Astrophysical interpretation of Pierre Auger Observatory measurements of the UHECR energy spectrum and mass composition

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Outline

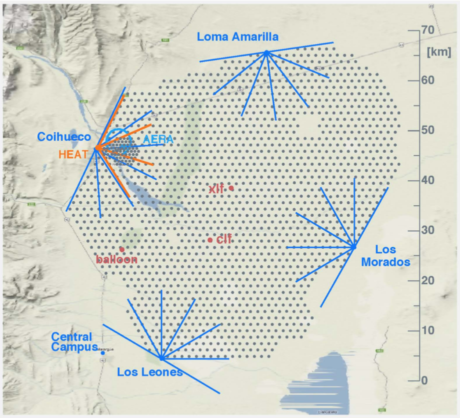
1. Introduction
2. The models we used
    - The astrophysical sources
    - The propagation through intergalactic space
    - Interactions in the atmosphere
3. Our results
    - The reference fit
    - Effects of systematic uncertainties
4. Discussion and conclusions

The Pierre Auger Observatory NIM A 798 (2015) 172–213 [`arXiv:1502.01323`]

The baseline array (for highest-energy CRs):

Surface detector (SD) 1660 water Cherenkov stations on a 1500 m triangular grid (3 000 km^2); $\approx$ 100% duty cycle; energy scale calibrated via SD+FD hybrid events

Fluorescence detector (FD) 24 telescopes at 4 sites around the array; $\approx$ 15% duty cycle; near-calorimetric energy measurements; primary mass-sensitive observable $X_{\max}$



plus various extensions for lower-energy CRs, R&D, interdisciplinary studies, ...

Pierre Auger Collaboration: $\approx$500 members from 86 institutions in 18 countries

The fit

- This fit is only intended as a demonstration of the constraining power of Auger data; therefore we use a simple source model not intended to be astrophysically realistic.
- Since the ankle is hard to model, for the ‘main’ fit we only use data above $10^{18.7}$ eV:
  - Combined energy spectrum in fifteen $\log_{10}(E/\text{eV})$ bins $[18.7, 18.8), \ldots, [20.1, 20.2)$ (presented by A. Schulz for the Auger Collab., ICRC 2013 #769 [`arXiv:1307.5059`])
  - FD events in nine $\log_{10}(E/\text{eV})$ bins $[18.7, 18.8), \ldots, [19.4, 19.5), [19.5, 20.0)$ and X_max bins of width 20 g/cm^2 from 0 to 2 000 g/cm^2 (110 non-empty bins; published in PRD 90 (2014) 122005 [`arXiv:1409.4809`])
- Most of these results already presented by AdM for the Auger Collab., ICRC 2015 #249 [`arXiv:1509.03732`], and CRIS 2015 [`arXiv:1512.02314`]
- Work in progress to update and improve the fit; journal paper in preparation for submission (most likely to JCAP)

Outline

The injection spectrum and composition

- We assume:
  - Identical sources, homogeneously distributed in comoving volume.
  - Injection consisting of hydrogen-1, helium-4, nitrogen-14, and iron-56, whose fractions p_i at $E_\text{inj} = 1$ EeV are free parameters (except that $\sum_i p_i = 1$).
  - Power-law injection spectrum with rigidity-dependent broken exponential cutoff,

$$Q_i(E_\text{inj}) = \begin{cases} Q_0 p_i (E_\text{inj}/\text{EeV})^{-\gamma}, & E_\text{inj} \leq Z_i R_\text{cut}; \\ Q_0 p_i (E_\text{inj}/\text{EeV})^{-\gamma} \exp(1 - E_\text{inj}/Z_i R_\text{cut}), & E_\text{inj} \geq Z_i R_\text{cut}. \end{cases}$$

- This choice is just for numerical convenience, not for astrophysical plausibility; but we will also show what happens with a different cutoff shape.
- Six fit parameters (Q_0, R_cut, γ, and three p_i)

Outline

The propagation through intergalactic space

- Propagation simulated using:

  SimProp v2r3 [`arXiv:1602.01239`], a simple and fast Monte Carlo code using many (reasonable) approximations

  CRPropa 3 (JCAP 05 (2016) 038 [`arXiv:1603.07142`]), a more detailed simulation with almost all known relevant processes

  See JCAP 10 (2015) 063 [`arXiv:1508.01824`] for comparisons between these codes.
- Magnetic fields neglected (rectilinear propagation)
- Photon backgrounds:

  CMB cosmic microwave background (very well known spectrum, $T = 2.725$ K black body)

  EBL extragalactic background light (poorly known spectrum, especially in the far IR)
- Processes:
  - Adiabatic energy loss due to the expansion of the Universe (well known rate, RW metric)
  - Pair photoproduction (very well known cross sections, Bethe–Heitler formula)
  - Photodisintegration (unknown partial cross sections for certain channels, models needed)
  - Pion photoproduction (reasonably well known cross sections, accelerator measurements)

The propagation models we used

	MC code	photodis.[1]	EBL model
SPG	*SimProp*	PSB	Gilmore+ ’12
SPD	*SimProp*	PSB	Domínguez+ ’11
STG	*SimProp*	TALYS	Gilmore+ ’12
CTG	CRPropa	TALYS	Gilmore+ ’12
CTD	CRPropa	TALYS	Domínguez+ ’11
CGD	CRPropa	Geant4	Domínguez+ ’11

[1] See JCAP 10 (2015) 063 [`arXiv:1508.01824`] for details.

