Interactions of UHE Cosmic Rays

What do we learn from Nuclear Physics aspects?

Denise Boncioli

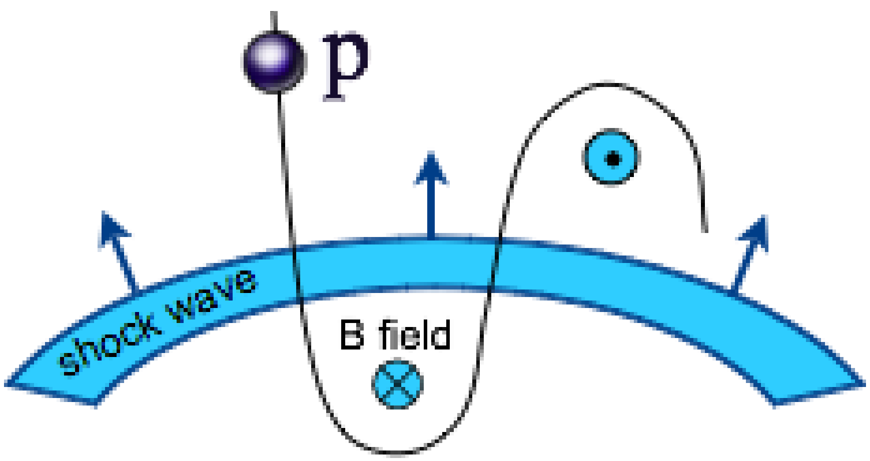
GSSI, L'Aquila, Italy

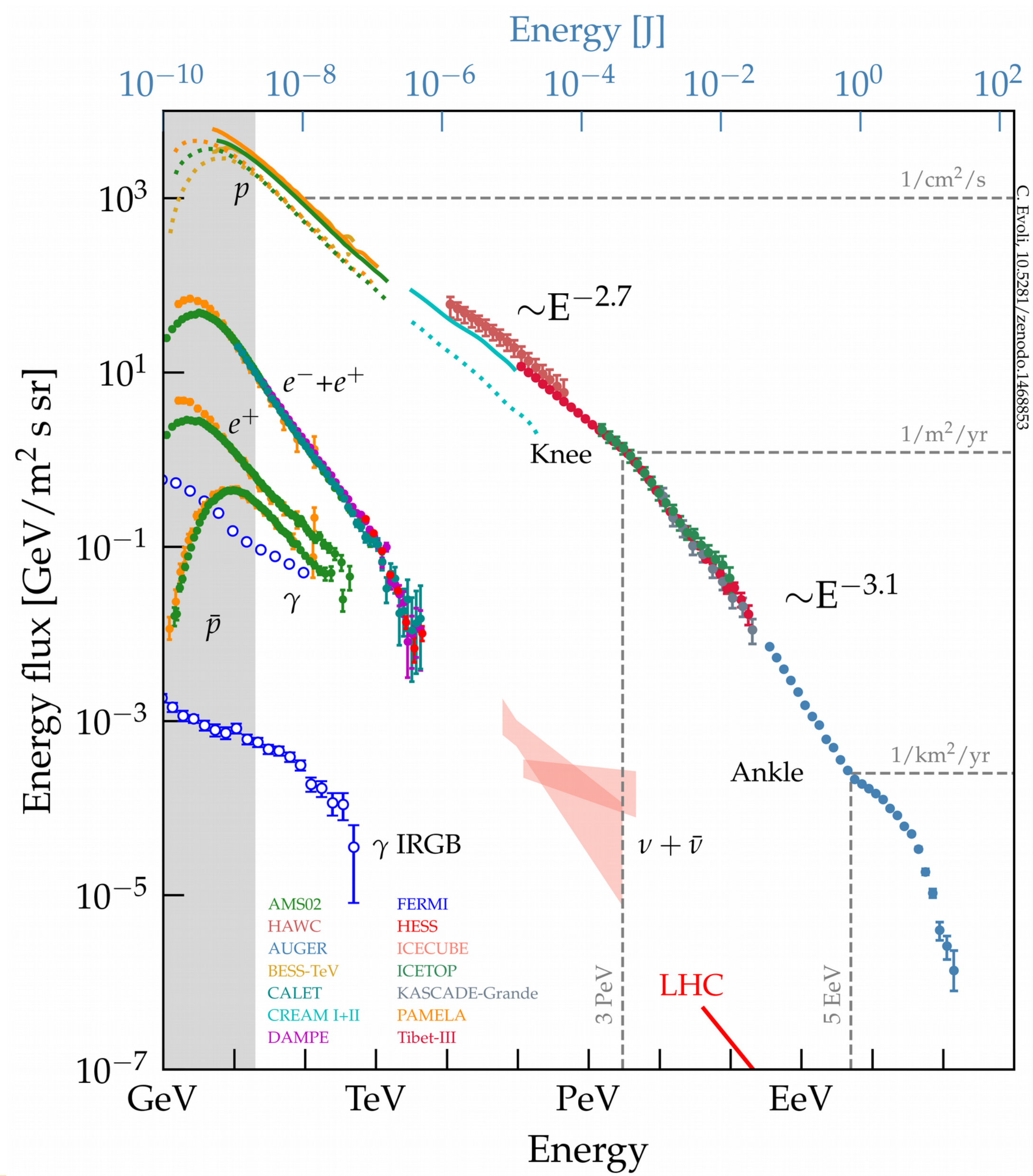
Women in Nuclear and Hadron Theoretical Physics: the last frontier - WTPLF 2018

Genova, 10-11 December 2018

What do we observe? Cosmic Ray Flux

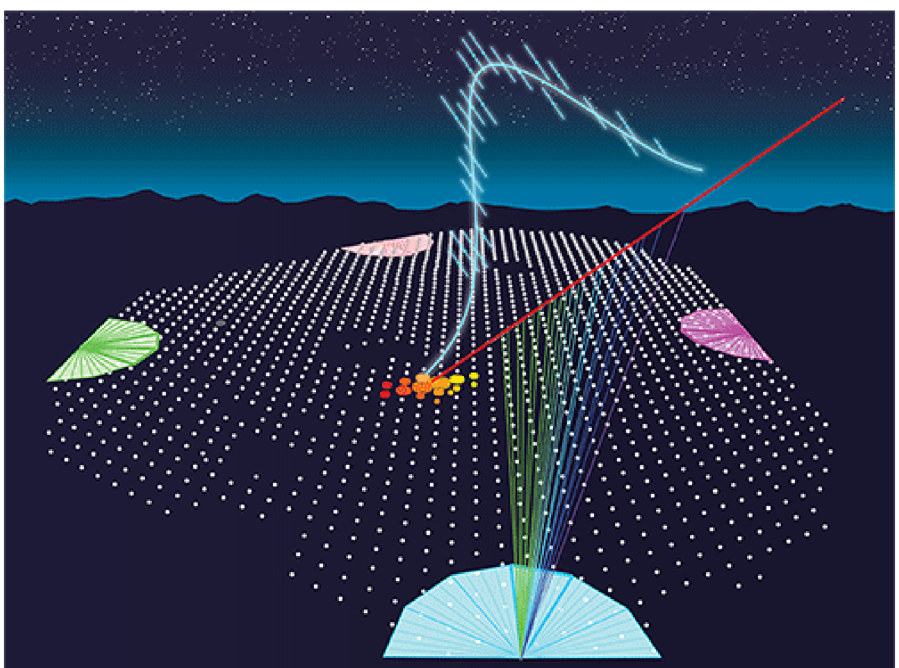
- It extends over many orders of magnitude, different techniques needed for measurements
- Power-law → similar mechanisms of production at different energies ?
  - Acceleration in shocks → Astrophysical objects with jet formation: Gamma-Ray Bursts, Active Galactic Nuclei, ...

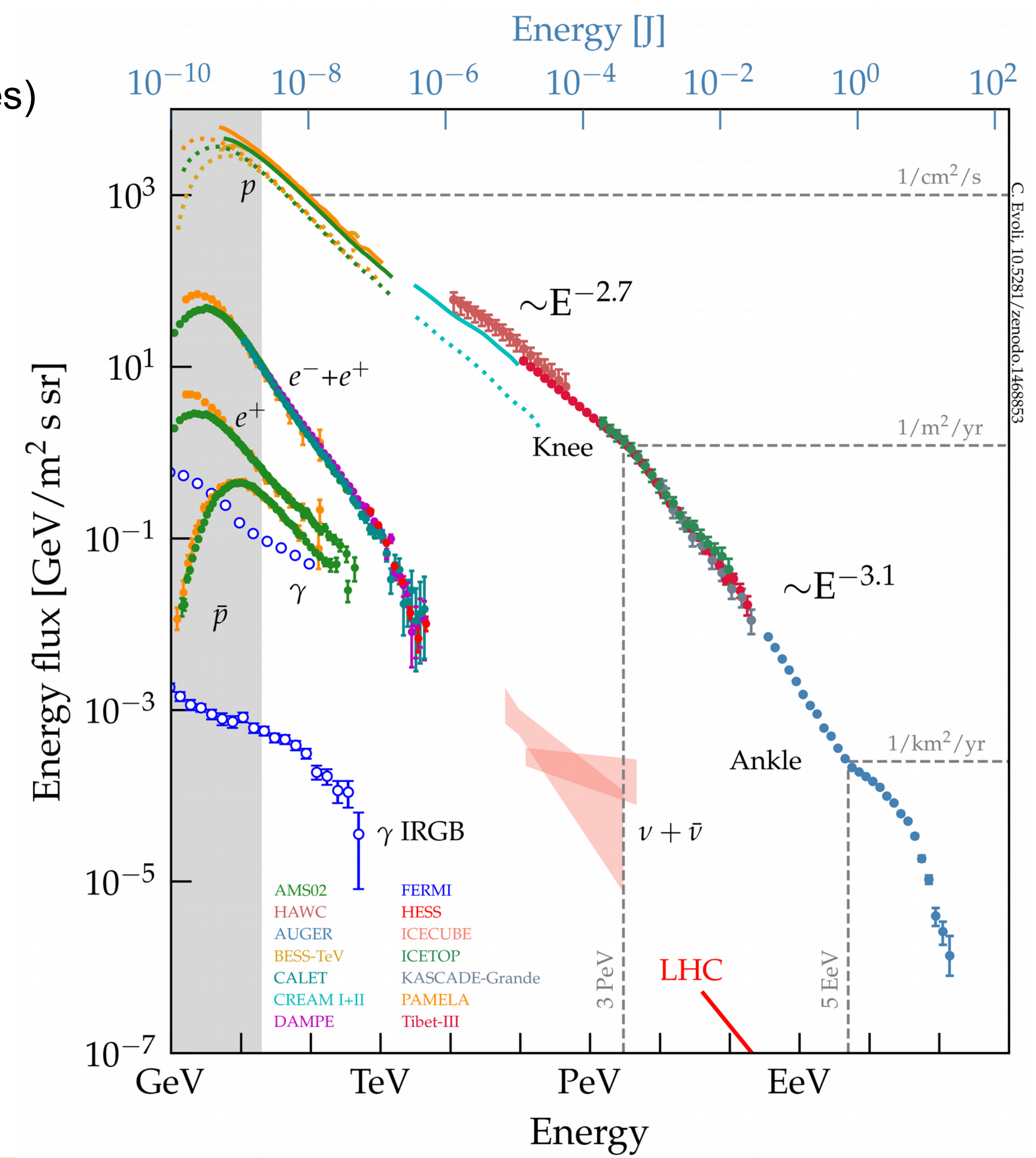




What do we observe? Cosmic Ray Flux

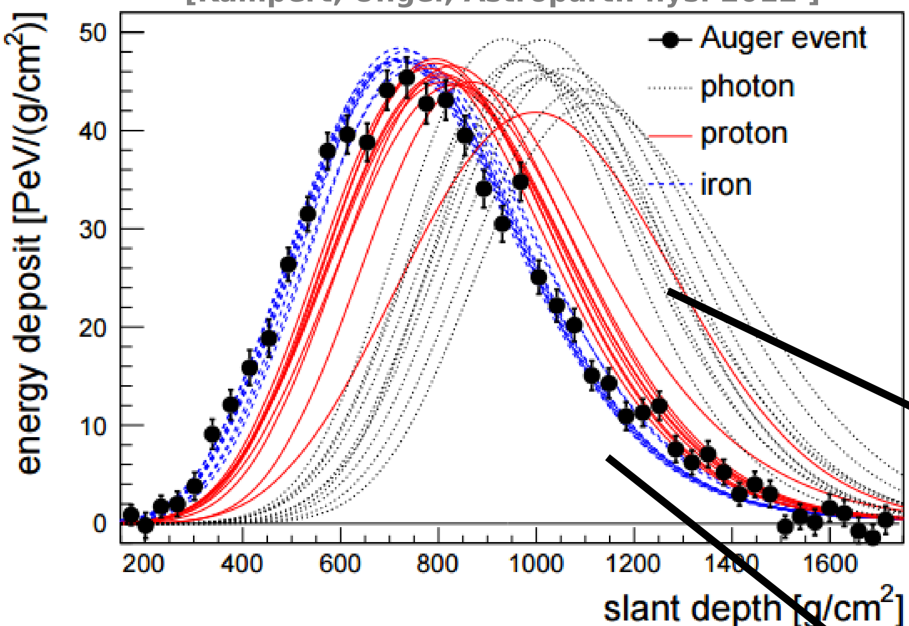
- It extends over many orders of magnitude, different techniques needed for measurements
- Ultra-High Energies (mostly extragalactic sources)
  - → Pierre Auger Observatory
  - → Telescope Array
    - Measurement of energy deposit in atmosphere
    - Collection of particles at ground



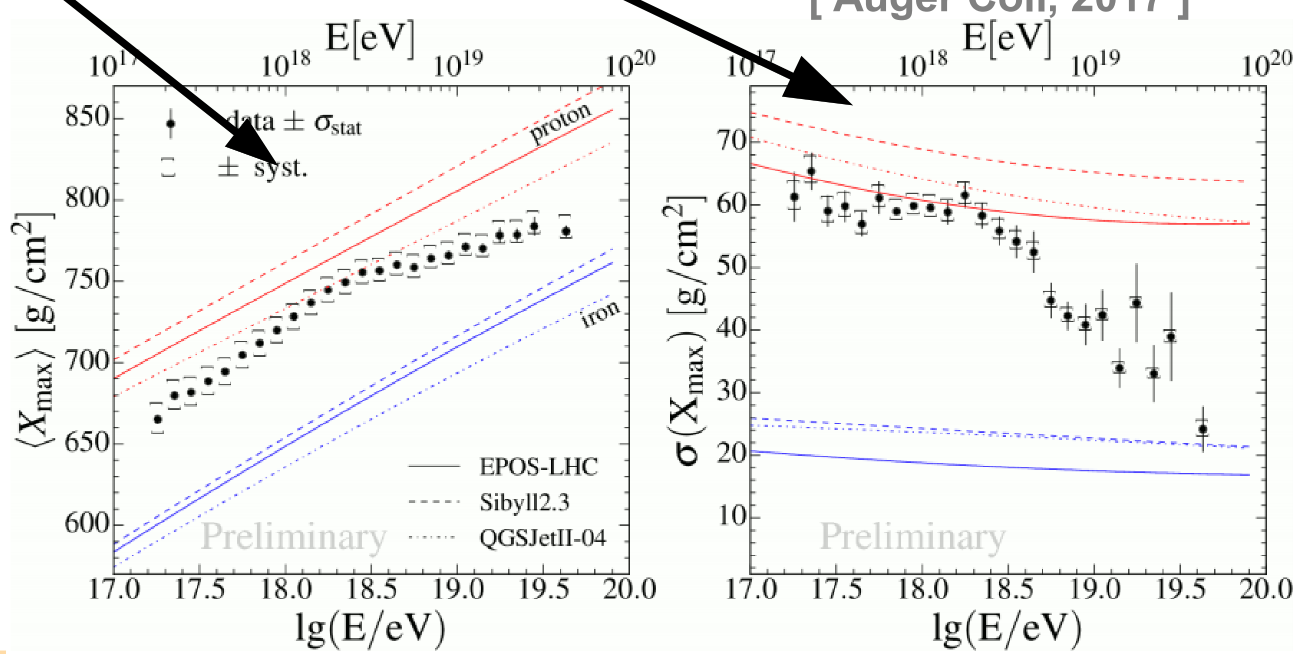


What do we observe? UHECR Composition

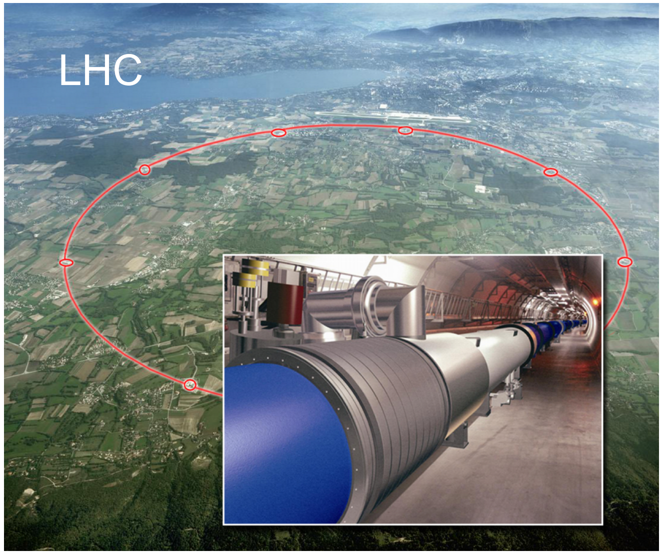
[Kampert, Unger, Astropart.Phys. 2012]



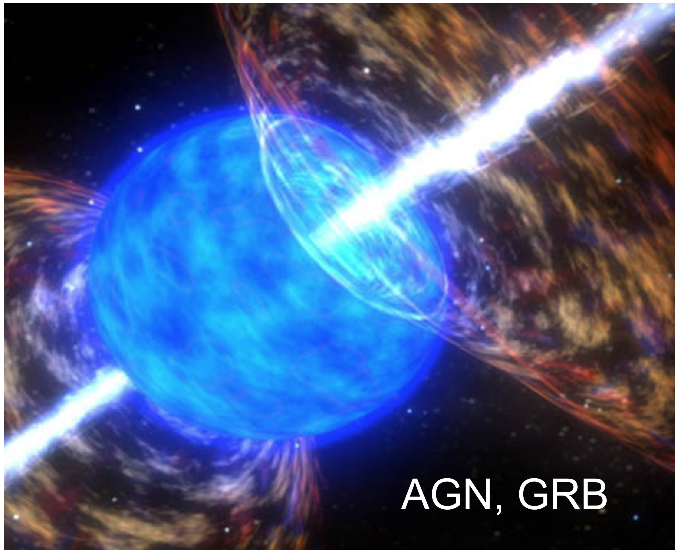
[Auger Coll, 2017]



Cosmic Ray accelerators



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



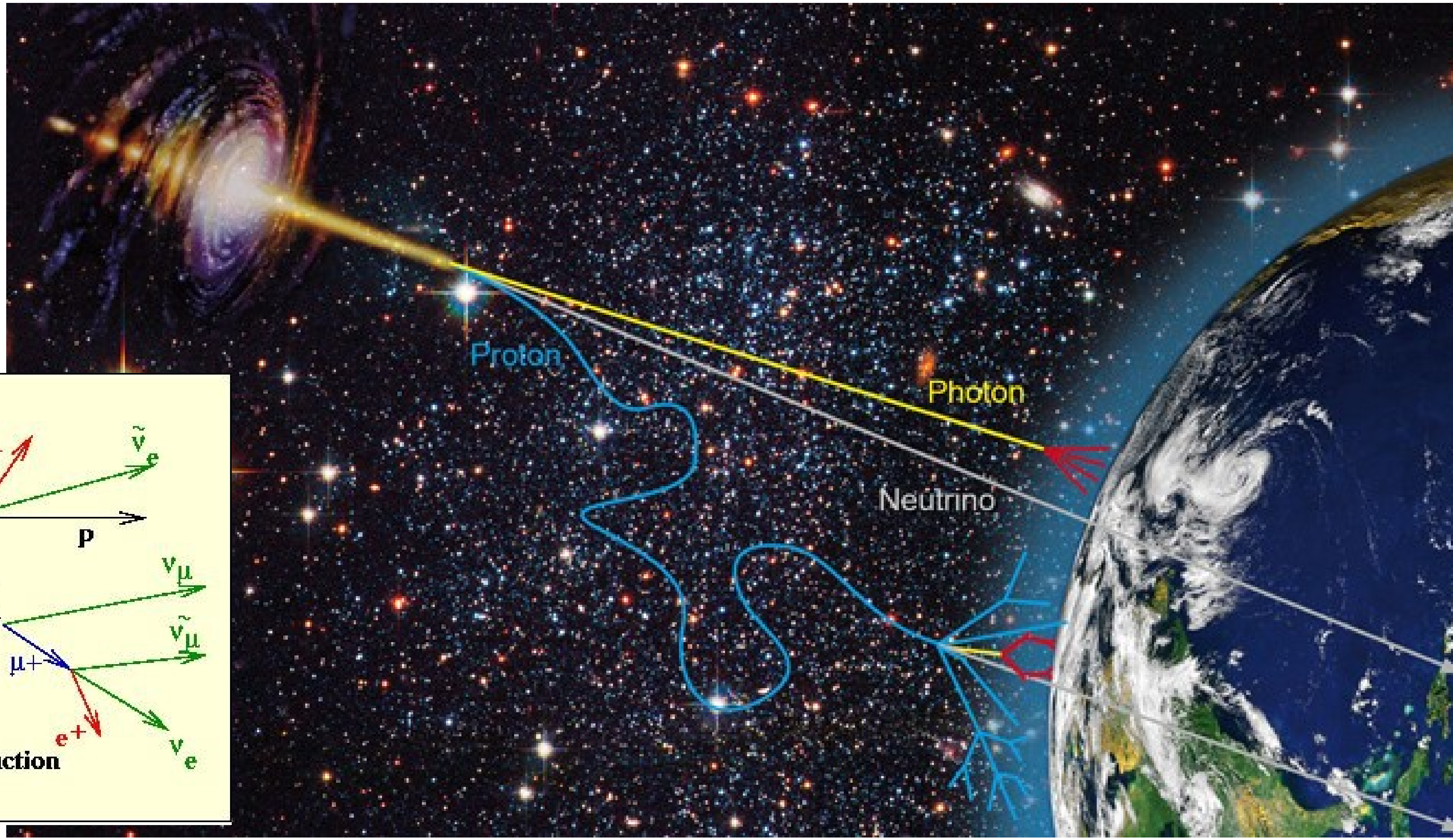
$E_{max} \sim 13$ TeV

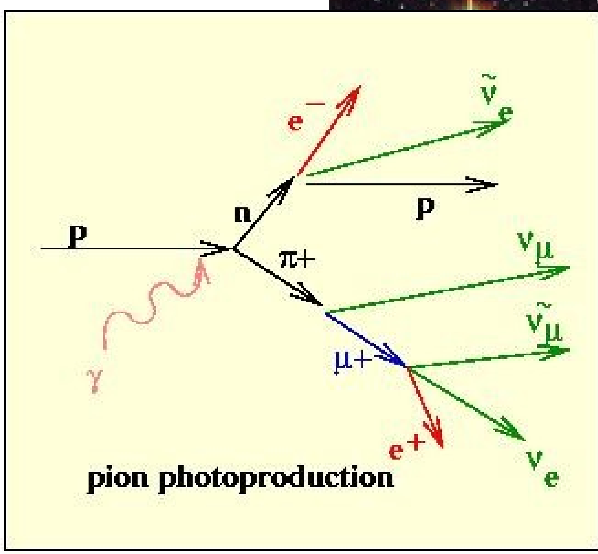
$E_{max} >$ **10^8 TeV**

Main difference: size of accelerator !

