Cosmogenic neutrinos from a fit to the Auger spectrum and composition

…and their dependence on the disintegration and air shower model

Jonas Heinze
TeVPA Berlin
31.8.2018

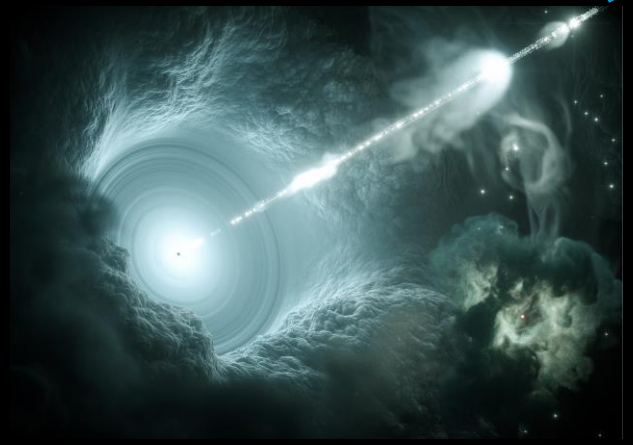
JH, A. Fedynitch, D. Boncioli, W. Winter
in preparation

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

UHE Cosmic Rays and Cosmogenic Neutrinos

Model inputs

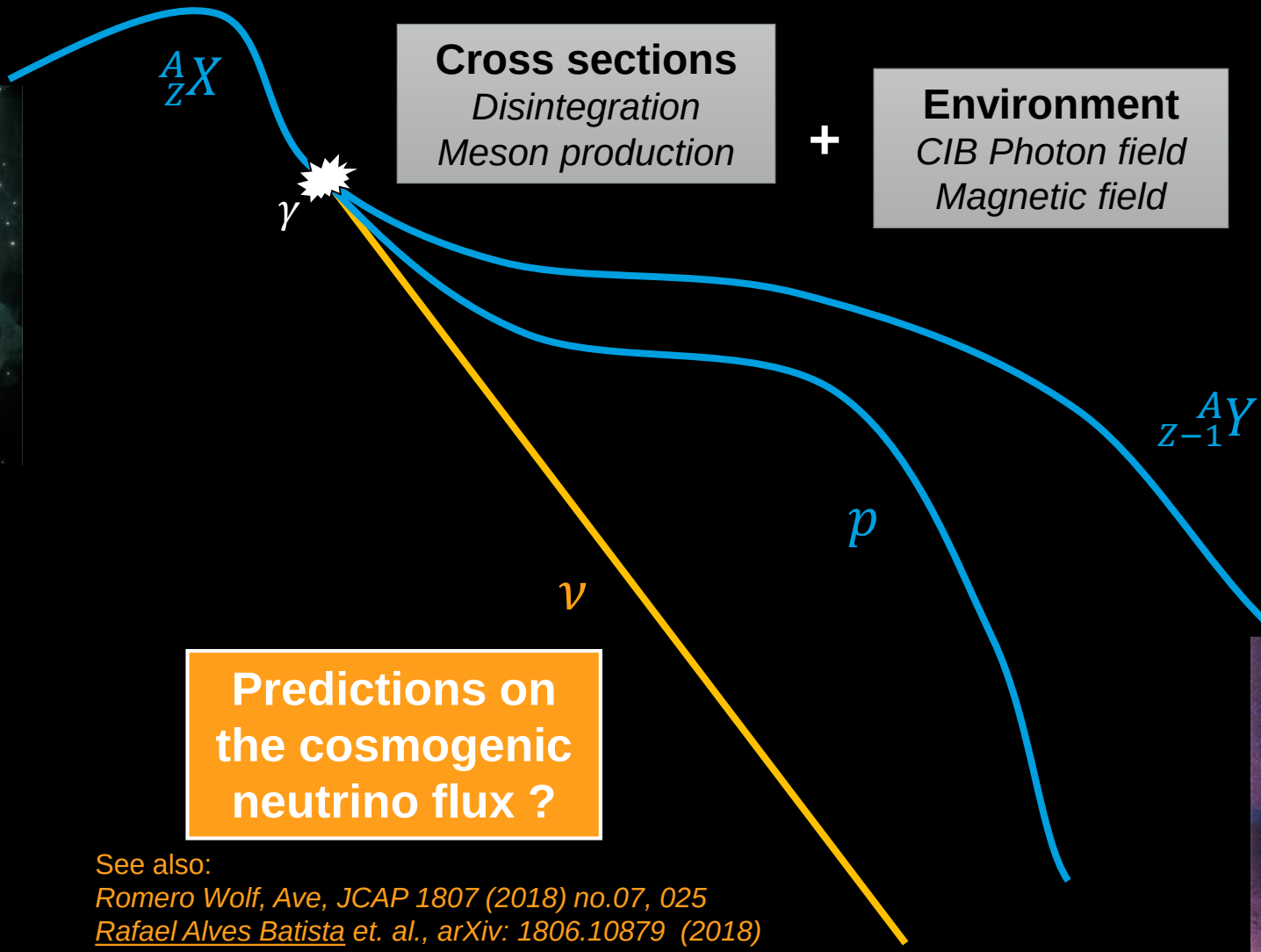
Source: DESY



Source Model
Spectral shape
Composition

+

Source Evolution

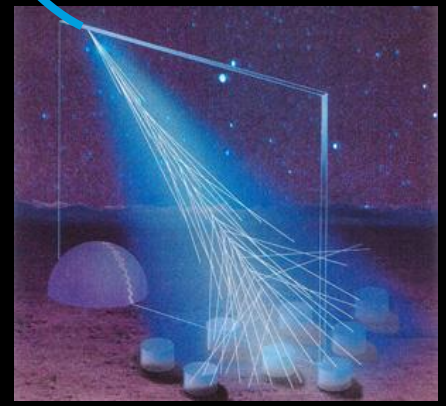


Cross sections
Disintegration
Meson production

+

Environment
CIB Photon field
Magnetic field

Detection
Air shower model



Source: Auger

Predictions on the cosmogenic neutrino flux ?

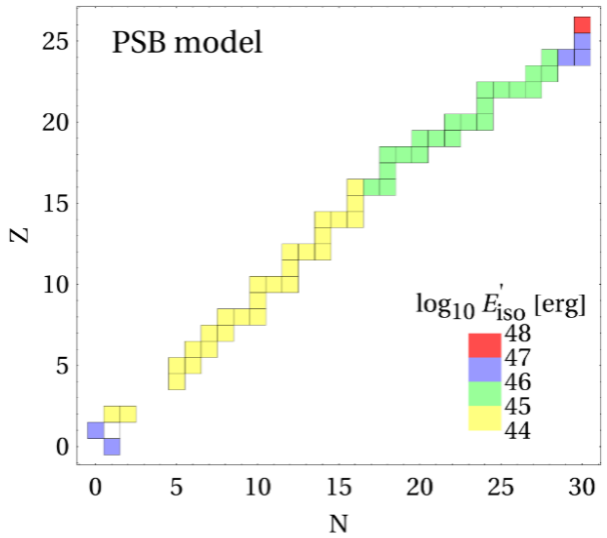
See also:
Romero Wolf, Ave, JCAP 1807 (2018) no.07, 025
Rafael Alves Batista et. al., arXiv: 1806.10879 (2018)

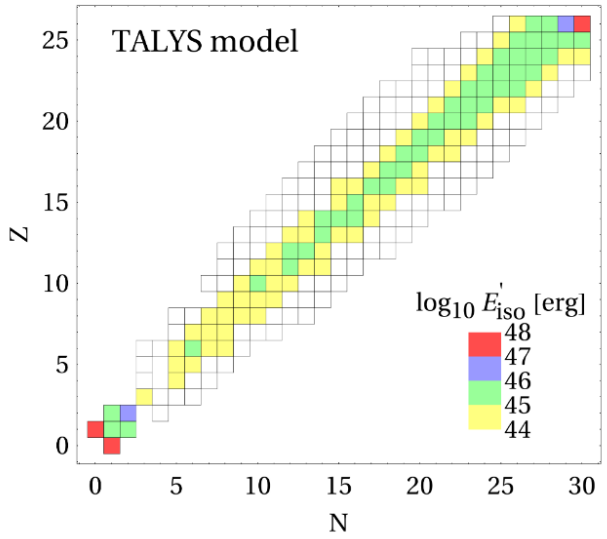
UHE Cosmic Ray Composition

Assuming we know the injected composition perfectly…

Photohadronic model

- Disintegration at lower energies
  - Models PSB, Talys, Peanut
- Meson-prod. at higher energies
  - Superposition - Model?
  - see poster by Leonel Morejon

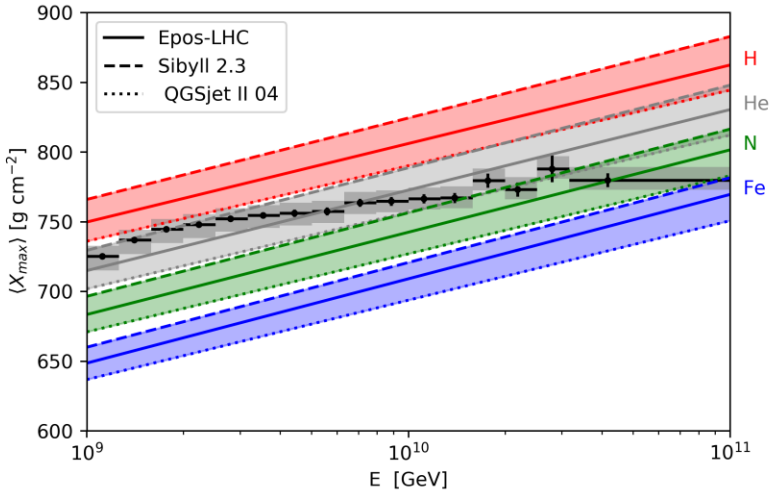




Boncioli, Fedynitch, Winter
Scientific Reports 7 (2017) 4882

Air-Shower Model

- To compare composition to X_{max}
- Shower model can change the interpretation significantly!

