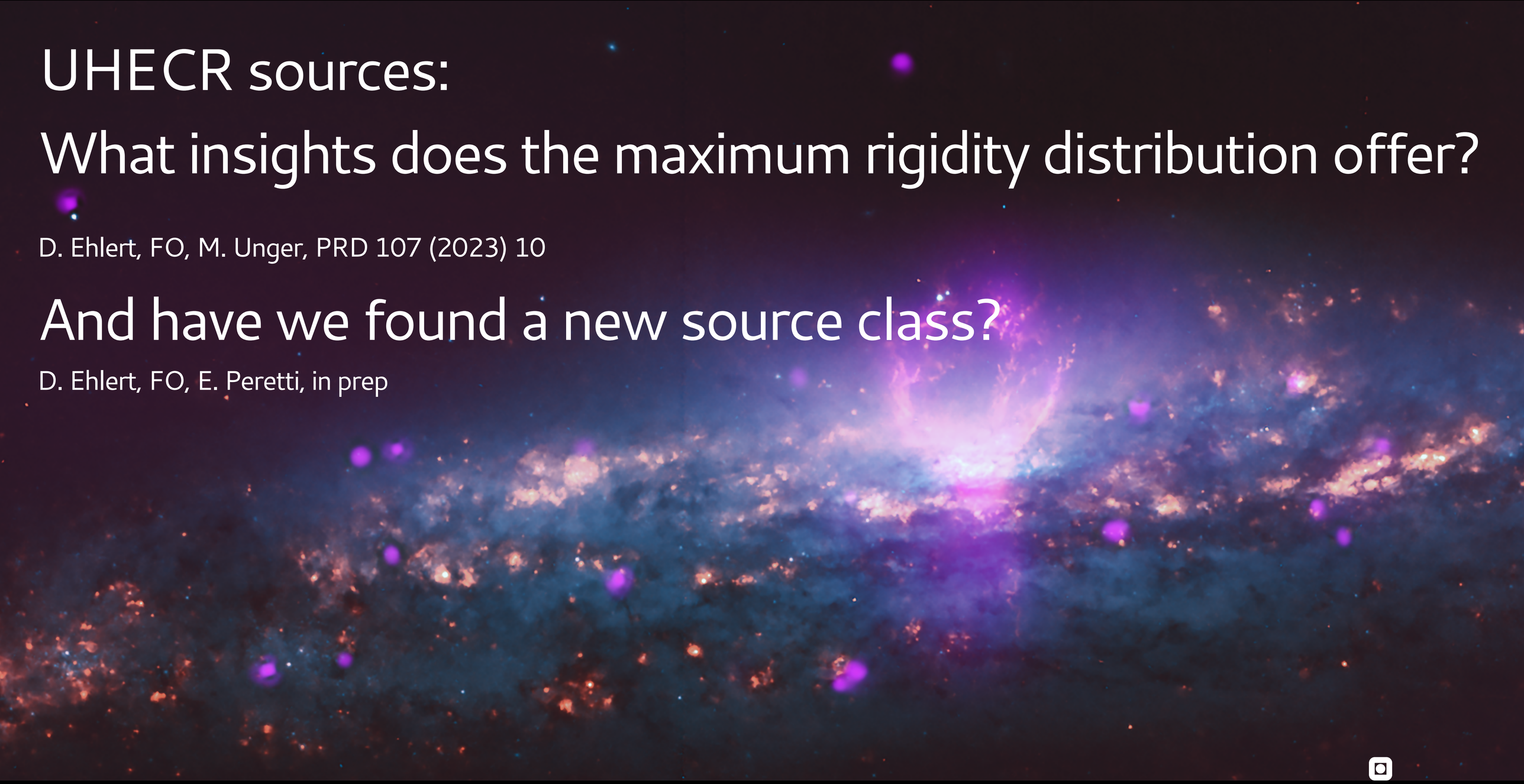
UHECR sources:

What insights does the maximum rigidity distribution offer?

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

And have we found a new source class?

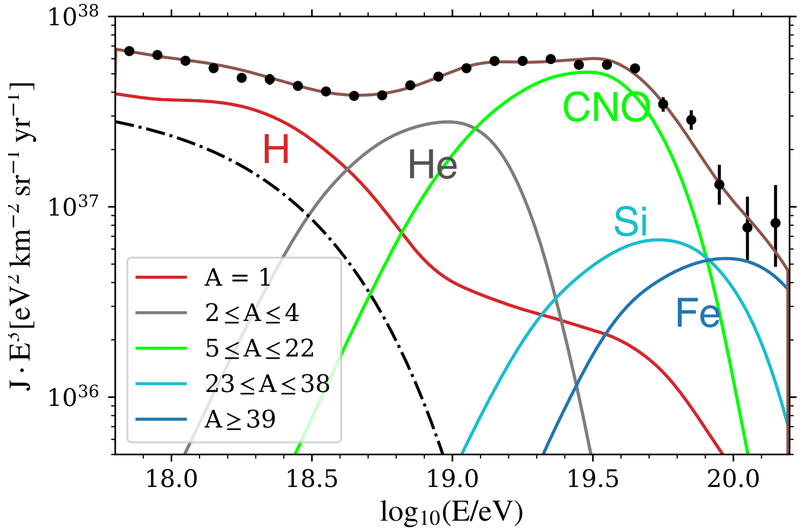
D. Ehlert, FO, E. Peretti, in prep

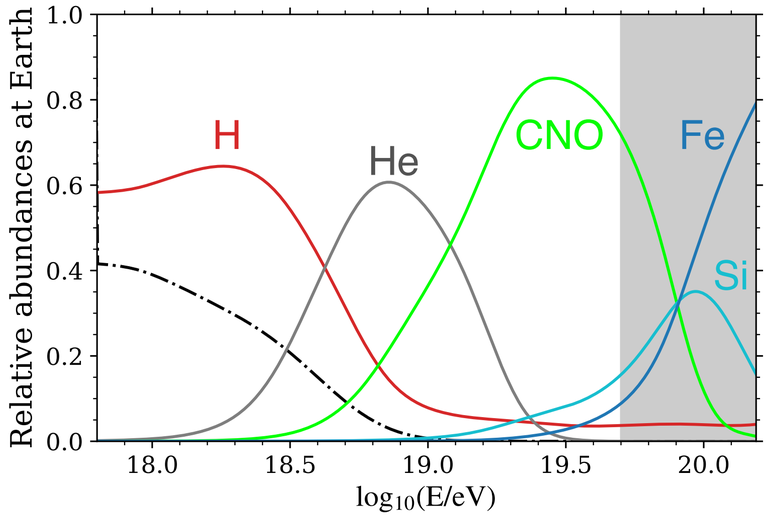


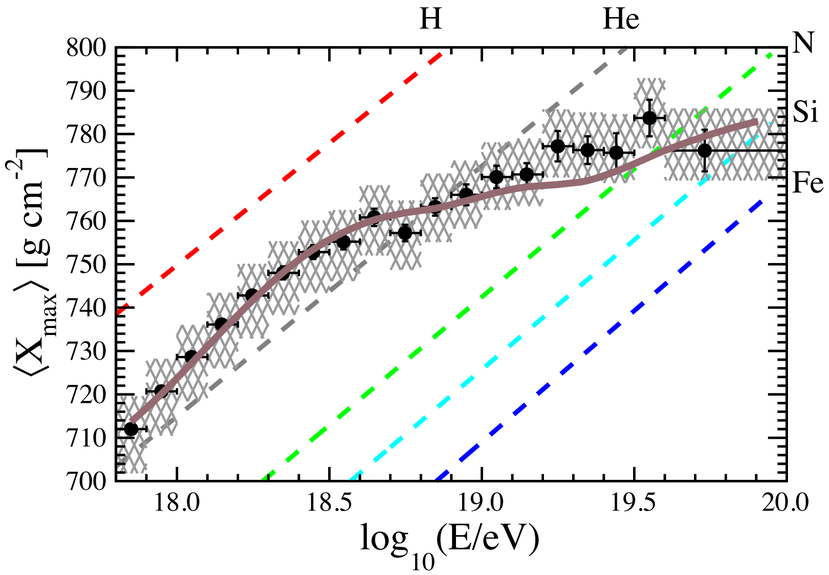
F. Oikonomou, IFPU, Feb 21st 2024

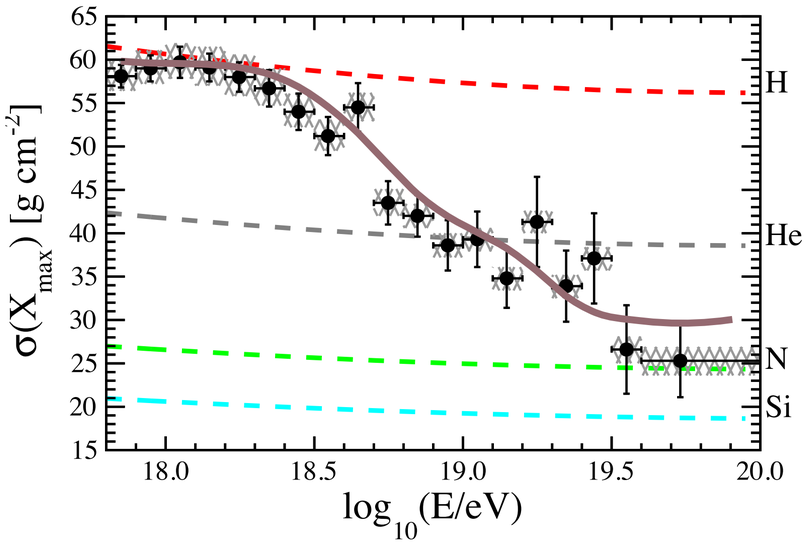
NTNU
Norwegian University of Science and Technology

Searching for the UHECR sources: Combined fit approach









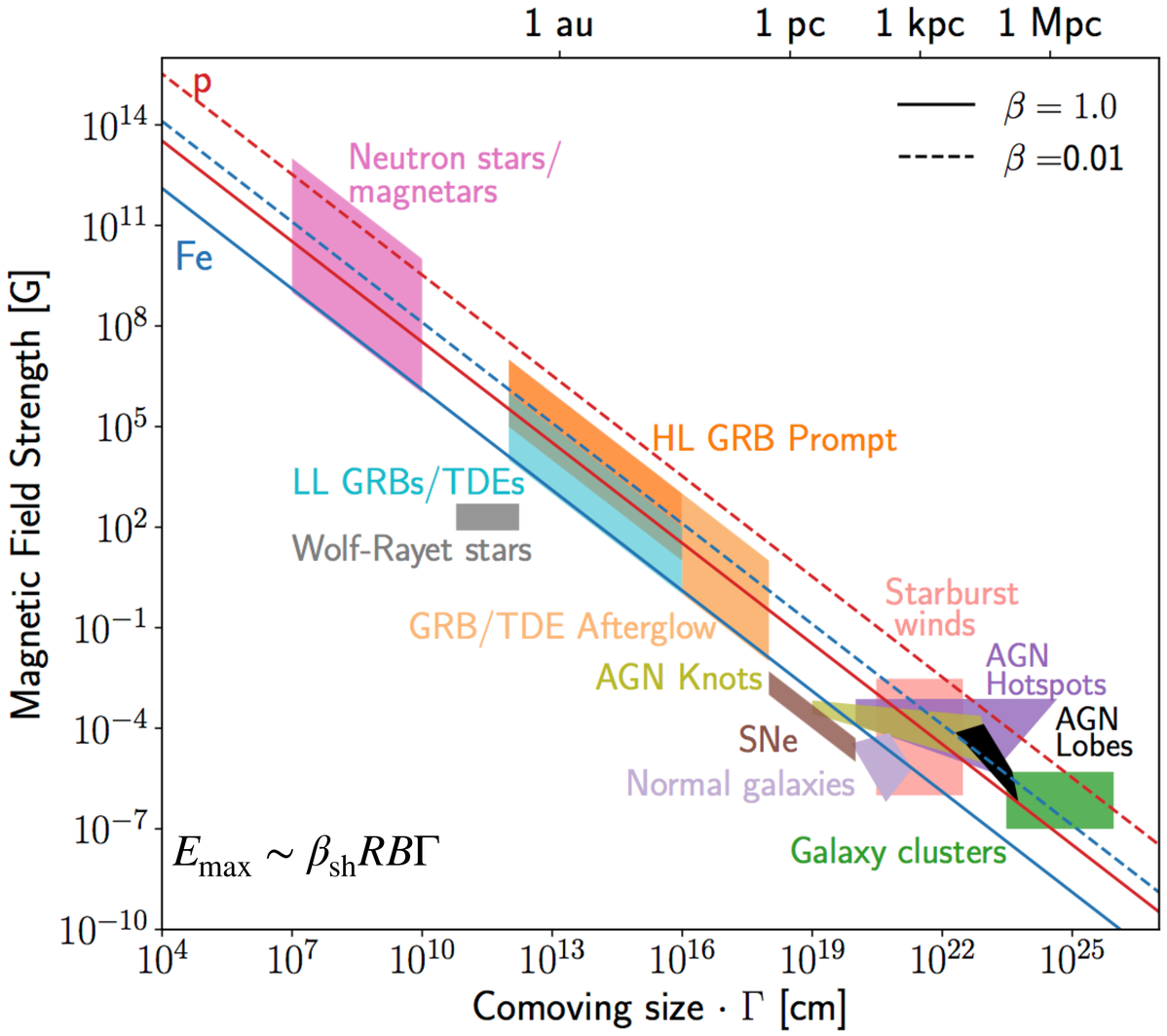
Generic Source Properties:
Allard et al 2007, 8, Hooper et al 2007, Unger et al 2015, Auger Coll 2016, Kachelriess et al 2017, Muzio et al 2019, 2022, Mollerach et al 2020, Das et al 2021.

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

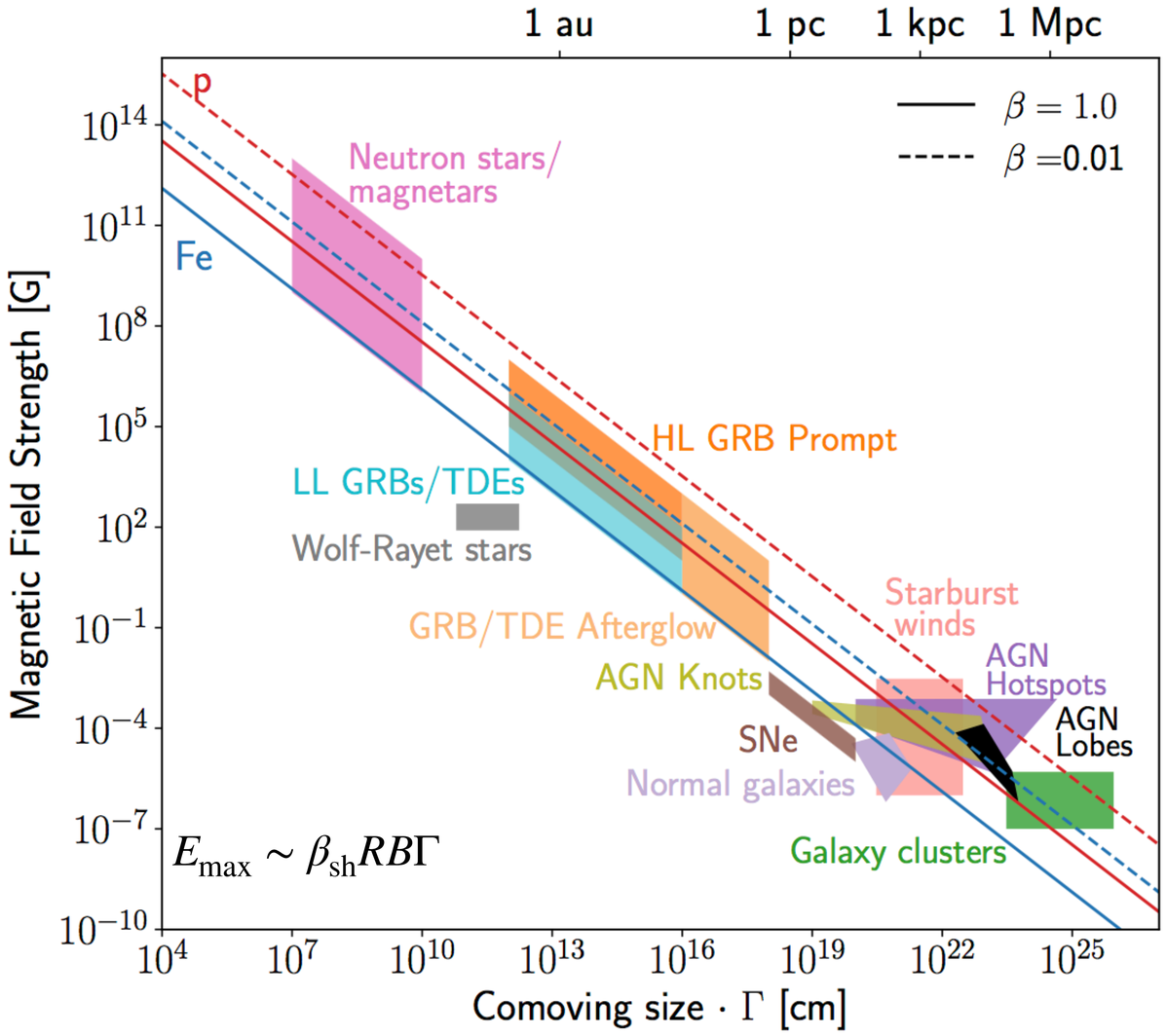
Distribution of maximum energies:
UHECR protons: *Kachelriess & Semikoz 2007*
Galactic sources: *Shibata et al 2010*
Discrete AGN: *Eichmann, Kachelriess, FO 2022*

Maximum UHECR energy



Alves Batista et al 2019, FrASS, 6, 23

Maximum UHECR energy

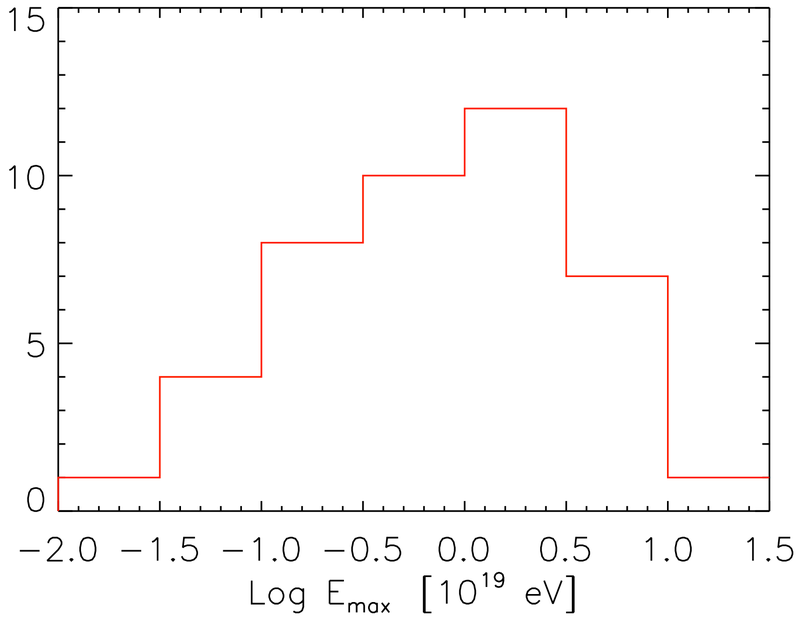


Alves Batista et al 2019, FrASS, 6, 23

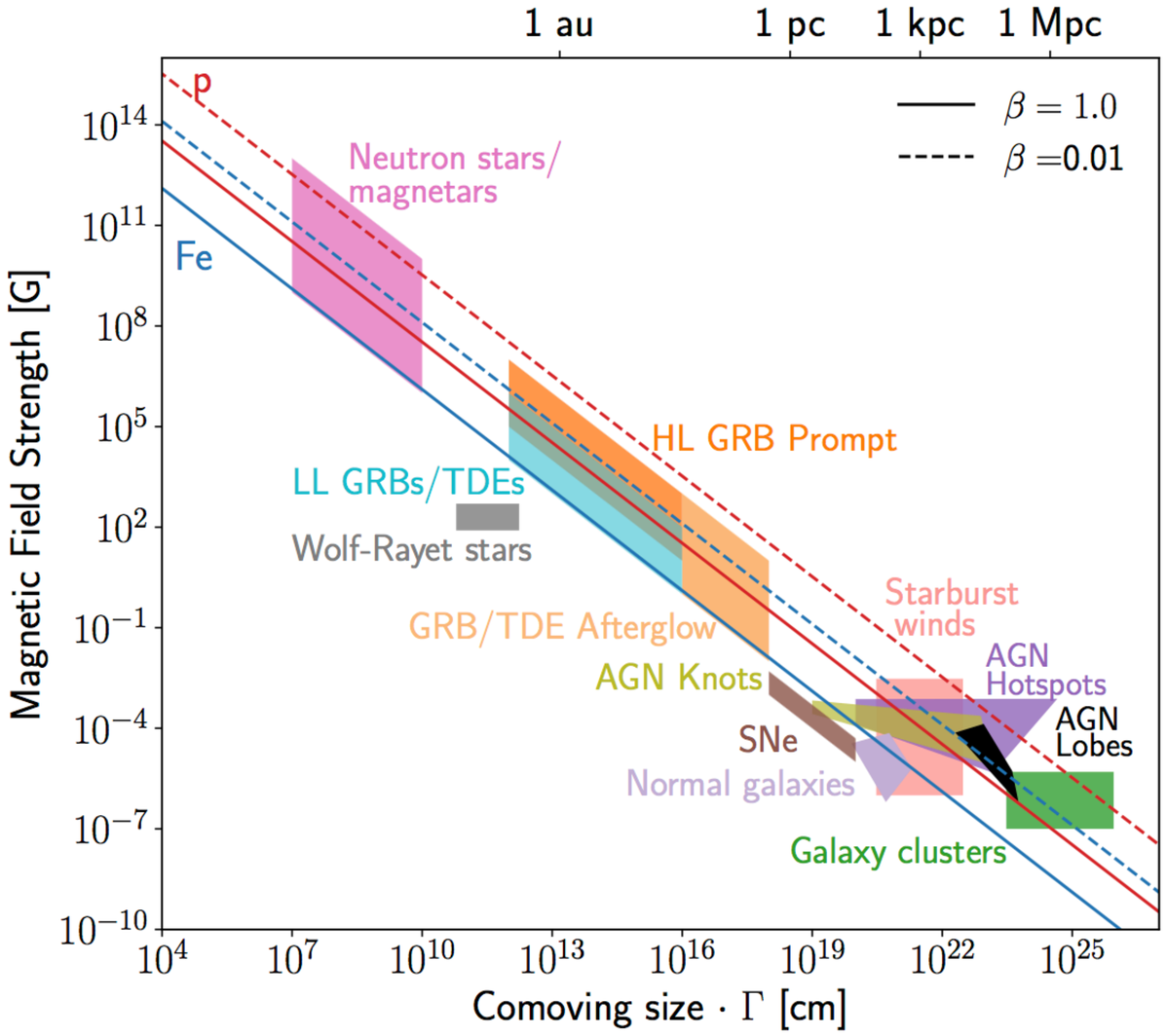
$E_{\rm max} \sim \beta_{\rm sh} RB\Gamma$

e.g. 43 TeV emitting blazars in minimal SSC model
B ~ 10^{-4} - 10 G
R~10^{15} - 10^{17} cm
Γ~ 10-50
E_{max} ~ 10^{17} - 10^{20} eV

Tavecchio, FO, Righi 2019



Maximum UHECR energy



Hillas energy *(Hillas 1984)*:

$$E_{\rm max} \sim \beta_{\rm sh} RB\Gamma Ze$$

Espresso acceleration *(Caprioli 2015)*:

$$\langle E_{\rm max} \rangle \sim \Gamma^2 E_{\rm max,Galactic}$$

In general $E_{\rm max} \propto \Gamma^{\alpha}$

Blazar population:
(MOJAVE ~200 blazars tracked over 5 years, Lister et al 2019)

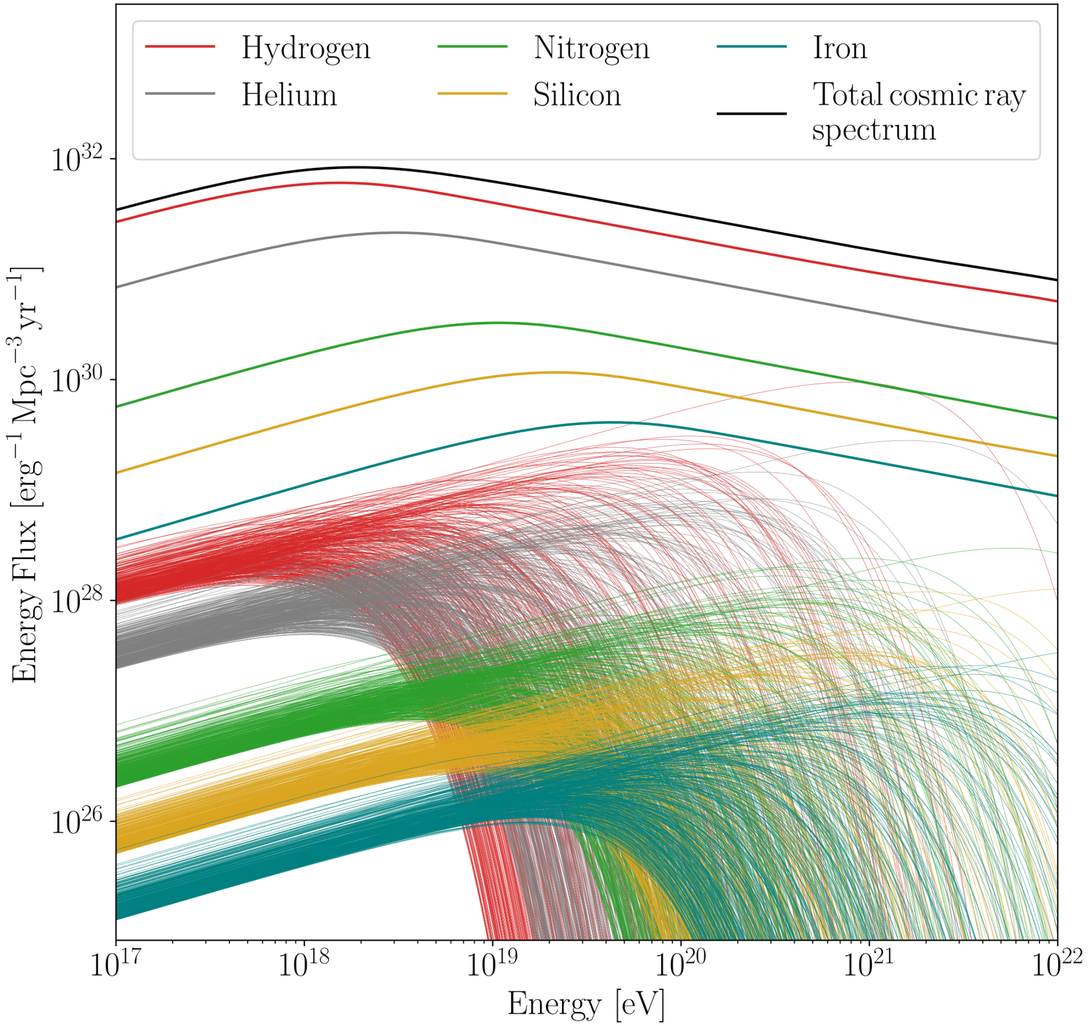
$$dN(\Gamma)/d\Gamma = \Gamma^{-\eta}, 1.25 < \Gamma < 50,\ \eta \approx 1.4$$