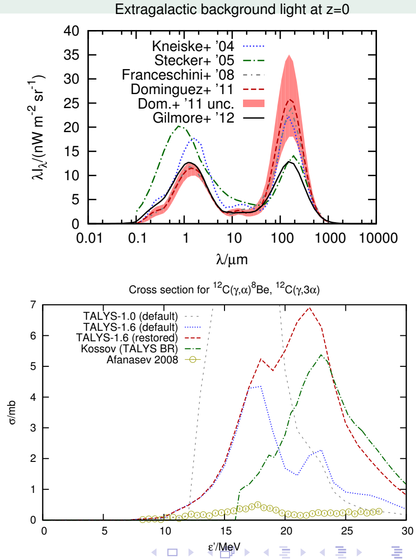


Figure: Comparison of various EBL (top) and photodisintegration (bottom) models

Outline

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 (M. De Domenico et al., JCAP 1307 (2013) 050 [`arXiv:1305.2331`]):

$$p(X_{\text{max}}|E,A) = \frac{\lambda^{\lambda}\exp\left(-\lambda z - \lambda\exp(-z)\right)}{\sigma\Gamma(\lambda)}, \qquad \text{where} \quad z = \frac{X_{\text{max}}-\mu}{\sigma}$$

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

- Distributions multiplied by detector acceptance, convolved with detector resolution

$$p(X_{\text{max}}^{\text{rec}}|E,A) = \int \mathcal{R}(X_{\text{max}}^{\text{rec}} - X_{\text{max}}^{\text{true}}|E)\mathcal{A}(X_{\text{max}}^{\text{true}},E)p(X_{\text{max}}^{\text{true}}|E,A)\,\mathrm{d}X_{\text{max}}^{\text{true}}$$

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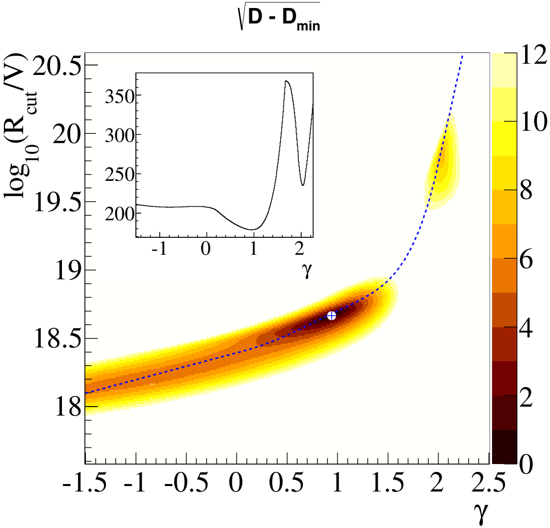
The reference fit (SPG propagation, EPOS-LHC air interactions)



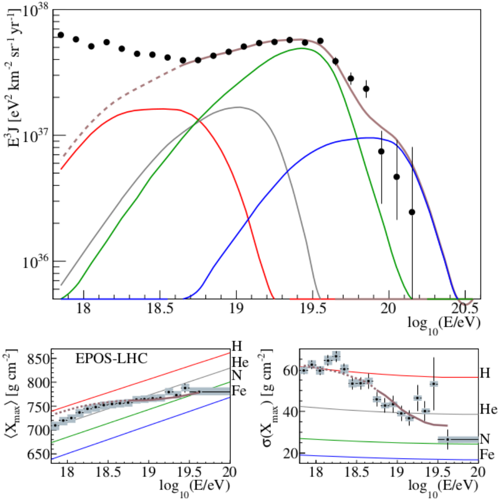
Best fit

- $\gamma = 0.94^{+0.09}_{-0.10}$, $\log_{10}(R_{cut}/V) = 18.67^{+0.03}_{-0.03}$
- 62.0% He, 37.2% N, 0.8% Fe (at 1 EeV)
- $D/n = 178.5/119\ (18.8 + 159.8)$
- $p = 2.6\%$

