Nuclear Physics meets the sources of UHECRs

D. Boncioli, A. Fedynitch and W. Winter, arxiv:1607.07989

Denise Boncioli

DESY Zeuthen, Germany

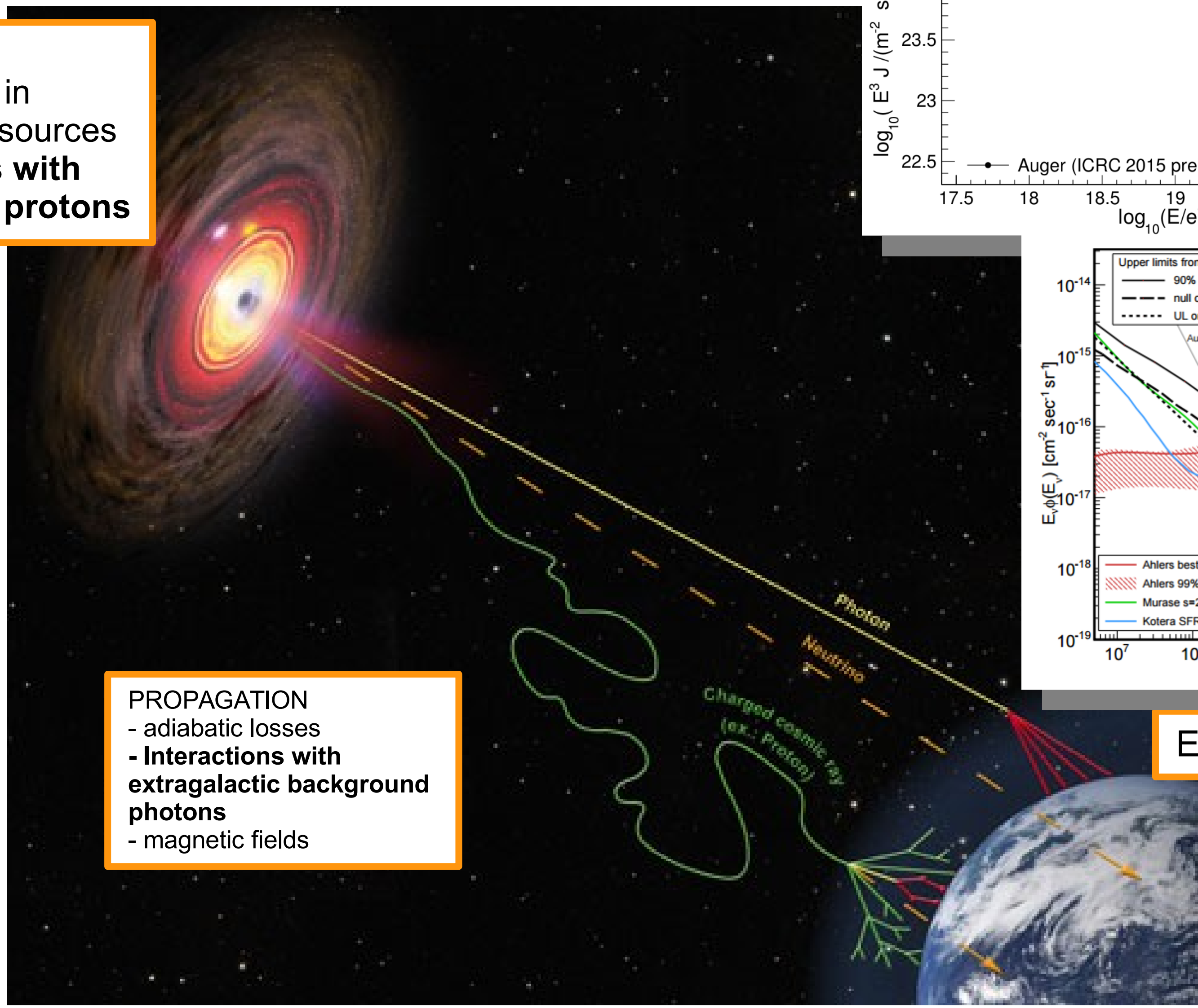
TeVPA 2016
CERN
September 12th – 16th, 2016

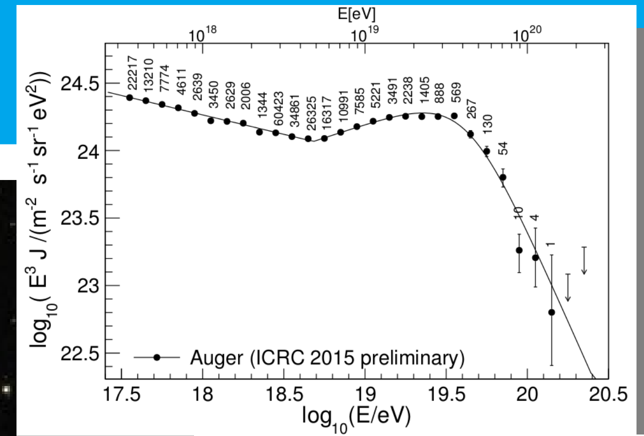
HELMHOLTZ ASSOCIATION

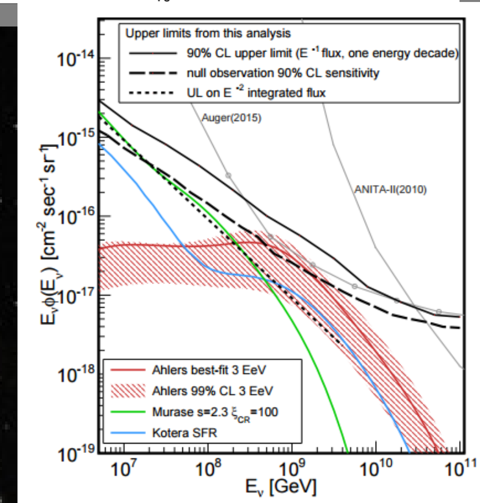
DESY

From sources to detection...

SOURCE
- Acceleration in astrophysical sources
- **Interactions with photons and protons**







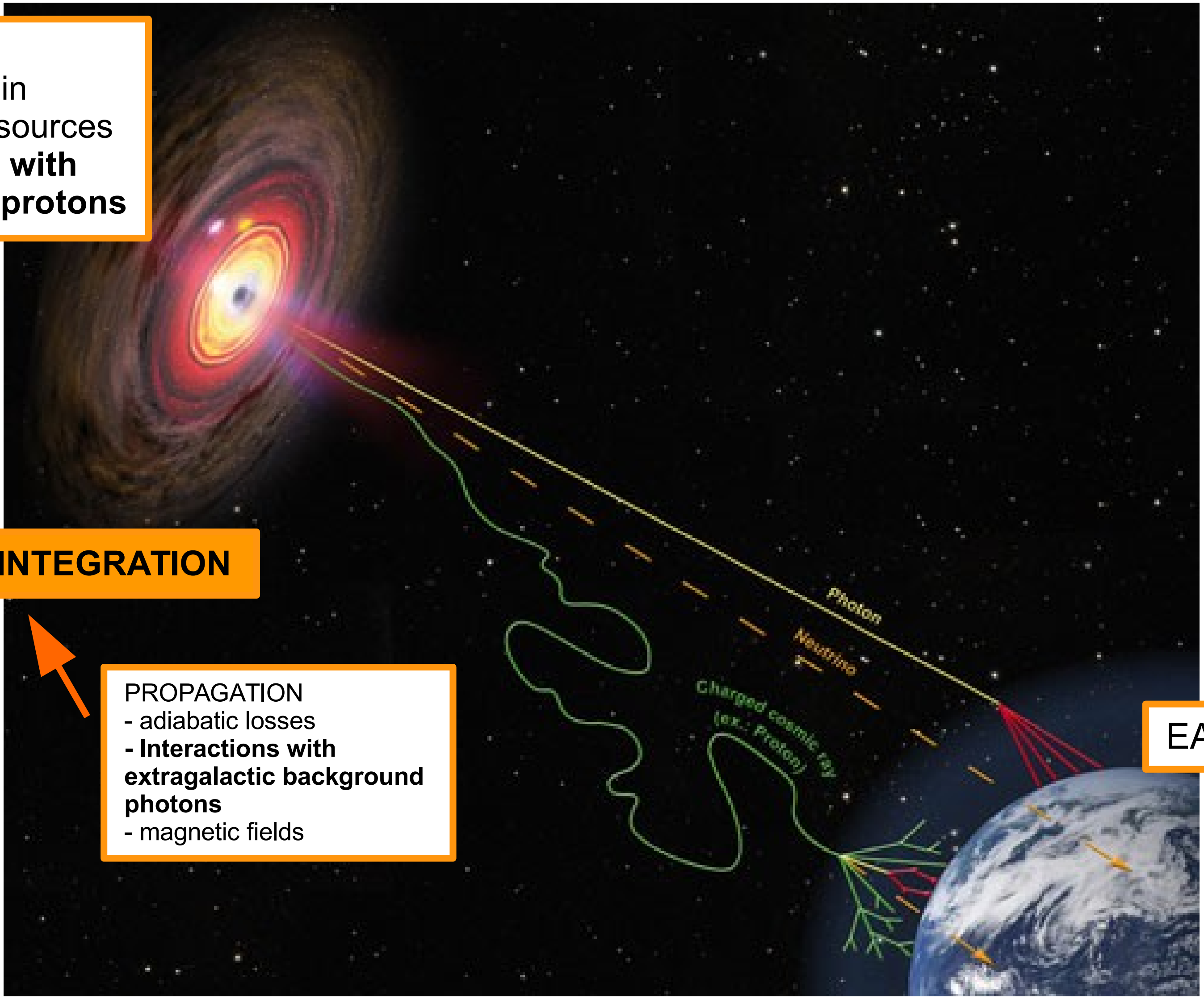
PROPAGATION
- adiabatic losses
- **Interactions with extragalactic background photons**
- magnetic fields

EARTH

From sources to detection...

SOURCE
- Acceleration in astrophysical sources
- **Interactions with photons and protons**

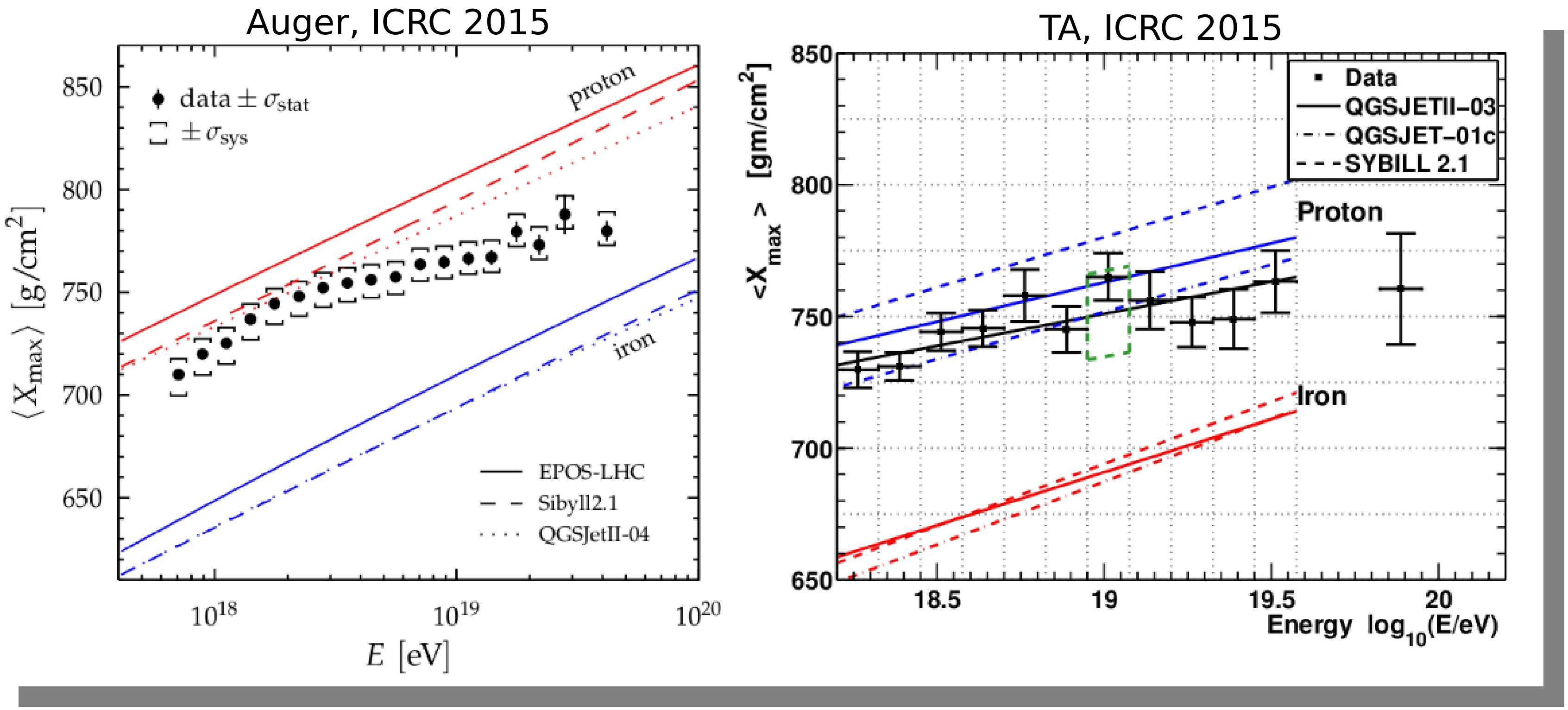
PHOTO-DISINTEGRATION



PROPAGATION
- adiabatic losses
- **Interactions with extragalactic background photons**
- magnetic fields

EARTH

UHECR composition



- Indication of proton composition → TA experiment
  - Challenged by <u>multimessenger approach</u> (neutrino and photon fluxes) → see talk by J. Heinze
- <u>Indication of a trend towards heavy composition at highest energies from Auger measurements</u>
  - → What are the conditions for escape of nuclei from the various source classes?
  - → How does the presence of nuclei affect the expected flux of neutrinos?

