Fitting the UHECR spectrum and composition

… and the impact of different nuclear disintegration and air-shower models

Jonas Heinze
CRPropa face-to-face meeting
Zeuthen, 2.10.2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

erc

NEUCOS

DESY

UHE Cosmic Rays and Cosmogenic Neutrinos

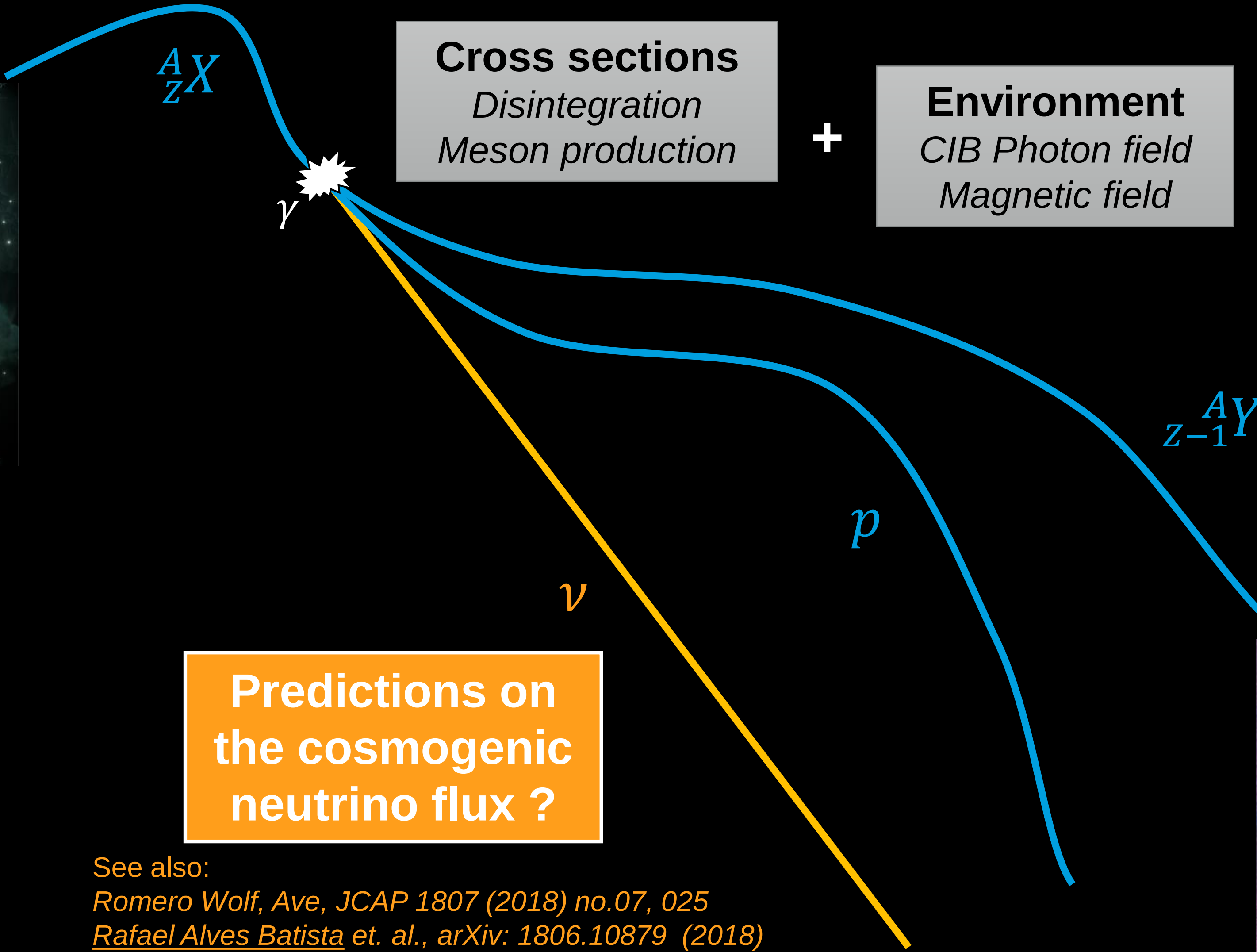
Model inputs

Source: DESY

Source Model
Spectral shape
Composition

+

Source Evolution

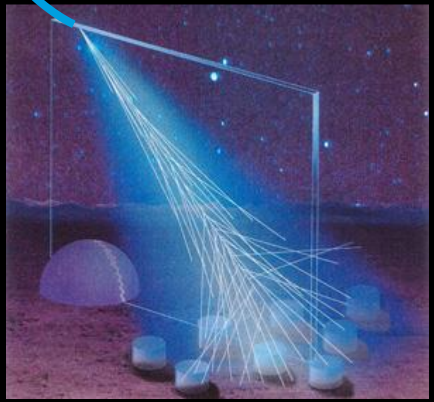


Cross sections
Disintegration
Meson production

+

Environment
CIB Photon field
Magnetic field

Detection
Air shower model



Source: Auger

Predictions on the cosmogenic neutrino flux ?

See also:
Romero Wolf, Ave, JCAP 1807 (2018) no.07, 025
Rafael Alves Batista et. al., arXiv: 1806.10879 (2018)

UHE Cosmic Ray Propagation - Uncertainties

Assuming we would know the source perfectly…

Extragalactic Environment

- Photon fields: CMB and CIB
  - Different CIB models with different z scaling
- Magnetic fields

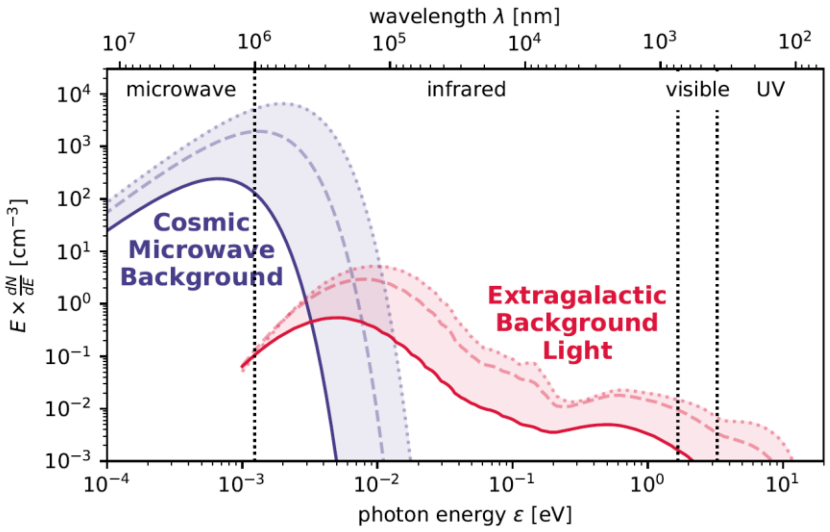
Not in this Talk though!

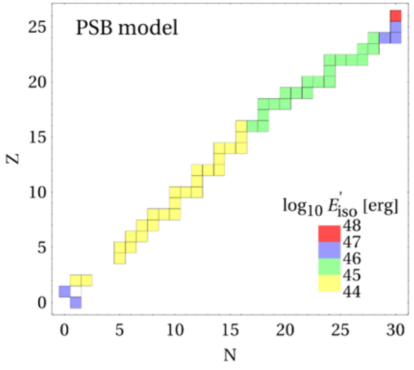
Photohadronic model

- Nuclear Disintegration at lower energies ($\epsilon_r \leq 150$ MeV)
  - Models: PSB, Talys, Peanut
- Meson-production at higher energies ($\epsilon_r \geq 150$ MeV)
  - Superposition - Model?!

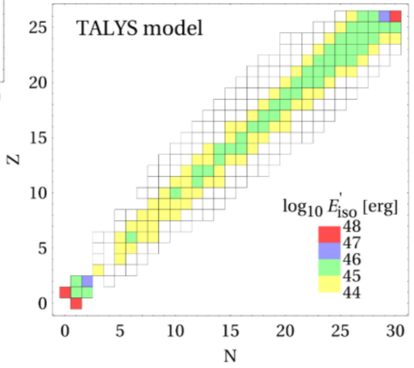
Air-Shower Model

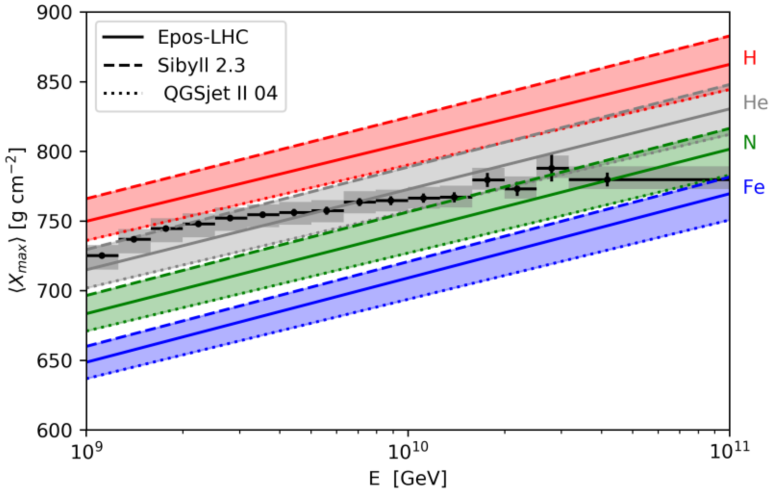
- To convert composition to X_{max}
- Models: Epos-LHC, Sibyll 2.3, QGSjet-II.4





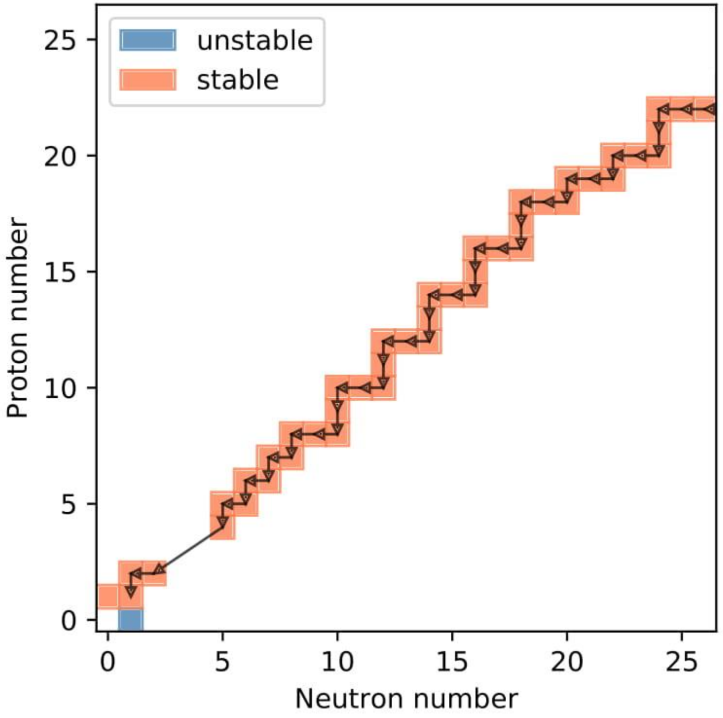
Boncioli, Fedynitch, Winter
Scientific Reports 7 (2017) 4882



