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Populations of UHECR sources

How diverse are they?

How different can the sources be?

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multiple populations
e.g. FSRQs & BL Lacs
part 2,
DE, A. van Vliet, F. Oikonomou, W. Winter arXiv:2304.07321

intra-population variance
i.e. non-identical sources
part 1,
DE, F. Oikonomou, M. Unger
PRD 107 (2023) 10, 103045

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Kachelriess & Semikoz, Phys. Lett. B 634, 143 (2006),
Shibata et al, Astrophys. J. 716, 1076 (2010)

How different can the sources be?

current paradigm:

All sources are <u>identical</u>.

(for a particular population)

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Unger et al, Phys. Rev. D 92, 123001 (2015),
Aab et al. (Pierre Auger), JCAP 04, 038,
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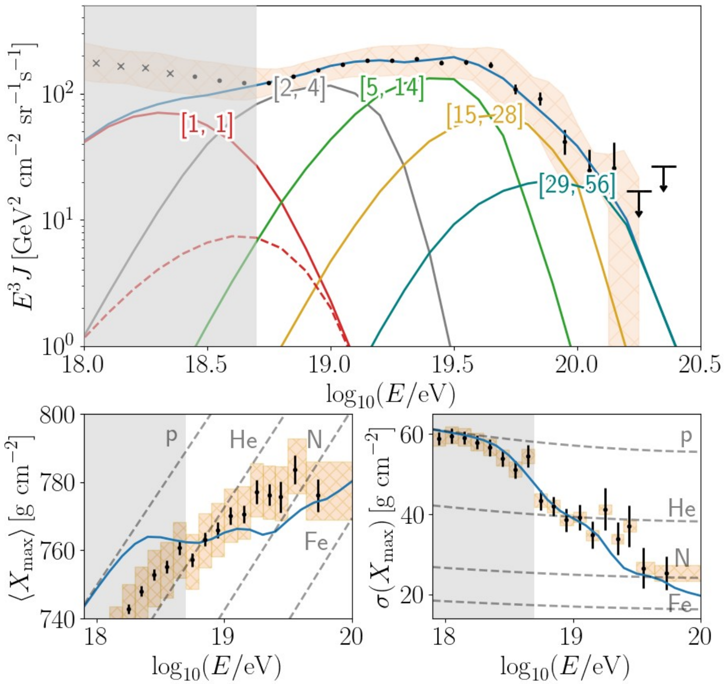


How different can the sources be?

current paradigm:

All sources are identical. → Is this physically motivated?

(for a particular population)

How different can the sources be?

current paradigm:

All sources are identical. → Is this physically motivated?

(for a particular population)

NO!

see diversity of luminosity, size, magnetic field, jet power, etc.

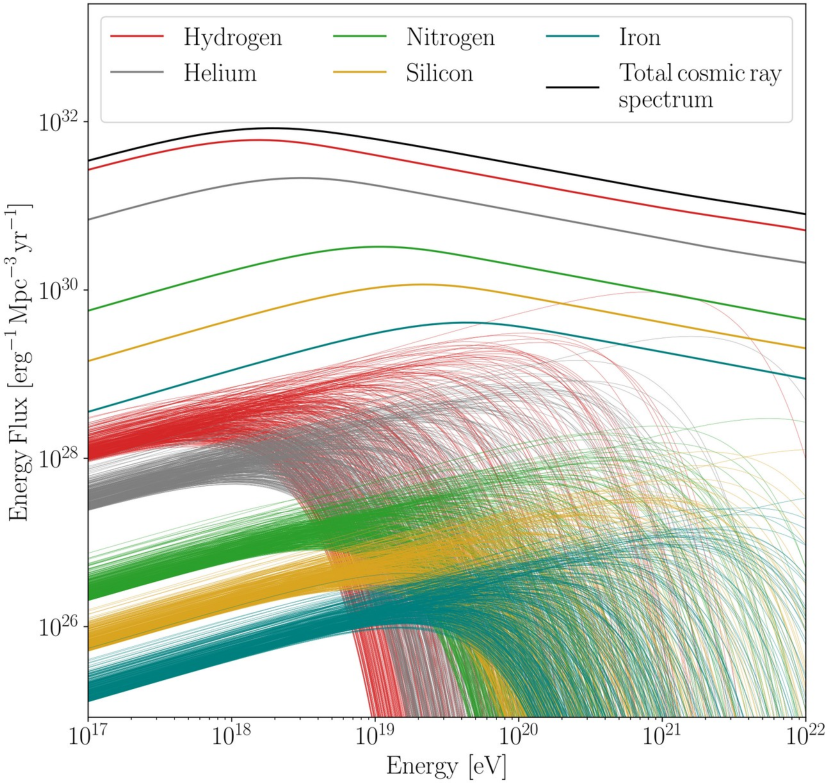
How different can the sources be?

What if sources are not identical?

- here: different R_{max}

> spectral index

> composition

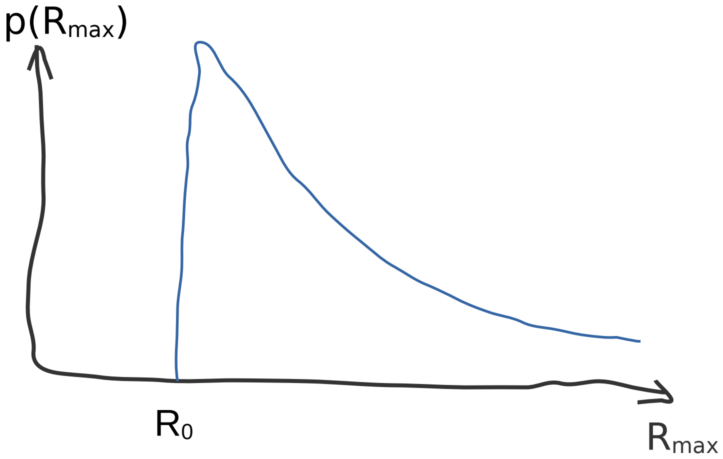


Population of non-identical sources

Distribution of maximum rigidities

standard: $R_{max} \rightarrow \delta(R_{max})$

here: $R_{max} \rightarrow \frac{dp}{dR_{max}}$



Assume powerlaw:

Kachelriess+, Phys. Lett. B 634, 143 (2006)

(physics motivation later)

$$p(R_{\max}) = \begin{cases} 0 & R_{\max} < R_0 \\ \frac{\beta_{\text{pop}}-1}{R_0}\left(\frac{R_{\max}}{R_0}\right)^{-\beta_{\text{pop}}} & \text{otherwise,} \end{cases}$$

Population of non-identical sources

Population Spectrum

$$\phi_{pop} = \int_0^\infty dR_{max} \left[\phi_{src}(R, R_{max}) \cdot p(R_{max}, R_0) \right]$$

