

Ultra-High-Energy Cosmic Rays from a Population of Non-identical Sources



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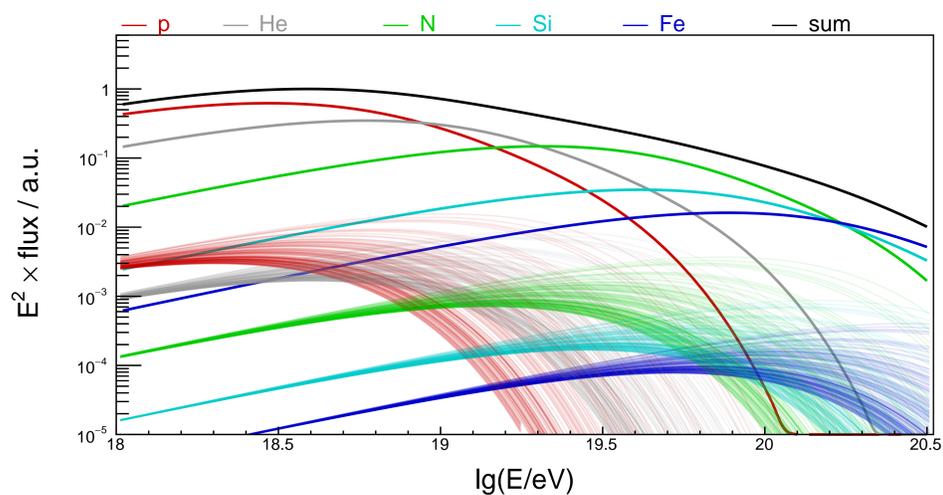
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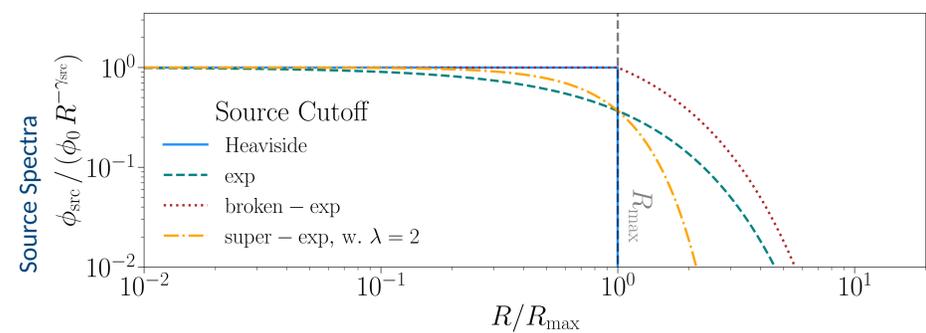
Overview

I. Propose **parametrisation of population variance** for non-identical sources with power-law distribution of max. energies.

II. Find that sources must have **nearly identical maximum energies** – within factor of three or less for 90% of sources.



Population Spectrum of Non-identical Sources



Population spectrum: Combined contributions from all sources within some volume.

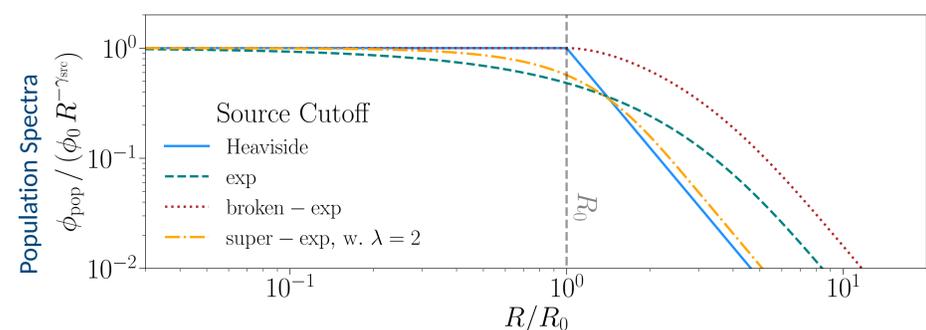
Continuous source distribution: convolution of individual source spectra $\phi_{src}(R, R_{max})$ with distribution of maximum rigidities dp/dR_{max} .

$$\phi_{pop} = \int dR_{max} \left[\phi_{src}(R, R_{max}) \times \frac{dp}{dR_{max}} \right] \quad (1)$$