→ AGN, GRBs: R ~ 100,000 – 10,000,000,000 km

UHECRs from sources to detection



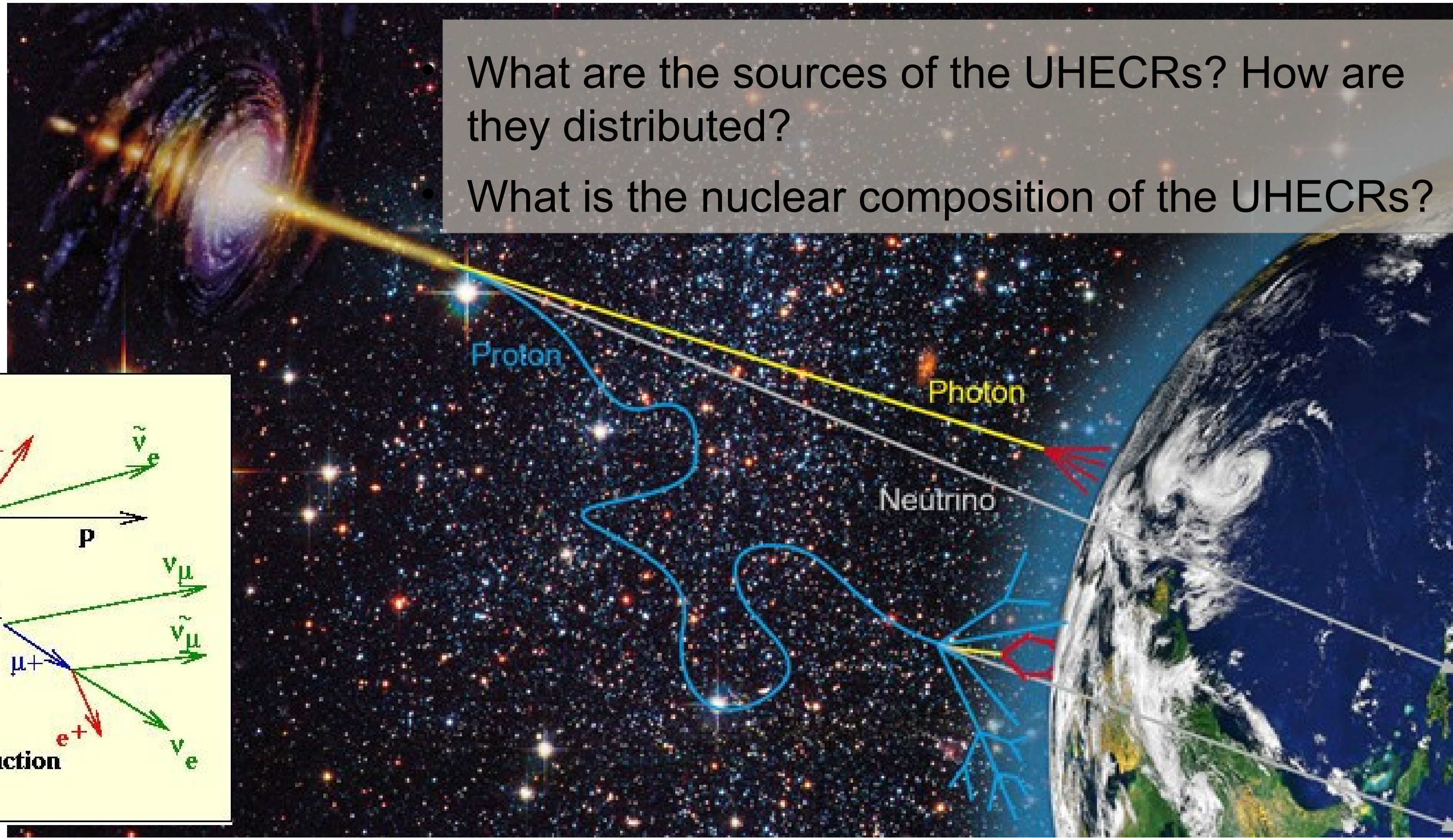


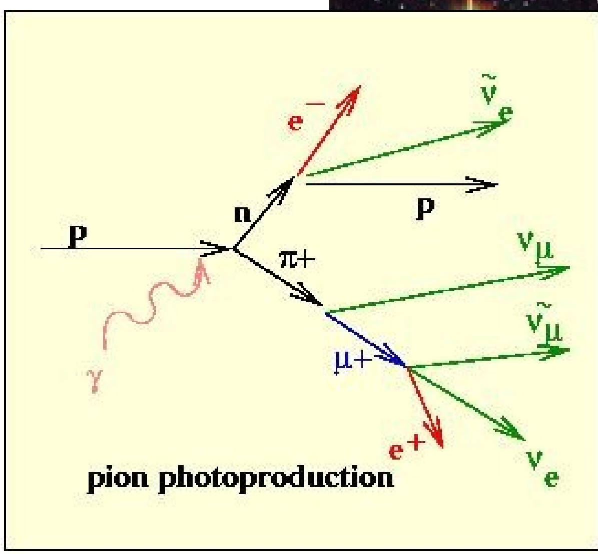
Source of UHECRs | Detection

$E^{-\gamma}$ + other details **x** Extragal propagation **=** UHECRs, cosmogenic neutrinos and gamma

UHECRs from sources to detection

- What are the sources of the UHECRs? How are they distributed?
- What is the nuclear composition of the UHECRs?





pion photoproduction

Source of UHECRs		Detection

$E^{-\gamma}$
+ other details

x

Extragal propagation

=

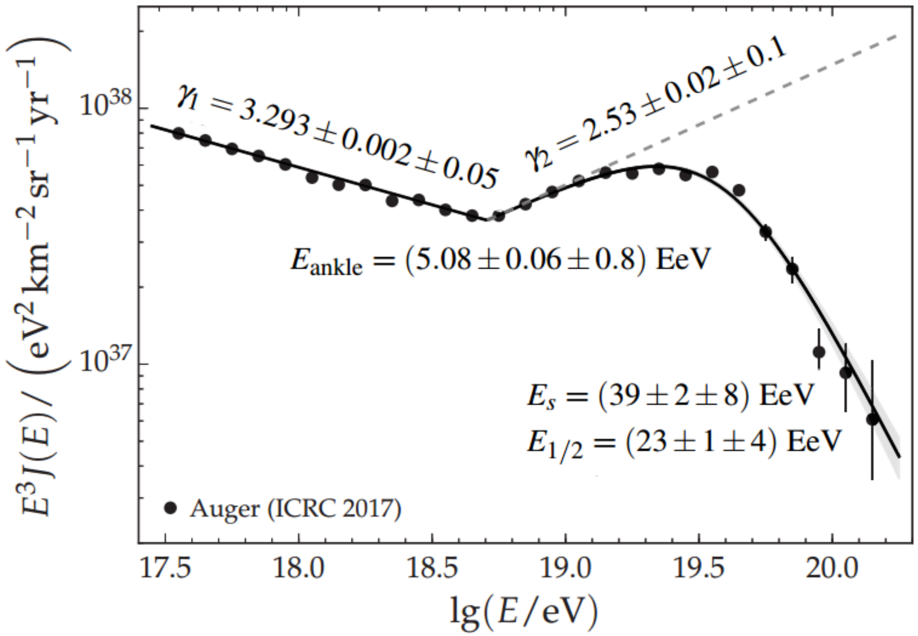
UHECRs, cosmogenic neutrinos and gamma

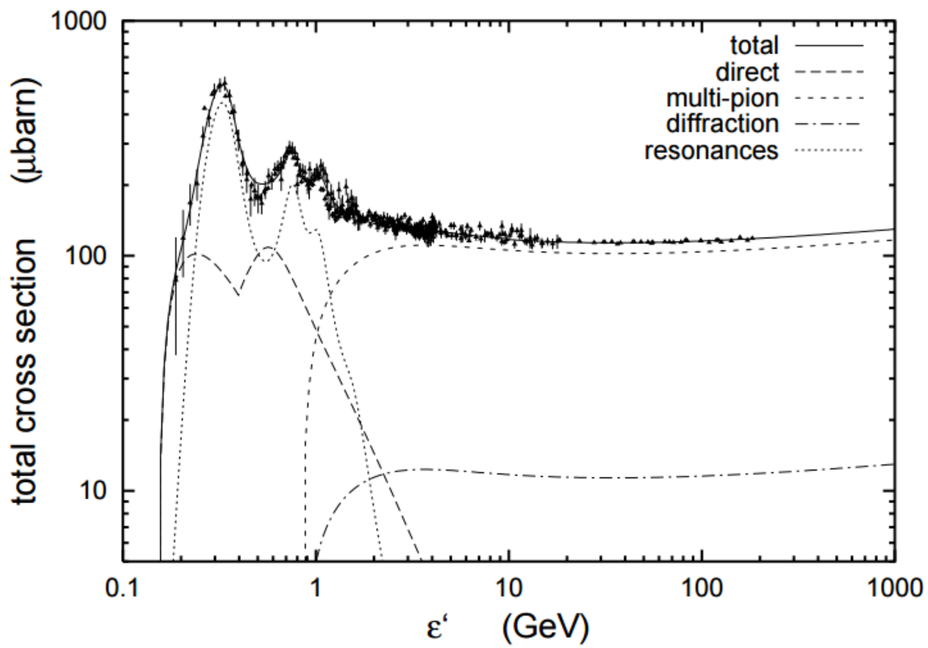
UHECR interactions in the extragalactic space

UHECR interactions

Example: protons interacting with CMB photons

- CR proton in the extragalactic space with 10^{20} eV (Lorentz factor $\Gamma \sim 10^{11}$)
- CMB photons ~ 10^{-3} eV (Lab frame)
- Energy scale of the processes: energy of the photon in the proton rest frame, $\varepsilon' \simeq \Gamma \varepsilon$, for this example order of ~ 100 MeV → ~ pion mass



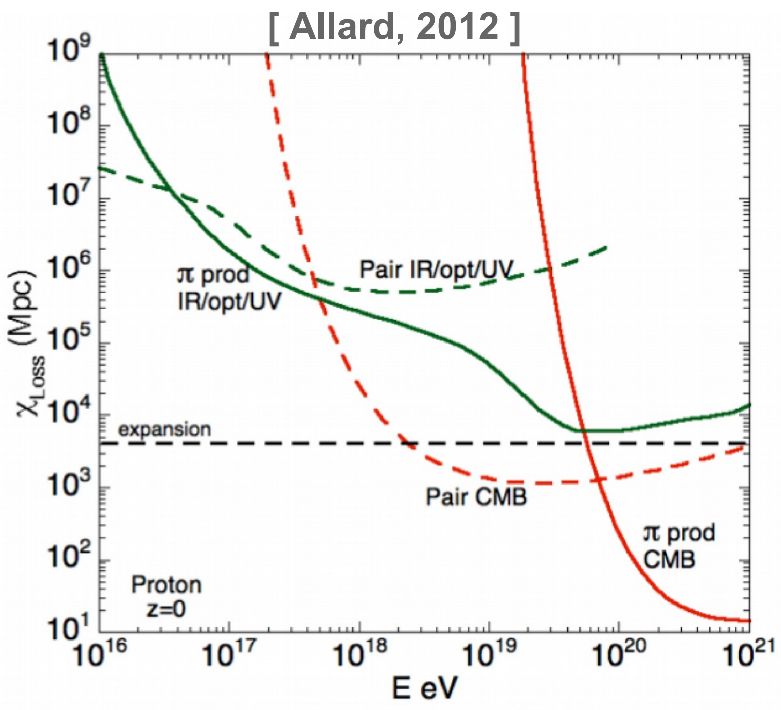


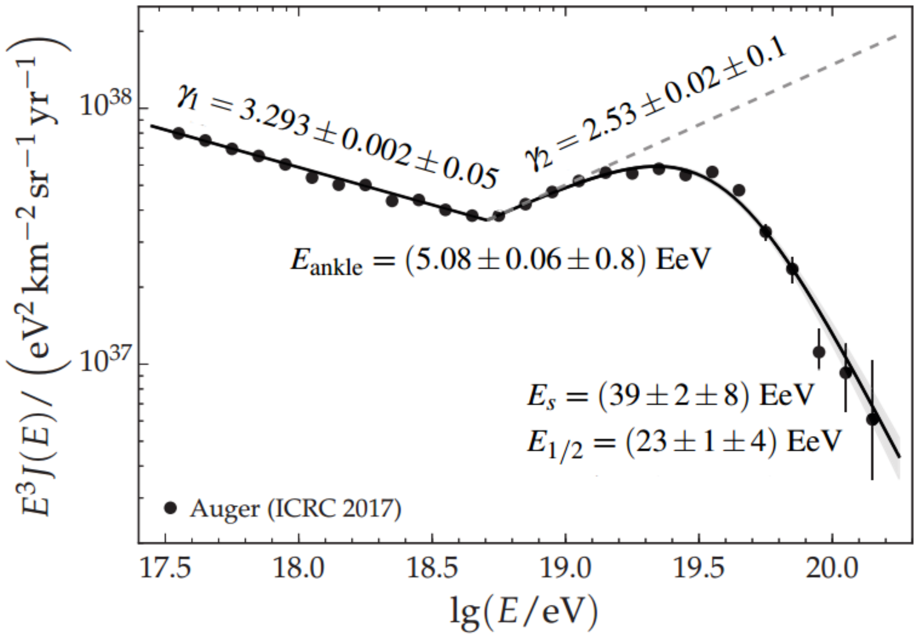
[Muecke et al, 1999]

- Photo-meson production is triggered → **consequences:**
  - **Energy loss of protons**
  - **Production of secondary neutrinos and photons**

UHECR interactions

Example: protons interacting with CMB photons





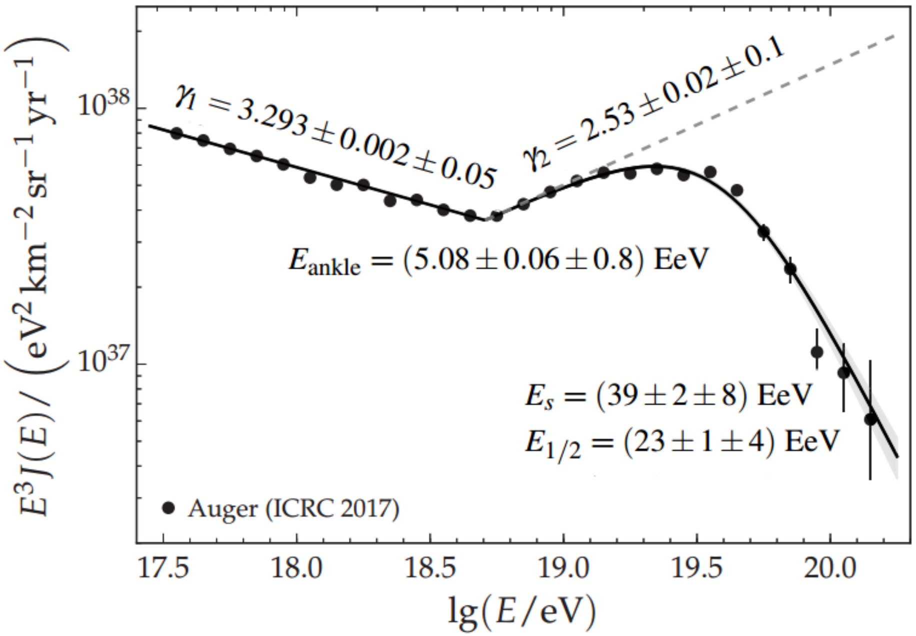
- Highest energies: suppression of the spectrum → **GZK effect** (maybe)
- Intermediate energies: dip → energy losses due to pair production (more robust feature wrt suppression)

- **CAVEAT**: this is valid for **pure proton composition at the sources !**

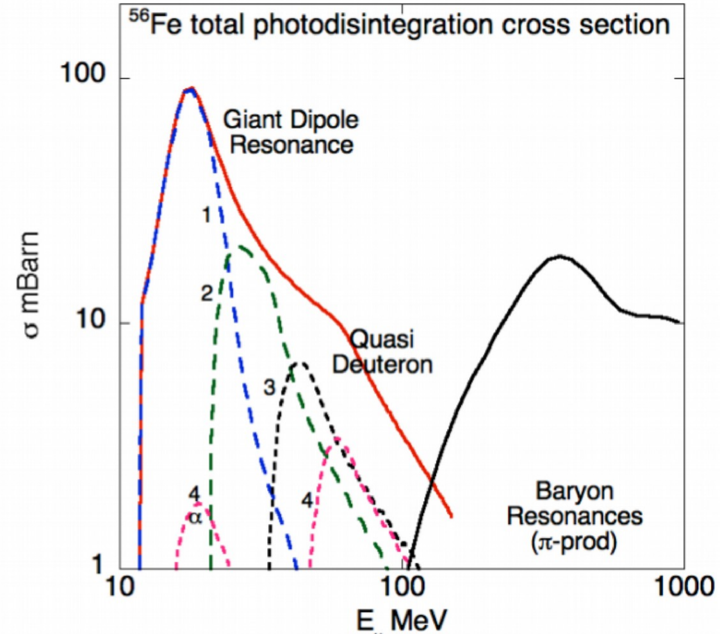
UHECR interactions

Example: Fe nuclei interacting with CMB photons

- **CR iron** in the extragalactic space with 10^{20} eV → simple treatment: Fe-56 isotope is a superposition of 56 nucleons (Lorentz factor $\Gamma \sim 2 \times 10^9$)
- CMB photons ~ 10^{-3} eV (Lab frame)
- Not enough for pion production !



- Other relevant processes at UHE (**photo-disintegration**):
  - Giant Dipole Resonance ~ 10 MeV in the NRF
  - Quasi-Deuteron → above ~ 30 MeV in the NRF, up to the threshold for photo-pion production



- **Consequences**:
  - **Suppression of the flux** → **if nuclei**, due to photo-disintegration
  - **Production of neutrinos and photons connected to GZK effect** → **if nuclei**, less efficient !

Extragalactic Cosmic Ray Propagation

Source of UHECRs | | | | Detection

$E^{-\gamma}$
+ other details **x** Extragal propagation **=** UHECRs, cosmogenic neutrinos and gamma

- In order to <u>infer source properties from observations</u>, we need to take into account:
  - adiabatic energy losses (expansion of the Universe)
  - interactions with extragalactic background photons
  - deflection of magnetic fields
- Simulation codes for extragalactic propagation
  - **SimProp**, Aloisio, Boncioli, di Matteo, Grillo, Petrera, Salamida, JCAP 2017
  - **CRPropa 3**, Alves Batista, Dundovic, Erdmann, Kampert, Kuempel, Müller, Sigl, van Vliet, Walz, Winchen, JCAP 2016
  - **TransportCR**, Kalashev & Kido, J.Exp.Theor.Phys 2016
  - **HERMES**, De Domenico, J.Exp.Theor.Phys 2013
  - **PRINCE**, Heinze & Fedynitch, in preparation

Extragalactic Cosmic Ray Propagation

Source of UHECRs		Detection

$E^{-\gamma}$
+ other details

x

Extragal propagation

=

UHECRs, cosmogenic neutrinos and gamma

- In order to infer source properties from observations, we need to take into account:

  - adiabatic energy losses (expansion of the Universe)

  - interactions with extragalactic background photons

  → subject to uncertainties related to interaction cross sections and background photon fields

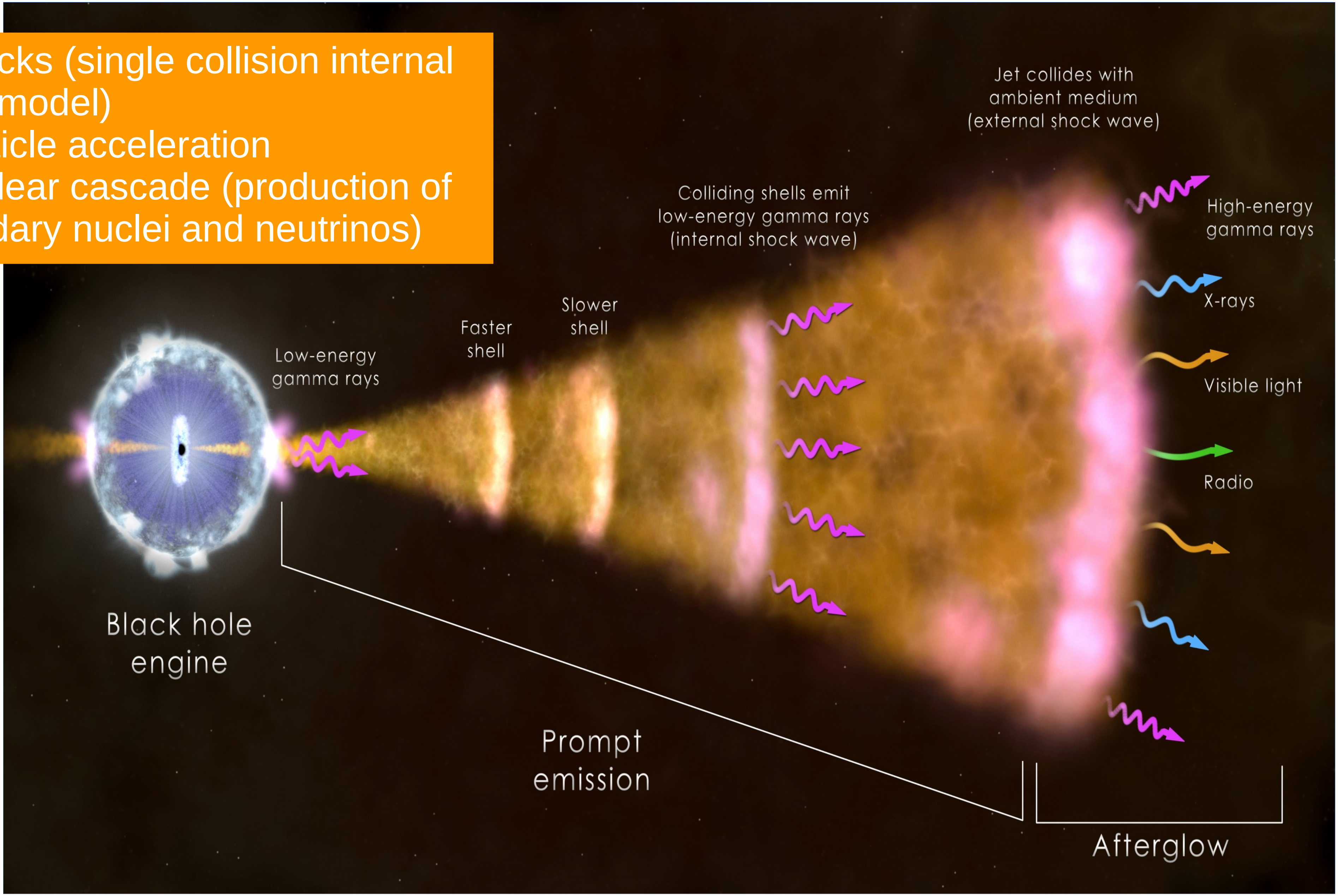
  → similar uncertainties concern also interactions in the source