(1) Heaviside

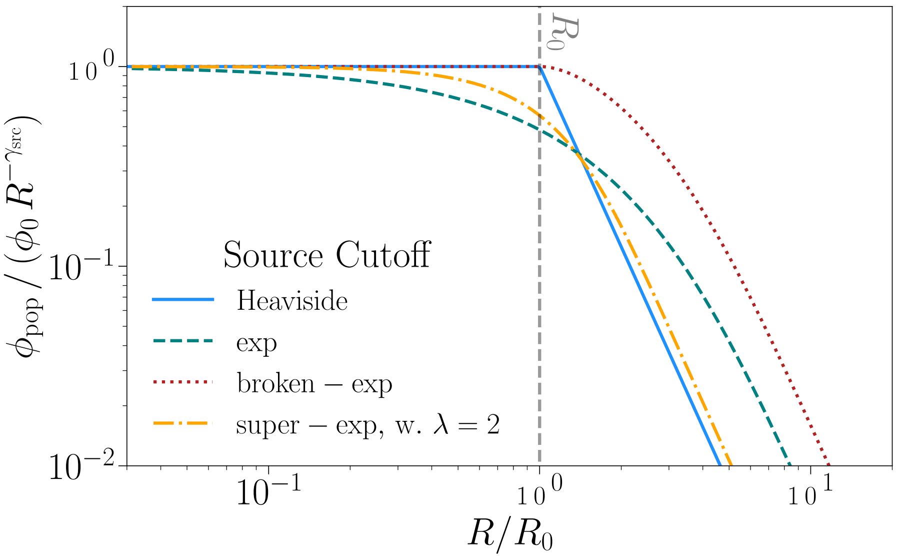
$$\phi_{\rm pop}^{\rm hs} = \phi_0 \, R^{-\gamma_{\rm src}} \begin{cases} 1 & R < R_0 \\ \left(\frac{R}{R_0}\right)^{-\beta_{\rm pop}+1} & \text{otherwise} \end{cases}$$

(2)Broken-Exponential

$$\phi_{\rm pop}^{\rm b\text{-}exp} = \phi_0 \, R^{-\gamma_{\rm src}} \begin{cases} 1 & R < R_0 \\ \left(\frac{R}{R_0}\right)^{-\beta_{\rm pop}+1} f\left(\frac{R}{R_0}, \beta_{\rm pop}\right) & \text{otherwise} \end{cases}$$

(3)(Super-)Exponential

$$\phi_{\rm pop}^{\rm s\text{-}exp} = \phi_0 \, R^{-\gamma_{\rm src}} \left(\frac{R}{R_0}\right)^{-\beta_{\rm pop}+1} \frac{\beta_{\rm pop}-1}{\lambda_{\rm cut}} \times \gamma\left(\frac{\beta_{\rm pop}-1}{\lambda_{\rm cut}}, \left(\frac{R}{R_0}\right)^{\lambda_{\rm cut}}\right)$$



Astrophysical motivation

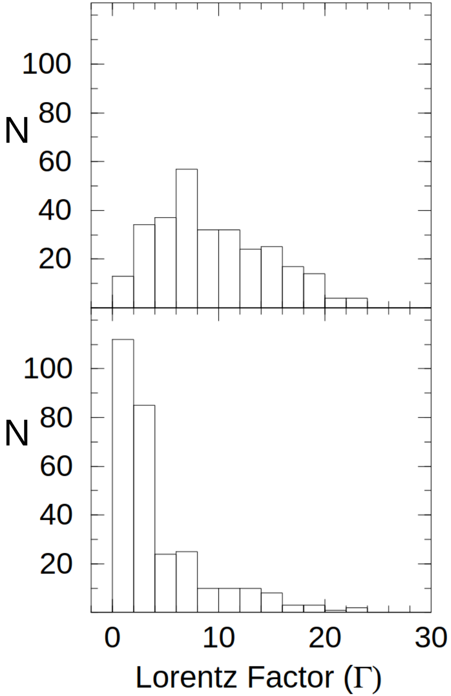
1. Jet Lorentz Factors

$$R_{max} = R_0 \Gamma_{jet}^{\alpha}$$

α = 1 (Hillas)
α = 2 (Espresso)

$$\frac{dp}{d\Gamma_{jet}} = (\eta - 1)\Gamma_{jet}^{-\eta}, \quad \eta > 1$$

(Lister et al. 1996)



$$p(R_{\max}) = \frac{\mathrm{d}p}{\mathrm{d}\Gamma_{\mathrm{jet}}} \left| \frac{\mathrm{d}\Gamma_{\mathrm{jet}}}{\mathrm{d}R_{\max}} \right|$$

$$= \frac{\eta - 1}{\alpha} R_0^{-1} \left(\frac{R_{\max}}{R_0} \right)^{\frac{1-\eta}{\alpha} - 1} \theta(R_{\max} - R_0)$$

Retrieve regular powerlaw

$$p(R_{\max}) = (\beta_{\mathrm{pop}} - 1)\, R_0^{\beta_{\mathrm{pop}} - 1}\, R_{\max}^{-\beta_{\mathrm{pop}}}\, \vartheta(R_{\max} - R_0) \quad , \quad \text{for } \beta_{\mathrm{pop}} = \frac{\eta - 1}{\alpha} + 1$$

Astrophysical motivation

2. Luminosity

$$L_0 \approx 10^{45.5} \, \frac{1}{\beta} \left(\frac{R_0}{10^{20}\,\mathrm{V}} \right)^2 \ \mathrm{erg\ s^{-1}}$$

minimum source luminosity required for acceleration to R_0
(Lovelace, Blandford, Waxman)

i.e. $R_{\mathrm{max}} \sim R_0 \, \beta^{1/2} \left(\frac{L}{L_0} \right)^{1/2}$

$$\Rightarrow \quad p(R_{\mathrm{max}}|z) = \frac{\mathrm{d}p}{\mathrm{d}L}(z) \left| \frac{\mathrm{d}L}{\mathrm{d}R_{\mathrm{max}}} \right|$$

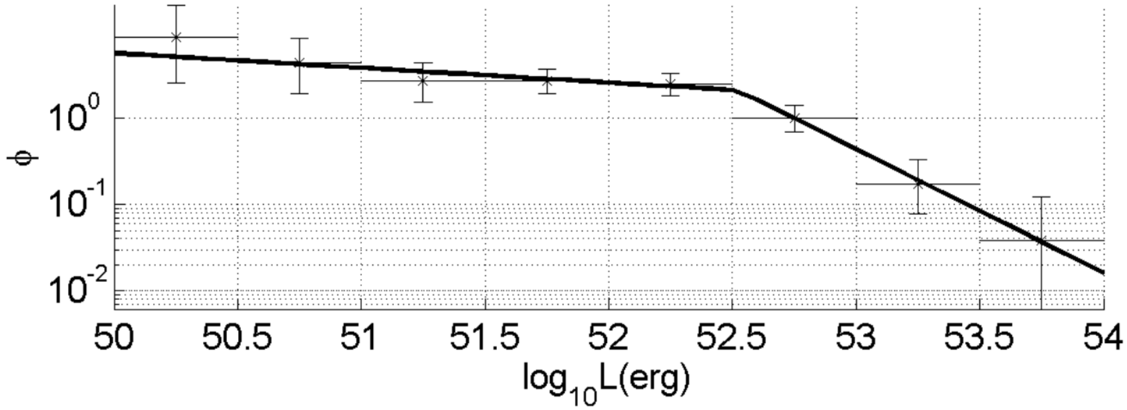
$$\frac{\mathrm{d}p}{\mathrm{d}L} = \frac{y_2 - 1}{L_0} \left(\frac{L}{L_0} \right)^{-y_2}$$

powerlaw in R_{max}

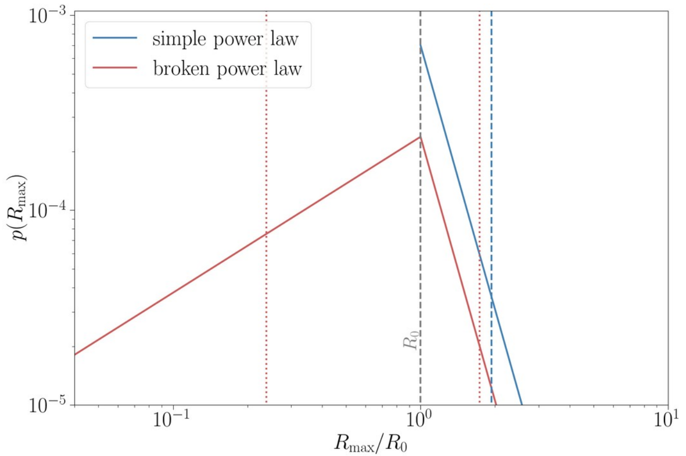
$$p(R_{\mathrm{max}}) = \frac{2\,(y_2 - 1)}{R_0} \left(\frac{R_{\mathrm{max}}}{R_0} \right)^{-2y_2+3}$$

