Interactions of Cosmic Rays around the Universe

Models for UHECR data interpretation

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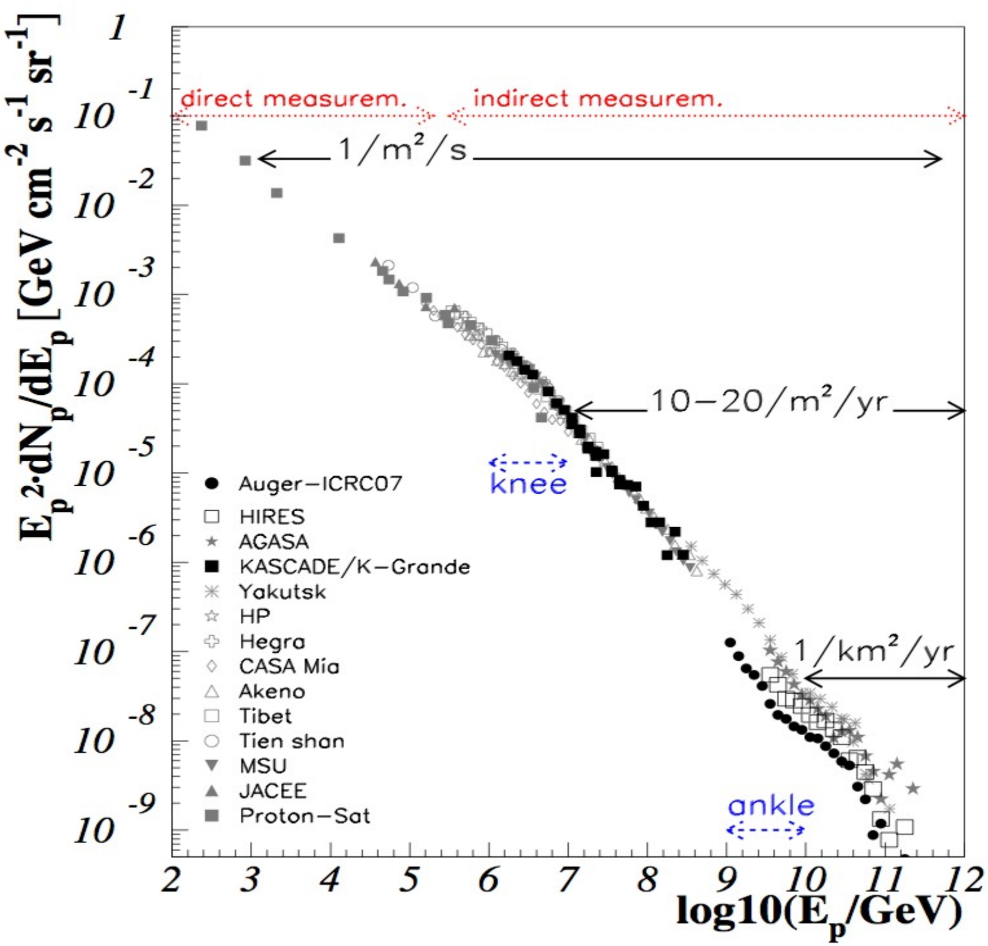
DESY

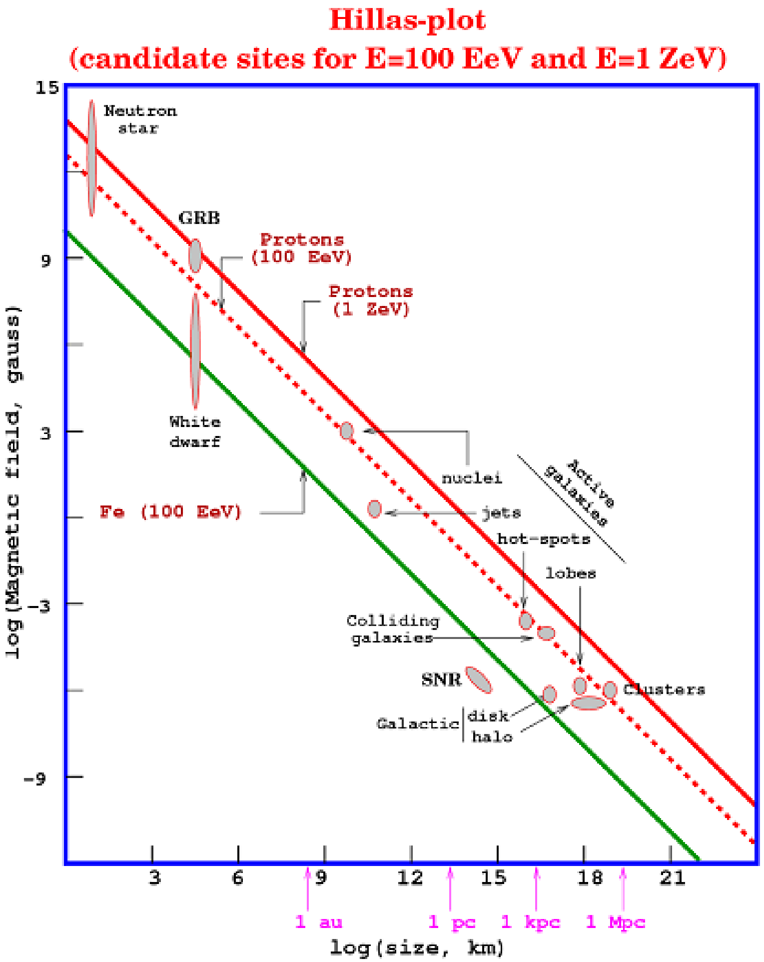
Introduction

- UHECRs: extragalactic sources?

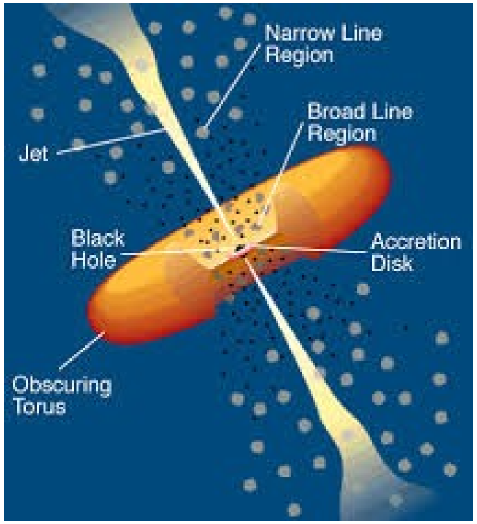
  - Magnetic fields trap particles in the Galaxy
  → the confinement is no longer efficient
  for particles with log(E/eV) > 18

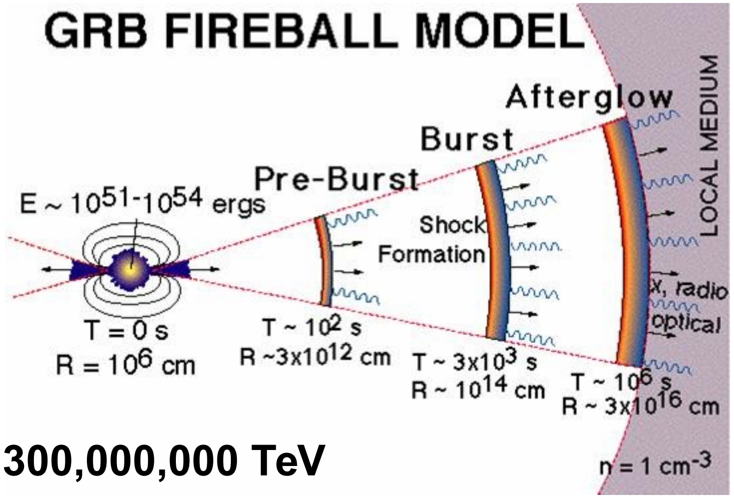
$E_{max} \sim q\,B\,R$





Cosmic vs. terrestrial particle accelerators



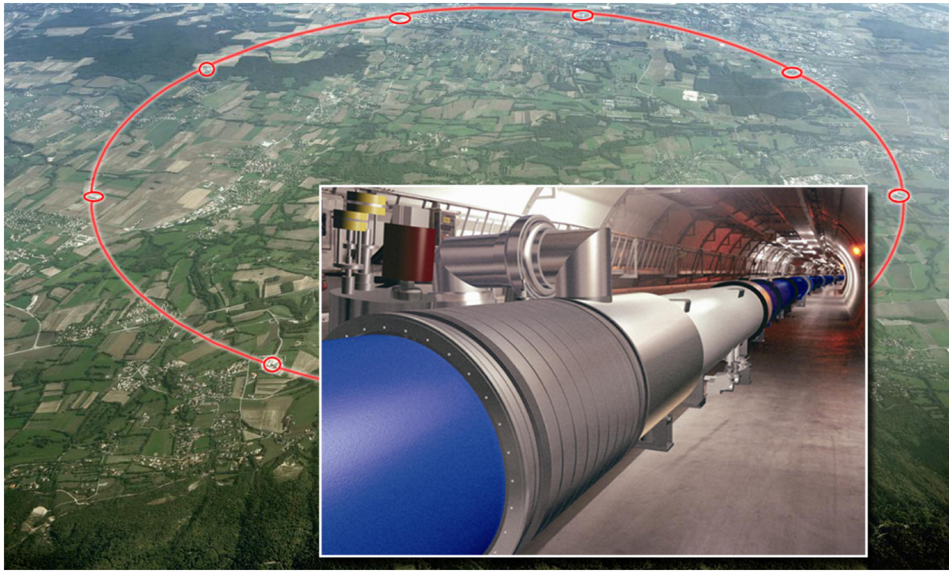


E_{max} ~ **300,000,000 TeV**

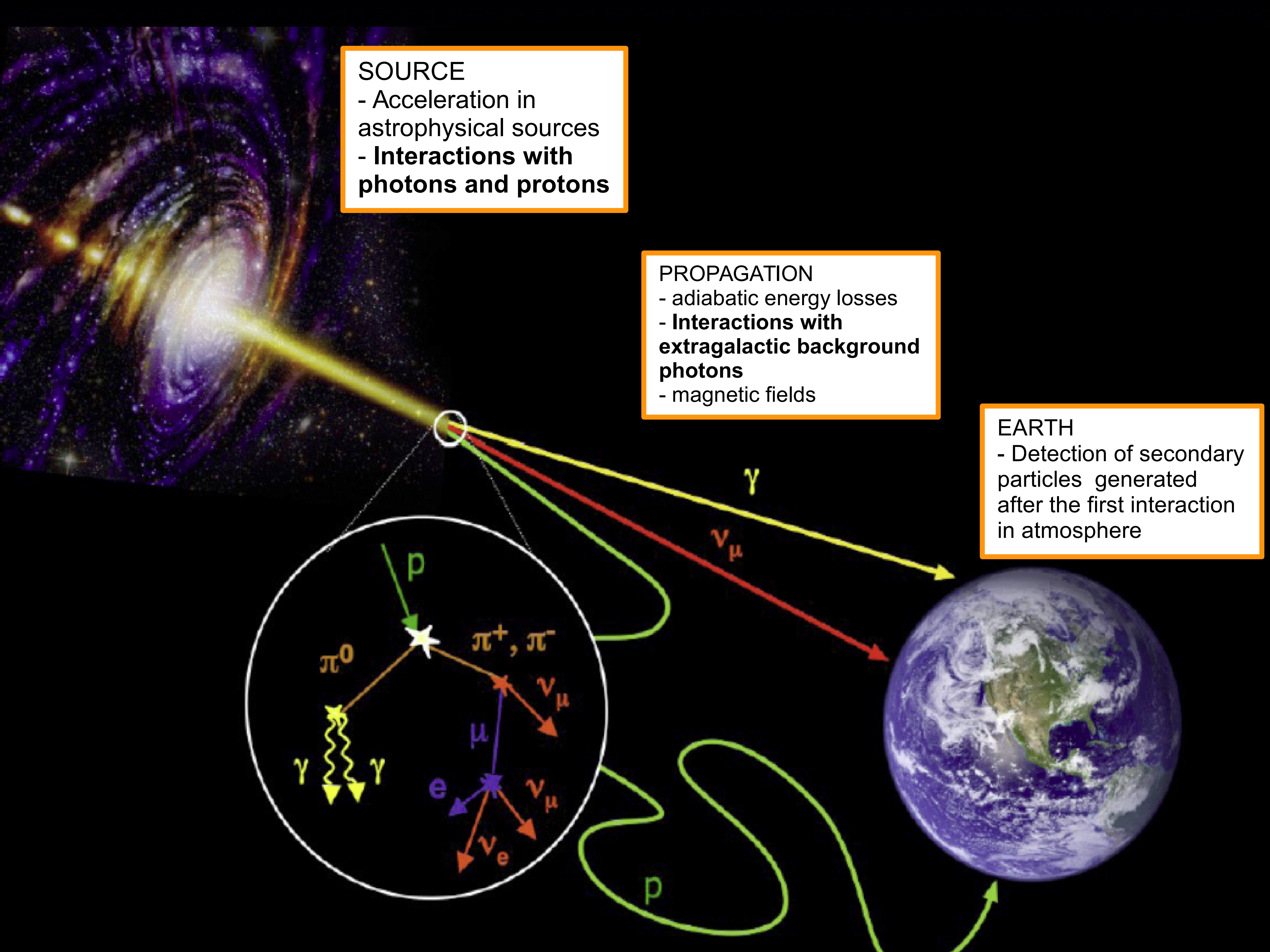
B ~ 1 mT – 1 T

R ~ 100,000 – 10,000,000,000 km

$E_{max} \sim q\,B\,R$

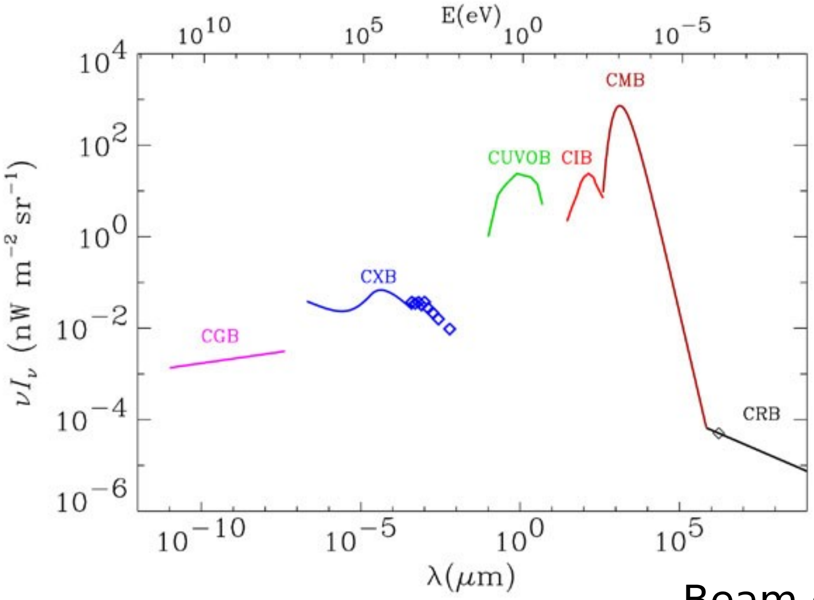


E_{max} ~ 13 TeV

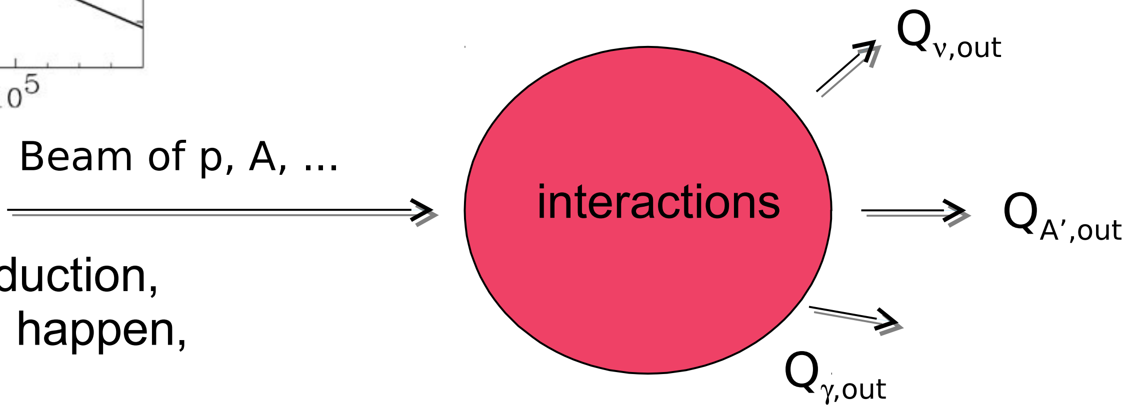

SOURCE
- Acceleration in astrophysical sources
- **Interactions with photons and protons**
PROPAGATION
- adiabatic energy losses
- **Interactions with extragalactic background photons**
- magnetic fields
EARTH
- Detection of secondary particles generated after the first interaction in atmosphere
γ
ν_μ
p
π^0
π^+, π^-
ν_μ
μ
γ
γ
e
ν_μ
ν_e
p

Energy scale of the processes

- Diffuse extragalactic background spans over 20 decades in energy, from radio waves up to the high-energy gamma ray photons. It consists of light emitted at all epochs, modified by redshifting and dilution due to the expansion of the universe



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

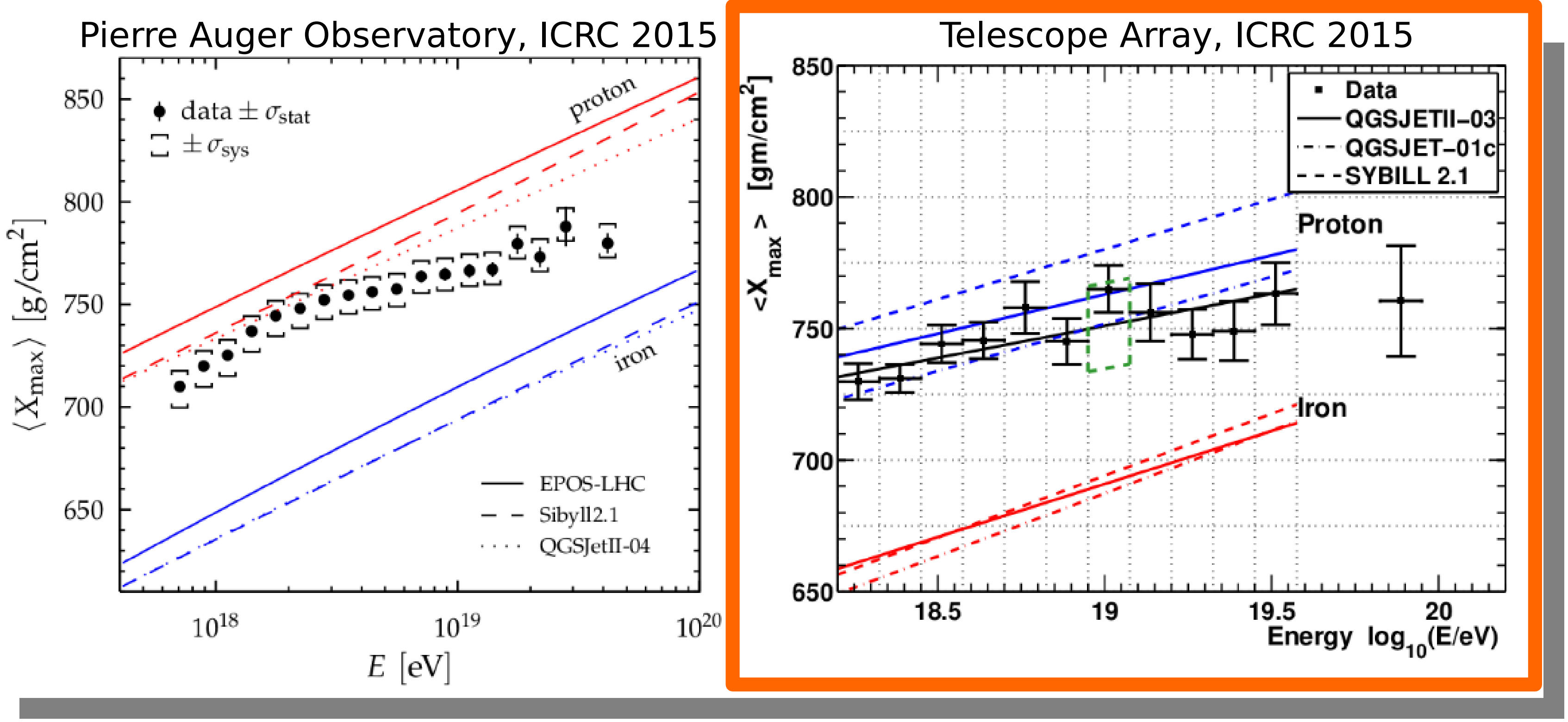


➔Energy scale $\varepsilon' \propto \Gamma \varepsilon$
➔Pair production, photopion production, photodisintegration (if nuclei) can happen, with a rate $\lambda \propto 1/(\rho \sigma)$

