UHECRs demand nuclear physics.

Uncertainties and relevance of photo-nuclear processes for UHECR interactions

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XSCRC 2019: Cross sections for Cosmic Rays @ Cern

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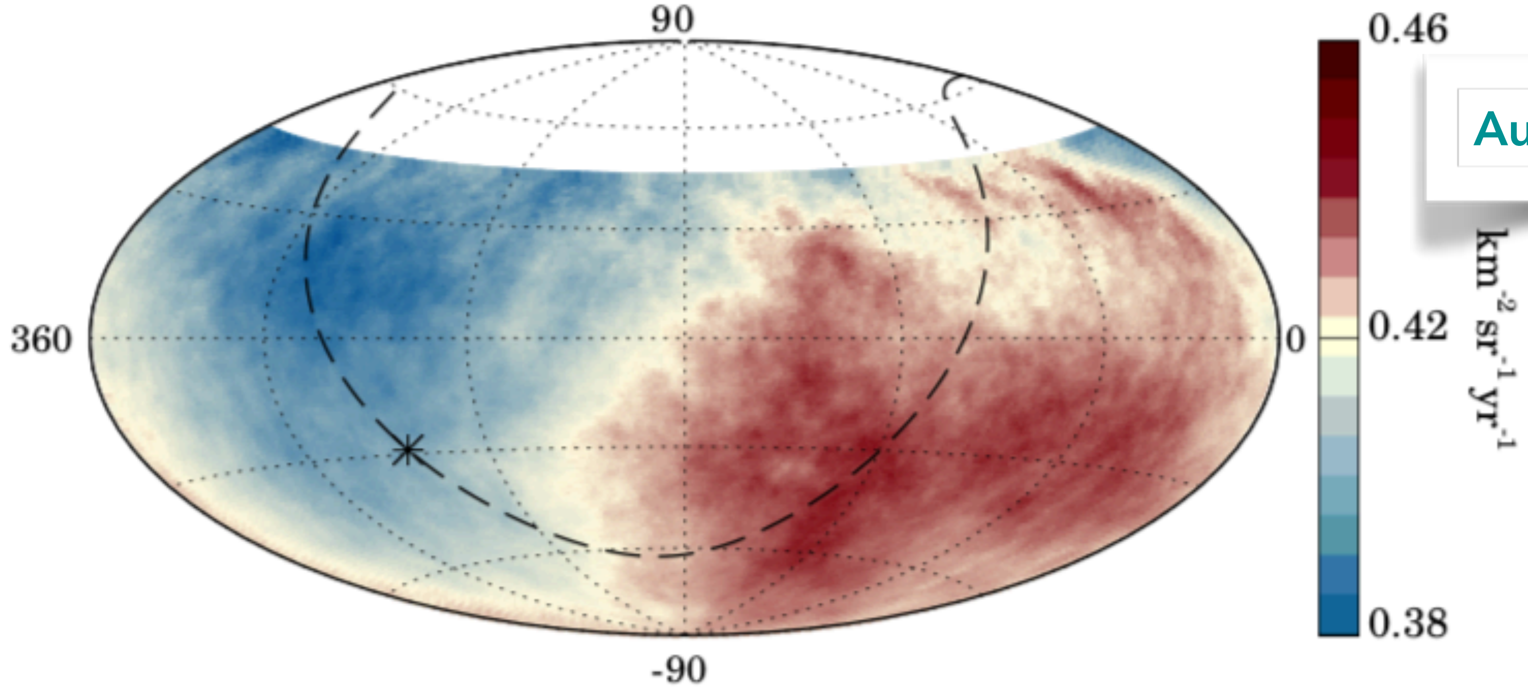
Outline

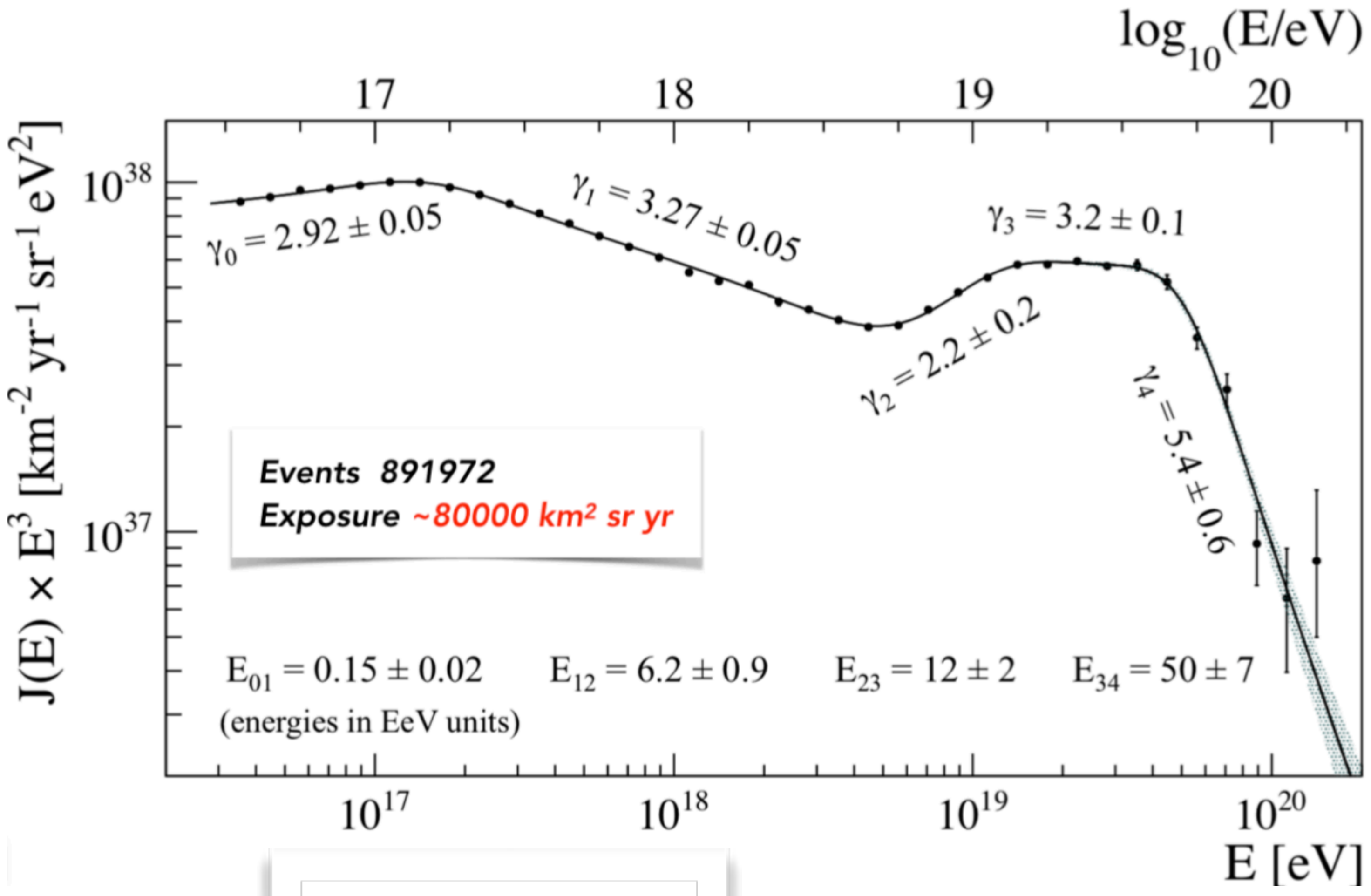
- UHECR results
- Ingredients for computation of UHECR interactions in extragalactic space
- Interpretation of UHECR data in terms of astrophysical model
- Effects of uncertainties of disintegration models in interpretation of data
- Description of disintegration models and lack of measurements
- Summary

UHECR measurements

- UHECR spectrum measured with several techniques
  - Several features are visible



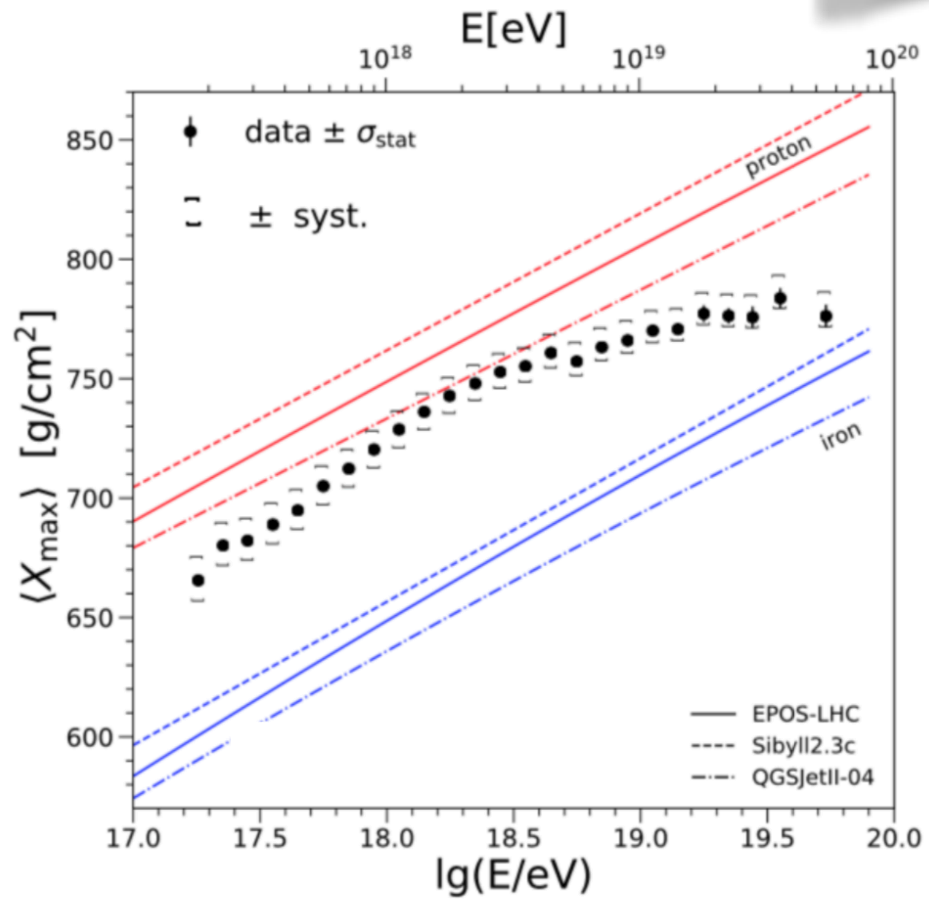
Auger, Science 2017

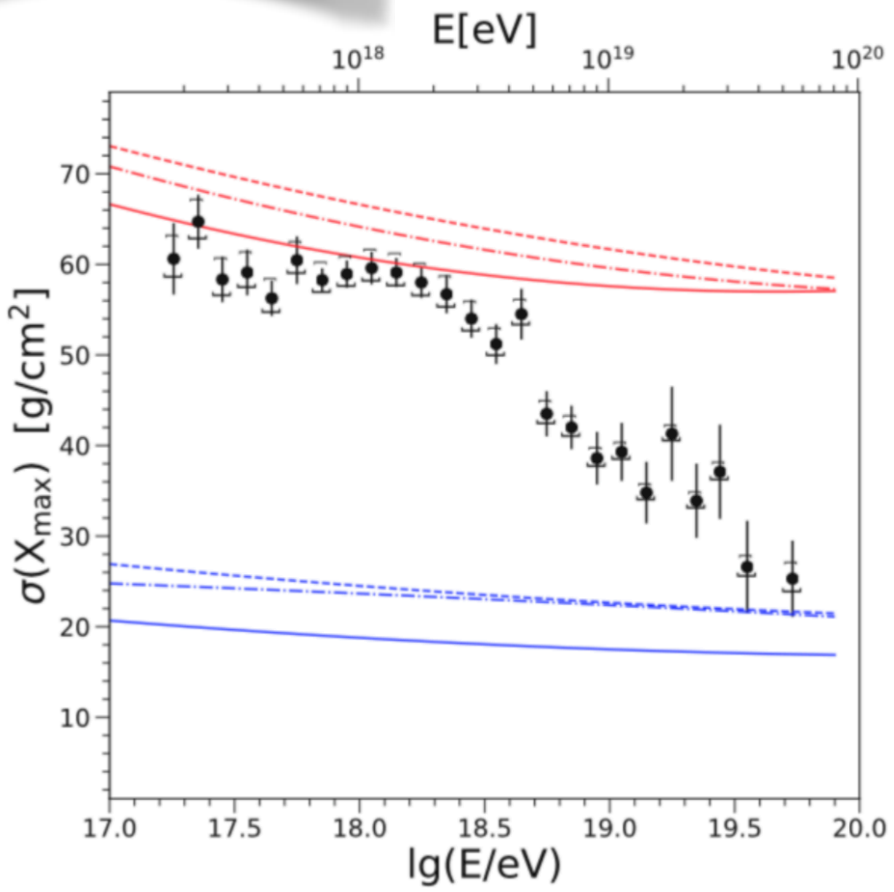


Auger ICRC2019

- Large scale anisotropy results suggest extragalactic origin of UHECRs

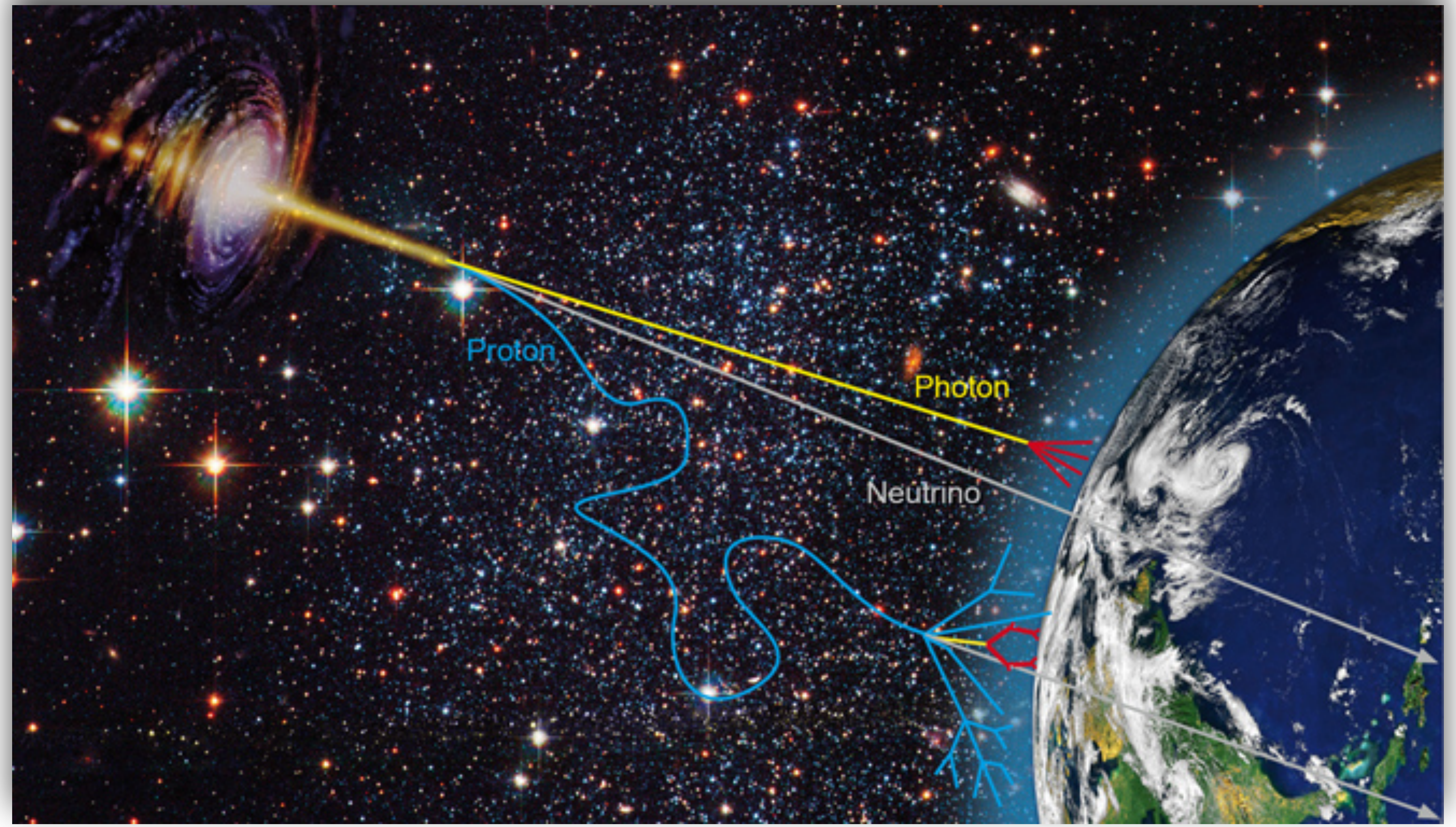
- Composition gets lighter and then heavier increasing energy
- sigma(Xmax) compatible with:
  - light or mixed composition at low energy
  - pure and heavy at high energy





UHECR properties

- Class of UHECR sources still unidentified
- Connection of observables at Earth to theoretical models including UHECR properties
  - What happens in between sources and detection has to be taken into account!

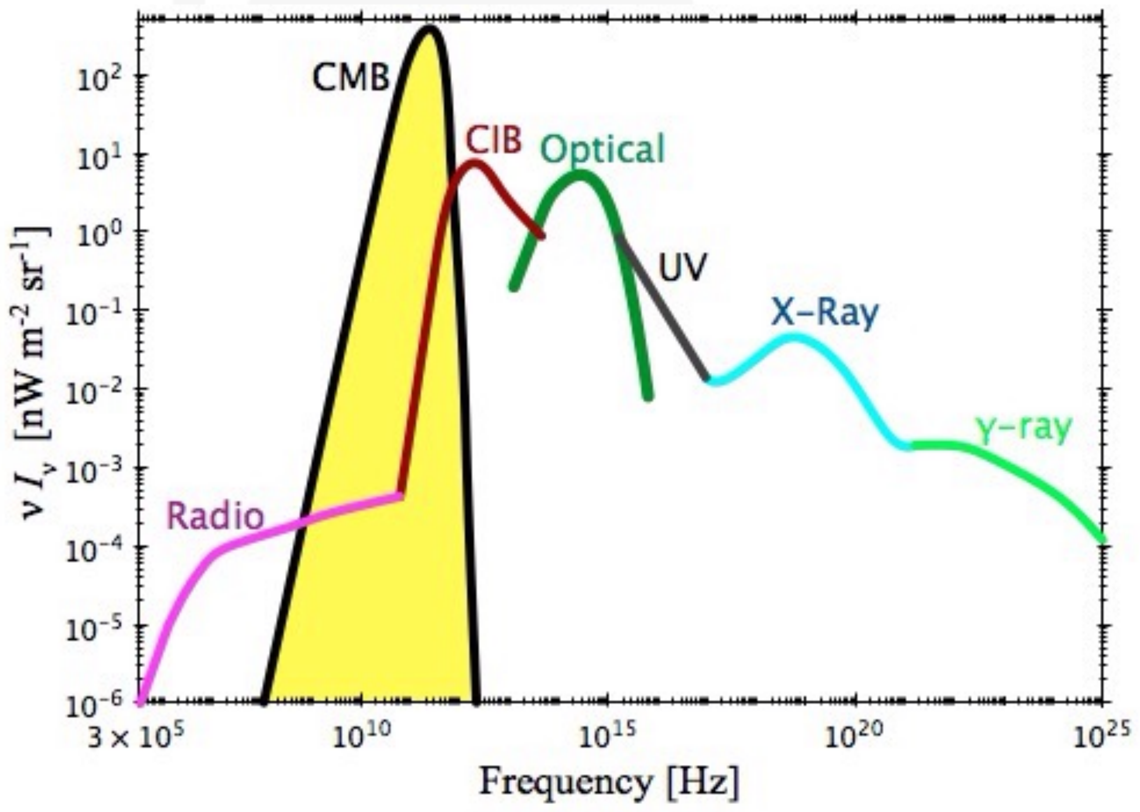


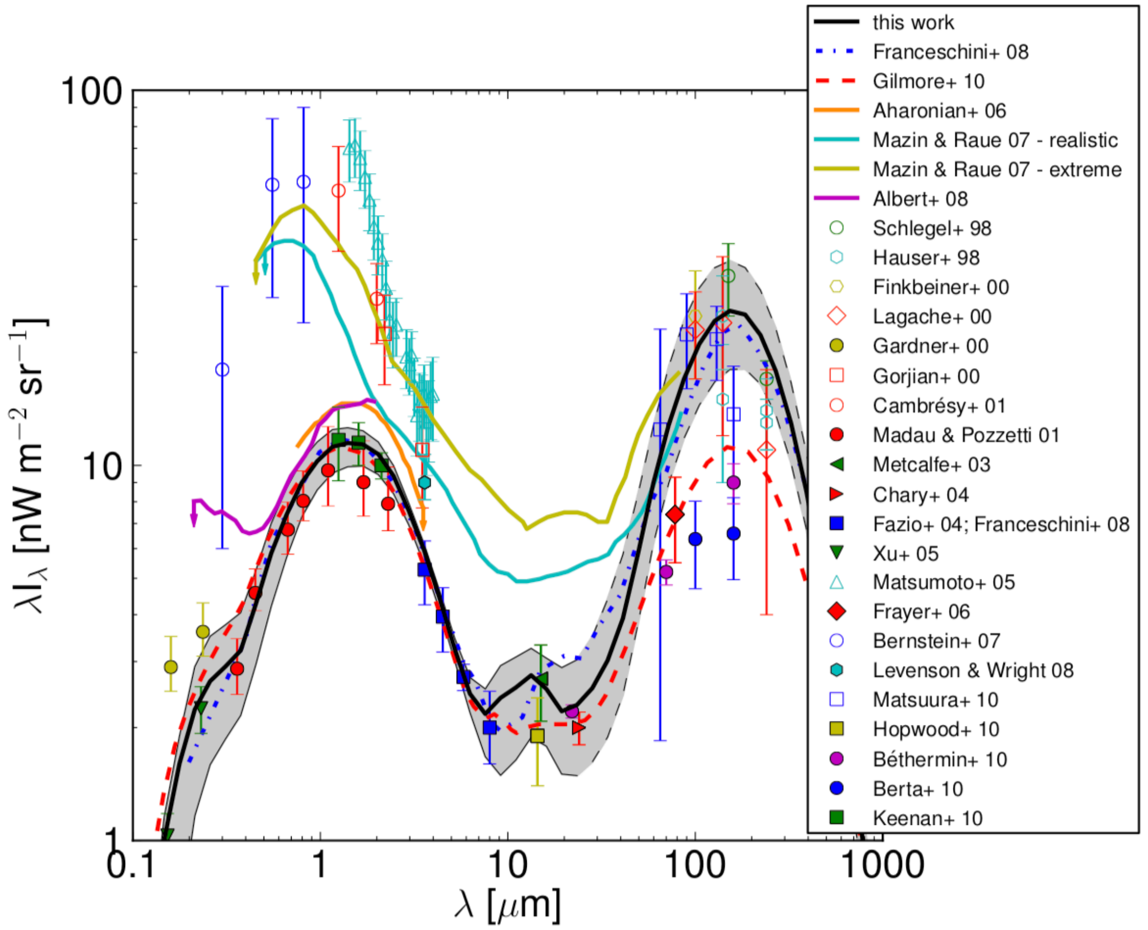
- Several codes for UHECR propagation available; for this talk, simulations of
  - **SimProp** (Aloisio, DB, di Matteo, Grillo, Petrera & Salamida, JCAP 2017) and
  - **CRPropa** (Alves Batista, Dundovic, Erdmann, Kampert, Kuempel, Muller, Sigl, van Vliet, Walz & Winchen, JCAP 2016)

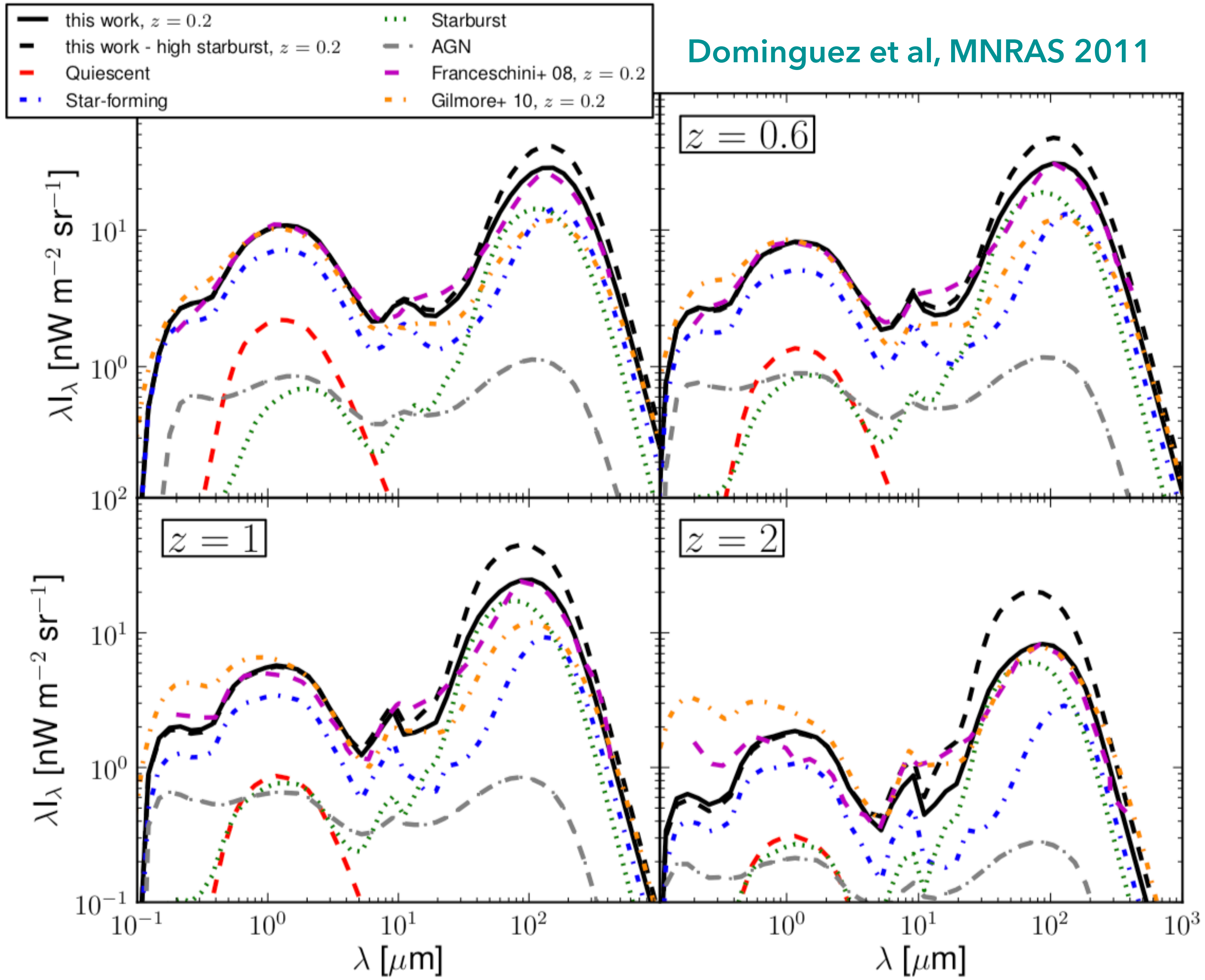
will be used.

