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Two Source Population Models of Ultra-High Energy Cosmic Rays

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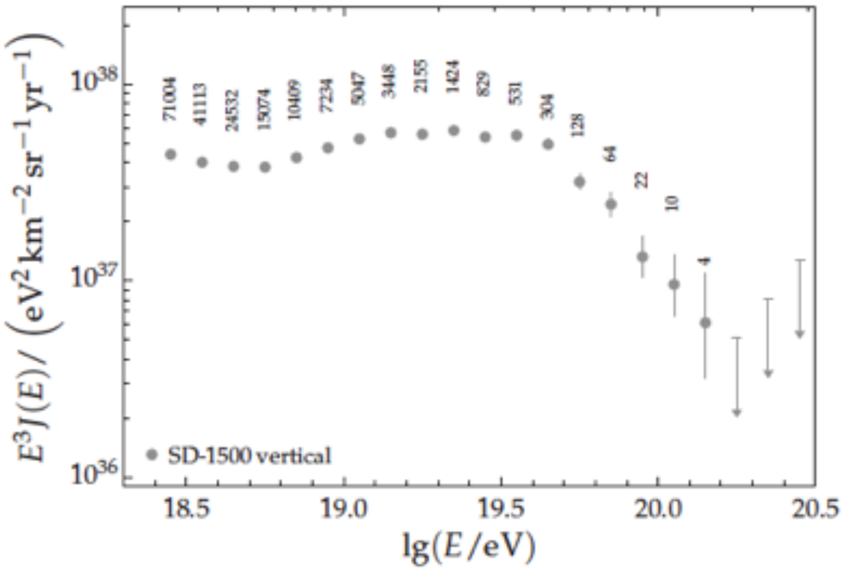
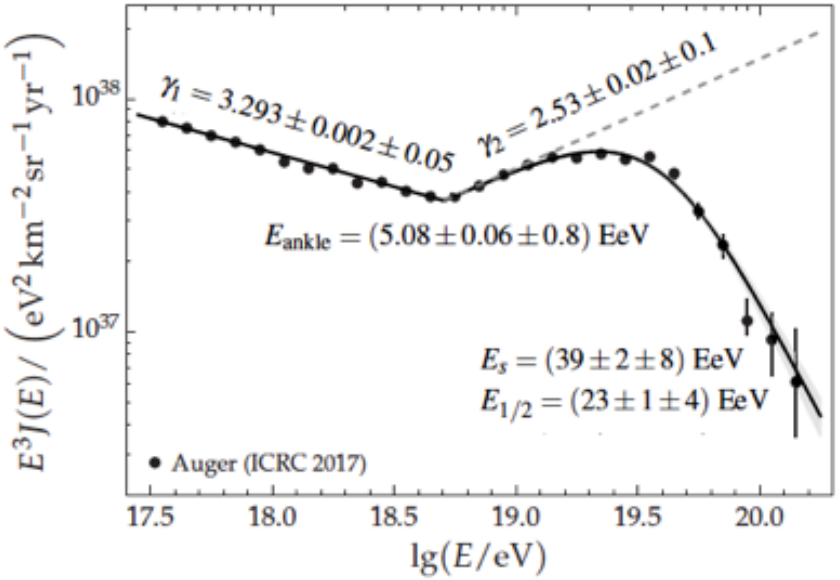
UHECR Spectrum