→ interaction rate proportional to density of photons and cross section

UHECR interactions in a candidate source

Example: Gamma-Ray Burst

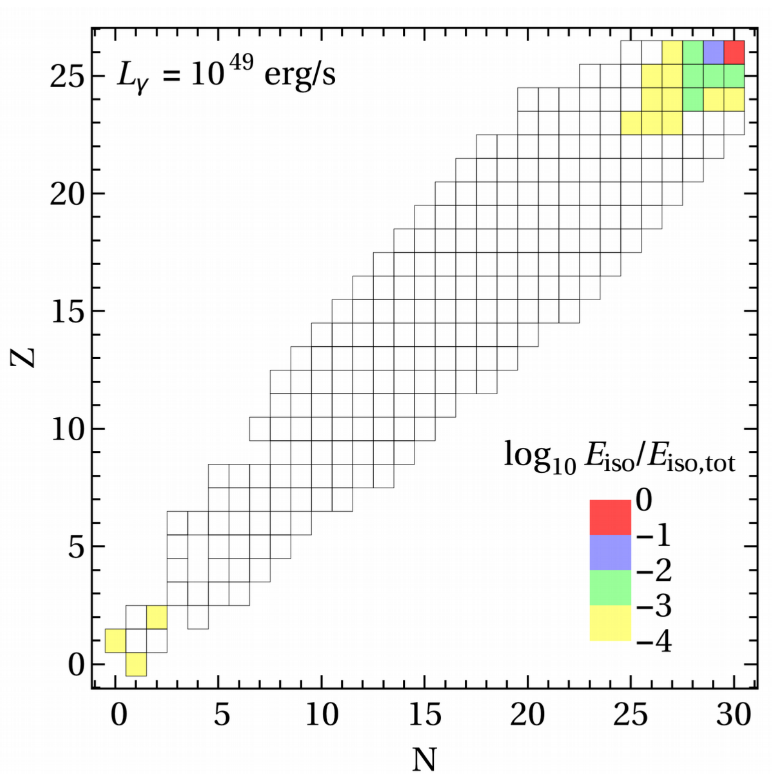
→ shocks (single collision internal shock model)
→ particle acceleration
→ nuclear cascade (production of secondary nuclei and neutrinos)

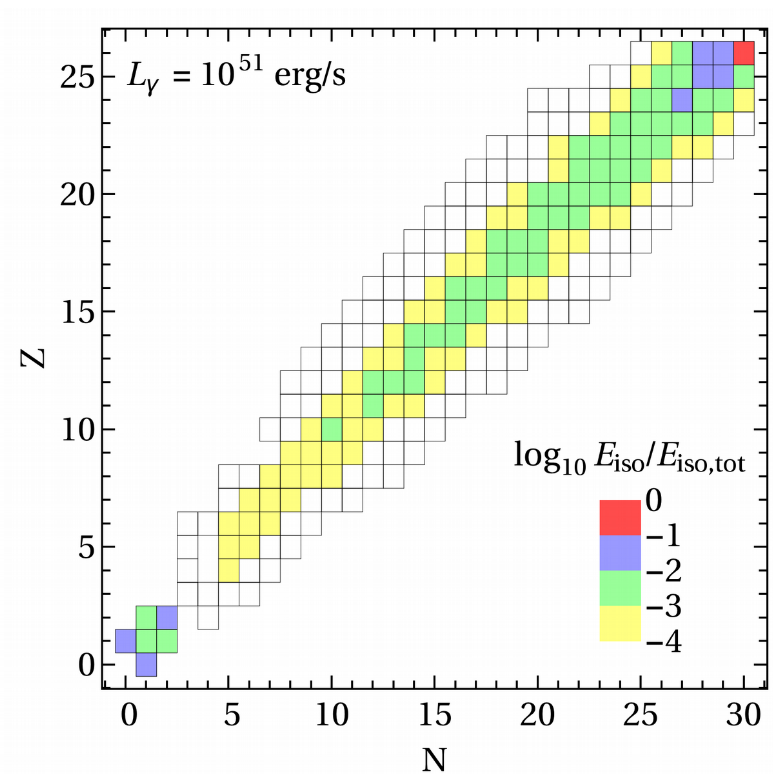


Nuclear Cascade in a GRB

[Biehl, Boncioli, Fedynitch, Winter, A&A 2017]

Luminosity





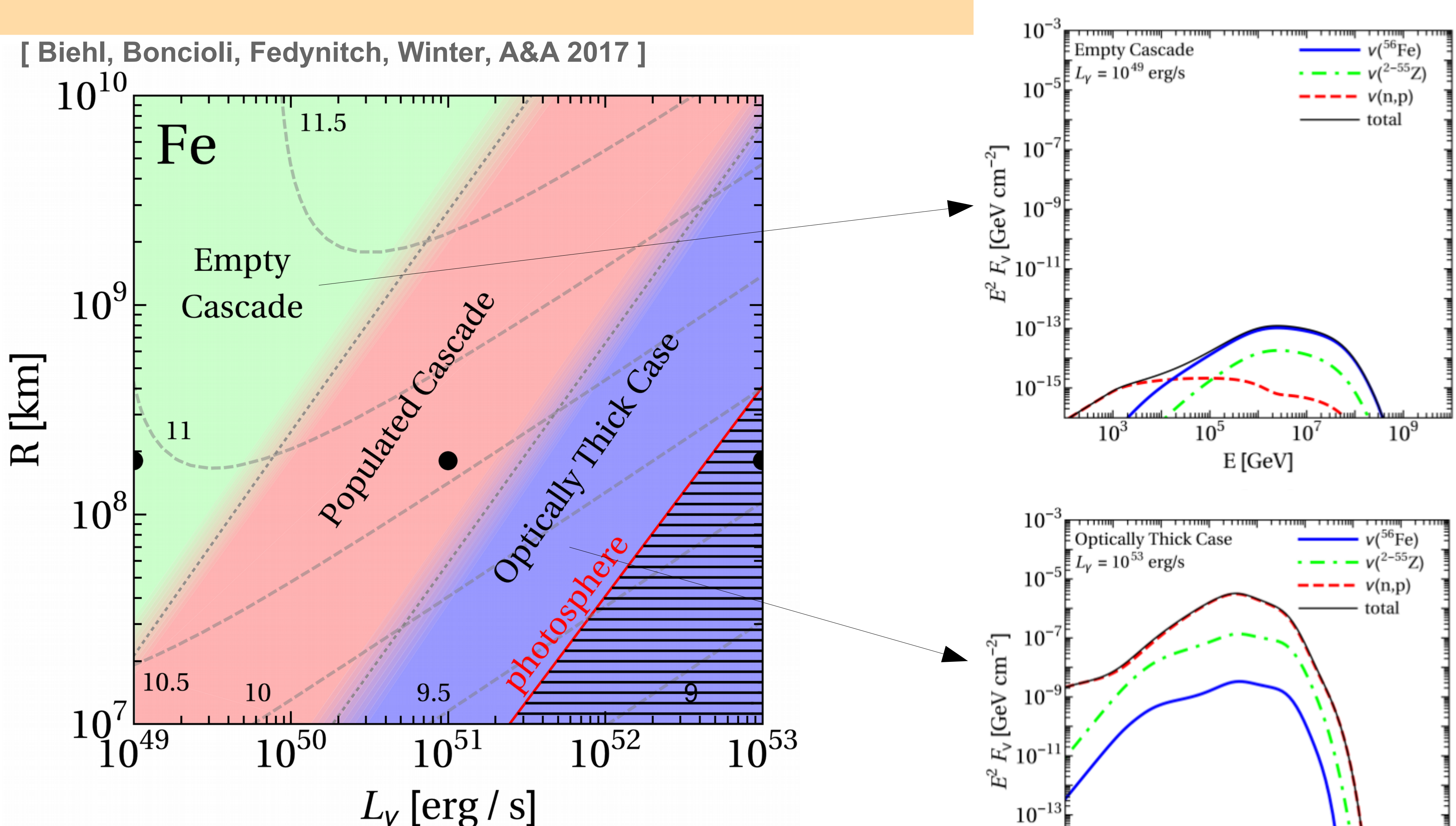
- Example calculated in a GRB shell, but a similar calculation can be performed with the photon fields of the extragalactic space
- Main control parameters for the development of the cascade

  - typical radius of the collisions

  - luminosity of the source

Classification

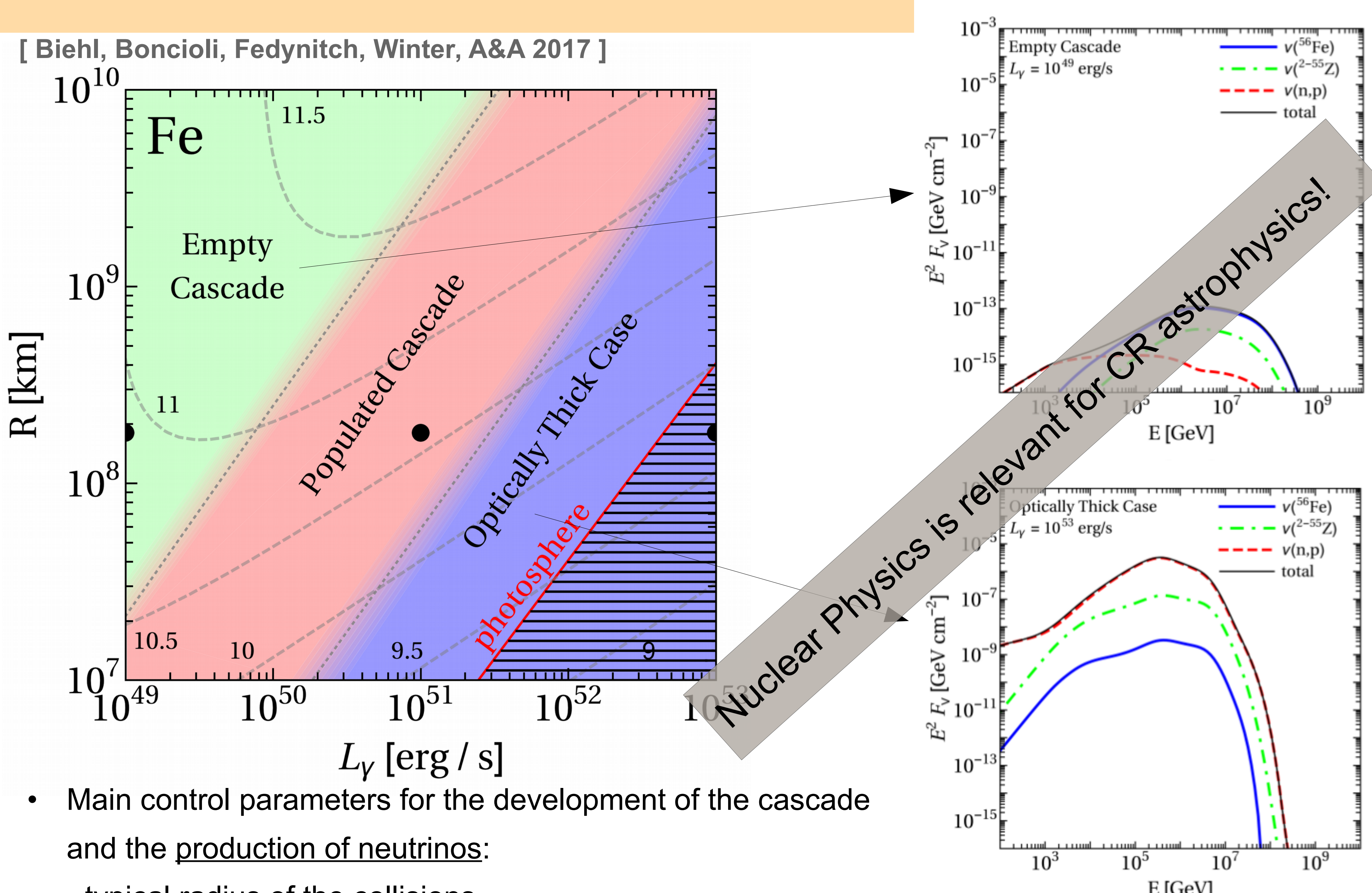
[Biehl, Boncioli, Fedynitch, Winter, A&A 2017]



- Main control parameters for the development of the cascade and the production of neutrinos:
  - typical radius of the collisions
  - luminosity of the source

Classification

[Biehl, Boncioli, Fedynitch, Winter, A&A 2017]

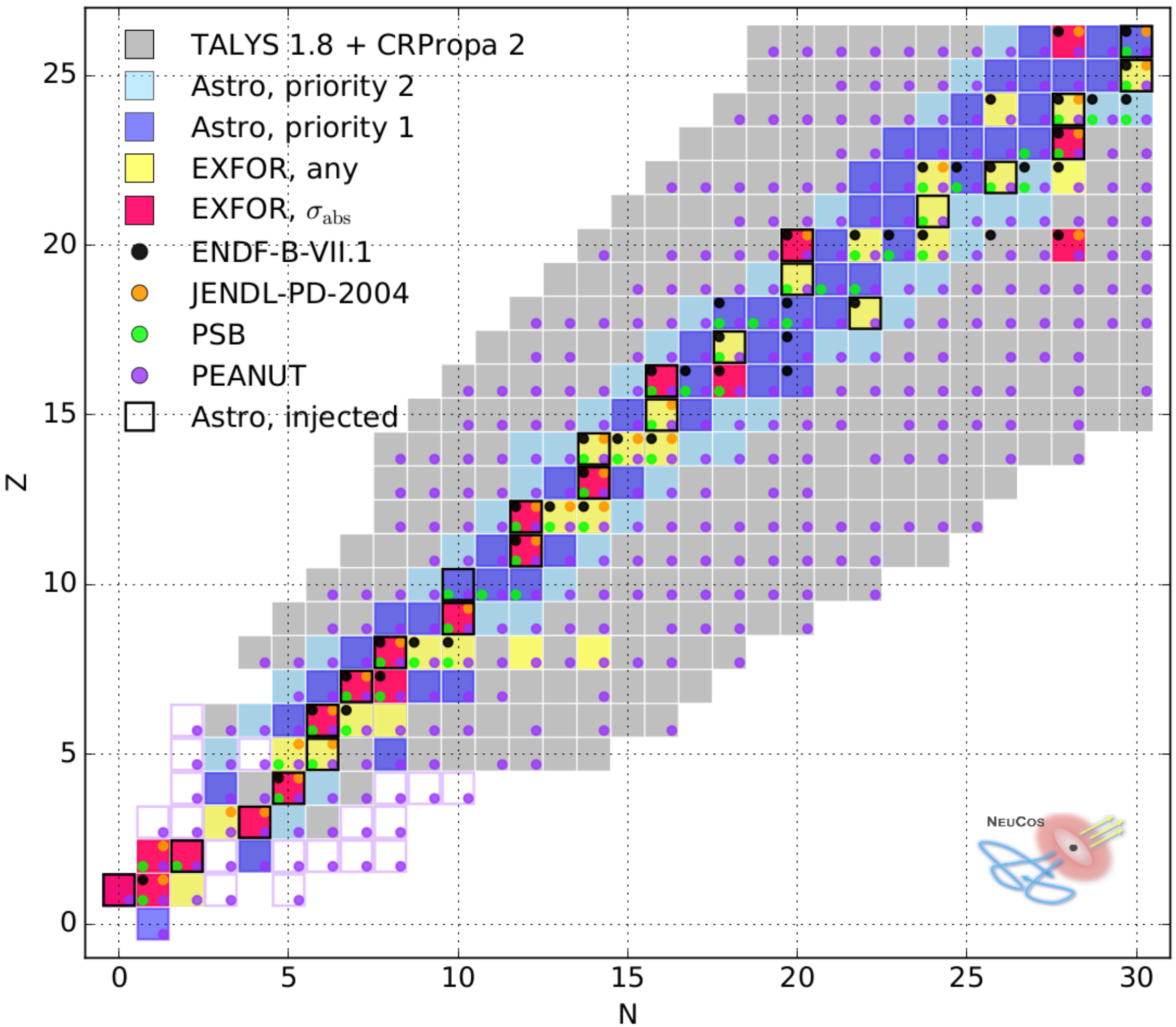


- Main control parameters for the development of the cascade and the production of neutrinos:
  - typical radius of the collisions
  - luminosity of the source

Nuclear Physics uncertainties

Photo-disintegration – current status

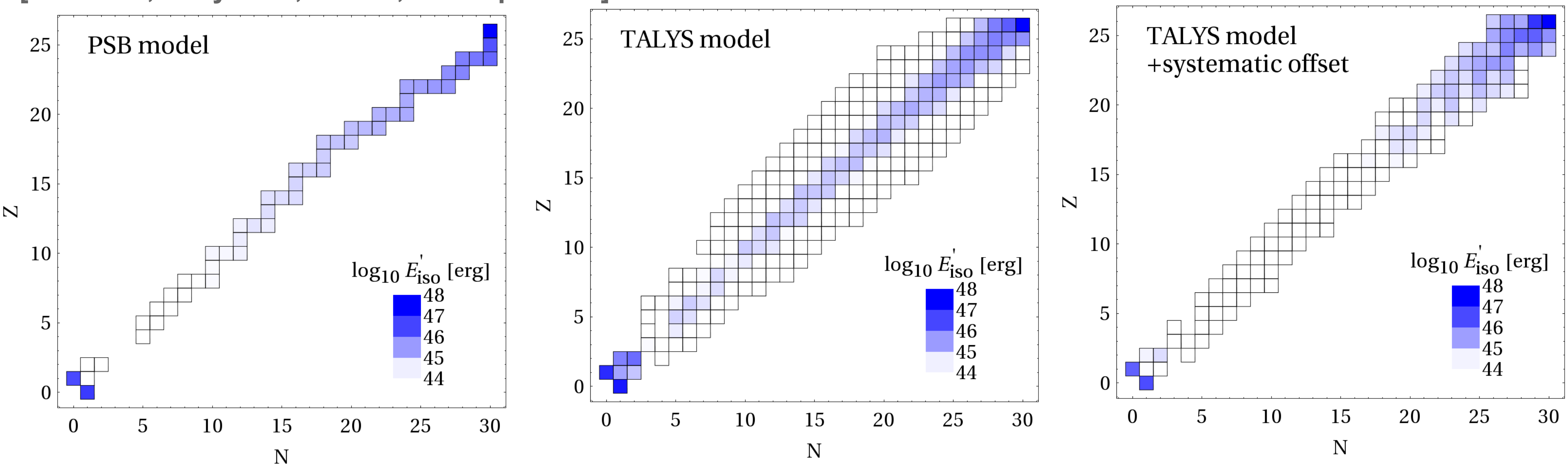
[Boncioli, Fedynitch, Winter, Sci.Rep. 2017]



- 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

Photo-disintegration – developmment of the cascade

[Boncioli, Fedynitch, Winter, Sci.Rep. 2017]



- GRB photon field, Fe injected
- TALYS vs PSB: disintegration is more efficient, more channels are included
- If only measured cross section are included, cascade cannot fully develop (as in the PSB case)

- Precise knowledge of cross sections can influence the expectation on composition!

