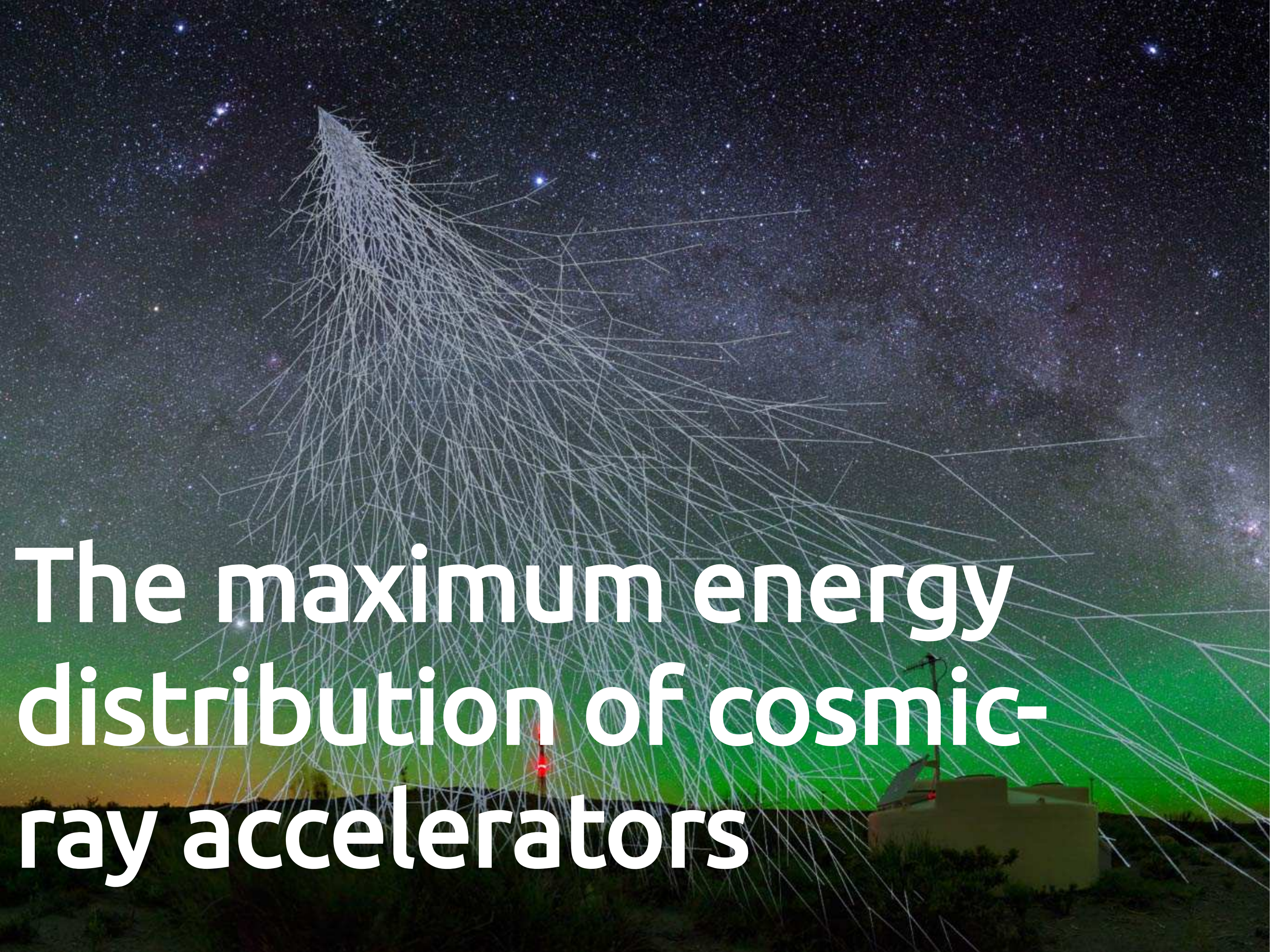


The maximum energy distribution of cosmic-ray accelerators

NTNU
Norwegian University of Science and Technology

Domenik Ehlert
NPACT Meeting 2025
NTNU, Trondheim

image: © A. Chantelauze, S. Staffi, and L. Bret

Cosmic Rays

1912
Victor Hess discovers CRs in a series of balloon flights.

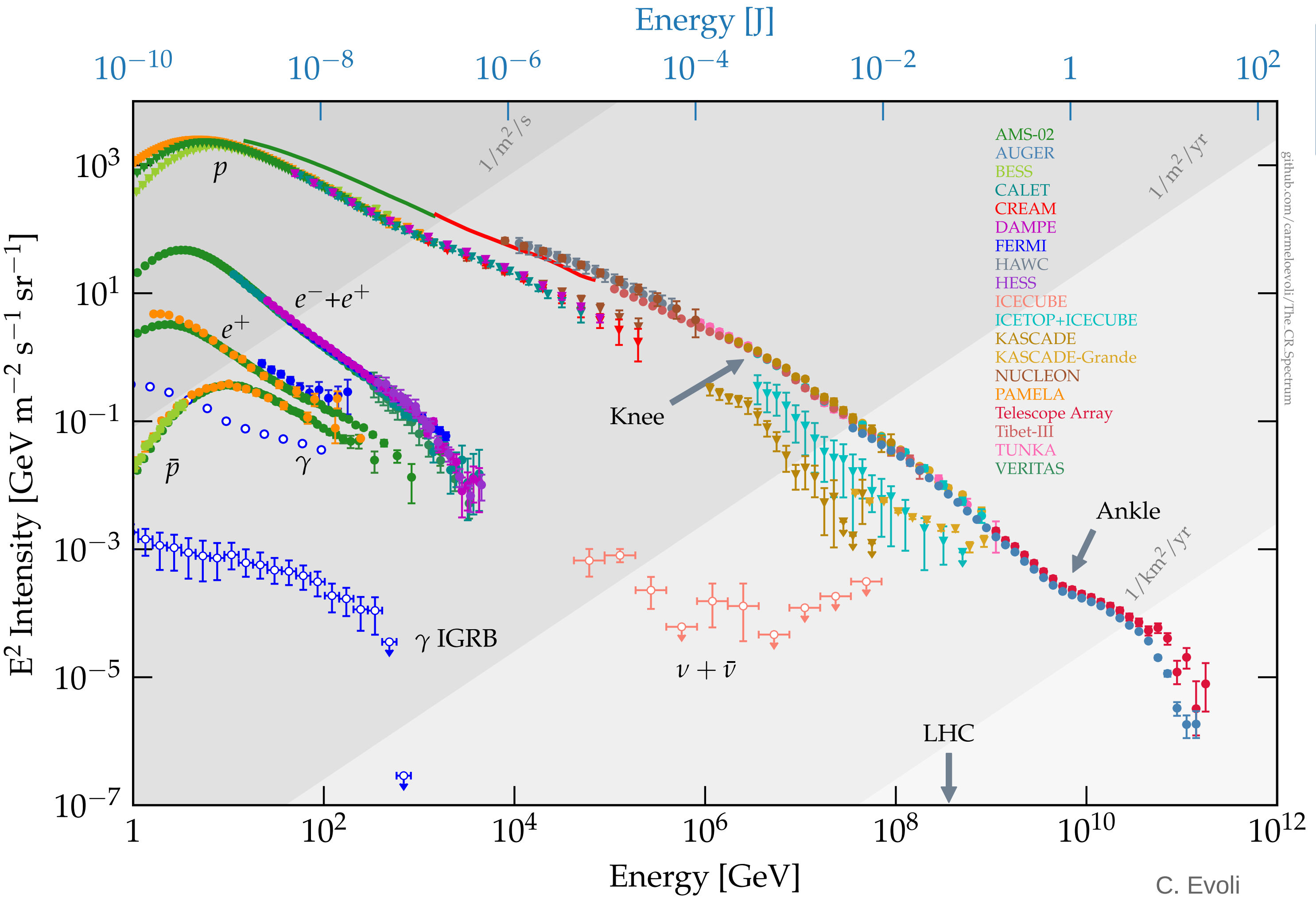
1920
Robert Millikan calls them “Cosmic Rays”
(but thinks they're photons)

1927
Jacob Clay concludes they must be charged particles

1938
Pierre Auger discovers CR “air showers” -> $E > 10^{15}$eV

Cosmic Rays

- Charged nucleons + 1% electrons
- Broken power law spectrum
- 1^{st} Knee ~10^{15} eV
- 2^{nd} Knee ~10^{17} eV
- Ankle ~$10^{18.7}$ eV
- instep' ~10^{19} eV
  Auger, Phys.Rev.Lett. 125 (2020) 12, 121106
- Cutoff >$5 \cdot 10^{19}$ eV

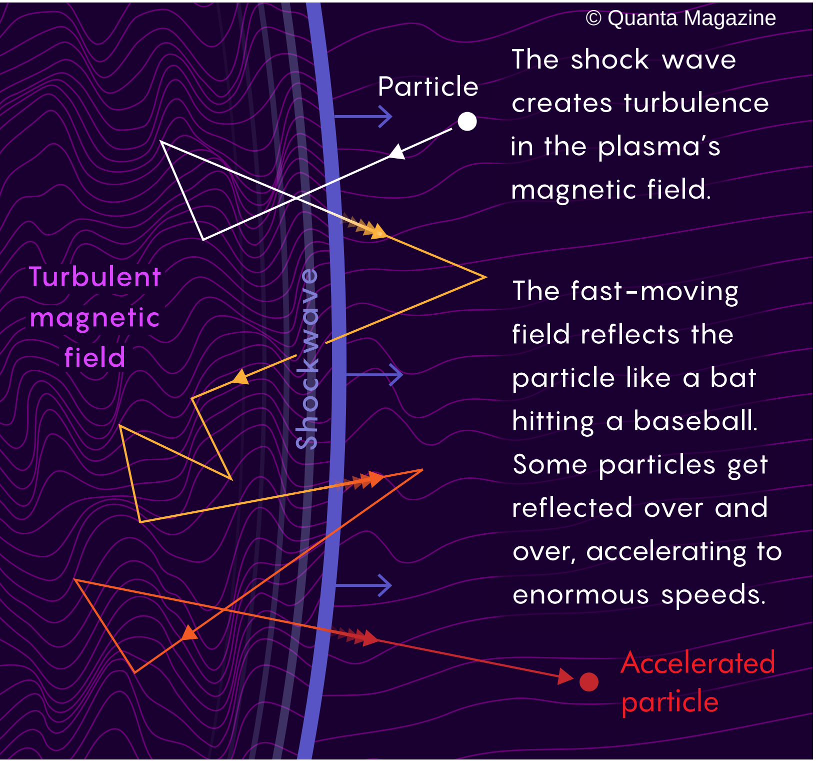


C. Evoli

Note: diffuse flux!

