# A new view on Auger data and cosmogenic neutrinos in light of different nuclear disintegration and air-shower models


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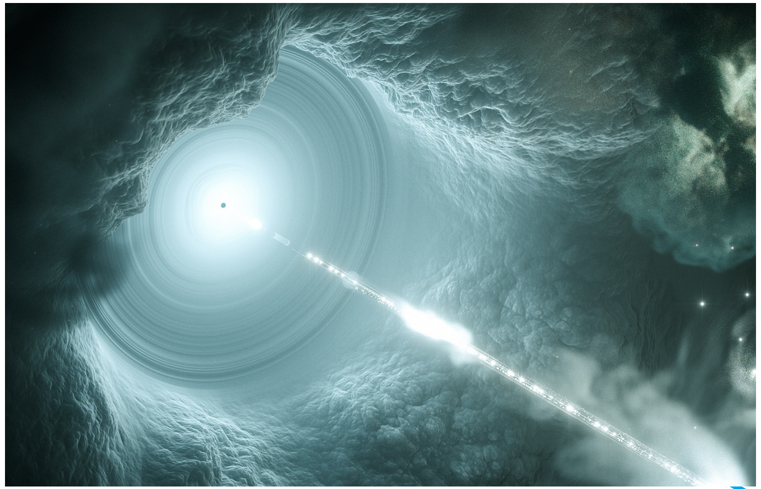
# Origin of the features in UHECR spectrum and composition?

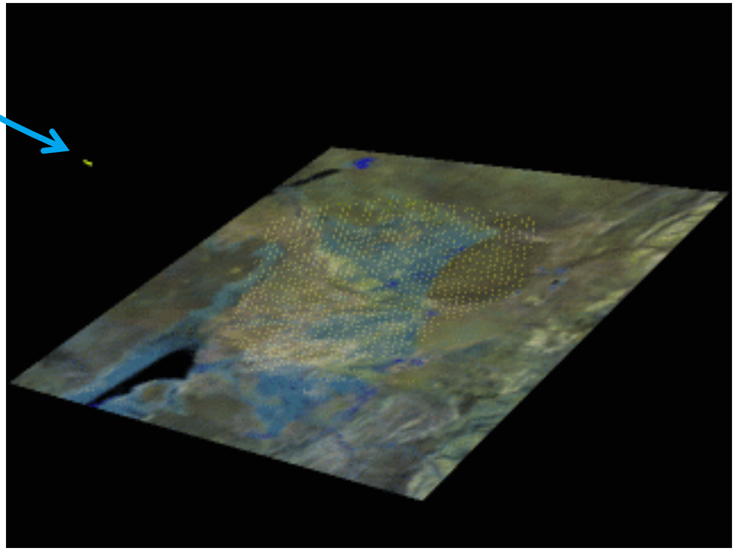
**Generic** accelerator



**Simulate transport** of cosmic rays through extragalactic medium

**Assume** that there is **one dominant type** of UHECR accelerators

**Interpret Pierre Auger data**

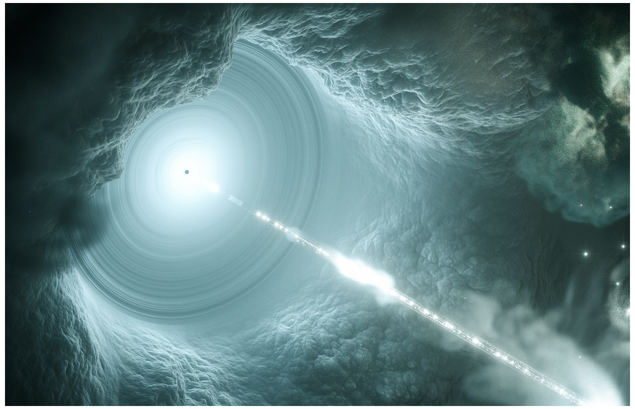


This talk: Heinze, AF, Boncioli & Winter, ApJ 873 (2019)

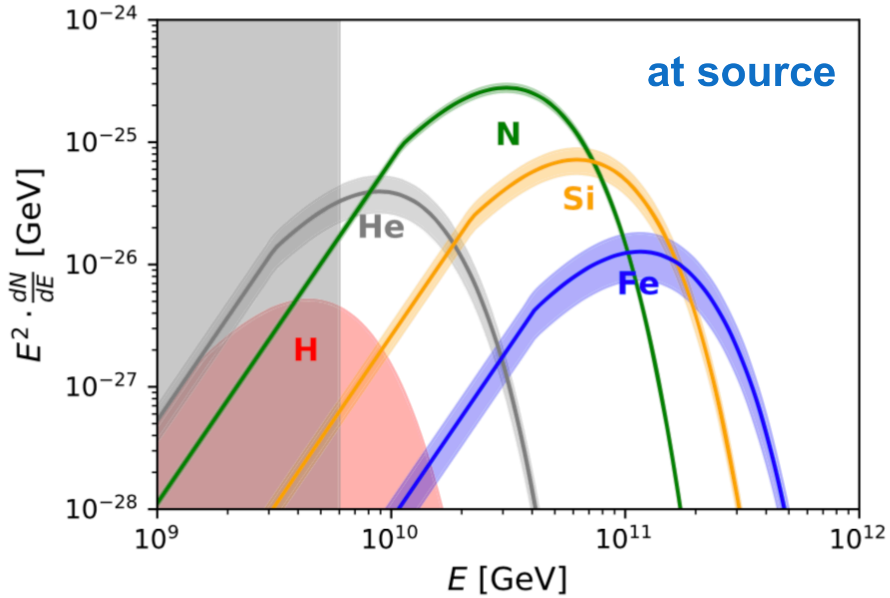
Related works:
Aab et al. (PAO), JCAP 1704, 038 (2017)
Alves Batista et al., JCAP 1901, 002 (2019)

# Source model

**One** dominant accelerator type



**Rigidity-dependent** cutoff
**Five** injection masses




**Source spectrum:**

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

**Cosmological density evolution:** $n_{\mathrm{evol}}(z) = (1+z)^m$

- seven free parameters
- Choice of cutoff shape
- Choice of injection masses

# Transport model

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

comoving particle density

adiabatic cooling

pair - production

photo-nuclear

Injection

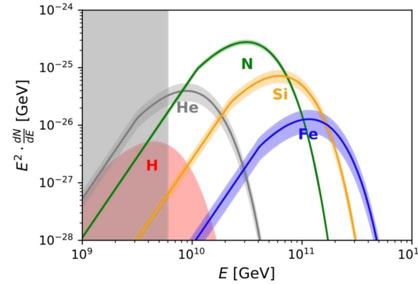
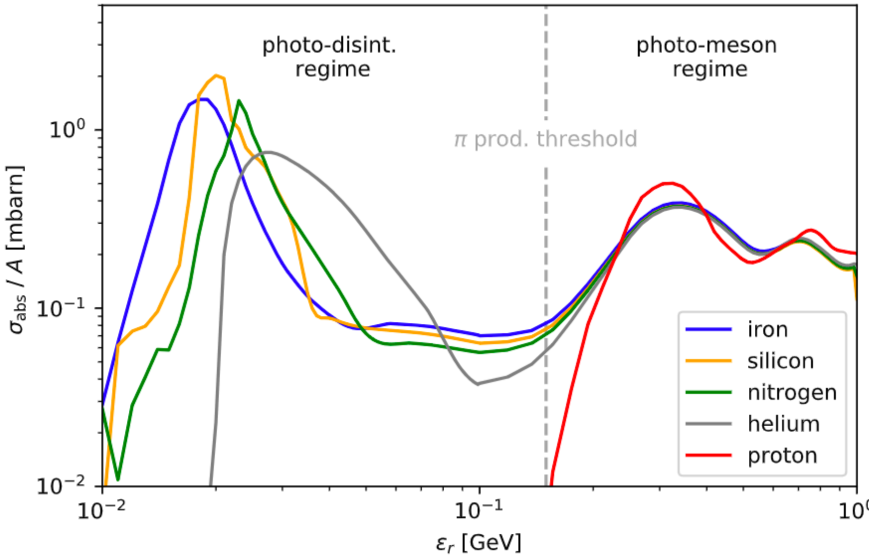
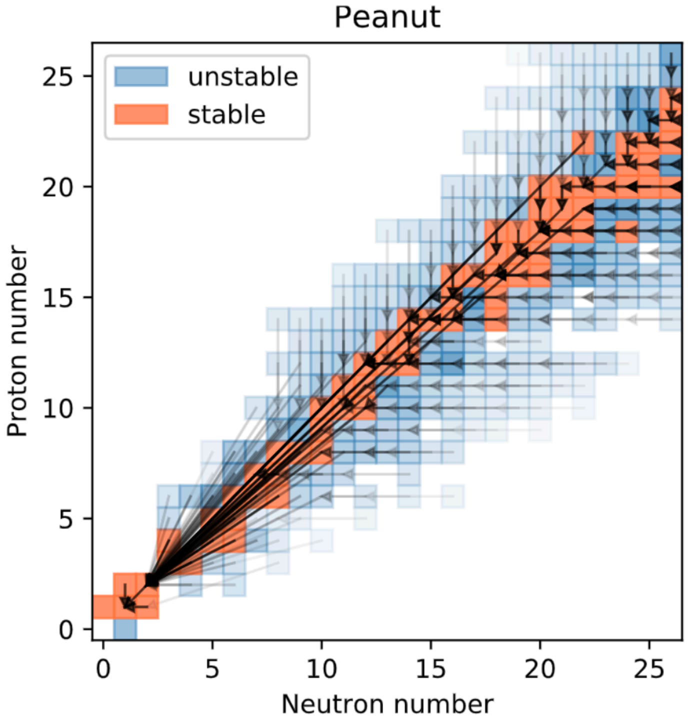