Nuclear Physics and the interpretation of UHECR data

Interpretation of UHECR data - flux

Source of UHECRs

$E^{-\gamma}$

+ other details

x

Extragal propagation

=

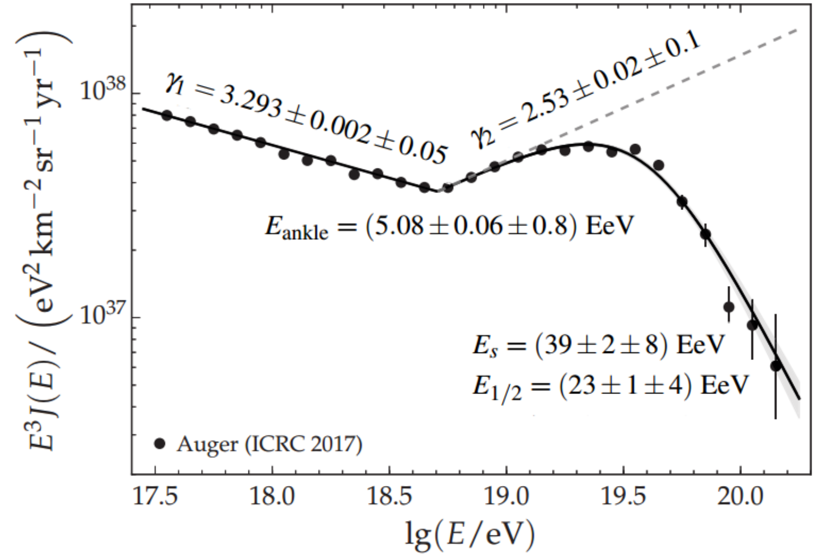
Detection

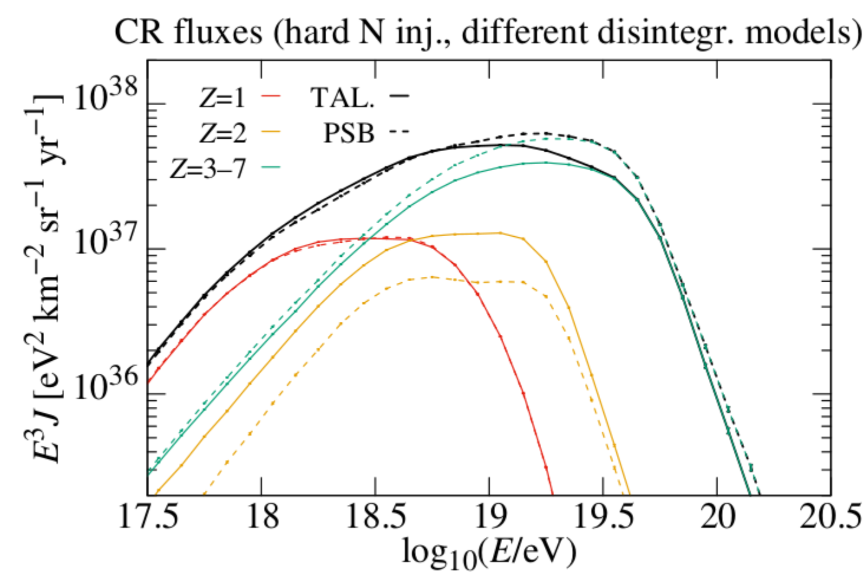
UHECRs, cosmogenic neutrinos and gamma

- <u>Final aim: infer properties of UHECR sources from data</u>
- **Exercise**: fix spectral index and composition at the source → how the spectra after propagation change if different disintegration models are used?
- If disintegration is more efficient, the propagated spectra are more depleted, especially at the highest energies → a softer spectral index at the injection is required to obtain the same spectra as with the less efficient disintegration

[**Alves Batista, Boncioli, di Matteo, van Vliet, Walz, JCAP 2015**]

[**Alves Batista, Boncioli, di Matteo, van Vliet, in prep.**]

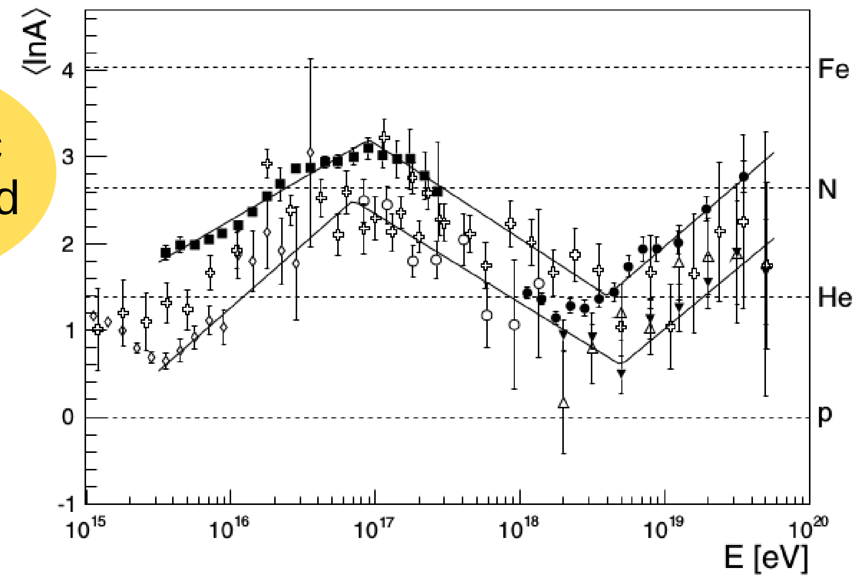




Interpretation of UHECR data - composition

Source of UHECRs

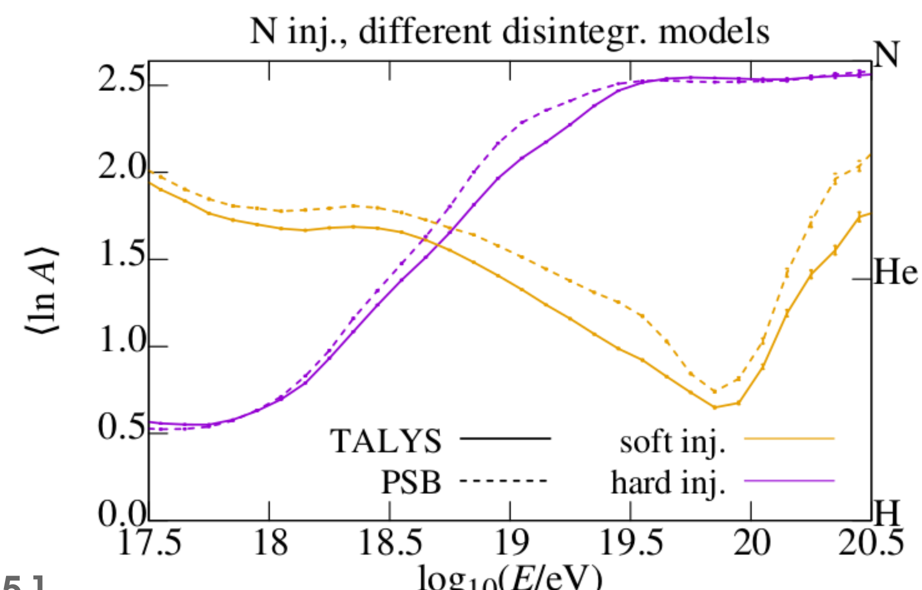
$E^{-\gamma}$ + other details **x** Extragal propagation **=** UHECRs, cosmogenic neutrinos and gamma



- <u>Final aim: infer properties of UHECR sources from data</u>

- If disintegration is more efficient, the composition at Earth is lighter

  → a heavier composition at injection is allowed



[Alves Batista, Boncioli, di Matteo, van Vliet, Walz, JCAP 2015]

[Alves Batista, Boncioli, di Matteo, van Vliet, in prep.]

Other uncertainties affecting UHECR physics

- UHECR source distribution
- UHECR propagation:
- - EBL spectrum and evolution: factor-of-2 uncertainty in the far IR, even in modern models → influences the photodisintegration (Alves Batista, Boncioli, di Matteo, van Vliet, Walz JCAP 2015, Auger Collaboration JCAP 2017)

  - Magnetic fields: stronger IGMF → softer injection spectrum required (Auger Collaboration, ICRC 2017)

- UHECR composition estimates rely on extrapolations of hadronic interactions at energies not accessible at LHC → large differences

- Experimental measurements → differences among spectrum and (interpretation of) composition results by different experiments

Conclusions

- The study of UHECR interactions is needed for the understanding of the features of the UHECR spectrum and the UHECR composition

- Complementary information provided by secondary messengers (neutrinos and photons produced in the propagation) helps for having a deeper knowledge of sources → cosmological evolution of UHECR sources cannot be investigated only with UHECRs (“horizon” problem)

- Scarce knowledge about relevant aspects of nuclear physics in cosmic ray astrophyisics may introduce problems in interpretation of UHECR data

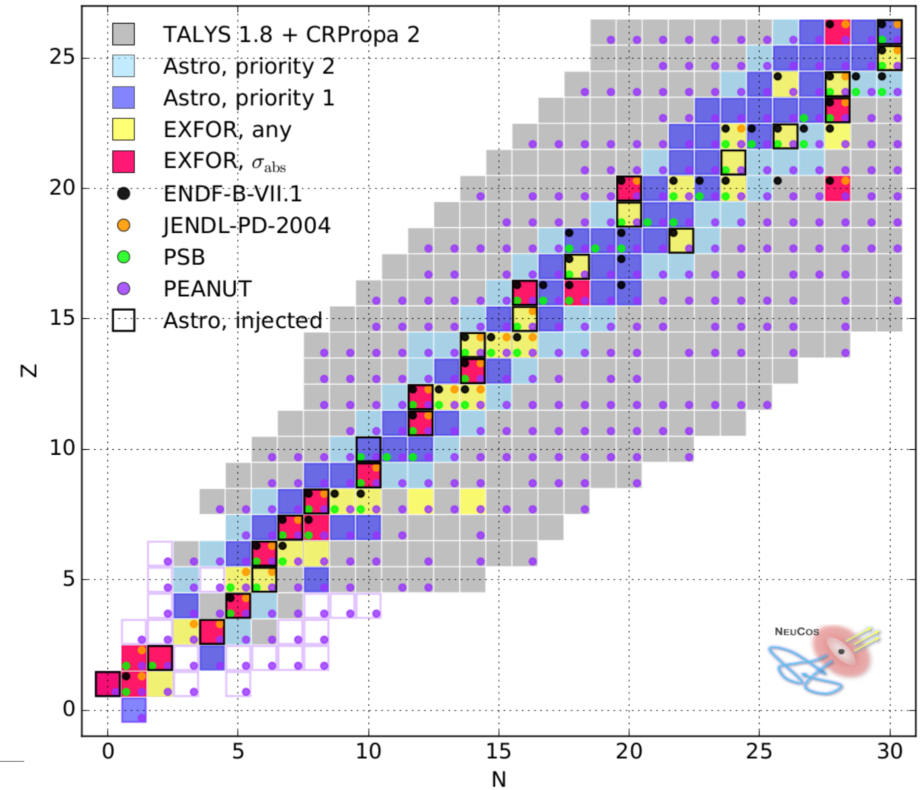
What we aim for the future

- UHECR experiments: better understanding of systematics and determination of UHECR composition

- Gamma-ray experiments: constraints on EBL spectrum and evolution

- Neutrino experiments: help in constraining UHECR source evolution

- 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

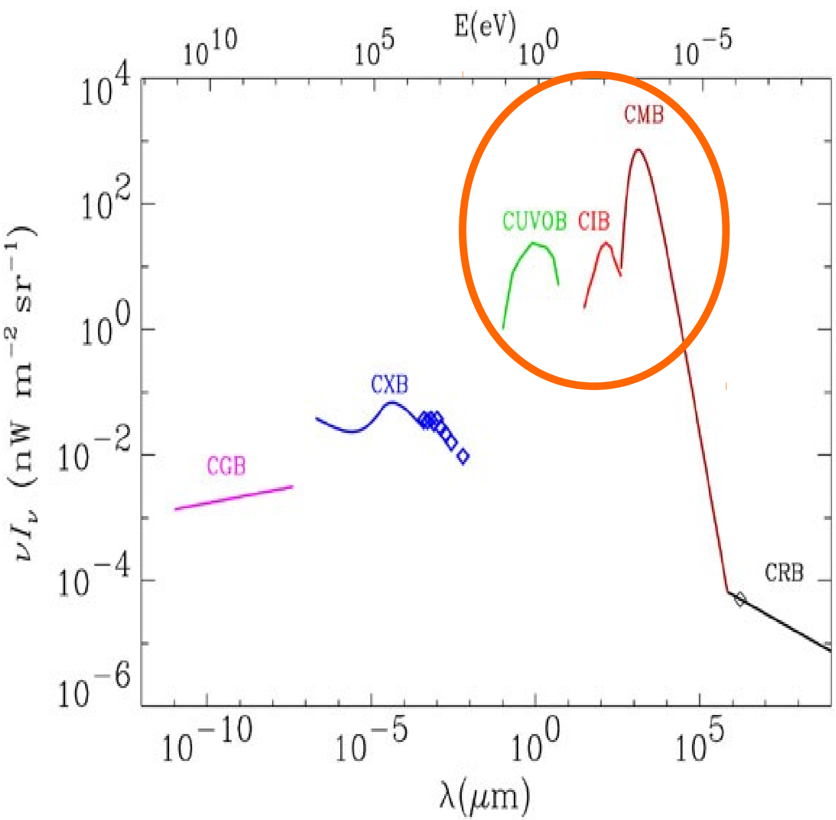


➔ We propose systematic measurements to improve the predictability of unmeasured cross sections → measuring the total absorption cross section for two or more different isobars

Backup slides

UHECR interactions: extragalactic photons

Relevant backgrounds	(ϵ = photon energy in lab frame)
$\epsilon \lesssim 3$ meV (MW):	cosmic microwave background (CMB)
1 meV $\lesssim \epsilon \lesssim 10$ eV (IR to UV):	extragalactic background light (EBL)



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

$$\varepsilon' \simeq \Gamma\,\varepsilon$$

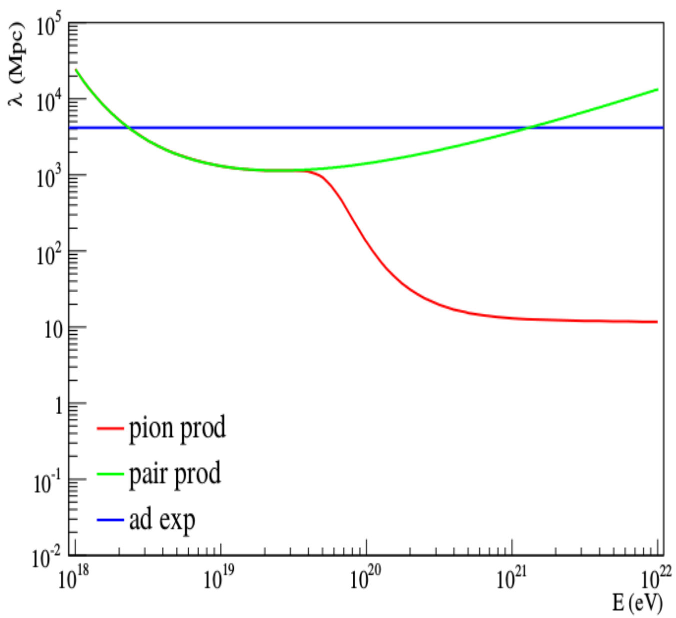
- EBL + intermediate energy CRs
- CMB → higher density wrt EBL

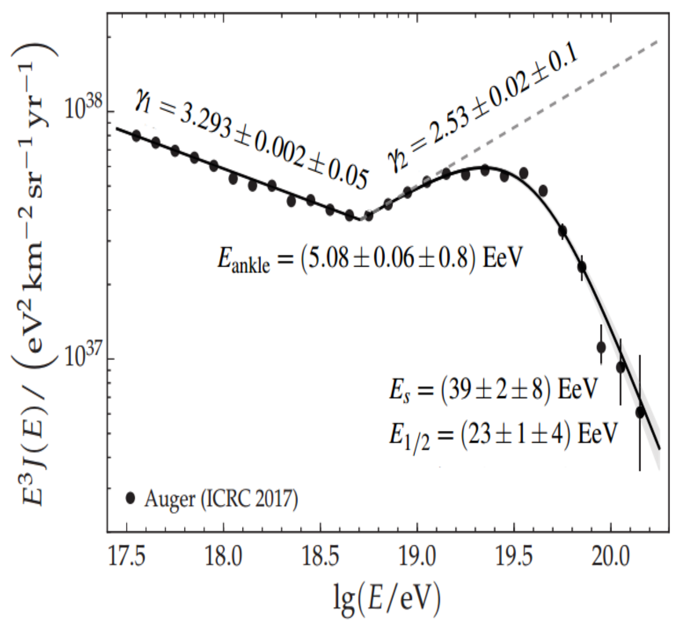
UHECR interactions: protons

Main processes	(ϵ' = photon energy in nucleus rest frame)
$\epsilon' \gtrsim 1$ MeV:	pair production, $N + \gamma \to N + e^+ + e^-$

➔A.M. Hillas, Phys. Lett. 24A 677 (1967)
➔G.R. Blumenthal, Phys. Rev. D Vol 1 1596 (1970)

- Robustness of dip feature: protons are collected from a large volume → feature not sensitive to local over-density or deficit of sources





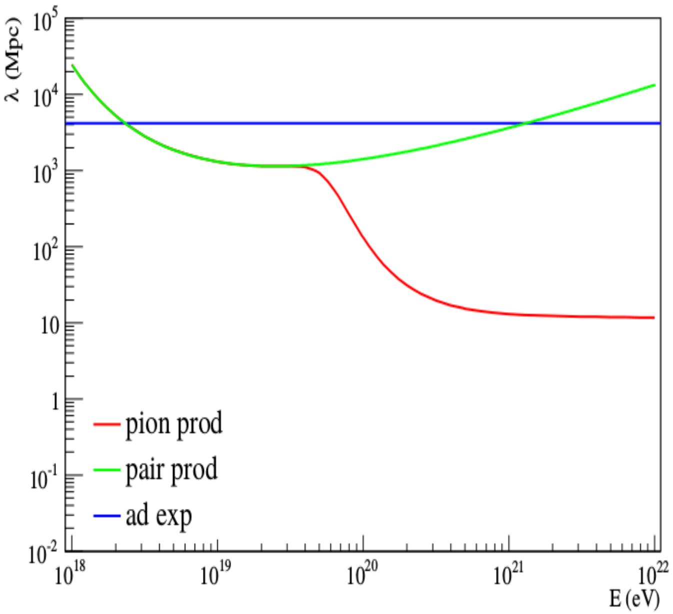
- Its observation has been considered as evidence for proton composition, for example Berezinzky, Gazizov, Grigorieva Phys.Rev. D74 (2006) 043005

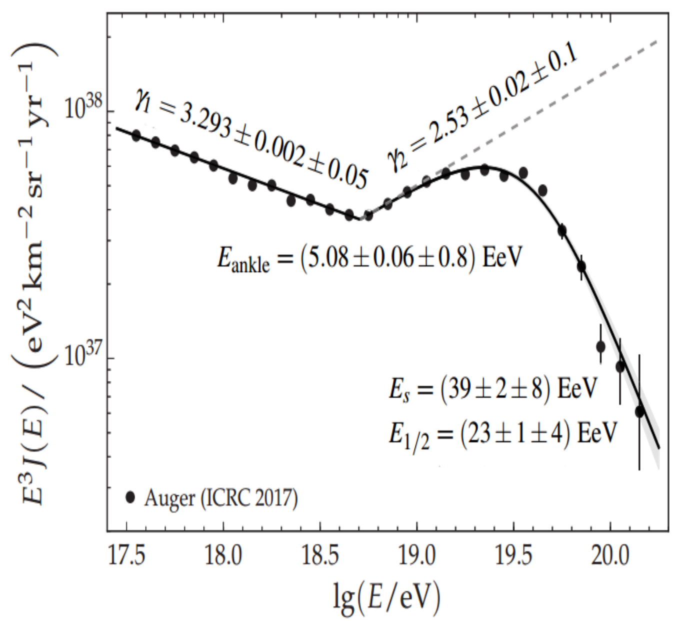
UHECR interactions: protons

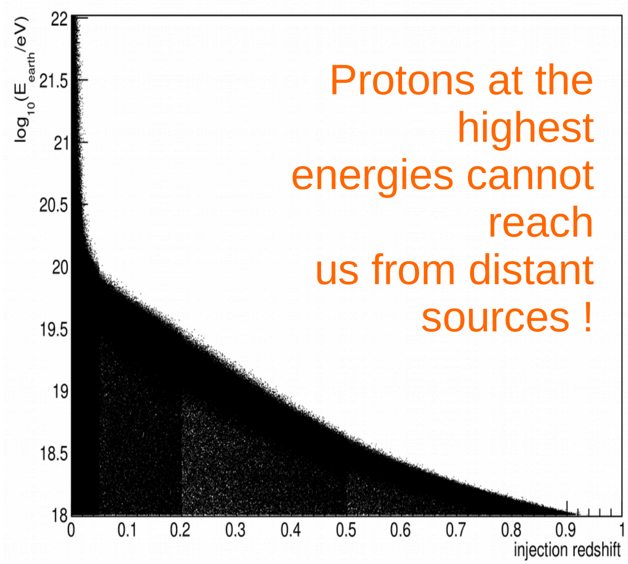
Main processes	(ϵ' = photon energy in nucleus rest frame)
$\epsilon' \gtrsim 1$ MeV:	pair production, $N + \gamma \to N + e^+ + e^-$

$\epsilon' \gtrsim 150$ MeV: pion production, e.g. $p + \gamma \to n + \pi^+$

➔K. Greisen, PRL 16 748 (1966),
➔G.T. Zatsepin and V.A. Kuzmin, Sov. Phys. JETP Lett. 4 78





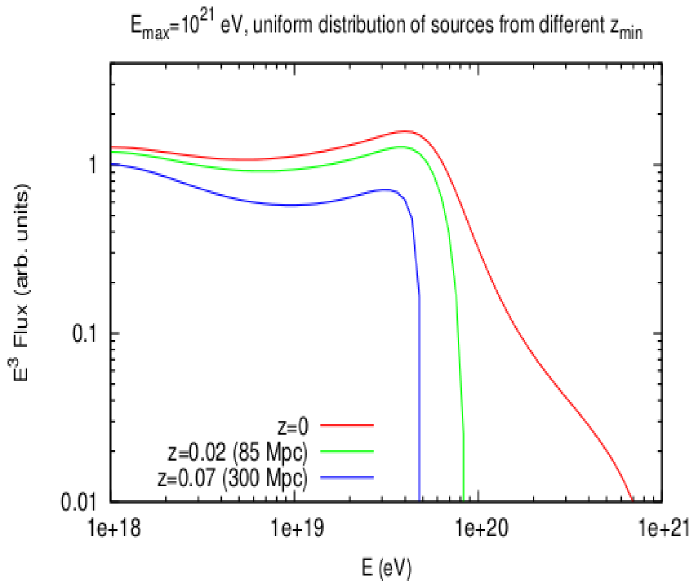


- <u>Suppression</u>: can be mimicked by acceleration cutoff and/or deficit of sources

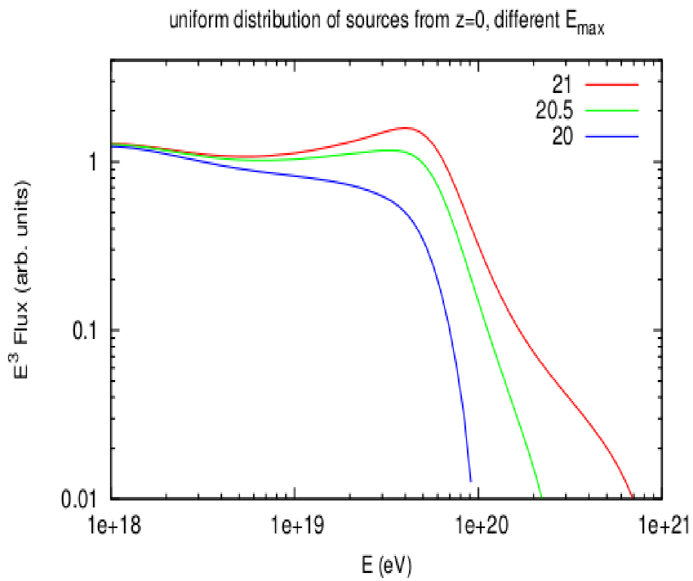
UHECR interactions and effects in the observables

[Aloisio & Boncioli, Astrop. Phys. 2011]

- Suppression due to effect of the minimum distance of the sources



- Suppression due to maximum energy of acceleration of injected protons

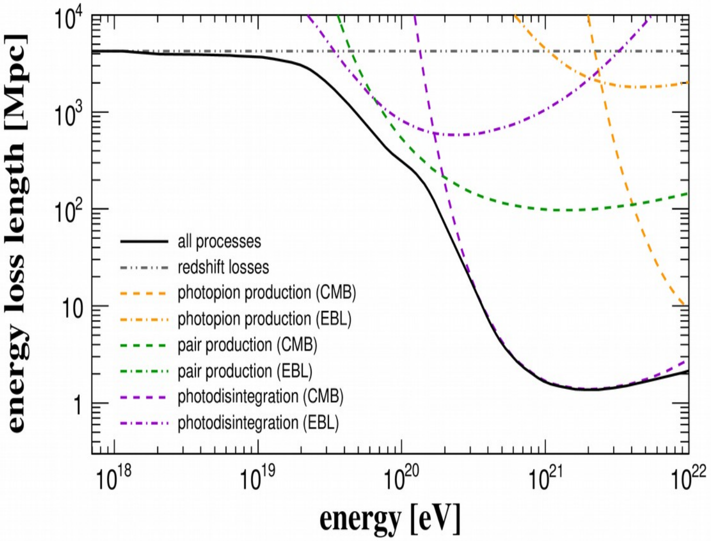


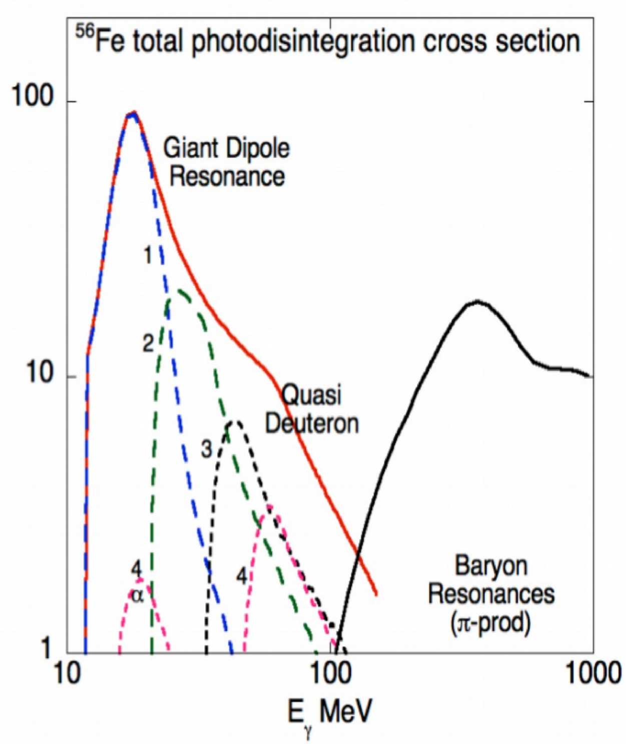
- Even in the simple case of a pure proton composition, the suppression can be due to different aspects or to a combination of them.
- In general, degenerate scenarios looking at the spectrum → can be distinguished with secondary particles !

