Cosmogenic neutrinos from a fit to the Auger spectrum and composition

…and their dependence on the disintegration and air shower model

Jonas Heinze
UHECR-workshop, Paris
9.10.2018

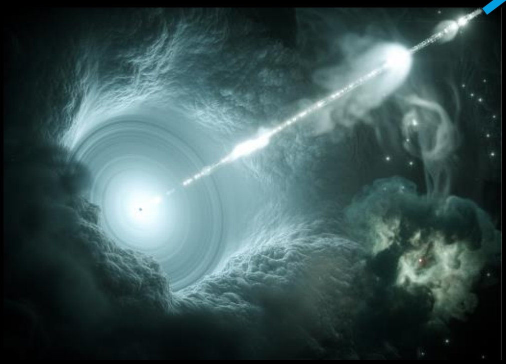
JH, A. Fedynitch, D. Boncioli, W. Winter
in preparation

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

UHE Cosmic Rays and Cosmogenic Neutrinos

Model inputs

Source: DESY



$^{A}_{Z}X$

Cross sections
Disintegration
Meson production

+

Environment
CIB Photon field
Magnetic field

γ

$^{A}_{Z-1}Y$

ν

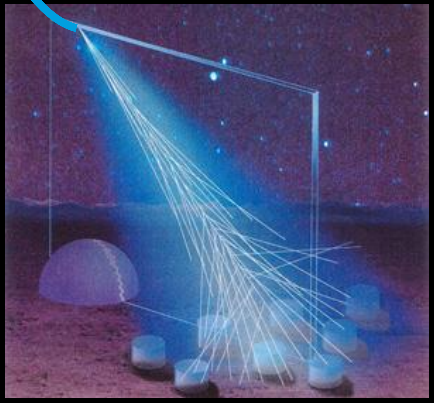
p

Source Model
Spectral shape
Composition

+

Source Evolution

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 Composition

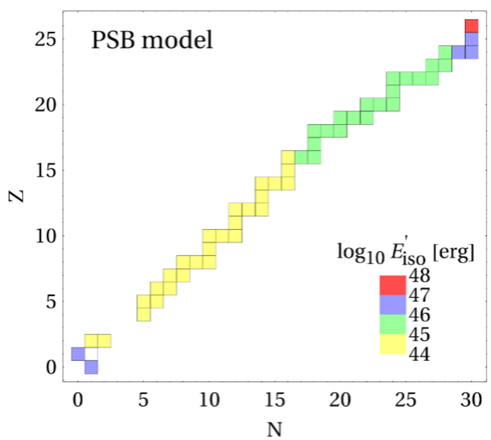
Assuming we know the injected composition perfectly…

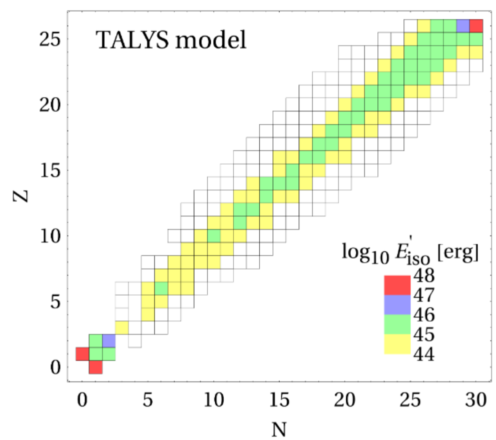
Photohadronic model

- 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?!

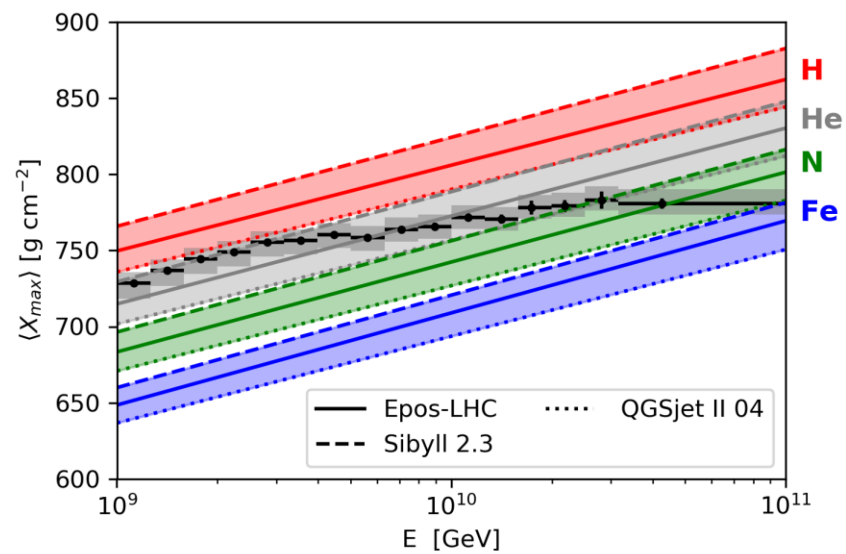
Air-Shower Model

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





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



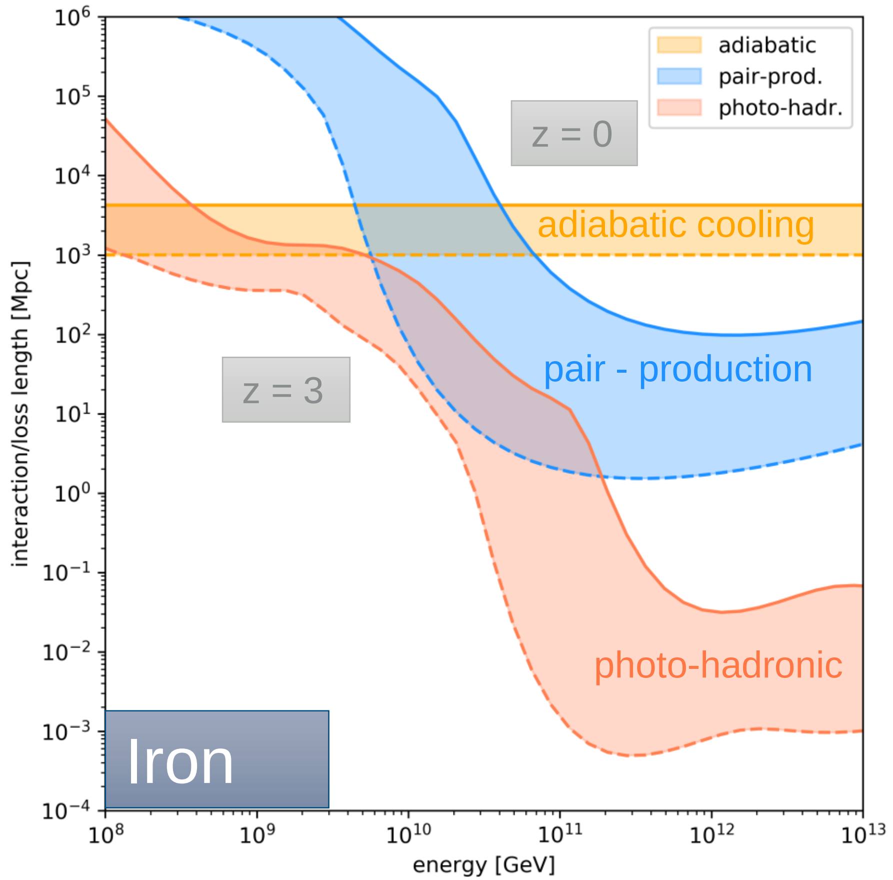
Which model has more impact on the astrophysical interpretation?

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



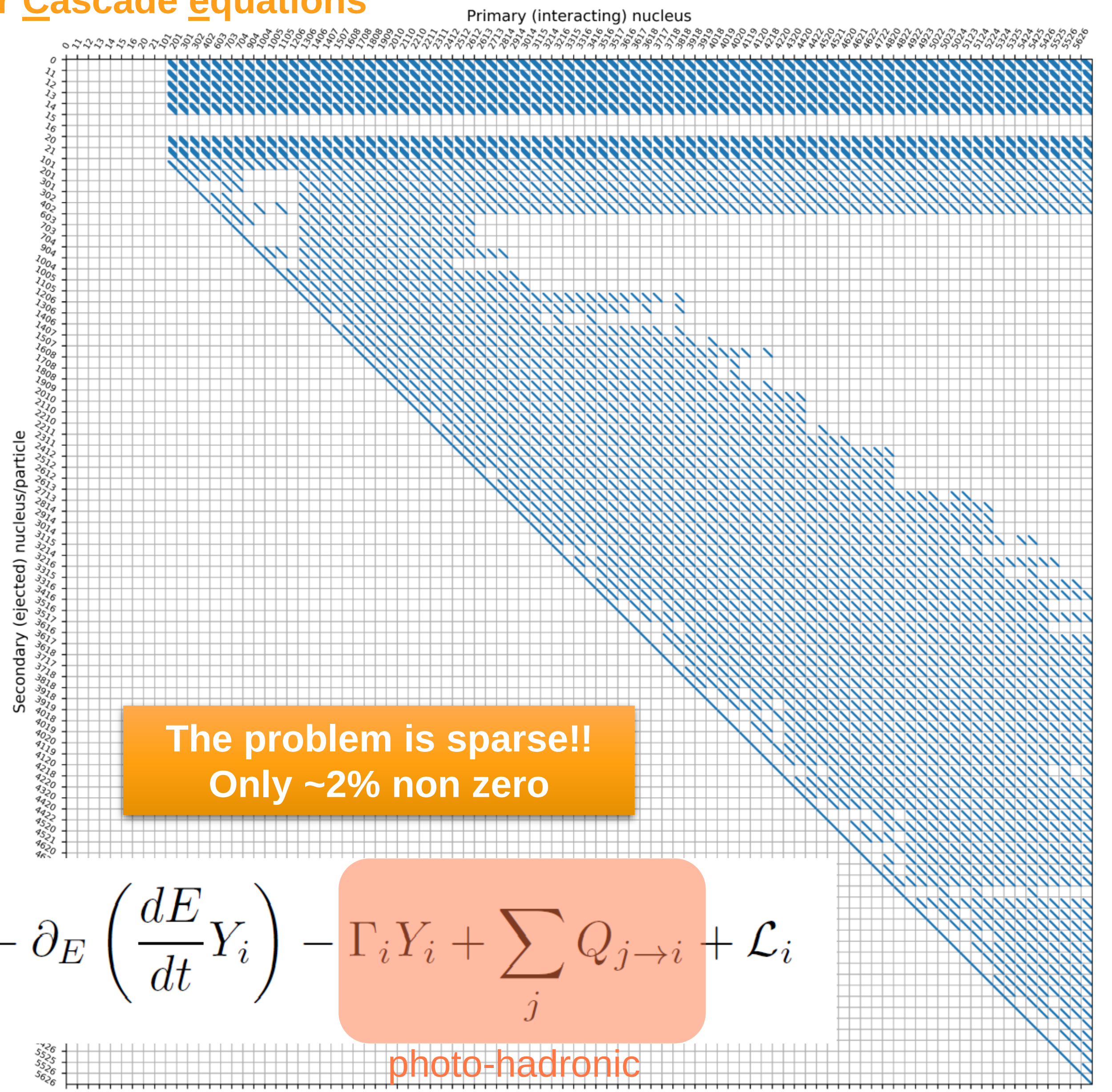
$$\partial_t Y_i(E,z) = + \partial_E(HEY_i) - \partial_E\left(\frac{dE}{dt}Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i} + \mathcal{L}_i$$

adiabatic cooling | pair - production | photo-hadronic | Injection

Propagation Code - PriNCe

Propagation including Nuclear Cascade equations

- Written in pure Python using Numpy and Scipy
- Specifically makes use of sparse matrix structure
- **20s – 40s** for single spectrum (depending on number of system species)
- More efficient to study model uncertainties than Monte-Carlo (cross-section, photon fields etc.)