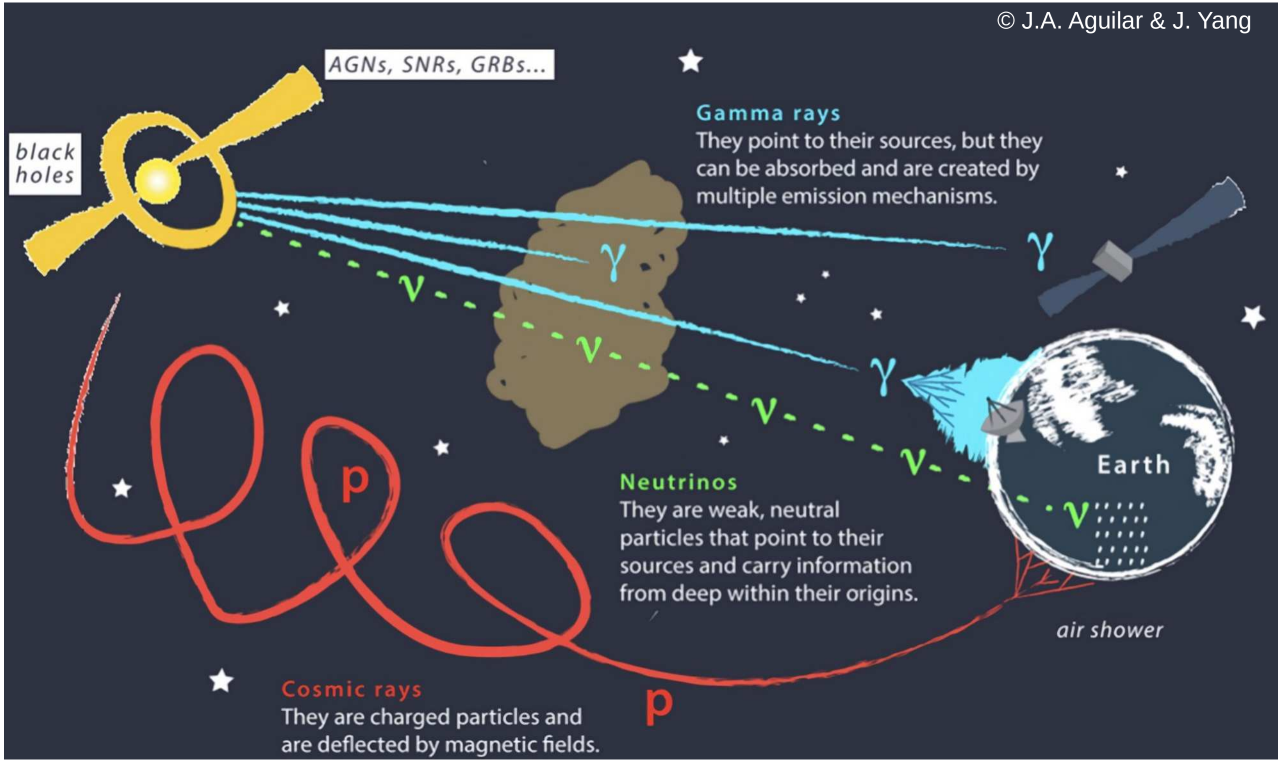
Cosmic Rays

Acceleration



different acceleration mechanisms but generally believed to be "stochastic"

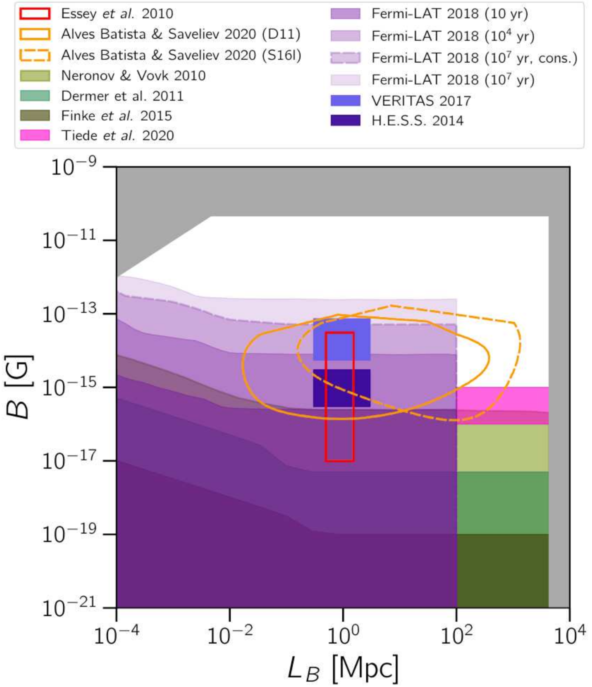
Propagation



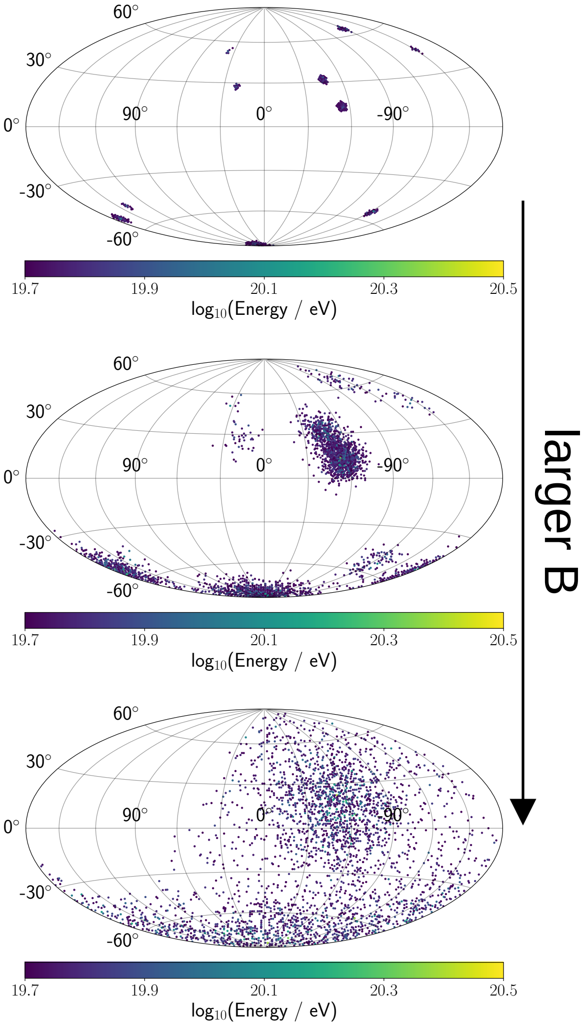
- CRs deflected in magnetic fields
- multimessenger observations necessary

