

Combined fit of spectrum and composition data as measured by the Pierre Auger Observatory

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Outline

1 Introduction

- The models (sources, propagation, air interactions)
- The data (energy spectrum and X_{max})

2 Results

- Best fit and second local minimum
- Dependence on propagation models, systematics, and air interaction models

3 Conclusions

The sources

We try to fit Pierre Auger Observatory data on UHECR spectrum and composition to a simple astrophysical scenario:

- Identical sources homogeneously distributed in a comoving volume
- Injection consisting only of ^1H , ^4He , ^{14}N and ^{56}Fe nuclei (approximately equally spaced in $\ln A$)
- Power-law spectrum with rigidity-dependent broken exponential cutoff

$$\frac{dN_{\text{inj},i}}{dE} = \begin{cases} J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma}, & E/Z_i < R_{\text{cut}} \\ J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(1 - \frac{E}{Z_i R_{\text{cut}}}\right), & E/Z_i > R_{\text{cut}} \end{cases}$$

- Six free parameters ($J_0, \gamma, R_{\text{cut}}, p_{\text{H}}, p_{\text{He}}, p_{\text{N}}$); $p_{\text{Fe}} = 1 - p_{\text{H}} - p_{\text{He}} - p_{\text{N}}$

The propagation

- Propagation potentially strongly sensitive to:
 - ▶ Photodisintegration cross sections (esp. into α particles)
 - ▶ Extragalactic background light spectrum (esp. in the far IR)
- We used:
 - SPG** *SimProp*, PSB cross sections, Gilmore 2012 EBL model
 - SPD** *SimProp*, PSB cross sections, Domínguez 2011 EBL model
 - STG** *SimProp*, TALYS cross sections, Gilmore 2012 EBL model
 - CTG** CRPropa, TALYS cross sections, Gilmore 2012 EBL model
 - CTD** CRPropa, TALYS cross sections, Domínguez 2011 EBL model
 - CGD** CRPropa, Geant4 cross sections, Domínguez 2011 EBL model
- For details, see R. Alves Batista, D. Boncioli, A. di Matteo, A. van Vliet and D. Walz,
Effects of uncertainties in simulations of extragalactic UHECR propagation, using CRPropa and SimProp, prepared for submission to *JCAP* (**coming soon on arXiv**)
- We neglect magnetic fields → 1D propagation

Interactions in the atmosphere

- X_{\max} distributions for each A computed from CONEX simulated showers assuming:
 - ▶ EPOS-LHC
 - ▶ Sibyll 2.1
 - ▶ QGSJet II-04
- Distributions fitted to a Gumbel parametrization (JCAP 1307 (2013) 050, arXiv:1305.2331)

$$p(X_{\max}|\mu, \sigma, \lambda) = \frac{\lambda^{\lambda} \exp(-\lambda z - \lambda \exp(-z))}{\sigma \Gamma(\lambda)}$$