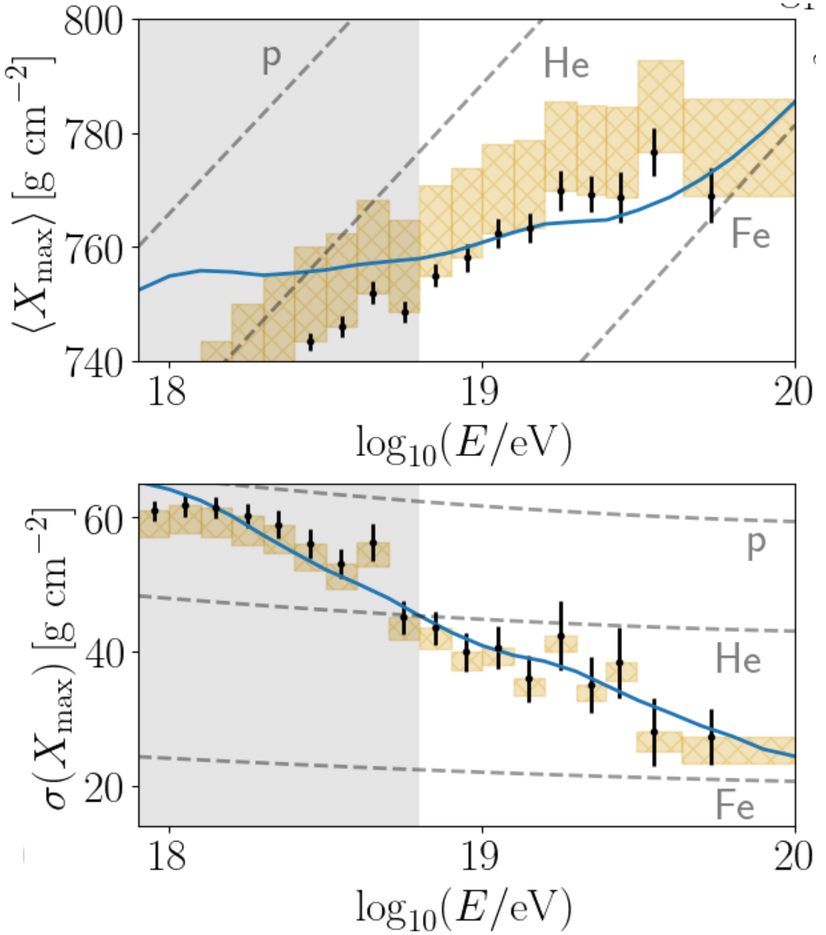
Therefore

$$\frac{dN}{dE_{\rm max}} = \frac{dN}{d\Gamma}\left|\frac{d\Gamma}{dE_{\rm max}}\right| \propto E_{\rm max}^{\frac{1-\eta}{\alpha}-1} \begin{cases} E_{\rm max}^{-1.4} & \text{Hillas} \\ E_{\rm max}^{-1.2} & \text{Espresso} \end{cases}$$

Alves Batista et al 2019, FrASS, 6, 23

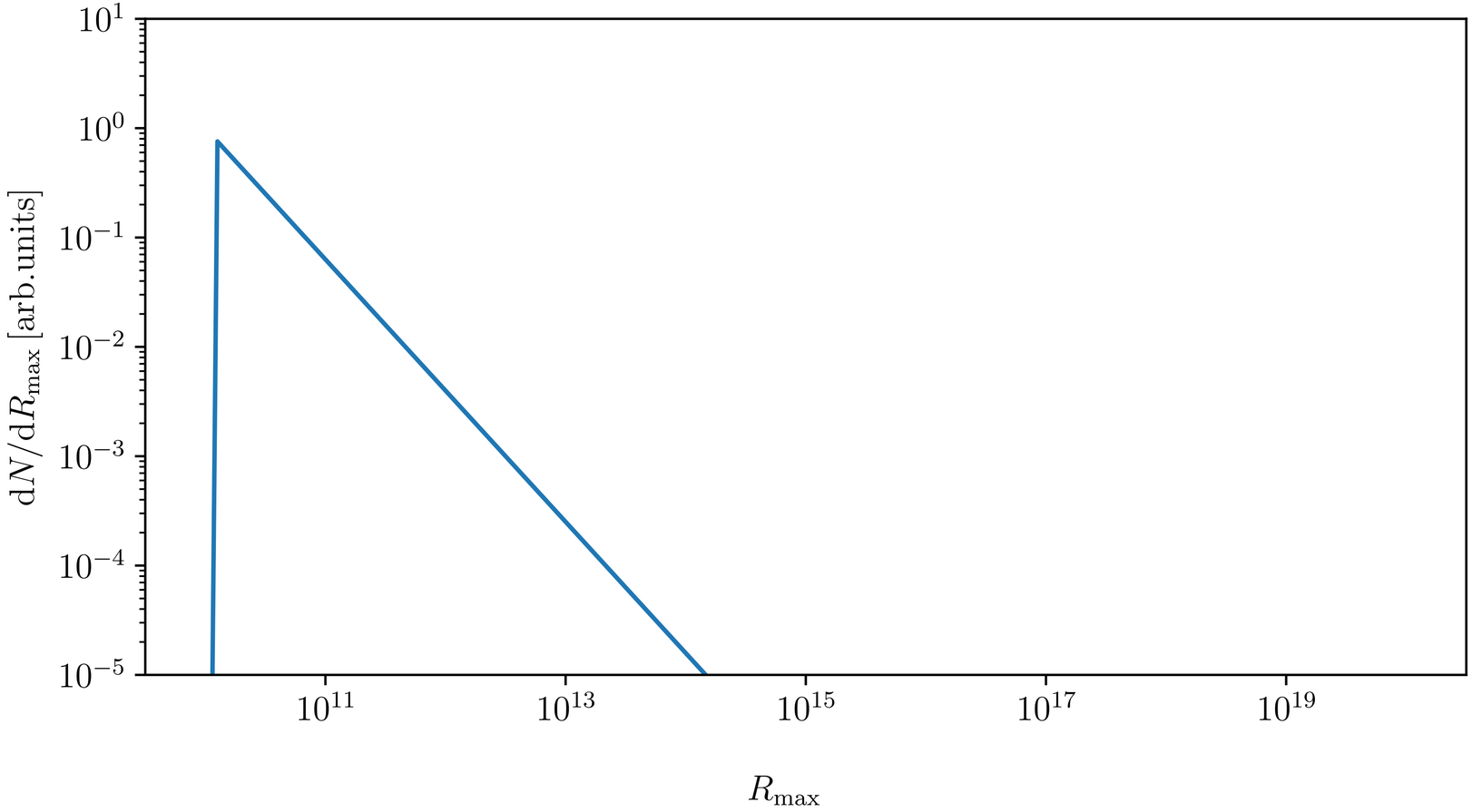
UHECRs from a population with a range of maximum energies





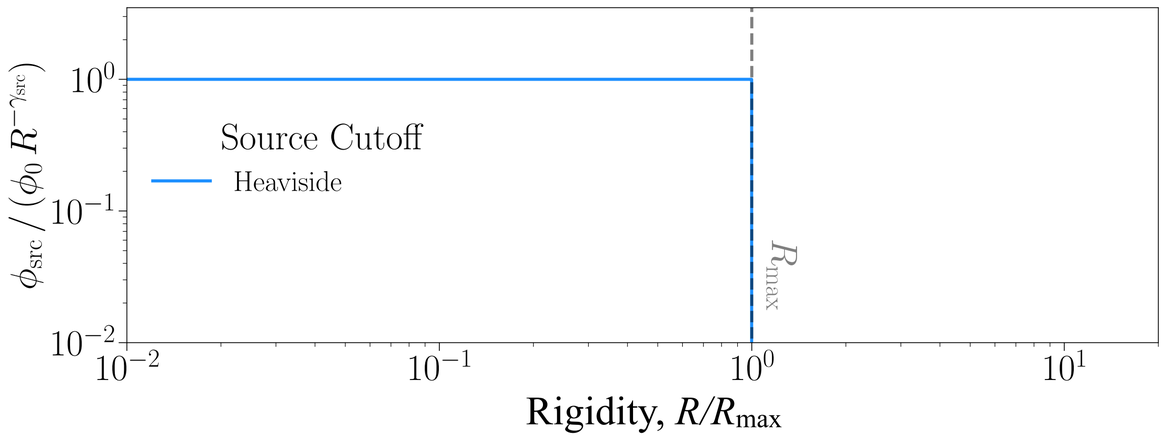
From identical sources to maximum rigidity distribution

$$\text{Rigidity, } R = \frac{\text{Energy}}{Z}$$

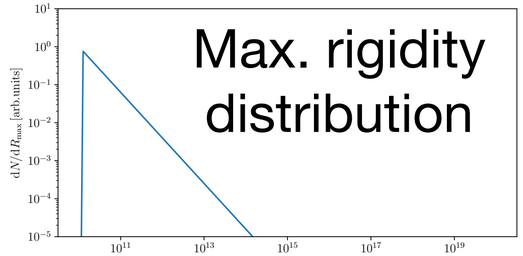


From single source to population spectrum

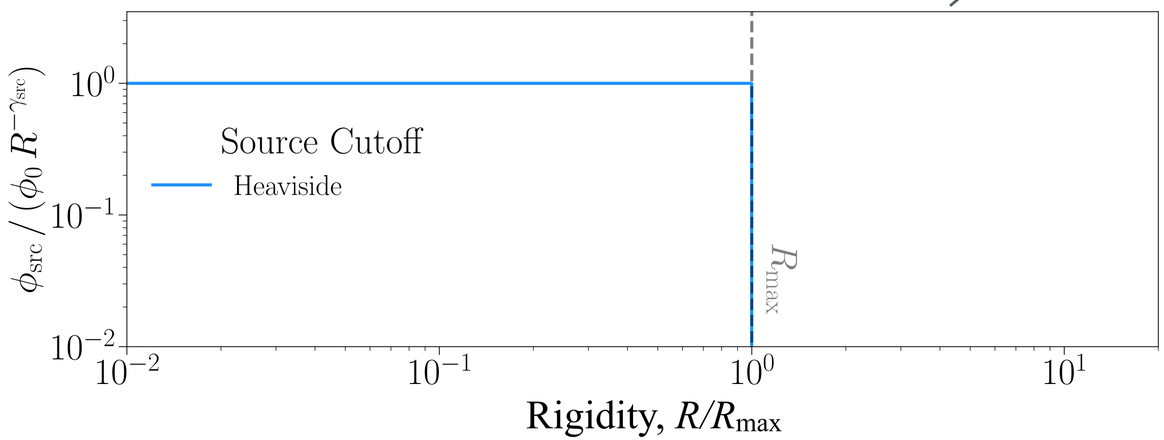
Single Source UHECR Spectrum



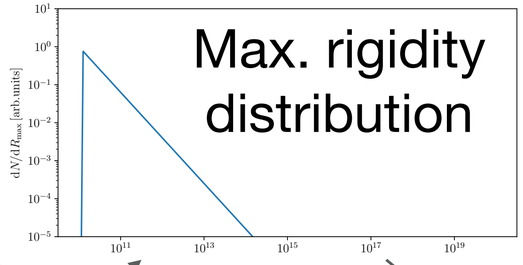
From single source to population spectrum



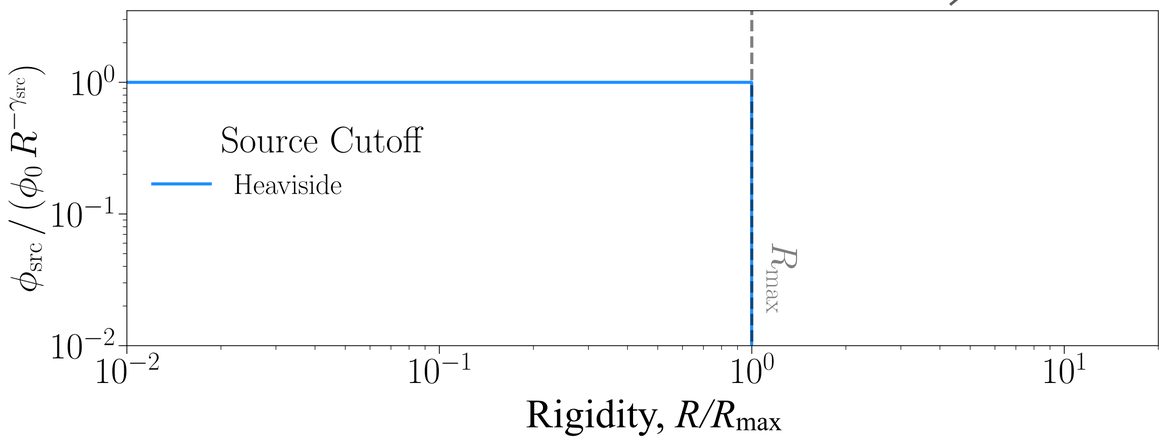
Single Source UHECR Spectrum



From single source to population spectrum

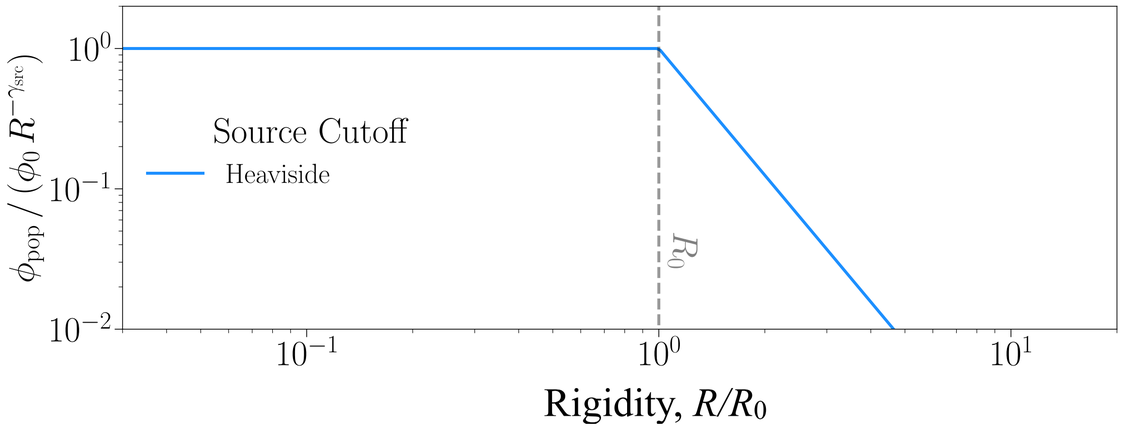


Single Source UHECR Spectrum



Population Spectrum

Power-law distributed maximum rigidity



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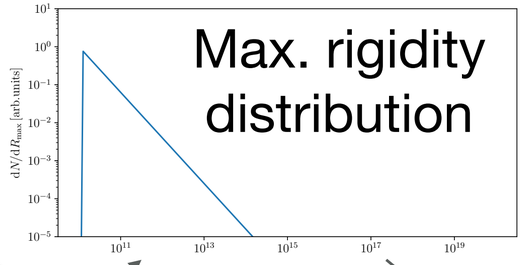
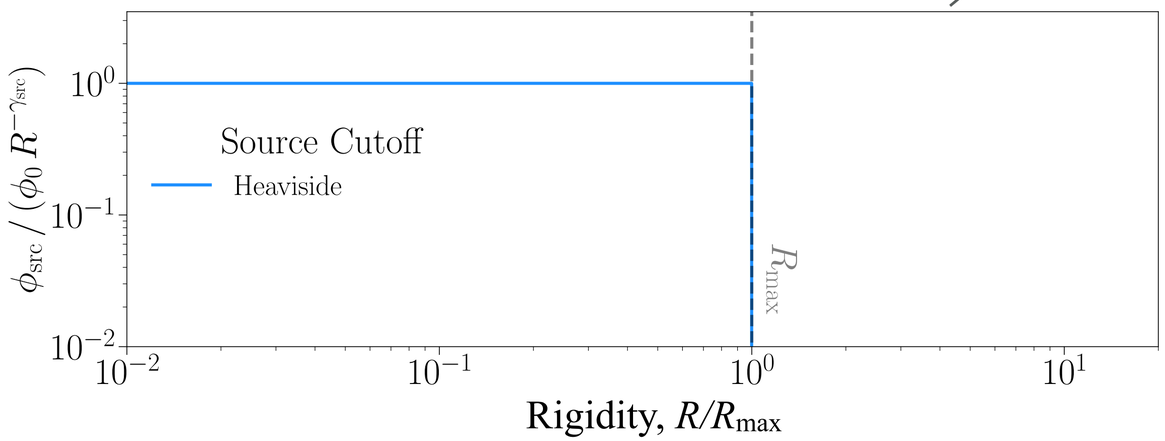
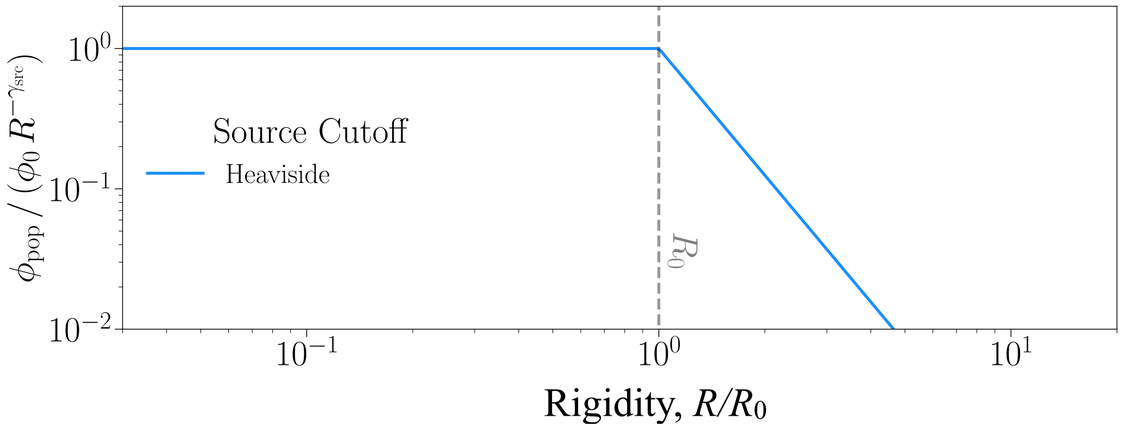


Single Source UHECR Spectrum



Population Spectrum

Power-law distributed maximum rigidity

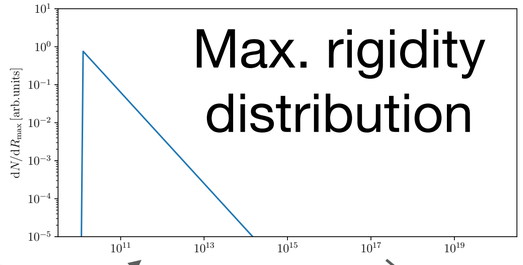


$$\frac{\mathrm{d}N}{\mathrm{d}R} \propto R^{-\gamma_{\mathrm{src}}}$$

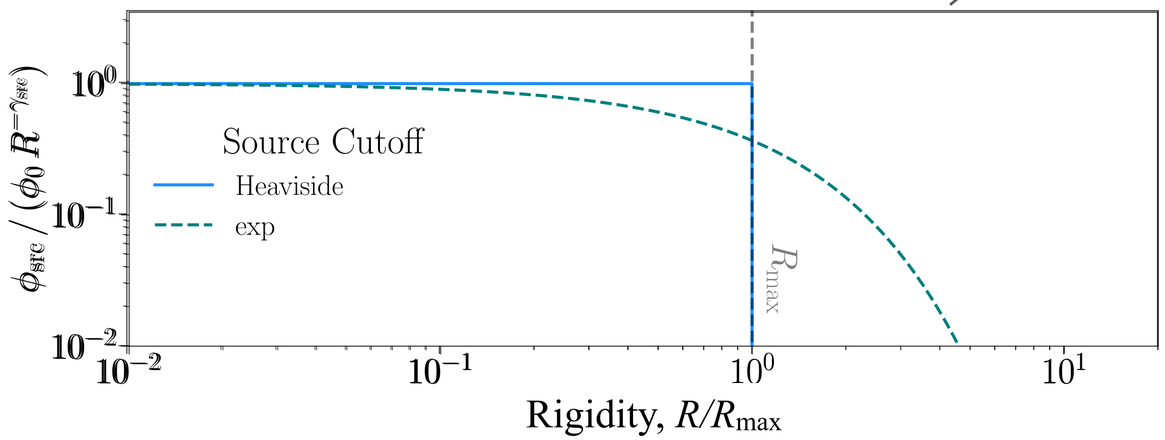
$$\frac{\mathrm{d}N}{\mathrm{d}R_{\mathrm{max}}} \propto R_{\mathrm{max}}^{-\beta_{\mathrm{pop}}}$$

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

From single source to population spectrum



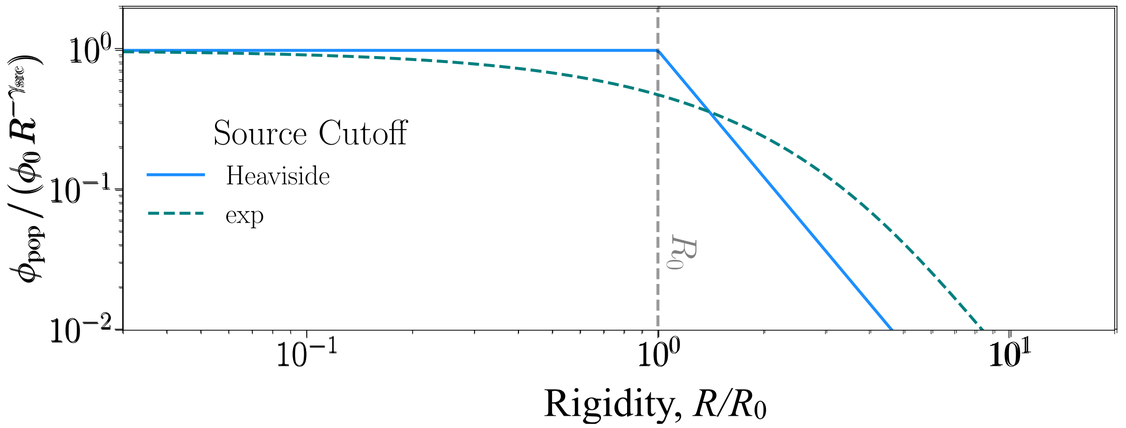
Single Source UHECR Spectrum



$$\frac{\mathrm{d}N}{\mathrm{d}R} \propto R^{-\gamma_{\mathrm{src}}}$$

Population Spectrum

Power-law distributed maximum rigidity



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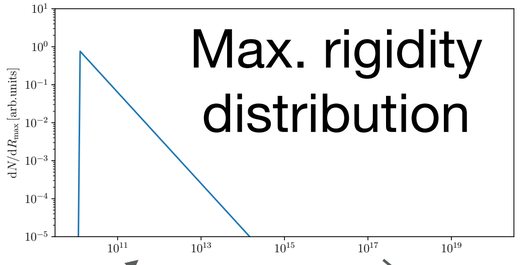
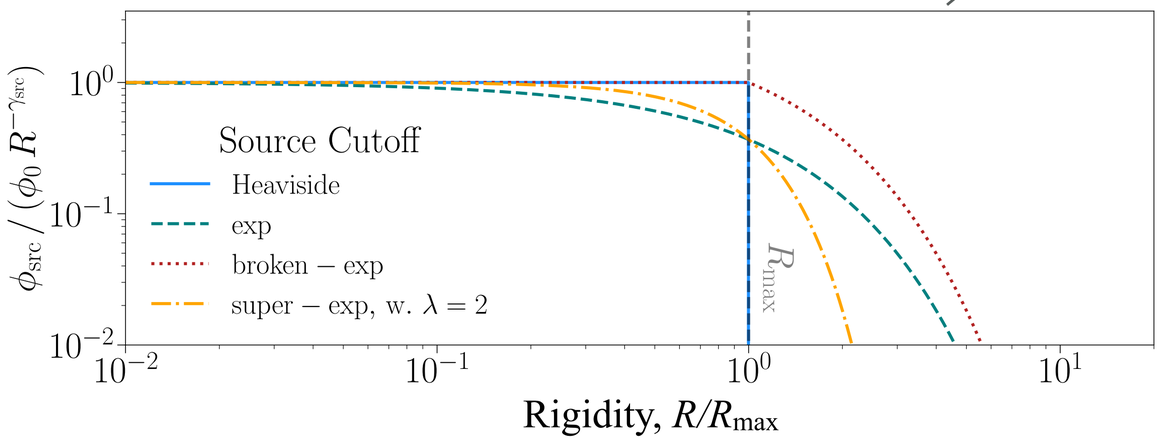
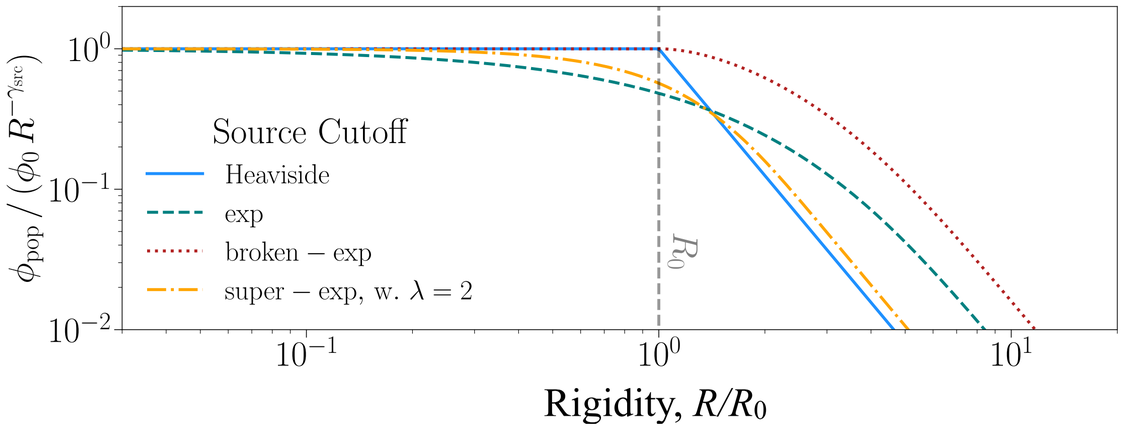