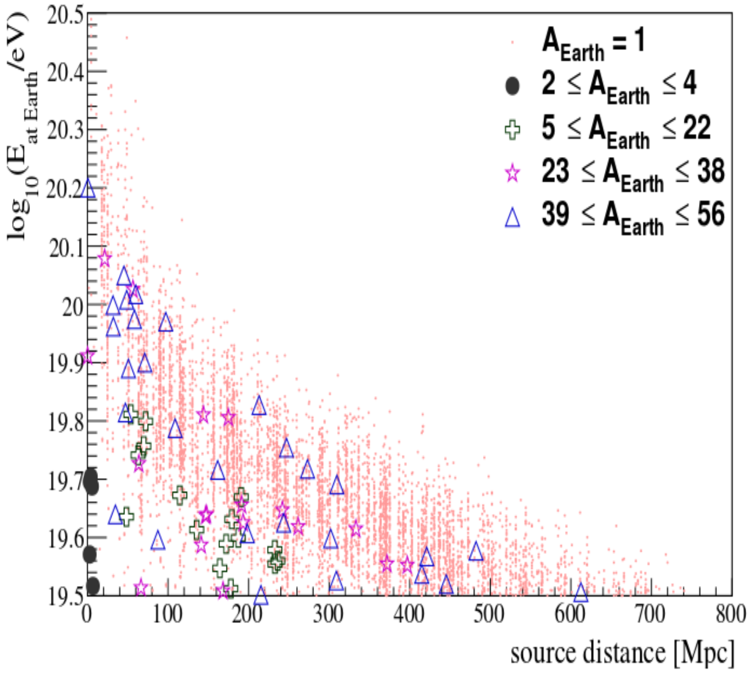
UHECR interactions: nuclei

Main processes	(ϵ' = photon energy in nucleus rest frame)
$\epsilon' \gtrsim 1$ MeV:	pair production, $N + \gamma \to N + e^+ + e^-$
$\epsilon' \gtrsim 8$ MeV:	disintegration, e.g. $Z^A + \gamma \to Z^{A-1} + n$
$\epsilon' \gtrsim 150$ MeV:	pion production, e.g. $p + \gamma \to n + \pi^+$

[Alves Batista, Boncioli, di Matteo, van Vliet, Walz, JCAP2015]

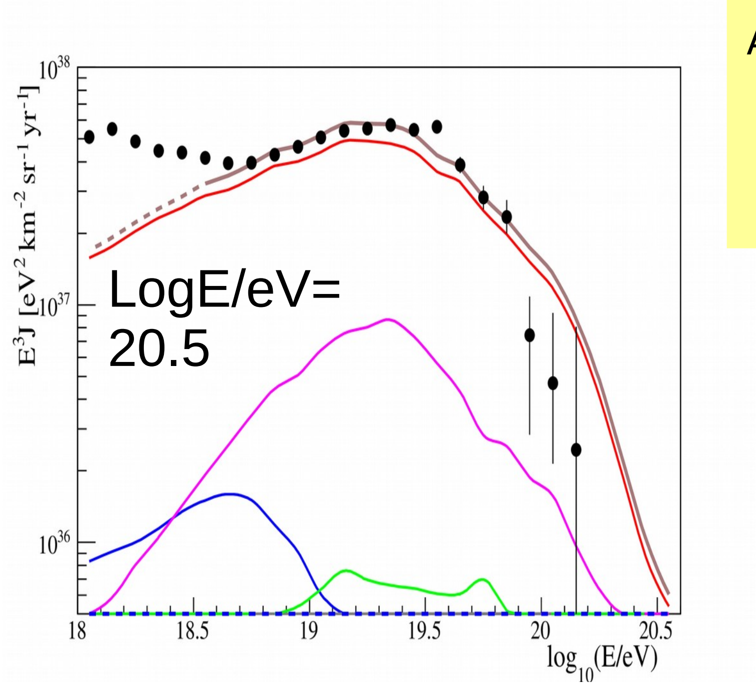


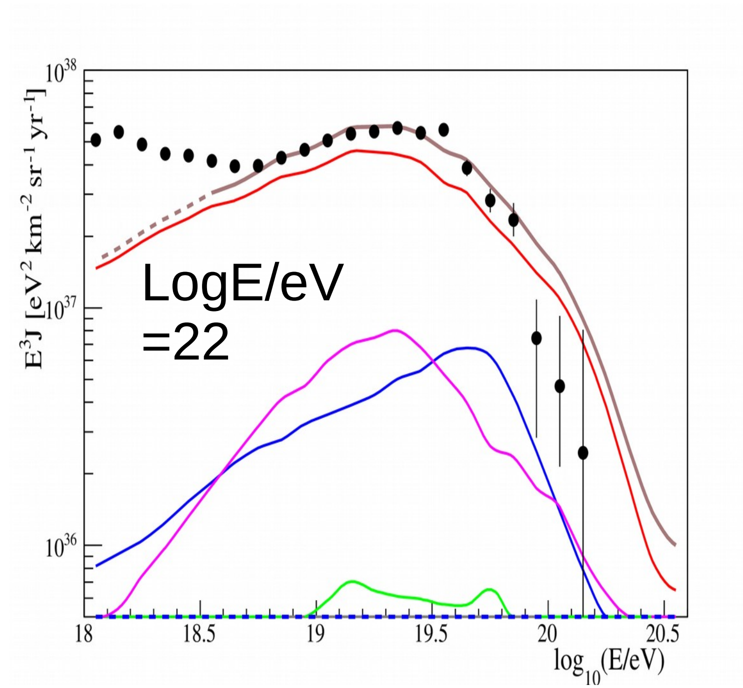




UHECR interactions and effects in the observables

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



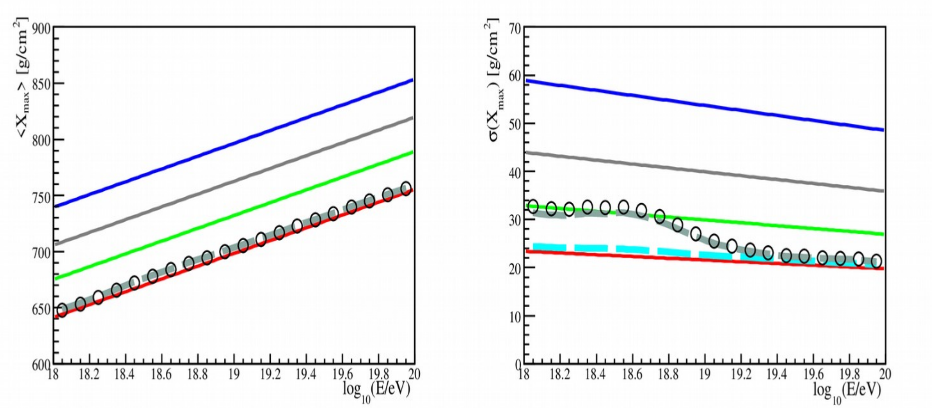


→ Secondary nucleons produced in the photo-disintegration chain have energies not larger than E(Fe) /A ⇒ in the case of cut-off=20.5 the secondary protons are confined at low energies wrt the case of cut-off=22
→ this affects the composition observables

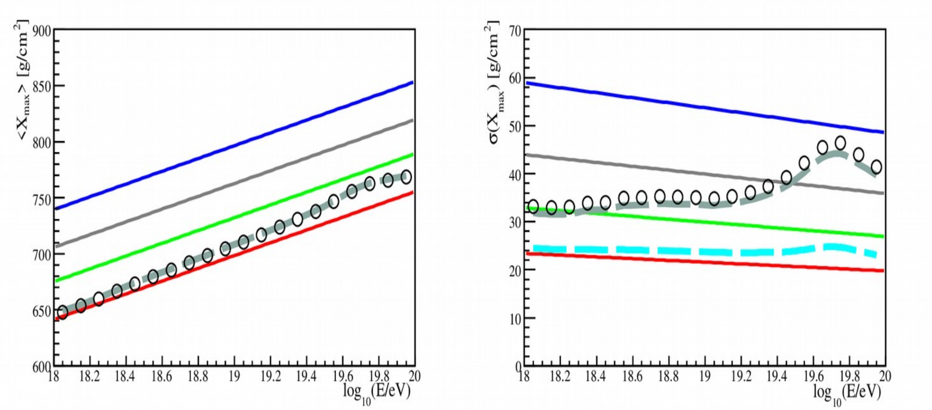
- Suppression of the flux → established, but not its origin:
  Maximum energy or Photo-disintegration scenario?

UHECR interactions and effects in the observables

cut-off: 20.5



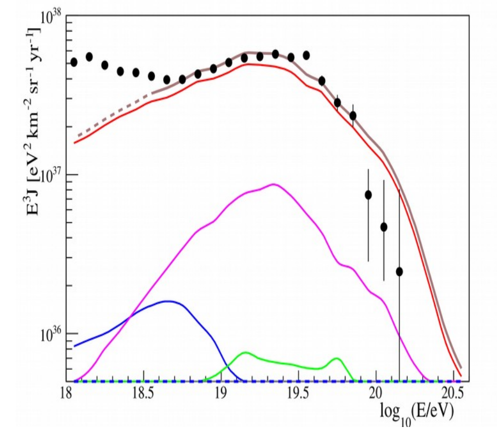
cut-off: 22.0

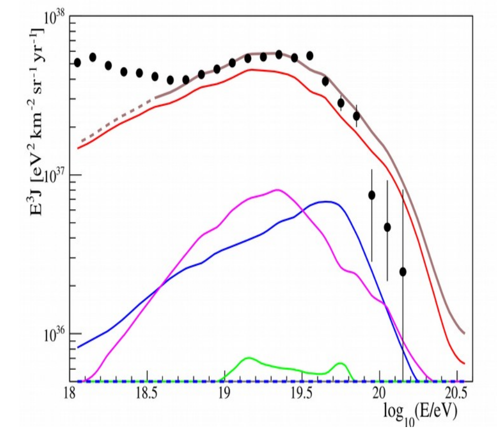


$$\langle X_{max} \rangle = \langle X_{max} \rangle_p + f_E \langle \ln A \rangle$$

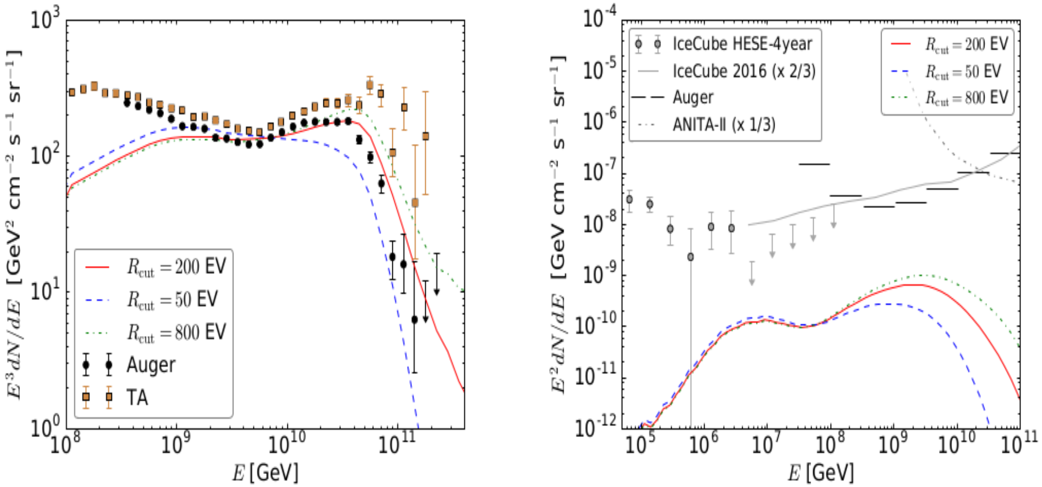
$$\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f_E^2 \sigma^2_{\ln A}$$

- Degenerate scenarios looking at the spectrum → can be distinguished with composition, thanks to propagation!

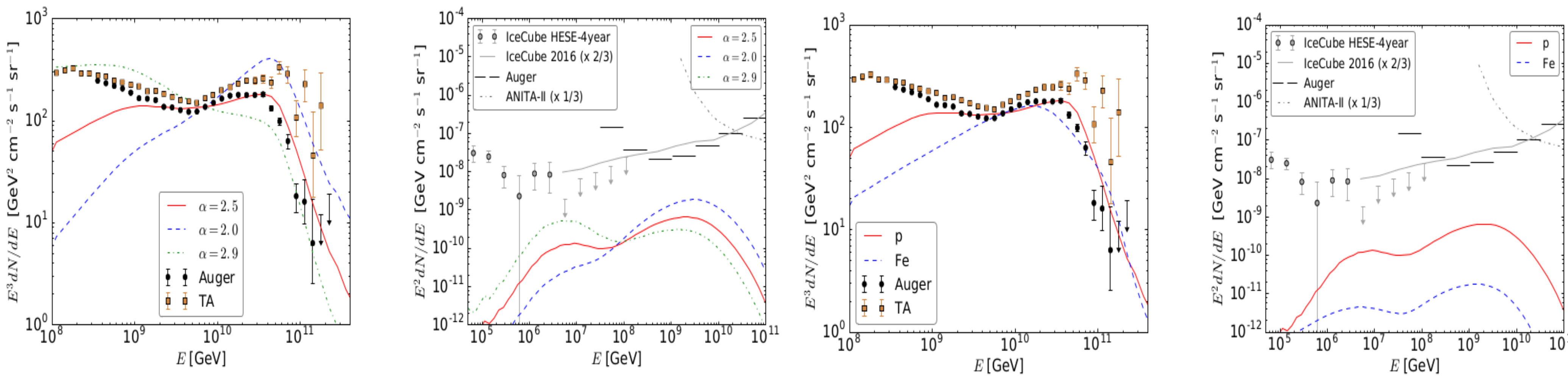




UHECRs and cosmogenic neutrinos



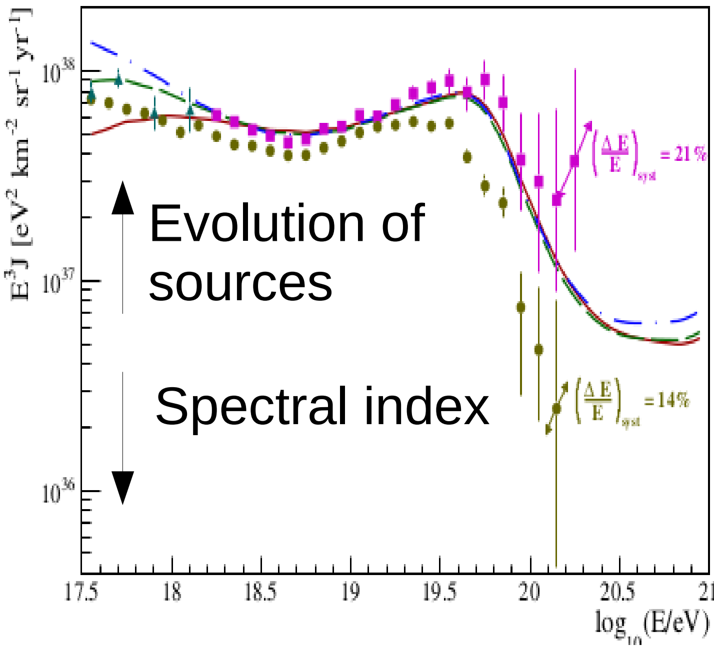
- Normalization of the CR flux, injection spectral index and maximum energy
- Composition
- Source evolution history → not possible to constrain with only CR measurements !
- Details of EBL and cross section models

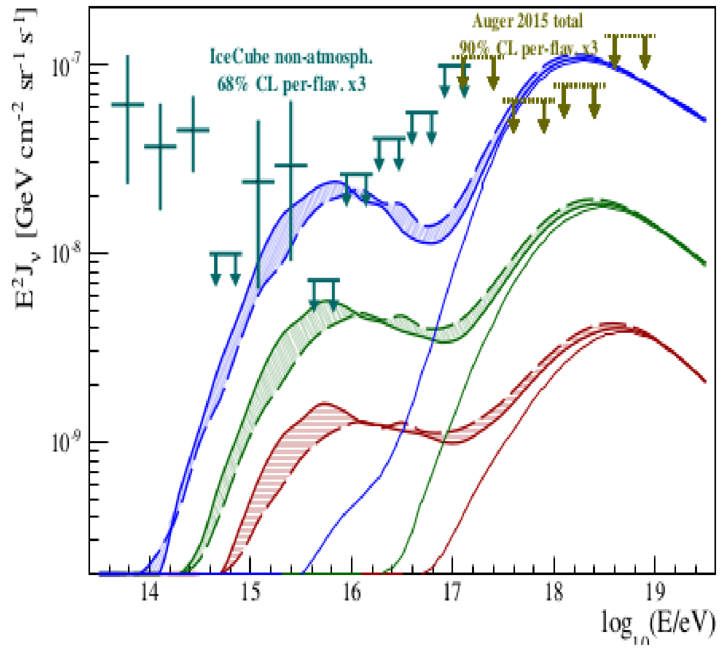


[van Vliet, Horandel, Alves Batista, ICRC 2017]

UHECRs and cosmogenic neutrinos

[Aloisio, Boncioli, di Matteo, Grillo, Petrera, Salamida, JCAP 2015]



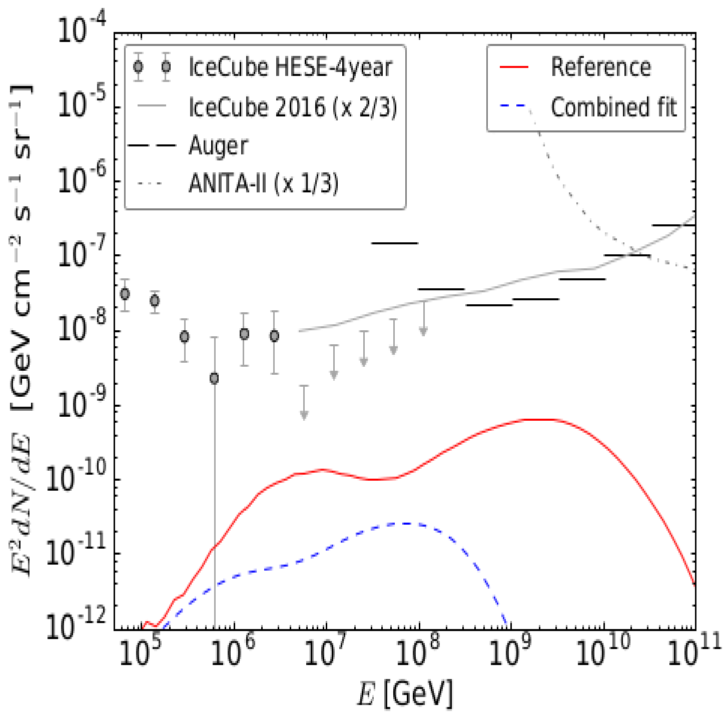


- Source evolution history → not possible to constrain with only CR measurements !

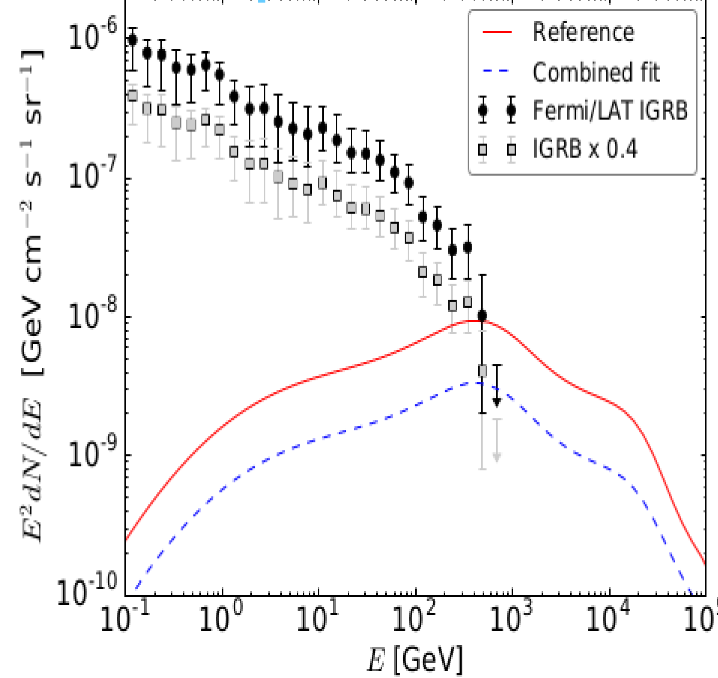
  → see also Heinze, Boncioli, Bustamante, Winter, ApJ 2016

- Neutrino flux also dependent on EBL models !