**Photo-nuclear** interaction cross sections




Yields of **secondary nuclei**

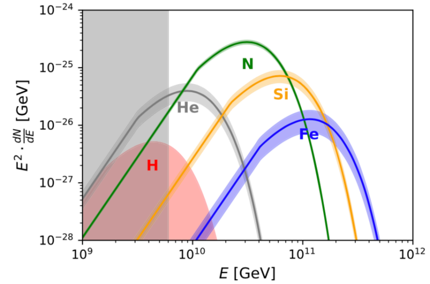



- Choice of photo-nuclear model
- (Choice of photo-meson model)

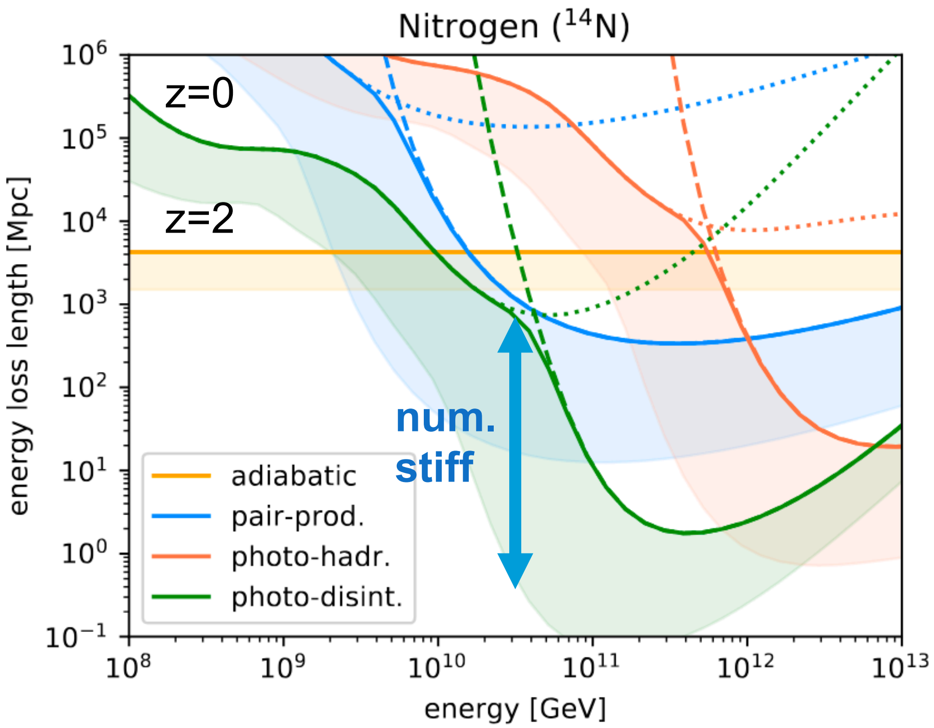
# Transport model

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

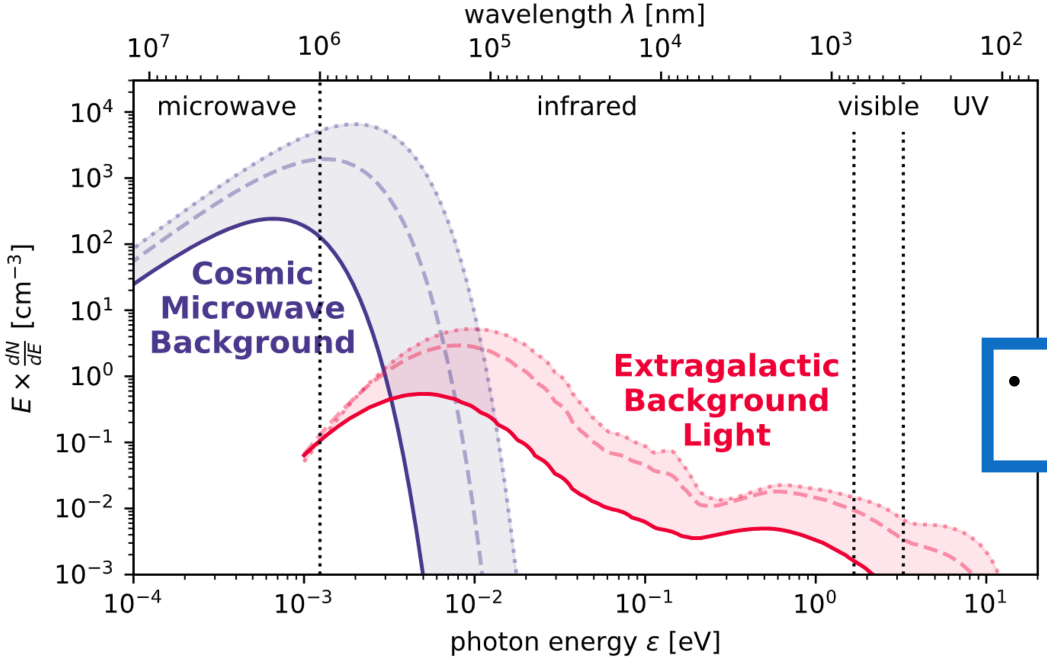
comoving particle density | adiabatic cooling | pair - production | photo-nuclear | Injection




Redshift dependence of **interaction rates**




**Target photons**




- Choice of EBL model

CIB: Gilmore+, MNRAS422, (2012)

# Transport code - PriNCe

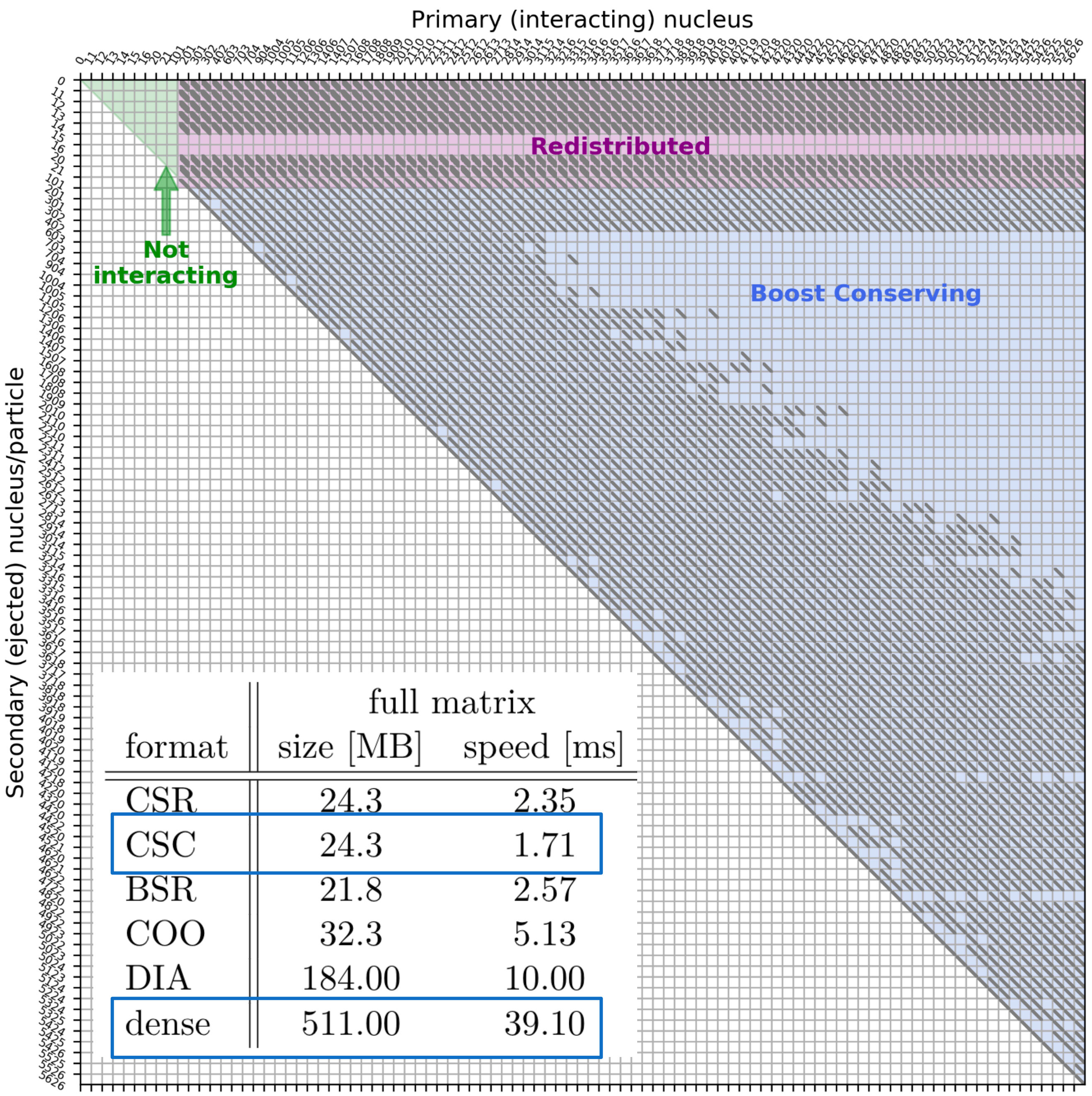
**All interaction rates are redshift dependent**

particle density

$$Q_{j\to i}(Y_j,\, E_i) = \int_{E_i}^{\infty} dE_j\; Y_j(E_j,\, z)$$
$$\times \int d\varepsilon\; n_\gamma(\varepsilon)\; h_{j\to i}(E_i,\, E_j,\, y(E_j,\, \varepsilon))$$