Deflection in Magnetic Fields

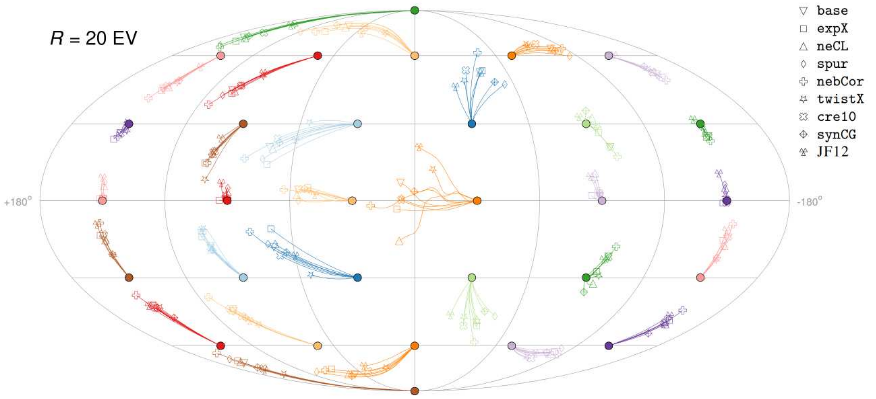
Extragal. Magn. Field



Batista et al. Front. Astron. Space Sci., 04 June 2019



Galactic Magnetic Field



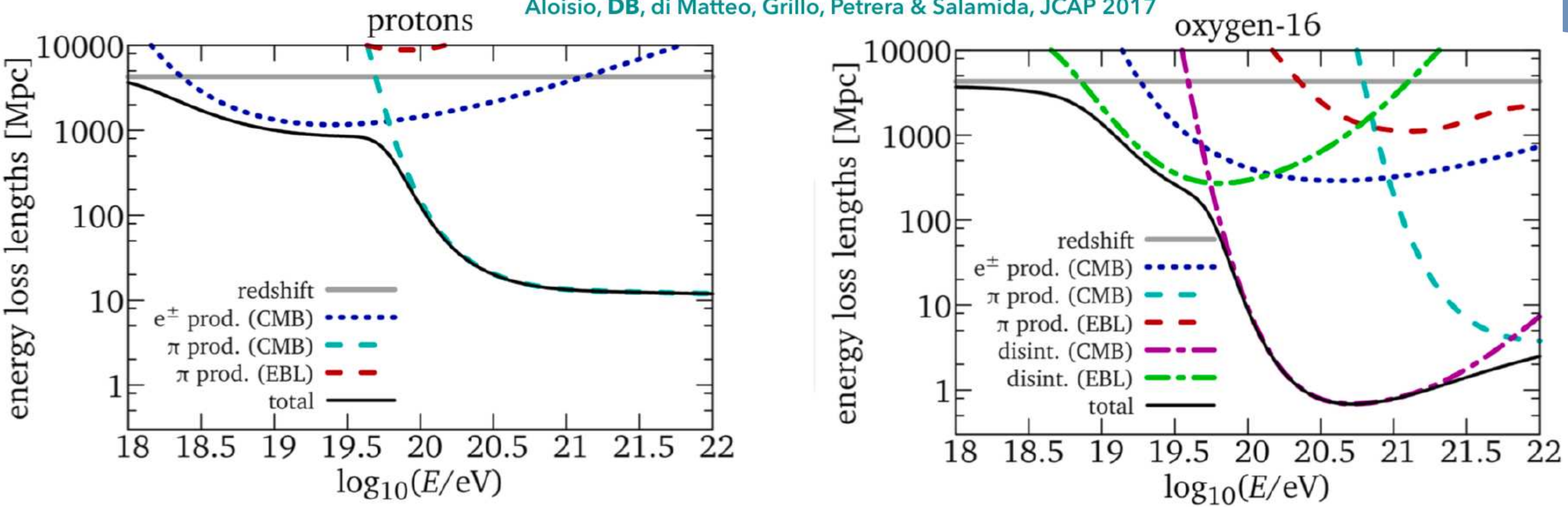
Unger & Farrar, Astrophys.J. 970 (2024) 1, 95

- B_{EGMF} poorly constrained
- B_{gal}~O(μG) but shape unclear

The Energy Loss Horizon

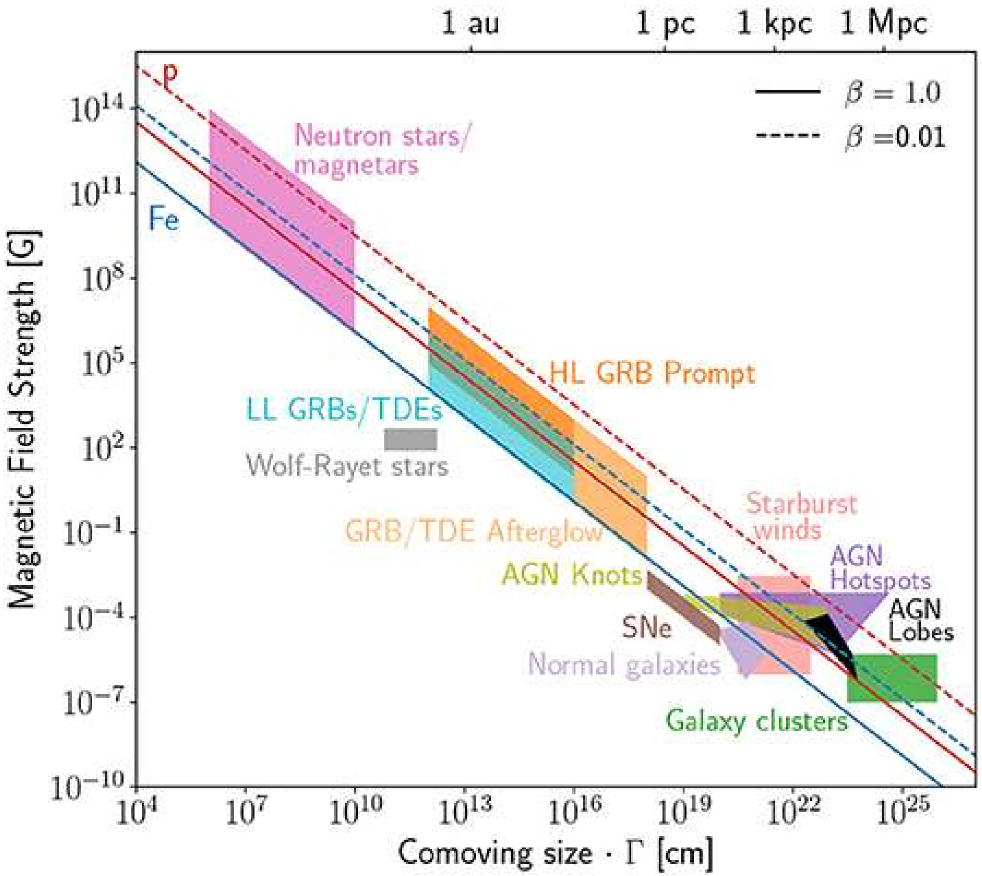
Plots by A. di Matteo, using **SimProp** MC code:

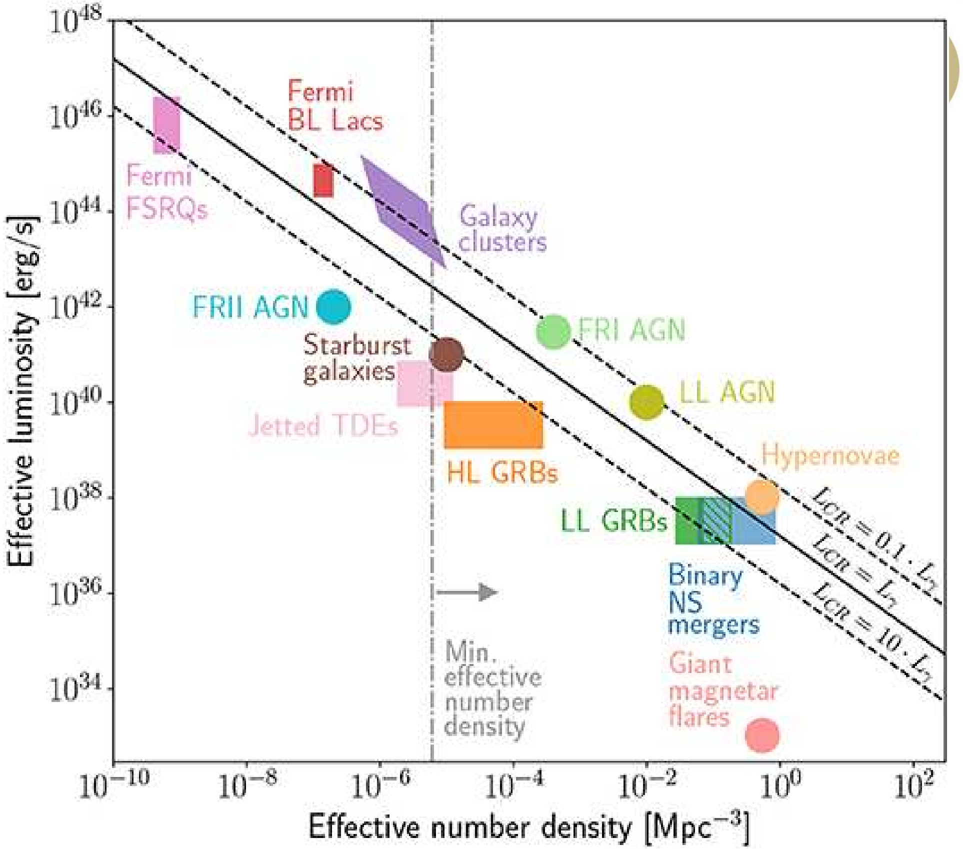
Aloisio, **DB**, di Matteo, Grillo, Petrera & Salamida, JCAP 2017



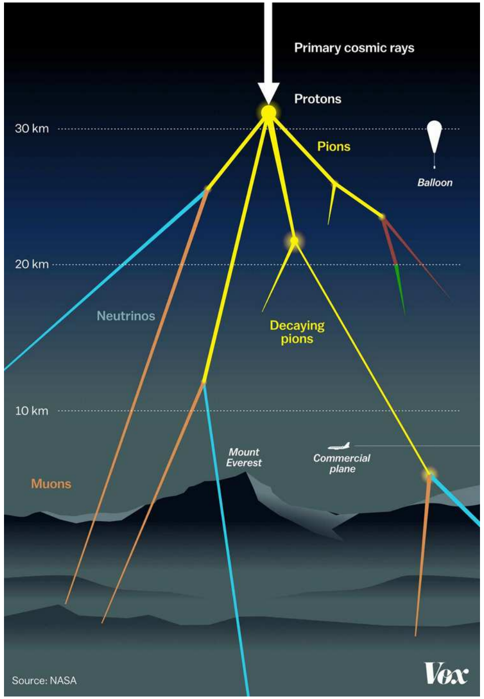
- strong energy loss via CMB & EBL at UHE
- highest-energy sources must be nearby