➔Similar approach can be used in photon fields in the sources

UHECR → Protons

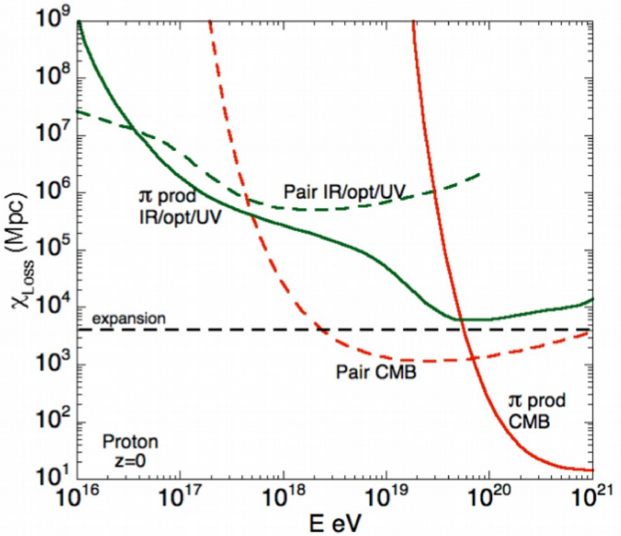
- Proton Hypothesis

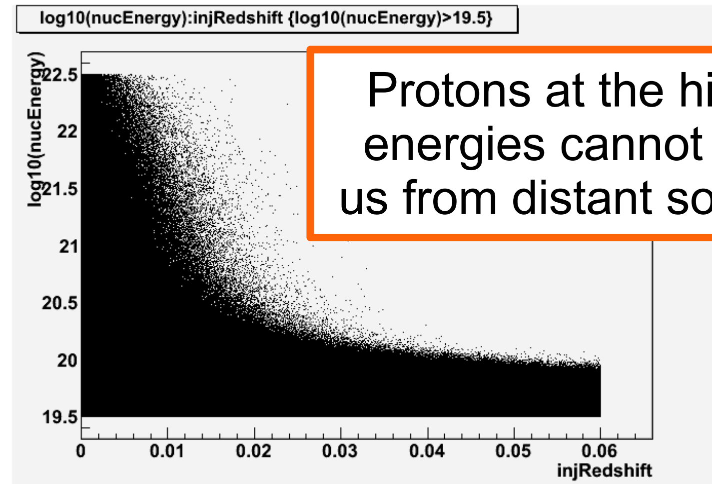


Propagation of protons

- Loss mechanisms and their relevance for propagation of protons pointed out early after the discovery of the cosmic microwave background (CMB) in 1965

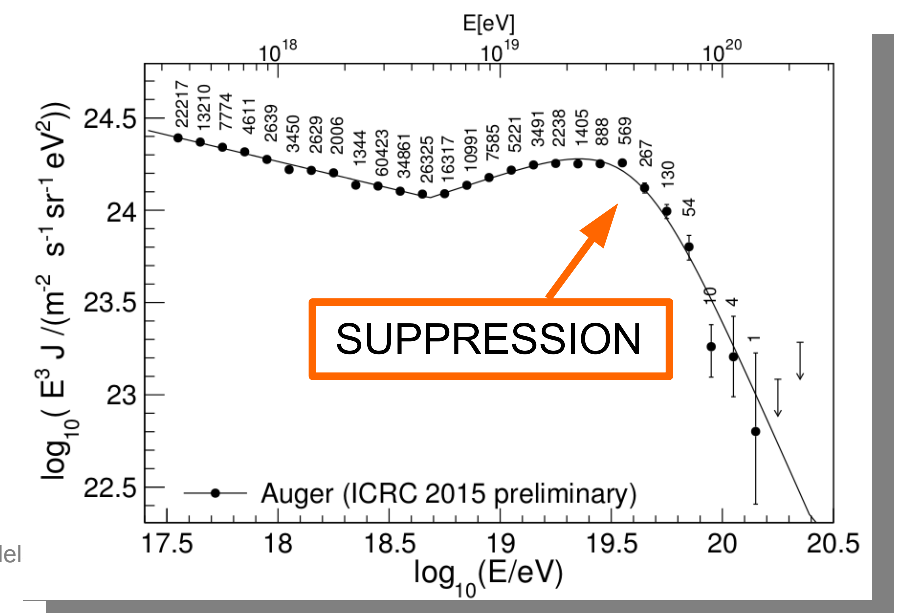
D. Allard, Astropart. Phys. 39-40 (2012) 33-43





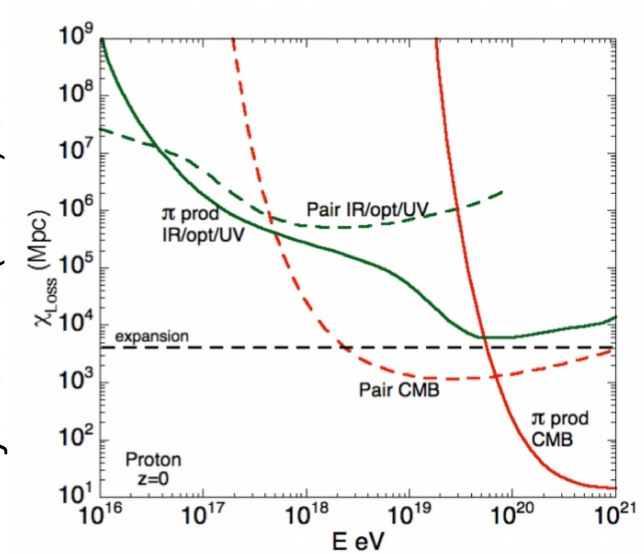
Protons at the highest energies cannot reach us from distant sources !

- Greisen, Zatsepin and Kuzmin estimated the opacity of the universe for CR protons above 100 EeV and predicted the existence of the suppression of the flux at the highest energies (GZK cut-off)
  → K. Greisen, PRL 16 748 (1966), G.T. Zatsepin and V.A. Kuzmin, Sov. Phys. JETP Lett. 4 78 (1966)



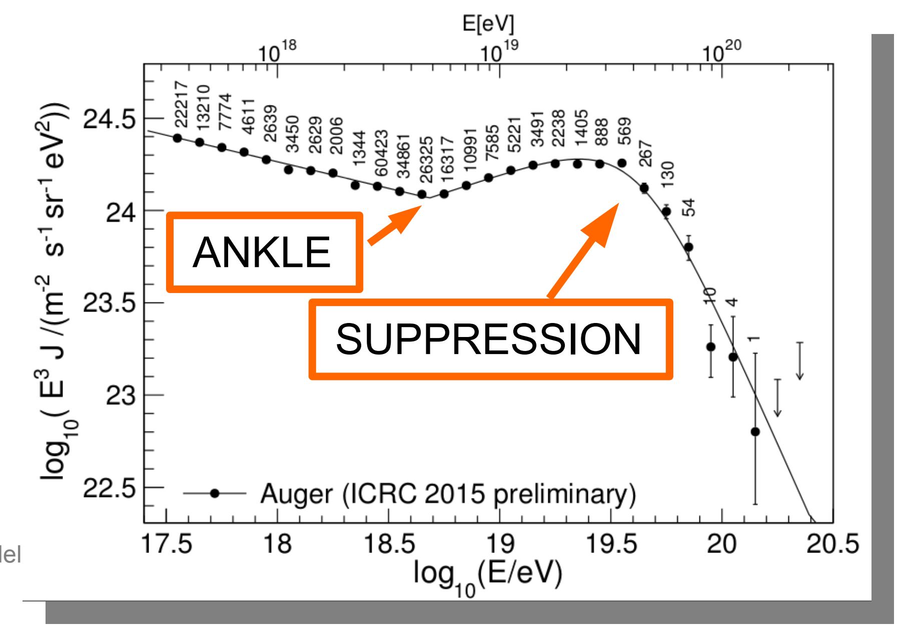
Propagation of protons and spectrum features

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



- "Dip model" → features of the energy spectrum are due to properties of interactions of protons (extragalactic, energies > 1 EeV) with CMB
- Other models used to reproduce the spectrum
  - "ankle model"
  - "mixed composition"
- How can these models be tested?

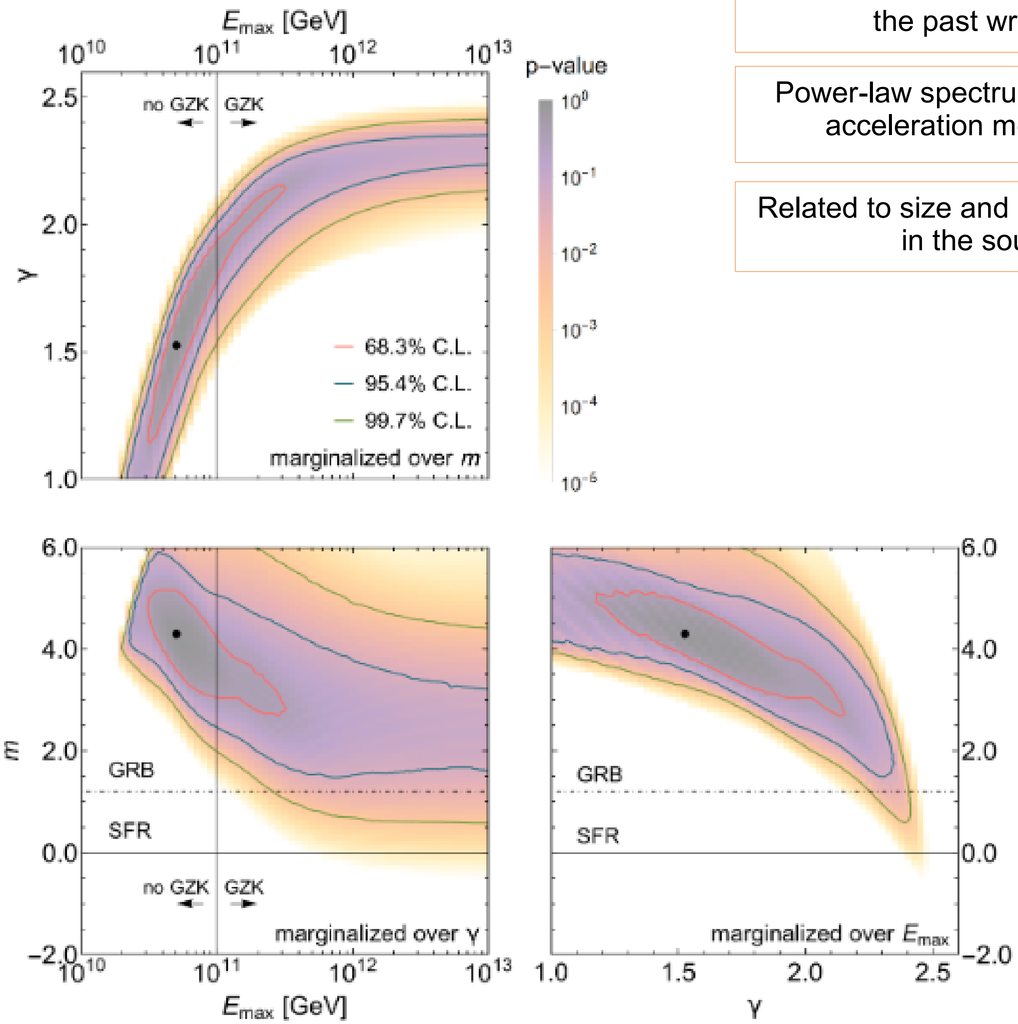
- Greisen, Zatsepin and Kuzmin estimated the opacity of the universe for CR protons above 100 EeV and predicted the existence of the suppression of the flux at the highest energies (GZK cut-off)
  → K. Greisen, PRL 16 748 (1966), G.T. Zatsepin and V.A. Kuzmin, Sov. Phys. JETP Lett. 4 78 (1966)
- Hillas and Blumenthal studied the effect of pair production on protons above 1 EeV
  → A.M. Hillas, Phys. Lett. 24A 677 (1967), G.R. Blumenthal, Phys. Rev. D Vol 1 1596 (1970)

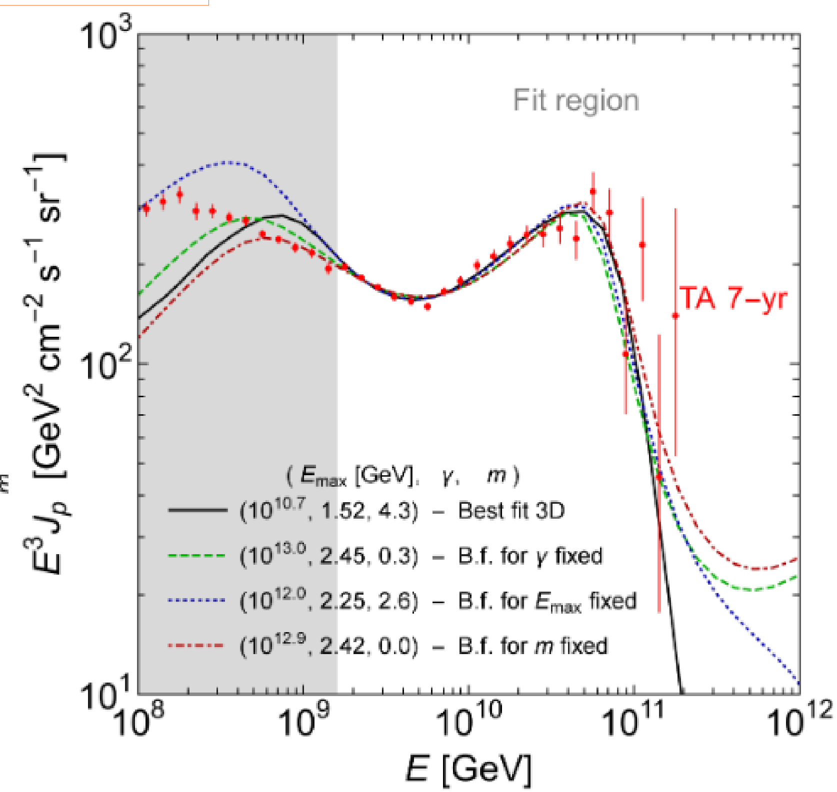


Propagation of protons: multimessenger approach

$$J_p^{\rm inj}(E) \propto H(z) E^{-\gamma} \exp(-E/E_{\rm max})$$

- Source evolution: Sources were more luminous in the past wrt now
- Spectral index: Power-law spectrum from Fermi acceleration mechanism
- Max energy: Related to size and magnetic fields in the source

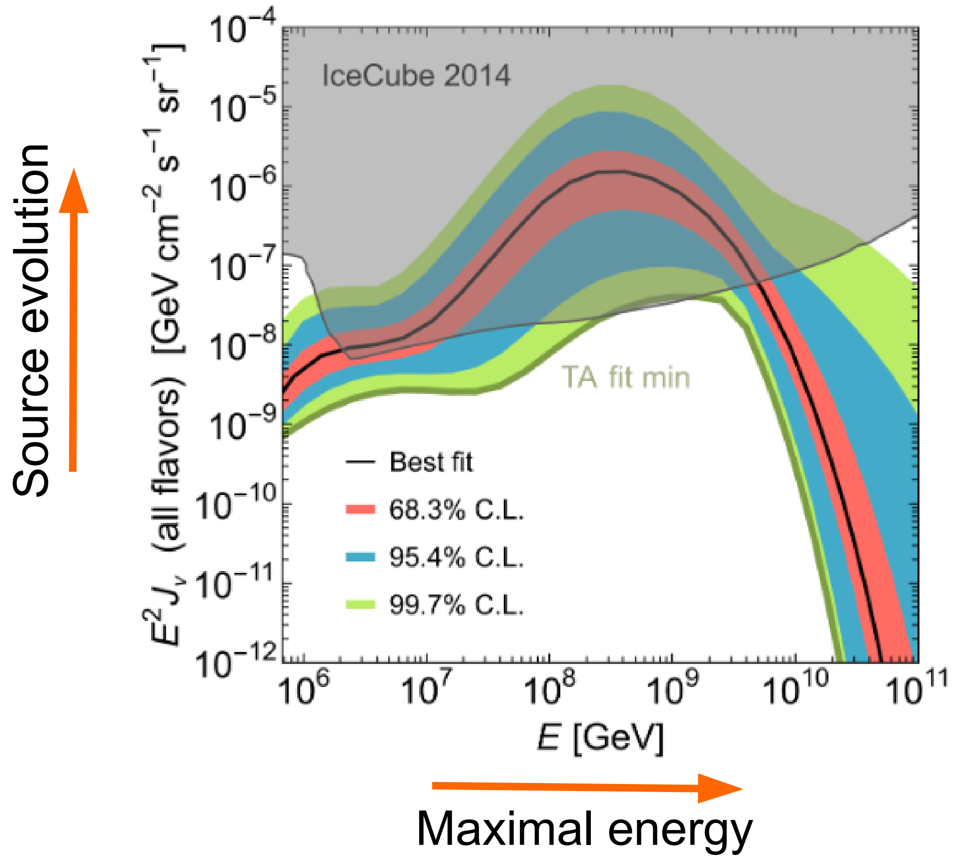




J. Heinze, **DB**, M. Bustamante, W. Winter, ApJ 825 (2016)

Propagation of protons: multimessenger approach

- Taking into account the neutrino flux associated to the proton spectrum, the proton dip model is challenged!