GSSI

Ingredient (1): astrophysics







Dominguez et al, MNRAS 2011

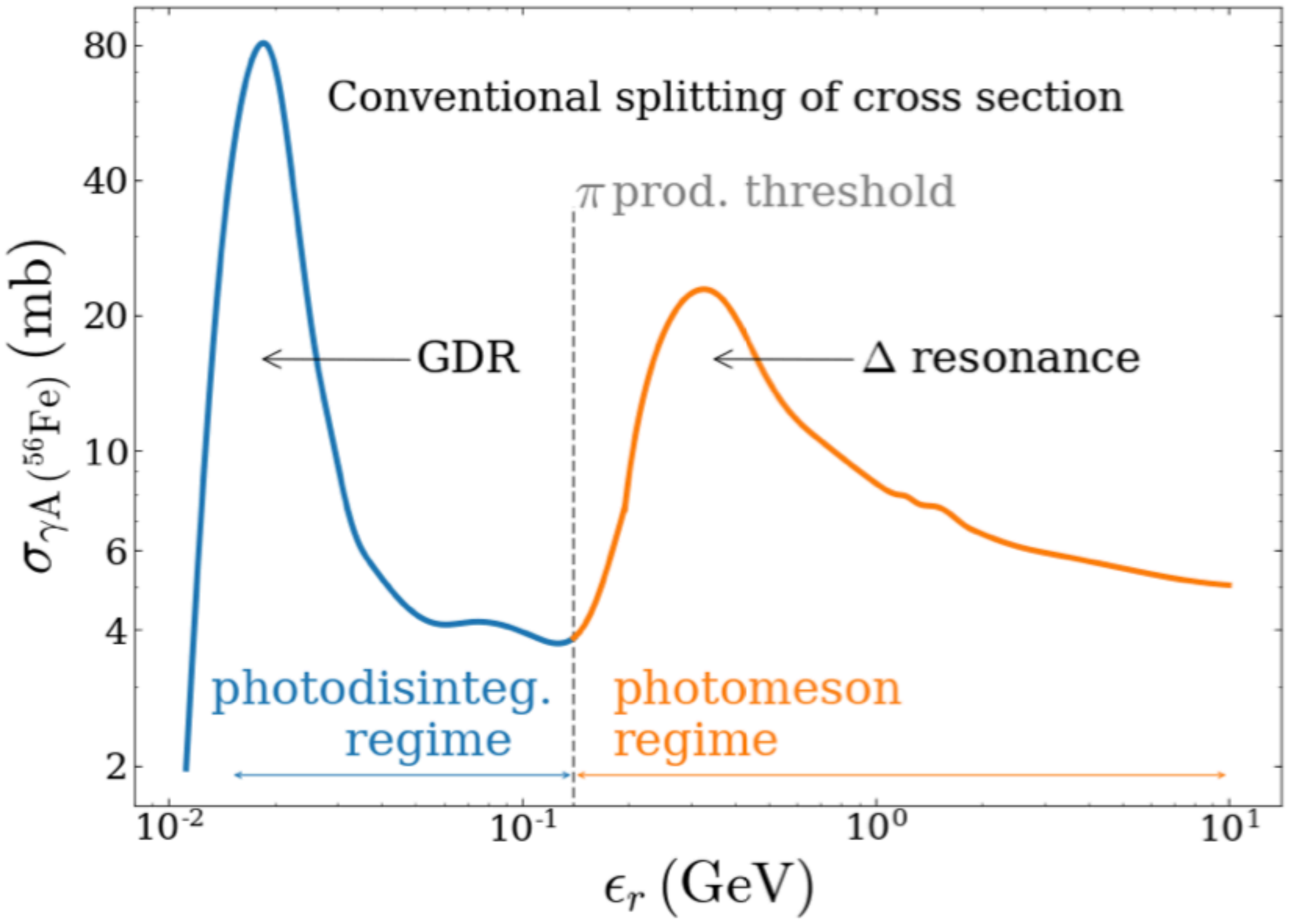
- Example: photons in extragalactic space (CMB + IR/opt/UV)

-> several methods used to evaluate EBL at z=0 and to extrapolate it to z>0

Ingredient (2): nuclear physics

- Main reactions:
  - **Photo-disintegration** (through excitation of Giant Dipole Resonance)
  - **Photo-meson production** (through excitation of Delta resonance)

Morejon, Fedynitch, **DB**, Biehl & Winter, JCAP 2019



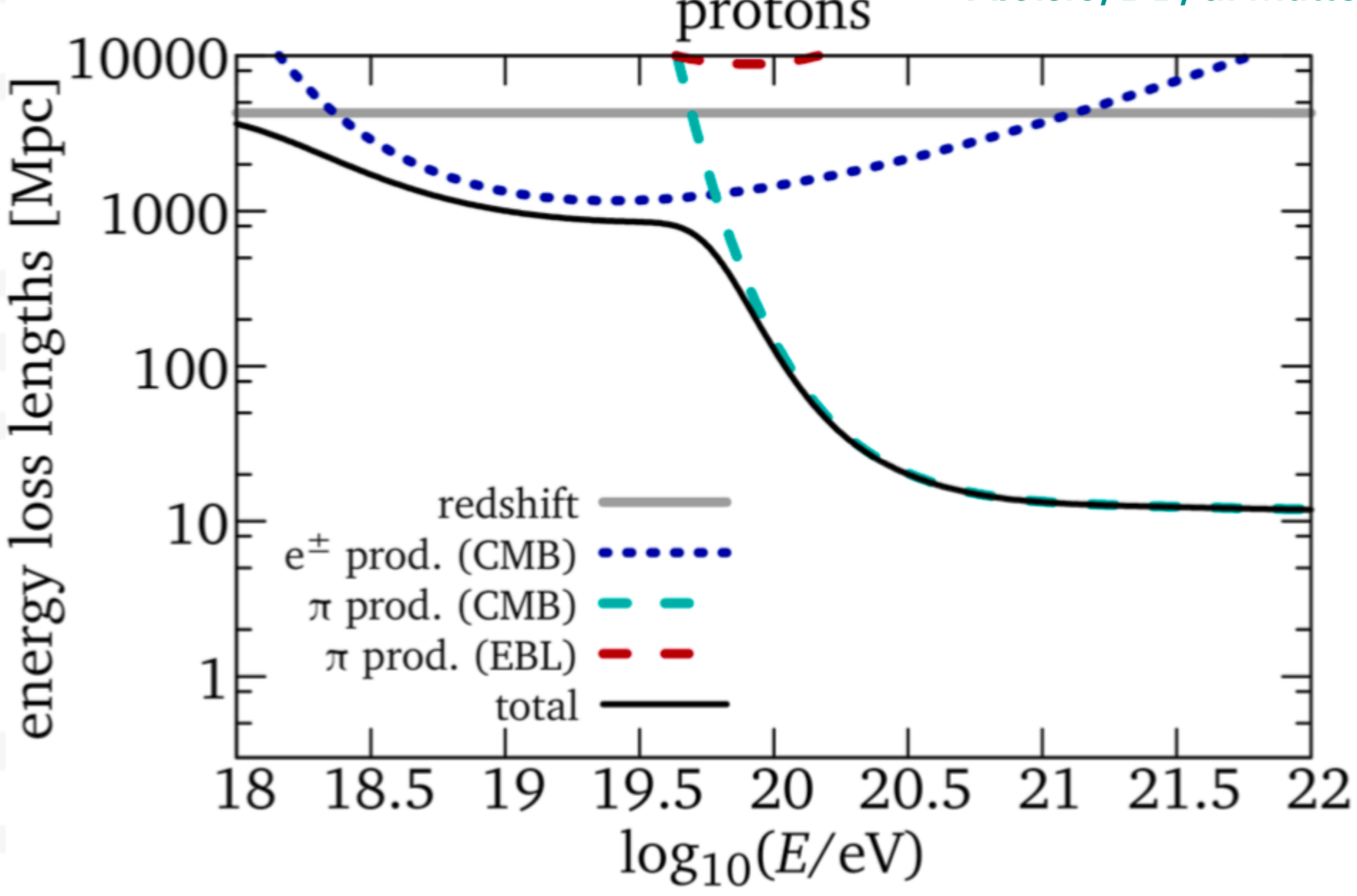
- Energy scale of interactions: $\epsilon_r \approx \Gamma \epsilon$
- Development of nuclear cascade -> <u>more complicate situation than pure proton composition!</u>
- Threshold energy for photo-meson production shifted by A -> <u>implication of nuclear composition on production of secondary messengers</u>

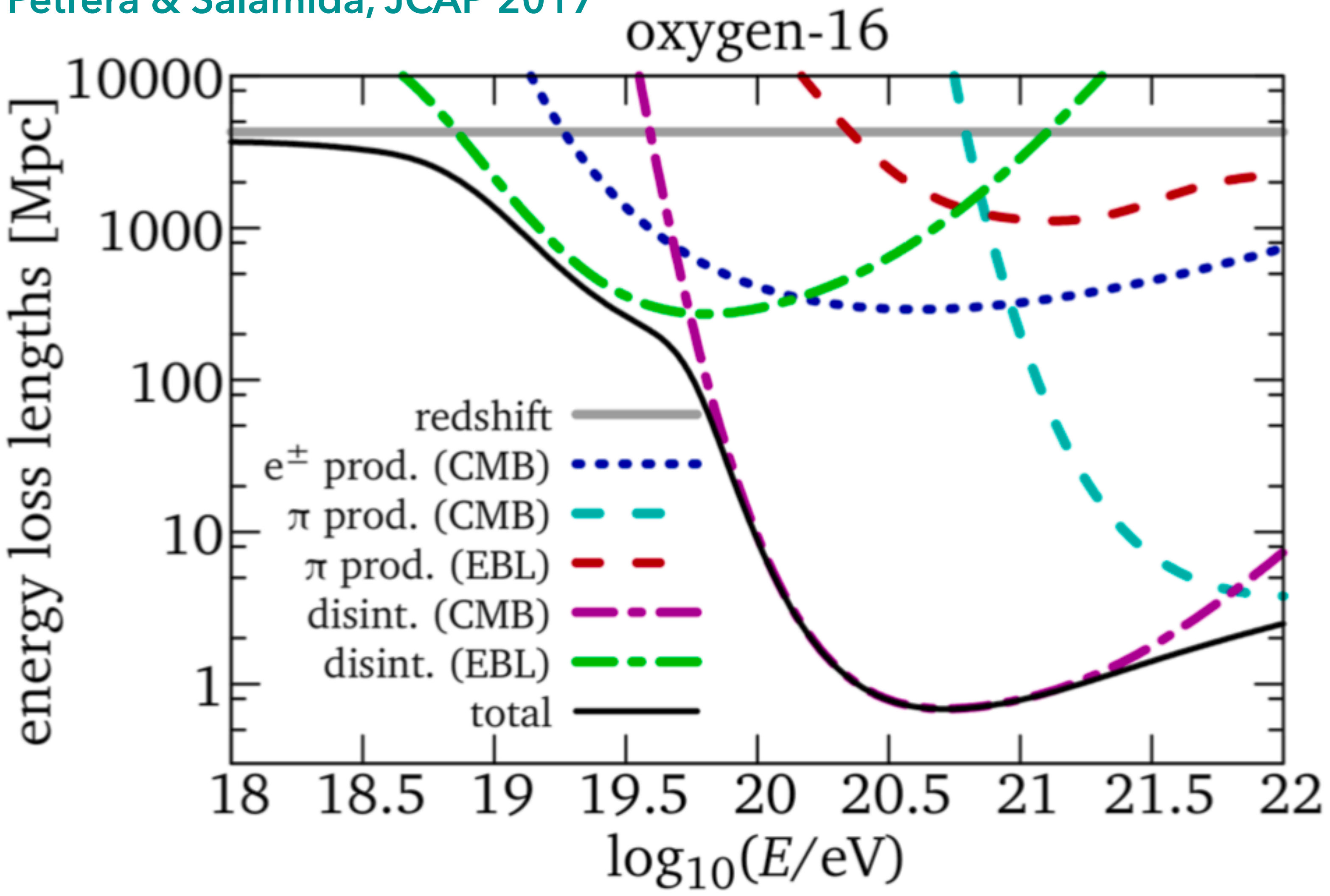
G S S I

Interaction lengths of UHECRs

Plots by A. di Matteo, using **SimProp** MC code:

Aloisio, **DB**, di Matteo, Grillo, Petrera & Salamida, JCAP 2017





$$\frac{1}{\tau} = \frac{1}{2\Gamma^2} \int_{\epsilon'=0}^{2\Gamma\epsilon} \int_{\epsilon=0}^{+\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} \, d\epsilon \, \sigma(\epsilon')\epsilon' \, d\epsilon'$$

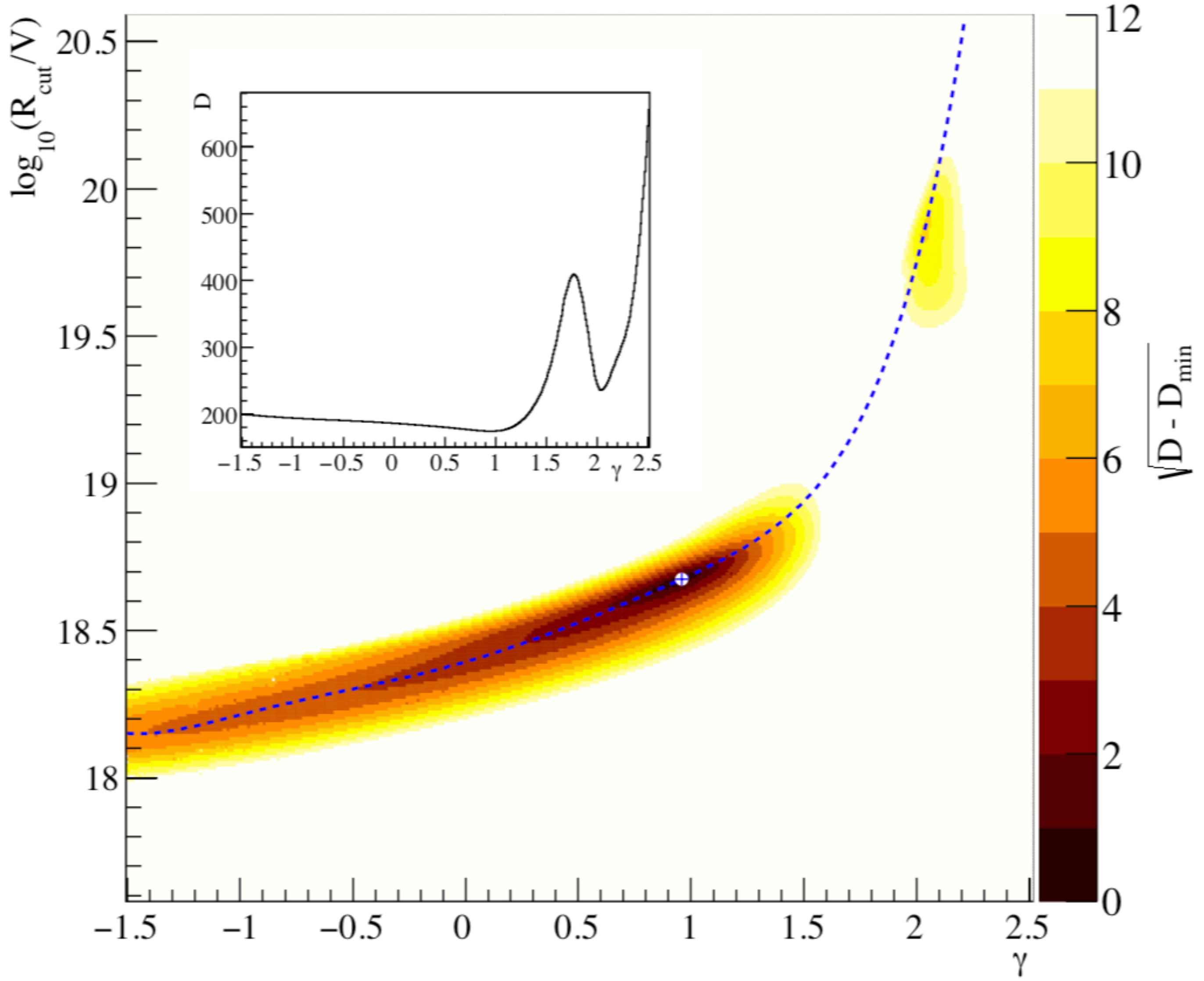
$$\frac{\partial N_i(E)}{\partial t} = \frac{\partial}{\partial E}(-b(E)N_i(E)) - \frac{N_i(E)}{\tau} + Q_{ji}(E)$$

- Different reactions are relevant at similar energies, depending on the nuclear composition of cosmic-ray particle
- Origin of flux suppression at UHE (?)

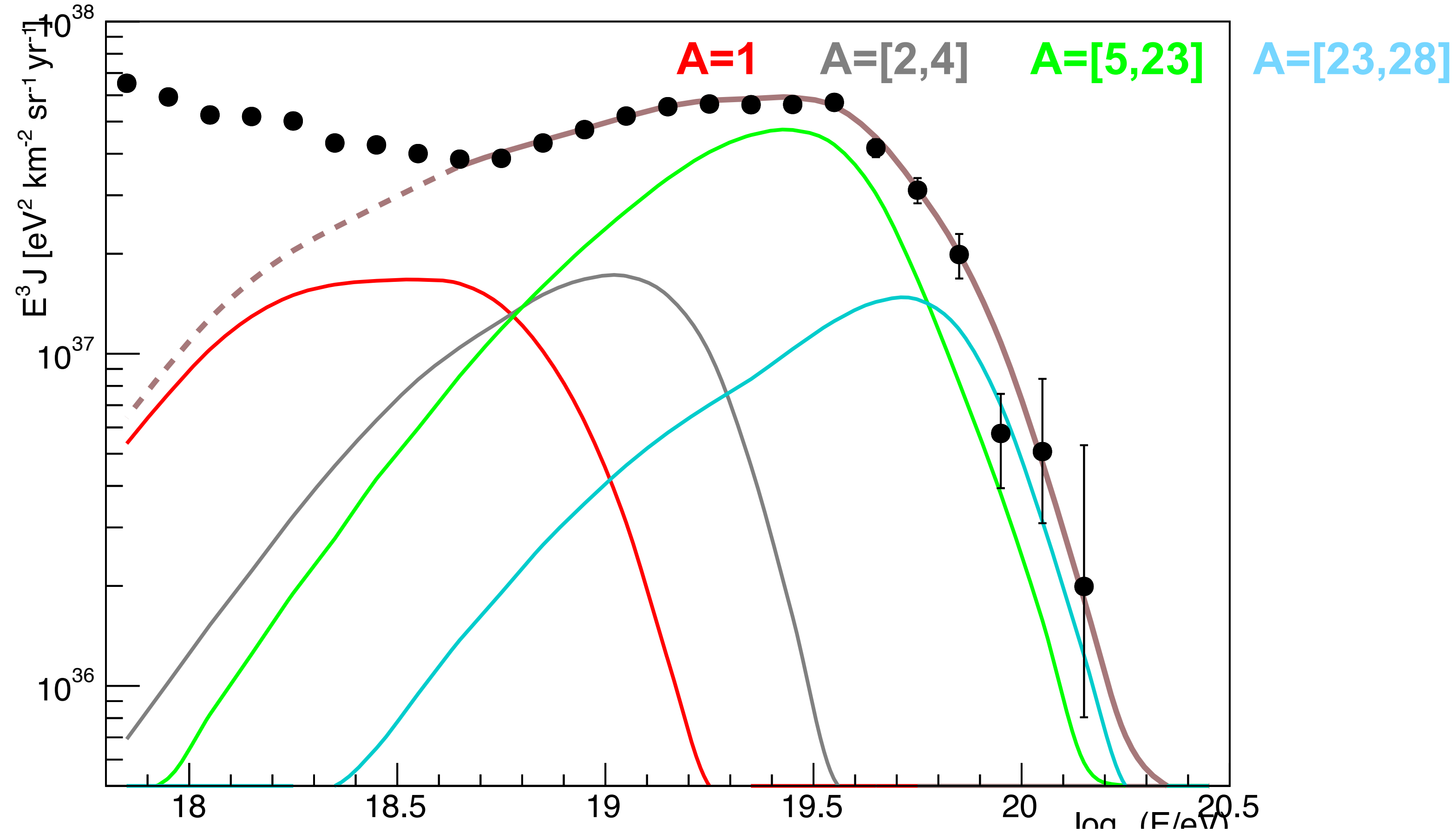
Interpretation of UHECR data

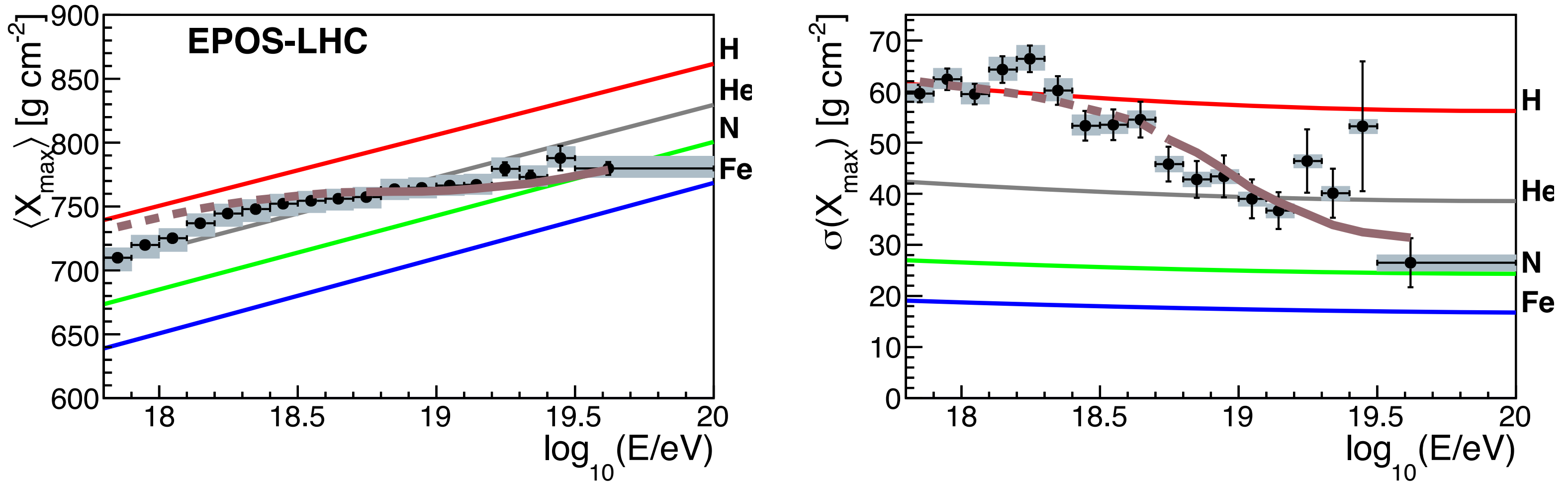
$$\frac{dN_A}{dE} = J_A(E) = f_A J_0 \left(\frac{E}{10^{18}\ \mathrm{eV}}\right)^{-\gamma} \times f_{\mathrm{cut}}(E, Z_A R_{\mathrm{cut}})$$