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

Sources – Generic model

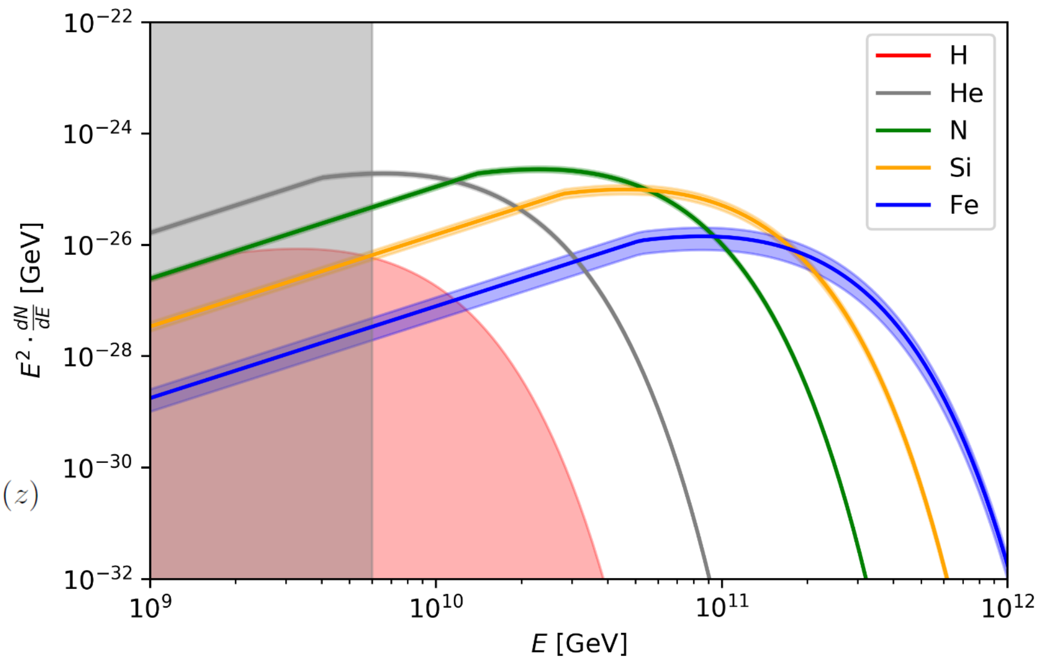
Generic assumptions

- 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

Results: Fit to spectrum and Composition

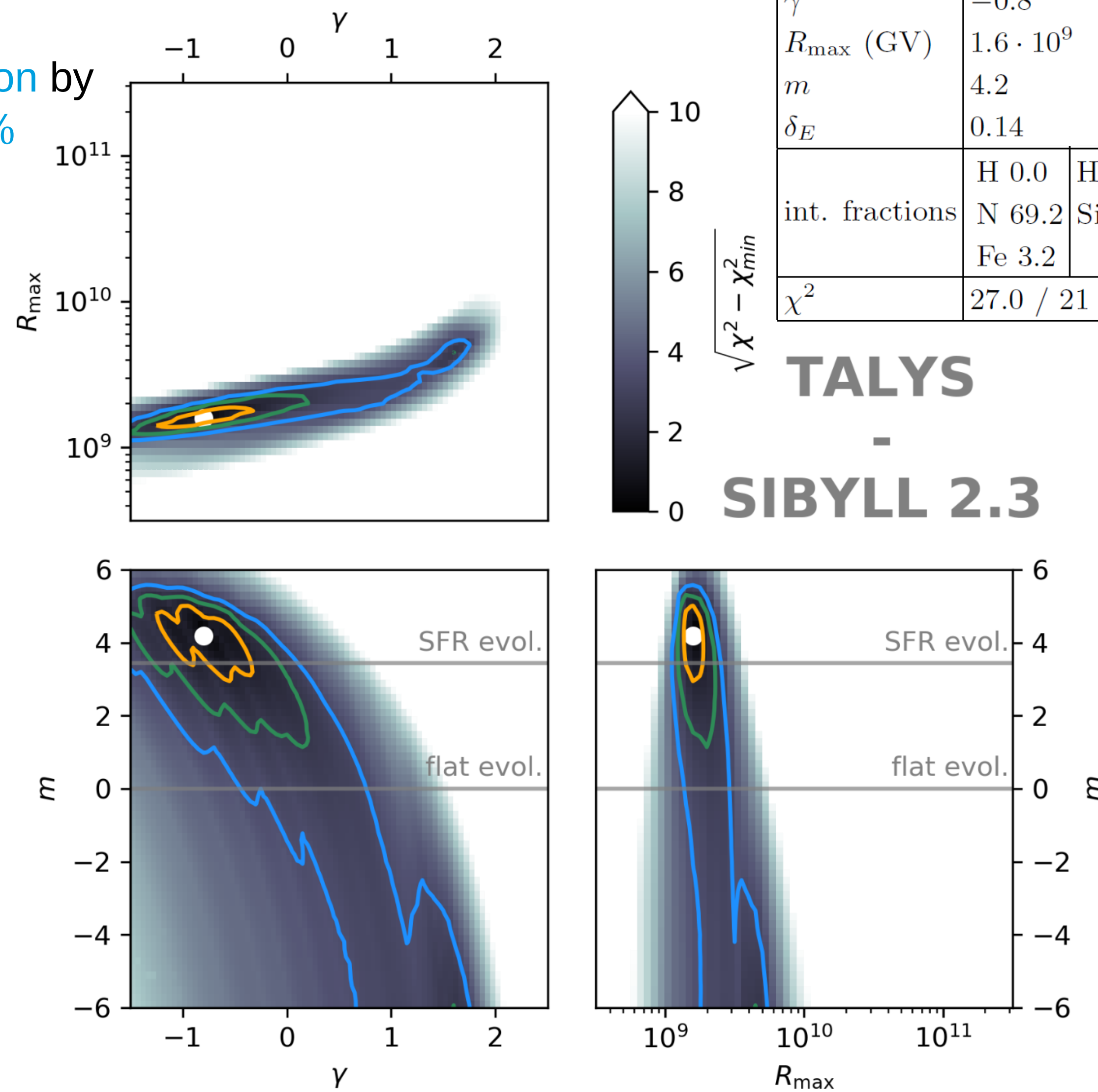
For combination Talys – Sibyll 2.3

- Fit **2017** spectrum + composition by χ^2-fit and energy shift of $\pm 14\ \%$
- 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

	best fit	
γ	-0.8	
$R_{\max}$ (GV)	$1.6 \cdot 10^9$	
m	4.2	
δ_E	0.14	
int. fractions	H 0.0	He 9.8
	N 69.2	Si 17.9
	Fe 3.2	
χ^2	27.0 / 21	

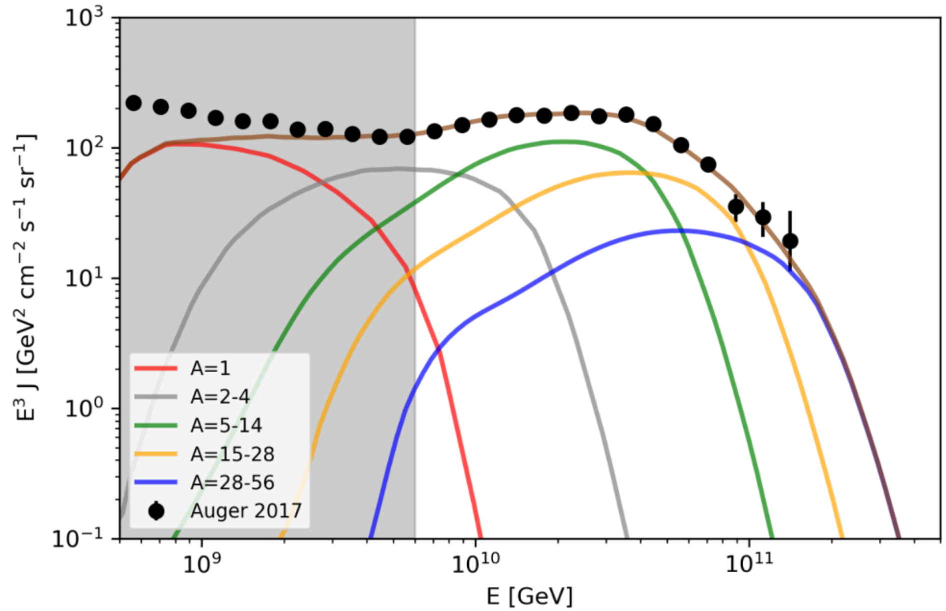


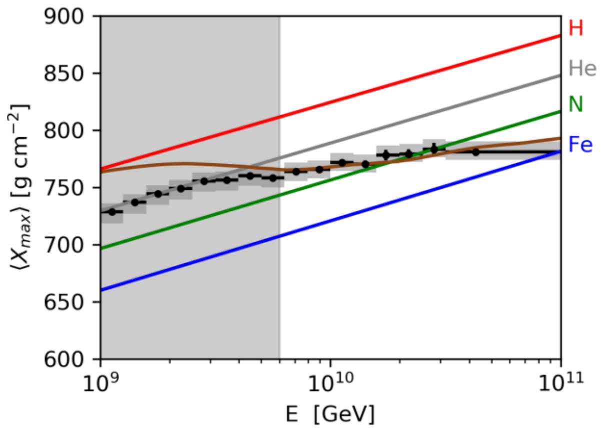
TALYS - SIBYLL 2.3

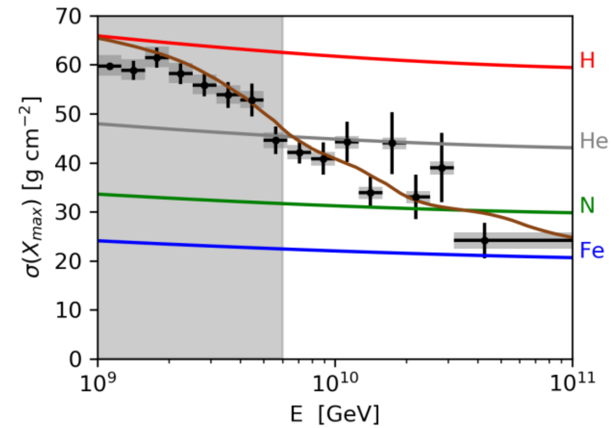
Results: Best fit spectrum

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)





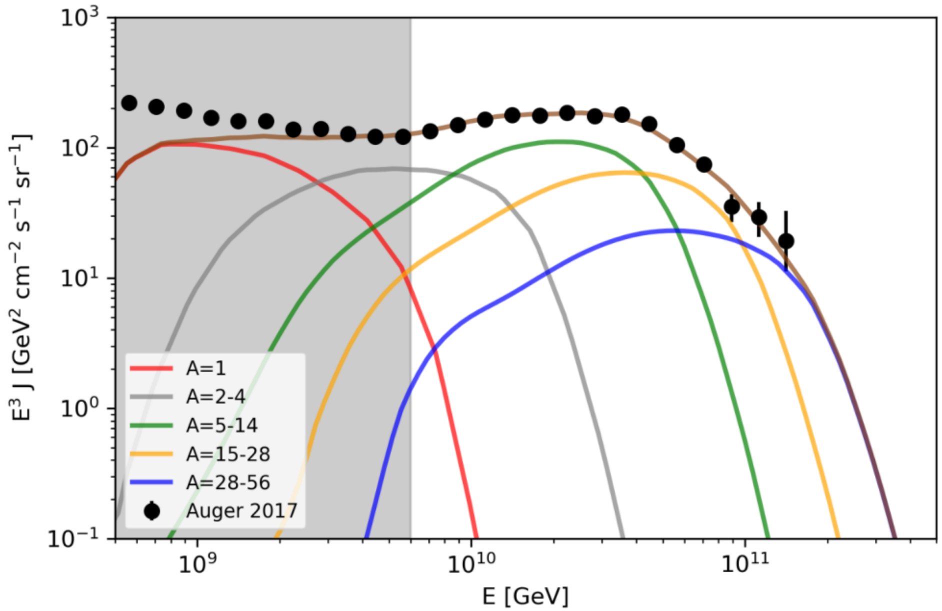


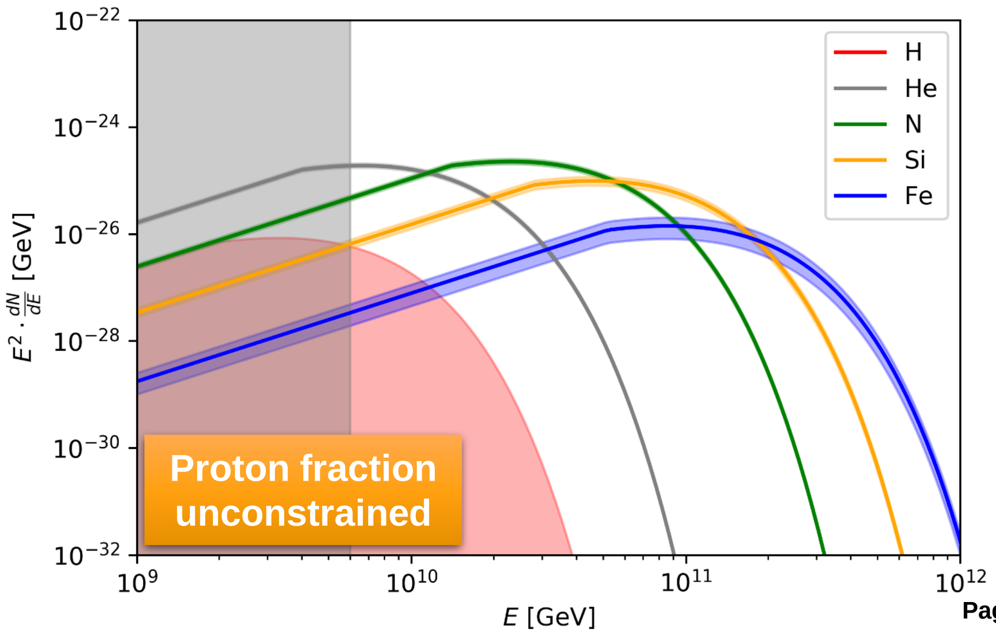
Results: Best fit spectrum

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)

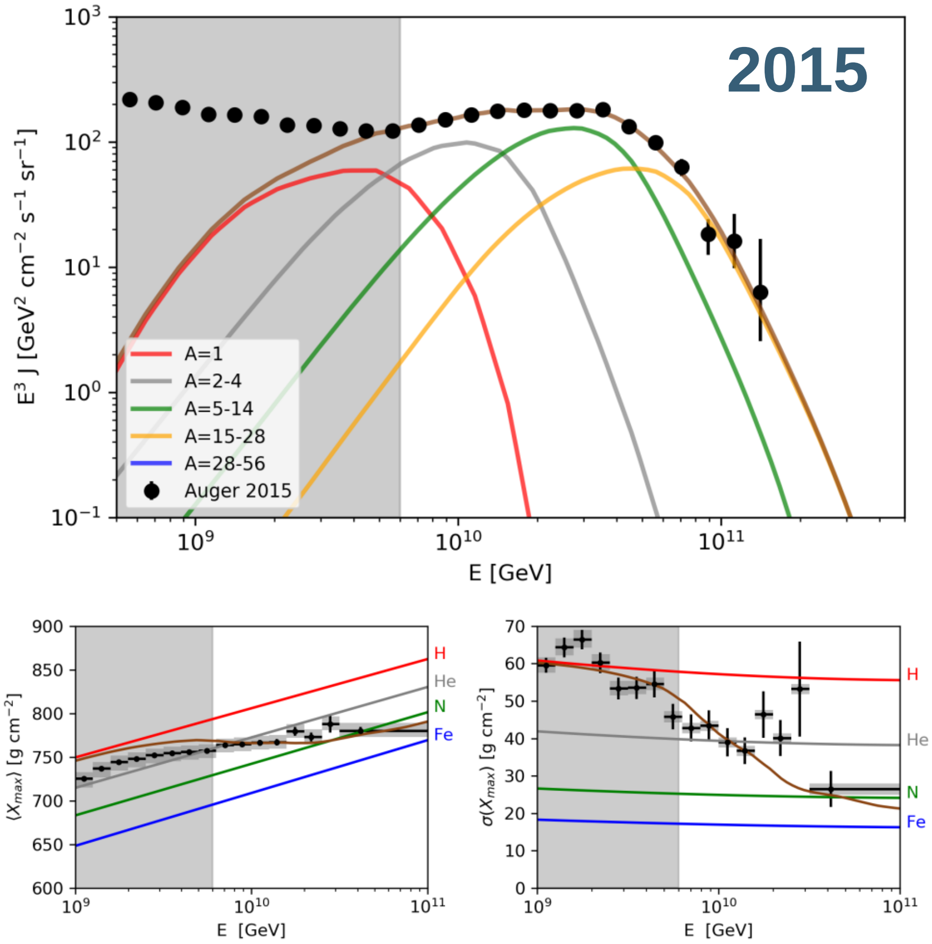
Iron fraction constrained! (Only with 2017 data)