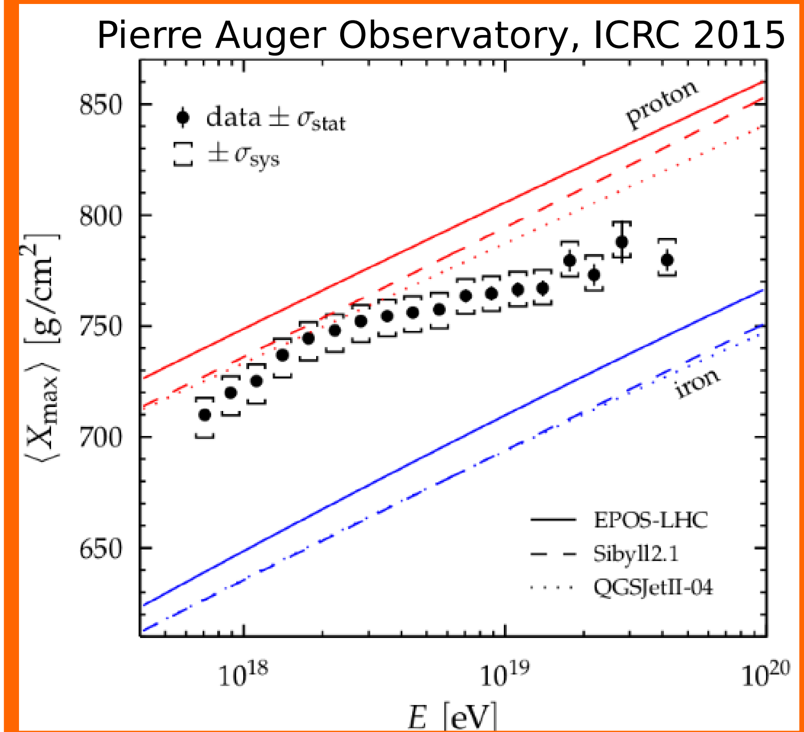
The sensitivity of the neutrino (and photon) flux can be used as a tool to limit the astrophysical scenarios that are compatible with the interpretations of the measured UHECR spectrum → can be done **independently from the composition measurements**

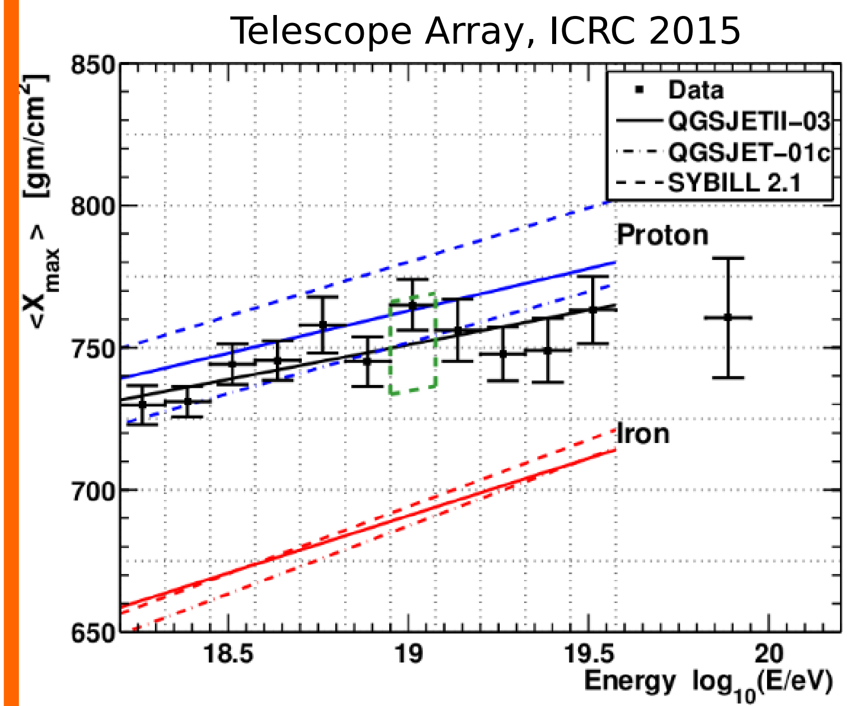
→ **other options to be verified: "ankle model", mixed composition**

J. Heinze, **DB**, M. Bustamante, W. Winter, ApJ 825 (2016)

UHECR → Nuclei

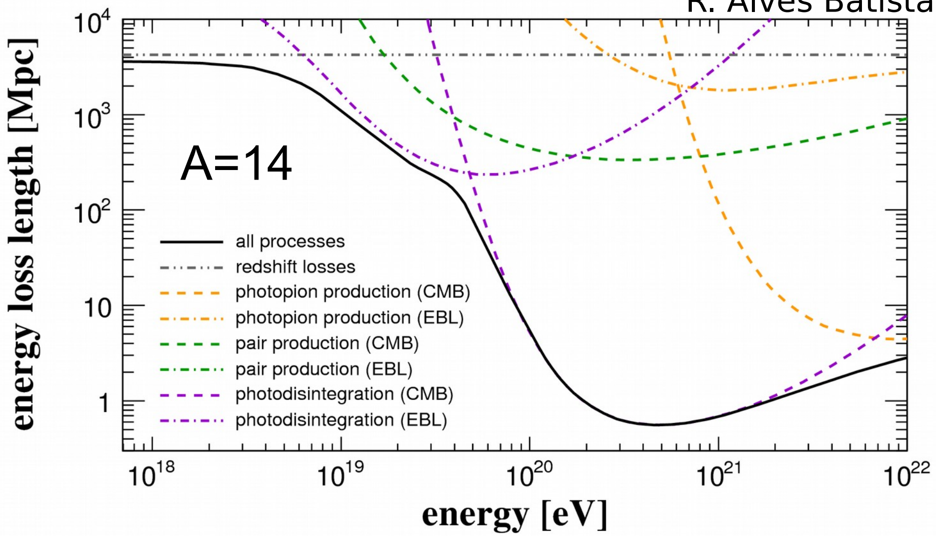
- Nuclei Hypothesis

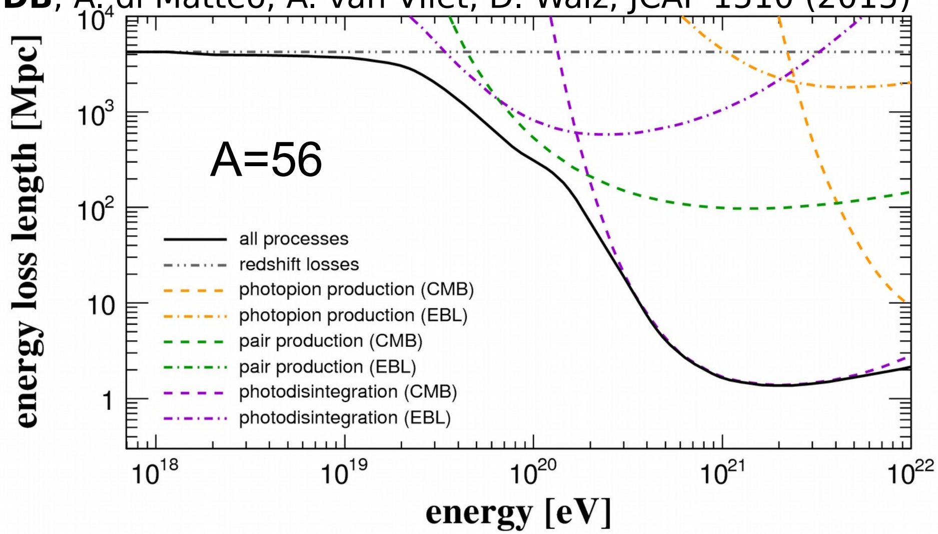




Propagation of nuclei

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

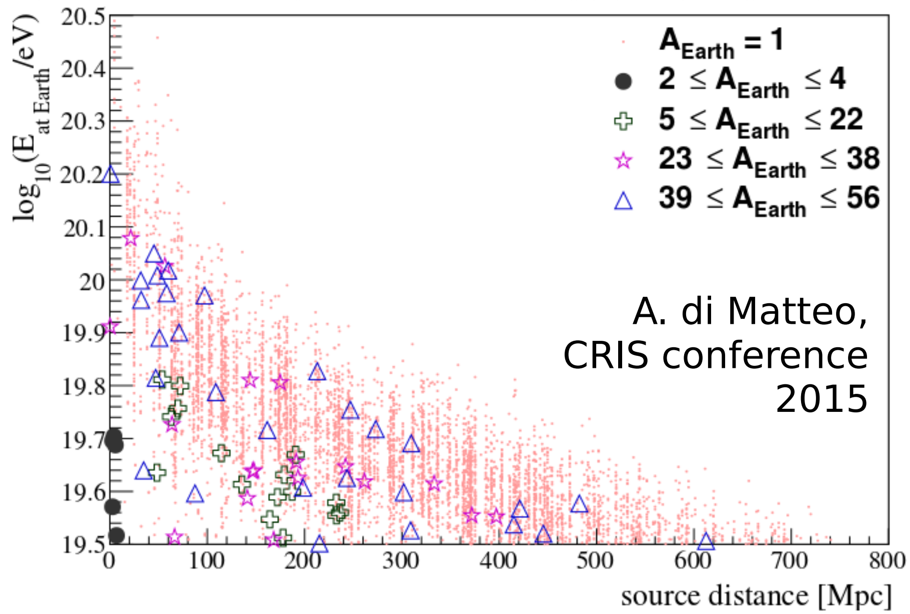




- If UHECR are predominantly nuclei, a suppression of the flux is expected as for protons, but the responsible process is **photodisintegration** → <u>how good is our knowledge of these processes?</u>

- Infrared background becomes more important wrt propagation of protons → <u>how good is our knowledge of photon fields other than CMB?</u>

- Dedicated codes are developed to simulate the UHECR propagation, as:
  - **CRPropa**, `http://crpropa.desy.de`
  - **SimProp**, R. Aloisio, **DB**, A.F. Grillo, S. Petrera, F. Salamida, JCAP 1210 (2012) 007, last release: arXiv:1602.01239

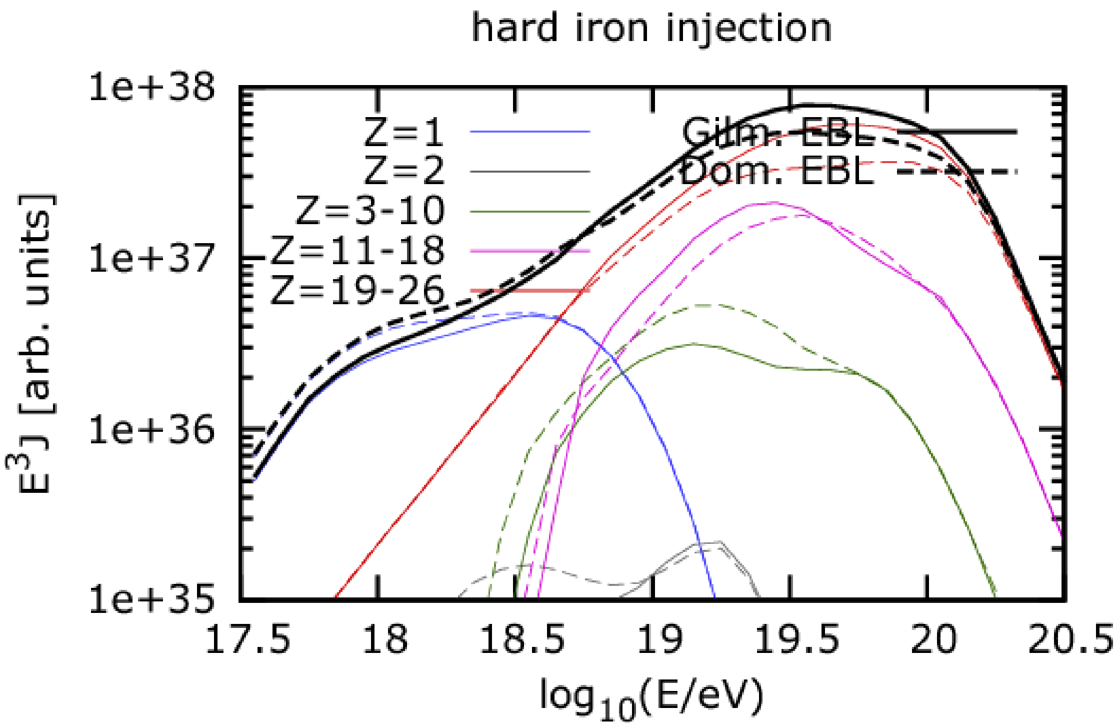


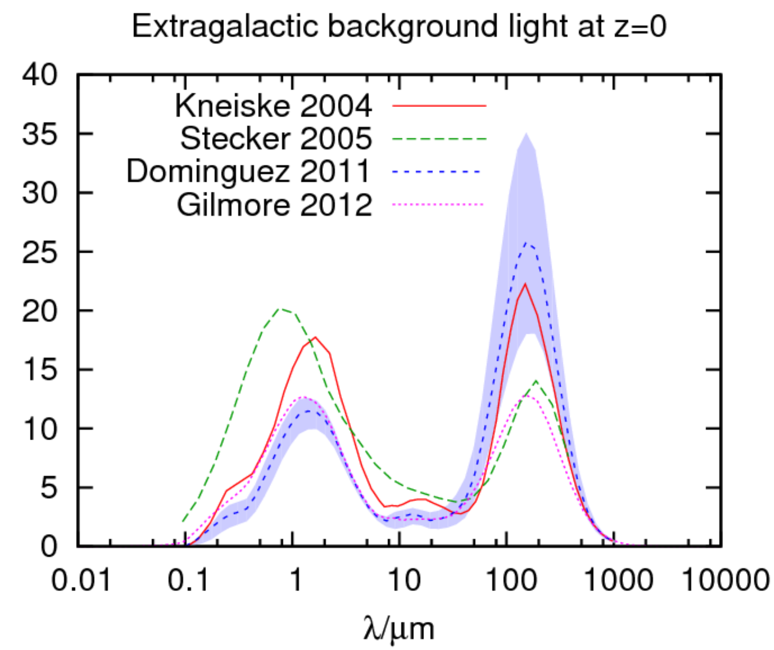
A. di Matteo, CRIS conference 2015

Effect of EBL models on photodisintegration of nuclei

→ different intensities of the photon fields (at different energy ranges) influence the efficiency of photodisintegration

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

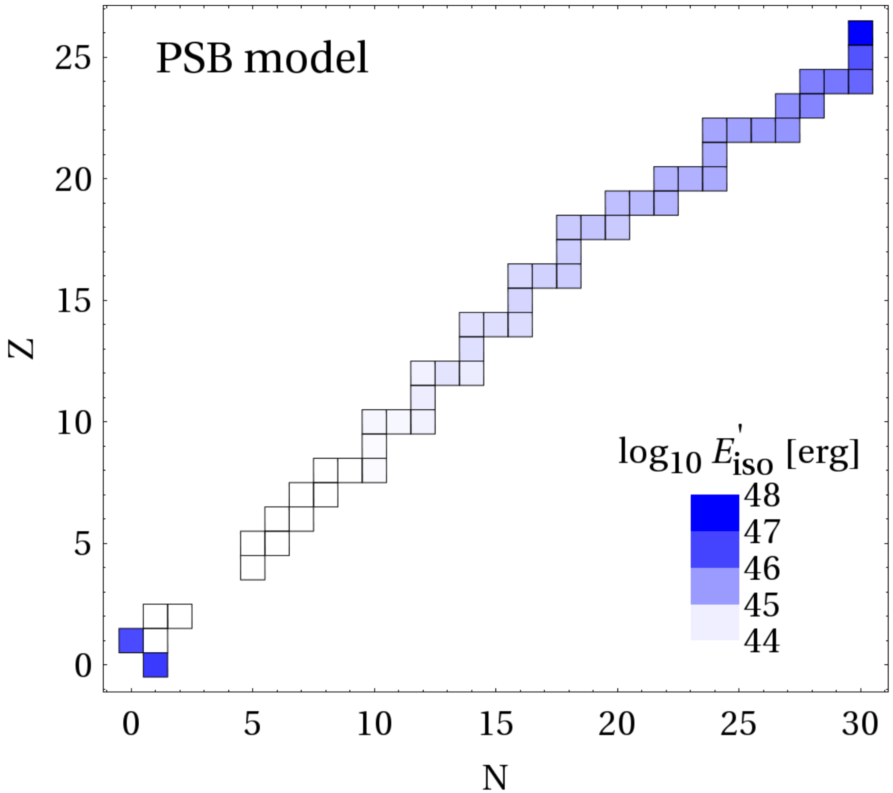


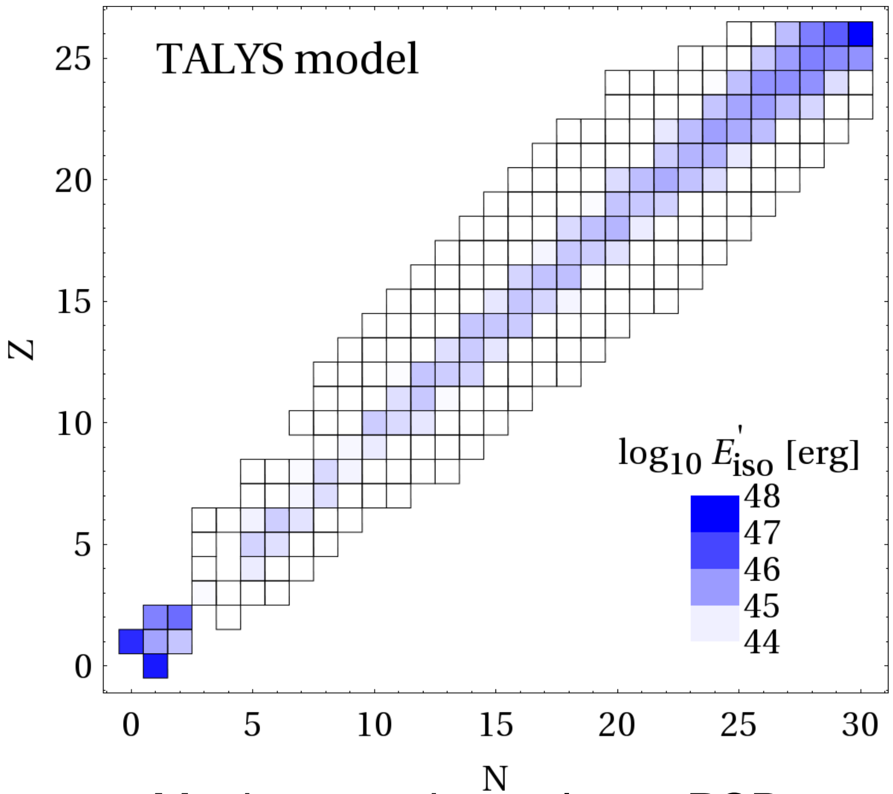


→ the brighter is the EBL, the more efficient is the photodisintegration

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

Effect of cross-section models in nuclear cascades



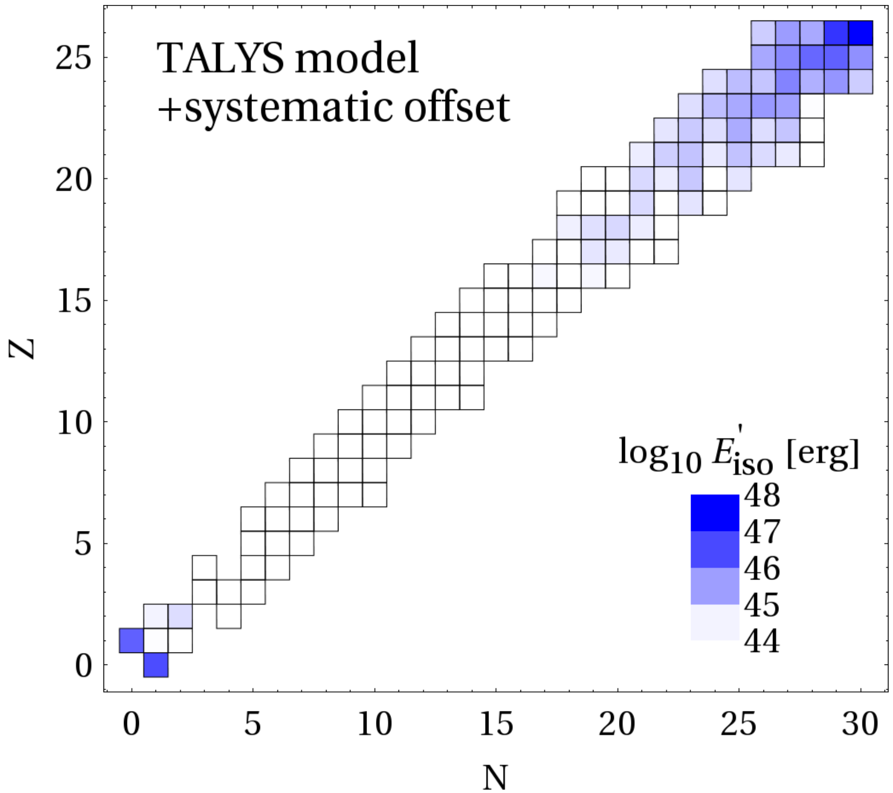


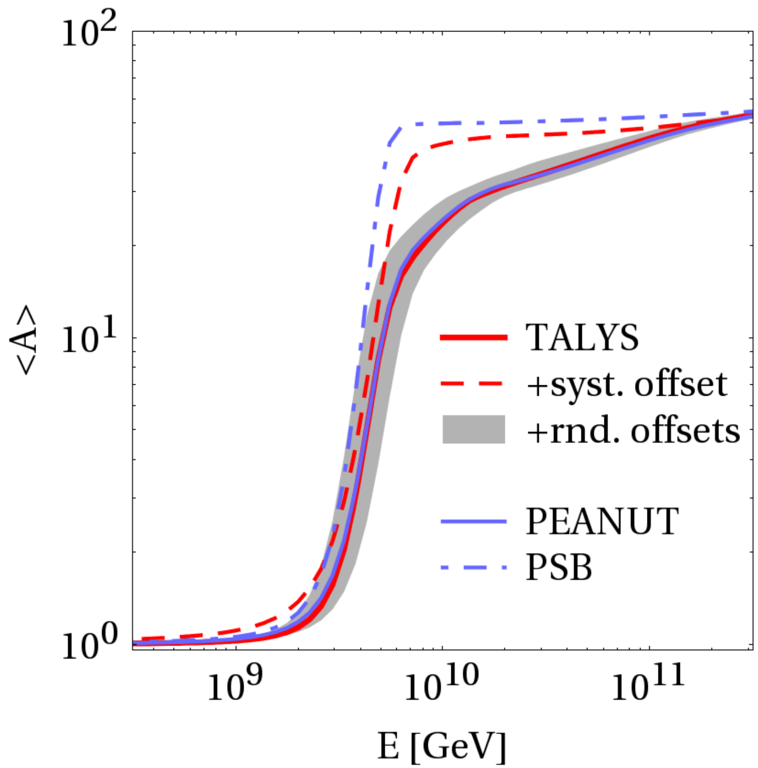
- One nuclide for each A
- Only small fragments can be ejected in photodisintegration
- The cascade is not completed, smaller masses are not populated