- Identical sources uniformly distributed
- Simple astro model at the source
- Fit of source parameters taking into account extragalactic propagation



The Pierre Auger Collaboration, JCAP 2017



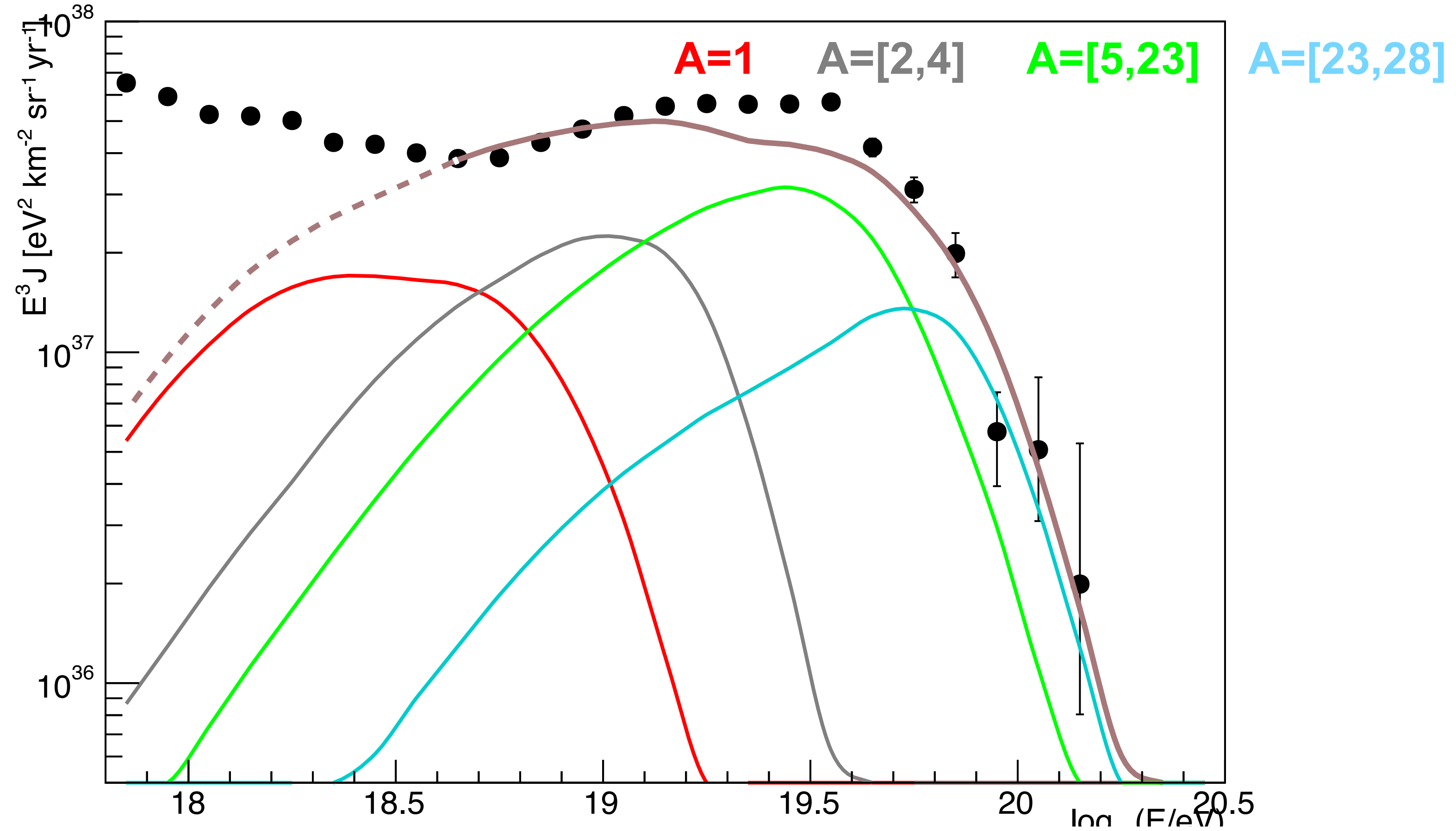


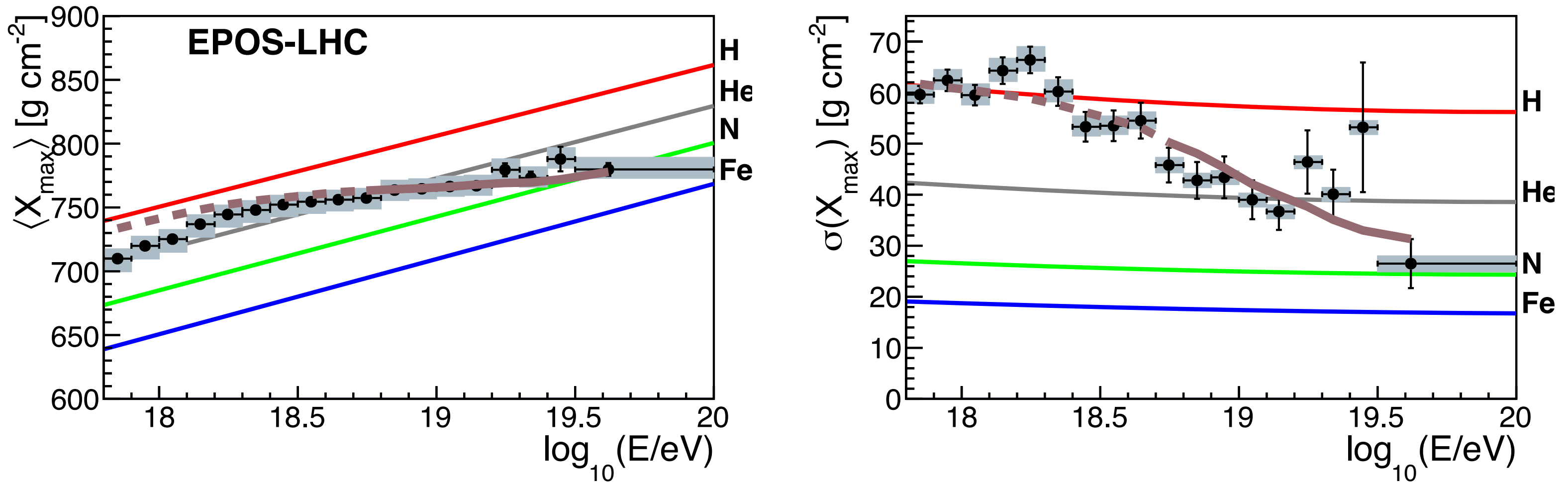
- Basic **disintegration model** used (**PSB**, from Puget, Stecker & Bredekamp, Astroph. J. 1976)
  - One nucleus for each A
  - No disintegration in fragments

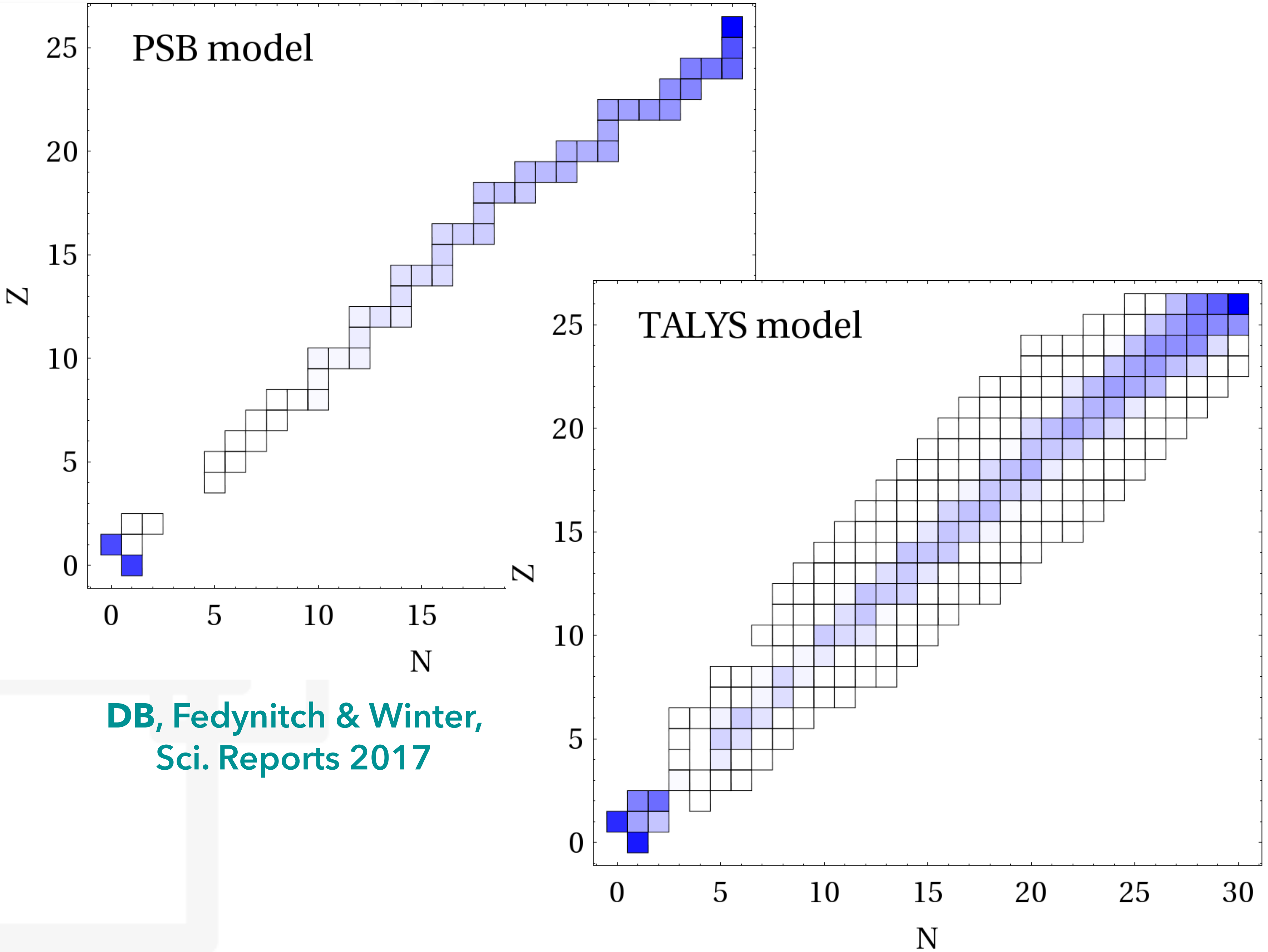
Interpretation of UHECR data

- **Exercise** -> expected spectrum and composition obtained with:
  - Best fit parameters found with basic disintegration model
  - Simulations obtained with more realistic disintegration model: **TALYS software**

The Pierre Auger Collaboration, JCAP 2017





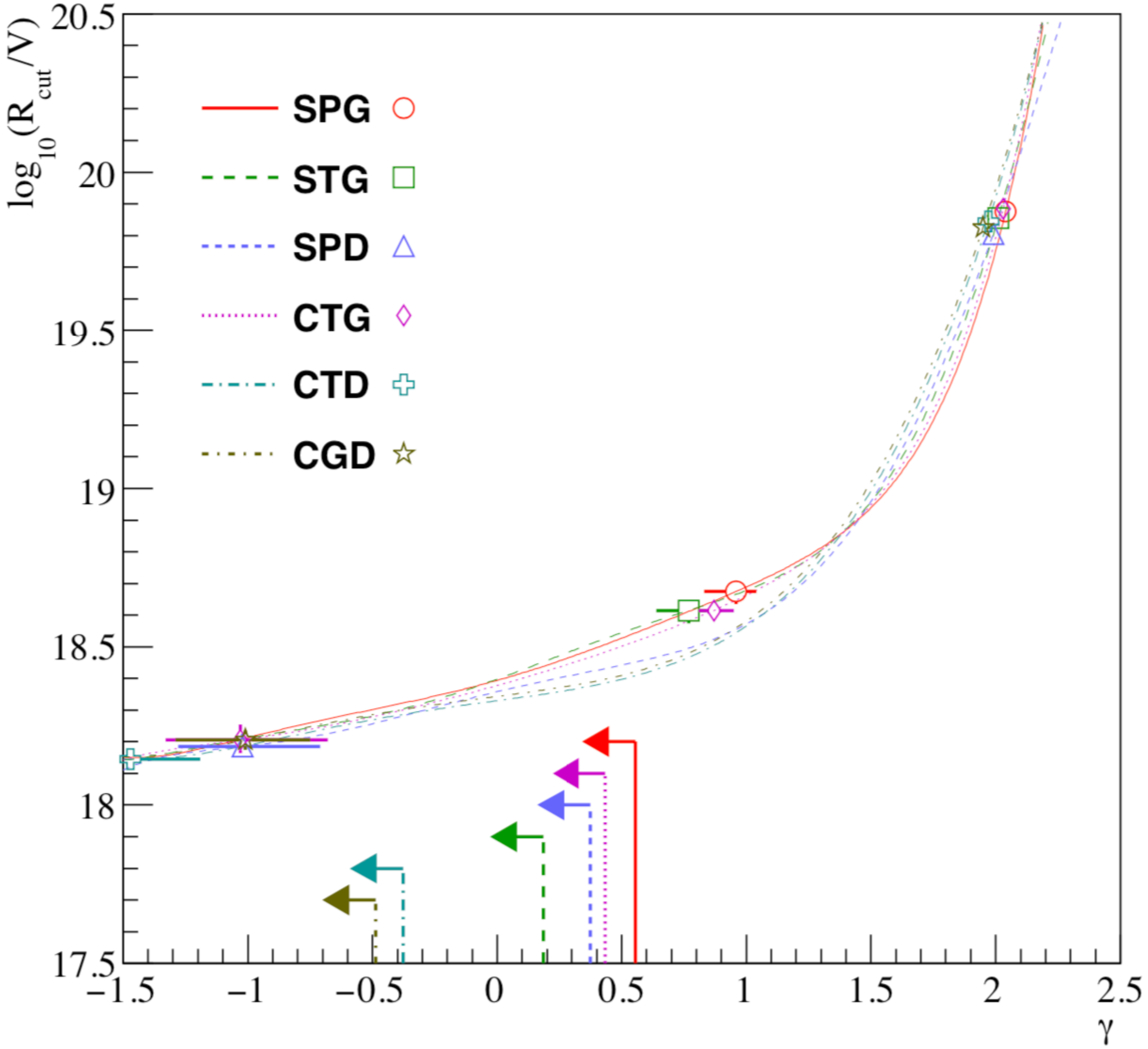


DB, Fedynitch & Winter, Sci. Reports 2017

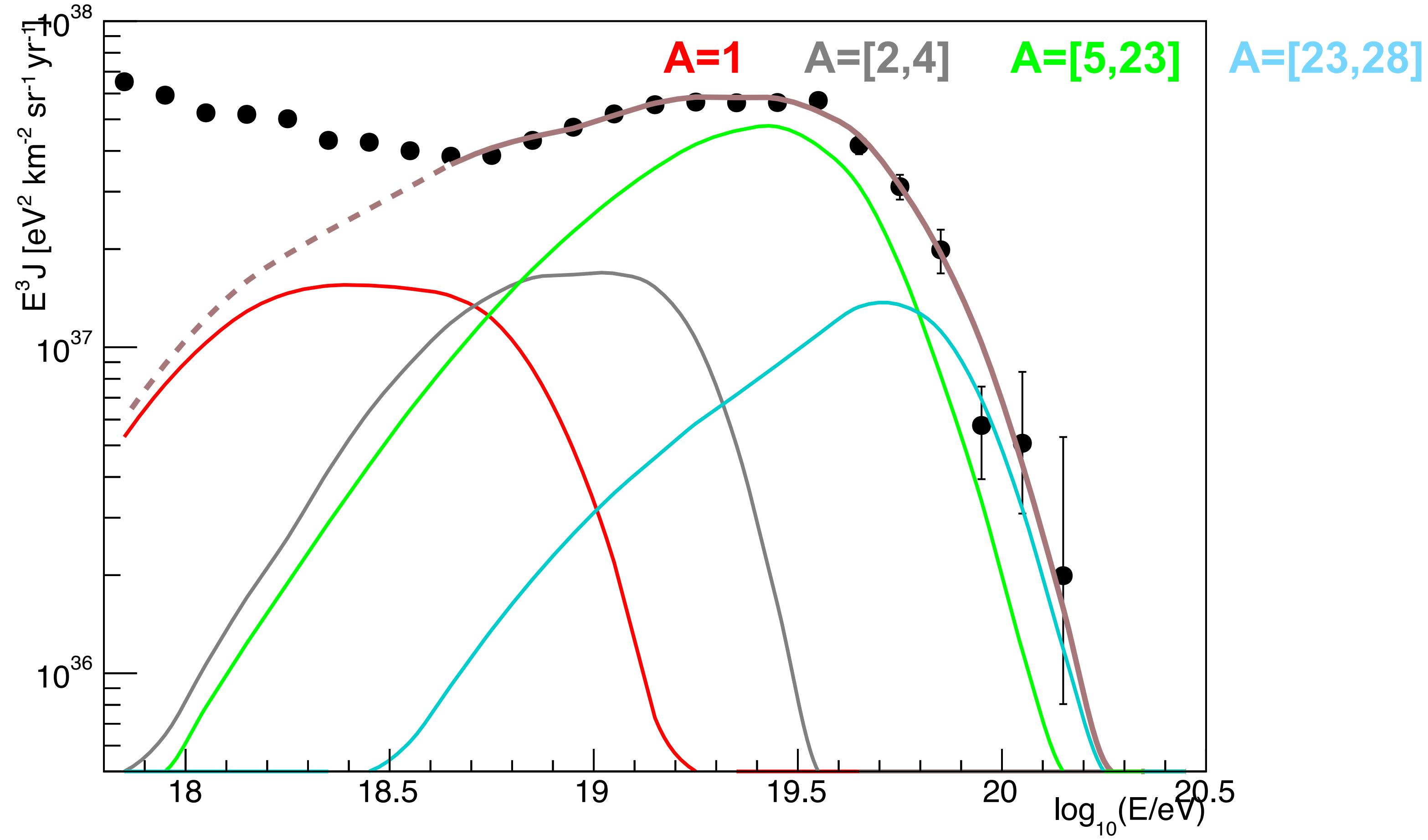
- Overall increase of disintegration implies larger depletion of high-energy flux
  - Change of spectral index for expected flux (-> change injected flux, including max energy)
  - Change of mass fractions at source

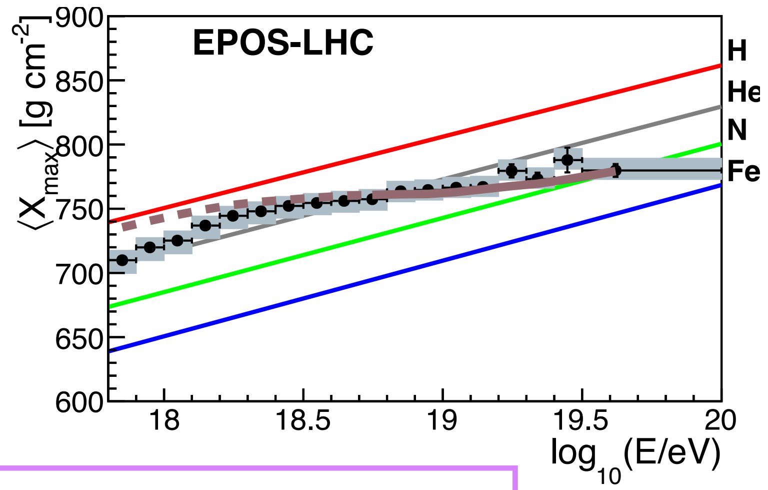
Interpretation of UHECR data

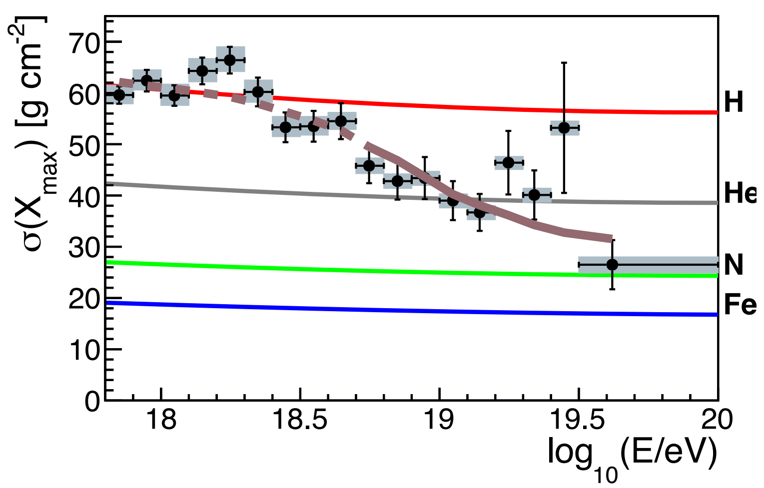
- Disintegration models influence the predictive power of astrophysical models used to interpret UHECR data in terms of UHECR spectra at the source



The Pierre Auger Collaboration, JCAP 2017







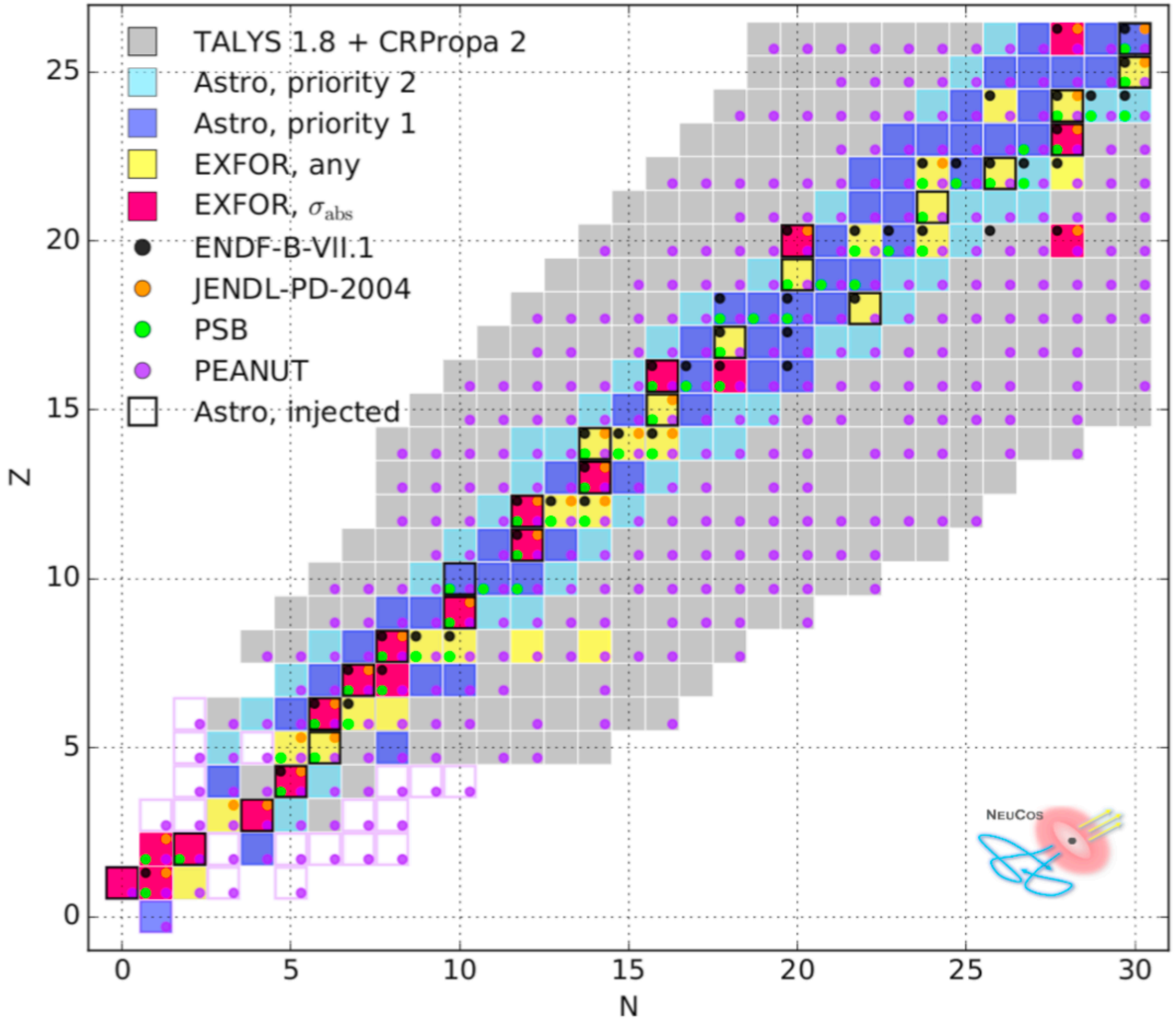
model	γ	$\log_{10}(R_{cut}/V)$
SPG	$+0.96^{+0.08}_{-0.13}$	$18.68^{+0.02}_{-0.04}$
STG	$+0.77^{+0.07}_{-0.13}$	$18.62^{+0.02}_{-0.04}$

model	f_H	f_{He}	f_N	f_{Si}	$\frac{\mathcal{L}_H}{\mathcal{L}_0}$	$\frac{\mathcal{L}_{He}}{\mathcal{L}_0}$	$\frac{\mathcal{L}_N}{\mathcal{L}_0}$	$\frac{\mathcal{L}_{Si}}{\mathcal{L}_0}$
SPG	0%	67%	28%	5%	0%	33%	50%	17%
STG	0%	7%	85%	8%	0%	1%	81%	17%