Data from the Pierre Auger Observatory

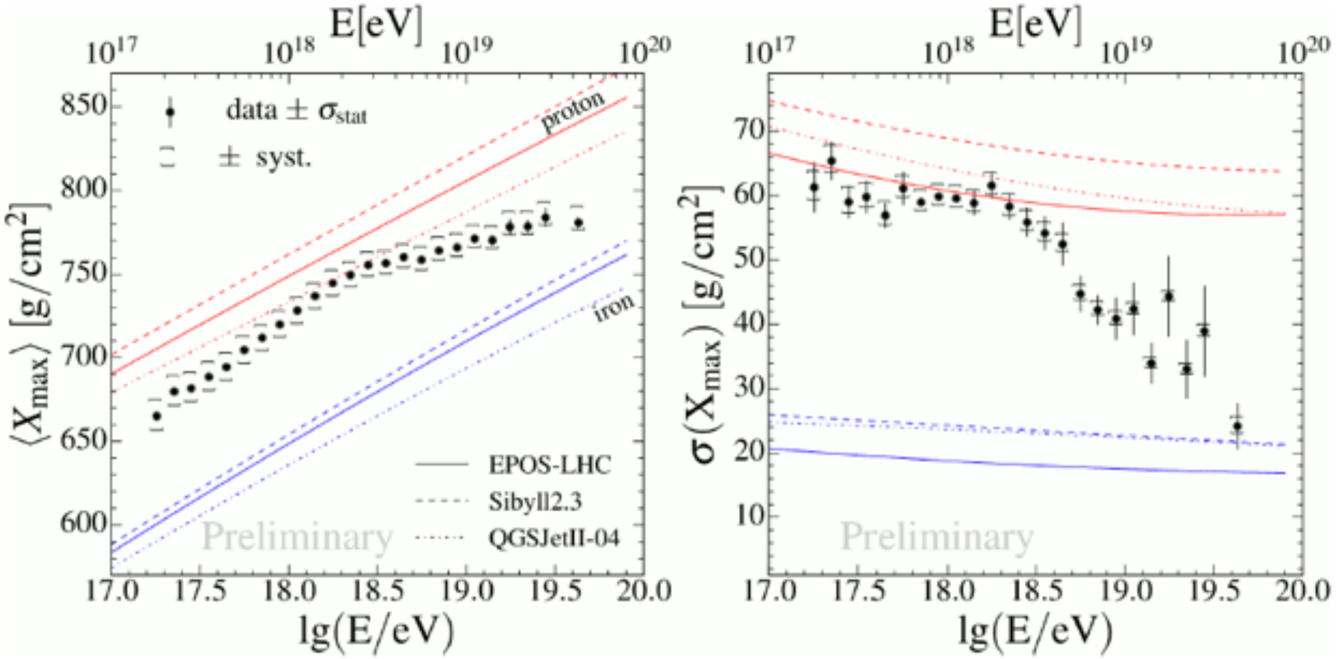




- Huge number of events at low energy but still few at > 10^20 eV
- A rollover of the spectrum is confirmed but physical origin is controversial and complicated
- Significant differences exist in energy calibration among experiments

UHECR Composition

Data from the Pierre Auger Observatory



Two main indicators:

- Average shower profile maximum <Xmax>
- Variation of Xmax from shower to shower

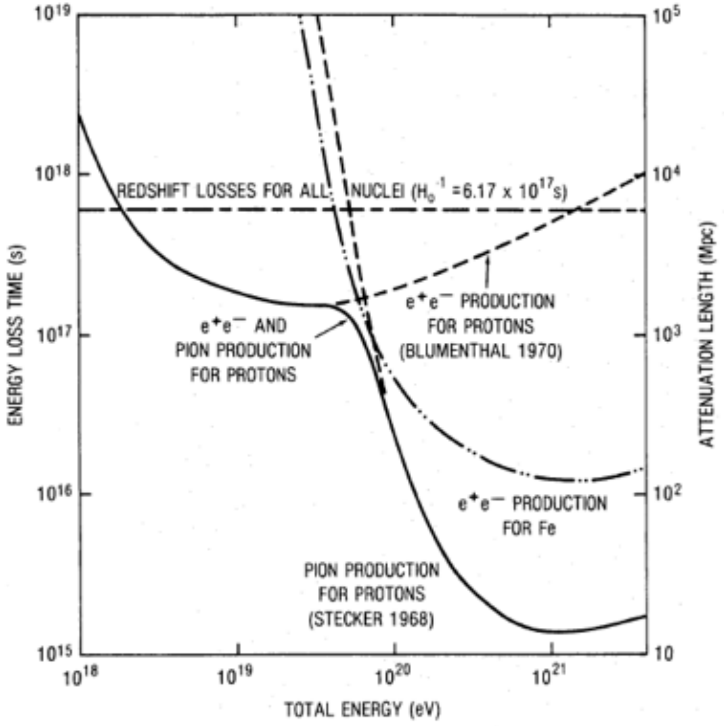
Pure proton composition of UHECR is disfavored at > 10^{19} eV

- *No collider data exists at this energies*
- *Significant differences exists among high-energy particle interaction model*

UHECR Propagation

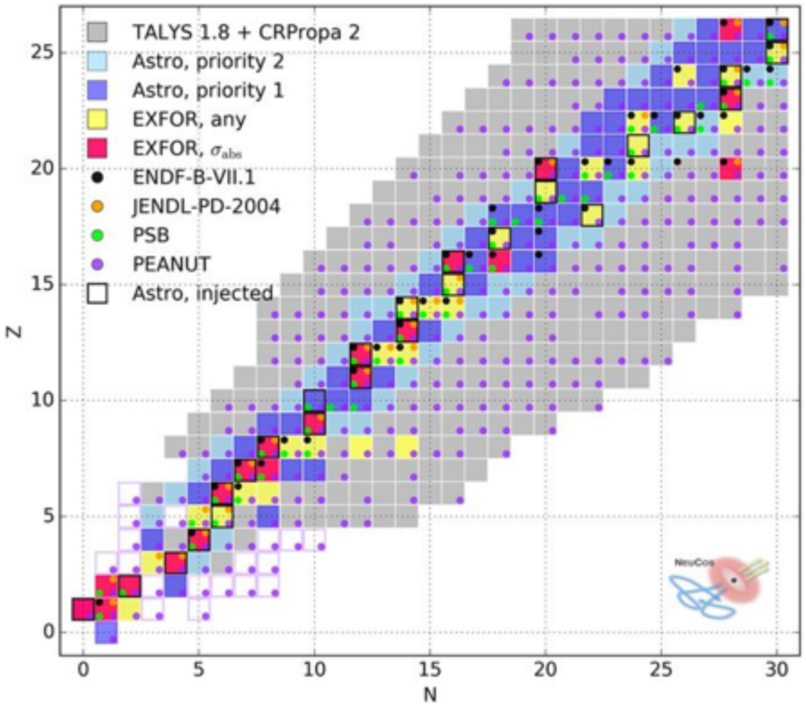
The sources of CRs above $5x10^{19}$ eV should be very nearby to avoid catastrophic energy losses during propagation: GZK radius ~ few hundred Mpc