- 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)

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

Effect of cross-section models in nuclear cascades





- No propagation effects considered
- Mass composition trend is 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

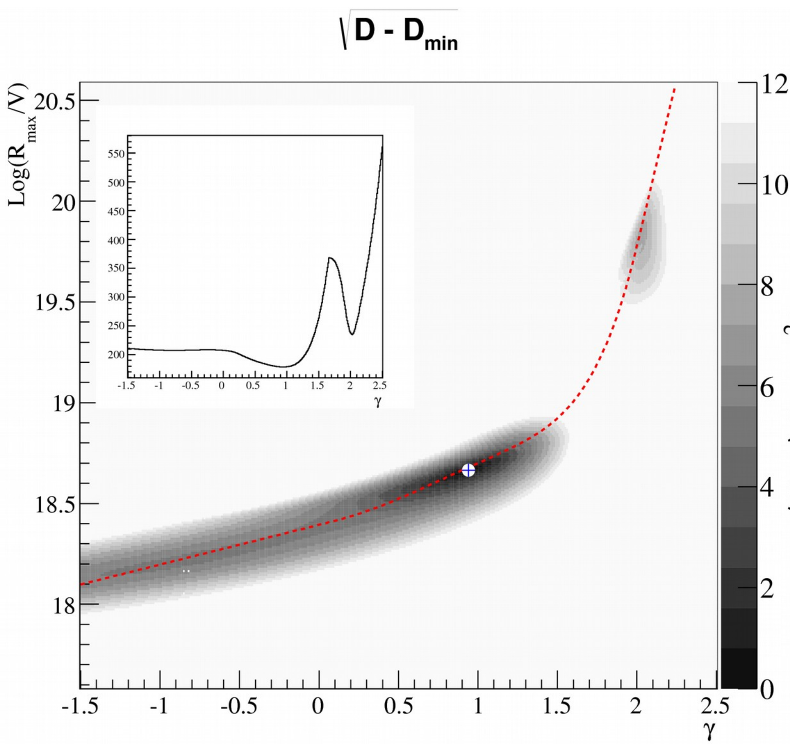
DB, A. Fedynitch, W. Winter, arxiv:1607.07989

Global interpretation of UHECR data

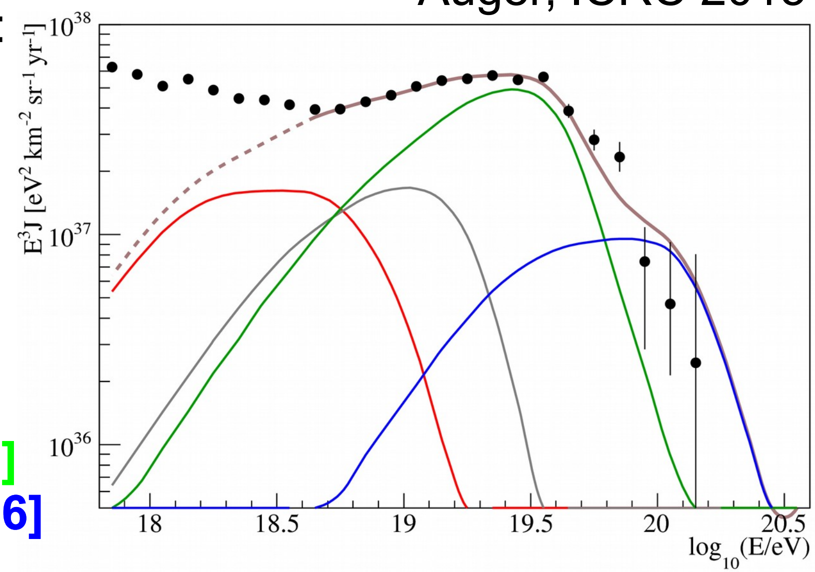
$$\frac{dN_{\mathrm{inj},i}}{dE} = \begin{cases} J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma}, & E/Z_i < R_{\mathrm{cut}} \\ J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(1 - \frac{E}{Z_i R_{\mathrm{cut}}}\right), & E/Z_i > R_{\mathrm{cut}} \end{cases}$$

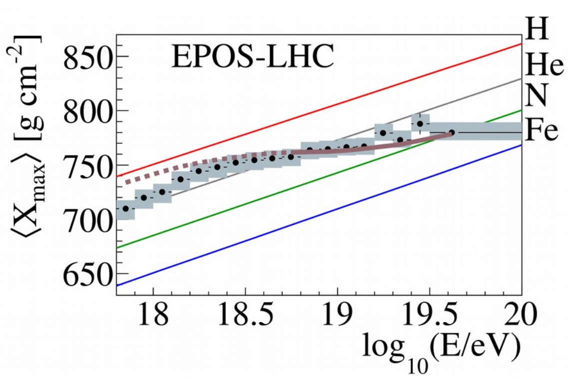
- Models can be distinguished by the choice of:
  - Cross section model for propagation
  - EBL model
  - Interaction in atmosphere

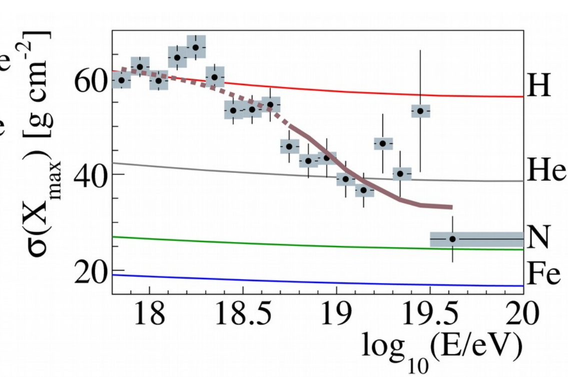
Auger, ICRC 2015



A=1
A=[2,4]
A=[5,26]
A=[27,56]



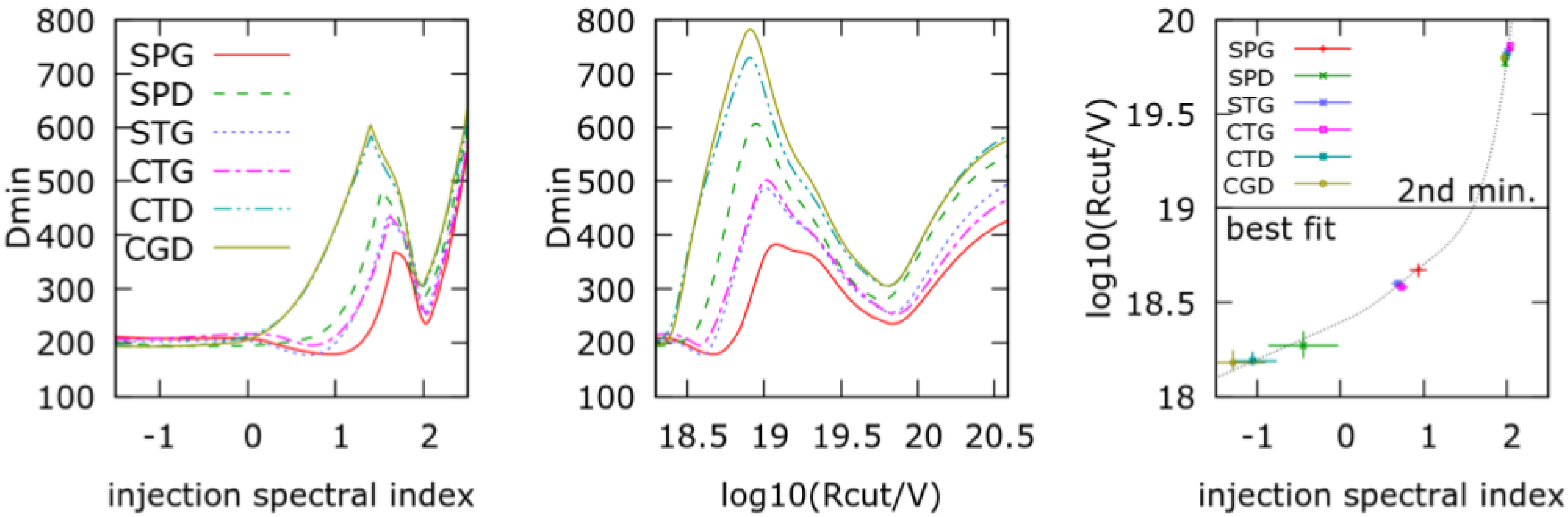




Global interpretation of UHECR data

- Variations of the "propagation model"

Auger, ICRC 2015



- The higher the interaction rates, the lower the injection cutoff and the spectral index

“Nuclei” versus “Protons”

- **UHECR → protons**: can be tested with a “multimessenger approach”

  - neutrino flux, photon flux, derived from propagation of protons

  - “dip model” is challenged independently from composition measurements

- **UHECR → nuclei**: uncertainties in cross sections for photodisintegration and EBL models

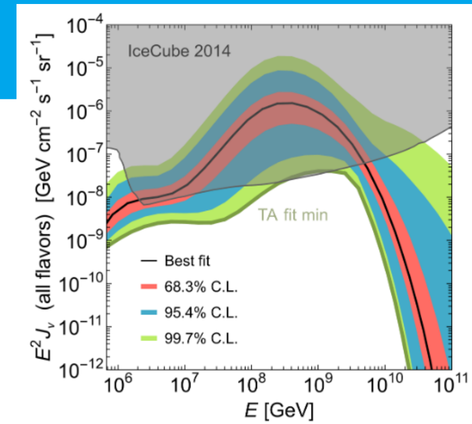
  - global interpretation of UHECR data is affected by these uncertainties;

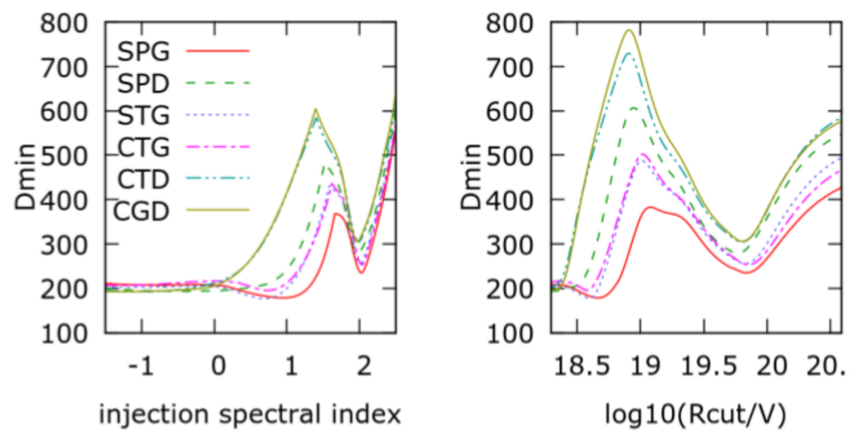
  - however, a <u>preference toward “less interactions”</u> is seen;

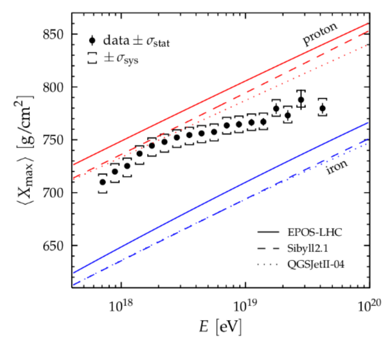
  - scenarios with hard spectral index (~1) and low maximal cutoff energies are favored

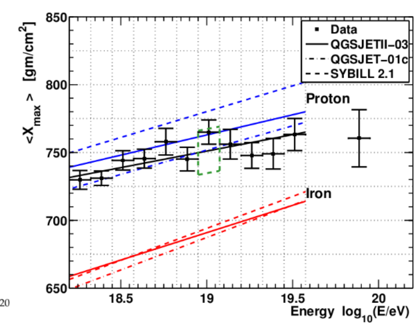
  - scenarios with soft spectral index (~2) are much less sensitive to propagation details, but disfavored by Xmax distribution width

- **Nuclei vs Protons** → intepretation relies also on the accuracy of hadronic multiparticle production









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Summary

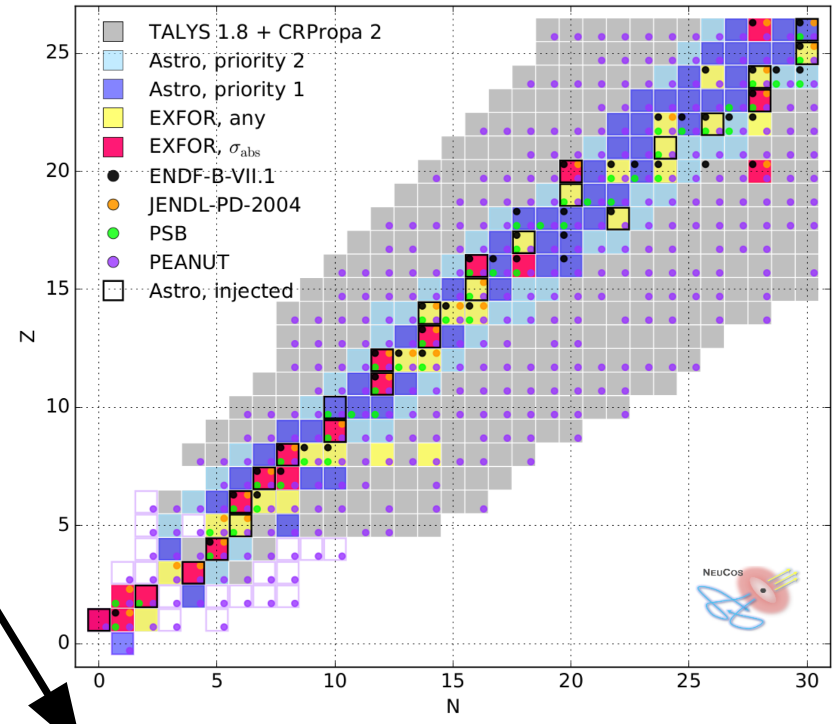
- Overview on characteristics of UHECR propagation and features of energy spectrum → composition dependent
- Interpretation of UHECR data:

  - if protons, need to use a multimessenger approach: neutrino and photon flux

  - if nuclei, spectrum + composition, but…

  → additional uncertainties wrt the "simple" proton case have to be considered:
  ▲uncertainties in photodisintegration cross sections: lack of measurements and limited prediction power of the current nuclear models! (*)
  ▲uncertainties in extragalactic photon fields

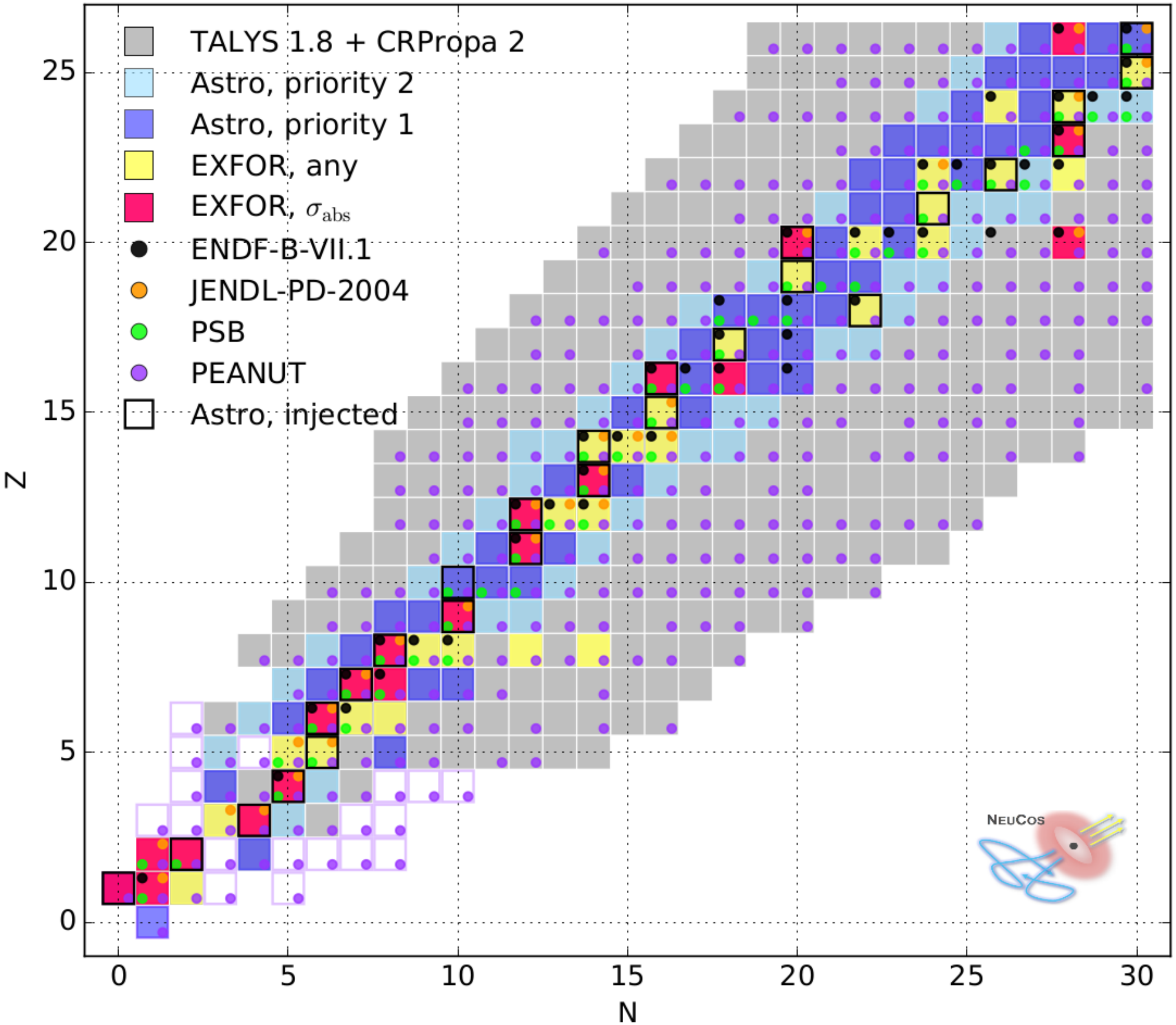
  → hard spectral index (~1) and low maximal cutoff energies are preferred (**)



effects on interpretation of UHECR data!