where

$$z = \frac{X_{\max} - \mu}{\sigma}$$

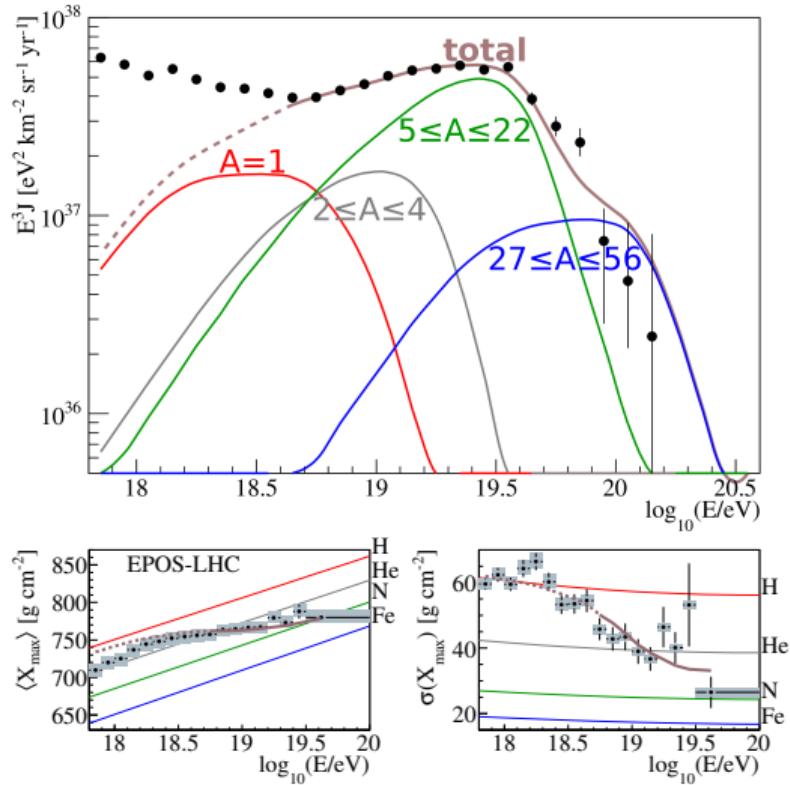
(μ, σ, λ = quadratic functions of $\ln A$ and $\log_{10}(E/E_0)$)

- Distributions multiplied by detector acceptance and convoluted with detector resolution

The data

- Fit only above $10^{18.7}$ eV
- The spectrum (ICRC 2013, arXiv:1307.5059):
 - ▶ $\log_{10}(E/\text{eV})$ bins [18.7, 18.8], [18.8, 18.9], ..., [20.1, 20.2] (15 bins)
 - ▶ Statistical uncertainties approximated as Gaussian
 - ▶ Systematic uncertainty on E : $\pm 14\%$
- The composition (PRD 90 (2014) 122005, arXiv:1409.4809):
 - ▶ $\log_{10}(E/\text{eV})$ bins [18.7, 18.8], ..., [19.4, 19.5], [19.5, 20.0] (9 bins)
 - ▶ $X_{\max}/(\text{g/cm}^2)$ bins [0, 20], [20, 40], ..., [1980, 2000] (most empty)
 - ▶ 110 non-empty bins in total
 - ▶ Multinomial X_{\max} distribution in each $\log_{10}(E/\text{eV})$ bin
 - ▶ Systematic uncertainty on X_{\max} : $\approx \pm 8 \text{ g/cm}^2$ (energy-dependent)

The best fit (SPG propagation, EPOS-LHC air interactions)

