et al A&A 686 (2024) A292 for interpretation]*

# Searching for the UHECR sources: Combined fit approach



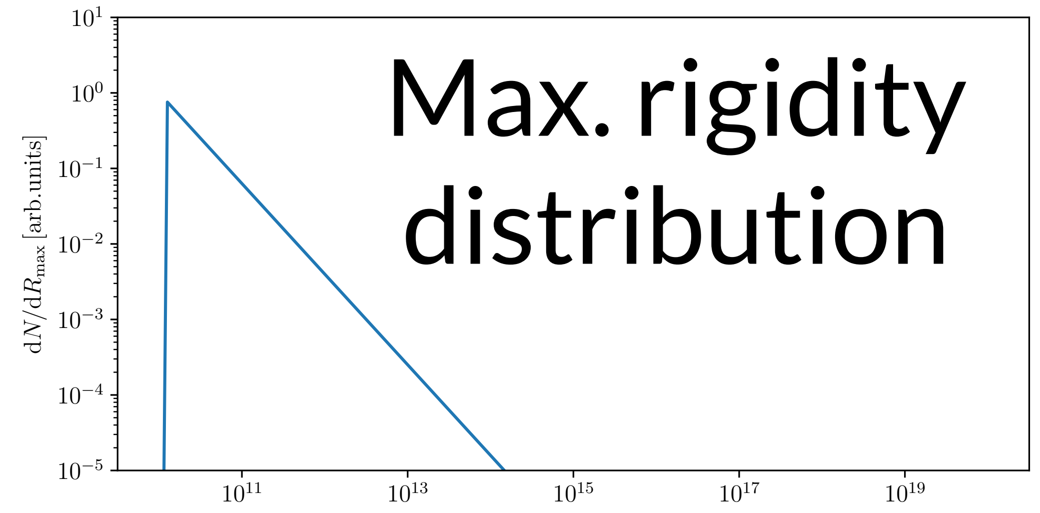

**Generic Source Properties:**
*Allard et al 2007, 8, Hooper et al 2007, Unger et al 2015, Auger Coll 2016, Kachelriess et al 2017, Muzio et al 2019, 2022, Mollerach et al 2020, Das et al 2021, Auger Coll 2022, Guido et al 2023, Trimarelli et al 2023*

**Specific source classes:**
**Jetted AGN** - *Eichmann et al 2017, 2022, Fang et al 2018, Kimura et al 2018, Rodrigues et al 2021*
**GRBs** - *Globus et al 2015, Biehl et al 2017, Zhang et al 2018, Boncioli et al 2018, 2019, Rudolf 2019,2022, Heinze et al 2020*
**TDEs** - *Biehl et al 2017, Guepin et al 2017, Zhang et al 2019*
**Transrelativistic Supernovae -** *Zhang & Murase 2019*
**Starburst galaxies** - *Condorelli et al 2022*

**Sources generally assumed to be intrinsically identical**

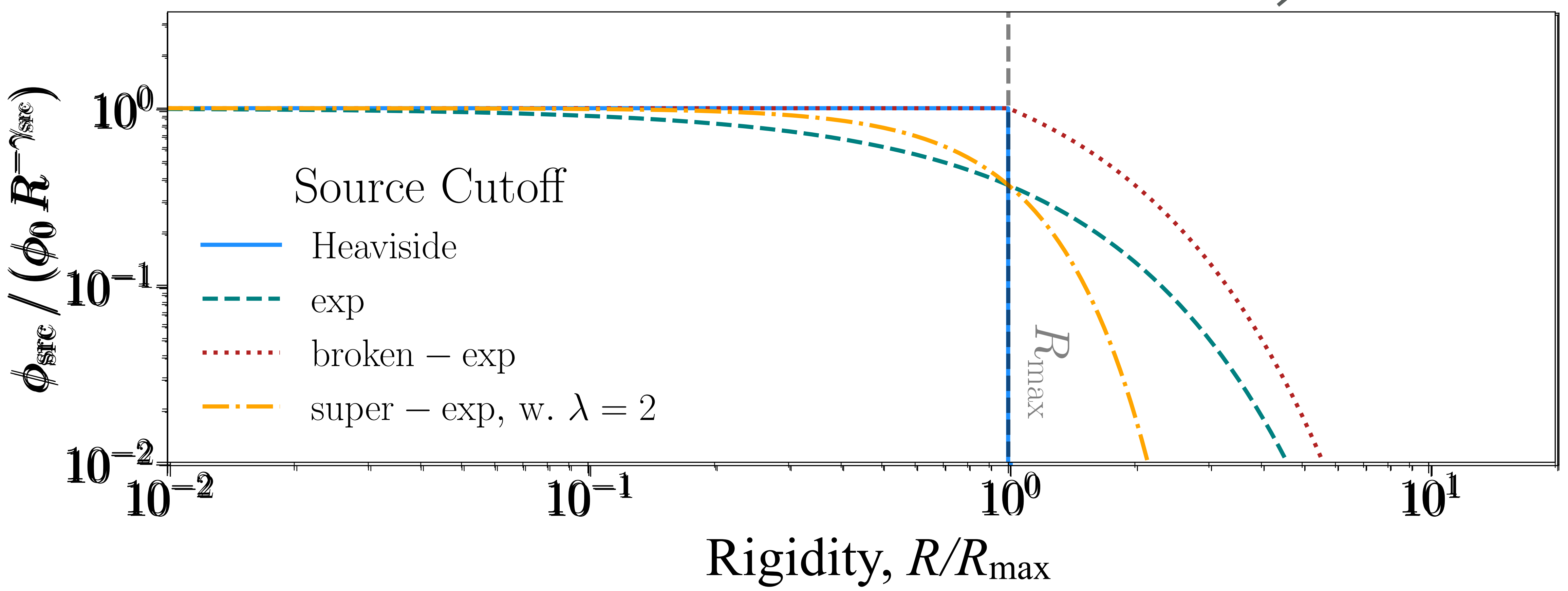
Distribution of maximum energies:
UHECR protons: *Kachelriess & Semikoz 2006*
Galactic sources: *Shibata et al 2010*
Discrete AGN: *Eichmann, Kachelriess, FO 2022*

# From single source to population spectrum



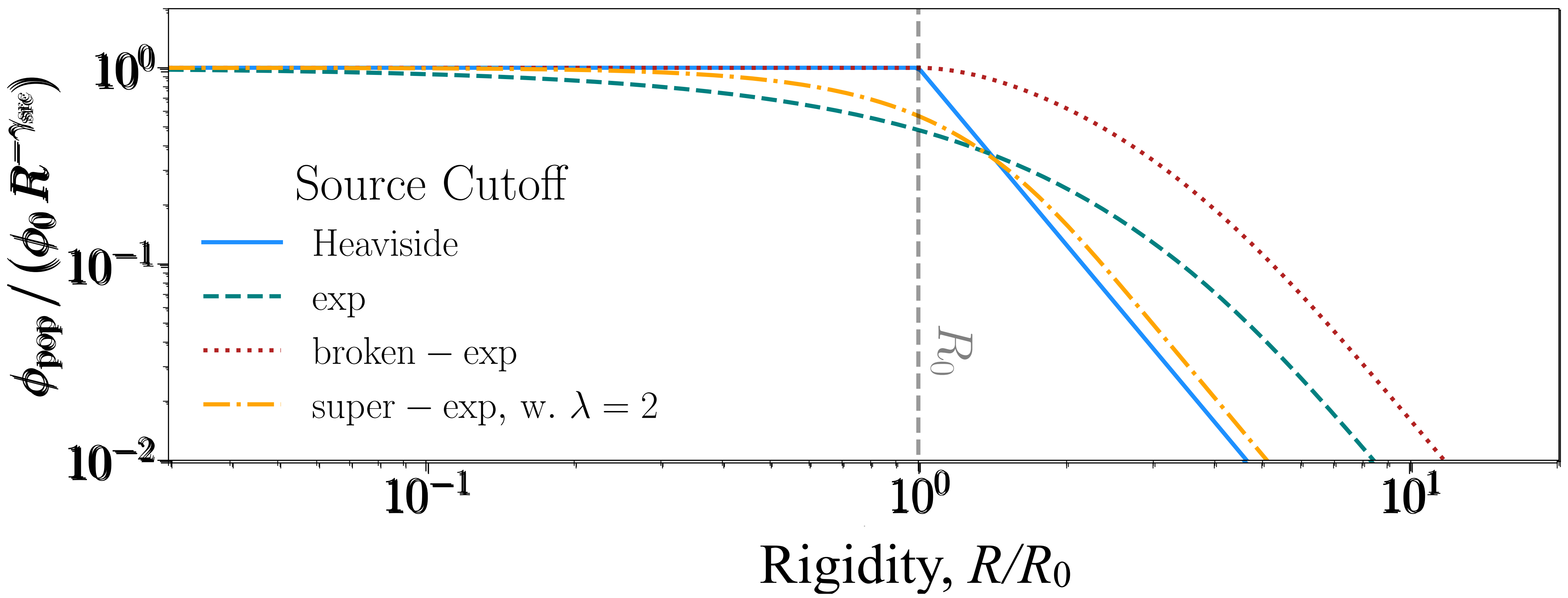

*Kachelriess and Semikoz, PLB 634 (2006) 143*

## Single Source UHECR Spectrum




## Population Spectrum

Power-law distributed maximum rigidity




$R = E/Z$ $\qquad \frac{\mathrm{d}N}{\mathrm{d}R} \propto R^{-\gamma_{\rm src}}$ $\qquad \gamma_{\rm src} \approx -2$ diff. shock accel. $\qquad \frac{\mathrm{d}N}{\mathrm{d}R_{\rm max}} \propto R_{\rm max}^{-\beta_{\rm pop}}$

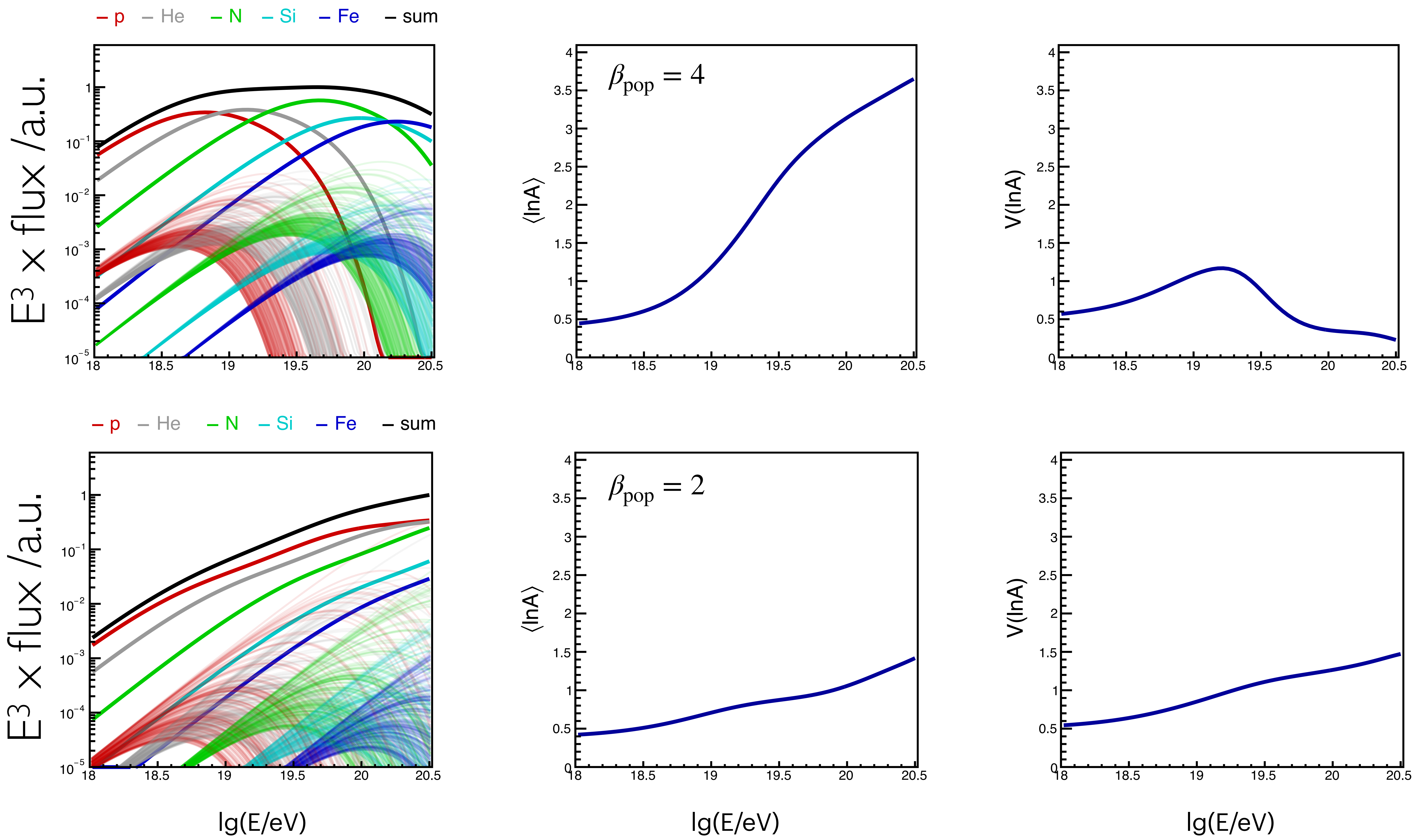
$$\phi_{\rm pop} \propto \begin{cases} R^{-\gamma_{\rm src}} & R \ll R_0 \\ R^{-\gamma_{\rm src}-\beta_{\rm pop}+1} & R \gg R_0 \end{cases}$$

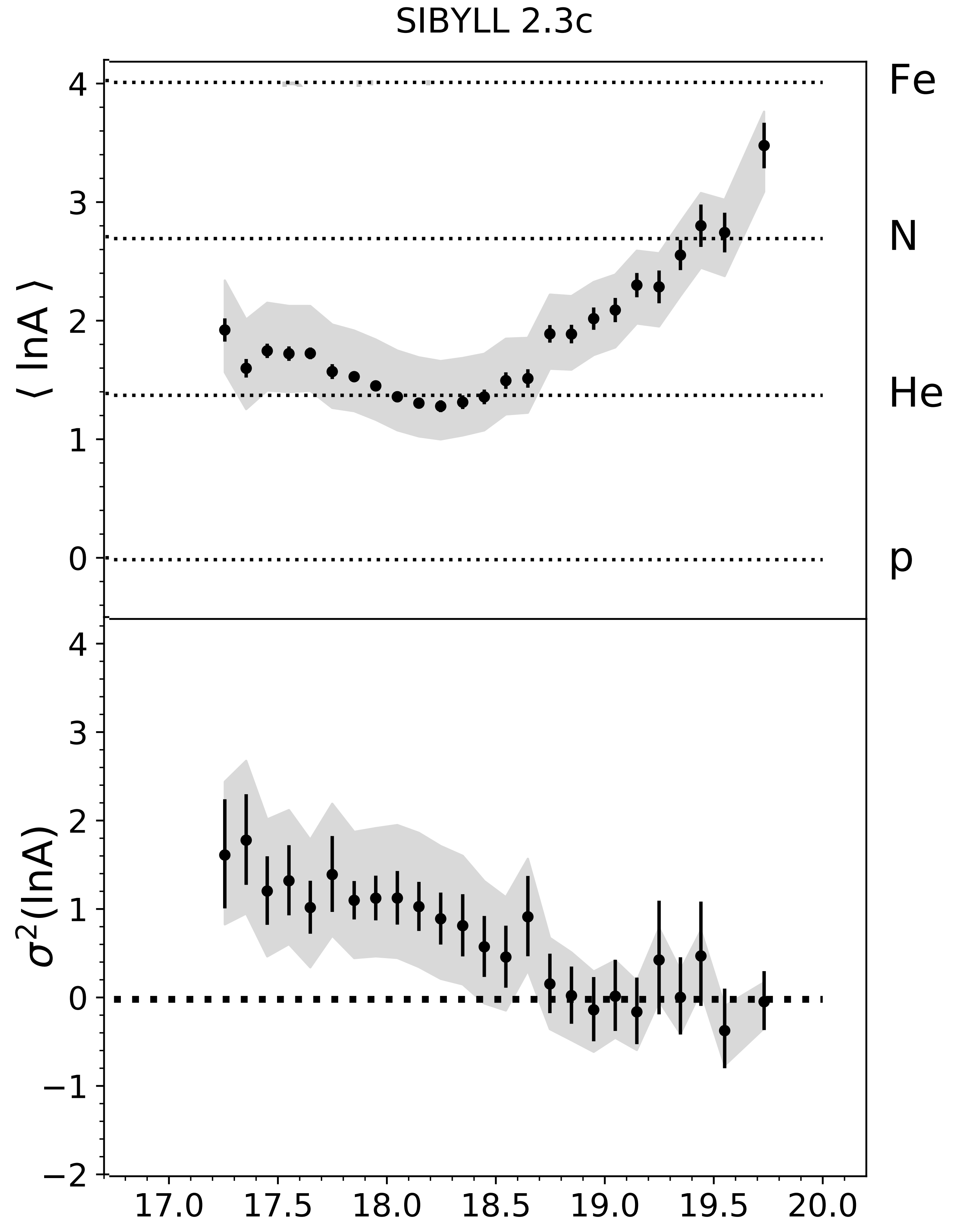
*Broken exponential, e.g. Auger Combined Fit (Aab et al 2017)*
*Super exponential in case of DSA with synchrotron losses with* $\mathrm{d}N/\mathrm{d}R \propto \exp - R^{\lambda}, \lambda = 2$ *e.g. Zirakasvili & Aharonian 2007*