- Studies of both cosmogenic neutrinos and neutrinos produced in the source can help in understanding characteristics of UHECR sources (***) → **work in progress**

Summary (*)



- 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

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Summary (**)

- In models with no significant evolution with redshift the injected spectrum from the sources of the UHECRs must exhibit a very hard spectral index → difficult to accommodate? → softer injected spectra can be found with negative evolutions, see Taylor, Ahlers, Hooper, Phys.Rev. D92 (2015)

Parameter	$n=-6$ Best-fit Value	$n=-6$ Posterior Mean & Standard Deviation	$n=-3$ Best-fit Value	$n=-3$ Posterior Mean & Standard Deviation	$n=0$ Best-fit Value	$n=0$ Posterior Mean & Standard Deviation	$n=3$ Best-fit Value	$n=3$ Posterior Mean & Standard Deviation
f_p	0.03	0.14 ± 0.12	0.08	0.15 ± 0.13	0.17	0.17 ± 0.16	0.19	0.20 ± 0.16
f_{He}	0.50	0.21 ± 0.17	0.42	0.17 ± 0.16	0.53	0.20 ± 0.17	0.32	0.23 ± 0.20
f_N	0.40	0.50 ± 0.18	0.42	0.51 ± 0.19	0.29	0.47 ± 0.19	0.43	0.45 ± 0.21
f_{Si}	0.06	0.11 ± 0.12	0.08	0.12 ± 0.13	0.0	0.11 ± 0.12	0.06	0.078 ± 0.086
f_{Fe}	0.01	0.052 ± 0.039	0.0	0.053 ± 0.042	0.01	0.050 ± 0.038	0.0	0.044 ± 0.034
α	1.8	1.83 ± 0.31	1.6	1.67 ± 0.36	1.1	1.33 ± 0.41	0.6	0.64 ± 0.44
$\log_{10}\left(\frac{E_{Fe,max}}{eV}\right)$	20.5	20.55 ± 0.26	20.5	20.52 ± 0.27	20.2	20.38 ± 0.25	20.2	20.16 ± 0.18

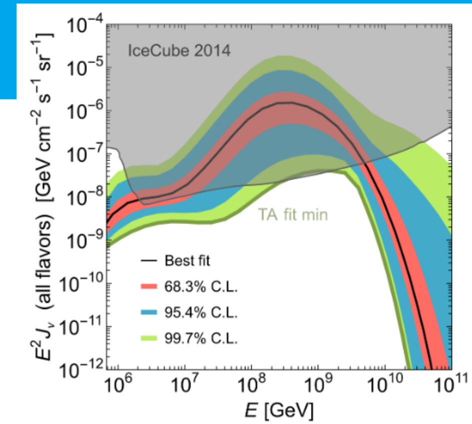
→ injection index is the most sensitive parameter

→ m>0: increasing number of protons

It means that the contribution of local sources is increased → consistent with neutrino upper limits and Fermi results for gamma-rays → consistent with low-luminosity gamma-ray BL Lac objects

- Preference of the global fit for "less interactions": galactic origin is investigated, for example in → Eichler, Globus, Kumar, Gavish, Astrophys.J. 821 (2016)

Summary (***)

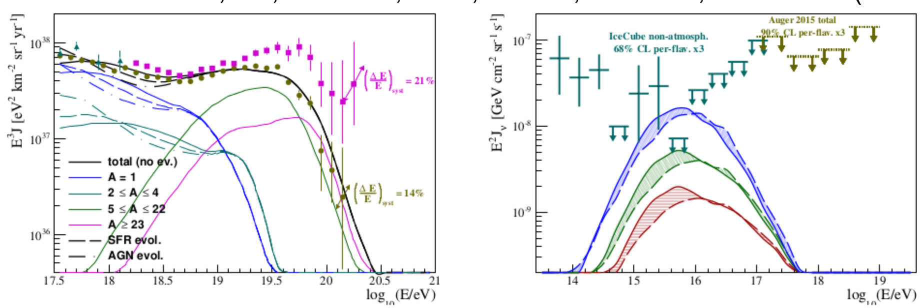


- If UHECRs are protons:

  - cosmogenic neutrinos studies have in principle the power to rule out astrophysical sources with high evolution → GRBs, AGN

  - from "on-source" neutrinos studies: connections between UHECR escape and neutrino production in sources may not be 1:1, ⟶ Baerwald, Bustamante, Winter, Astrophys.J. 768 (2013) 186

Aloisio, **DB**, di Matteo, Grillo, Petrera, Salamida, JCAP 1510 (2015)



- If UHECRs are nuclei:

  - from cosmogenic neutrinos studies, hard to constrain

  - from "on-source" neutrino studies: prediction studied for (few) sources, like inner jets of AGNs ⟶ Murase, Inoue, Dermer, Phys.Rev. D90 (2014) ; nuclei accelerated in internal shocks in GRBs, studies of connections between UHECRs and neutrinos, Murase, Ioka, Nagataki, Nakamura Phys.Rev.D 78 (2008) ⟶ <u>need to know **photon fields** and **cross sections** for important processes inside the source</u>

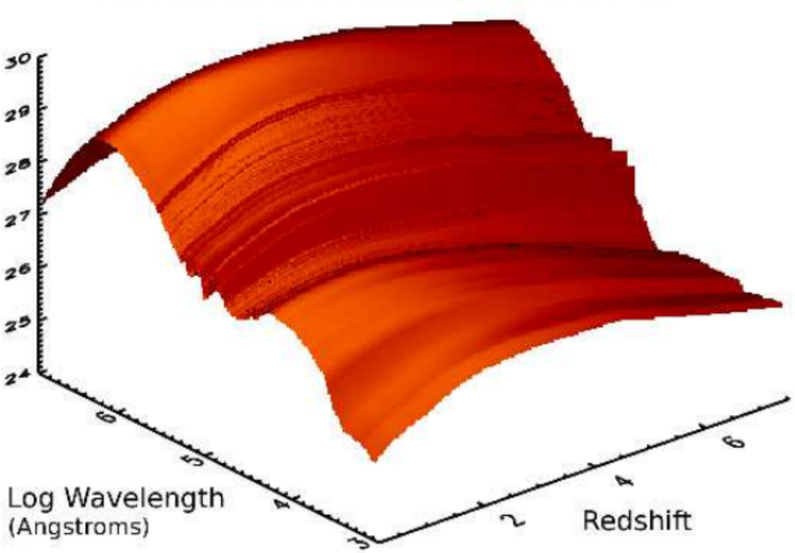
Uncertainties in photon fields and cross sections for nuclei interactions affect both UHECR production and propagation

Backup

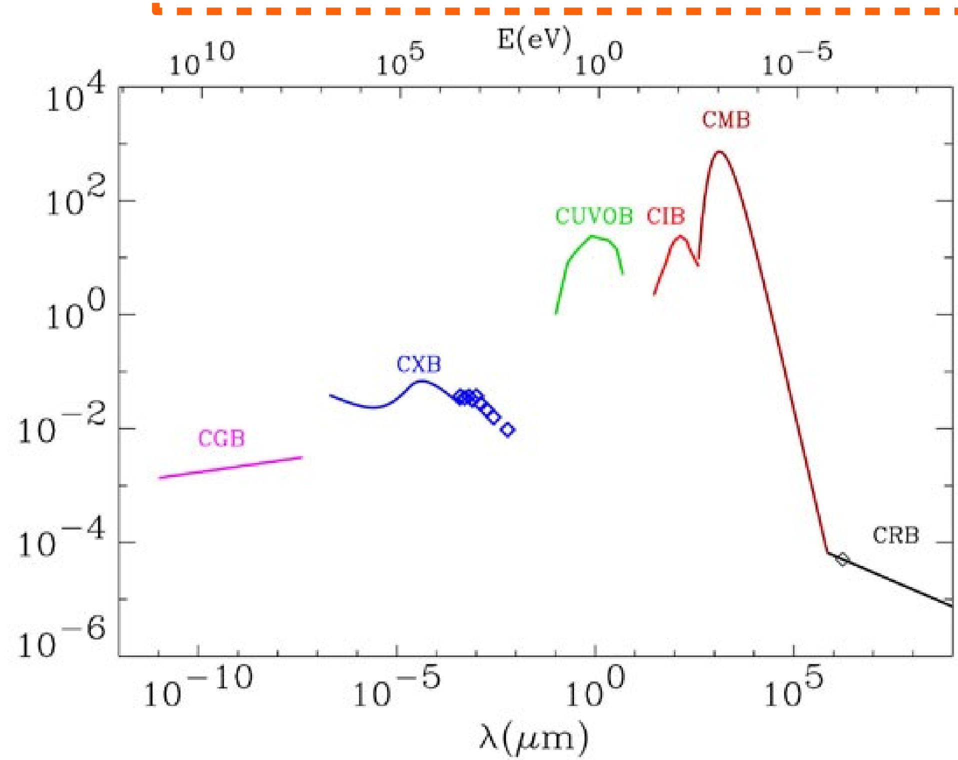
Extragalactic background light

- The cosmic microwave background (CMB), the relic blackbody radiation from the Big Bang, is the dominant background field, followed by ultraviolet/optical and infrared backgrounds.
- UV, optical and nearIR is due to direct starlight
- From midIR to submm wavelengths, EBL consists of reemitted light from dust particles

Different intensities and energy ranges of EBL allow different interactions of UHE particles



Gilmore et al. Mon.Not.Roy.Astron.Soc. 422 (2012) 3189



M.G. Hauser and E. Dwek, Ann. Rev. Astron. Astrop. 39 (2001) 249

Photon backgrounds

Measurements of the local EBL fall into 2 categories:

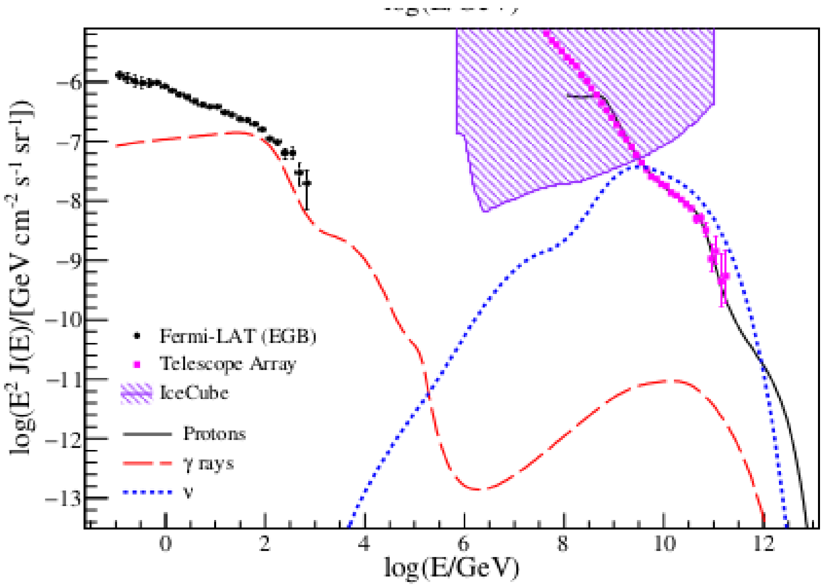
- Direct sky photometries → provide an absoulte measurement of the background light without regard of the source responsible, but require subtraction of the foreground sources present in our galaxy in order to isolate the extragalactic signal
- Integration of galaxy counts (galaxies per unit sky area at a given magnitude)

Understanding how the EBL is produced and how his spectral energy distribution evolves in redshift requires an understanding of the sources responsible for its production

- Forward evolution: predictions of evolution of galaxy emissivities are made by beginning from the universe in its primordial state and simulating the process of galaxy formation (semi-analitical models, Gilmore+2012)
- Backward evolution: begin with the present day galaxy luminosity function and attempt to trace this function backwards in time by assuming a funcional form for the redshift evolution (Stecker+2006)
- Direct observation of evolution in galaxy properties over the redshifts providing the major contribution to the background light (Dominguez+2011)

Neutrino and photon flux

$$S(z) = \begin{cases} (1+z)^m & z \leq 1 \\ 2^{m-n}\,(1+z)^n & z > 1 \;\&\; z \leq 6 \\ 0 & z > 6 \end{cases}$$



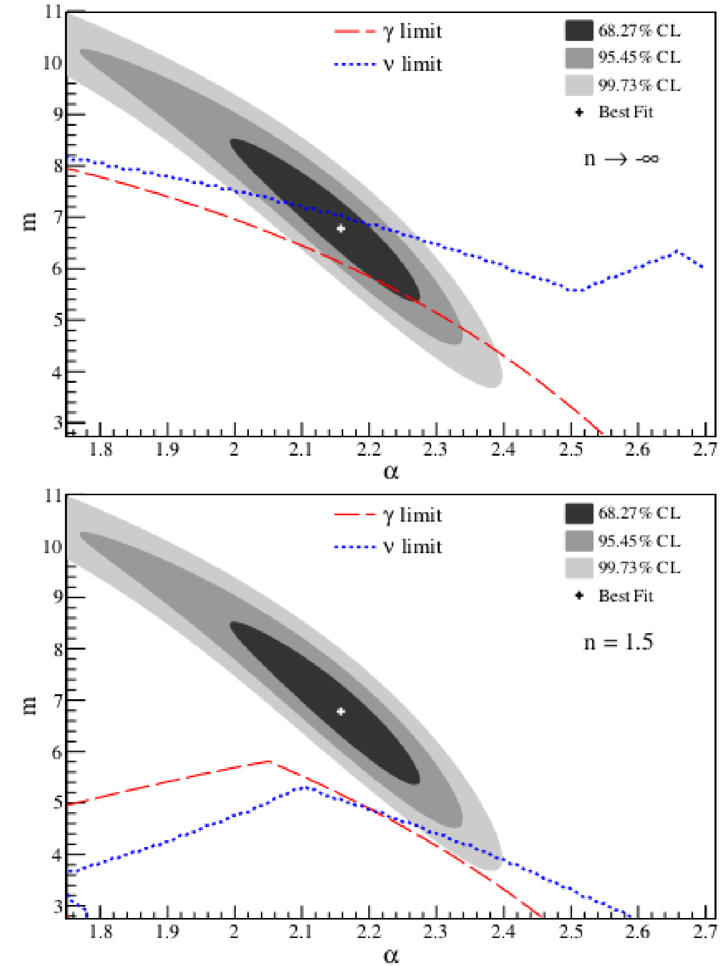
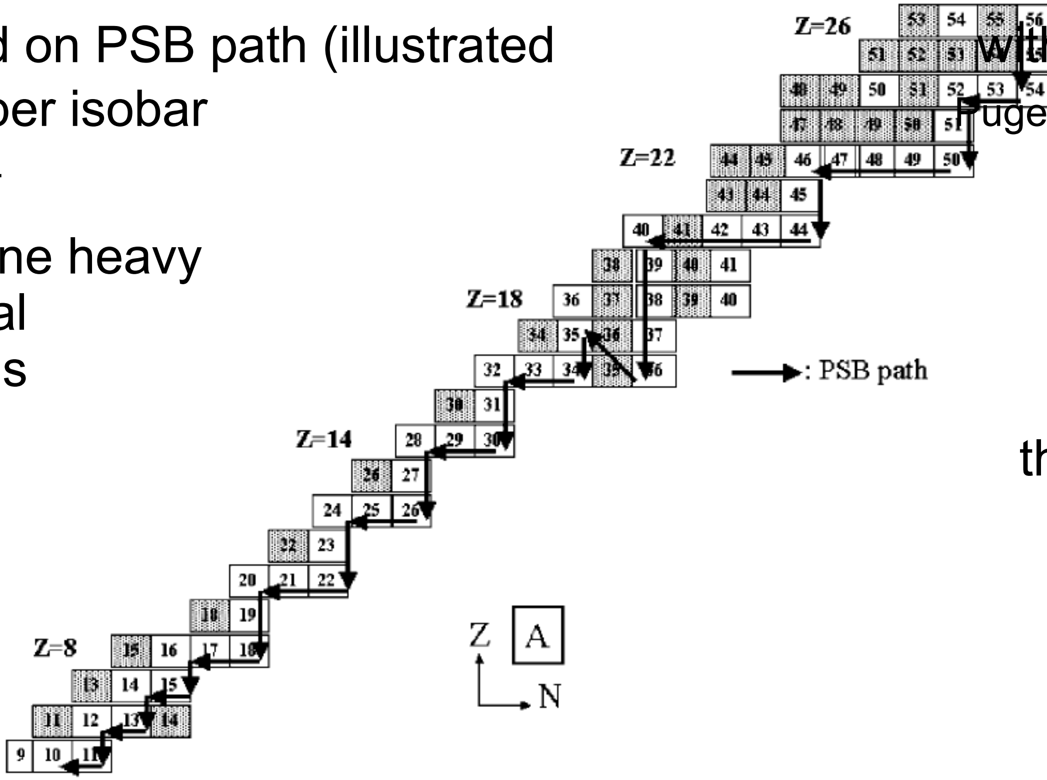


FIG. 2. Top panel: Best fit and confidence regions for $n \to -\infty$. The allowed regions corresponding to gamma-ray and neutrino observations are below the dashed and dotted curves, respectively. Bottom panel: Best fit and confidence regions for $n = 1.5$. The allowed regions corresponding to gamma-ray and neutrino observations are below the larger dashed and dotted curves and above the smaller ones in the bottom-left corner, respectively. The EBL model of Ref. [44] is considered and $E_{cut} = 10^{21}$ eV.

What do we need to model interactions in photon fields?

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

- Basic calculations were based on PSB path (illustrated with →), only one stable isotope per isobar Puget et al Astrophys.J. 205 (1976) 638-654
- In each photodisintegration, one heavy nucleus is produced in the final state, together with N nucleons
- No competitive channels in the same isobar



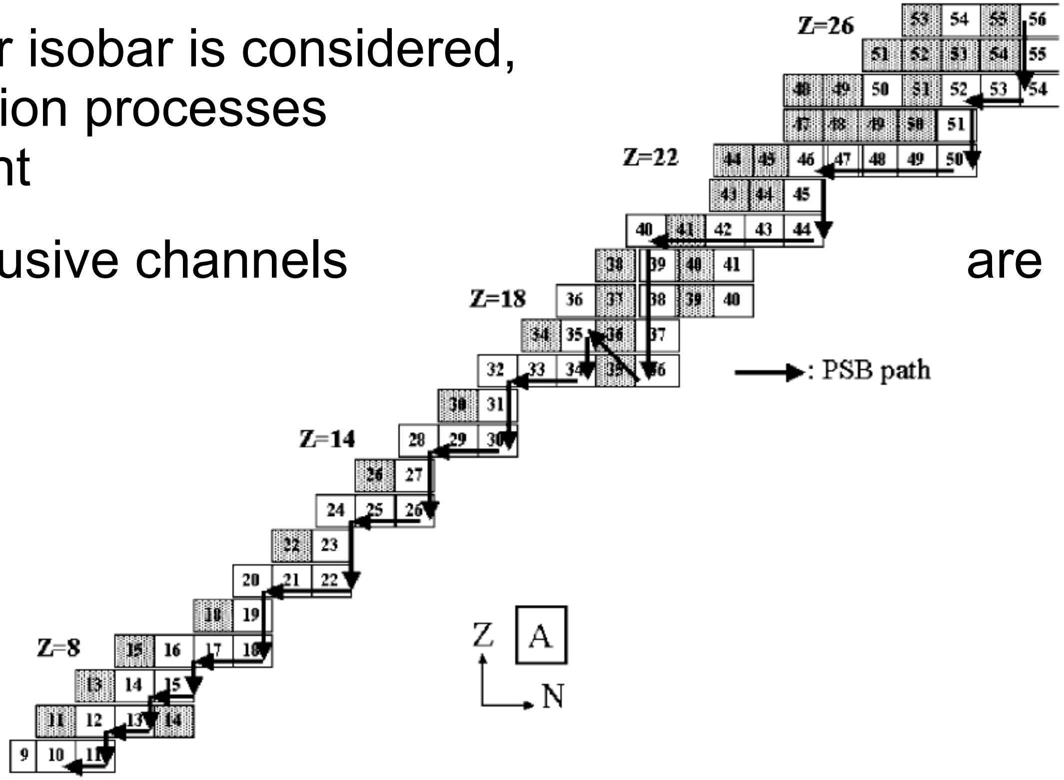
1) Is a nucleus able to escape the source without disintegrate?

→ 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>

What do we need to model interactions in photon fields?