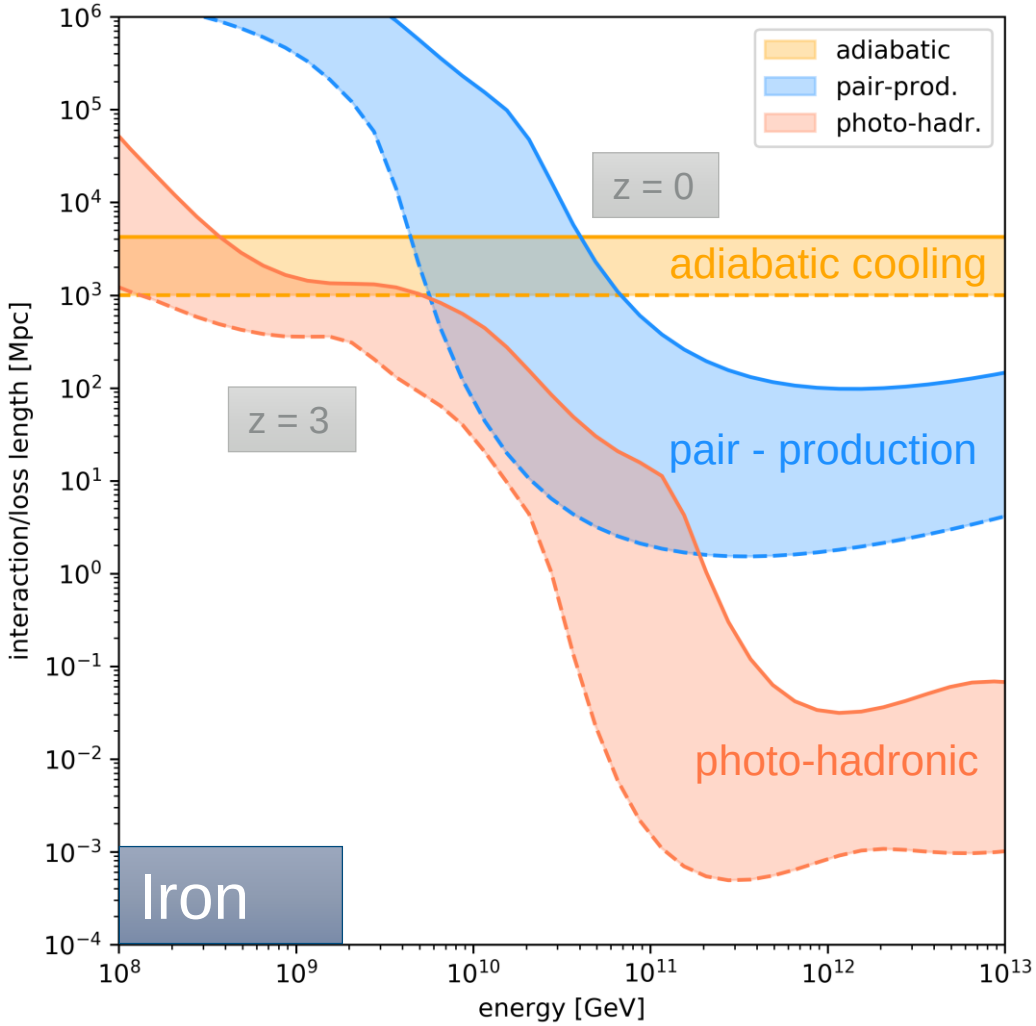


UHECR Transport Equation

- About 50 coupled differential equations
- Non-linear in time and energy

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

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



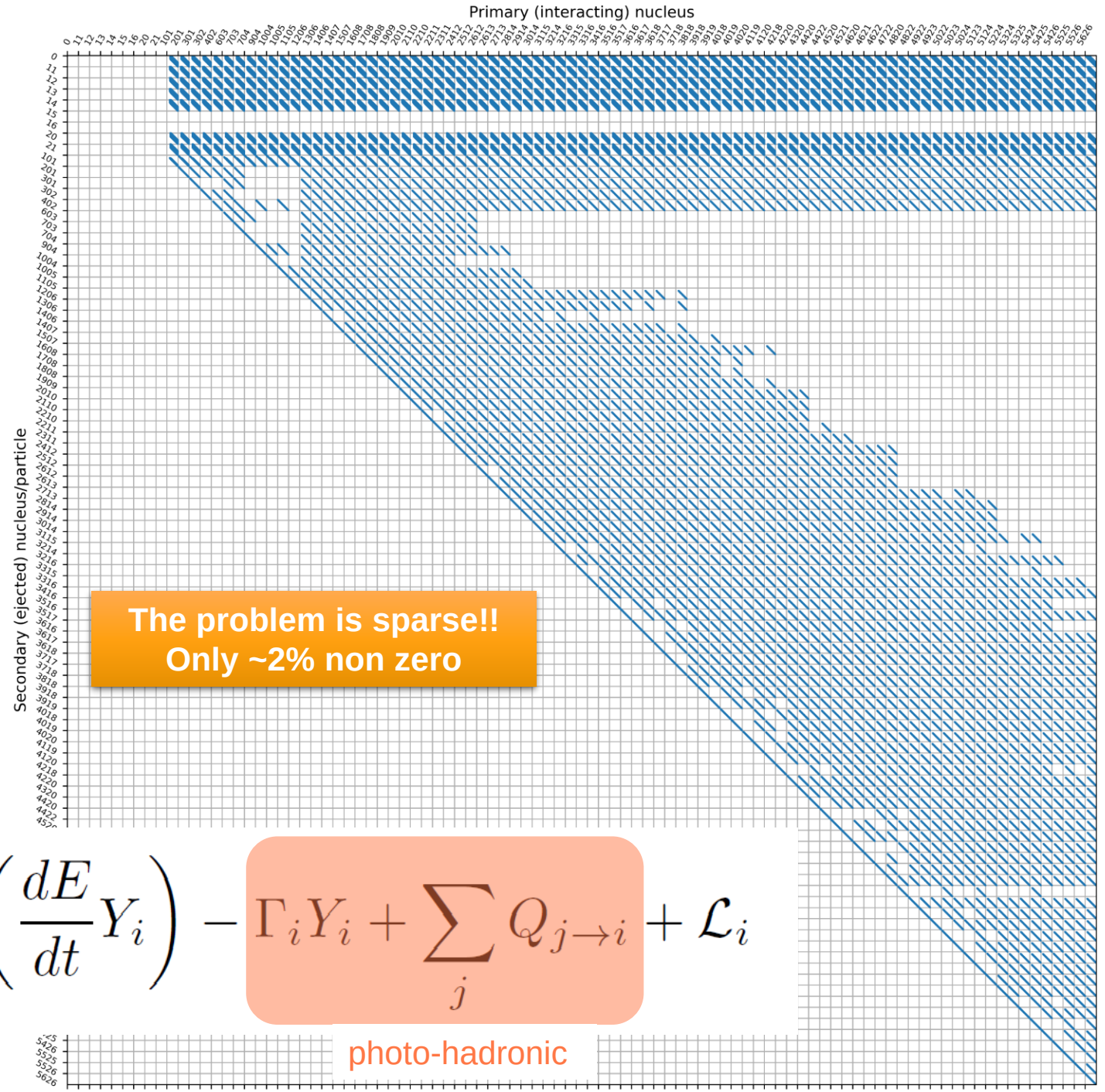
$$\partial_t Y_i(E,z) = +\partial_E(HEY_i) - \partial_E\left(\frac{dE}{dt}Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i} + \mathcal{L}_i$$

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

Propagation Code - PriNCe

Propagation including Nuclear Cascade

- Written in pure Python using Numpy and Scipy
- Large speed boost from sparse matrix algorithms
- Speed: **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.)



