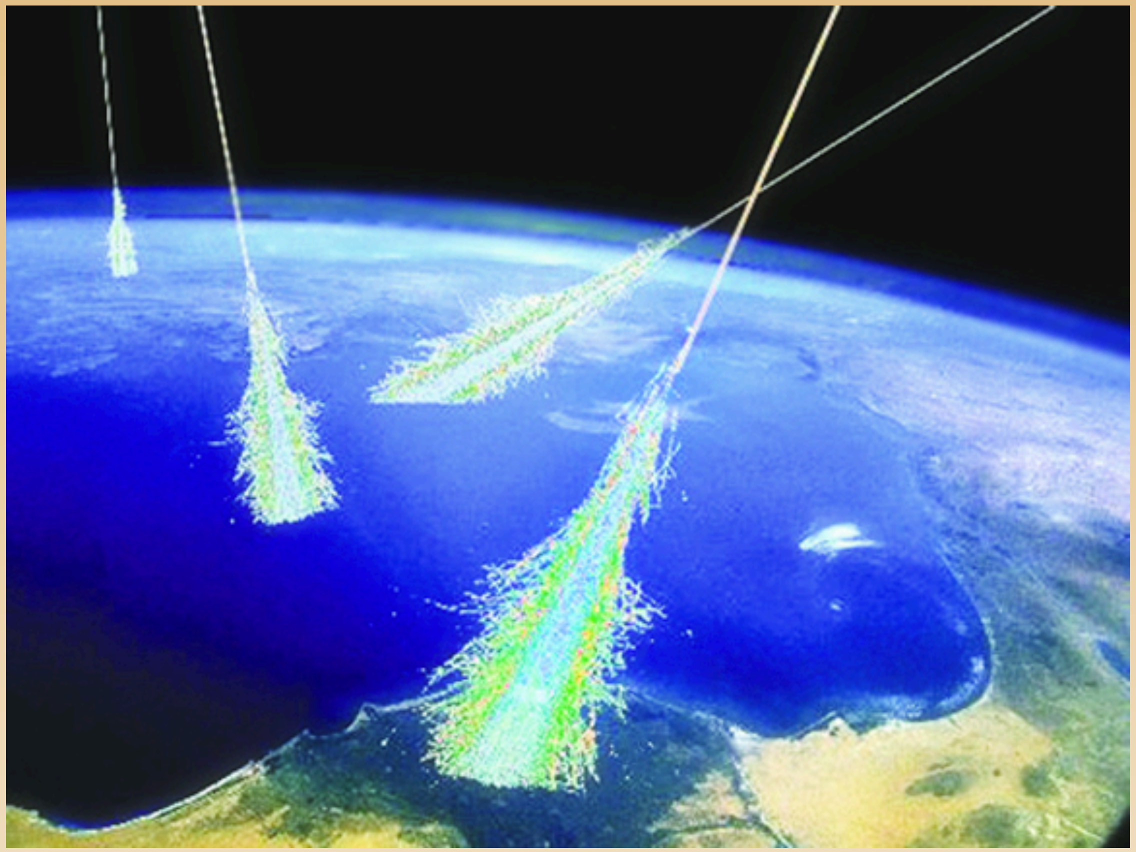
ULTRAHIGH-ENERGY COSMIC RAYS & NEUTRINOS FROM LIGHT NUCLEI COMPOSITION



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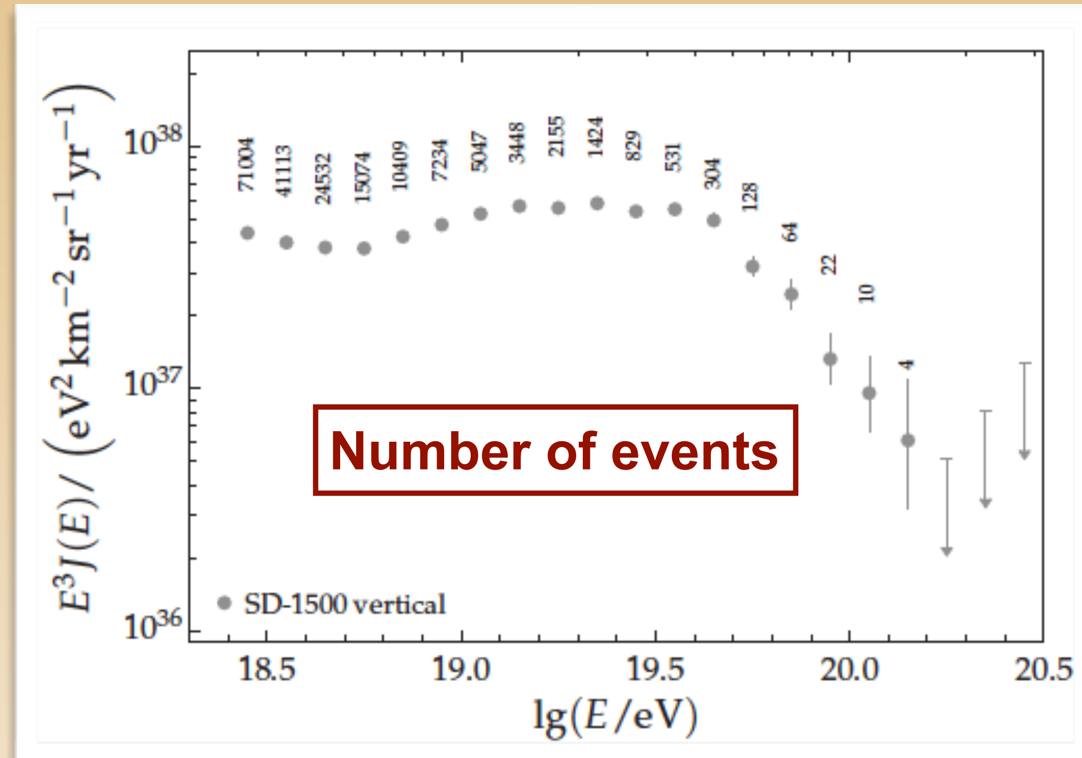
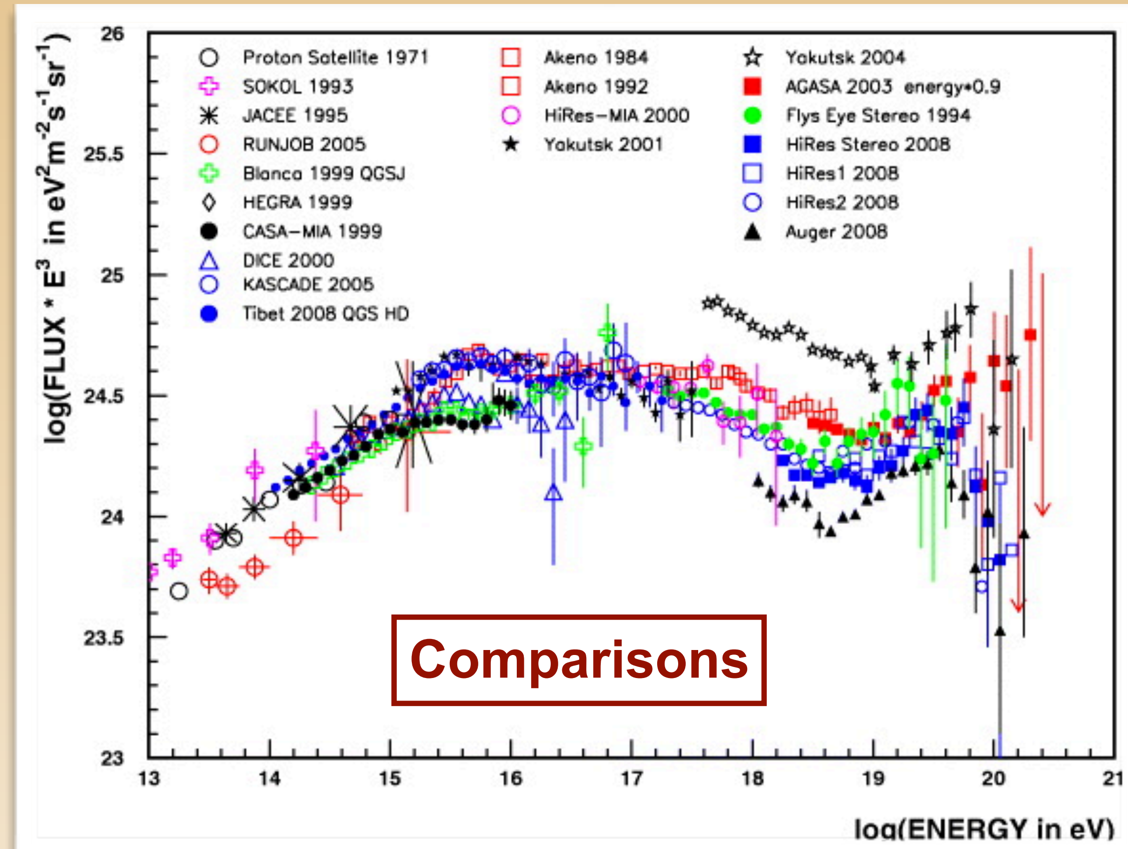
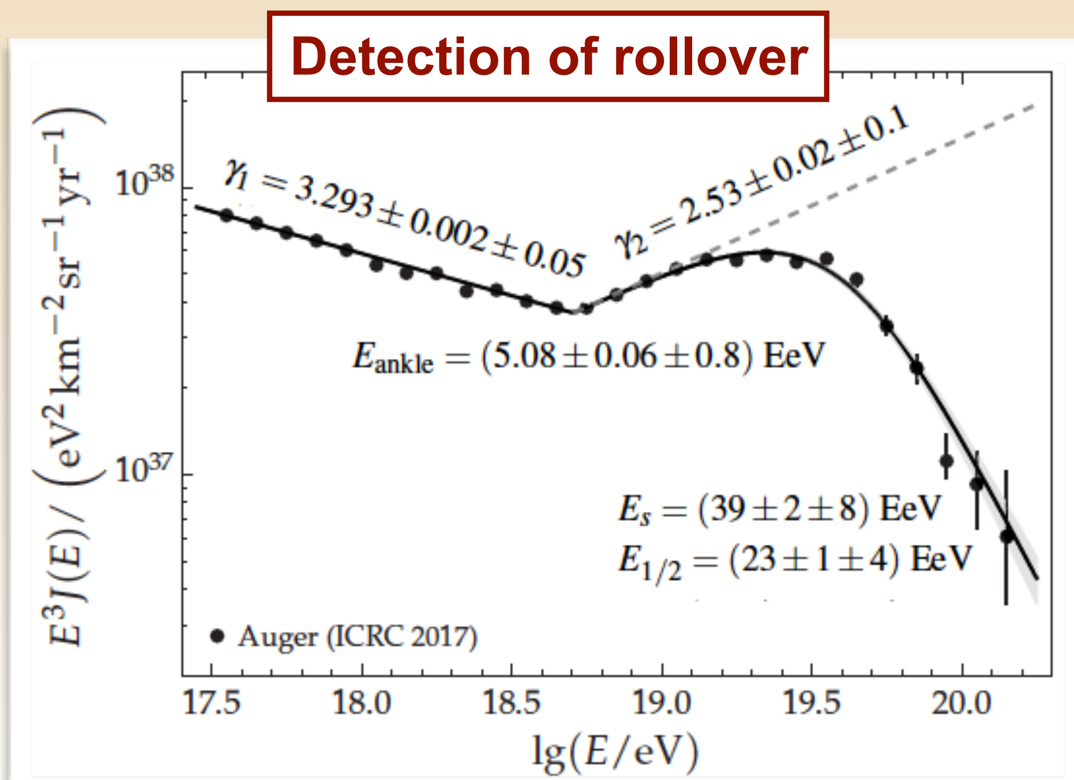
arXiv:1809.05321