Work in progress

Interaction framework

Boltzmann Equations for each particle species (and energy bin)

$$\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E}\left(-b(E)N_i(E)\right) - \frac{N_i(E)}{t_{\rm esc}} + \tilde{Q}_{ji}(E)$$

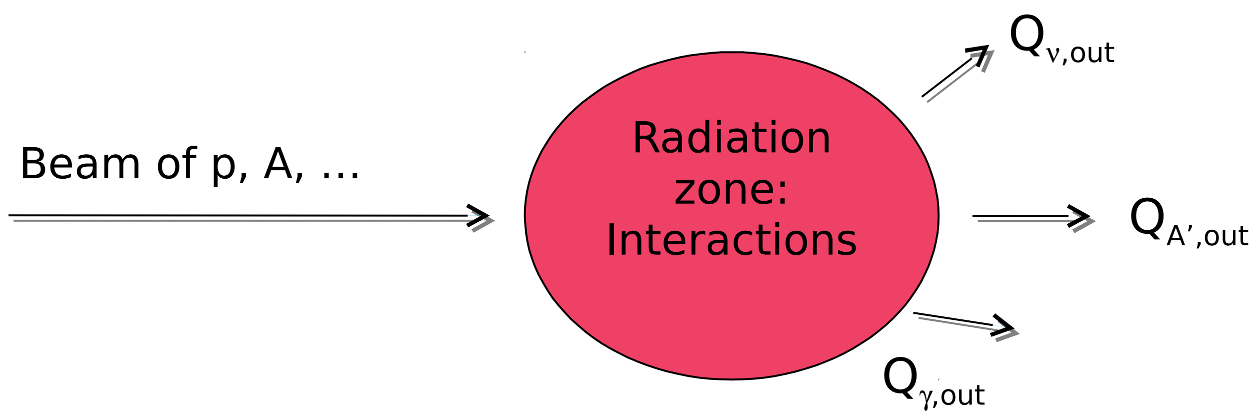
Evolution of density for particle species i

Energy loss:
- synchrotron
- adiabatic
- …

Escape:
- interactions
- decays
- …

$$\tilde{Q}_{ji}(E) = Q_i(E) + Q_{ji}(E)$$

Injection from:
- acceleration zone
- interactions or decays



How does nuclear physics enter?

- How often does a nucleus/particle in a source interact?

$$\tilde{Q}_{ji}(E) = Q_i(E) + Q_{ji}(E)$$

  - Depends on:
    - target photon field
    - nucleus-photon cross section

$$\Gamma_j(E_j) = \int d\varepsilon \int_{-1}^{+1} \frac{d\cos\theta_{j\gamma}}{2} (1 - \cos\theta_{j\gamma}) \cdot n_\gamma(\varepsilon, \cos\theta_{j\gamma}) \, \sigma_j^{\mathrm{abs}}(\epsilon_r)$$

Photon energy in nucleus rest frame

$$\epsilon_r = \frac{E_j \, \varepsilon}{m_j} (1 - \cos\theta_{j\gamma})$$

- The uncertainties in cross sections and extragalactic photon fields are partially studied for the case of <u>propagation of UHECRs</u>
→ see for example Batista, **DB**, di Matteo, van Vliet and Walz, JCAP 1510 (2015) 10, 063
- In the current work, we want to:
- model cosmic ray interactions in photon fields
- <u>check situation of available cross section measurements and models</u>
- apply to candidate sources for cosmic ray, in order to study the necessary conditions for UHECR escape and for high radiation densities

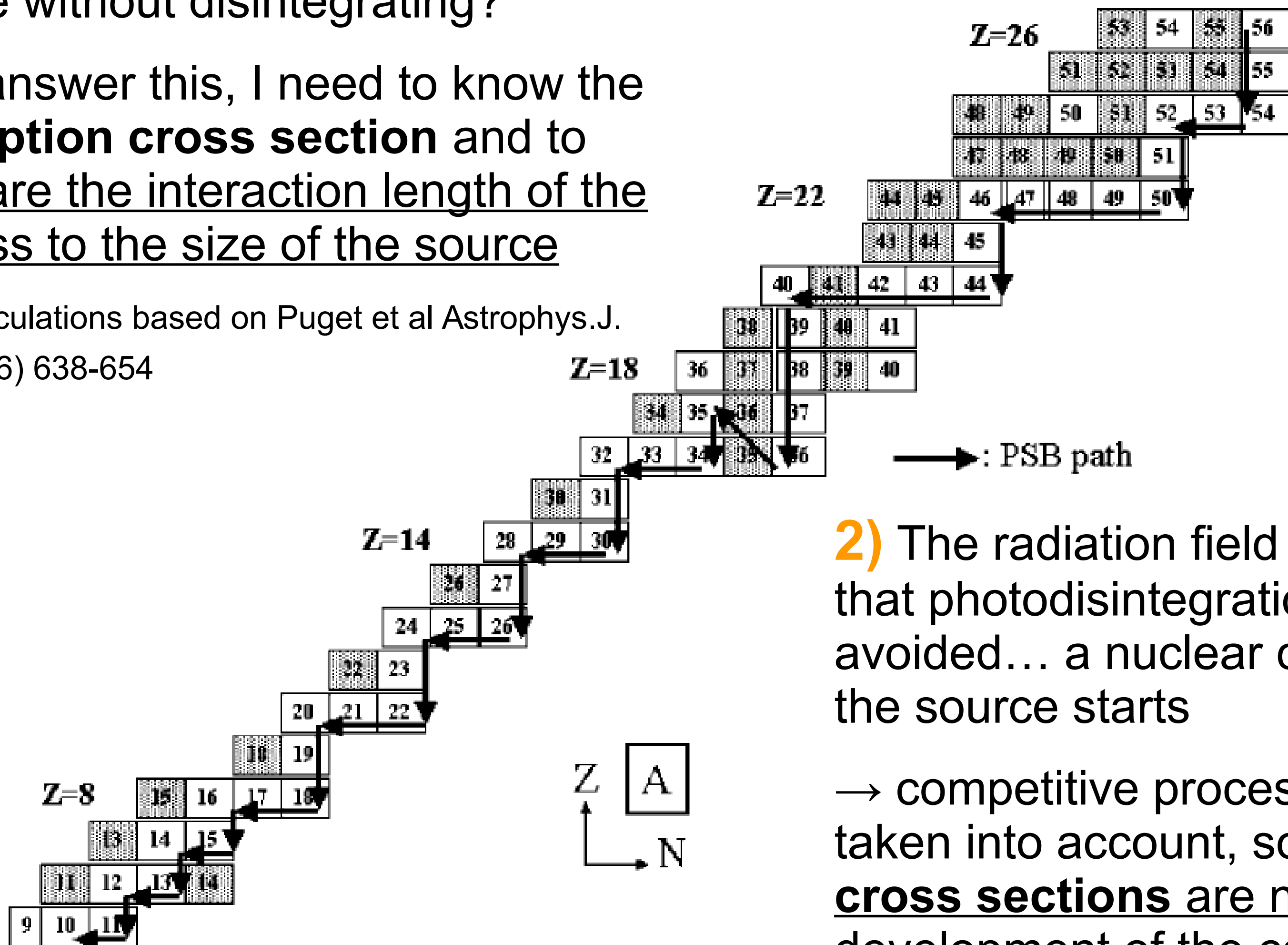
What do we need to model interactions in photon fields?

1) Is a nucleus able to escape the source without disintegrating?

→ to answer this, I need to know the **absorption cross section** and to <u>compare the interaction length of the process to the size of the source</u>

basic calculations based on Puget et al Astrophys.J. 205 (1976) 638-654

Khan et al, Astropart.Phys. 23 (2005) 191-201



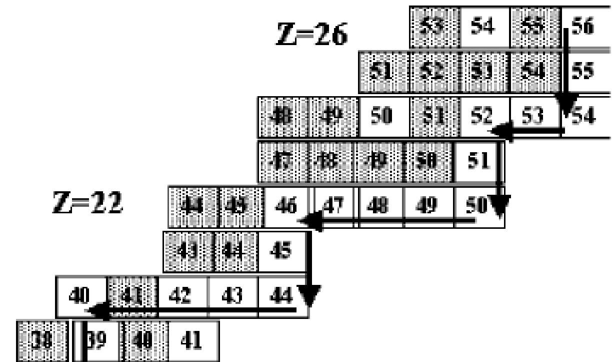
2) The radiation field is so dense that photodisintegration cannot be avoided… a nuclear cascade inside the source starts

→ competitive processes have to be taken into account, so <u>**residual cross sections** are needed for the development of the cascade</u>

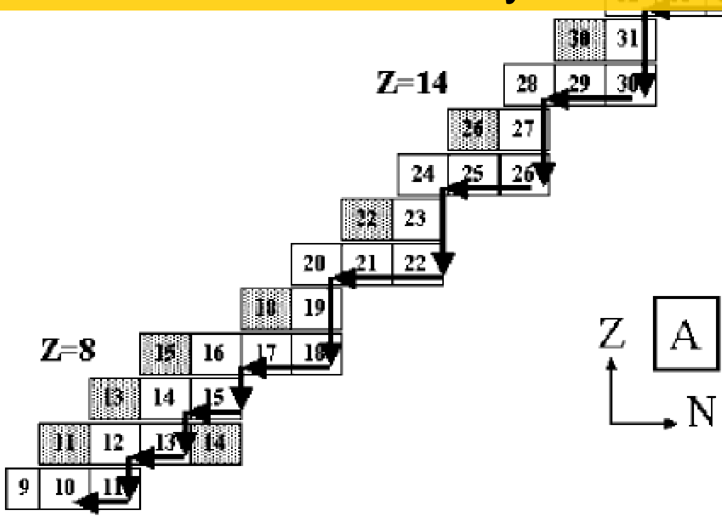
What do we need to model interactions in photon fields?

1) Is a nucleus able to escape the source without disintegrating?

→ to answer this, I need to know the **absorption cross section** and to <u>compare the interaction length of the process to the size of the source</u>



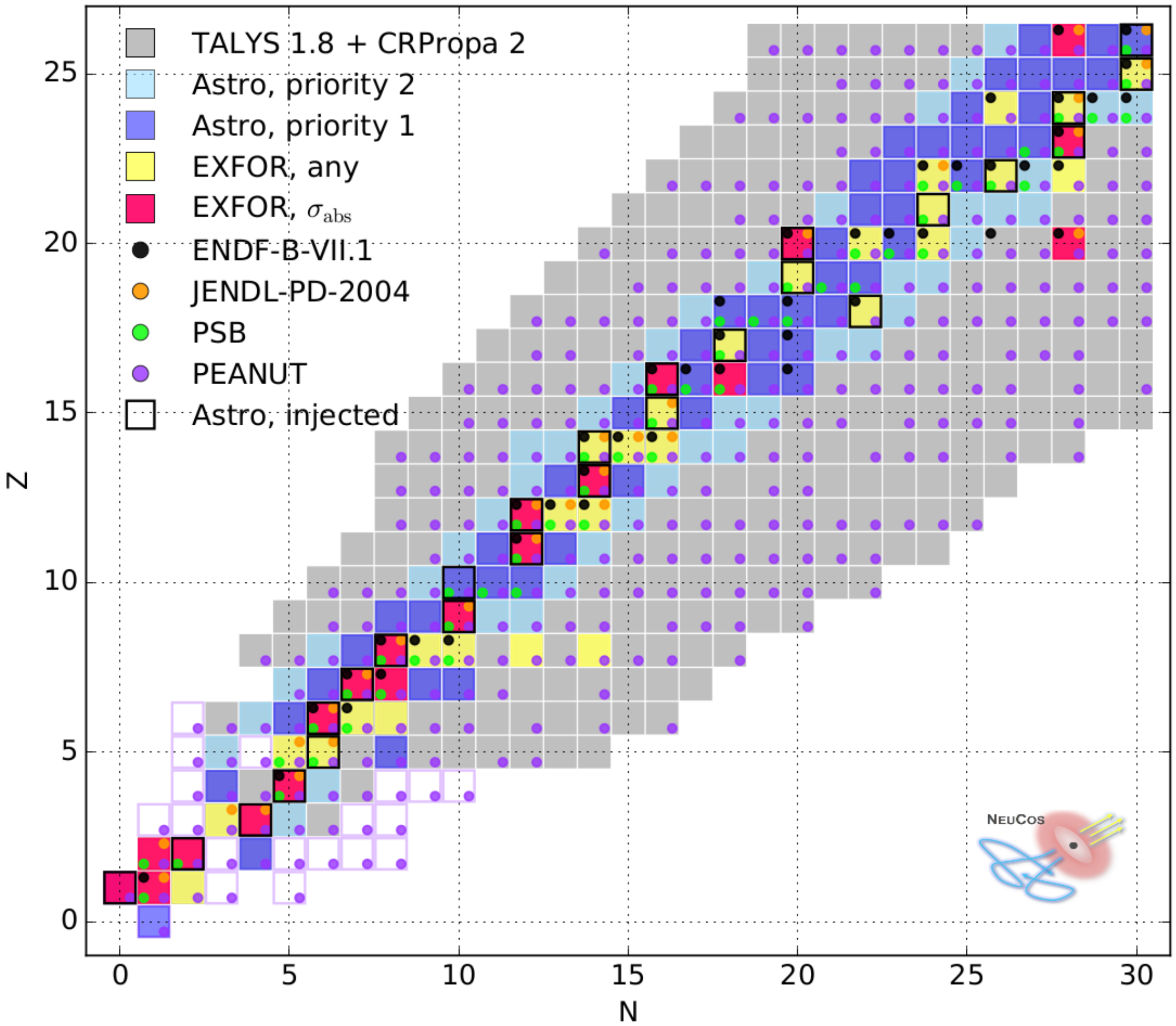
Unstable elements are important! Their lifetime is dilated due to relativistic boost → they can re-interact and create other secondaries



2) The radiation field is so dense that photodisintegration cannot be avoided… a nuclear cascade inside the source starts

→ competitive processes have to be taken into account, so <u>**residual cross sections** are needed for the development of the cascade</u>