Possible Sources

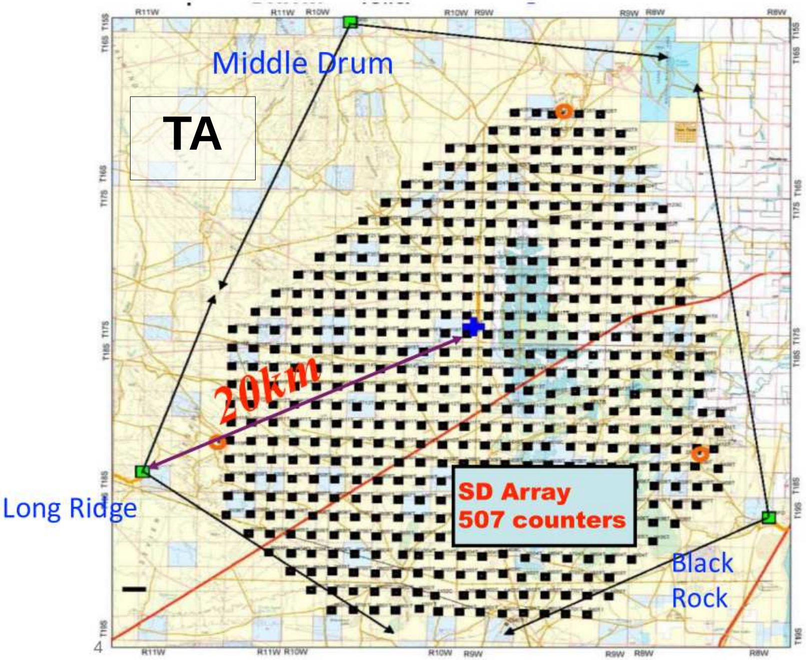


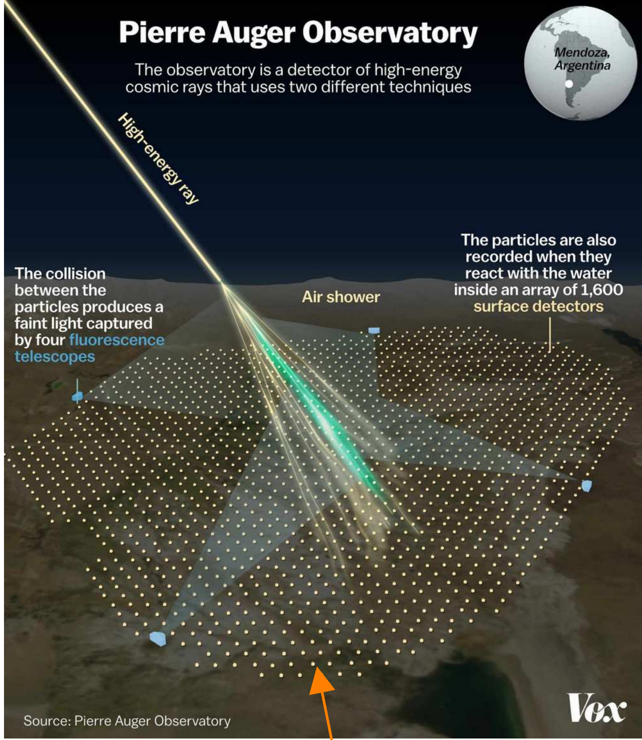


Cosmic Ray Observations: Auger & TA



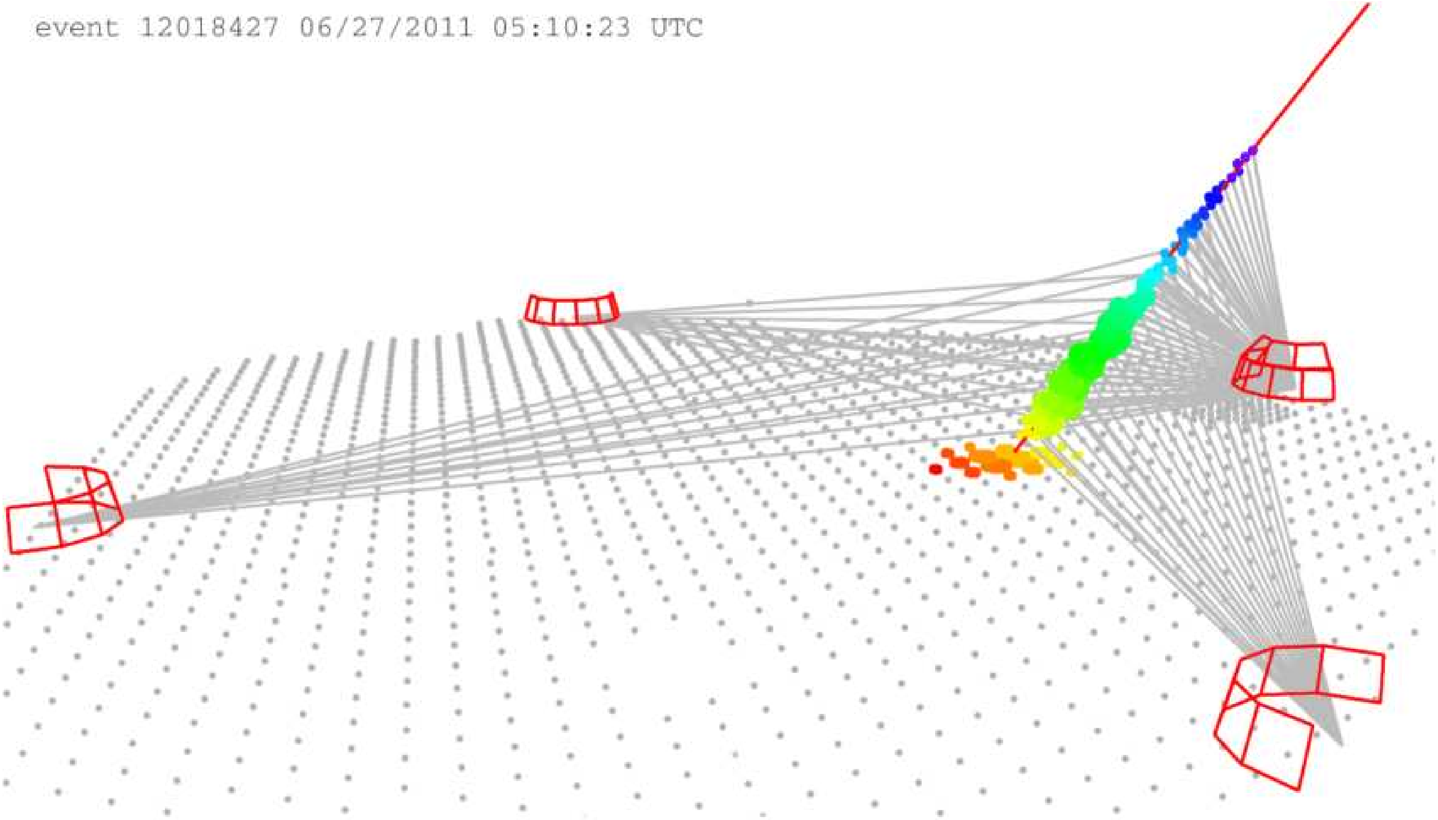
Y. Tsunesada, APC Workshop 2024





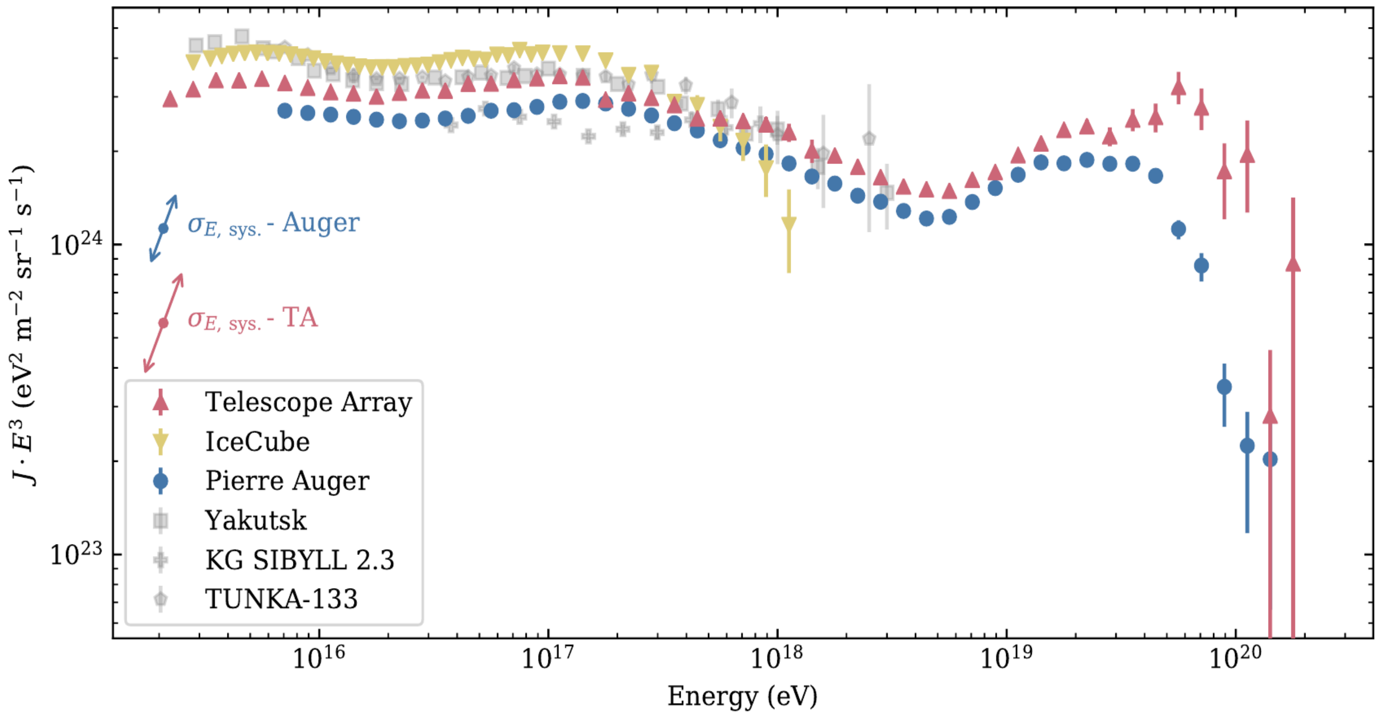
- indirect, hybrid observations:
  particle “showers” in atmosphere
- two major facilities: Telescope Array (Utah), Pierre Auger Observatory (Argentina)