# Combined fit with a population of non-identical sources

Toy example with power-law distributed maximum energy $\frac{\mathrm{d}N}{\mathrm{d}E_{\max}} \propto E_{\max}^{-\beta_{\mathrm{pop}}}$

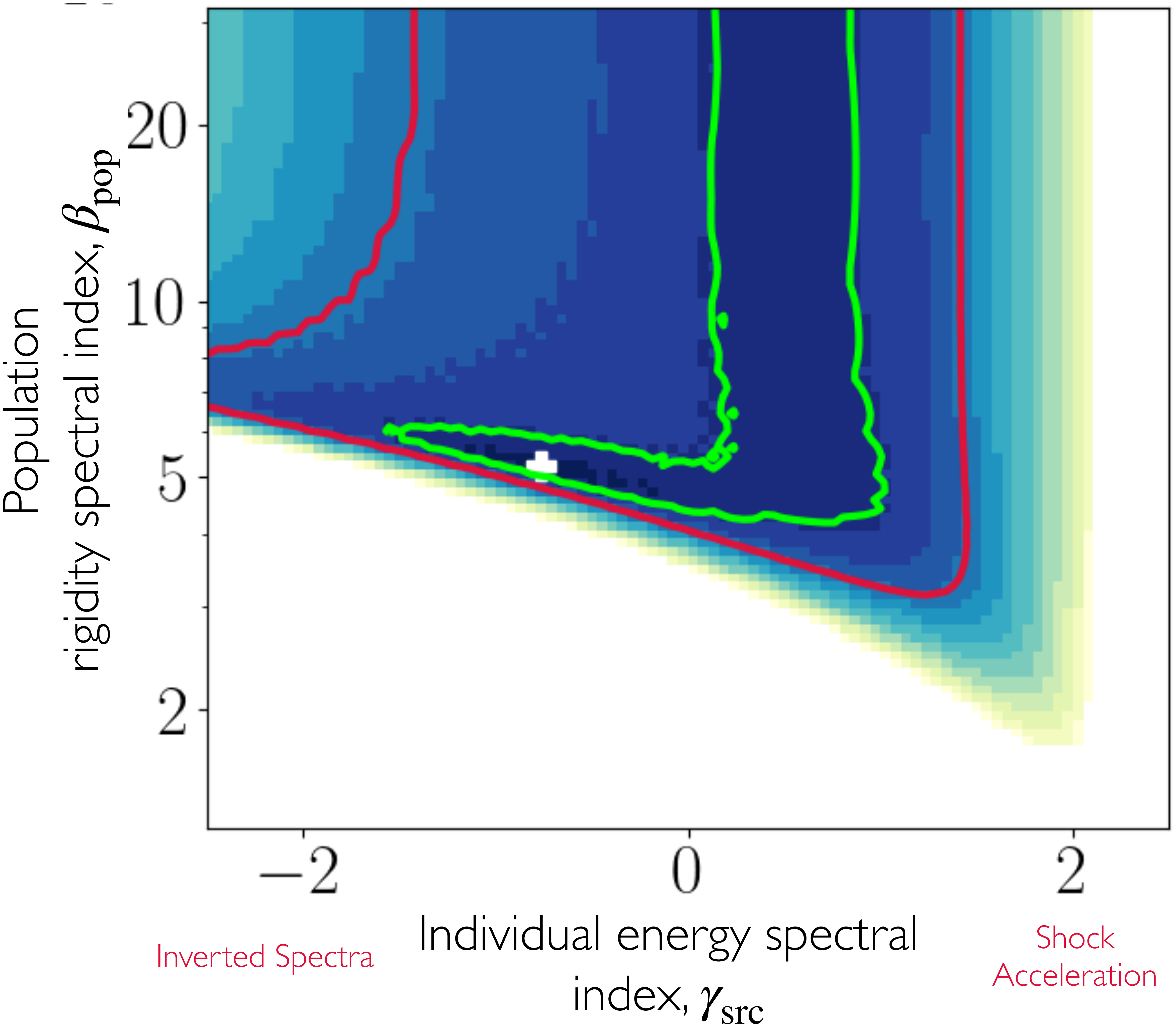
*D. Ehlert, FO, M. Unger, PRD 107 (2023) 10*



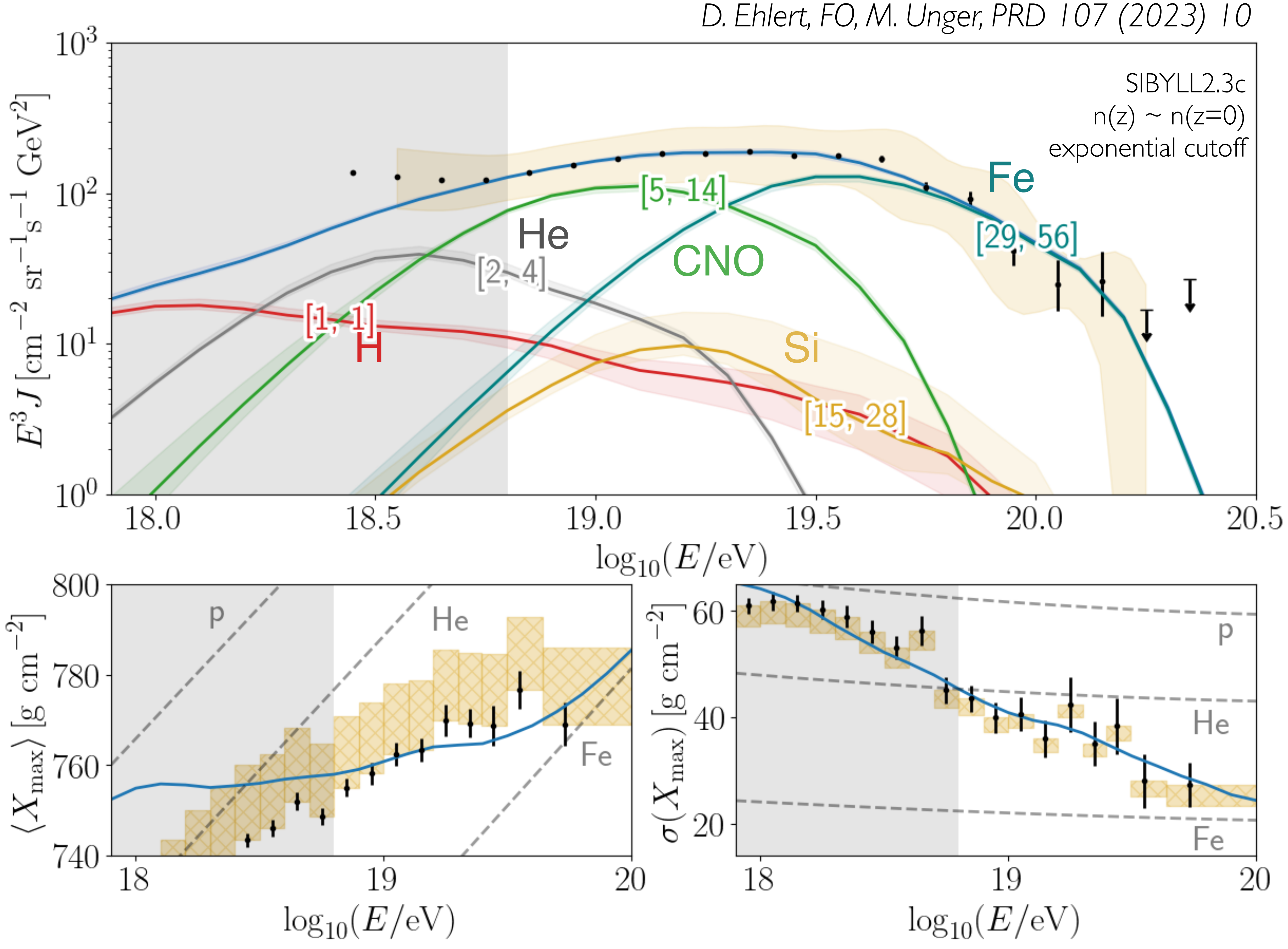




*A. Yushkov for the Auger Coll, ICRC 2019*

# A curious maximum rigidity distribution

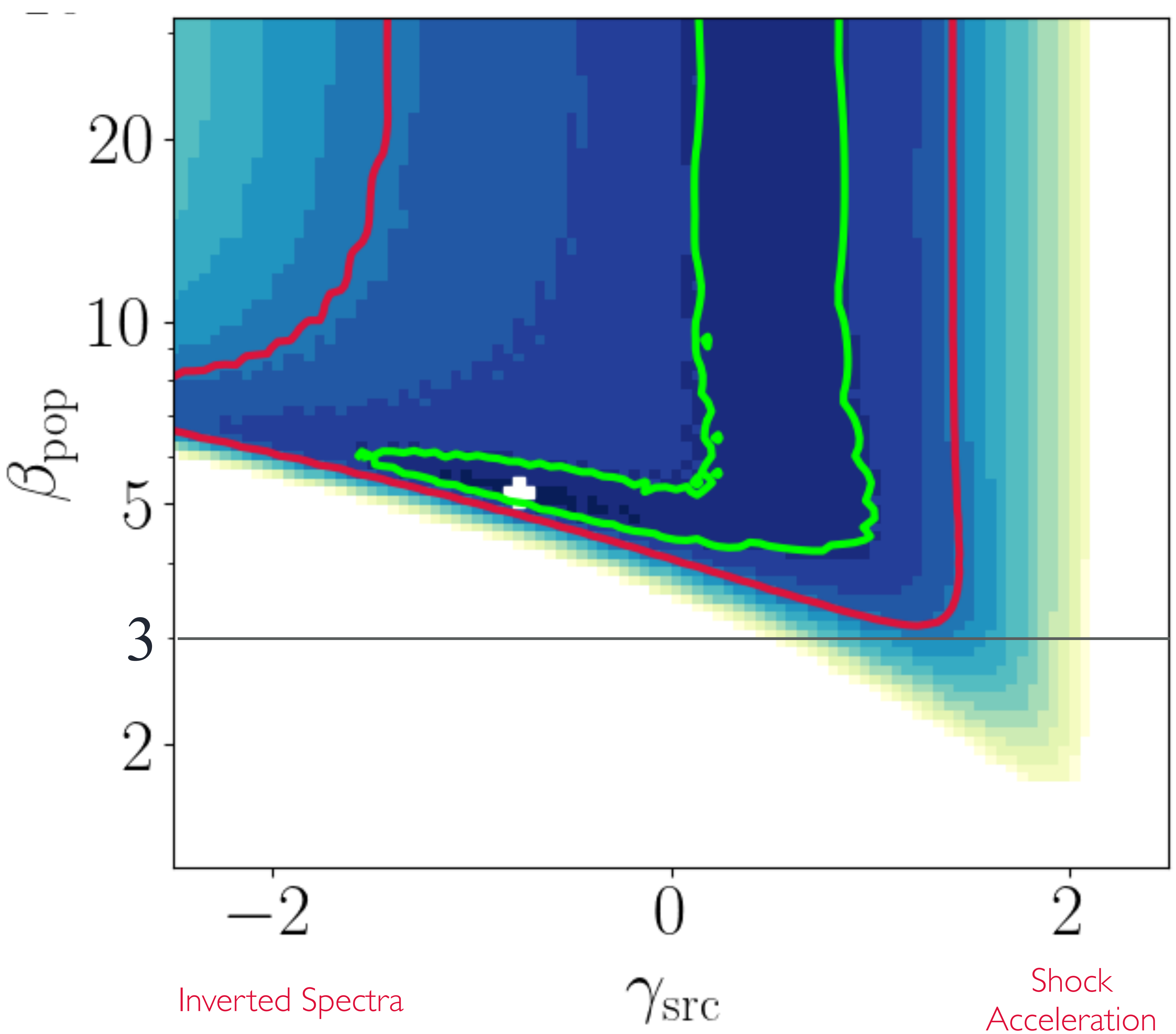



D. Ehlert, FO, M. Unger, PRD 107 (2023) 10



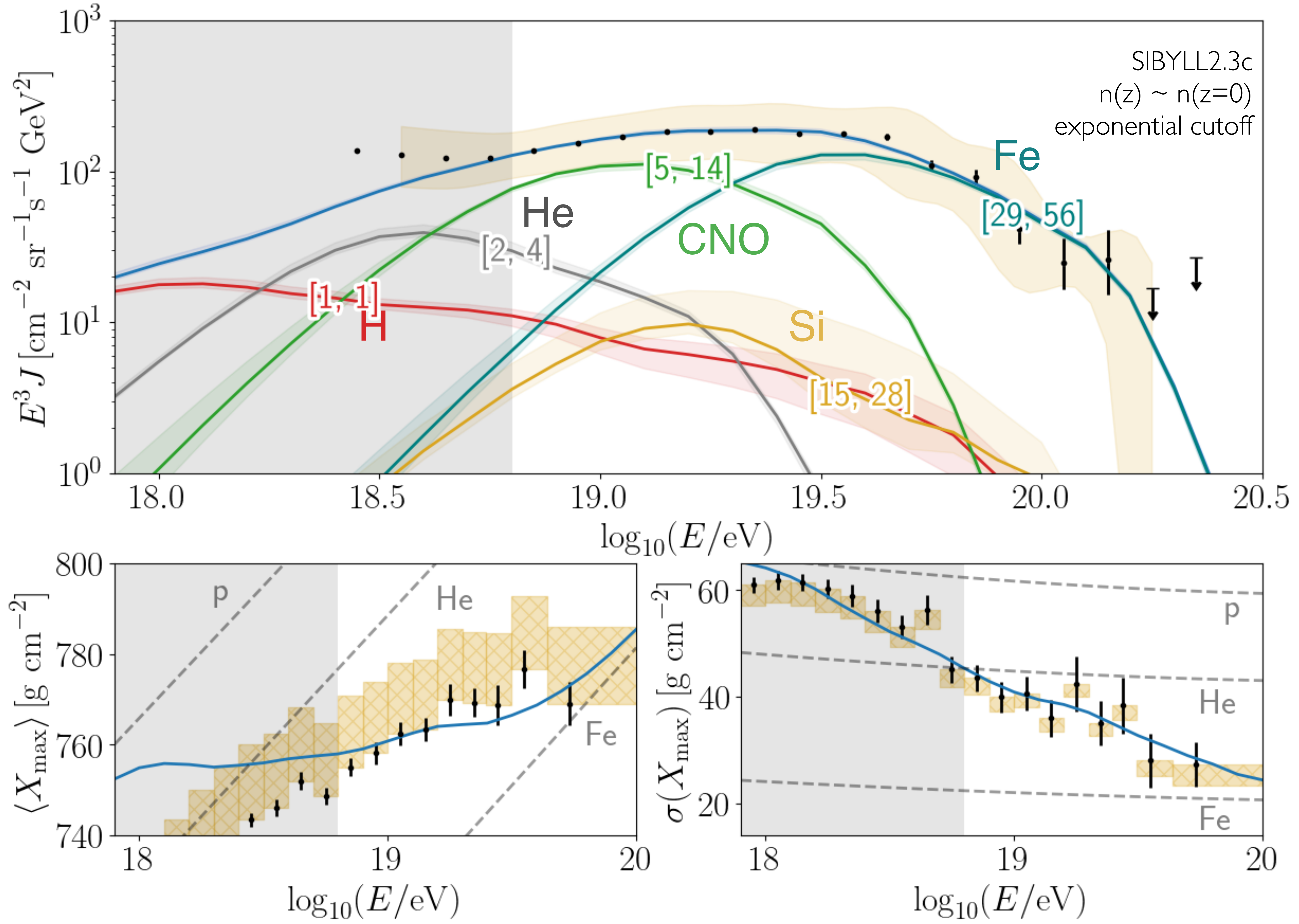

$$\frac{\mathrm{d}N}{\mathrm{d}R} \propto R^{-\gamma_{\rm src}} \qquad \frac{\mathrm{d}N}{\mathrm{d}R_{\max}} \propto R_{\max}^{-\beta_{\rm pop}} \qquad \phi_{\rm pop} \propto \begin{cases} R^{-\gamma_{\rm src}} & R \ll R_0 \\ R^{-\gamma_{\rm src}-\beta_{\rm pop}+1} & R \gg R_0 \end{cases}$$