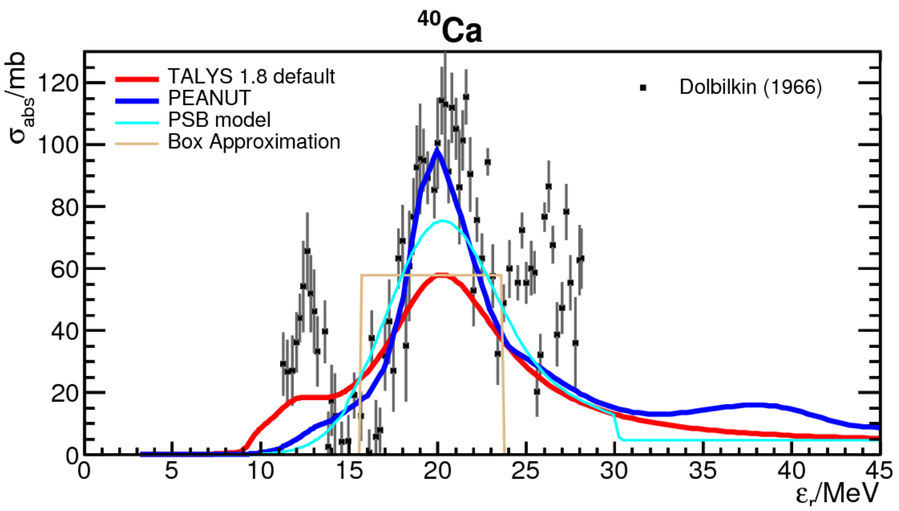
Situation on experimental data and theoretical models

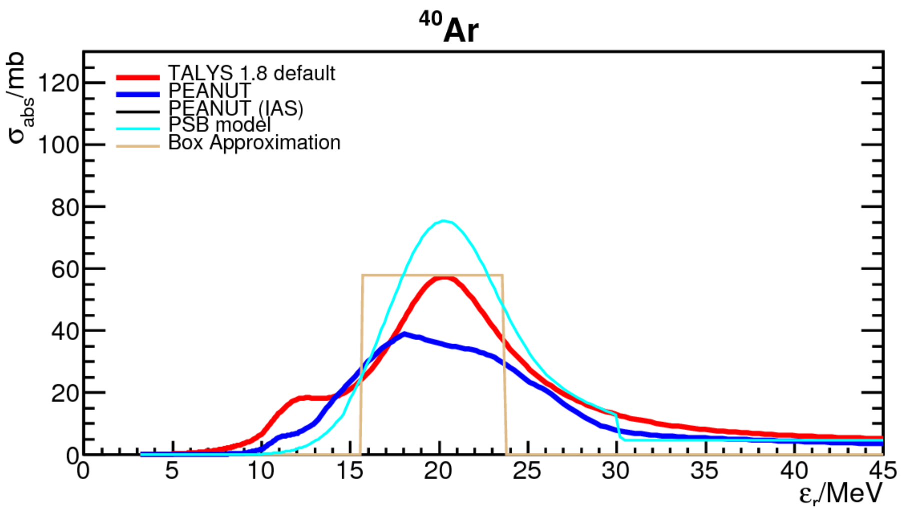


- EXFOR contains 14 absorption cross sections < Fe
- 47 measurements where at least one inclusive cross section available
- Located mostly on main diagonal (stable elements)
- All other isotopes need model prediction → not always well reproducing data

DB, A. Fedynitch, W. Winter, arxiv:1607.07989

Impact of nuclear cross sections on astrophysical quantities

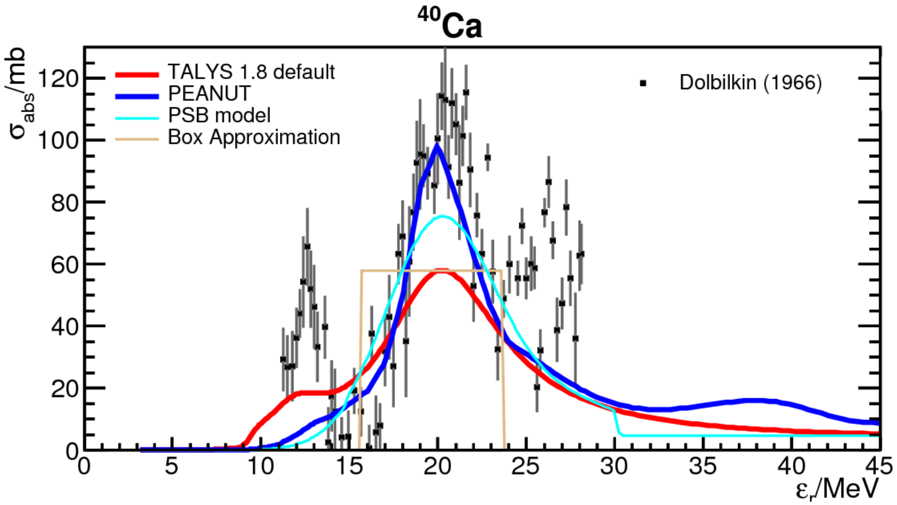




- Ca-40: double magic nucleus
- TALYS predictions not dependent on the element
- PEANUT predictions are different in the same isobar; if data available, at least the central GDR peak is reproduced
- Box approximation, used for example in Murase and Beacom, Phys Rev. D81 2010, underestimates data and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

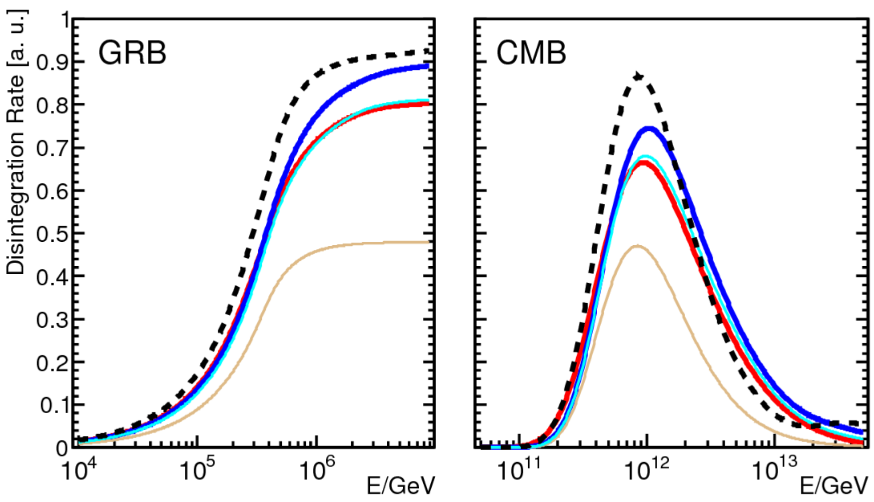
DB, A. Fedynitch, W. Winter, arxiv:1607.07989

Impact of nuclear cross sections on astrophysical quantities



CMB, propagation

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



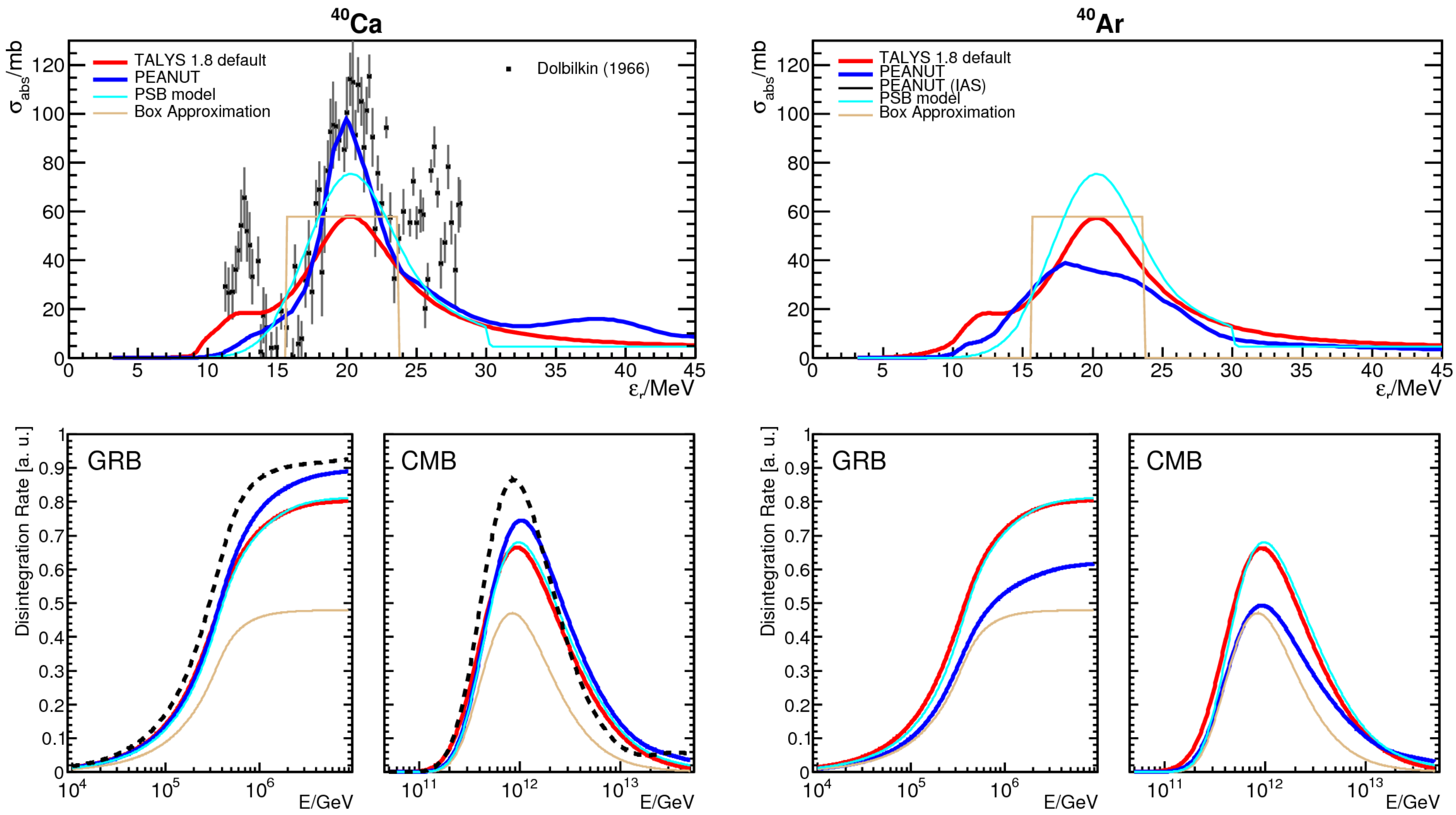
GRB, source

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

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

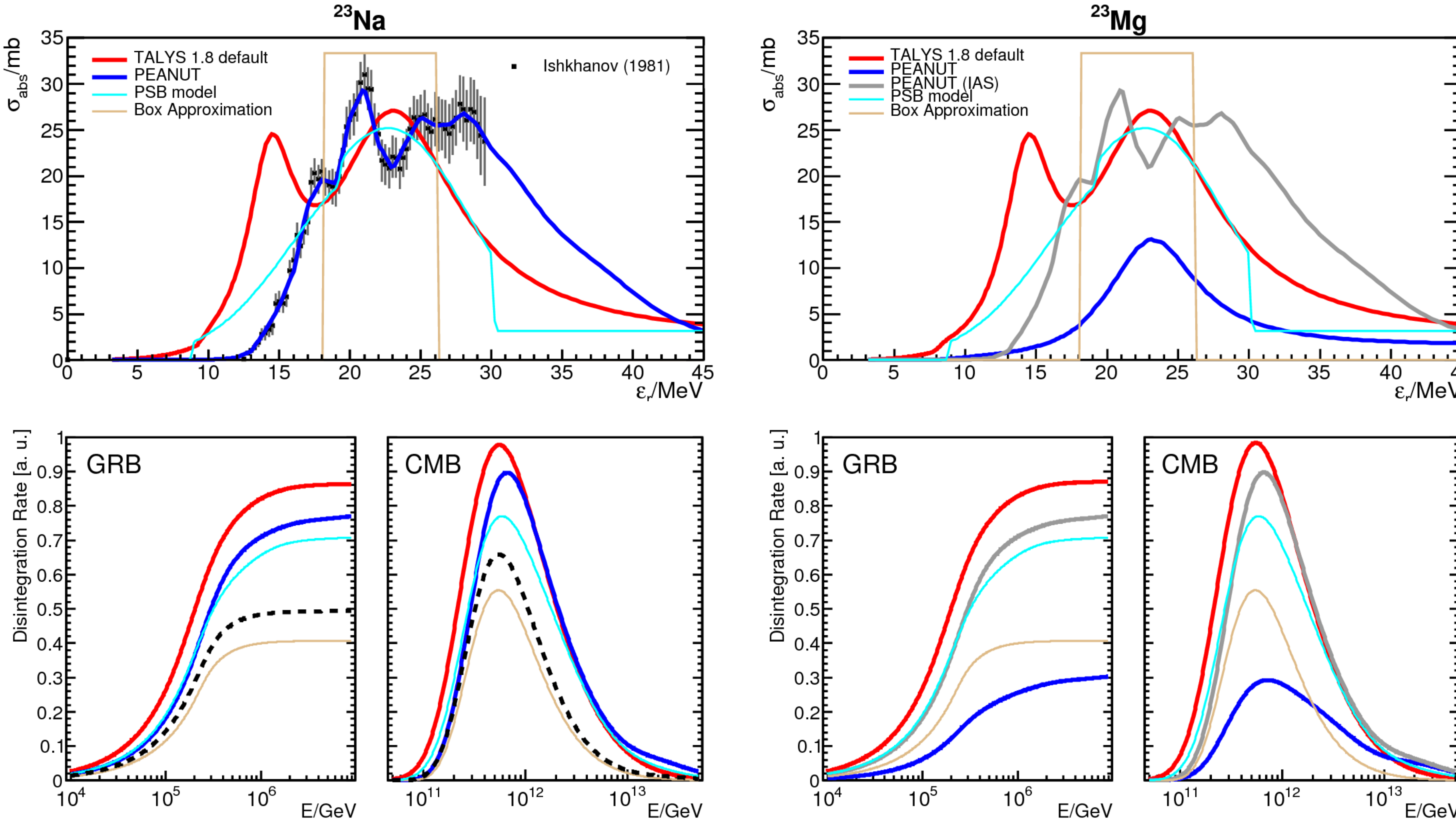
DB, A. Fedynitch, W. Winter, arxiv:1607.07989