UHECR Spectrum





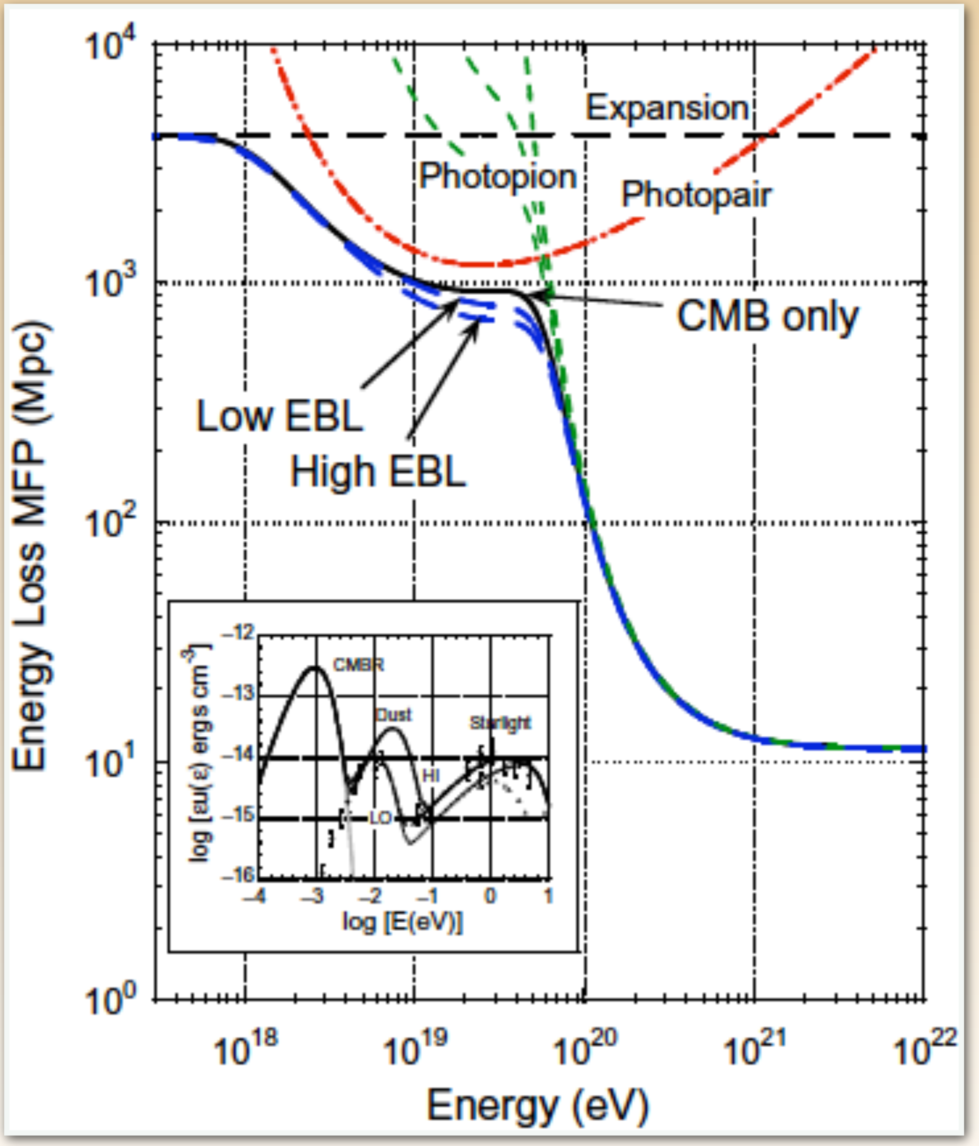


- Huge number of events at low energy but still few at > 10^20 eV
- A rollover of the spectrum is confirmed but physical origin is controversial and complicated
- Significant differences exist in energy calibration among experiments

UHECR Propagation

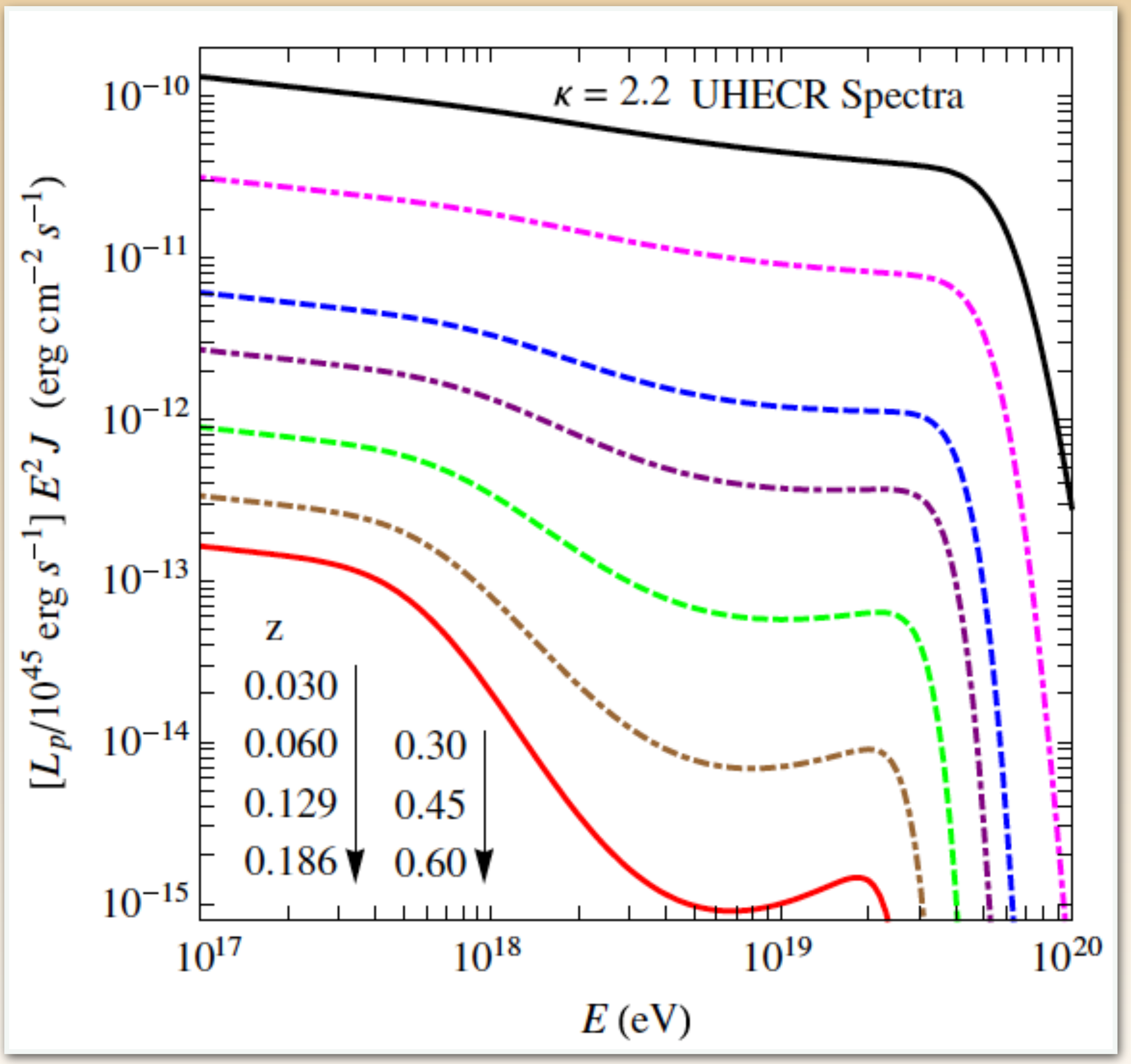
The sources of CRs above 10^19 eV should be very nearby to avoid catastrophic energy losses during propagation: GZK radius ~ few hundred Mpc