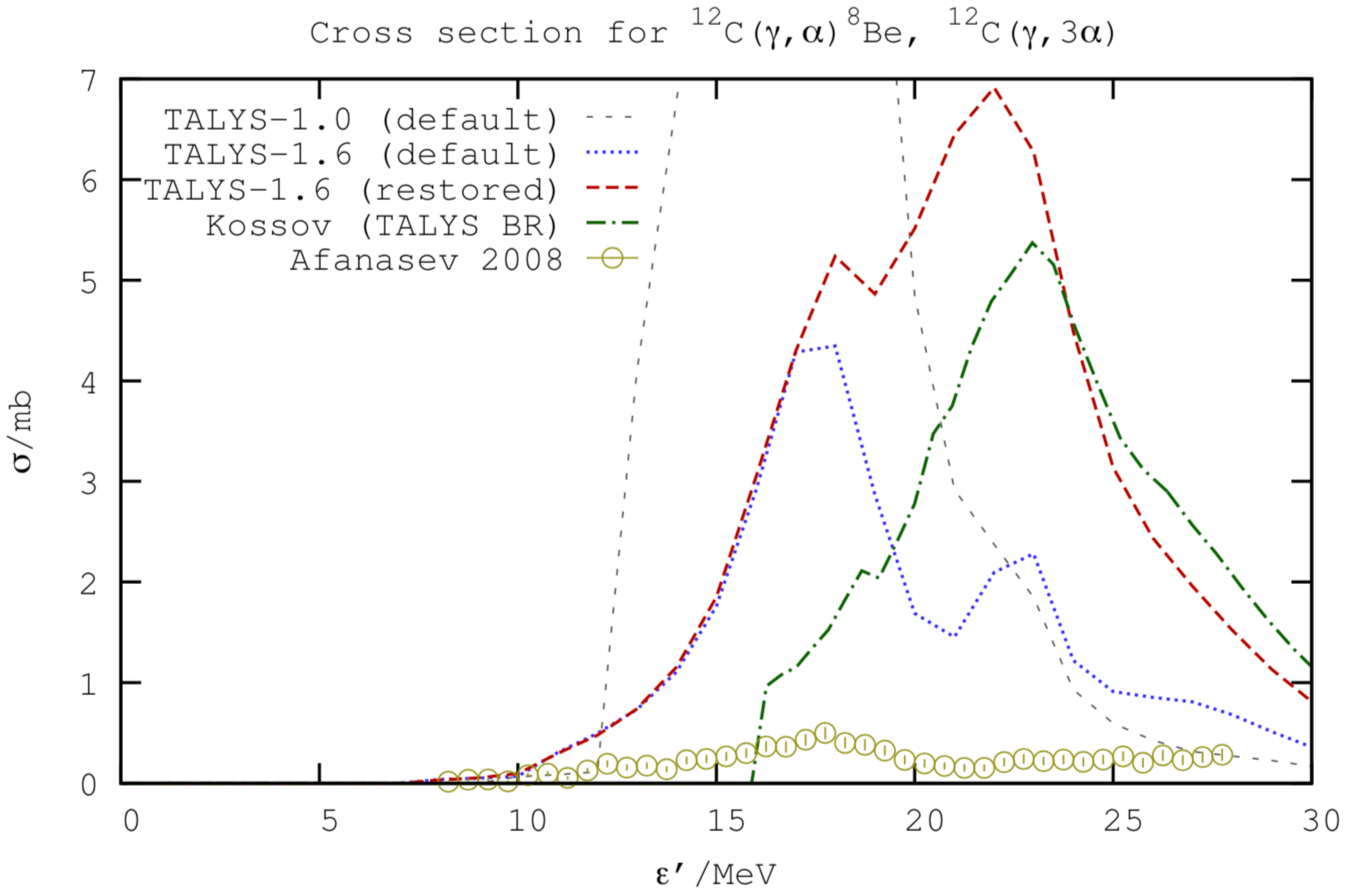
Comparison of cross sections from models and available data

- Available measurements are sparse

DB, Fedynitch & Winter, Sci. Reports 2017



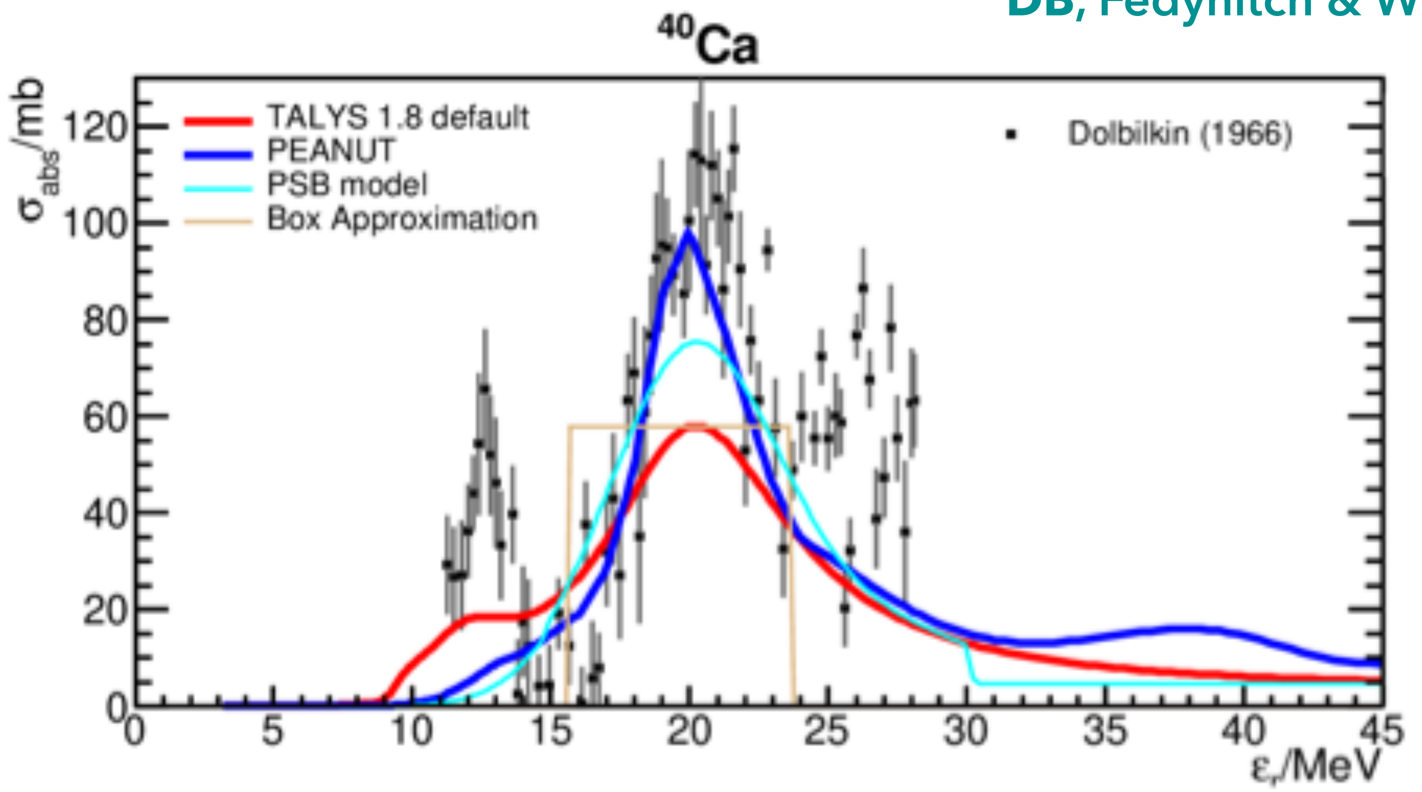
Alves Batista, **DB**, di Matteo, van Vliet & Walz, JCAP 2015

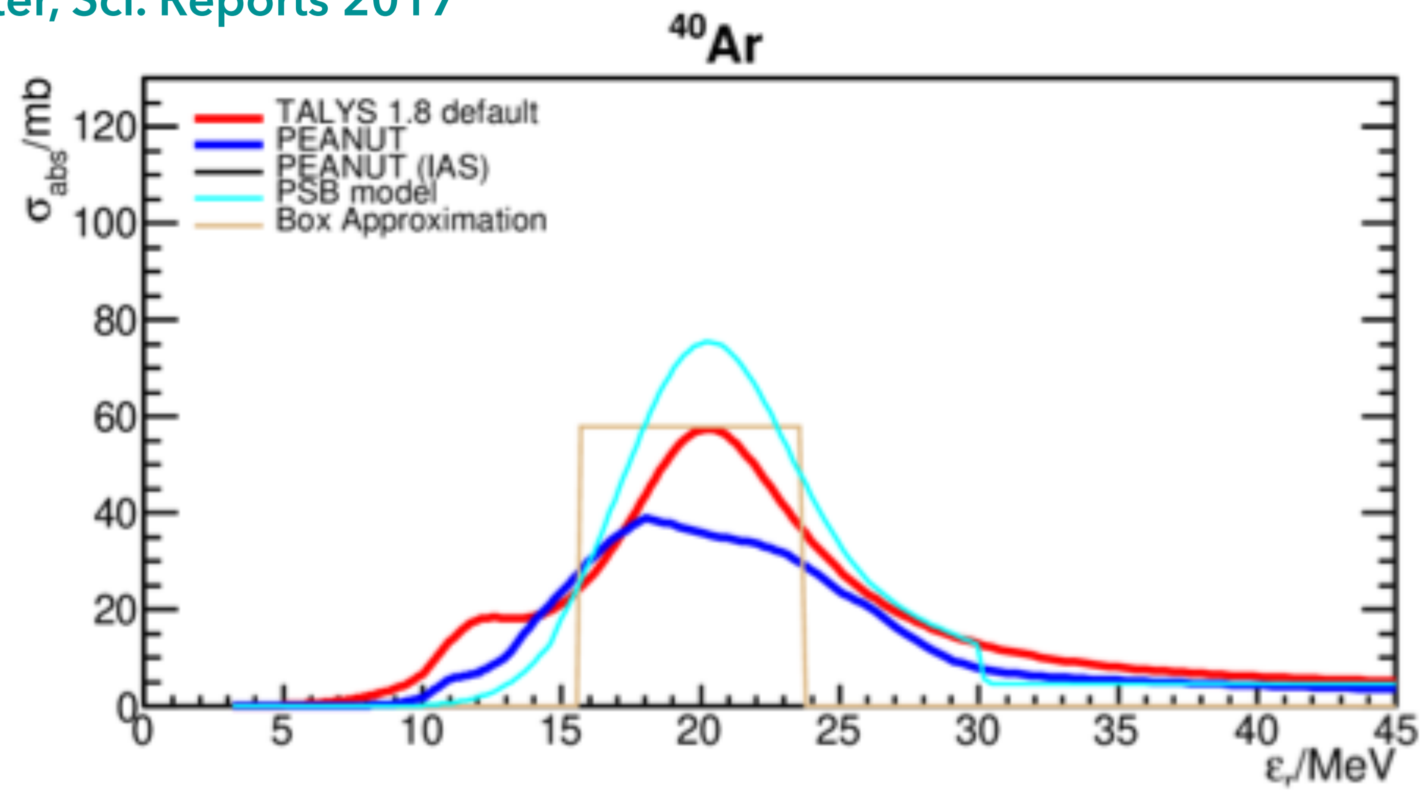


- Theoretical models do not always reproduce (available) data

Comparison of cross sections from models and available data

DB, Fedynitch & Winter, Sci. Reports 2017

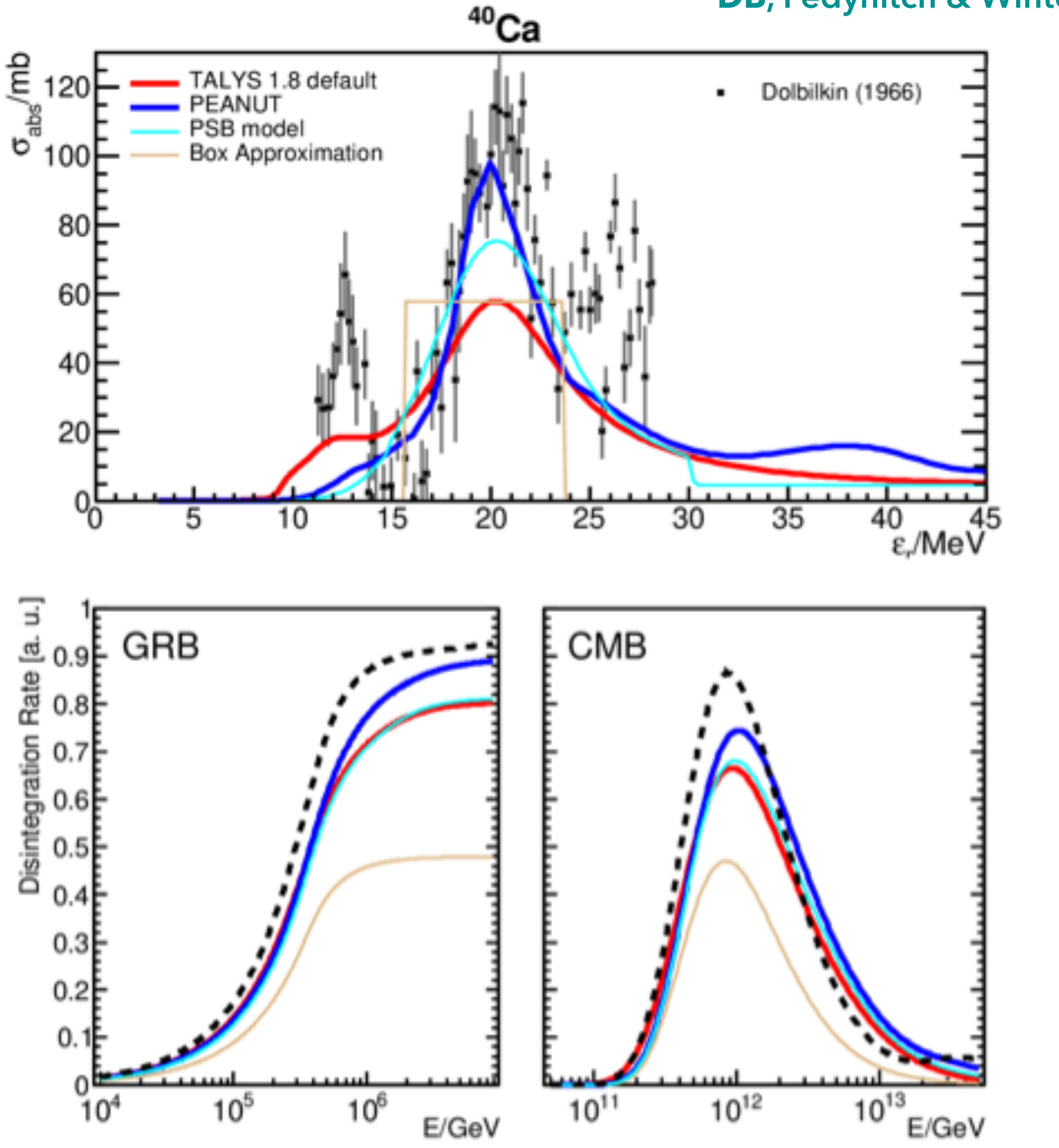




- Ca-40: double magic nucleus
- TALYS predictions not dependent on the element
- PEANUT predictions are different in the same isobar; if data available, at least the central GDR peak is reproduced
- Box approximation, used for example in Murase and Beacom, Phys Rev. D81 2010, underestimates data and models for A=40

Comparison of cross sections from models and available data

DB, Fedynitch & Winter, Sci. Reports 2017



CMB, propagation

$$n_\gamma(\epsilon) = \frac{1}{\pi^2(\hbar c)^3}\frac{\epsilon^2}{\exp(\epsilon/KT)-1}$$

GRB, source

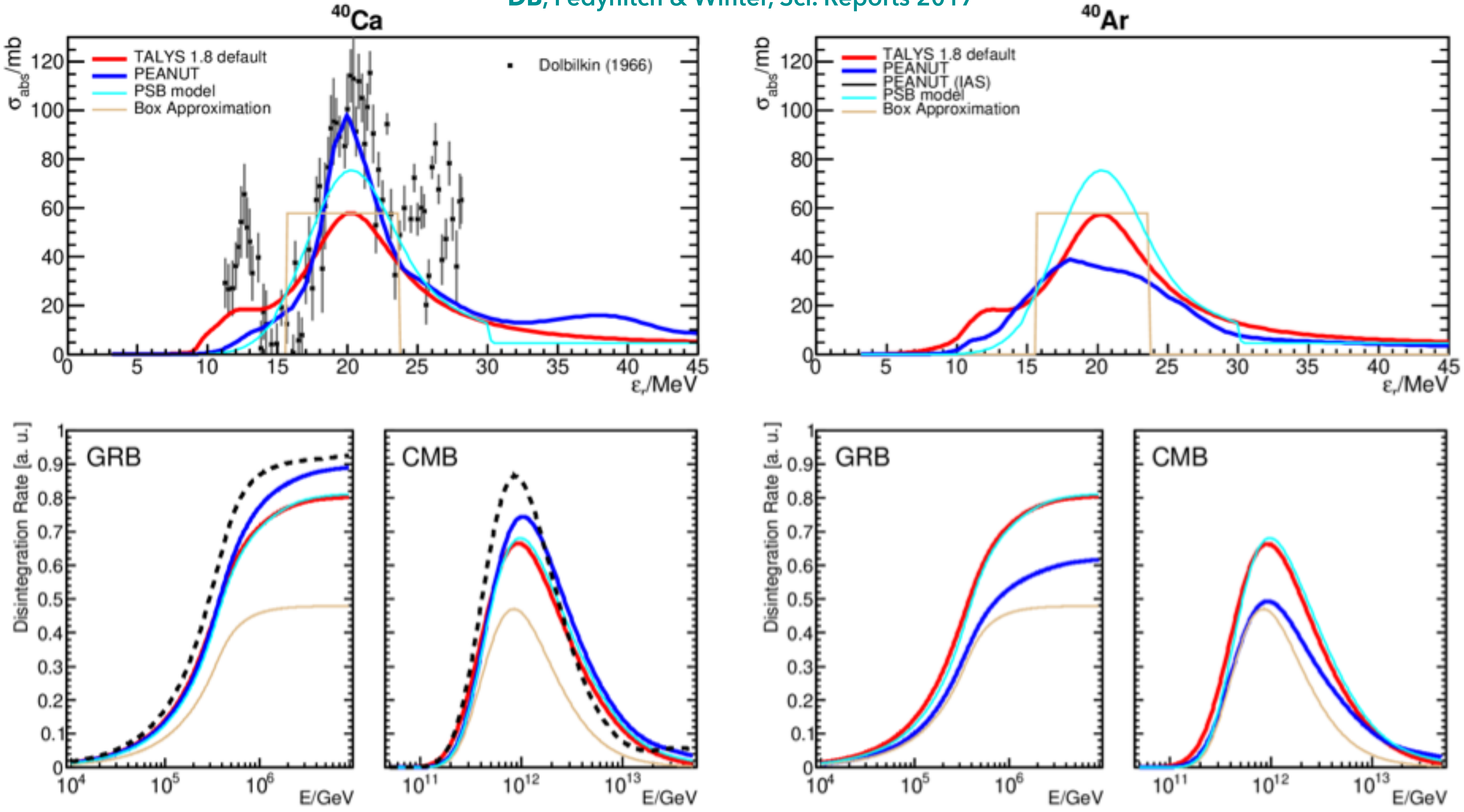
Baerwald, Bustamante and Winter, Astrophys. J. 768 (2013) 186

$$N'_\gamma(\varepsilon') \propto \begin{cases} \left(\frac{\varepsilon'}{\varepsilon'_{\gamma,\mathrm{break}}}\right)^{-\alpha_\gamma} & \varepsilon'_{\gamma,\mathrm{min}} \leq \varepsilon' < \varepsilon'_{\gamma,\mathrm{break}} \\ \left(\frac{\varepsilon'}{\varepsilon'_{\gamma,\mathrm{break}}}\right)^{-\beta_\gamma} & \varepsilon'_{\gamma,\mathrm{break}} \leq \varepsilon' < \varepsilon'_{\gamma,\mathrm{max}} \\ 0 & \mathrm{else} \end{cases}$$

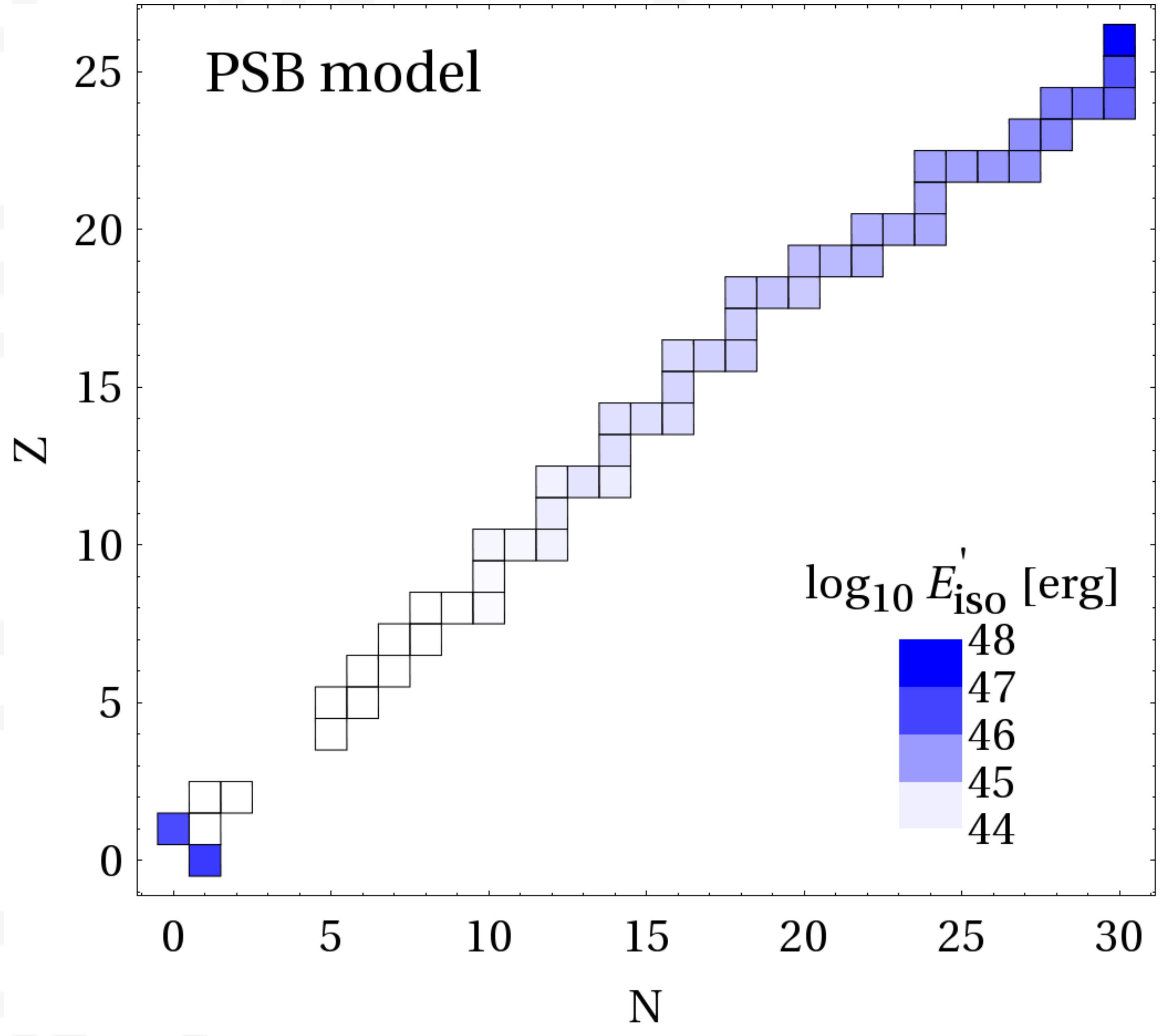
GSI

Comparison of cross sections from models and available data

DB, Fedynitch & Winter, Sci. Reports 2017



Effect on nuclear cascade

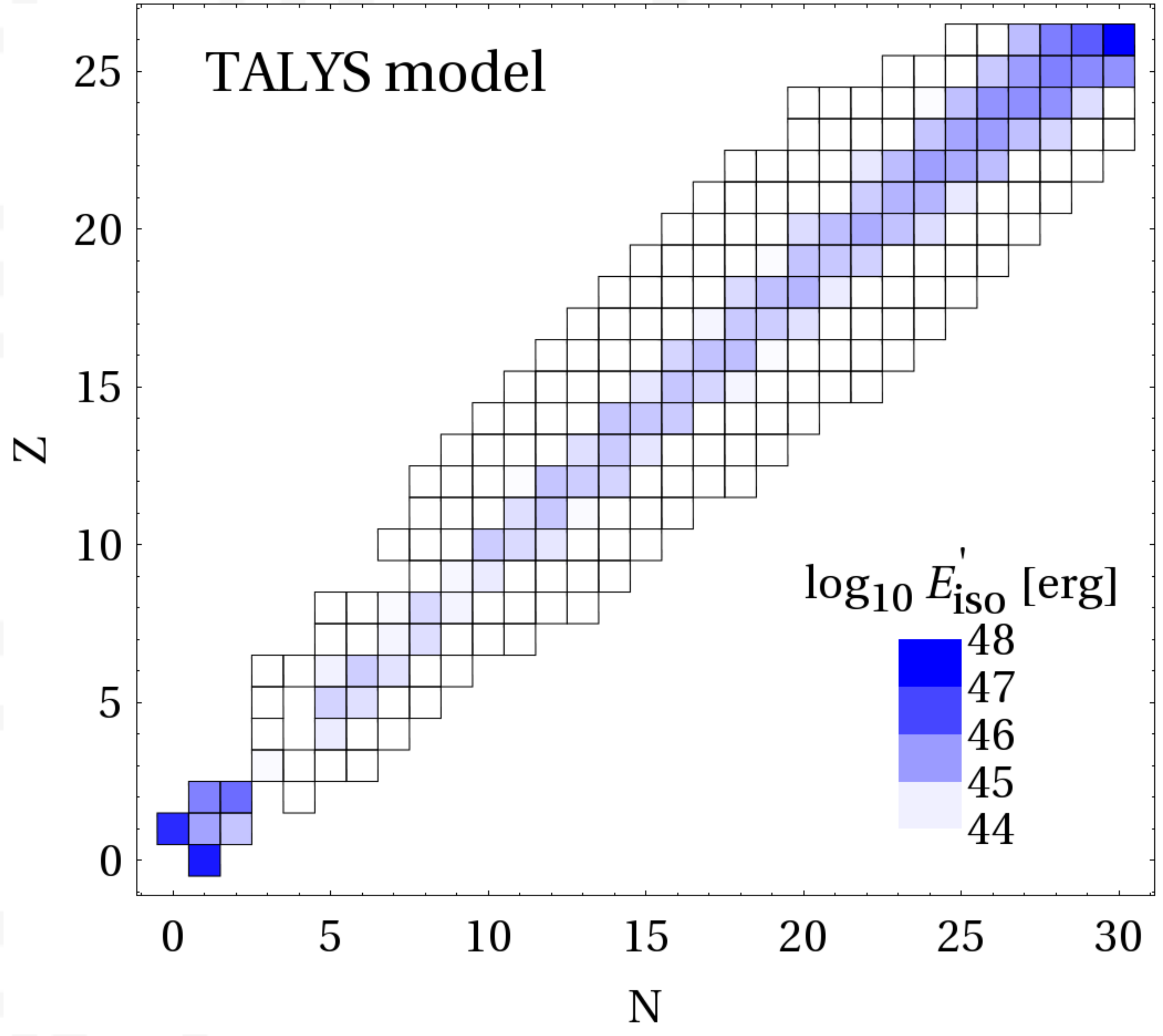


DB, Fedynitch & Winter, Sci. Reports 2017

- One nuclide for each A
- Only small fragments can be ejected in photo-disintegration
- The cascade is not completed, smaller masses are not populated