Comparisons of UHECR proton and Fe



Puget, Stecker & Bredekamp 1976

Nuclear isotopes interesting for CR propagation



Boncioli, Fedynitch & Winter 2017

Simulations of UHECR Propagation

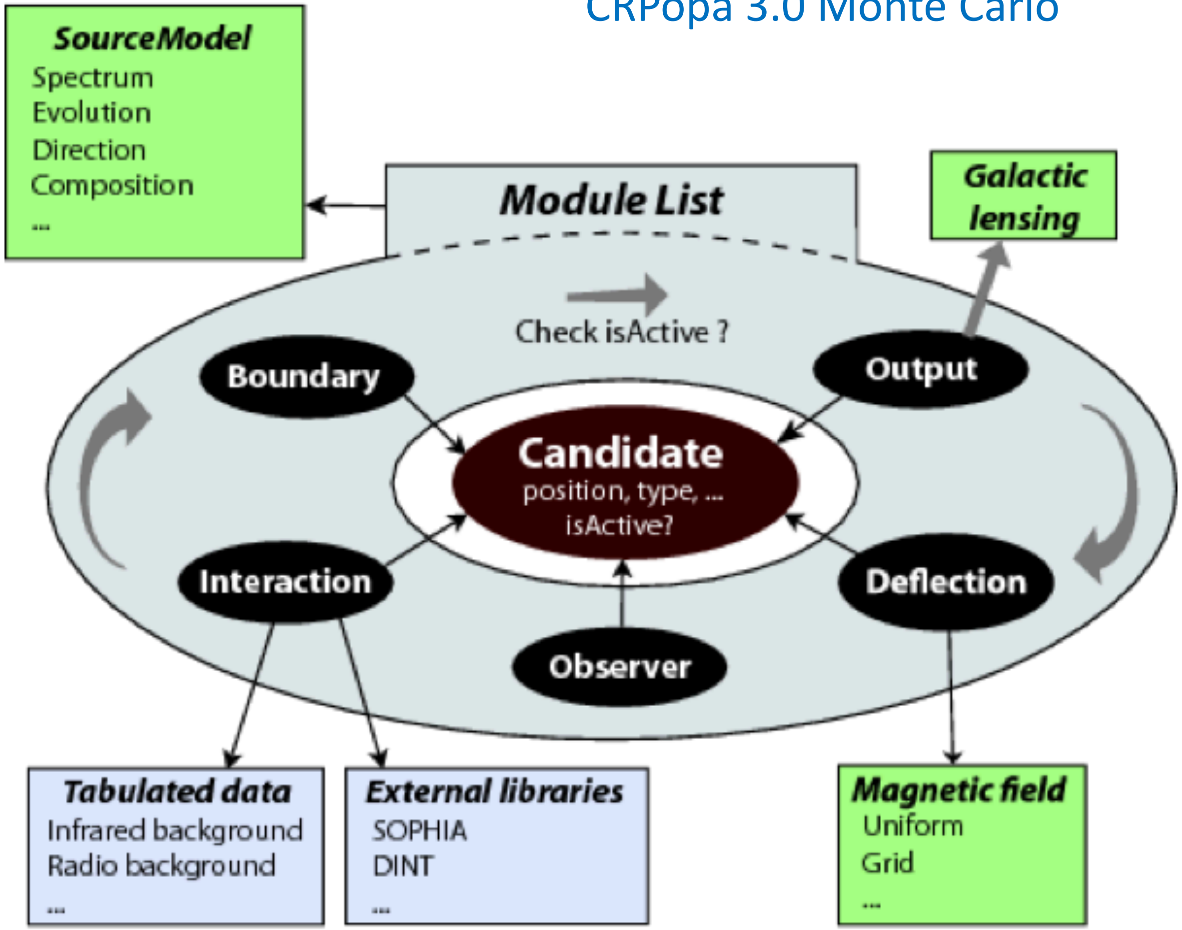
CRPopa 3.0 Monte Carlo

Batista et al. 2013

Sources are distributed uniformly in space in comoving volumes, each emitting the same spectra of UHECRs