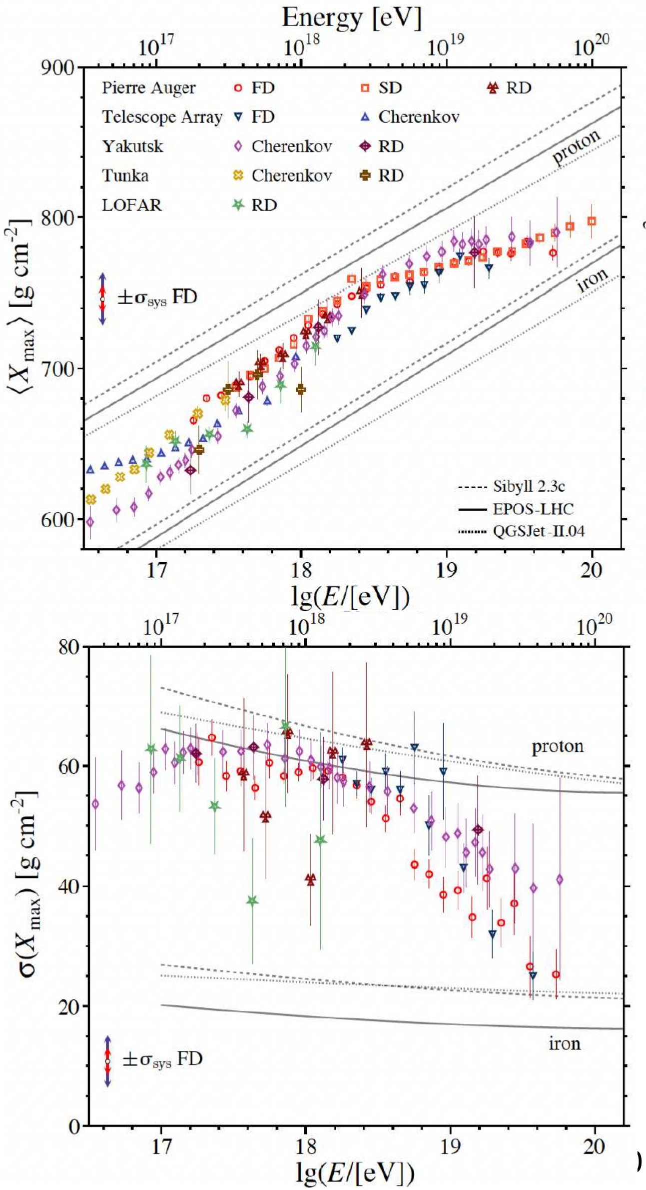
Cosmic Ray Observations: Auger & TA



Spectrum & Composition

Coleman et al. Astropart.Phys. 149 (2023) 102819

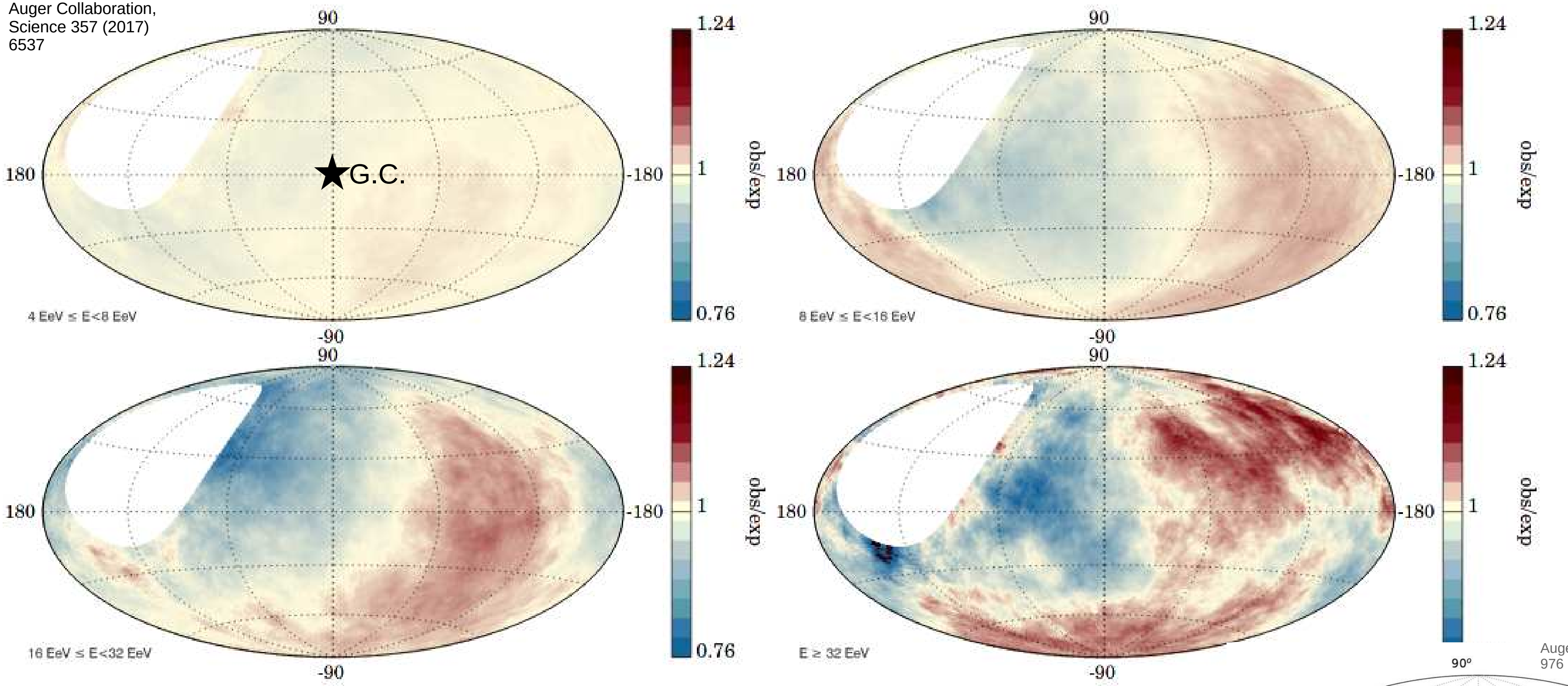




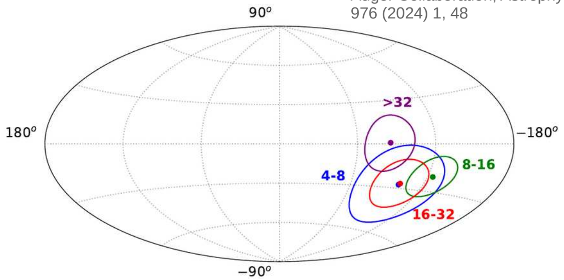
The UHECR Dipole

(galactic coordinates)

Auger Collaboration,
Science 357 (2017)
6537

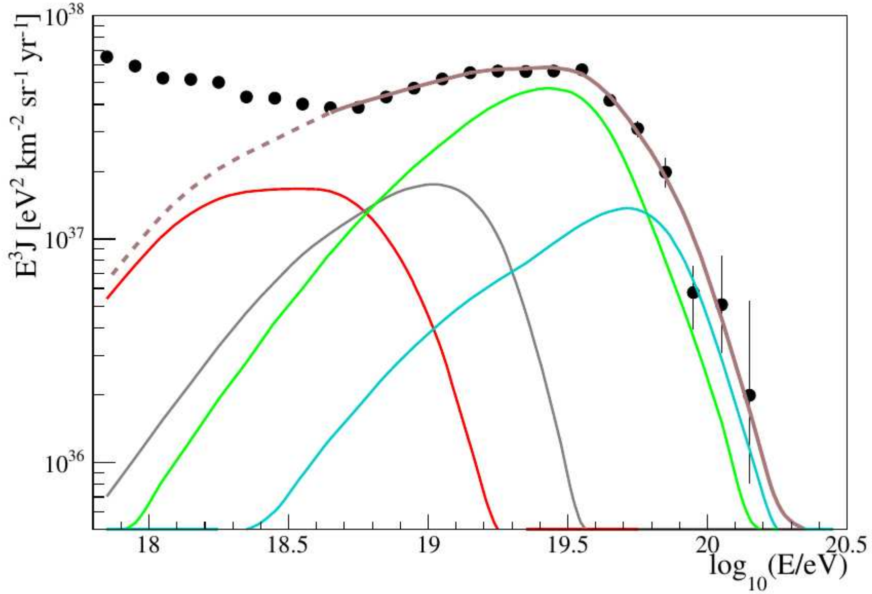


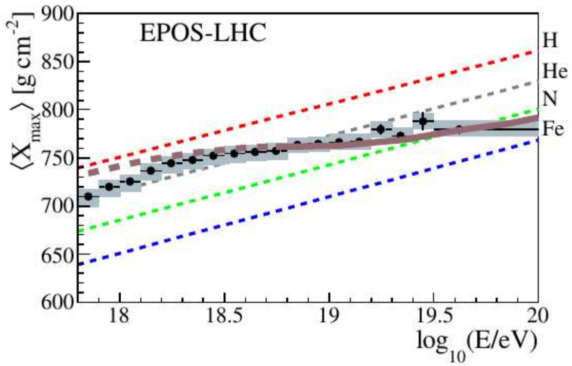
Auger Collaboration, Astrophys.J.
976 (2024) 1, 48