# A curious maximum rigidity distribution



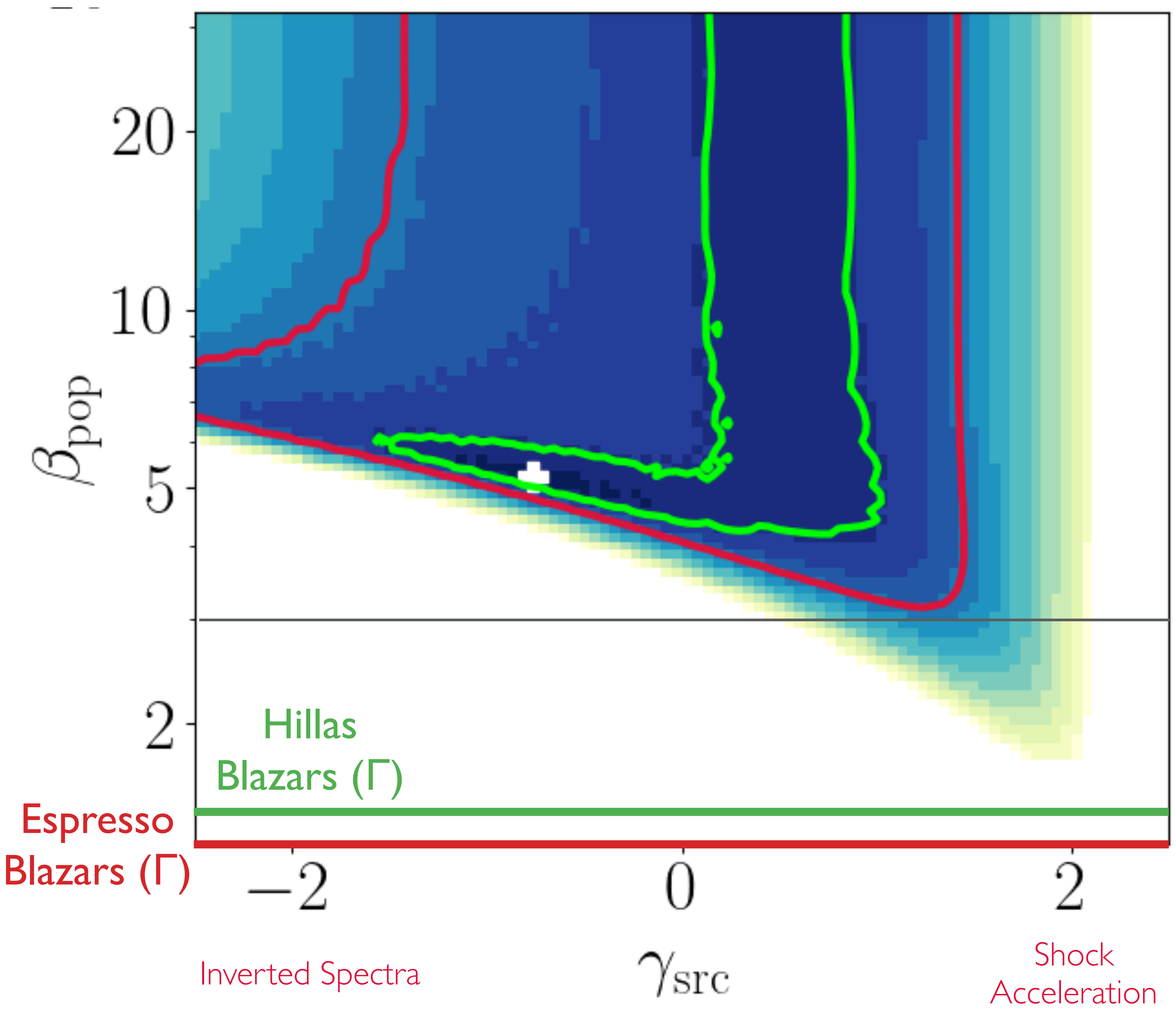

Inverted Spectra

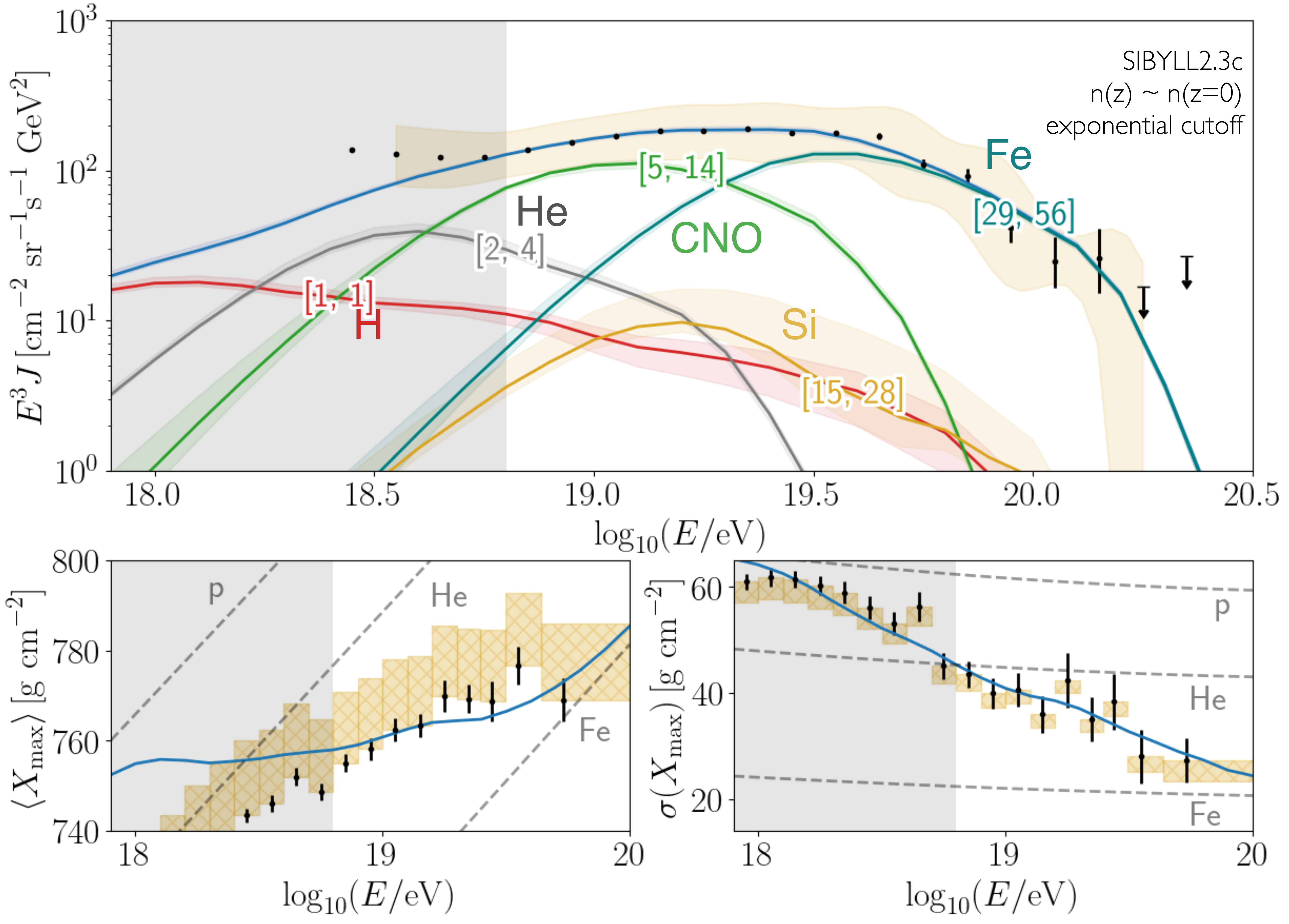
Shock Acceleration




$$\frac{\mathrm{d}N}{\mathrm{d}R} \propto R^{-\gamma_{src}} \qquad \frac{\mathrm{d}N}{\mathrm{d}R_{max}} \propto R_{max}^{-\beta_{pop}} \qquad \phi_{pop} \propto \begin{cases} R^{-\gamma_{src}} & R \ll R_0 \\ R^{-\gamma_{src}-\beta_{pop}+1} & R \gg R_0 \end{cases}$$

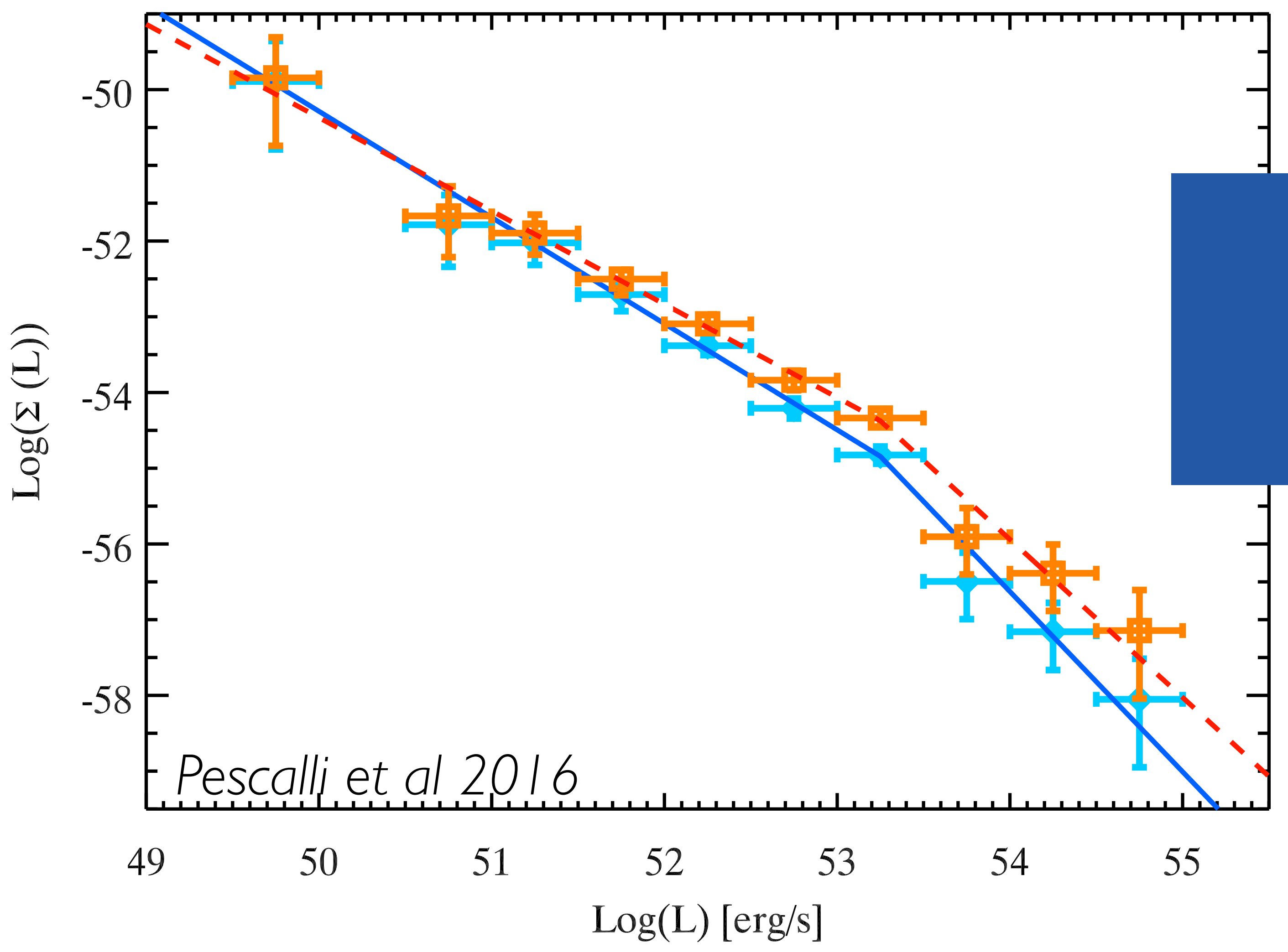
# A curious maximum rigidity distribution



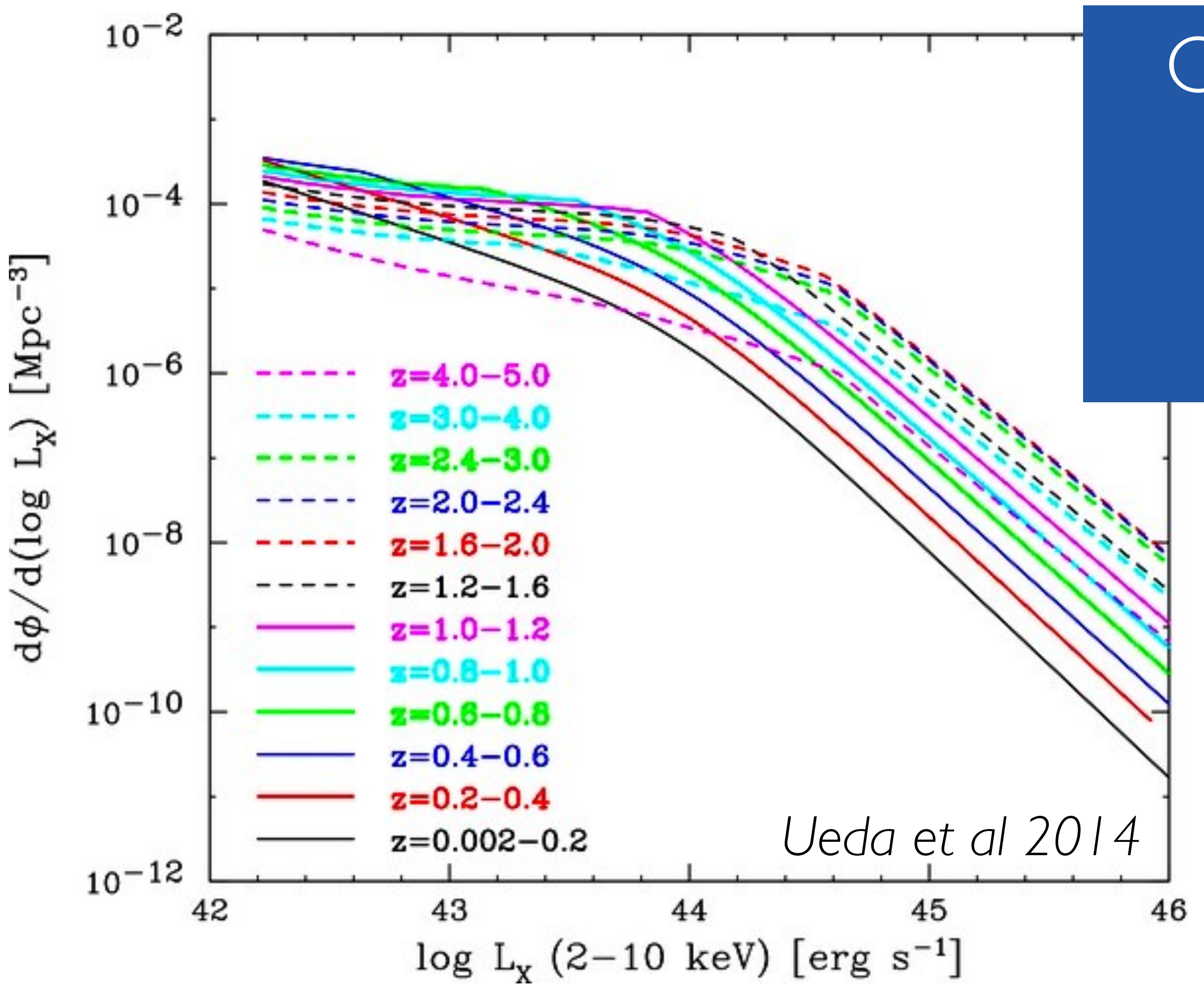




$$\frac{dN}{dR} \propto R^{-\gamma_{src}} \qquad \frac{dN}{dR_{max}} \propto R_{max}^{-\beta_{pop}} \qquad \phi_{pop} \propto \begin{cases} R^{-\gamma_{src}} & R \ll R_0 \\ R^{-\gamma_{src}-\beta_{pop}+1} & R \gg R_0 \end{cases}$$