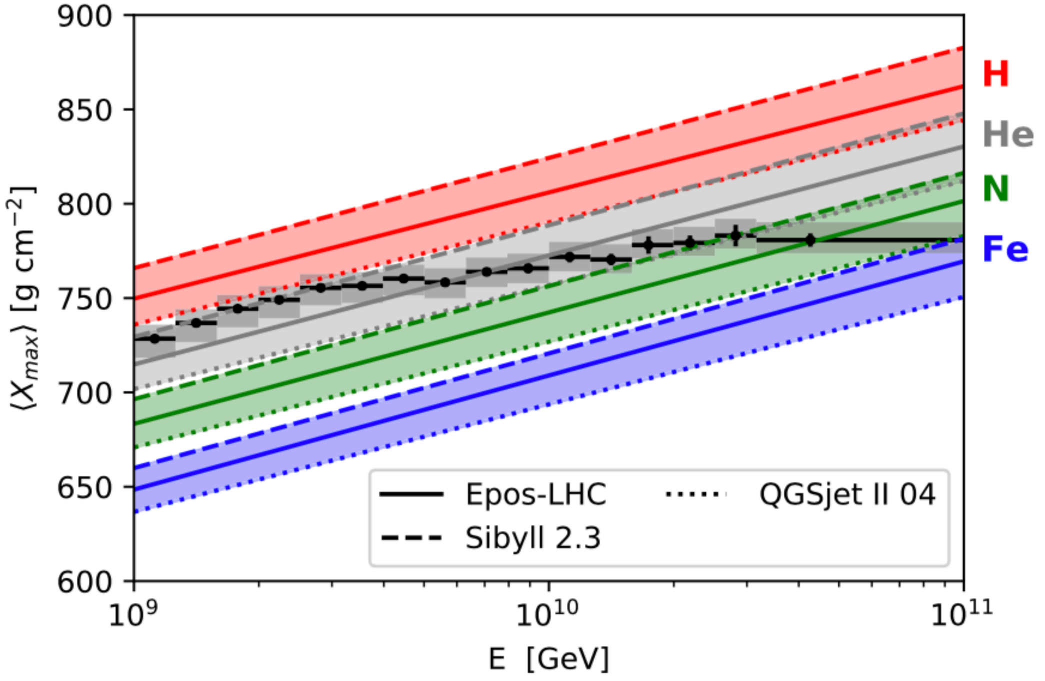
Photon density    Photo-nuclear c.s.

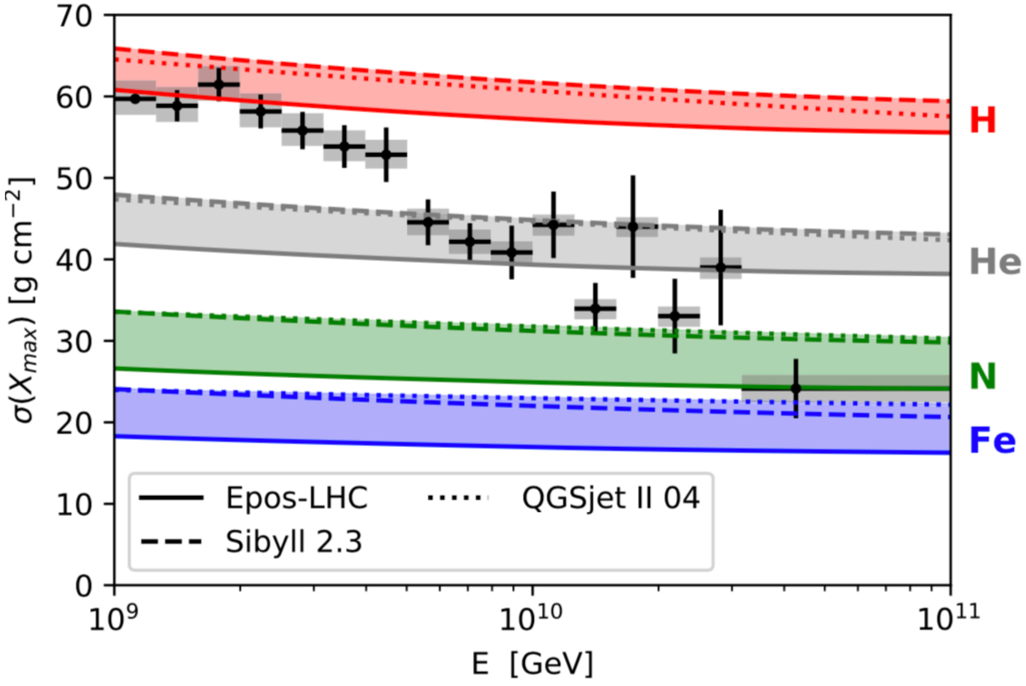
- Photo-hadronic interactions requires **double-integrals at ~each redshift** (z) step
- Exploit efficiency of sparse matrix multiplication
- PriNCe: 800**ms for proton** propagation, ~**30 seconds for Fe from z=1**
- Models can be chosen freely, **no precomputation**




| format | full matrix size [MB] | full matrix speed [ms] |
|---|---|---|
| CSR | 24.3 | 2.35 |
| CSC | 24.3 | 1.71 |
| BSR | 21.8 | 2.57 |
| COO | 32.3 | 5.13 |
| DIA | 184.00 | 10.00 |
| dense | 511.00 | 39.10 |