Impact of nuclear cross sections on astrophysical quantities



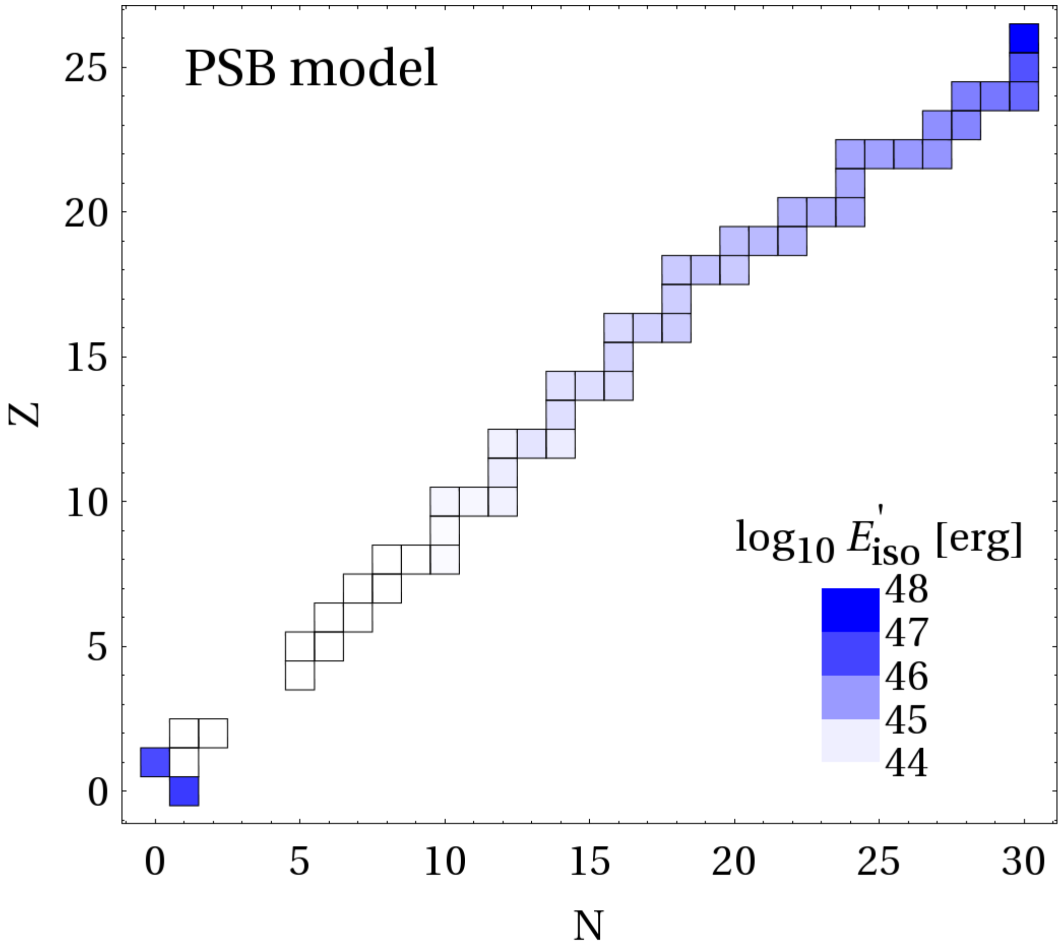
DB, A. Fedynitch, W. Winter, arxiv:1607.07989

Impact of nuclear cross sections on astrophysical quantities



DB, A. Fedynitch, W. Winter, arxiv:1607.07989

Effects on the nuclear cascade

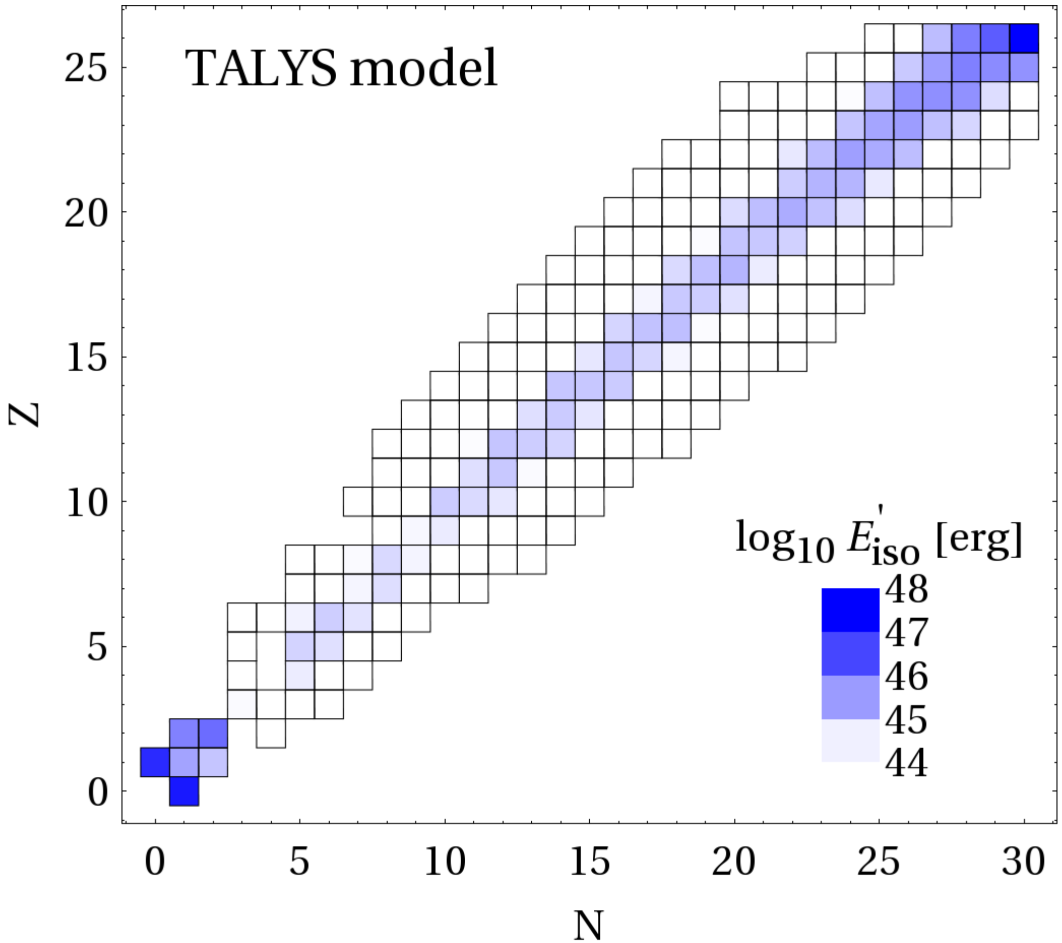


- One nuclide for each A
- Only small fragments can be ejected in photodisintegration
- The cascade is not completed, smaller masses are not populated

- Population of isotopes in terms of total energy per isotope and collision in the shock rest frame

DB, A. Fedynitch, W. Winter, arxiv:1607.07989

Effects on the nuclear cascade

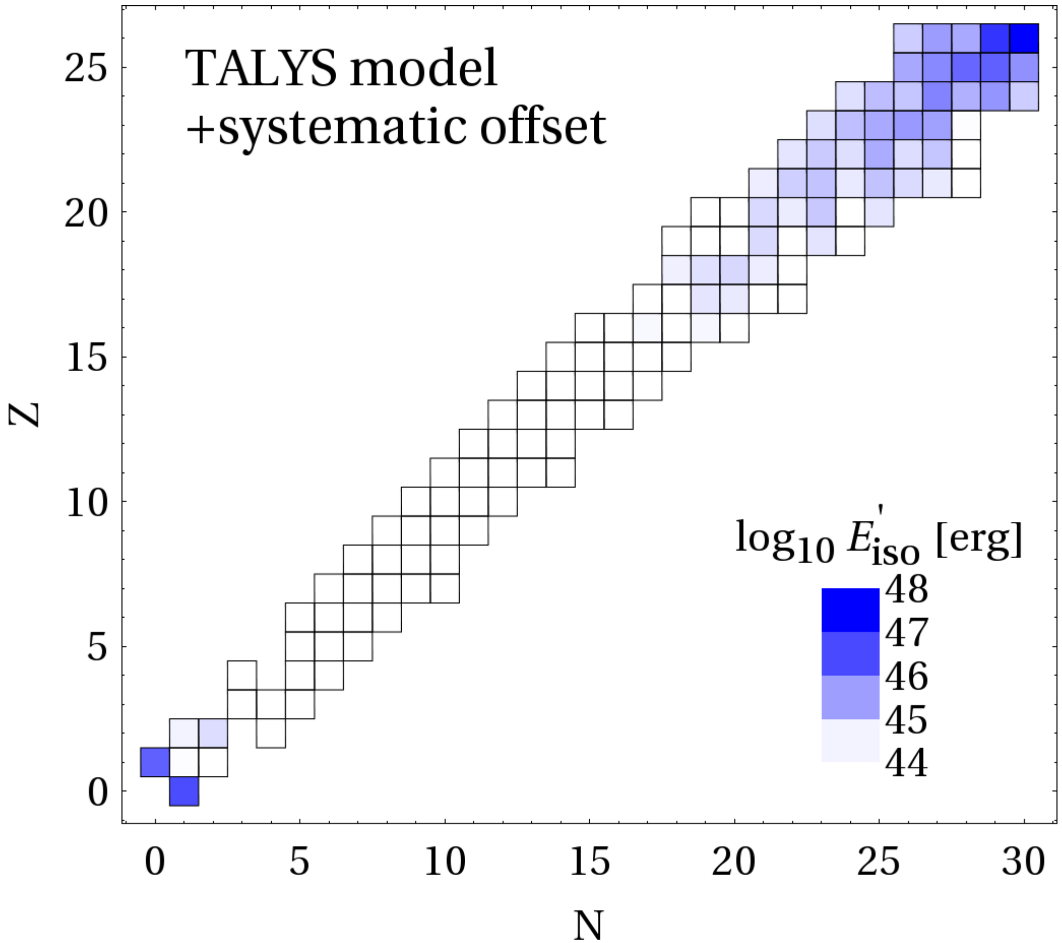


- Much more channels wrt PSB
- Small fragments ejected: p, n, d, t, He-3, He-4
- Chart almost fully populated (however, this also depends on the target photon density)
- PEANUT gives similar results

- Population of isotopes in terms of total energy per isotope and collision in the shock rest frame

DB, A. Fedynitch, W. Winter, arxiv:1607.07989

Effects on the nuclear cascade

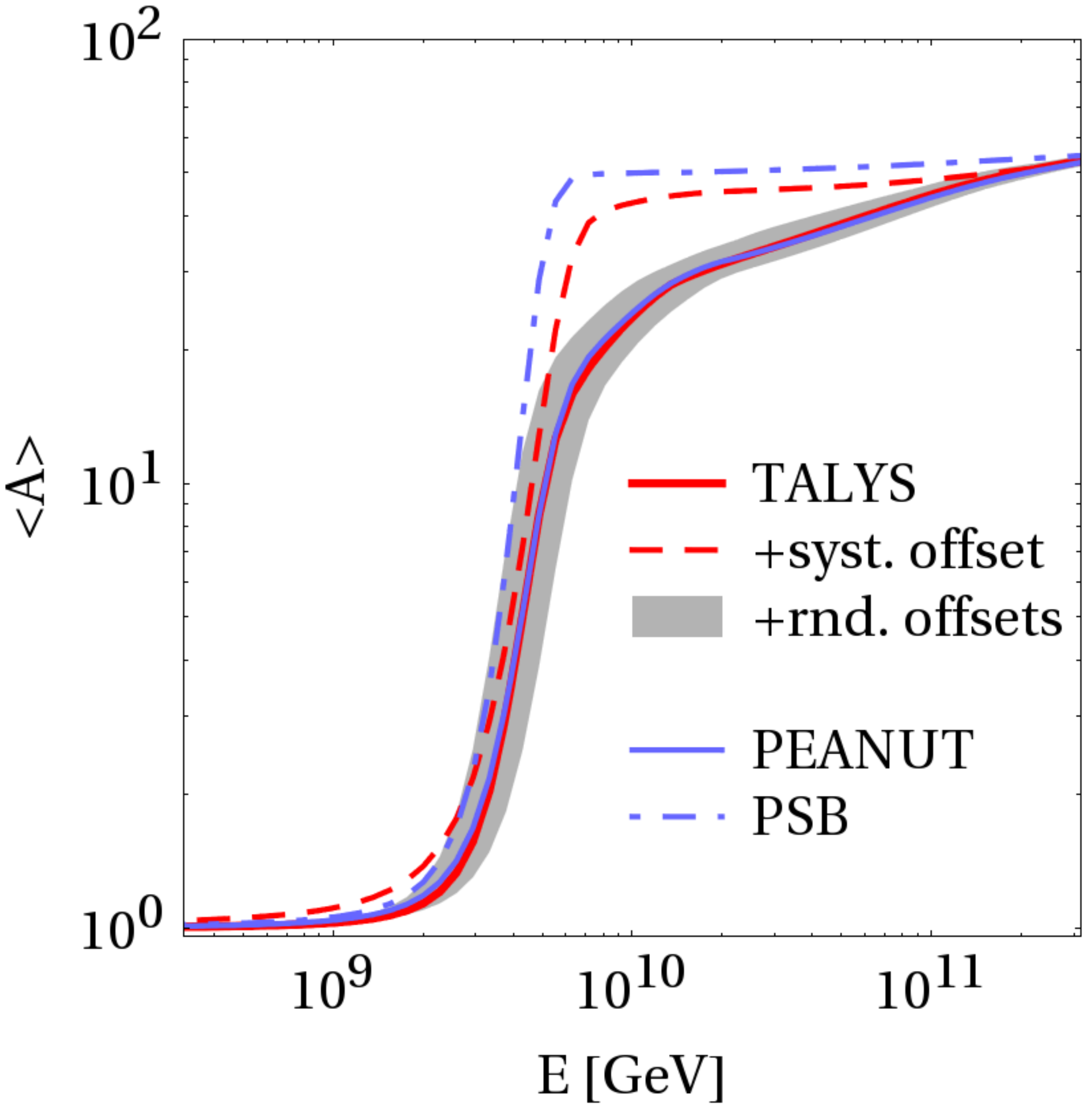


- Cross sections reduced by:
  - 1 if the absorption cross section is measured
  - 0.5 if any other cross section is measured
  - 0 if no data available
- Relying on data, the cascade cannot be populated