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

photo-hadronic

Sources – Generic model

Generic assumptions

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

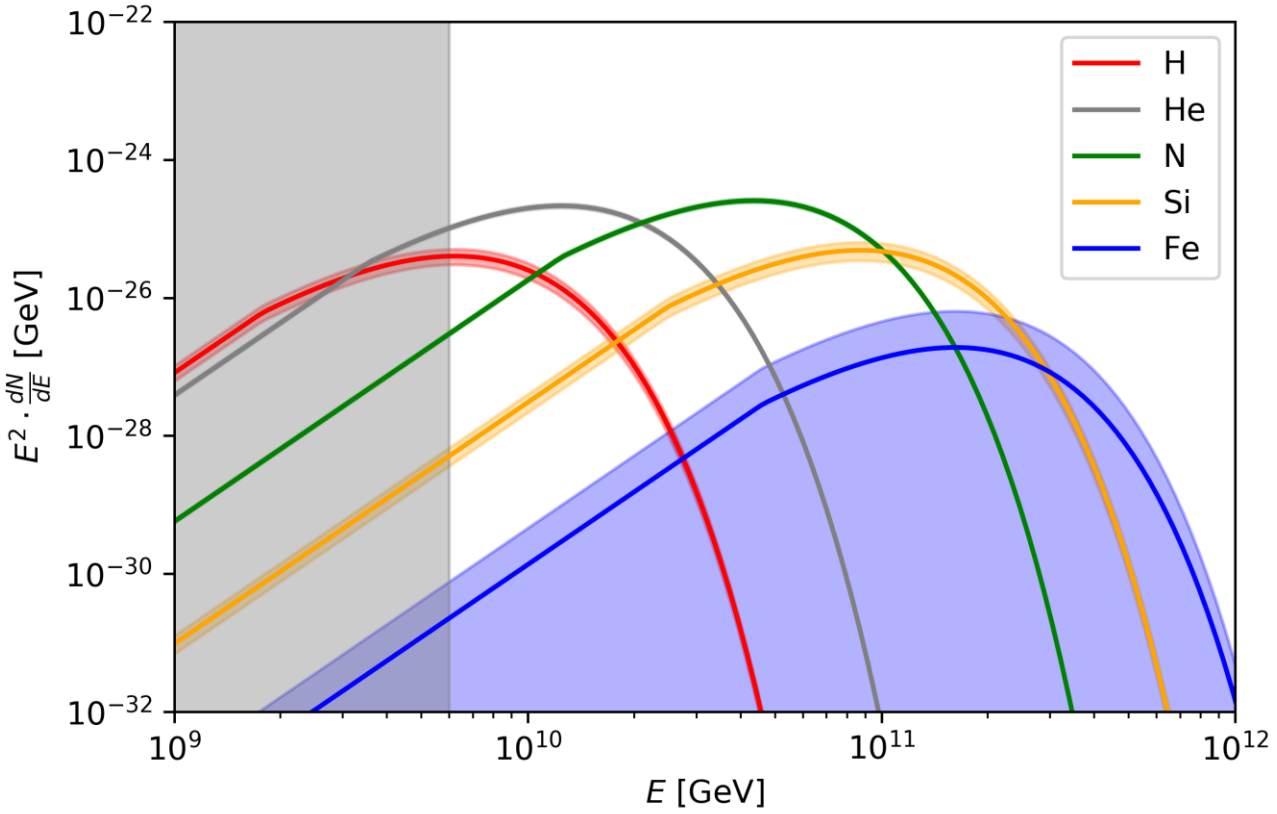
- Only five injection elements:
  H, He, N, Si, Fe

- Simple Power-law with rigidity dependent cut-off

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

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

Total of 8 free parameters



Results: Fit to spectrum and Composition

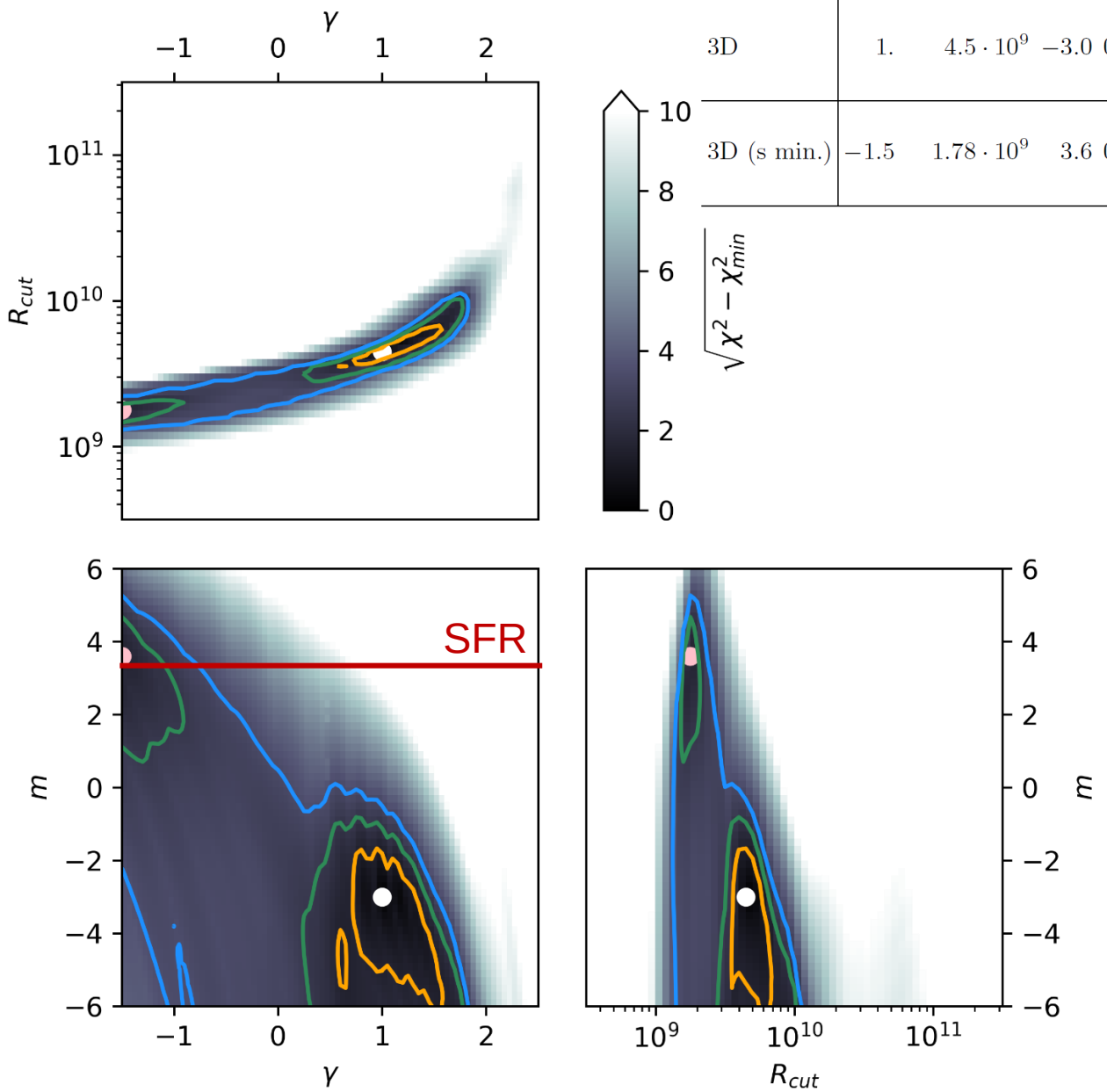
For combination PSB – Epos-LHC

- Fit to spectrum + composition by χ^2-fit and allow for an energy shift of ± 14 %
- Shown as 2D profiles by minimizing over all other fit-parameters
- Consistent with Auger Combined Fit

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

- Two distinct local minima
  - Hard γ – strong source evol.
  - Soft γ – weak source evol.

	γ	R_{cut} (GeV)	m	δ_E	fractions	χ^2
3D	1.	$4.5 \cdot 10^9$	−3.0	0.14	He 75.3 N 23.1 Si 1.6	33.7 / 21
3D (s min.)	−1.5	$1.78 \cdot 10^9$	3.6	0.11	H 66.6 He 33.5 N 0.5	36.4 / 21



Results: Best fit spectra

For combination PSB – Epos-LHC

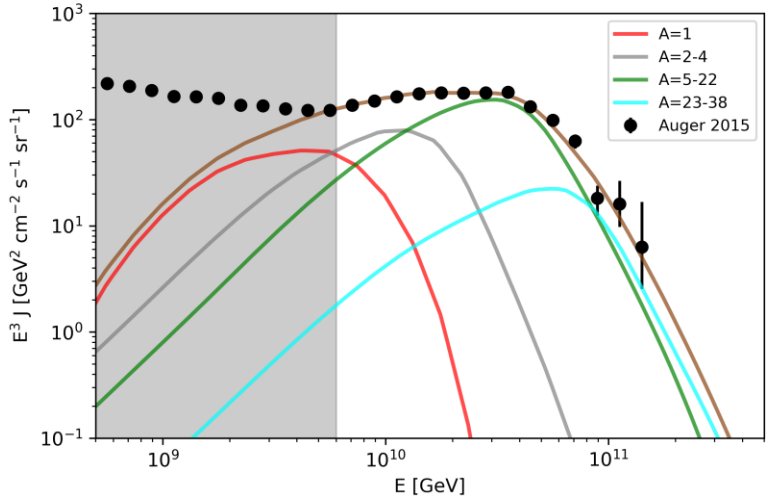
- Fit-range very similar by eye…
- ... but not in the injection spectra!

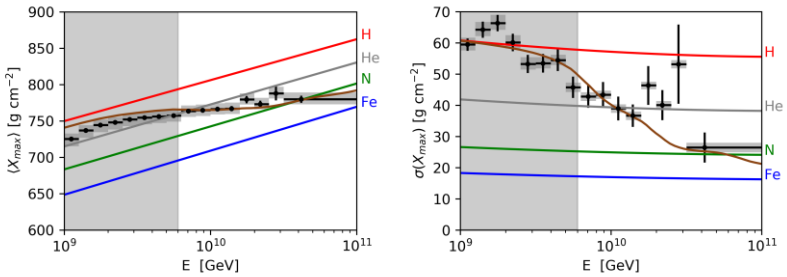
- Fit mainly sensitive to envelope of cutoffs
- Iron fraction unconstrained

- Fit-range insensitive above z = 1!