Single Source UHECR Spectrum



Population Spectrum

Power-law distributed maximum rigidity



$$\frac{\mathrm{d}N}{\mathrm{d}R} \propto R^{-\gamma_{\rm src}}$$

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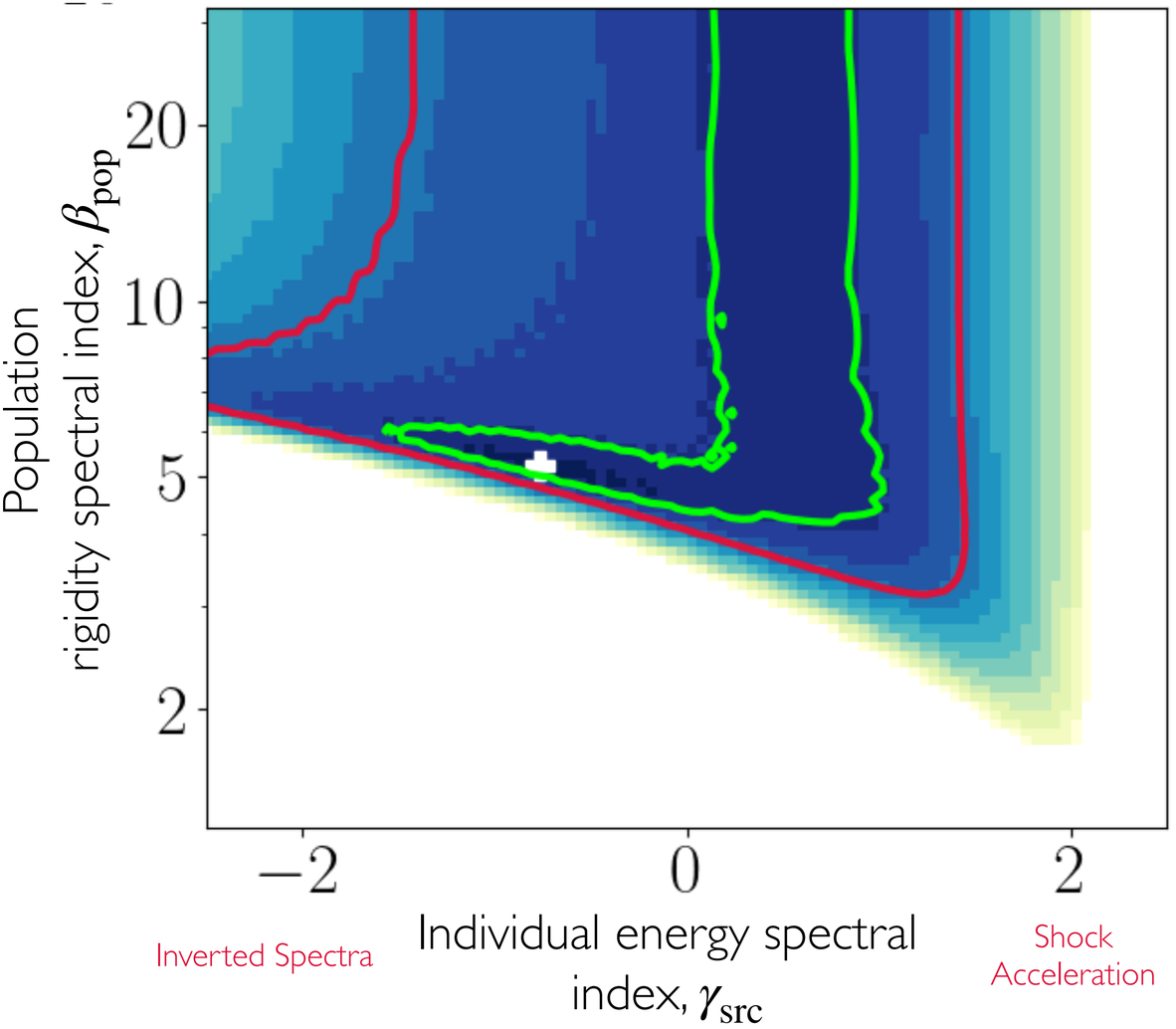
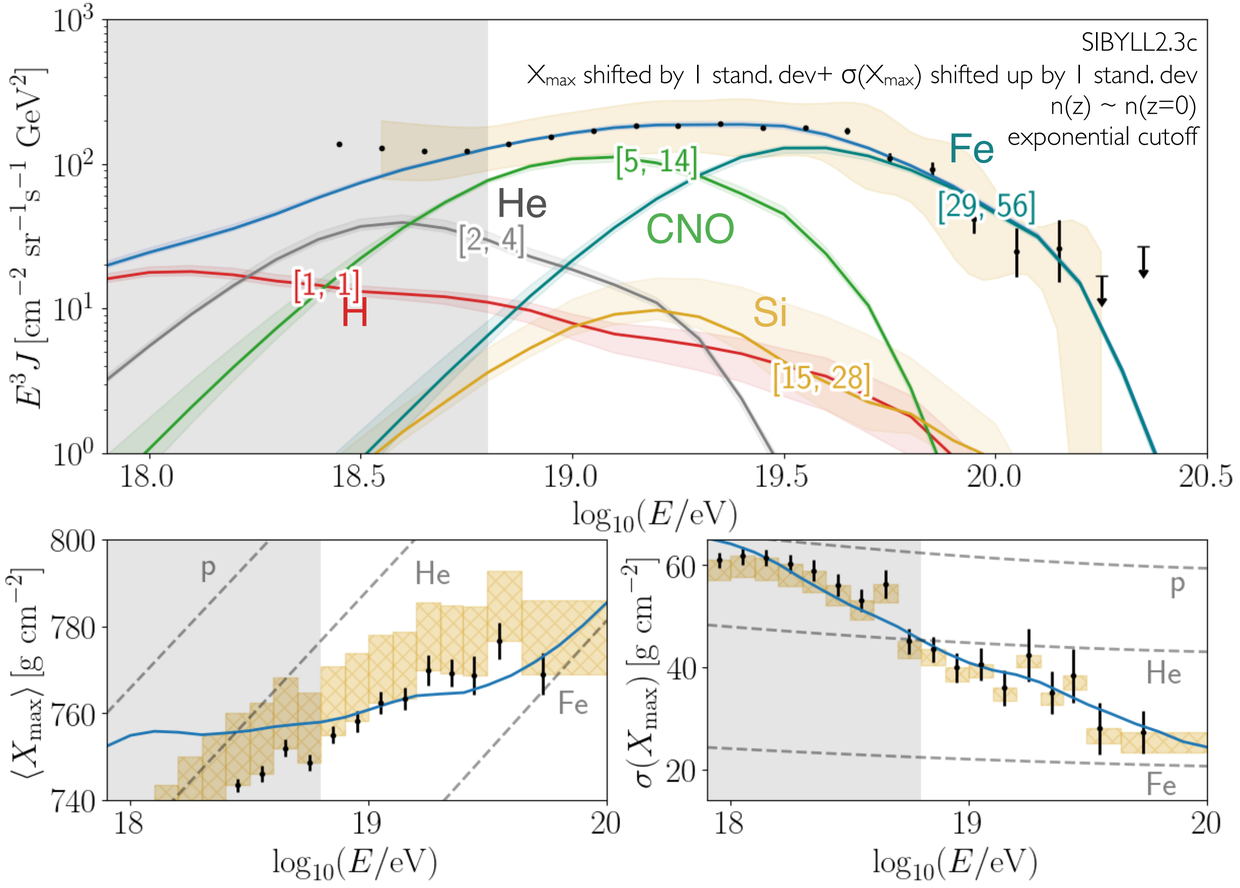
$$\phi_{\rm pop} \propto \begin{cases} R^{-\gamma_{\rm src}} & R \ll R_0 \\ R^{-\gamma_{\rm src}-\beta_{\rm pop}+1} & R \gg R_0 \end{cases}$$

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*

A curious maximum rigidity distribution

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

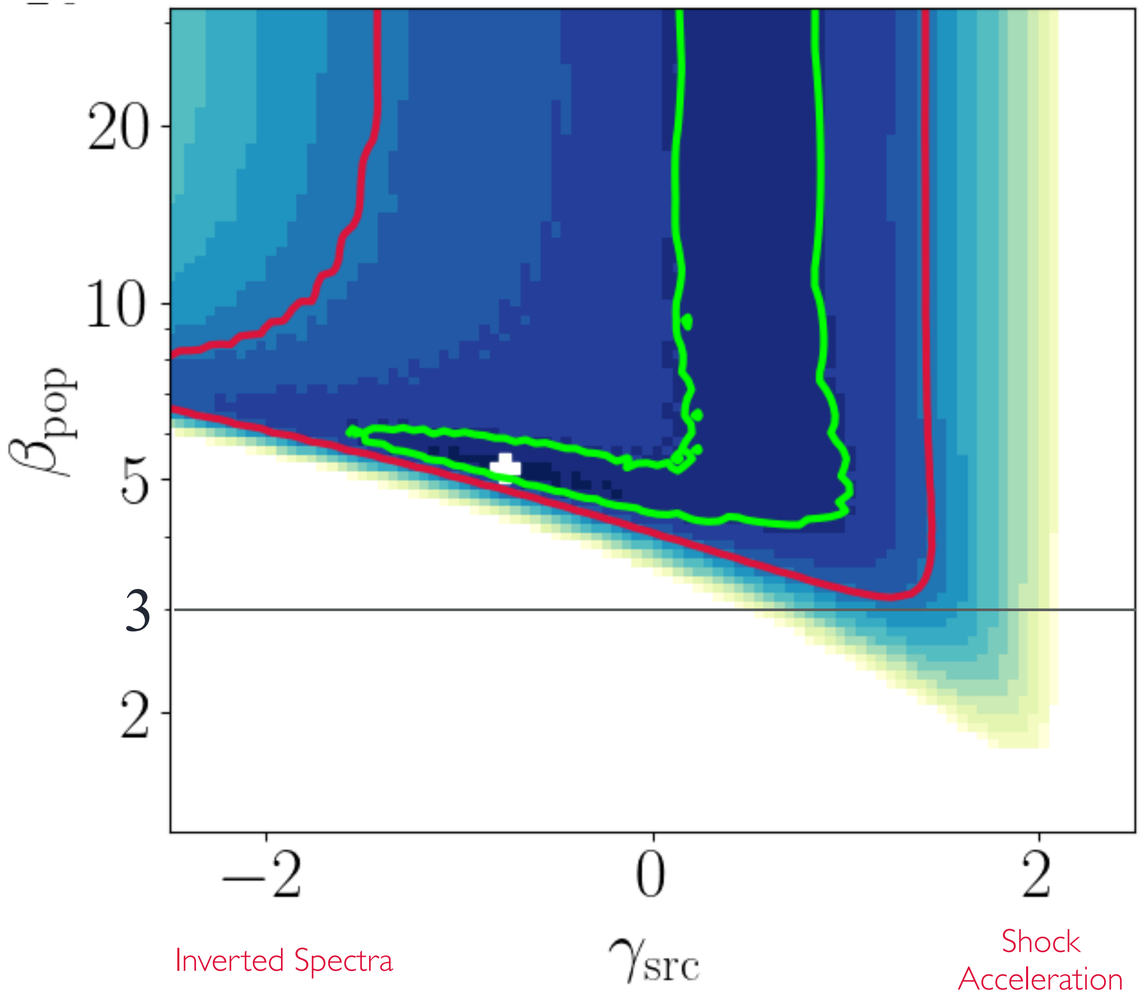




$$\frac{\mathrm{d}N}{\mathrm{d}R} \propto R^{-\gamma_{\rm src}} \qquad \frac{\mathrm{d}N}{\mathrm{d}R_{\rm max}} \propto R_{\rm max}^{-\beta_{\rm pop}} \qquad \phi_{\rm pop} \propto \begin{cases} R^{-\gamma_{\rm src}} & R \ll R_0 \\ R^{-\gamma_{\rm src}-\beta_{\rm pop}+1} & R \gg R_0 \end{cases}$$

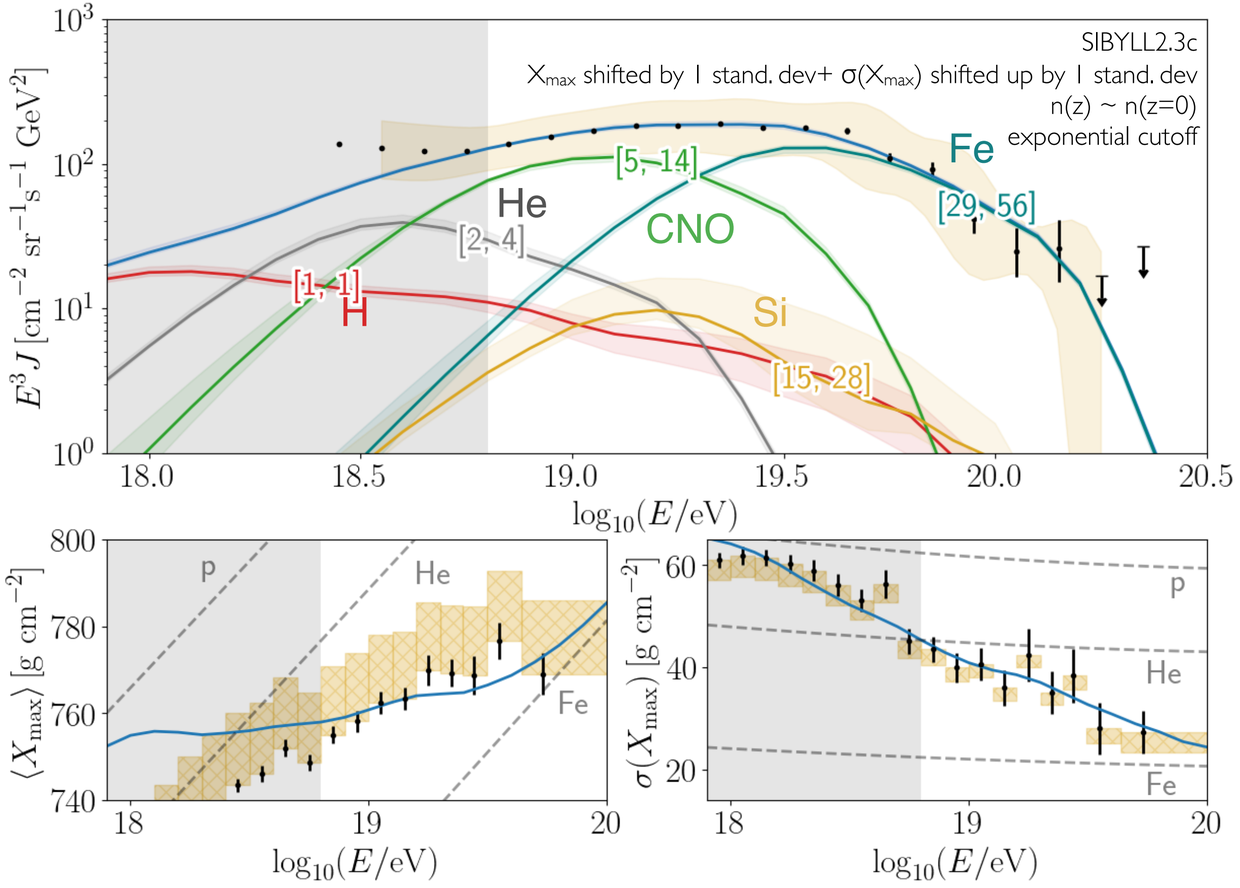
A curious maximum rigidity distribution

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



Inverted Spectra

Shock Acceleration



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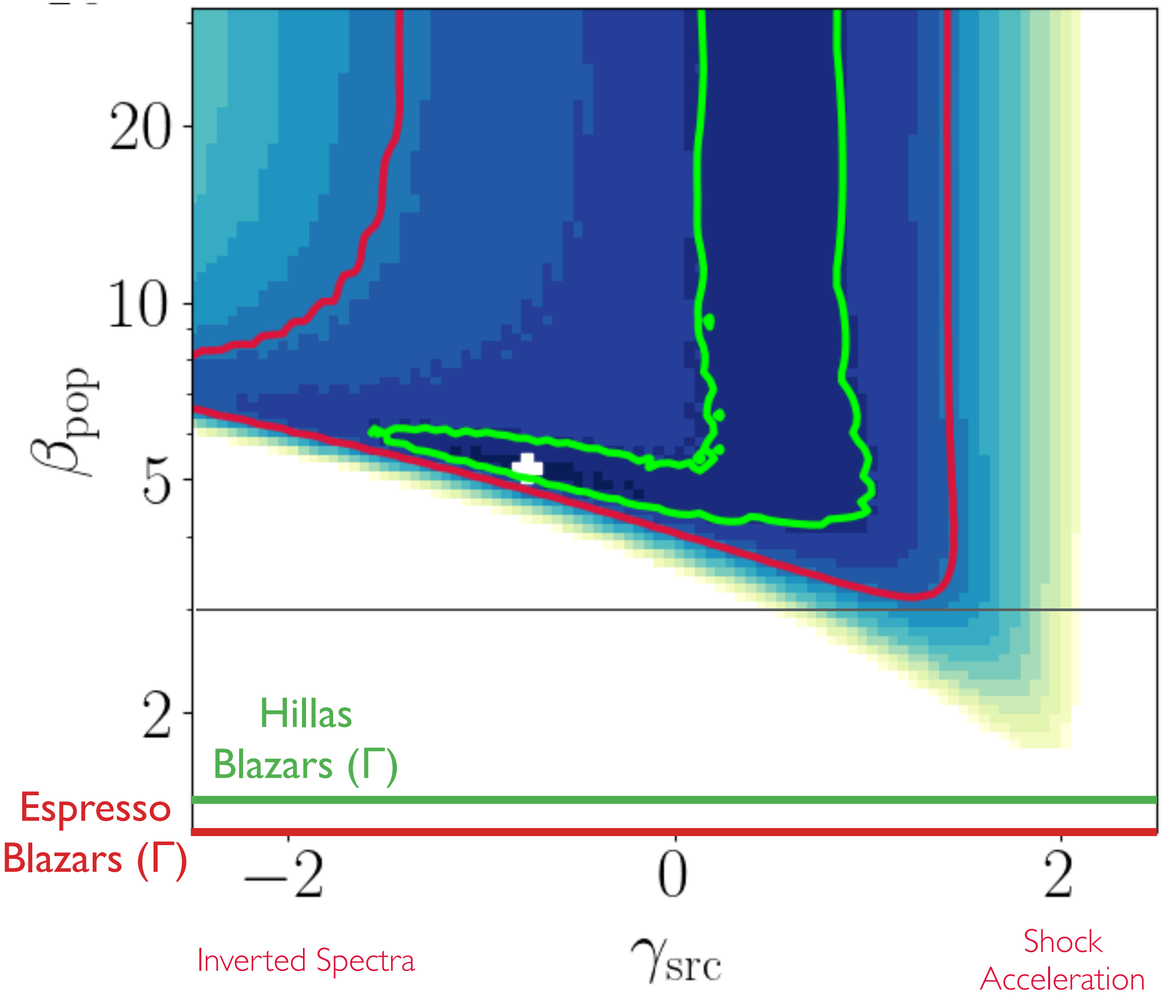
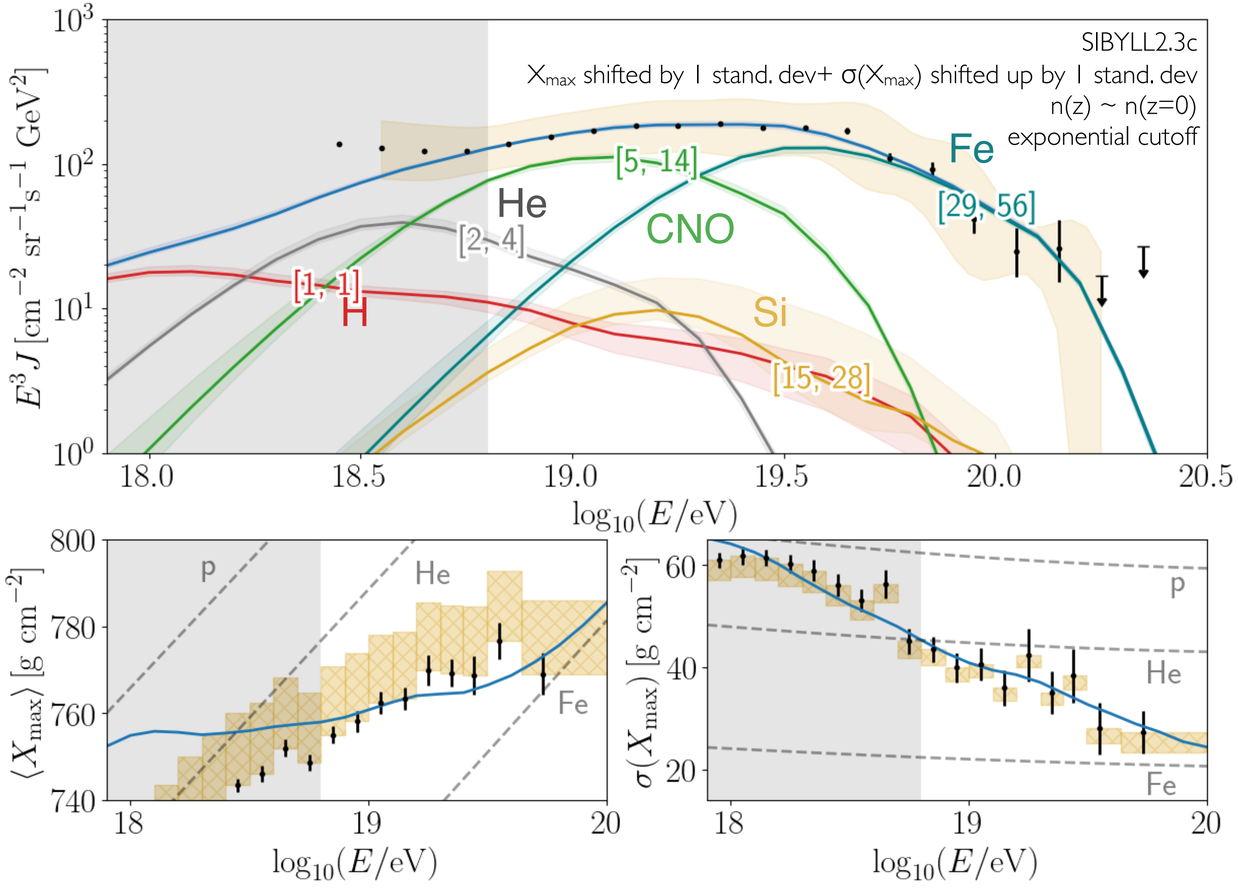
A curious maximum rigidity distribution

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





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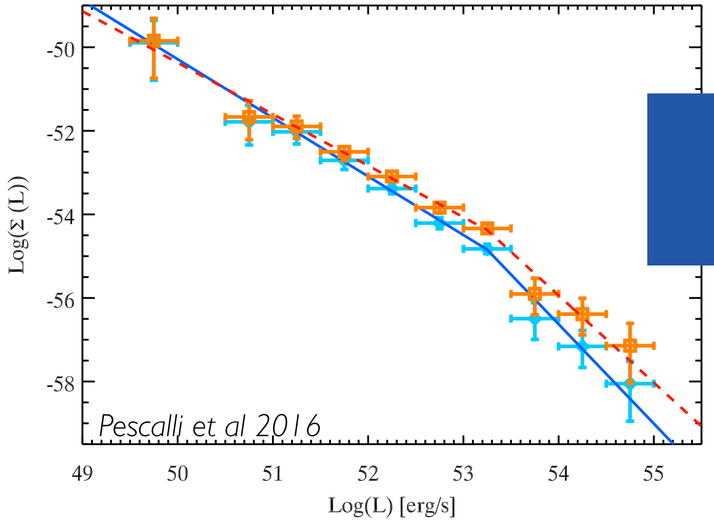
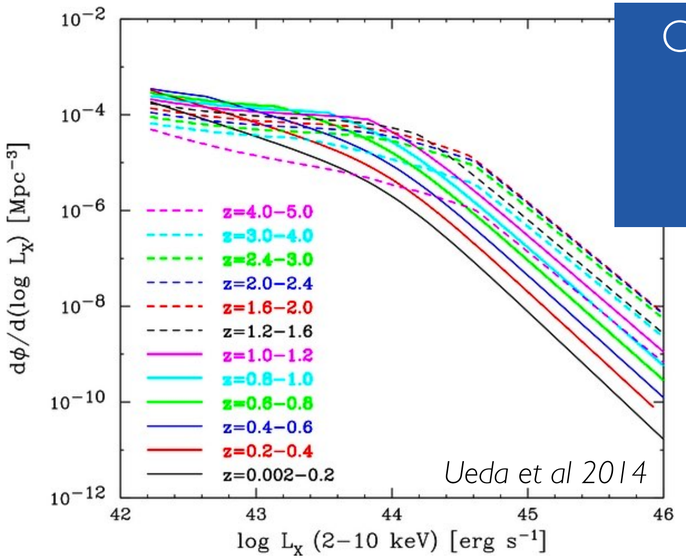
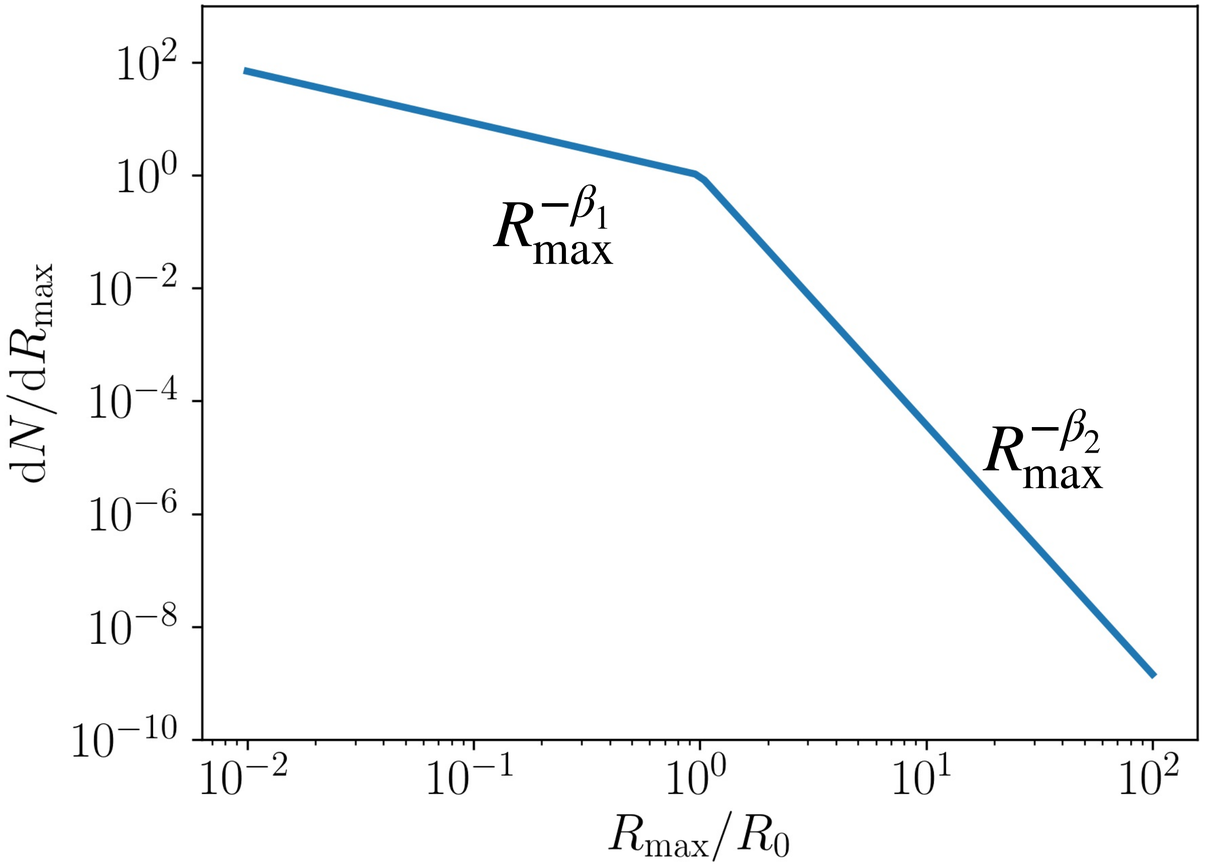
Broken-power-law distributed maximum rigidity