> Population of isotopes in terms of total energy per isotope and collision in the shock rest frame of a GRB shell

Effect on nuclear cascade

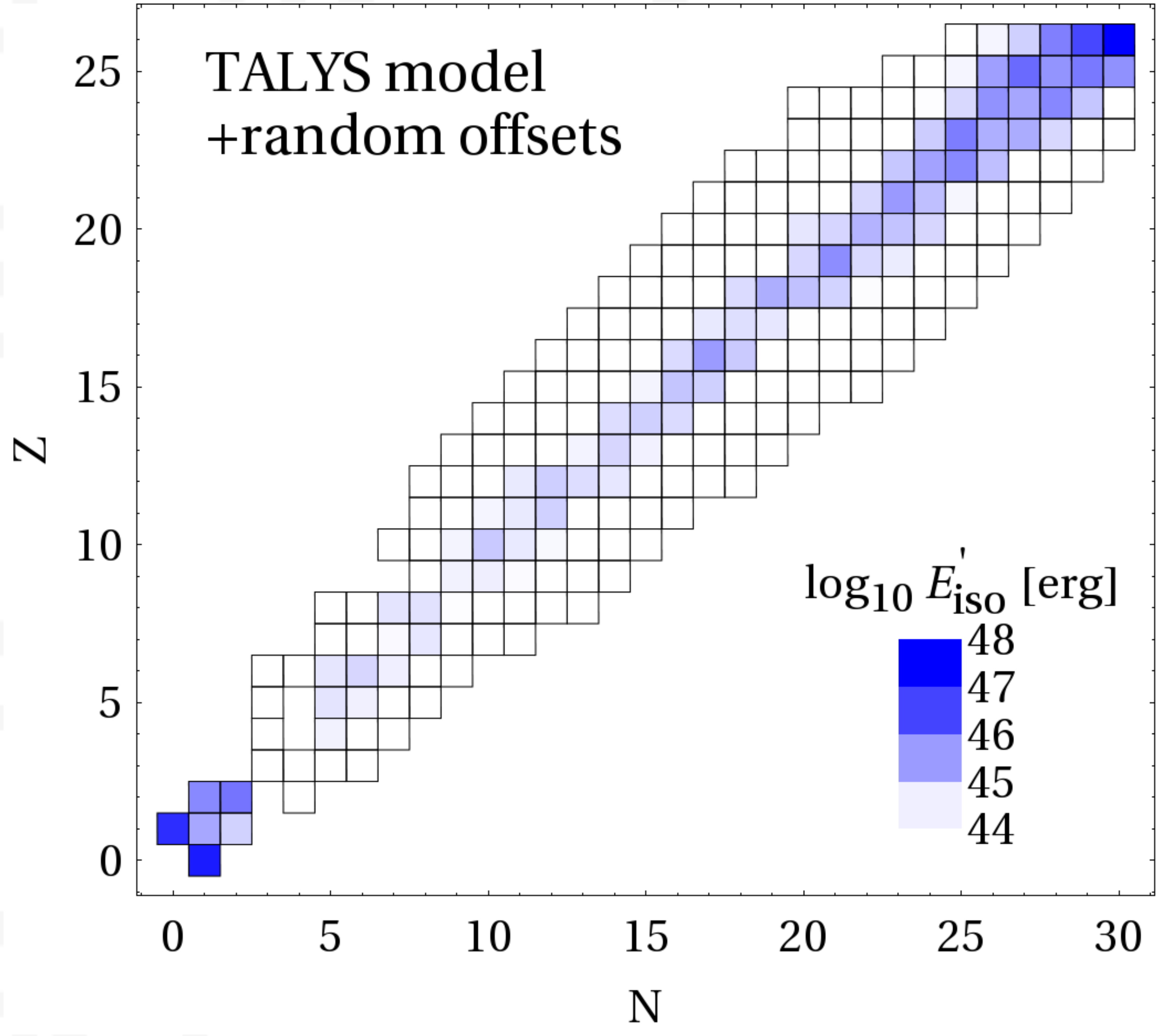


DB, Fedynitch & Winter, Sci. Reports 2017

- Much more channels wrt PSB
- Small fragments ejected: p, n, d, t, He-3, He-4
- Chart almost fully populated (however, this also depends on the target photon density)

> Population of isotopes in terms of total energy per isotope and collision in the shock rest frame of a GRB shell

Effect on nuclear cascade

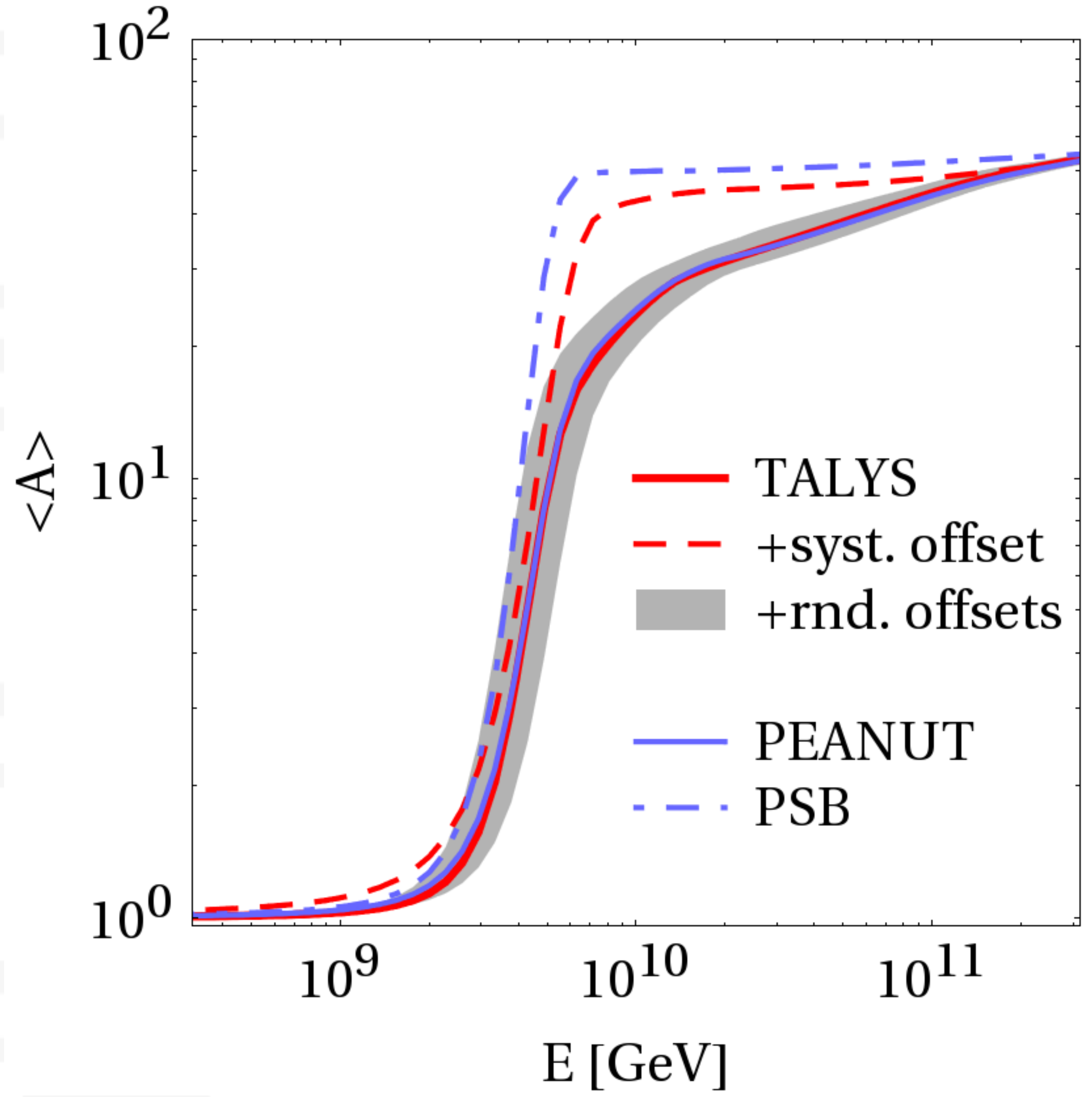


DB, Fedynitch & Winter, Sci. Reports 2017

- Cross sections reduced by:
  - 1 if the absorption cross section is measured
  - 0.5 if any other cross section is measured
  - 0 if no data available
- Relying on data, the cascade cannot be populated

> Population of isotopes in terms of total energy per isotope and collision in the shock rest frame of a GRB shell

Effect on mass composition



DB, Fedynitch & Winter, Sci. Reports 2017

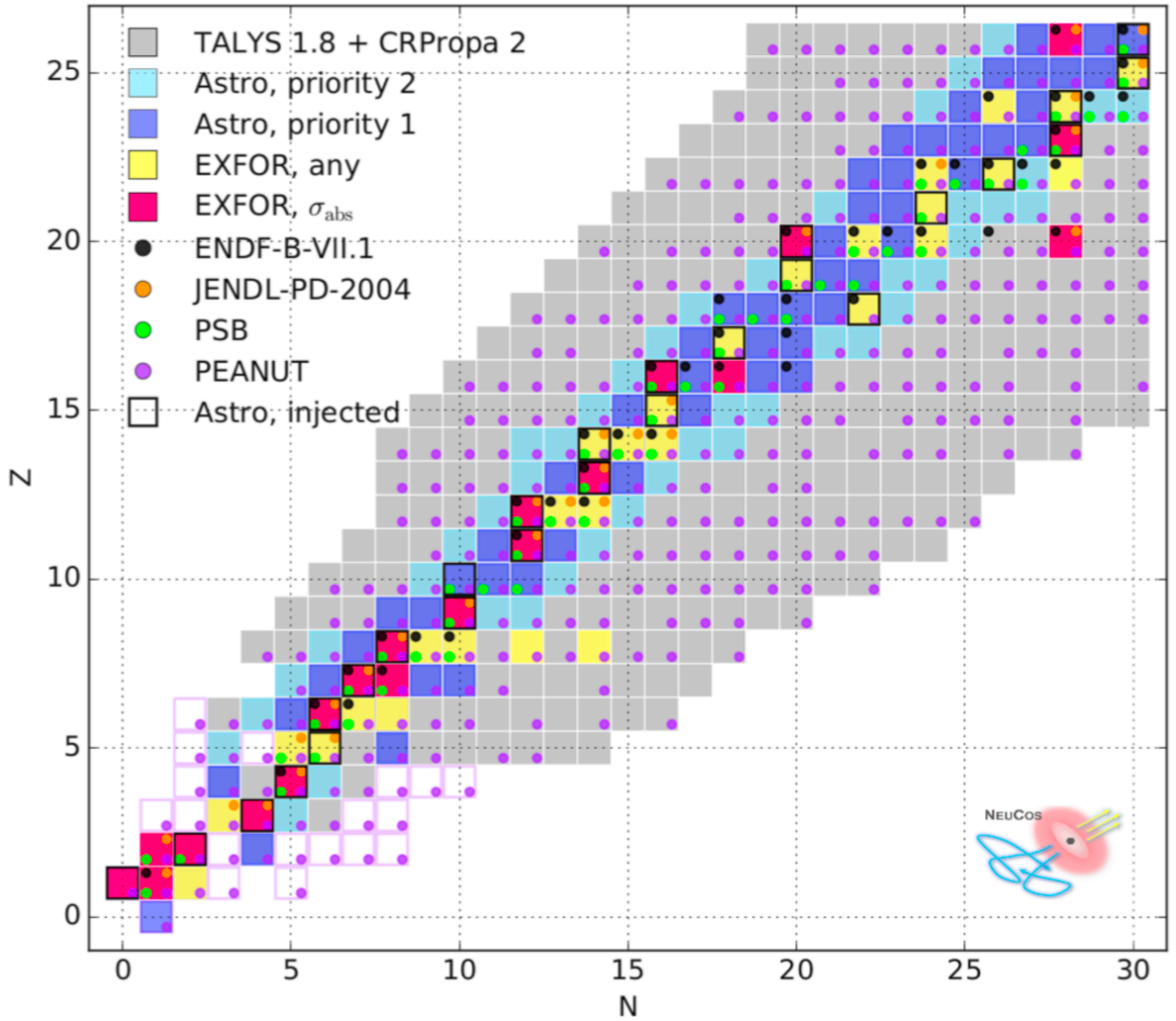
- No propagation effects considered
- Auger results qualitatively reproduced
- Simplified model PSB leads to a sharper increase of composition wrt more sophisticated models
- If only measured cross sections are included in the models, similar results to PSB

Summary

- **The origin of UHECRs can be investigated by taking into account spectrum and mass composition measurements**
- Interactions of cosmic-ray **nuclei** need to be taken into account, due to **mass composition results**
- Uncertainties in photo-disintegration cross sections
  - Lack of measurements
  - Disagreement with available data
- **Predictions of astrophysical models reproducing UHECR data are affected by uncertainties in nuclear physics**
  - UHECR data are described by models with low Emax -> photo-disintegration details matter!

- Open issues:
  - Mainly measurements in main diagonal
  - No measurements in the same isobar

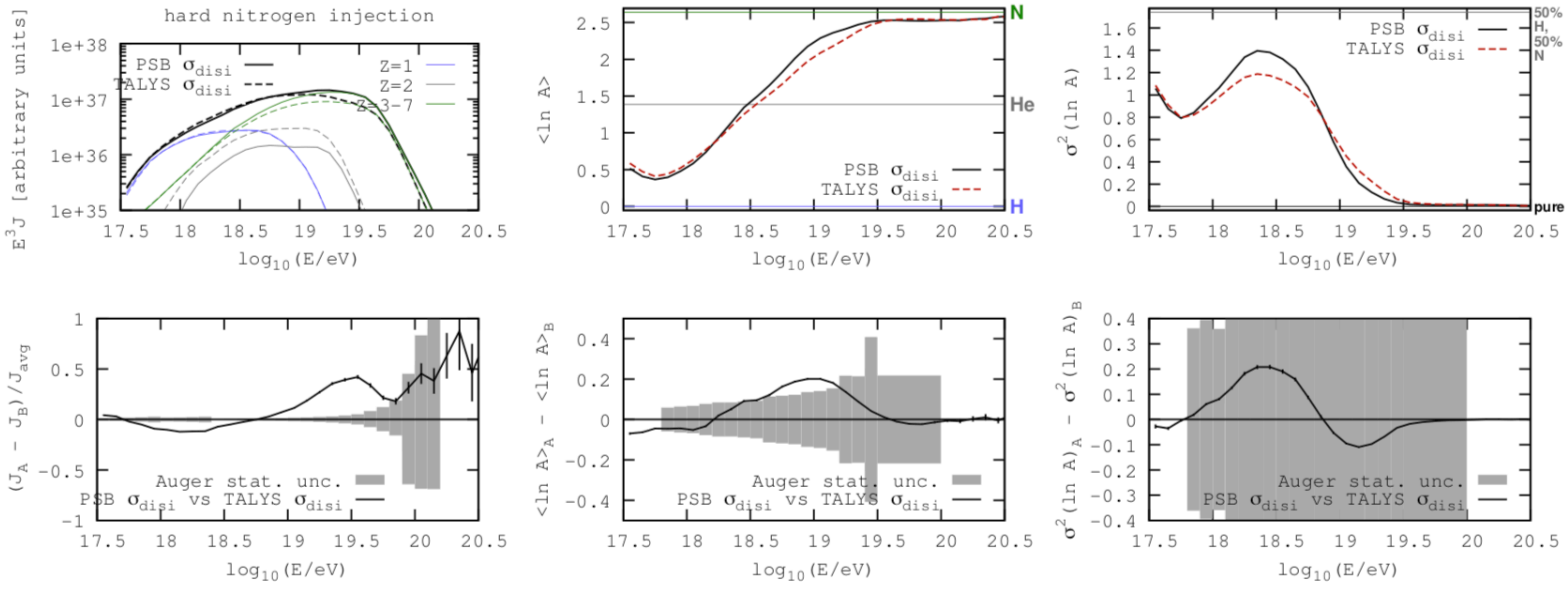
Need of larger predictive power of models !



BACKUP SLIDES

Effect of uncertainties in photo-disintegration models

Alves Batista, **DB**, di Matteo, van Vliet & Walz, JCAP 2015



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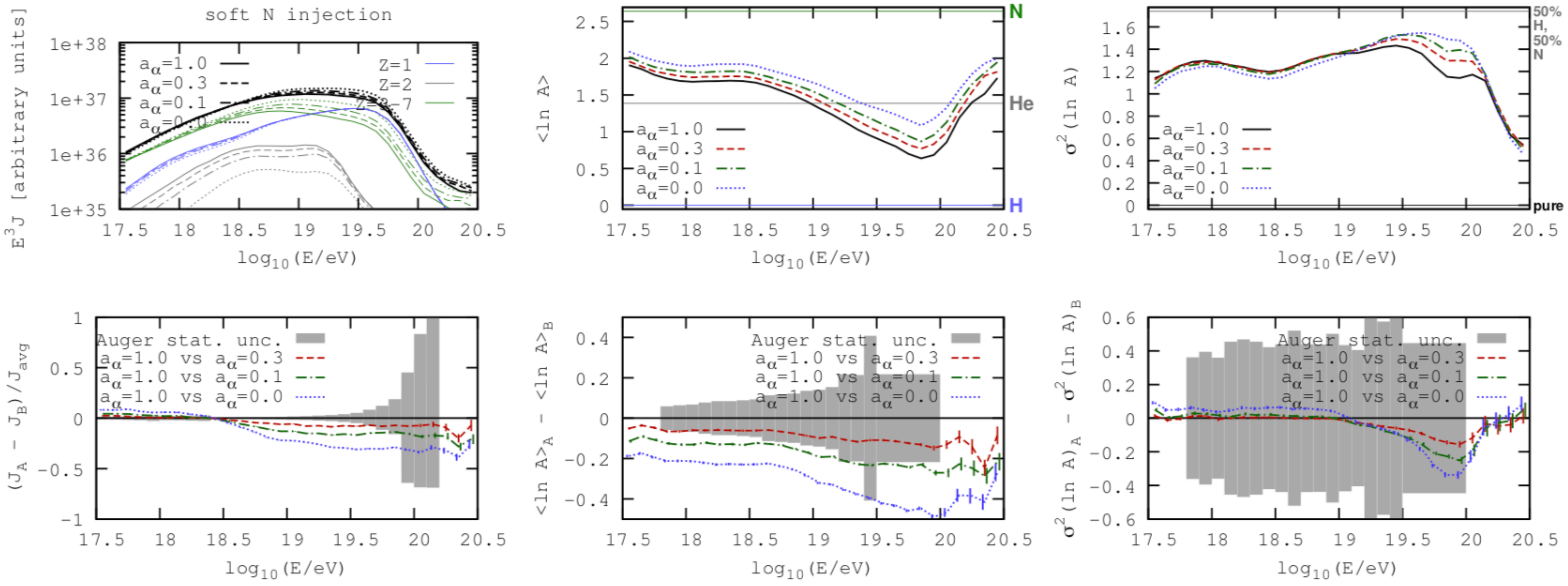

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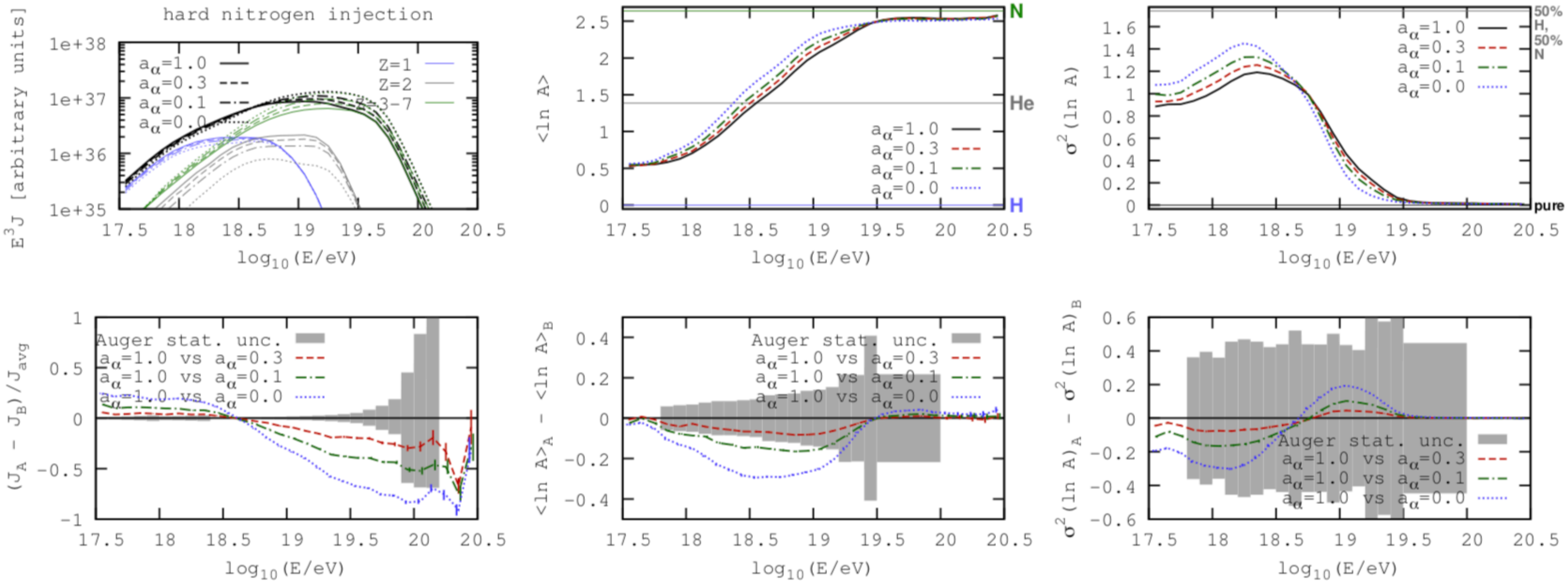
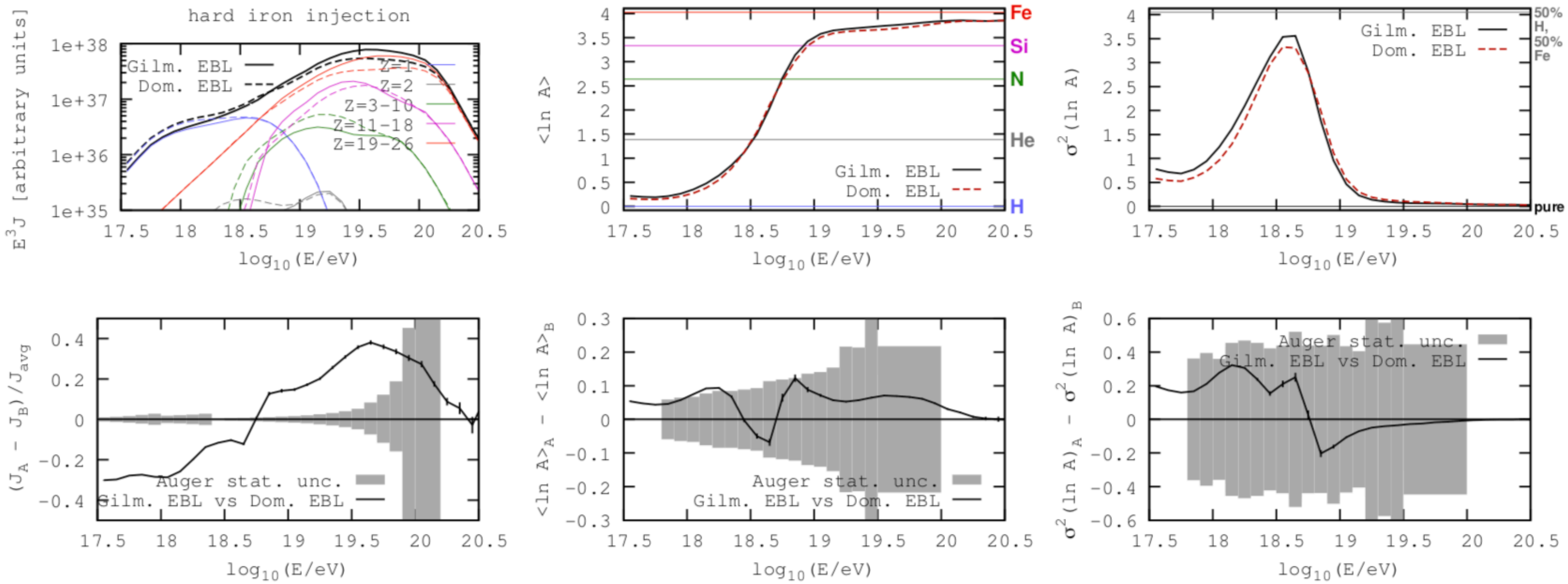