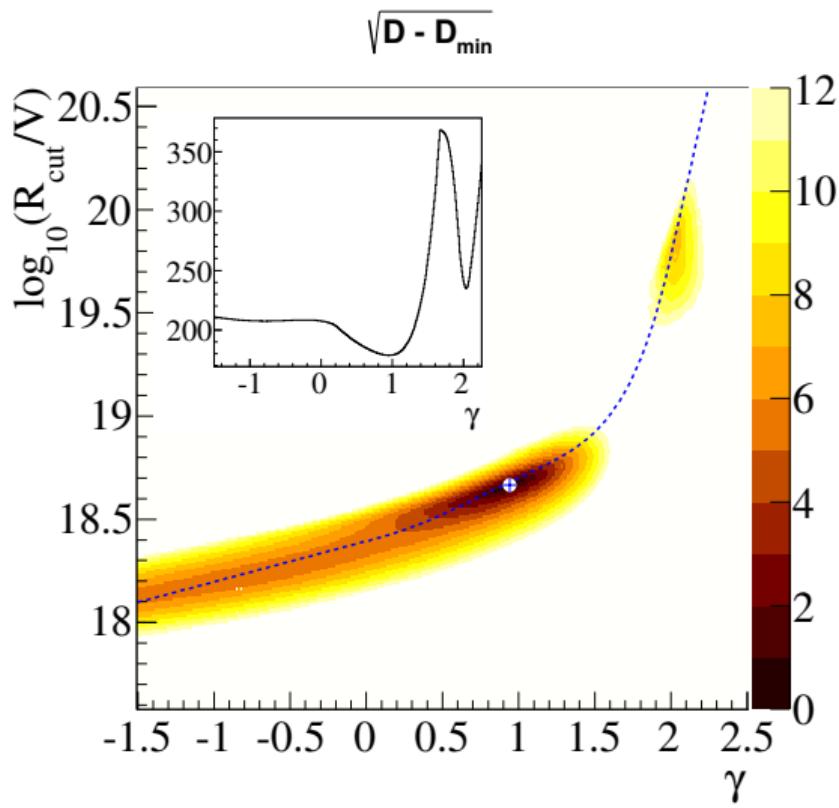


- $J_0 = 7.17 \times 10^{18} \text{ eV}^{-1} \text{ Mpc}^{-3} \text{ yr}^{-1}$ (at 10^{18} eV)
($\mathcal{L}_0 = 5.15 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$ total)
- $\gamma = 0.94^{+0.09}_{-0.10}$
- $R_{\text{cut}} = 10^{18.67 \pm 0.03} \text{ V}$
- $0.0^{+29.9\%}_{-0.0\%}$ H, $62.0^{+3.5\%}_{-22.2\%}$ He, $37.2^{+4.2\%}_{-12.6\%}$ N,
 $0.8^{+0.2\%}_{-0.3\%}$ Fe (at 10^{18} eV)
(0.0% H, 28.9% He, 65.6% N, 5.5% Fe total)
- $D/n = 178.5/119$ ($D_J = 18.8$, $D_{X_{\max}} = 159.8$)
- $p = 0.026$

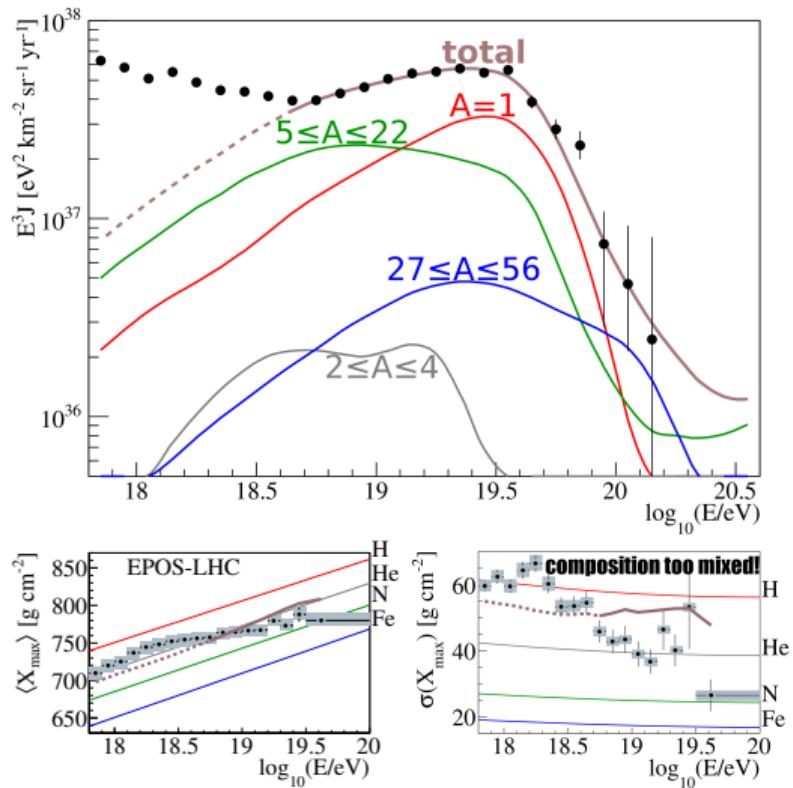
Comments on the result

- Hard, metal-rich injection, as also found by:
 - ▶ R. Aloisio, V. Berezinsky and P. Blasi [arXiv:1312.7459]
 - ▶ A. Taylor, M. Ahlers and D. Hooper [arXiv:1505.06090],
unless source density increases with decreasing redshift
 - ▶ N. Globus, D. Allard and E. Parizot [arXiv:1505.01377]
- Results mainly due to narrow X_{\max} distributions
→ little mixing of different masses at the same energy