- Population of isotopes in terms of total energy per isotope and collision in the shock rest frame

DB, A. Fedynitch, W. Winter, arxiv:1607.07989

UHECR composition at the source

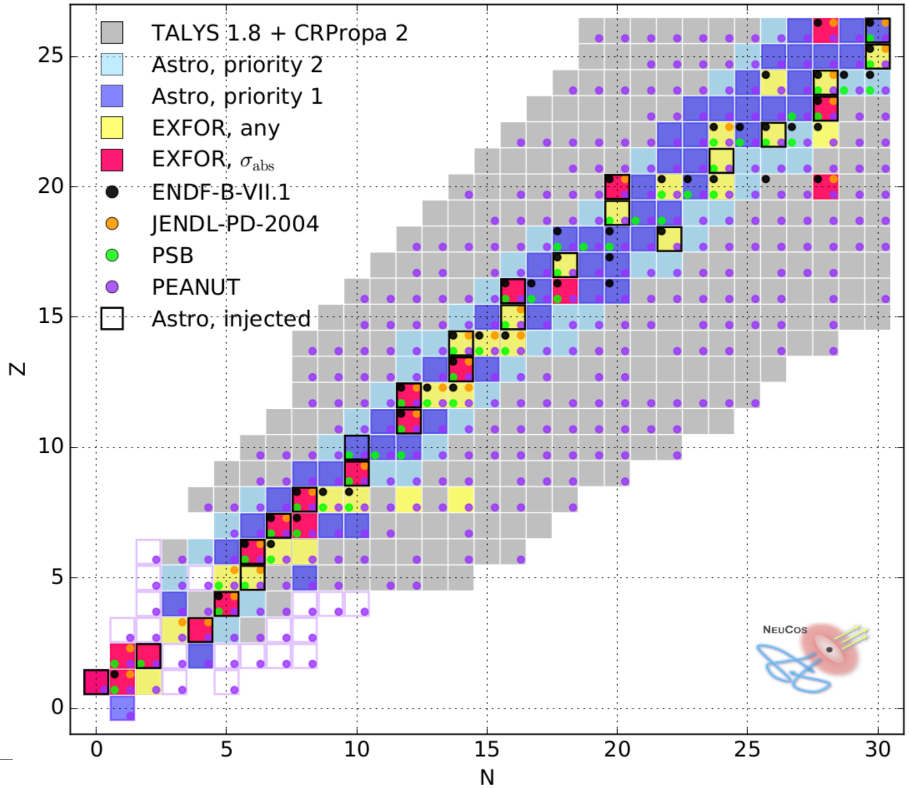


- No propagation effects considered
- Simplified model PSB leads to a sharper increase of composition wrt more sophisticated models
- If only measured cross sections are included in the models, similar results to PSB

DB, A. Fedynitch, W. Winter, arxiv:1607.07989

- The study of interactions of nuclei in sources and extragalactic photon fields is critical for our understanding of cosmic-ray astrophysics
- In particular, we are interested in understanding the conditions for escape of nuclei from the sources and the connections with neutrinos → work in progress

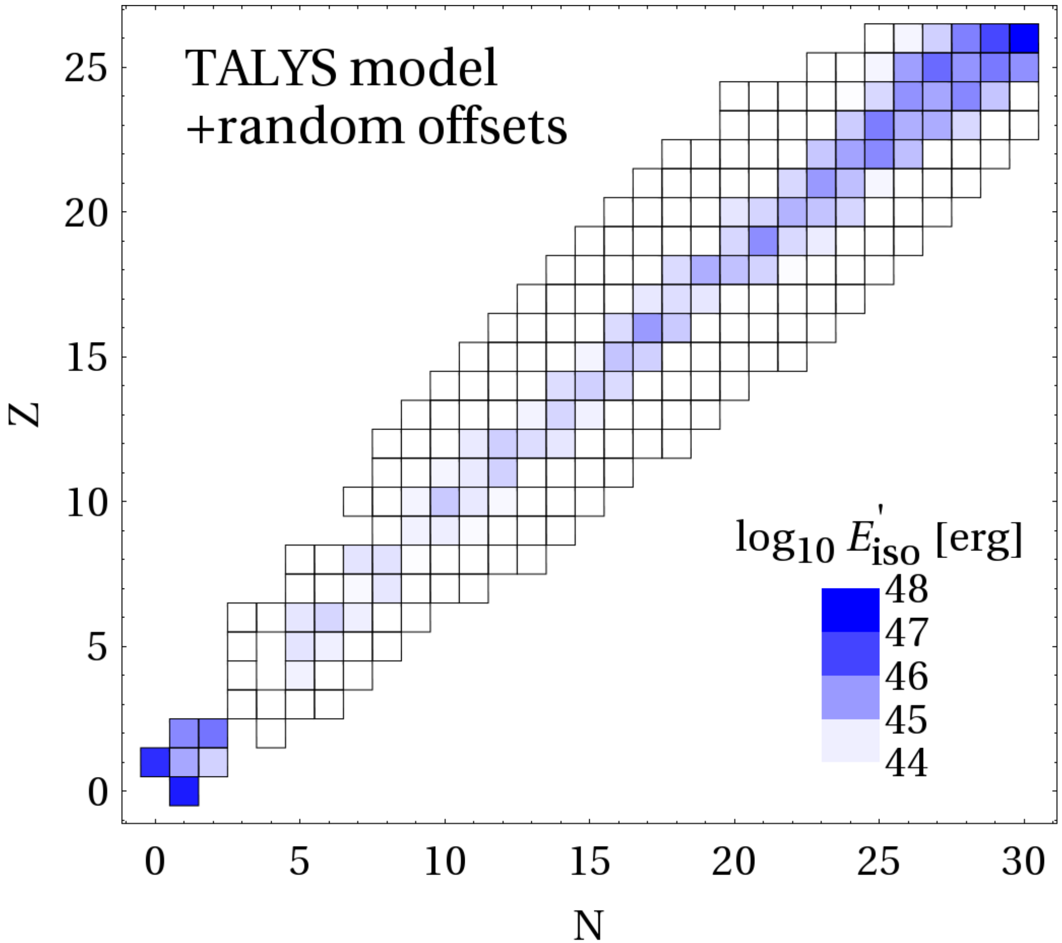
- Measurements of **total absorption cross sections**
  → needed for interaction rate calculations
  → measurements are sparse
- Especially, clarify **isobar situation** (unstable elements)
- Development of the cascade depends on branching ratios/multiplicities for different channels → data on **residual cross sections** will ensure that we don't have systematic offsets in models



➔ We propose systematic measurements to improve the predictability of unmeasured cross sections → measuring the total absorption cross section for two or more different isobars

Backup slides

Effects on the nuclear cascade



- Cross sections reduced by:

  - 1 if the absorption cross section is measured

  - factor between 0.5 and 1.5 if any other cross section is measured

  - factor between 0 and 2 if no data available

- Population of isotopes in terms of total energy per isotope and collision in the shock rest frame

DB, A. Fedynitch, W. Winter, arxiv:1607.07989

Pre-selection of isotopes

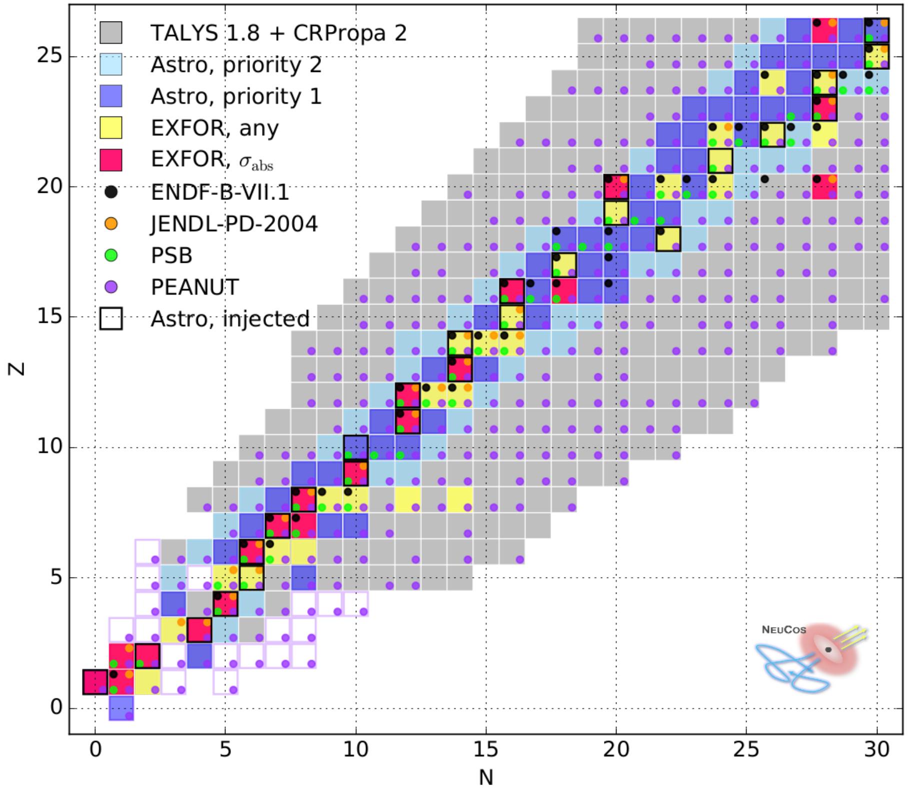
For an efficient computation, we need to pre-select the isotopes which are dominantly populated. Our isotope selection scheme is a fully automated recursive algorithm starting (in this case) with ^{56}Fe, following all disintegration and beta decay paths recursively. We also allow for

again. Since one isotope has typically very many (disintegration) branchings into daughters, some of these being very small, we impose a cutoff on the secondary multiplicity (number of secondaries produced on average) at a value of 0.01. As a further complication, the multi-

TALYS disintegration model, the software uses 481 isotopes, about 41000 inclusive disintegration channels and about 3000 photo-meson channels as primary input, selects 233 isotopes, and attaches 4943 disintegration, 10 beta decay (relevant on the GRB timescale) and 1344 photo-meson channels to them. With this level of com-

DB, A. Fedynitch, W. Winter, arxiv:1607.07989

Pre-selection of isotopes



The choice of isotopes in Fig. 1 labeled "Astro, priority 1" and "Astro, priority 2" has been obtained with a similar method by repeating the above recursive procedure for a number of possible injection elements: we inject for each atomic number the most abundant stable isotope. The multiplicity threshold has been chosen to be 0.2 for priority 1 and 0.05 for priority 2. As these numbers are

DB, A. Fedynitch, W. Winter, arxiv:1607.07989

Interaction framework and terminology

- We are interested in the total photoabsorption cross section and in the inclusive cross sections

$$\sigma_j \times dn_{j\to i}/dE_i = d\sigma^{\mathrm{incl}}_{j\to i}/dE_i$$

Total cross section

Distribution of secondaries of type i per final state energy interval

$$\int (dn_{j\to i}/dE_i)\, dE_i = M_{j\to i}$$

Average number of secondaries produced per interaction

Comparison of models and measurements in the following

$$\sigma_j\, M_{j\to i} \equiv \sigma^{\mathrm{incl}}_{j\to i}$$

$$\sigma^{\mathrm{incl}}_{j\to i} = \sum_k N_i^{(k,i)} \sigma^{\mathrm{excl},(k,i)}_{j\to i}$$

Inclusive cross section

Number of secondaries of type i produced per interaction

$$\sigma^{\mathrm{excl},k}_{j\to i} = \mathrm{Br}_{j\to(k,i)}\, \sigma_j\,.$$

Exclusive cross section

All exclusive cross sections with the same number of neutron and proton units in the outgoing channel sum up to the same residual nucleus production cross section for the final nucleus → residual cross section, as measured and used in the following

Interaction framework and terminology

- Interactions of cosmic rays in the source environment or in the propagation can be rigorously followed with a system of differential equations describing the evolution of the differential particle density wrt time, taking into account all interactions that can modify their number and energy.

$$\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E}\left(-b(E)N_i(E)\right) - \frac{N_i(E)}{t_{\rm esc}} + \tilde{Q}_{ji}(E)$$

$$\tilde{Q}_{ji}(E) = Q_i(E) + Q_{ji}(E)$$

$$Q_{ji}(E_i) = \int dE_j\, N_j(E_j)\,\Gamma_j(E_j)\,\frac{dn_{j\to i}}{dE_i}(E_j, E_i)$$

- Production rate of particles of species *i* and energy *Ei* from the interactions or decay of the parent *j*

- After considering isotropy of the photon distribution, and calculating the quantities in the shock rest frame:

$$\boxed{\Gamma_j(E_j) = \int d\varepsilon\, n_\gamma(\varepsilon)\, f_j\,(y)}$$

$$f_j(y) \equiv \frac{1}{2y^2}\int_0^{2y} d\epsilon_r\, \epsilon_r\, \sigma_j(\epsilon_r)$$

$$y \equiv (E_j\varepsilon)/m_A$$

Escape rate of the primary particle

- All integrations need to be performed only once if the target photon density is constant over time → the interaction rate is only a function of energy

Data set used in the current work

Volume 17, number 1 PHYSICS LETTERS 15 June 1965

NUCLEAR γ-RAY ABSORPTION CROSS SECTION OF ^{40}Ca IN THE GIANT RESONANCE REGION

B. S. DOLBILKIN, V. I. KORIN, L. E. LAZAREVA and F. A. NIKOLAEV
P. N. Lebedev Physical Institute, Moscow, USSR

The nuclear gamma-ray absorption cross section of ^{40}Ca has been measured with the 260 MeV electron synchrotron of the Levedev Physical Institute, using the total absorption method with a 9-channel pair magnetic spectrometer as a detector. The resolution of the spectrometer for γ-quanta of energy E_{γ} = 20 MeV was approximately 220 keV. A block of natural calcium (96.97% ^{40}Ca), 70.84 g/cm^2 thick, was used as absorber

---

Yad.Fiz. 33, 581 (1981)

B.S.Ishkhanov, I.M.Kapitonov, V.I.Shvedunov, A.I.Gutii, A.M.Parlag

Spectra of photoprotons from the nucleus Na-23 are measured in the bremsstrahlung beam. Cross sections of the reaction Na-23(gamma,p)Ne-22 with production of the final nucleus in various states are obtained from the photoproton spectra.

