UHECR propagation in the extragalactic space

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DESY, Zeuthen

Arbeitstreffen Kernphysik, Schleching, February 18th – 25th, 2016

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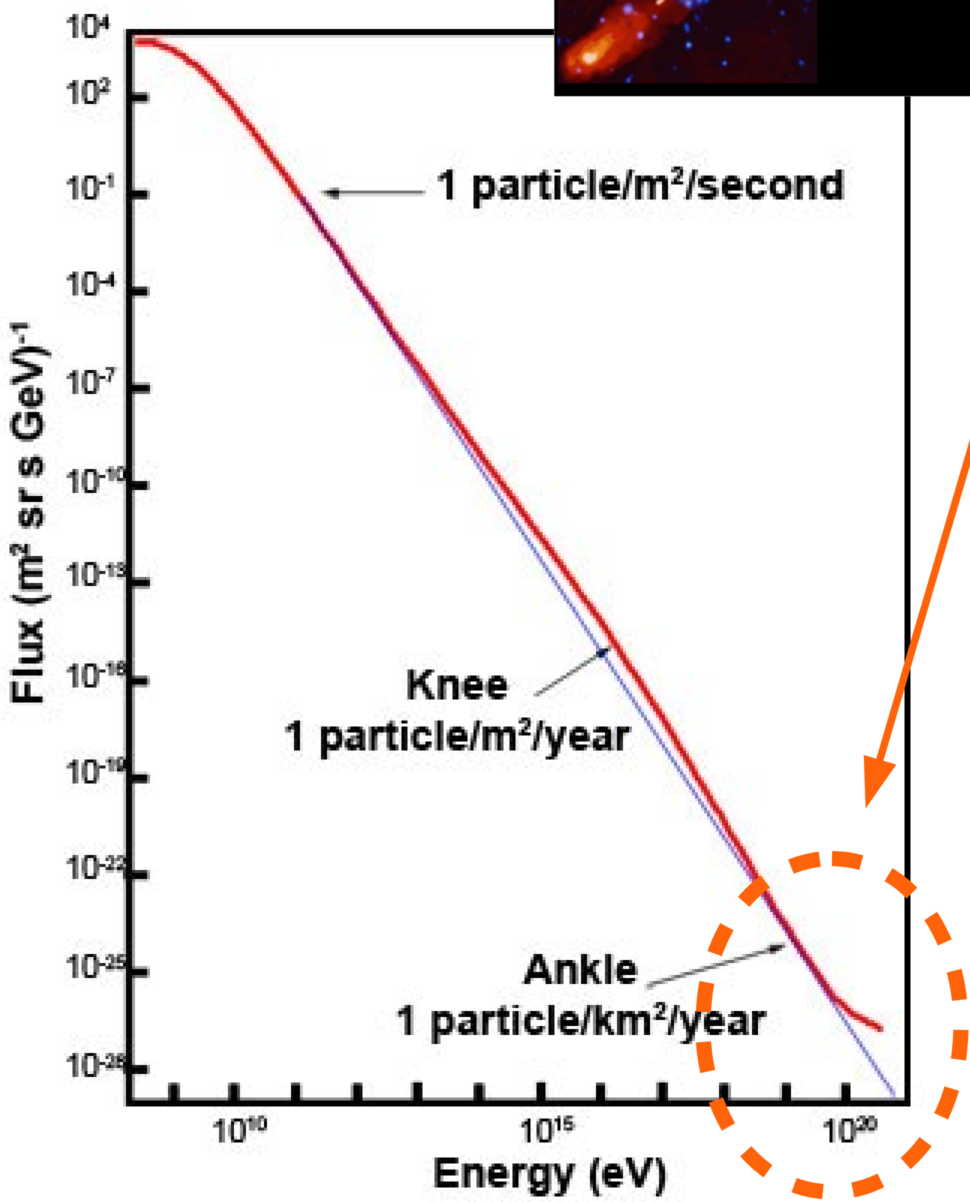
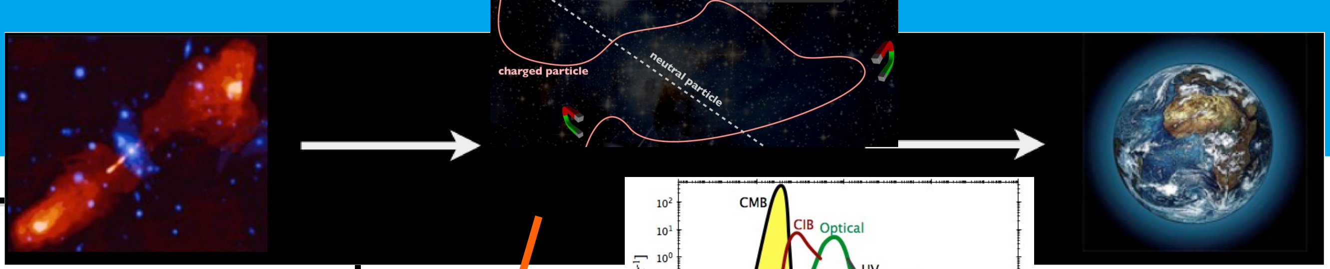
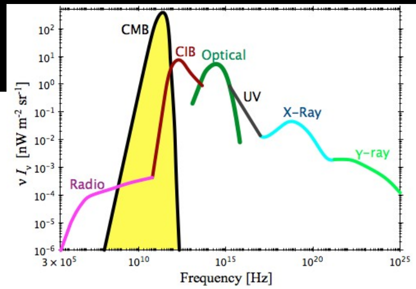
Introduction