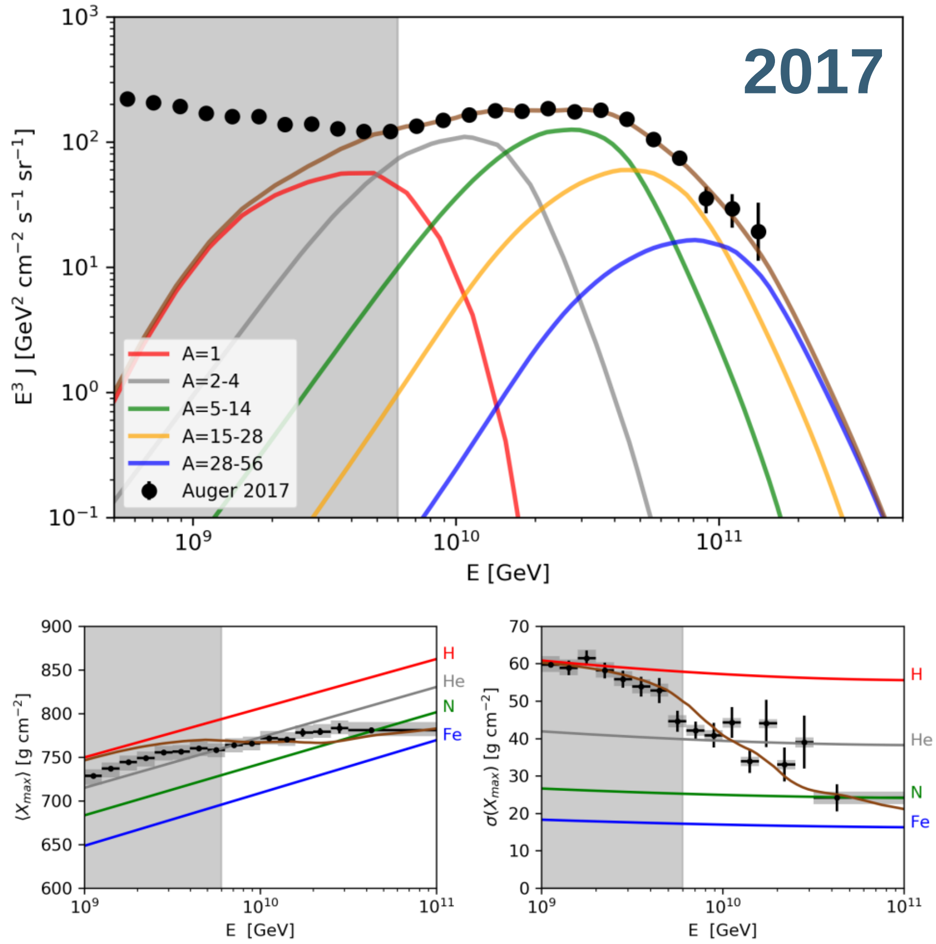




Auger 2015 vs Auger 2017 data

Best fit Spectra using flat evolution





Cosmogenic neutrinos

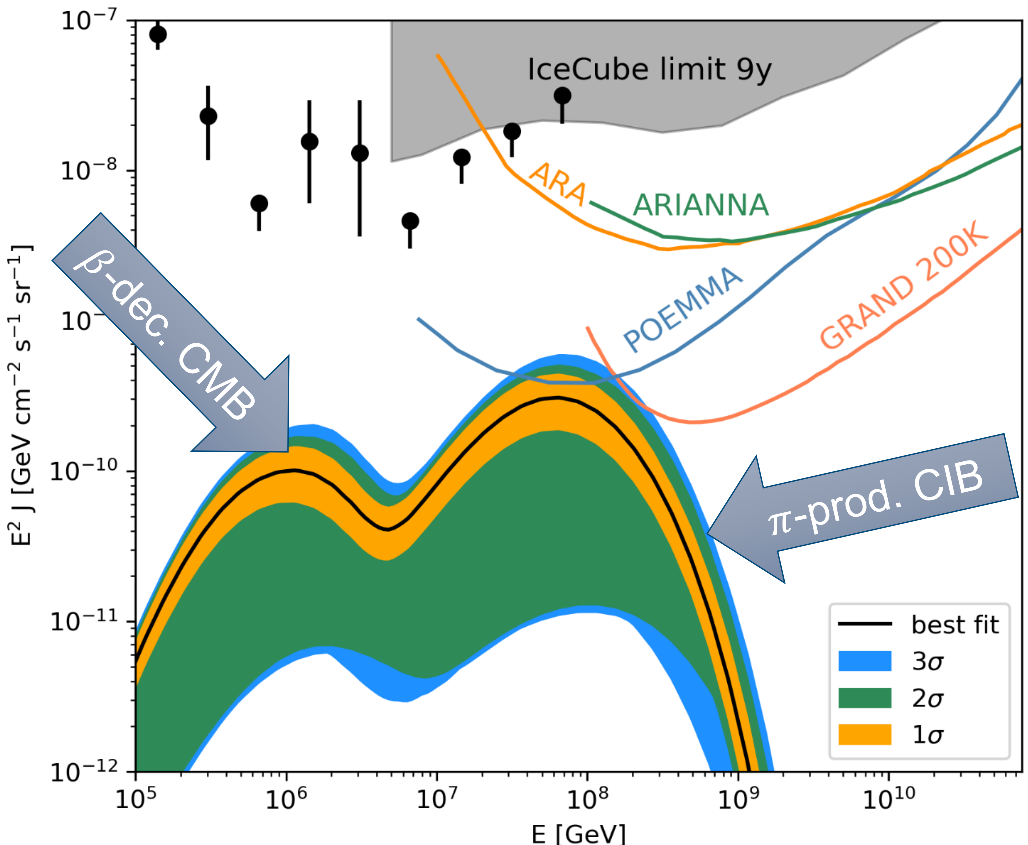
For combination Talys – Sibyll 2.3

- Neutrino bands
  from UHECR fit contours

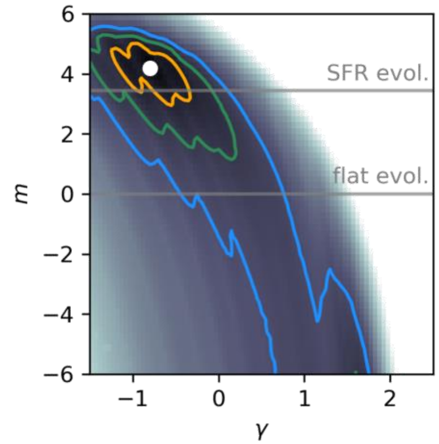
- Flux mainly depends on source evol.

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

- UHECRs sensitive to z ≲ 1



How to continue at higher redshift?