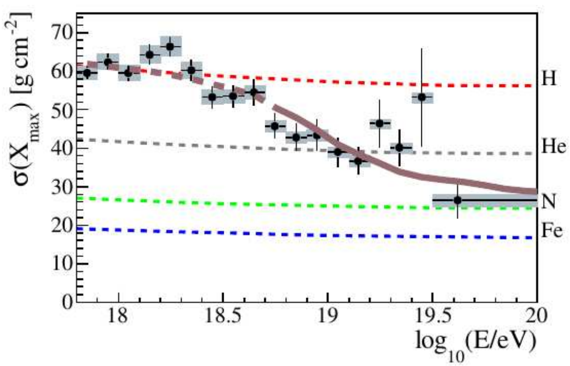


dipolar excess of ~6% at E > 8 EeV

Fitting the Data







typical fit with hard injection spectrum

$$\frac{dN}{dE} \propto E^{-\gamma} \exp\left(\frac{-E}{Z\,E_{max}}\right)$$

acceleration
expect γ ~ 2

best fit
γ < 1

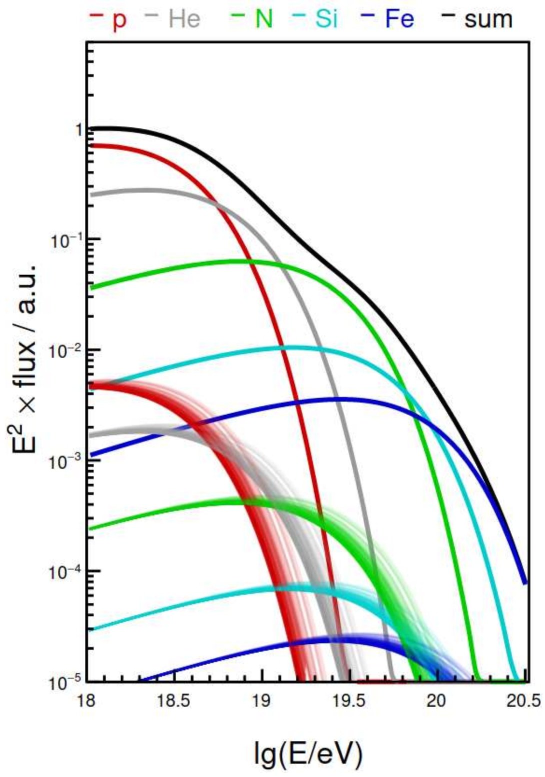
Caveat:

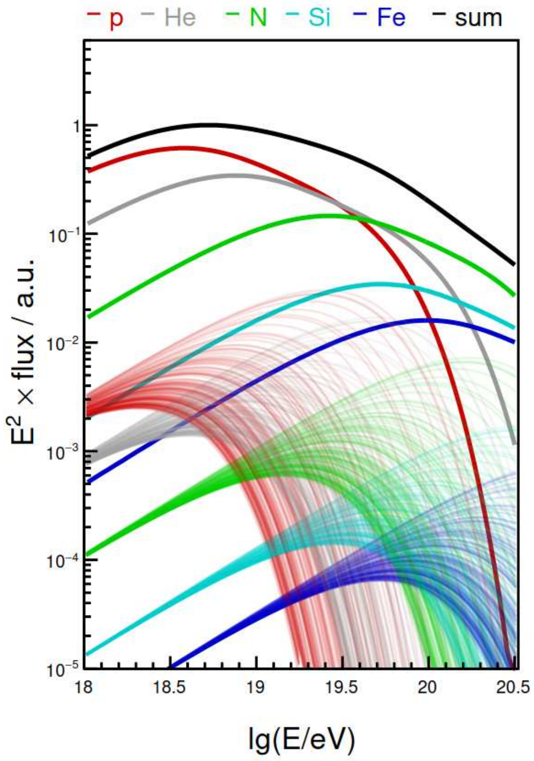
Sources are assumed to be identical.

(for a particular population)

→ **Not physically motivated!**

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





The Source Spectrum

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

Choice of UHE Cutoff:

(1) Heaviside

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

(2) Exponential

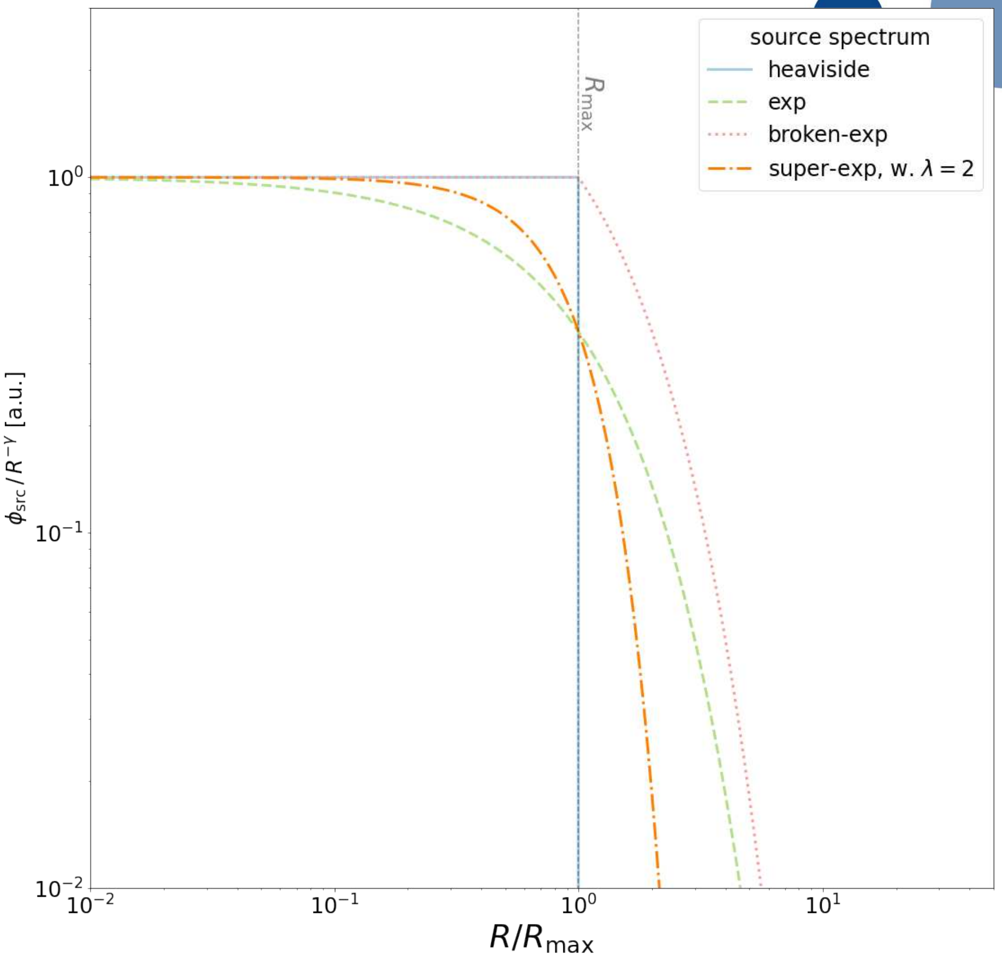
(3) Broken-Exponential

$$\phi_{\rm src} = \phi_0 \, R^{-\gamma_{\rm src}} \, \exp\left(-\frac{R}{R_{\rm max}}\right)$$

(4) Super-Exponential

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

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

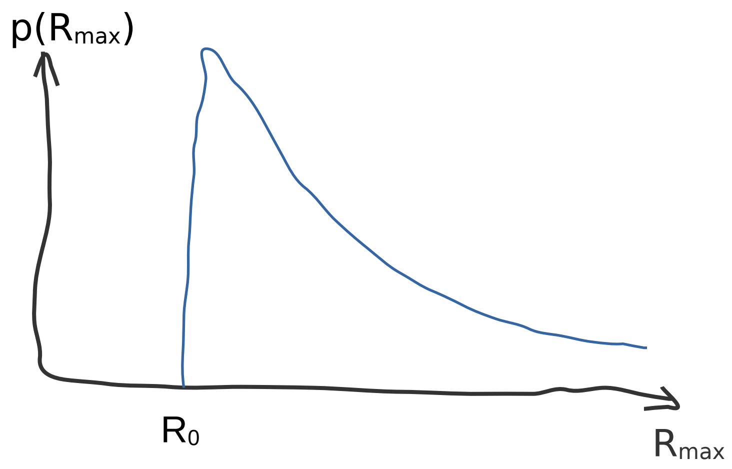


Population of non-identical sources

Distribution of
maximum rigidities

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

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



Assume powerlaw:

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

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

e.g. distribution of

1) Lorentz factors
2) luminosities

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

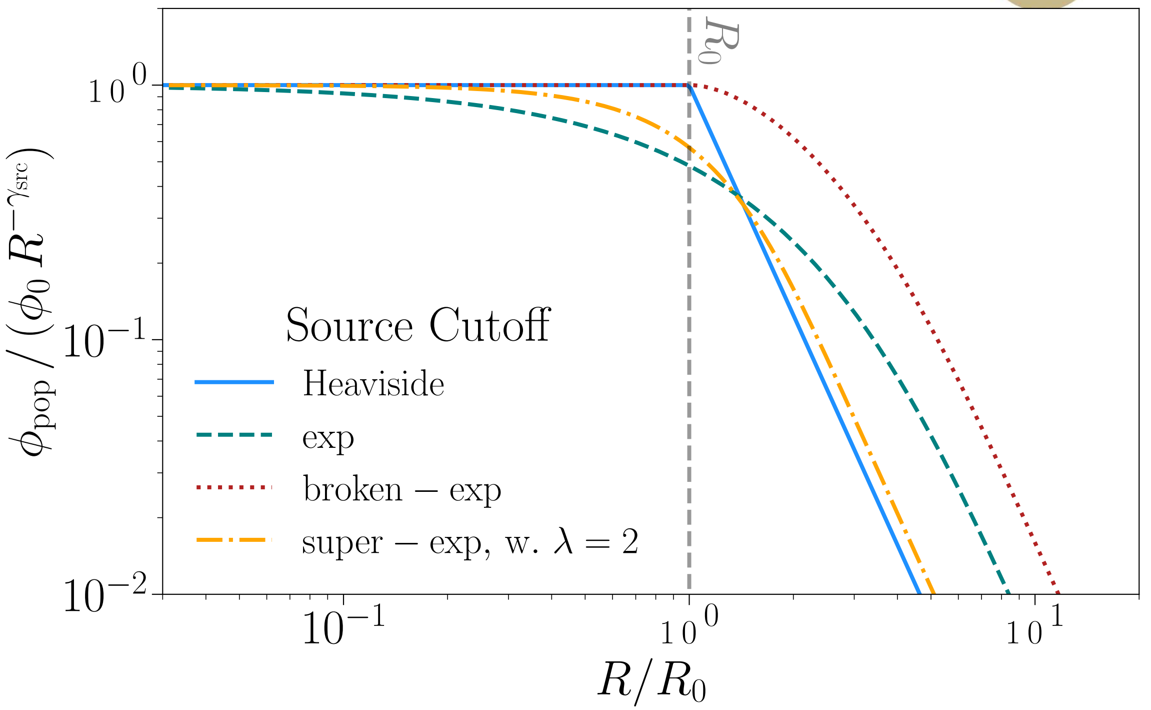
$$\phi_{\rm pop}^{\rm hs} = \phi_0 \, R^{-\gamma_{\rm src}} \begin{cases} 1 & R < R_0 \\ \left(\frac{R}{R_0}\right)^{-\beta_{\rm pop}+1} & \text{otherwise} \end{cases}$$