Investigation of the Reaction ^{23}Na(γ, p)^{22}Ne with Production of the Final Nucleus in Various States

---

Total Photonuclear Cross Sections for Low Atomic Number Elements

J. M. Wyckoff, B. Ziegler, H. W. Koch, and R. Uhlig
Phys. Rev. **137**, B576 – Published 8 February 1965

Total photonuclear cross sections have been measured in an attenuation experiment using a scintillation pair spectrometer and an x-ray spectrum with a fixed maximum energy of 90 MeV. The cross sections as a function of x-ray photon energy for beryllium, carbon, oxygen, sodium, magnesium, aluminum, silicon, sulfur, calcium, nickel, cobalt, copper, and silver show detailed structure in many cases at x-ray energies of 15-30 MeV and display a consistent trend in shapes and magnitudes. The integrated cross sections up to 35 MeV relative to the classical dipole sum rule show a monotonic increase with atomic weight. Other analyses of the total photonuclear cross sections in terms of mean energies and of the ratios of the total cross sections to photoneutron cross sections are also presented.

Situation on experimental data and theoretical models

- We use the EXFOR database
  `https://www-nds.iaea.org/exfor/exfor.htm`
- **No measurements of <u>absorption cross section</u> for the same isobar**

Our current model:

- TALYS 1.8 is used with the strenght function `strenght 1`, based on a Kopecky-Uhl generalized Lorentzian model, as in Khan et al. paper
- TALYS is not recommended for A<12. For these nuclei we use a collection from CRPropa2 (Khampert et al, Astropart.Phys. 42 (2013) 41-51), based partially on data

What is TALYS? `www.talys.eu`

TALYS is software for the simulation of nuclear reactions. Many state-of-the-art nuclear models are included to cover all main reaction mechanisms encountered in light particle-induced nuclear reactions. **TALYS** provides a complete description of all reaction channels and observables, and is user-friendly.

Situation on experimental data and theoretical models

- Model predictions and parametrizations
  $\rightarrow$ use of interpolated or fitted absorption cross sections where available, as done in PEANUT, ENDF-B-VII.1, JENDL/PD-2004

  $\rightarrow$ use of parametrizations if cross sections are totally unknown

Other models:

- PSB model is obtained from Puget, Stecker and Bredekamp, Astrophys. J. 205, 638 (1976). Use of one nucleus for each mass; cross section for one and two nucleon emissions is approximated by a Gaussian in the low energy range and by a constant above 30 MeV. Threshold for reactions taken from Stecker and Salamon, Astrophys. J. 512 (1999). The list of nuclei has been slightly modified to be used in the current code for photodisintegration

- Box approximation is used in Murase and Beacom, Phys Rev. D81 2010

$$\sigma_{\rm GDR} \approx 1.45 \times 10^{-27} A \ {\rm cm}^2$$

Situation on experimental data and theoretical models

ENDF-B-VII.1 [18] is an evaluated nuclear data library based on calculations using the GNASH code system. Its photo-nuclear part contains absorption cross-sections a sometimes inclusive emission spectra of neutrons and protons, but no residual cross-sections. Comparisons with data reveal a very good agreement with the measurements.

JENDL/PD-2004 [19] is another evaluated library, based on Lorentz fits at GDR energies and quasi-deuteron emission above. Elements without σ_{abs} measurements are evaluated through branching ratios from pre-quilibrium and evaporation models, together with photo-neutron data. The description of σ_{abs} is good for all measured elements.

DB, A. Fedynitch, W. Winter, arxiv:1607.07989

GRB parameters used in the current work

- GRB observations exhibit strong time variability over a scale t_v (in the observer frame)
- The fireball has a time evolution: <u>first zone</u>, the shell gets accelerated, powered by the energy transfer from the thermal photons to the baryons in the shell. The Lorentz factor of the shell grows with the radius until a maximum value is reached. The <u>second zone</u> starts: the shell is accelerated to its maximal velocity, so it coasts with constant Lorentz factor.
- Development of the cascade of nuclei in the GRB field depends on the photon density

$$L_{\gamma,\mathrm{iso}} = 10^{52}\,\mathrm{erg/s},\ \Gamma = 300,\ t_v = 0.01\,\mathrm{s},\ z = 2$$

$$E_{\mathrm{Fe,max}} \simeq 10^{11}\,\mathrm{GeV}$$

Injection parameters

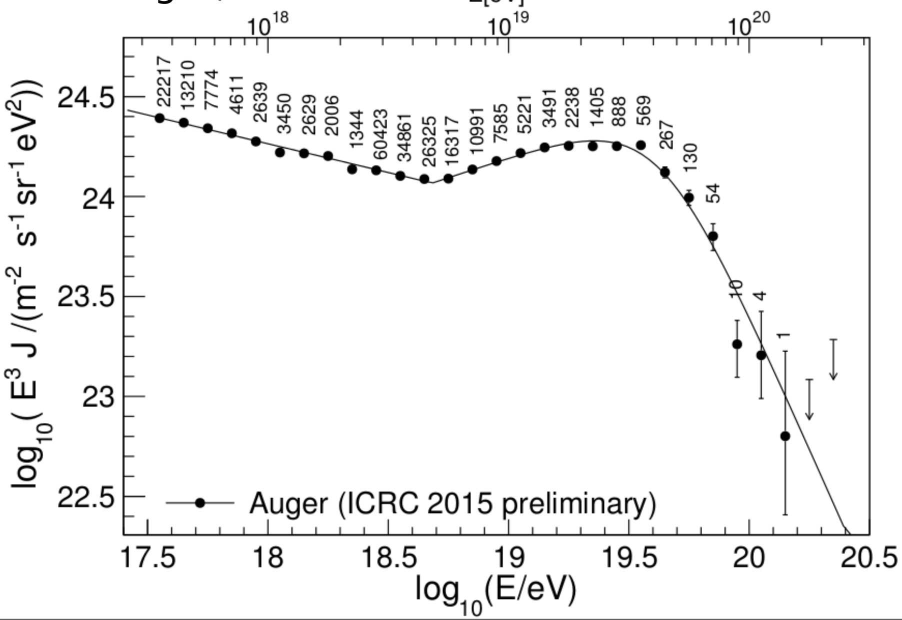
we only inject ^{56}Fe into the system with a power law $E^{-2}\exp\left(-(E/E_{\mathrm{Fe,max}})^2\right)$, where $E_{\mathrm{Fe,max}}$ is determined by balancing the dominant energy loss process with the acceleration rate $t_{\mathrm{acc}}^{-1} = \eta c/R_L$. Here R_L is the Larmor radius and a relatively high $\eta \simeq 10$ has been chosen to reproduce the composition transition observed by Auger [3].[1] The target photons are assumed to follow a broken power law with a break at 1 keV in the shock rest frame between the power law index -1 (low energy) and -2 (high energy). Note that we choose the minimal photon energy low enough such that photodisintegration will always dominate at the highest energies. The baryonic loading is assumed to be ten, which means that there is ten times more energy injected into iron compared to electrons, and energy equipartition between magnetic field, electron and photon energy is assumed.

For the nuclear energy losses, we include synchrotron losses, adiabatic losses, pair production losses, and photonuclear losses, where we distinguish between photodisintegration (focus of this work, dominated by the GDR) and photo-meson production (dominated by the Δ-resonance and other processes) by ϵ_r. The photodisintegration is implemented in different models, as discussed in the main text of this work. We include photo-meson production based on SOPHIA [34] using an improved and extended version of Ref. [35] with a superposition interaction model assuming that the cross section scales $\propto A$.

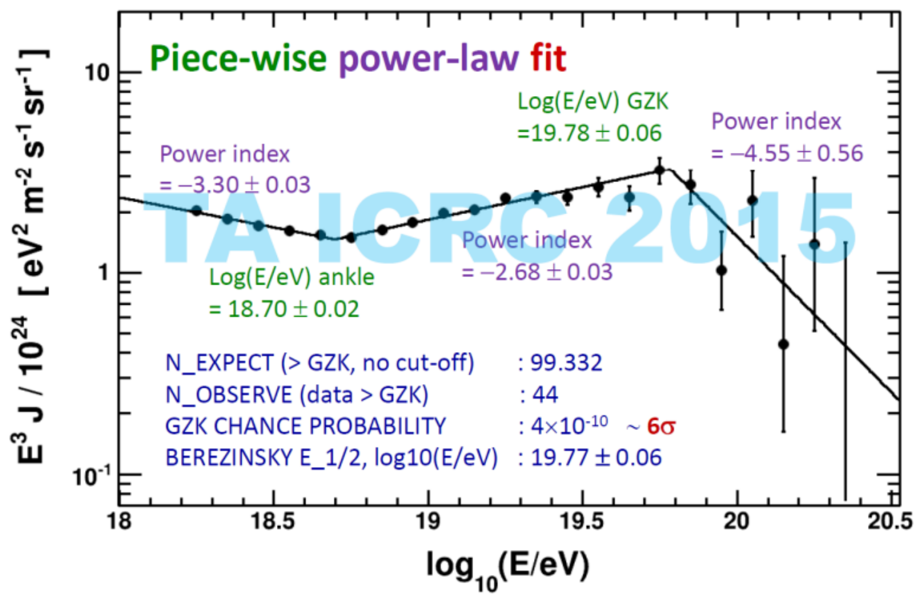
DB, A. Fedynitch, W. Winter, arxiv:1607.07989

What we measure: UHECR energy spectrum

Auger, ICRC 2015



TA, ICRC 2015

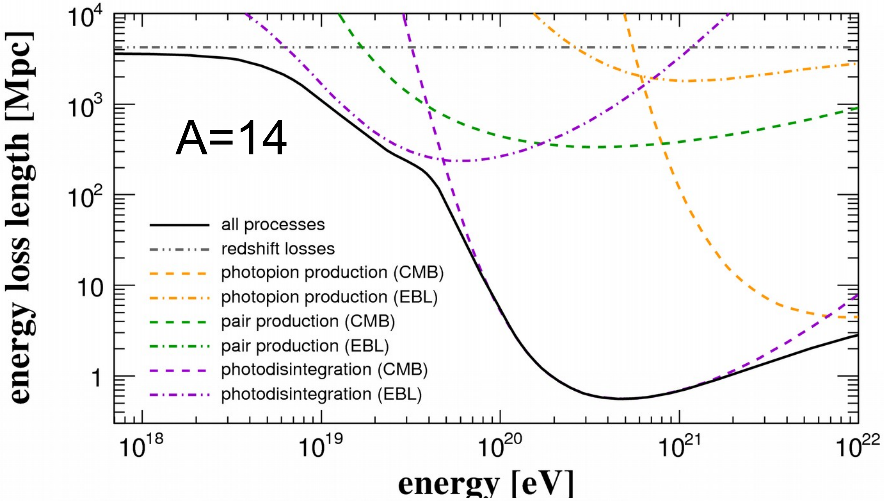


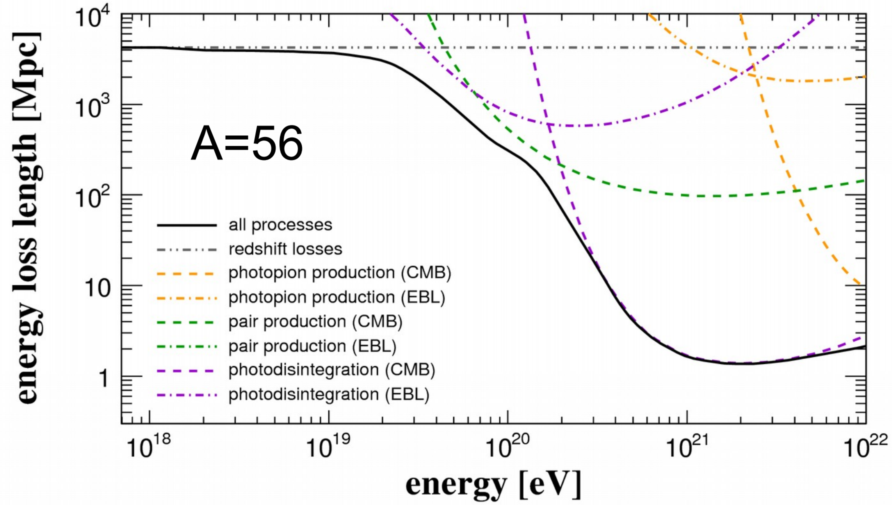
- Features of the spectrum (ankle, suppression) are associated with properties of:
  - Sources (distribution of sources, source evolution)
  - Transport (modeling of Extragalactic Background Light EBL)
  - Composition (protons, nuclei)