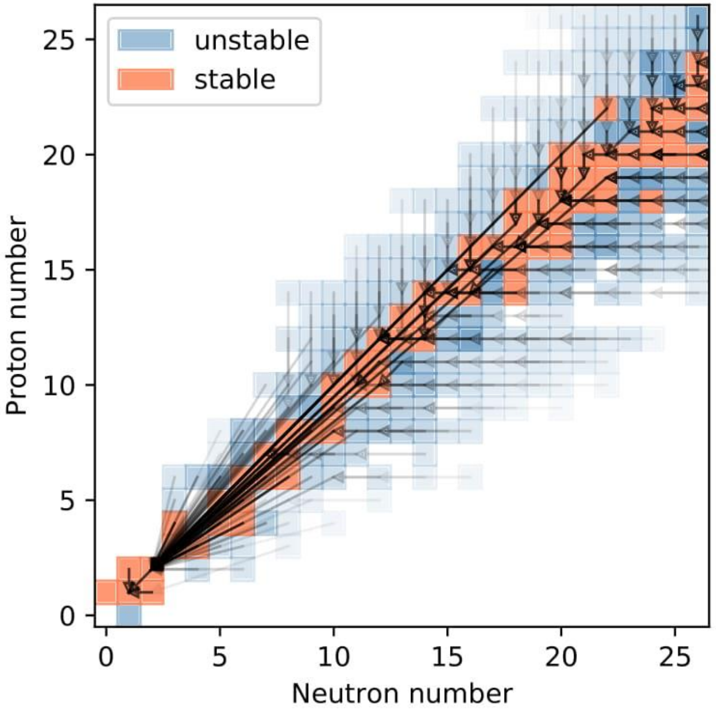


Disintegration models

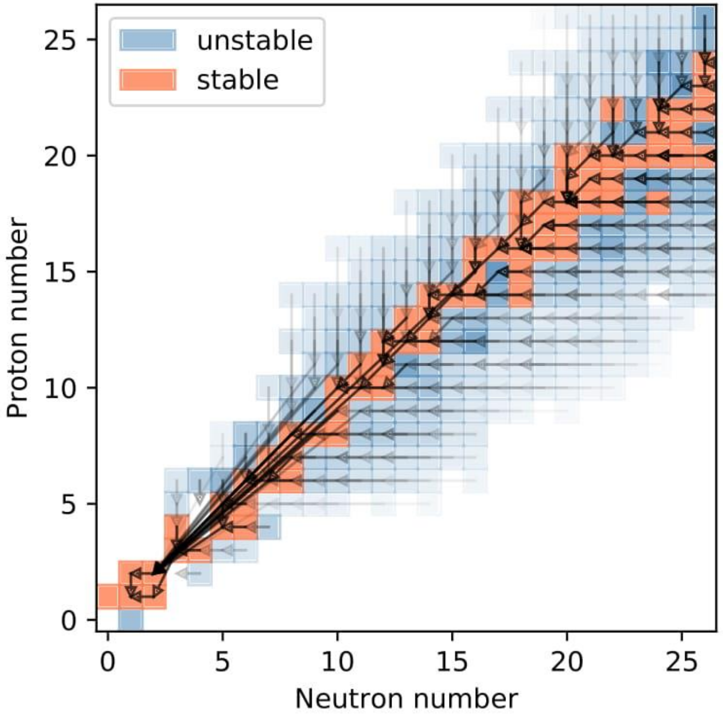
PSB



Peanut

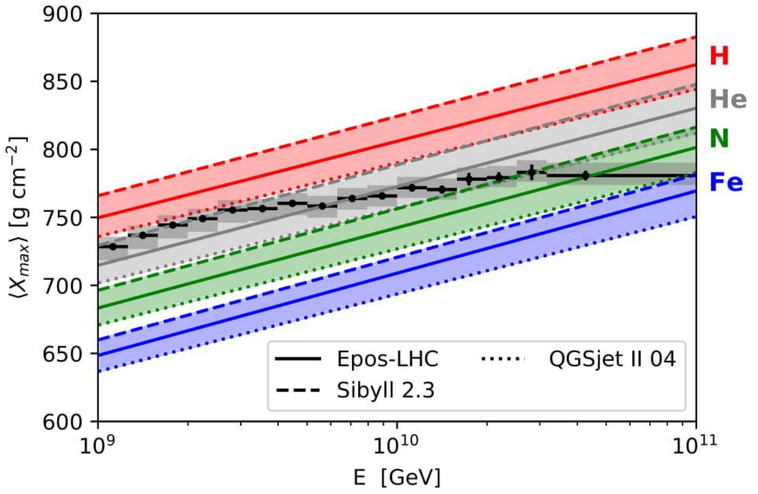


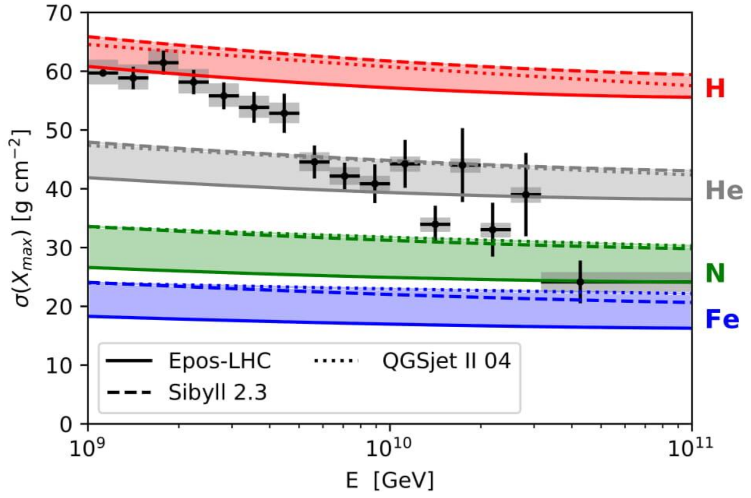
Talys

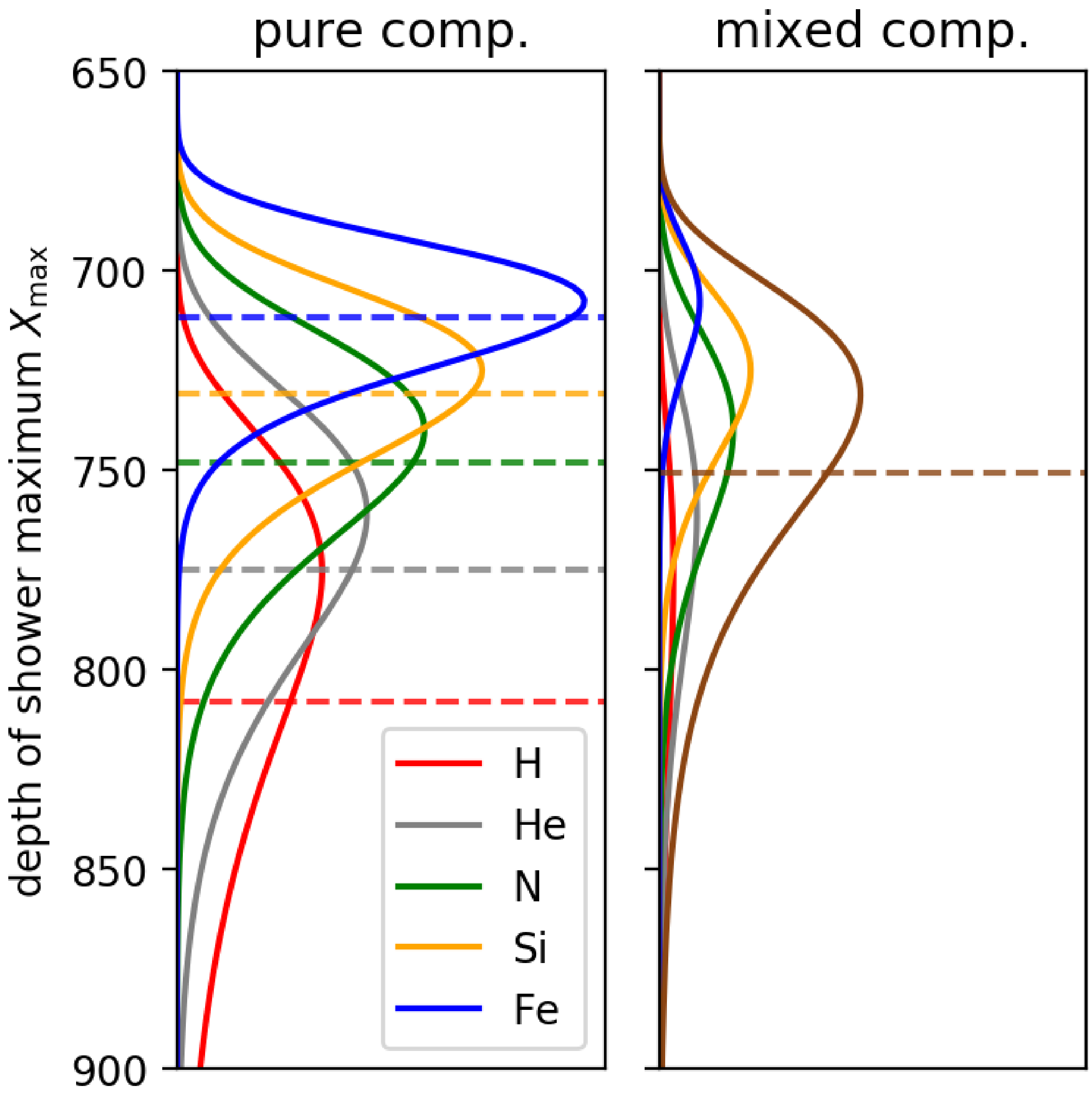


X_{max} first two moments

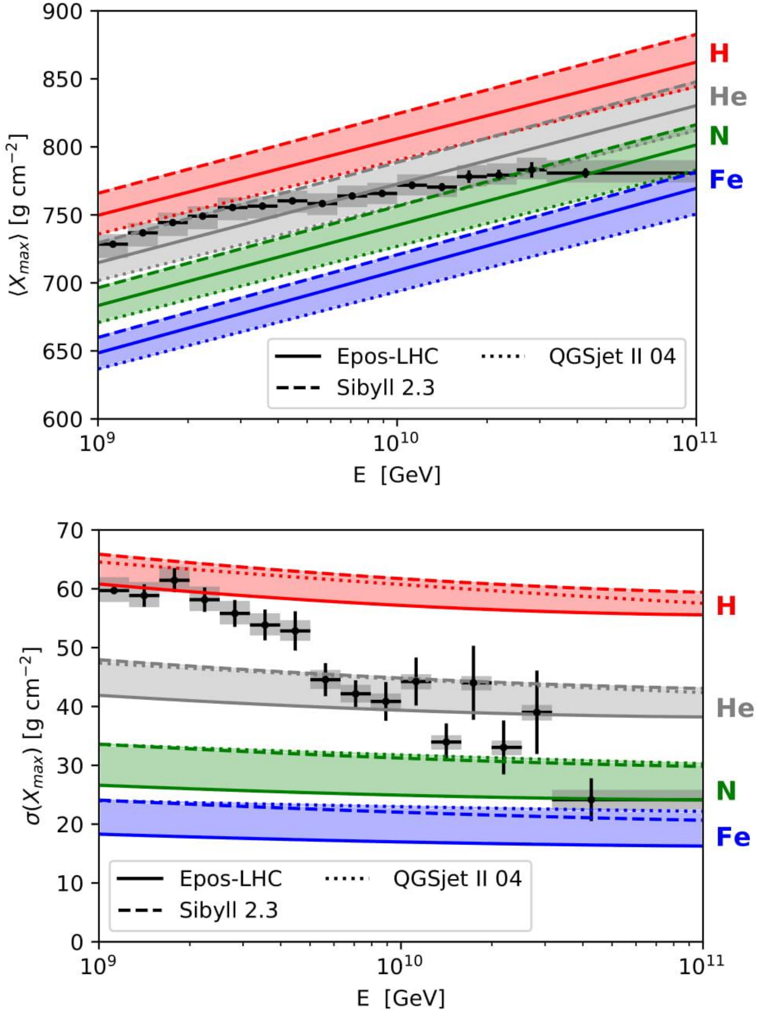
… and the Gumble distribution

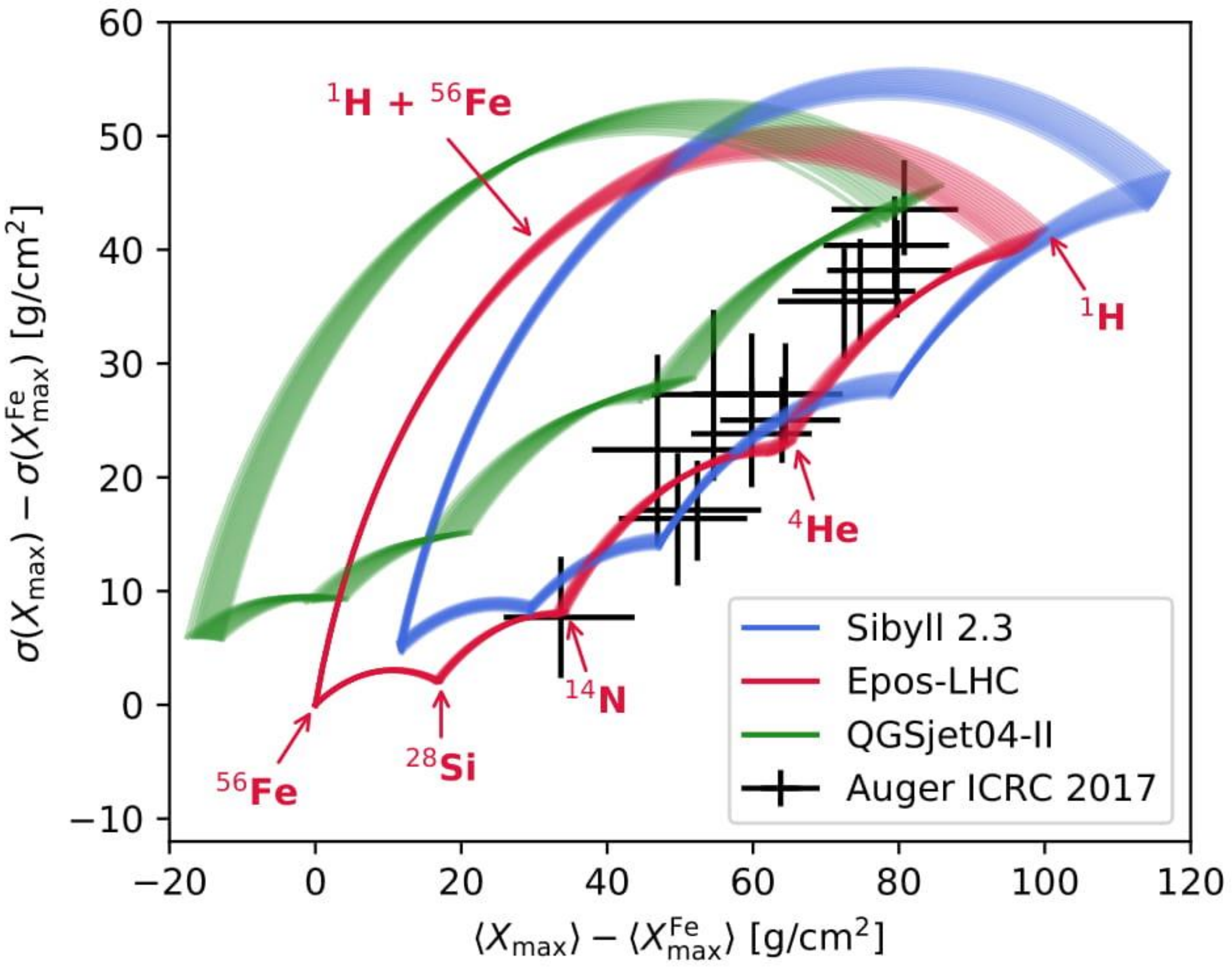






$X_{\max}$ and air-shower models



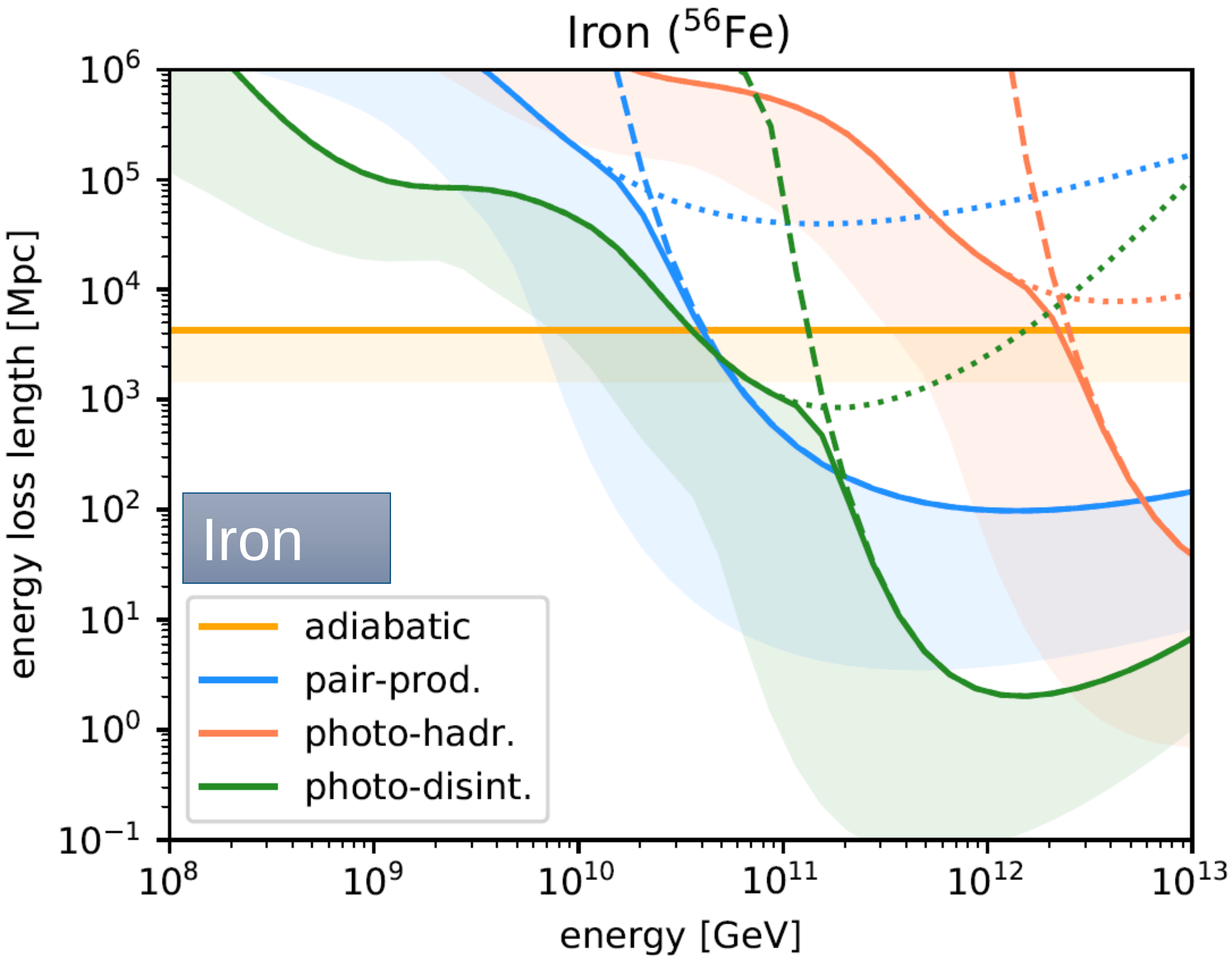


UHECR Transport Equation

- About 50 × number of E-bins coupled differential equations
- All coefficients time and energy dependent