Likelihood plot (SPG propagation, EPOS-LHC air interactions)



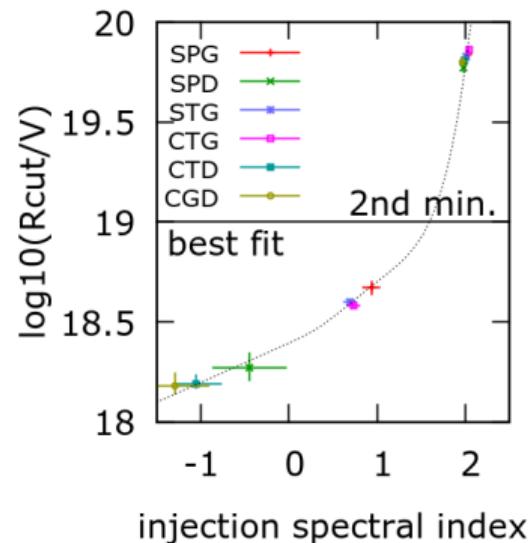
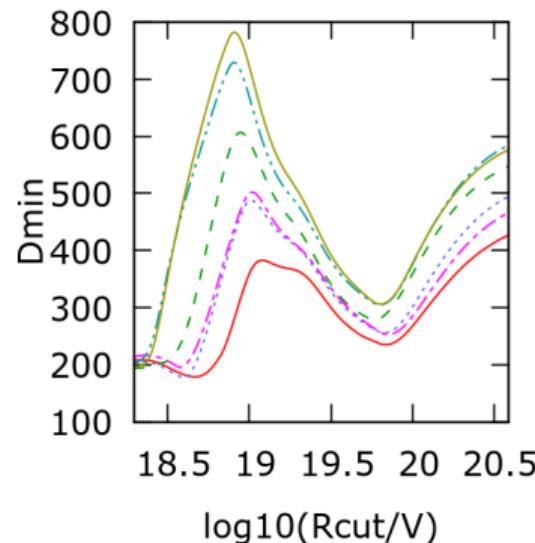
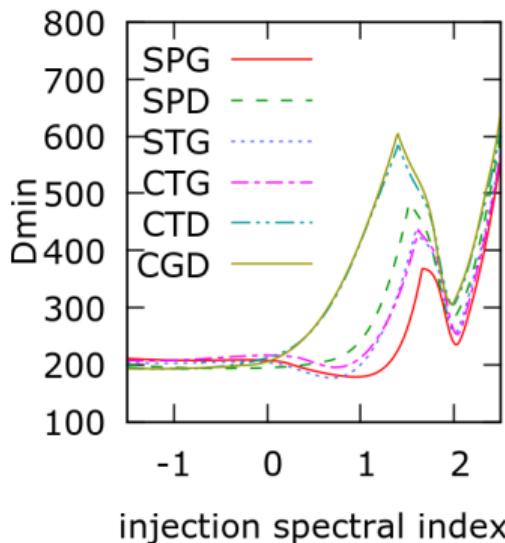
2nd local minimum (SPG propagation, EPOS-LHC air interactions)



- $J_0 = 4.53 \times 10^{19} \text{ eV}^{-1} \text{ Mpc}^{-3} \text{ yr}^{-1}$ (at 10^{18} eV)
- $\gamma = 2.03$
- $R_{\text{cut}} = 10^{19.84} \text{ V}$
- 0.0% H, 0.0% He, 94.2% N, 5.8% Fe (at 10^{18} eV)
- $D/n = 235.0/119$ ($D_J = 14.5$, $D_{X_{\max}} = 220.5$)
- $p = 5 \times 10^{-4}$
disfavoured at the 7.5σ level