Broken powerlaw in R_{max}

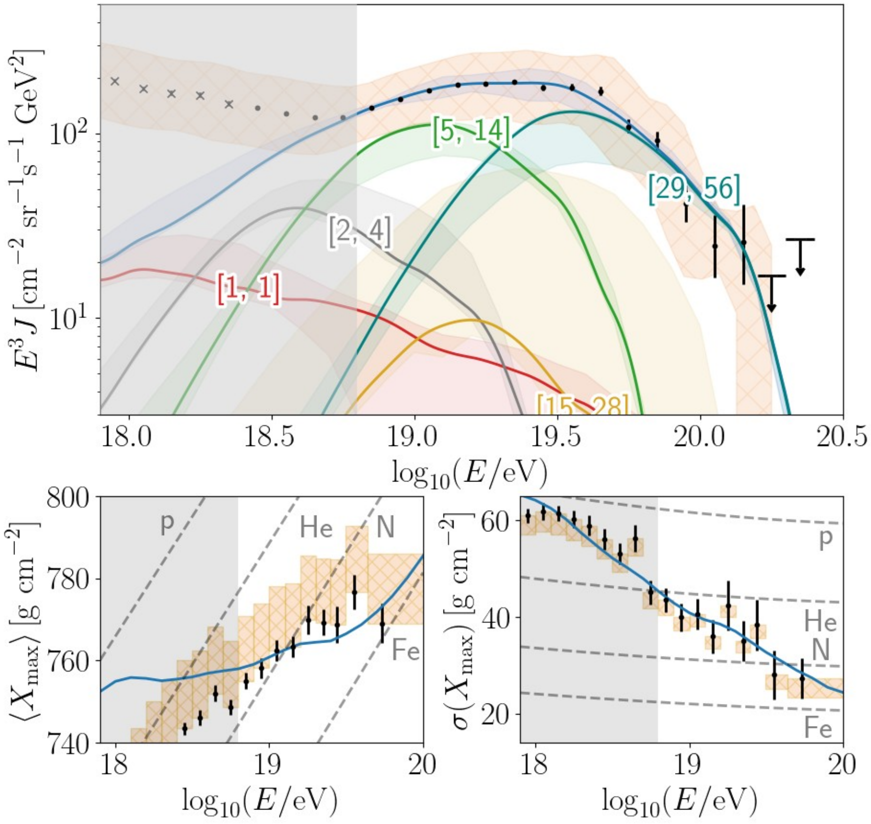
Luminosity Function Swift GRBs (Wanderman & Piran)



$$p(R_{\max}) = \frac{R_0^{-1}}{C} \cdot \begin{cases} \left(\frac{R_{\max}}{R_0}\right)^{-\beta_1} & R_{\max} \le R_0 \\ \left(\frac{R_{\max}}{R_0}\right)^{-\beta_2} & R_{\max} > R_0 \end{cases}$$



Fitting the data



$$\chi^2 = \sum_{E_i \geq E_{\min}} \left(\frac{d_i - m(E_i, \mathbf{p})}{\sigma_{\mathrm{stat}}(d_i)} \right)^2 + \chi^2_{\mathrm{UL}} + \chi^2_{\mathrm{zero}} + \chi^2_{\mathrm{shifts}}$$

upper limit points $\quad \chi^2_{\mathrm{zero}} = \sum_{i=1}^{\mathrm{ULs}} 2 n_i^{\mathrm{model}}$

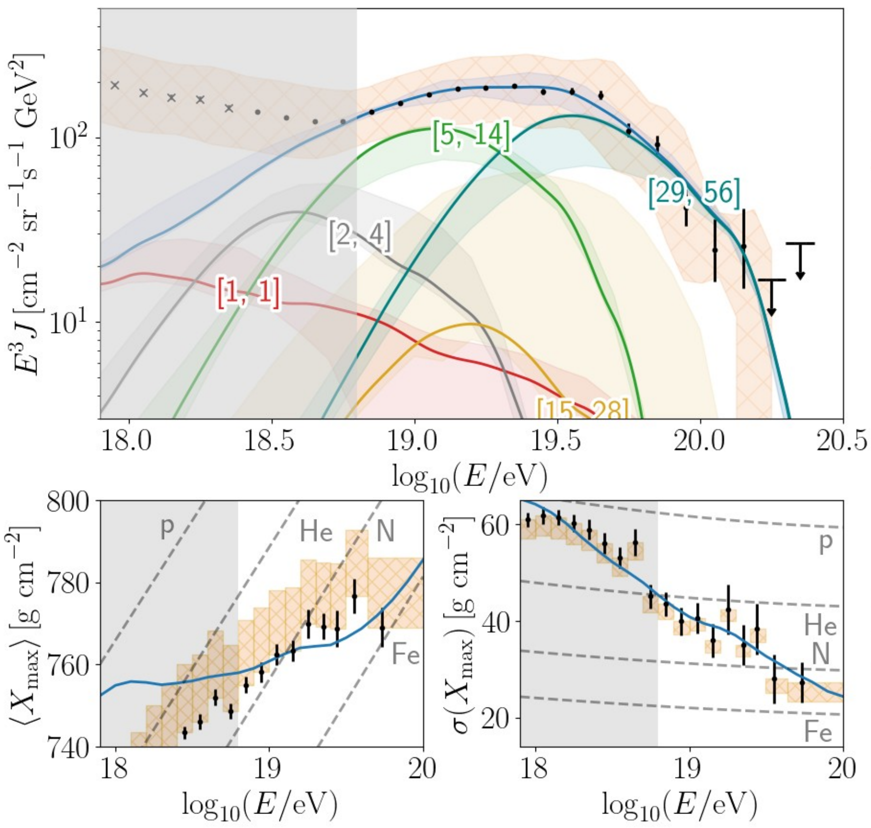
scale shifts $\quad \chi^2_{\mathrm{shifts}} = \sum_{k \in \{E, \langle X_{\max}\rangle, \sigma(X_{\max})\}} \left(\frac{\delta_k}{\sigma_k} \right)^2$

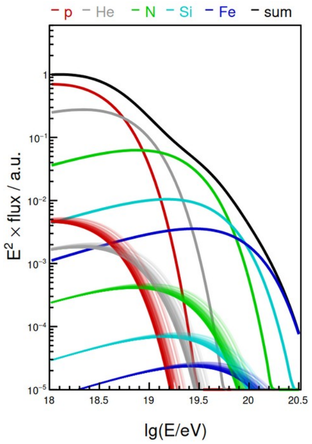
Fit R_0, β, γ, f_A^R, L_0 (m, ...)