Propagation models and secondary messengers



[van Vliet, Horandel, Alves Batista ICRC2017]

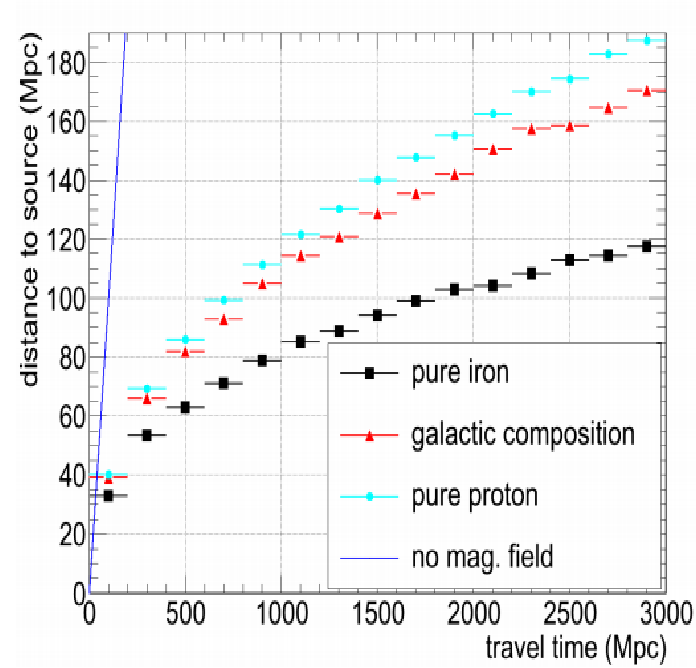


- Cosmogenic neutrinos and photons corresponding to proton scenario and mixed composition scenario (hard spectral index and low energy cutoff)
- Complete fit of composition, shape of initial spectrum and source evolution, including neutrinos and photons can help to have a global picture and constrain/exclude scenarios (photons can give more stringent constraints than neutrinos in the local universe, see for example Supanitski 2016)

Extragalactic magnetic fields

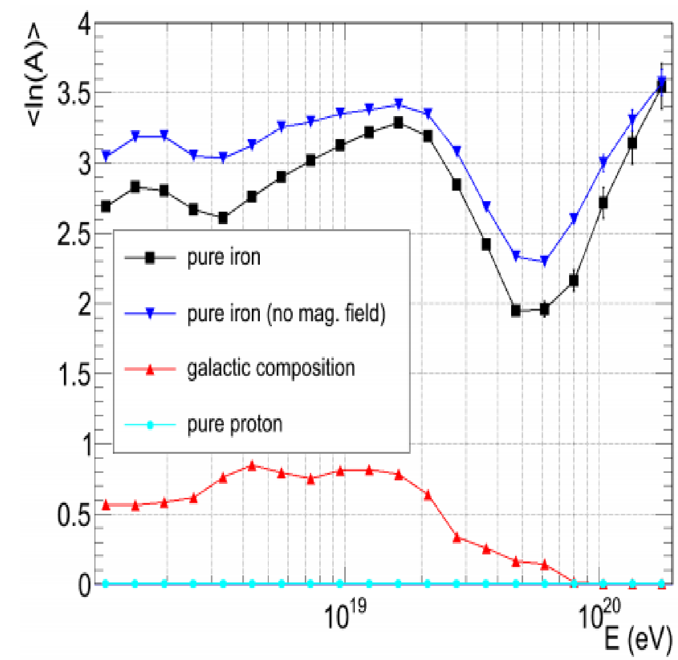
[CRPropa 2, Astropart. Phys. 2013]

- Effect of magnetic fields on the propagation
  - It is higher for heavier masses
  - It limits the horizon of the universe contributing to the UHECRs
  - The average mass at Earth is lighter



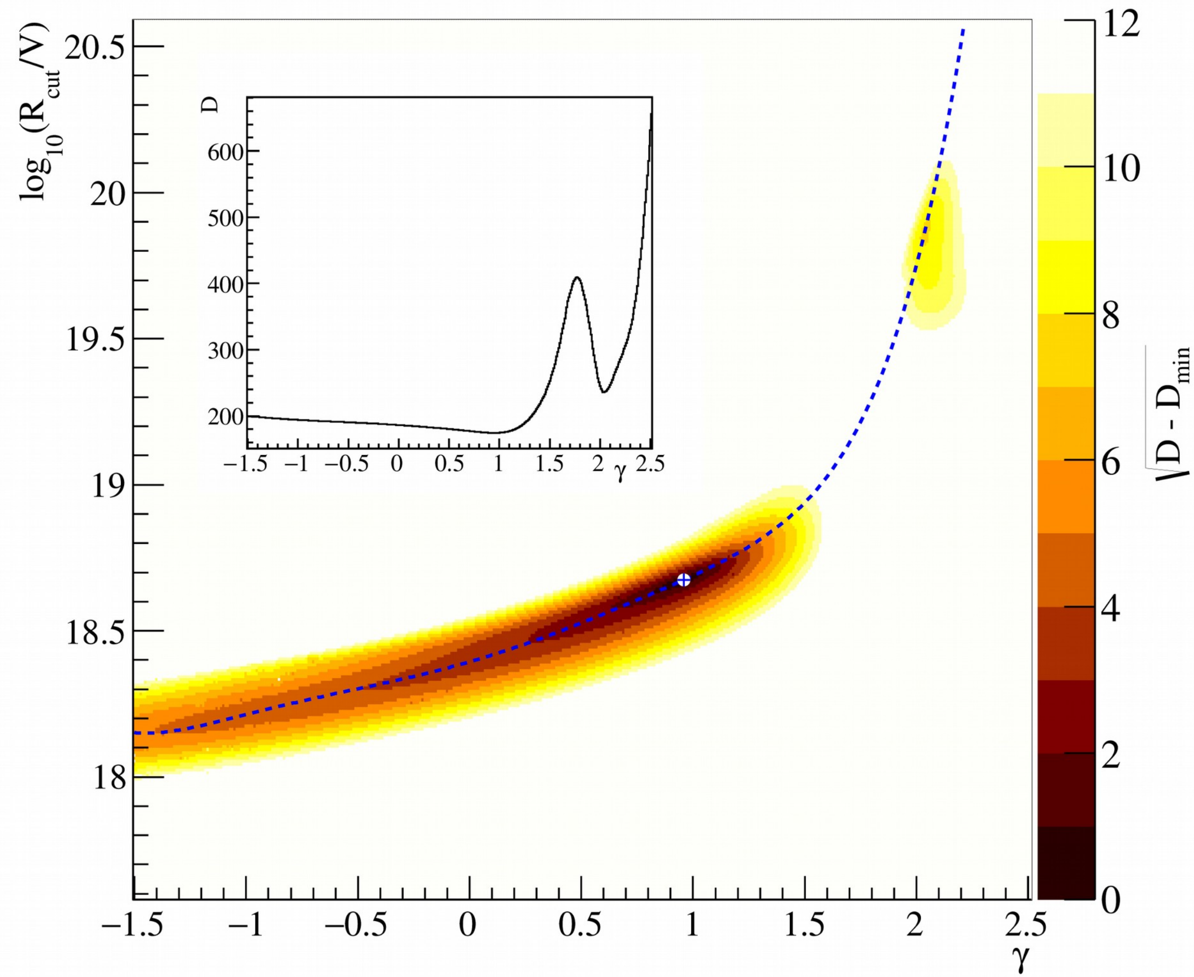
- Global effect: more interactions → softer spectra (at the injection) can describe the data, because the magnetic fields naturally suppress the heavy nuclei at low energies

  (as found for example in Mollerach & Roulet 2013 and Wittkowski for the Auger Coll, ICRC 2017)



Interpretation of UHECR data

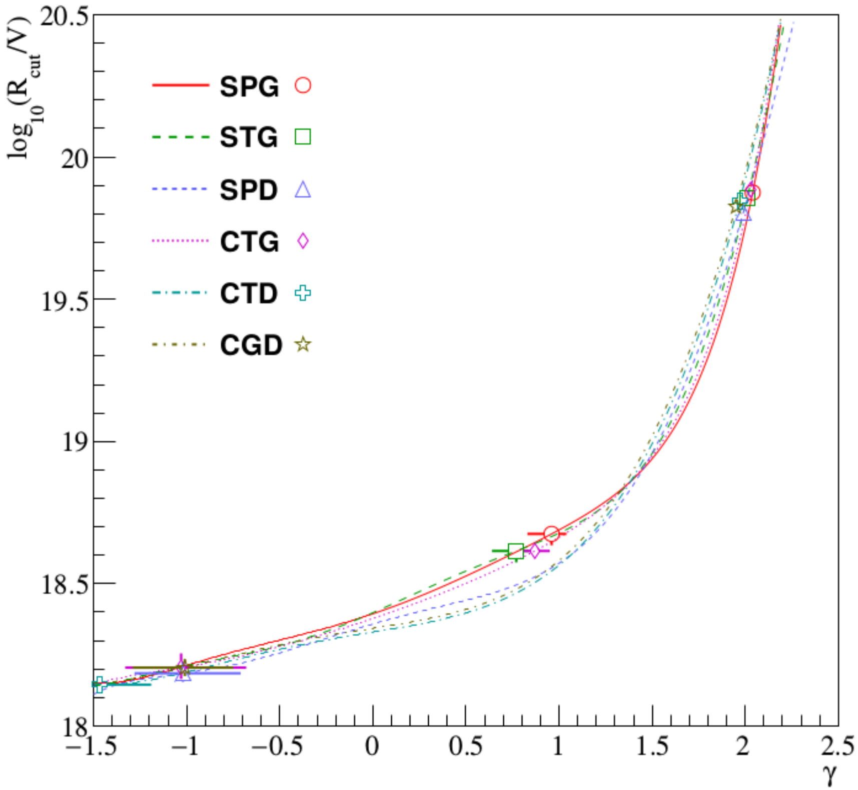
[Auger Coll, JCAP 2017]



Interpretation of UHECR data

Fit CR data: spectrum and composition results

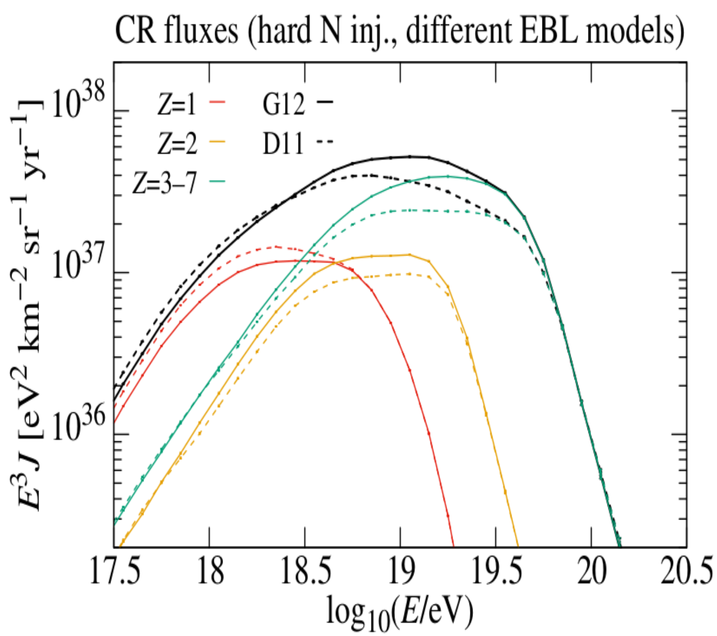
[Auger Coll, JCAP 2017]

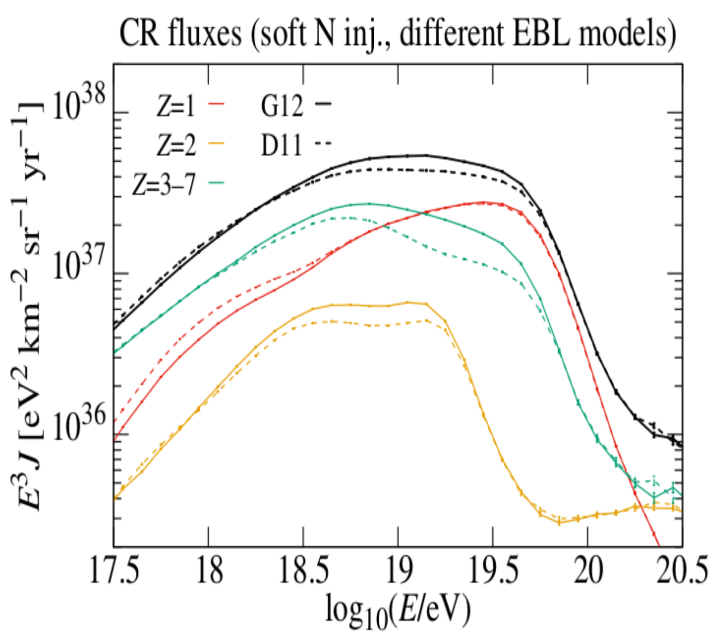


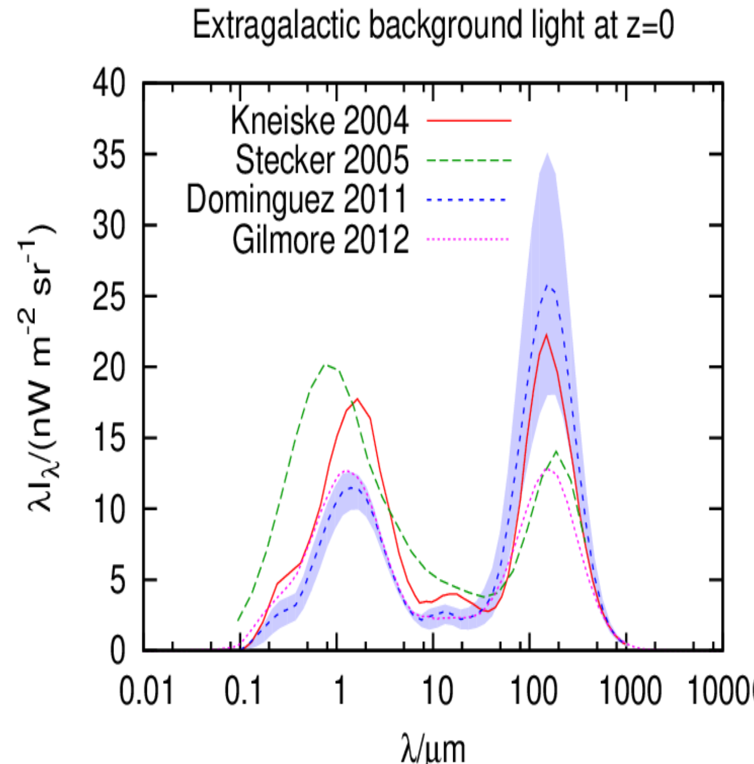
	MC code	$\sigma_{\text{photodisint.}}$	EBL model
SPG	SimProp	PSB	Gilmore 2012
STG	SimProp	TALYS	Gilmore 2012
SPD	SimProp	PSB	Domínguez 2011
CTG	CRPropa	TALYS	Gilmore 2012
CTD	CRPropa	TALYS	Domínguez 2011
CGD	CRPropa	Geant4	Domínguez 2011

- Uncertainties of cross section models and EBL in CR sources and propagation
  - Effect on CR observables:
    - Alves Batista, Boncioli, di Matteo, van Vliet, Walz, JCAP 2015
    - Boncioli, Fedynitch, Winter, Sci. Reports 2017
  - Effect on cosmogenic neutrinos and photons
    - Aloisio, Boncioli, di Matteo, Grillo, Petrera, Salamida, JCAP 2015
    - Alves Batista, Boncioli, di Matteo, van Vliet, in prep.

Uncertainties: EBL models







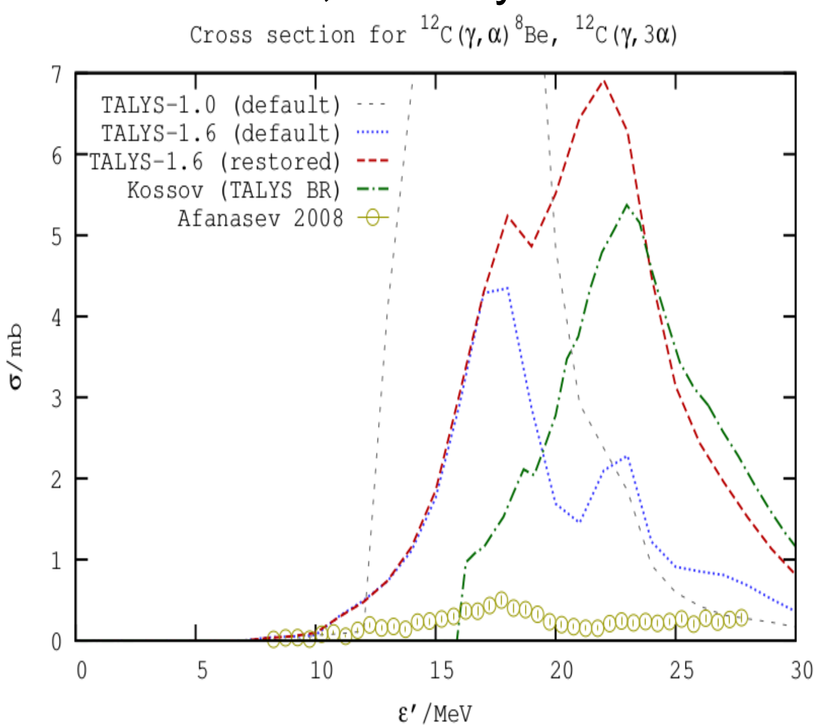
- High energies → interactions happen mainly with CMB photons
- Low energies and light masses → effect of enhanced interactions with EBL and accumulation of lighter masses
- Difference is increased in the “hard” injection scenario → higher than Auger statistical errors in the spectrum !

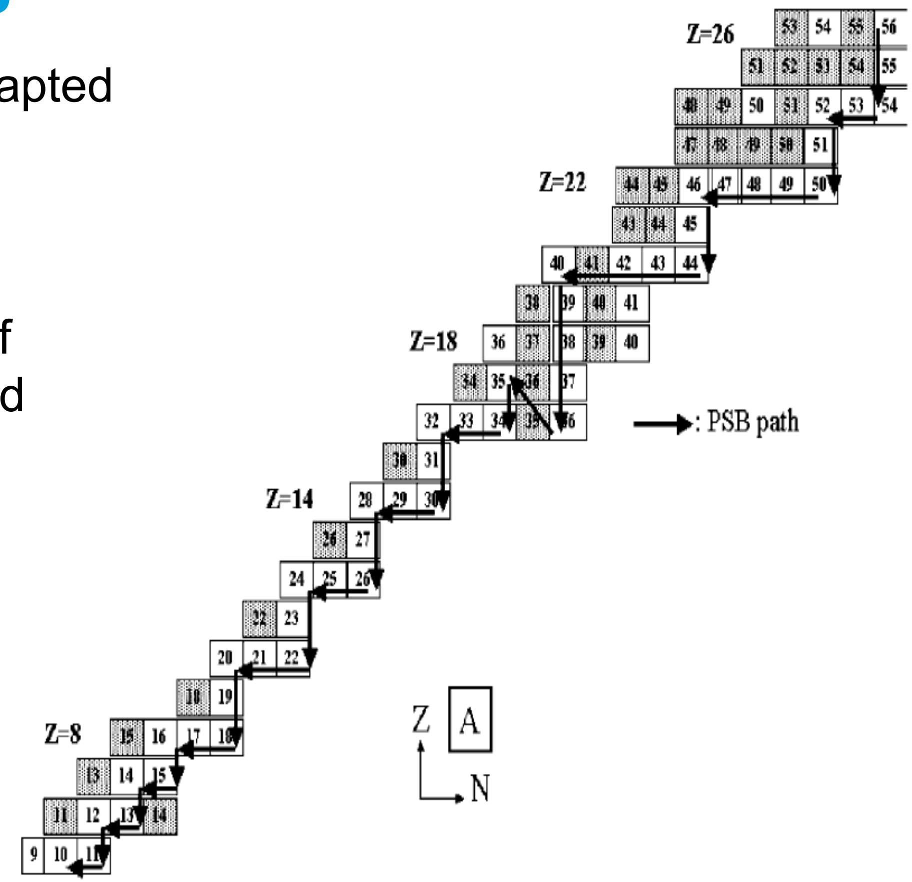
[Alves Batista, Boncioli, di Matteo, van Vliet, Walz , JCAP 2015]

[Alves Batista, Boncioli, di Matteo, van Vliet, in prep.]