of UHECRs

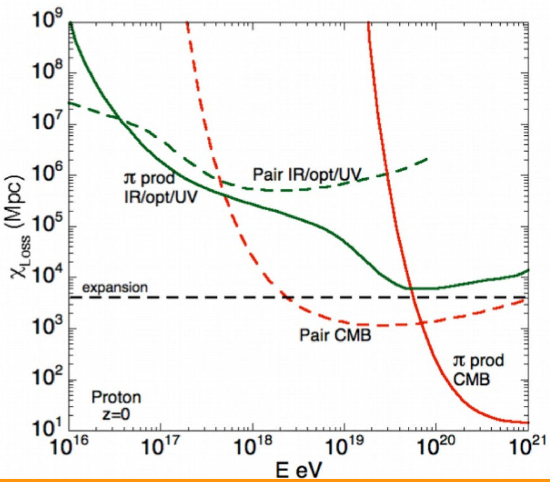
Interactions of nuclei

R. Alves Batista, **DB**, A. di Matteo, A. van Vliet, D. Walz, JCAP 1510 (2015)

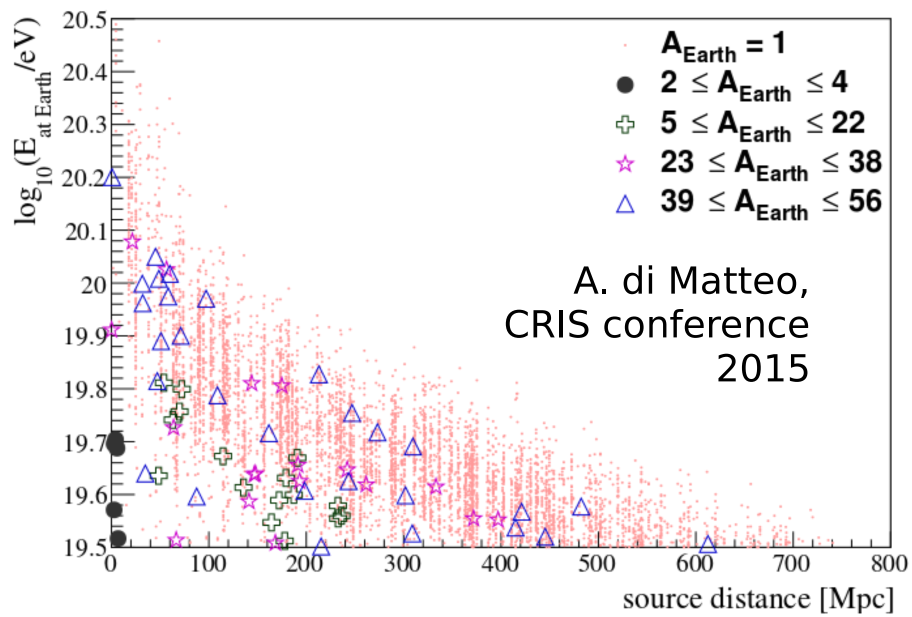




D. Allard, Astropart. Phys. 39-40 (2012) 33-43



- Different processes create similar features in the energy spectrum: suppression of the flux. But...



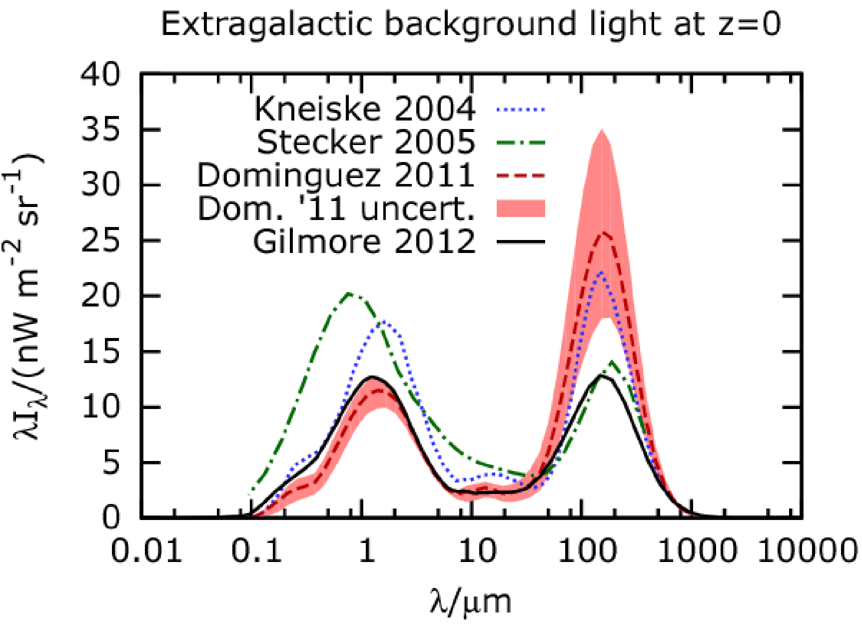
A. di Matteo, CRIS conference 2015

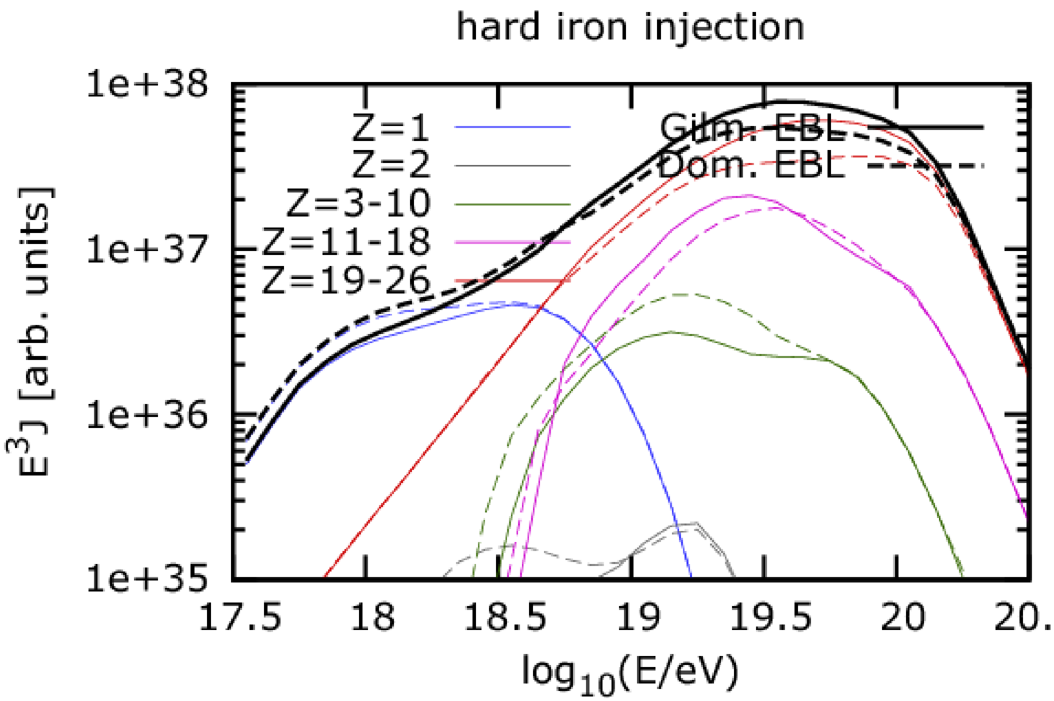
- If UHECR are predominantly nuclei, more uncertainties have to be considered wrt the case of protons: photon fields (sources and propagation), details of interactions (cross section for photodisintegration)

Effect of different EBL models on propagated spectra

→ differences are more visible in:

- hard injection scenarios than in soft ones, because they are mainly due to different numbers of low energy secondaries (in soft injection scenarios low energy secondaries are subdominant wrt residual primaries)
- low-energy intermediate mass secondaries of iron, because they are produced via repeated photodis by EBL





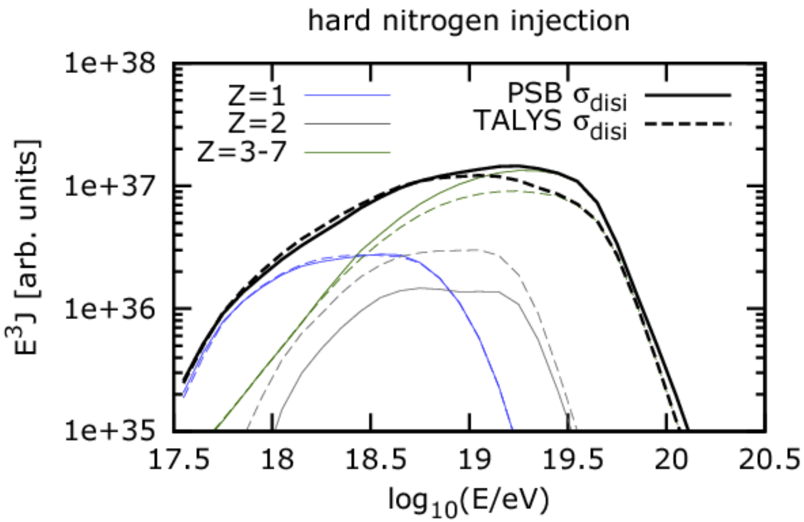
★ brighter EBL → softer spectrum at Earth and lighter composition

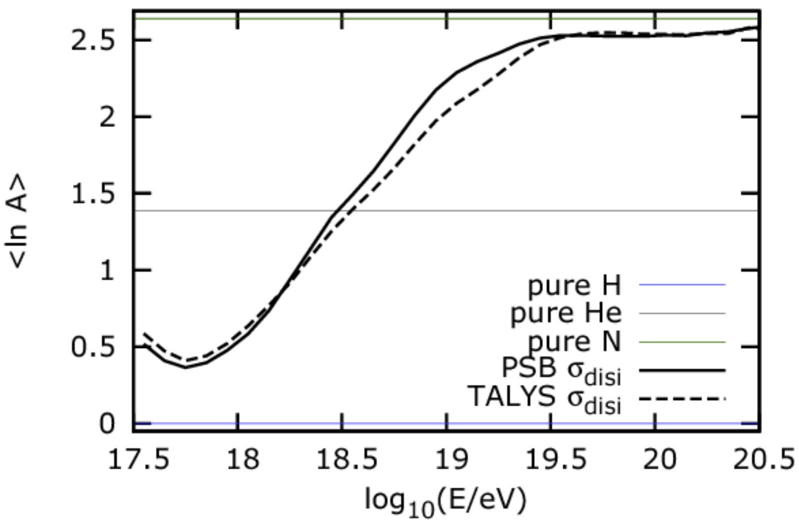
R. Alves Batista, DB, A. di Matteo, A. van Vliet and D. Walz, JCAP 1510 (2015) 10, 063

Effect of different choices of cross section for photodis

Stecker and Salamon, Astrop.J. 512, (1999), 521-526

> We also note that although the thresholds are lowest for α emission (because of the α's large binding energy), the integrated cross section for α emission from ^{56}Fe, for example, is over 2 orders of magnitude lower than the Σ_d value for that nuclide (Skopic, Asai, & Murphy 1980; see also Fuller & Gerstenberg 1983). We therefore neglect the α emission channels entirely in our calculation.





→ alpha particle ejection results in secondaries with 4 times the energy of the nucleon secondaries

→ including alpha-ejection: softer spectra at Earth and lighter composition

R. Alves Batista, DB, A. di Matteo, A. van Vliet and D. Walz, JCAP 1510 (2015) 10, 063

DESY

Fitting models to Auger data

- Auger spectrum and composition fitted above 10^18.7 eV (ankle)
- Sources assumed to be identical, homogeneously distributed, injecting 1-Hydrogen, 4-Helium, 14-Nitrogen and 56-Iron with

$$\frac{\mathrm{d}N_{\mathrm{inj},i}}{\mathrm{d}E} = \begin{cases} J_0 p_i \left(\frac{E}{1\ \mathrm{EeV}}\right)^{-\gamma}, & E/Z_i < R_{\mathrm{cut}} \\ J_0 p_i \left(\frac{E}{1\ \mathrm{EeV}}\right)^{-\gamma} \exp\left(1 - \frac{E}{Z_i R_{\mathrm{cut}}}\right), & E/Z_i > R_{\mathrm{cut}} \end{cases}$$

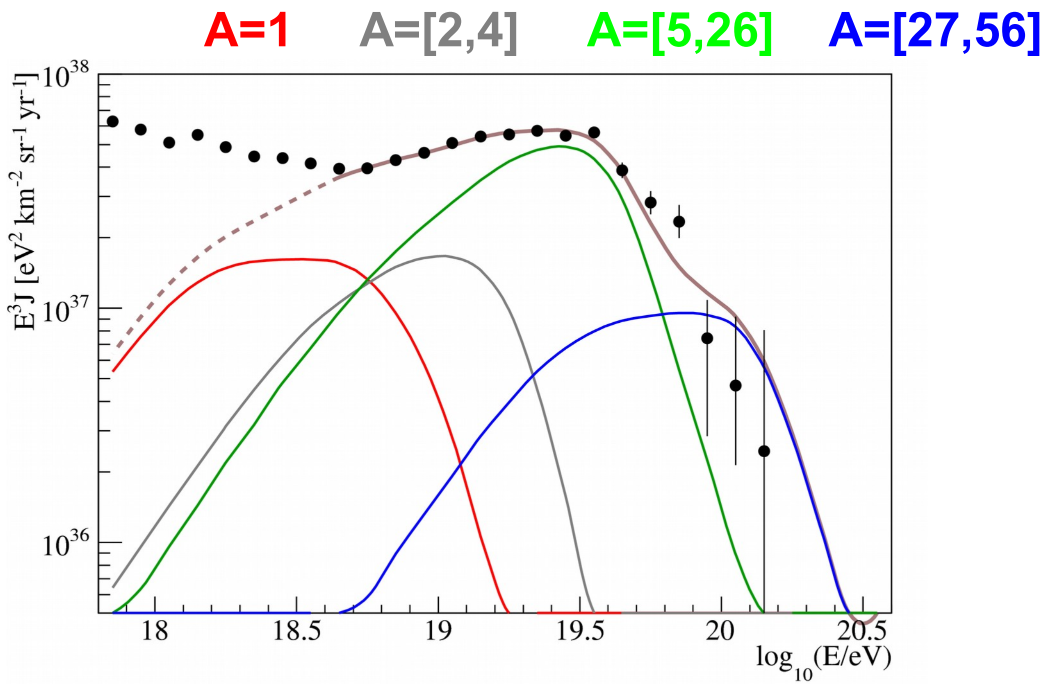
- Various models for propagation (*SimProp* and CRPropa propagation codes with different choices for cross sections and EBL models) and air interactions were used
- See A. di Matteo for the Pierre Auger Collaboration, PoS(ICRC2015)249 for details