(2)Broken-Exponential

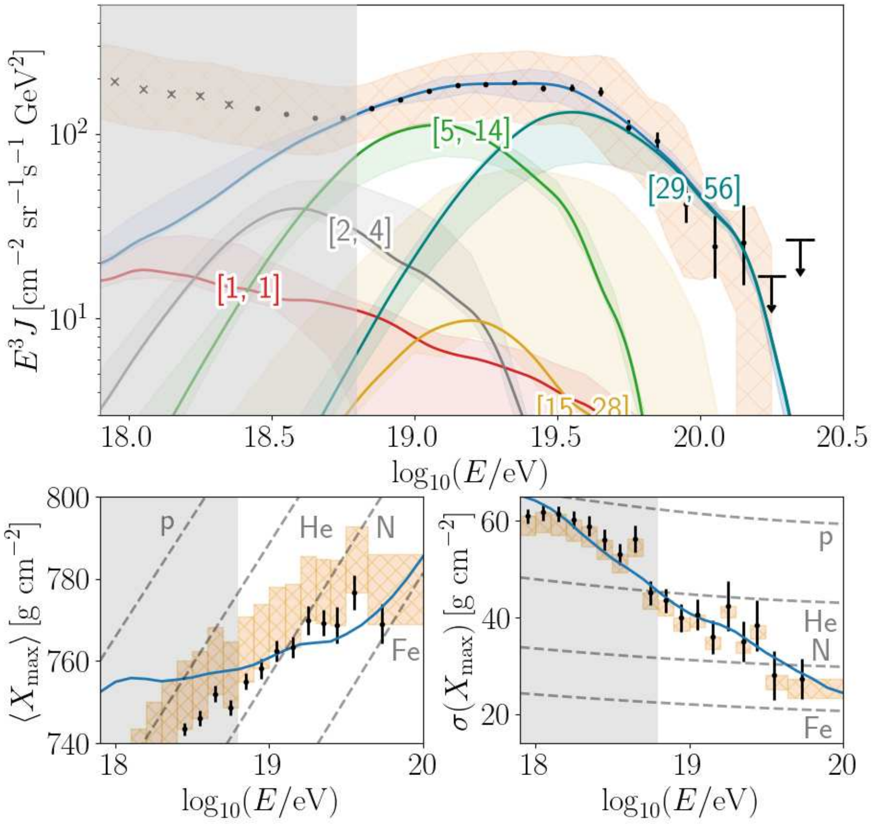
$$\phi_{\rm pop}^{\rm b\text{-}exp} = \phi_0 \, R^{-\gamma_{\rm src}} \begin{cases} 1 & R < R_0 \\ \left(\frac{R}{R_0}\right)^{-\beta_{\rm pop}+1} f\left(\frac{R}{R_0}, \beta_{\rm pop}\right) & \text{otherwise} \end{cases}$$

(3)(Super-)Exponential

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



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

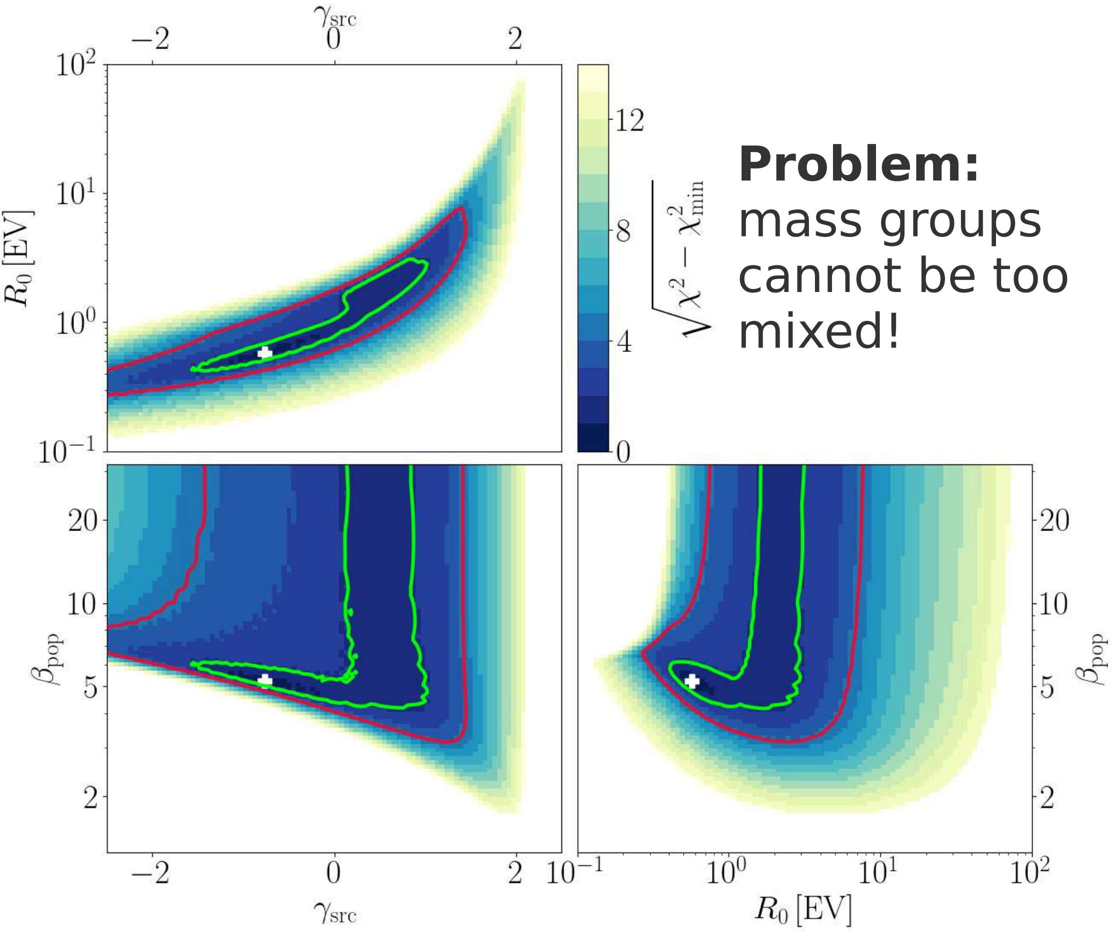
scale shifts $\quad \chi^2_{\mathrm{shifts}} = \sum_{k \in \{E, \langle X_{\max}\rangle, \sigma(X_{\max})\}} \left(\frac{\delta_k}{\sigma_k} \right)^2$

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`

Results - single powerlaw



Problem:
mass groups cannot be too mixed!

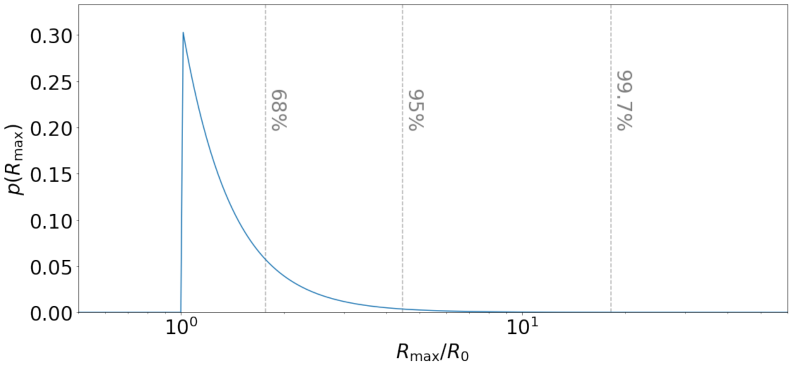
model	SIBYLL2.3c (no shifts)	SIBYLL2.3c (fid. shifts)	EPOS-LHC (fid. shifts)
R_0 [EV]	$1.73^{+0.20}_{-0.18}$	$0.57^{+1.88}_{-0.11}$	$1.6^{+0.6}_{-0.4}$
β_{pop}	$29.9^{+1.7*}_{-18.1}$	$5.2^{+26.4*}_{-0.5}$	$4.4^{+0.5}_{-0.5}$
γ_{src}	$-0.23^{+0.18}_{-0.26}$	$-0.8^{+1.4}_{-0.5}$	$0.1^{+0.4}_{-0.5}$
L_0 $[10^{44} \frac{erg}{Mpc^3\ yr}]$	$2.84^{+0.06}_{-0.05}$	$2.22^{+0.42}_{-0.04}$	$2.77^{+0.05}_{-0.07}$
$R^{0.90}_{max}$ $[R_0]$	$1.083^{+0.155}_{-0.005}$	$1.72^{+0.13}_{-0.64}$	$1.97^{+0.22}_{-0.17}$
f^R_A[%]	$\approx 0^{+0}_{-0}$	$\approx 0^{+80.8}_{-0}$	$\approx 0^{+0}_{-0}$
	$84.21^{+0.16}_{-1.04}$	$0^{+80.3}_{-0}$	$69.6^{+6.0}_{-30.2}$
	$14.47^{+0.96}_{-0.14}$	$98.16^{+0.22}_{-80.10}$	$27.1^{+26.0}_{-5.2}$
	$1.18^{+0.13}_{-0.13}$	$0.14^{+1.80}_{-0.14}$	$3.0^{+4.1}_{-1.2}$
	$0.130^{+0.014}_{-0.012}$	$1.69^{+0.07}_{-1.43}$	$0.205^{+0.102}_{-0.013}$
χ^2/dof	45.0/26	40.4/26	56.3/26