Uncertainties: photo-disintegration cross sections

- One-path for photo-disintegration (**PSB model**, adapted from Puget, Stecker, Bredekamp ApJ 1976)
- More sophisticated models (like **TALYS**, http://www.talys.eu/) compute cross sections for all exclusive photo-disintegration channels (ejection of protons, neutrons, deuterons, tritiums, helium-3 and helium-4 nuclei, and any combinations thereof)



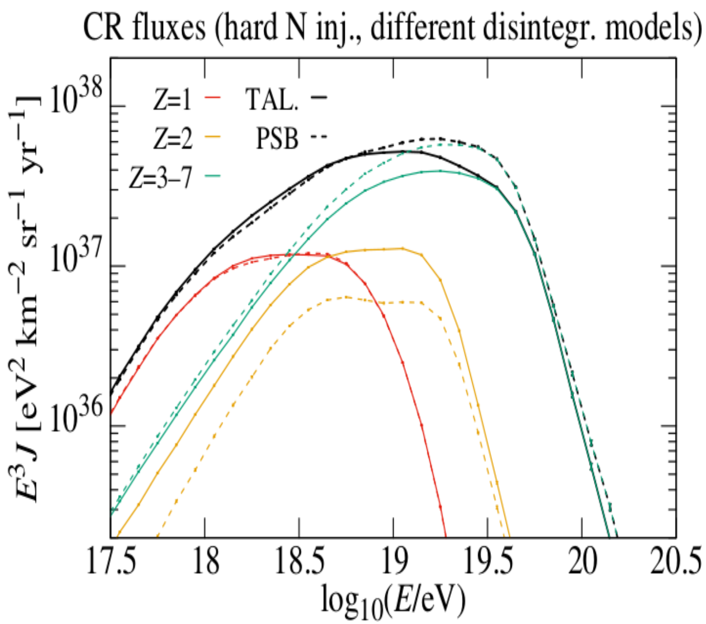


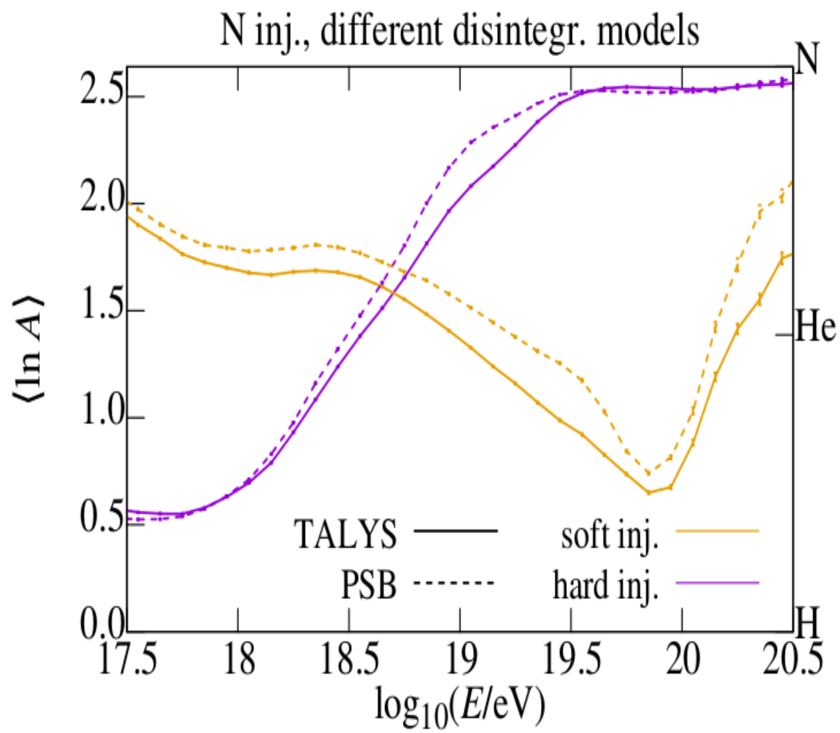
- **Problems**:
  - Models do not (always) agree with data !
  - Data is not totally available !

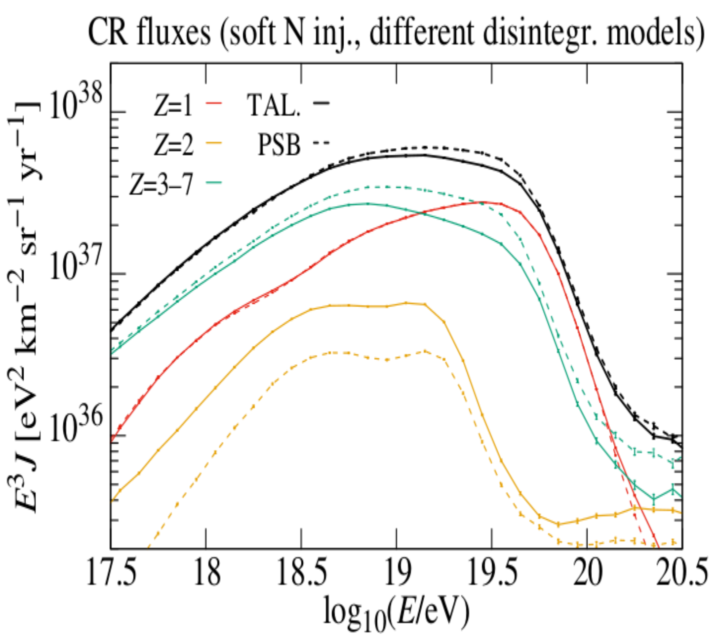
[Alves Batista, Boncioli, di Matteo, van Vliet, Walz, JCAP 2015] [Boncioli, Fedynitch, Winter, Sci.Rep. 2017]

[Alves Batista, Boncioli, di Matteo, van Vliet, in prep.]

Uncertainties: photo-disintegration cross sections







- Spectra at Earth → differences more visible in hard injection
- Composition:
  - Hard injection: more efficient disintegration gives smoother transition from light to heavy (also found in GRB sources, see Boncioli, Fedynitch, Winter, Sci. Reports 2017)
  - Soft injection: the composition at Earth is more mixed in the whole energy range

[Alves Batista, Boncioli, di Matteo, van Vliet, Walz, JCAP 2015]

[Alves Batista, Boncioli, di Matteo, van Vliet, in prep.]

Interaction framework and terminology

- We are interested in the total <u>photoabsorption cross section</u> and in the <u>inclusive cross sections</u>

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

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

<u>Comparison of models and measurements</u> 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 → <u>residual cross section</u>, 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.

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

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

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

- 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 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

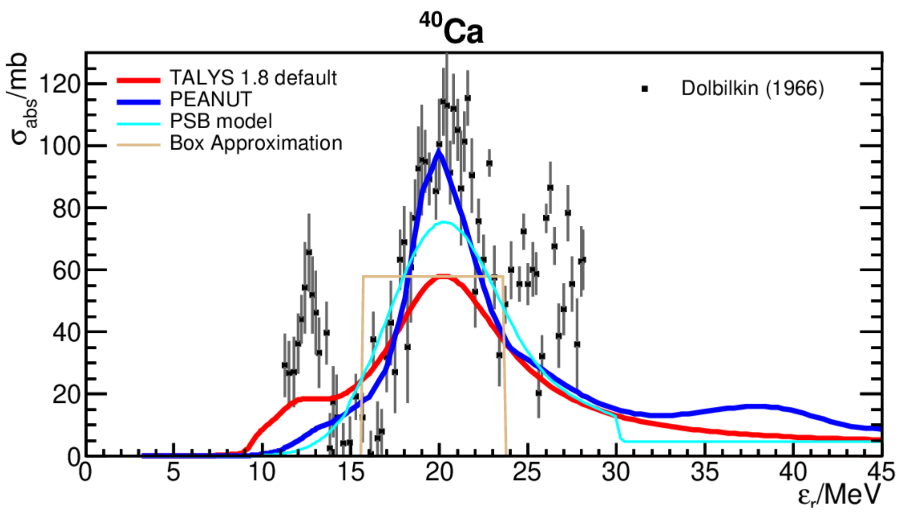
$$\sigma_{\mathrm{GDR}} \approx 1.45 \times 10^{-27} A \ \mathrm{cm}^2$$

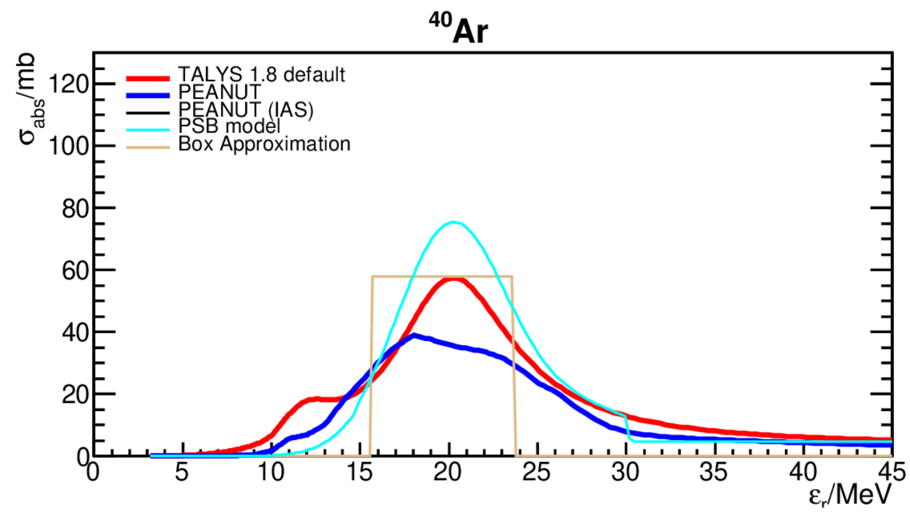
Situation on experimental data and theoretical models

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 $\sigma_{\rm abs}$ measurements are evaluated through branching ratios from pre-quilibrium and evaporation models, together with photo-neutron data. The description of $\sigma_{\rm abs}$ is good for all measured elements.

Photo-disintegration cross sections: current situation

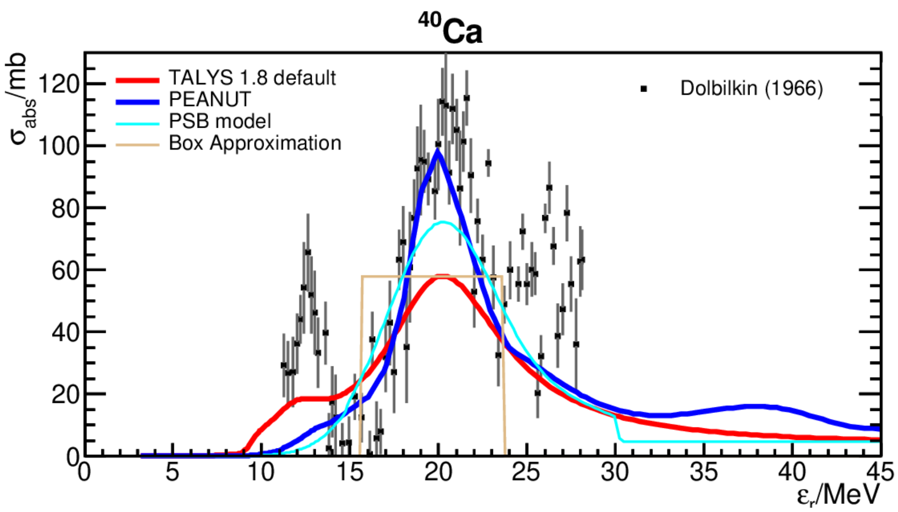




- Ca-40: double magic nucleus
- TALYS predictions not dependent on the element
- PEANUT predictions are different in the same isobar; if data available, at least the central GDR peak is reproduced
- Box approximation, used for example in Murase and Beacom, Phys Rev. D81 2010, underestimates data and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

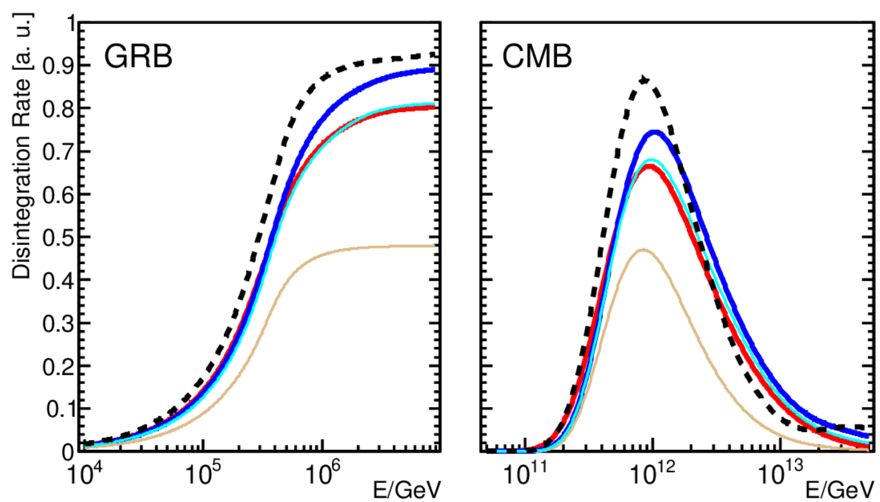
[Boncioli, Fedynitch, Winter, Sci.Rep. 2017]

Photo-disintegration cross sections: current situation



CMB, propagation

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



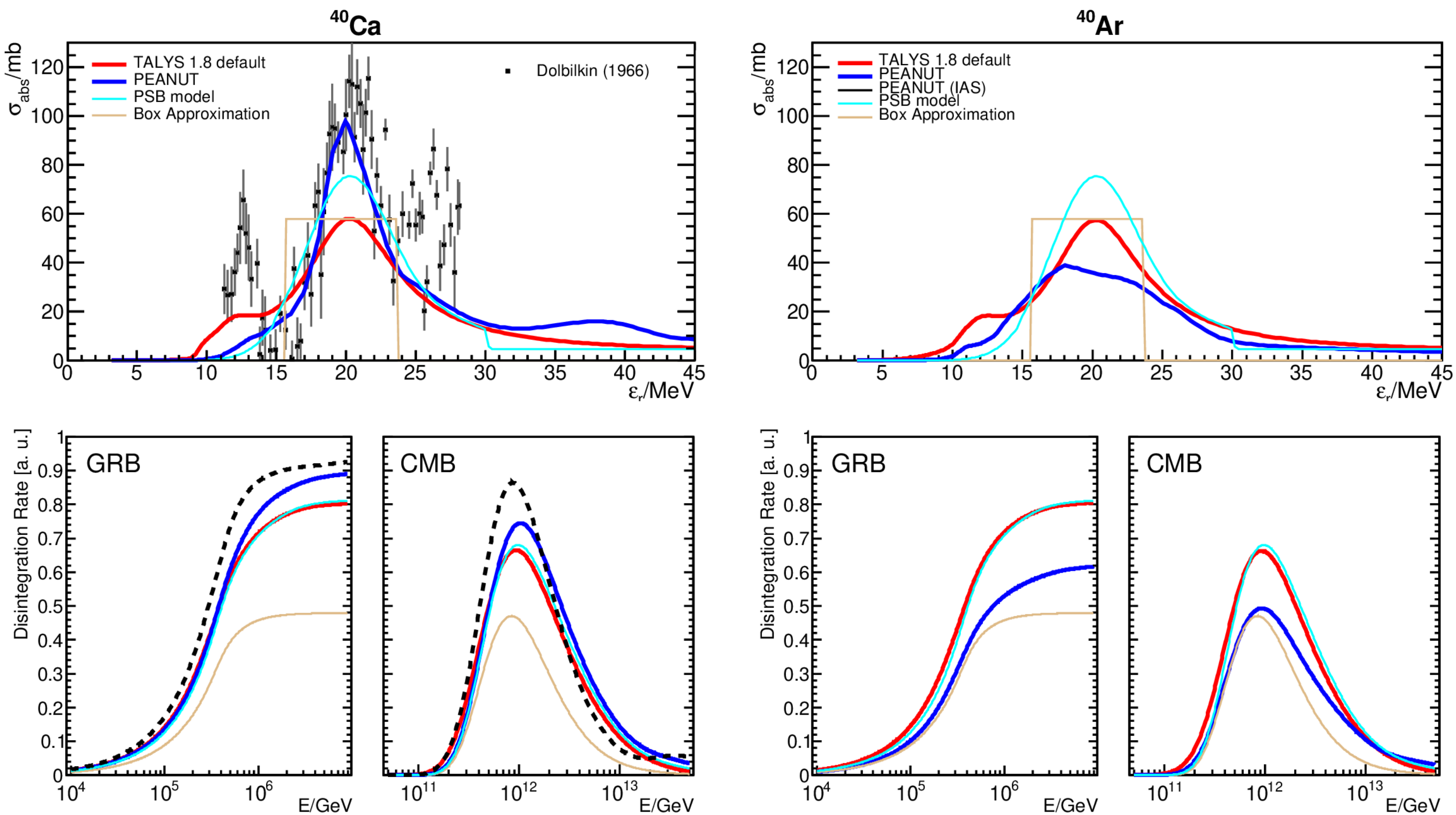
GRB, source

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

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

[Boncioli, Fedynitch, Winter, Sci.Rep. 2017]

Photo-disintegration cross sections: current situation



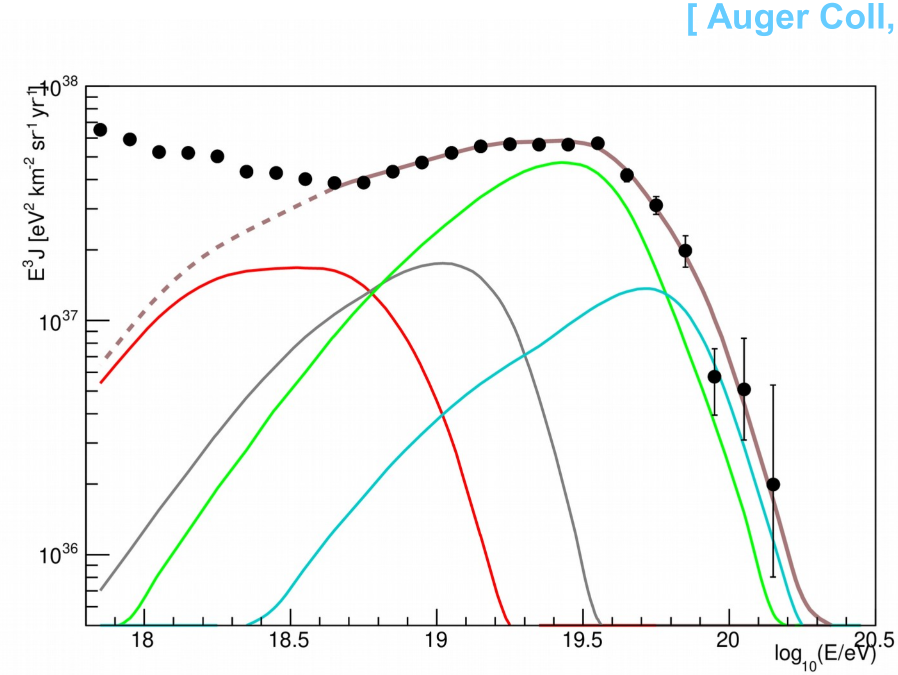
Interpretation of UHECR data → propagation model

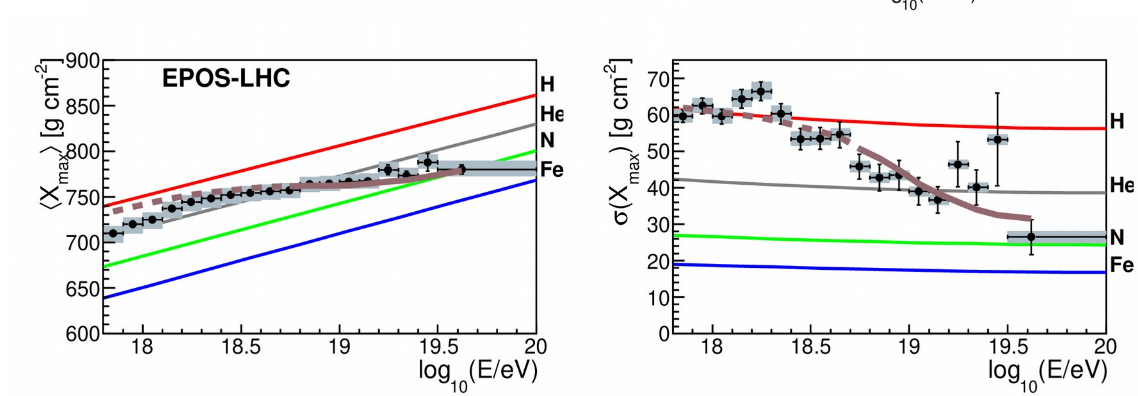
MODEL

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

[Auger Coll, JCAP 2017]

	parameters
Rcut	18.68
gamma	0.96
H	0.0
He	67.3
N	28.1
Si	4.6
Dmin	174.4/119





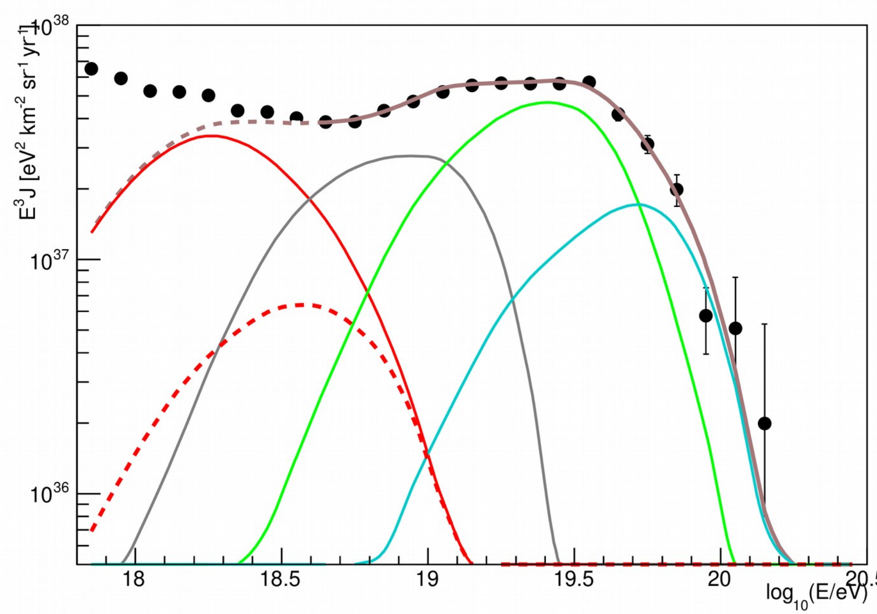
Interpretation of UHECR data → propagation model

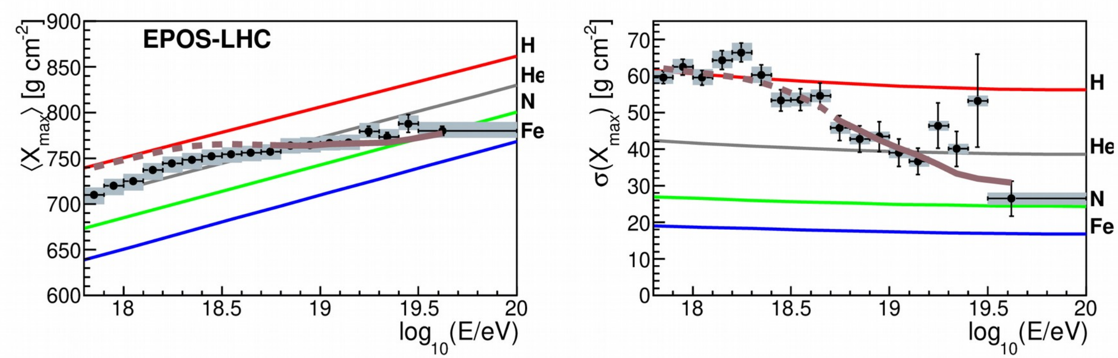
MODEL

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

	parameters
Rcut	18.19
gamma	-1.02
H	62.6
He	36.8
N	0.6
Si	0.03
Dmin	187.0/119

[Auger Coll, JCAP 2017]