Mean-free-path of UHECR proton



Dermer, Razzaque, Finke & Atoyan 2009

Effect of distance on the UHECR proton flux

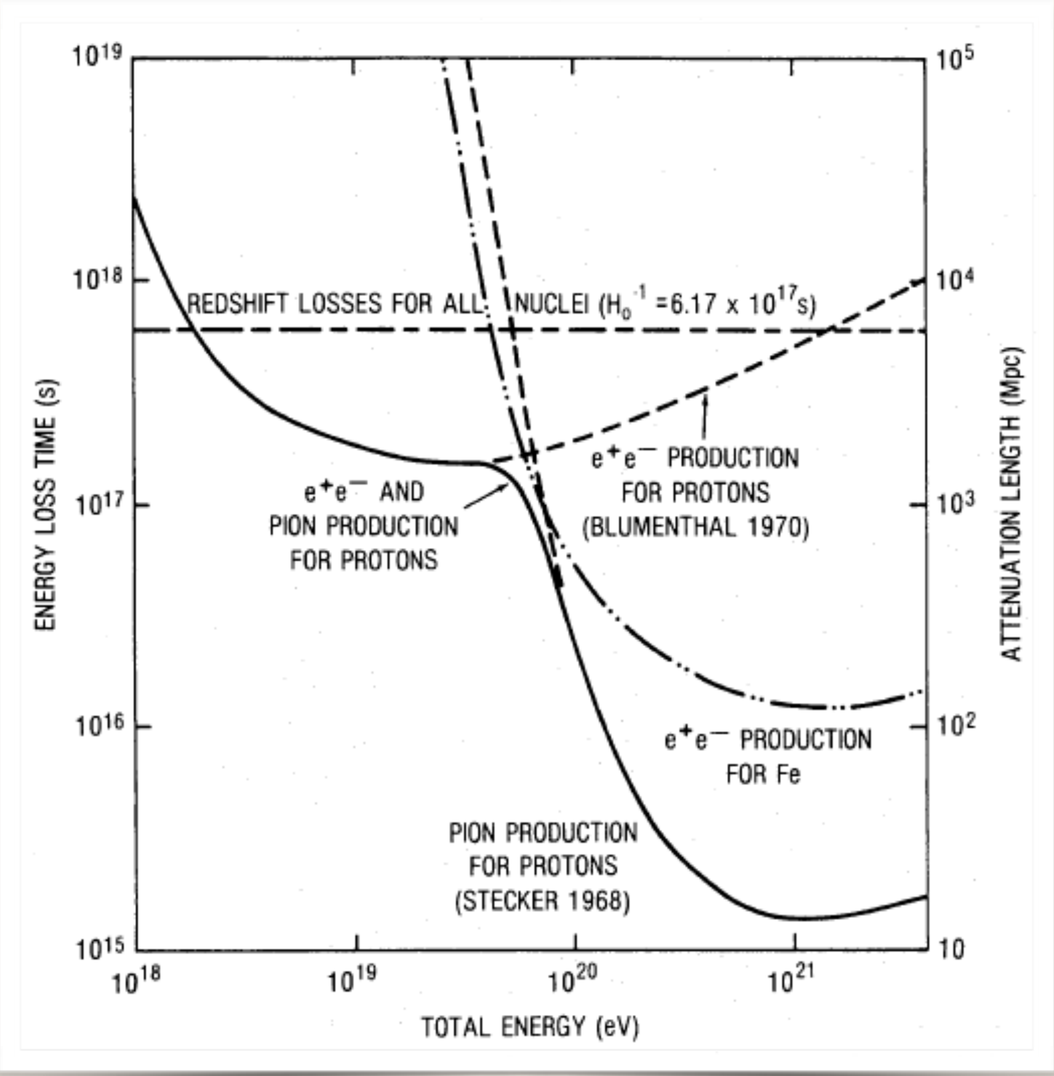


Razzaque, Dermer & Finke 2012

UHECR Propagation

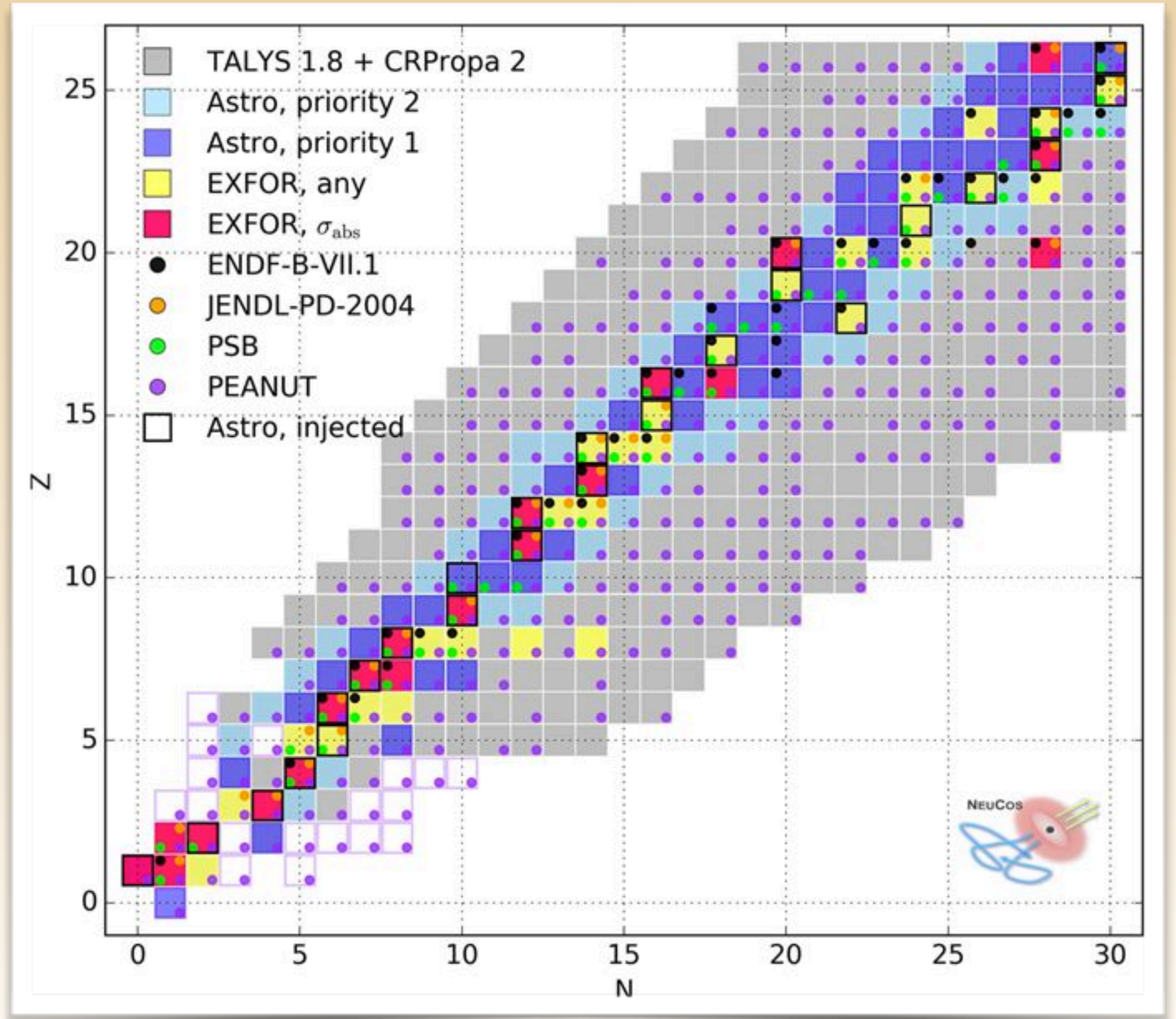
For heavy nuclei such as Fe the GZK radius is similar, but nuclear processes such as photo disintegration change the species

Comparisons of UHECR proton and Fe



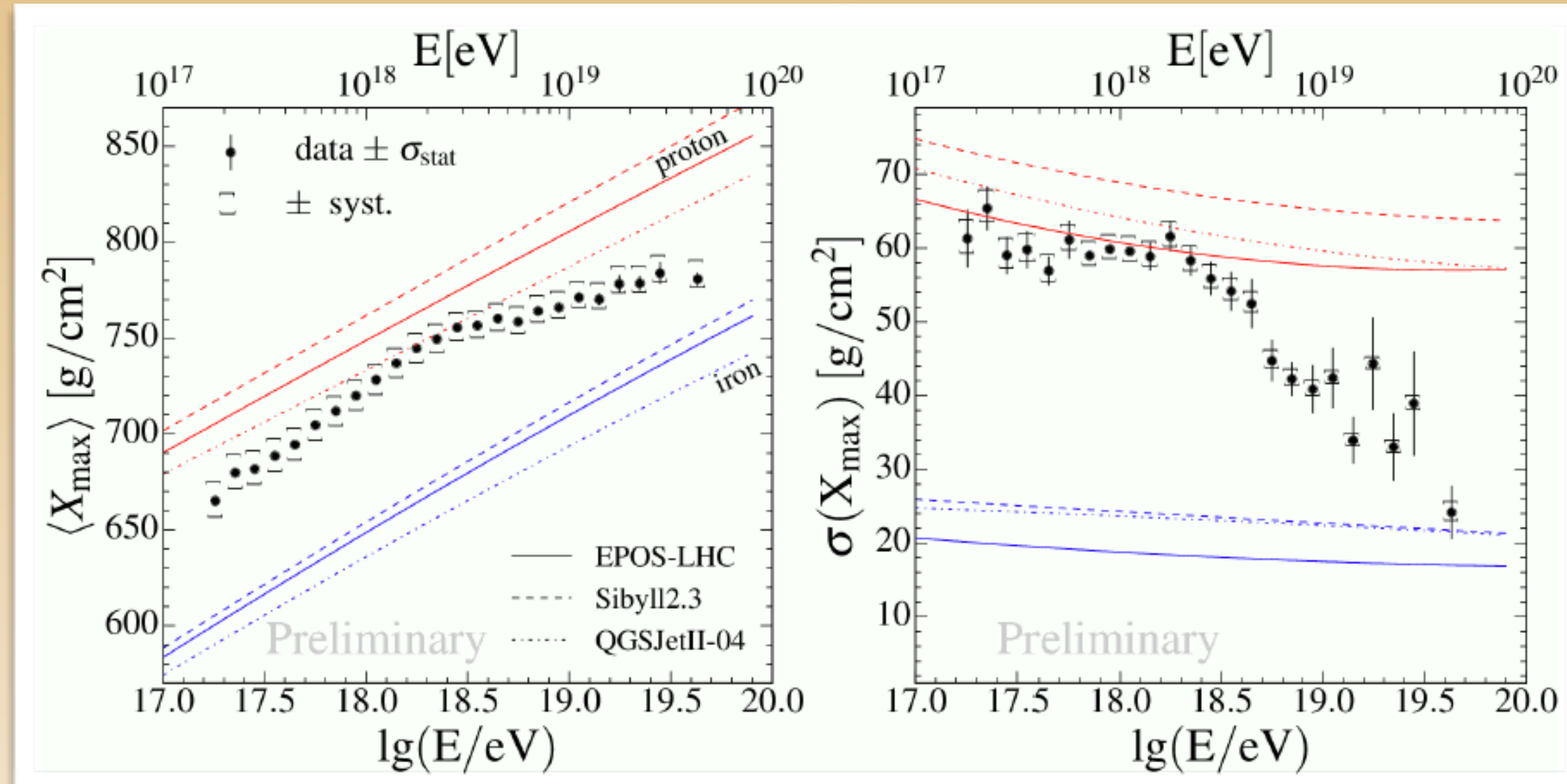
Puget, Stecker & Bredekamp 1976

Nuclear isotopes interesting for CR propagation



Boncioli, Fedynitch & Winter 2017

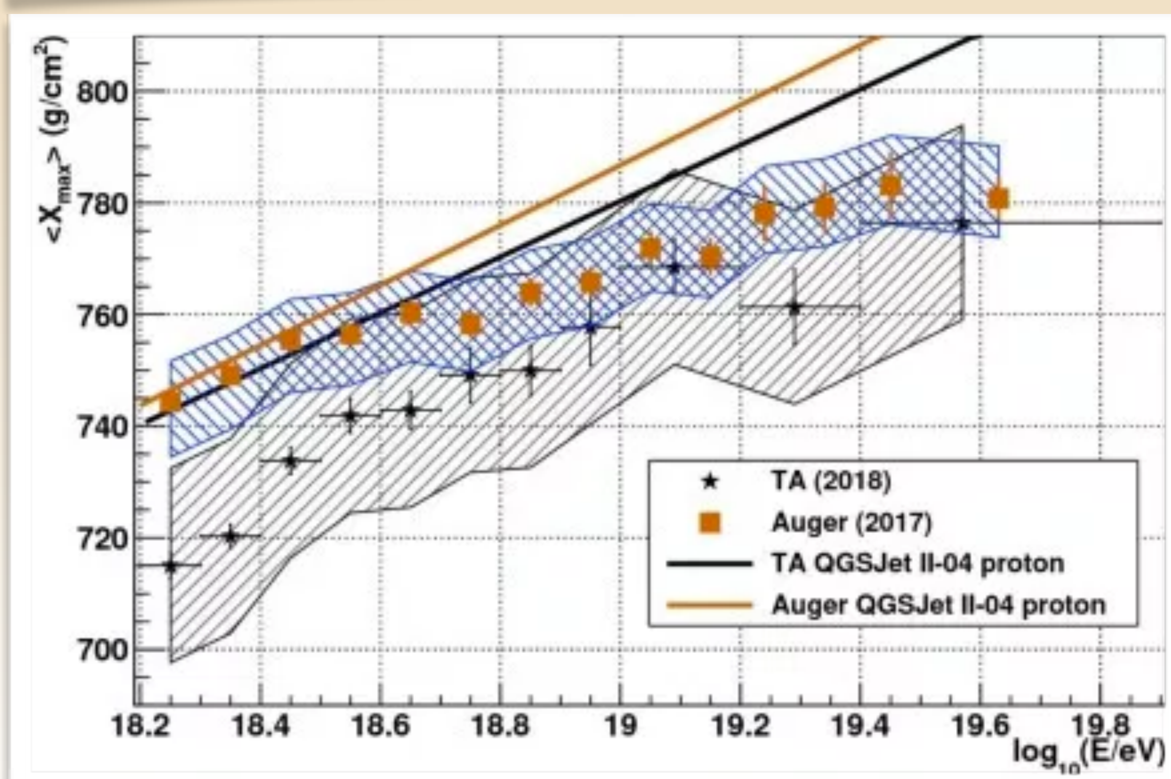
UHECR Composition



Two main indicators:

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

… and a lot of Monte Carlo simulations!