- Fast computation times needed to study cross-section / photon-field uncertainties

We have developed a new Code:
(with Anatoli Fedynitch)
PriNCe



$$\partial_t Y_i(E,z) = +\partial_E(HEY_i) - \partial_E\left(\frac{dE}{dt}Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i} + \mathcal{L}_i$$

adiabatic cooling

pair - production

photo-hadronic
+ disintegration

Injection

Propagation Code - PriNCe

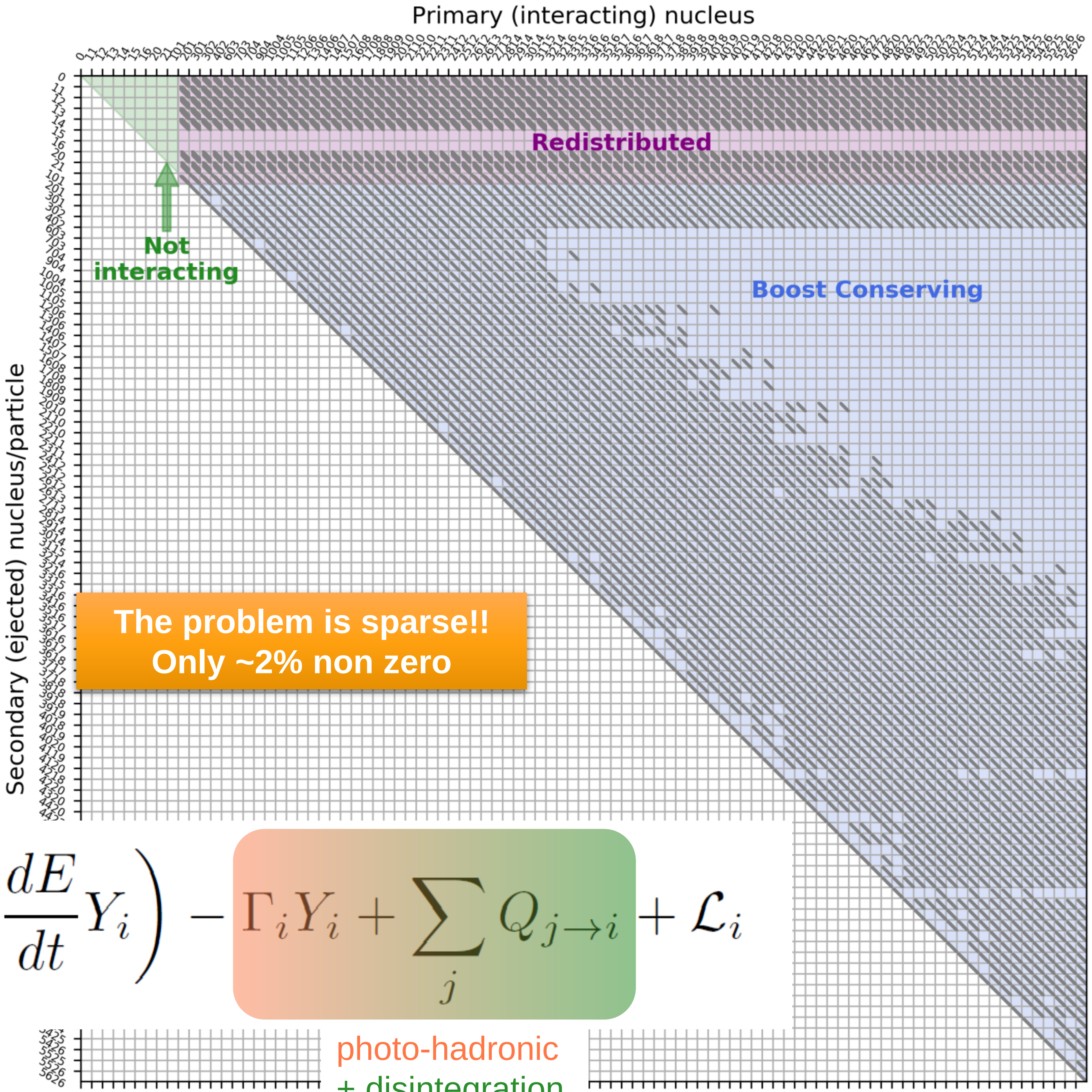
Propagation including Nuclear Cascade

- Written in pure Python using Numpy and Scipy
- Specifically makes use of sparse matrix structure

$$\partial_t \vec{Y} = \Phi \times \vec{Y} + \vec{J}$$

format	full matrix size [MB]	full matrix speed [ms]	only nuclear species size [MB]	only nuclear species speed [ms]
CSR	24.3	2.35	4.19	0.33
CSC	24.3	1.71	4.19	0.29
BSR	21.8	2.57	4.19	0.33
COO	32.3	5.13	5.55	0.75
DIA	184.00	10.00	38.00	1.67
dense	511.00	39.10	417	3100

- Speed: **20s – 40s** for single spectrum (depending on number of system species)



The problem is sparse!! Only ~2% non zero

$$\partial_t Y_i(E,z) = +\partial_E(HEY_i) - \partial_E\left(\frac{dE}{dt}Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i} + \mathcal{L}_i$$

photo-hadronic + disintegration

Sources – Generic model

Generic assumptions

- Choices following Auger Combined Fit
…extended to source evolution
Auger Collaboration, JCAP04(2017)038

- Only five injection elements:
H, He, N, Si, Fe

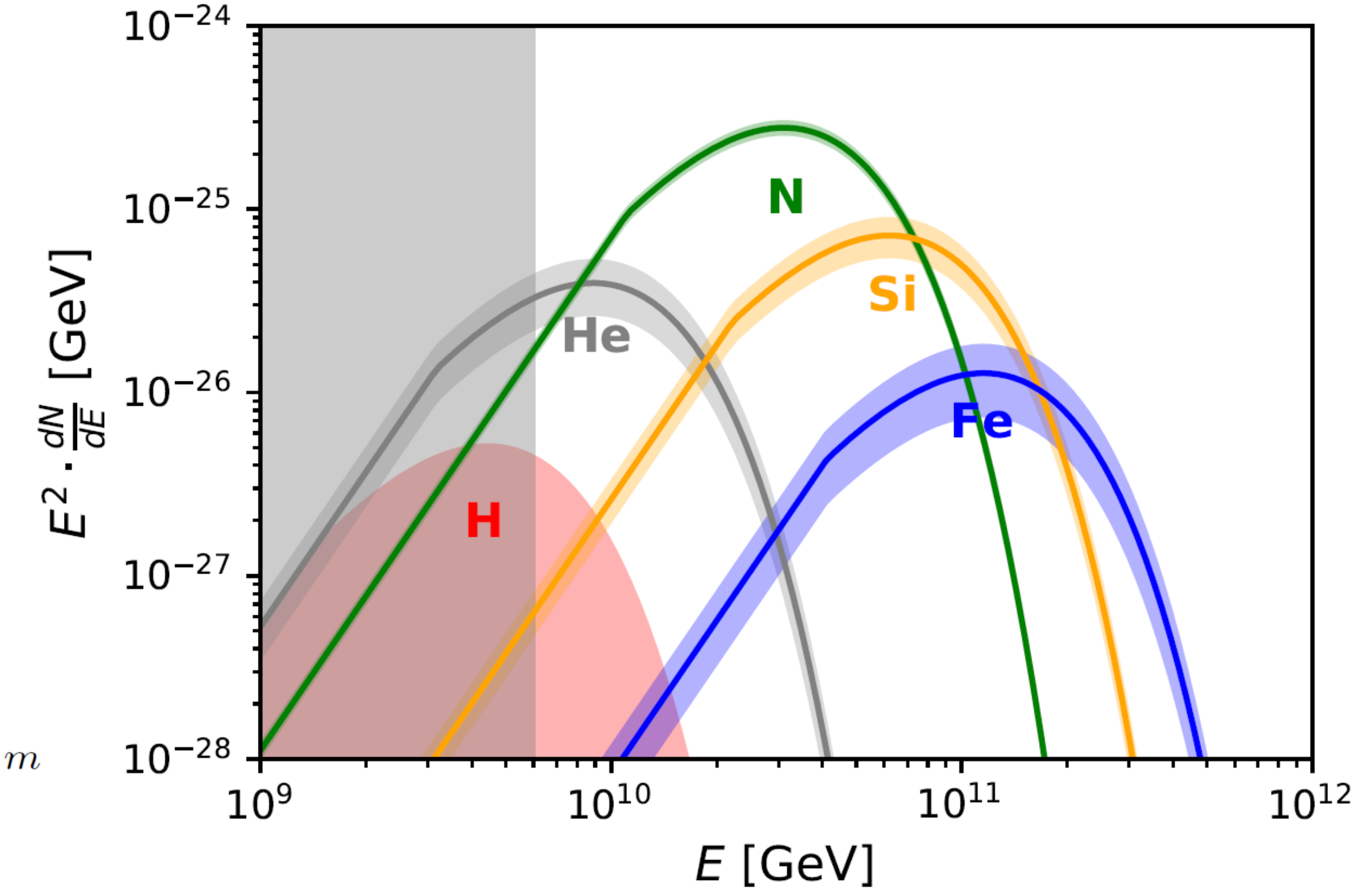
- Simple Power-law with
rigidity dependent cut-off

$$J_A(E) = \mathcal{J}_A \left(\frac{E}{10^9\ \mathrm{GeV}}\right)^{-\gamma} \times f_{\mathrm{cut}}(E, Z_A, R_{\mathrm{max}}) \times n_{\mathrm{evol}}(z)$$

- Source evolution locally as $n_{\mathrm{evol}}(z) = (1+z)^m$

Total of 8 free parameters

JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88



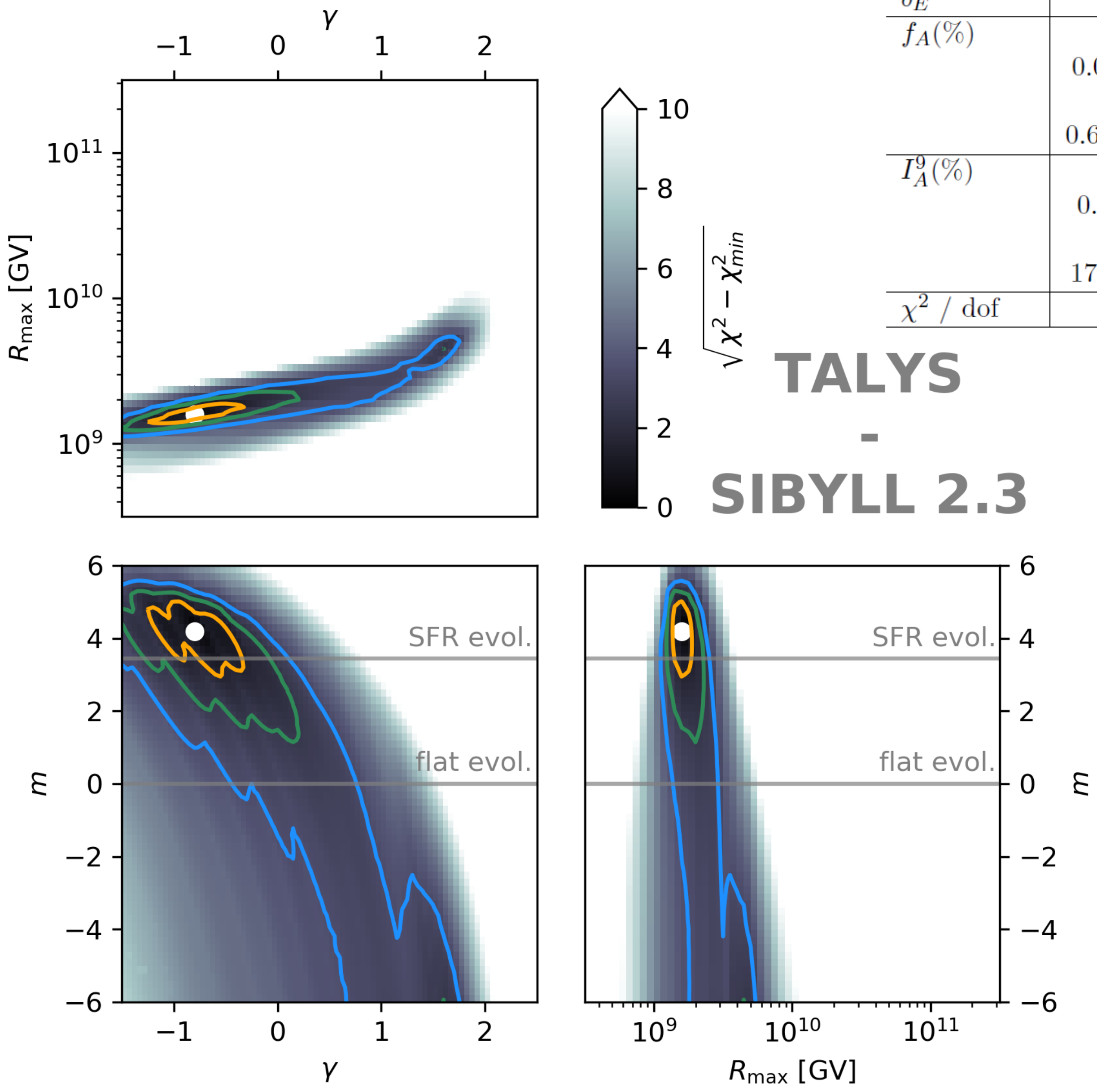
Results: Fit to spectrum and Composition

For combination Talys – Sibyll 2.3

- Fit **2017** spectrum + composition by χ^2-fit and energy shift of ± 14 %
- Shown as 2D profiles by minimizing over all other fit-parameters

- Features:
  - Narrow range in R_{max}
  - $\gamma - R_{max}$ correlation similar to flat evol. fit
  - Strong correlation in $\gamma - m$

- Two types of sources
  - Hard γ – ‘distant’ sources
  - Soft γ – ‘local’ sources