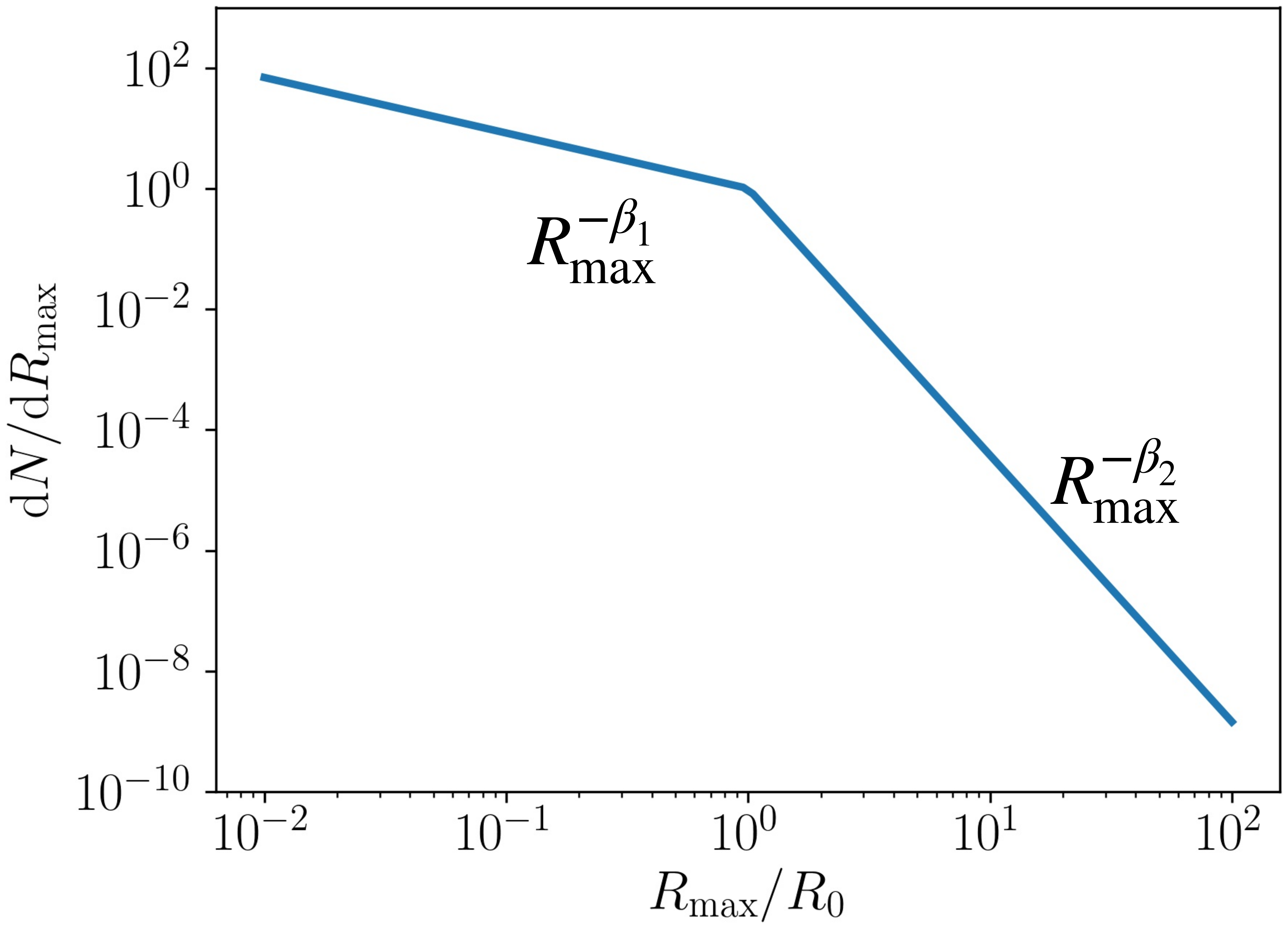
# Broken-power-law distributed maximum rigidity



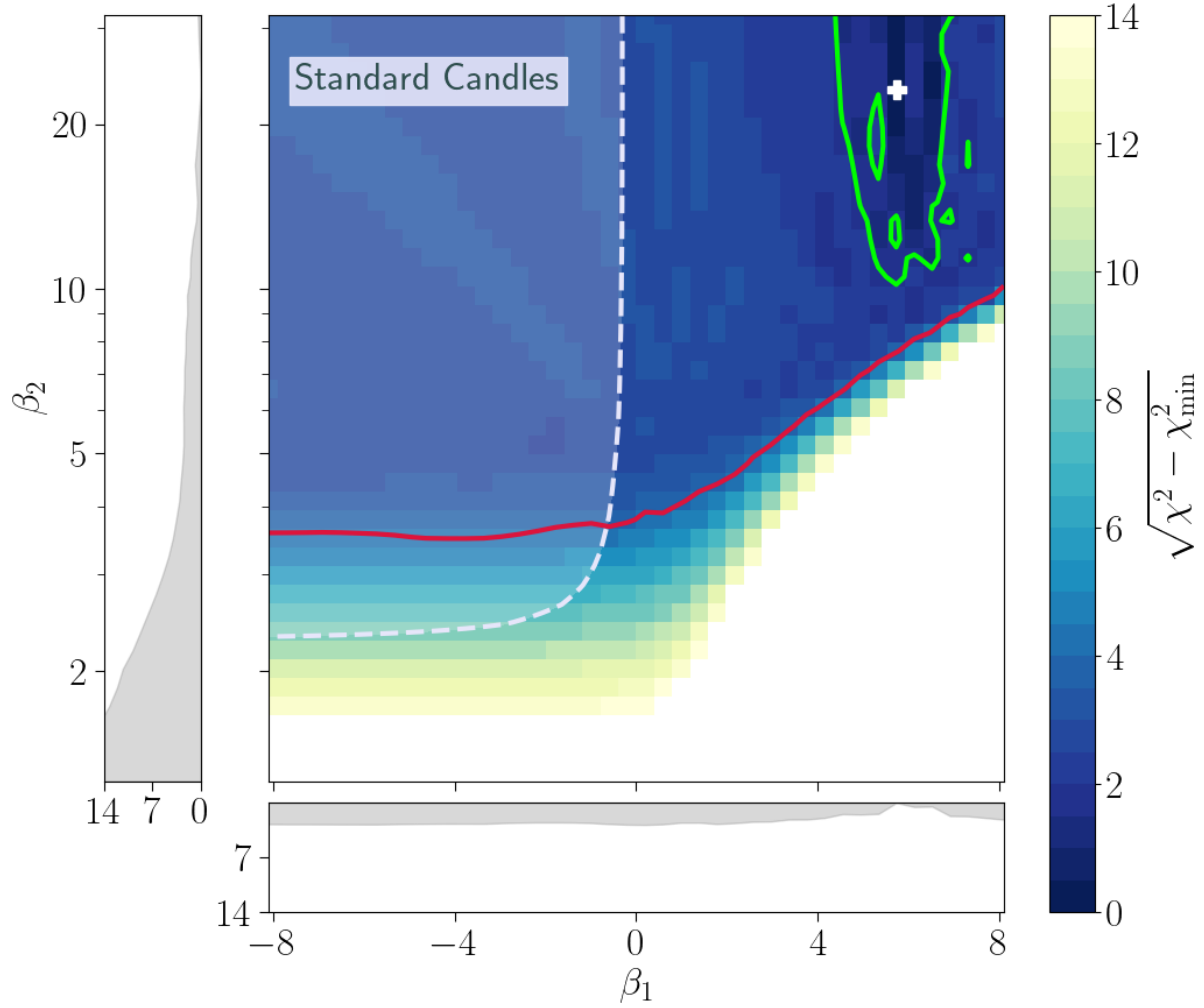

Long GRB luminosity function

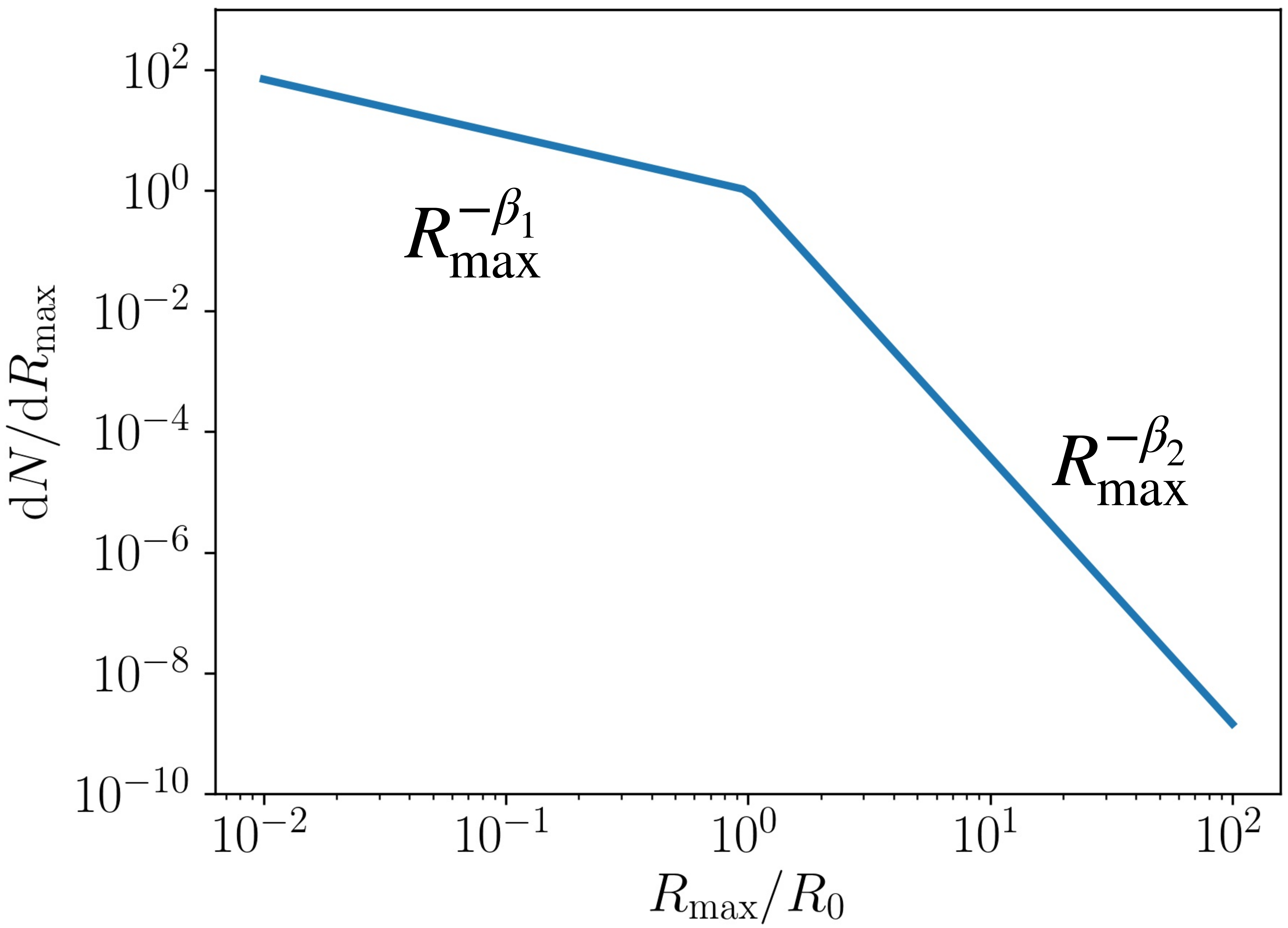



Compton thick AGN luminosity function

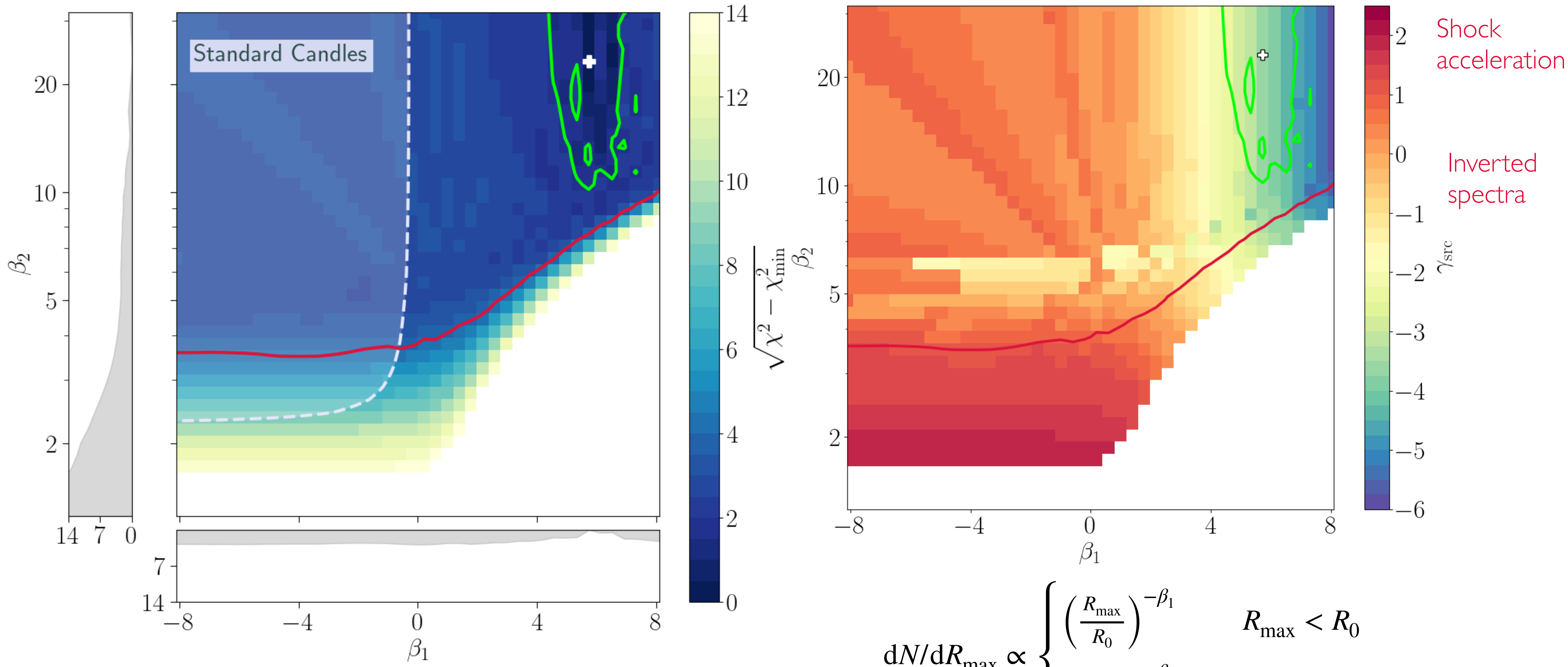


# Broken-power-law distributed maximum rigidity



# Broken-power-law distributed maximum rigidity




$$
\mathrm{d}N/\mathrm{d}R_{\max} \propto \begin{cases} \left(\frac{R_{\max}}{R_0}\right)^{-\beta_1} & R_{\max} < R_0 \\ \left(\frac{R_{\max}}{R_0}\right)^{-\beta_2} & R_{\max} > R_0 \end{cases}
$$