$z_{max} = 1$

Model dependence of the Fit

Compared in $\gamma - m$ space

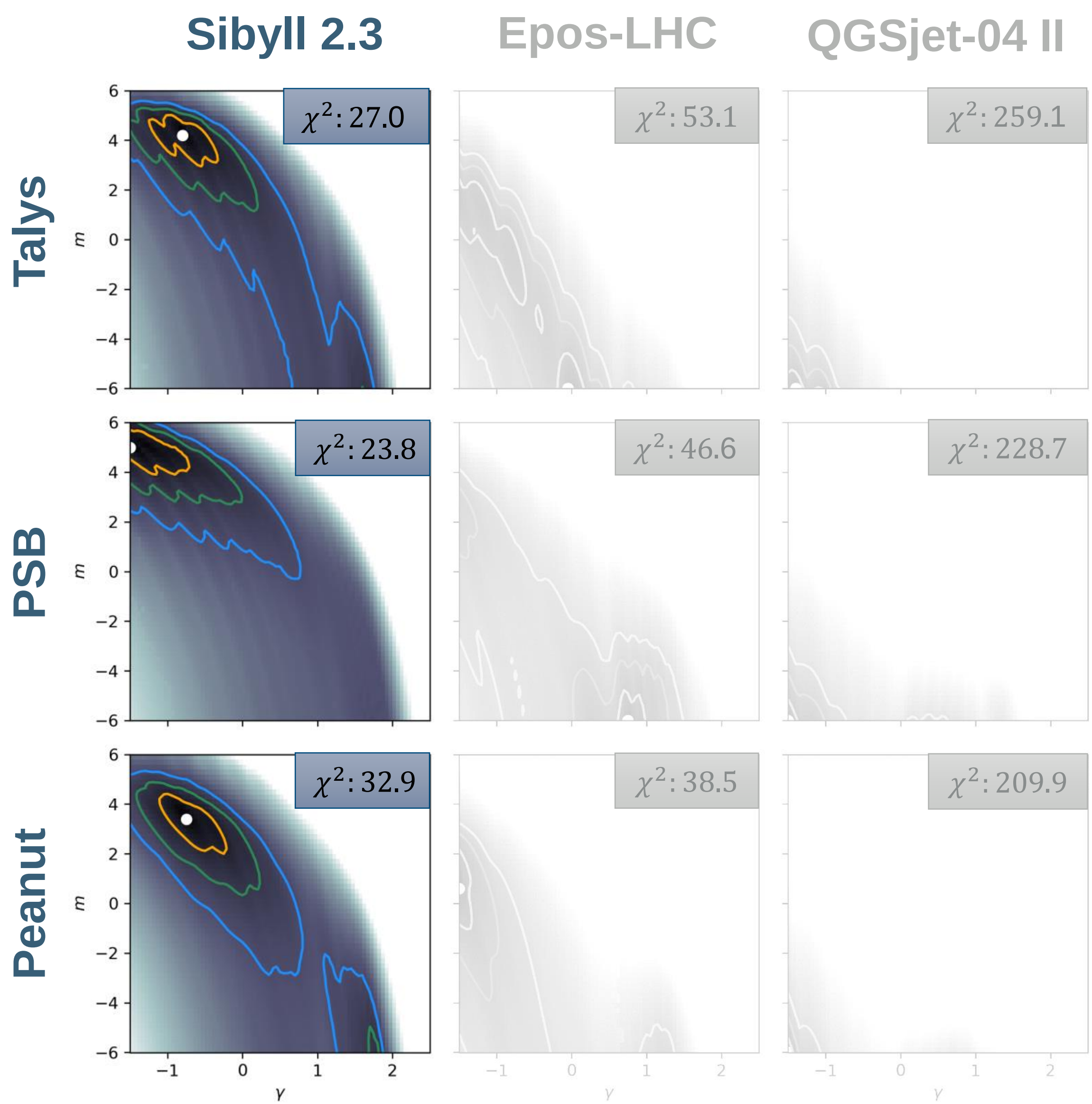
Disintegration model

- 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



Model dependence of the Fit

Compared in $\gamma - m$ space

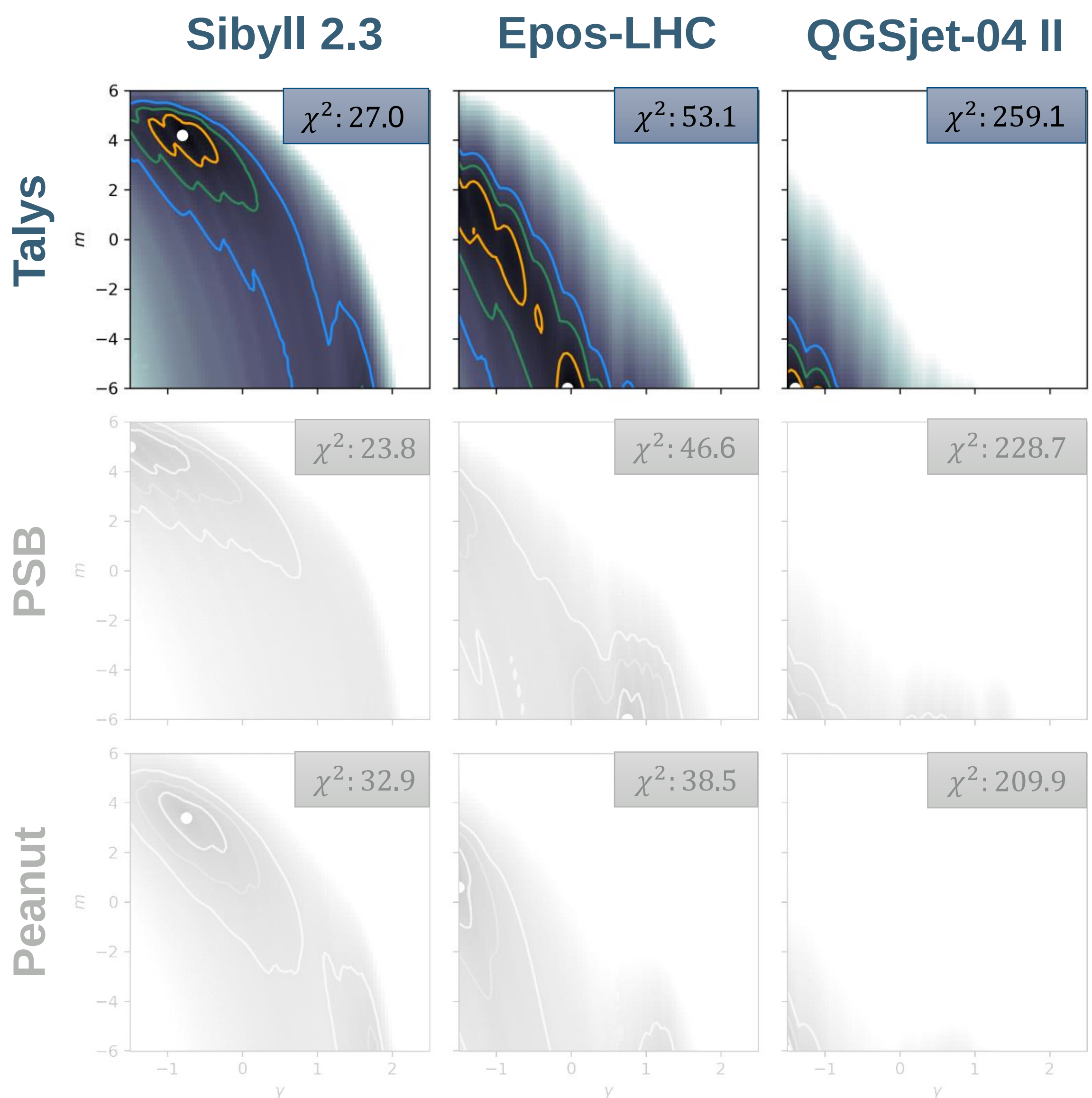
Disintegration model

- 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



Model dependence of the Fit

Compared in $\gamma - m$ space

Disintegration model

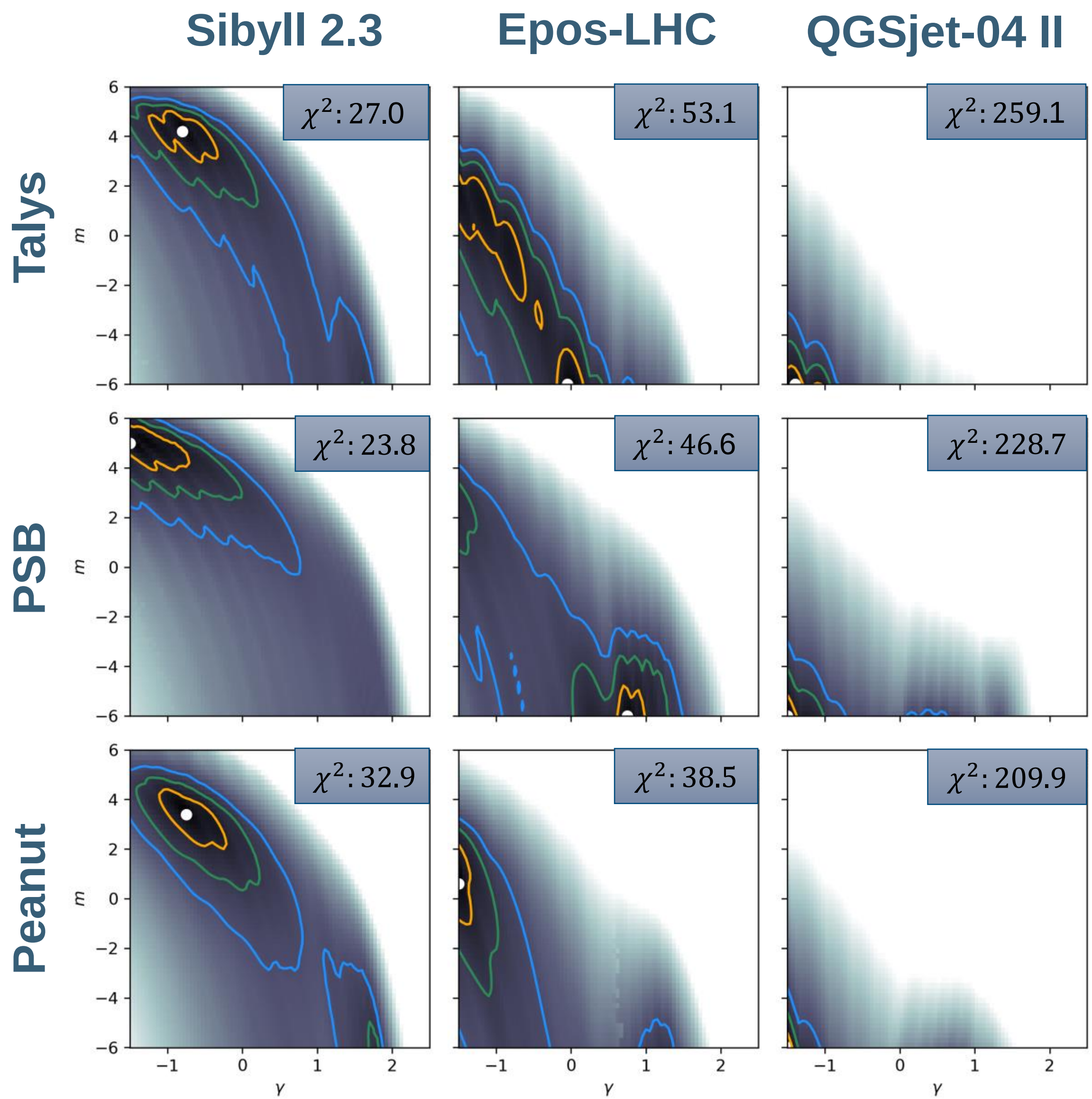
- Qualitatively similar fits
- PSB: Ligher injection
- Peanut/Talys: Heavier injection

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!



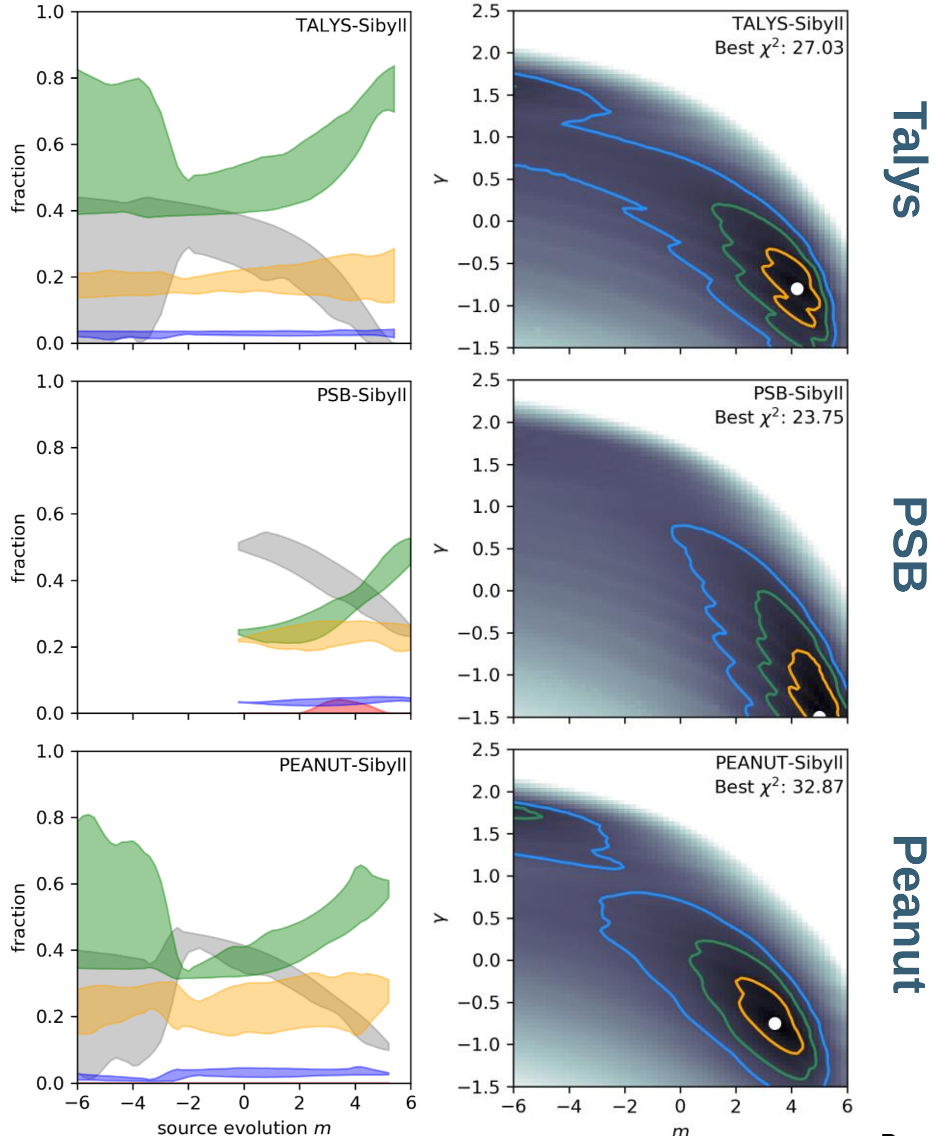
Model dependence of composition

Composition at the source: Sibyll 2.3

- **Fractions of total emissivity!**

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

- 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



Model dependence of composition

Composition at the source: Epos-LHC

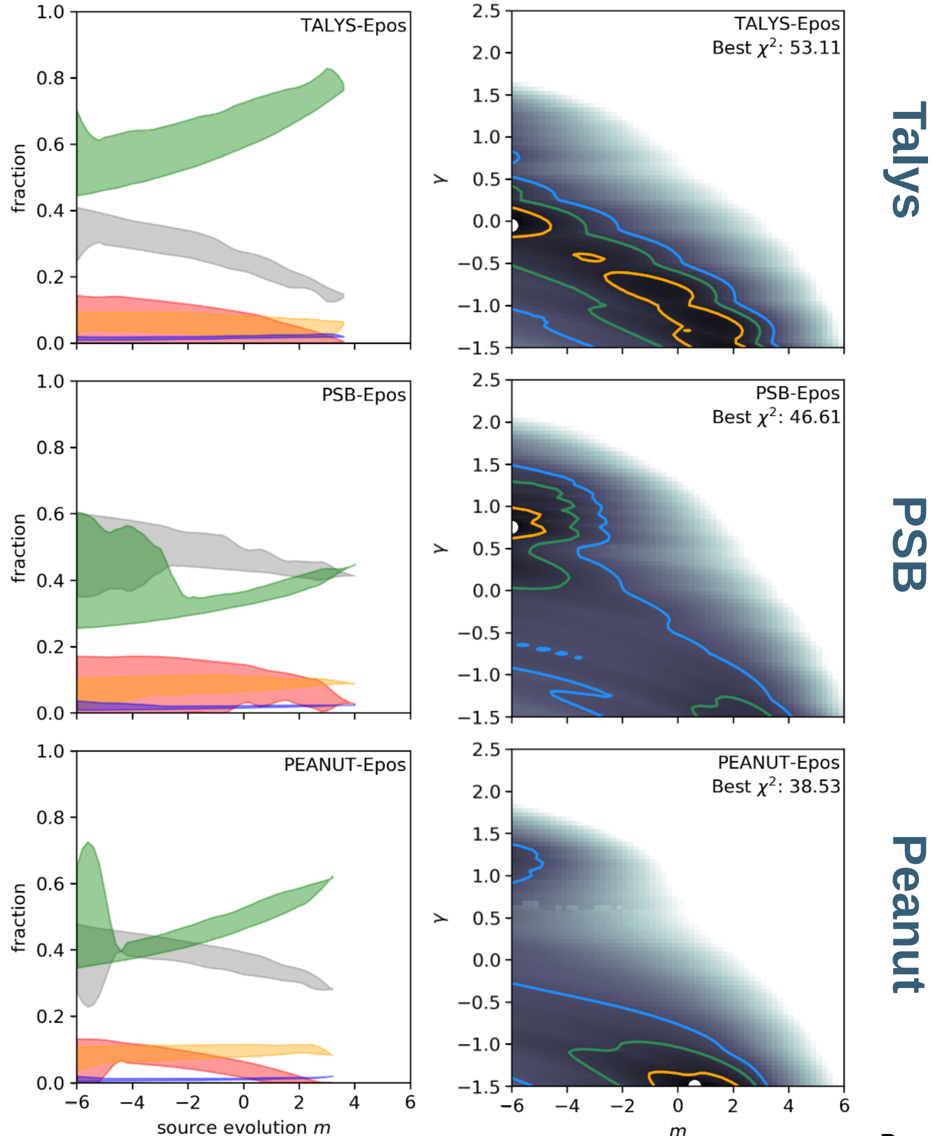
- **Fractions of total emissivity!**

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

- 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



Model dependence of composition

Composition at the source: Sibyll 2.3 vs Epos-LHC

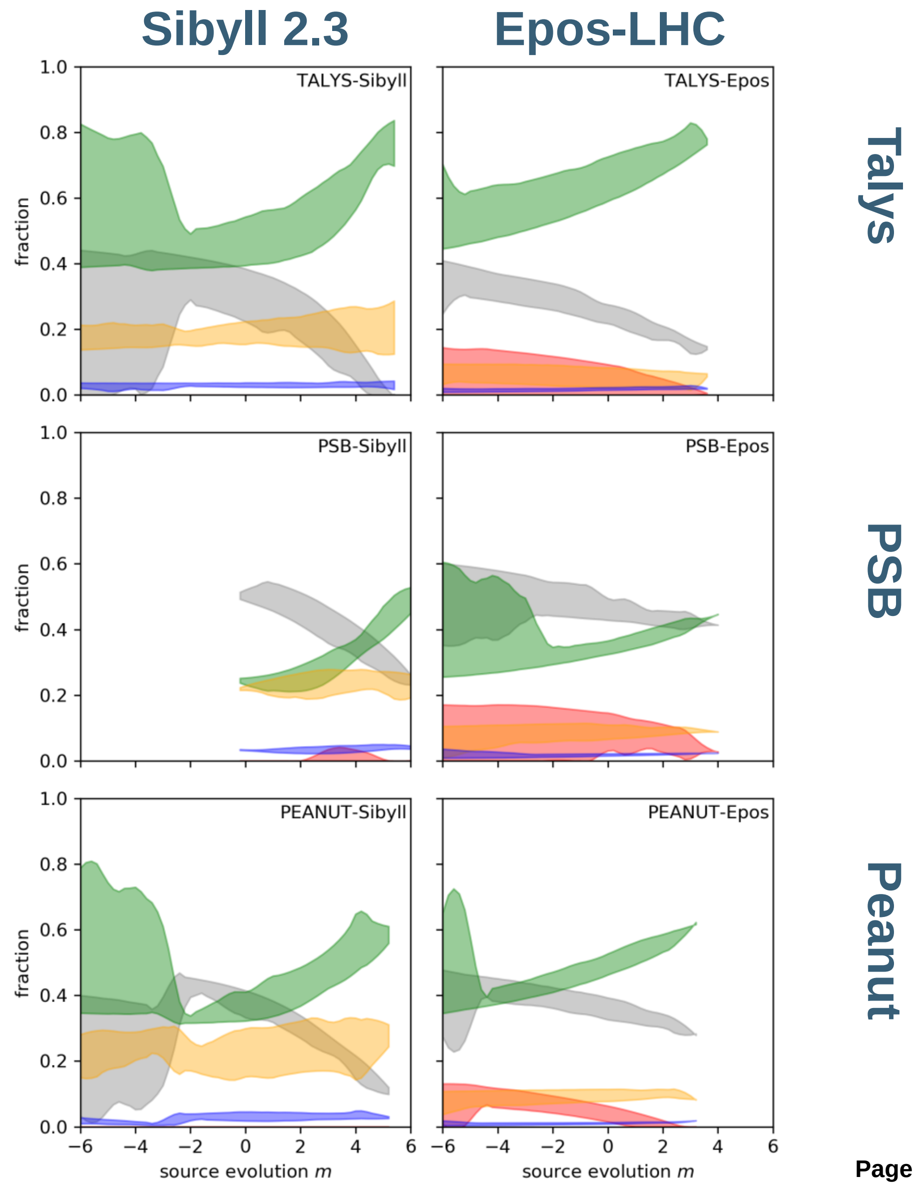
- **Fractions of total emissivity!**

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

- 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



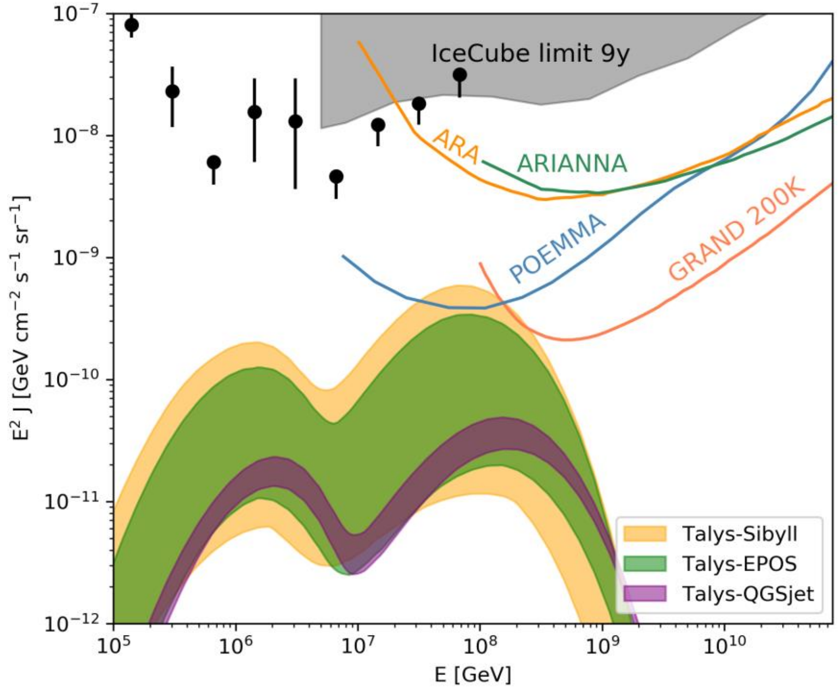
Model dependence of Cosmogenic Neutrinos