Dependence on propagation models

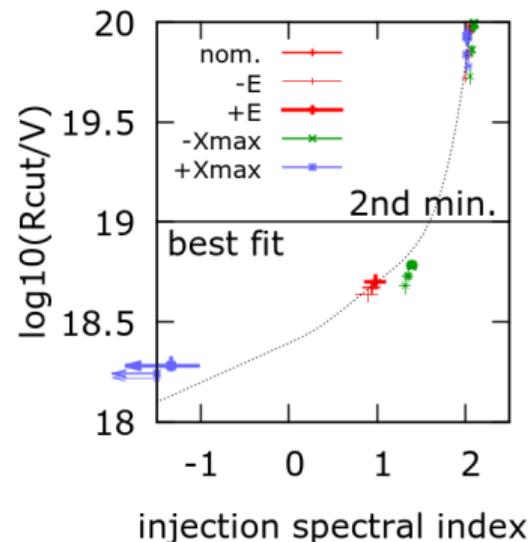
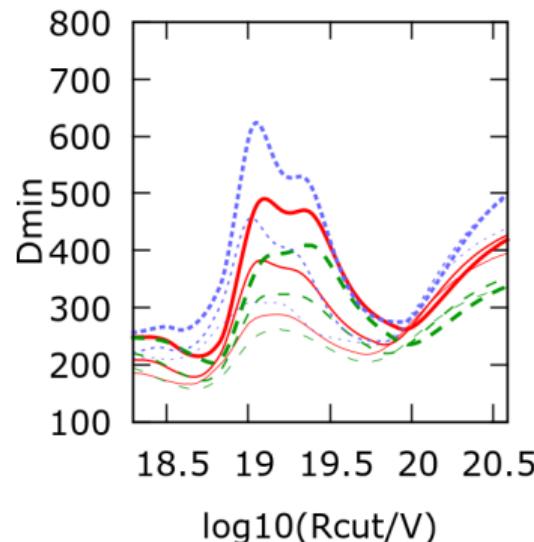
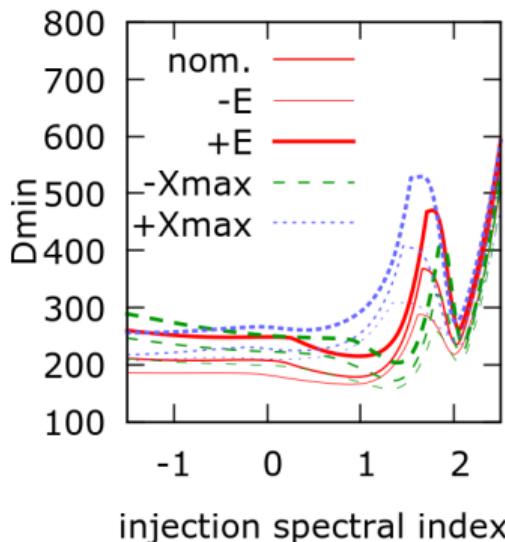
- Analysis repeated with other propagation models



- Models with lower interaction rates favoured
- The higher the interaction rates, the lower the injection cutoff and spectral index