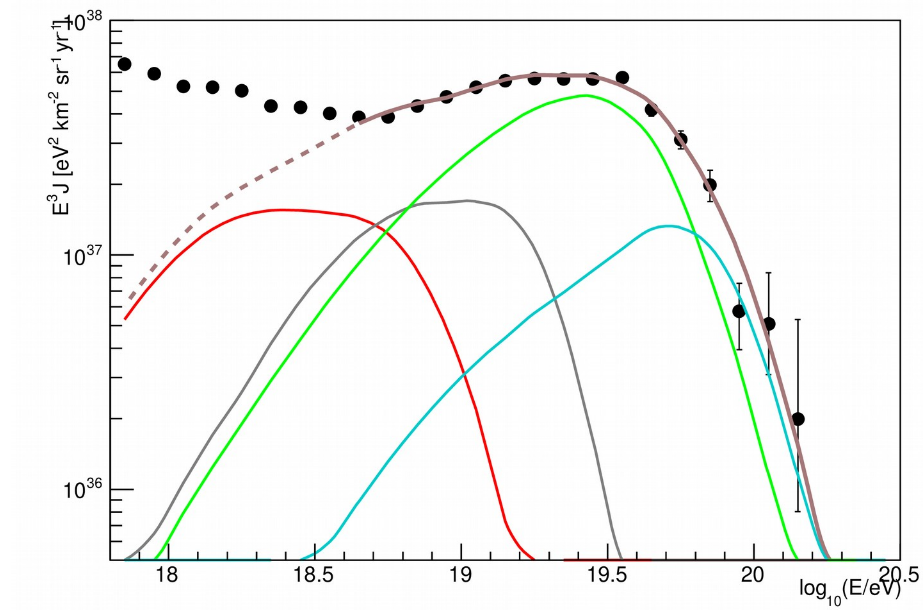
Interpretation of UHECR data → propagation model

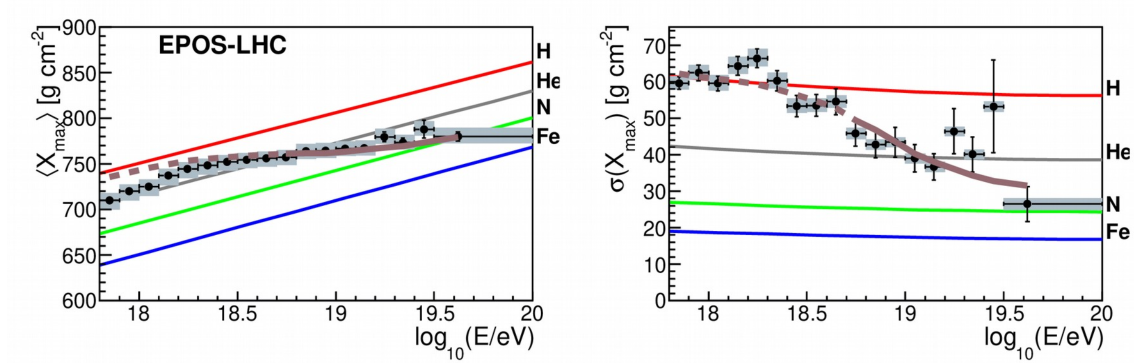
MODEL

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

[Auger Coll, JCAP 2017]

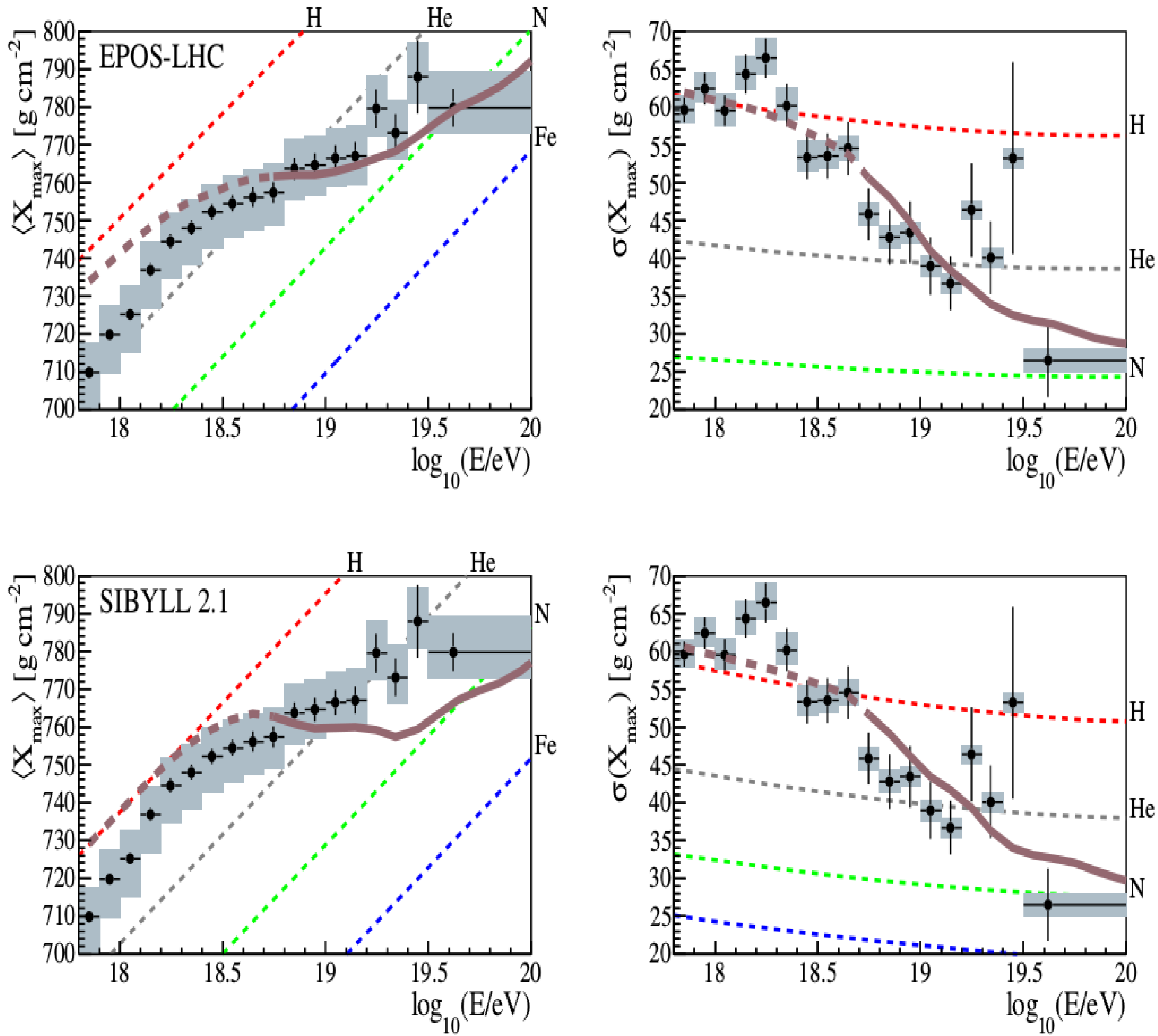
	parameters
Rcut	18.62
gamma	0.77
H	0.0
He	7.0
N	85.2
Si	7.7
Dmin	175.9/119



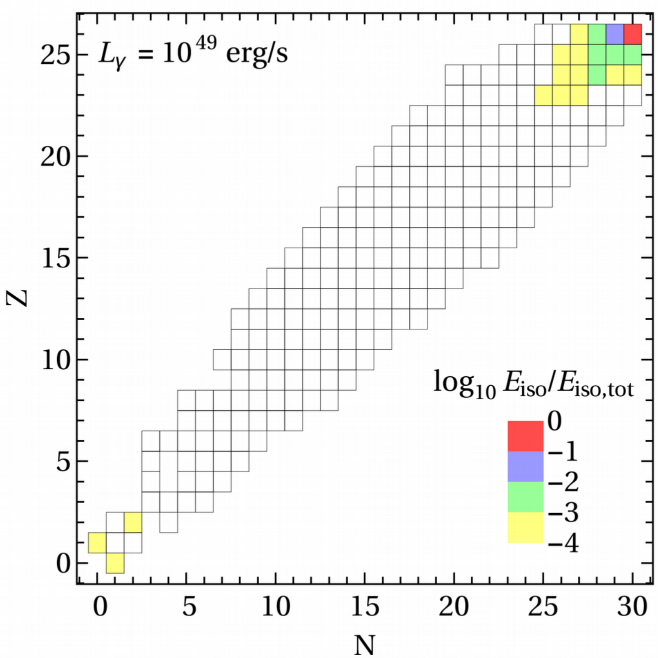


Interpretation of UHECR data → air interaction models

[Auger Coll, JCAP 2017]

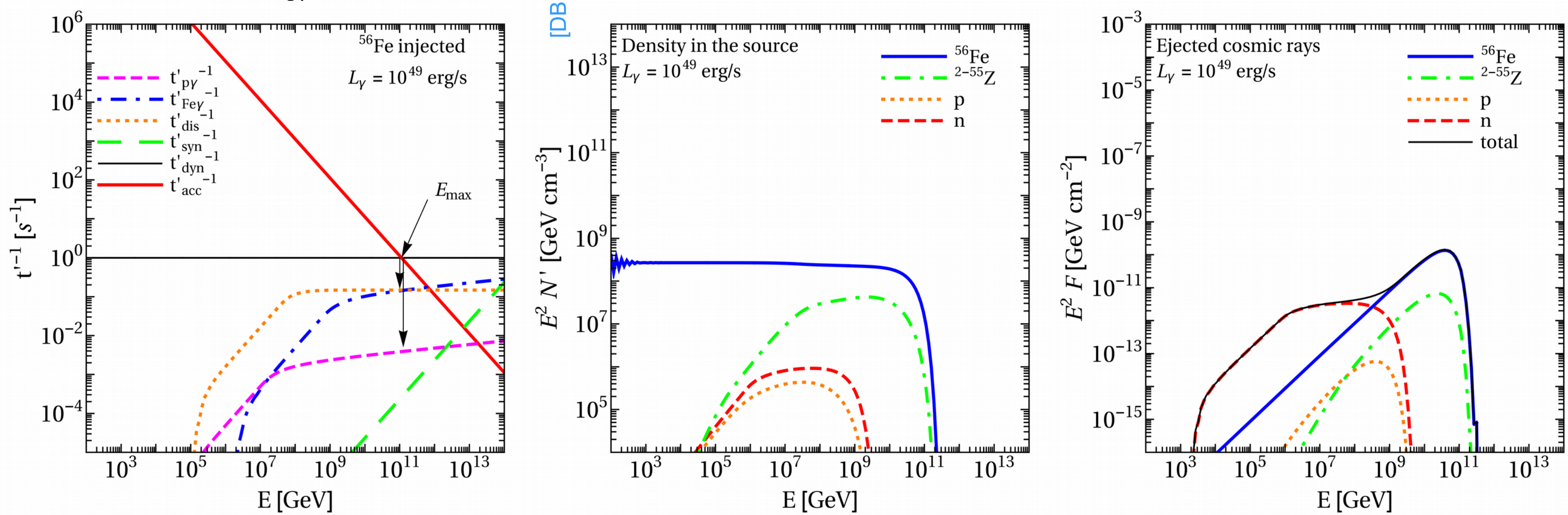


Source class I: Empty Cascade

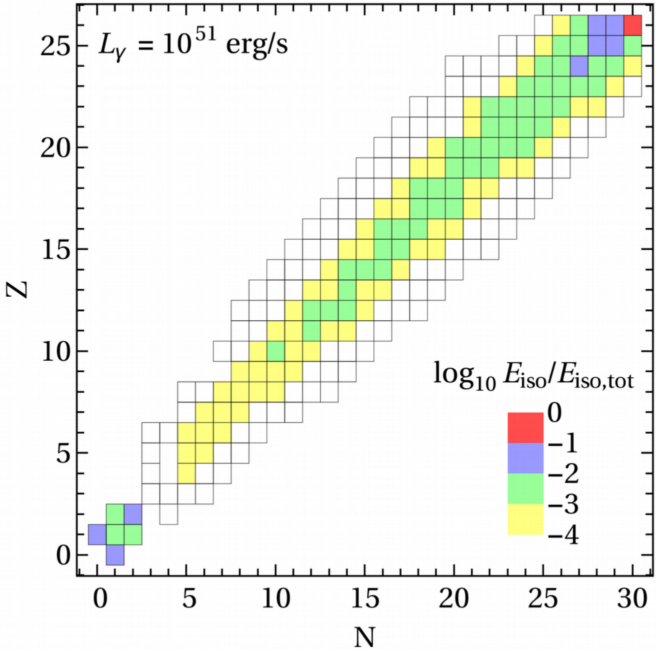


[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909]

- Low luminosity / large collision radii
- Only a few isotopes in the cascade populated relative to injected energy in primaries
- Maximum energy determined by adiabatic cooling, i.e. rigidity-dependent / Peters cycle
- Optically thin to photo-hadronic interactions of all species
- Nuclei stay mostly intact and escape as CR

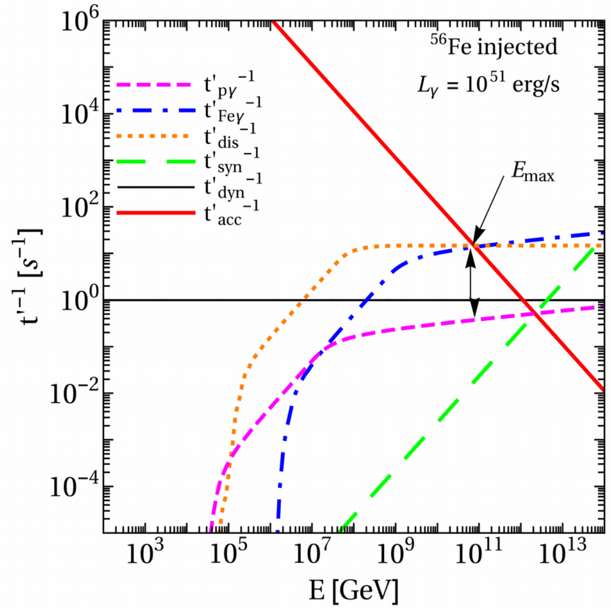


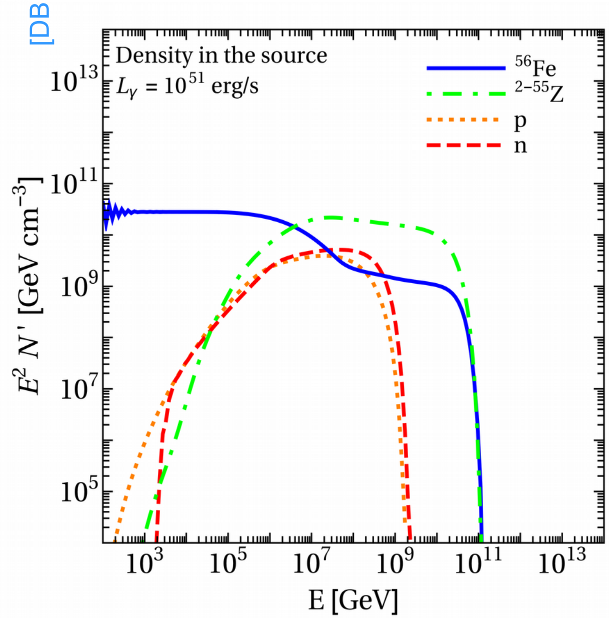
Source class II: Populated Cascade

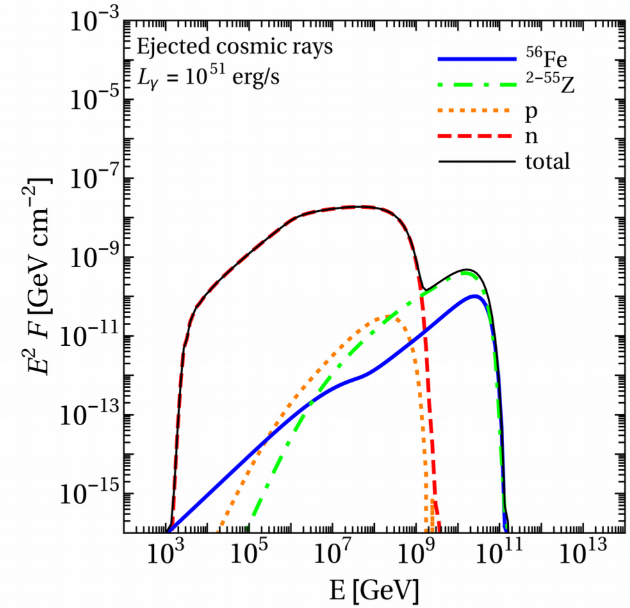


- Intermediate luminosity / collision radii
- Cascade broadly populated along the main diagonal relative to injected energy
- Maximum energy determined by photo- hadronic processes, no Peters cycle!
- Optically thick to photo-hadronic interactions of heavy nuclei, still opt. thin to light nuclei
- Nuclei disintegrate partially

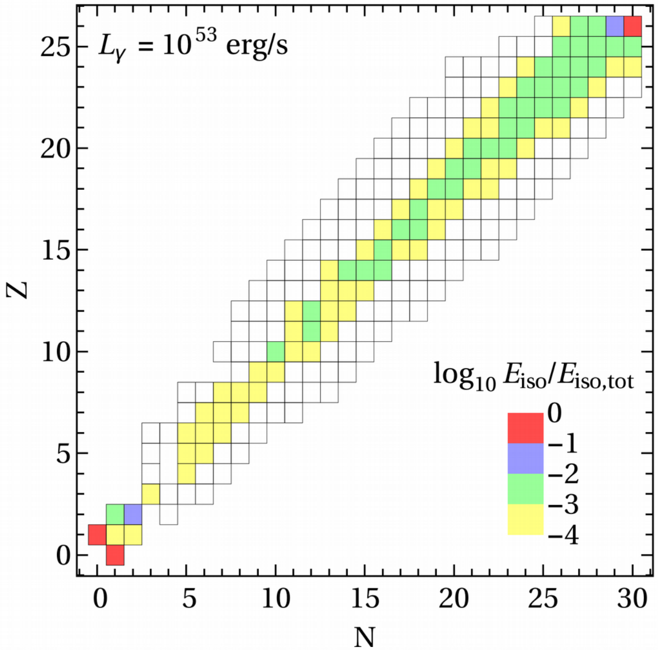
[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909]





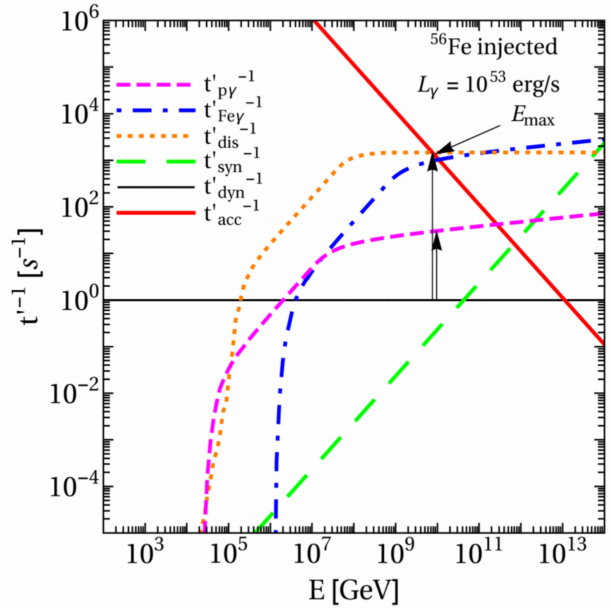


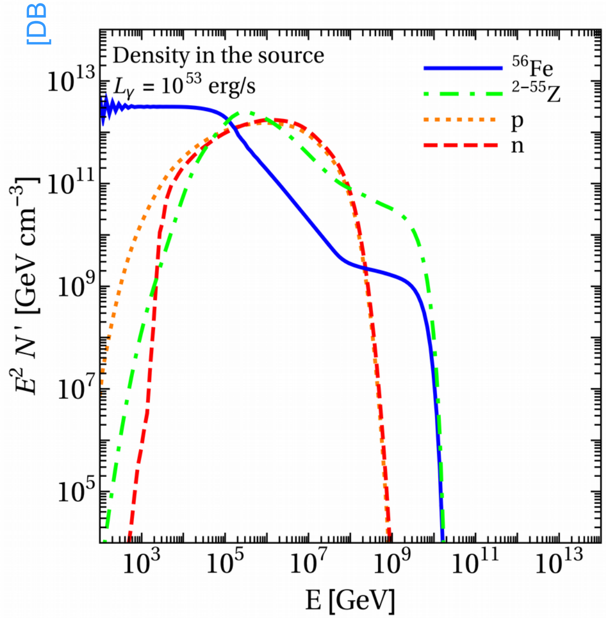
Source class III: Optically Thick Case

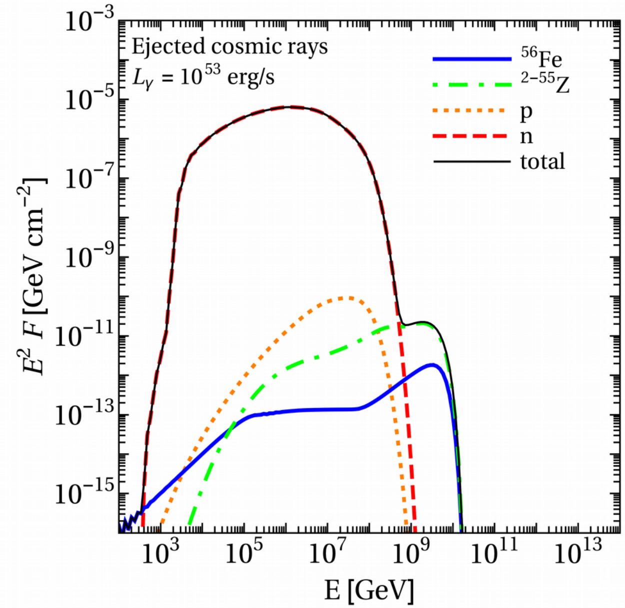


[DB, D. Boncioli, A. Fedynitch, W. Winter, arXiv:1705.08909]

- High luminosity / small collision radii
- Cascade populated but more narrow, most of the energy is dumped into nucleons
- Maximum energy determined by photo- hadronic processes, no Peters cycle!
- Optically thick to photo-hadronic interactions of all species
- Nuclei disintegrate very efficiently







Nuclear composition of GRB jets

- Usual assumption:

  - GRB jet initially consists of free nucleons

  - nucleons can recombine into deuterium or alpha as the jet expands and cool but nuclei heavier than carbon cannot be produced

- The mechanisms to launch a relativistic jet is not yet completely understood → initial composition is not necessarily free nucleons

  - some observations of GRBs suggest that their relativistic jets were initially dominated by the magnetic field energy flux, being able to involve also heavy nuclei (A=56)

- In Shibata & Tominaga, arXiv:1503.03662 [astro-ph.HE] , the jet is assumed to be due to falling matter during a relativistic jet-induced explosion. They adopt Wolf-Rayet stars as progenitors

- Other possibility: nucleosynthesis in from free nucleons in the central engine of GRBs (Metzger et al, 2011)