# Comparison with luminosity functions

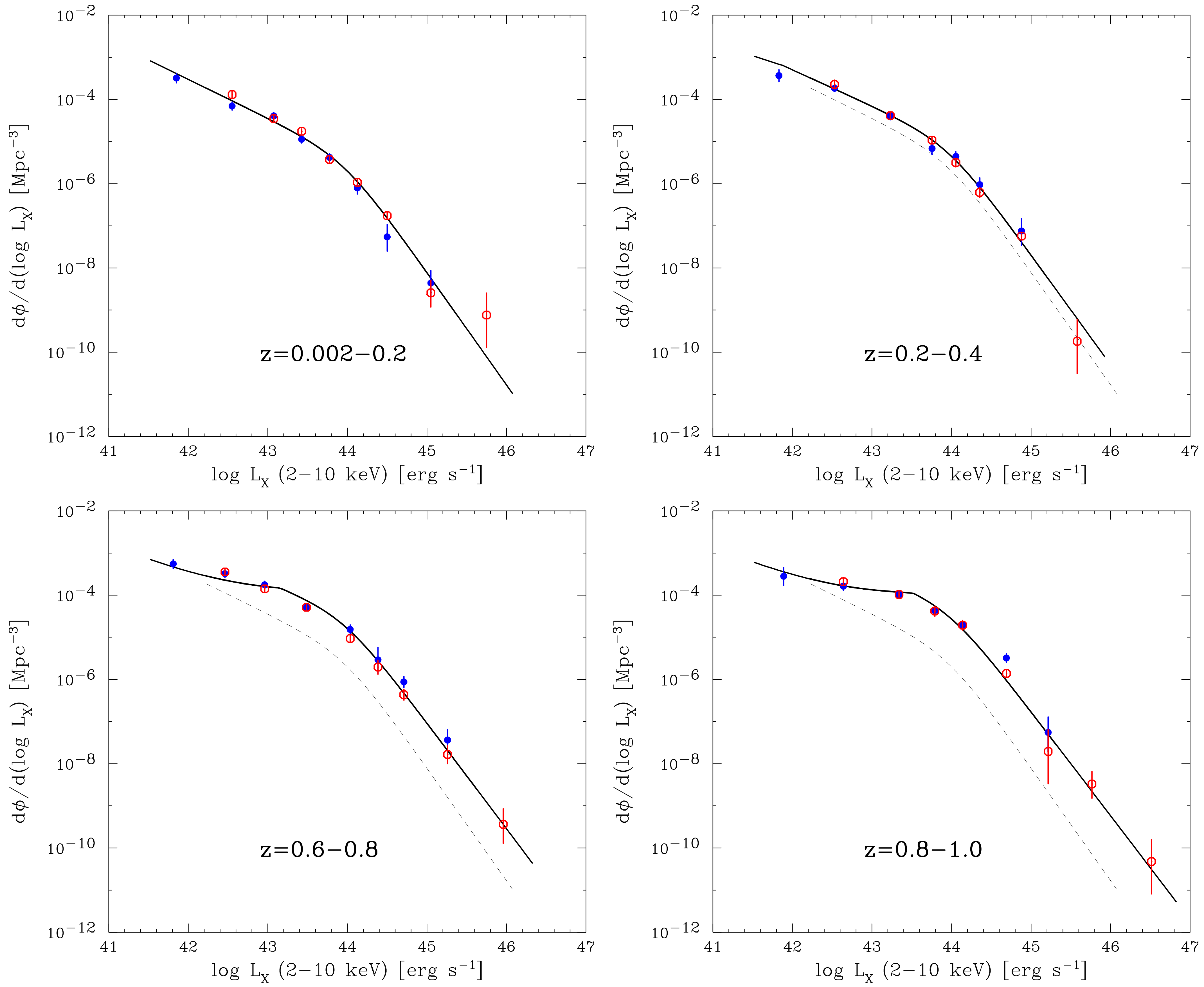
$$L \gtrsim L_B \sim \frac{U_B \cdot \text{Volume}}{t} \sim B^2 R^2 \Gamma^4 c$$

$$L_{\text{min}} \sim 10^{44.5}\ \text{erg/s} \cdot \Gamma^2 \cdot \left(\frac{E}{100\ \text{EeV}}\right)^2$$

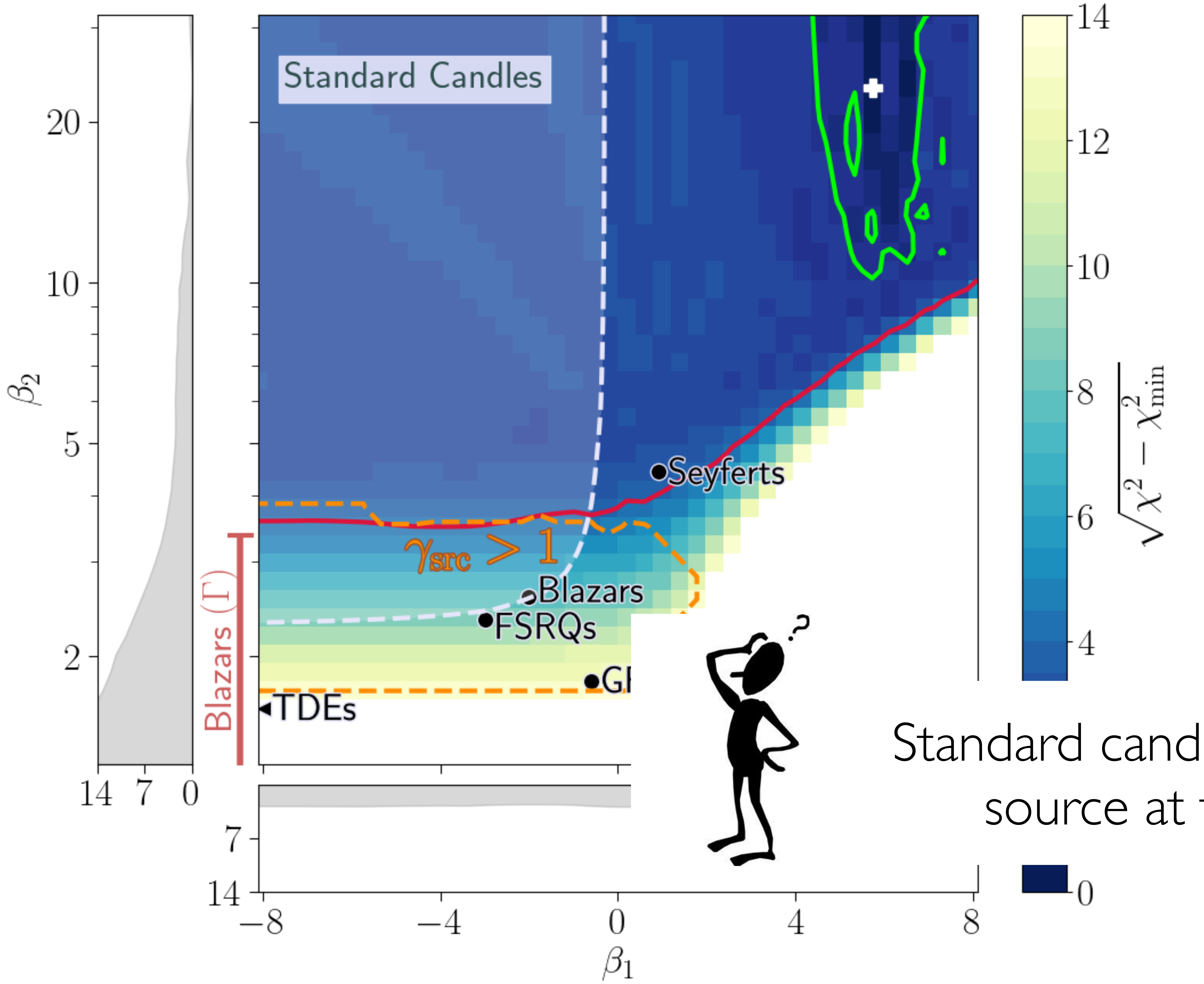
$$E_{\text{max}} \sim 100\ \text{EeV} \cdot \frac{1}{\Gamma} \cdot \left(\frac{L}{10^{45.5}\ \text{erg/s}}\right)^{1/2}$$

*Lovelace 1976, Waxman 1995, 2001, Blandford 2000, Lemoine & Waxman 2009, Farrar & Gruzinov 2009*

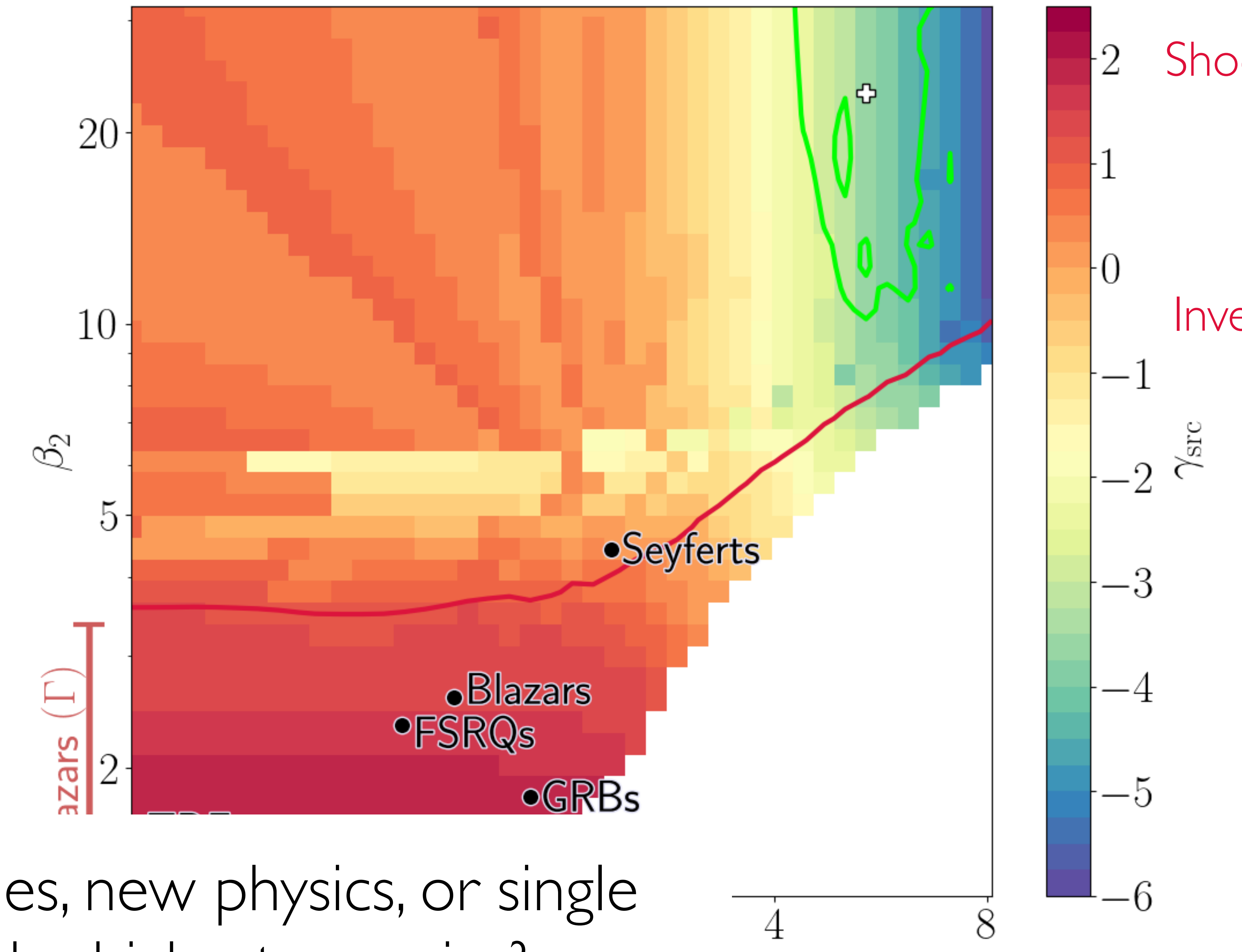
*Ueda et al 2014, X-ray AGN Luminosity Function*