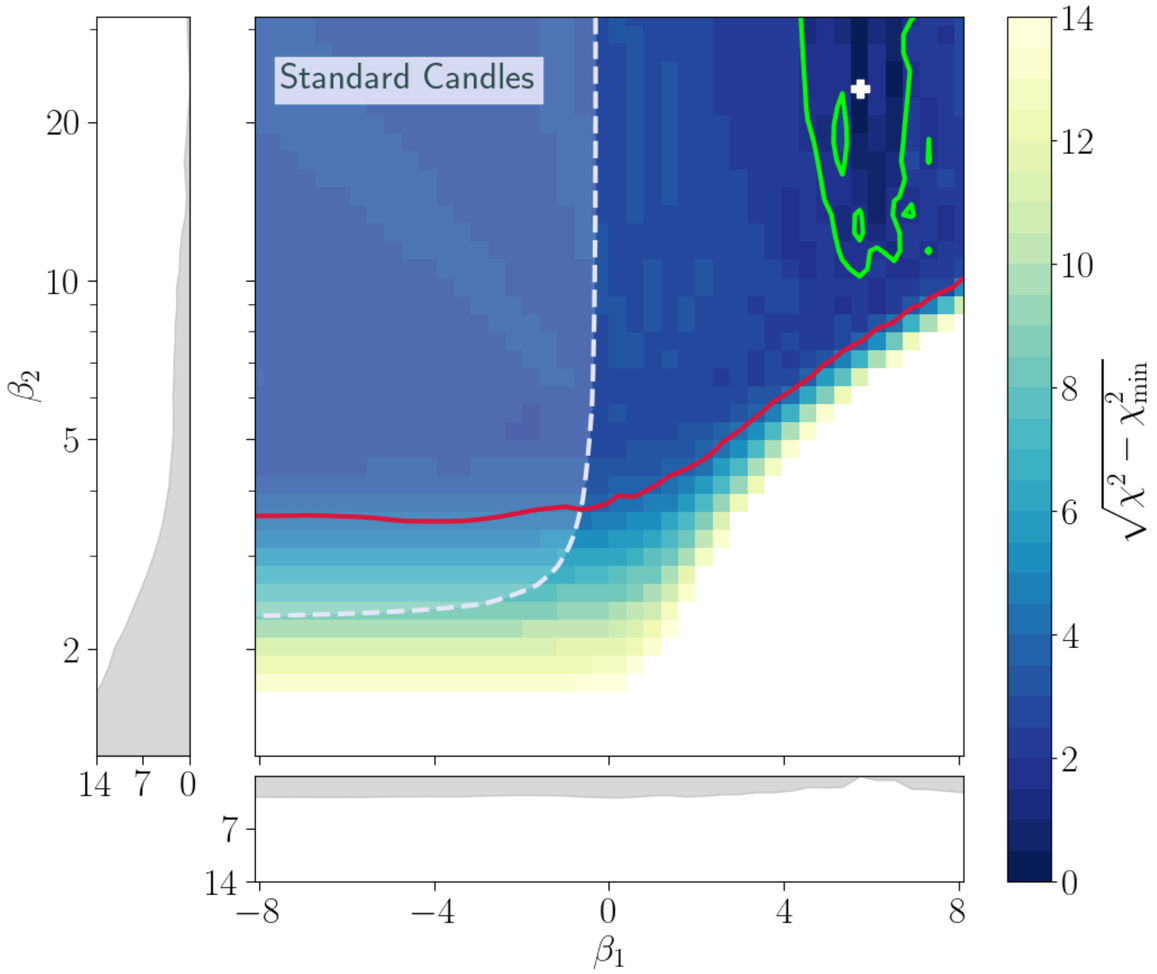
Long GRB luminosity function

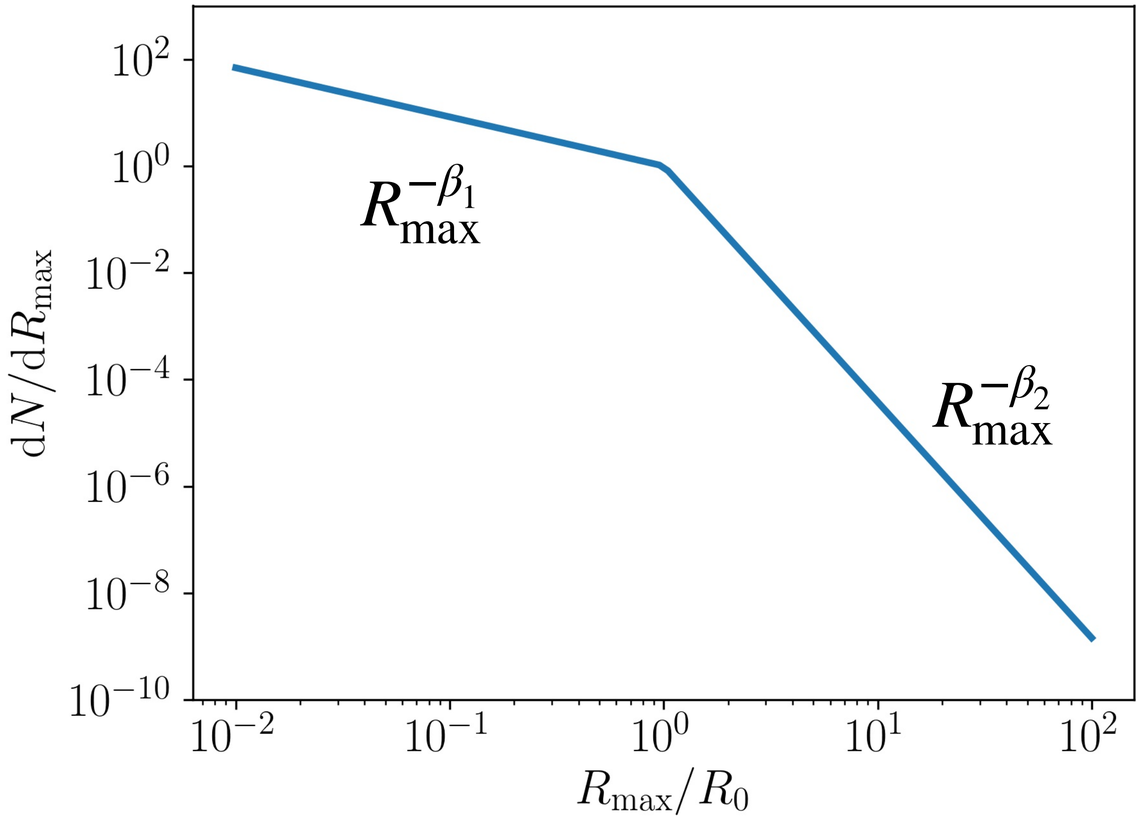


Compton thick AGN luminosity function



Broken-power-law distributed maximum rigidity





Broken-power-law distributed maximum rigidity

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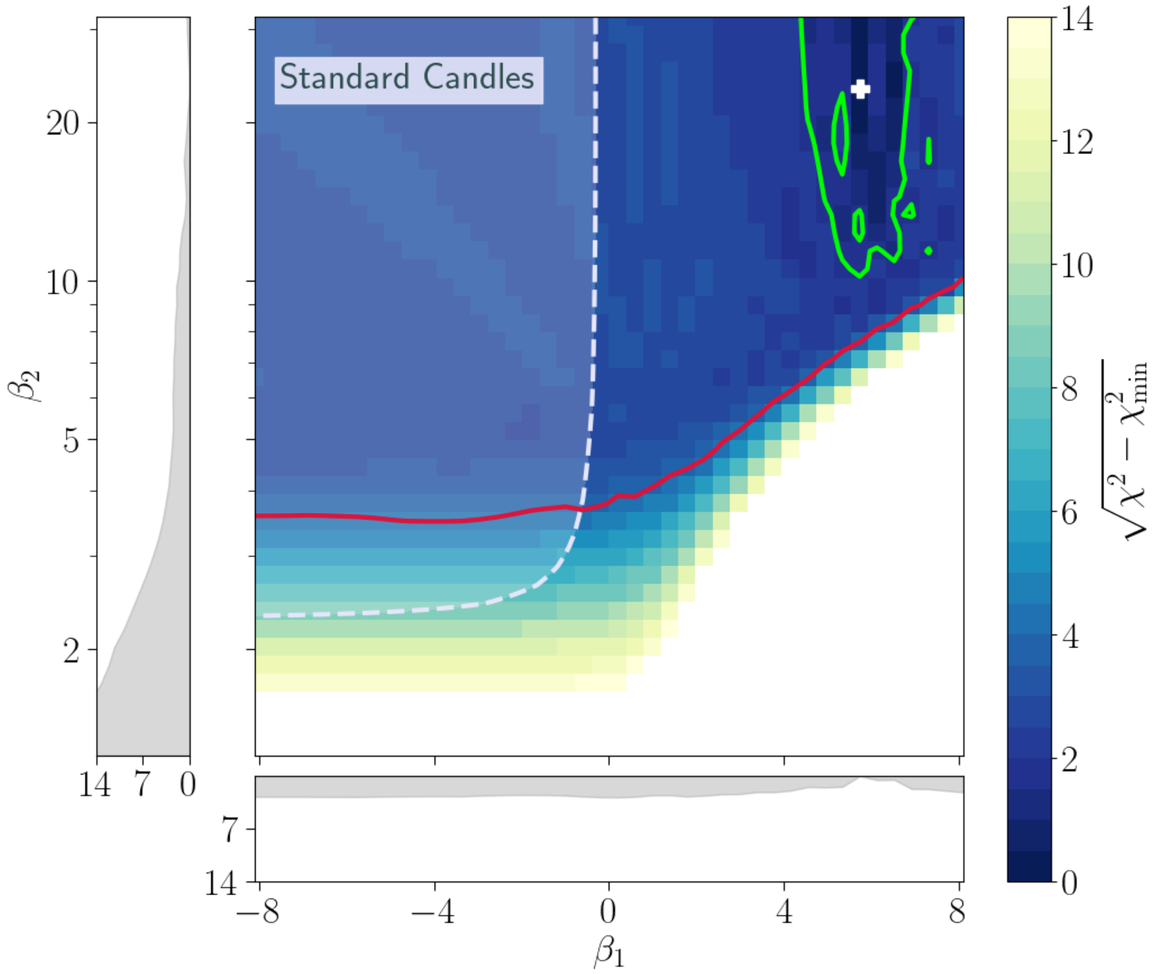

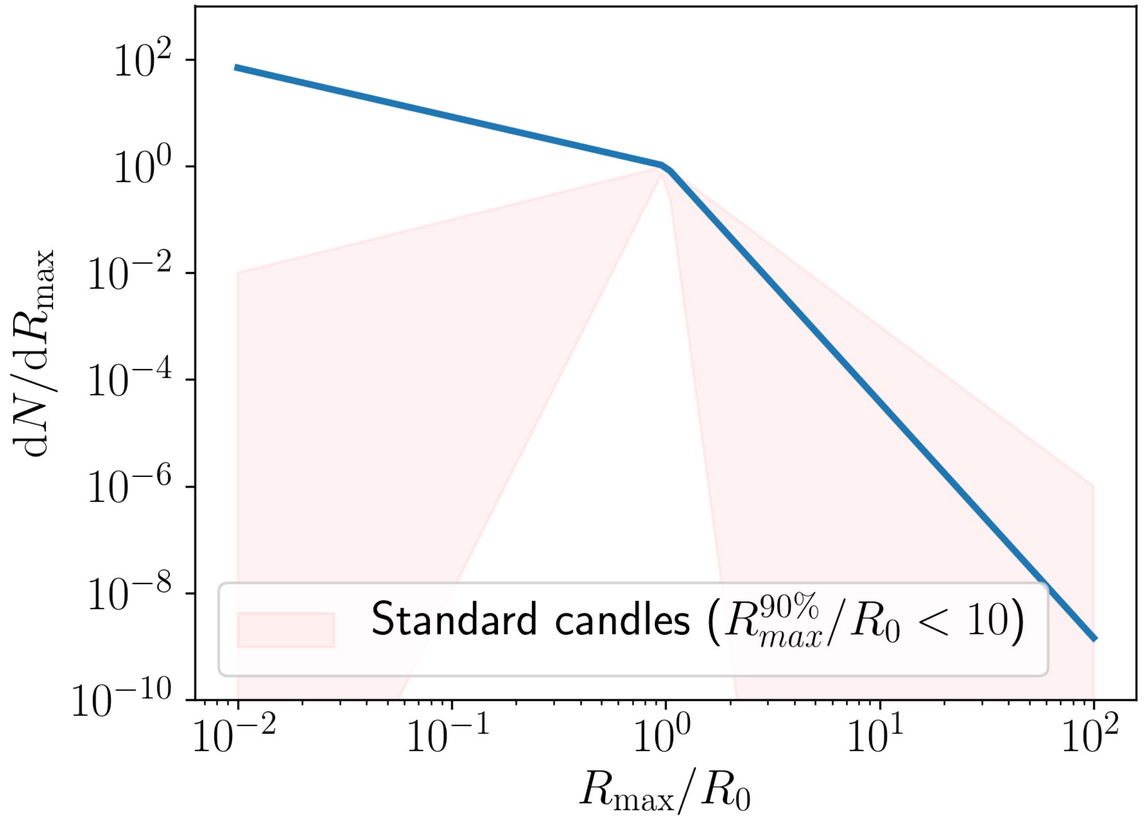

Broken-power-law distributed maximum rigidity

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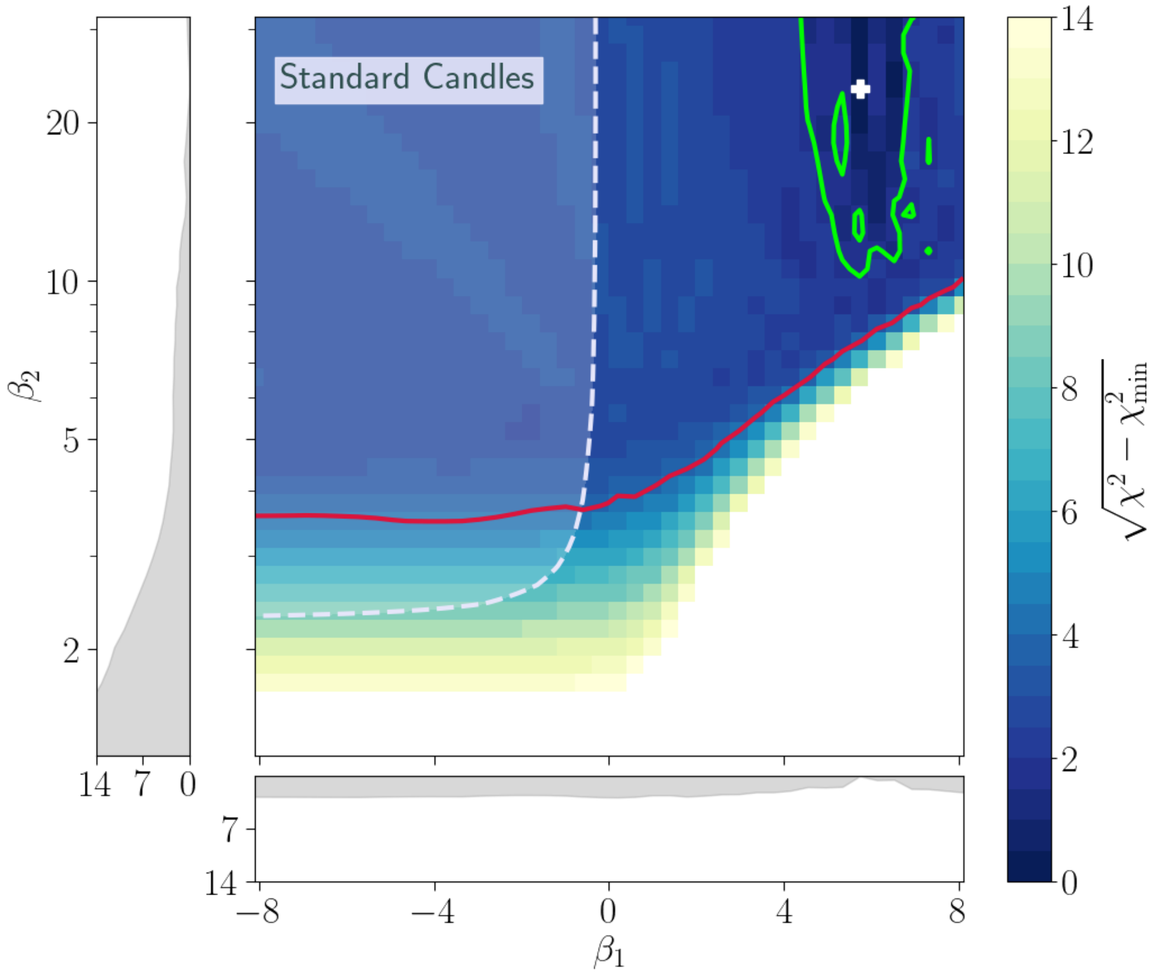

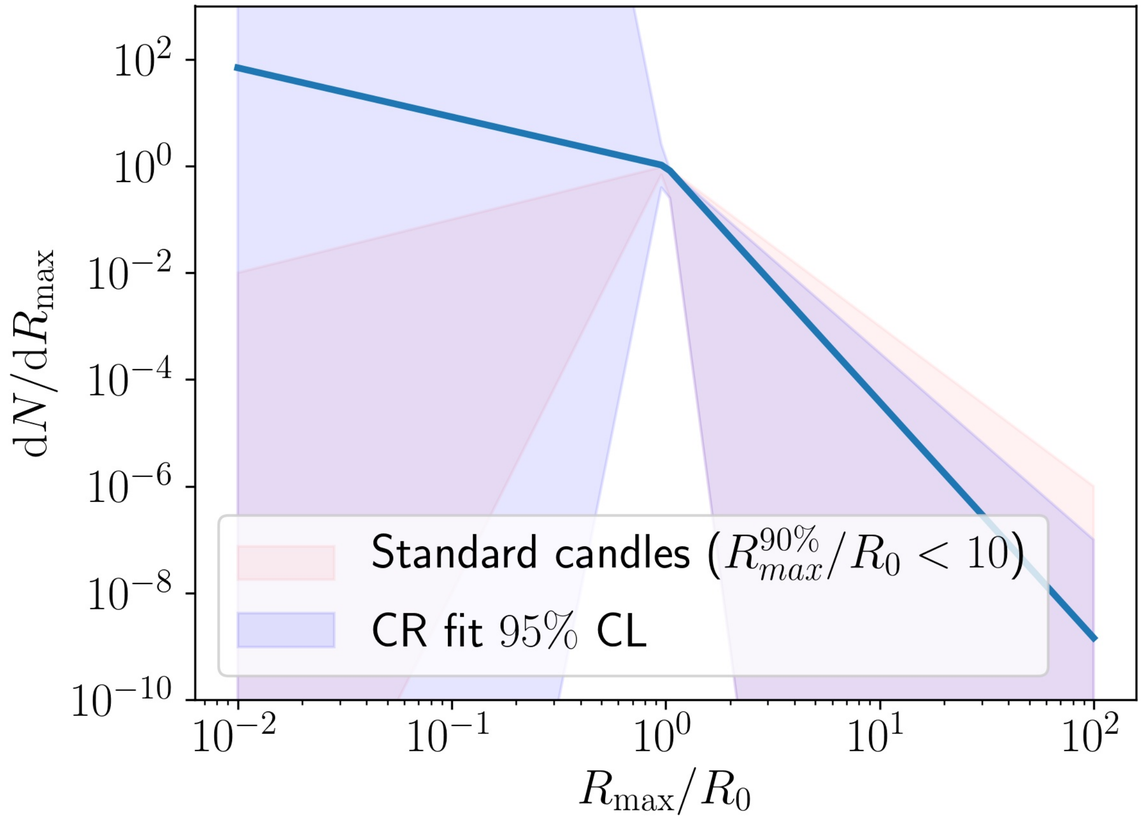

Broken-power-law distributed maximum rigidity

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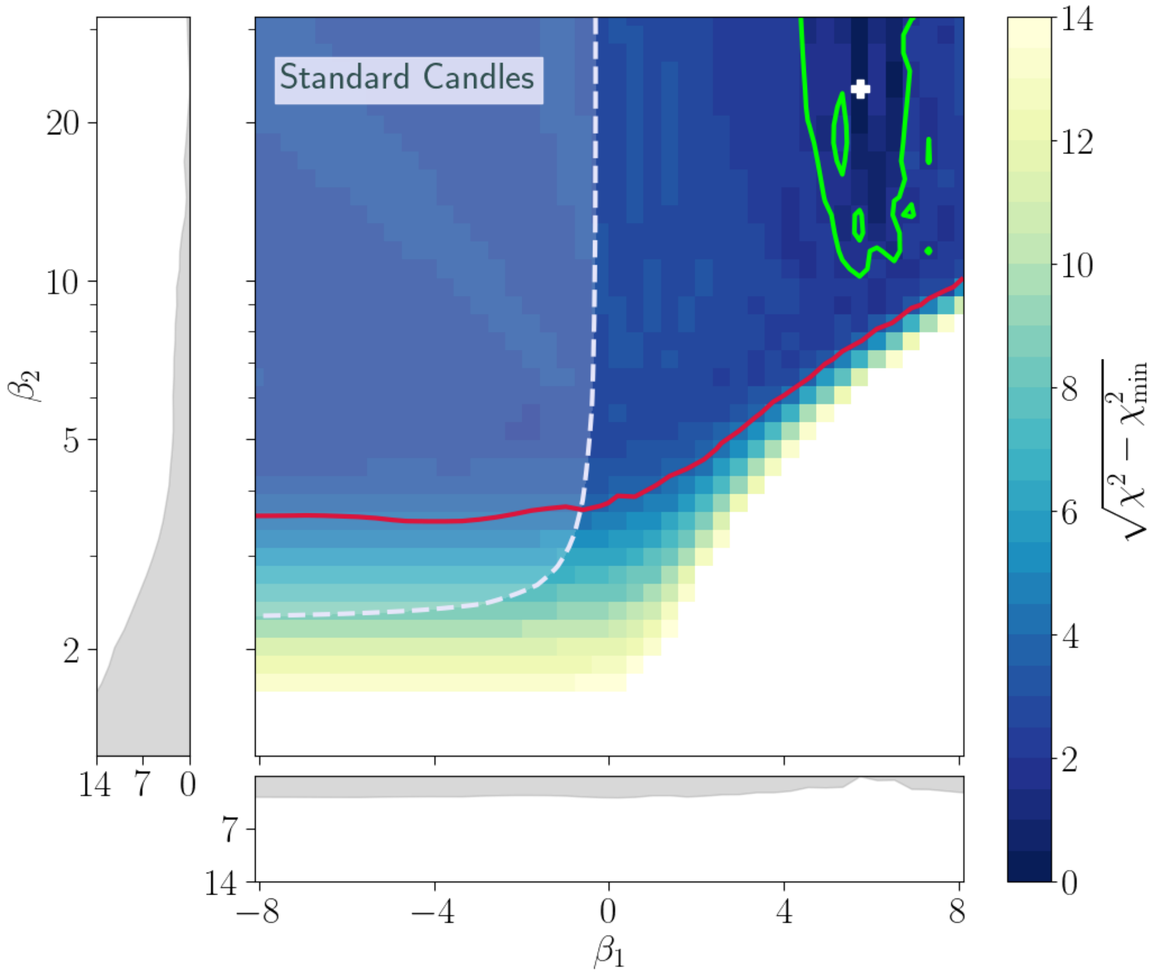

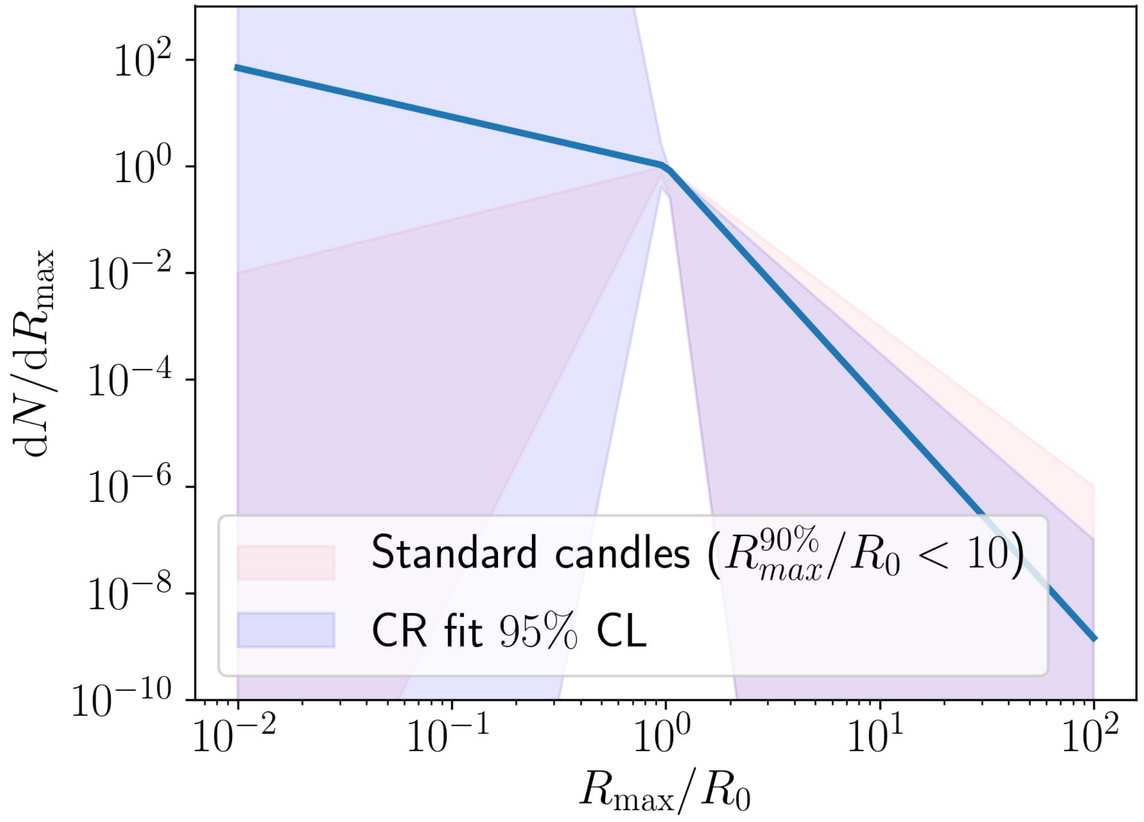

Broken-power-law distributed maximum rigidity

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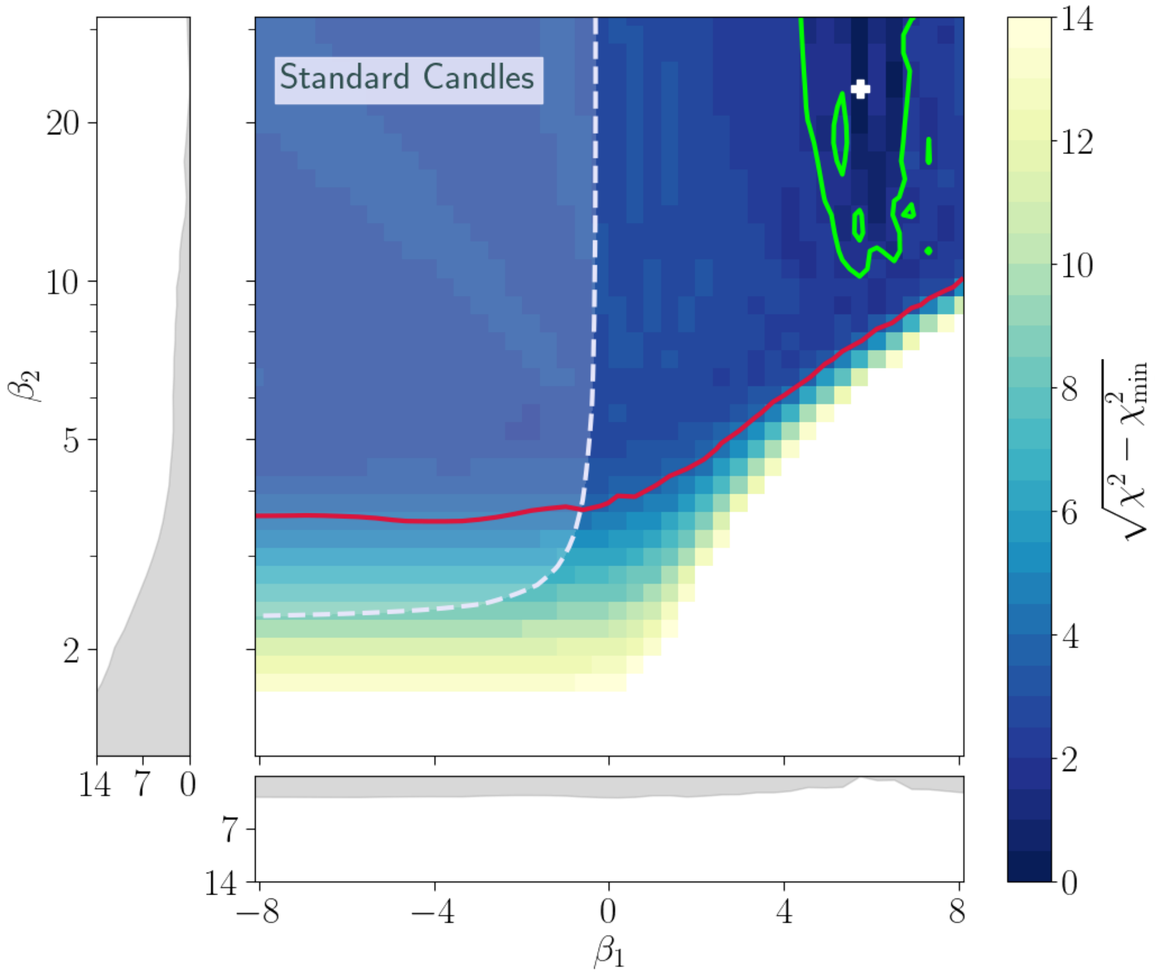
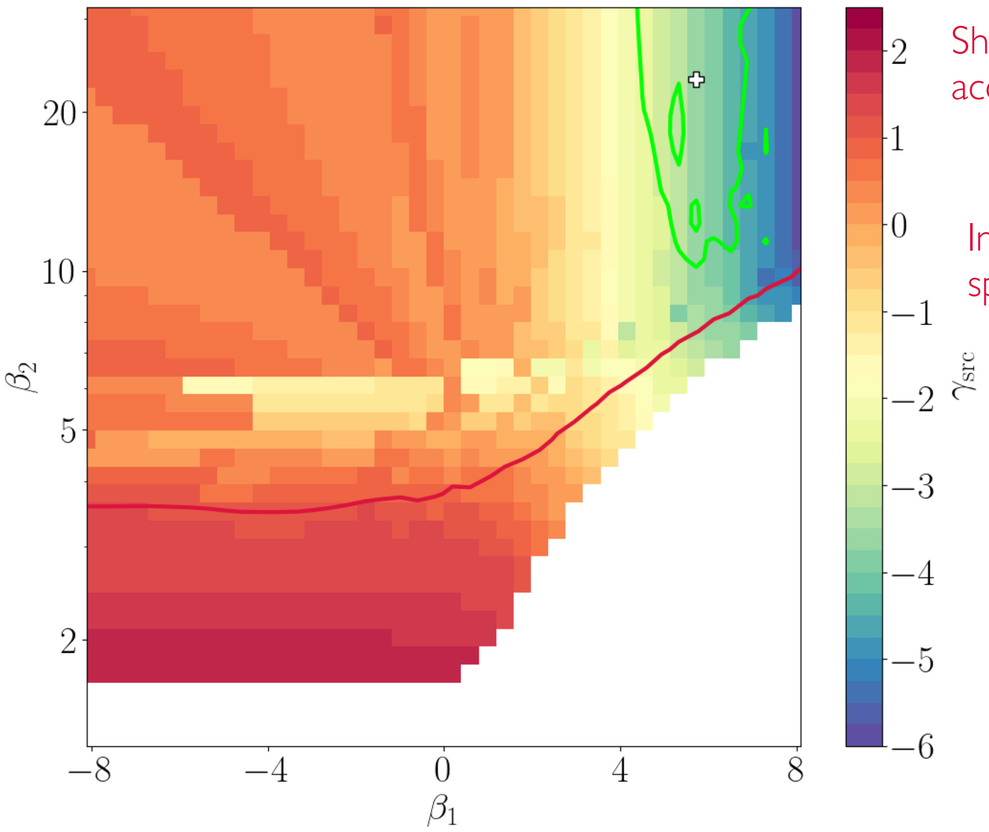