Dependence on energy and X_{\max} scale

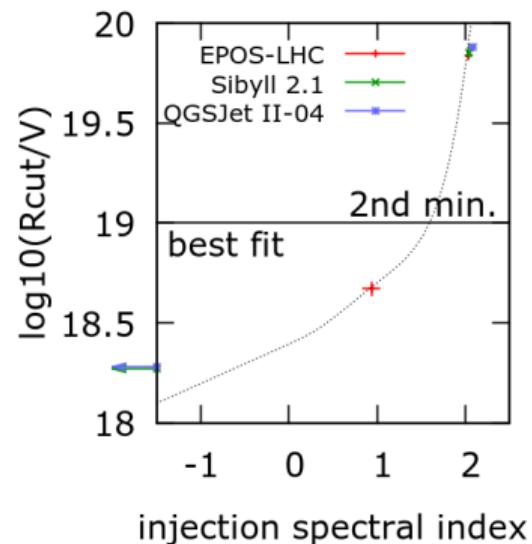
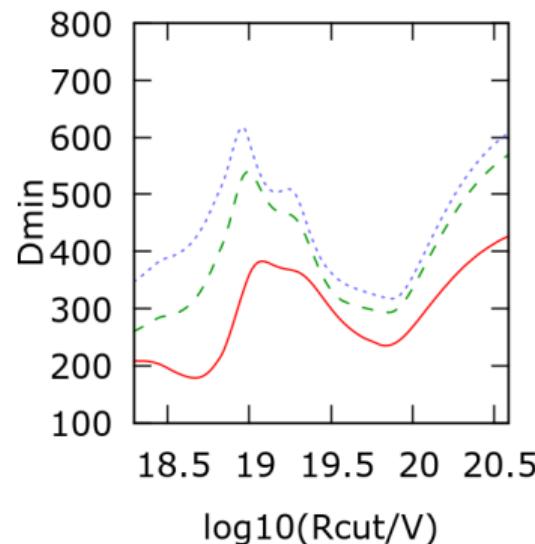
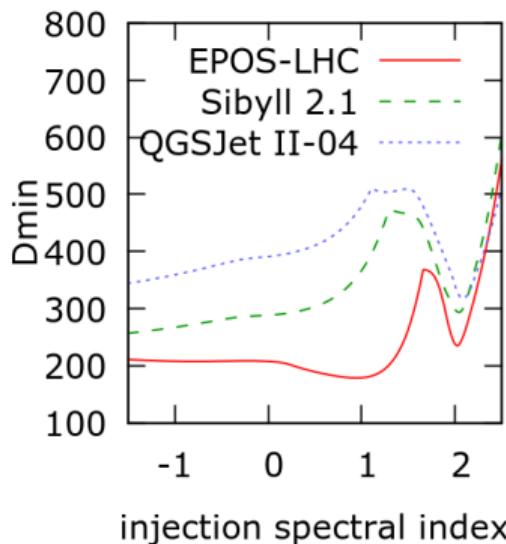
- Analysis repeated shifting E and/or X_{\max} by their syst. uncertainties



- Lowered energy and (to a lesser extent) X_{\max} scales favoured
- The deeper the showers, the harder the required injection spectrum

Dependence on UHECR-air interaction models

- Analysis repeated with other air interaction models



- EPOS-LHC favoured, QGSJet II-04 disfavoured
- Sibyll 2.1 and QGSJet II-04 require extremely hard injection spectra

Conclusions

- Hard injection ($\gamma \lesssim 1$) with low cutoff ($R_{\text{cut}} \lesssim 10^{18.7}$ V) favoured
- Qualitatively similar results for all models,
but model-dependent best-fit parameter values
- $\gamma \approx 2$ injection much less sensitive on propagation details,
but strongly disfavoured by X_{max} distribution width
- Lowered energy and (to a lesser extent) X_{max} scales favoured
- EPOS-LHC favoured over Sibyll 2.1 and QGSJet II-04

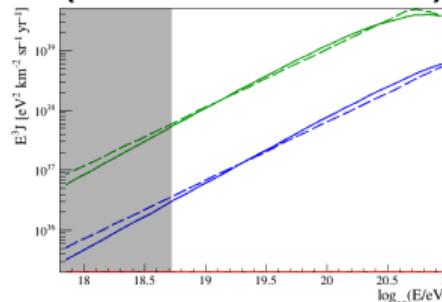
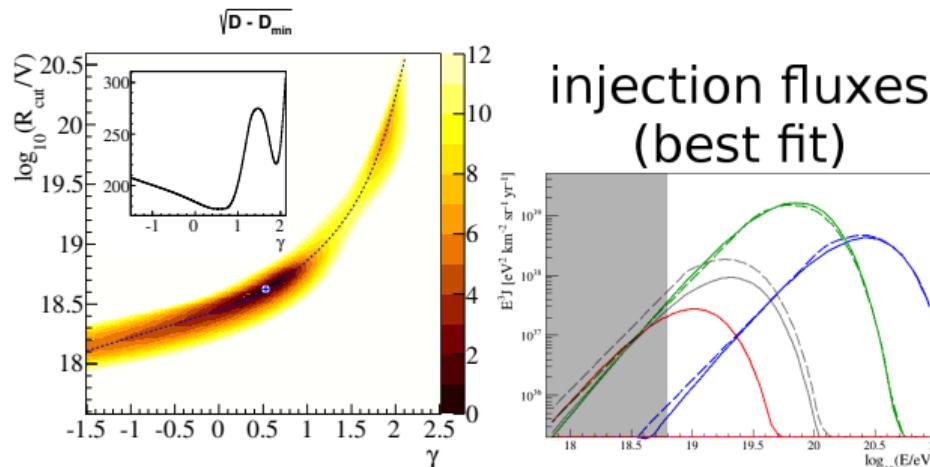
Journal paper in preparation