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

- If more than one nucleus per isobar is considered, competitive photodisintegration processes have to be taken into account
- Branching ratios for the exclusive channels are needed



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 **residual cross sections** are needed for the development of the cascade

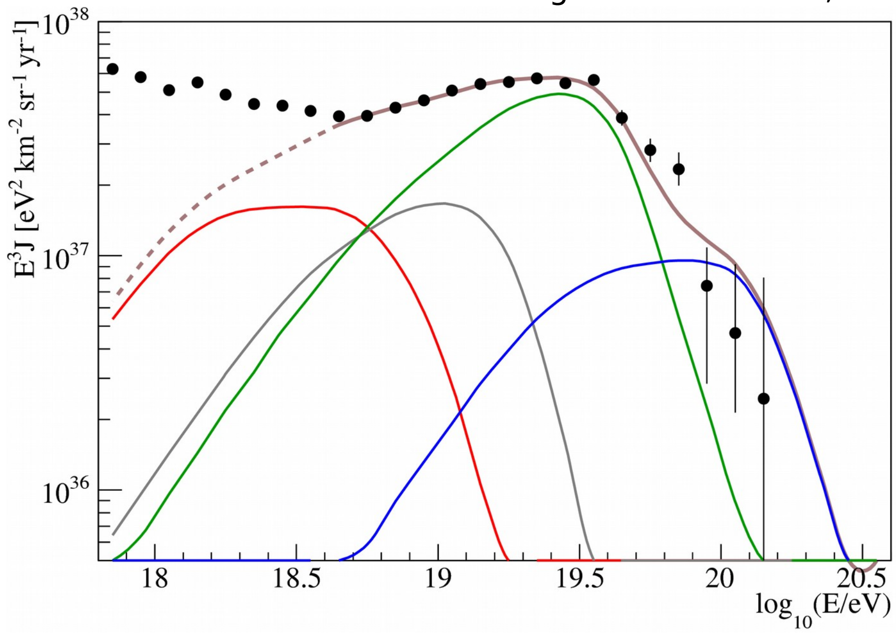
Dependence of astrophysical solutions on EBL models

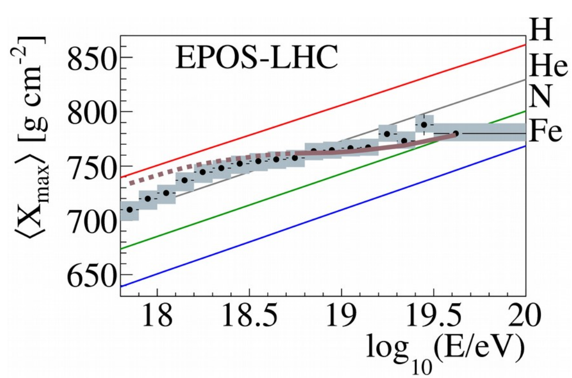
MODEL

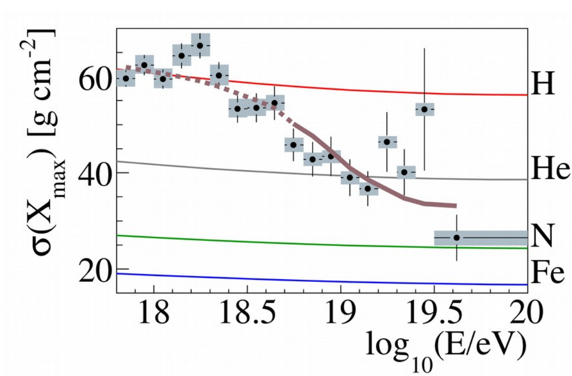
- *SimProp* propagation
- PSB cross sections
- Gilmore EBL
- EPOS-LHC air interactions

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

A. di Matteo for the Auger Collaboration, ICRC 2015







A=1 A=[2,4] A=[5,26] A=[27,56]

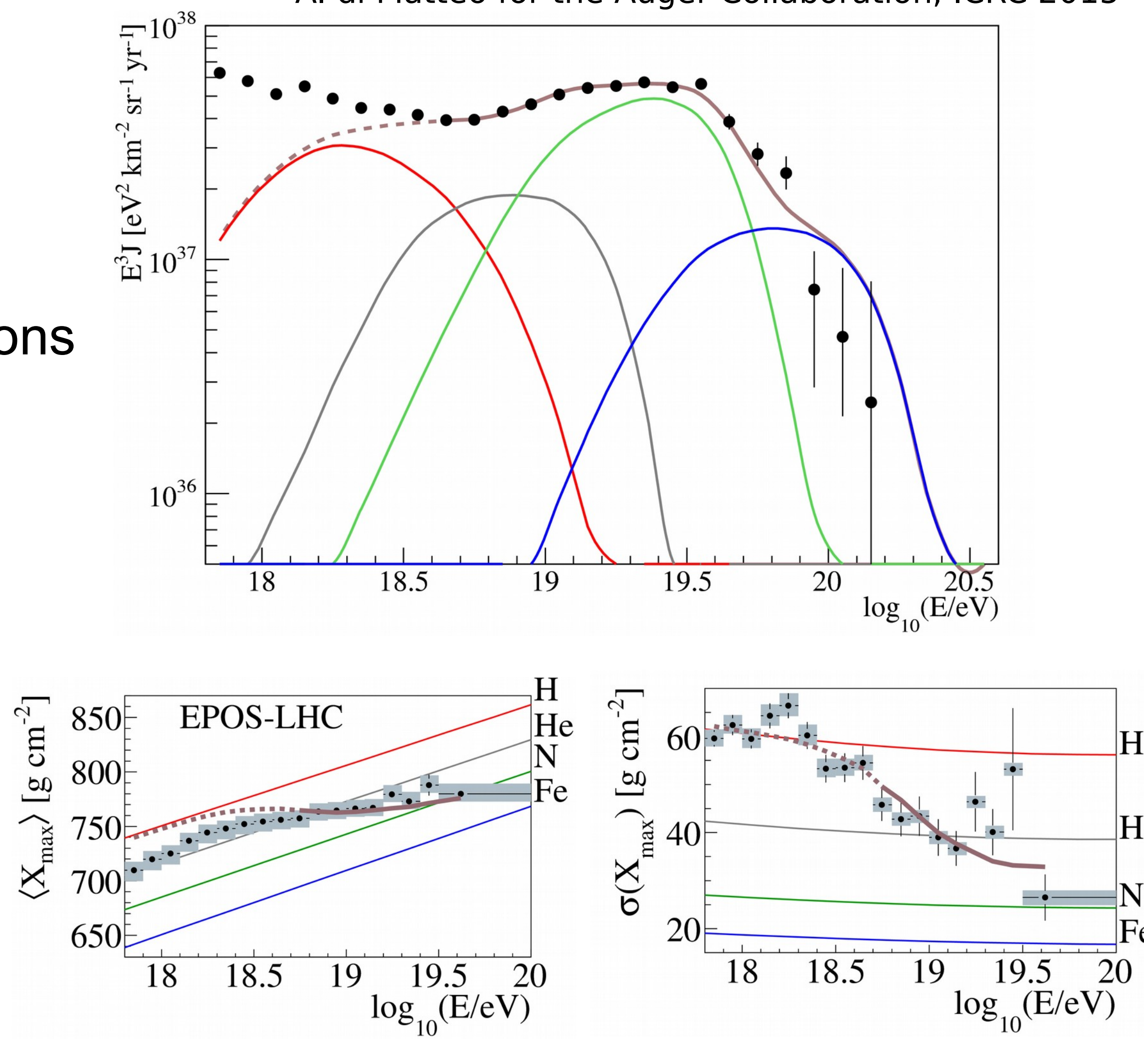
Dependence of astrophysical solutions on EBL models

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

A. di Matteo for the Auger Collaboration, ICRC 2015



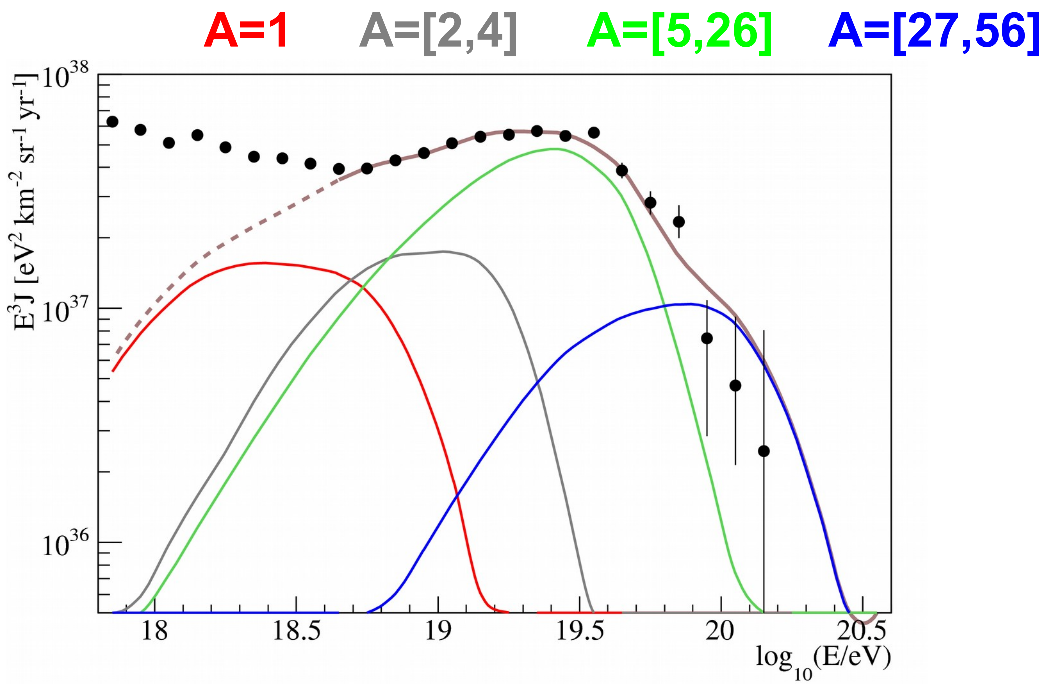
A=1 A=[2,4] A=[5,26] A=[27,56]

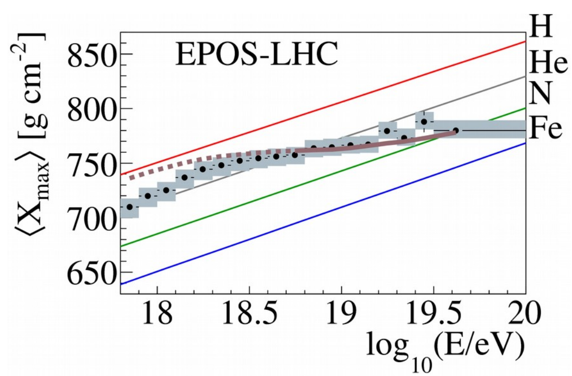
Fit results

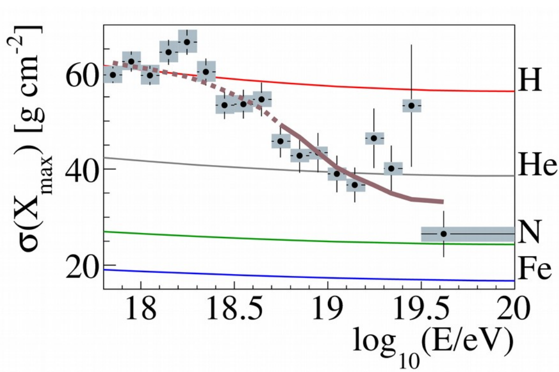
MODEL

- *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







DESY

Interaction framework and terminology

- We use the EXFOR database **https://www-nds.iaea.org/exfor/exfor.htm** to have a global view on measurements
- We are interested in the total photoabsorption cross section and in the inclusive cross sections

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

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

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

Inclusive cross section

Number of secondaries of type i produced per interaction

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

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

Impact of nuclear cross sections on astrophysical quantities

- 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:

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

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

Escape rate of the primary particle

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

- 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.

De

Description of 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.

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: first zone, 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 second zone 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

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

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

Situation on experimental data and theoretical models

- We use the EXFOR database
  https://www-nds.iaea.org/exfor/exfor.htm
- **No measurements of absorption cross section 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
  → use of interpolated or fitted absorption cross sections where available, as done in PEANUT, ENDF-B-VII.1, JENDL/PD-2004

  → use of parametrizations if cross sections are totally unknown

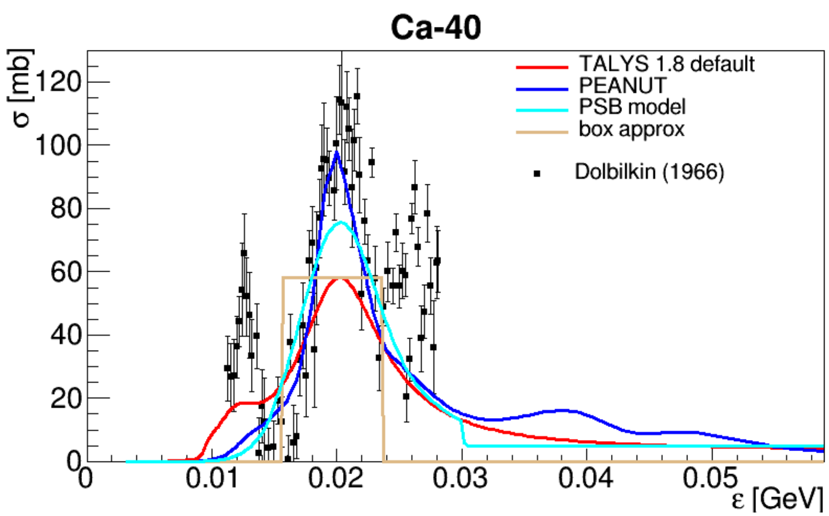
Other models:

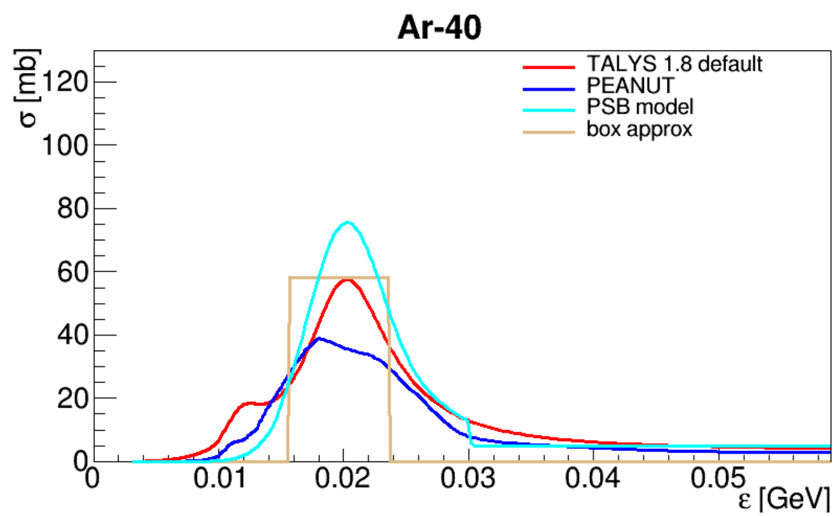
- PSB model is obtained from Puget, Stecker and Bredekamp, Astrophys. J. 205, 638 (1976). Use of one nucleus for each mass; cross section for one and two nucleon emissions is approximated by a Gaussian in the low energy range and by a constant above 30 MeV. Threshold for reactions taken from Stecker 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

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

Impact of nuclear cross sections on astrophysical quantities



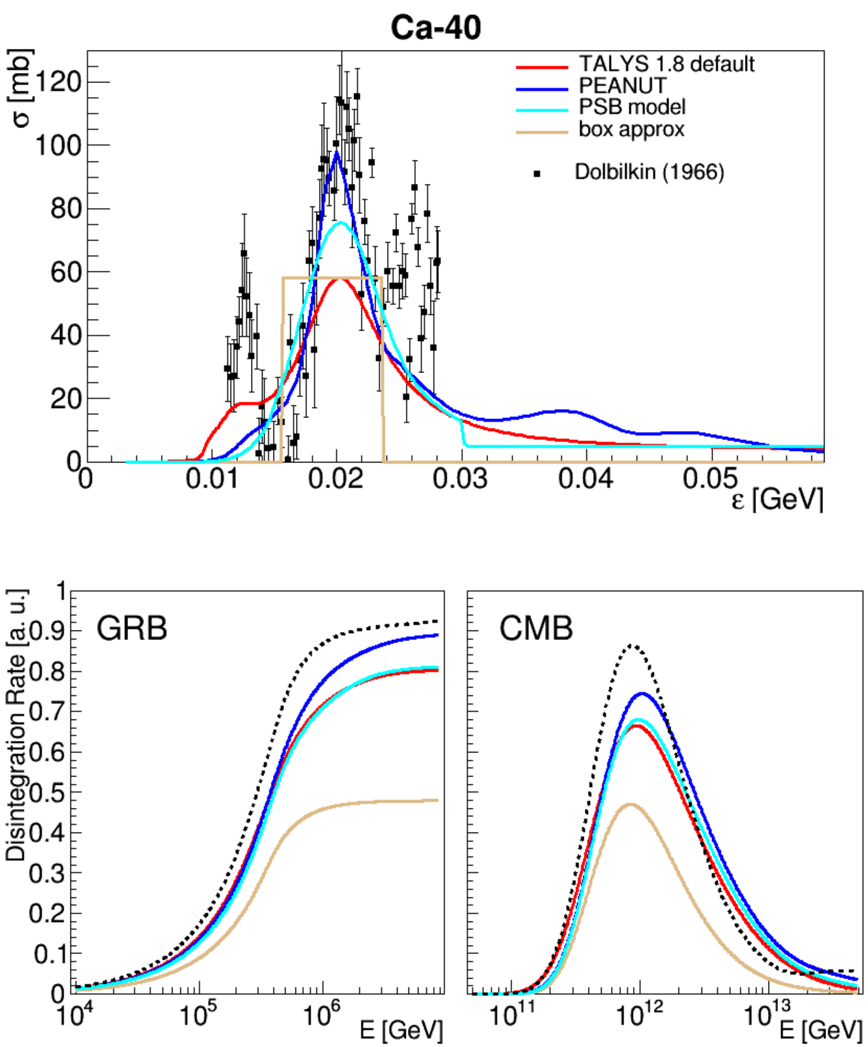


- TALYS predictions not dependent on the element
- PEANUT predictions are different in the same isobar; if data are available, at least the central GDR peak is reproduced
- Box approximation, used for example in Murase and Beacom, Phys Rev. D81 2010, underestimates data and models for A=40

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

DESY

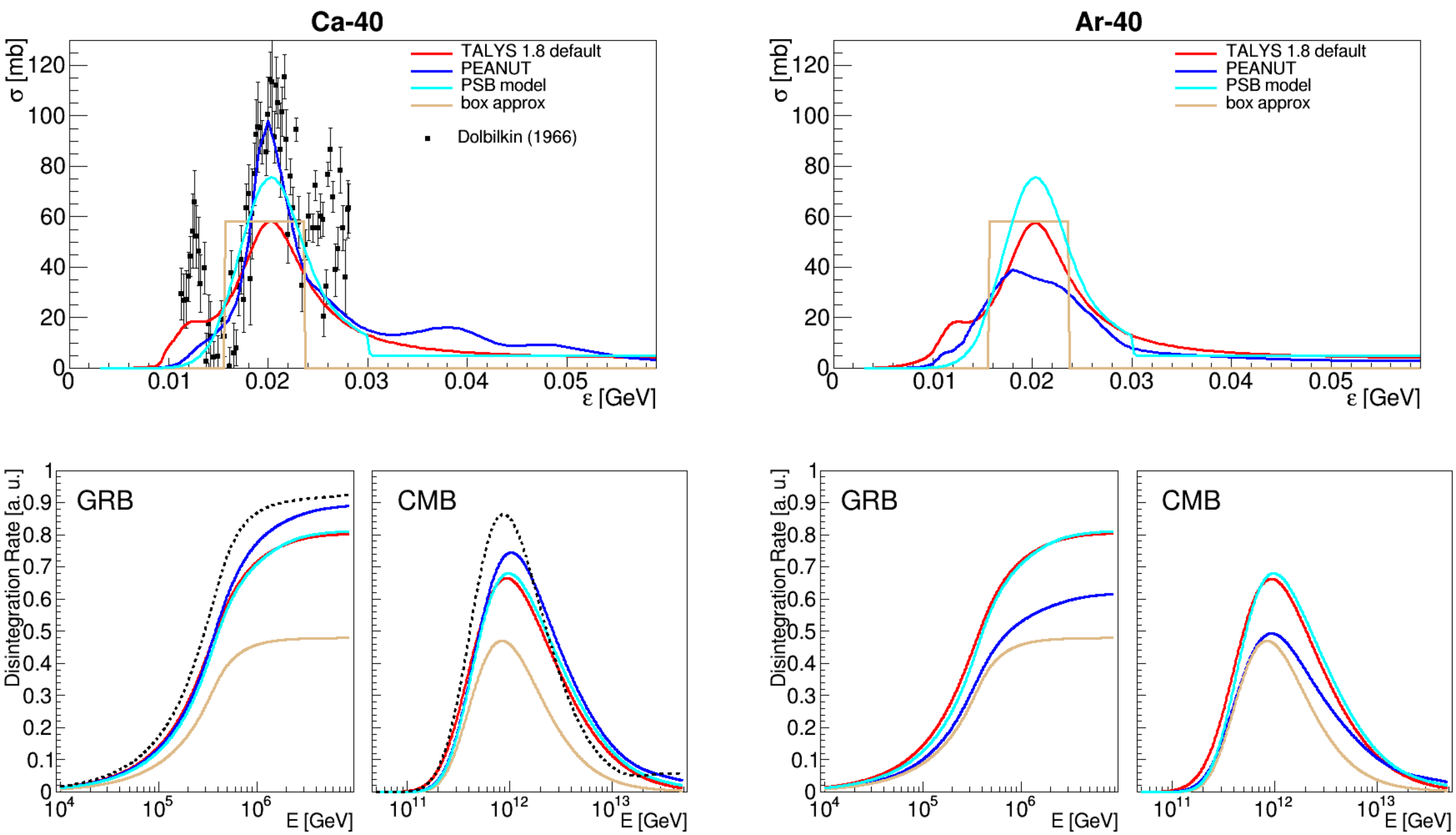
Impact of nuclear cross sections on astrophysical quantities



- Differences are more pronounced in the GRB case
- The interaction length is strongly affected by the cumulative effect of widths of the peaks in the cross sections than from the height of the main peak
- Measurements stop at a certain energy: visible effect in the corresponding interaction rates.