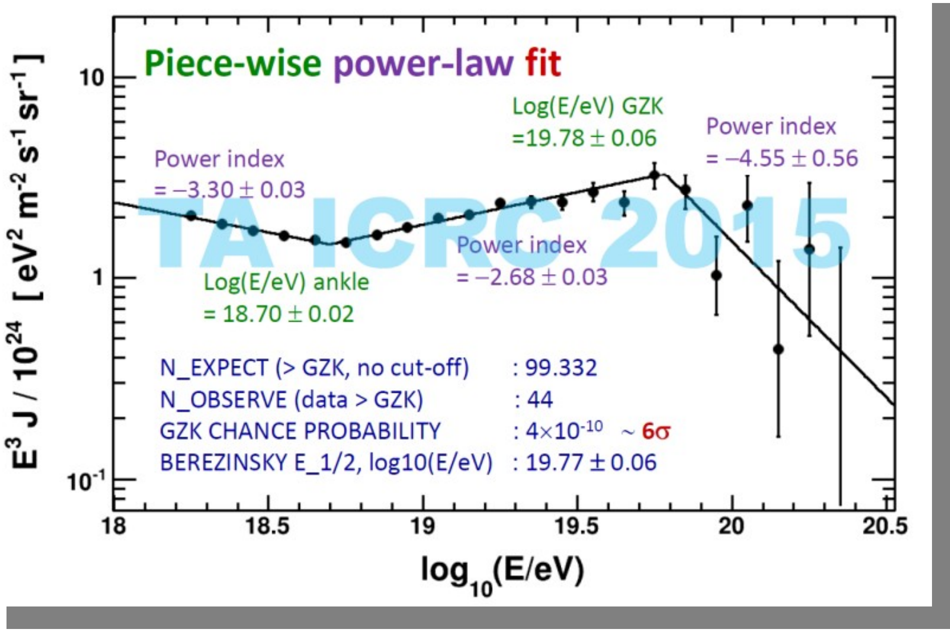


- Where do UHECRs come from?
- What is their chemical composition?
- What is the origin of the features of the measured spectrum?
- What can we learn by studying the interactions of UHECRs in the extragalactic space?