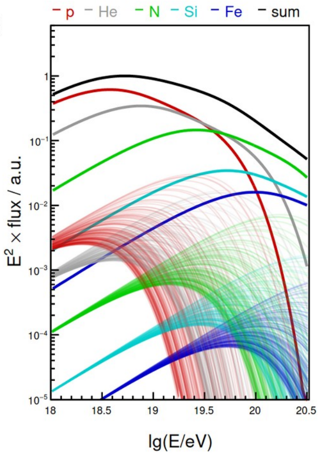
$$f_A^E = \frac{J_A|_{10^{18}\mathrm{eV}}}{\sum_A J_A|_{10^{18}\mathrm{eV}}} \qquad f_A^R = f_A^E \cdot Z(A)^{-\gamma+1}$$

Simulate propagation with `CRPropa`

Fitting the data







Aim:
constrain maximum allowed source variance

Required:
minimise intrinsic shower variance $\sigma(X_{max})$
i.e. want heaviest composition

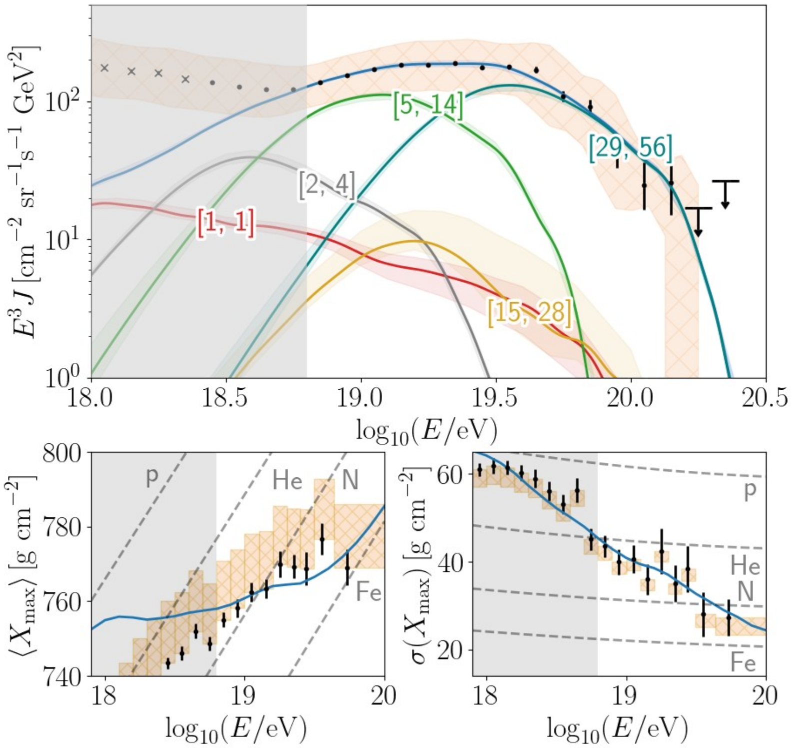
-> **Fiducial Model:**

> Sibyll2.3c

> $\delta_{<X_{max}>} = -1\sigma$

> $\delta_{\sigma(X_{max})} = +1\sigma$

Results - fiducial



Model	SIBYLL2.3c (no shifts)	SIBYLL2.3c (fid. shifts)	EPOS-LHC (fid. shifts)
R_0 [EV]	$1.73^{+0.20}_{-0.18}$	$0.57^{+1.88}_{-0.11}$	$1.6^{+0.6}_{-0.4}$
β_{pop}	$29.9^{+1.7*}_{-18.1}$	$5.2^{+26.4*}_{-0.5}$	$4.4^{+0.5}_{-0.5}$
γ_{src}	$-0.23^{+0.18}_{-0.26}$	$-0.8^{+1.4}_{-0.5}$	$0.1^{+0.4}_{-0.5}$
$f^R_A[\%]$	0^{+0}_{-0}	$0^{+36.4}_{-0}$	0^{+0}_{-0}
	$58.1^{+0.4}_{-1.9}$	$0^{+51.3}_{-0}$	$36.9^{+7.4}_{-22.8}$
	$35.0^{+1.6}_{-0.2}$	$93.7^{+0.5}_{-53.5}$	$50.3^{+16.3}_{-5.4}$
	$5.7^{+0.5}_{-0.6}$	$0.3^{+7.7}_{-0.3}$	$11.3^{+6.6}_{-3.8}$
	$1.16^{+0.12}_{-0.11}$	$6.0^{+0.2}_{-3.8}$	$1.41^{+0.27}_{-0.04}$
$R^{0.90}_{max}$ [R_0]	$1.083^{+0.155}_{-0.005}$	$1.72^{+0.13}_{-0.64}$	$1.97^{+0.22}_{-0.17}$
χ^2/d.o.f.	45.0/26	40.4/26	56.3/26

Results – model variations

Model	Parameter	β_{pop}	γ_{src}	χ^2
fd		$5.2^{+26.4*}_{-0.5}$	$-0.8^{+1.4}_{-0.5}$	40.4
bp	β_1, β_2	$18.4^{+8.5}_{-11.2}$	$-3.5^{+0.2}_{-0.8}$	34.7
zr	$q \in [-5, 2]$	$4.8^{+26.9*}_{-0.5}$	$-0.19^{+0.89}_{-0.18}$	33.7
zn	$m = -3$	$4.4^{+23.9}_{-0.5}$	$0.2^{+0.8}_{-0.4}$	37.3
	$m = 3$	$6.46^{+0.36}_{-0.34}$	$-2.0^{+0.4}_{-0.5*}$	42.5
	$m = 6$	$6.46^{+0.36}_{-0.34}$	$-2.24^{+0.35}_{-0.18}$	68.9
zm	$z_{\mathrm{min}} = 0.01$	$29.9^{+1.7*}_{-25.5}$	$0.38^{+0.18}_{-1.22}$	46.2
sc	$\lambda \in [1, 50]$	$4.0^{+3.2}_{-0.4}$	$1.43^{+0.16}_{-0.16}$	33.6
fg	f_A^R	$4.9^{+0.5}_{-0.5}$	$0.73^{+0.16}_{-0.16}$	45.5
ex	EPOS-LHC	$3.17^{+0.18}_{-0.17}$	$1.43^{+0.09}_{-0.09}$	40.6
	SIBYLL2.3c	$3.5^{+0.6}_{-0.5}$	$1.69^{+0.09}_{-0.09}$	34.7