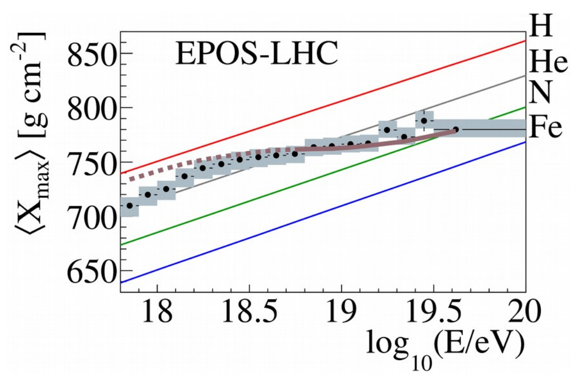
Fit results

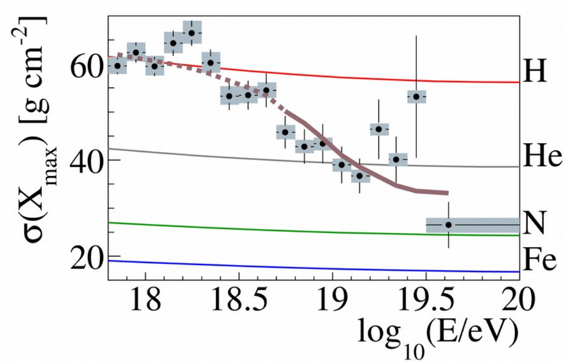
MODEL

- *SimProp* propagation
- PSB cross sections
- Gilmore EBL
- EPOS-LHC air interactions

	parameters
Rcut	18.67
gamma	0.94
H	0.0
He	62.0
N	37.2
Fe	0.8
Dmin	178.5/119





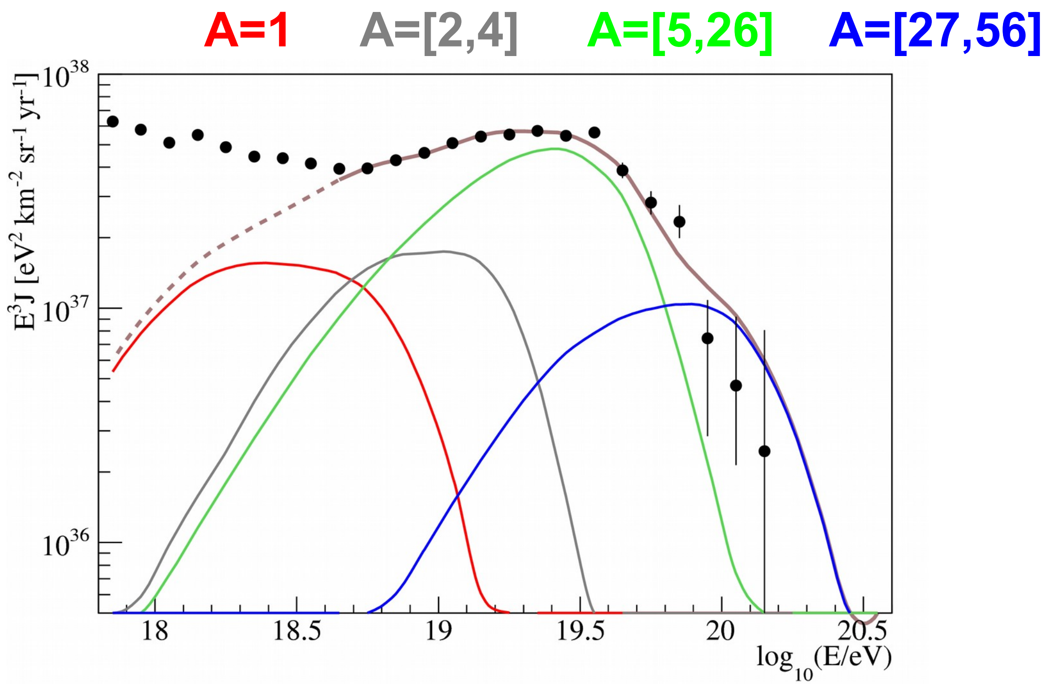


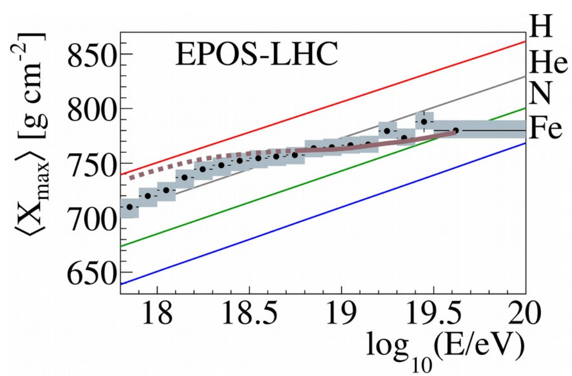
Fit results

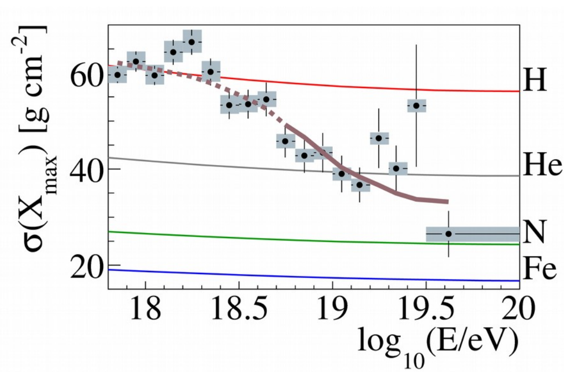
MODEL

- *SimProp* propagation
- TALYS cross sections
- Gilmore EBL
- EPOS-LHC air interactions

	parameters
Rcut	18.60
gamma	0.69
H	0.0
He	0.0
N	98.95
Fe	1.05
Dmin	176.5/119





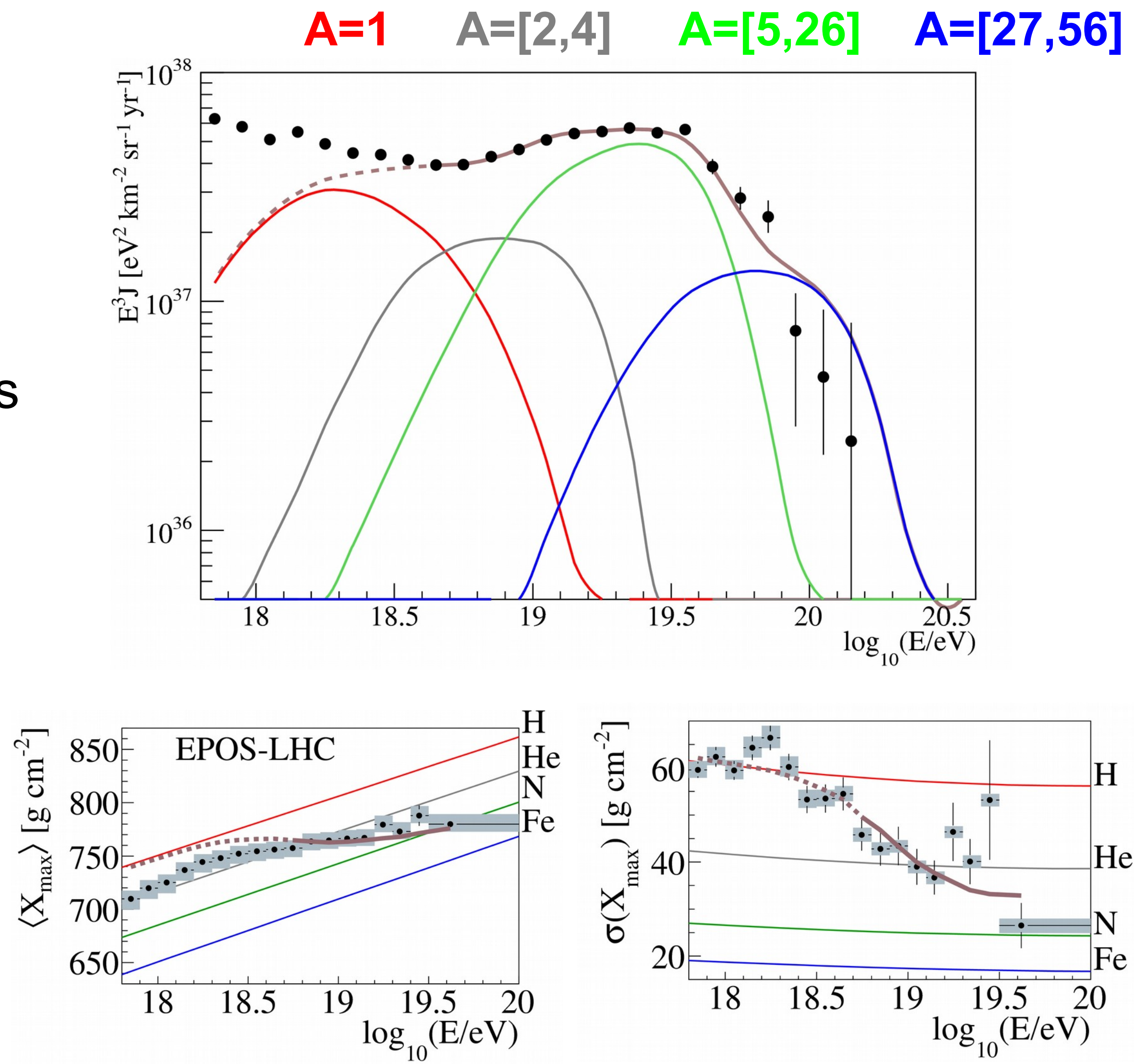


Fit results

MODEL

- *SimProp* propagation
- PSB cross sections
- Dominguez EBL
- EPOS-LHC air interactions

	parameters
Rcut	18.27
gamma	-0.45
H	76.1
He	21.9
N	1.9
Fe	0.0
Dmin	193.4/119

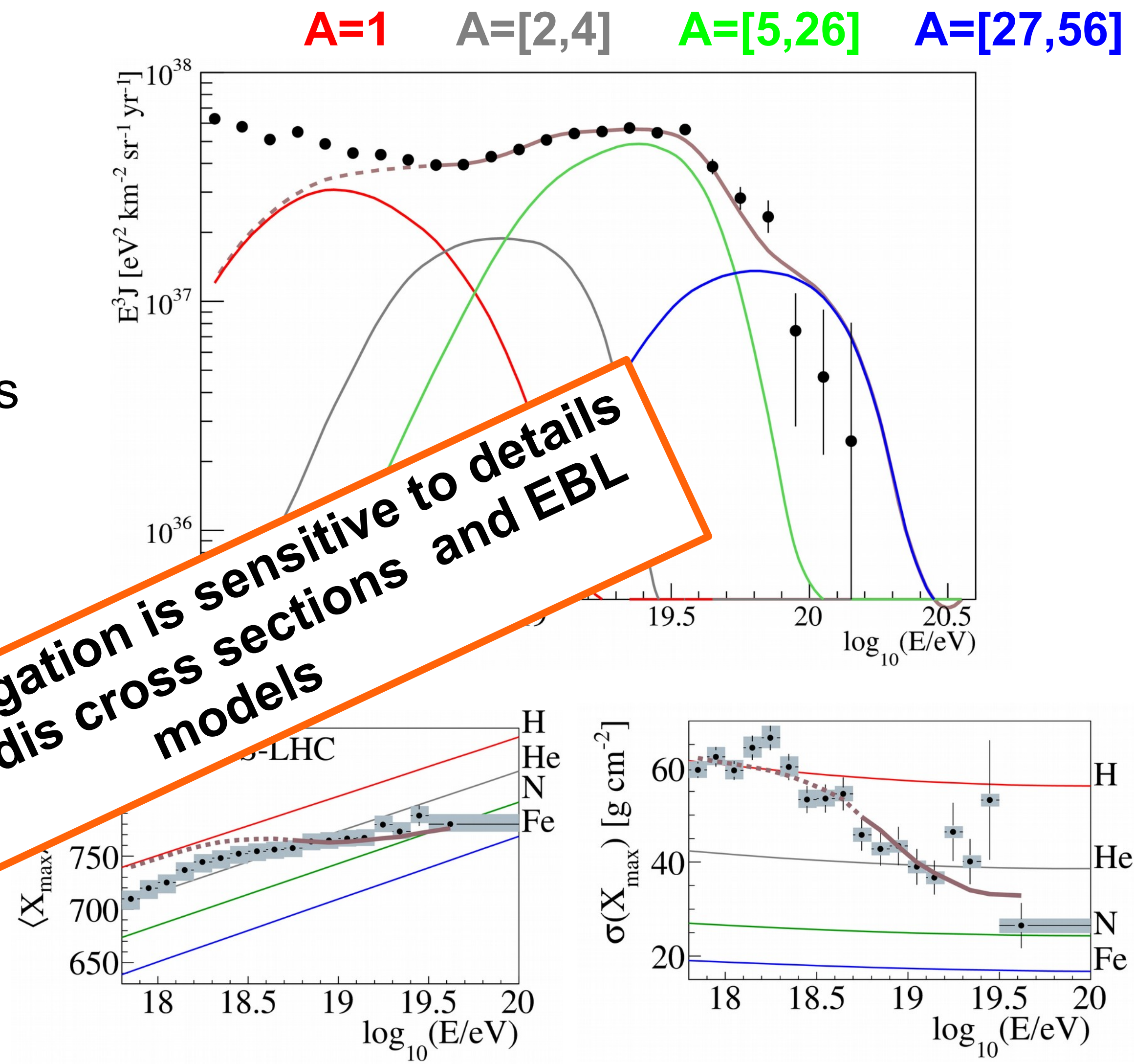


Fit results

MODEL

- *SimProp* propagation
- PSB cross sections
- Dominguez EBL
- EPOS-LHC air interactions

	parameters
Rcut	18.27
gamma	-0.45
H	[illegible]
He	[illegible]
N	[illegible].9
Fe	0.0
Dmin	193.4/119



The propagation is sensitive to details of photodis cross sections and EBL models

DESY