Back-up slides

4 Simple exponential cutoff

5 X_{\max} distributions

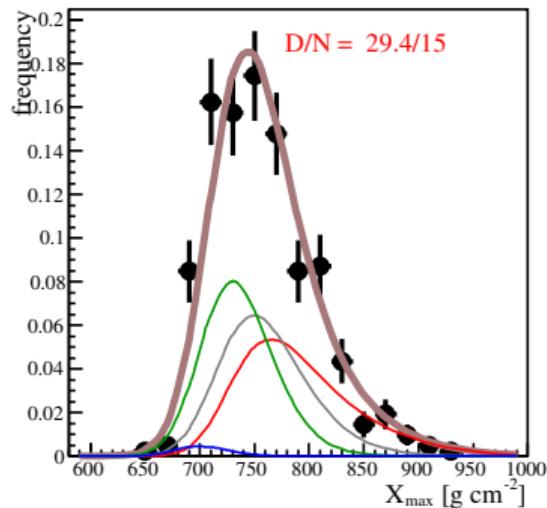
Simple exponential cutoff



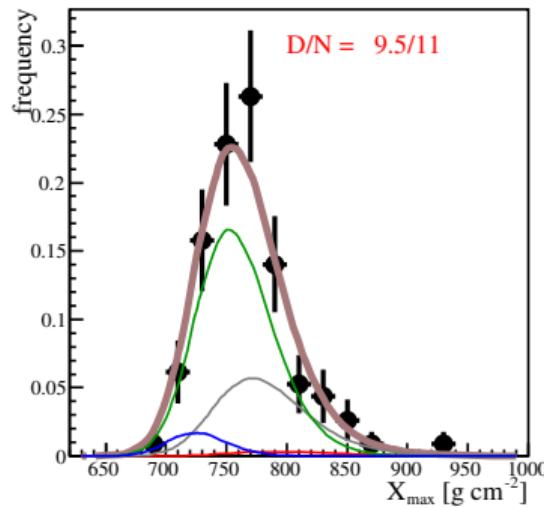
cutoff	best fit				2nd min			
	γ	R_{cut}/V	D_{\min}	$\frac{D(J)}{D(X_{\max})}$	γ	R_{cut}/V	D	$\frac{D(J)}{D(X_{\max})}$
broken exp	$0.94^{+0.09}_{-0.10}$	$10^{18.67 \pm 0.03}$	178.5	$\begin{matrix} 18.8 \\ 159.8 \end{matrix}$	2.03	$10^{19.84}$	235.0	$\begin{matrix} 14.5 \\ 220.5 \end{matrix}$
simple exp	$0.53^{+0.21}_{-0.18}$	$10^{18.63^{+0.09}_{-0.06}}$	177.2	$\begin{matrix} 17.3 \\ 159.9 \end{matrix}$	1.89	$10^{19.94}$	221.0	$\begin{matrix} 14.6 \\ 206.5 \end{matrix}$