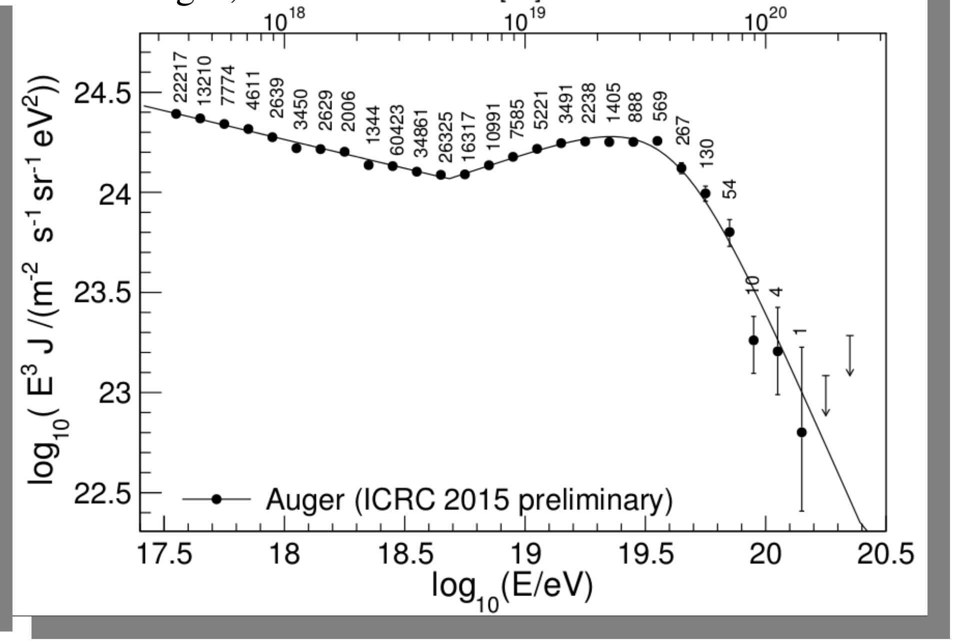
What we measure: UHECR energy spectrum

- The energy spectrum has a strong suppression at the highest energies

TA, ICRC 2015

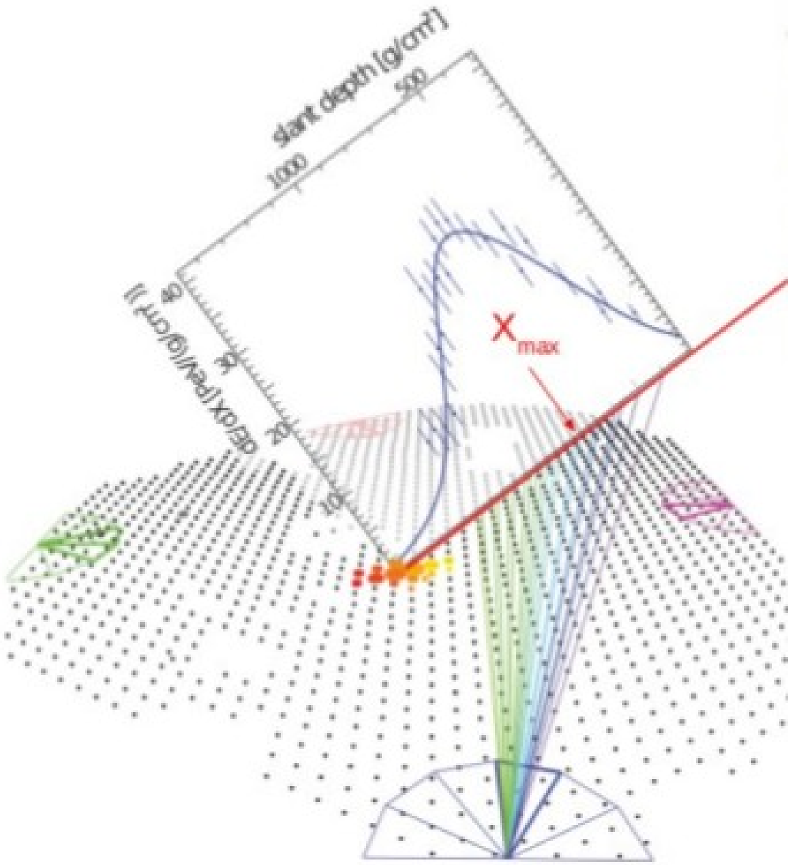


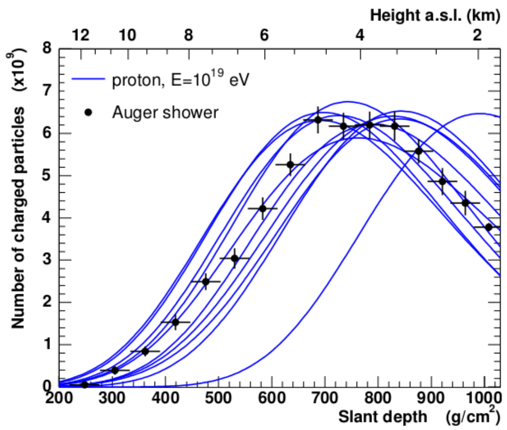
Auger, ICRC 2015

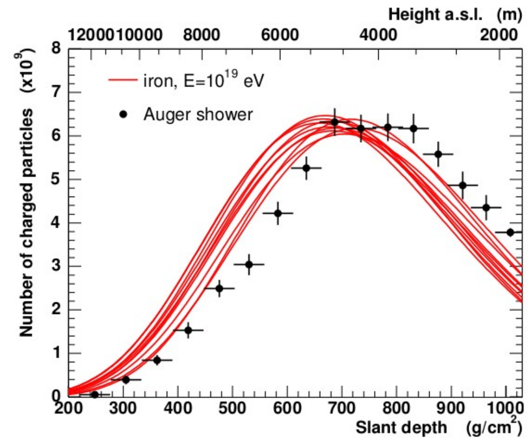


- <u>What we do not know</u>: what is the origin of this suppression?