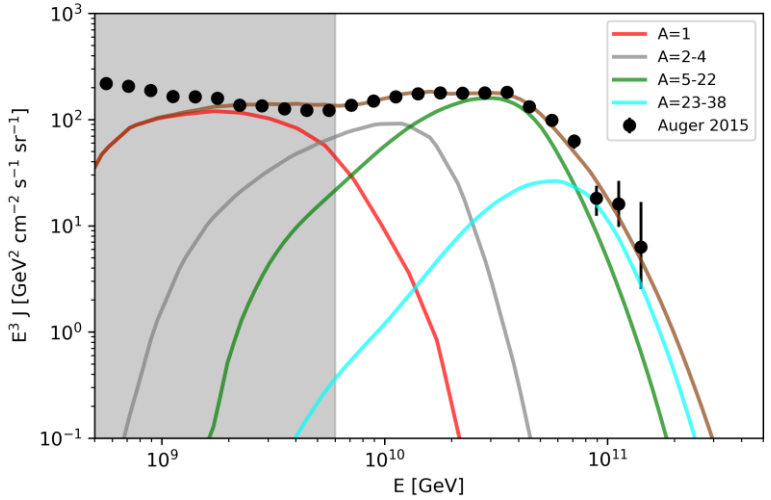
	γ	$R_{\rm cut}$ (GeV)	m	δ_E	fractions	χ^2
3D	1.	$4.5 \cdot 10^9$	−3.0	0.14	He 75.3 N 23.1 Si 1.6	33.7 / 21
3D (s min.)	−1.5	$1.78 \cdot 10^9$	3.6	0.11	H 66.6 He 33.5 N 0.5	36.4 / 21

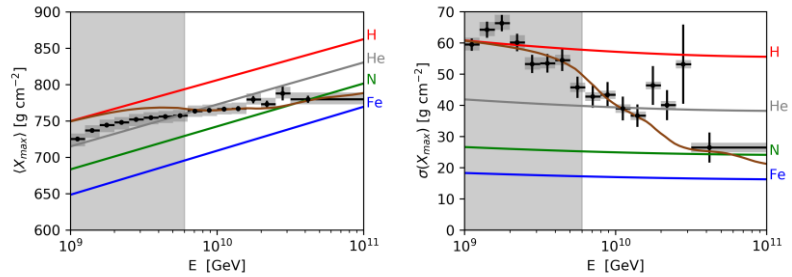
Best fit
weak source evolution





Second Local Minimum
strong source evolution





Results: Best fit spectra

For combination PSB – Epos-LHC

- Fit-range very similar by eye…
- ... but not in the injection spectra!

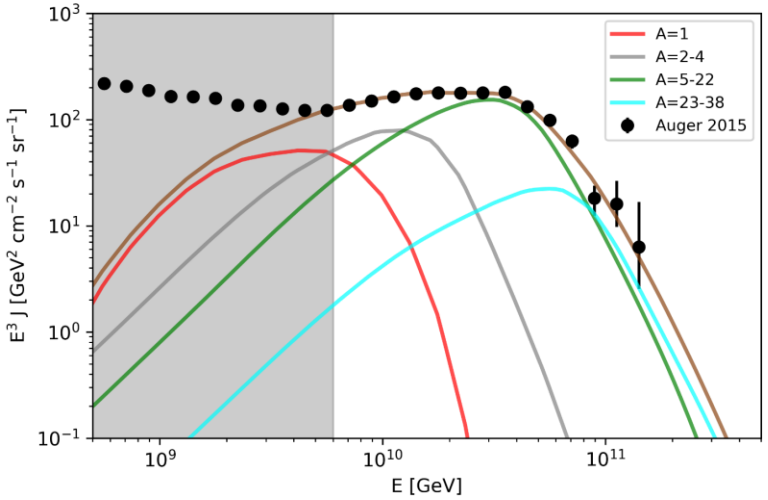
- Fit mainly sensitive to envelope of cutoffs
- Iron fraction unconstrained

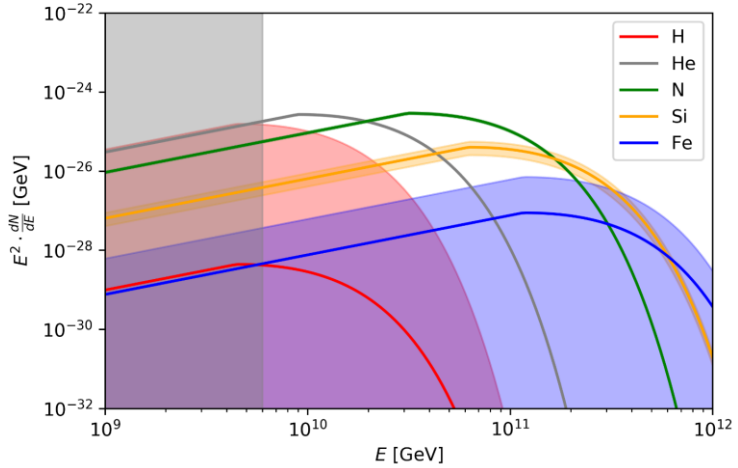
- Fit-range insensitive above z = 1!

	γ	R_{cut} (GeV)	m	δ_E	fractions	χ^2
3D	1.	$4.5 \cdot 10^9$	−3.0	0.14	He 75.3 N 23.1 Si 1.6	33.7 / 21
3D (s min.)	−1.5	$1.78 \cdot 10^9$	3.6	0.11	H 66.6 He 33.5 N 0.5	36.4 / 21