Interactions and energy losses are simulated

Secondary particles are tracked until they reach observer or drop out of the flux



Deflection of charged CRs in the magnetic fields

Different magnetic field models for the intergalactic space and Milky Way

TALYS 1.8 photodisintegration + Dominguez et al. EBL

CRPropa Simulations Setup

Injection spectra of nuclei at the sources: $$\frac{dN}{dE} = A_0 \sum_i K_i E^{-\alpha} \times f_{\rm cut}(E, ZR_{\rm cut})$$

Rigidity-dependent cutoff of the spectrum: $$f_{\rm cut}(E, ZR_{\rm cut}) = \begin{cases} 1 & (E < ZR_{\rm cut}) \\ \exp\left(1 - \frac{E}{ZR_{\rm cut}}\right) & (E > ZR_{\rm cut}) \end{cases}$$

Evolution of the source density with redshift: ~ $(1+z)^m$

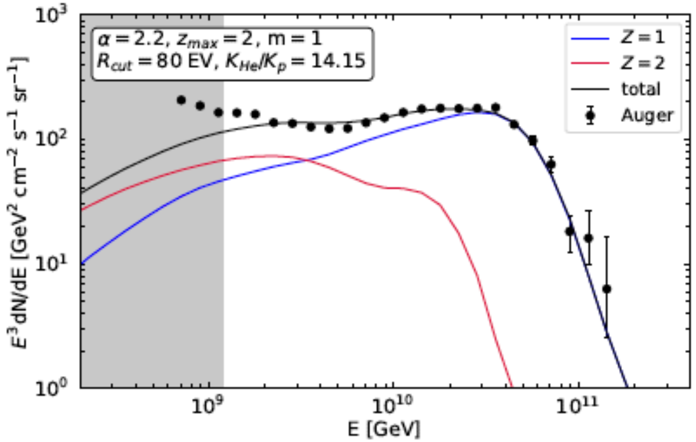
Deflection in intergalactic and Galactic magnetic fields ignored - OK for diffuse flux

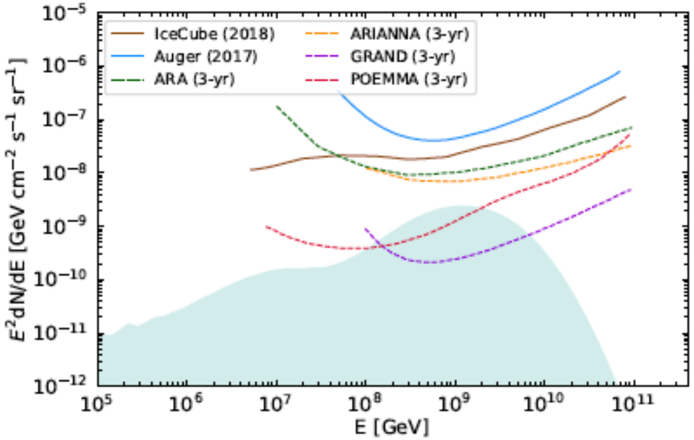
Single Population Model Fits – Light Nuclei

Fit to Auger Spectrum

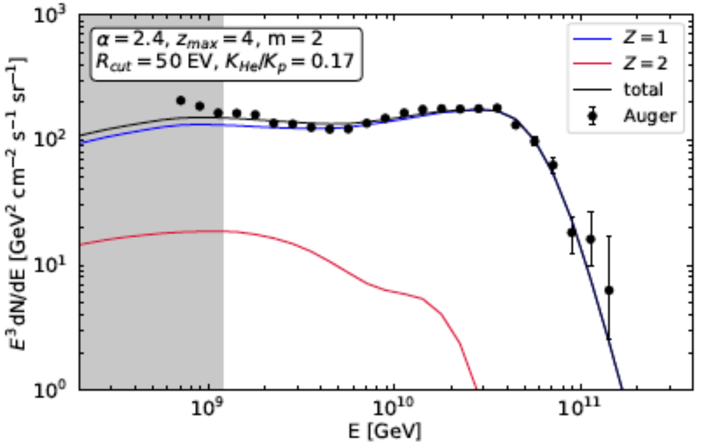
Cosmogenic Neutrinos

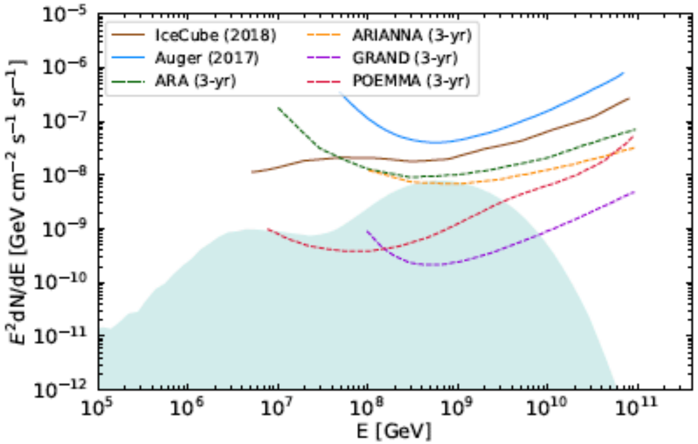
H + He at injection





$$\alpha = 2.2,\ R_{\rm cut} = 80\ \text{EV}$$
$$m = 1,\ z_{\max} = 2$$
$$K_{\rm He}/K_p = 14.15$$





$$\alpha = 2.4,\ R_{\rm cut} = 50\ \text{EV}$$
$$m = 2,\ z_{\max} = 4$$
$$K_{\rm He}/K_p = 0.17$$