Assumptions:

- Acceler. universal in rigidity [1], w. super-exp. cutoff: $\phi_{src} \propto \exp(-[R/R_{max}]^{\lambda_{cut}})$
- Power-law distribution of maximum rigidities [2]: $dp/dR_{max} \propto R_{max}^{-\beta_{pop}}$

$$\Rightarrow \phi_{pop}^{s-exp} = \phi_0 R^{-\gamma_{src}} \left(\frac{R}{R_0}\right)^{-\beta_{pop}+1} \frac{\beta_{pop}-1}{\lambda_{cut}} \times \gamma \left(\frac{\beta_{pop}-1}{\lambda_{cut}}, \left(\frac{R}{R_0}\right)^{\lambda_{cut}}\right) \quad (2)$$



With (i) $\phi_{pop} \propto R^{-\gamma_{src}}$ for $R/R_0 \rightarrow 0$ and (ii) $\phi_{pop} \propto R^{-\gamma_{src}-\beta_{pop}+1}$ for $R/R_0 \rightarrow \infty$.

Expected Population Variance

Candidate astrophysical accelerators show large diversity in relevant parameters, e.g. size, magnetic field strength, luminosity and Lorentz factor.

Relate R_{max} to (jet) Lorentz factor Γ_{jet}

$$1. R_{max} = R_0 \Gamma_{jet}^\alpha \quad \wedge \quad 2. p(\Gamma_{jet}) \propto \Gamma_{jet}^{-\eta}$$

$$\Rightarrow \beta_{pop} = (\eta + \xi - 1)/\alpha + 2 - \gamma_{src}$$

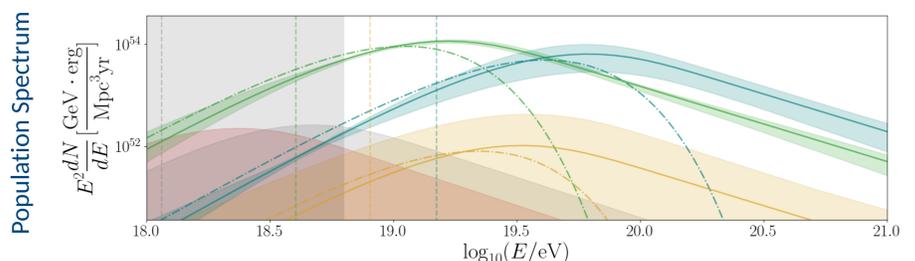
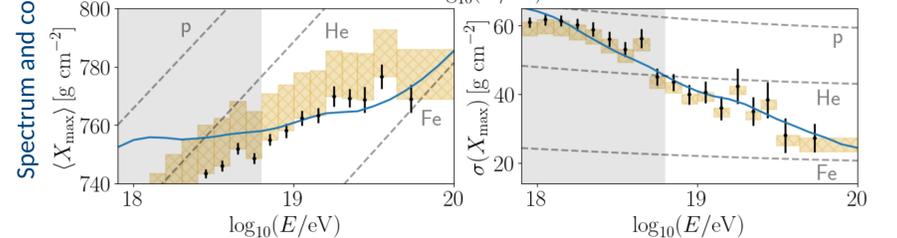
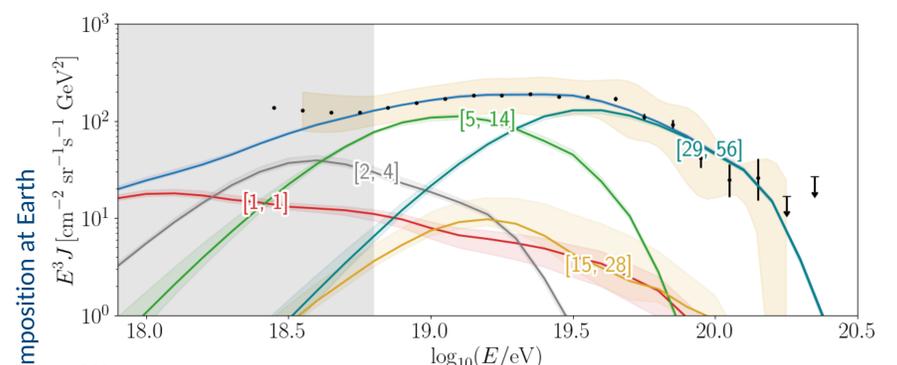
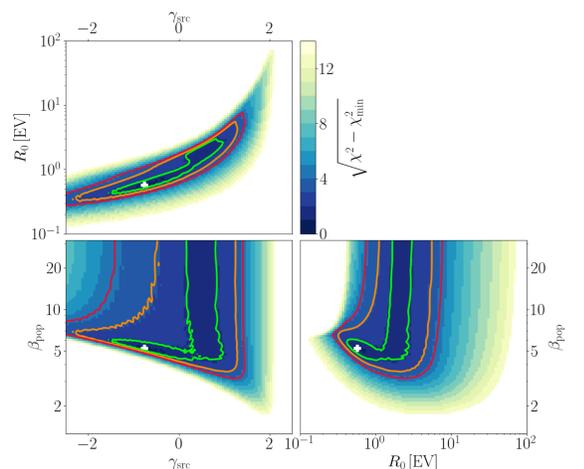
Sources	$\beta_{pop,max}$
AGN: $\eta = 1.4$	
+ Hillas: $\alpha = 1, \xi = 1$	3.4 – γ_{src}
+ Espresso: $\alpha = 2, \xi = 0$	2.2 – γ_{src}