Effect of uncertainties in EBL models

Alves Batista, **DB**, di Matteo, van Vliet & Walz, JCAP 2015



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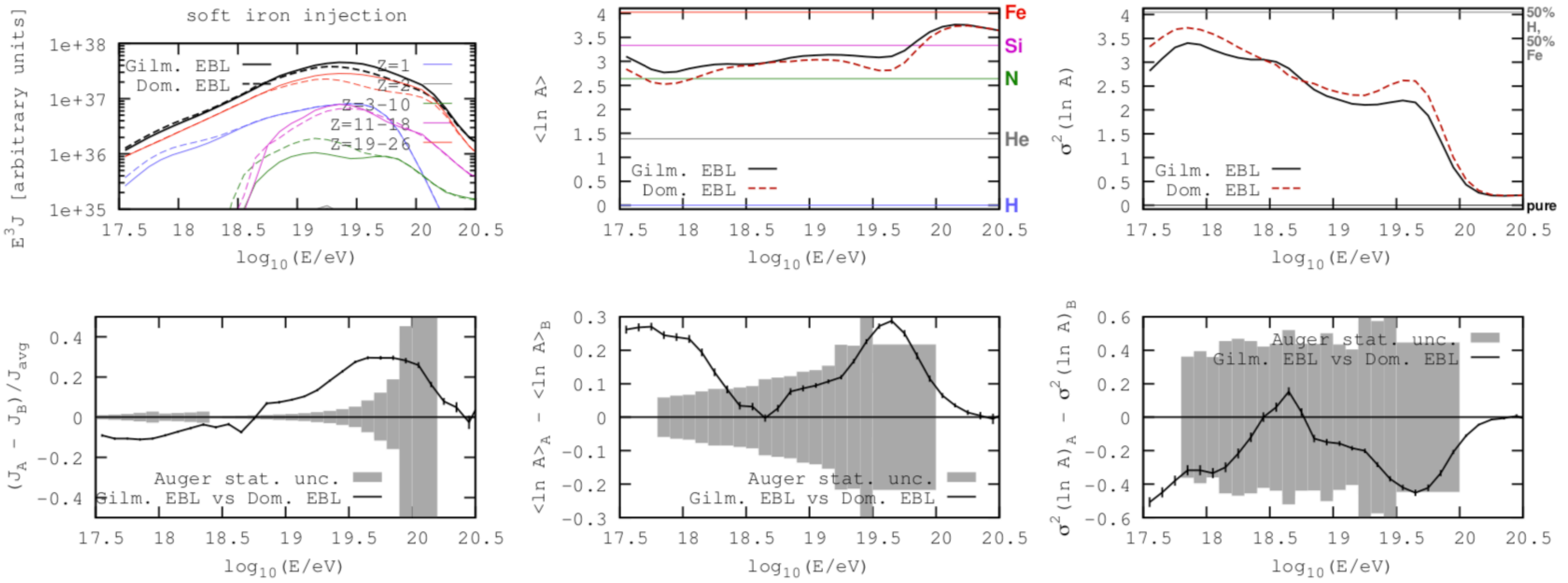
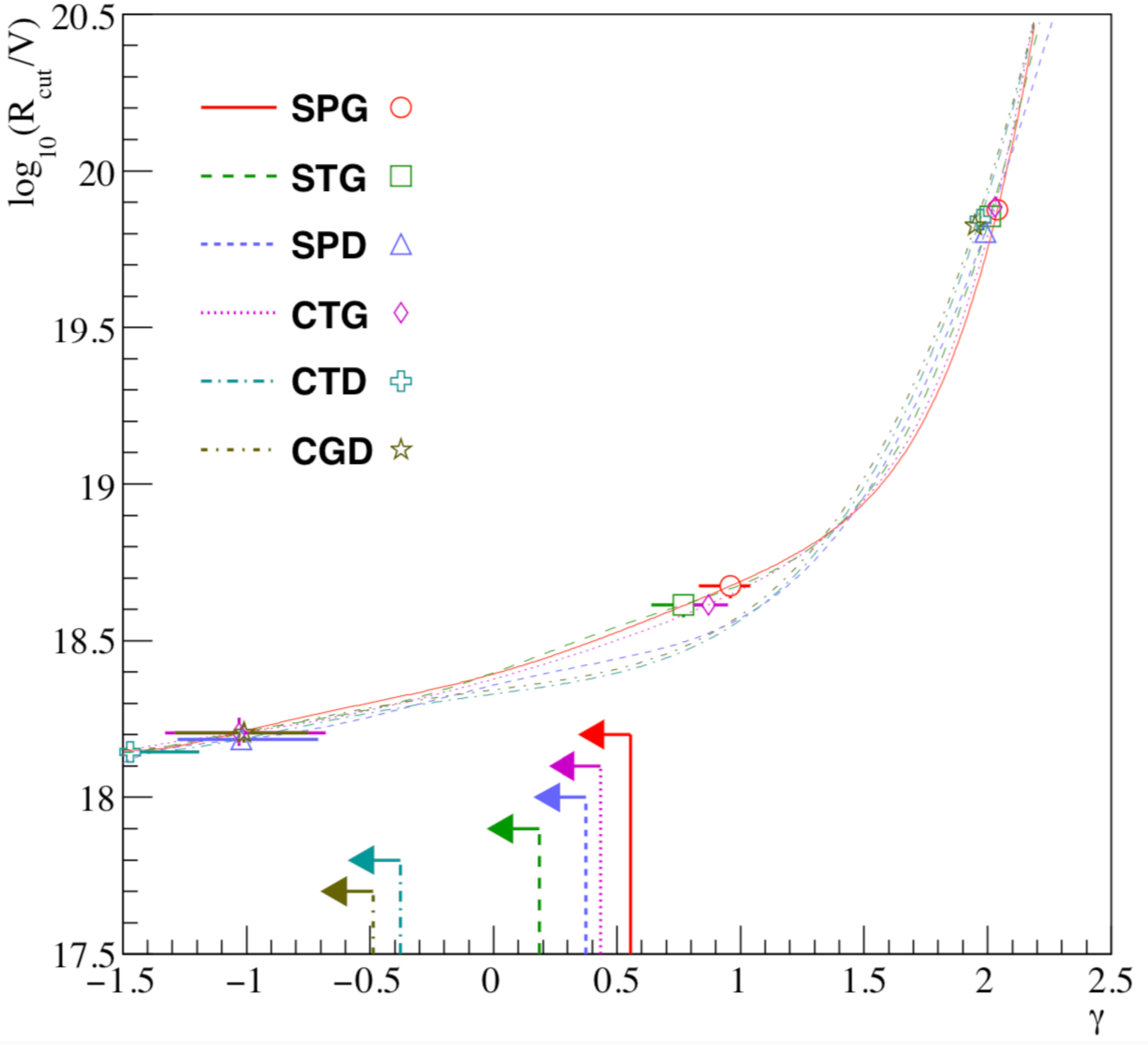
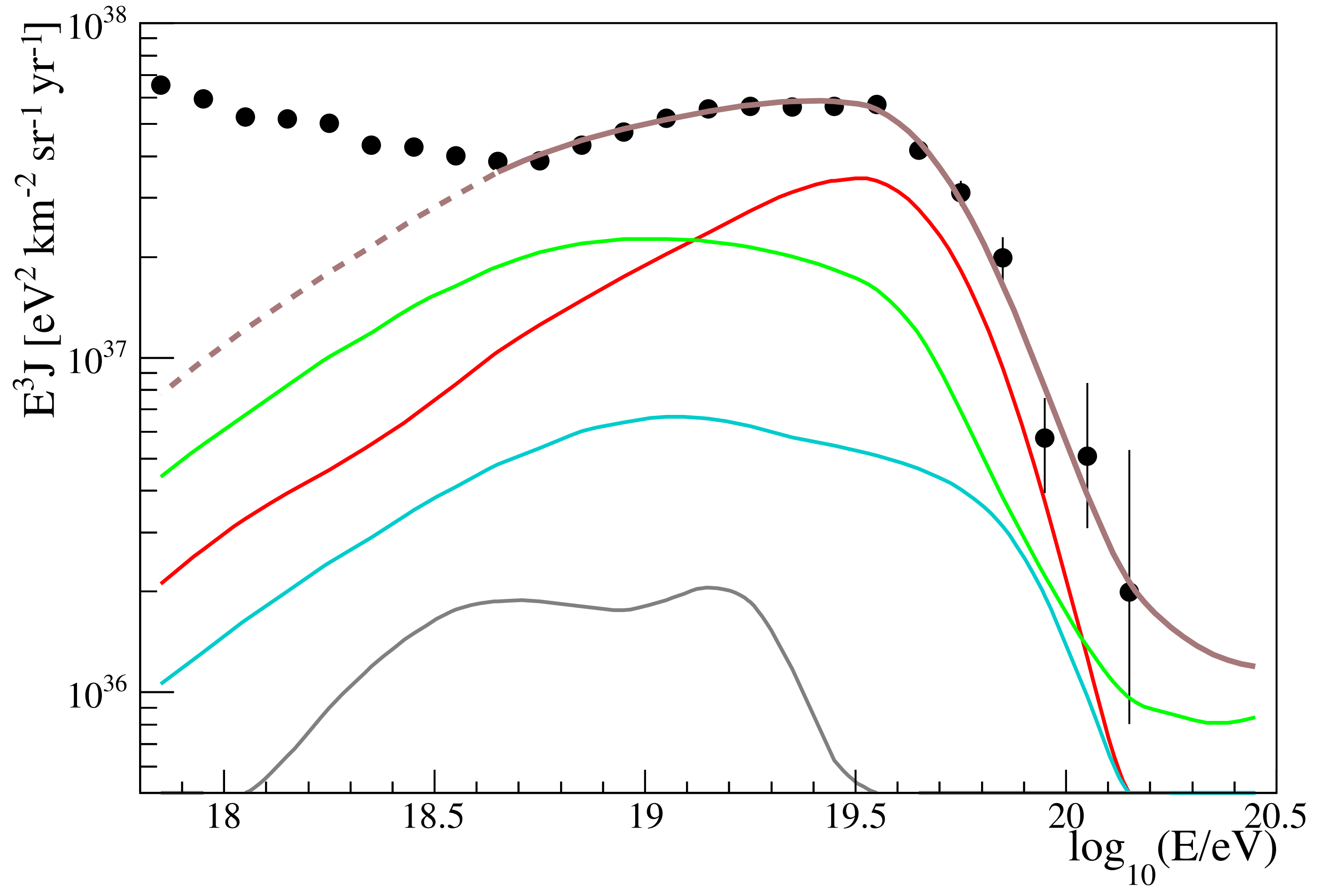
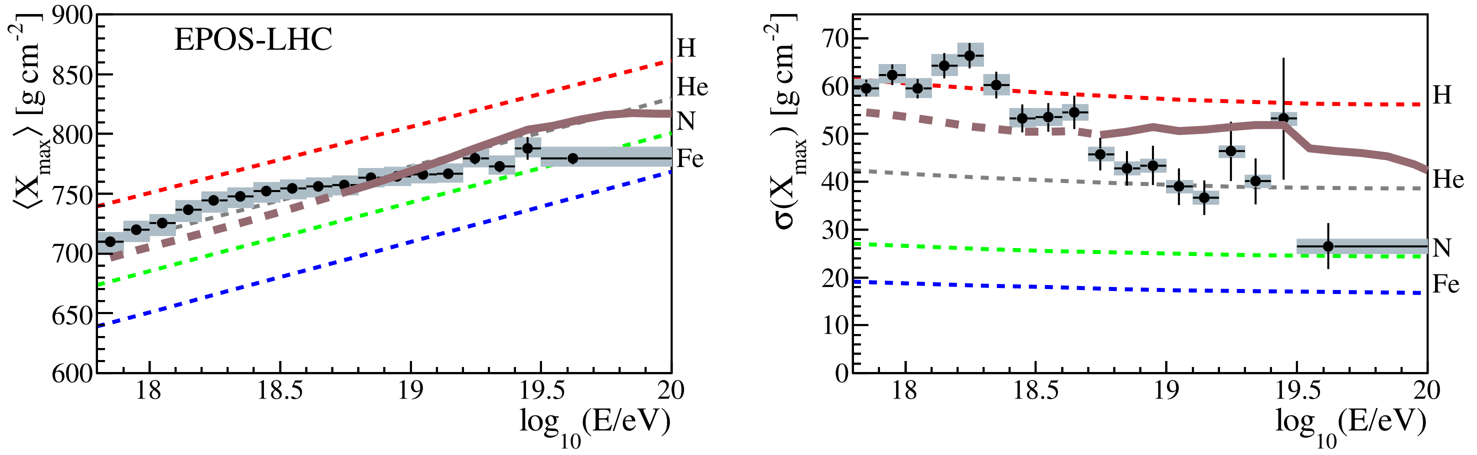


Interpretation

- Local minimum

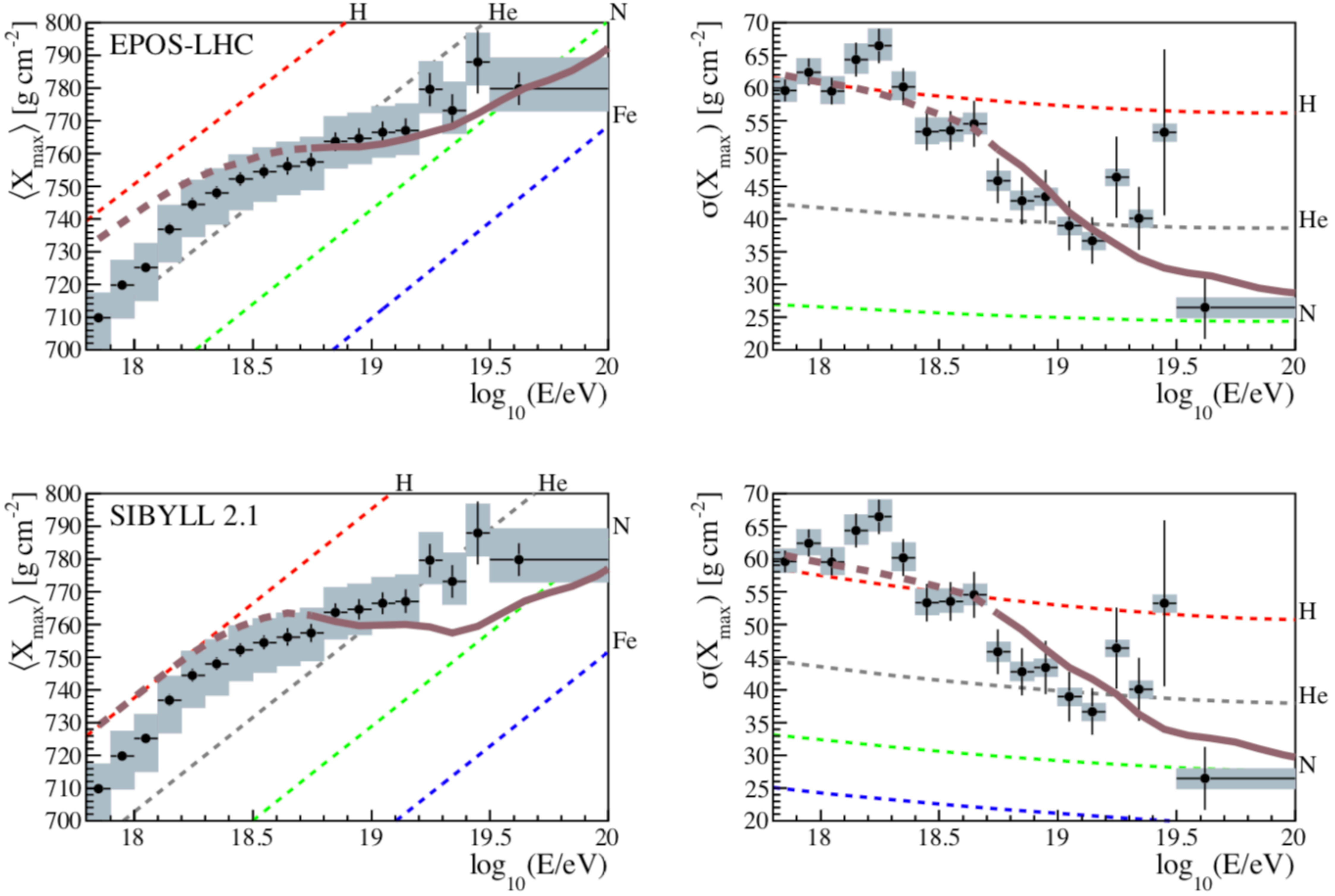






Interpretation

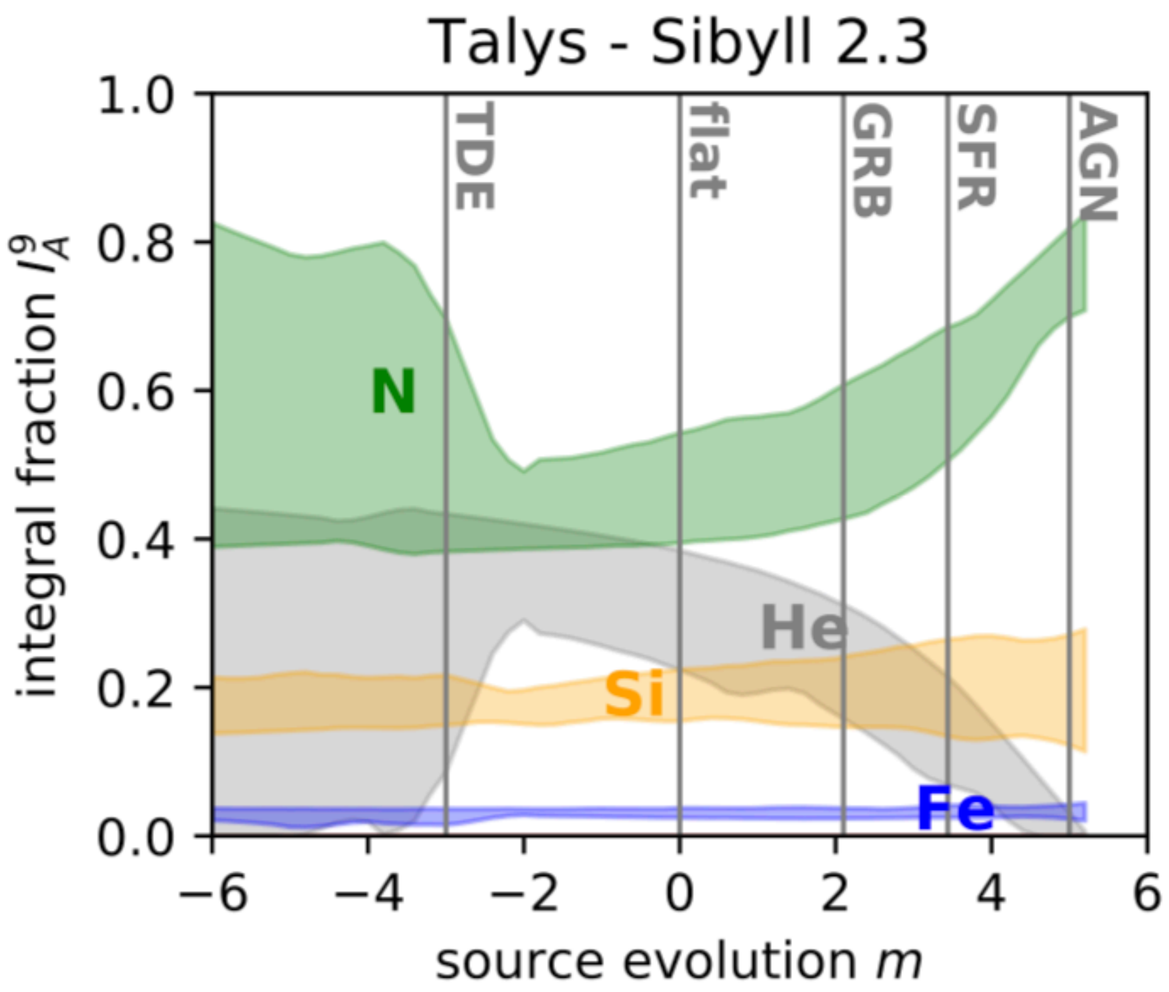
- Effect of different interaction models in atmosphere