Comparison with other experiment: Telescope Array (TA)

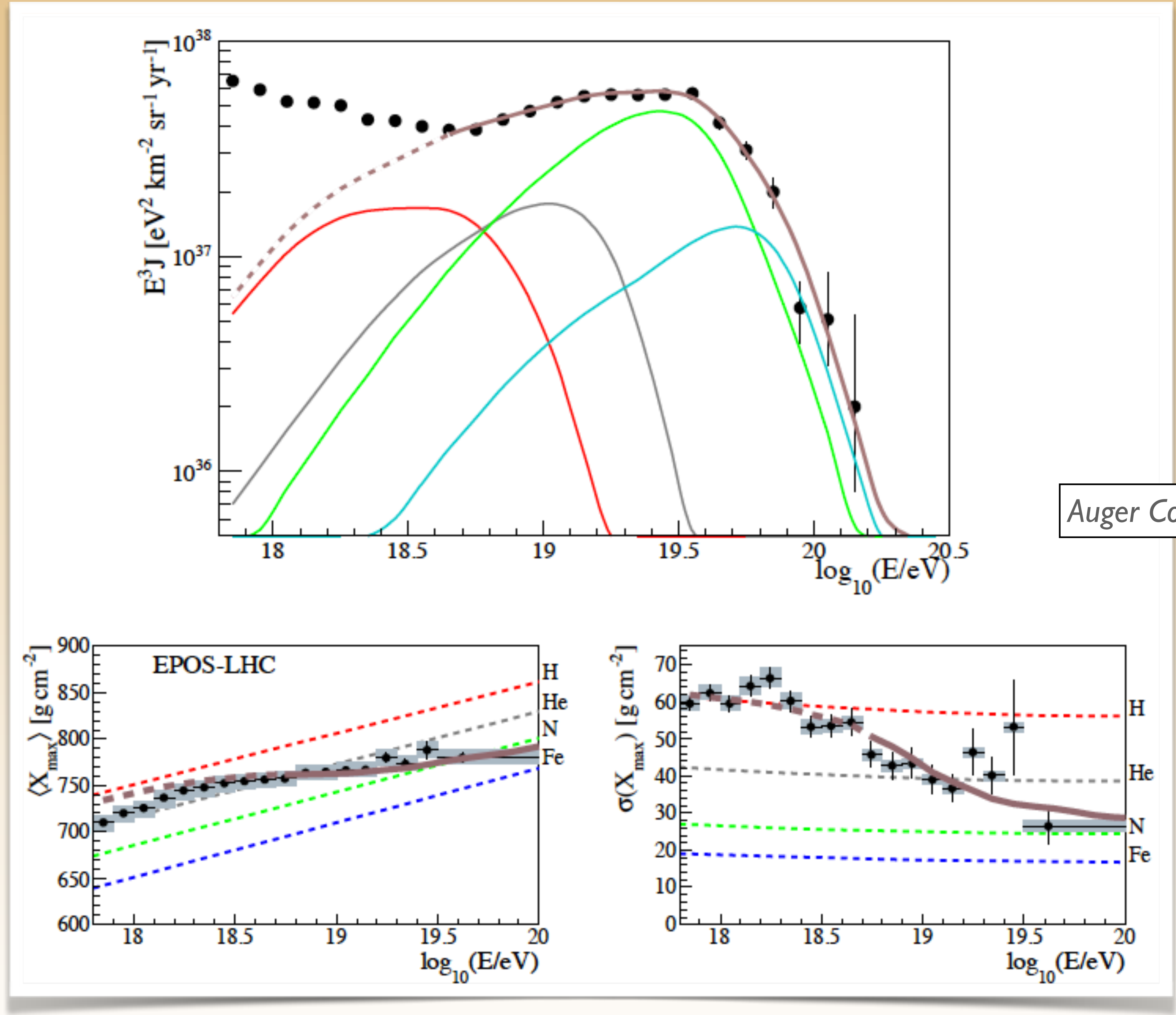
Pure proton composition of UHECR is disfavored at > 10^19 eV

Caveats:

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

Earlier Attempts to Model w/Mix Comp.

H (red)
He (grey)
N (green)
Fe (blue)



Auger Collab. 2017

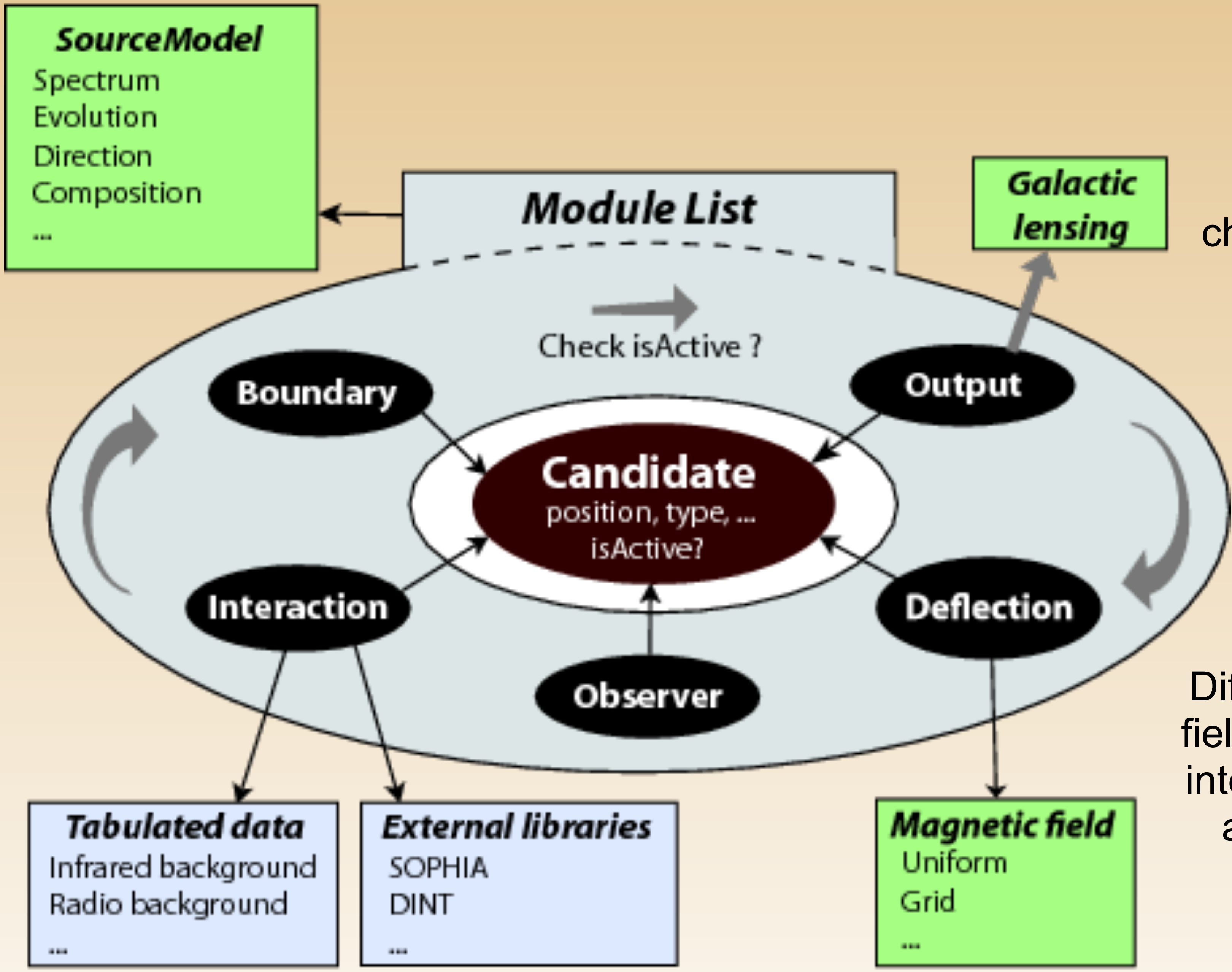
CRPropa 3.0 Propagation Code

Monte Carlo Code *Batista et al. 2013*

Sources are distributed uniformly in space in comoving volume, 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

We use this code to model UHECR spectrum measured by Pierre Auger with light nuclei composition

TALYS 1.8 photodisintegration + Dominguez et al. EBL

CRPropa Simulations Setup

Injection spectra of nuclei:

$$\frac{dN}{dE} = A_0 \sum_i K_i E^{-\alpha} \times f_{\rm cut}(E, ZR_{\rm cut})$$

Rigidity-dependent cutoff

$$f_{\rm cut}(E, ZR_{\rm cut}) = \begin{cases} 1 & (E < ZR_{\rm cut}) \\ \exp\left(1 - \frac{E}{ZR_{\rm cut}}\right) & (E > ZR_{\rm cut}) \end{cases}$$

Evolution of number of sources with redshift: ~ (1+z)^m

Ranges of parameters scanned

Parameter	Description	Values
α	Source spectral index	$2.2 \leqslant \alpha \leqslant 2.6$
$R_{\rm cut}$	Cut-off rigidity	$40 \leqslant R_{\rm cut} \leqslant 100$ EV
$z_{\rm min}$	Minimum redshift	$z_{\rm min} = 0.0007$
$z_{\rm max}$	Cut-off redshift	$2 \leqslant z_{\rm max} \leqslant 4$
m	Source evolution index	$0 \leqslant m \leqslant 3$
K_i	abundance fraction	$0.0\% \leqslant K_i < 100\%$
A_0	Flux normalisation	$A_0 > 0$

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

Fitting procedure for Auger Spectrum

- Simple Chi^2 fits with 17 d.o.f.
- Parameters vary in restricted ranges
- Acceptable fits when Chi^2 < 27.95
- Some models are disfavored from composition data and/or neutrino flux upper limits