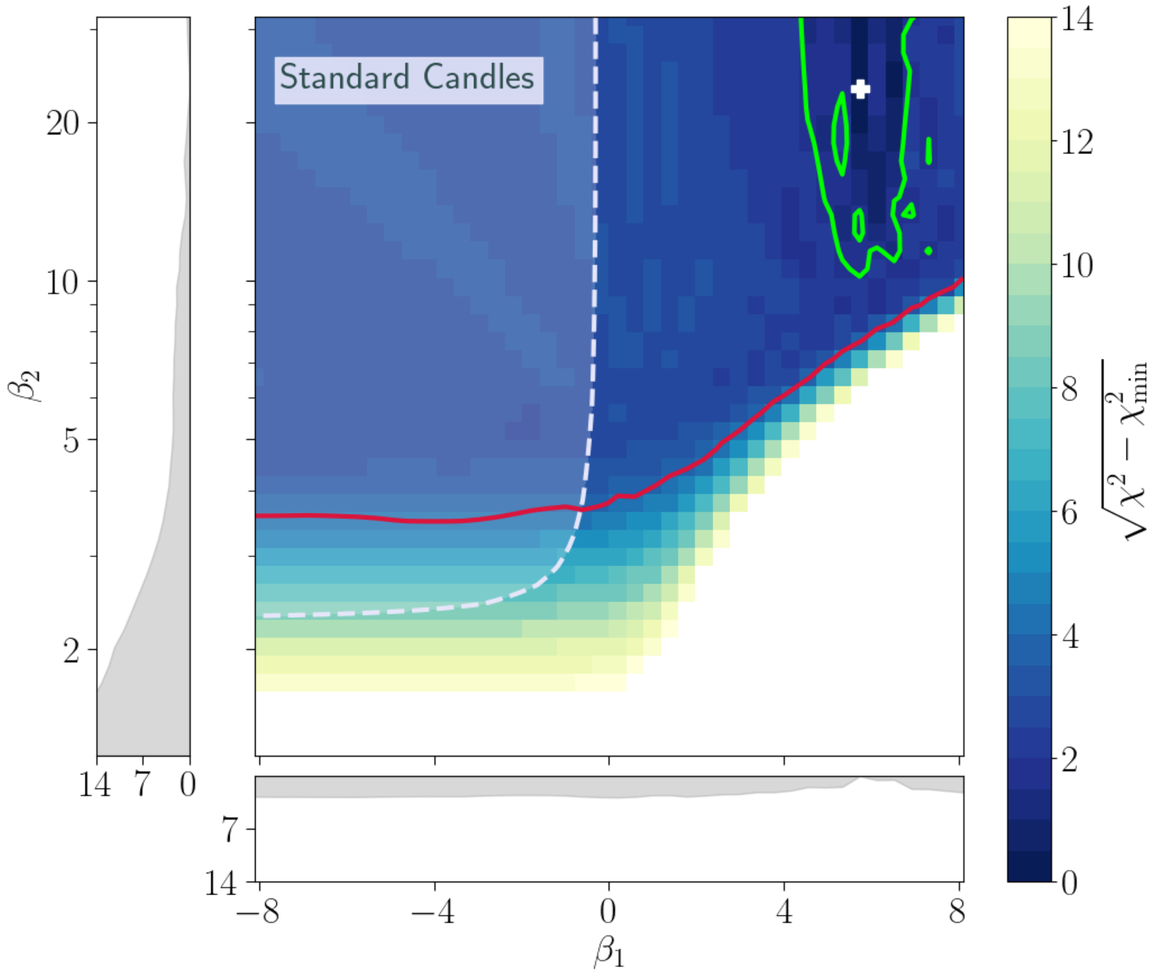
Shock acceleration

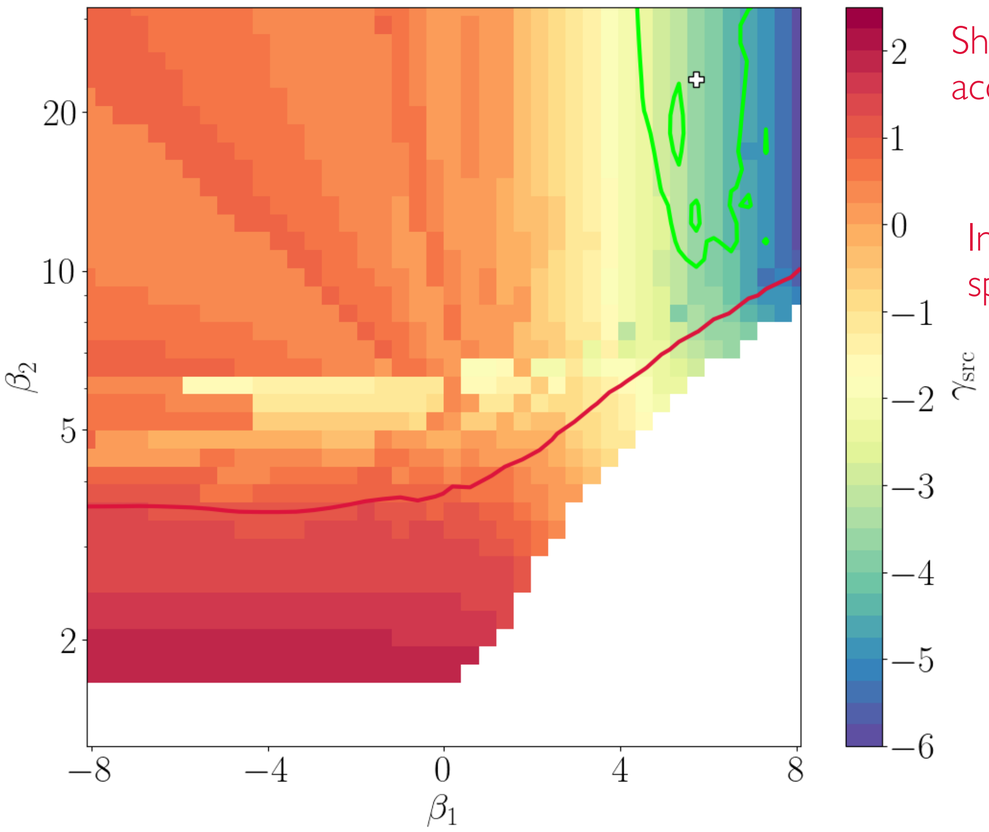
Inverted spectra

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

Broken-power-law distributed maximum rigidity

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





Shock acceleration

Inverted spectra

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

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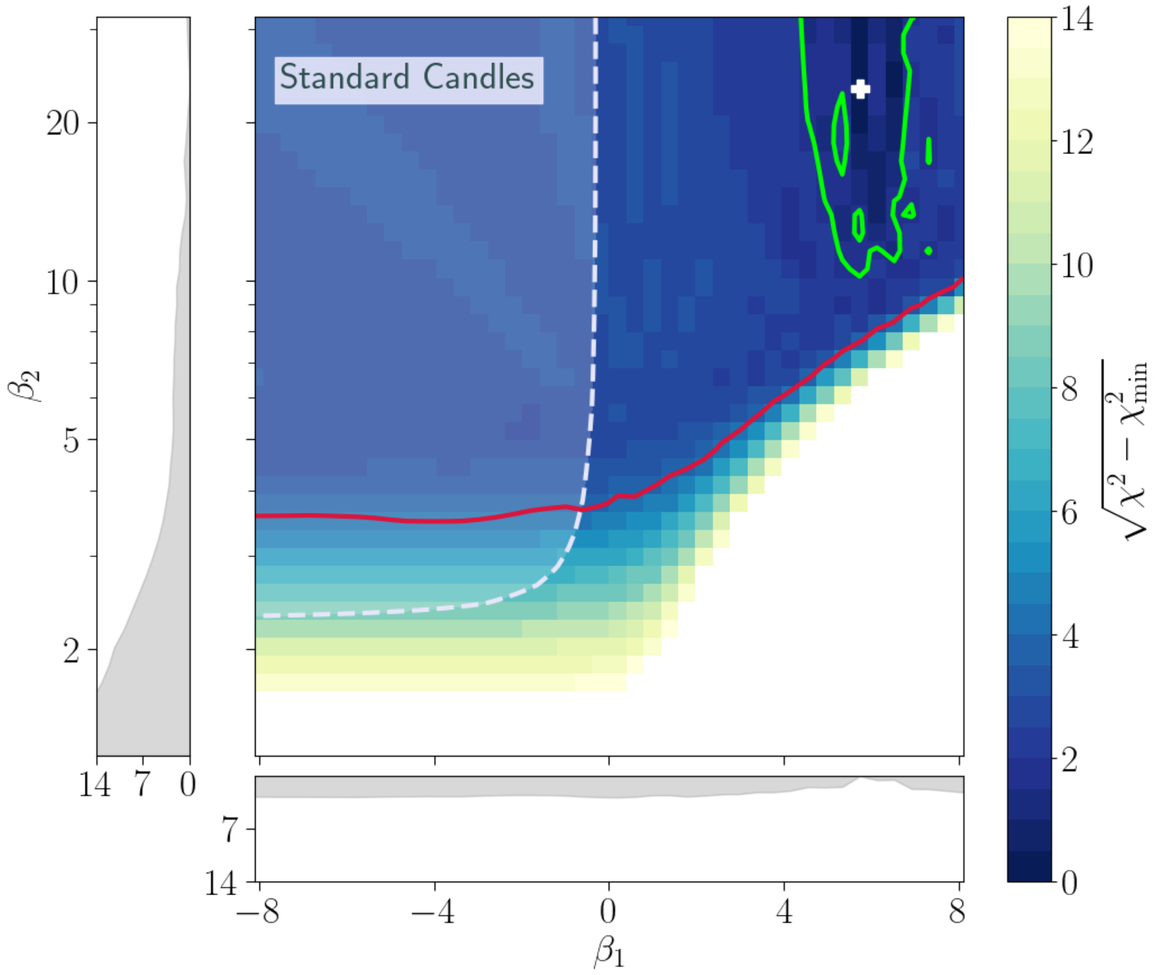

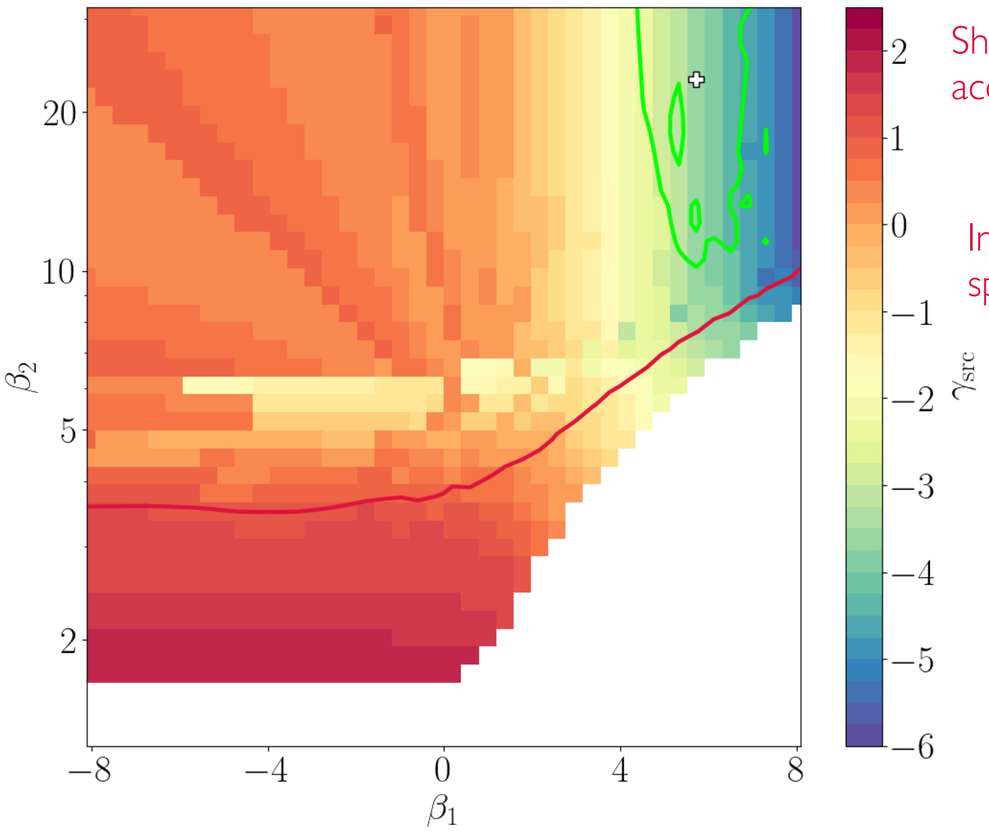

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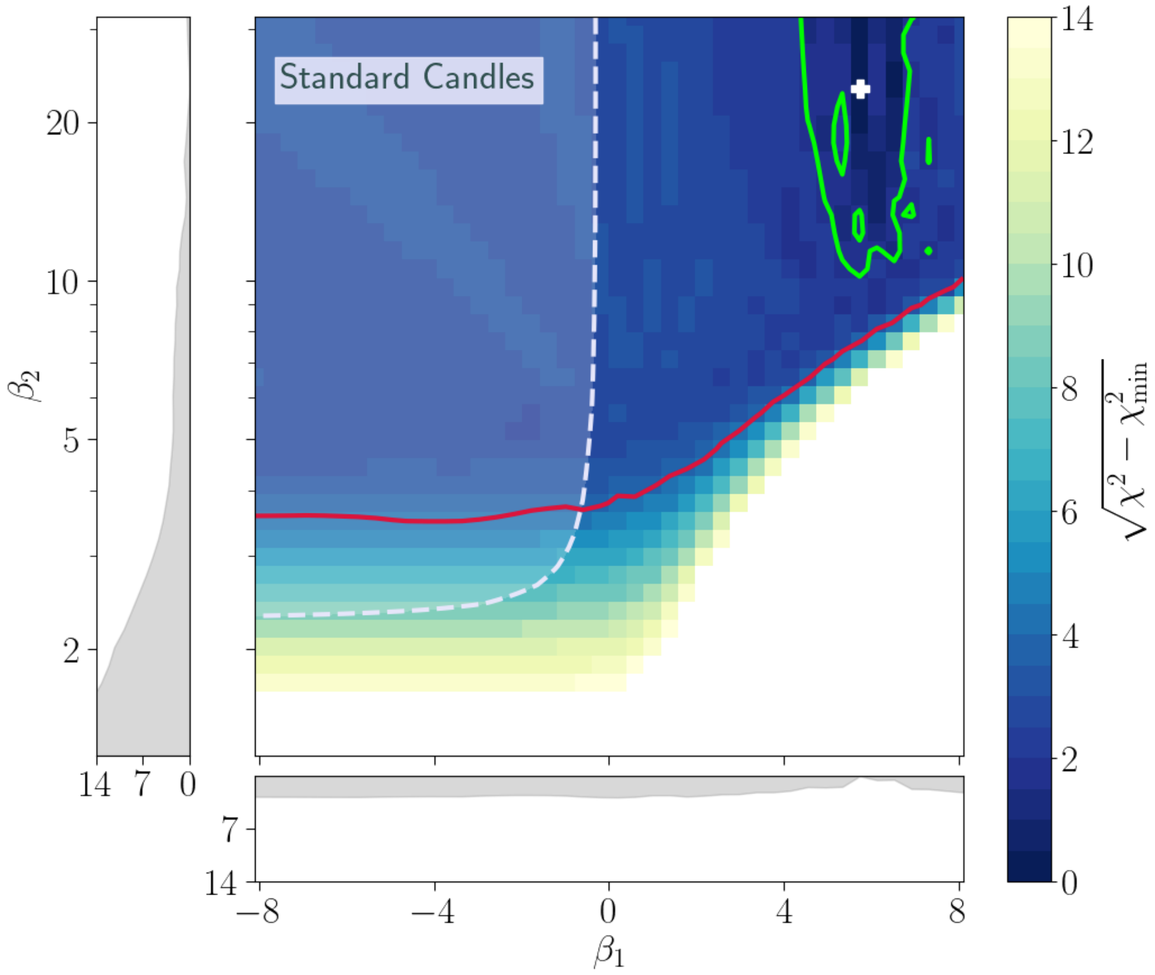

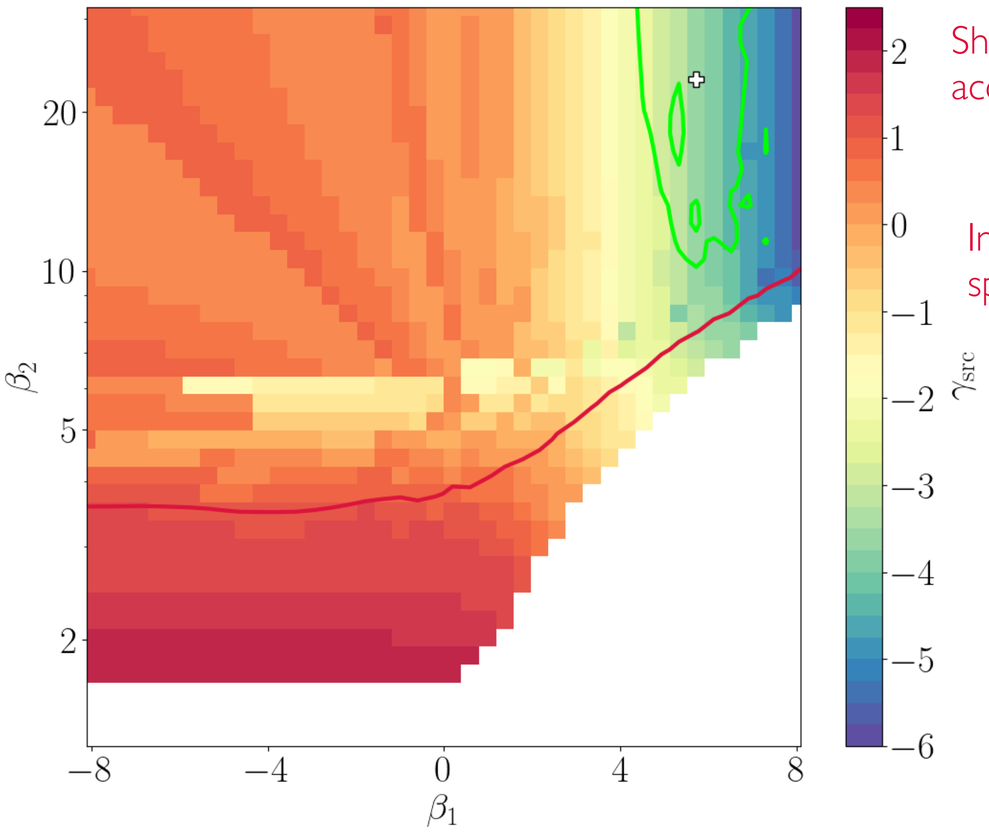

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Comparison with luminosity functions

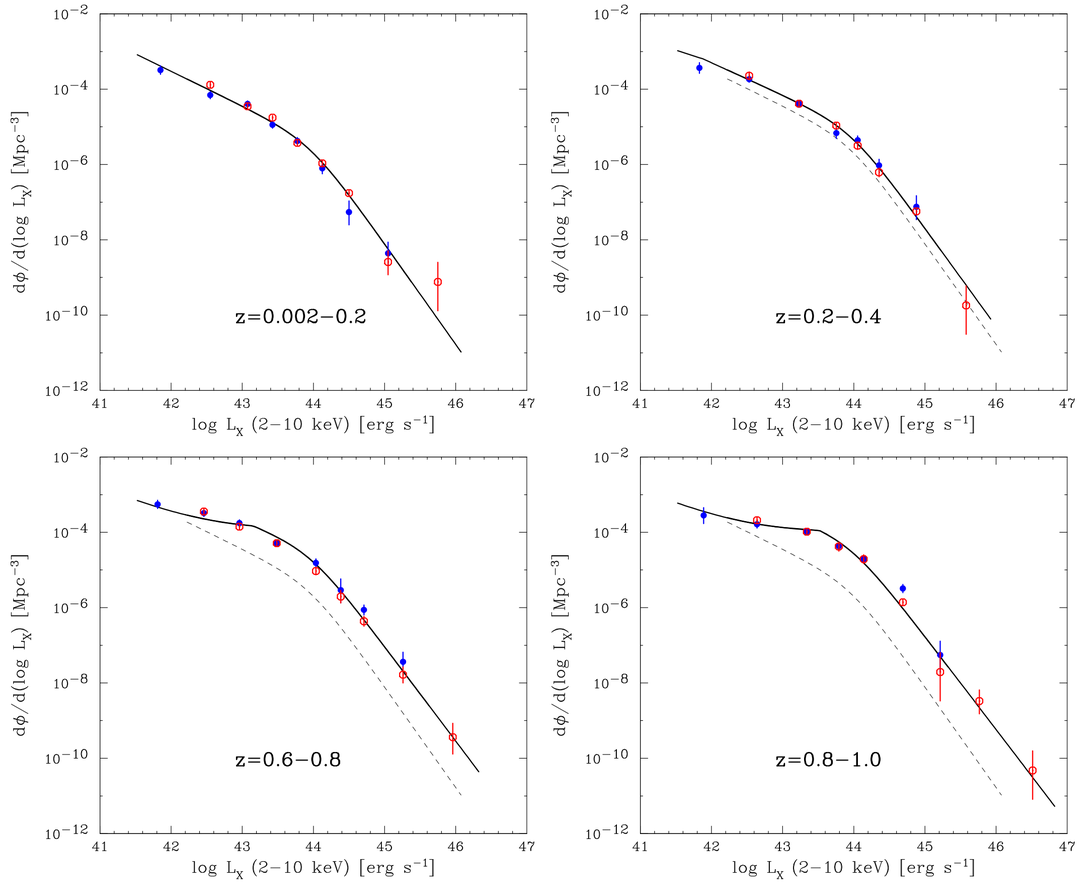
$$L \gtrsim L_B \sim \frac{U_{\rm mag} R^3}{t} \sim B^2 R^2 \beta$$

$$L_{\rm min} \sim \frac{10^{45.5}\ {\rm erg/s}}{\beta} \left(\frac{E}{100\ {\rm EeV}} \right)^2$$

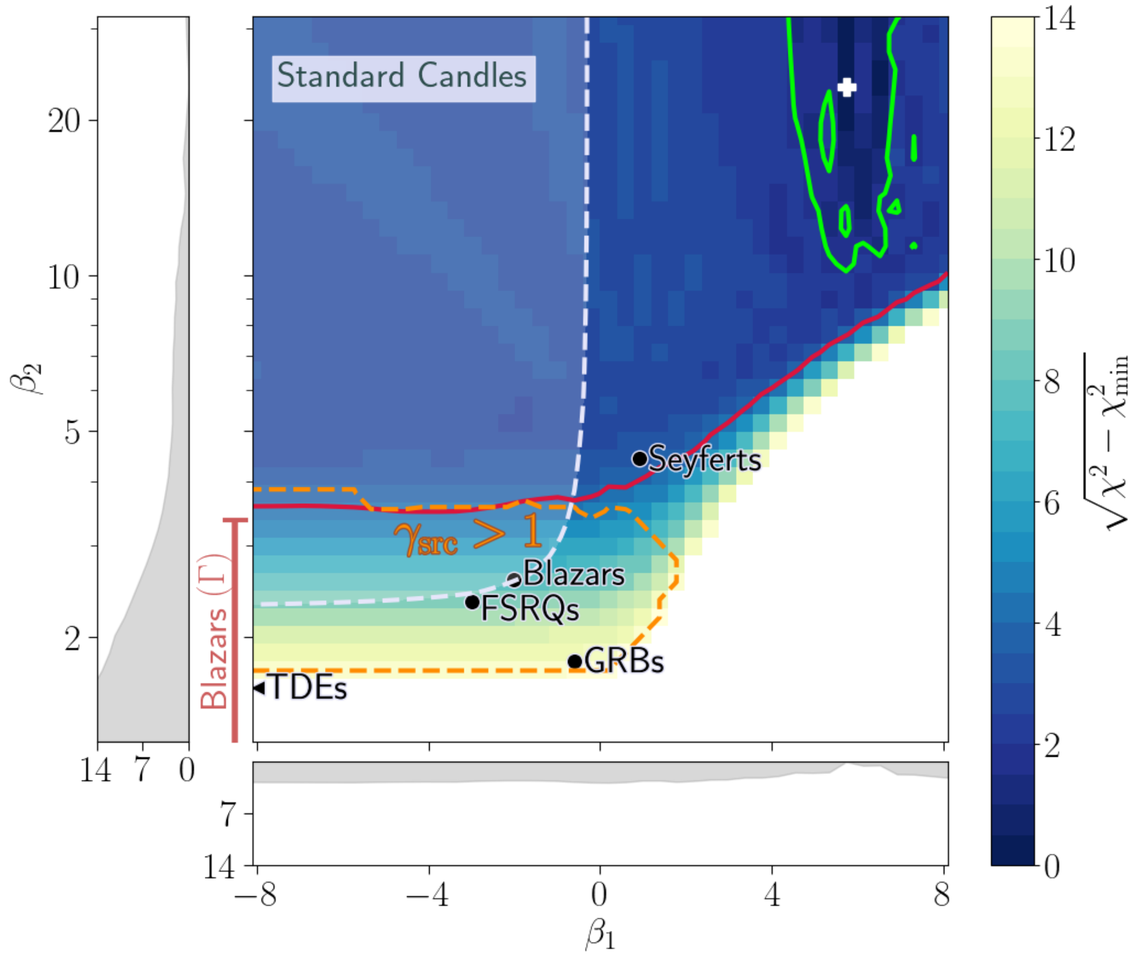
$$E_{\rm max} \sim 100\ {\rm EeV}\ \beta^{1/2} \left(\frac{L}{10^{45.5}\ {\rm erg/s}} \right)^{1/2}$$

Lovelace 1976, Waxman 1995, 2001, Blandford 2000, Lemoine & Waxman 2009

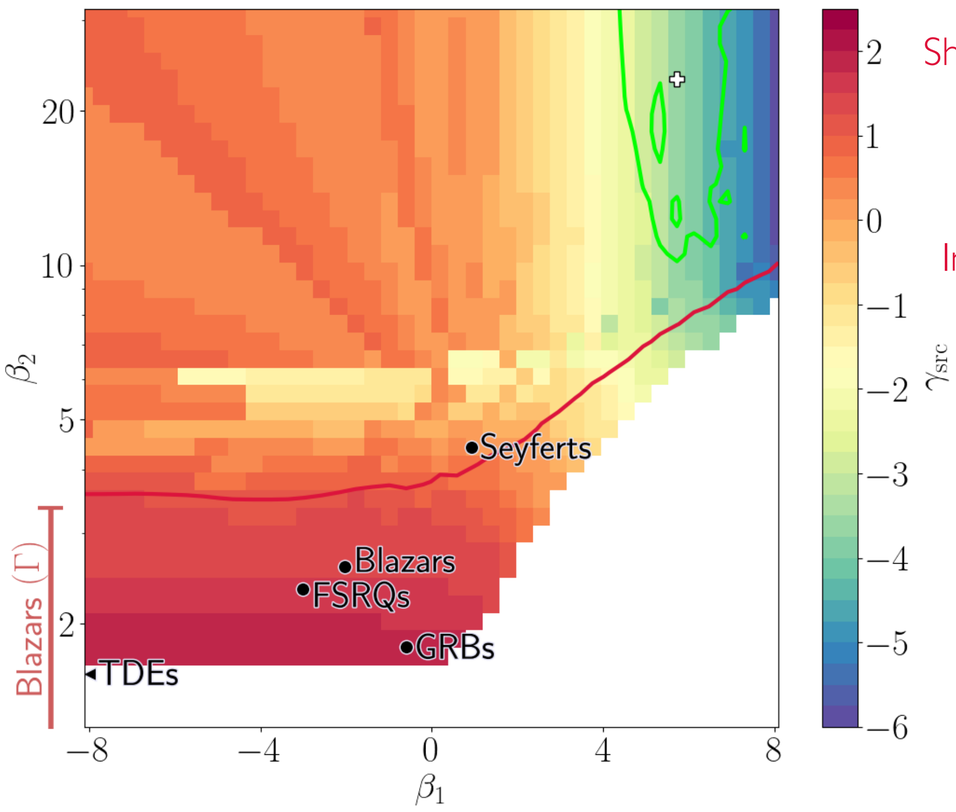
Ueda et al 2014, X-ray AGN Luminosity Function