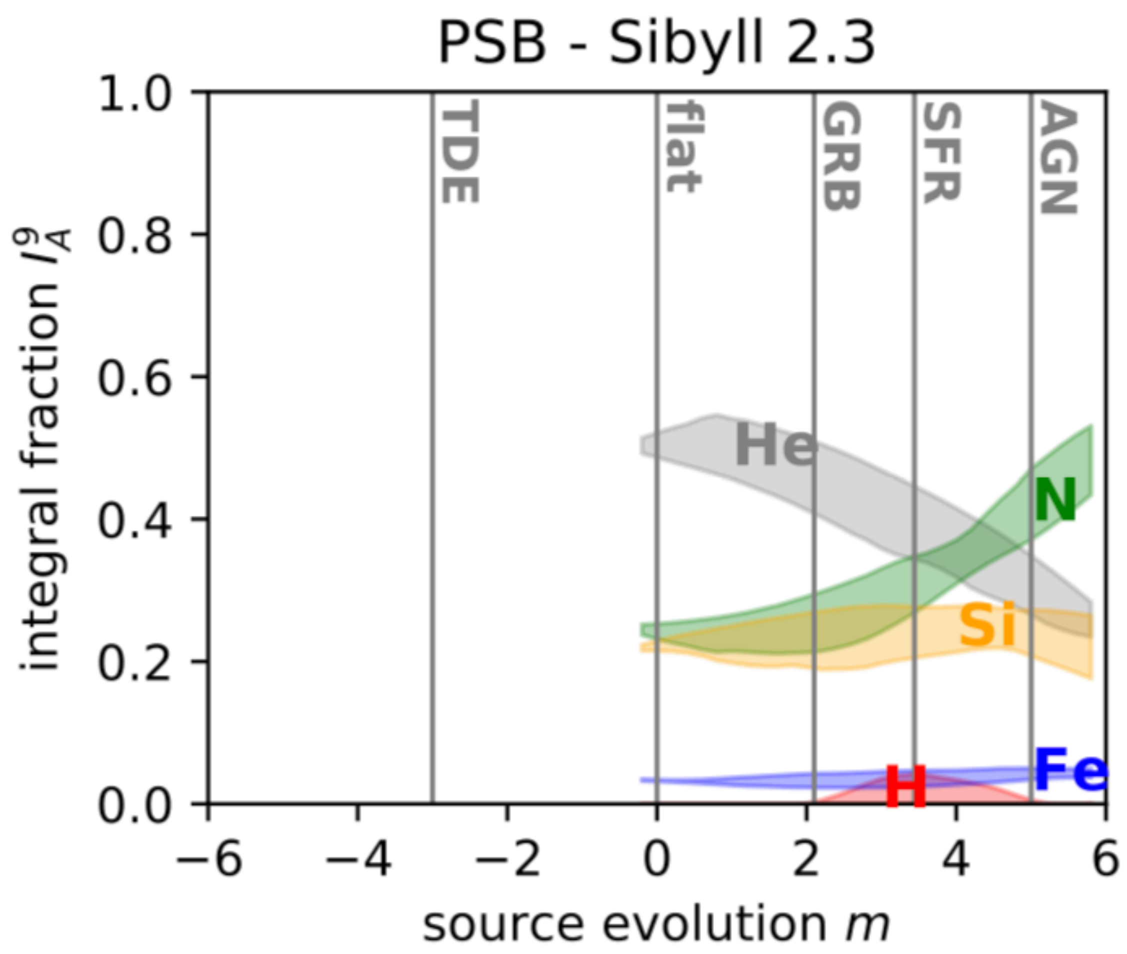


Interpretation

- Effect of disintegration models and source evolution

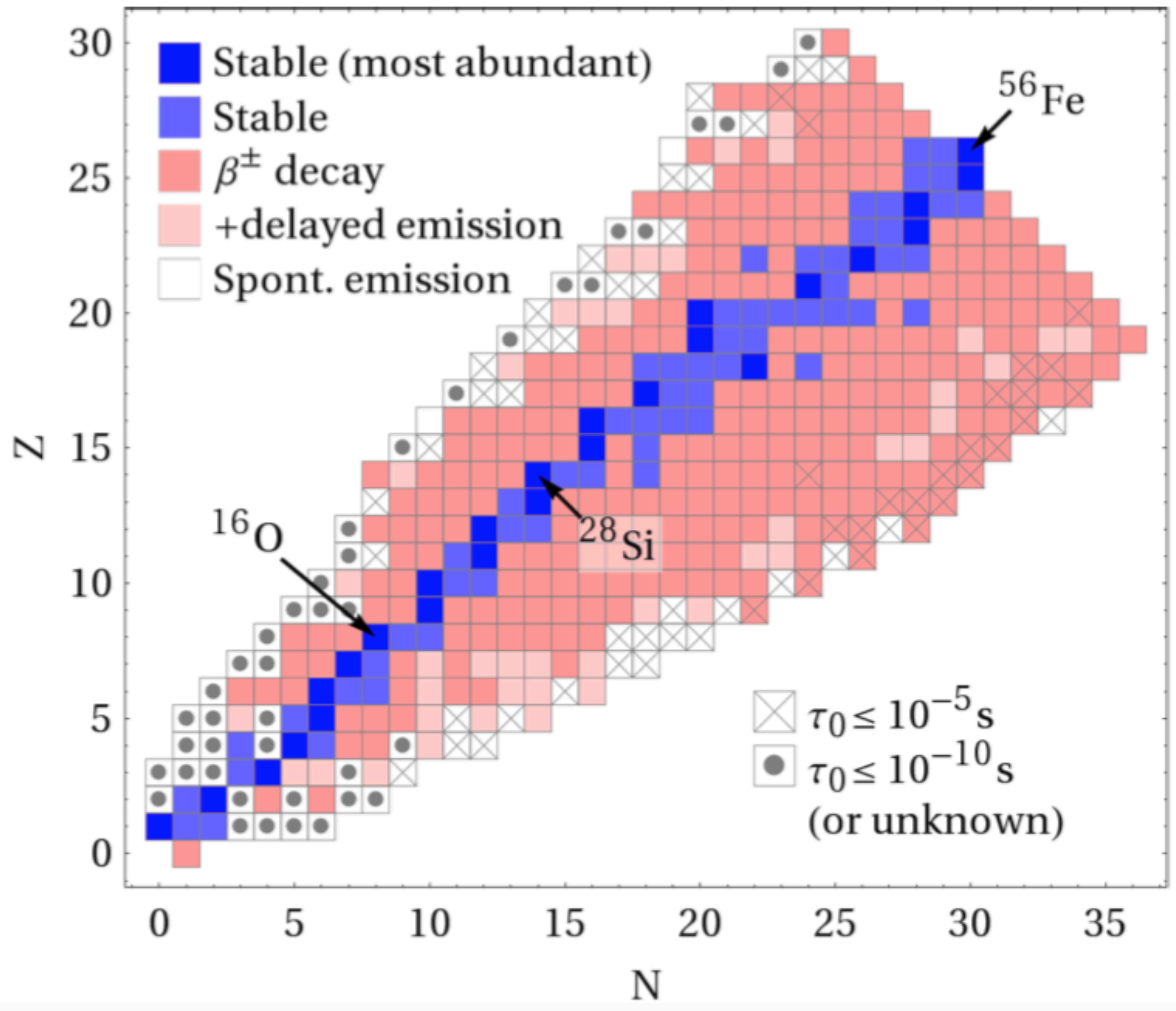
Heinze, Fedynitch, **DB** & Winter, ApJ 2019



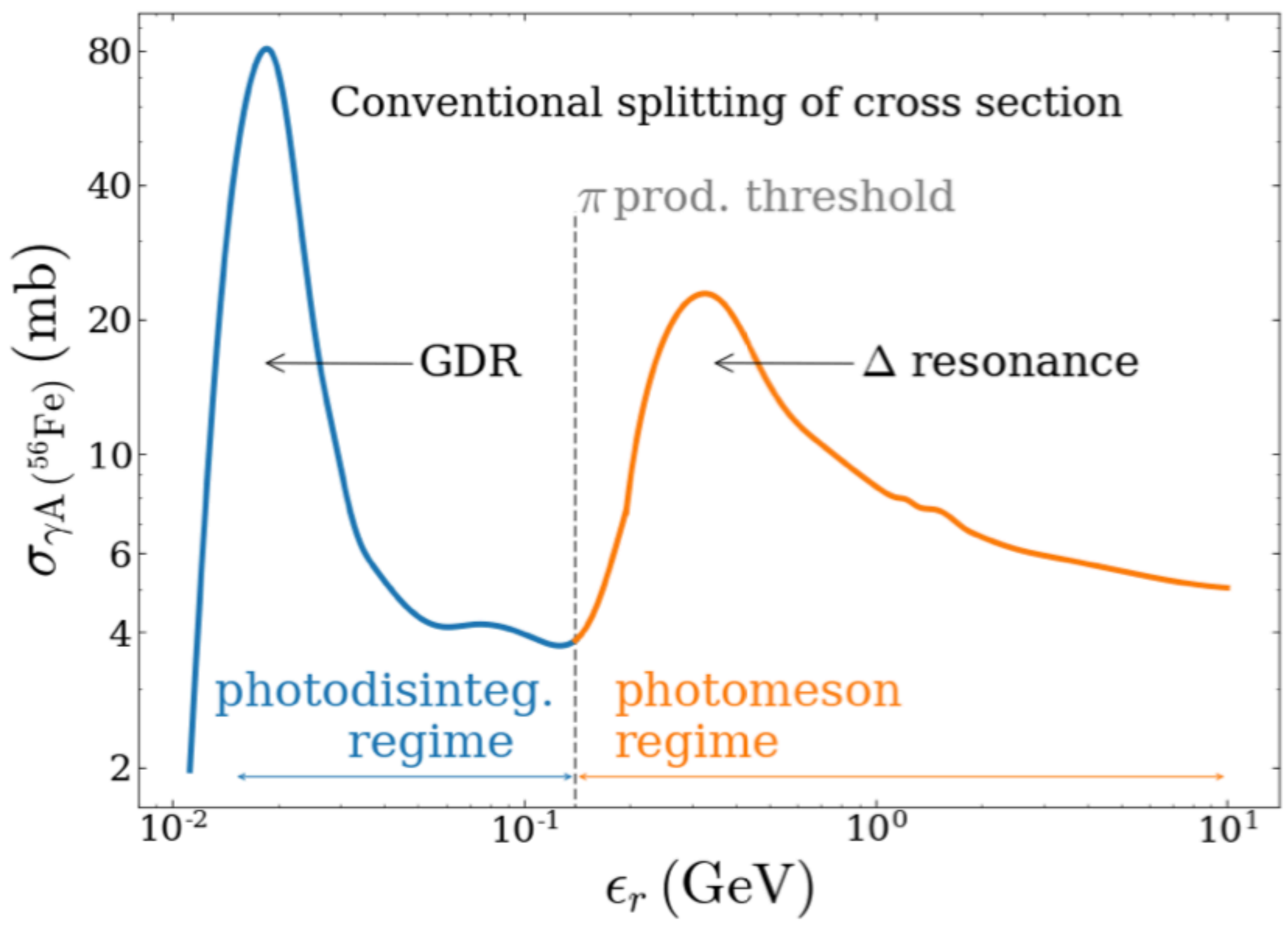


How to deal with nuclei?

Biehl, **DB**, Fedynitch, Winter, A&A 2018



Morejon, Fedynitch, **DB**, Biehl, Winter, arXiv1904.07999v2, accepted for publication in JCAP



- Several codes available: in this talk, results from NEUCOSMA (see Biehl, **DB**, Fedynitch, Winter A&A 2018 and references therein) and *SimProp* (Aloisio, **DB**, di Matteo, Grillo, Petrera, Salamida JCAP 2017) are shown

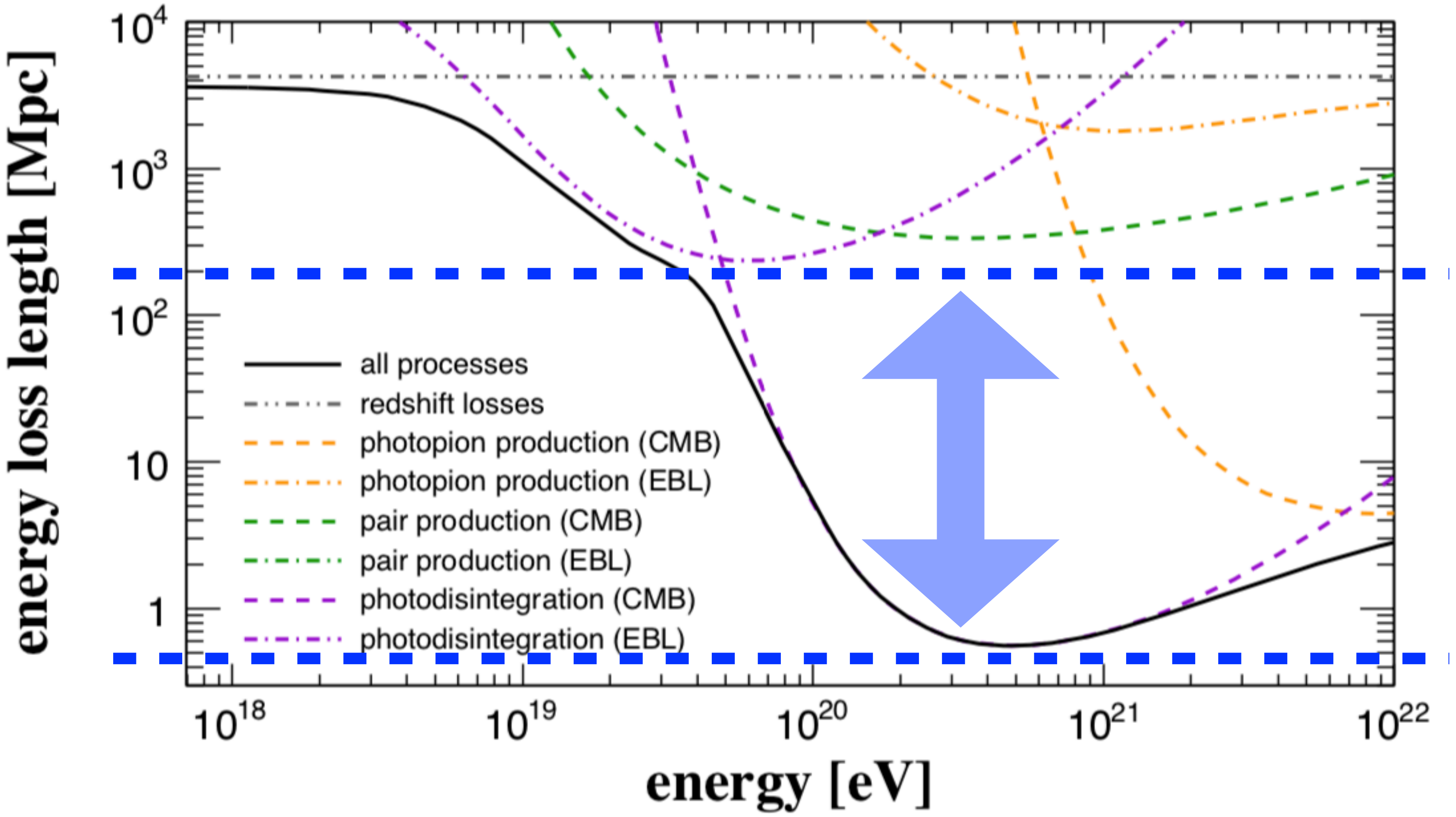
Which parameters do influence the neutrino flux? (1)

- **Radiation field**:
  - Intensity -> normalization of interaction rate
  - Min and max energy -> define range of interaction rate
  - Power law, energy break (if broken power law) or energy peak (if black body radiation) -> change shape and/or shift interaction rate
  - "Size" of radiation field
  - Density of matter

$$\epsilon' \approx \Gamma \epsilon$$

$$\frac{1}{\tau} = \frac{1}{2\Gamma^2} \int_{\epsilon'=0}^{2\Gamma\epsilon} \int_{\epsilon=0}^{+\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} \, d\epsilon \, \sigma(\epsilon') \epsilon' \, d\epsilon'$$

Example: interactions in extragalactic propagation



Alves Batista, **DB**, di Matteo, van Vliet, Walz, JCAP 2016

Which parameters do influence the neutrino flux? (1)

$$\epsilon' \approx \Gamma\epsilon$$

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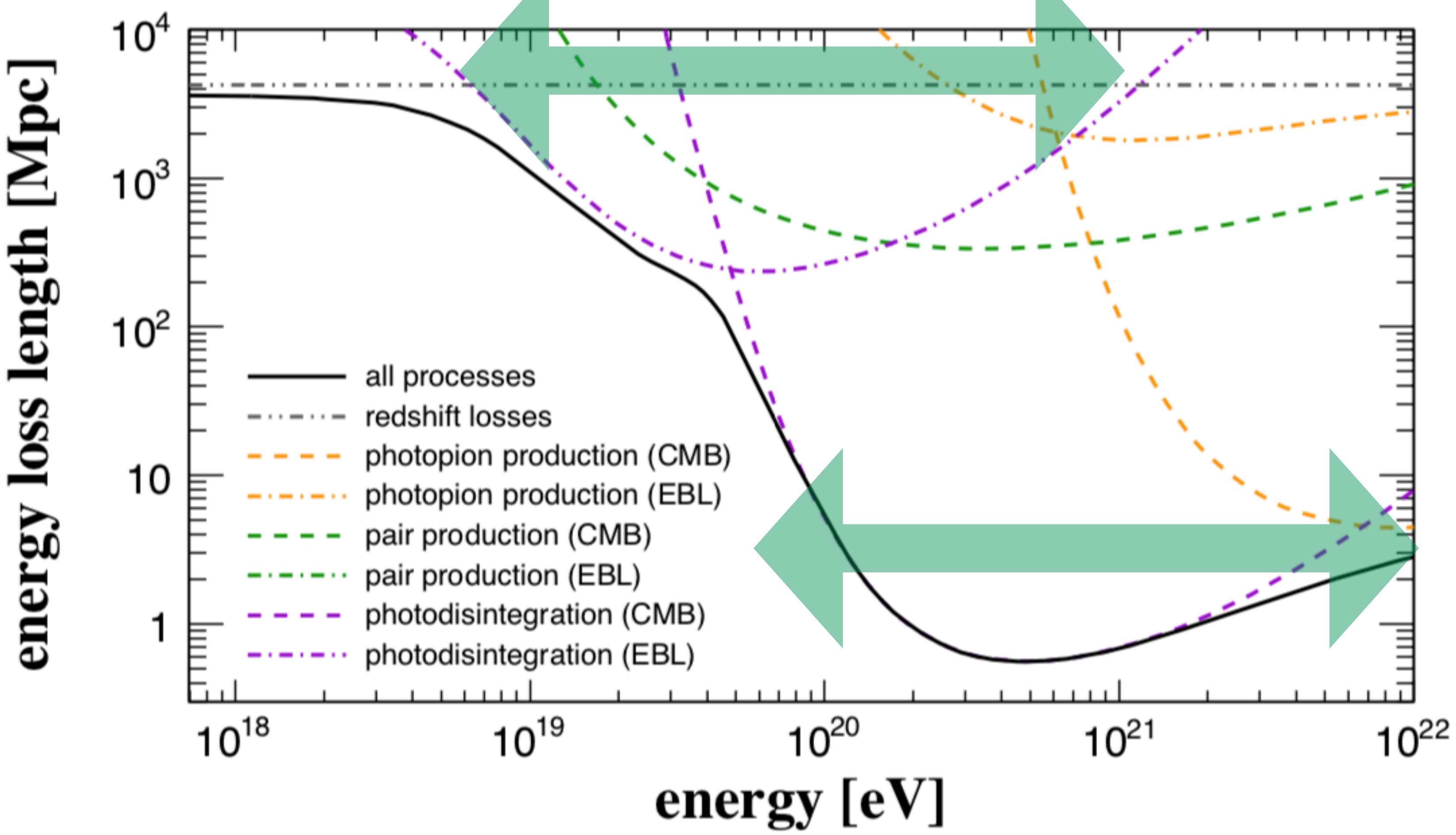


Alves Batista, **DB**, di Matteo, van Vliet, Walz, JCAP 2016

Which parameters do influence the neutrino flux? (1)

- **Radiation field**:
  - Intensity -> increase interaction rate
  - Min and max energy -> define range of interaction rate
  - Power law, energy break (if broken power law) or energy peak (if black body radiation) -> change shape and/or shift interaction rate
  - "Size" of radiation field
  - Density of matter

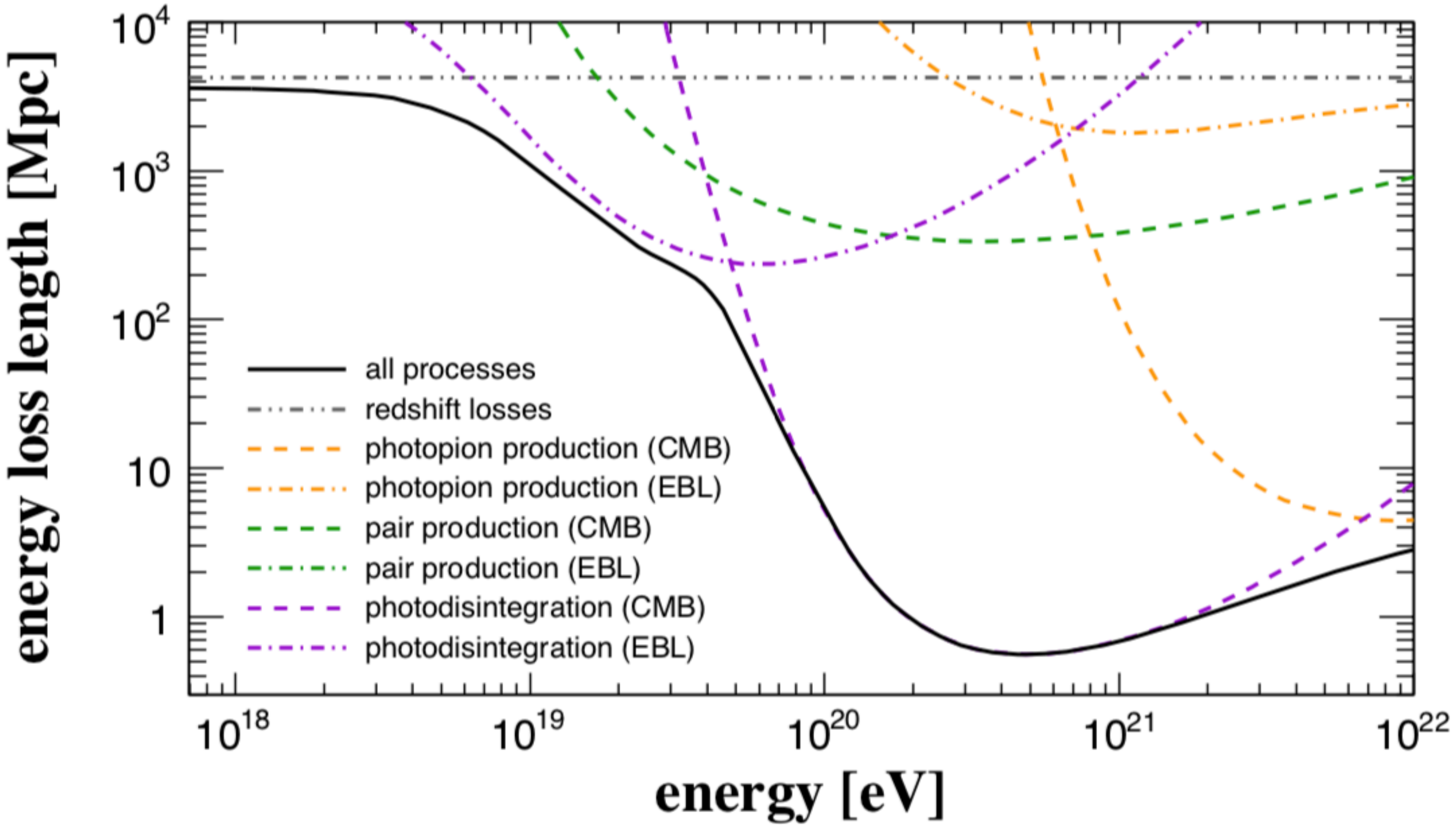
$$\epsilon' \approx \Gamma \epsilon$$

$$\frac{1}{\tau} = \frac{1}{2\Gamma^2} \int_{\epsilon'=0}^{2\Gamma\epsilon} \int_{\epsilon=0}^{+\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} \mathrm{d}\epsilon \, \sigma(\epsilon') \epsilon' \, \mathrm{d}\epsilon'$$

- Influence on radiation density in sources
- Influence on escape probability, diffusion of charged particles

- pp interactions

Example: interactions in extragalactic propagation



Alves Batista, **DB**, di Matteo, van Vliet, Walz, JCAP 2016

- **Nuclear Physics** aspects: effects from photo-meson, photo-disintegration
  - See Alves Batista, **DB**, di Matteo, van Vliet, Walz JCAP 2016 - **DB**, Fedynitch, Winter Sci. Rep. 2017 - Alves Batista, **DB**, van Vliet JCAP 2019 - Morejon, Fedynitch, **DB**, Biehl, Winter arXiv:1904.07999v2

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Which parameters do influence the neutrino flux? (2)

- **Cosmic Ray Injection**
  - Mass of primary particles
  - Maximum energy of CR spectra
  - Slope of CR spectra
  - Source evolution
  - Maximum distance of sources

Not possible to be constrained only with UHECRs!
See for example:
- Heinze, **DB**, Bustamante & Winter, ApJ 2016
- Alves Batista, de Almeida, Lago & Kotera, JCAP 2019
- Heinze, Fedynitch, **DB** & Winter, ApJ 2019
- van Vliet, Alves Batista & Hoerandel, PRD 2019

$$\frac{\partial N_i(E)}{\partial t} = \frac{\partial}{\partial E}(-b(E)N_i(E)) - \frac{N_i(E)}{t_{\rm esc}} + Q_{ji}(E)$$

Coupled system of equations, arising because:

$$Q_{ji} = Q_i(E) + Q_{j\to i}(E)$$

$$b(E) = E/t_{\rm loss}$$

$Q_i(E)$ Injection of CR (accelerated spectrum)