TABLE IV: Best-fits to UHECR spectrum for p+He composition

α	z_{max}	m	R_{cut}(EV)	K_p	K_{He}	K_{He}/K_p	χ^2_{spec}	Case	Neutrino flux (GeV cm^{-2} s^{-1} sr^{-1})	Remarks
2.2	2	0	80	1.7	98.3	57.82	38.409	1	1.385×10^{-9}	Disfavored
		1	80	6.6	93.4	14.15	25.689	2	2.347×10^{-9}	
		2	80	13.2	86.8	6.58	17.060	3	4.366×10^{-9}	
		3	60	42.7	57.3	1.34	12.578	4	8.704×10^{-9}	
	3	0	80	1.3	98.7	75.92	36.343	5	1.488×10^{-9}	Disfavored
		1	90	0.0	100.0	undefined	23.687	6	2.809×10^{-9}	
		2	80	12.7	87.3	6.87	15.405	7	5.949×10^{-9}	
		3	70	31.3	68.7	2.19	12.003	8	1.464×10^{-8}	
	4	0	80	1.3	98.7	75.92	37.149	9	1.530×10^{-9}	Disfavored
		1	80	6.2	93.8	15.13	24.37	10	2.983×10^{-9}	
		2	80	12.8	87.2	6.81	15.763	11	7.159×10^{-9}	
		3	60	42.3	57.7	1.36	11.364	12	2.079×10^{-8}	
2.4	2	0	50	67.9	32.1	0.47	21.914	13	1.456×10^{-9}	
		1	50	76.2	23.8	0.31	17.411	14	2.459×10^{-9}	
		2	50	86.4	13.6	0.16	14.385	15	4.524×10^{-9}	
		3	50	99.0	1.0	0.01	12.781	16	9.055×10^{-9}	Disfavored
	3	0	50	68.6	31.4	0.46	20.878	17	1.595×10^{-9}	
		1	50	77.0	23.0	0.3	16.73	18	2.947×10^{-9}	
		2	50	87.5	12.5	0.14	14.047	19	6.301×10^{-9}	
		3	50	100.0	0.0	0.0	12.717	20	1.541×10^{-8}	Disfavored
	4	0	50	67.4	32.6	0.48	20.019	21	1.611×10^{-9}	
		1	50	75.6	24.4	0.32	15.543	22	3.172×10^{-9}	
		2	50	85.8	14.2	0.17	12.581	23	7.595×10^{-9}	
		3	50	98.3	1.7	0.02	11.044	24	2.183×10^{-8}	Disfavored
2.6	2	0	60	100.0	0.0	0.0	27.886	25	1.553×10^{-9}	Disfavored
		1	60	100.0	0.0	0.0	36.205	26	2.456×10^{-9}	Disfavored
		2	70	100.0	0.0	0.0	52.563	27	4.509×10^{-9}	Disfavored
		3	90	100.0	0.0	0.0	79.96	28	8.980×10^{-9}	Disfavored
	3	0	60	100.0	0.0	0.0	29.015	29	1.686×10^{-9}	Disfavored
		1	60	100.0	0.0	0.0	38.718	30	2.920×10^{-9}	Disfavored
		2	70	100.0	0.0	0.0	56.445	31	6.140×10^{-9}	Disfavored
		3	90	100.0	0.0	0.0	85.32	32	1.464×10^{-9}	Disfavored
	4	0	60	100.0	0.0	0.0	24.886	33	1.716×10^{-9}	Disfavored
		1	60	100.0	0.0	0.0	32.603	34	3.168×10^{-9}	Disfavored
		2	70	100.0	0.0	0.0	48.702	35	7.378×10^{-9}	Disfavored
		3	90	100.0	0.0	0.0	75.93	36	2.062×10^{-9}	Disfavored

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Best Fits for injection index 2.2 (H+He)

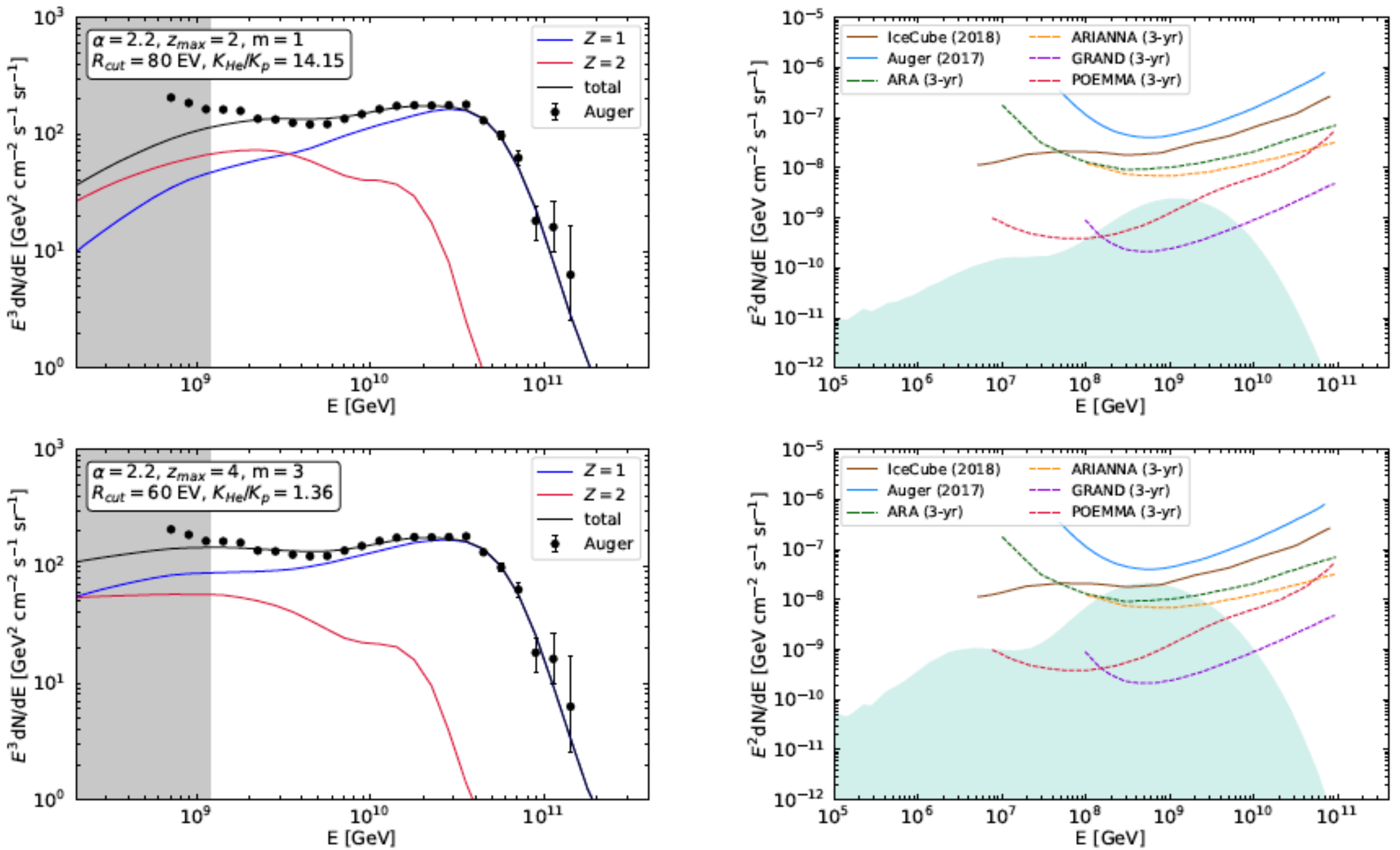


FIG. 1: UHECR spectra (left) and cosmogenic neutrino spectra (right) for $\alpha = 2.2$. The top (case 2) and bottom (case 12) panels show the best-fit cases listed in Appendix A for which the difference in the cosmogenic neutrino flux is the maximum.

Best Fits for injection index 2.4 (H+He)

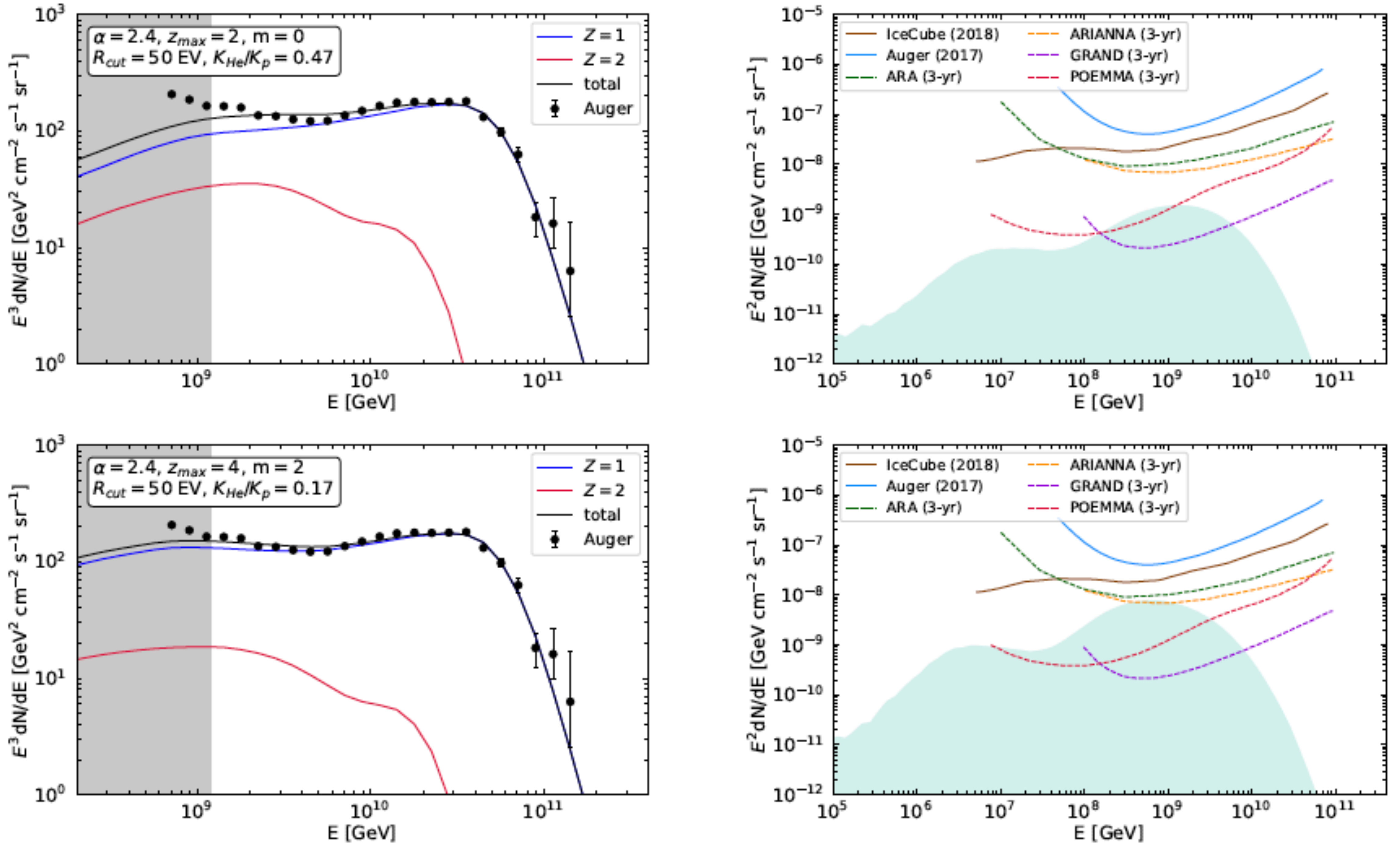


FIG. 2: UHECR spectra (left) and cosmogenic neutrino spectra (right) for $\alpha = 2.4$. The top (case 13) and bottom (case 23) panels show the best-fit cases listed in Appendix A for which the difference in the cosmogenic neutrino flux is the maximum.