# Broken-power-law distributed maximum rigidity




Individual source energy spectral index



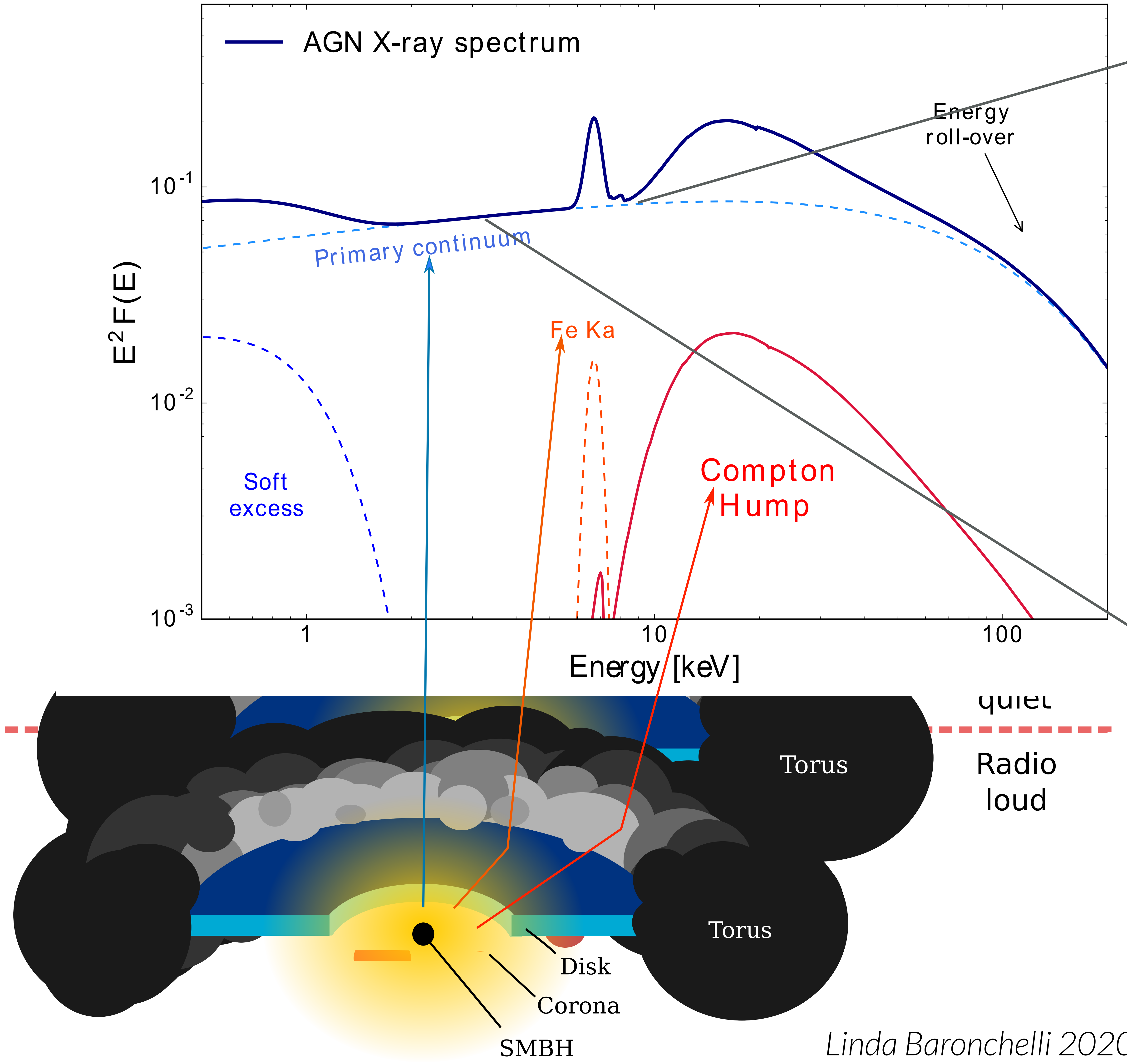

Shock acceleration

Inverted spectra

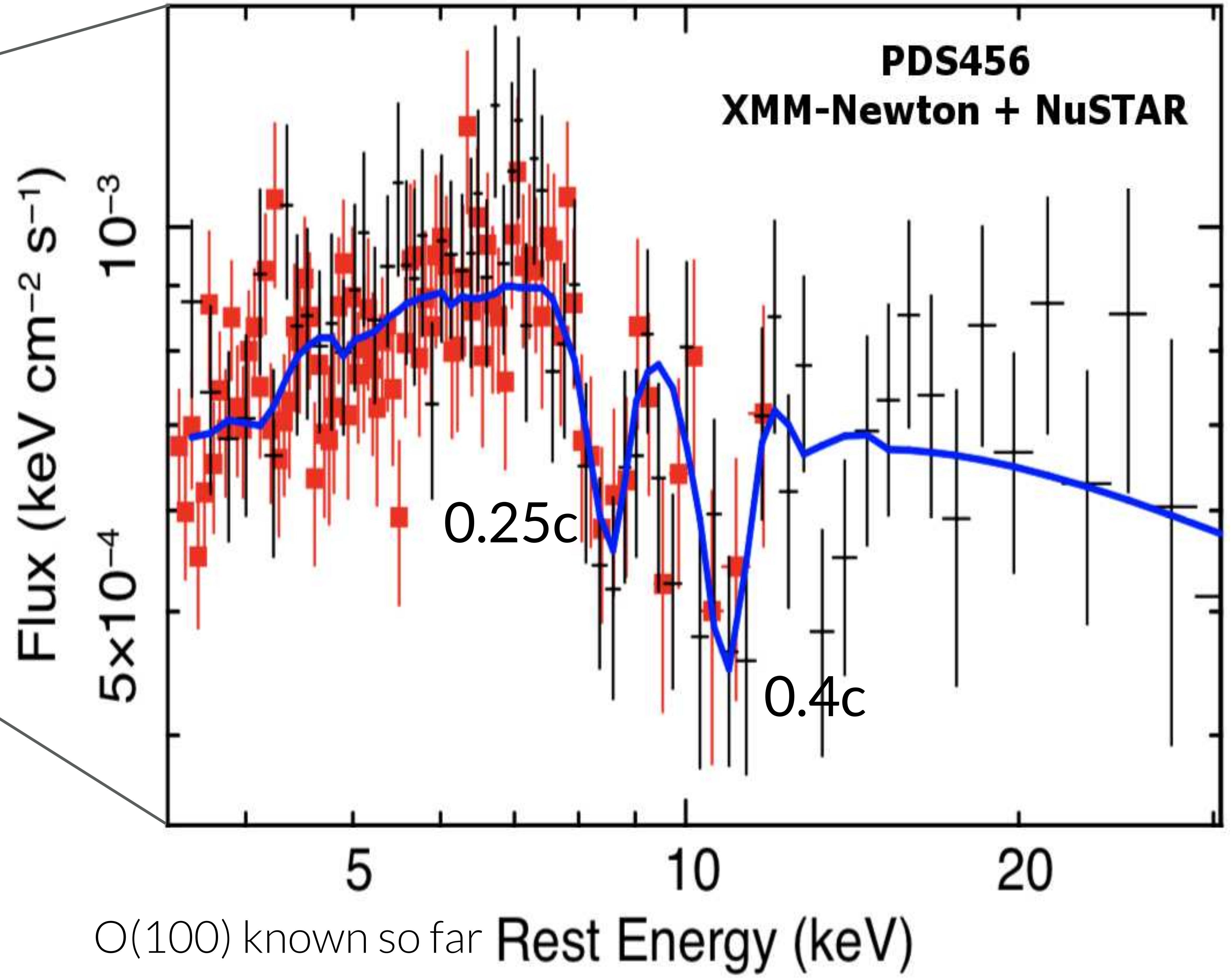
Standard candles, new physics, or single source at the highest energies?

$$\mathrm{d}N/\mathrm{d}R_{\max} \propto \begin{cases} \left(\frac{R_{\max}}{R_0}\right)^{-\beta_1} & R_{\max} < R_0 \\ \left(\frac{R_{\max}}{R_0}\right)^{-\beta_2} & R_{\max} > R_0 \end{cases}$$

# X-ray absorbers in AGN




Nardini et al 2015



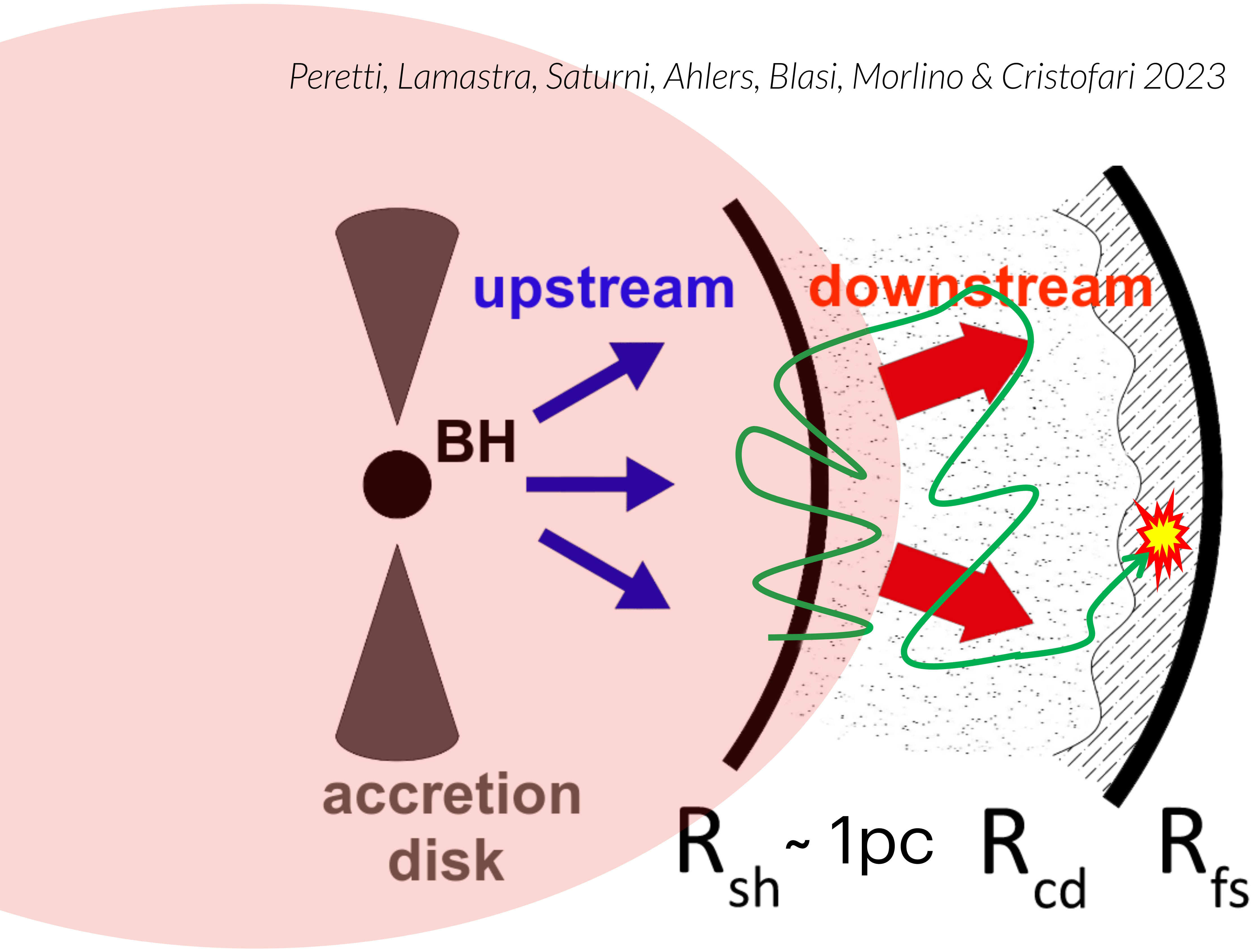

O(100) known so far

Observed in 50% of jetted and non-jetted AGN

Correlated with starburst activity (e.g. NGC 4945)

# UHECR acceleration in UFOs?

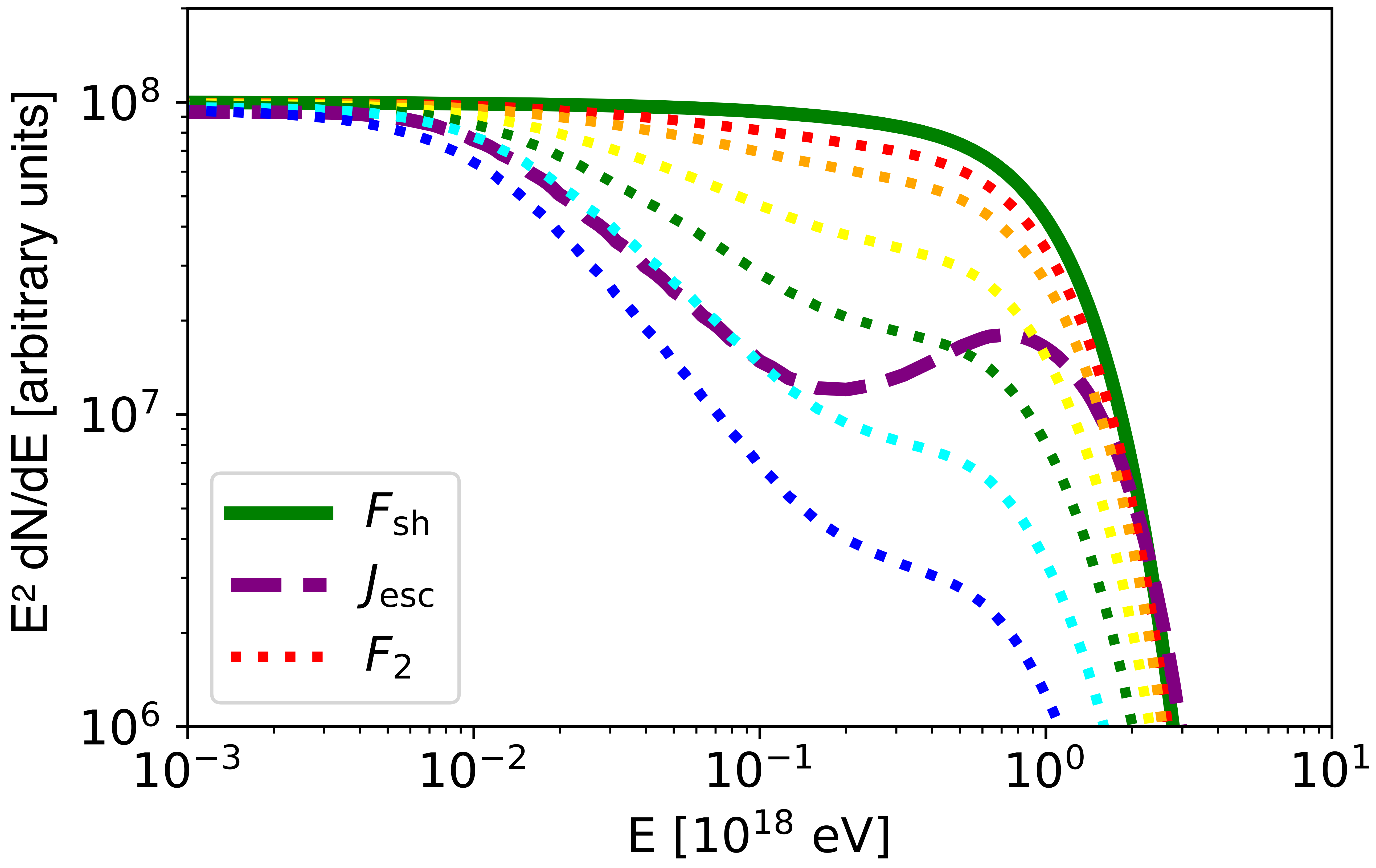
Peretti, Lamastra, Saturni, Ahlers, Blasi, Morlino & Cristofari 2023




IR torus $L_{IR} \sim 0.5 L_{disk}$

$$R_{IR} \sim 1 \text{ pc} \cdot \left(\frac{L_{disk}}{10^{45} \text{ erg/s}}\right)^{1/2}$$

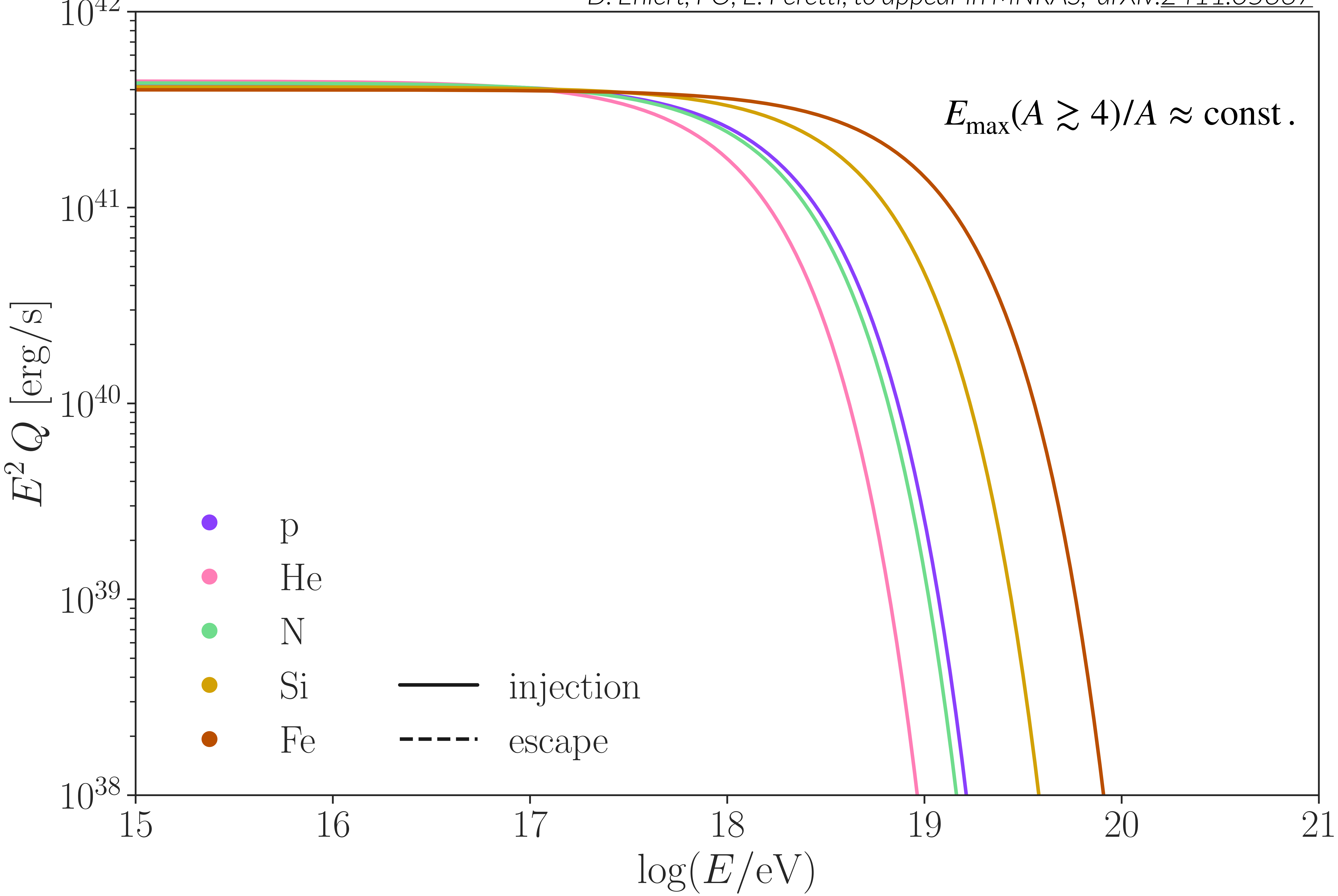
Peretti, Lamastra, Saturni, Ahlers, Blasi, Morlino & Cristofari 2023




$$E_{p,max} \sim 1 \text{ EeV} \left(\frac{\dot{M}}{0.1\ M_\odot \text{ yr}^{-1}}\right)^{1/2} \frac{v_{UFO}}{0.2c}$$