Broken-power-law distributed maximum rigidity



Individual source energy spectral index



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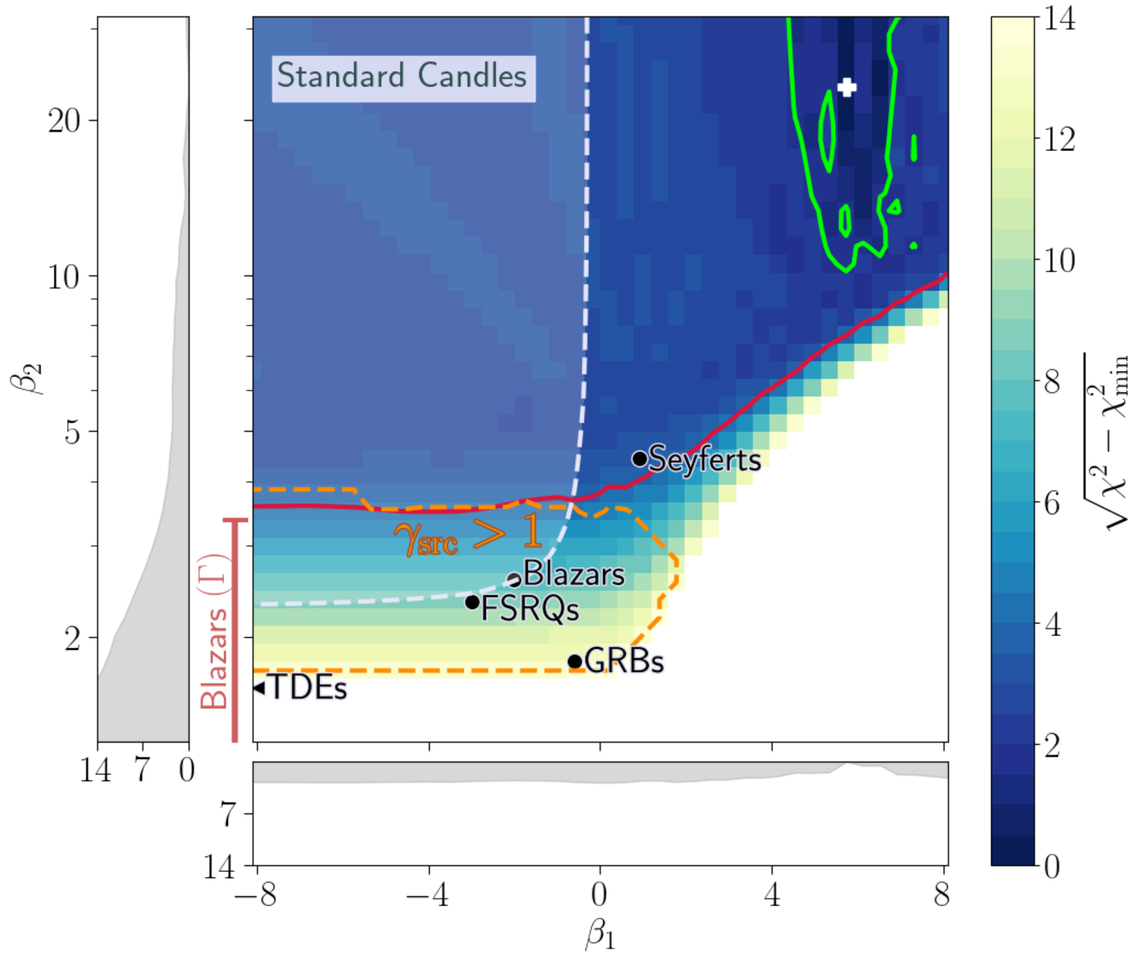

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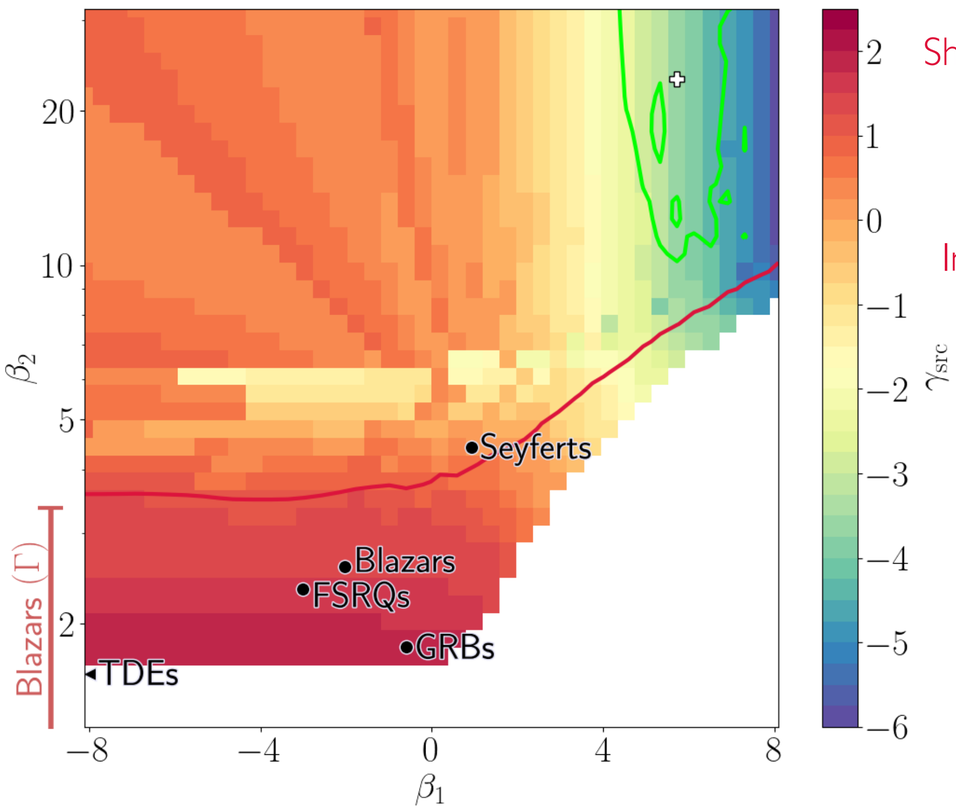

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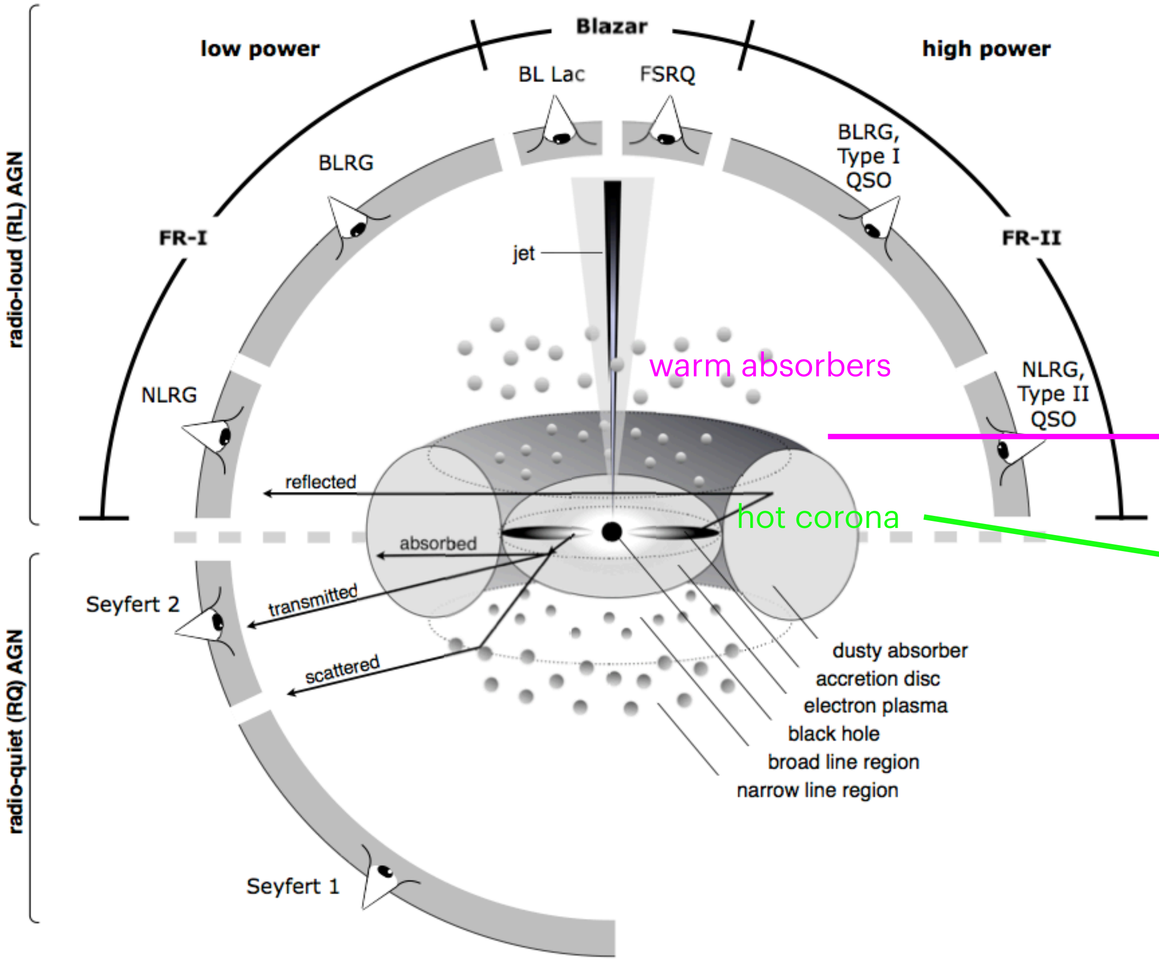
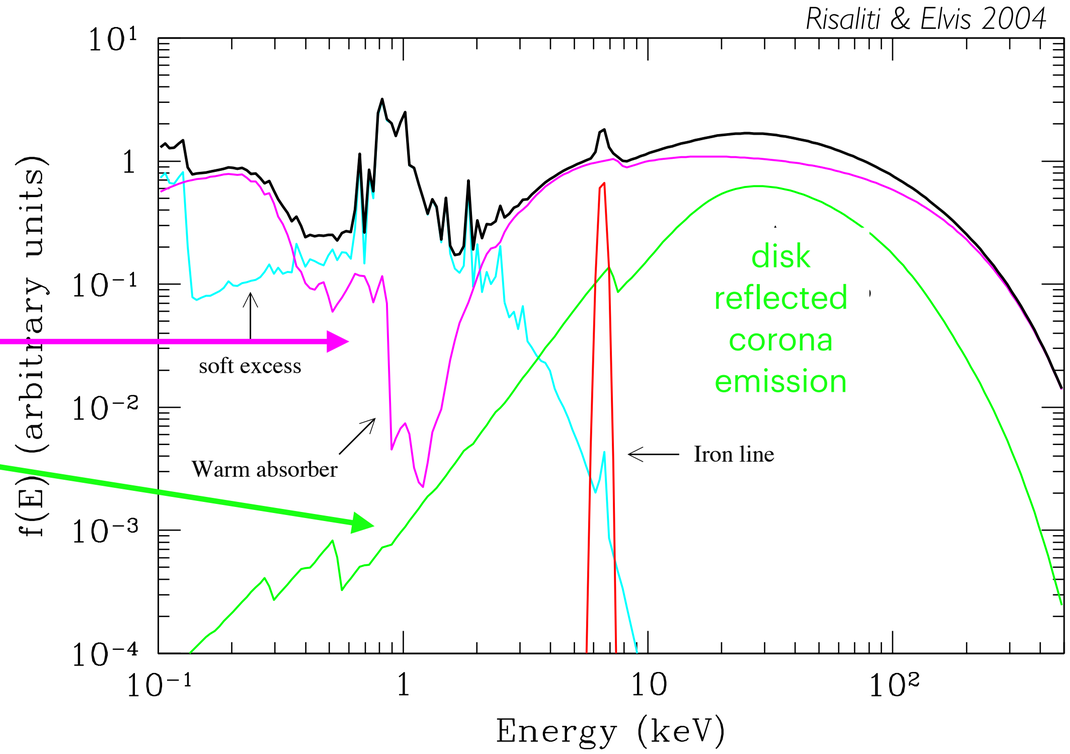
X-ray absorbers in AGN





Beckmann & Shrader 2012

NALs

$\log[\xi\ (\text{erg cm s}^{-1})] = 0–1.5$
$\log[N_H\ (\text{cm}^{-2})] = 18–20$
Velocity = 100–1,000 km s^{-1}
Distance scale = ~1 pc–1 kpc

WAs

$\log[\xi\ (\text{erg cm s}^{-1})] = -1–3$
$\log[N_H\ (\text{cm}^{-2})] = 21–22.5$
Velocity = 100–2,000 km s^{-1}
Distance scale = 0.1 pc–1 kpc

Observed in ~50% of Seyfert I

BALs

$\log[\xi\ (\text{erg cm s}^{-1})] = 0.5–2.5$
$\log[N_H\ (\text{cm}^{-2})] = 20–23$
Velocity = 10,000–60,000 km s^{-1}
Distance scale = 0.001 pc–500 pc

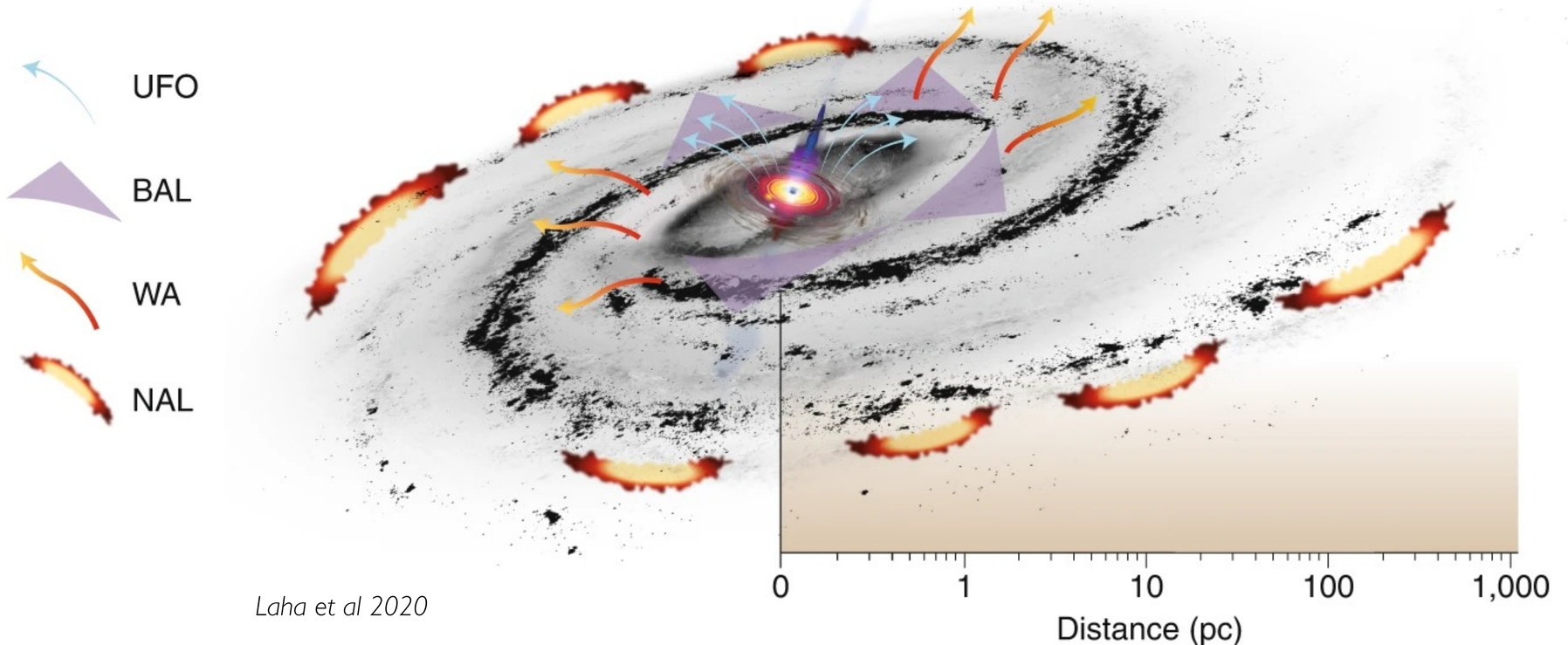
UFOs

$\log[\xi\ (\text{erg cm s}^{-1})] = 3–5$
$\log[N_H\ (\text{cm}^{-2})] = 22–23.5$
Velocity = 10,000–70,000 km s^{-1}
Distance scale = 0.001 pc–10 pc

Observed in ~40% of radio loud and radio quiet AGN

v ~ 0.03 - 0.3 c

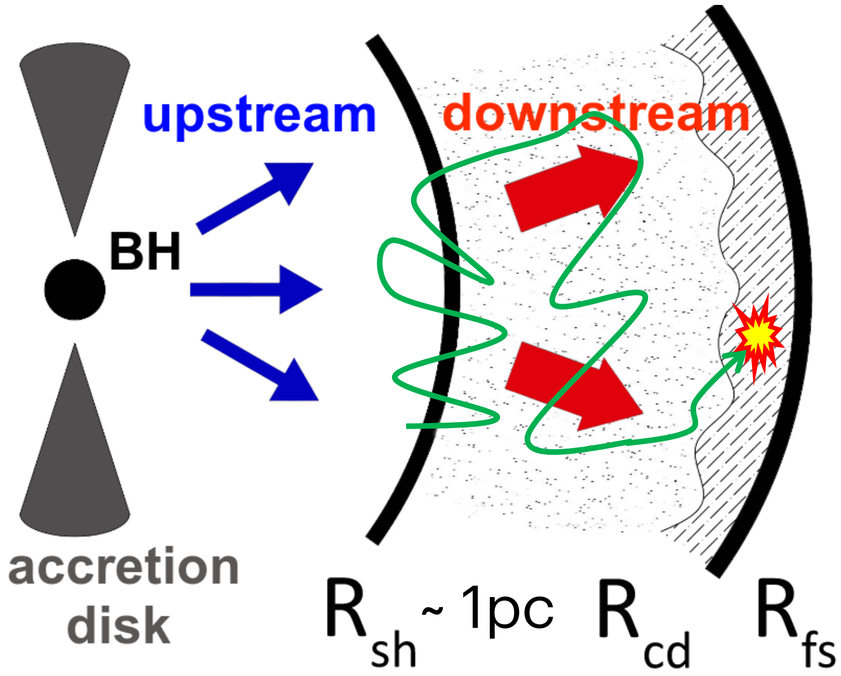
(Tombesi et al 2010,2011, 2012, 2014)



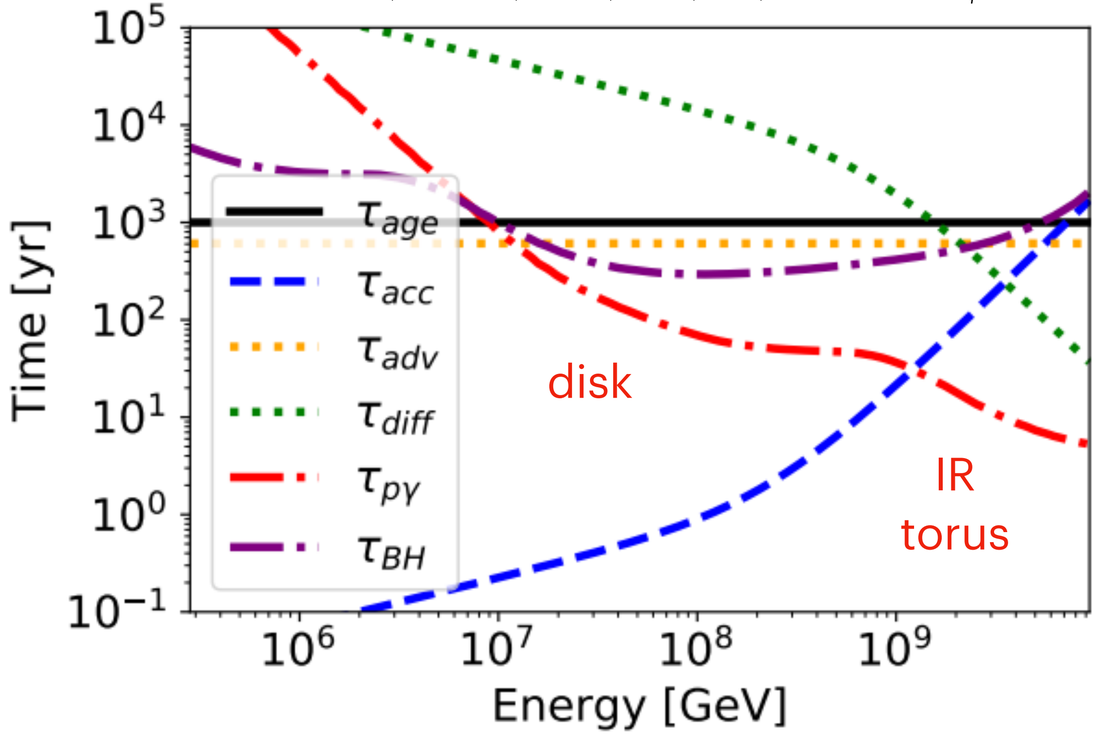
Laha et al 2020

Can UFOs accelerate protons to UHE?

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



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



$$E_{p,\max} \sim 1\ \mathrm{EeV} \left(\frac{\epsilon_B}{5\,\%} \frac{M}{0.1\ M_\odot\ \mathrm{yr}^{-1}} \frac{1\ \mathrm{pc}}{R_{\mathrm{shock}}} \right)^{1/2} \frac{v_{\mathrm{UFO}}}{0.2c}$$

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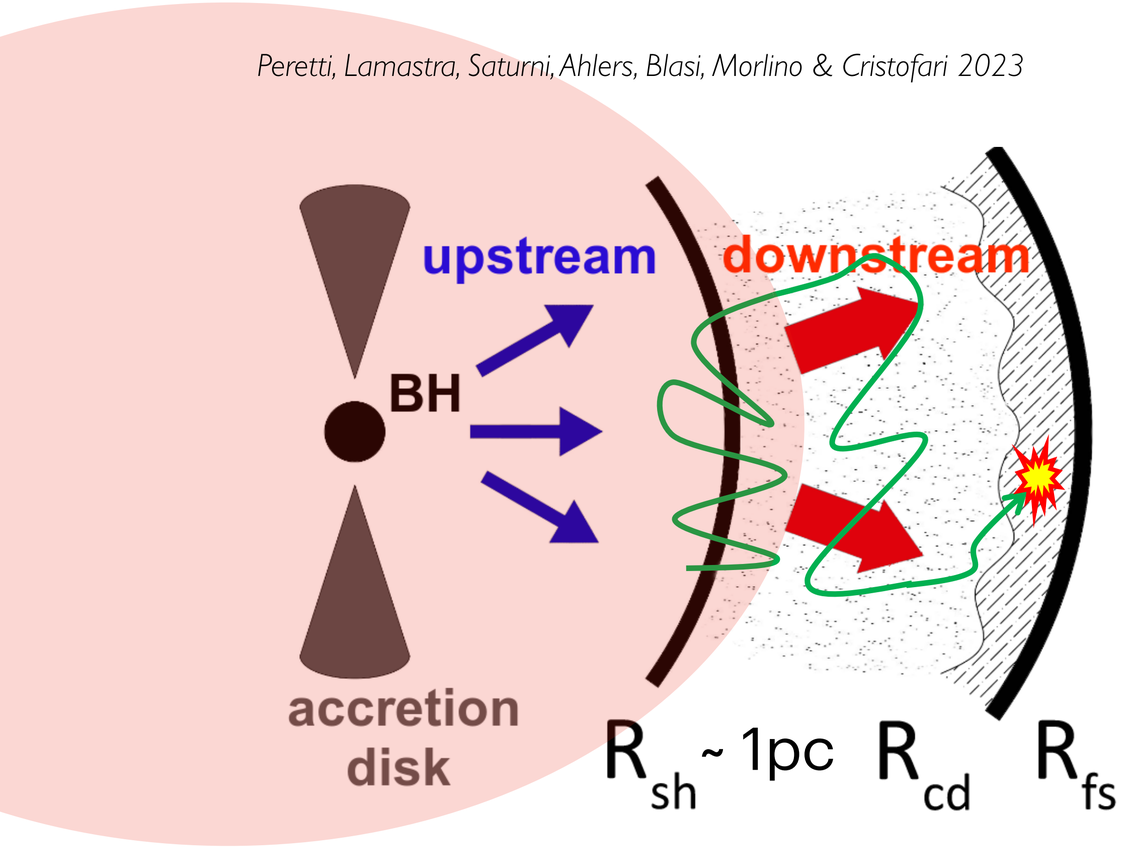
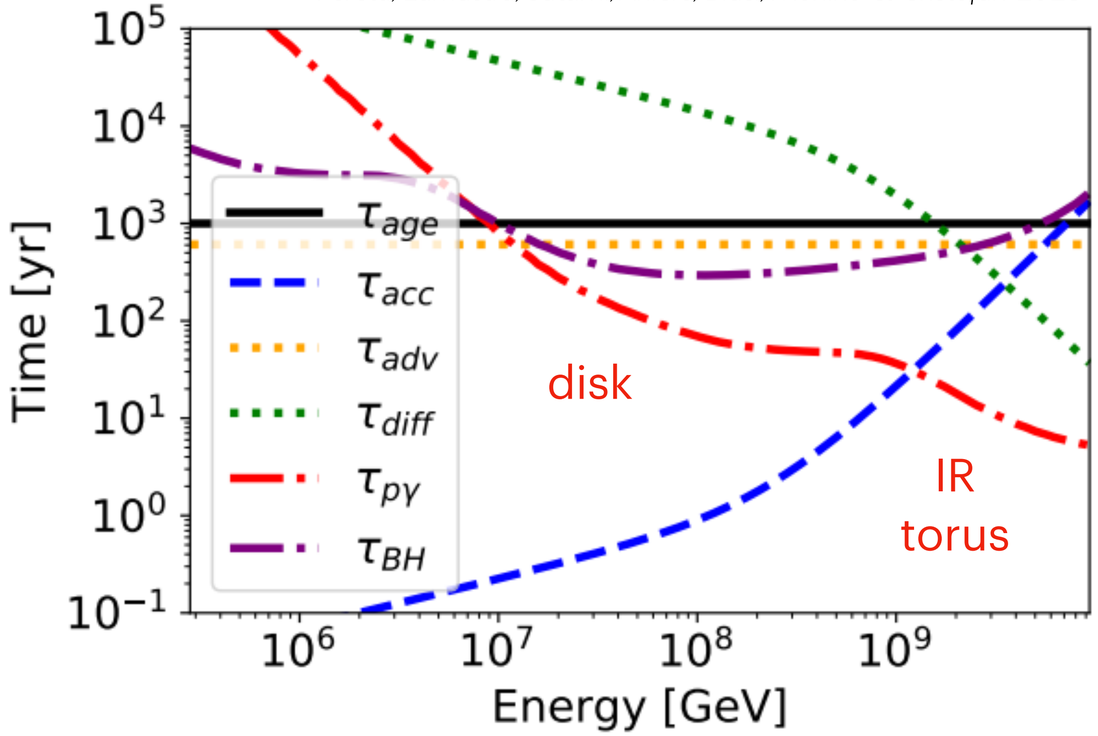