Best Fits for injection index 2.6 (H+He)

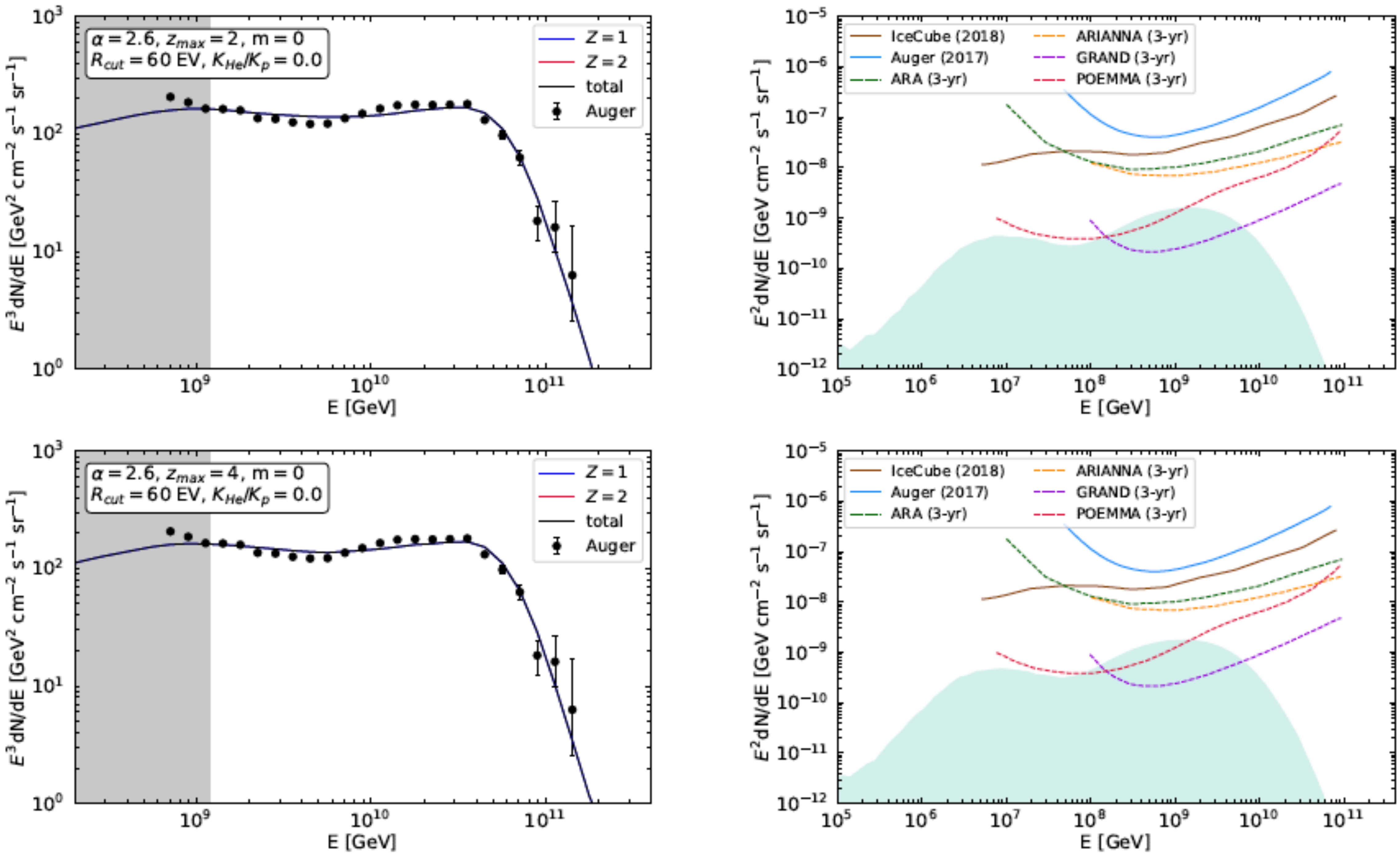
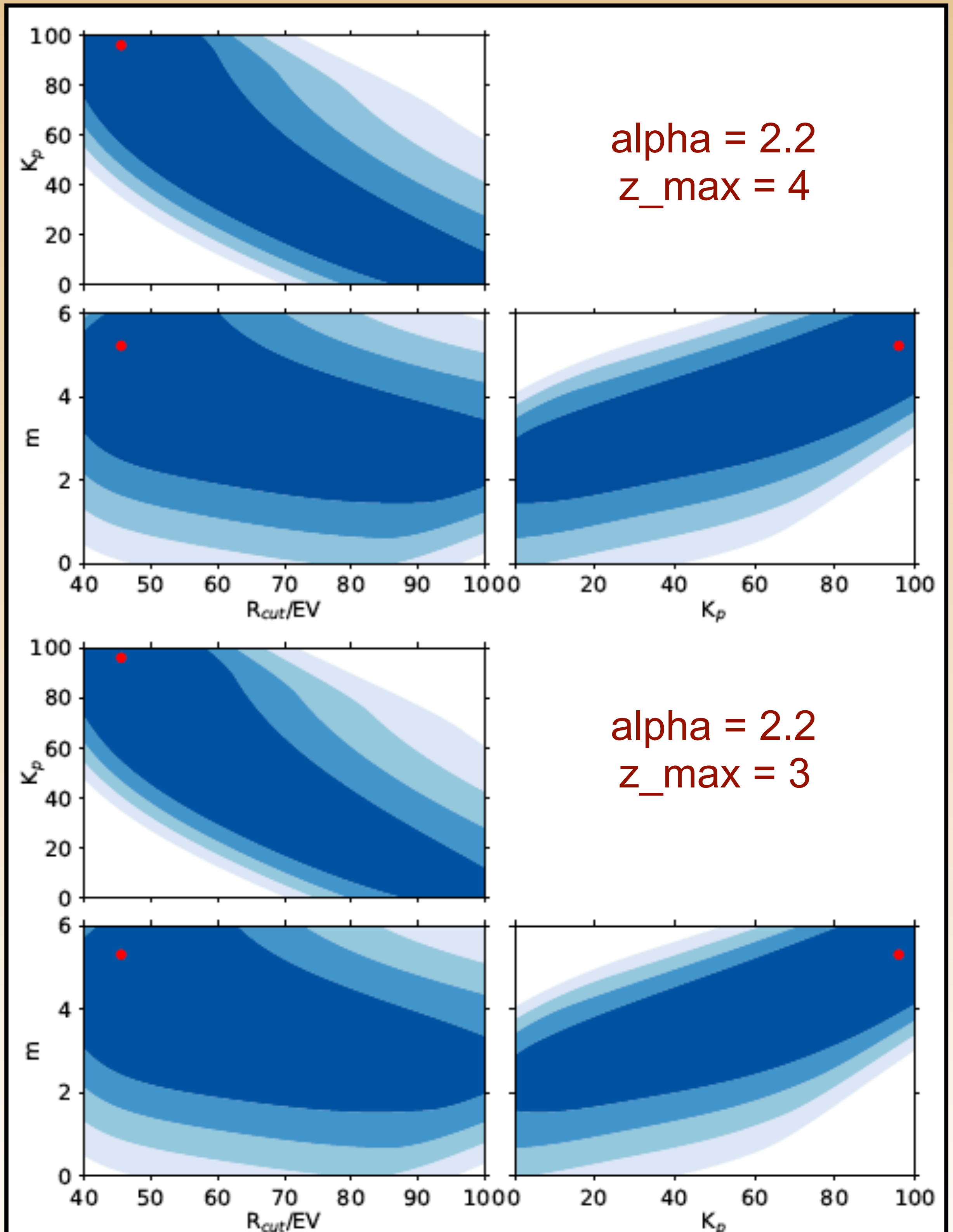


FIG. 3: UHECR spectra (left) and cosmogenic neutrino spectra (right) for $\alpha = 2.6$. The top (case 25) and bottom (case 33) panels show the best-fit cases listed in Appendix A for which the difference in the cosmogenic neutrino flux is the maximum.

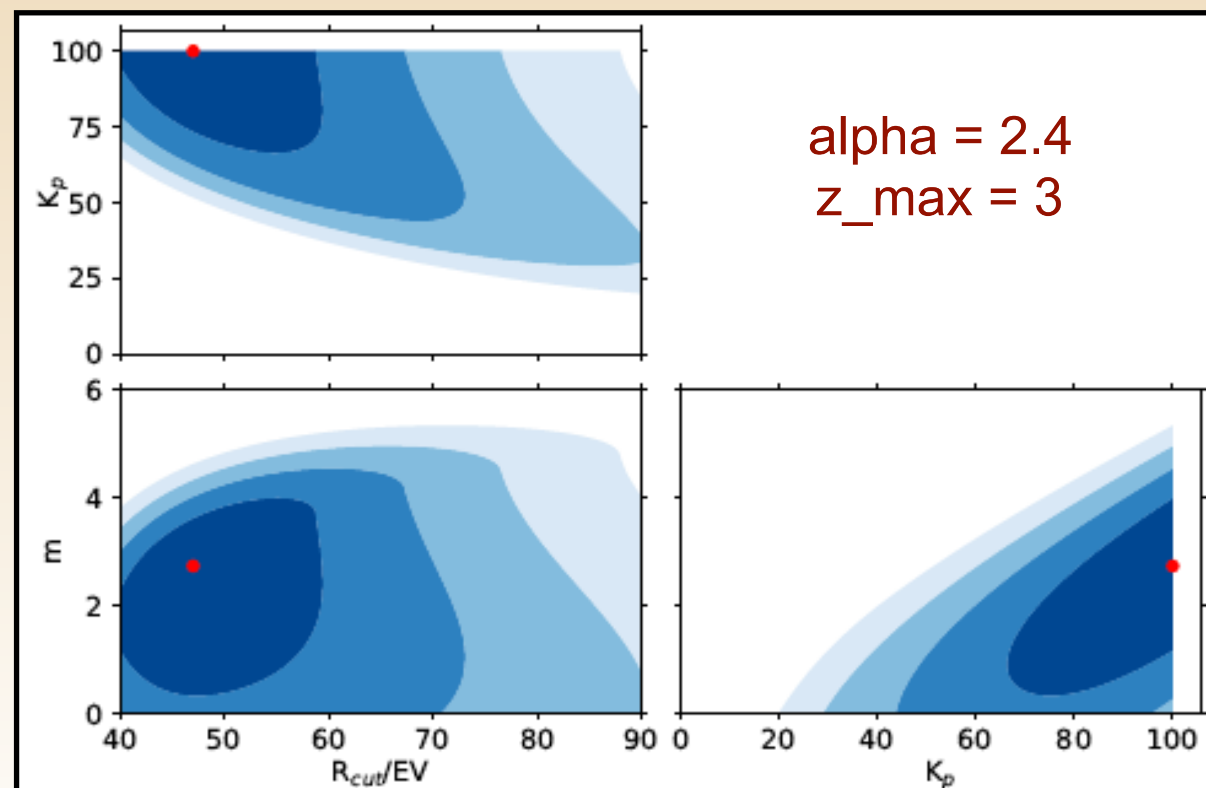
Correlation between Fit Parameters (H+He)



- Not all the parameters are independent, but it is not known a priori the mathematical nature of dependence
- Use large grid space to explore the confidence intervals for the parameters

- 40 EV < R_cut < 100 EV with 0.5 EV spacing
- 0 < m < 6 with 0.03 spacing
- 0 < K_p < 100 with 0.01 spacing

121 x 201 x 101 grid points!