# UHECR nuclei in UFOs?

D. Ehlert, FO, E. Peretti, to appear in MNRAS, arXiv:2411.05667



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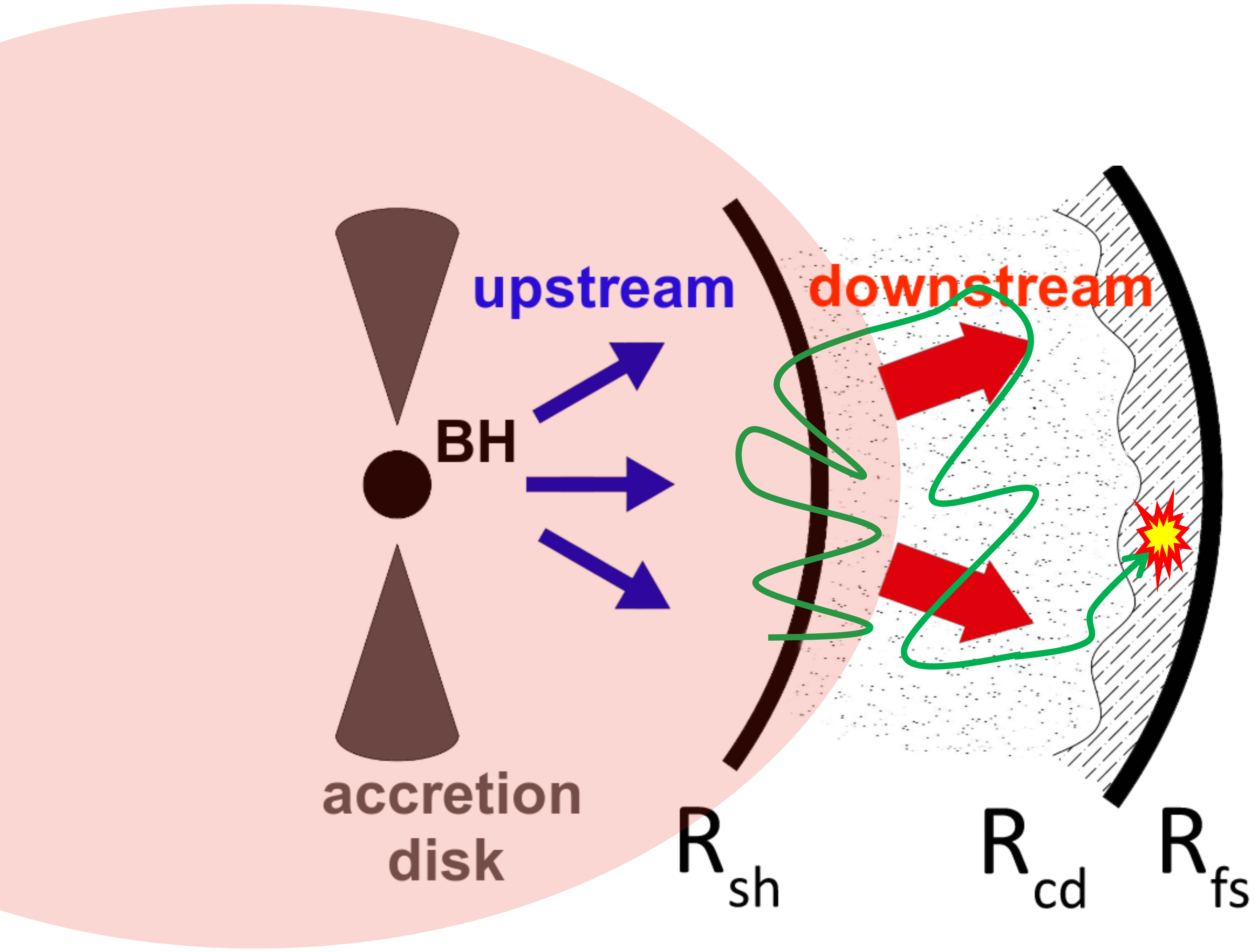


IR torus $L_{IR} \sim 0.5 L_{disk}$

$$R_{IR} \sim 1 \text{ pc} \cdot \left(\frac{L_{disk}}{10^{45} \text{ erg/s}}\right)^{1/2}$$

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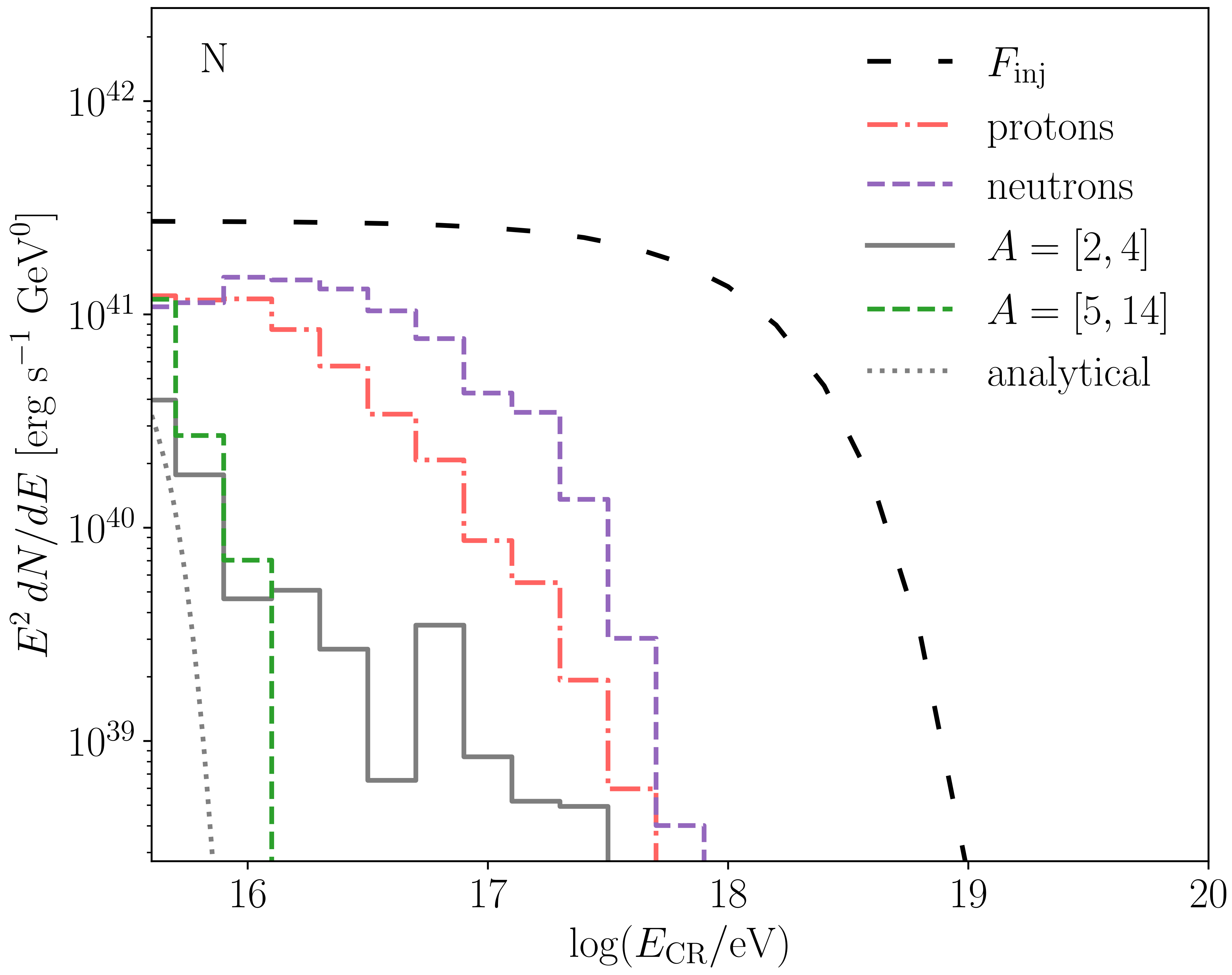

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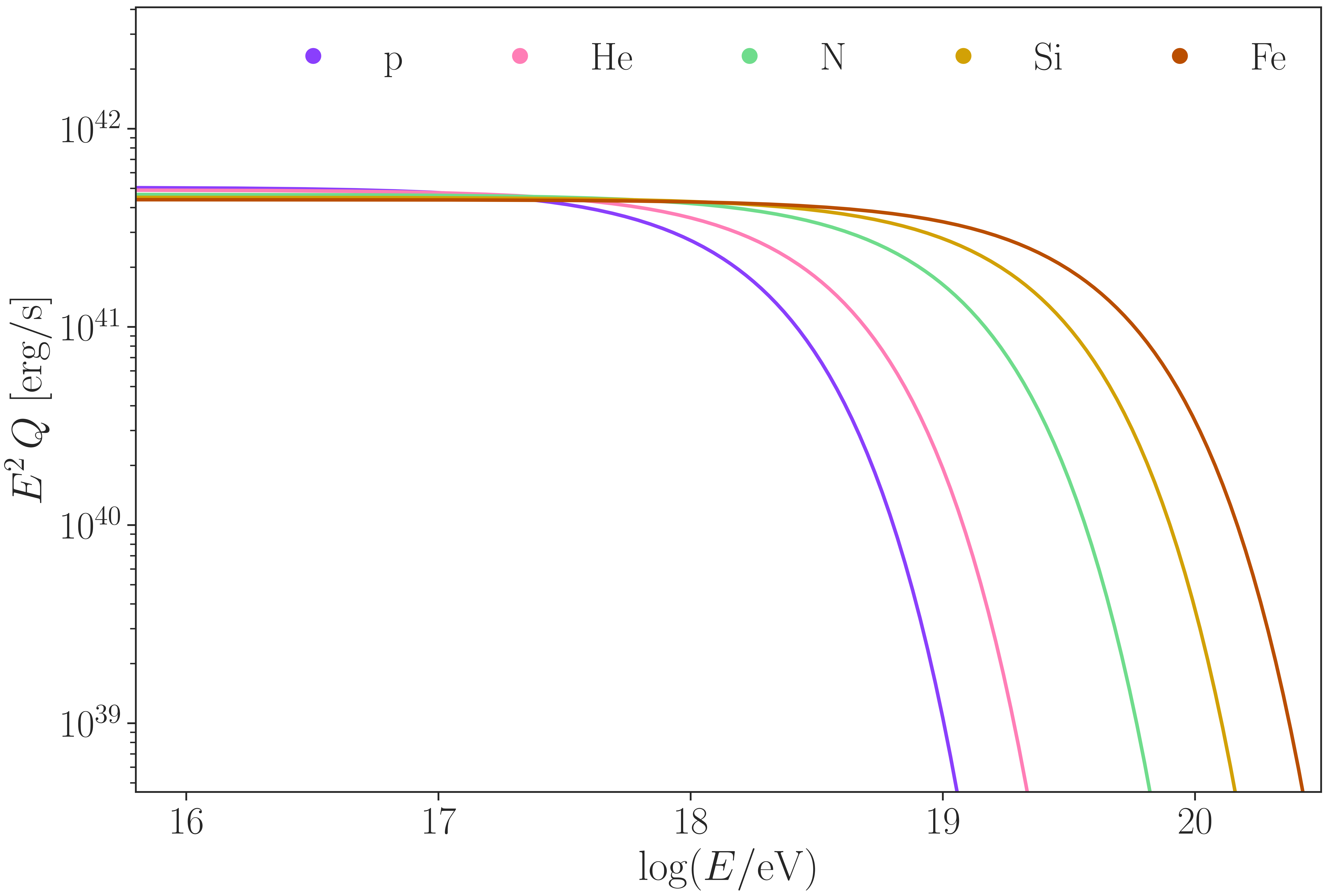

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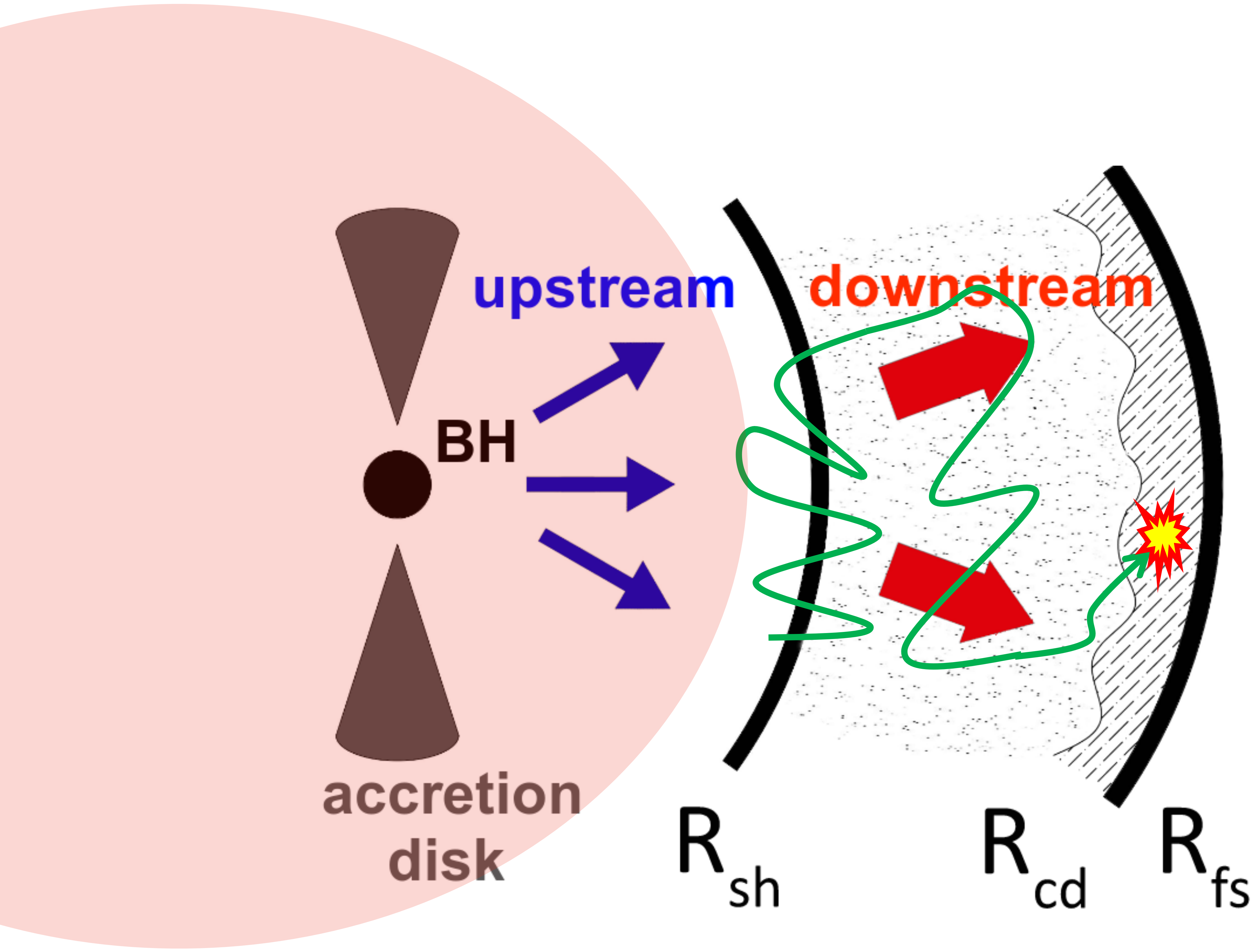