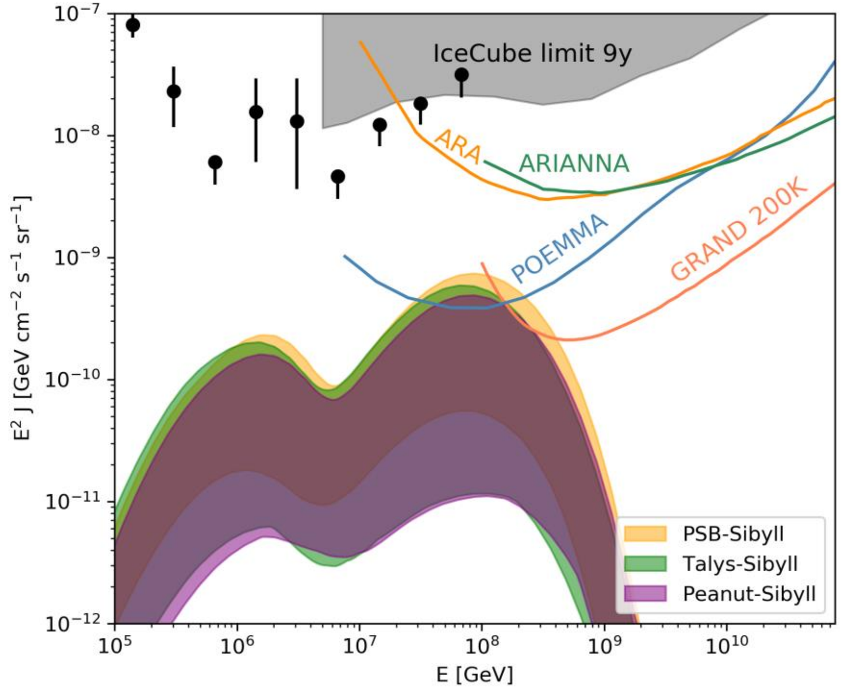
Shower Model

- Sibyll 2.3 slightly higher than Epos-LHC
- QGSjet low flux (bad UHECR fit)

Disintegration Model

- Varies within a factor 2
- Lower limit due to minimal *m*





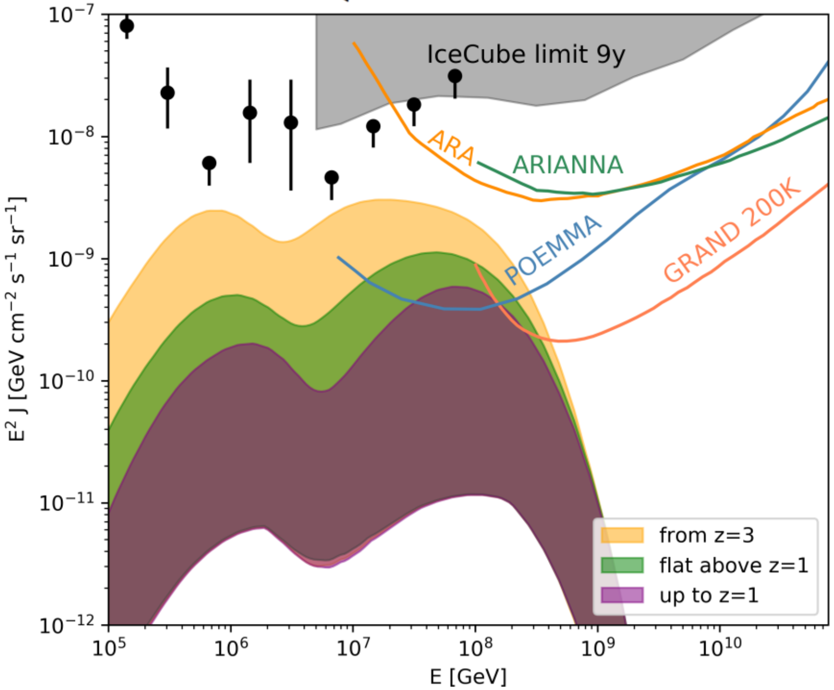
Maximal flux level robust within a factor 2-3

Redshift extrapolation beyond z = 1

Source evolution

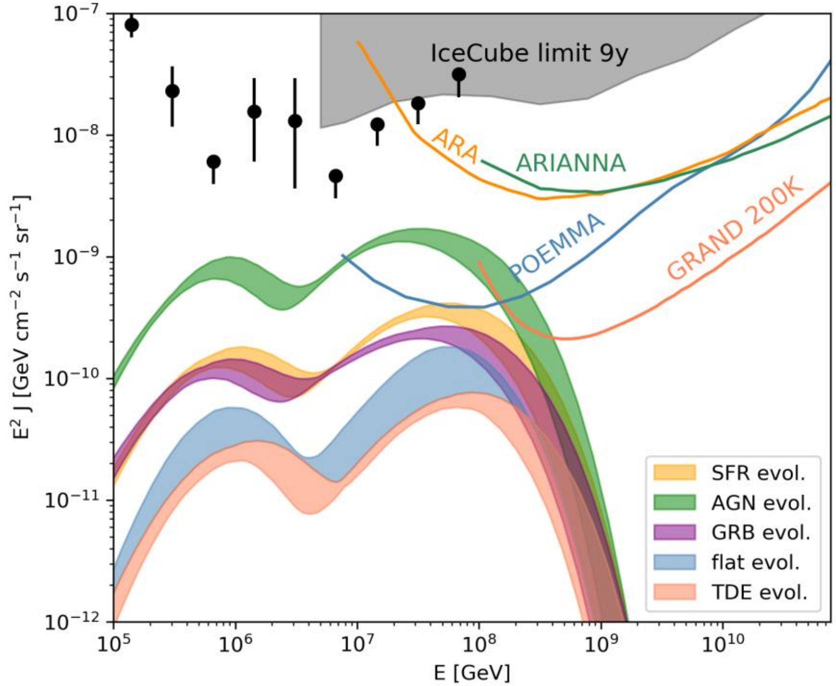
- How to continue above z = 1?

$$n_{\mathrm{evol}}(z) = \begin{cases} (1+z)^m & , z \leq 1 \\ ? & , z > 1 \end{cases}$$



Specific source classes

- AGN: $m \sim 5$
- GRB: $m \sim 2.1$
- TDE: $m \sim -3$
- SFR: $m \sim 3.4$
- Flat: $m = 0$



Sensitivities peak at too high energy (except POEMMA)

Conclusions

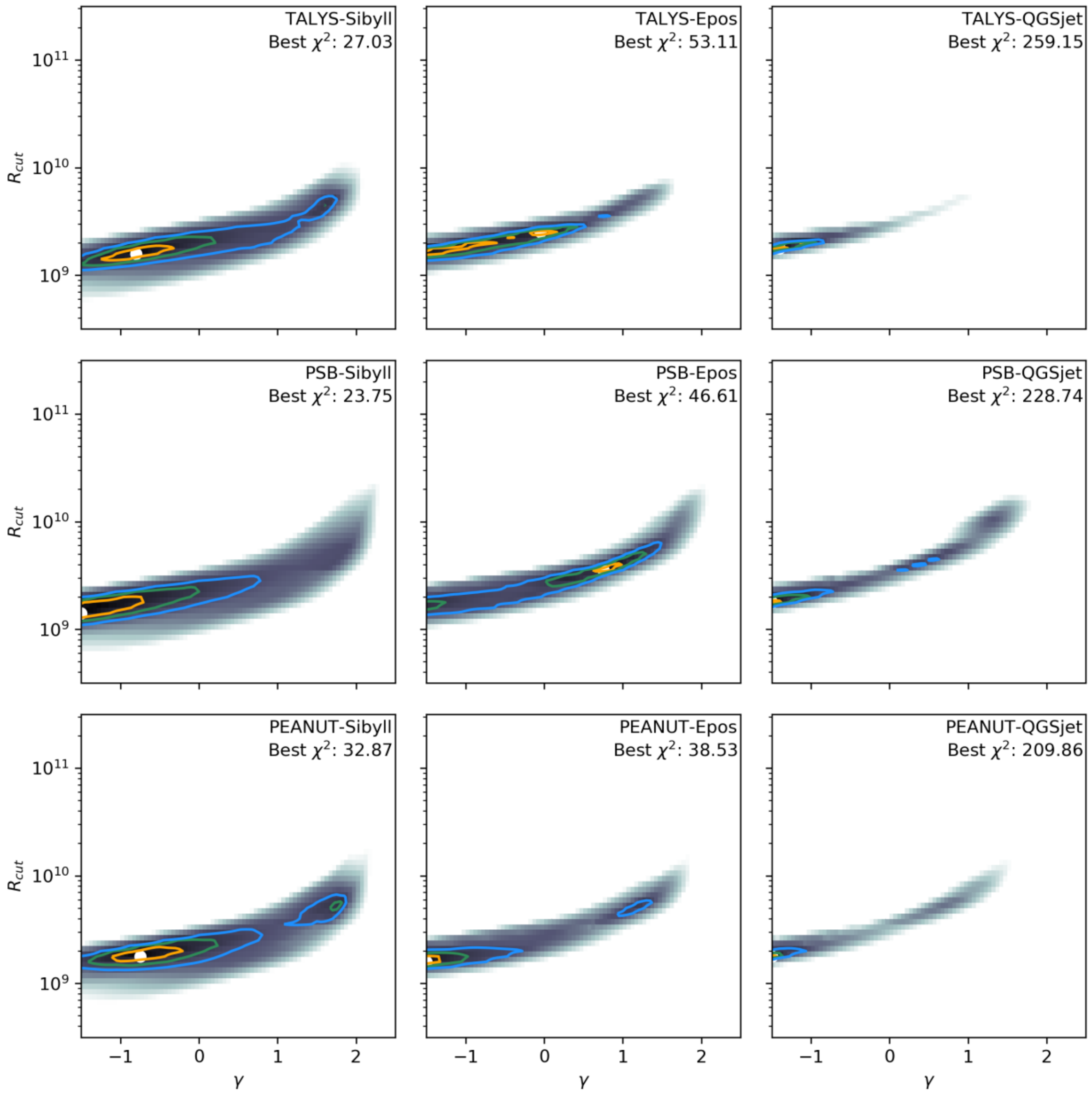
- Two distinct source populations favoured by fit:
  - Strong source evolution … but almost mono-chromatic sources
  - Soft spectral-index … but very local sources
- UHECR fit driven by envelope of rigidity-dependent cut-offs

- SIBYLL, EPOS, QGSJET indicate different source class interpretations
- The shower-model has a stronger impact on the injection composition interpretation than the disintegration-model

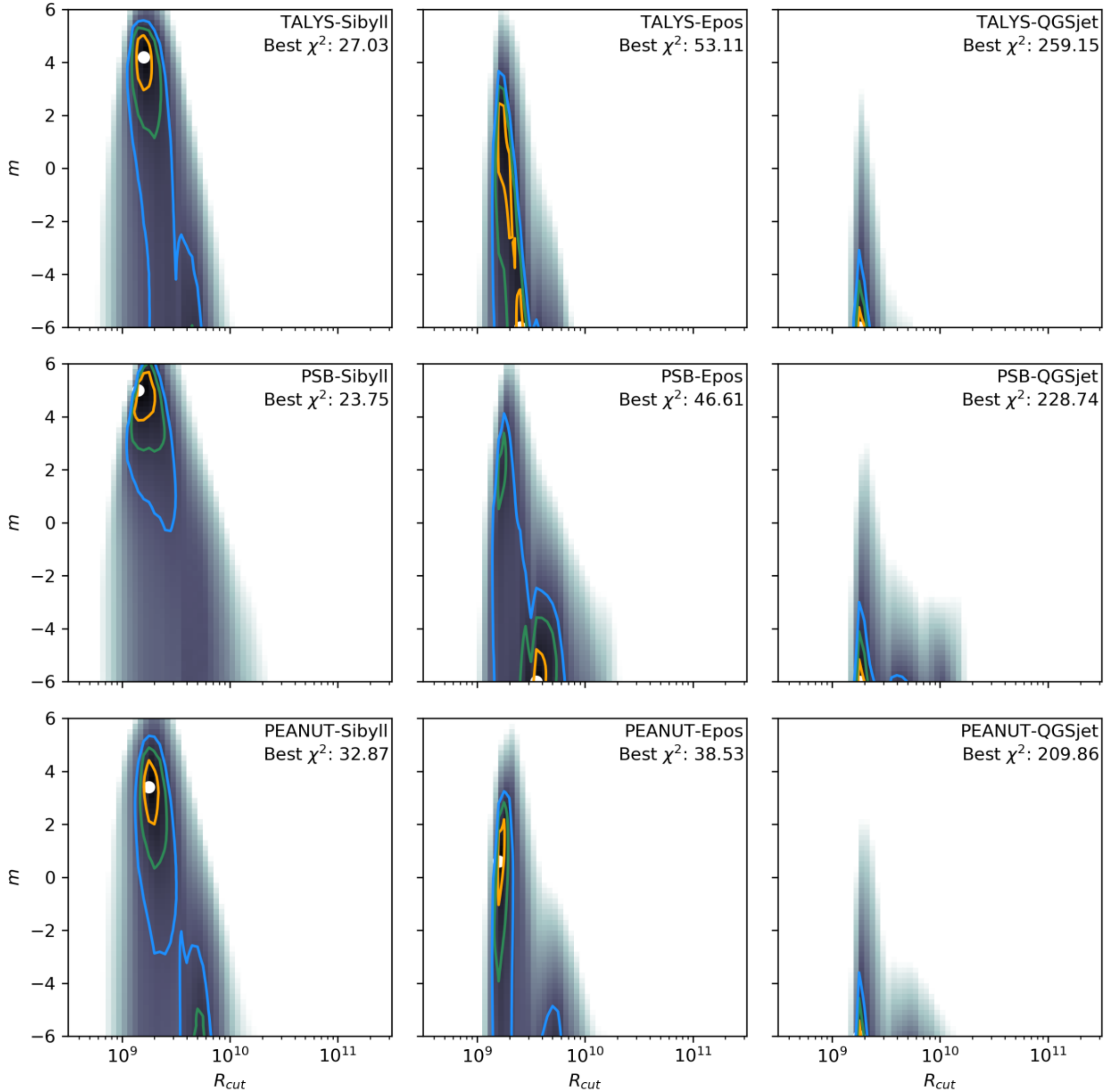
- The flux of cosmogenic neutrinos is relatively robust to disintegration and shower model and mainly dependent on source evolution
- Cosmogenic flux level might be too low for proposed experiments
- … Less background for detecting **source neutrinos!**