# Model dependence from air-shower detection



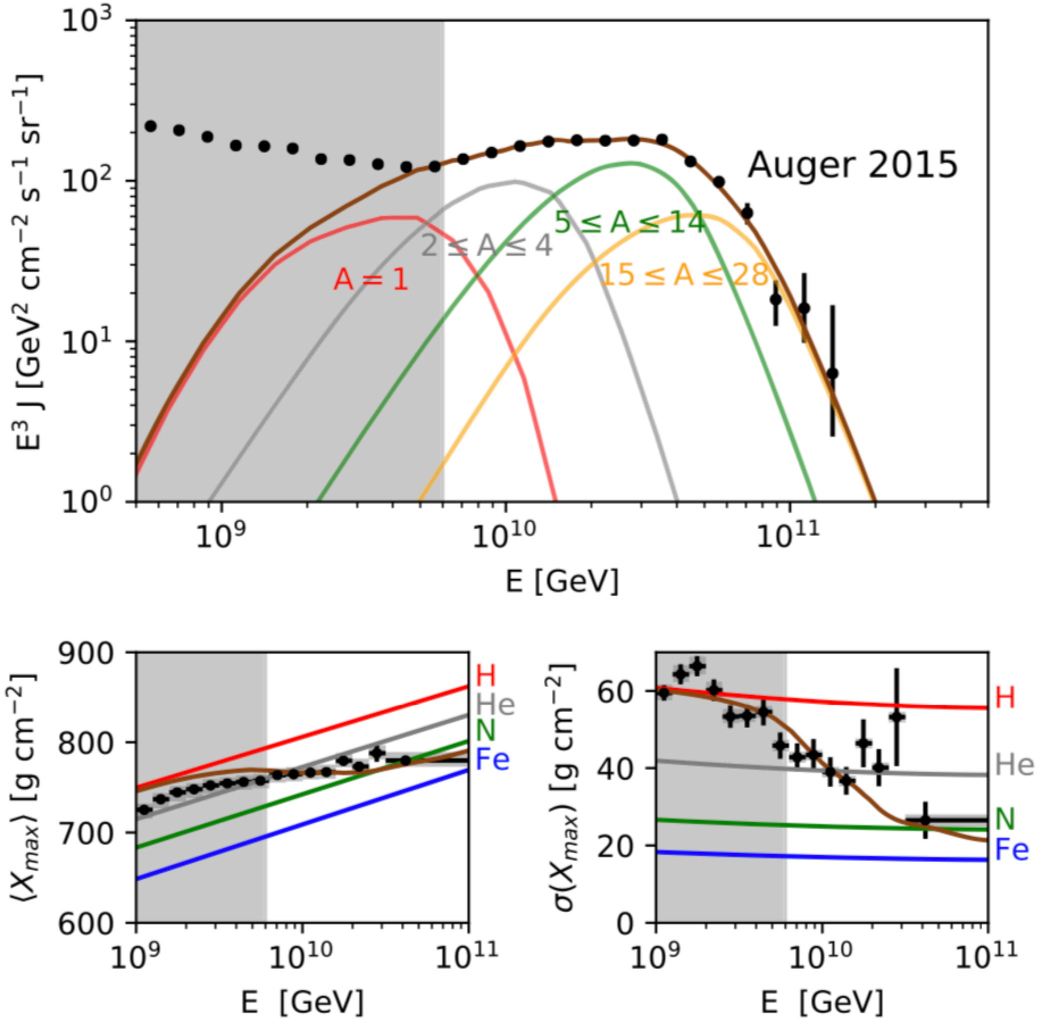



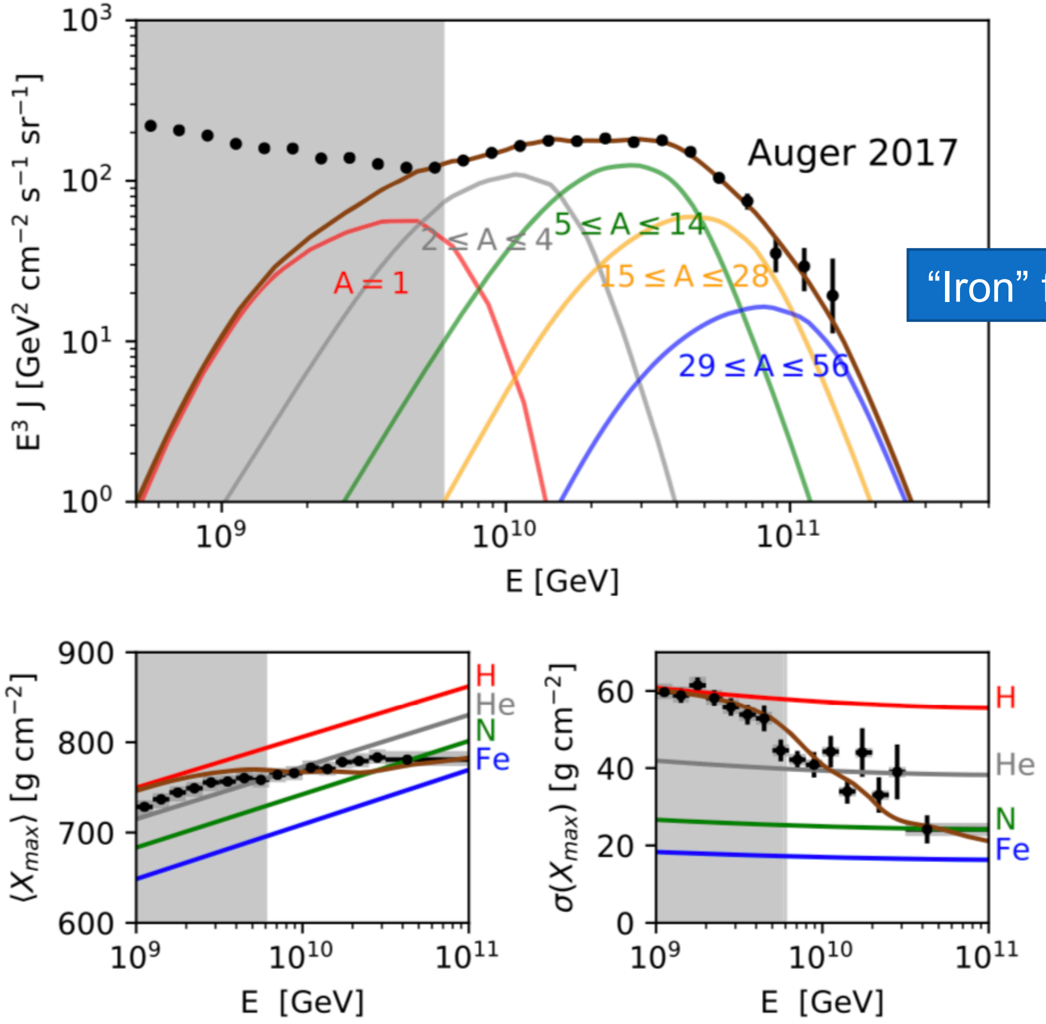

- Translation from mass composition at Earth → $X_{max}$
- **Absolute requirement: fit spectrum + both moments**
- **Choice of three** post-LHC hadronic **models**

Auger ICRC 2017: Bellido+; Fenu+

Heinze, AF, Boncioli, Winter, ApJ 873