X_{\max} distributions at best fit

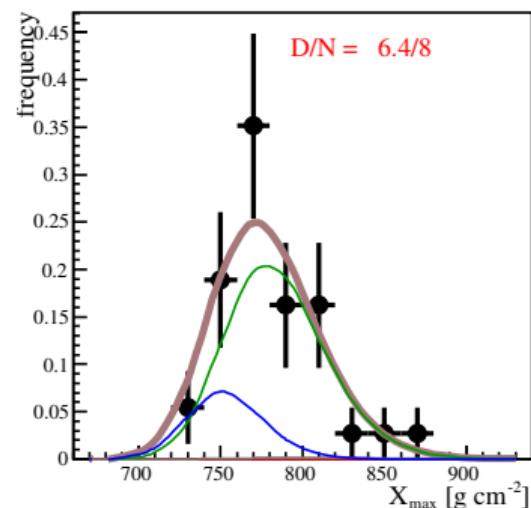
$18.7 < \lg(E/eV) < 18.8$



$19.1 < \lg(E/eV) < 19.2$



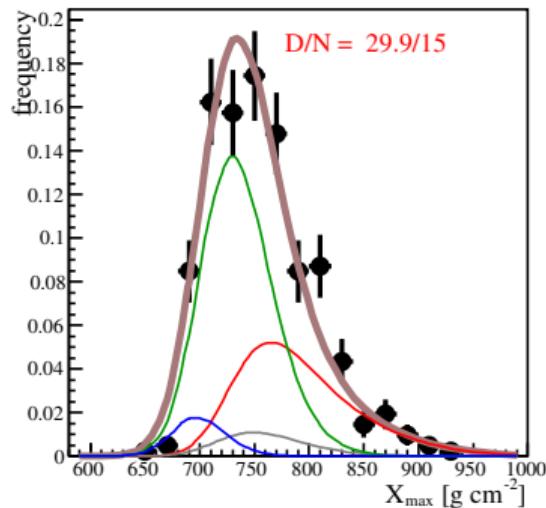
$19.5 < \lg(E/eV) < 20.0$



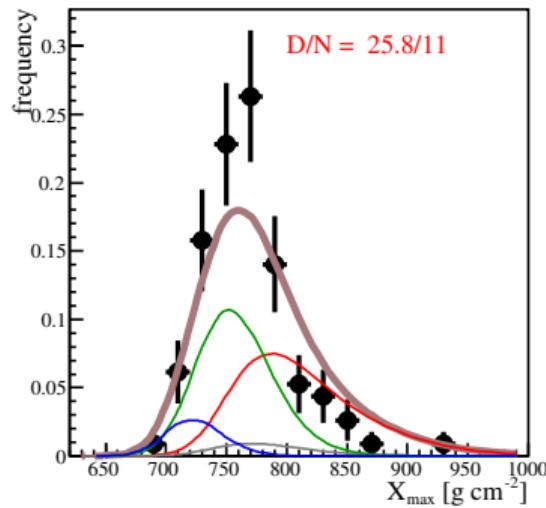
- red: $A = 1$
- gray: $2 \leq A \leq 4$
- green: $5 \leq A \leq 22$
- blue: $A \geq 23$
- thick brown: total
- black dots: Auger data

X_{\max} distributions at 2nd local minimum

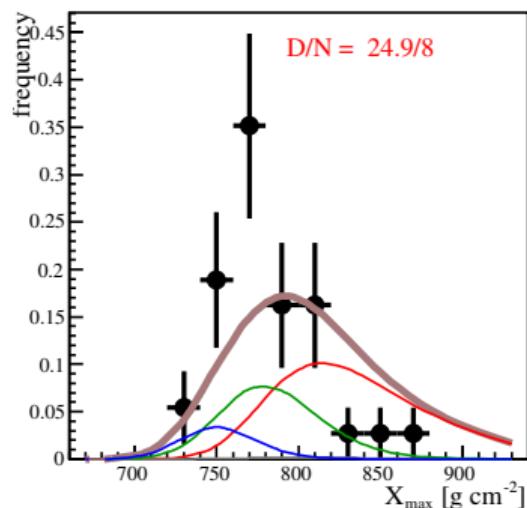
$18.7 < \lg(E/eV) < 18.8$



$19.1 < \lg(E/eV) < 19.2$



$19.5 < \lg(E/eV) < 20.0$



- red: $A = 1$
- gray: $2 \leq A \leq 4$

- green: $5 \leq A \leq 22$
- blue: $A \geq 23$

- thick brown: total
- black dots: Auger data