Second local minimum

- $\gamma = 2.03^{+0.01}_{-0.01}$, $\log_{10}(R_{cut}/V) = 19.84^{+0.02}_{-0.02}$
- 94.2% N, 5.8% Fe (at 1 EeV)
- $D/n = 235.0/119\ (14.5 + 220.5)$
- $p = 5 \times 10^{-4}$ (mostly due to X_{max} width)

Best fit (left) and second local minimum (right)



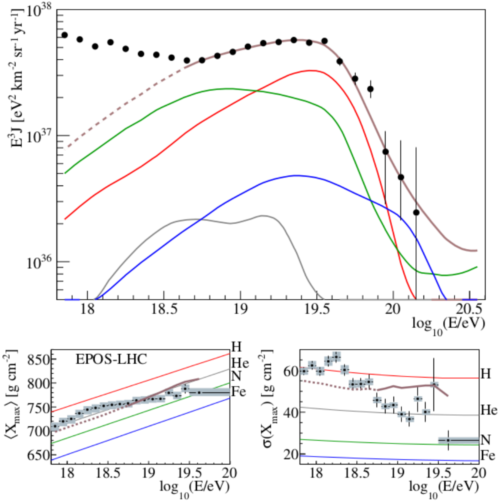
$A = 1$

$2 \leq A \leq 4$

$5 \leq A \leq 26$

$27 \leq A \leq 56$

total



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 $\mathcal{L} \propto (1+z)^m$, $m < 0$
  - N. Globus, D. Allard and E. Parizot [`arXiv:1505.01377`] ... and many others
- Best-fit region extends to very low spectral indexes, because changes in the spectral index can be compensated by changes in cut-off rigidity and mass fractions.
- In this model, the high-energy cut-off in the all-particle spectrum at Earth is mostly given by the photodisintegration of medium-heavy elements.
- On the other hand, at the best fit the injection cut-off does limit the flux of secondary protons with $E > Z_{\text{inj}} R_{\text{cut}} / A_{\text{inj}} \approx 2.4$ EeV. (Also, energy per nucleon way below threshold for pion production on CMB → negligible cosmogenic EeV neutrino flux; and $R \sim 5$ EV $\to \Delta\theta_{\text{magnetic}} \gtrsim 30$–$80^\circ$ even for nearby sources [`arXiv:1509.09033`].)
- At the second local minimum, this doesn't happen and the prediction composition at each energy is more mixed than the width of measured X_{max} distributions suggest.

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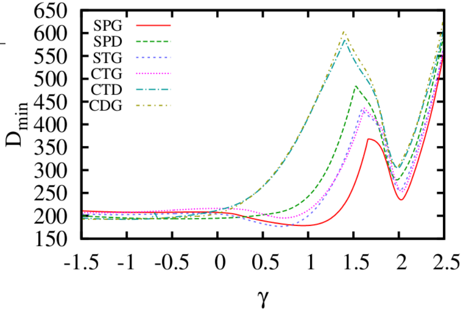
Dependence on intergalactic propagation models

- Fit repeated with other intergalactic propagation models

	γ (1st min)	$\log_{10}(R_\text{cut}/\text{V})$	$D\,^{D(J)}_{D(X_\text{max})}$
SPG	$+0.94^{+0.09}_{-0.10}$	18.67 ± 0.03	$178.5\,^{18.8}_{159.8}$
SPD	-0.45 ± 0.41	$18.27^{+0.07}_{-0.06}$	$193.4\,^{21.1}_{172.3}$
STG	$+0.69^{+0.07}_{-0.06}$	18.60 ± 0.01	$176.9\,^{19.5}_{157.4}$
CTG	$+0.73^{+0.07}_{-0.06}$	18.58 ± 0.01	$195.3\,^{33.6}_{161.7}$
CTD	$-1.06^{+0.29}_{-0.22}$	$18.19^{+0.04}_{-0.02}$	$192.3\,^{21.2}_{171.1}$
CGD	$-1.29^{+0.38}_{*}$	$18.18^{+0.06}_{-0.04}$	$192.5\,^{19.2}_{173.3}$

*This interval extends all the way down to −1.5,

the lowest value of γ we considered.



- Same qualitative features, but generally speaking, the more the interactions (brighter EBL, larger cross sections), the lower the required γ, R_cut (by several σ_stat) and the worse the fit