# Impact of “more data” on the fit



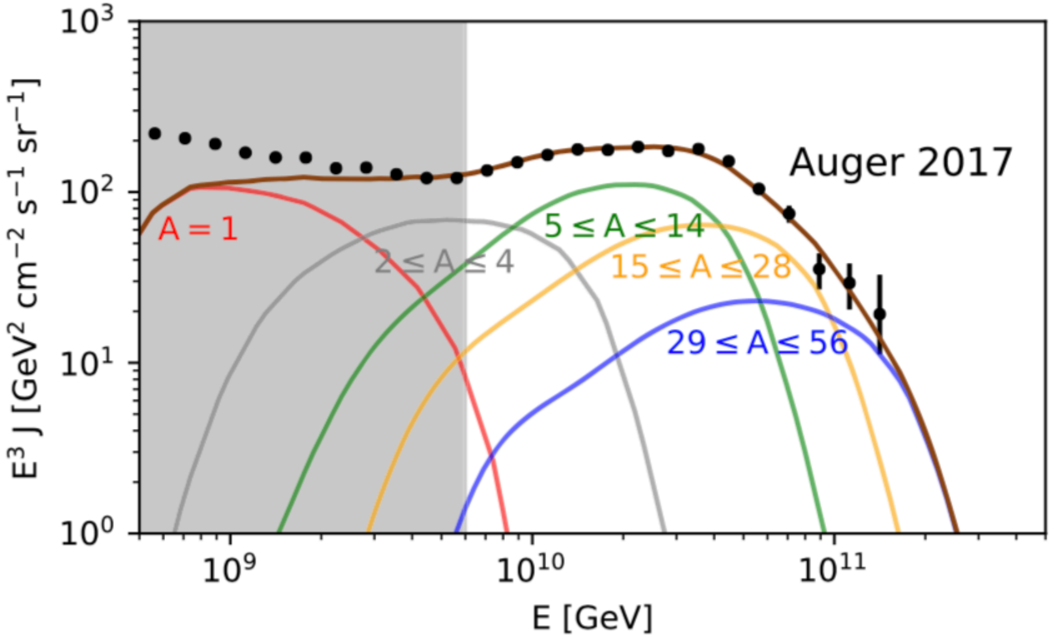

“Iron” fraction!

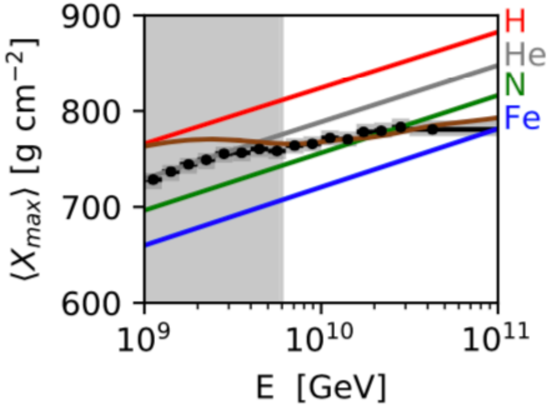
Auger ICRC 2015: Valino+, Porcelli+
Auger ICRC 2017: Bellido+; Fenu+

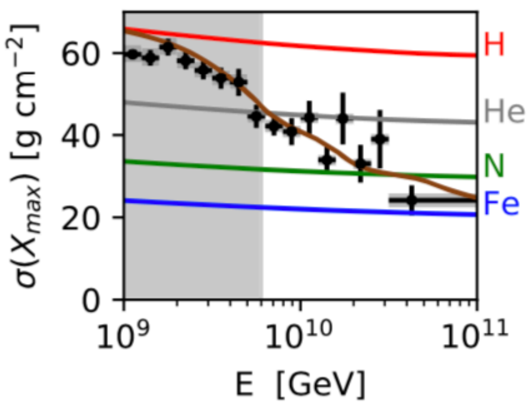
Fit conditions identical to Auger’s “Combined Fit”
Aab+ JCAP04(2017)038, i.e. flat evolution (m=0)

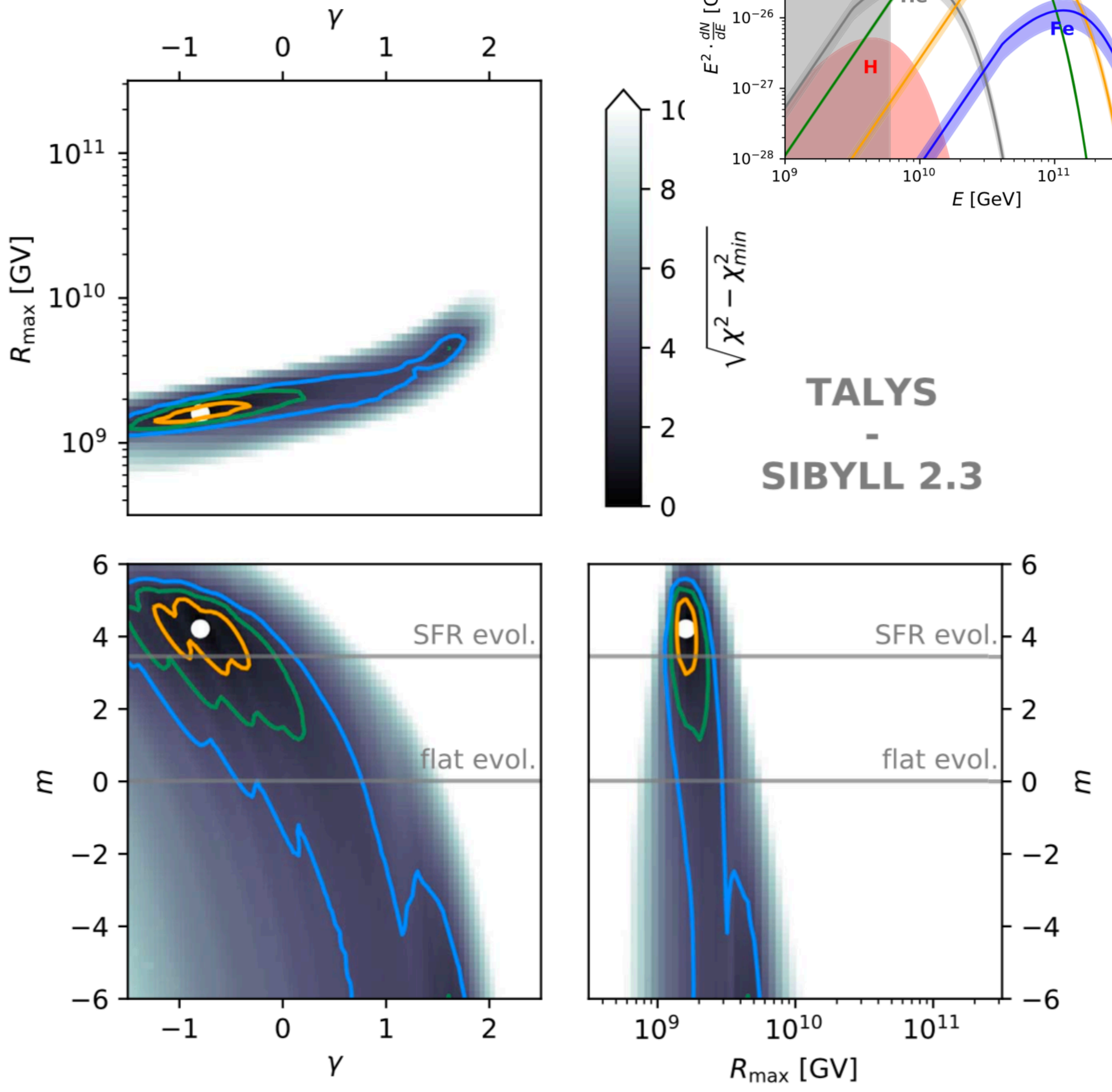
# Best ‘3D’ fit (m, $R_{max}$, $\gamma$)