Best fit

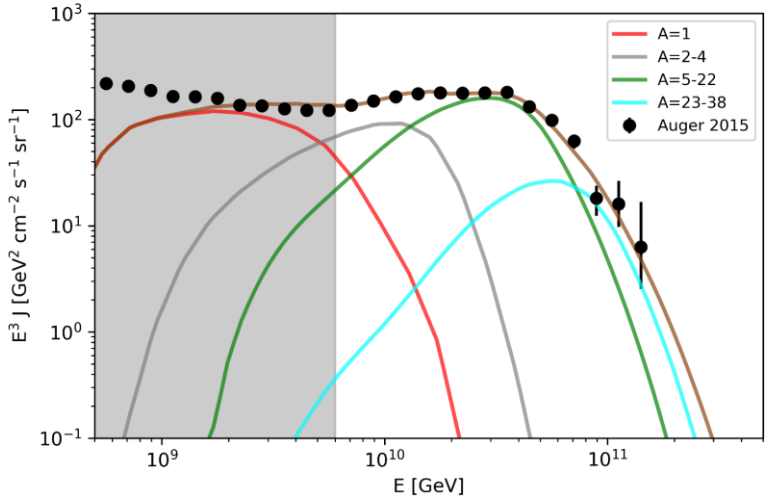
weak source evolution

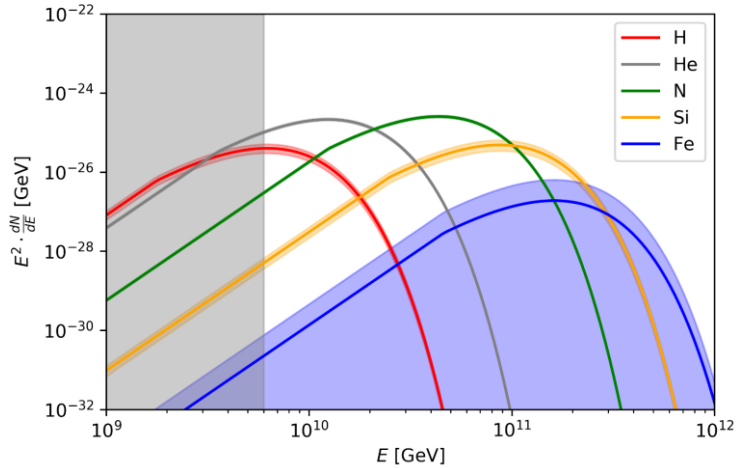




Second Local Minimum

strong source evolution





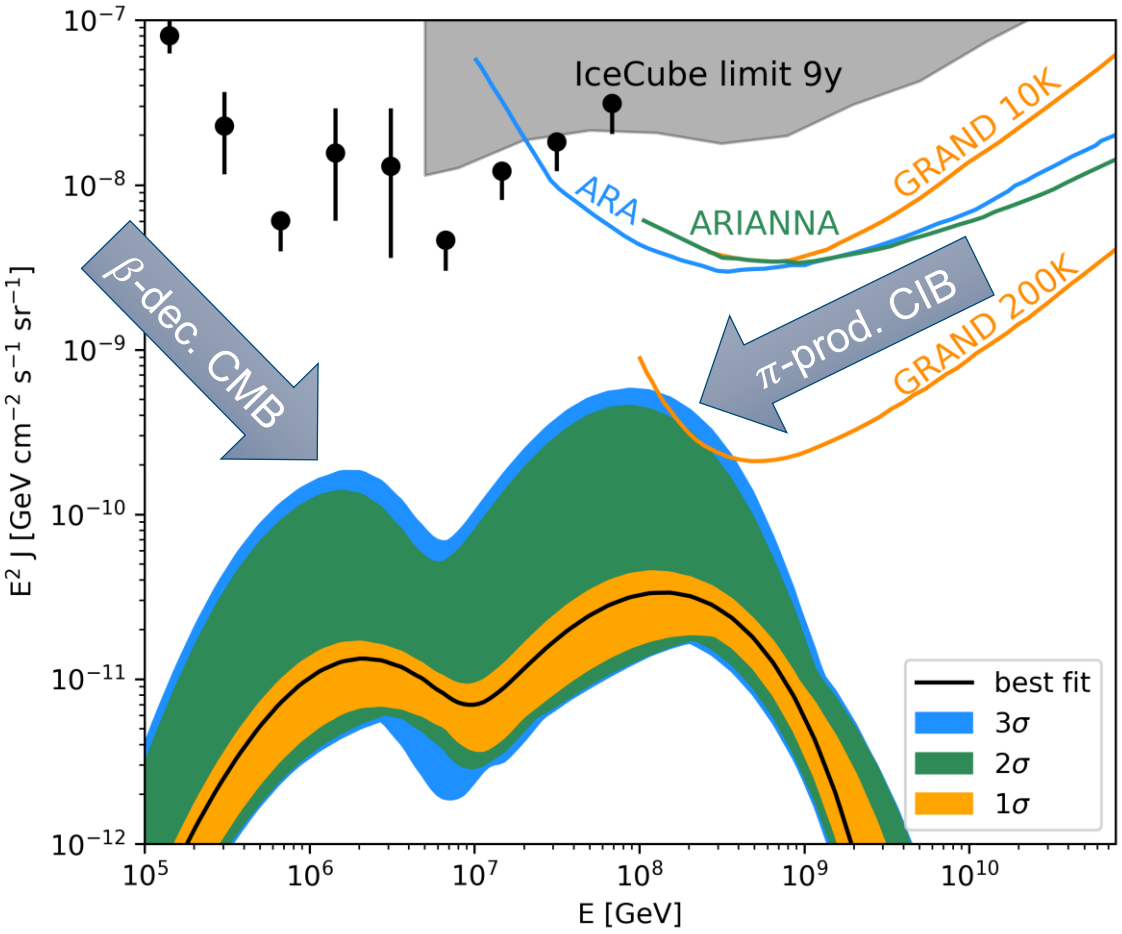
Cosmogenic neutrinos

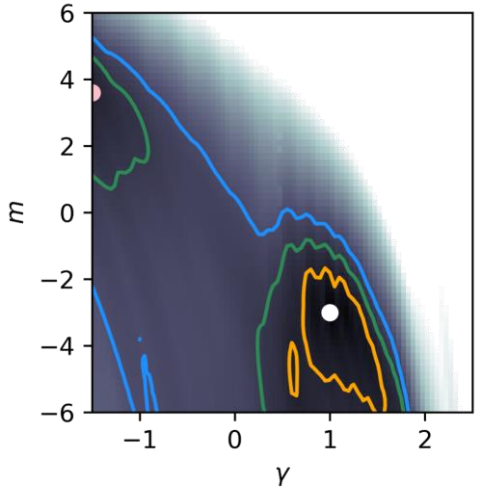
For combination PSB – Epos-LHC

- Neutrino bands from contours
- Flux mainly depends on source evol.
- Computed only from redshift 1 !!

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

- UHECRs only sensitive to z = 1
  How do we continue
  at higher redshift?





Model dependence of the Fit

Compared in $\gamma - m$ space

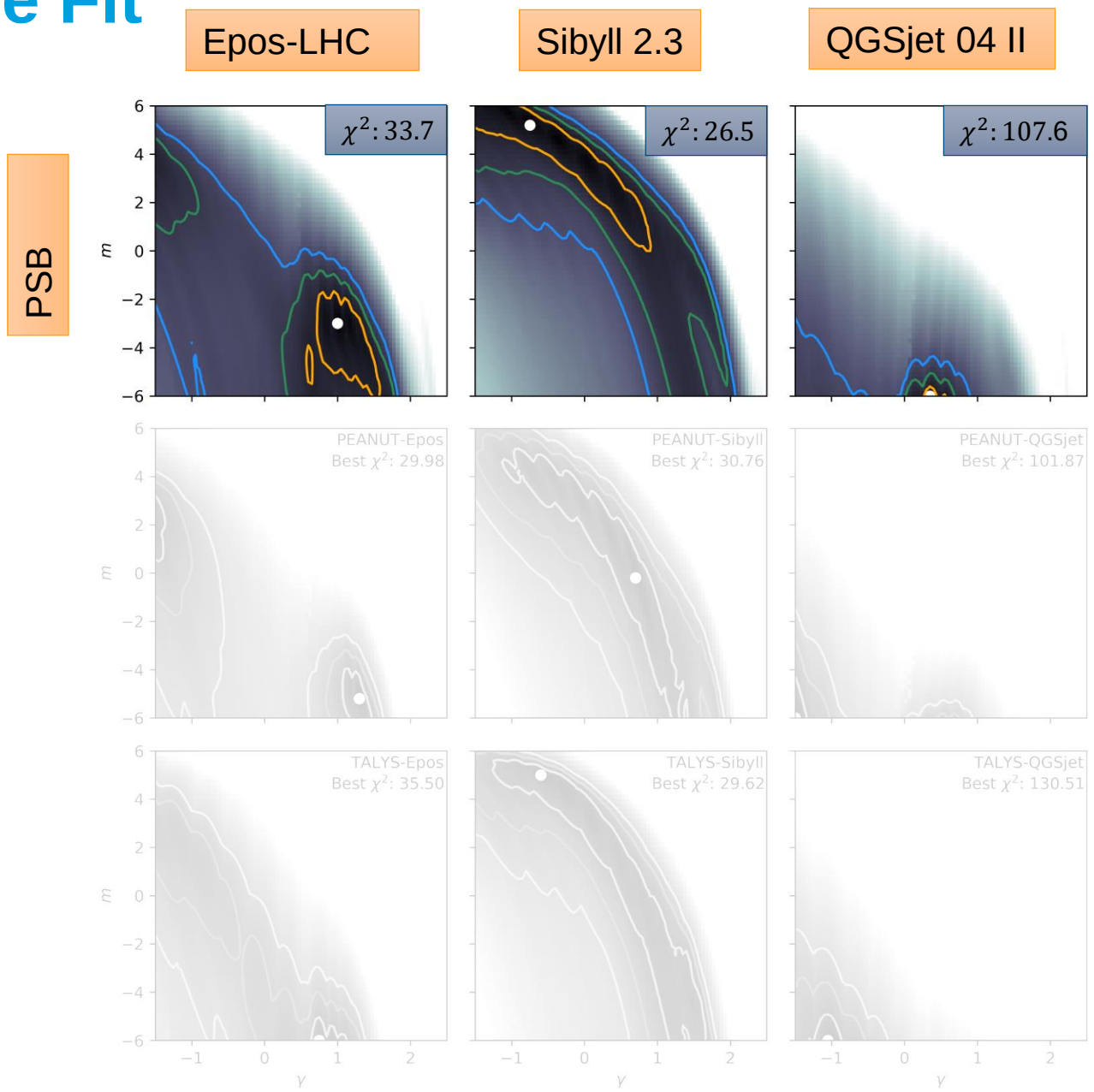
Shower model

- 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 JCAP 02 (2013) 026

Disintegration model

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



Model dependence of the Fit

Compared in $\gamma - m$ space

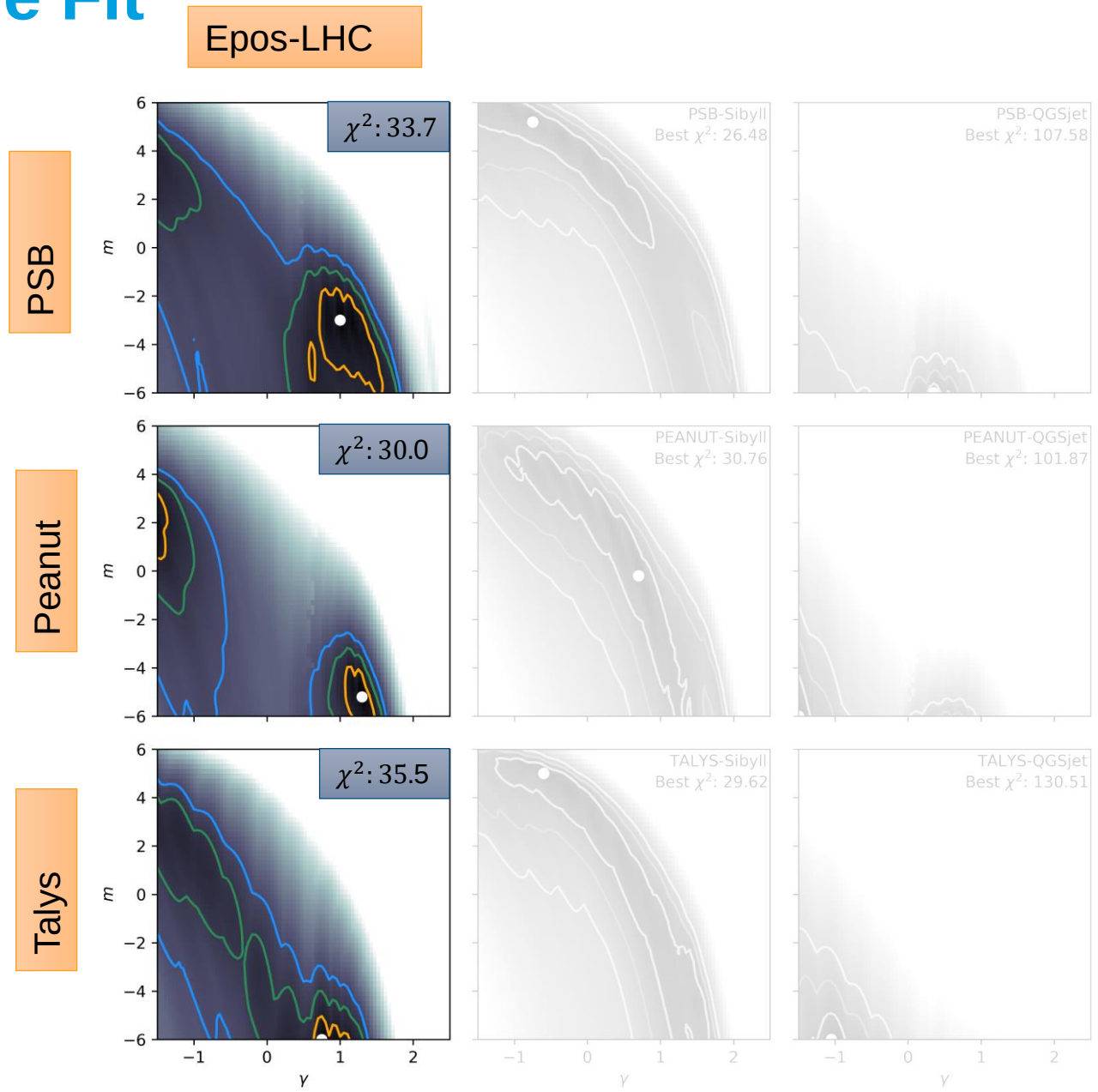
Shower model

- 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 JCAP 02 (2013) 026

Disintegration model

- Qualitatively similar fits for each model
- PSB: Ligher injection
- PSB: Heavier injection