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

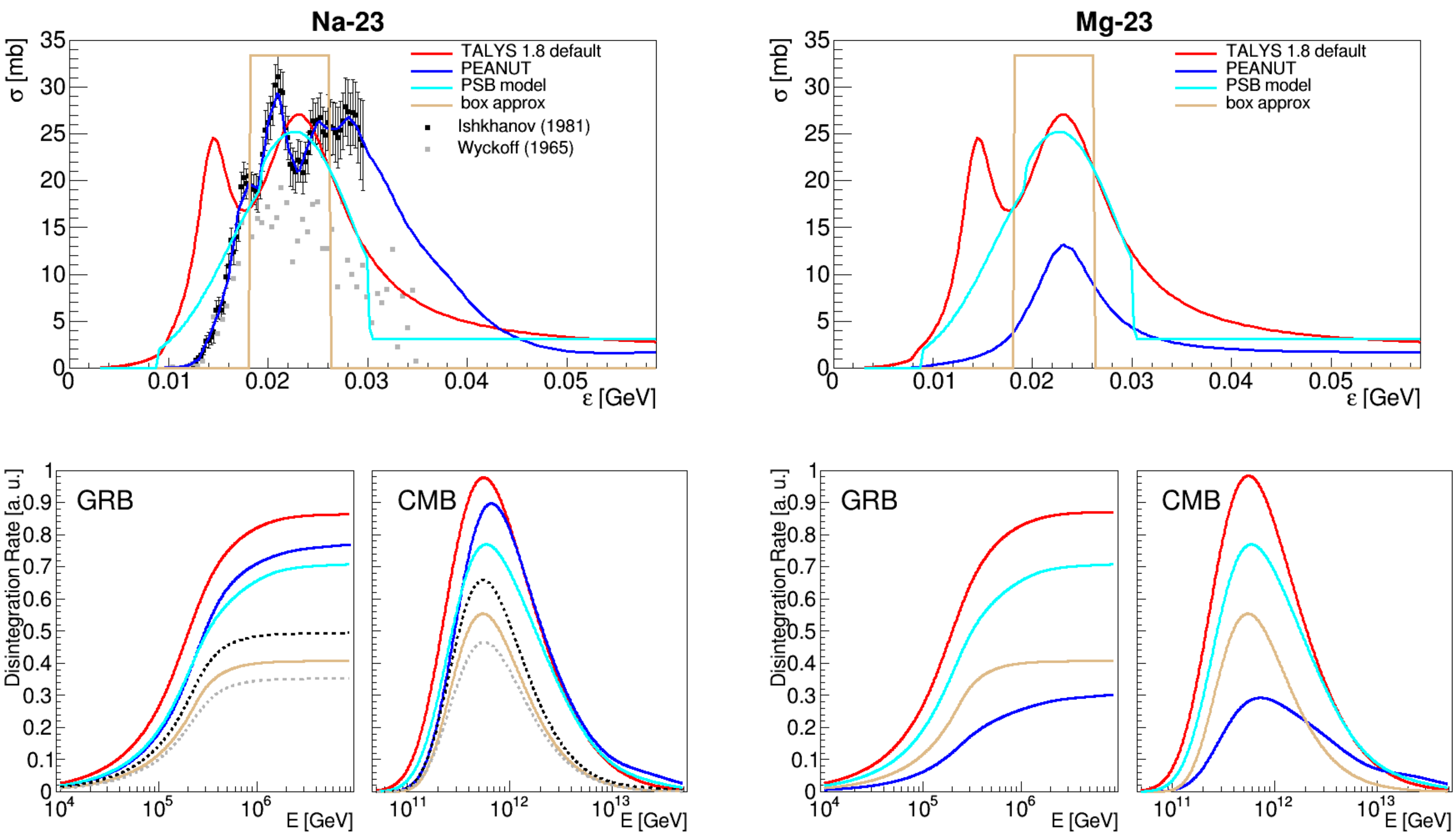
Impact of nuclear cross sections on astrophysical quantities



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

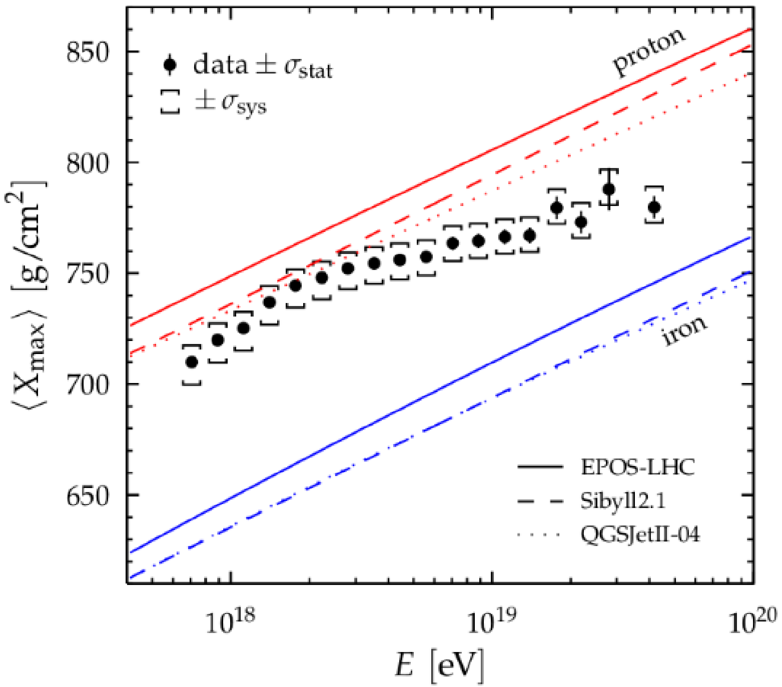
DESY

Impact of nuclear cross sections on astrophysical quantities



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

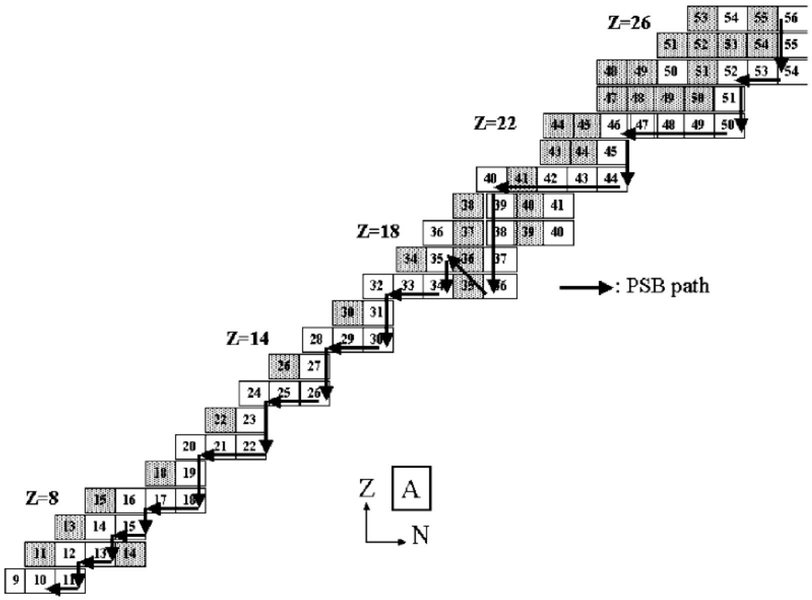
Effects on the nuclear cascade



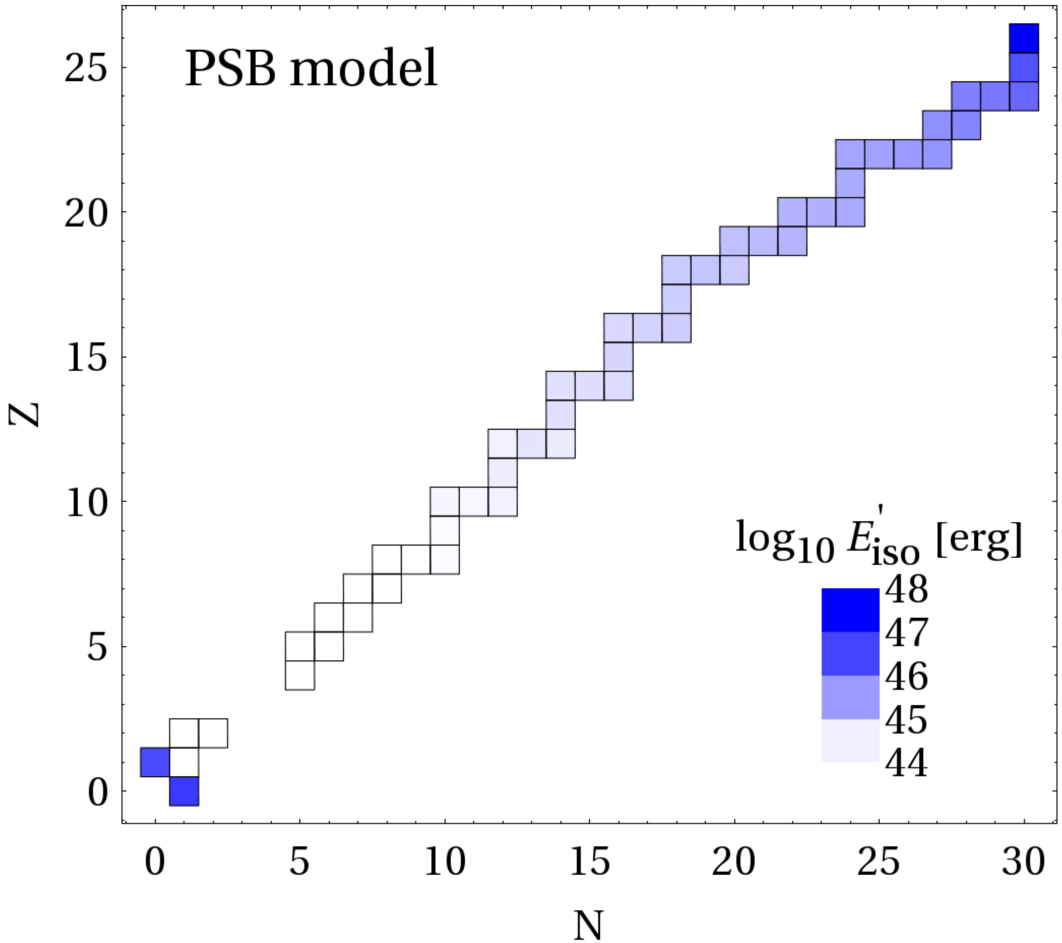
- Indication of heavy composition in UHECRs at the highest energies: if heavy masses are accelerated in the source site, they should be able to escape the source without being disintegrated → comparison between the **disintegration rate** and the **source size** is necessary → it is dependent on the photoabsorption cross sections

- Depending on the radiation density of the photon field in the source, a **nuclear cascade** may develop:

- even injecting only Fe, also other smaller masses will be emitted from the source



Effects on the nuclear cascade

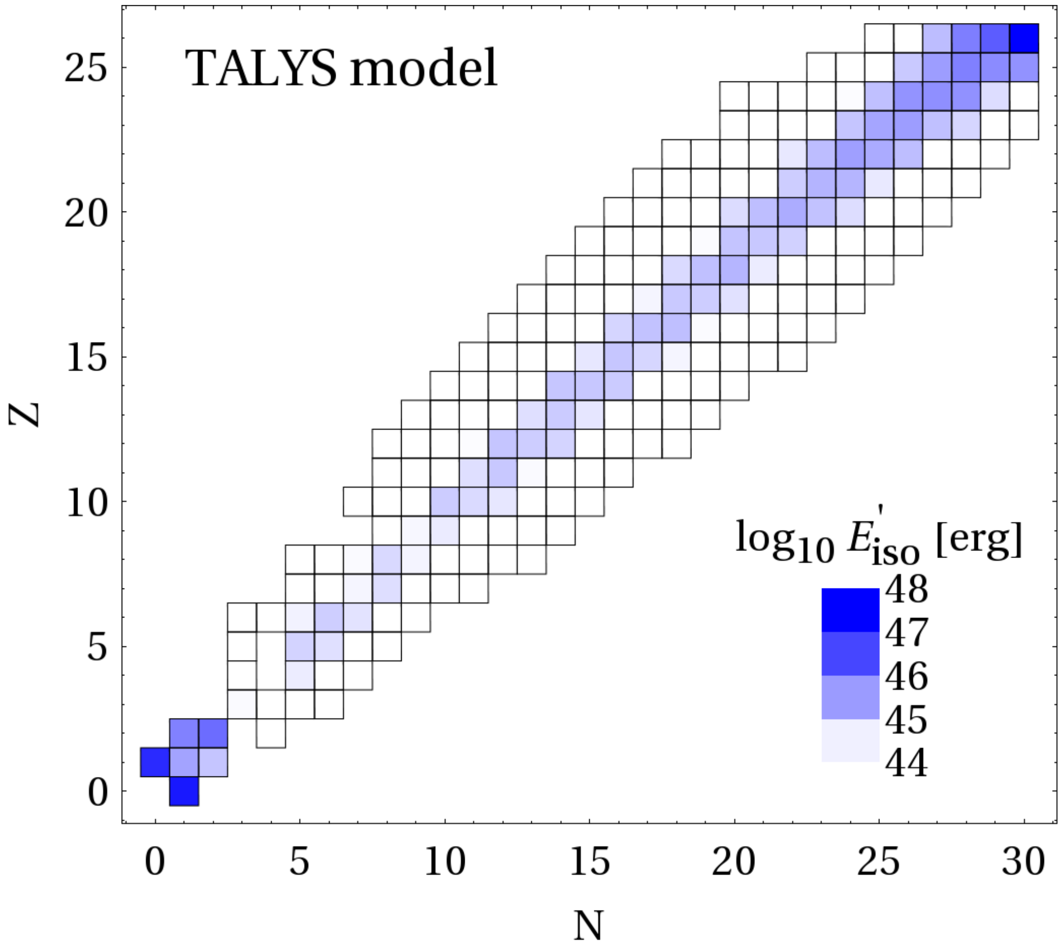


- One nuclide for each A
- Only small fragments can be ejected in photodisintegration
- The cascade is not completed, smaller masses are not populated

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

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

Effects on the nuclear cascade

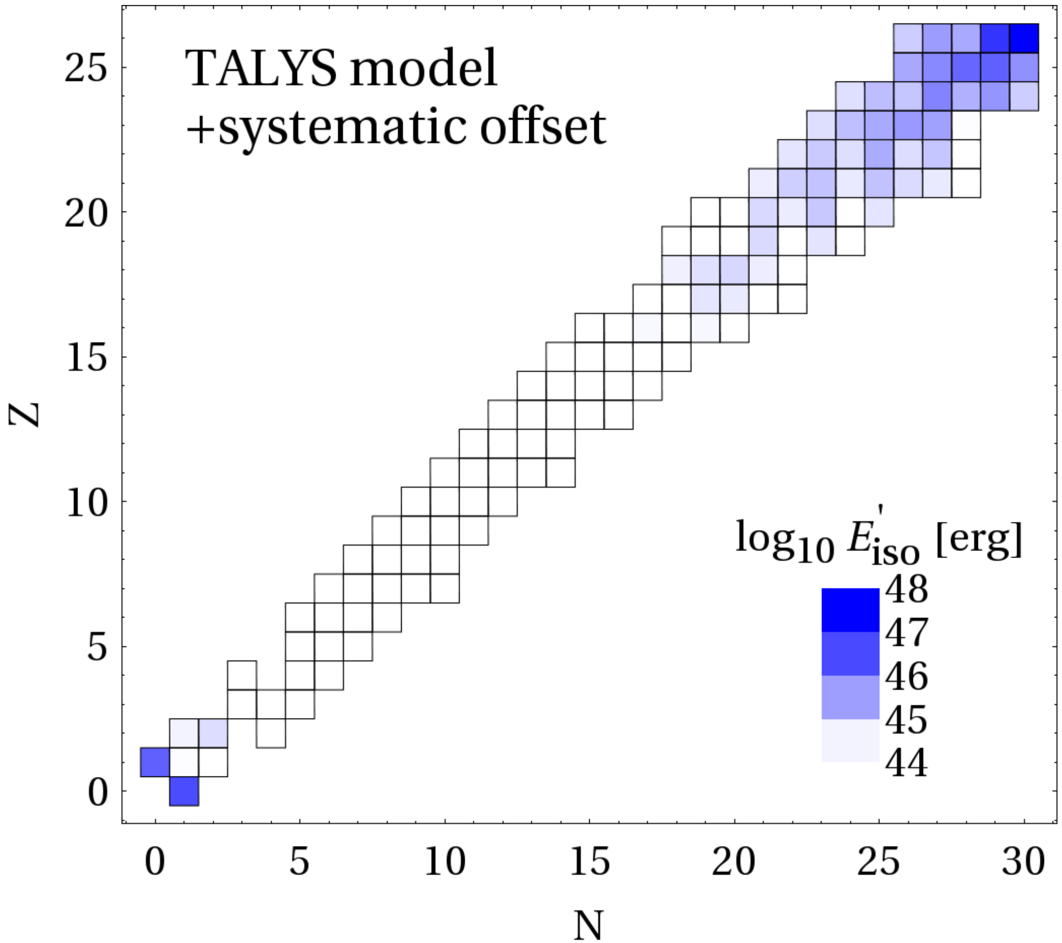


- Much more channels wrt PSB
- Small fragments ejected: p, n, d, t, He-3, He-4
- Chart almost fully populated (however, this also depends on the target photon density)
- PEANUT gives similar results

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

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

Effects on the nuclear cascade

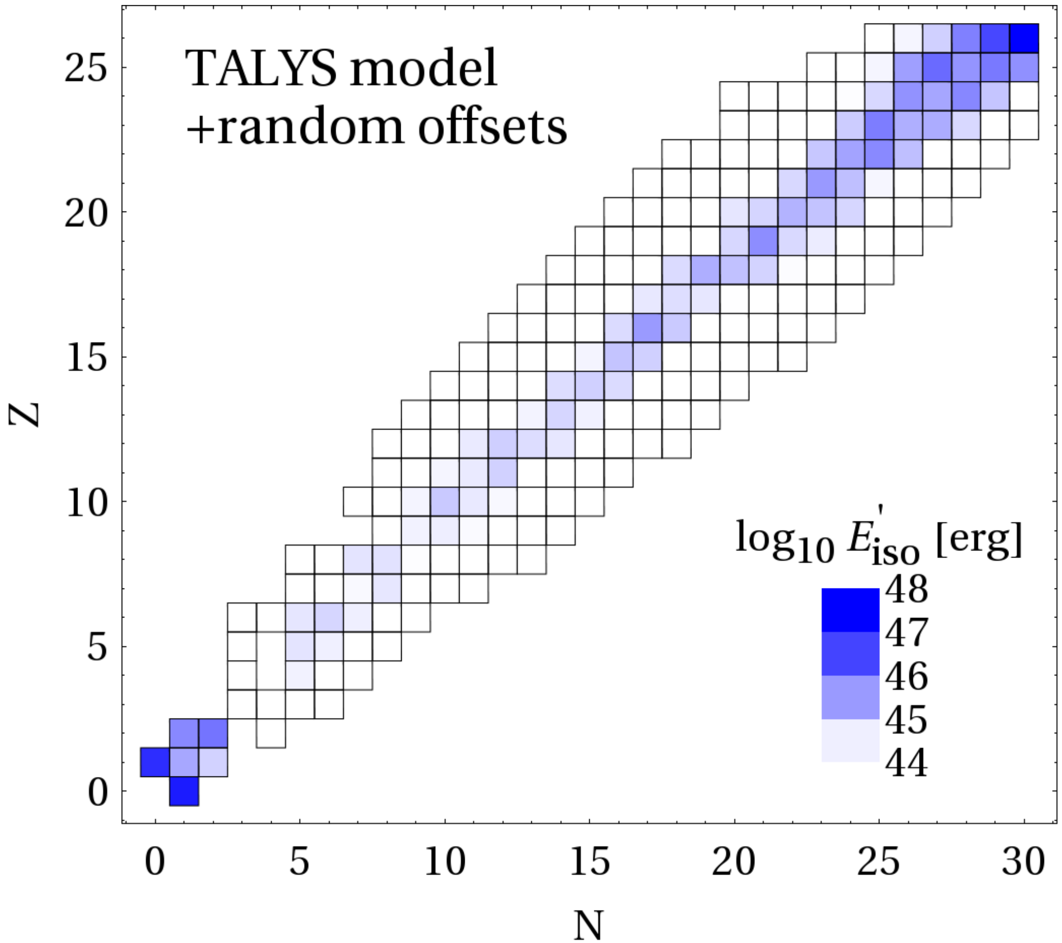


- Cross sections reduced by:
  - 1 if the absorption cross section is measured
  - 0.5 if any other cross section is measured
  - 0 if no data available
- Relying on data, the cascade cannot be populated