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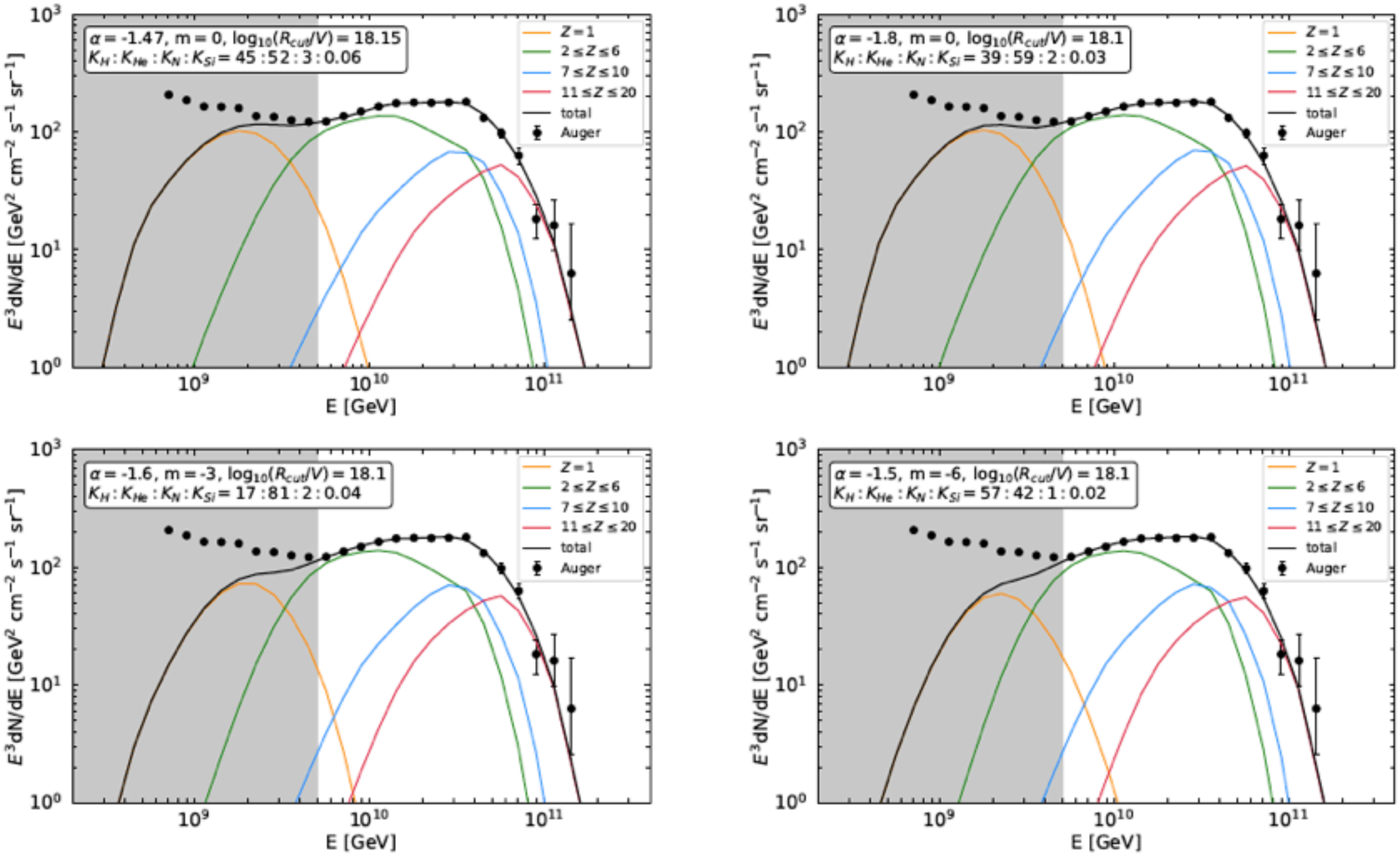
Single Population Model Fits – Intermediate Nuclei



H + He + N + Si
at injection

Requires:

- Very hard injection spectrum
- No or negative source evolution

$$\alpha < 0$$

$$m \leq 0$$

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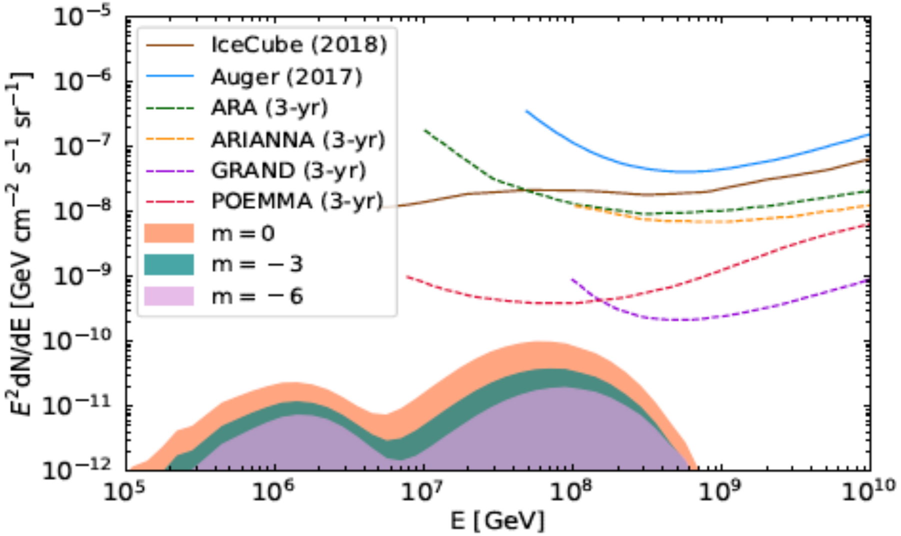
Single Population Model Fits – Intermediate Nuclei

TABLE III. Best-fit values in parameter space [H + He + N + Si] and in the energy range $E > 10^{18.7}$ eV.

m	α	$\log_{10}(R_{cut}/V)$	K_H	K_{He}	K_N	K_{Si}	χ^2
0	−1.8	18.1	39	59	2	0.03	2.59
−3	−1.6	18.1	17	81	2	0.04	2.57
−6	−1.5	18.1	57	41	1	0.02	2.66

H + He + N + Si
at injection

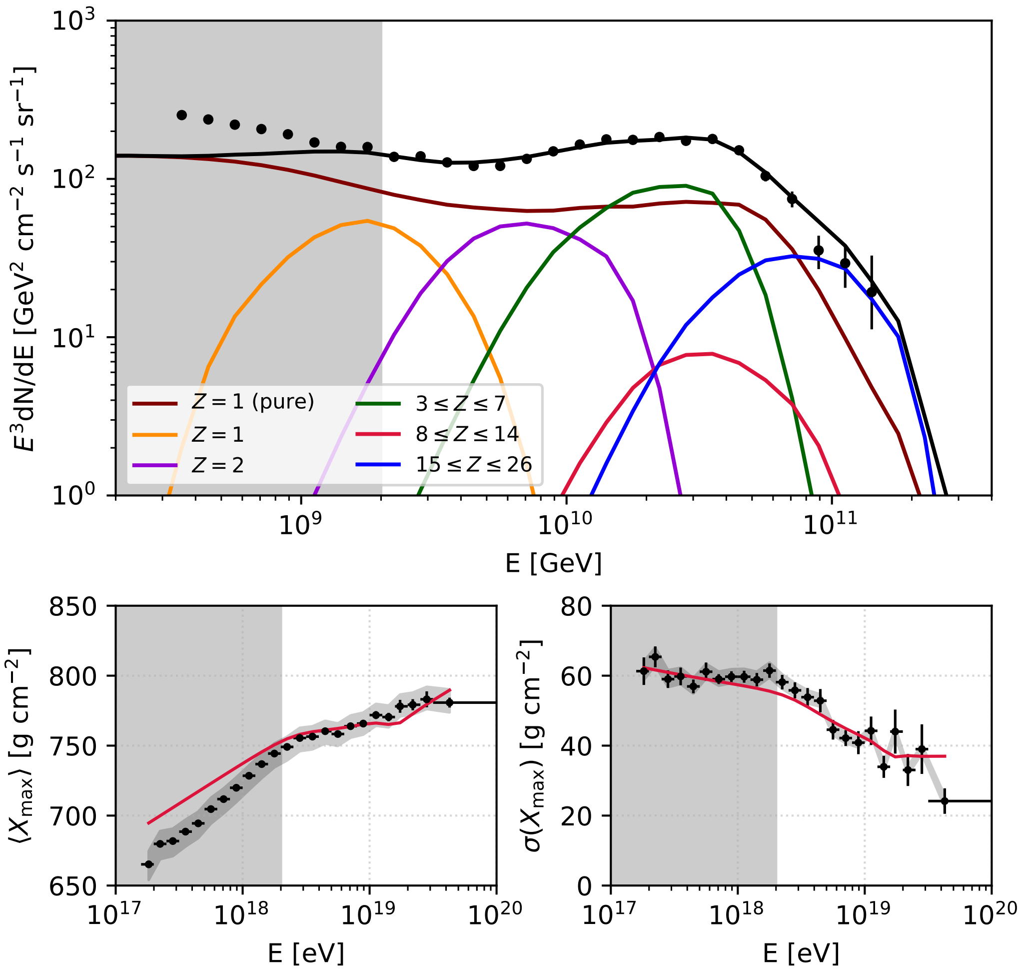
Some model parameter values from fits



Very low /undetectable
cosmogenic neutrinos flux

Das, Razzaque, Gupta, PRD 2019

Two Population Model Fits – Example 1



Population – I (Mixed Nuclei)