Model dependence of the Fit

Compared in $\gamma - m$ space

Shower model

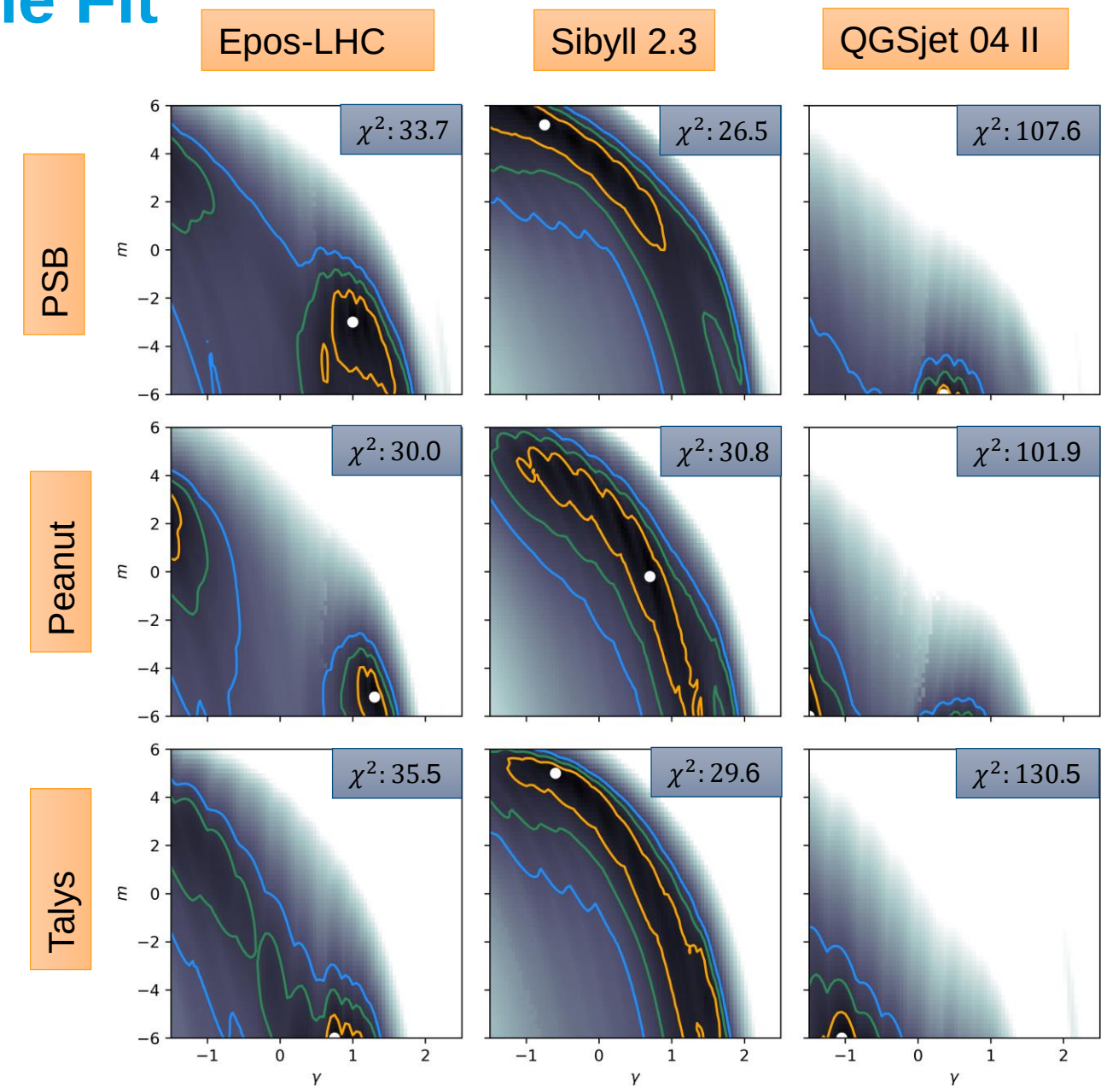
- Epos-LHC: Two distinct minima
  avoids disintegration
- Sibyll 2.3: Larger allowed space
  prefers disintegration
- QGSjet 4 II: Overall rather bad fit

See also: Auger Collaboration JCAP 02 (2013) 026

Disintegration model

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

The shower model has a stronger qualitative impact!



Model dependence of Cosmogenic Neutrinos

Shower Model

- Sibyll slightly higher than Epos-LHC
- QGSjet low flux (but bad fit anyway…)

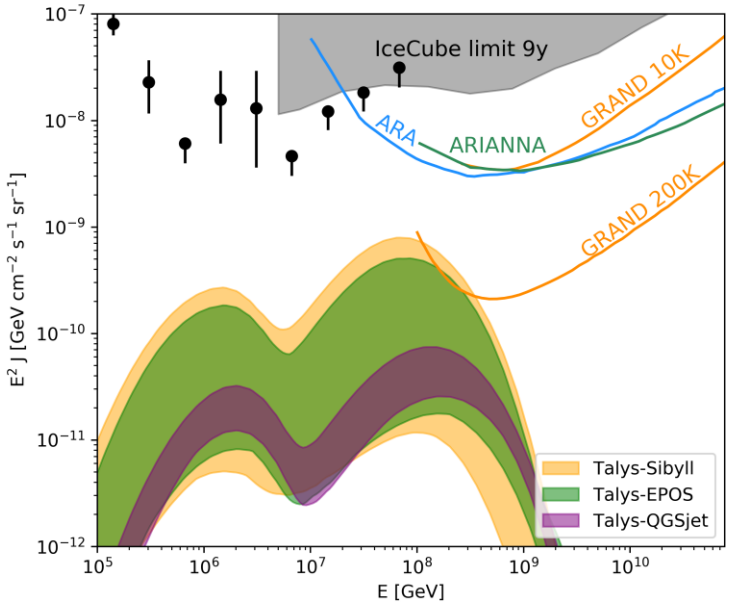
Disintegration Model

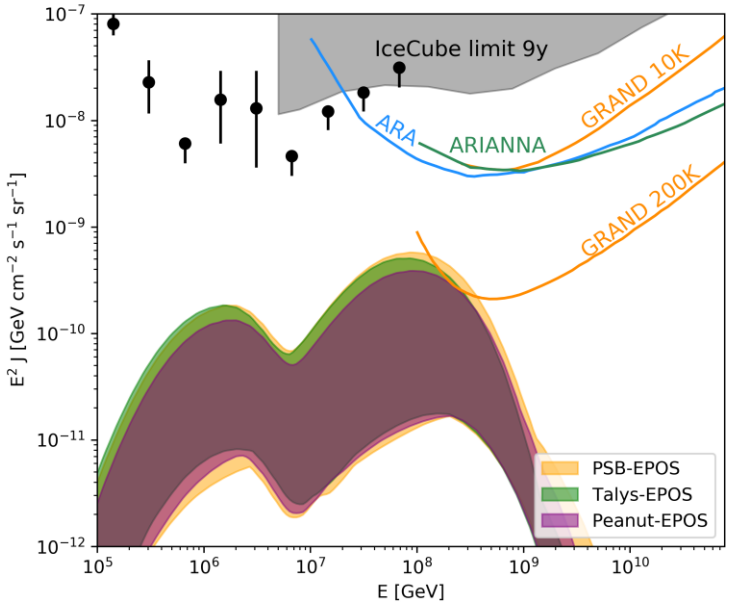
- Varies within a factor 2

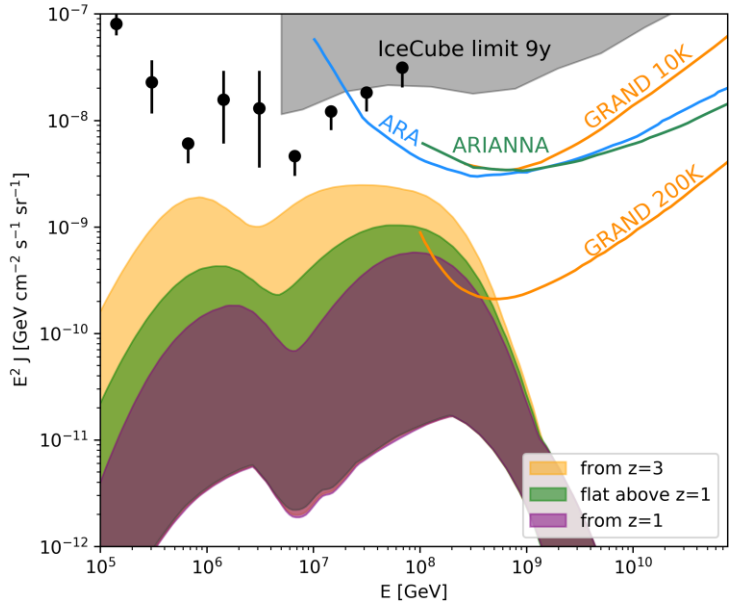
Source evolution

- How to continue above z = 1?