What we measure: Composition observables





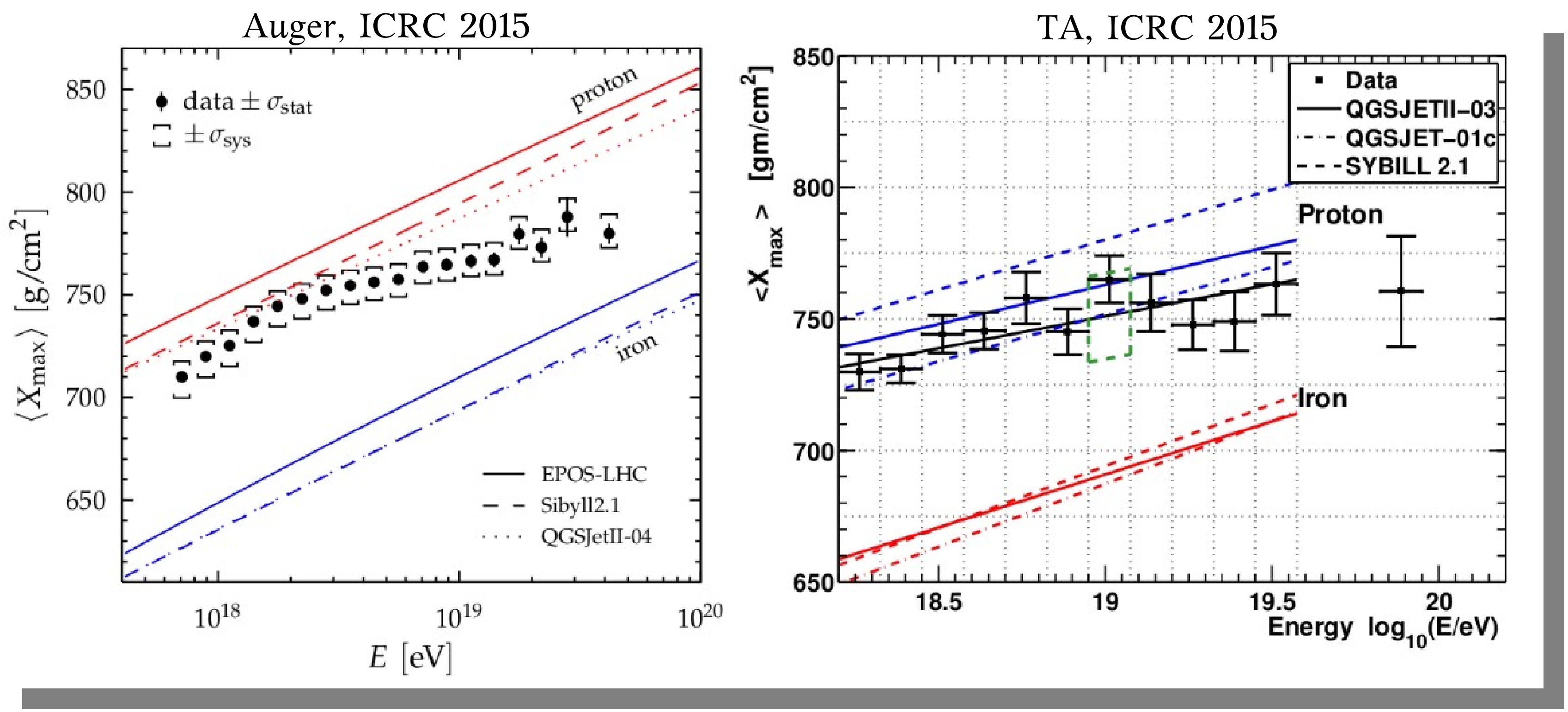


depth of shower

fluctuations

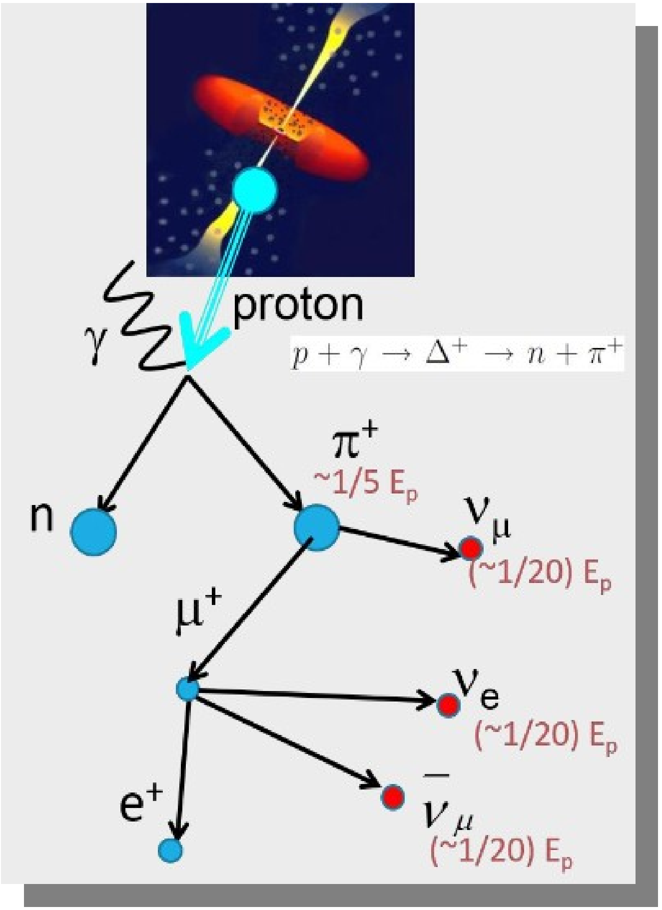
muon number

What we measure: Composition observables

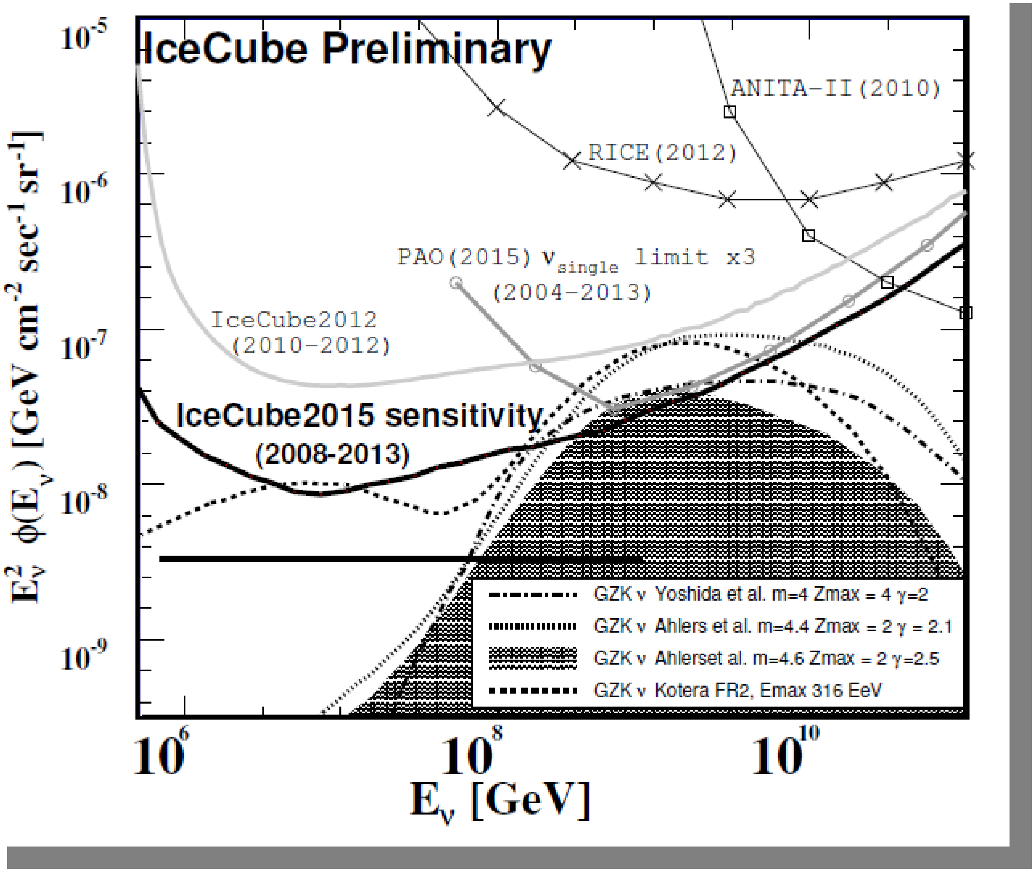


- After accounting for the different resolutions, acceptances and analysis strategies of the two experiments, the results are found in good agreement within systematics → see TA and Auger working group @ ICRC 2015
- Considering a mixed composition or a pure proton one, the possible interpretation of the suppression changes...