The Case for Low Population Variance

Observation: Fit of UHECR spectrum [3] and composition favours (nearly)identical sources.

Problem: Large variance implies strong high-energy tail of the population spectrum since $\phi_{pop} \propto R^{-\gamma_{src}-\beta_{pop}+1}, R/R_0 \rightarrow \infty$.

Consequence: Increased fragmentation of the primary CRs
 \Rightarrow more mixing of mass groups
 \Rightarrow tension with observed pure composition at UHE



Variations of the Source Model

Shift observed composition for all scenarios: $\langle X_{max} \rangle - 1\sigma_{syst}$ & $\sigma(X_{max}) + 1\sigma_{syst}$
 \rightarrow Least intrinsic shower variance \rightarrow Upper limit for population diversity

- (fd)** fiducial model
Sibyll2.3c, $n(z) = \text{const}$
- (zr)** redshift evol. of $p(R_{max})$
w. $R_0(z) = R_0^{z=0} \times (1+z)^q$
 \rightarrow best fit $q = -4.3_{-0.8}^{+1.0}$
- (zn)** red. evol. of source density
w. $n(z) \propto (1+z)^m, z < 1.5$
- (sc)** super-exp. src. cutoff fct.
 \rightarrow best fit $\lambda = 5.4_{-2.3}^{+1.7}$
- (fg)** GCR-like injection fractions
- (ex)** extreme scenario
neg. evol. $n(z)$, sharp src. cutoff

ID	Parameter	β_{pop}	γ_{src}	χ^2
fd	Sibyll2.3c, $n(z) = \text{const}$	$5.2_{-0.5}^{+26.4*}$	$-0.8_{-0.5}^{+1.4}$	40.4
zr	$q \in [-5, 2]$	$4.8_{-0.5}^{+26.9*}$	$-0.19_{-0.18}^{+0.89}$	33.7
zn	$m = -3$	$4.4_{-0.5}^{+23.9}$	$0.2_{-0.4}^{+0.8}$	37.3
	$m = 3$	$6.46_{-0.34}^{+0.36}$	$-2.0_{-0.5*}^{+0.4}$	42.5
	$m = 6$	$6.46_{-0.34}^{+0.36}$	$-2.24_{-0.18}^{+0.35}$	68.9
sc	$\lambda \in [1, 50]$	$4.0_{-0.4}^{+3.2}$	$1.43_{-0.16}^{+0.16}$	33.6
fg	f_A^R	$3.16_{-0.16}^{+0.17}$	$1.07_{-0.08}^{+0.08}$	110.8
ex	Epos-LHC	$3.17_{-0.17}^{+0.18}$	$1.43_{-0.09}^{+0.09}$	40.6
	Sibyll2.3c	$3.5_{-0.5}^{+0.6}$	$1.69_{-0.09}^{+0.09}$	34.7

Contact



References

- [1] B. Peters. *Il Nuovo Cimento* 22.4 (Nov. 1961).
- [2] M. Kachelriess and Dmitry V. Semikoz. *Phys. Lett. B* 634 (2006).
- [3] Auger Collaboration. *Phys. Rev. D* 102.6 (2020), p. 062005.