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







Maximal flux level robust within a factor 2

Can change an order of magn. (But UHECRs insensitive)

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

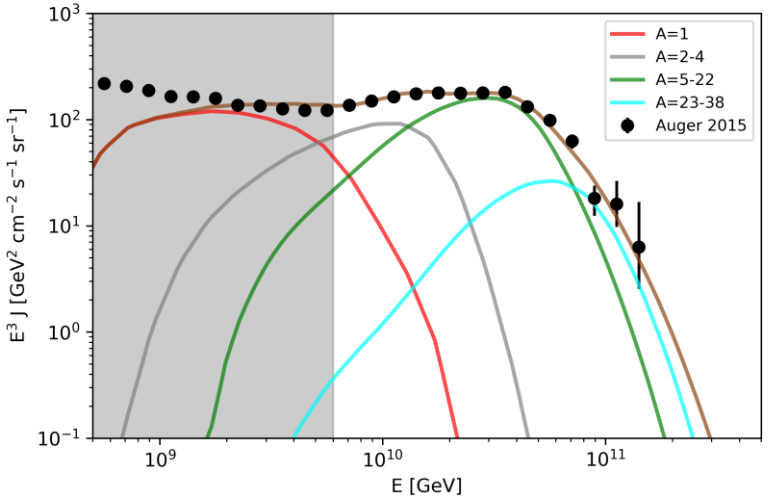
- The shower-model has a stronger impact on the injection composition interpretation than the disintegration-model

- 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

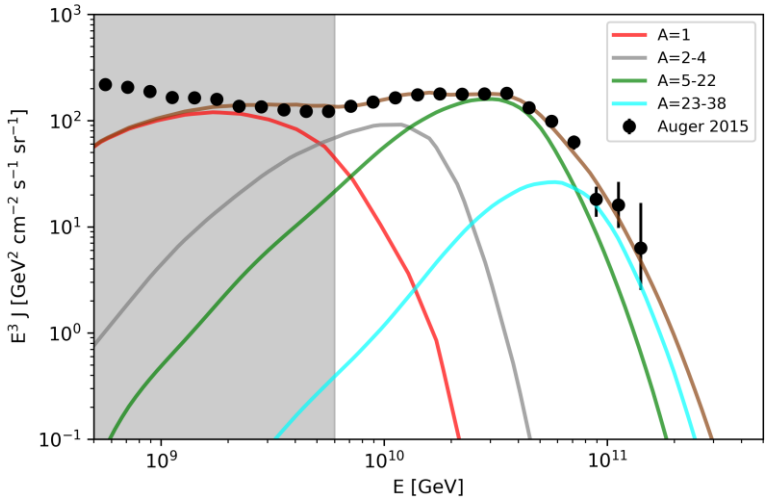
Spectrum for high redshift

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

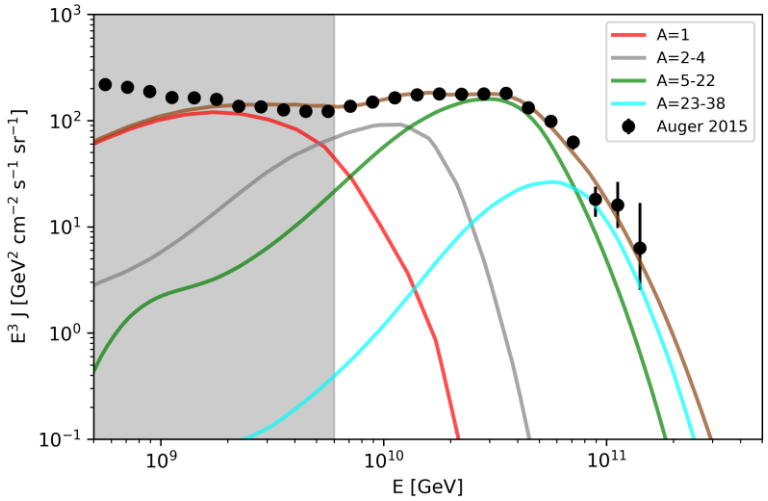


Second minimum
$m = 3.6$

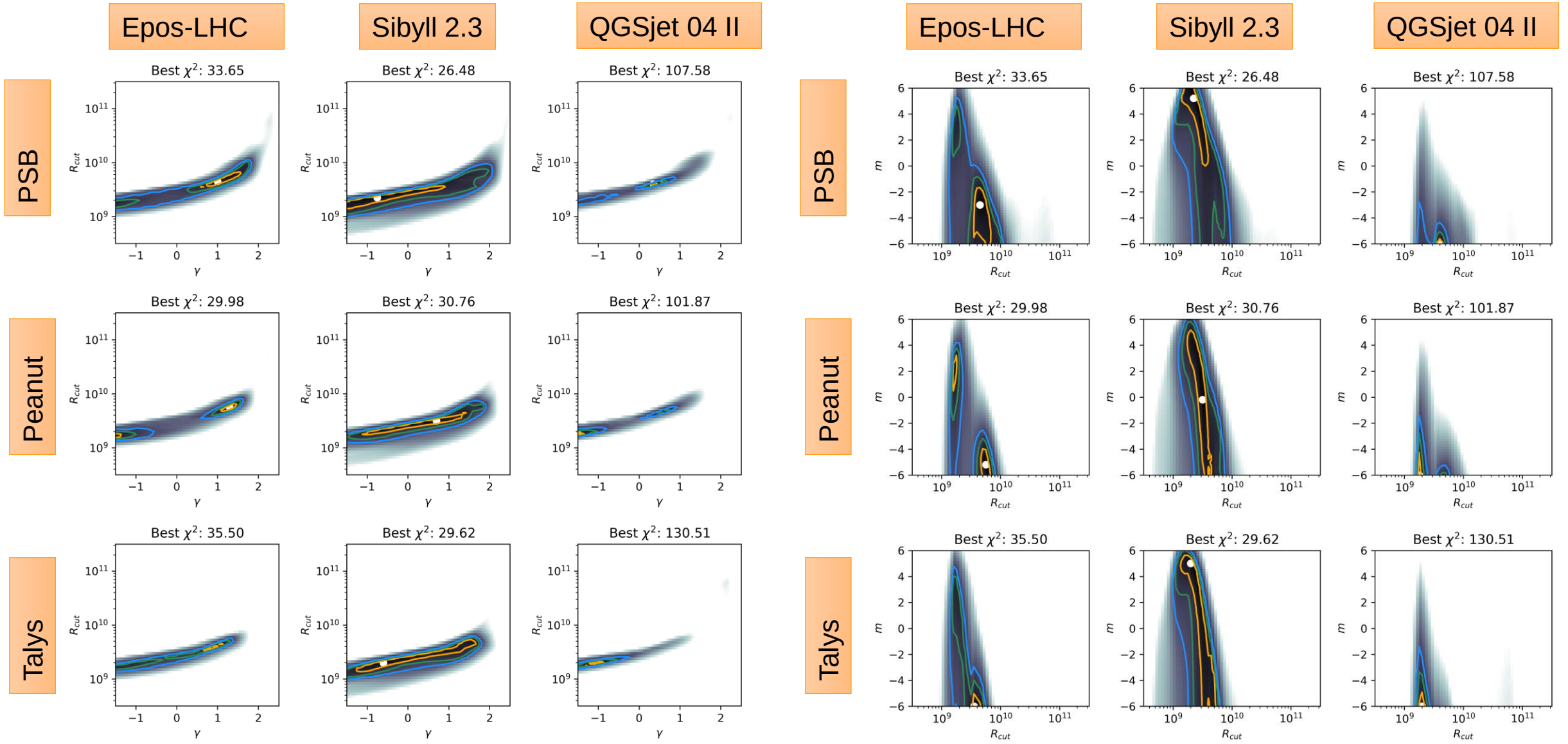
continue flat evol.