TALYS - SIBYLL 2.3

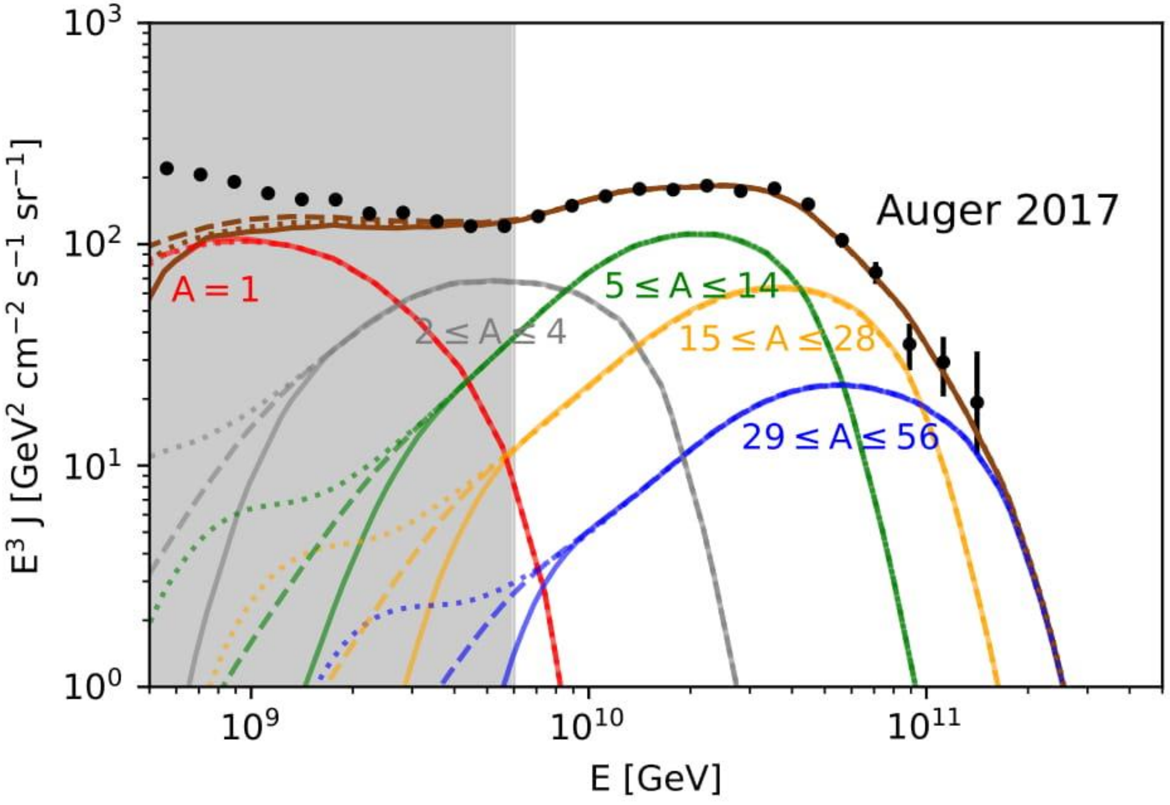
	best fit (●)		
γ			$-0.80^{+0.27}_{-0.23}$
$R_{\max}$ (GV)			$(1.6 \pm 0.2) \cdot 10^9$
m			$4.2^{+0.4}_{-0.6}$
δ_E			$0.14^{+0.00}_{-0.03}$
$f_A(\%)$	H	He	N
	$0.0^{+42.6}_{-0.0}$	$82.0^{+3.8}_{-6.4}$	$17.3^{+1.0}_{-1.1}$
	Si	Fe	
	0.6 ± 0.1	$(2.0 \pm 0.8) \cdot 10^{-2}$	
$I^9_A(\%)$	H	He	N
	$0.0^{+1.2}_{-0.0}$	$9.8^{+2.8}_{-2.9}$	$69.2^{+1.5}_{-1.6}$
	Si	Fe	
	$17.9^{+3.2}_{-3.5}$	$3.2^{+1.2}_{-1.3}$	
χ^2 / dof			27.0 / 21

JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

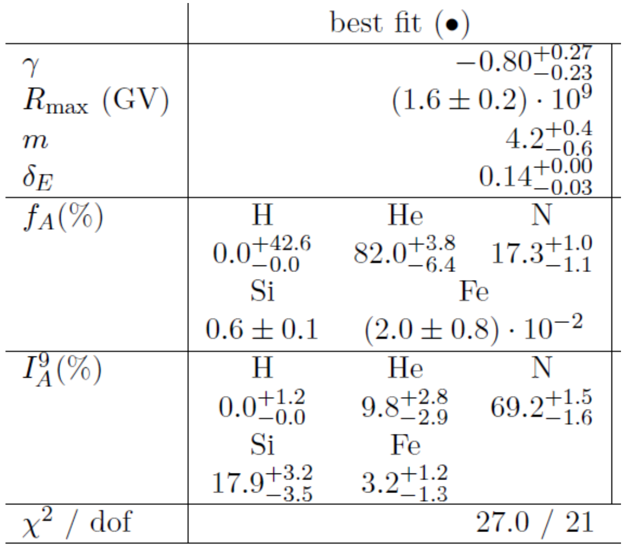
Results: Best fit spectrum

For combination Talys – Sibyll 2.3

- Fit mainly sensitive to envelope of cutoffs
- Fit-range insensitive above z = 1!
- Composition below ankle proton dominated (by construction) …
- … additional heavy component needed (galactic)



JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88



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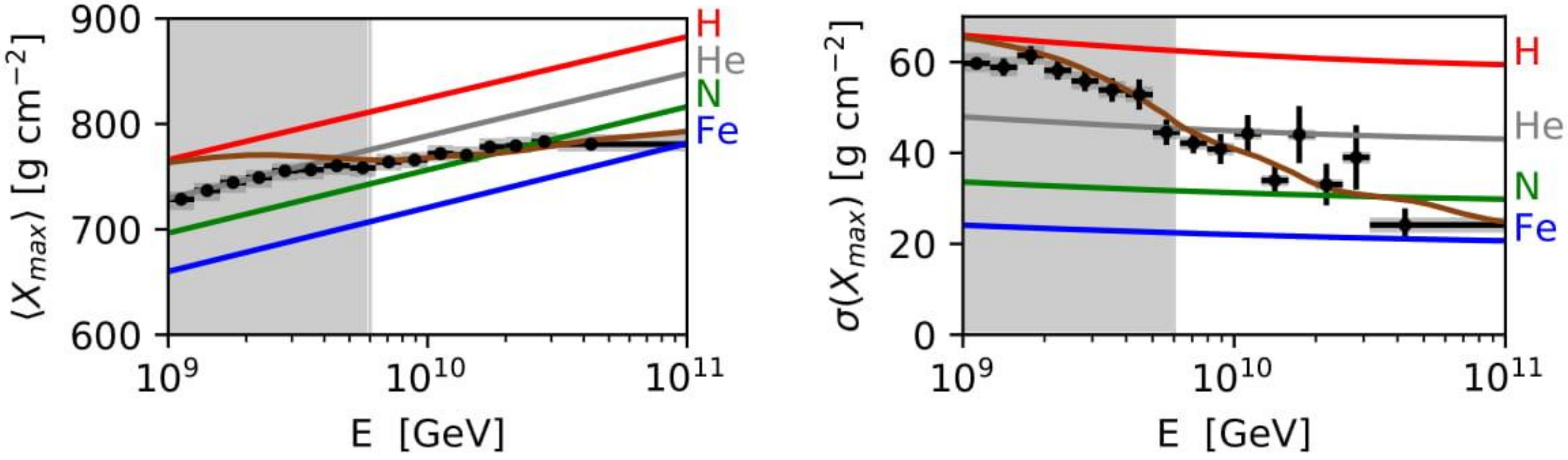
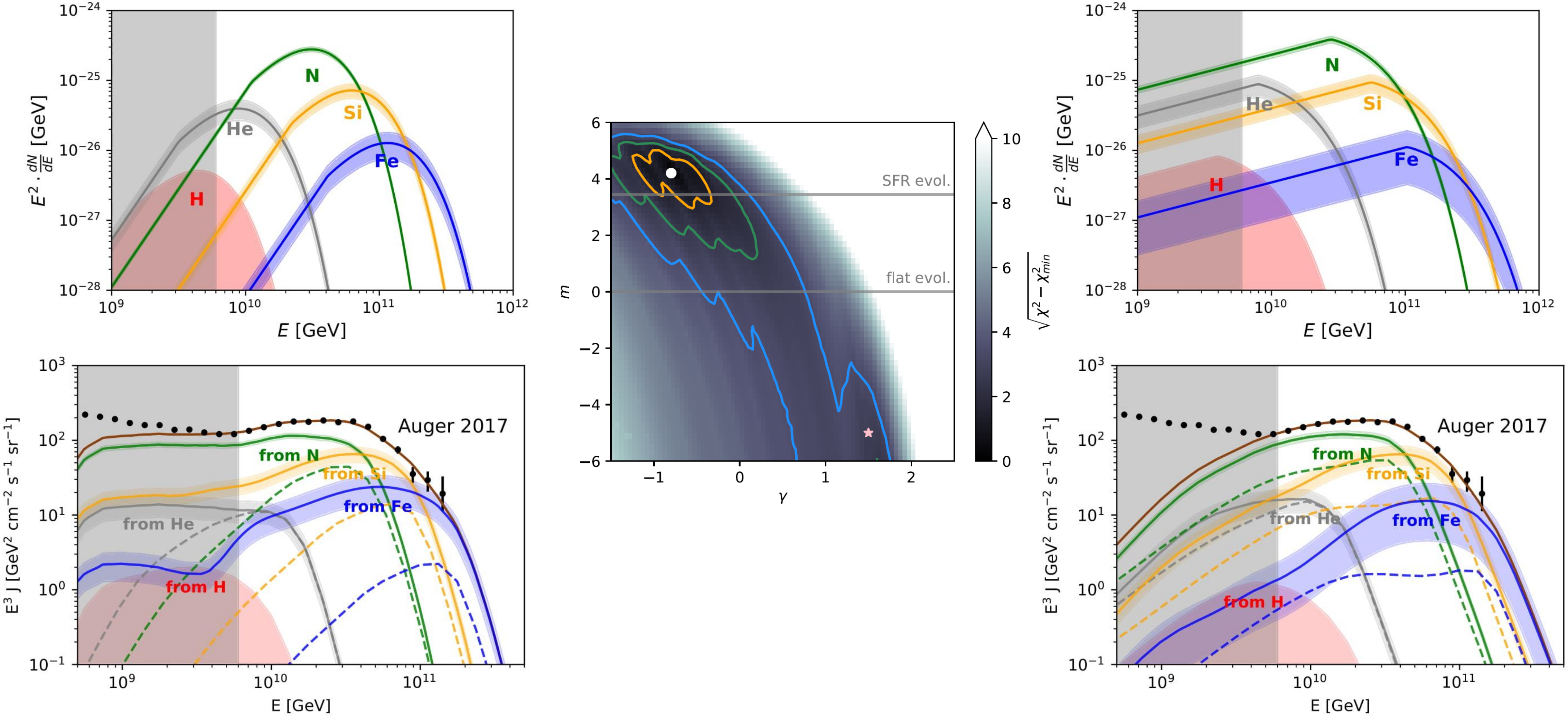


Injection spectra for different source evolution



JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

DESY.

Model dependence of the Fit

Compared in $\gamma - m$ space

Disintegration model

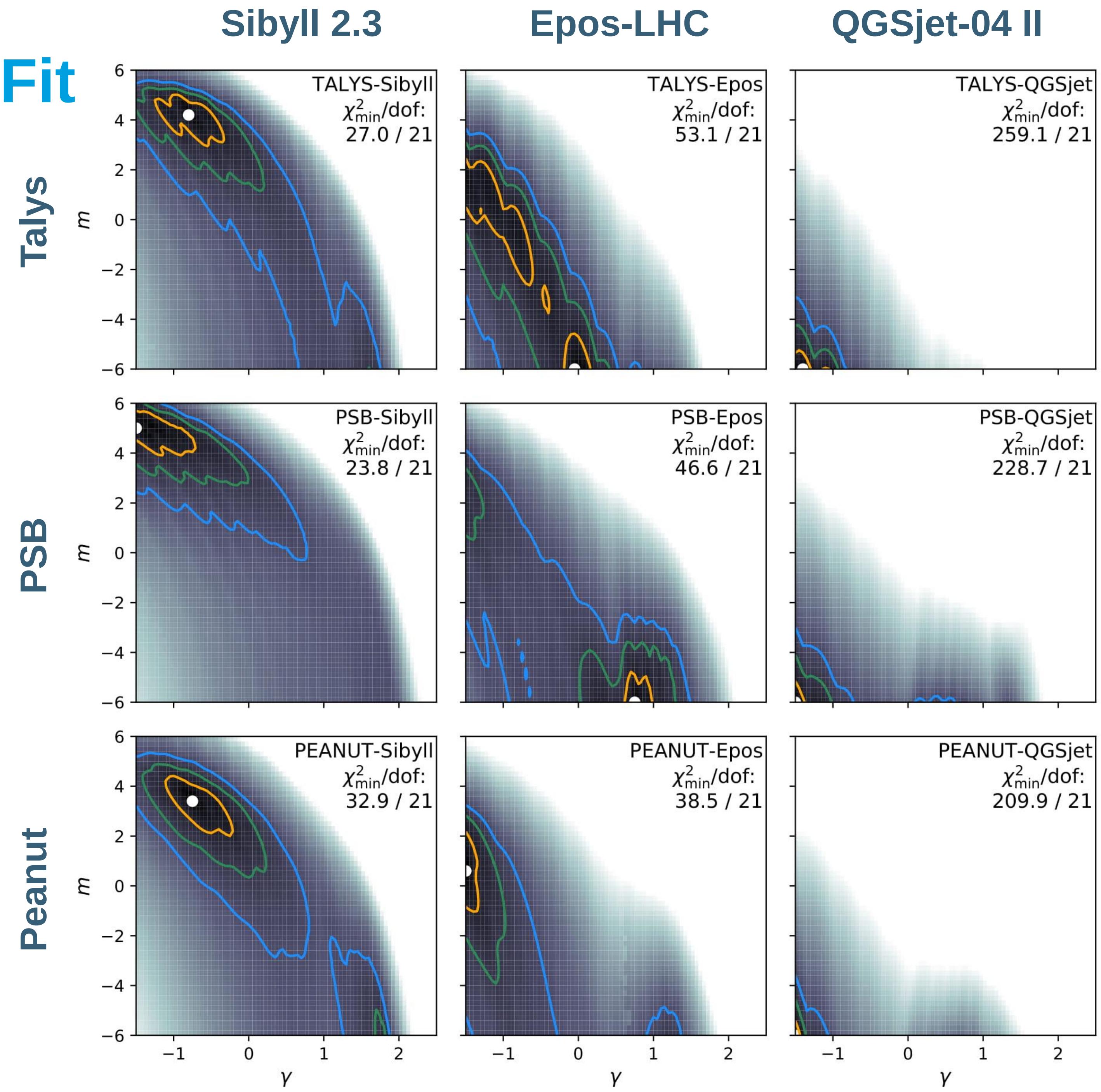
- Qualitatively similar fits
- PSB: Ligher injection
- Peanut/Talys: Heavier injection

Shower model

- Epos-LHC: Two distinct minima
  avoids disintegration
- Sibyll 2.3: Larger allowed space
  prefers disintegration
- QGSjet 4 II: Overall rather bad fit

See also: Auger Collaboration JCAP02(2013)026
Auger Collaboration JCAP04(2017)038

The shower model has a stronger qualitative impact!



JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

Model dependence of composition

Composition at the source

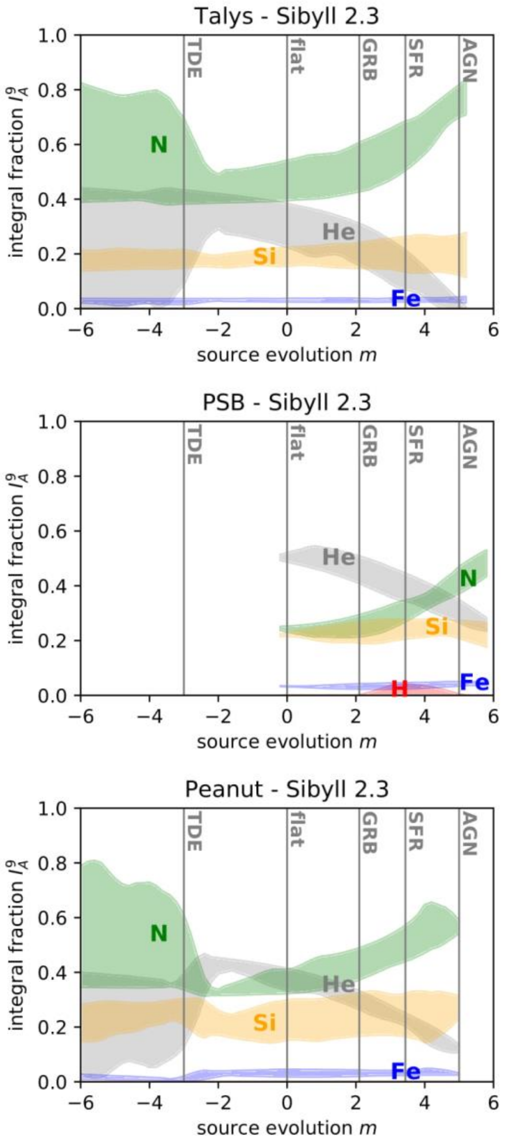
- **Fractions of total emissivity!**

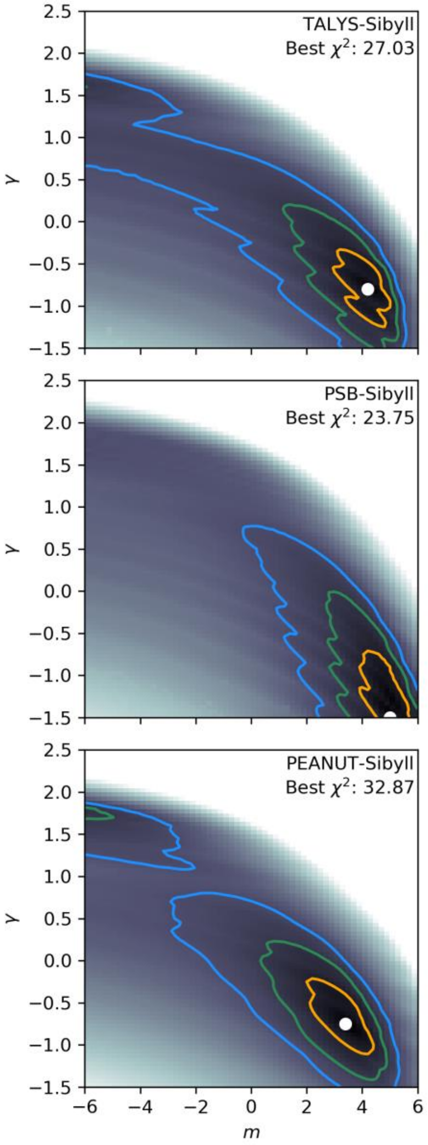
$$I_A = \frac{\int_{E_{\mathrm{min}}}^{\infty} J_A(E) E dE}{\sum_A \int_{E_{\mathrm{min}}}^{\infty} J_A(E) E dE}$$

- Ranges along m
  by min/max over other parameters

- Disintegration model
  affects mainly He / N ratio

- Shower model has stronger
  effect on composition:
  - Allowed proton fraction
  - Significant impact
    on silicon fraction





Talys

PSB

Peanut

JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

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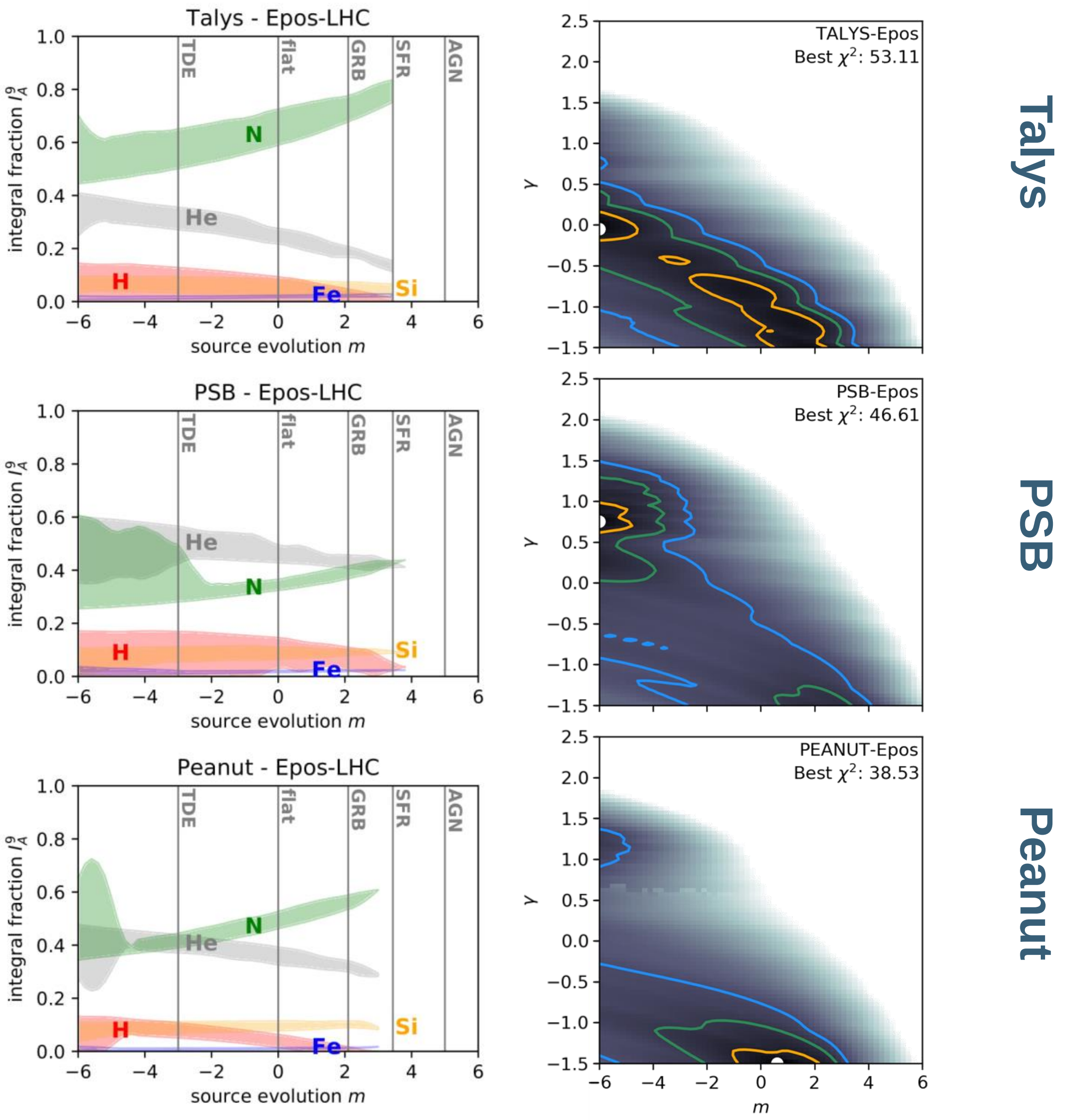

JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

Model dependence of composition

Composition at the source

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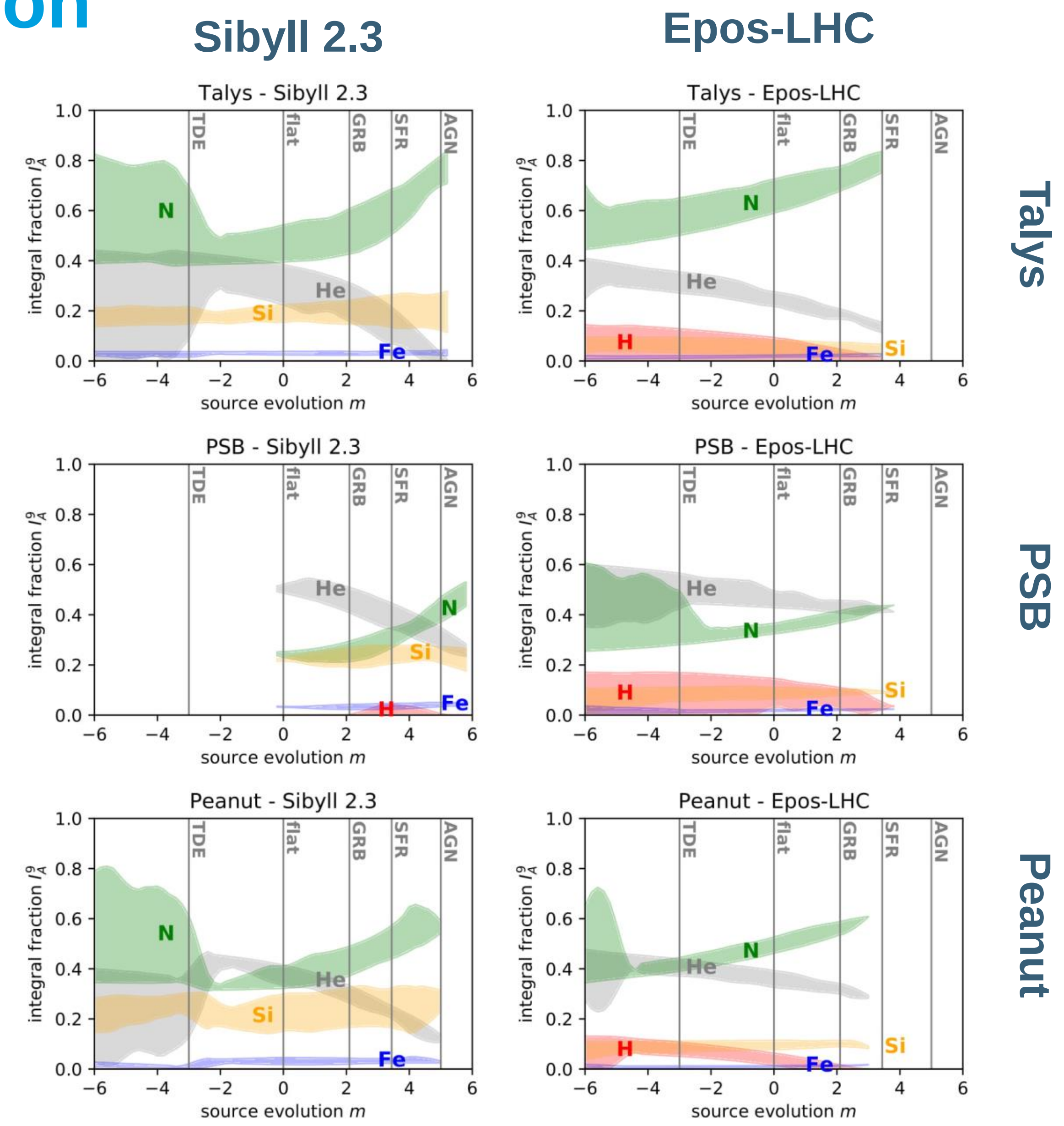


Cosmogenic neutrinos

For combination Talys – Sibyll 2.3

- Neutrino bands
  from UHECR fit contours

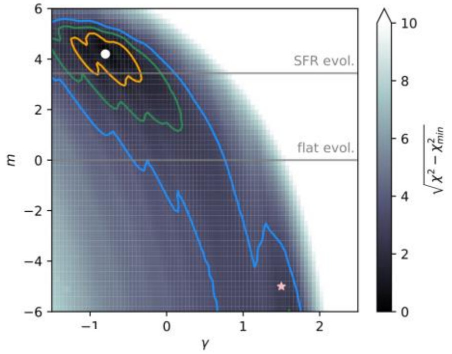
- Flux mainly depends on source evol.

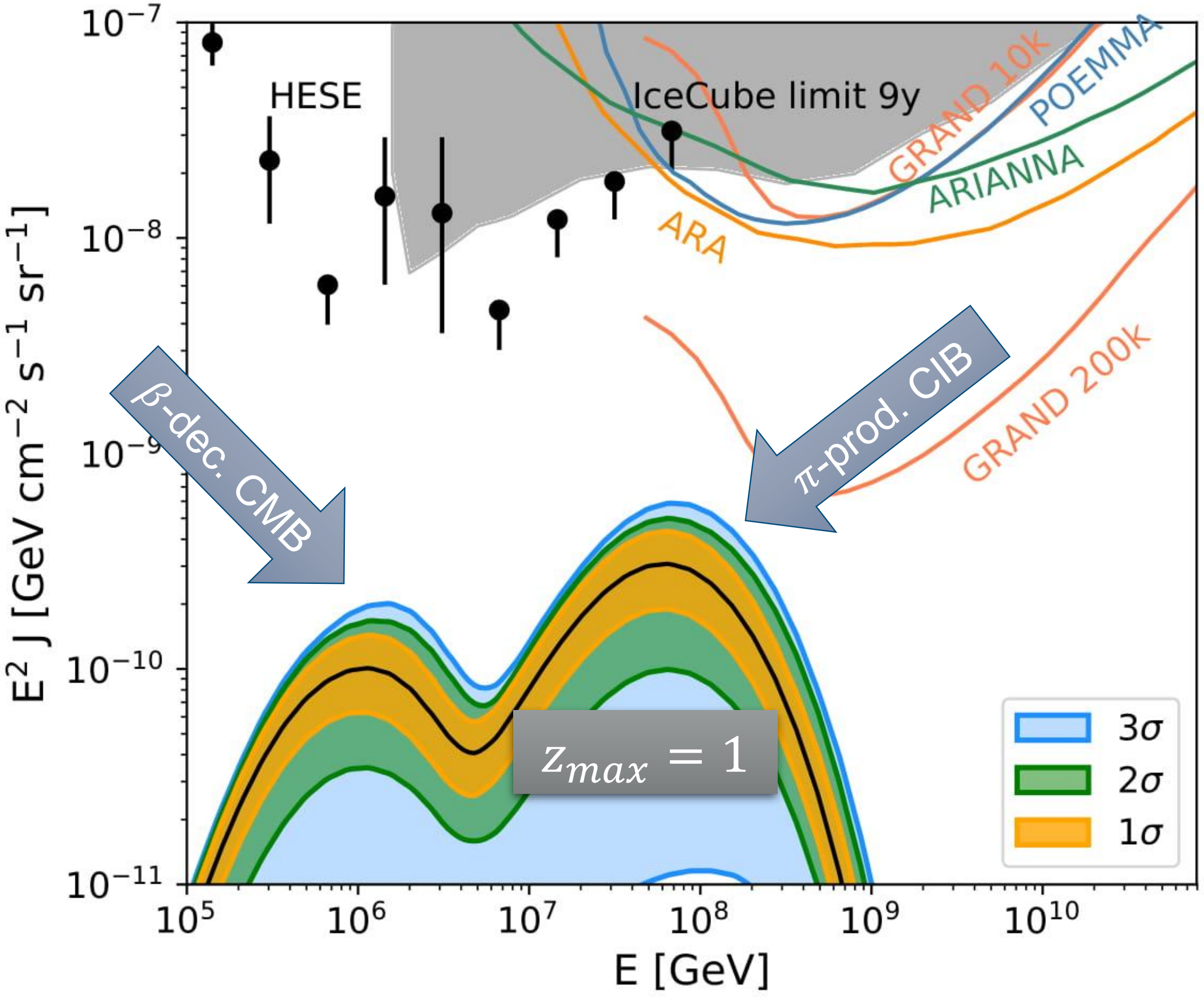
- How do contours change for different disintegration/ shower models?
  Are neutrinos affected?