$$m = 0,\ \alpha = -1.58,\ R_{\rm cut} = 10^{18.12}\ \rm V$$

$$K_{\rm He} \approx 71\%,\ K_{\rm N} \approx 29\%$$

$$K_{\rm Si} \approx 0.03\%,\ K_{\rm Fe} \approx 0.02\%$$

Population – II (Proton)

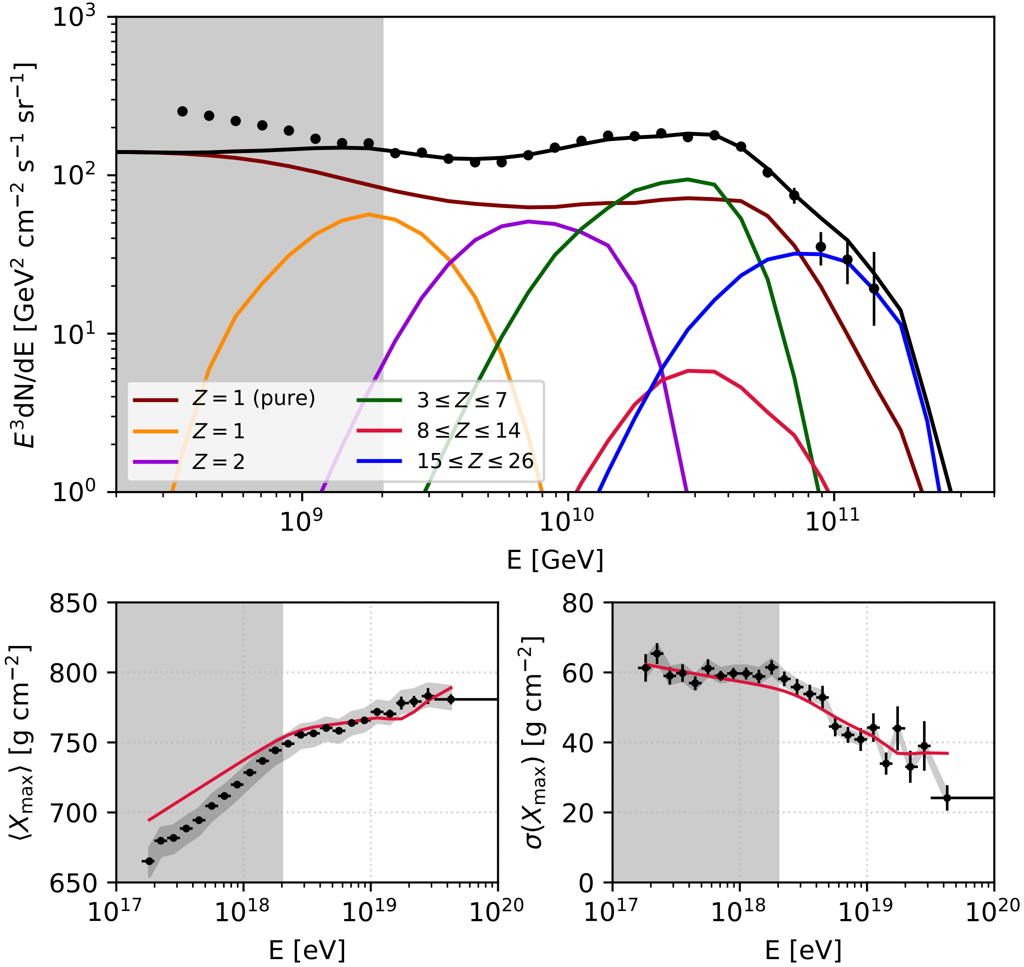
$$m = 3,\ \alpha = 2.6,\ R_{\rm cut} = 100$$