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	$17.7^{+10.3}_{-13.6}$	$-2.5^{+0.5}_{-2.5}$	36.7
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	$z_{min} = 0.01$	$29.9^{+1.7*}_{-25.5}$	$0.38^{+0.18}_{-1.22}$	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	$3.16^{+0.17}_{-0.16}$	$1.07^{+0.08}_{-0.08}$	110.8
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

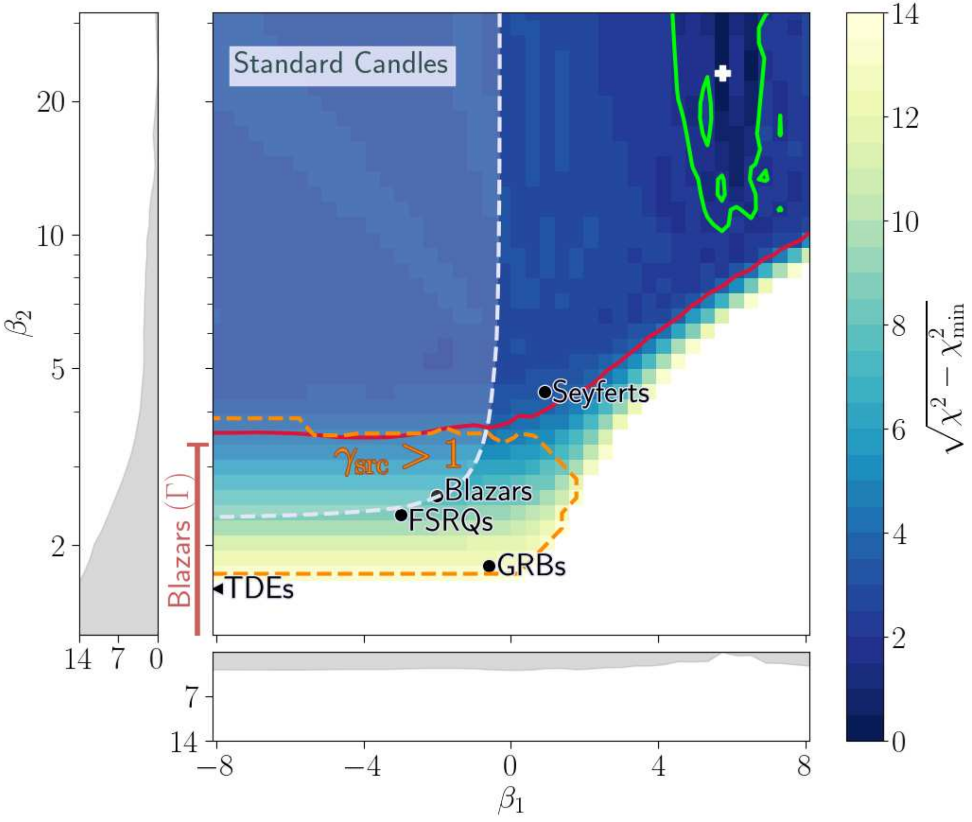
Largest	Conservative
$\beta_{pop} \sim 3$	$\beta_{pop} \sim 4-5$

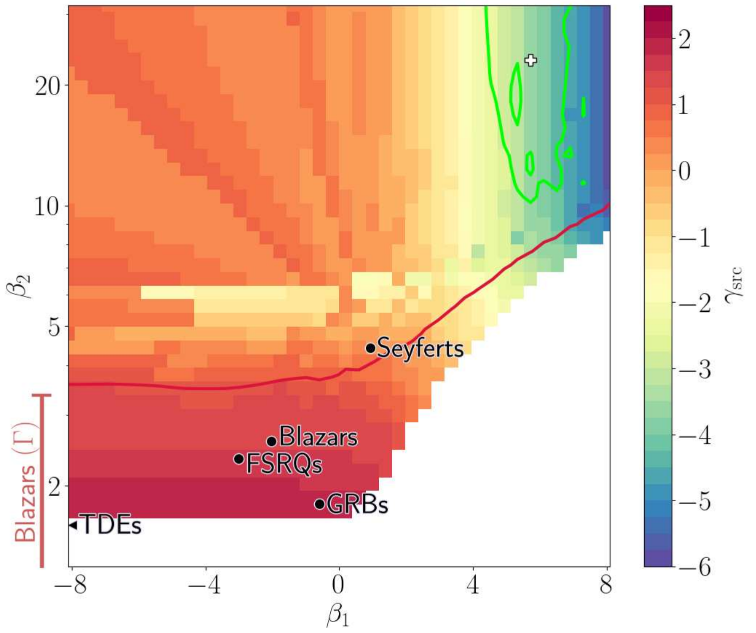


Theoretical Expectations

ID	Param.	Distribution	β_{pop}	γ_{pop}	Sources	$\beta_{\text{pop,max}}$
I.1	R_{max}	SPL, $p(R_{\text{max}} \vert \beta_{\text{pop}})$	β_{pop}	γ_{src}		
I.2	R_{max}	BPL, $p(R_{\text{max}} \vert \beta_1, \beta_2)$				
		$\beta_1 < 1$	$\approx \beta_2$	$\approx \gamma_{\text{src}}$		
		$\beta_1 > 1$	$\beta_2 - \beta_1 + 1$	$\gamma_{\text{src}} + \beta_1 - 1$		
II	$R_{\text{max}} \propto \Gamma^\alpha$	SPL, $\mathrm{d}p/\,\mathrm{d}\Gamma(\eta)$	$(\eta - 1)/\alpha + 2$	γ_{src}	Blazars [45] [a]: $\eta = 1.4_{\pm 0.2}$	
			$-\gamma_{\text{src}} + \xi/\alpha$		+ Hillas: $\alpha = 1,\ \xi = 1$	$3.4_{\pm 0.2} - \gamma_{\text{src}}$
					+ Espresso: $\alpha = 2,\ \xi = 0$	$2.2_{\pm 0.1} - \gamma_{\text{src}}$
III.1	$R_{\text{max}} \propto \sqrt{L}$	SPL, $\mathrm{d}p/\,\mathrm{d}L(y_2)$	$2\,y_2 - 3$	γ_{src}	BL Lacs [53] [b]: $y_2 = 2.61_{\pm 0.37}$	$2.22_{\pm 0.74}$
					FSRQs [54] [b]: $y_2 = 2.36_{\pm 0.10}$	$1.72_{\pm 0.20}$
					Blazars [54] [b]: $y_2 = 2.32_{\pm 0.08}$	$1.64_{\pm 0.16}$
					TDEs [55, 56]: $y_2 = 2.30_{\pm 0.20}$	$1.60_{\pm 0.40}$
III.2	$R_{\text{max}} \propto \sqrt{L}$	BPL, $\mathrm{d}p/\,\mathrm{d}L(y_1, y_2)$				
		$y_1 < 2$	$\approx 2\,y_2 - 3$	$\approx \gamma_{\text{src}}$	GRBs [57]: $y_1 = 1.2^{+0.2}_{-0.1}$, $y_2 = 2.4^{+0.3}_{-0.6}$	$1.8^{+0.6}_{-1.2}$
					FSRQs [54] [b]: $y_1 = 0_{\pm 2.07}$, $y_2 = 2.67_{\pm 0.17}$	$2.34_{\pm 0.34}$
					Blazars [54] [b]: $y_1 = 0.49_{\pm 1.15}$, $y_2 = 2.79_{\pm 0.19}$	$2.58_{\pm 0.38}$
					Seyferts [58]: $y_1 = 1.96_{\pm 0.04}$, $y_2 = 3.71_{\pm 0.09}$	$4.42_{\pm 0.18}$

Results - broken powerlaw





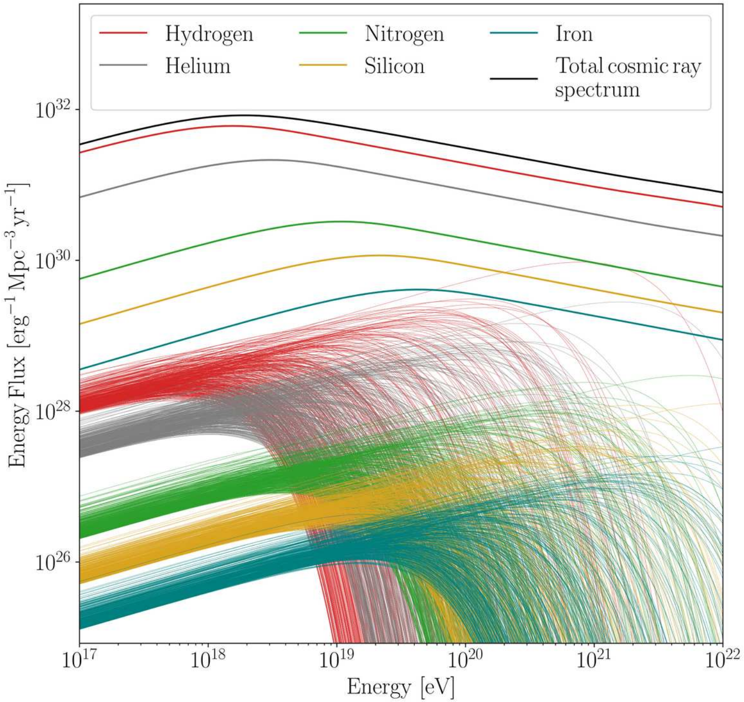
for $\beta_1 < 1$:	for $\beta_1 > 1$:	
$\beta_2 \gtrsim 4.5$	$\beta_2 \gtrsim \beta_1 + 3$	steepen by R_{max}^3
$\gamma_{src} = -0.6^{+1.2}_{-1.0}$	$\gamma_{pop} = 1.22^{+0}_{-0.04}$	γ_{src} -> β_1

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!