Backup Plots

Model comparison over $\gamma - R_{max}$

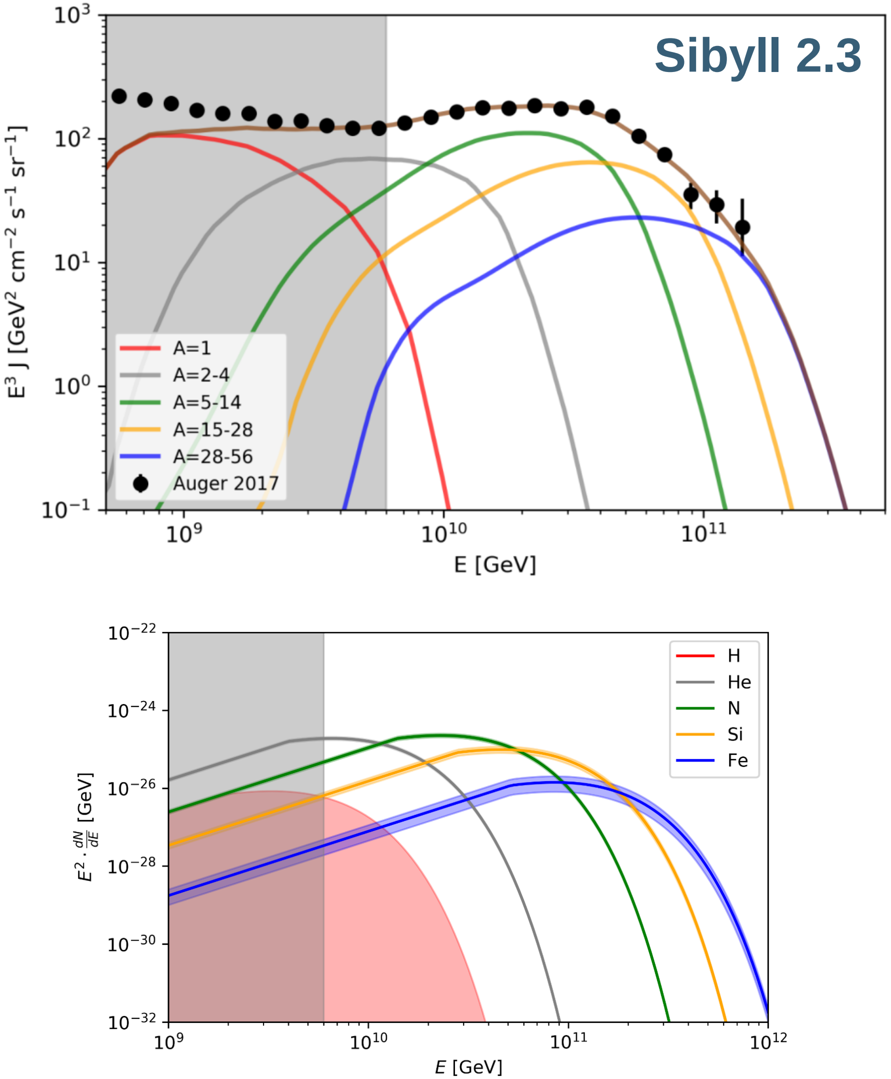


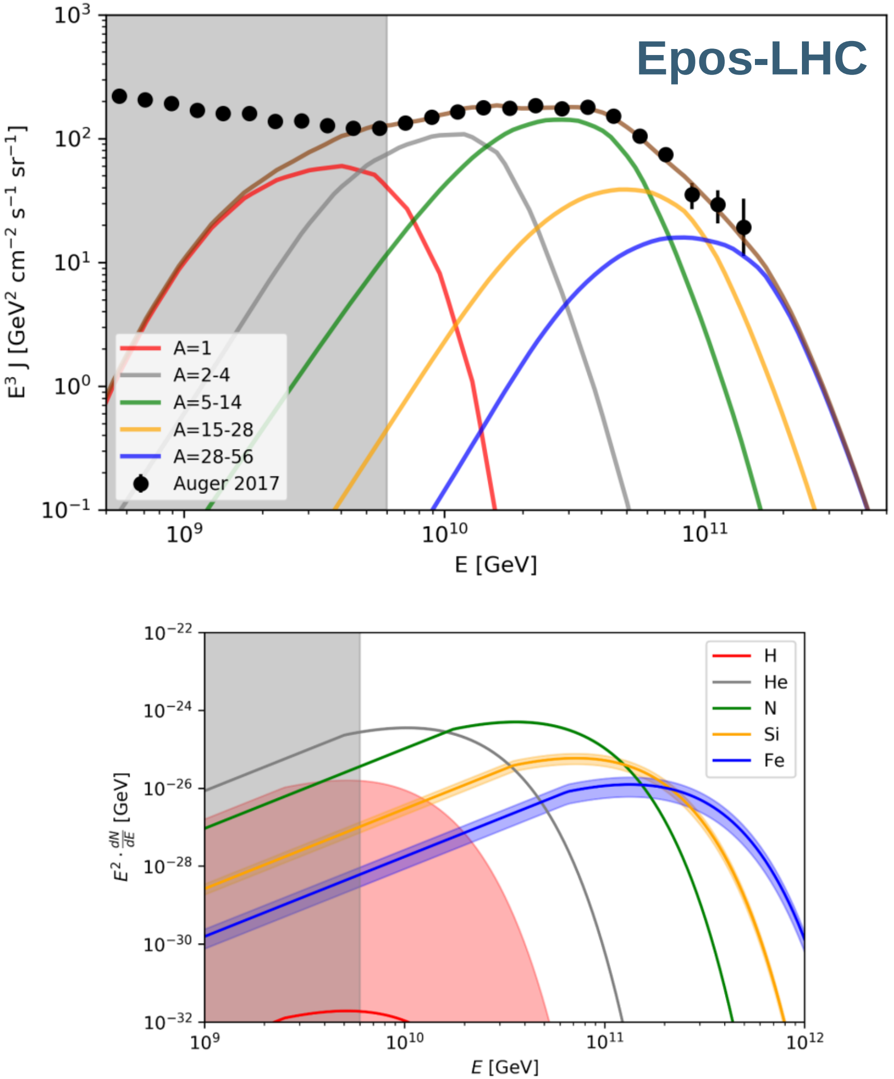
Model comparison over $R_{max} - m$



Best fit spectrum – effect of air shower model

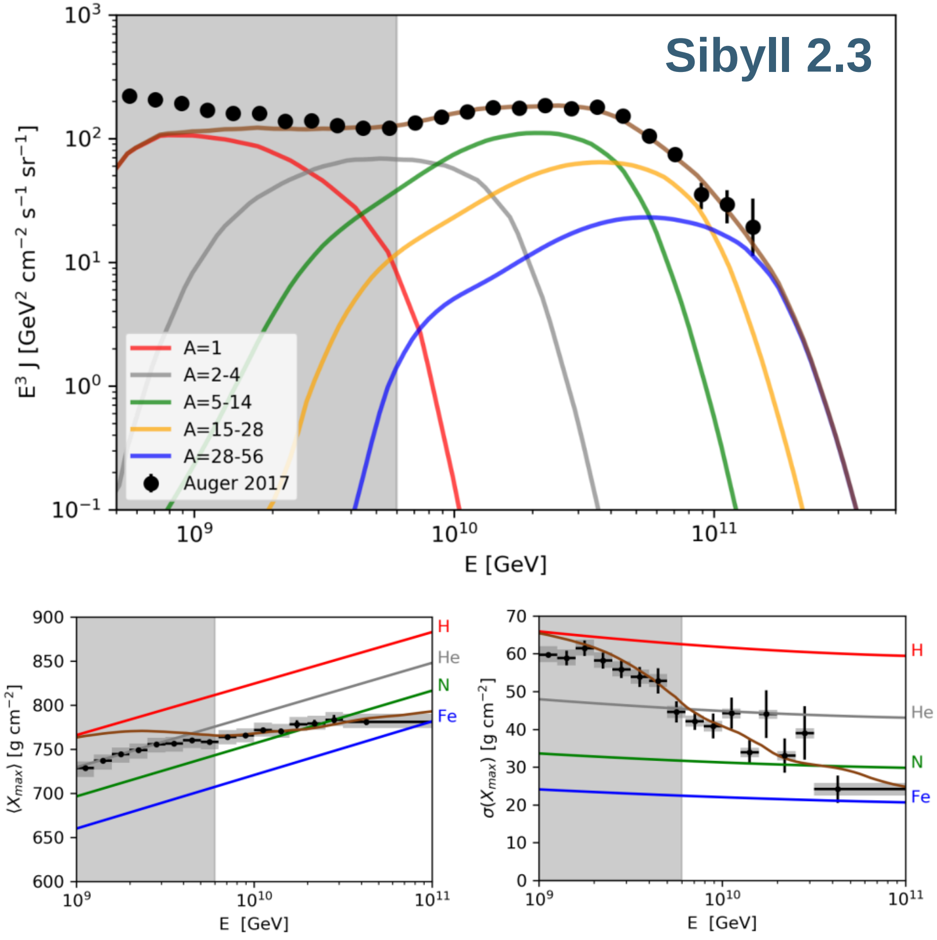
using Talys

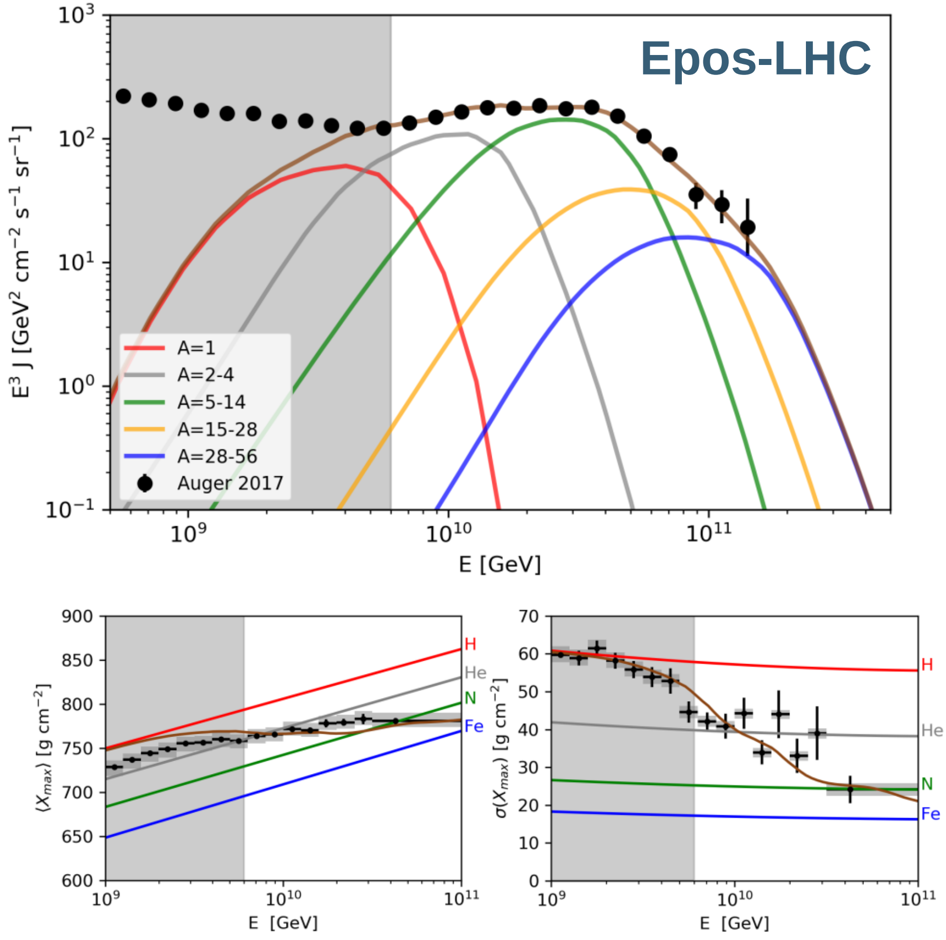




Best fit spectrum – effect of air shower model

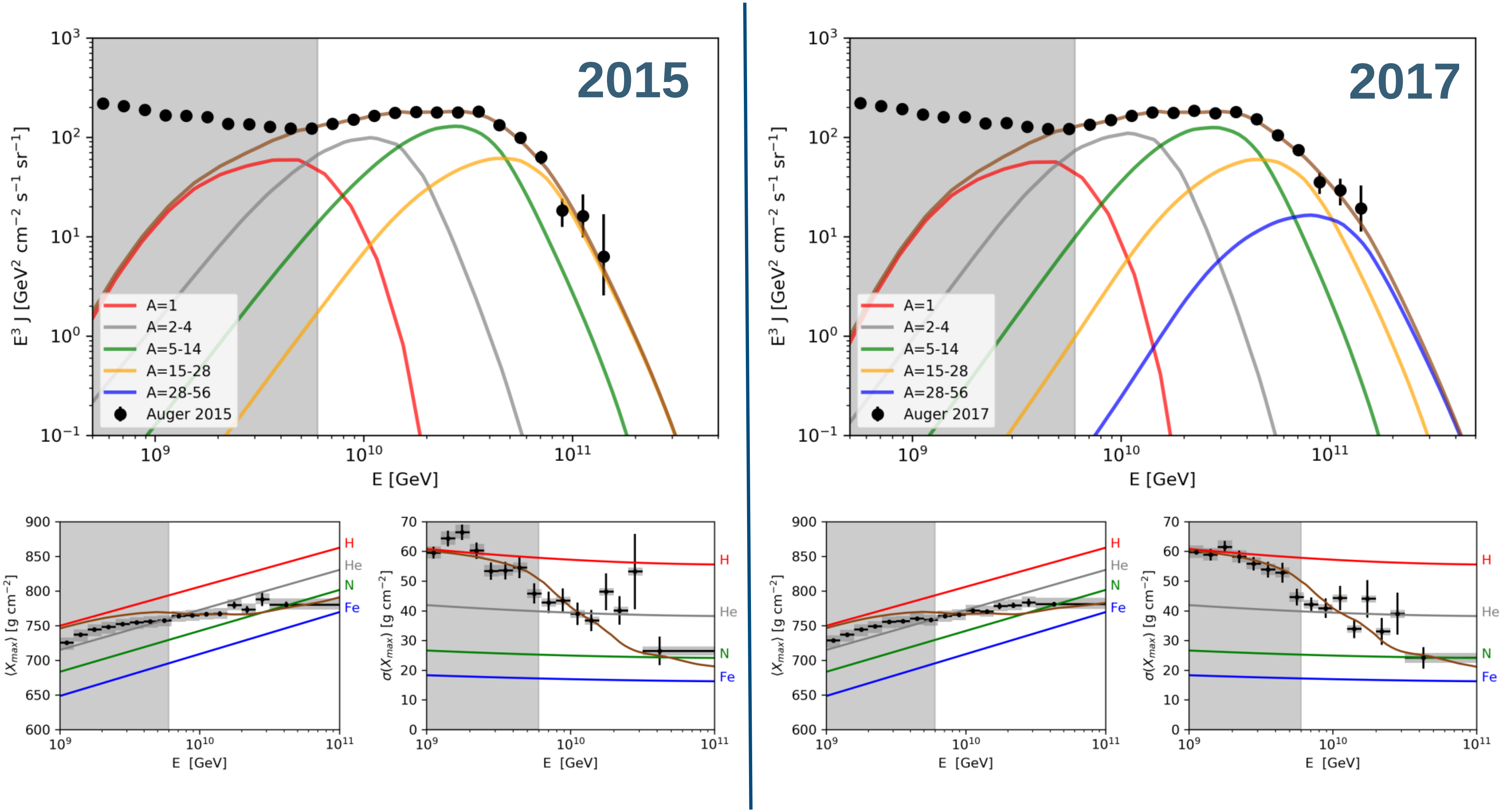
using Talys





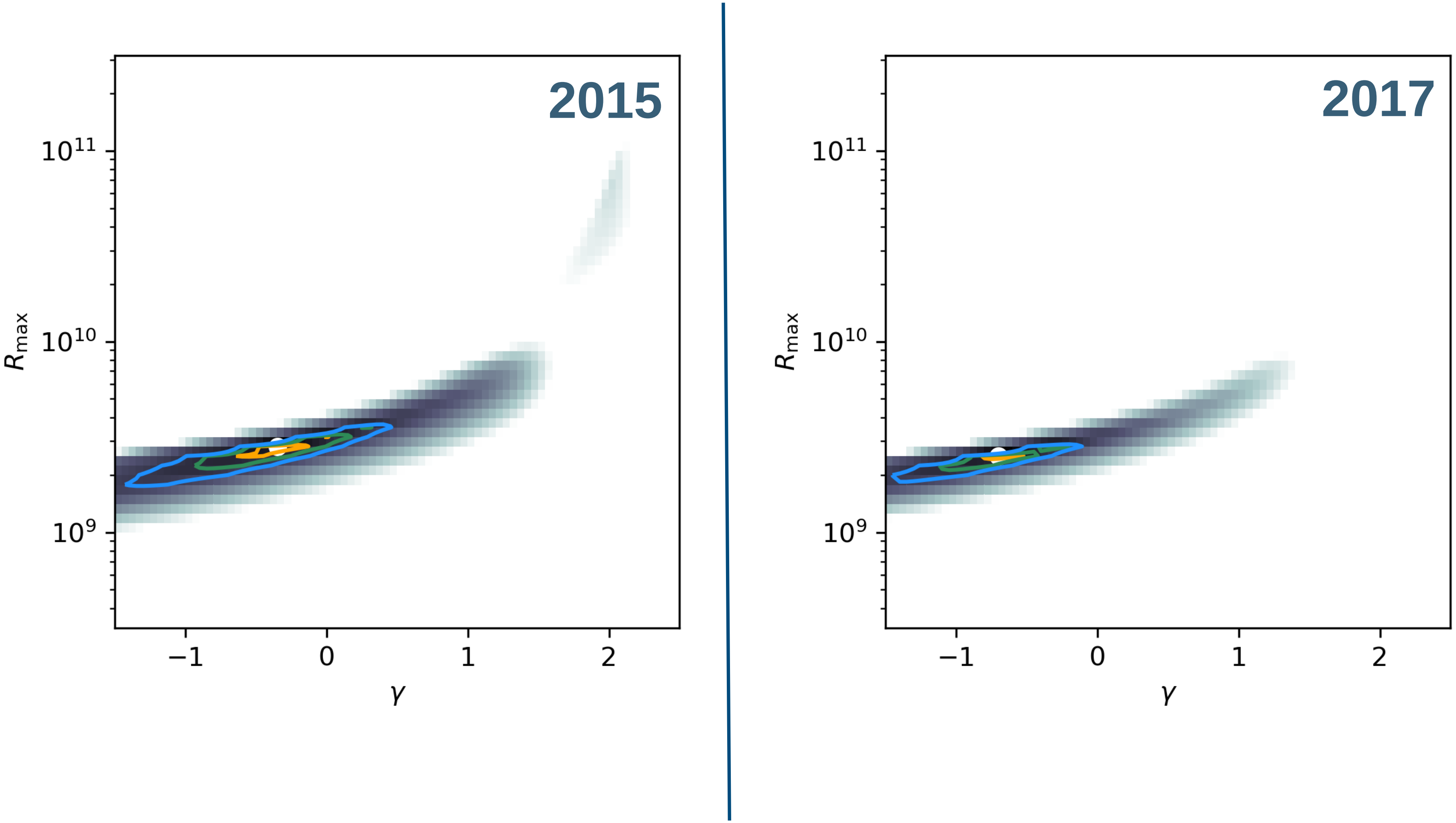
Auger 2015 vs Auger 2017 data

Best fit Spectra using flat evolution



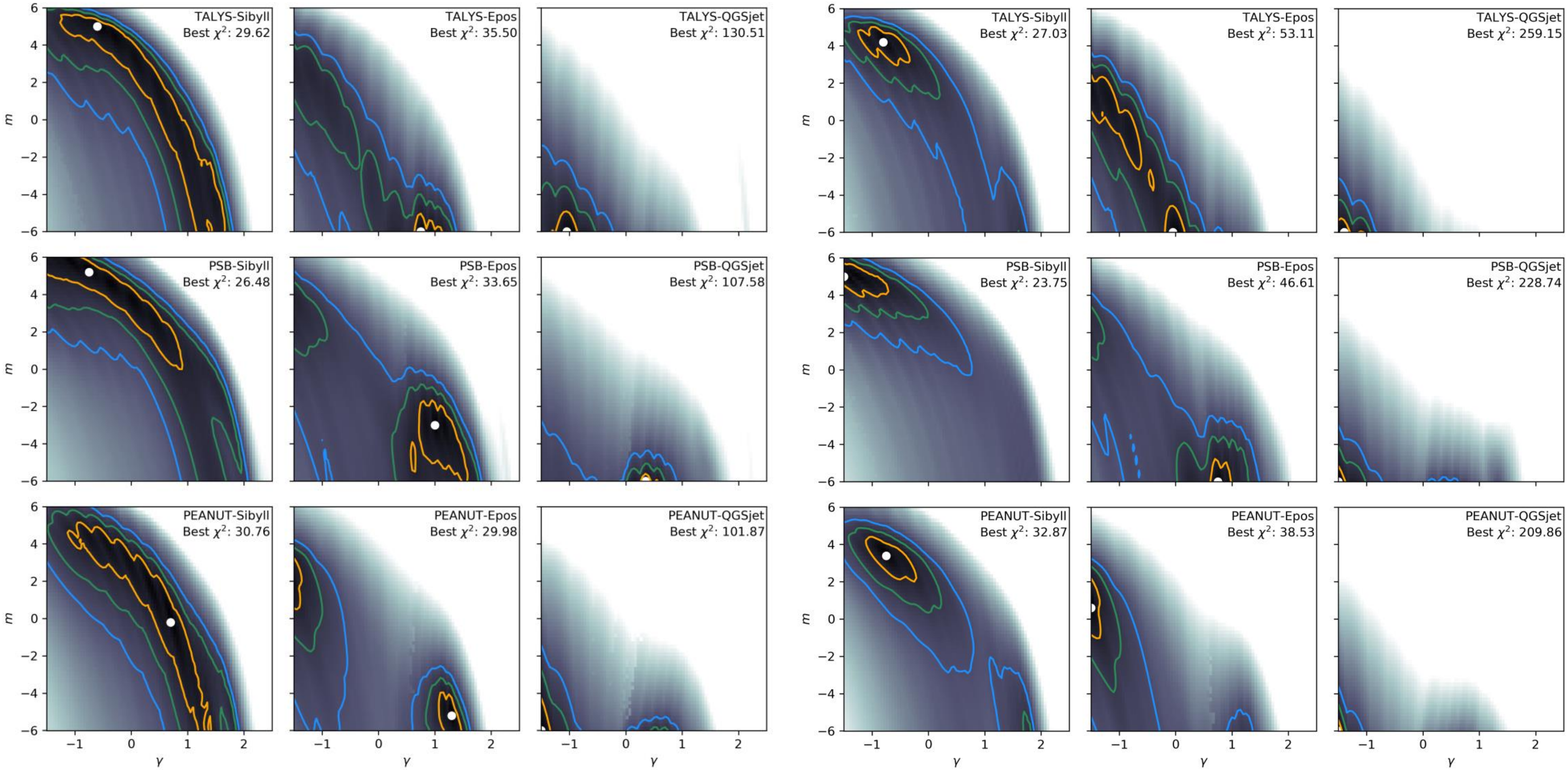