Dependence on air interaction models

- Fit repeated using QGSJet II-04 and Sibyll 2.1 instead of EPOS-LHC

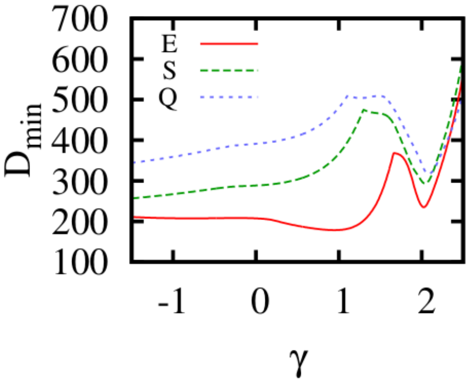


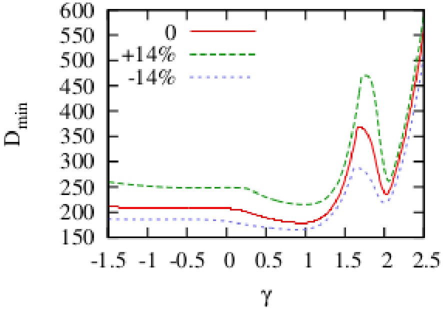
Figure: E: EPOS-LHC; Q: QGSJet II-04; S: Sibyll 2.1

(Note: Prediction uncertainty within each model ($\approx$ 35 g/cm^2) even larger than differences between models ($\approx$ 20 g/cm^2), see R.U. Abbasi and G.B. Thomson [`arXiv:1605.05241`])

- Models with lower $X_{\max}$ predictions than EPOS-LHC require extremely low γ, and even then the fit is very bad.

Dependence on the energy scale

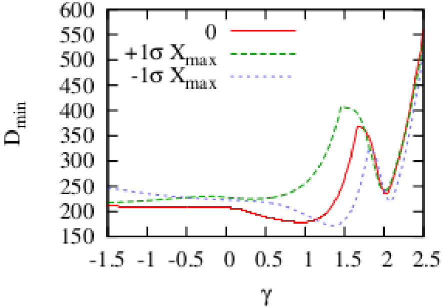
- Fit repeated shifting all Auger measured energies by $\pm 14\%$ $(1\sigma_{\mathrm{syst}})$



- Fit improves with negative shift, worsens with positive shift
- The fit tries to compensates for the shift by increasing/lowering $\gamma, R_{\mathrm{cut}}, p_{\mathrm{Fe}}$, by $\lesssim 1\sigma_{\mathrm{stat}}$

Dependence on the measured $X_{\max}$ systematic uncertainties

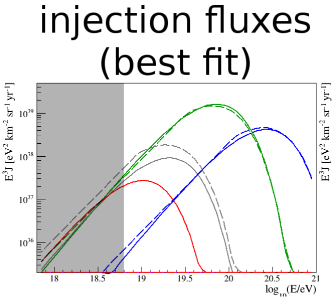
- Fit repeated shifting all Auger measured $X_{\max}$ by $\pm 1\sigma_{\text{syst}}$ ($\approx$ 6.8–9.3 g/cm^2)

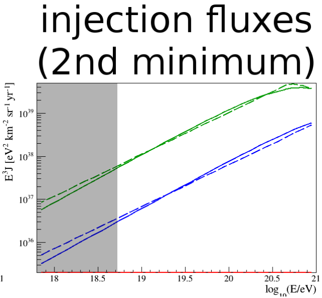


- Fit improves with negative shift, worsens with positive shift
- γ, R_{cut} shifted by many σ_{stat} in the opposite direction
- (This mirrors what happens with the different air interaction models.)

Dependence on cut-off shape

- Very little difference in the goodness of fit
- Injection spectra much less different than numerical values of parameters suggest


injection fluxes (best fit)


injection fluxes (2nd minimum)

cutoff	best fit				2nd min			
	γ	$R_{\mathrm{cut}}/\mathrm{V}$	D_{min}	$D(J)$ $D(X_{\mathrm{max}})$	γ	$R_{\mathrm{cut}}/\mathrm{V}$	D	$D(J)$ $D(X_{\mathrm{max}})$
broken exp	$0.94^{+0.09}_{-0.10}$	$10^{18.67\pm0.03}$	178.5	18.8 159.8	2.03	$10^{19.84}$	235.0	14.5 220.5
simple exp	$0.53^{+0.21}_{-0.18}$	$10^{18.63^{+0.09}_{-0.06}}$	177.2	17.3 159.9	1.89	$10^{19.94}$	221.0	14.6 206.5

Effects of uncertainties (from largest to smallest)

- X_{max} (better fit with higher predictions/lower data, which require higher γ, R_{cut})
  - We hope AugerPrime can help with this
- EBL (better fit with weaker far IR peak, which requires higher γ, R_{cut})
- Photodisintegration (better fit with smaller σ_{α}, which require higher γ, R_{cut})
- Energy scale (better fit with lowered scale, which requires lower γ, R_{cut})
- Shape of injection cutoff (goodness of fit almost unchanged between models we tried)

Work in progress (journal paper coming soon!)

- Updating fit to latest SD data
- Correctly taking into account SD energy resolution and Poisson statistics
- Including silicon-28 among possible injected elements
- Studying effects of possible evolutions of source emissivity ($\propto (1+z)^m$)
- Qualitative discussion of effects of possible extra sub-ankle components