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

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

Effects on the nuclear cascade



- Cross sections reduced by:

  - 1 if the absorption cross section is measured

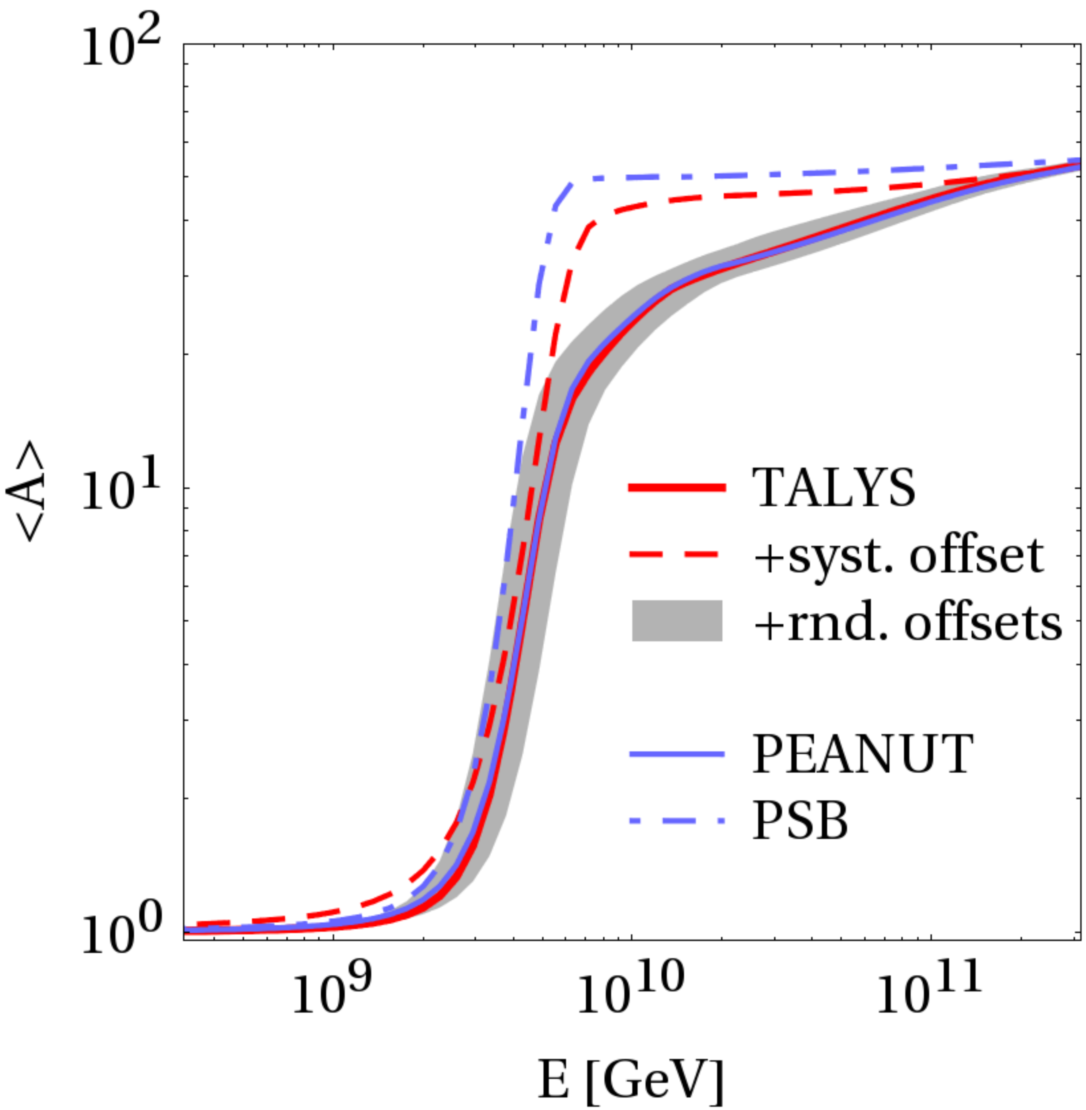
  - factor between 0.5 and 1.5 if any other cross section is measured

  - 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

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

UHECR composition at the source



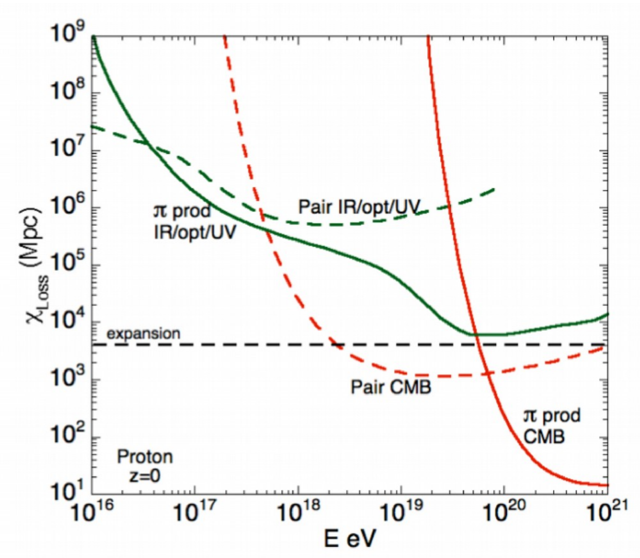
- No propagation effects considered
- Auger results qualitatively reproduced
- Simplified model PSB leads to a sharper increase of composition wrt more sophisticated models
- If only measured cross sections are included in the models, similar results to PSB

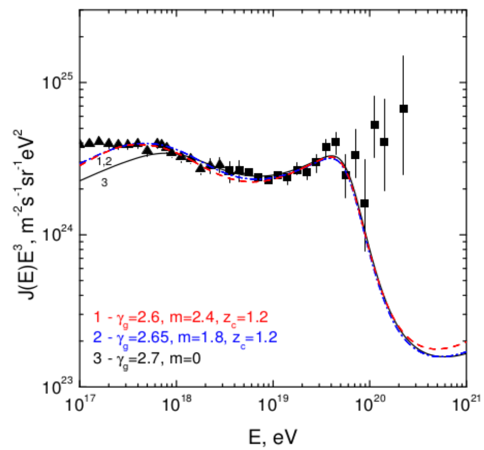
D. Boncioli, A. Fedynitch, W. Winter, in preparation

Interactions and energy losses for protons

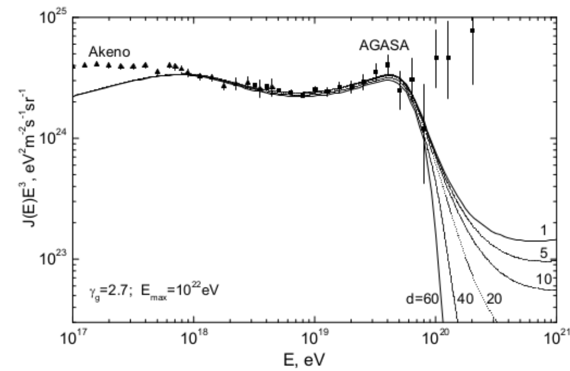
- Around 10^18.7 eV the spectrum exhibits a hardening: the "ankle"
- In the context of the dip model, the intermediate energy range is dominated by pair production

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





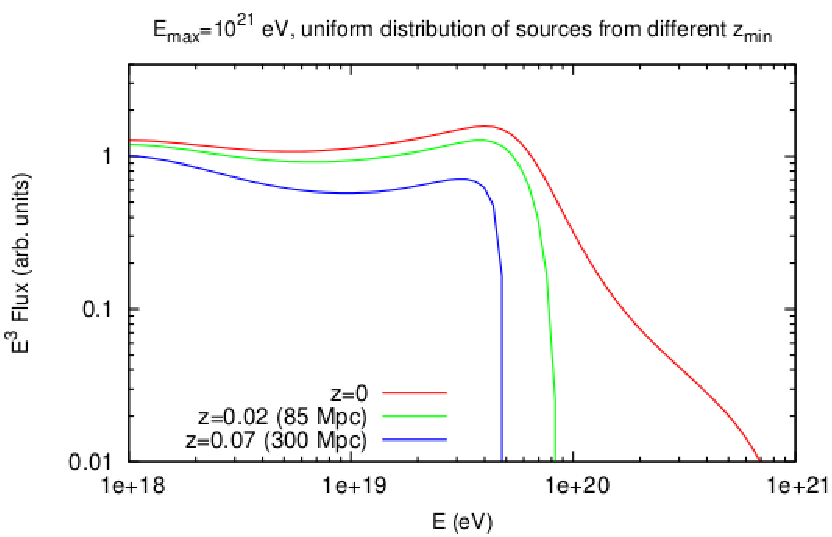
Berezinsky, Gazizov and Grigorieva, Phys.Rev.D 74 (2006)



- Due to the interaction length of the process, this feature is less sensitive to details of the distribution of sources wrt the suppression
- Hillas and Blumenthal studied the effect of pair production on protons above 1 EeV → Hillas, Phys. Lett. 24A 677 (1967), Blumenthal, Phys. Rev. D Vol 1 1596 (1970)

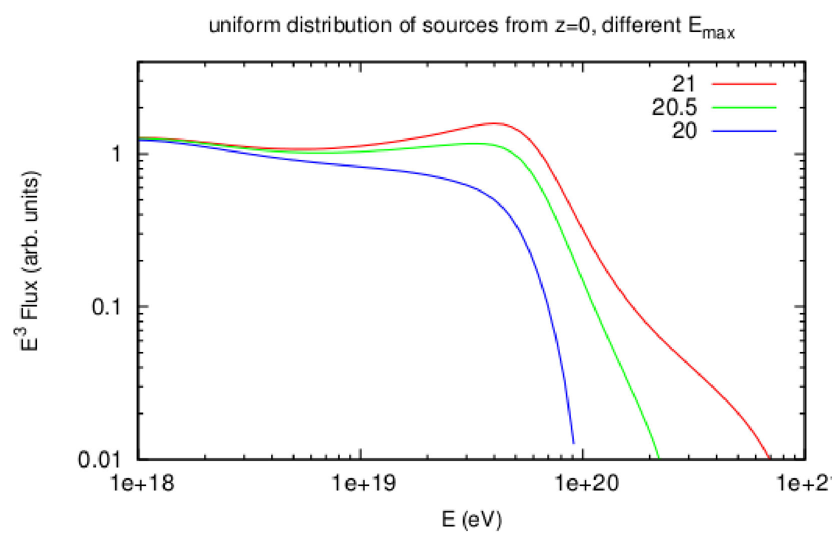
Propagated spectrum – pure protons at injection

- Suppression due to propagation: CR interactions with the photon background, effect of the minimum distance of the sources



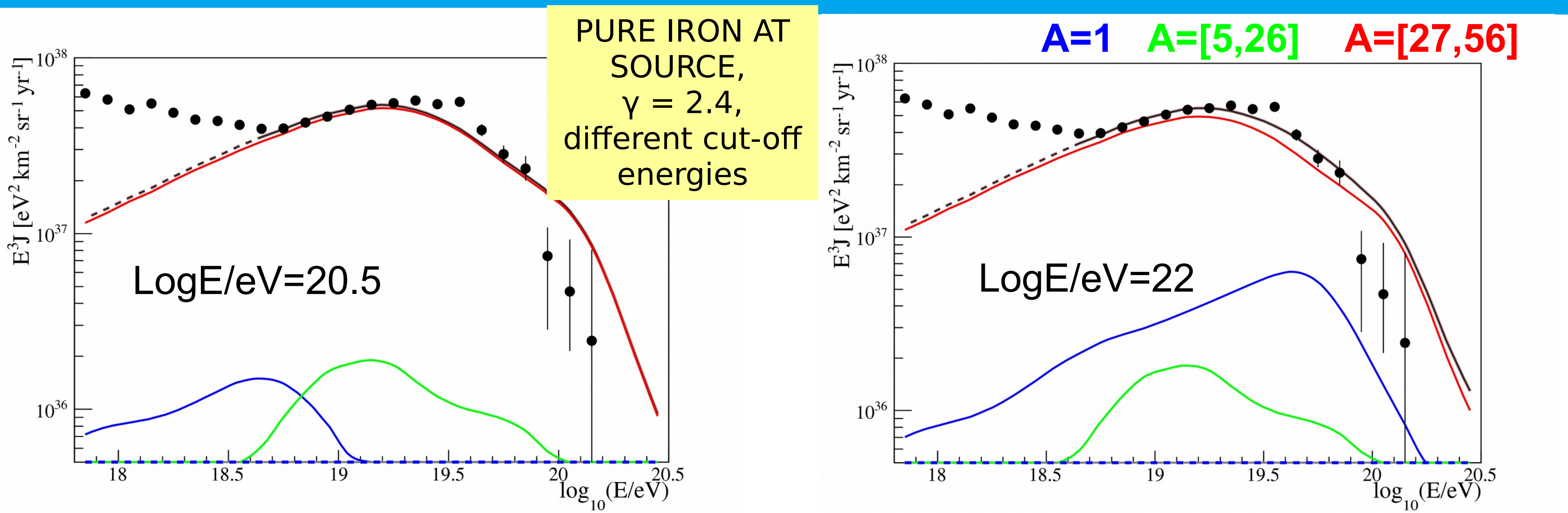
- Suppression due to properties of the sources: maximum energy of acceleration of injected protons

R. Aloisio & DB, Astrop. Phys. 35 (2011) 152-16



- Even in the simple case of a pure proton composition, the suppression can be due to different aspects or to a combination of them.
- With the assumption of pure proton composition, how can the spectrum features be investigated?

Propagated spectrum – pure iron nuclei at source



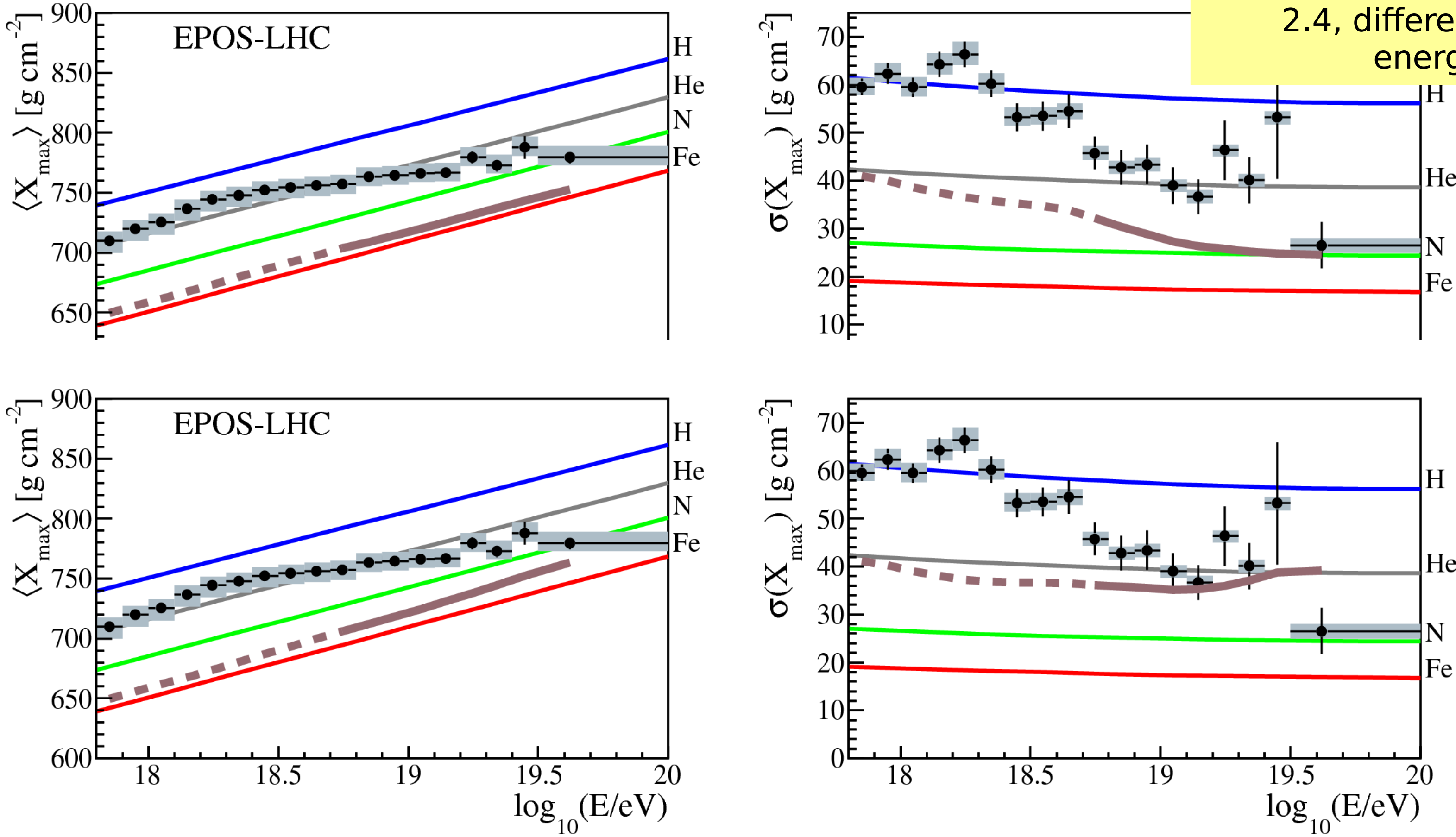
→ As for pure protons, <u>the spectrum has similar features with different hypotheses on the characteristics of the sources</u>

→ Secondary nucleons produced in the photodisintegration chain have energies not larger than E(Fe) /A ⇒ in the case of cut-off=20.5 the secondary protons are confined at low energies wrt the case of cut-off=22

→ this affects the composition observables

Composition observables – pure iron nuclei at the source

PURE IRON AT SOURCE, γ = 2.4, different cut-off energies



LogE/eV= 20.5

LogE/eV= 22

- The effect of propagation is seen in the RMS as responsible for the mass dispersion, making the RMS higher with respect to pure masses hitting the atmosphere → see Auger Collaboration, JCAP 1302 (2013) 026
- The suppression of the energy spectrum can be investigated by using the information added by the composition observables (if nuclei at the source)

Scales of Interactions

Let's consider a particle at energy $E = \Gamma m_N$

During the travel, the particle interacts with background photons:

$$s = m_N^2 + 2E\epsilon(1 - \beta\cos\theta) = m_N^2 + 2\mathrm{m}_N\epsilon'$$

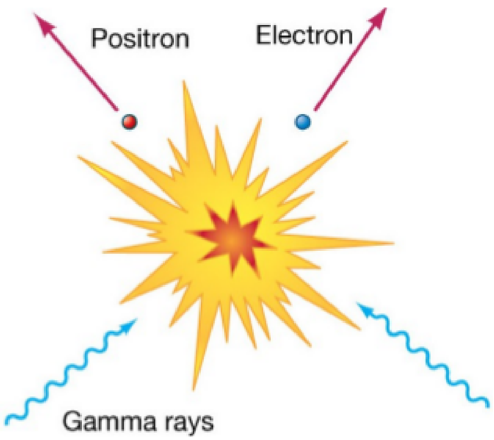
- Energy amount for the reaction: $\sqrt{s} - m_N \simeq \epsilon' + O(2\epsilon'/m_N)^2$

→ the relevant energy scale for the interaction is the energy of the background photon in the particle rest frame

- UHE particle in the lab frame → $\epsilon' \simeq \Gamma\epsilon$

→ low energy photons therefore appear as high energy gamma rays for the cosmic ray particle.

Scales of Interactions

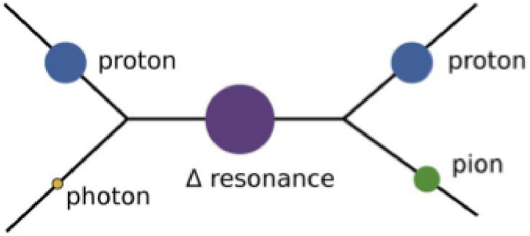


Photon energy in the particle rest frame:
$\varepsilon' > 1$ MeV

- CMB radiation
  $$\left(10^{-5} < \epsilon < 10^{-3}\, eV\right) \rightarrow \Gamma \approx 10^{9} \div 10^{11}$$
- Pair production can occur with lower Lorentz factor of the particle in the EBL with respect to CMB

Photon energy in the particle rest frame:
$\varepsilon' > 150$ MeV

- Photopion production shifted towards higher Lorentz factor values with respect to the pair production



Energy threshold for reactions depends on the mass of the particles → for example, photopion production for nuclei is shifted towards higher energies with respect to nucleons.