$Q_{j\to i}(E)$ Production of secondary particles

$$\mathcal{L}_i(z) = n(z)\int Q_i(E)E\,dE$$

CR luminosity density

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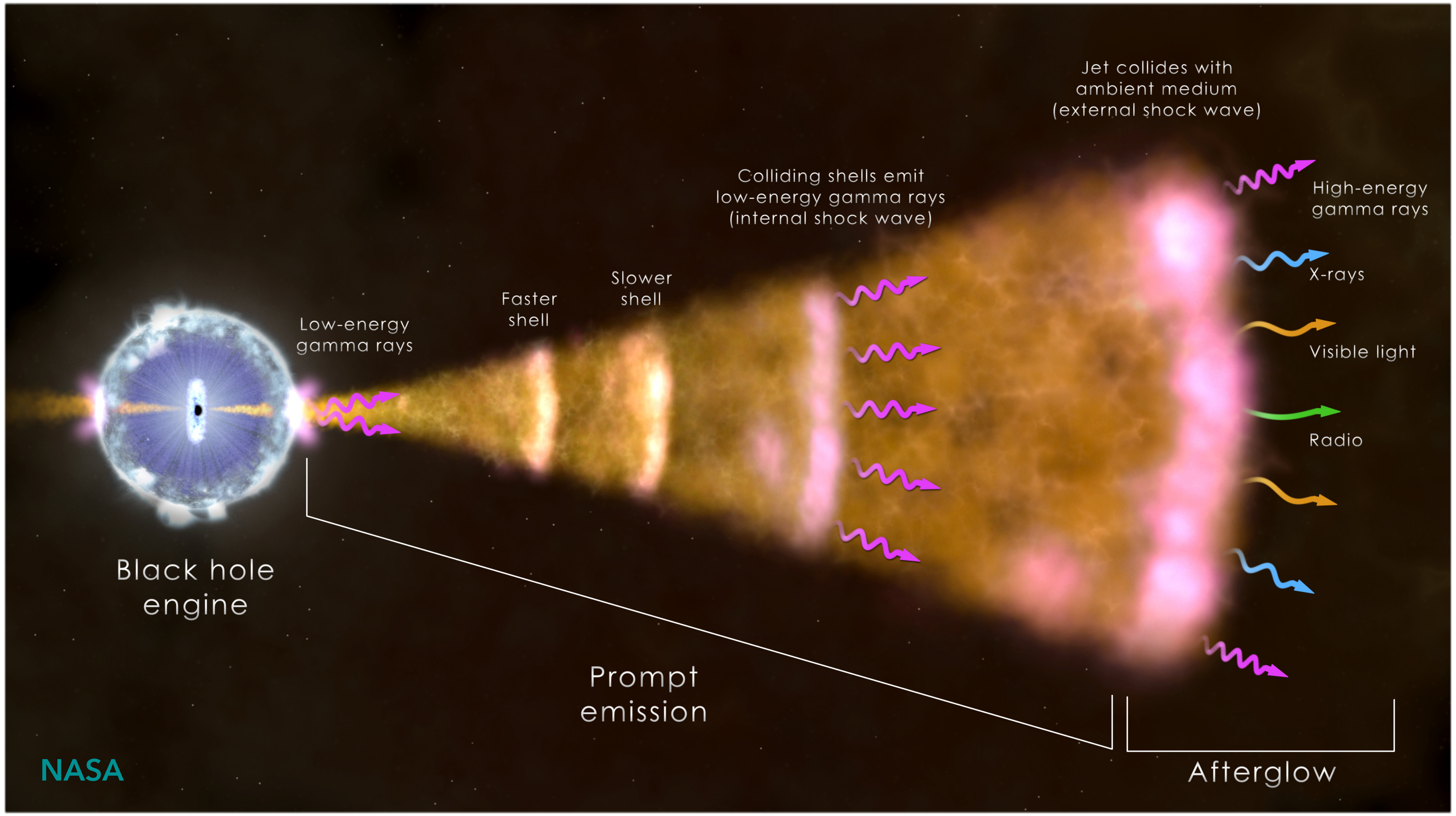
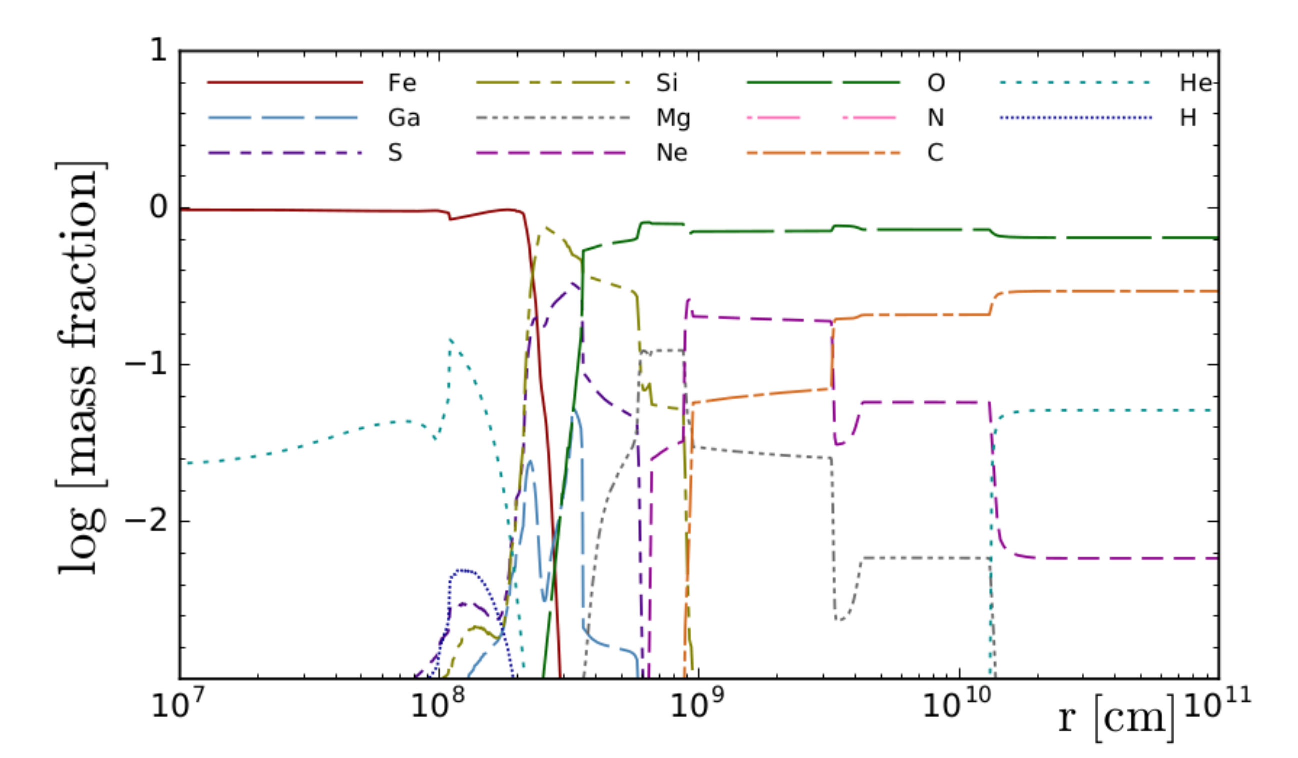
UHECR-neutrino candidate sources

- Gamma-Ray Bursts
  - Energy to power UHECR flux and efficiently produce neutrinos, see for example Murase & Fukugita, PRD 2019
  - Nuclear composition, see for example Zhang et al, PRD 2018 - Woosley et al, RevModPhys 2002





Zhang et al, PRD 2018

- Internal shock model (one zone)
  - **Geometry** → all collisions happen at the same radius, R (connected to the Lorentz factor and to the variability time)
  - **Luminosity** → isotropic equivalent luminosity

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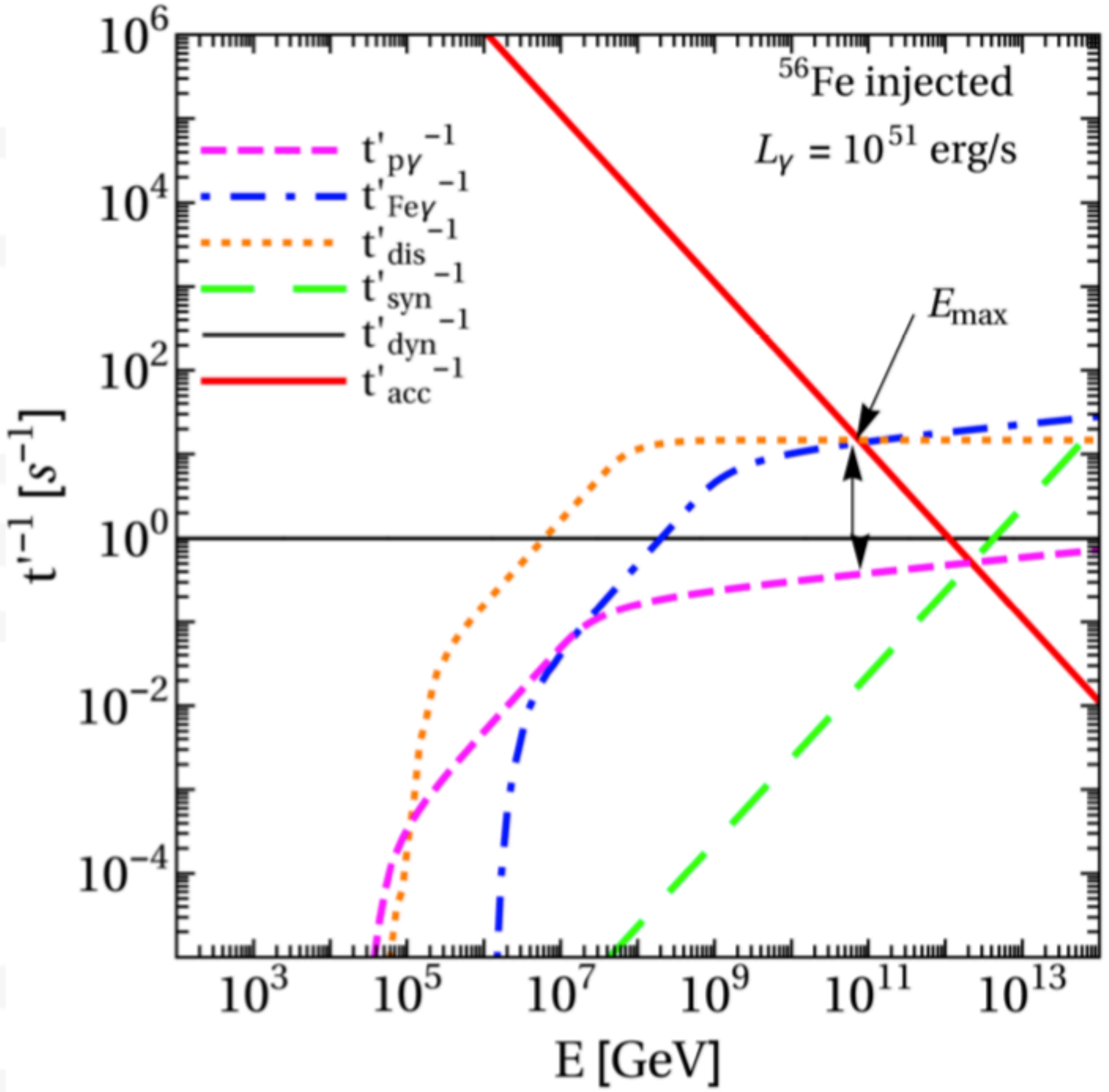
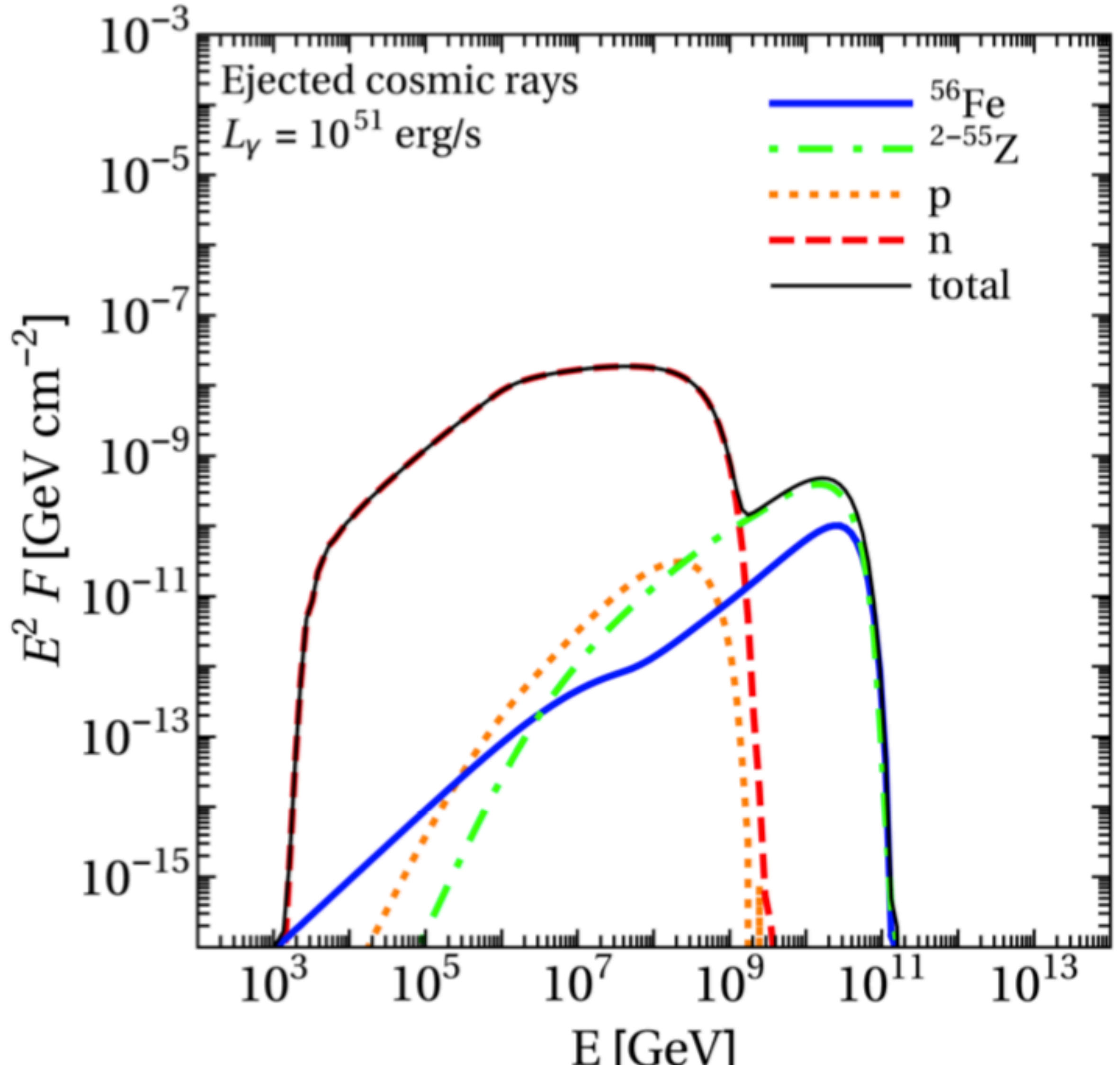
Interactions in GRB shells



- CR interactions in GRB photon field:
  - Determination of max energy of cosmic rays that can escape the source: balance of acceleration rate and losses
  - Density of primary CRs in the source is depleted, while secondary nuclei (and nucleons) increase

Biehl, **DB**, Fedynitch, Winter, A&A 2018

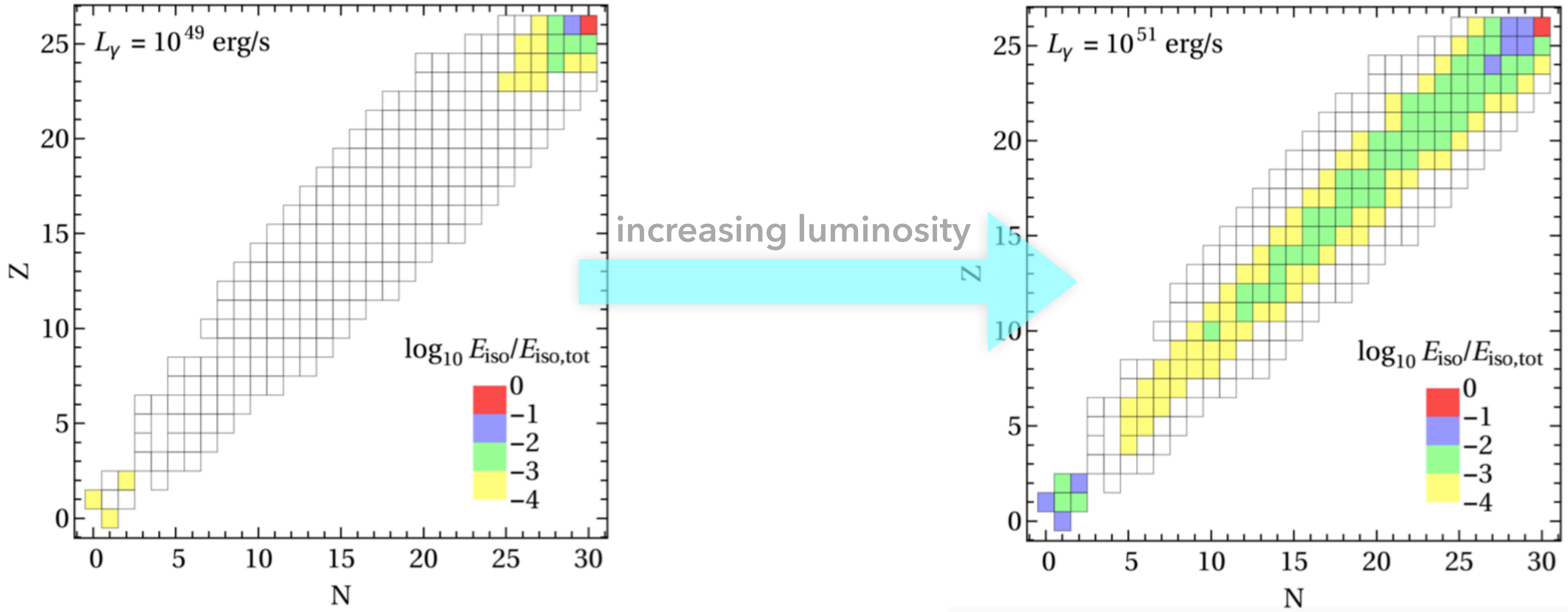


- CR escape:
  - Neutral particles escape freely
  - Charged particles escape easily only at high energy -> **hardening of the spectrum**

origin of the ankle?

Development of nuclear cascade

Biehl, **DB**, Fedynitch, Winter, A&A 2018

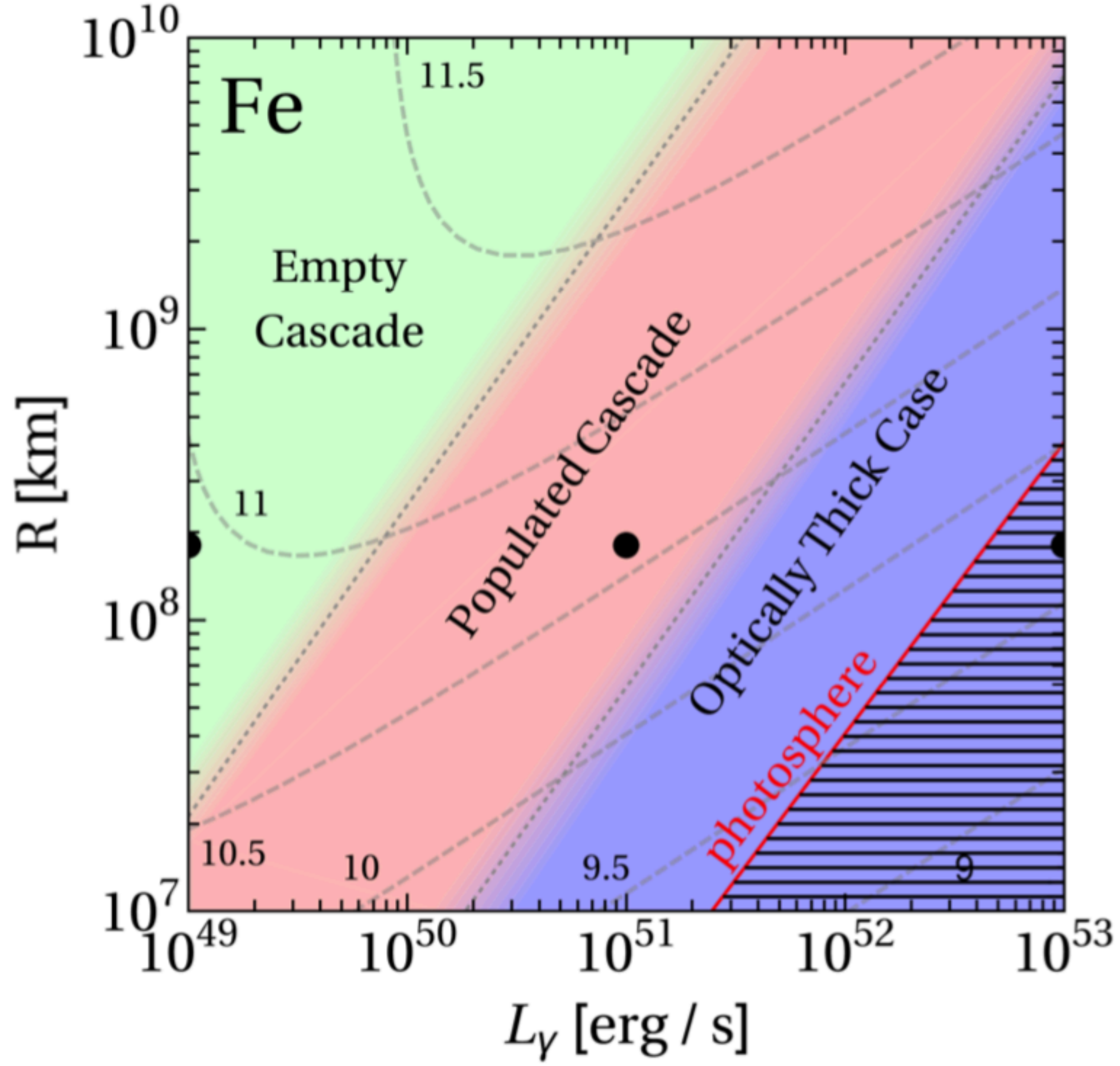


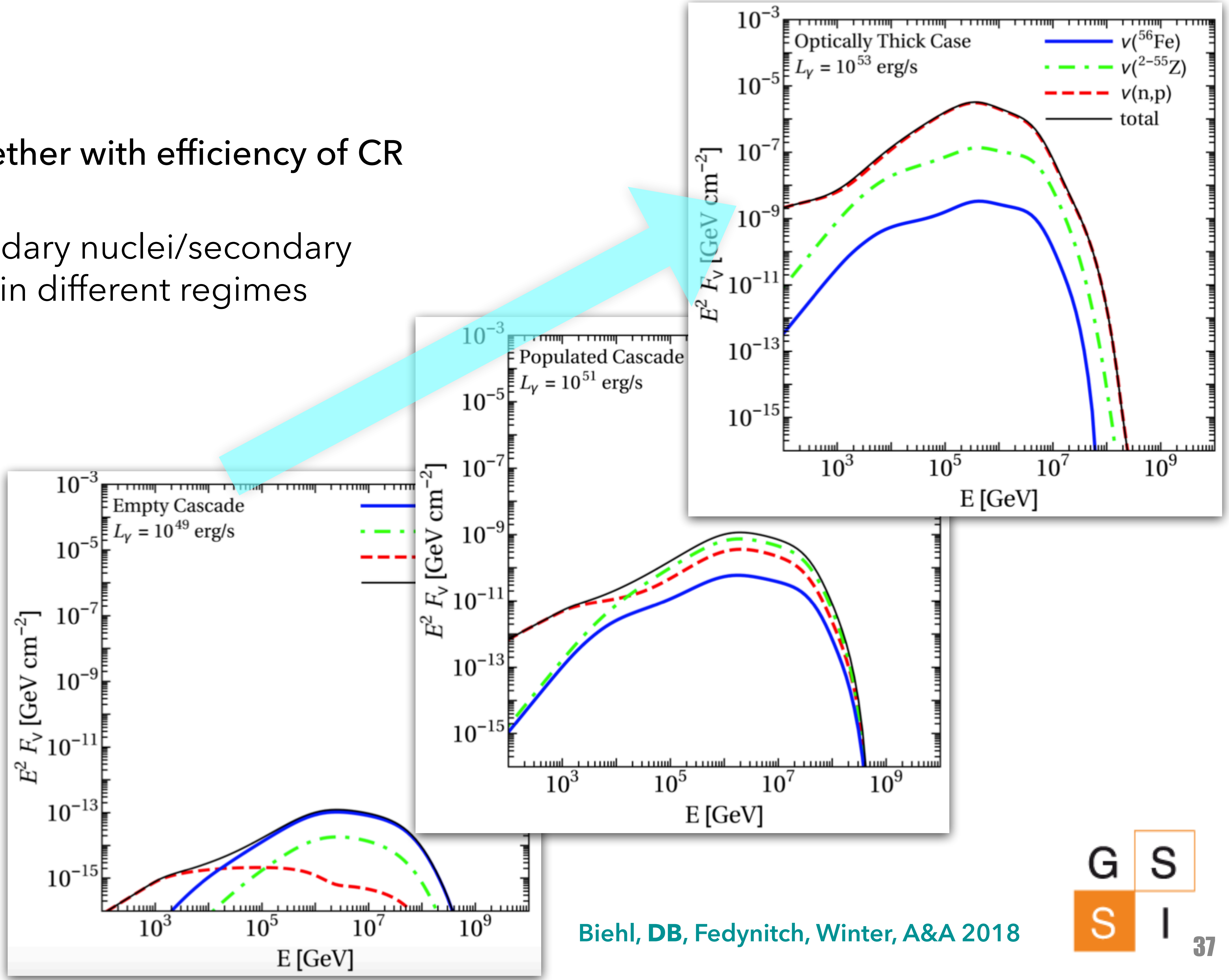
- Development of nuclear cascade strongly dependent on the radiation density in the shell
- Increase of luminosity implies increase of production of secondary nuclei and small fragments along the chain (helium, protons, neutrons)

Development of nuclear cascade

and neutrino production

- Increase of neutrino production together with efficiency of CR interactions in the source
- Neutrinos from primary nuclei/secondary nuclei/secondary nucleons dominate the neutrino flux in different regimes





Biehl, **DB**, Fedynitch, Winter, A&A 2018

GSI