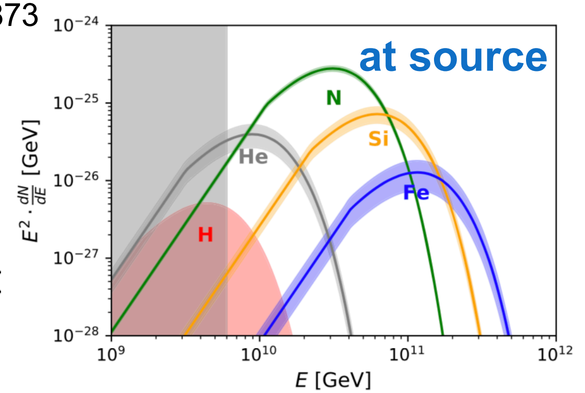
Heinze, AF, Boncioli, Winter, ApJ 873



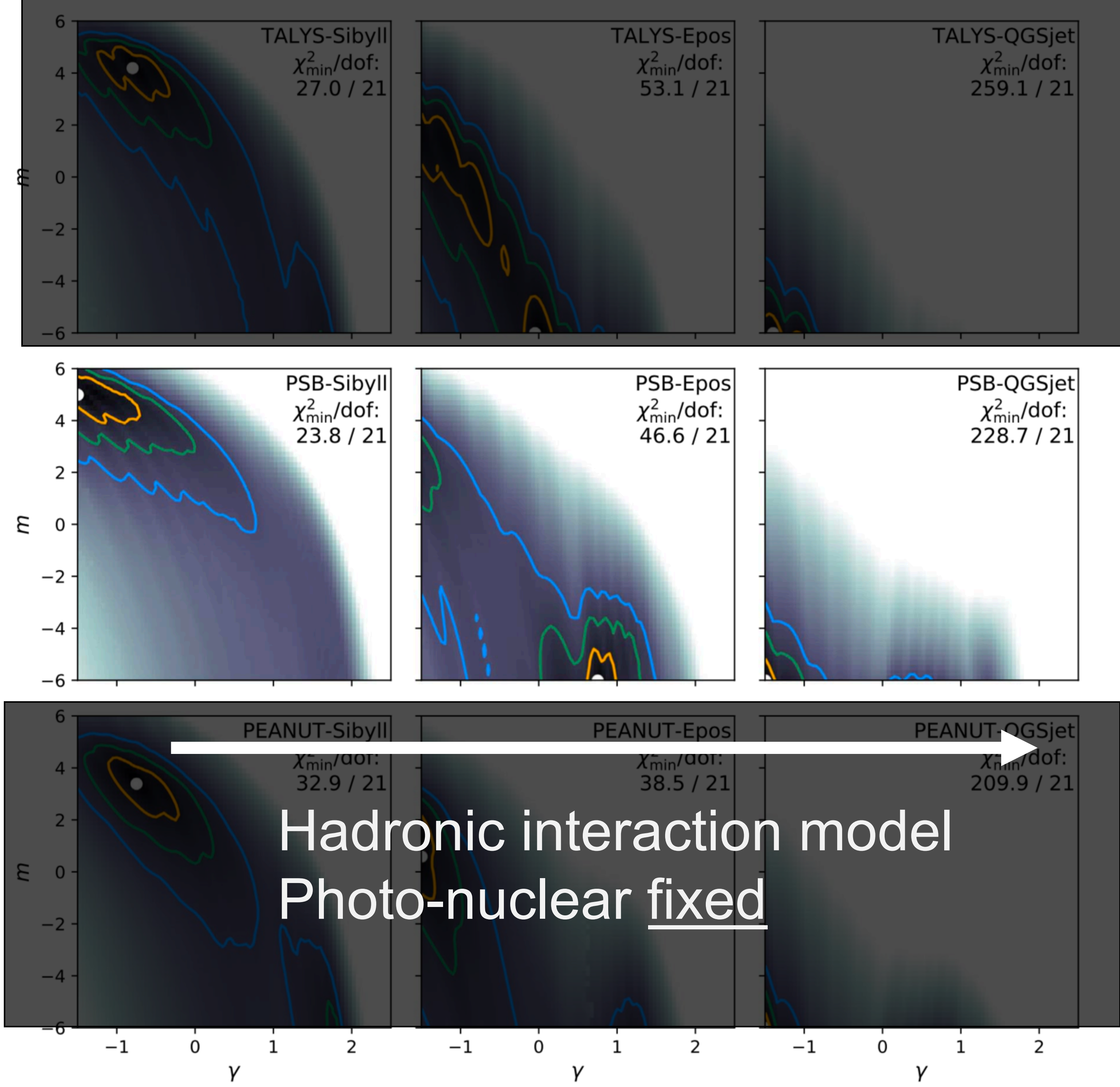



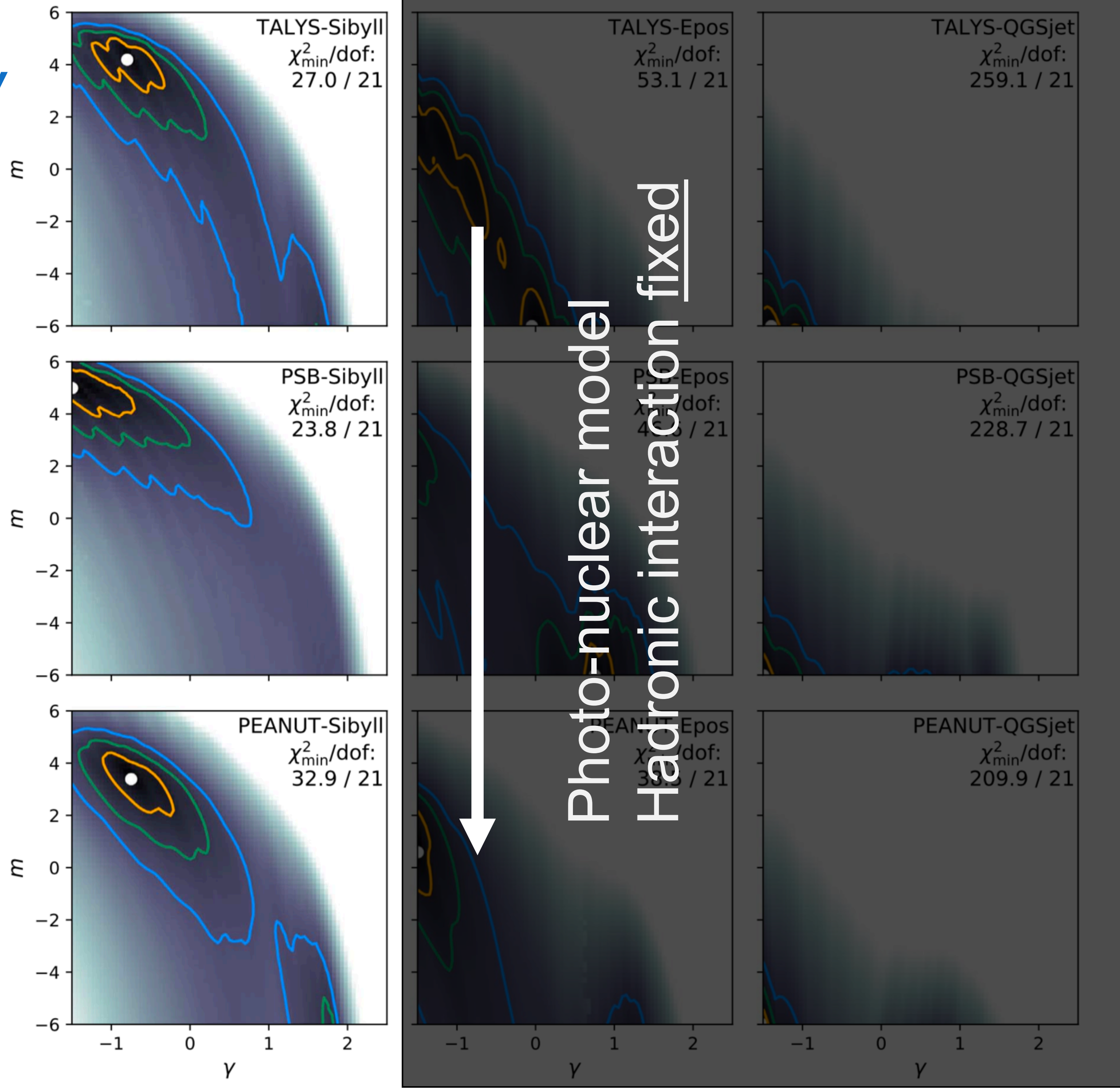
# Model-dependence in m - γ

- **Highest impact** on fit above the ankle from hadronic model



# Model-dependence in m - $\gamma$

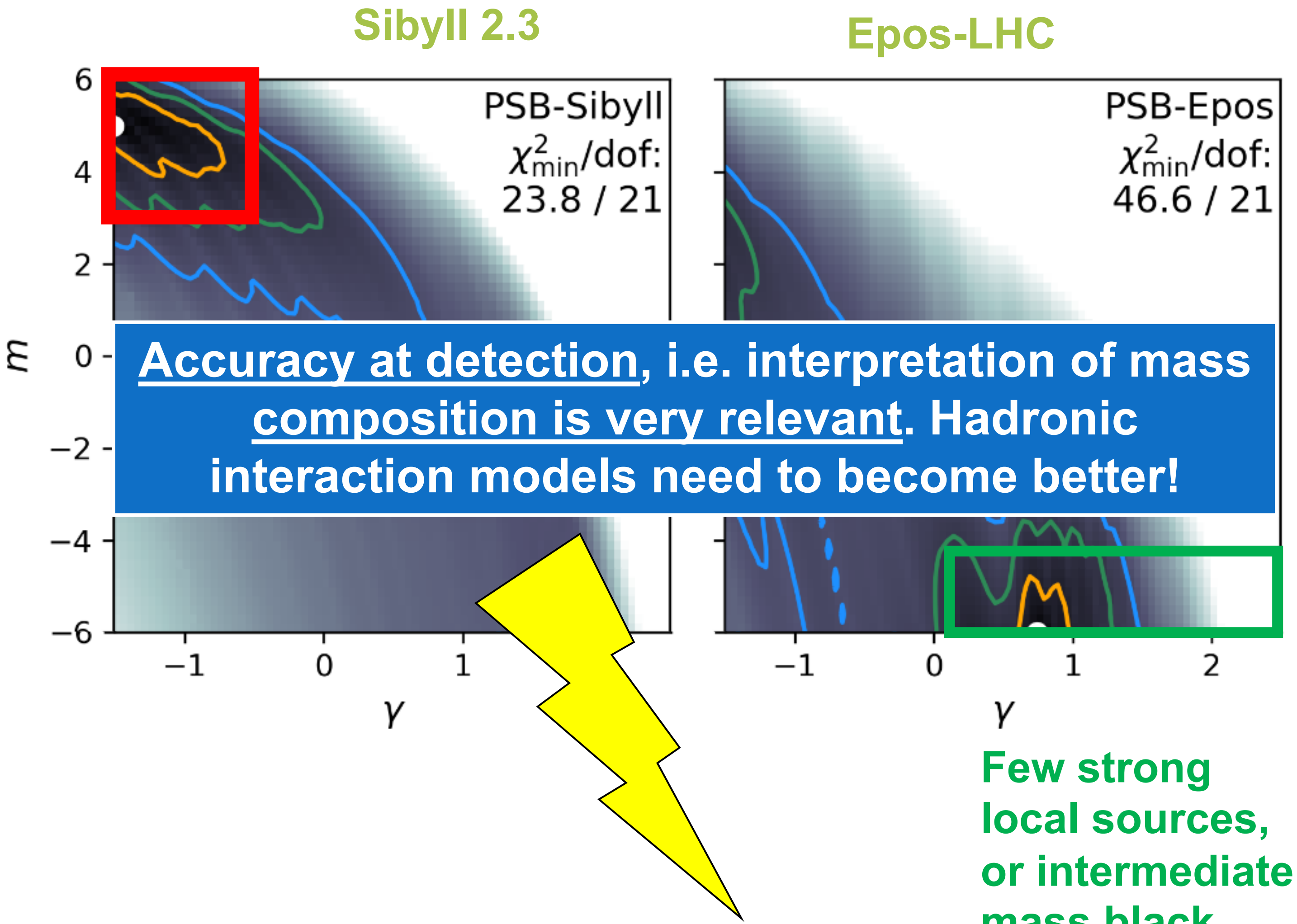
- **Highest impact** on fit above the ankle from hadronic model
- **Sub-leading impact** at highest energies from:
  1. Disintegration (GDR) model
  2. Extragalactic background light
  3. Photo-meson model
- **Fitting the ankle may break degeneracy**: but more astrophysical assumptions, magnetic fields etc.



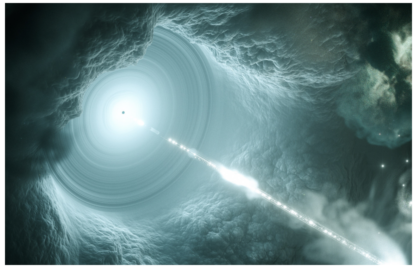
Heinze, AF, Boncioli, Winter, ApJ 873

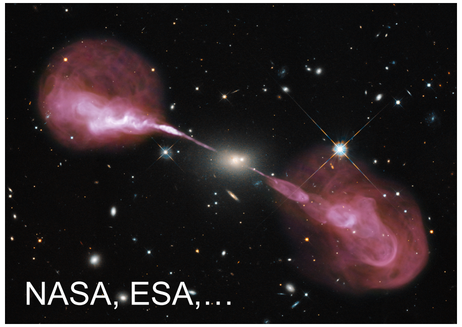
# In a nutshell

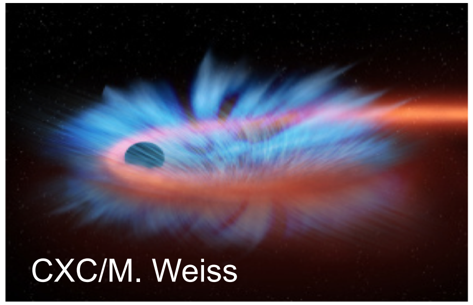
Density evolves like: Stars, Galaxies, Supernovae, AGN




**Accuracy at detection, i.e. interpretation of mass composition is very relevant. Hadronic interaction models need to become better!**