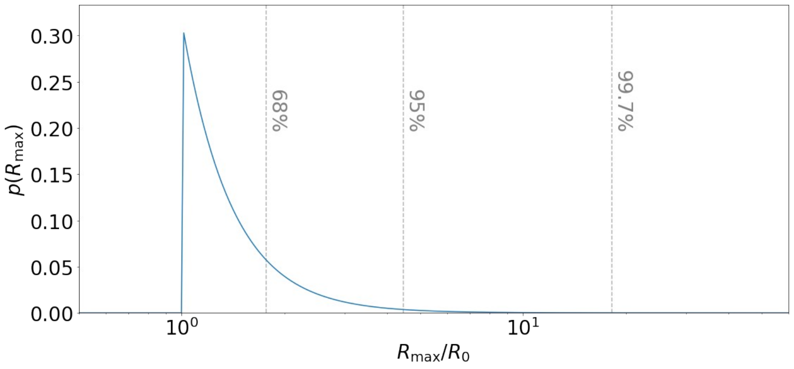
Source Variance

Largest

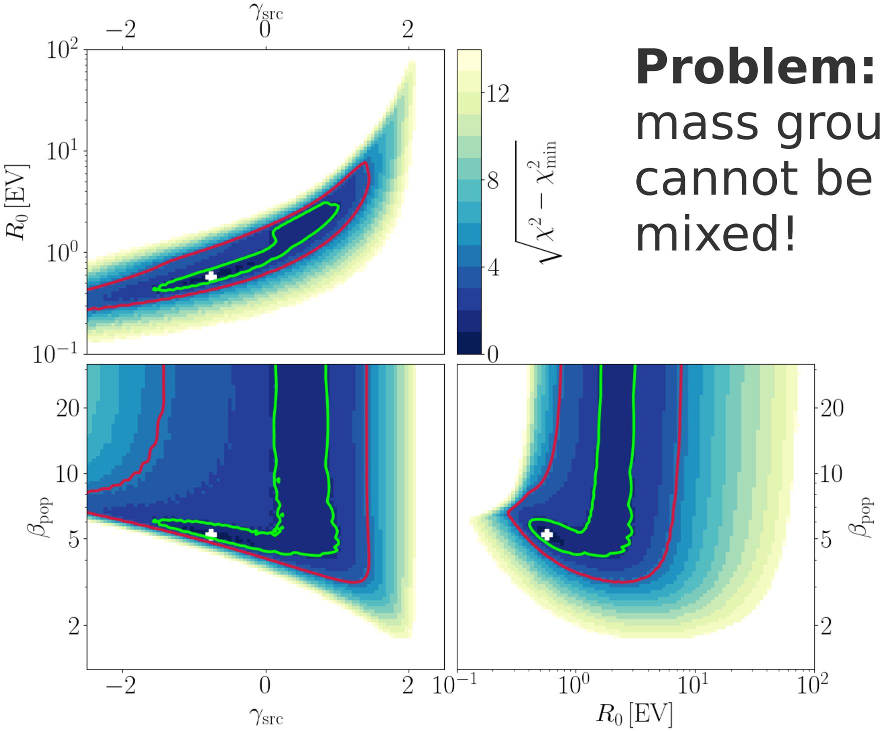
$\beta_{pop} \sim 3$

Commonly

$\beta_{pop} \sim 4-5$



Results



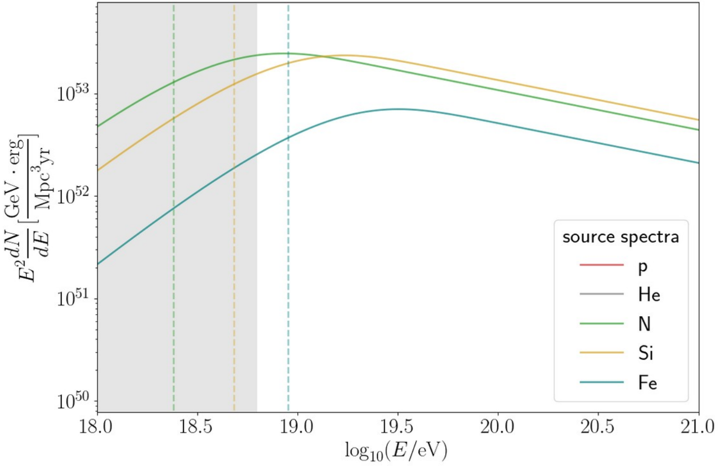
Problem: mass groups cannot be too mixed!

For R → ∞ :

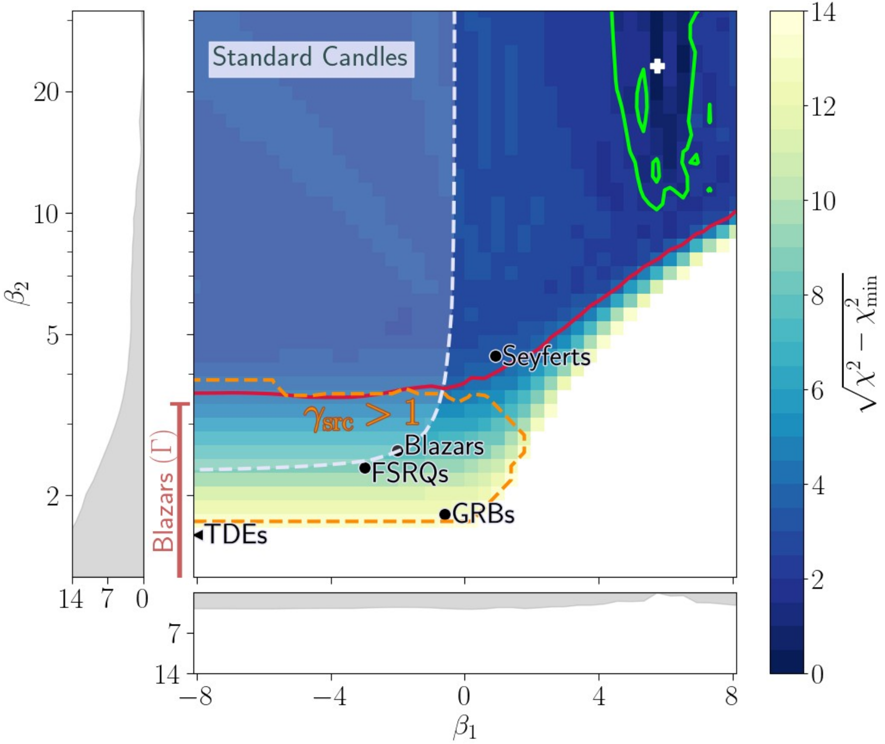
$$\phi_{pop} \propto R^{-\gamma-\beta+1}$$

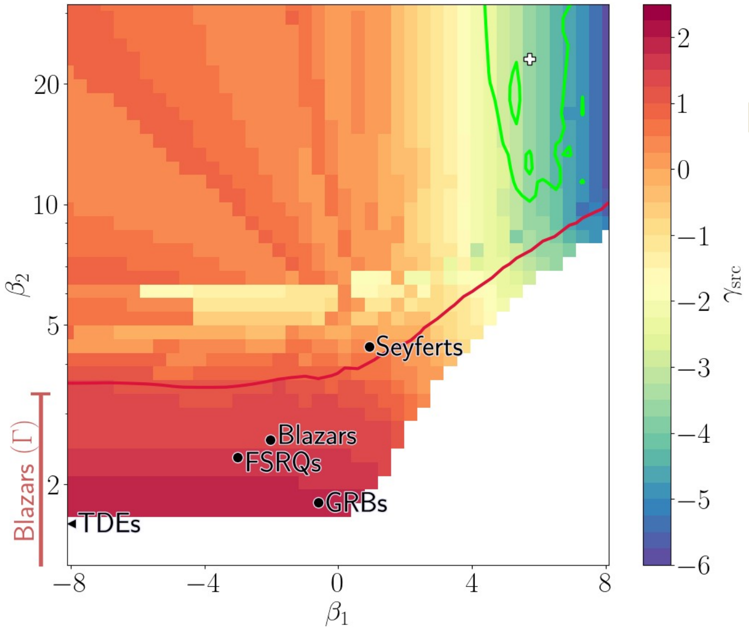
Strong eUHE tail if

$$\gamma + \beta > 4$$



Results - Broken powerlaw





for $\beta_1 < 1$:

$$\beta_2 \gtrsim 4.5$$

$$\gamma_{src} = -0.6^{+1.2}_{-1.0}$$

for $\beta_1 > 1$:

$$\beta_2 \gtrsim \beta_1 + 3$$

steepen by R_{max}^3

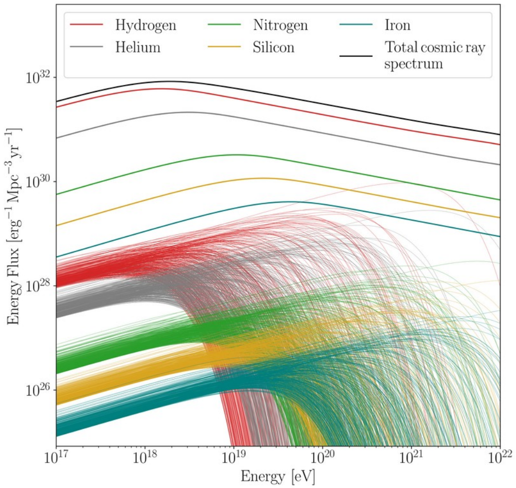
$$\gamma_{pop} = 1.22^{+0}_{-0.04}$$

$\gamma_{src} \rightarrow \beta_1$

Part 1: Conclusions

dp/dR_{max} as powerlaw:
-> **sources nearly identical!**

- Optimistic: $R_{max} \triangleright [R_0, 3R_0]^{90\%}$
- Conservative: $R_{max} \triangleright [R_0, 2R_0]^{90\%}$