Best Fits but Rejected! (H+He)

Neutrino flux violates upper limit

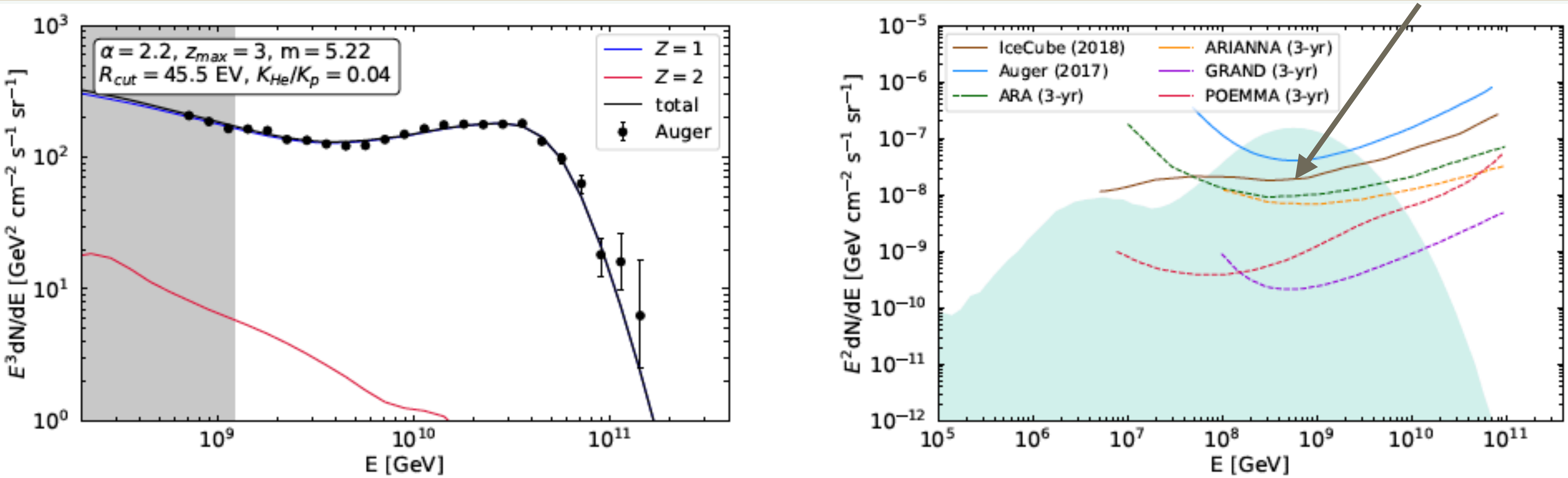
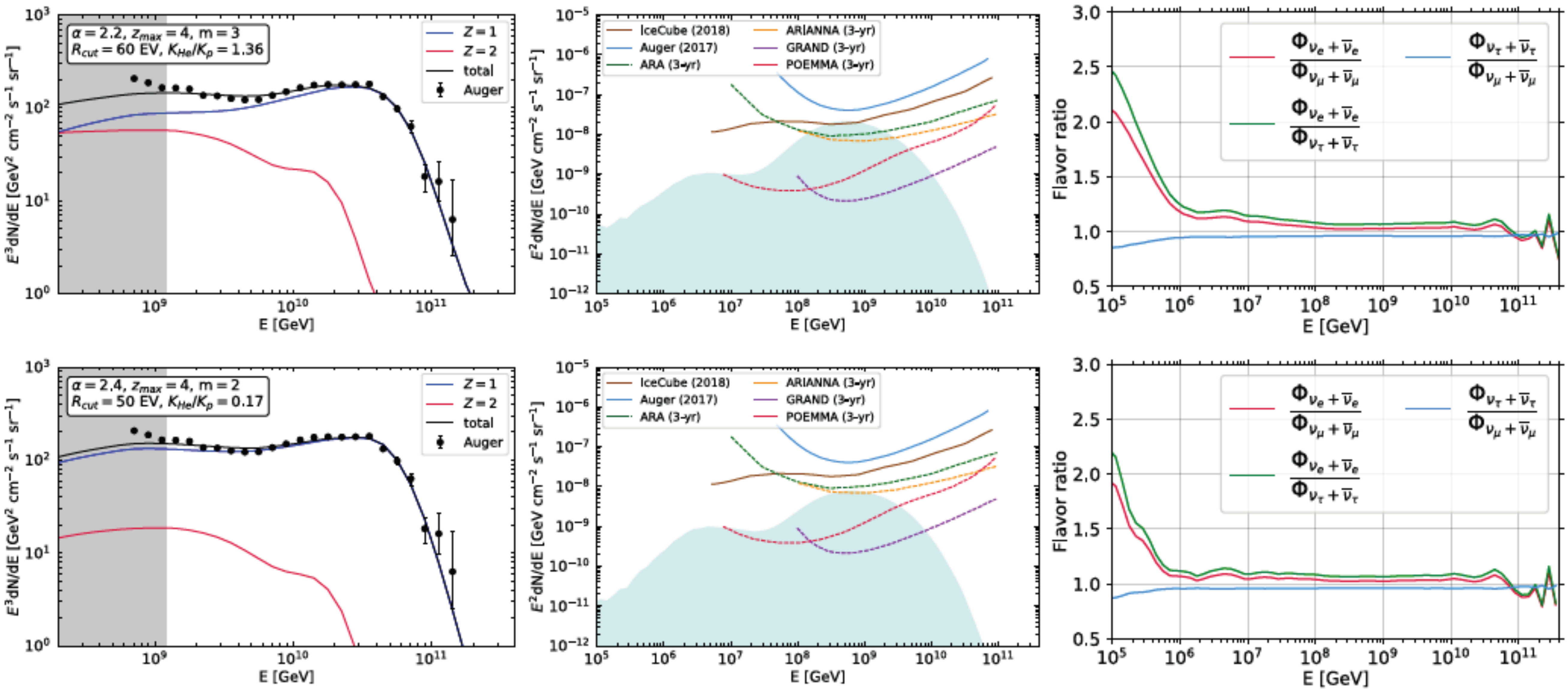


FIG. 6: UHECR spectrum (*left*) and cosmogenic neutrino flux (*right*) for the best-fit case corresponding to $\alpha = 2.2$ and $z_{\rm max} = 3$, found by scanning over a wide range of parameter space

TABLE II: Best-fit values in parameter space [p+He]

α	$z_{\rm max}$	m	$R_{\rm cut}$	$K_{\rm p}$	$K_{\rm He}$	χ^2
2.2	3	5.22	45.5 EV	96%	4%	8.29086
2.2	4	5.31	45.5 EV	96%	4%	7.04839
2.4	3	2.73	47.0 EV	100%	0%	12.01026

Neutrino flavor ratio: H+He Model



$R_{\rm cut}$ is varied between 40 – 100 EV. The source evolution index m is varied through 0, 1, 2, 3. We take $z_{\rm min} = 0.0007$, and vary $z_{\rm max}$ through 2, 3 and 4. We investigate three cases, $\alpha = 2.2$, 2.4, 2.6. We vary $K_{\rm p}$ and $K_{\rm He}$ from 0 to 100% with a precision of 0.1%, restricted by the condition, $K_{\rm p} + K_{\rm He} = 100\%$.

Can be an important indicator to discriminate between models - break parameter degeneracies

More Complex (H+He+N+Si) model

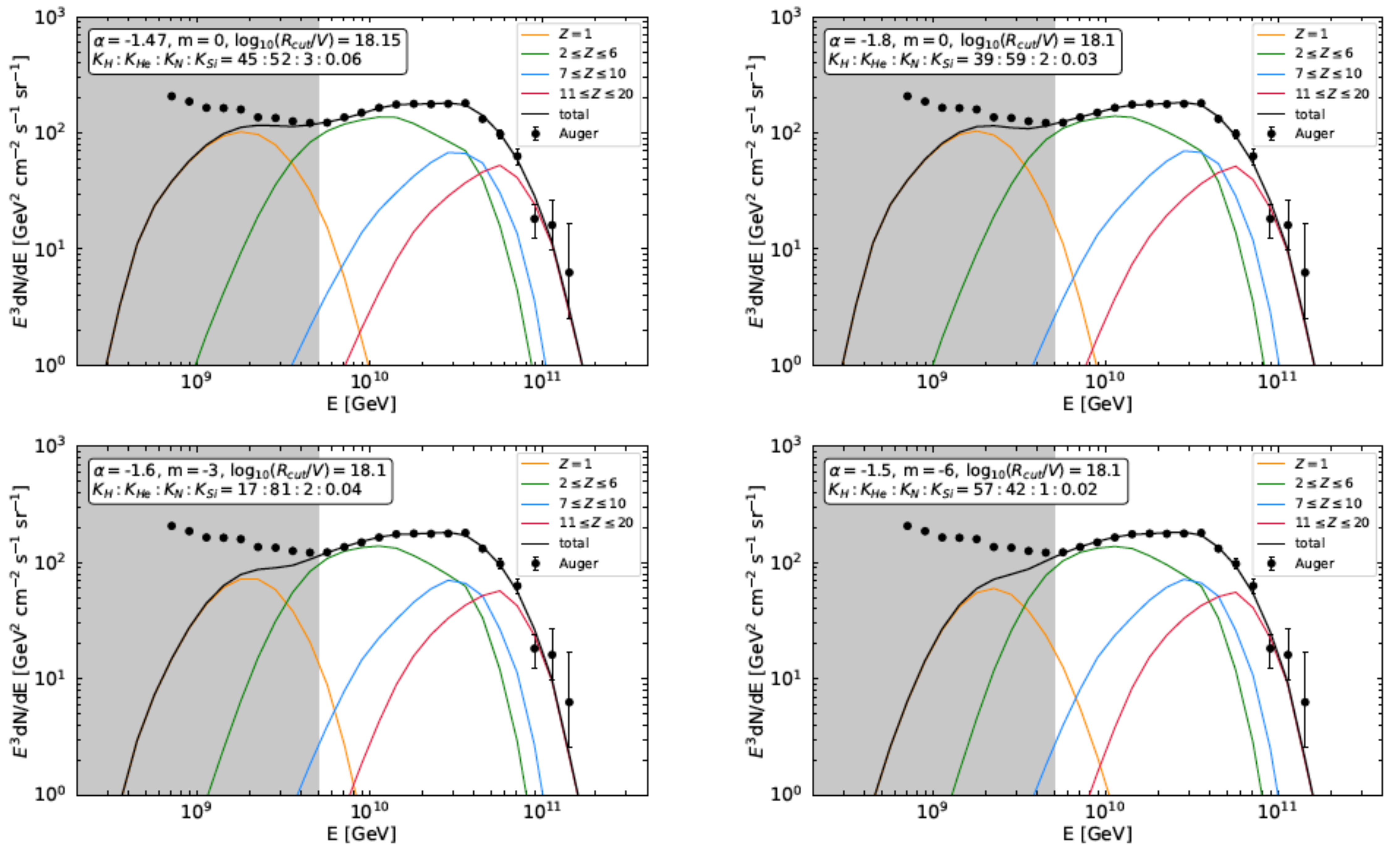
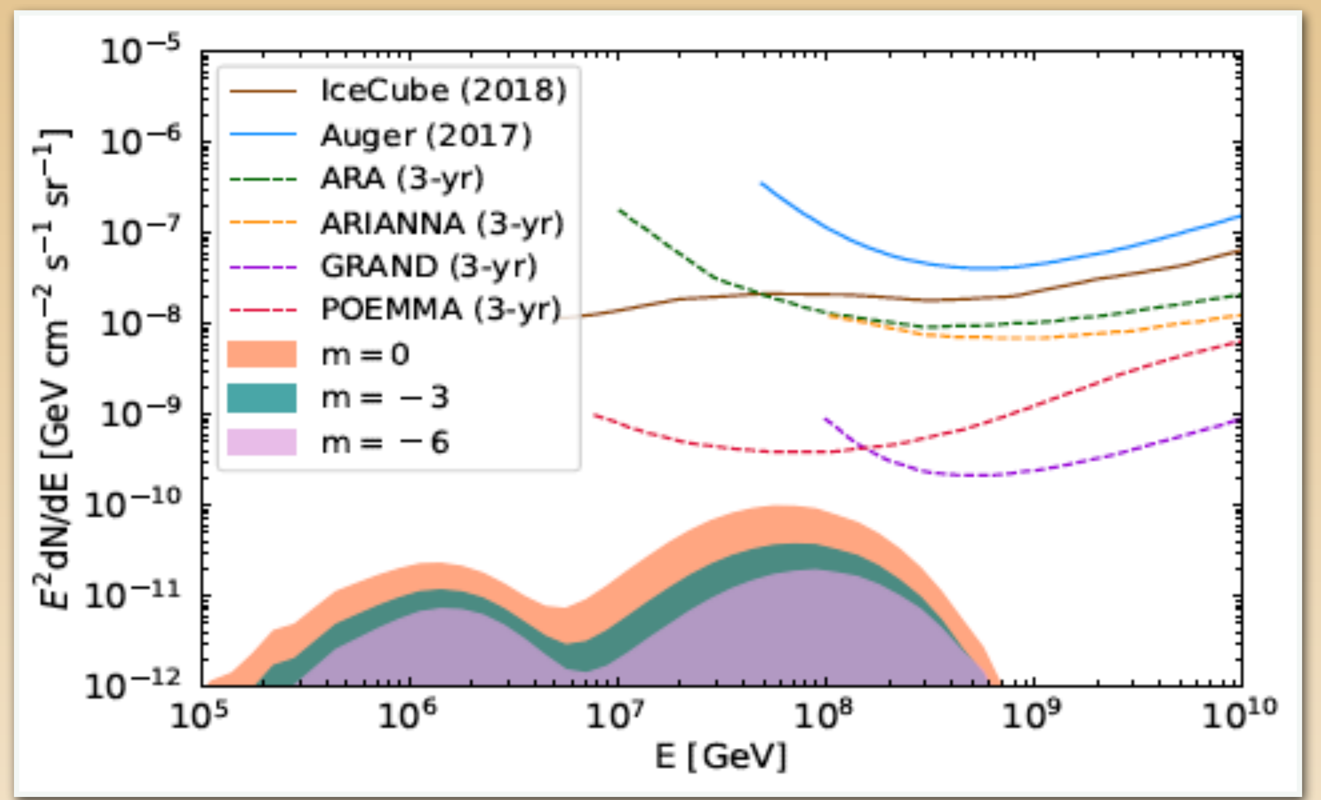