- UHECRs sensitive to $z \lesssim 1$

How to continue at higher redshift?

$z_{max} = 1$



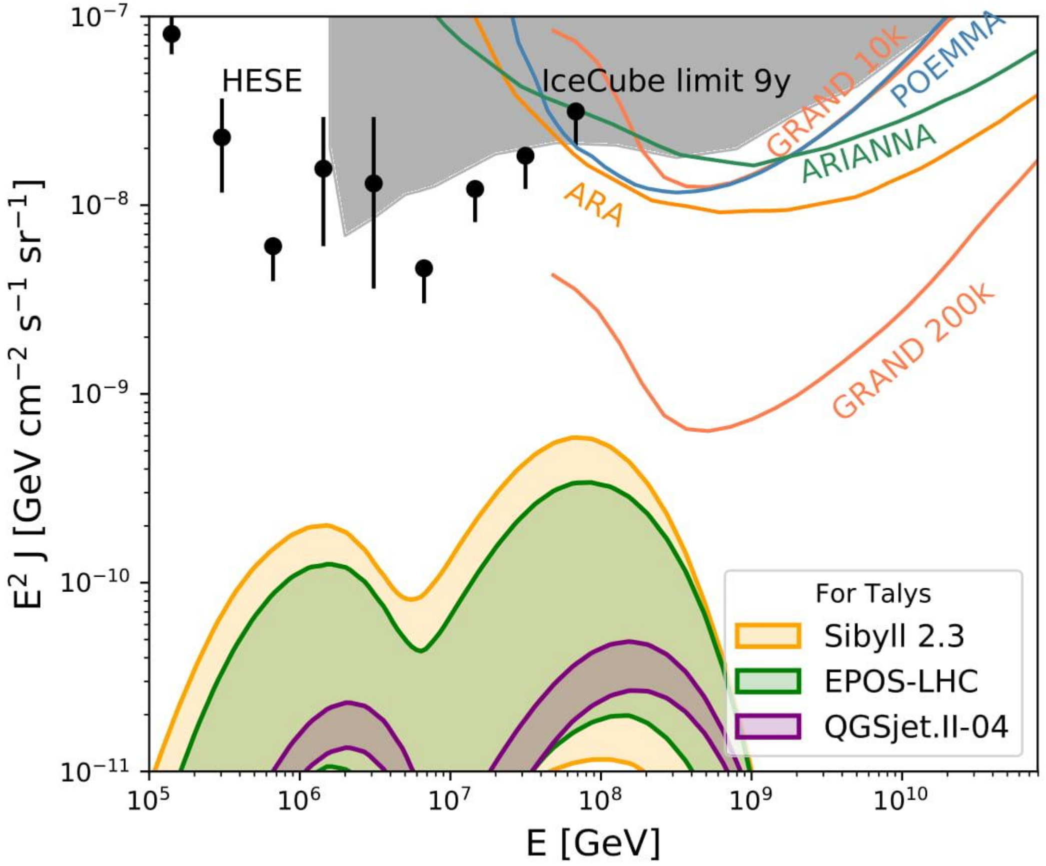


JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

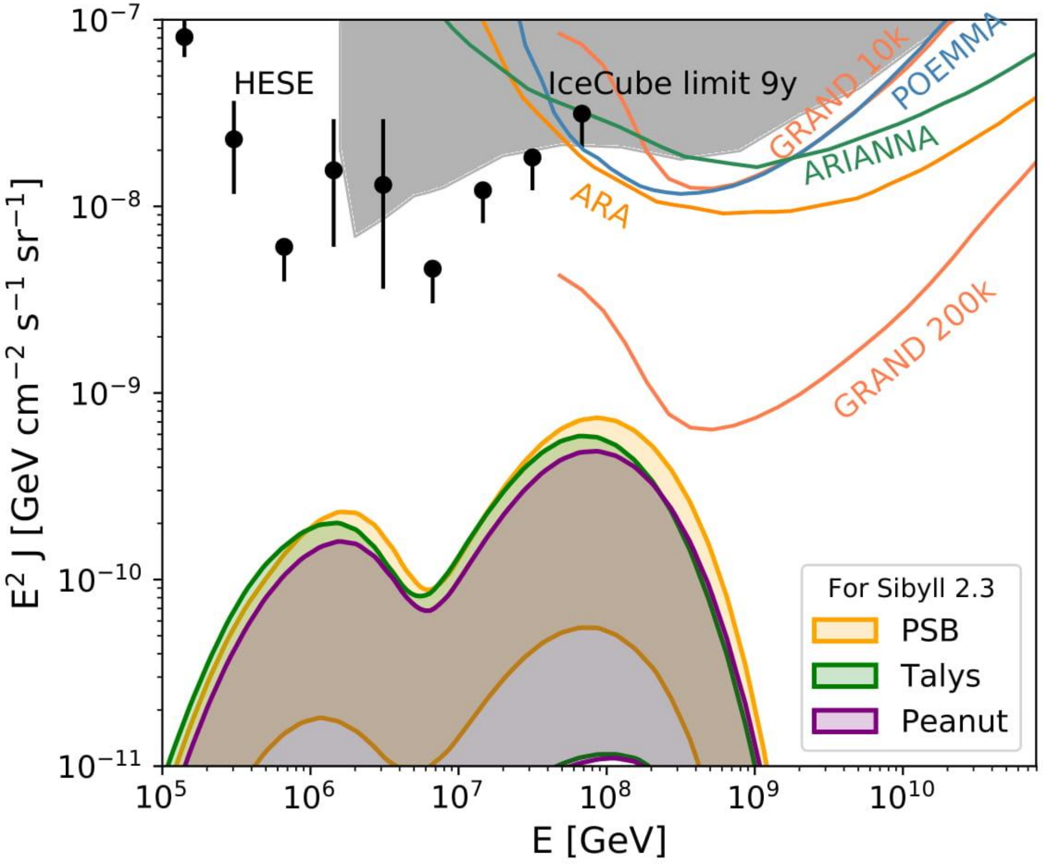
JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

Model dependence of Cosmogenic Neutrinos

Shower Model



Disintegration Model

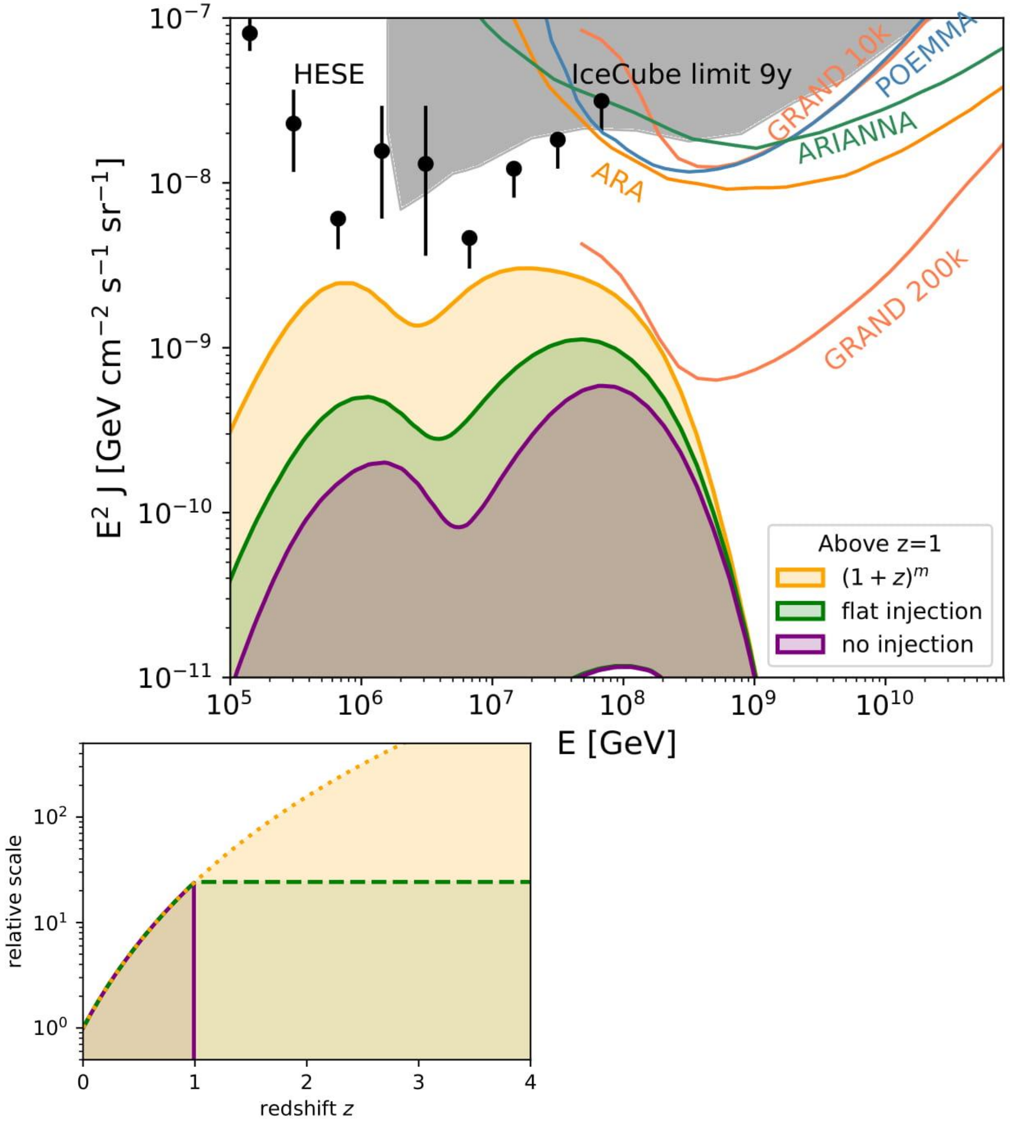


Maximal flux level robust within a factor 2-3

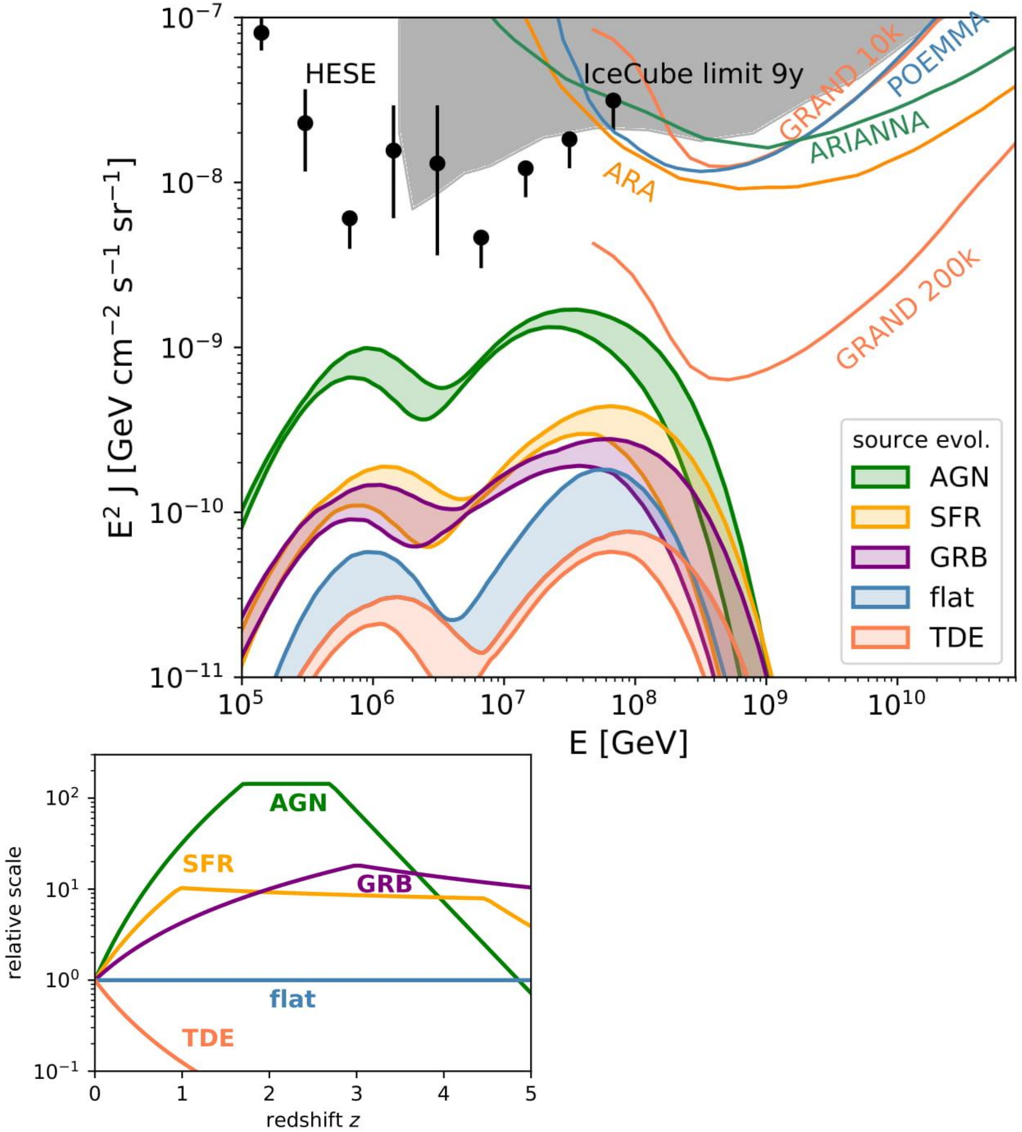
JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