What we measure: Neutrino flux

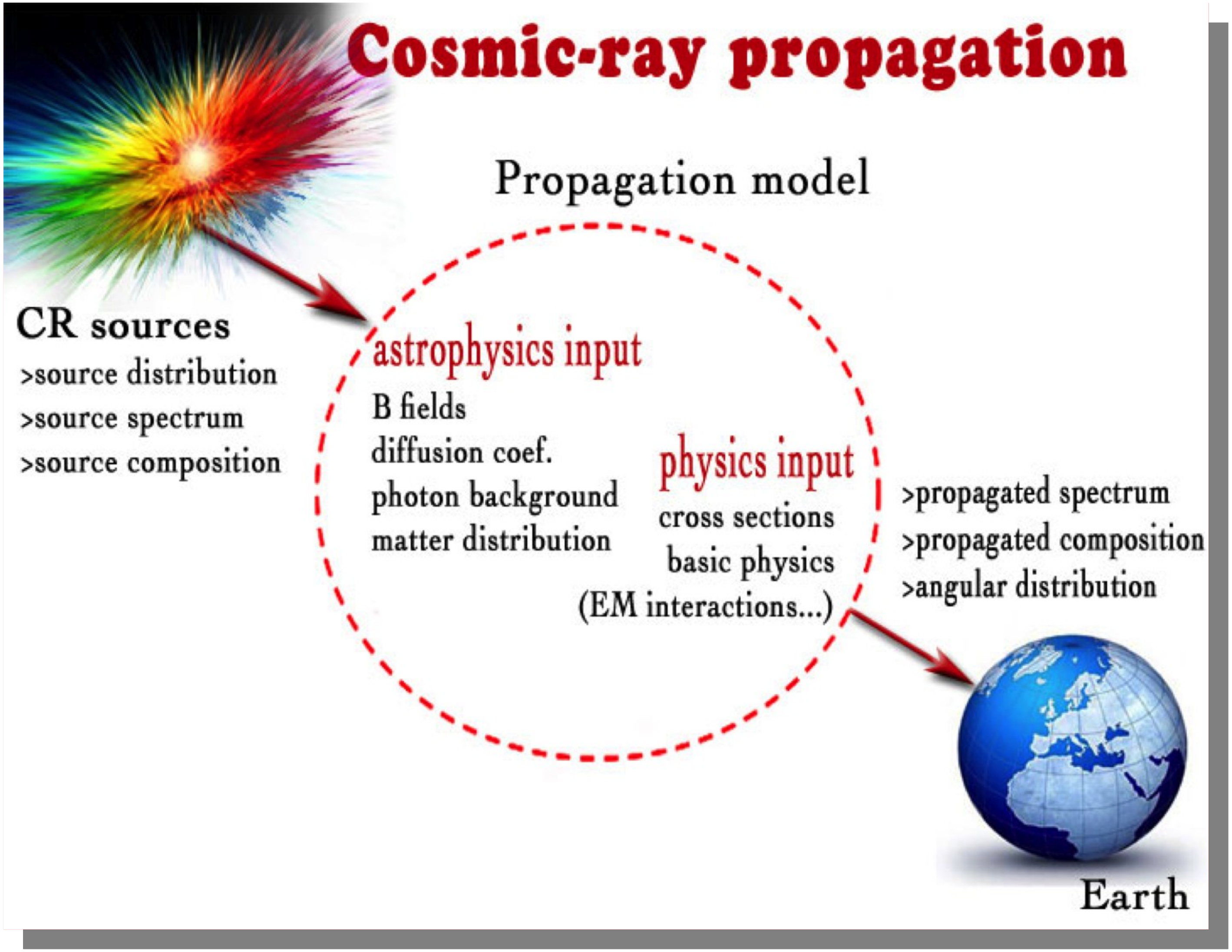


IceCube, ICRC 2015



- Secondary particles produced during propagation add information to the aim of understanding the UHECR properties

From acceleration to detection...