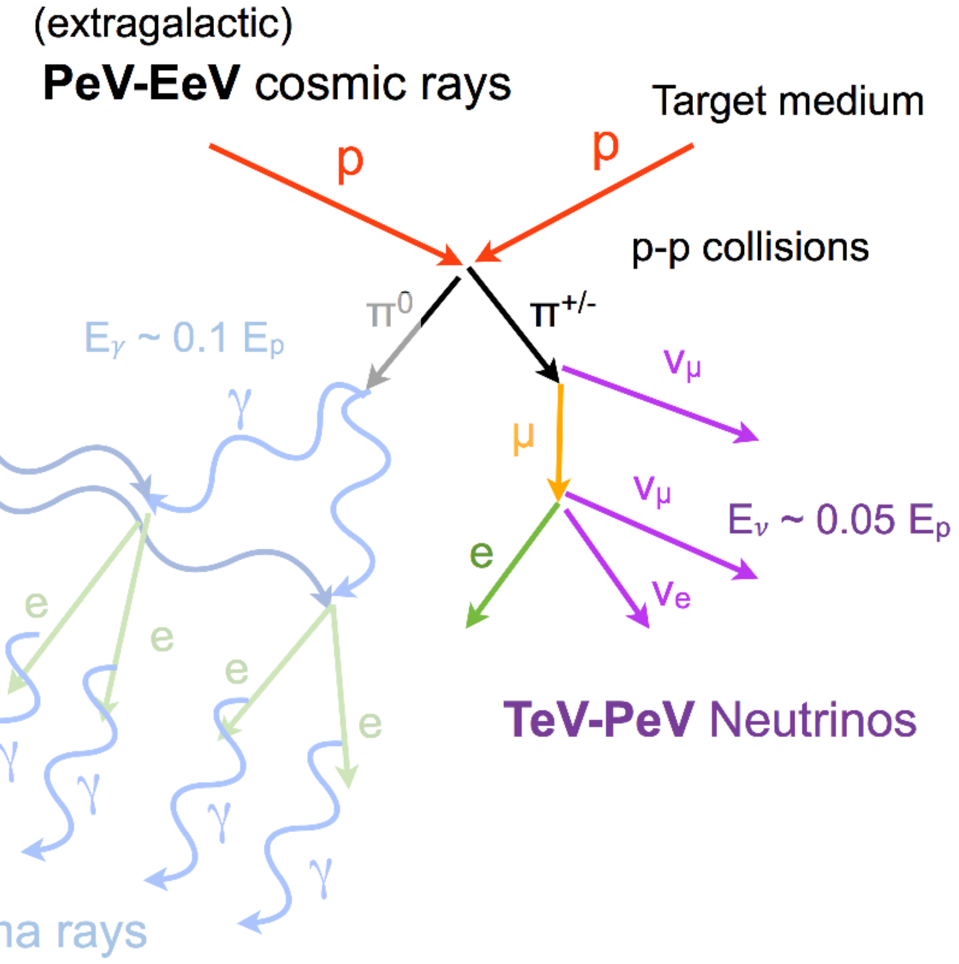



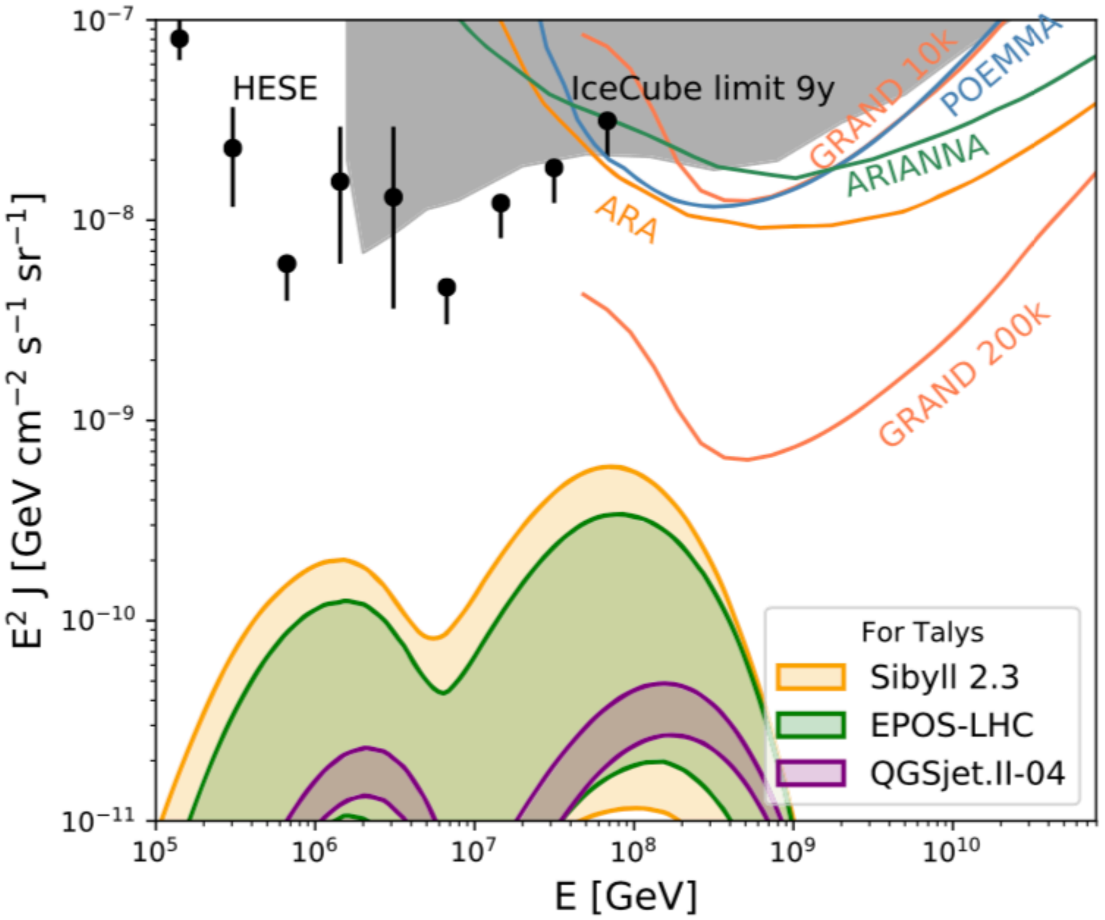

Few strong local sources, or intermediate mass black holes

Heinze, AF, Boncioli, Winter, ApJ 873

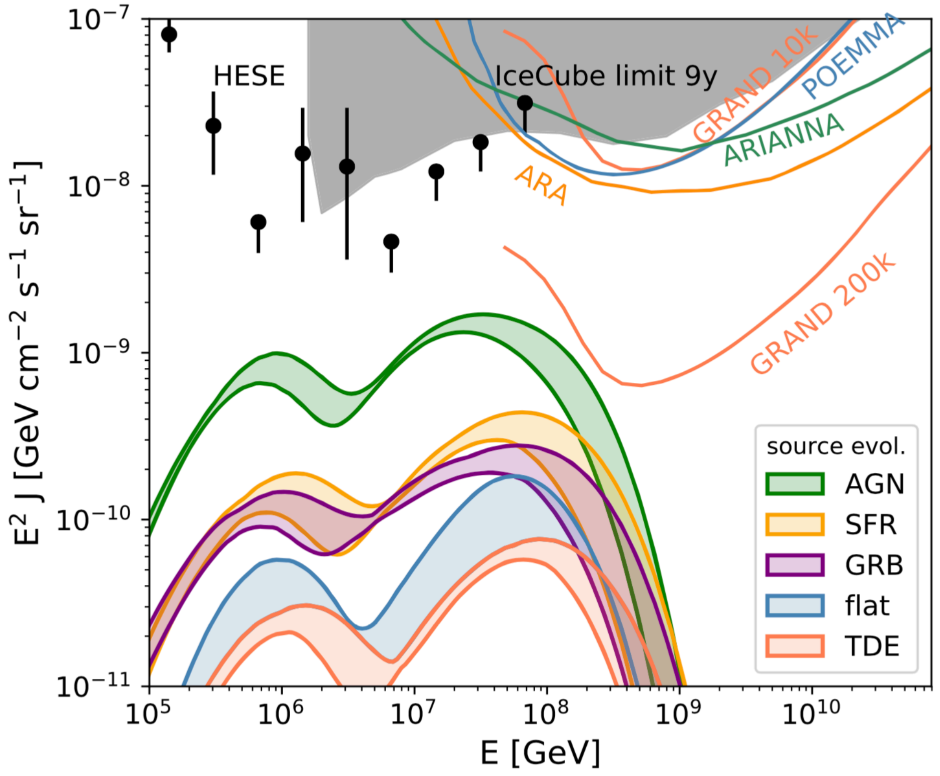
# What does it mean for cosmogenic neutrinos?