Proton flux on earth ~ 25% at the highest E

Sibyll 2.1 Hadronic int. model

Abreu et al. 2013

Two Population Model Fits – Example 2



Population – I (Mixed Nuclei)

$$m = 0,\ \alpha = -1.60,\ R_{\text{cut}} = 10^{18.14}\ \text{V}$$

$$K_{\text{He}} \approx 0\%,\ K_{\text{N}} \approx 100\%$$

$$K_{\text{Si}} \approx 0\%,\ K_{\text{Fe}} \approx 0.07\%$$

Population – II (Proton)

$$m = 3,\ \alpha = 2.6,\ R_{\text{cut}} = 100$$

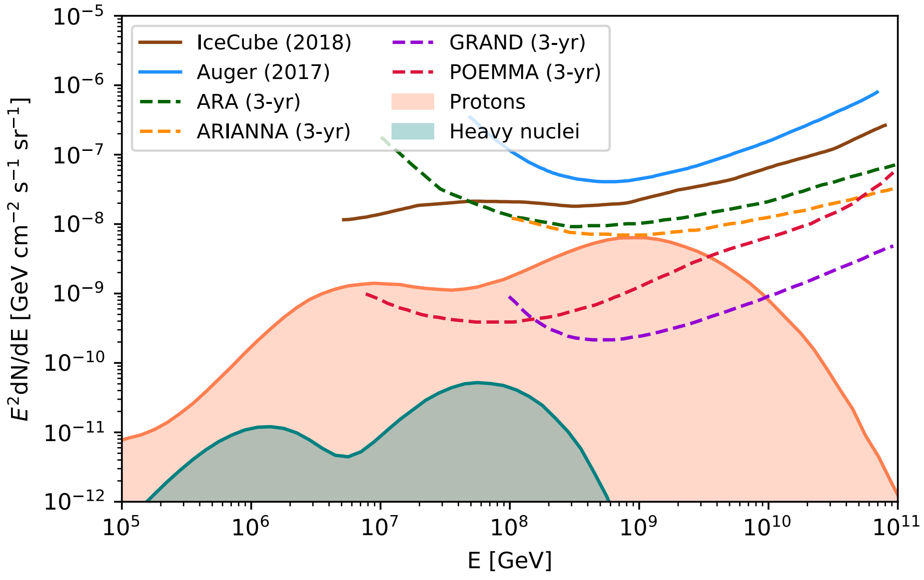
Proton flux on earth ~ 25% at the highest E

Sibyll 2.1 Hadronic int. model

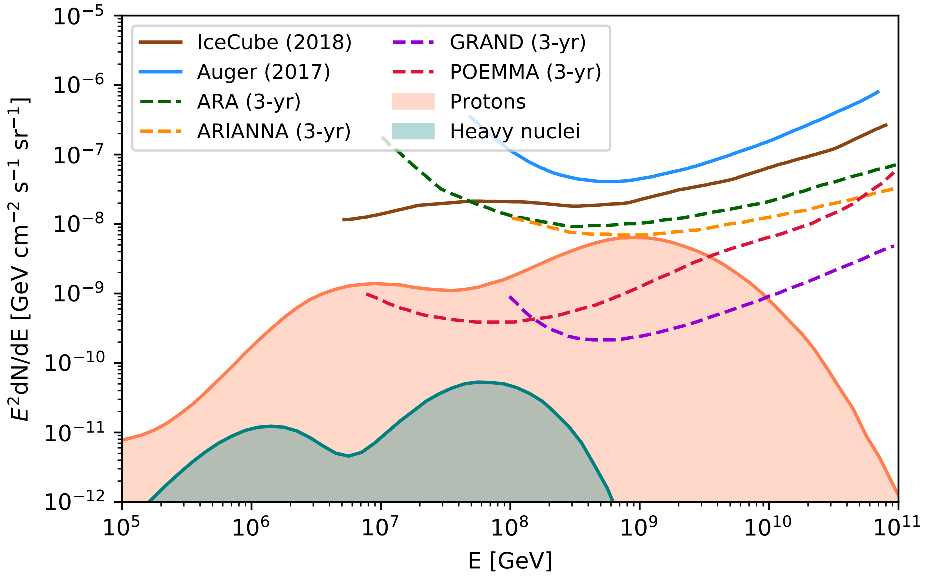
Abreu et al. 2013

Cosmogenic Neutrino Fluxes

Example 1



Example 2



Very similar neutrino fluxes, dominated by proton primaries

Summary and Outlook

We present new fits to the Pierre Auger UHECR spectrum

- Single Source Population Models
  - Light nuclei composition: H+He (Can fit spectrum >~ 10^{18} eV)
    - Injection index: -2.2, -2.4
    - Source evolution index: 0–3
    - Rigidity cutoff: ~50–80 EV
    - Redshift range: 0.0007–4
  - Light-intermediate nuclei composition: H+He+N+Si (Can fit spectrum >~ 5×10^{18} eV)
    - Injection index: -1.5, -1.8
    - Source evolution index: -6–0
    - Rigidity cutoff: ~1 EV
    - Redshift range: 0—1
- Two Source Population Models
  - Light-intermediate nuclei composition above + pure proton sources
  - Pure proton sources contribute ~25% of the observed flux at the highest energies
  - Pure proton sources evolve with redshift similar to luminous astrophysical objects