Peretti, Lamastra, Saturni, Ahlers, Blasi, Morlino & Cristofari 2023

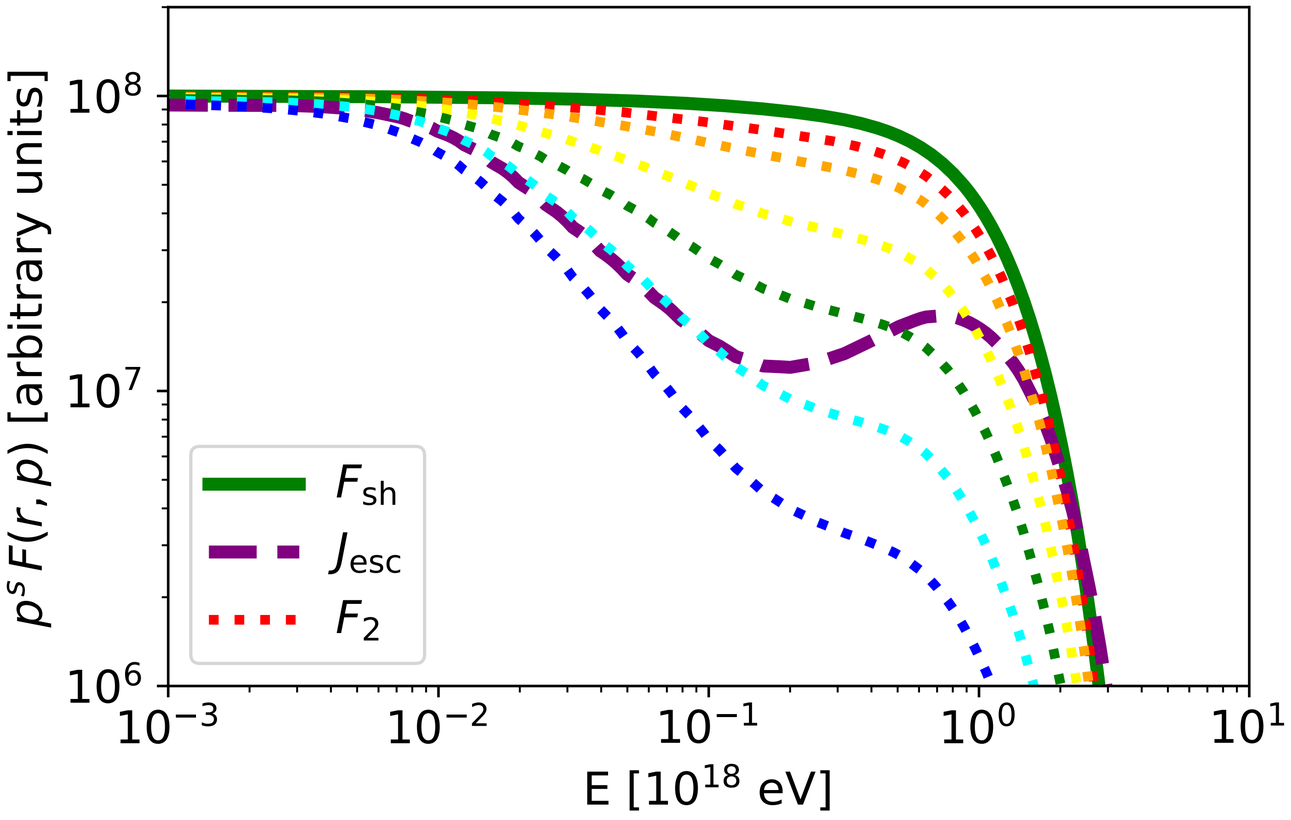


IR torus $L_{\rm IR} \sim 0.5 L_{\rm disk}$

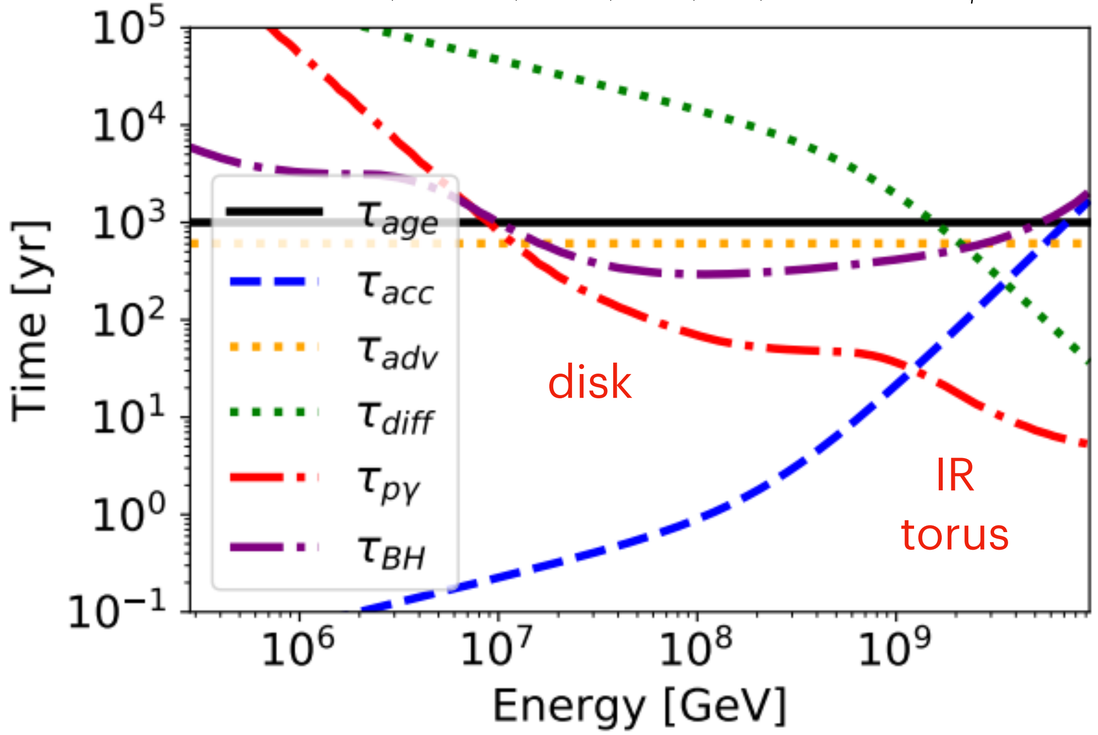
$$R_{\rm IR} \sim 1\ {\rm pc} \cdot \left(\frac{L_{\rm disk}}{10^{45}\ {\rm erg/s}} \right)^{1/2}$$

$$E_{p,\rm max} \sim 1\ {\rm EeV} \left(\frac{\epsilon_B}{5\,\%} \frac{M}{0.1\ M_\odot\ {\rm yr}^{-1}} \frac{1\ {\rm pc}}{R_{\rm shock}} \right)^{1/2} \frac{v_{\rm UFO}}{0.2c}$$

Can UFOs accelerate protons to UHE?



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

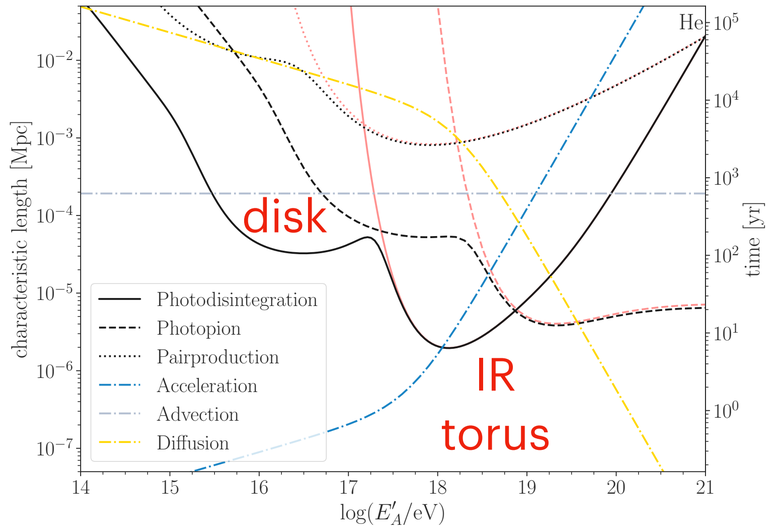


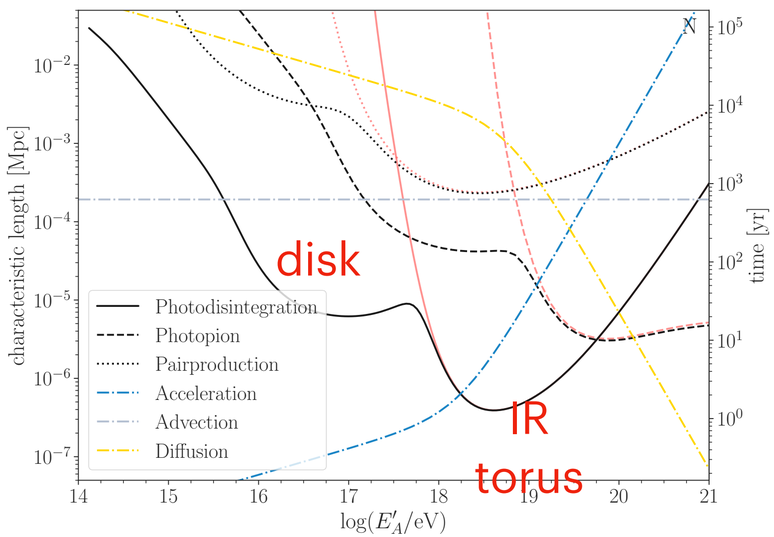
$$E_{p,\max} \sim 1\ \mathrm{EeV} \left(\frac{\epsilon_B}{5\,\%} \frac{M}{0.1\ M_\odot\ \mathrm{yr}^{-1}} \frac{1\ \mathrm{pc}}{R_{\mathrm{shock}}} \right)^{1/2} \frac{v_{\mathrm{UFO}}}{0.2c}$$

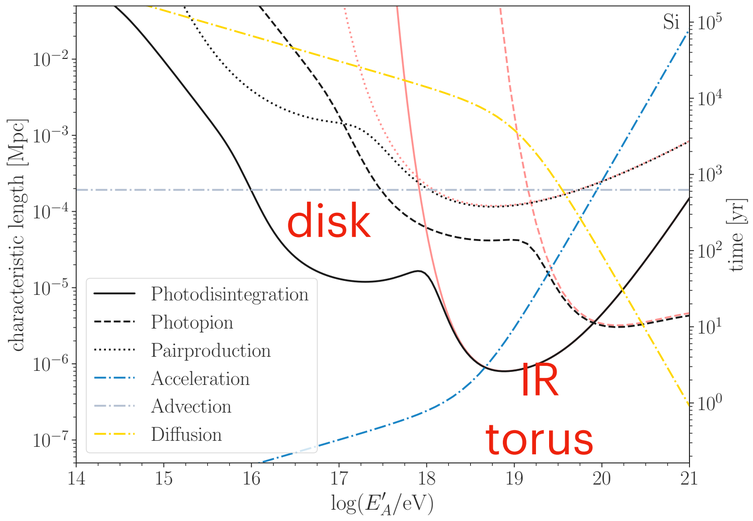
Maximum energy for nuclei in UFOs?

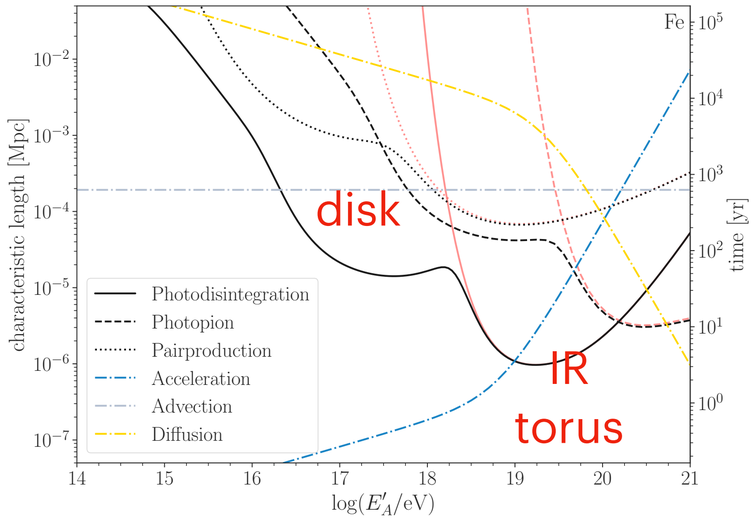
Benchmark scenario

D. Ehlert, FO, E. Peretti, in prep









Interaction rates calculated with CRPropa

AGN photon fields from Ghisellini + Tavecchio 2009

Maximum energy for nuclei in UFOs?

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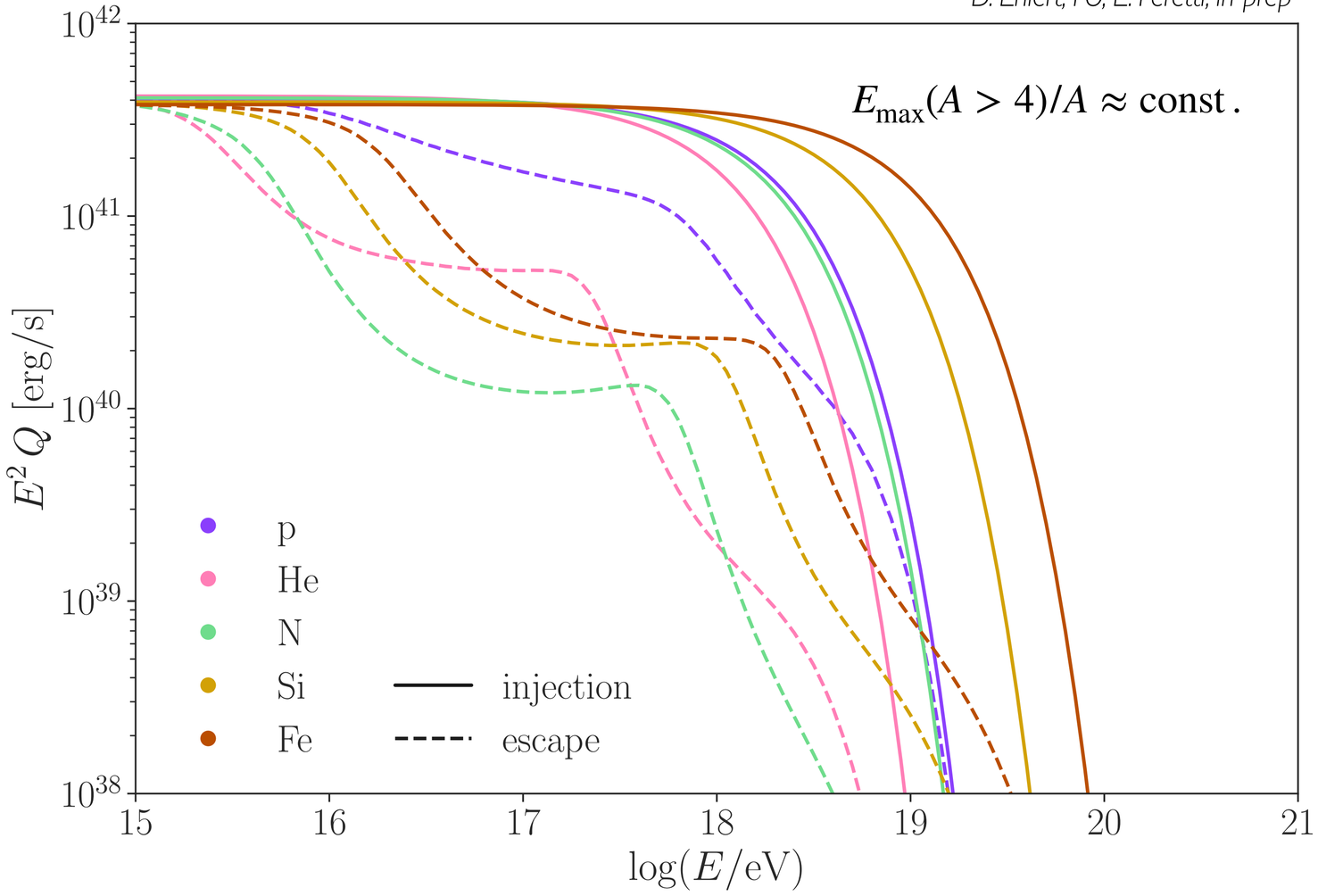
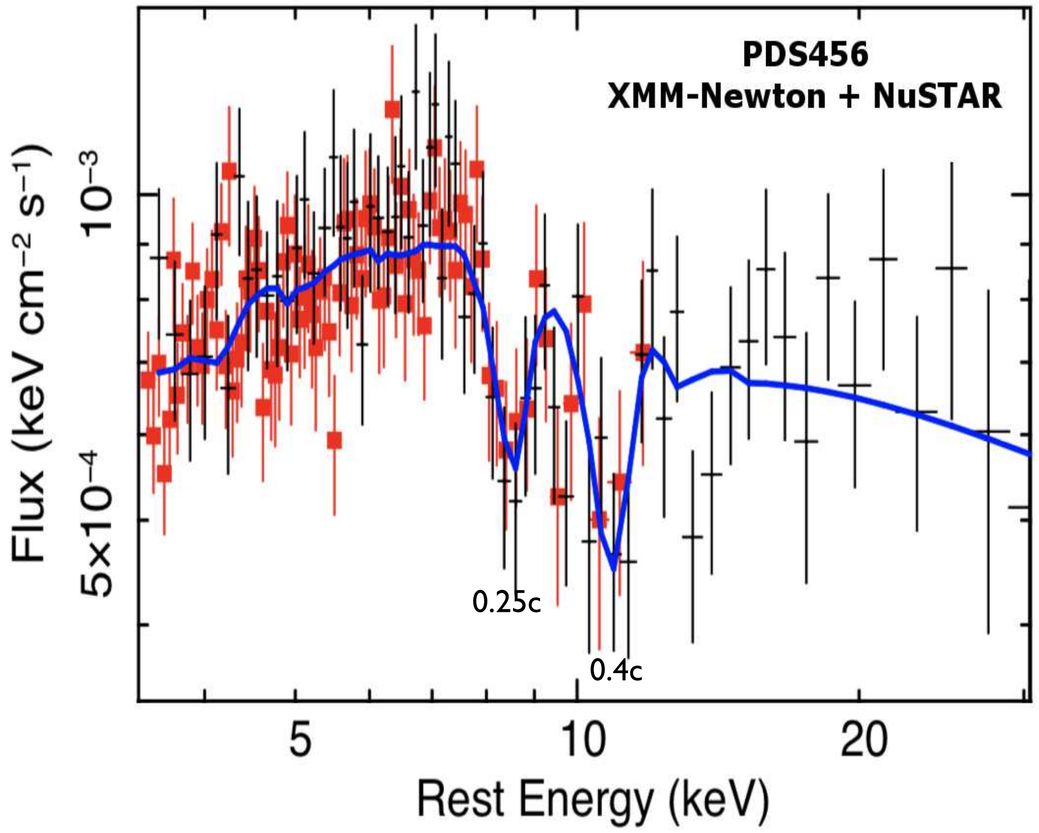
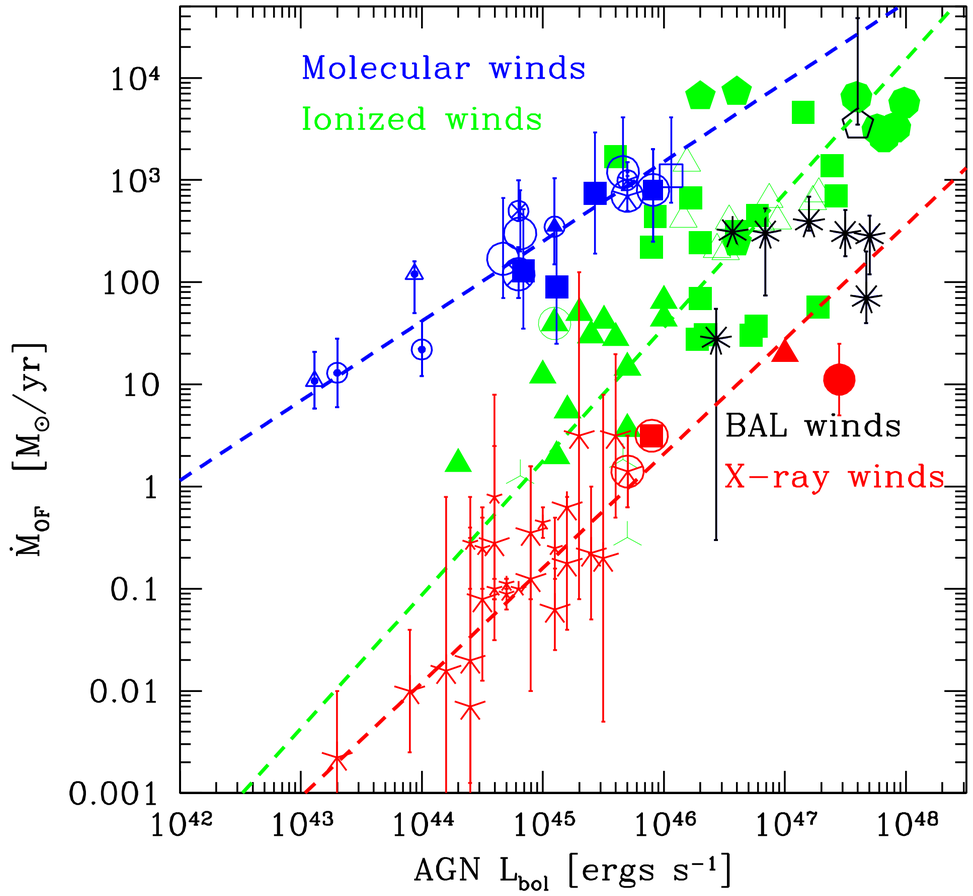


Application to observed UFOs



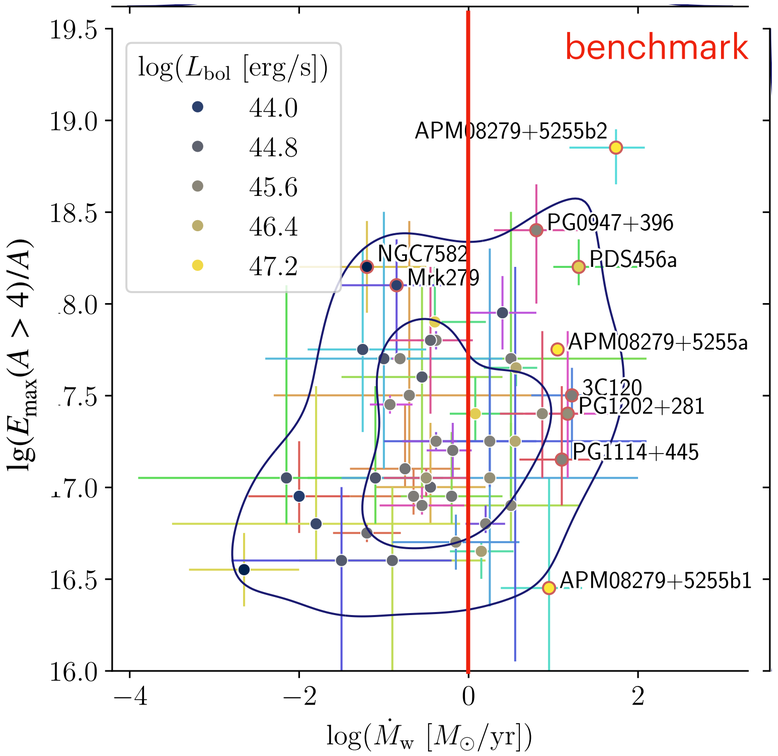
Fiore et al 2017

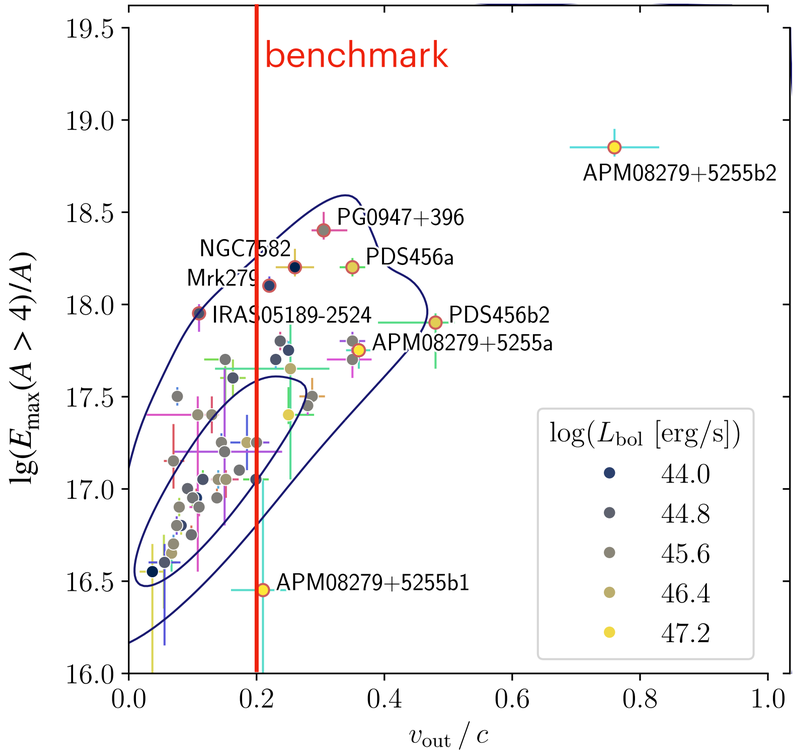


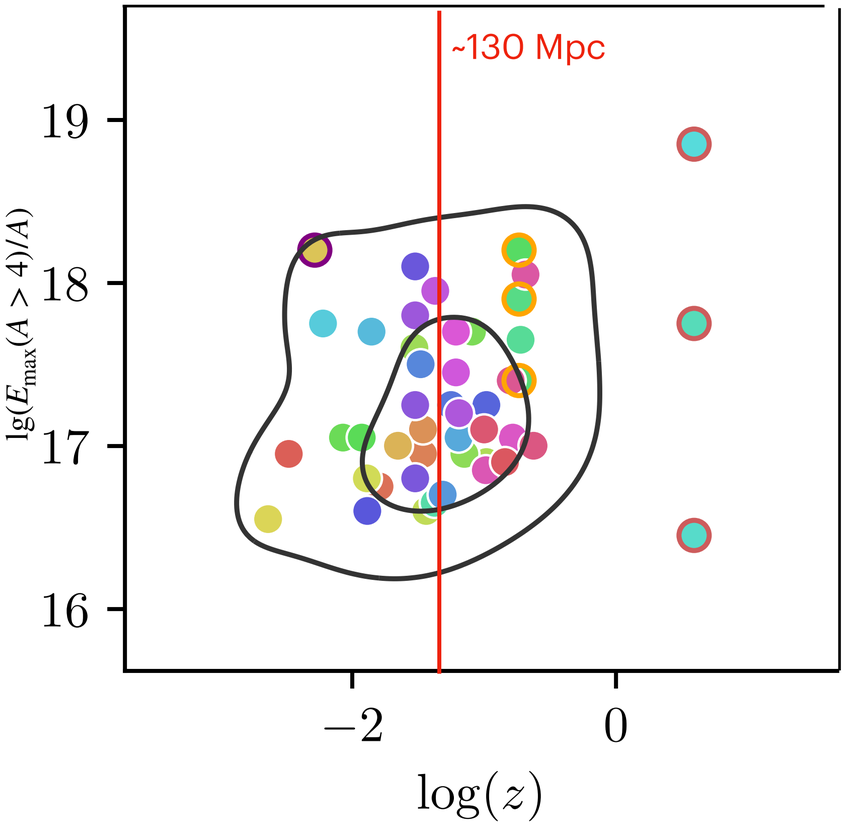
In total 48 from
Chartas et al 2009
Reeves et al 2009, 1
Riecchers et al 2009
Tombesi et al 2010,
Gofford et al 2015
Nardini et al 2015, 1
Braito et al 2018
Fiore et al 2017
Boissay-Malaquin 20
Smith et al 2019
Ajello et al 2021
Laurenti et al 2021