Redshift extrapolation beyond z = 1

Source evolution

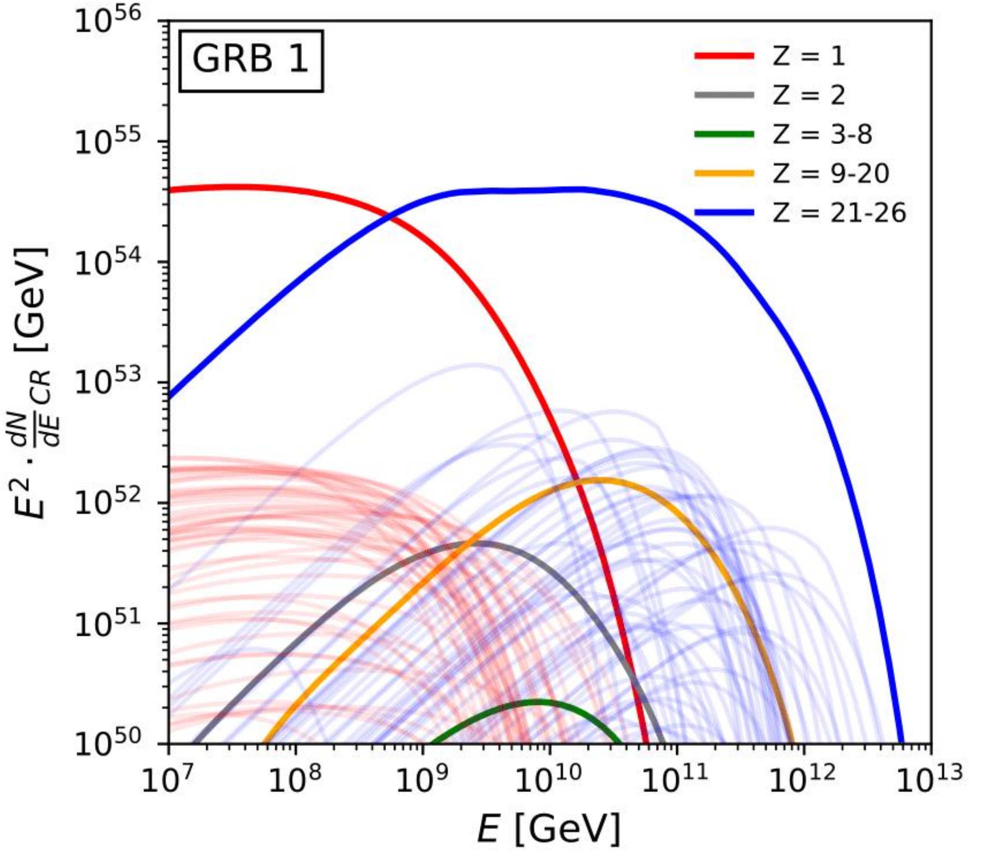


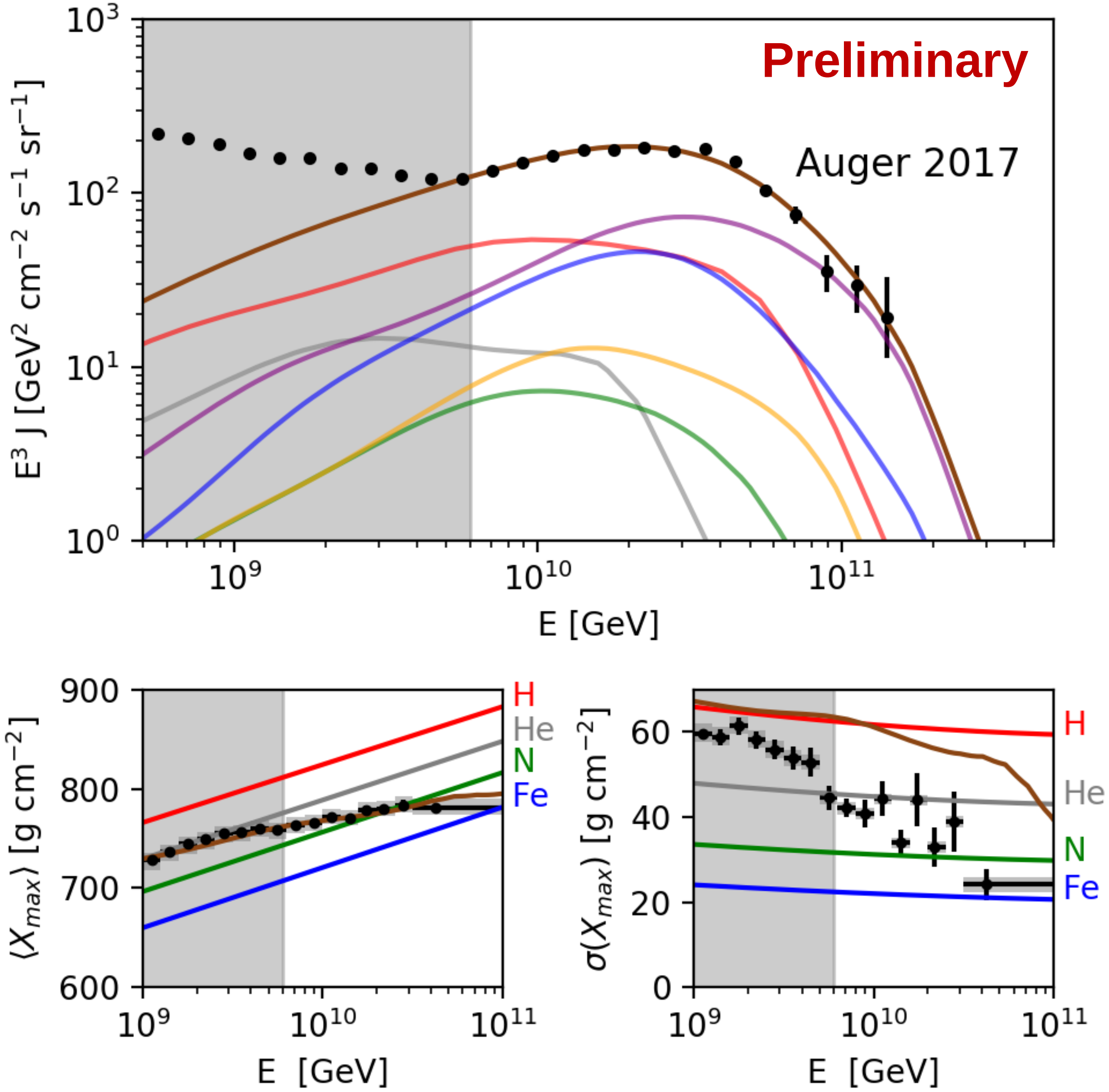
Specific source classes



Source example: GRB multi collision model

Multi Collision model - Stochastic engine





Conclusions

- Two distinct source populations favoured by fit:
  - Strong source evolution … but almost mono-chromatic sources
  - Soft spectral-index … but very local sources
- UHECR fit driven by envelope of rigidity-dependent cut-offs

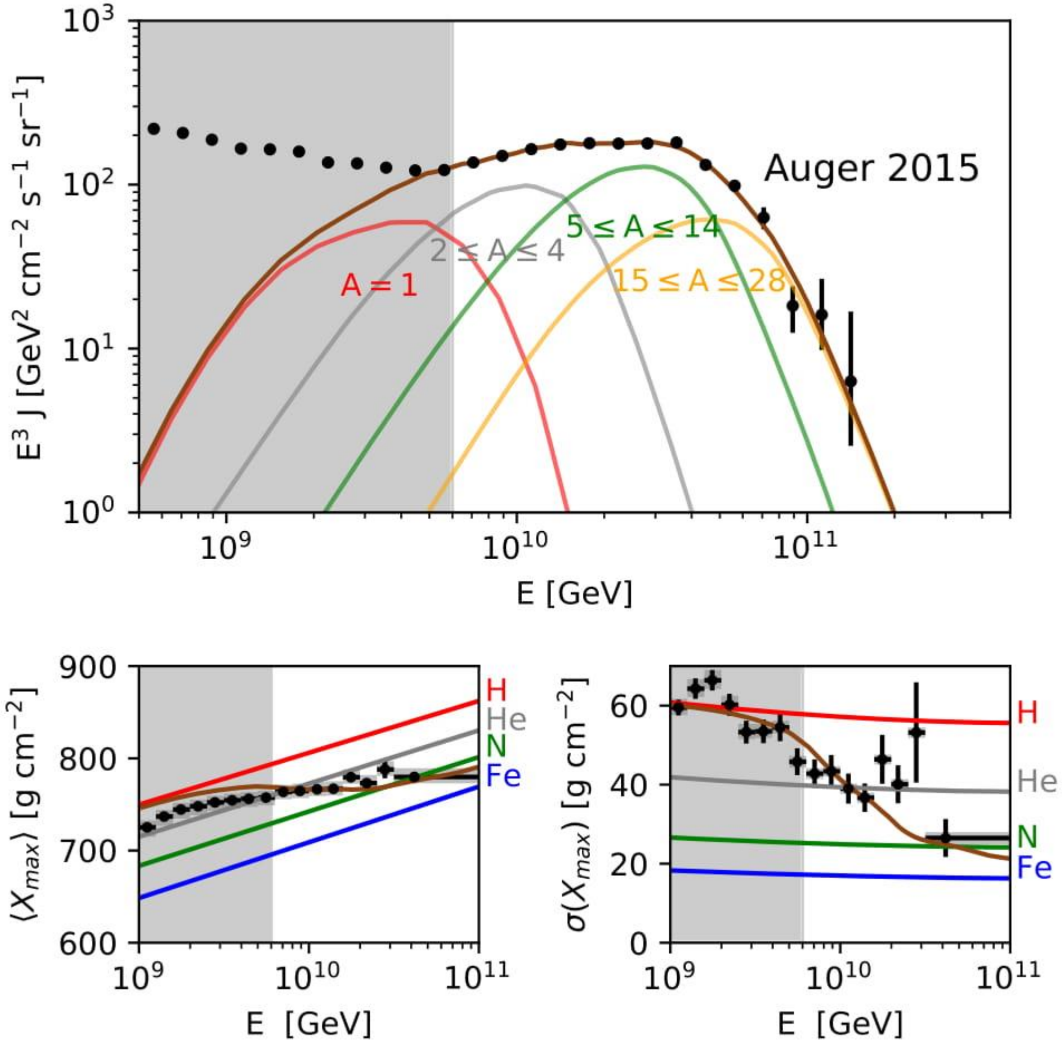
- The shower-model has a stronger impact on the injection composition interpretation than the disintegration-model

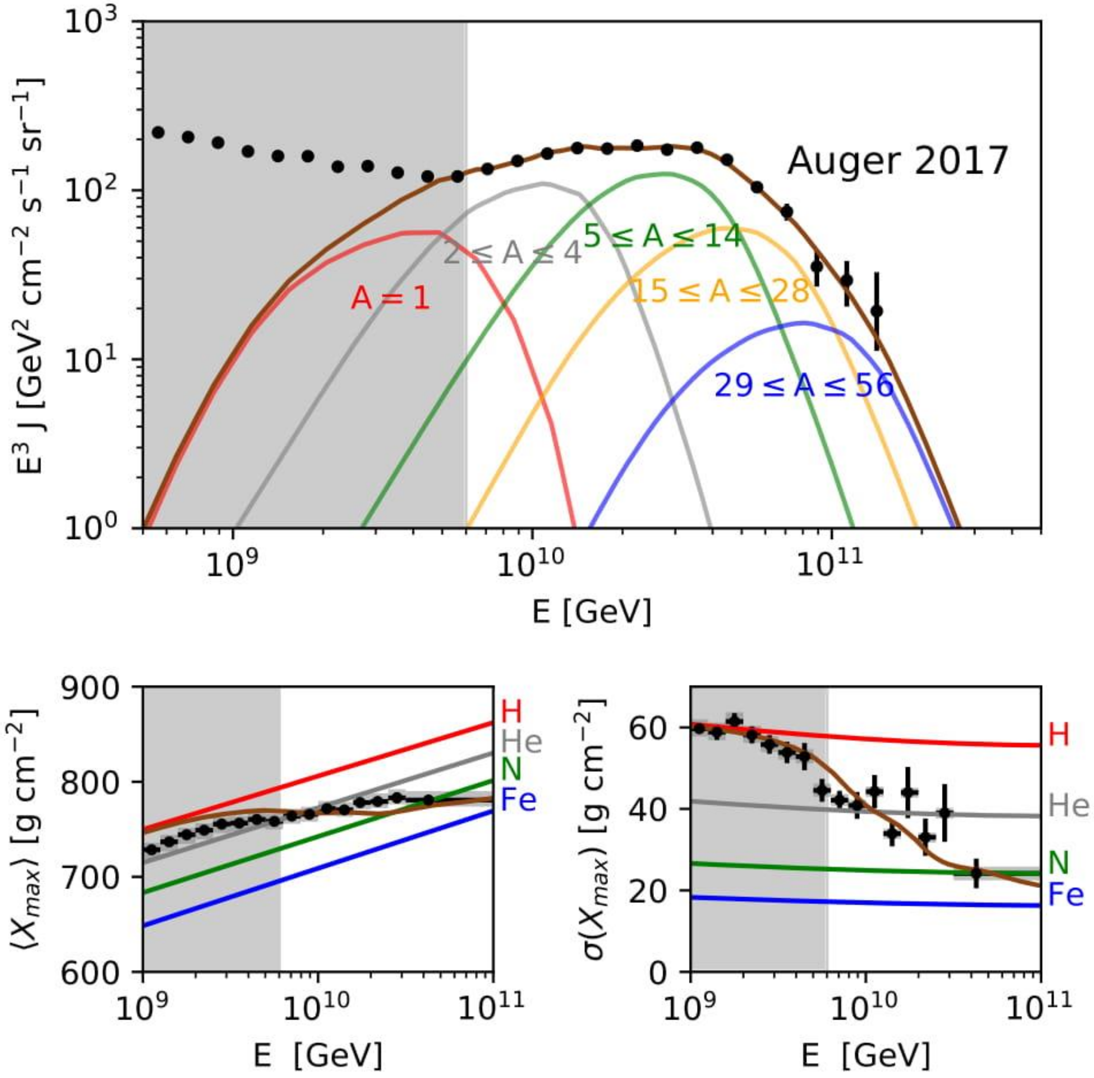
- The flux of cosmogenic neutrinos is relatively robust to disintegration and shower model and mainly dependent on source evolution
- Flux level might very low, given local source evolution