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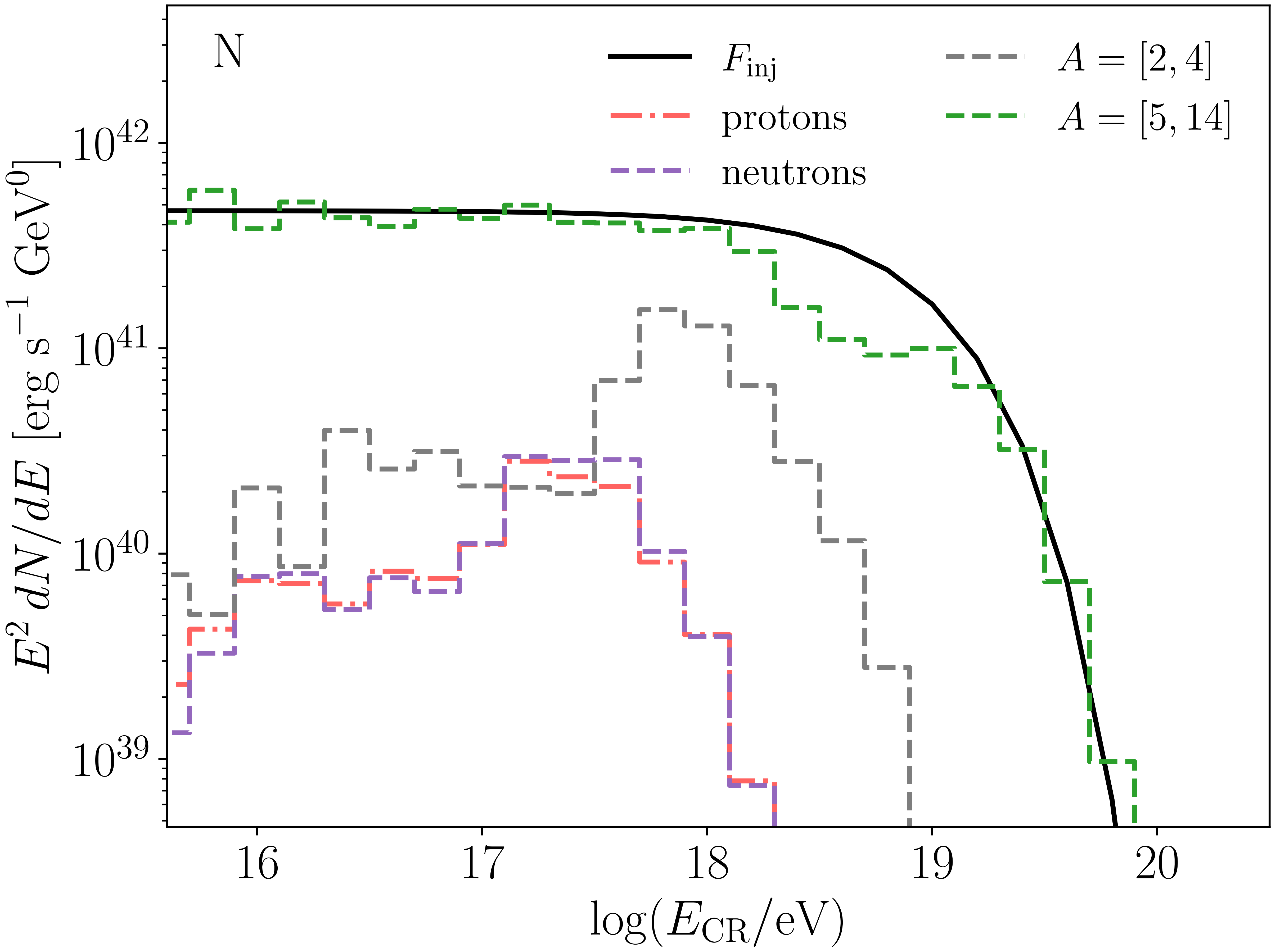
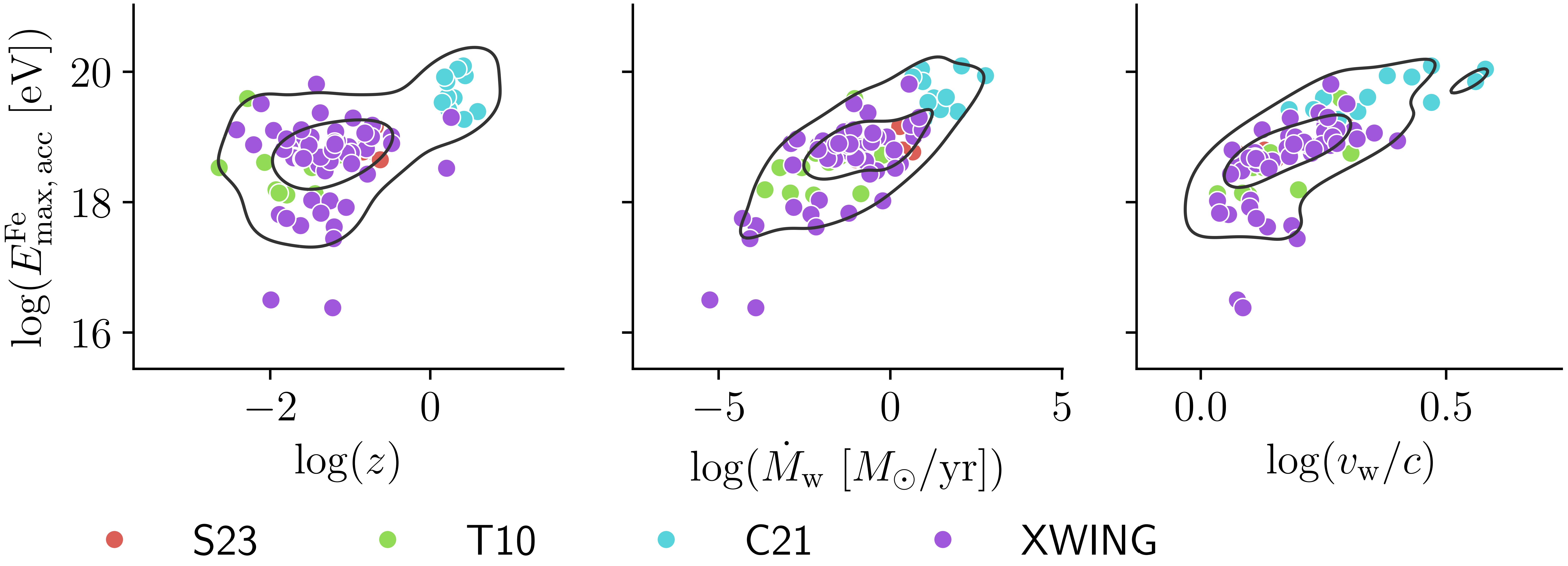
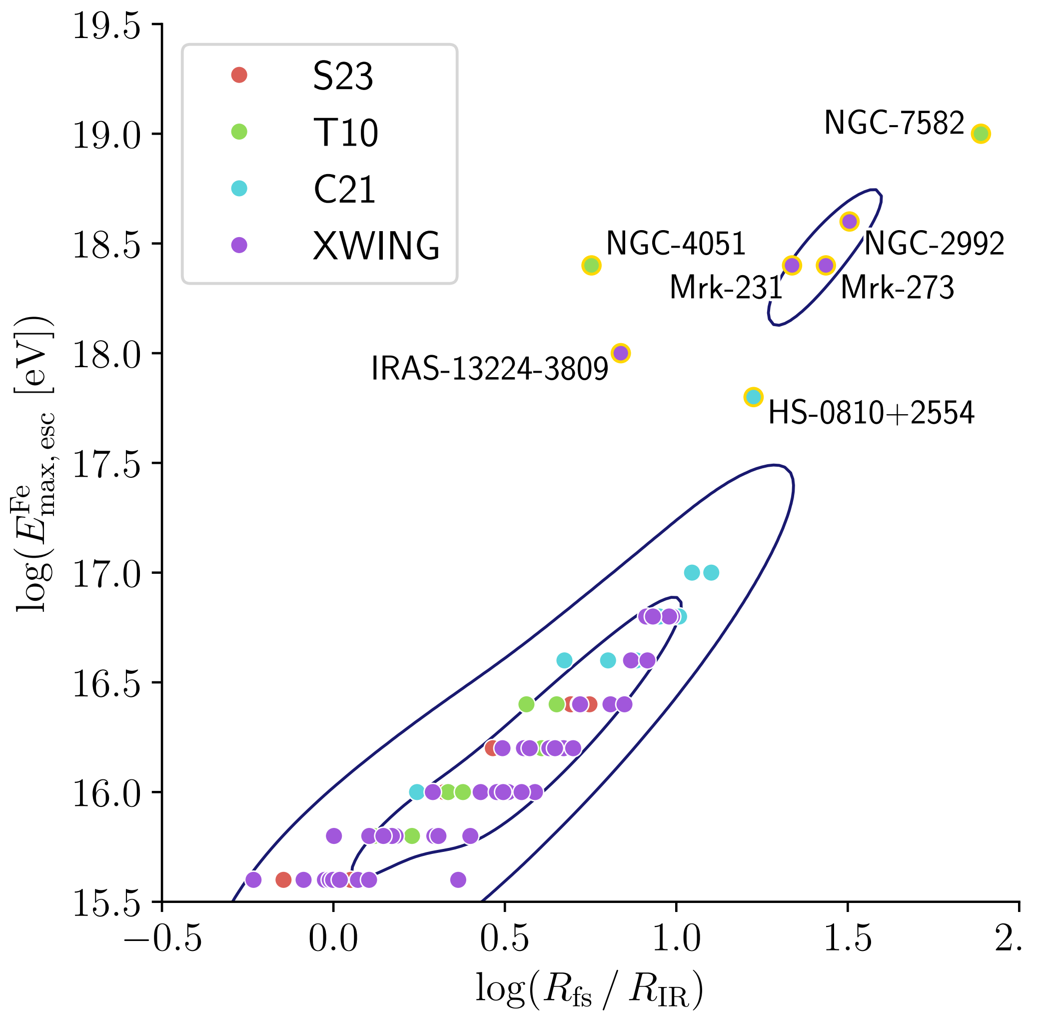


# Application to observed UFOs

**In total 87 UFOs from**

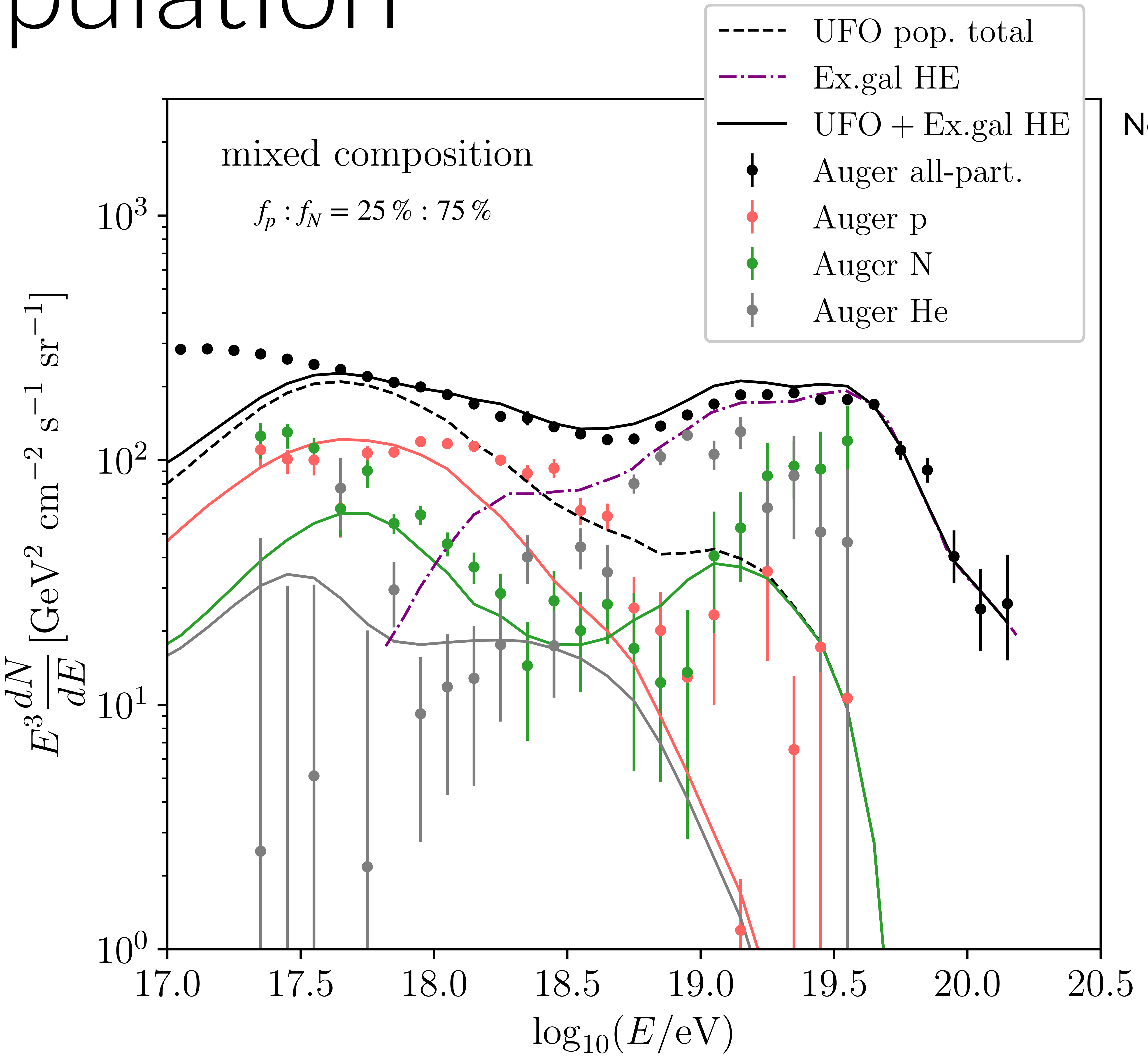
*Chartas et al 2009, Reeves et al 2009, 19, Riecchers et al 2009, Tombesi et al 2010, 12, 14, Gofford et al 2015*
*Nardini et al 2015, 18, Braito et al 2018, Fiore et al 2017, Boissay-Malaquin 2019, Smith et al 2019 , Ajello et al 2021, Laurenti et al 2021*



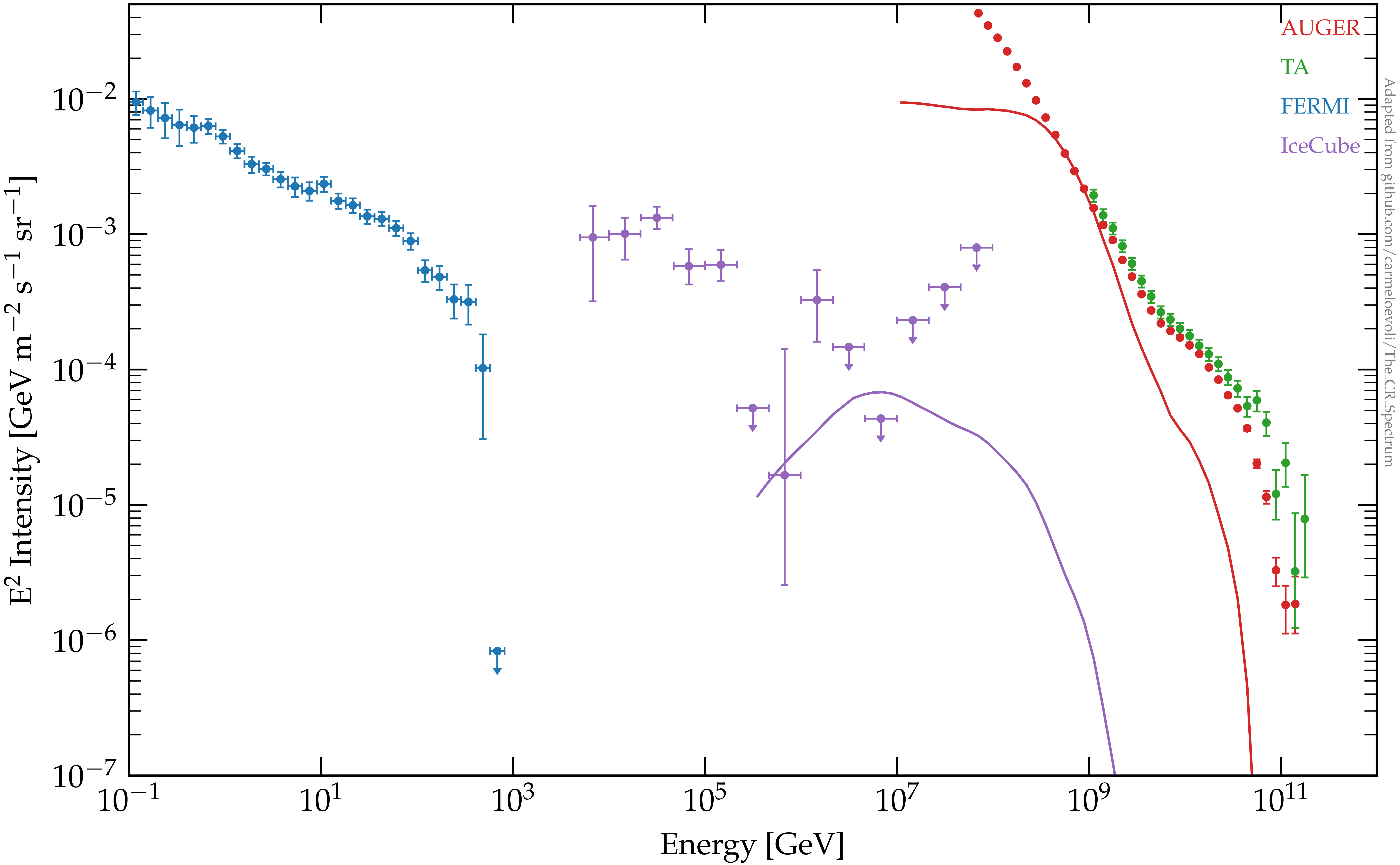
# AGN population

# AGN population




Not a fit

# UFO population: Diffuse neutrino flux



# Summary

**Maximum rigidity distribution:**

Sources with power-law distributed maximum rigidity required to be near identical

Additional variance expected from distribution of radius, magnetic field strength, photon fields…

Few sources? (In tension with arrival directions)
Near-identical sources?
Exotic physics?

**Ultra-fast outflows:**

Can ``fill'' the Galactic/Extra-galactic transition region

Maximum energy OK (most extreme UFOs)

Luminosity / energy budget OK

Observationally challenging. Starburst activity correlated with transients and AGN activity.