Possible Solutions:

(a) Standard Candle -like sources
≠ AGN, GRB, TDE

(b) Flux dominated by few local sources

(c) Broken-powerlaw dp/dR_{max} → **ask for more details!**

Part 2

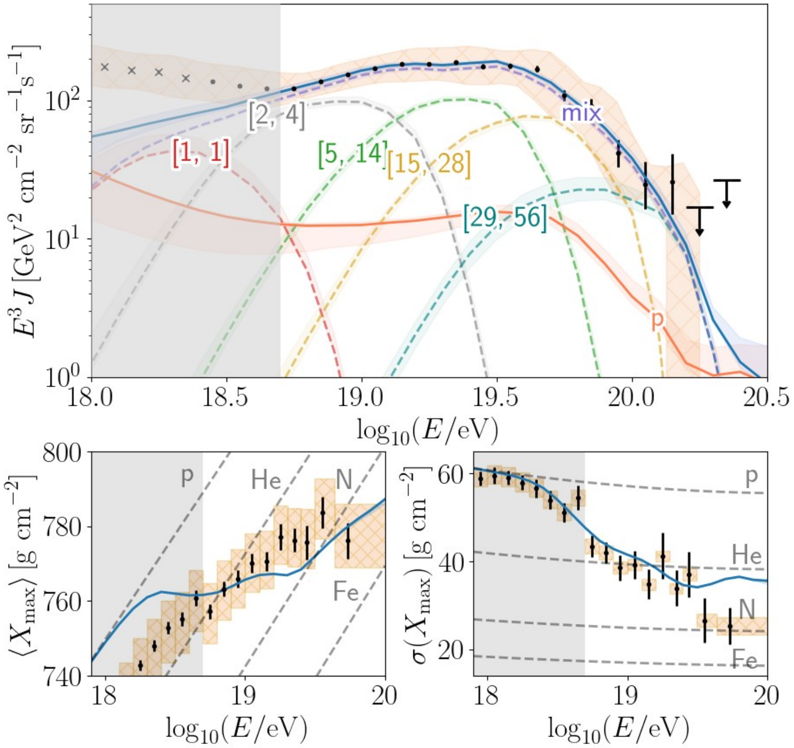
Identical sources
BUT with additional population of
UHE proton sources.

Part 2

Identical sources
BUT with additional population of
UHE proton sources.

New:
Second, independent, source population for UHE protons.
> 4(3) free parameters
(E_{max}^{pp}, γ^{pp}, m^{pp}, Q^{pp}_{E0})

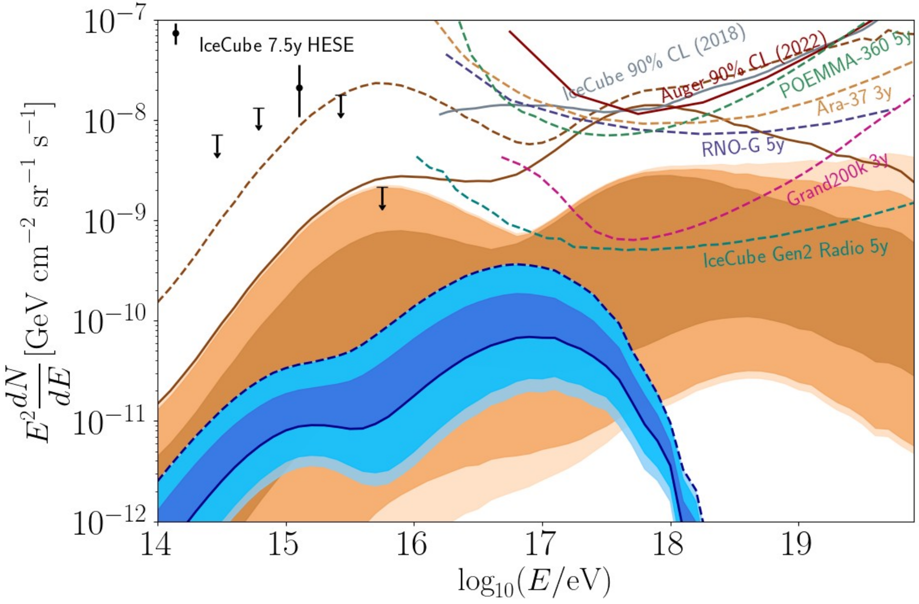
Part 2: Results – high R_{max}



Model	1SC	2SC-dip	
		Pop. 1	**Pop. 2**
max. rigidity R_{max} [EV]	$1.25^{+0.23}_{-0.19}$	$1.5^{+0.5}_{-0.4}$	10^5 (fix)
spectral index γ	$-2.5^{+1.0}_{-0}$	$-1.41^{+0.44}_{-0.22}$	$2.5^{+0.3}_{-0.3}$
redshift evolution m	$1.9^{+0.6}_{-4.1}$	-1^{+1}_{-3}	4^{+1}_{-10*}
luminosity L_0 [$10^{44}\,\frac{\mathrm{erg}}{\mathrm{Mpc}^3\,\mathrm{yr}}$]	$5.6^{+1.0}_{-3.4}$	$2.5^{+0.6}_{-1.0}$	$1.8^{+0.6}_{-1.4}$
proton fraction $f^{PP}(20\,\mathrm{EeV})$ [%]			$7.0^{+0.8}_{-0.5}$
χ^2/dof	101.0/29		74.4/26