Application to observed UFOs

D. Ehlert, FO, E. Peretti, in prep







Application to observed UFOs

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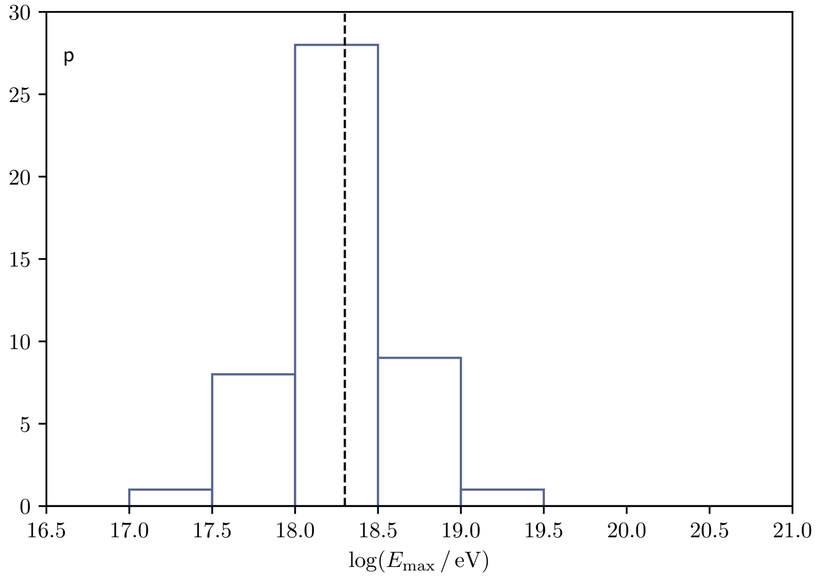
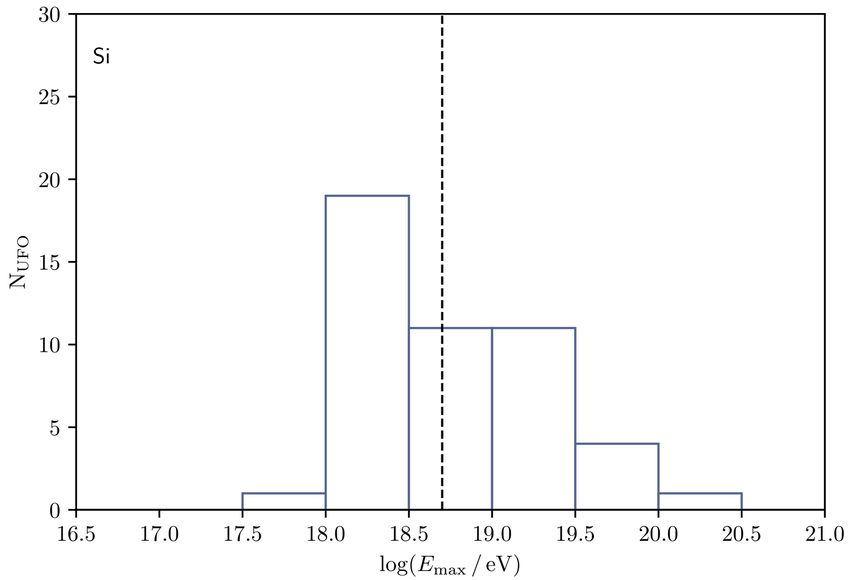
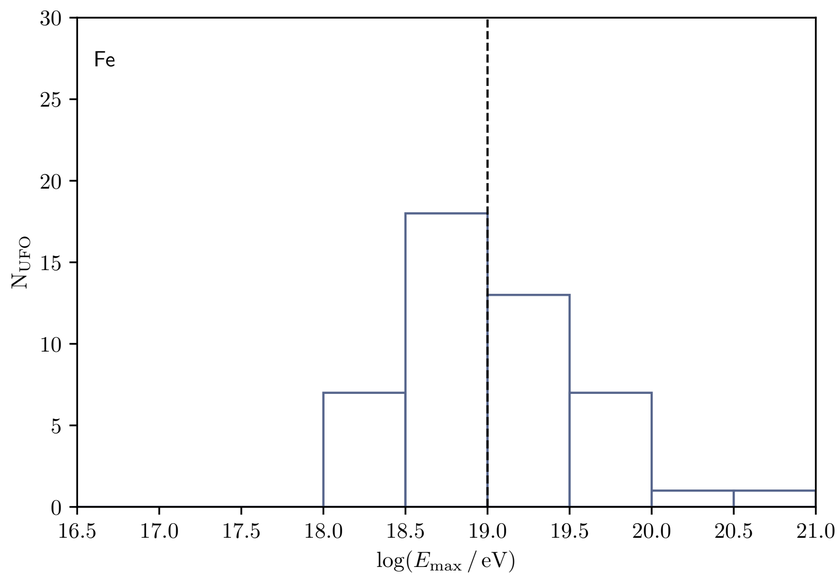
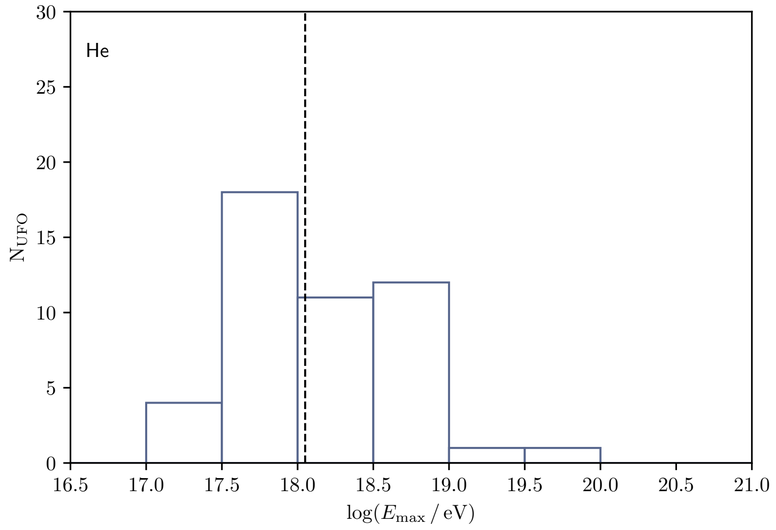
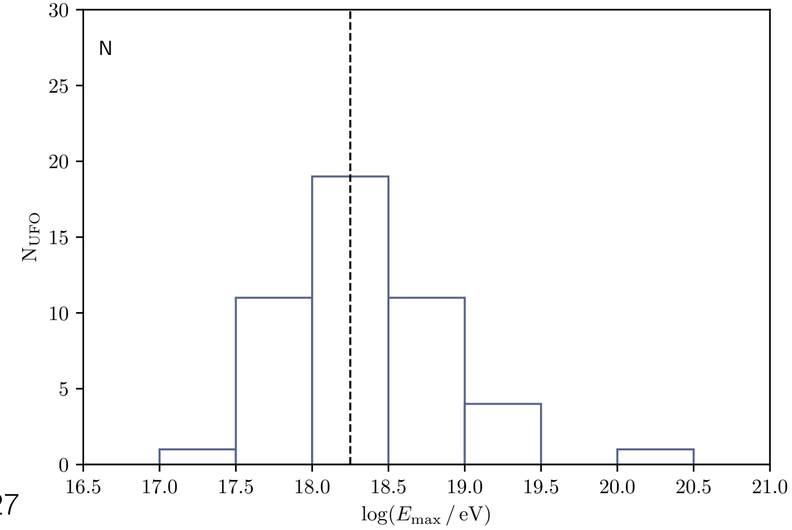


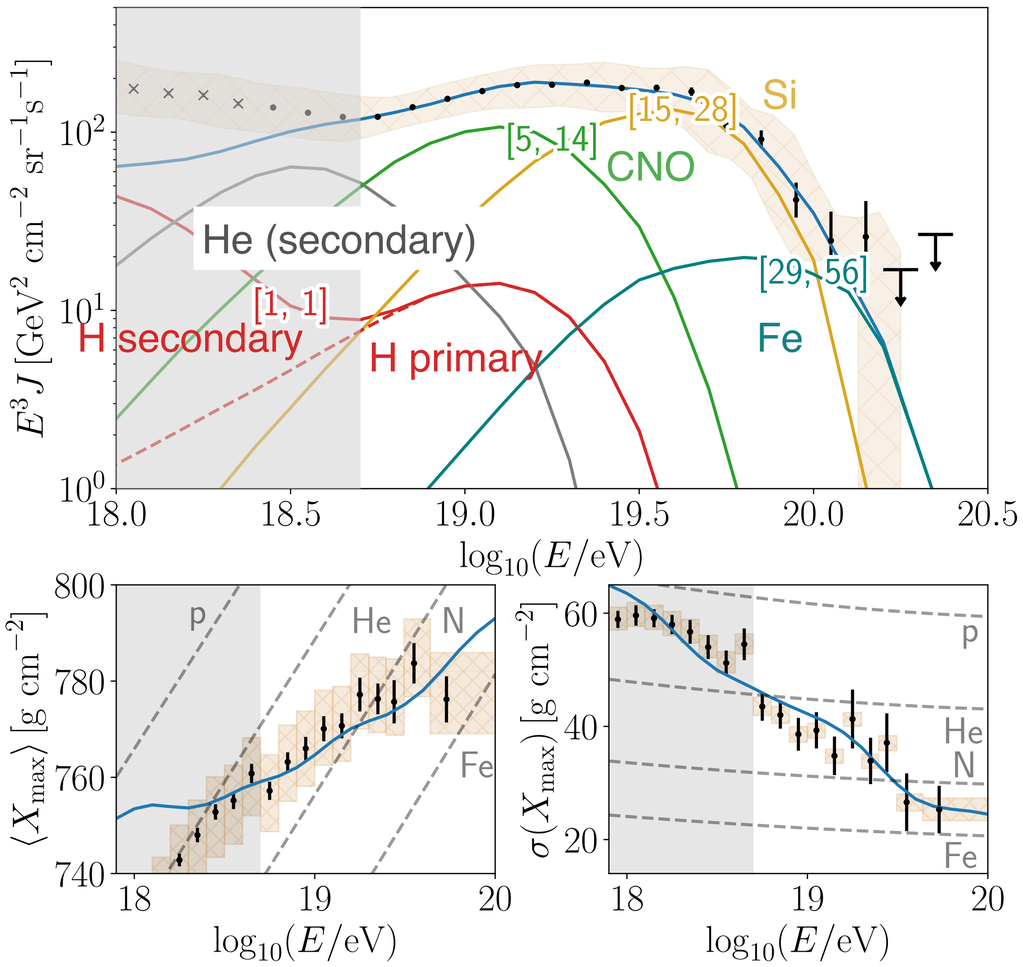








Combined fit



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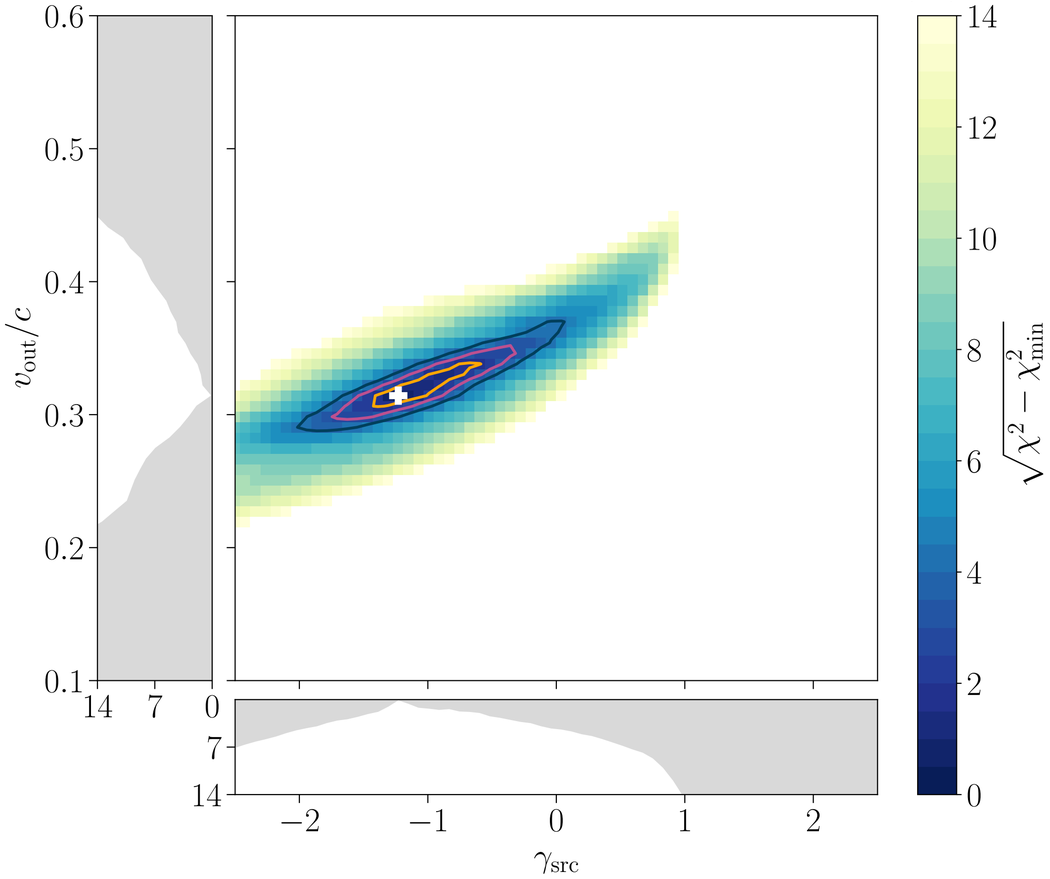


$E_{H,\mathrm{max}} = 3.7 \times 10^{18}$ eV

$E_{He,\mathrm{max}} = 3.3 \times 10^{18}$ eV

$E_{N,\mathrm{max}} = 4.2 \times 10^{18}$ eV

$E_{Si,\mathrm{max}} = 1.3 \times 10^{19}$ eV

$E_{Fe,\mathrm{max}} = 2.6 \times 10^{19}$ eV

$\chi^2/\mathrm{ndf} \approx 1.6$

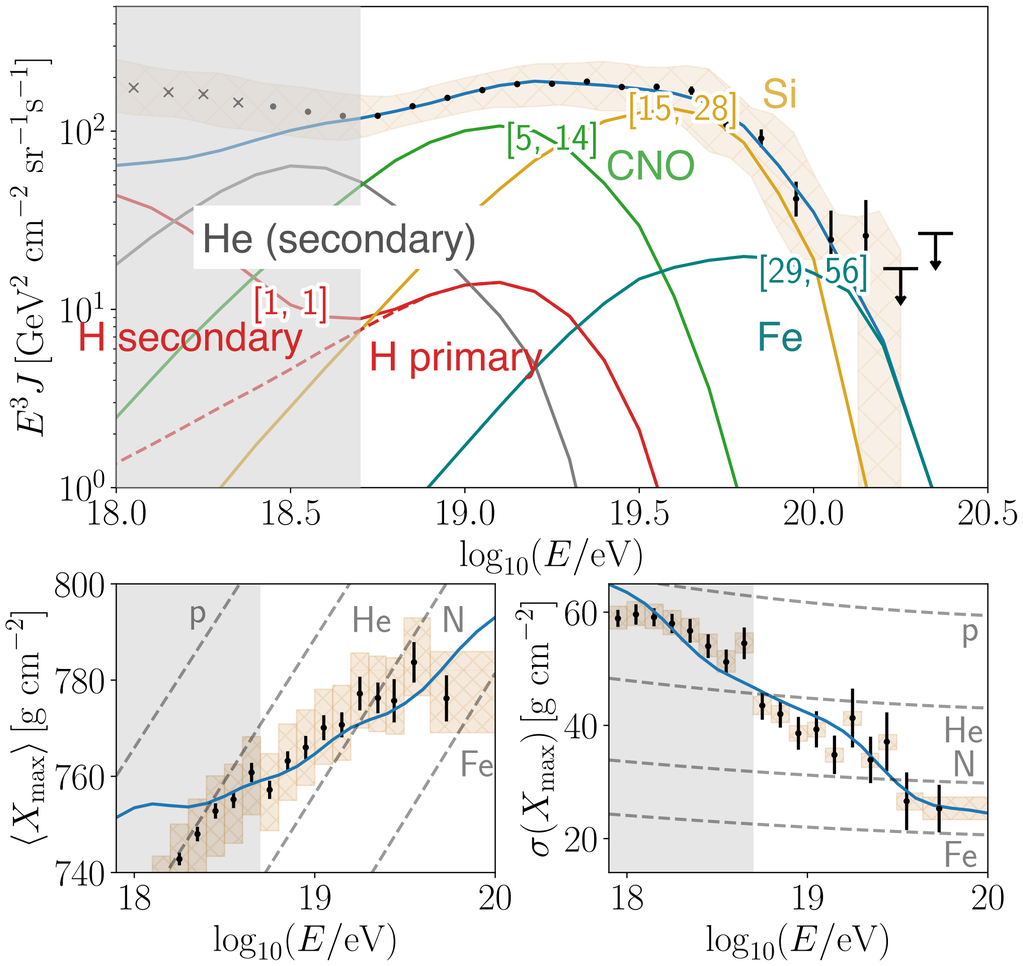
$\gamma_{\mathrm{src}} = -1.2^{+0.2}_{-0.1}$

$f_{p,He,Fe}(R = 1\ \mathrm{EV}) \approx 0\,\%$

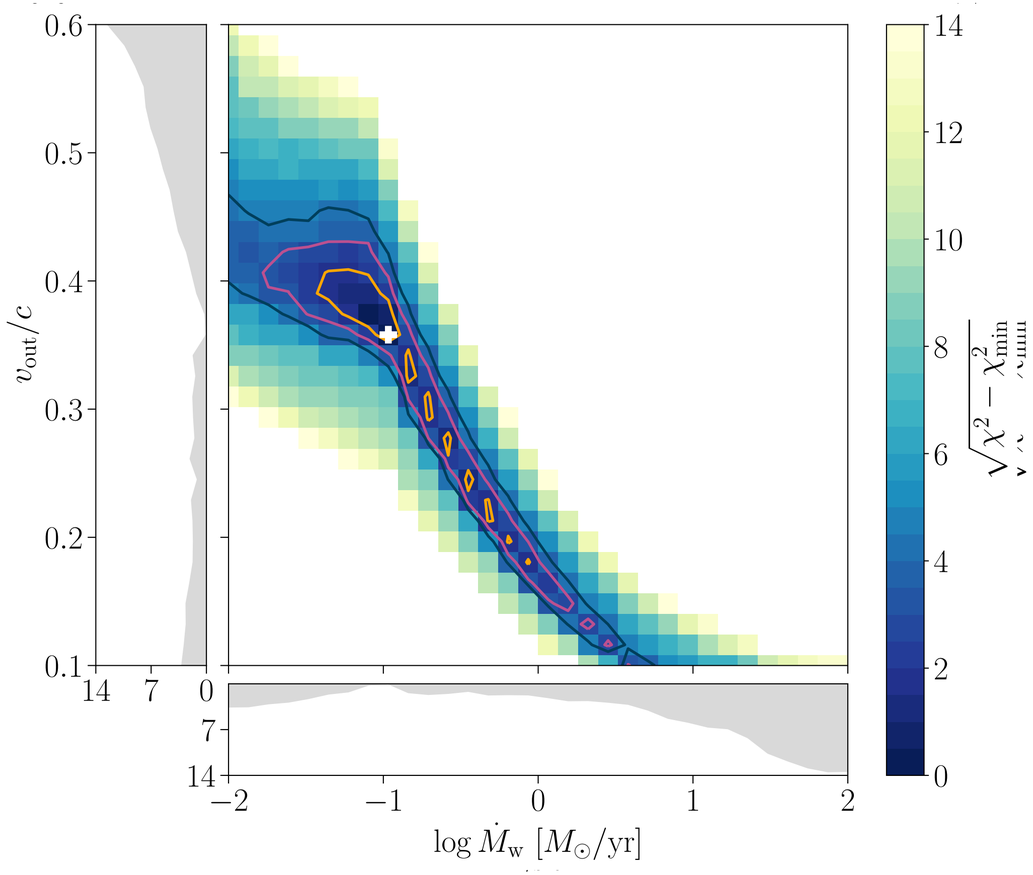
$f_{\mathrm{N}}(R = 1\ \mathrm{EV}) \approx 85\,\%$

$f_{\mathrm{Si}}(\mathrm{R} = 1\ \mathrm{EV}) \approx 15\,\%$

Combined fit



D. Ehlert, FO, E. Peretti, in prep



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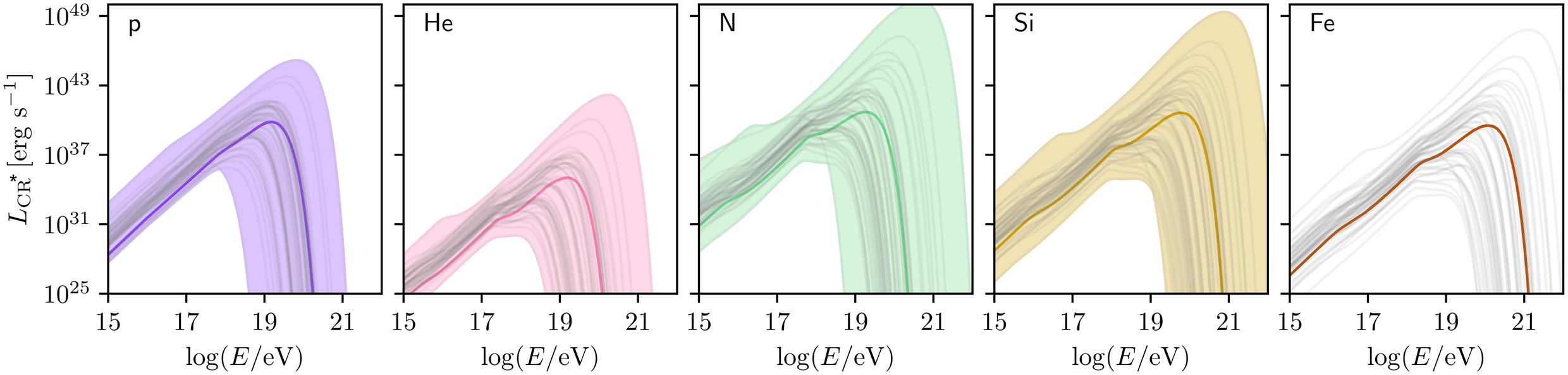
Combined fit

Problem: Hard spectra needed

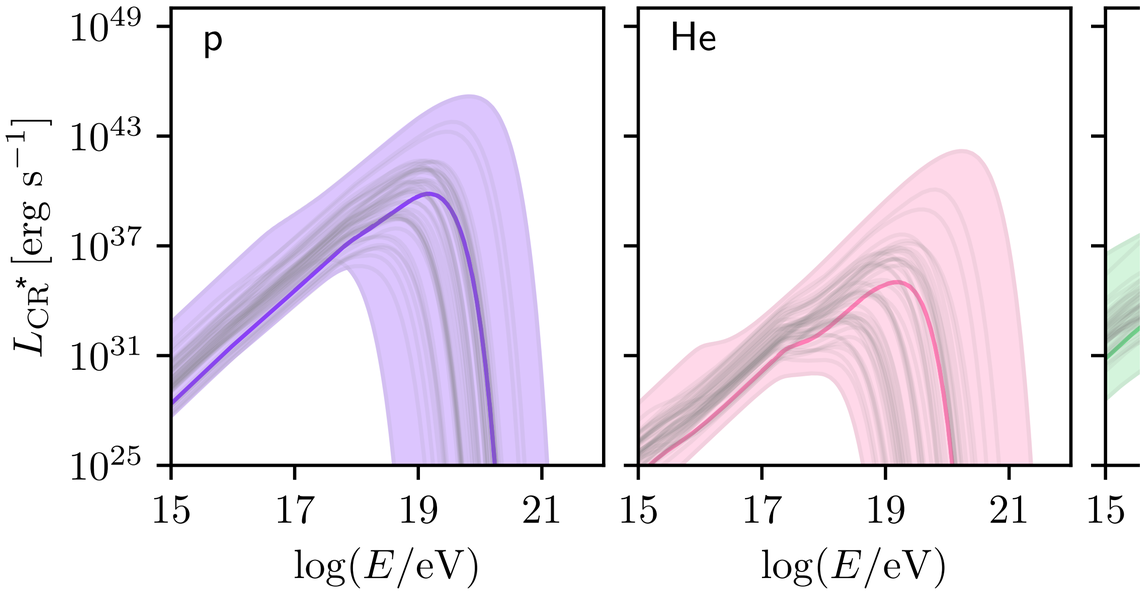
D. Ehlert, FO, E. Peretti, in prep



⋆Assuming $n_0 \sim 10^{-6}$ Mpc^{-3}, SFR evolution

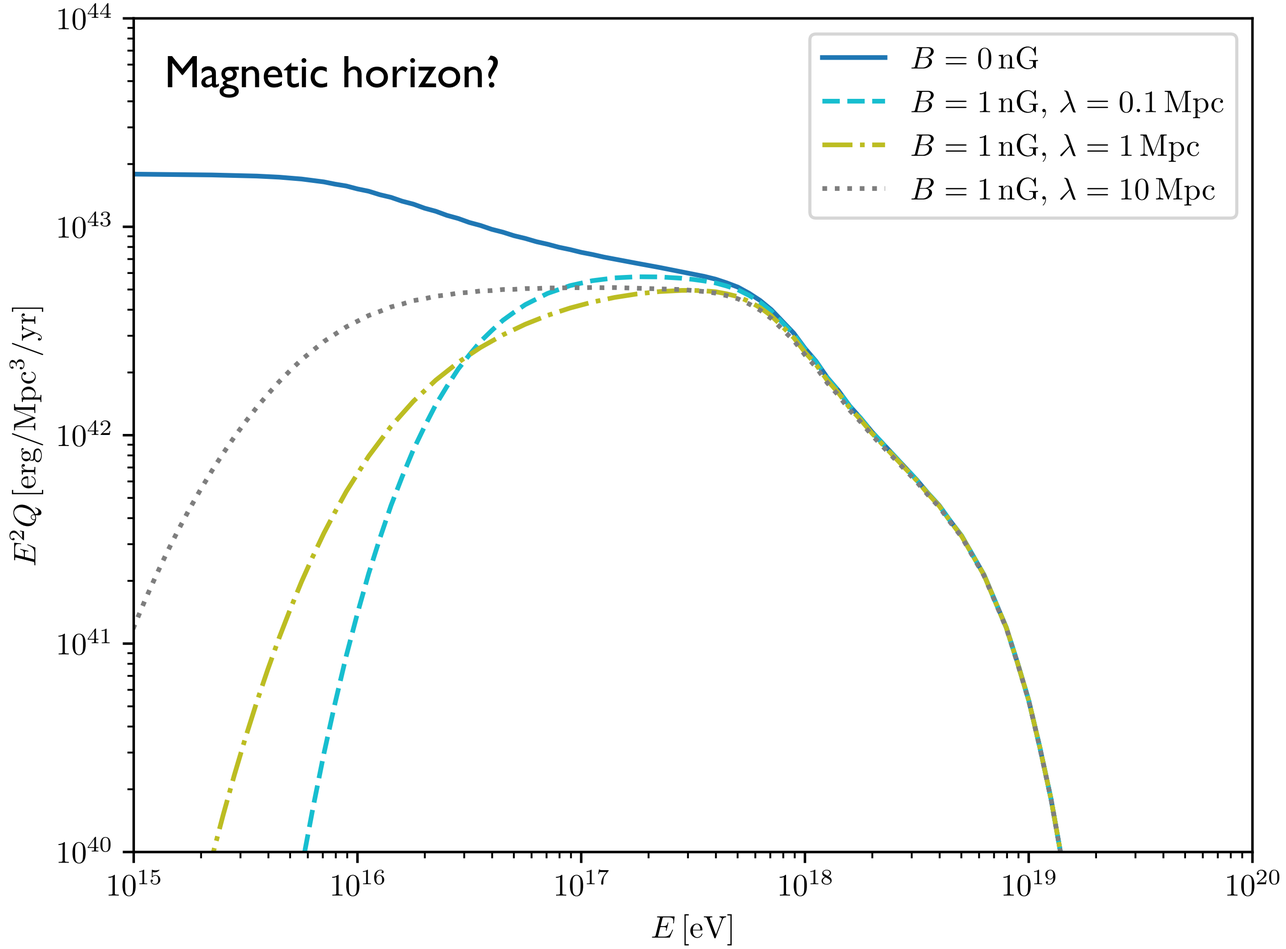
Combined fit

Problem: Hard spectra needed



⋆Assuming $n_0 \sim 10^{-6}$ Mpc^{-3}, SFR evolution

see Gonzalez, Mollerach, Roulet 2021



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?

UFOs:

Possible to reach highest energies with the most powerful UFOs

But: Hard spectra required by UHECR combined fit - inconsistent with DSA

Magnetic horizon + shocked ambient medium? — In progress