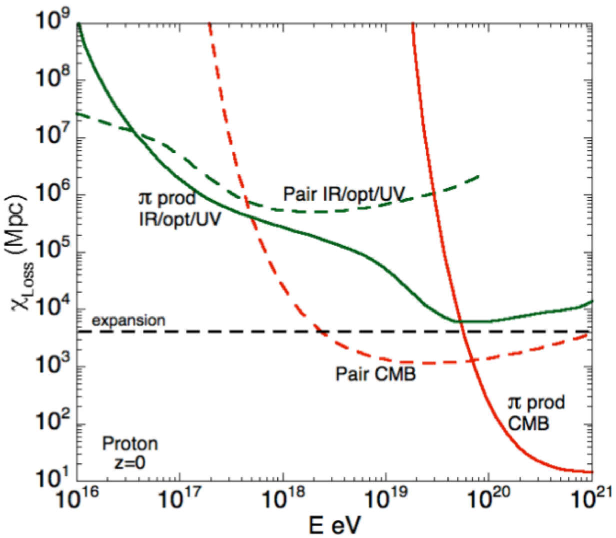
Hypothesis #1

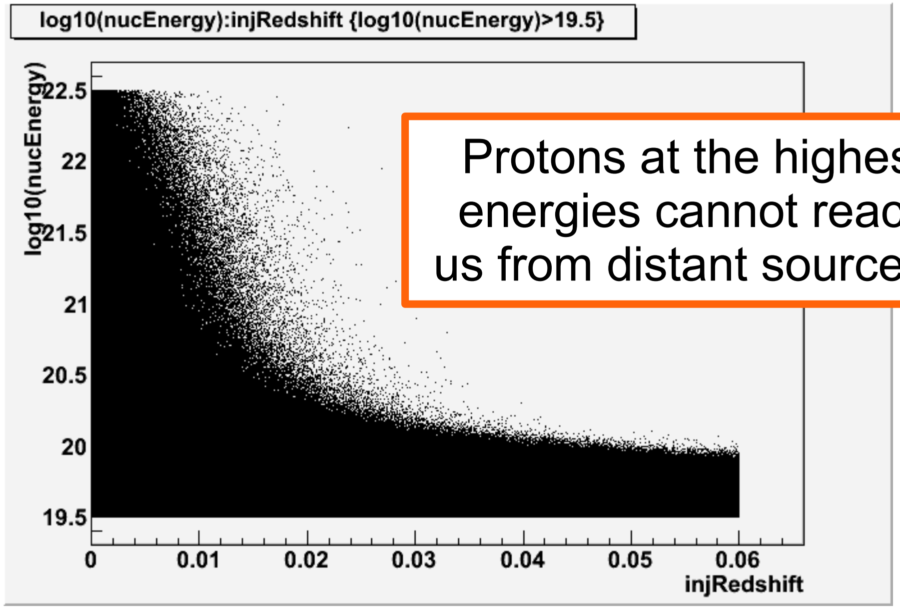
- Testing the proton composition at the source

Interactions and energy losses for 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 !

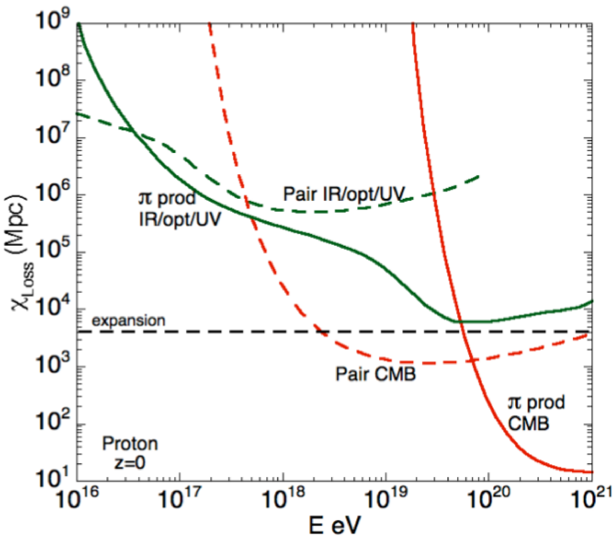
- Greisen, Zatsepin and Kuzmin estimated the opacity of the universe for CR protons above 100 EeV and predicted the existence of the suppression of the flux at the highest energies (GZK cut-off)

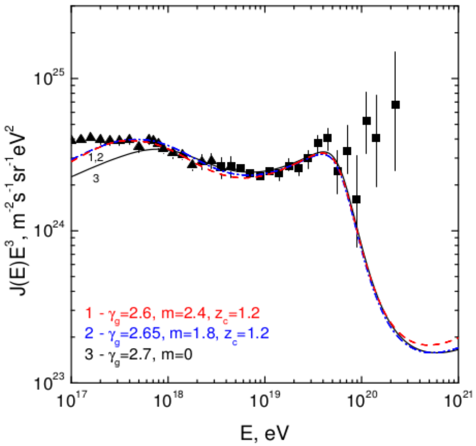
→ K. Greisen, PRL 16 748 (1966), G.T. Zatsepin and V.A. Kuzmin, Sov. Phys. JETP Lett. 4 78 (1966)