Auger 2015 vs Auger 2017 data

Fit contours



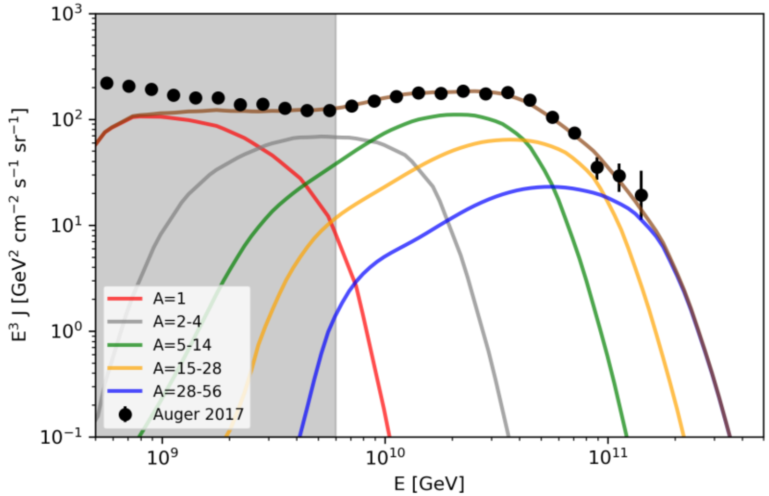
Auger 2015 vs Auger 2017 data

2015 | 2017



Spectrum for high redshift

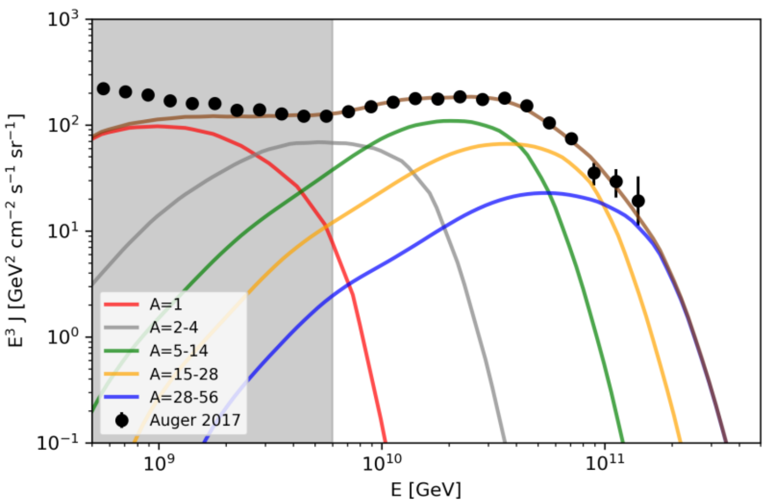
$$n_{\mathrm{evol}}(z) = \begin{cases} (1+z)^m & , z \leq 1 \\ ? & , z > 1 \end{cases}$$

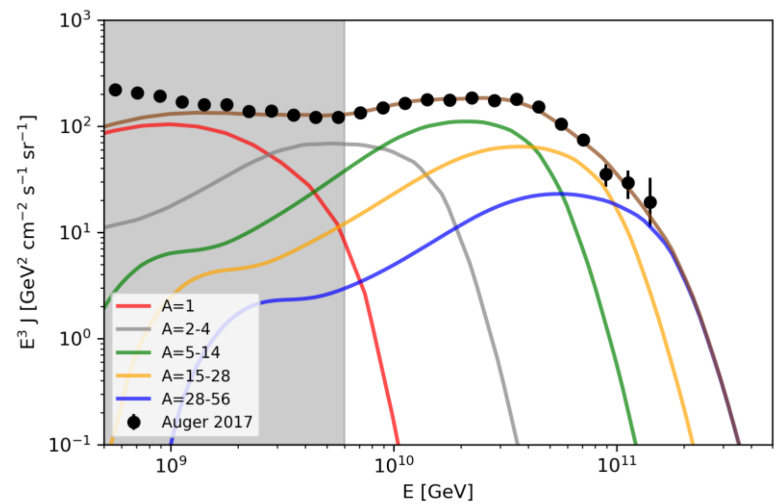


Second minimum
$m = 3.6$

continue flat evol.

continue to $z = 3$

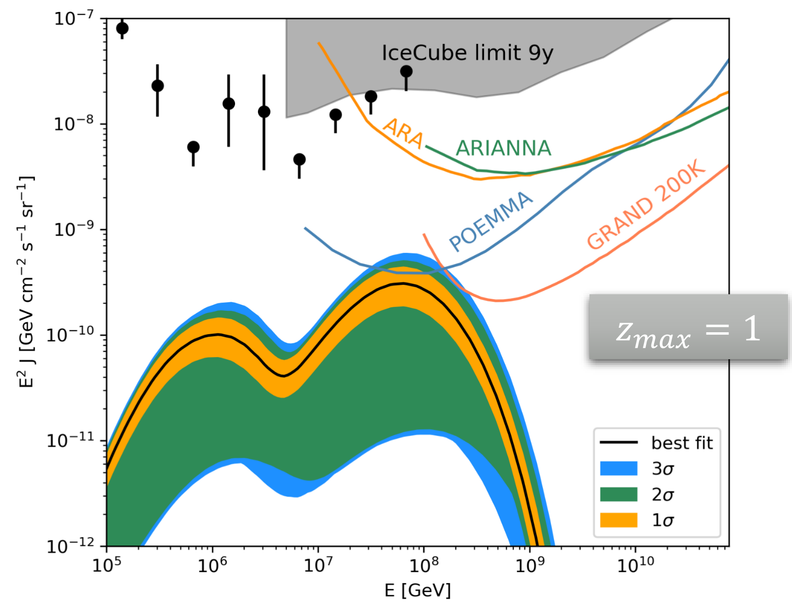


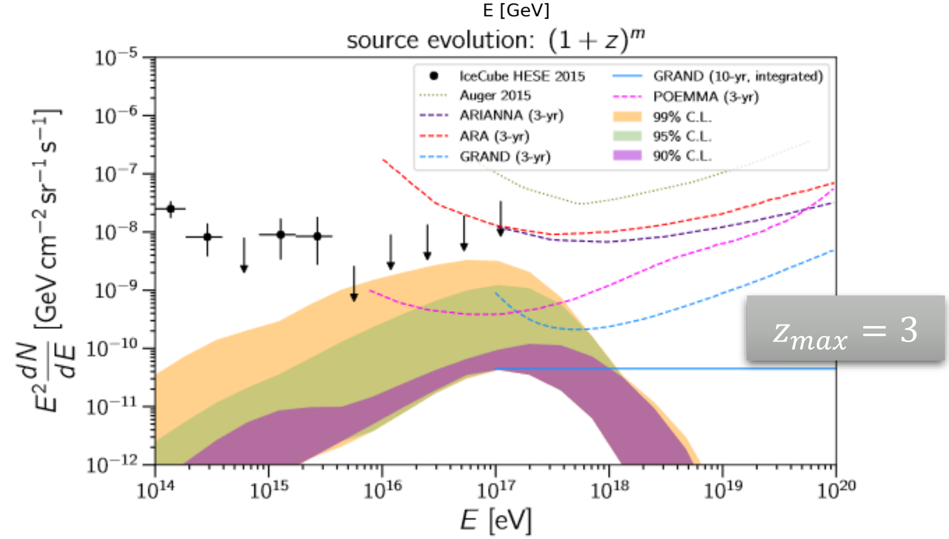


Compared to other calculation

Rafael Alves Batista et. al., arXiv: 1806.10879 (2018)