FIG. 8: UHECR spectra for the best-fit parameters of CTD model as found by PAO for $m = 0$ (top left), and that calculated in this work for $m = 0, -3, -6$ by extending the range of α used to scan the parameter space. The top right, bottom left and bottom right spectrum corresponds to $m = 0$, $m = -3$ and $m = -6$ respectively as indicated in the figure labels.

Implications for (H+He+N+Si) Model



No constraints on the models from neutrino observations by current or future detectors

Very hard injection index required — difficult to explain with commonly believed Fermi shock- acceleration processes

No or negative evolution of the sources — fewer and fewer sources of UHECRs at higher redshift

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

Summary and Outlook

We present new fits to the Pierre Auger UHECR spectrum with uniform astrophysical source distribution

- **Light nuclei composition: H+He (Can fit spectrum >~ 10^19 eV)**
  - Injection index: -2.2, -2.4
  - Source evolution index: 0–5
  - Rigidity cutoff: ~50–80 EV
  - Redshift range: 0.0007–4
- **Light-intermediate nuclei composition: H+He+N+Si (Can fit spectrum >~ 5x10^19 eV)**
  - injection index: -1.5, -1.8
  - Source evolution index: -6–0
  - Rigidity cutoff: ~1 EV
  - Redshift range: 0—1
- **Detection of cosmogenic neutrinos can severely constrain the light-intermediate nuclei composition models**
  - Additional constraints from neutrinos (flux and flavor ratios) can shed lights on degeneracies between model parameters
  - Science driver for upcoming/planned neutrino detectors

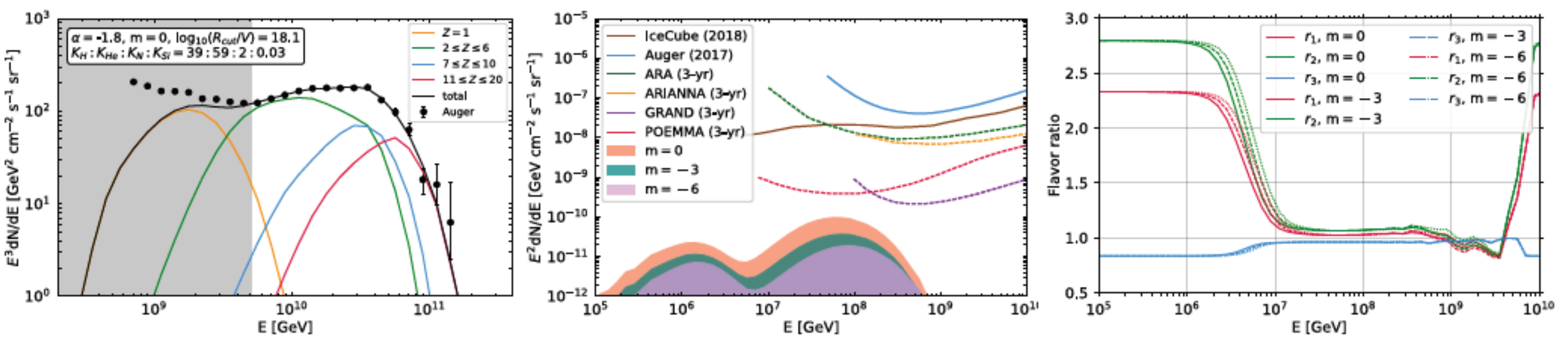
Invitation!

Important Dates

2019 Nov 01 - Abstracts Due
2019 Nov 07 - Early Registration Deadline
2019 Dec 07 - Regular Registration Deadline
2020 Jan 23 - Late Registration Deadline
2020 Jan 23 - Late Posters Deadline

Contact email:
capp@uj.ac.za

Neutrino flavor ratio: H+He+N+Si Model



We vary α in the interval $[-2.5,\ 0]$ and $\log_{10}(R_{\rm cut}/{\rm V})$ in the range $[17.8,\ 18.3]$. Since, for $Z > 1$, only particles originating from $z \lesssim 0.5$ are able to reach earth with $E > 10^{18.7}$ eV, we consider $z_{\rm max} = 1$ in the simulations and $z_{\rm min} = 0$ to cover the highest energy data points. The composition is restricted by the condition, $K_{\rm H} + K_{\rm He} + K_{\rm N} + K_{\rm Si} = 100\%$

Diffuse gamma-ray flux from UHECRs

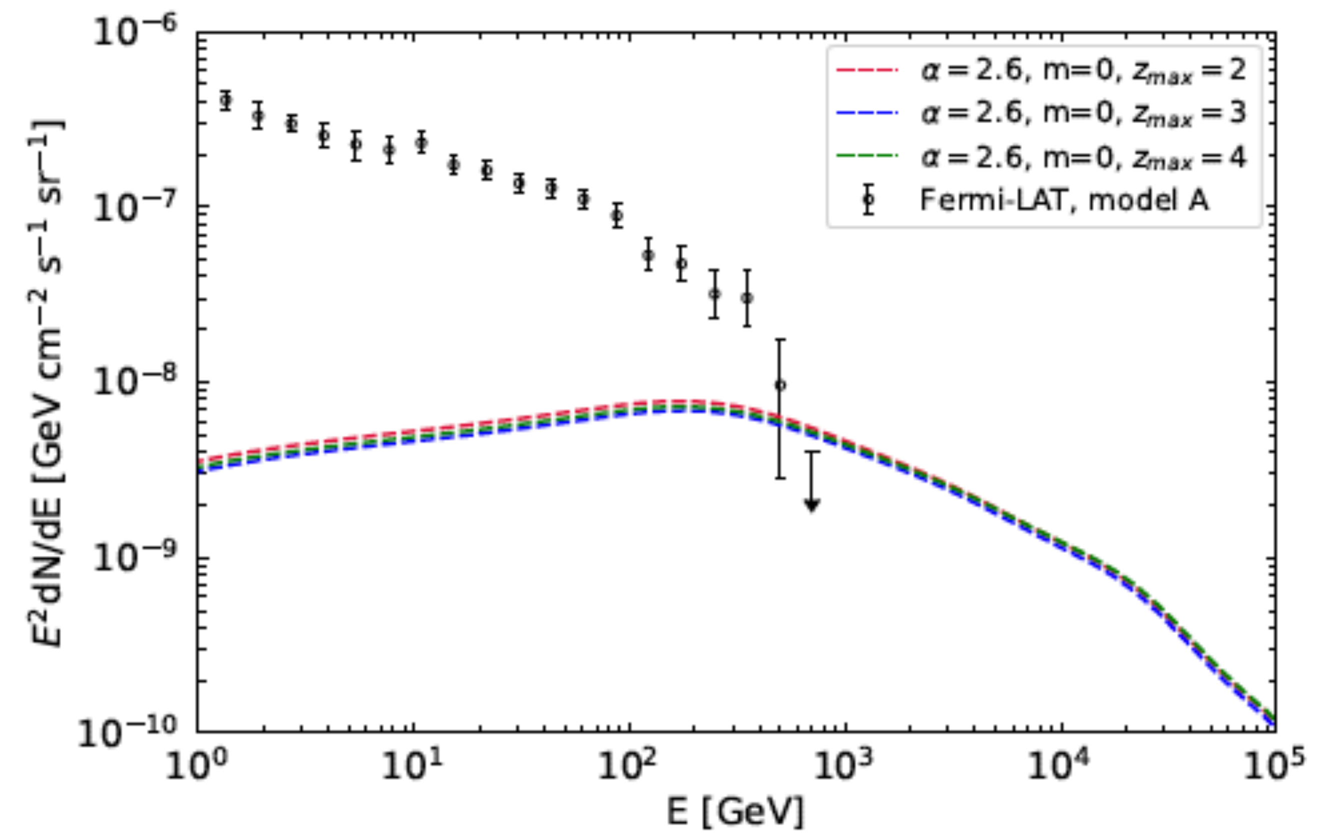


FIG. 7: Cosmogenic photon fluxes for the $m = 0$ best-fit cases, with $\alpha = 2.6$ and $z_{\max} = 2$, 3, and 4. The measured diffuse gamma-ray background by Fermi-LAT is also shown.

- A pure p-composition with alpha = 2.4, z_max = 3, m = 3 produces maximum allowed gamma-ray flux
- Mix composition lowers the gamma-ray flux
- For alpha = 2.4 case m = 0–2, z_max = 2—4 are allowed
- Most alpha = 2.2 cases are allowed because of high He fraction