Backup Plots

Impact of 2017 dataset

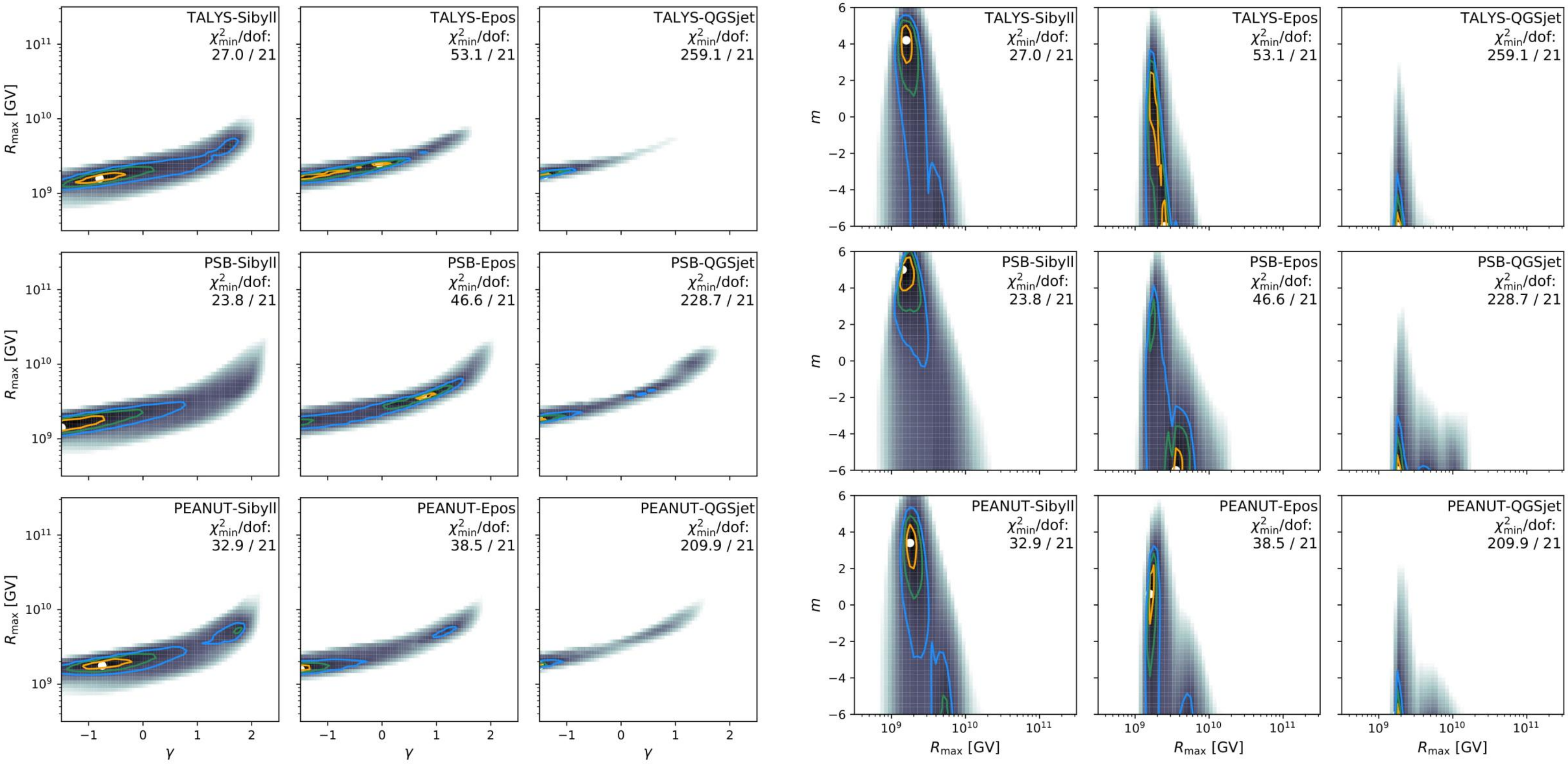
JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88





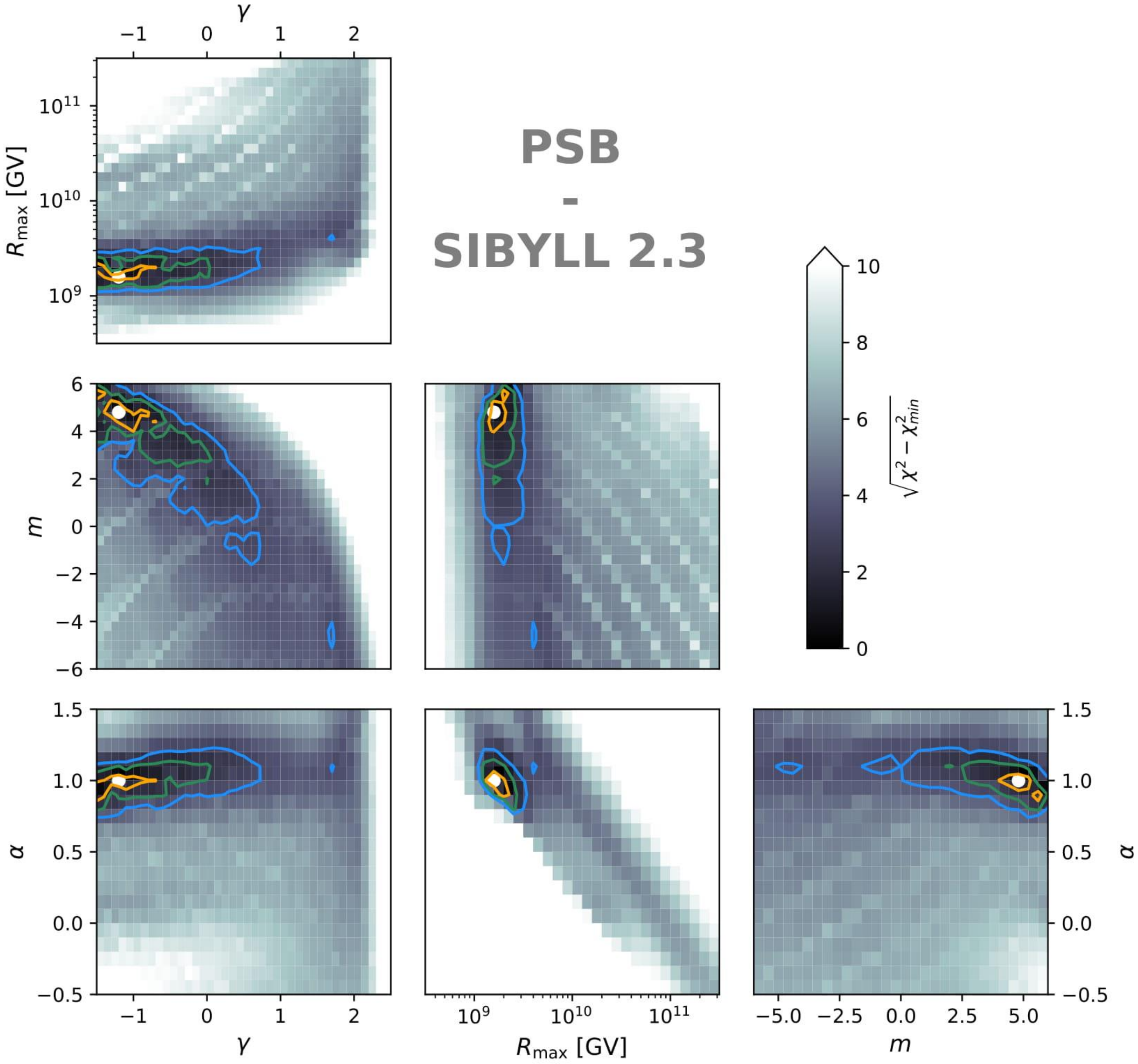
Model comparison

JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88



4D parameterscan

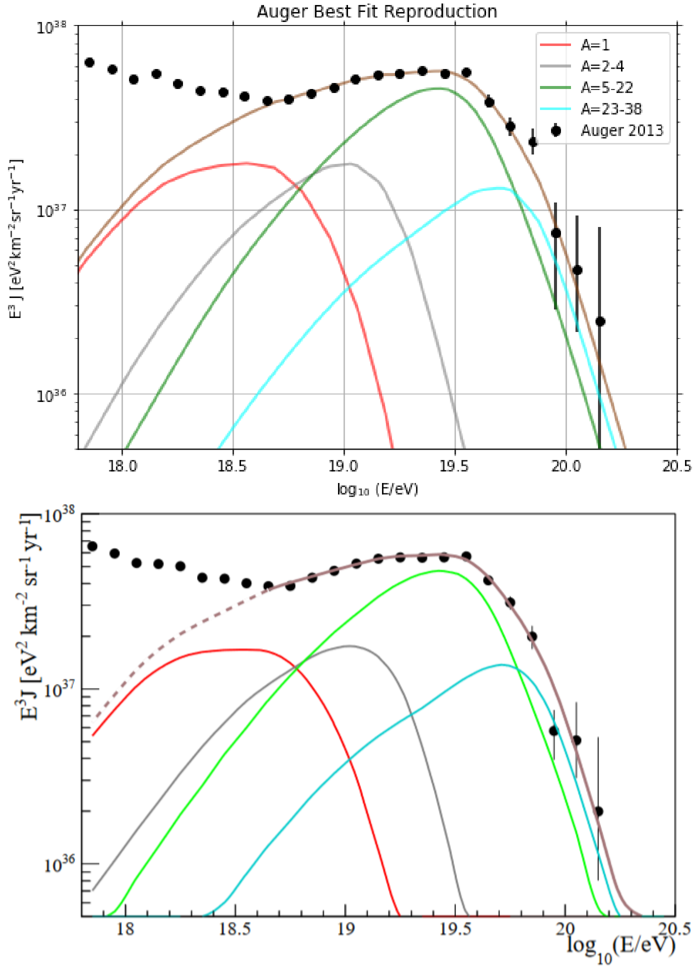
$$f_{\mathrm{cut}}(E) = \begin{cases} 1 & , E < Z_{\mathrm{A}}{}^{\alpha} R_{\max} \\ \exp\left(1 - \dfrac{E}{Z_{\mathrm{A}}{}^{\alpha} R_{\max}}\right) & , E > Z_{\mathrm{A}}{}^{\alpha} R_{\max} \end{cases}$$



PriNCe - some crosschecks

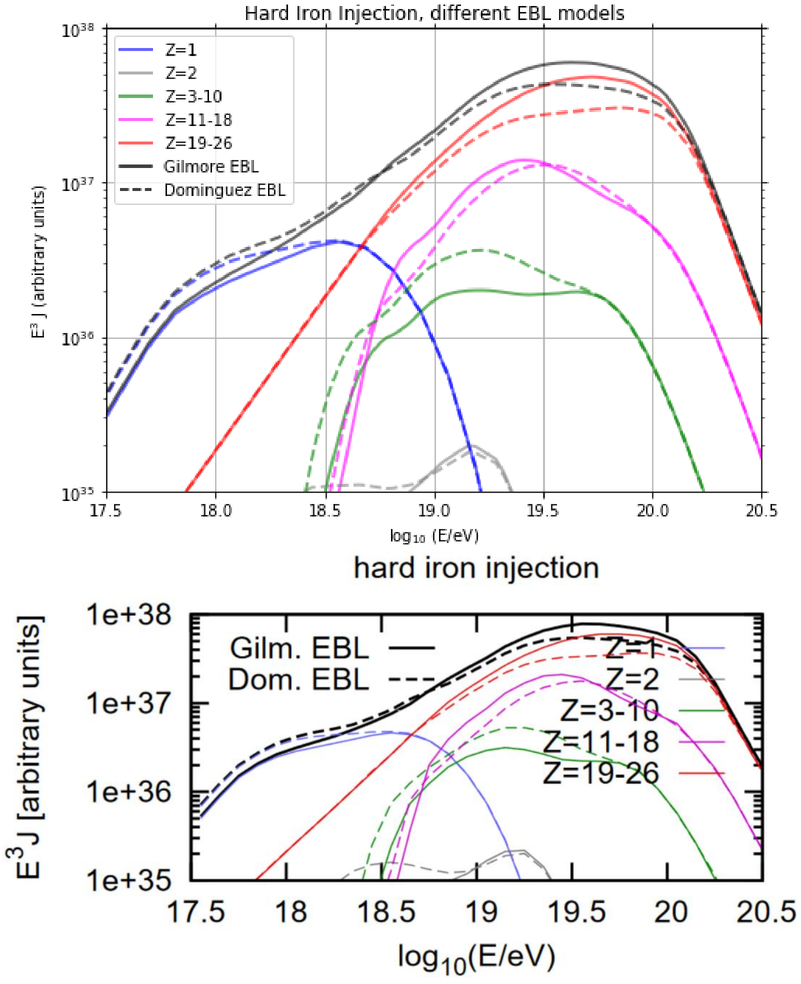
Compared to literature

Auger Combined fit



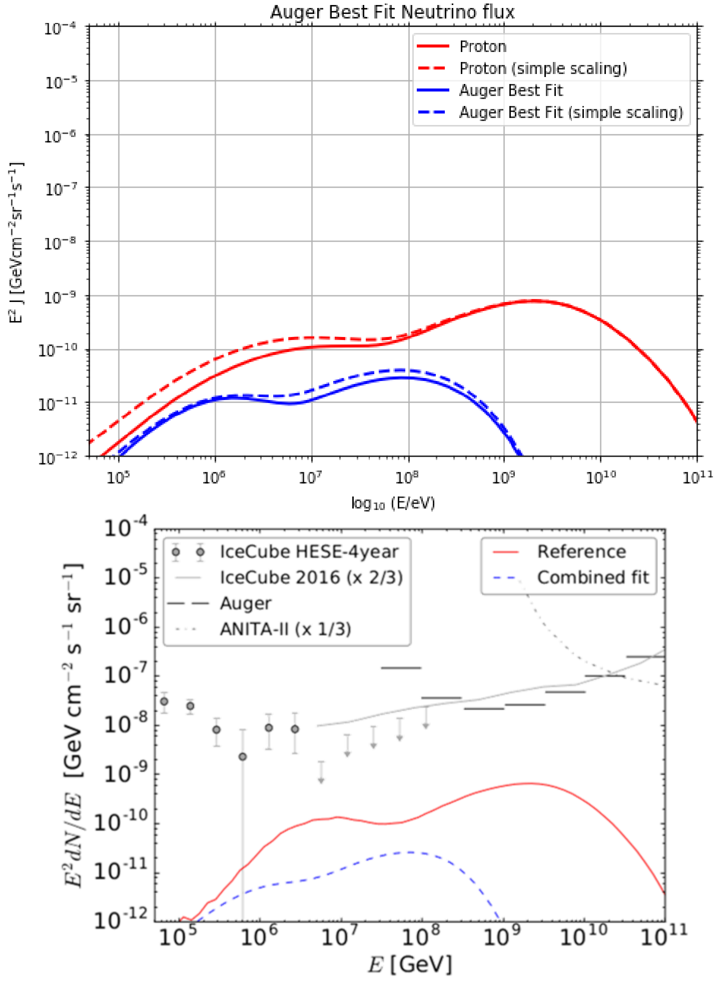
Auger Collaboration, JCAP04(2017)038

CIB dependency



Alves Batista, Boncioli, di Matteo, van Vliet, Walz, JCAP10(2015)063

Cosmogenic Neutrinos



van Vliet, Hörandel, Alves Batista, PoS(ICRC2017)562