- Similar neutrino ranges
  (Considering different z_{max})
- Their fit allows for slightly higher rigidity
- … leads to higher flux in SFR case



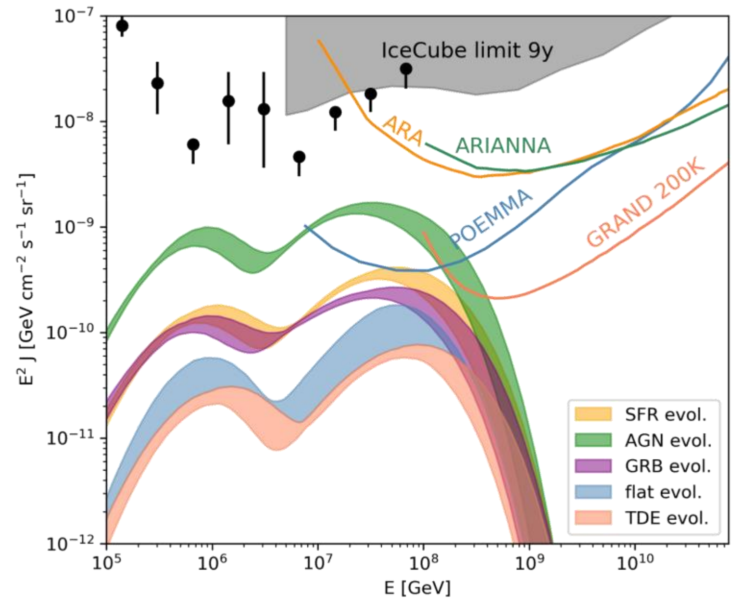


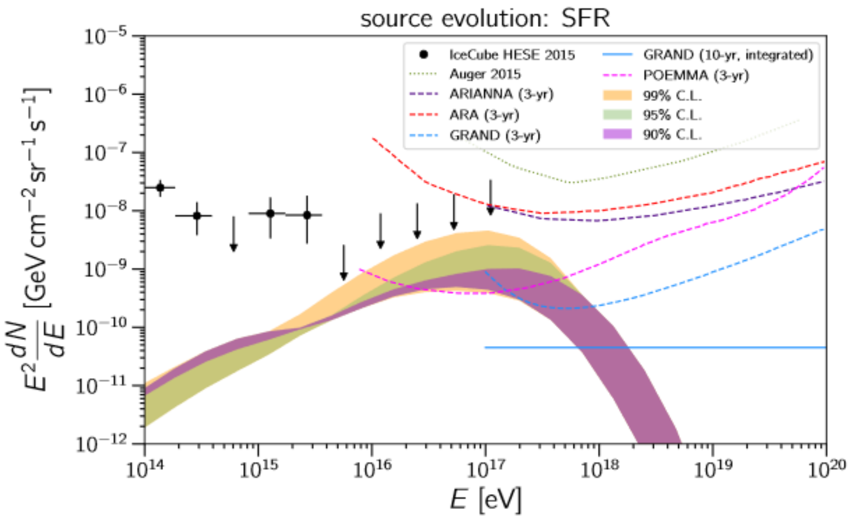
Rafael Alves Batista et. al., arXiv: 1806.10879 (2018)

Compared to other calculation

Rafael Alves Batista et. al., arXiv: 1806.10879 (2018)

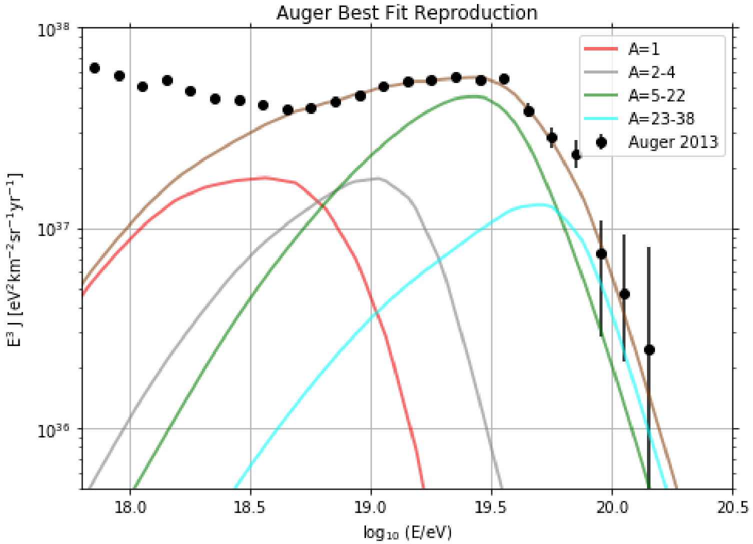
- Similar neutrino ranges
  (Considering different z_{max})
- Their fit allows for slightly higher rigidity
- … leads to higher flux in SFR case

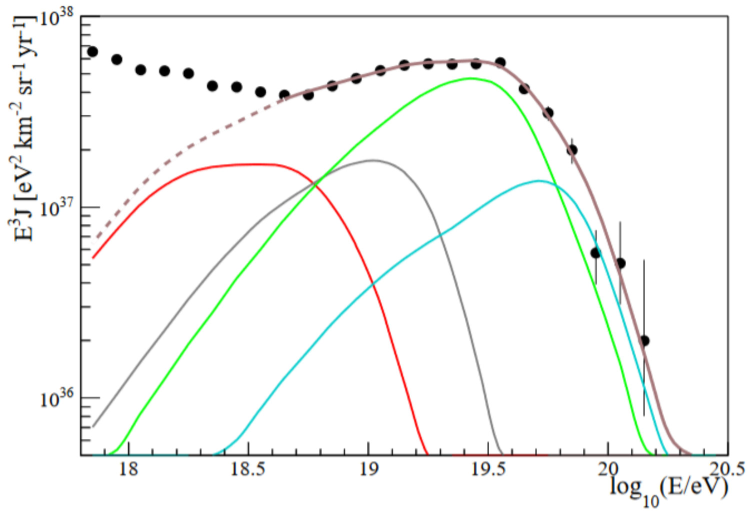




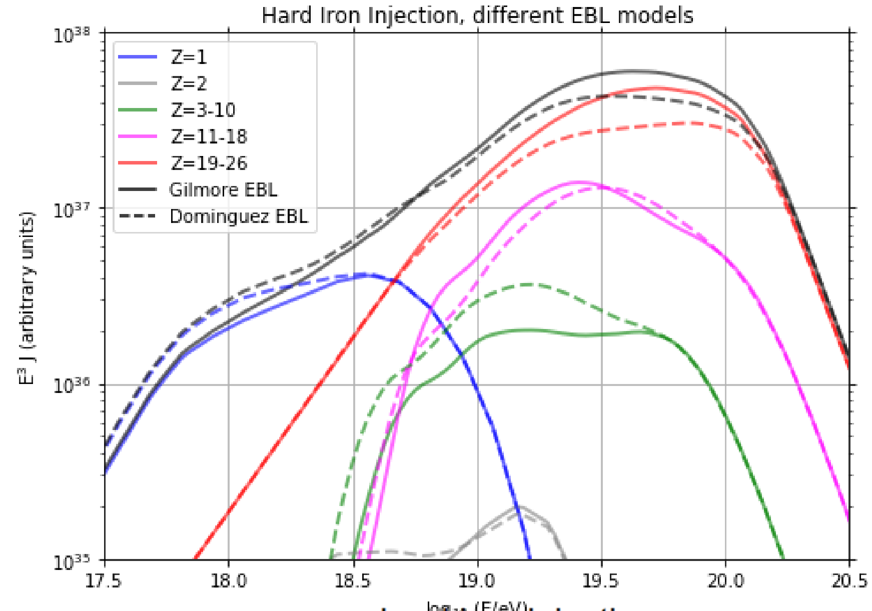
PriNCe - Cross checks

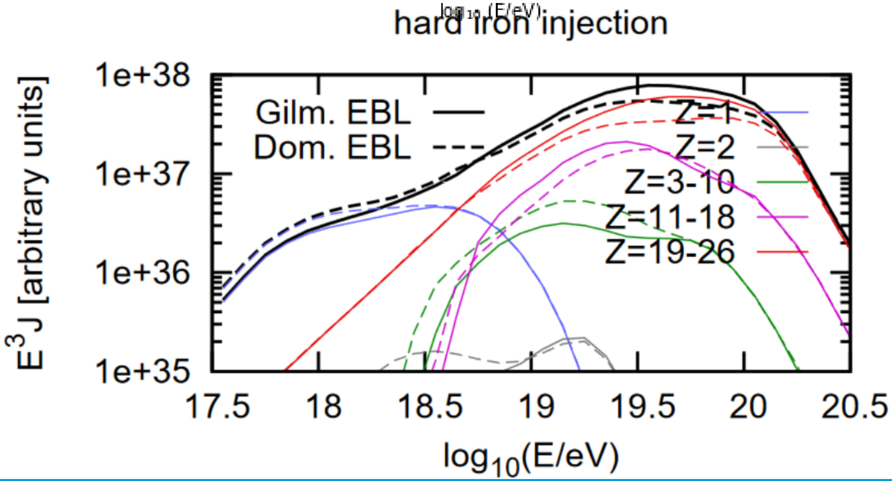
Auger Combined fit





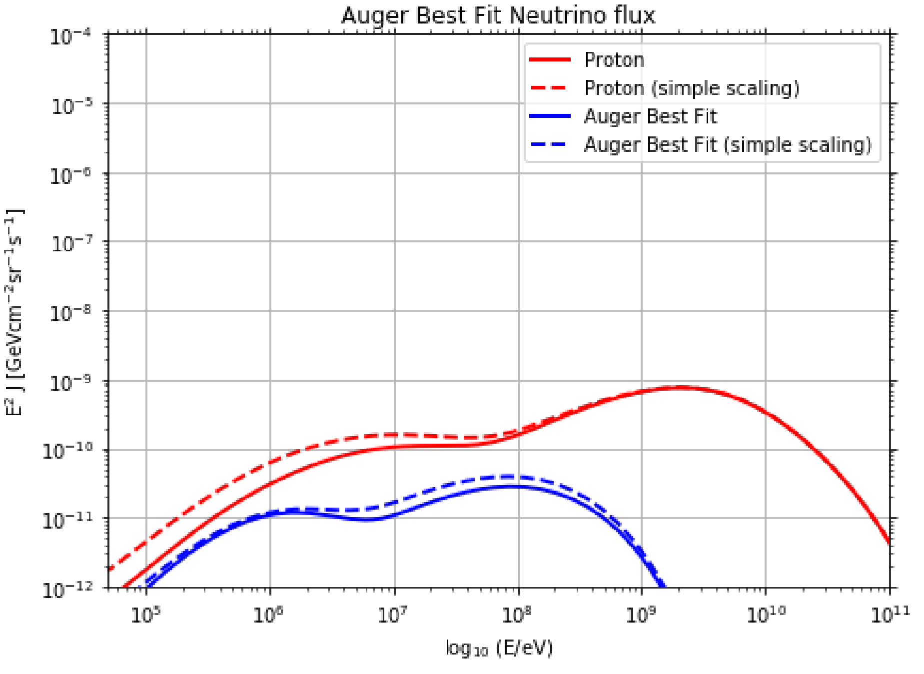
CIB dependency

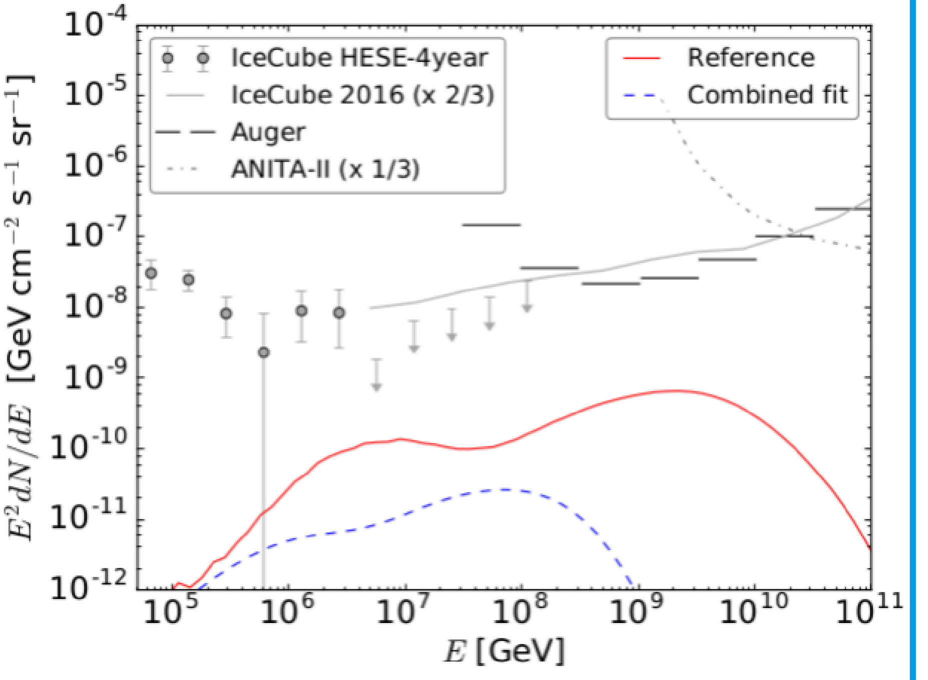




PriNCe - Cross checks

Cosmogenic Neutrinos





Cosmogenic Neutrinos for protons