Part 2: Results – high R_{max}

Cosmogenic Neutrinos



Reject realisations with

$$\Delta\chi^2_\nu + \Delta\chi^2_\gamma > 4$$

Neutrinos constrain source parameters

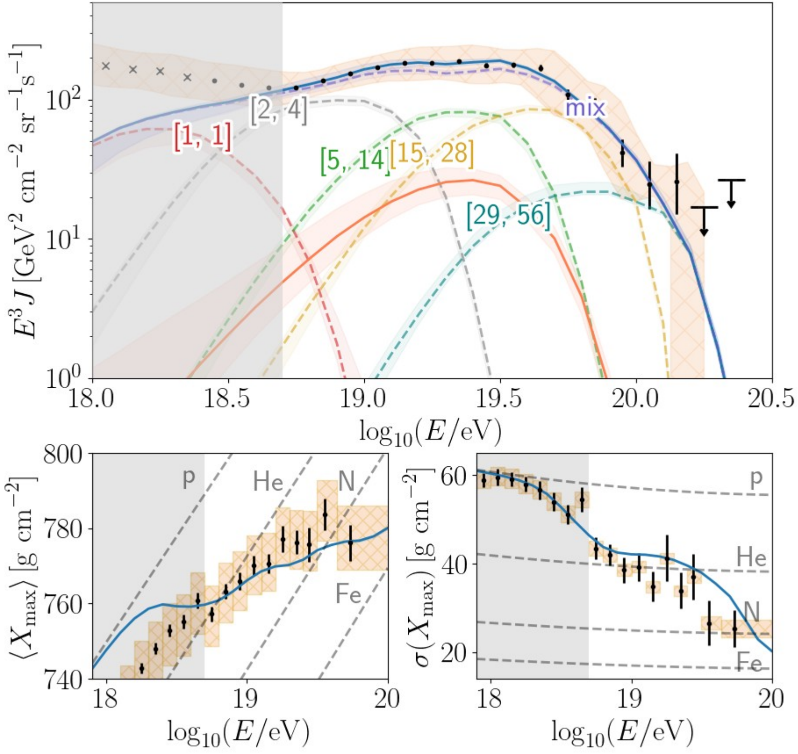
$$\gamma^{\mathrm{PP}} \gtrsim 1.6 \;, \; m^{\mathrm{PP}} \lesssim 4$$

$$\text{and } L_0^{\mathrm{PP}} \lesssim 10^{44.5} \, \frac{\mathrm{erg}}{\mathrm{Mpc}^3 \, \mathrm{y}}$$

Contribution to IceCube HESE flux (at 1.3 PeV)

$$f^{\mathrm{PP}}_{\mathrm{HESE}} \lesssim 20\%$$

Part 2: Results – low R_{max}

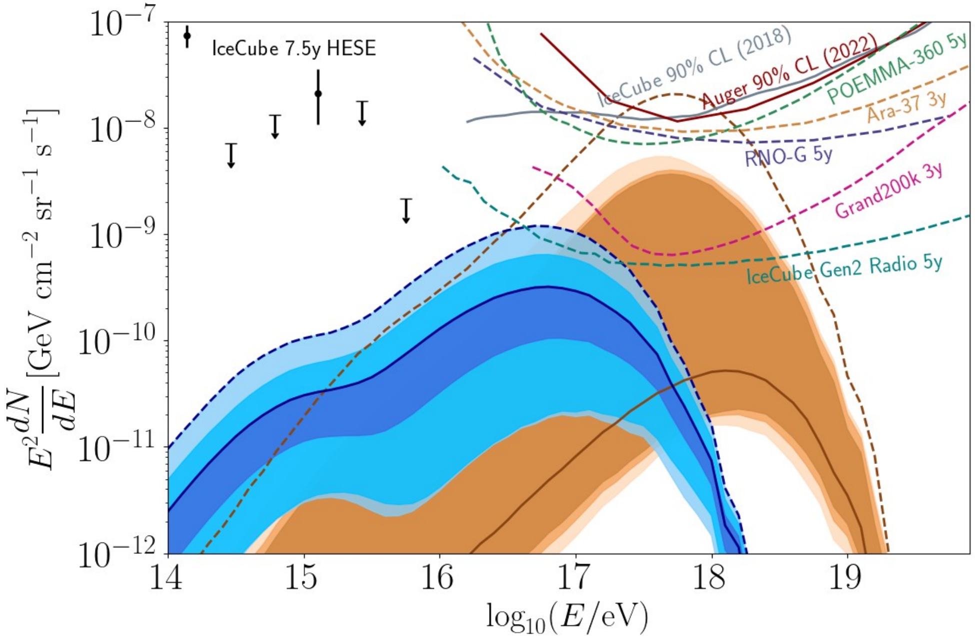


Model	2SC-uhecr	
	Pop. 1	**Pop. 2**
max. rigidity R_{max} [EV]	$1.5^{+0.5}_{-0.4}$	10 (fix)
spectral index γ	$-1.41^{+0.22}_{-0.22}$	$-0.25^{+0.50}_{-0.75}$
redshift evolution m	1^{+1}_{-2}	-3^{+9*}_{-3*}
luminosity L_0 [$10^{44}\,\frac{\mathrm{erg}}{\mathrm{Mpc}^3\,\mathrm{yr}}$]	$3.77^{+0.06}_{-1.39}$	$0.12^{+1.88}_{-0.06}$
proton fraction $f^{PP}(20\,\mathrm{EeV})$ [%]		$14.2^{+1.2}_{-0.5}$
χ^2/dof		58.0/26

cf. Muzio (ICRC'23)

Part 2: Results – low R_{max}

Cosmogenic Neutrinos



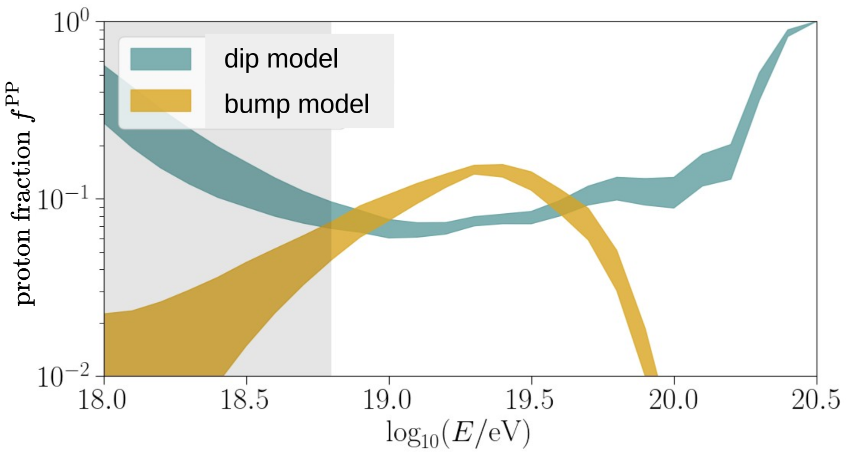
No protons at low energies
> additional neutrinos only at UHE

Independent PeV and EeV neutrino regimes

ν constraints: $m^{\mathrm{PP}} \lesssim 4$

No effective constraints from gamma rays.

Order of **10%** protons allowed by Auger data above the ankle.



Proton dip v2

- $E_{max}^{pp} >> E_{GZK}$
- Soft proton injection spectrum
- Large (constraining) cosmogenic neutrino flux

Proton bump x2

- E_{max}^{pp} = 10 EeV
- Hard injection spectrum

UHECR fit & neutrino limits:

$$m^{\mathrm{PP}} \lesssim 4$$

Extra Slides

Population of non-identical sources

Source spectrum

$$\phi_{src} = R^{-\gamma} \cdot f(R, R_{max})$$

Cutoff function:

(1) Heaviside

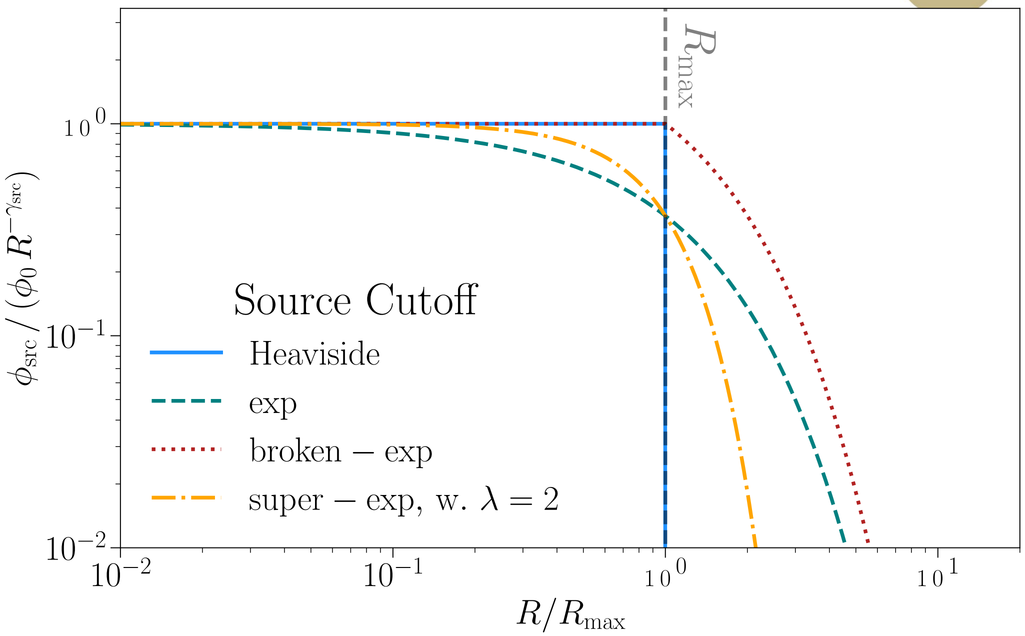
$$\phi_{\rm src} = \phi_0\, R^{-\gamma_{\rm src}}\, \vartheta(R_{\rm max} - R)$$

(2) Broken-Exponential

$$\phi_{\rm src} = \phi_0\, R^{-\gamma_{\rm src}} \begin{cases} 1 & \text{, for } R < R_{\rm max} \\ \exp\left(1 - \frac{R}{R_{\rm max}}\right) & \text{, else}\,. \end{cases}$$

(3) (Super-)Exponential

$$\phi_{\rm src} = \phi_0\, R^{-\gamma_{\rm src}}\, \exp\left[-\left(\frac{R}{R_{\rm max}}\right)^{\lambda_{\rm cut}}\right], \quad \lambda_{\rm cut} > 0$$



Broken powerlaw in R_{max}

Population spectrum

$$\phi_{\text{pop}} = \frac{\phi_0}{C \cdot \lambda_{\text{cut}}} R^{-\gamma_{\text{src}}} \cdot \left[L + H\right]$$

$$L = \left(\frac{R}{R_0}\right)^{-\beta_1+1} \cdot \Gamma\left(\frac{\beta_1 - 1}{\lambda_{\text{cut}}}, \left(\frac{R}{R_0}\right)^{\lambda_{\text{cut}}}\right)$$

$$H = \left(\frac{R}{R_0}\right)^{-\beta_2+1} \cdot \gamma\left(\frac{\beta_2 - 1}{\lambda_{\text{cut}}}, \left(\frac{R}{R_0}\right)^{\lambda_{\text{cut}}}\right)$$

Same as pwl for R -> ∞

$$\phi_{\text{pop}} \propto R^{-\gamma_{\text{src}}-\beta_2+1}$$

Broken powerlaw in R_{max}

Population spectrum

$$\phi_{\rm pop} = \frac{\phi_0}{C \cdot \lambda_{\rm cut}} R^{-\gamma_{\rm src}} \cdot \Big[L + H\Big]$$

$$L = \left(\frac{R}{R_0}\right)^{-\beta_1+1} \cdot \Gamma\left(\frac{\beta_1 - 1}{\lambda_{\rm cut}}, \left(\frac{R}{R_0}\right)^{\lambda_{\rm cut}}\right)$$

$$H = \left(\frac{R}{R_0}\right)^{-\beta_2+1} \cdot \gamma\left(\frac{\beta_2 - 1}{\lambda_{\rm cut}}, \left(\frac{R}{R_0}\right)^{\lambda_{\rm cut}}\right)$$

Same as pwl for R -> ∞

$$\phi_{\rm pop} \propto R^{-\gamma_{\rm src} - \beta_2 + 1}$$

Behaviour at R << R_{max} depends on β_1

$\beta_1 < 1$: $\lim_{R\to 0} \phi_{\rm pop} \propto R^{-\gamma_{\rm src}}$

$\beta_1 > 1$: $\lim_{R\to 0} \phi_{\rm pop} \propto R^{-\gamma_{\rm src} - \beta_1 + 1}$

redefine

$$(a) \quad \gamma_{\rm pop} = \gamma_{\rm src} + \beta_1 - 1$$
$$(b) \quad \beta_{\rm pop} = \beta_2 - \beta_1 + 1\,.$$

approximate BP as single pwl

⇒

$$\lim_{R\to 0} \phi_{\rm pop} \propto R^{-\gamma_{\rm pop}}$$
$$\lim_{R\to \infty} \phi_{\rm pop} \propto R^{-\gamma_{\rm pop} - \beta_{\rm pop} + 1}$$

Theoretical expectation

ID	Param.	Distribution	β_{pop}	γ_{pop}	Sources	$\beta_{pop,max}$
I.1	R_{max}	PL, $p(R_{max}\|\beta_{pop})$	β_{pop}	γ_{src}		
I.2	R_{max}	BPL, $p(R_{max}\|\beta_1, \beta_2)$				
		$\beta_1 < 1$	$\approx \beta_2$	$\approx \gamma_{src}$		
		$\beta_1 > 1$	$\beta_2 - \beta_1 + 1$	$\gamma_{src} + \beta_1 - 1$		
II	$R_{max} \propto \Gamma^\alpha$	PL, $dp/d\Gamma(\eta)$	$(\eta - 1)/\alpha + 2$	γ_{src}	Blazars [45] [a]: $\eta = 1.4_{\pm 0.2}$	
			$-\gamma_{src} + \xi/\alpha$		+ Hillas: $\alpha = 1,\ \xi = 1$	$3.4_{\pm 0.2} - \gamma_{src}$
					+ Espresso: $\alpha = 2,\ \xi = 0$	$2.2_{\pm 0.1} - \gamma_{src}$
III.1	$R_{max} \propto \sqrt{L}$	PL, $dp/dL(y_2)$	$2\,y_2 - 3$	γ_{src}	BL Lacs [54] [b]: $y_2 = 2.61_{\pm 0.37}$	$2.22_{\pm 0.74}$
					FSRQs [55] [b]: $y_2 = 2.36_{\pm 0.10}$	$1.72_{\pm 0.20}$
					Blazars [55] [b]: $y_2 = 2.32_{\pm 0.08}$	$1.64_{\pm 0.16}$
					TDEs [56, 57]: $y_2 = 2.30_{\pm 0.20}$	$1.60_{\pm 0.40}$
III.2	$R_{max} \propto \sqrt{L}$	BPL, $dp/dL(y_1, y_2)$				
		$y_1 < 2$	$\approx 2\,y_2 - 3$	$\approx \gamma_{src}$	GRBs [58]: $y_1 = 1.2^{+0.2}_{-0.1}$, $y_2 = 2.4^{+0.3}_{-0.6}$	$1.8^{+0.6}_{-1.2}$
					FSRQs [55] [b]: $y_1 = 0_{\pm 2.07}$, $y_2 = 2.67_{\pm 0.17}$	$2.34_{\pm 0.34}$
					Blazars [55] [b]: $y_1 = 0.49_{\pm 1.15}$, $y_2 = 2.79_{\pm 0.19}$	$2.58_{\pm 0.38}$
					Seyferts [59]: $y_1 = 1.96_{\pm 0.04}$, $y_2 = 3.71_{\pm 0.09}$	$4.42_{\pm 0.18}$