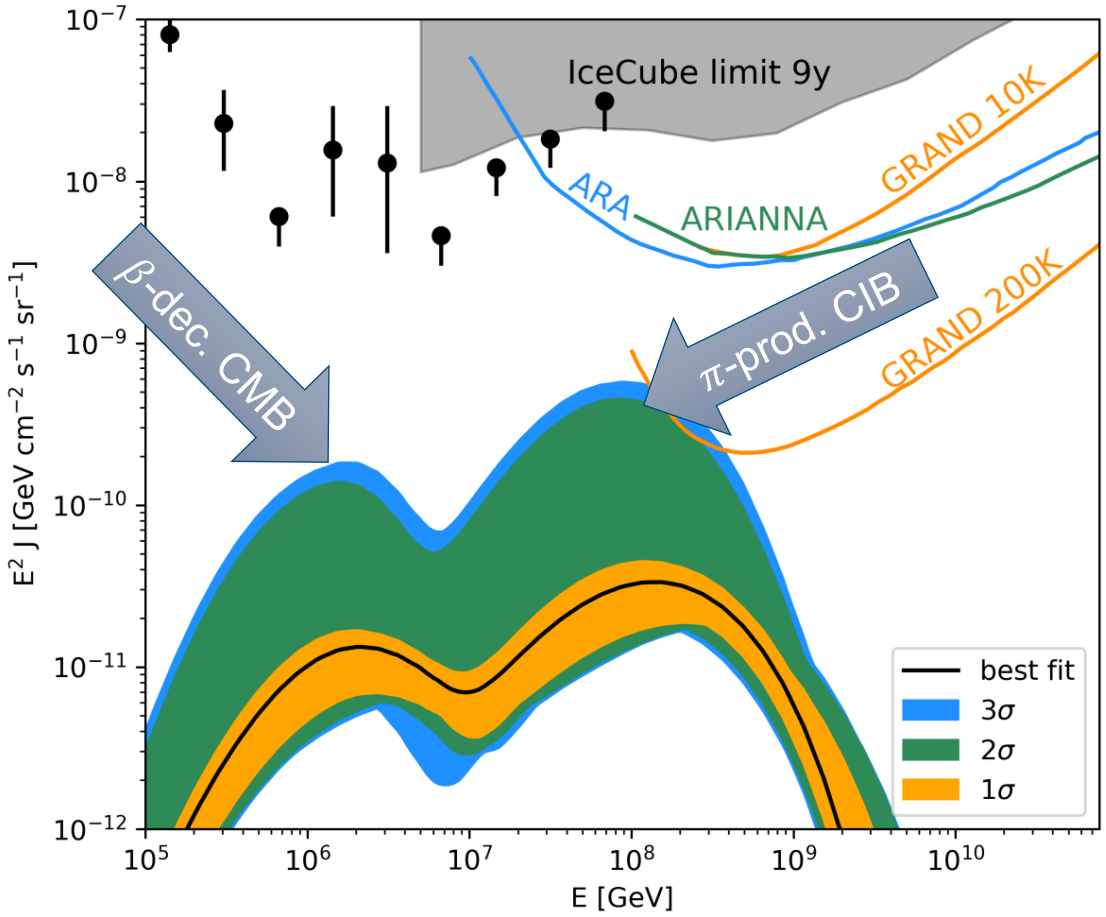
continue to $z = 3$

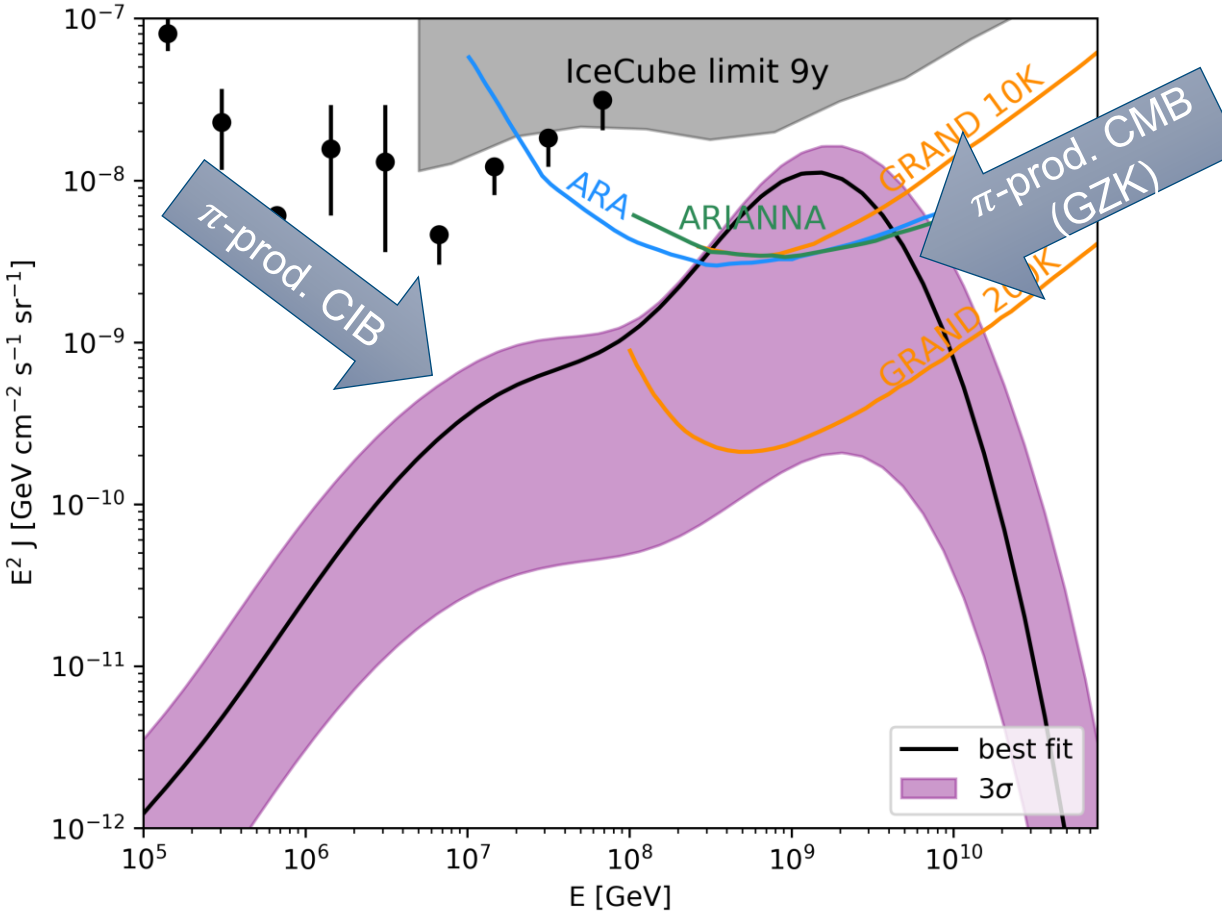


Model comparision

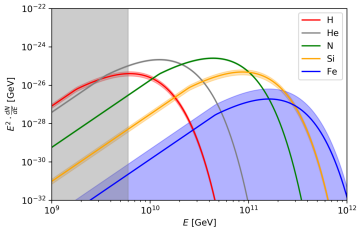


Cosmogenic Neutrinos for protons





Fit procedure



Disintegration Models:
Talys / PSB / Peanut

Auger Data:
Spectrum, X_{max}, $\sigma(X_{max})$

Generic Source
γ, R_{cut}, m

PriNCe
(Propagation)

Individual Spectra
H, He, N, Si, Fe

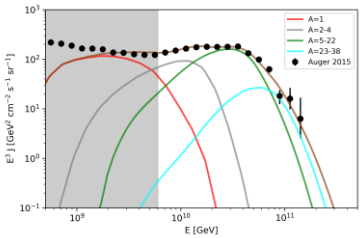
iMinuit
(χ^2 fit)

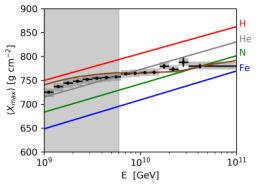
Best fit weights
$J_H, J_{He}, J_N, J_{Si}, J_{Fe}$

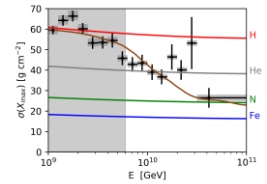
$$\mathcal{L}_A = J_A \left(\frac{E}{10^9 \mathrm{GeV}} \right)^{-\gamma} \times f_{\mathrm{cut}}(E, Z_A, R_{\mathrm{cut}}) \times n_{\mathrm{evol}}(z)$$

$$n_{\mathrm{evol}}(z) = (1+z)^m$$

Shower Models:
Epos-LHC, Sibyll 2.3,
QGSjet 04II







UHE Cosmic Ray Propagation - Uncertainties

Assuming we know the source perfectly…

Extragalactic Environment

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

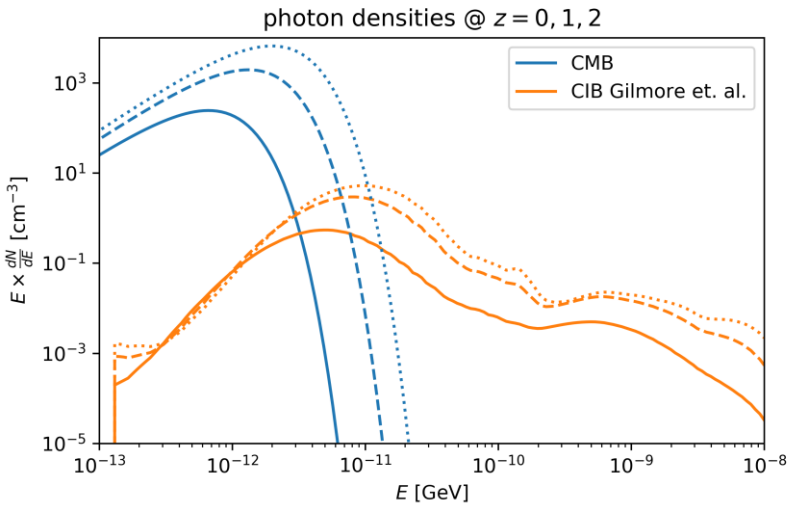
Not in this Talk though!

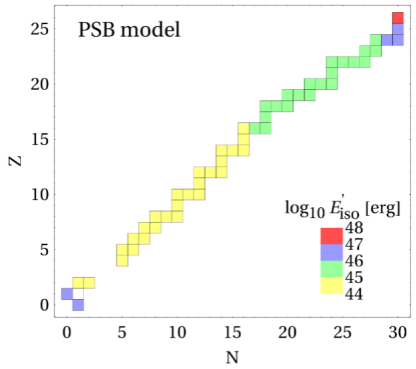
Photohadronic model

- Disintegration at lower energies
  - Models PSB, Talys, Peanut
- Meson-prod. at higher energies
  - Superposition - Model?
  - see poster by Leonel Morejon

Air-Shower Model

- To compare composition to X_{max}
- Shower model can change the interpretation significantly!





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