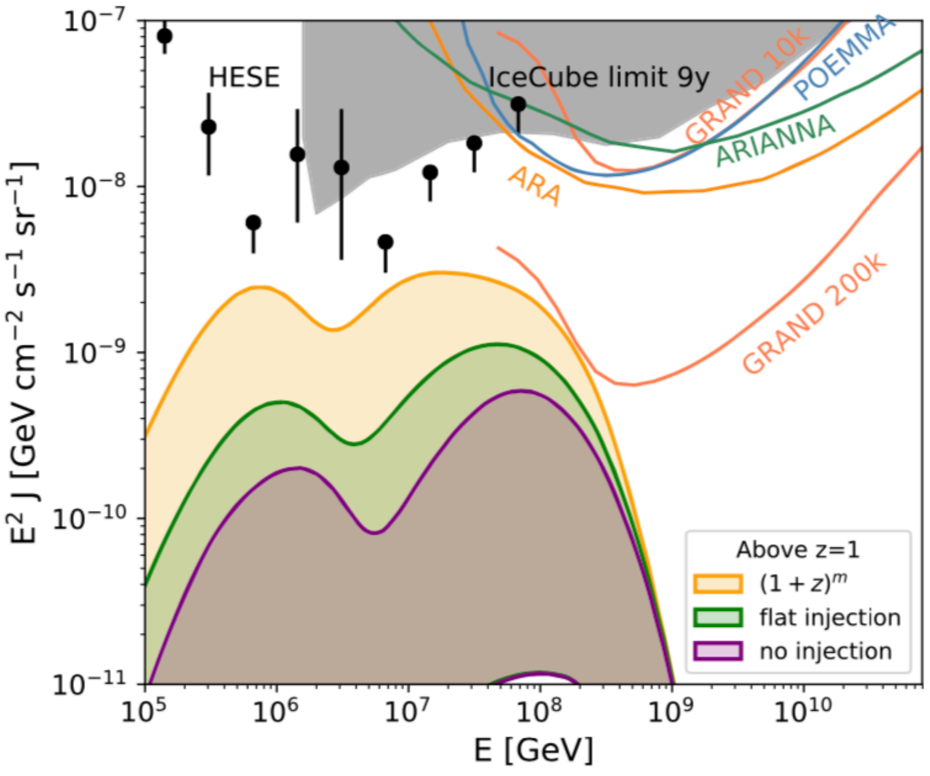



M. Ackermann



# Impact from sources with z>1



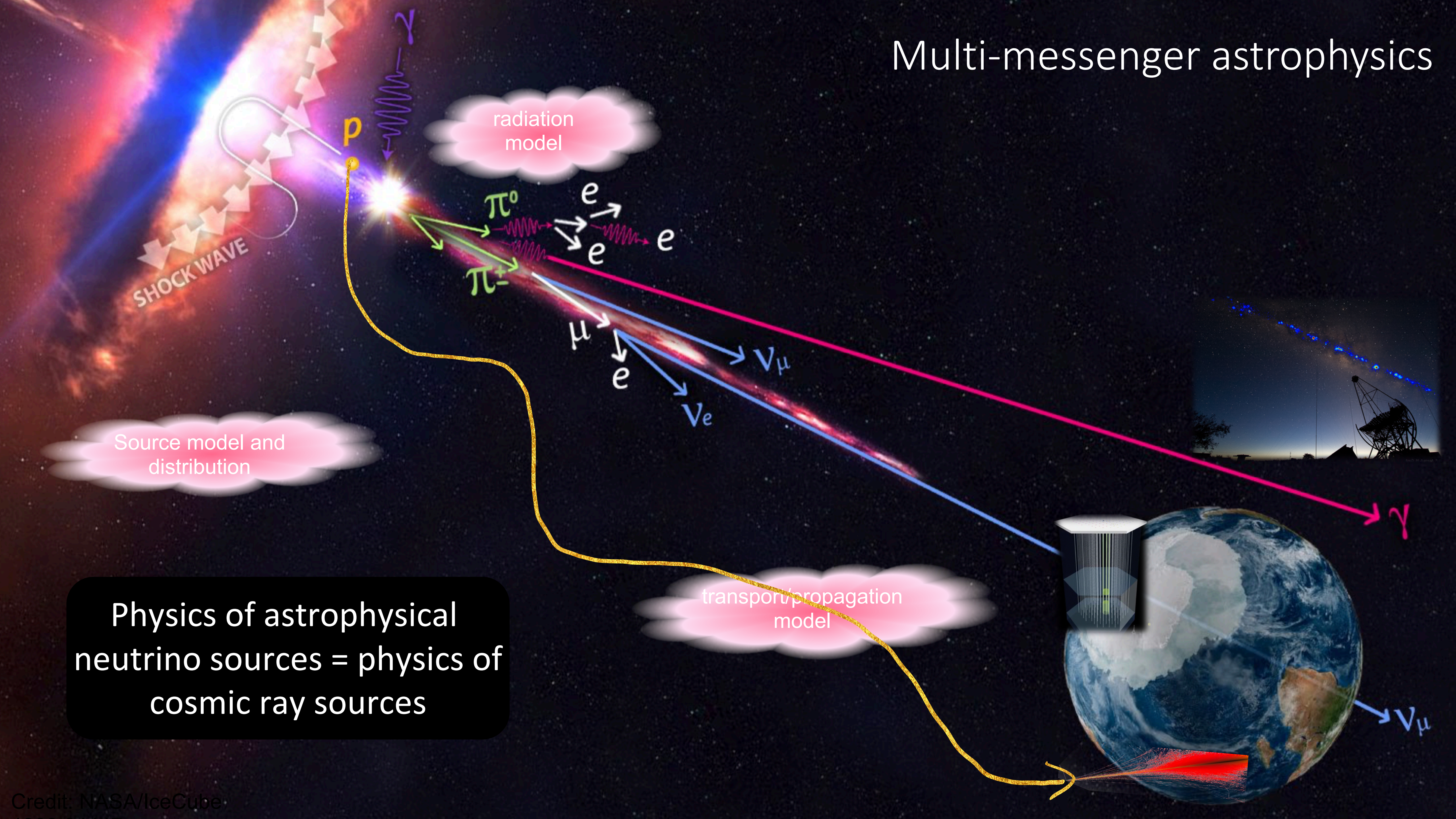




- **Detection unlikely**, if UHECR come from **one dominant nuclear source**
- A subset of protonic sources with high $E_{max}$ may give some small contribution (see A. van Vliet+ PoS(ICRC2019)1025 & M. S. Muzio+ PoS(ICRC2019)364 )
- **Cosmogenic** neutrinos constitute a **small background** for neutrino telescopes

# Conclusion

1. Astrophysical **interpretation** of highest energy cosmic ray observations significantly **limited by precision at detection**
2. **Planned detectors not sensitive enough to detect cosmogenic neutrinos** if only one dominant UHECR source type and Auger's composition results are taken at face value
3. At the same time, **cosmogenic neutrinos unlikely to be a large background** for UHE neutrino telescopes
4. **Composition is a crucial observable** that has to be better understood (**Upgrades** in Auger and TA are aiming towards improvements)
5. For present detectors, the **hadronic physics is a limiting factor**. Reliable composition only from fluorescence so far. **Hybrid** detection (radio, IceTop in-ice) looks **promising**. But **exposure** is in the **SD** data.
6. **Future** UHECR experiments have **to retain/improve composition sensitivity** (GRAND's $\delta X_{max}$ ~ 40g/cm$^2$ would be insufficient without additional hybrid detectors)

# Multi-messenger astrophysics



# Tables

**Table 2**
Best-fit Parameters Corresponding to the Results of the Fit with Flat Source Evolution for the Combination of PSB and EPOS-LHC, Using the 2015 and 2017 Auger Data Sets

| | Auger 2015 | | Auger 2017 | |
|---|---|---|---|---|
| $\gamma$ | $-0.35^{+0.15}_{-0.08}$ | | $-0.70^{+0.12}_{-0.08}$ | |
| $R_{\max}$ (GV) | $(2.8 \pm 0.2) \cdot 10^9$ | | $(2.5 \pm 0.1) \cdot 10^9$ | |
| $m$ | 0.0 (fixed) | | 0.0 (fixed) | |
| $\delta_E$ | 0.0 (fixed) | | 0.0 (fixed) | |
| $f_A$ (%) | H | He | H | He |
| | $5.8^{+22.0}_{-5.8}$ | $89.9^{+0.6}_{-0.7}$ | $9.7^{+17.1}_{-9.7}$ | $87.8^{+0.5}_{-0.6}$ |
| | N | Si | N | Si |
| | $4.0 \pm 0.2$ | $0.3 \pm 0.0$ | $2.4 \pm 0.2$ | $0.1 \pm 0.0$ |
| | Fe | | Fe | |
| | $0.0^{+4.6}_{-0.0} \cdot 10^{-3}$ | | $(3.7 \pm 2.0) \cdot 10^{-3}$ | |
| $I^9_A$ (%) | H | He | H | He |
| | $0.6^{+3.0}_{-0.6}$ | $46.7^{+1.6}_{-1.8}$ | $0.8^{+1.9}_{-0.8}$ | $47.9^{+1.3}_{-1.4}$ |
| | N | Si | N | Si |
| | $39.9^{+1.2}_{-1.3}$ | $12.8^{+1.1}_{-1.2}$ | $37.9^{+1.5}_{-1.6}$ | $11.4^{+2.2}_{-2.3}$ |
| | Fe | | Fe | |
| | $0.0^{+1.0}_{-0.0}$ | | $2.1 \pm 1.1$ | |
| $\chi^2$/dof | 44.4/22 | | 65.3/22 | |

**Note.** For all quantities, the 1 $\sigma$ uncertainties (for 1 dof) are given.

**Table 3**
Best-fit Parameters for the 3D Parameter Scan with Free Source Evolution for the Baseline Case of the Combination TALYS–SIBYLL 2.3

| | TALYS–SIBYLL 2.3 | | |
|---|---|---|---|
| $\gamma$ | $-0.80^{+0.27}_{-0.23}$ | | |
| $R_{\max}$ (GV) | $(1.6 \pm 0.2) \cdot 10^9$ | | |
| $m$ | $4.2^{+0.4}_{-0.6}$ | | |
| $\delta_E$ | $0.14^{+0.00}_{-0.03}$ | | |
| $f_A$ (%) | H | He | N |
| | $0.0^{+42.6}_{-0.0}$ | $82.0^{+3.8}_{-6.4}$ | $17.3^{+1.0}_{-1.1}$ |
| | Si | Fe | |
| | $0.6 \pm 0.1$ | $(2.0 \pm 0.8) \cdot 10^{-2}$ | |
| $I^9_A$ (%) | H | He | N |
| | $0.0^{+1.2}_{-0.0}$ | $9.8^{+2.8}_{-2.9}$ | $69.2^{+1.5}_{-1.6}$ |
| | Si | Fe | |
| | $17.9^{+3.2}_{-3.5}$ | $3.2^{+1.2}_{-1.3}$ | |
| $\chi^2$/dof | 27.0/21 | | |

**Note.** For all quantities, the $1\sigma$ uncertainties (for 1 dof) are given.

# Allowed composition ranges

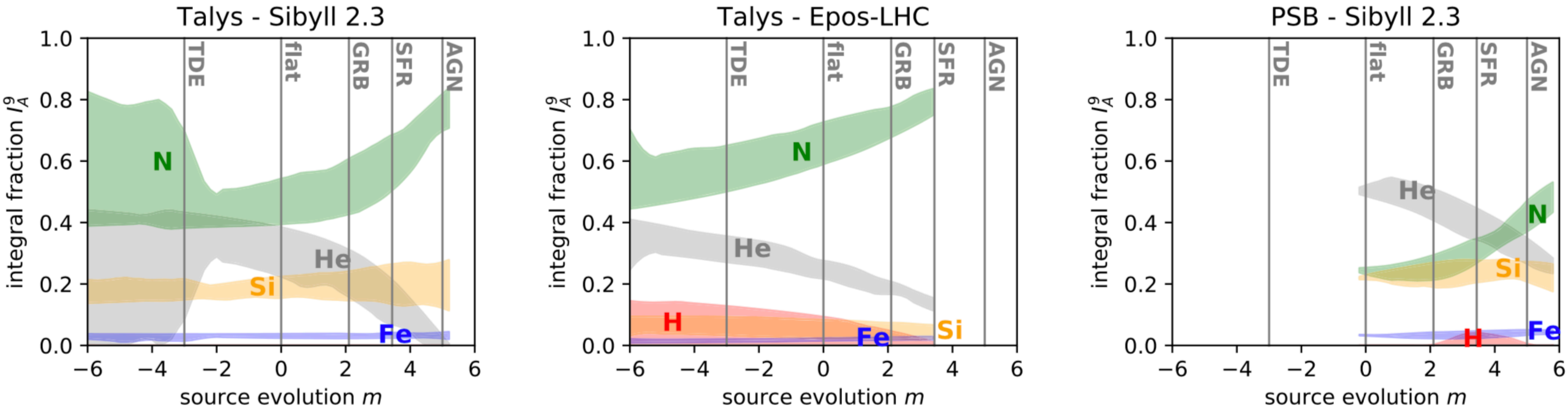



**Figure 8.** Ranges in the fraction allowed within $3\sigma$ (for 2 dof) as a function of the source evolution parameter. The fractions are defined by integrating the injection spectrum from $E_{\min} = 10^9$ GeV; see Equation (6). Left: TALYS–SIBYLL 2.3 (baseline model); middle: TALYS–EPOS-LHC; right: PSB–SIBYLL 2.3.