Interactions and energy losses for protons

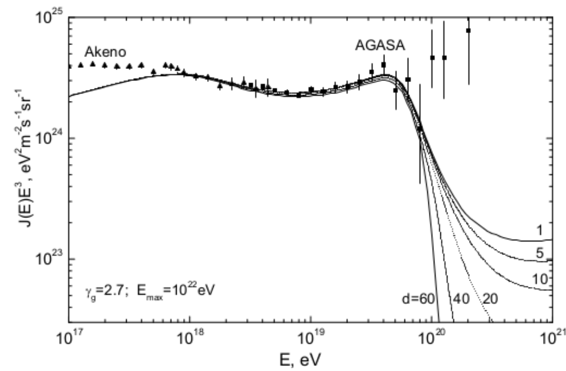
- Around 10^18.7 eV the spectrum exhibits a hardening: the "ankle"
- In the context of the dip model, the intermediate energy range is dominated by pair production

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





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

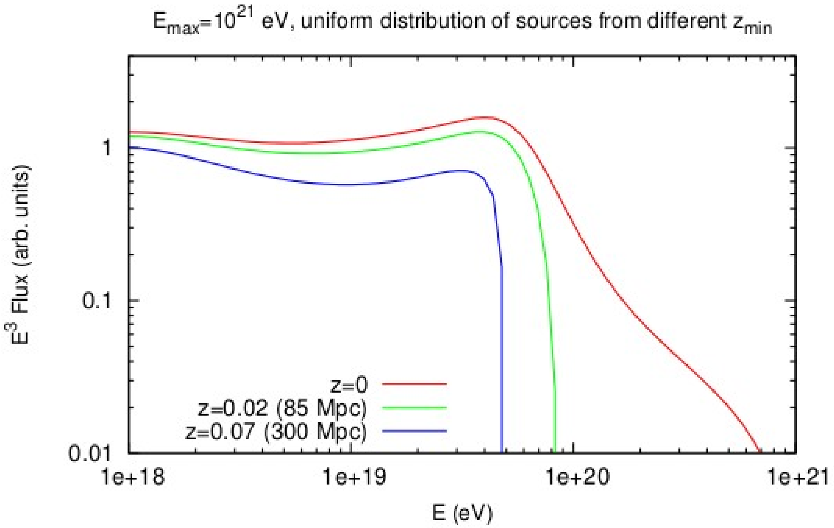


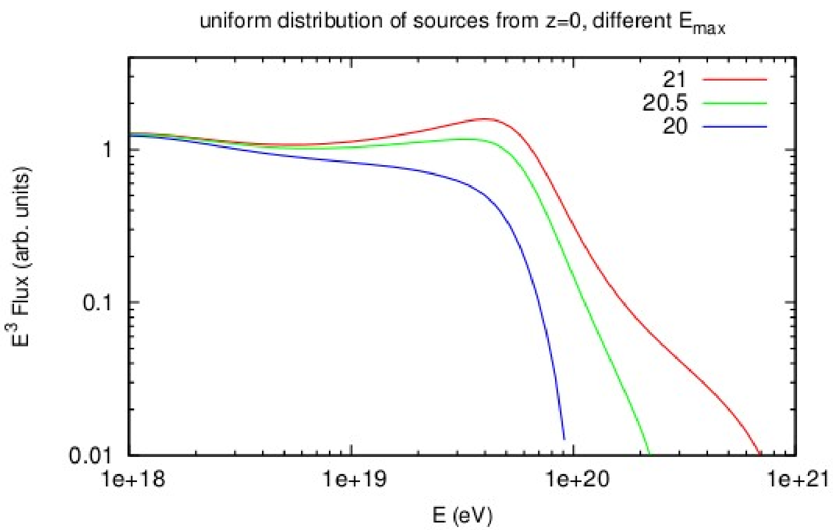
- Due to the interaction length of the process, this feature is less sensitive to details of the distribution of sources wrt the suppression
- Hillas and Blumenthal studied the effect of pair production on protons above 1 EeV → Hillas, Phys. Lett. 24A 677 (1967), Blumenthal, Phys. Rev. D Vol 1 1596 (1970)

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) 152-160





- 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?

Simulation of UHECR propagation and fit - protons

- Propagation computed numerically via a transport equation that includes:
  - adiabatic energy losses due to the expansion of the Universe
  - pair production
  - photopion production
- Resulting neutrino flux is also computed

- TA spectrum fitted above 10^18.2 eV
- Sources assumed to be identical, homogeneously distributed, with proton injection:

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

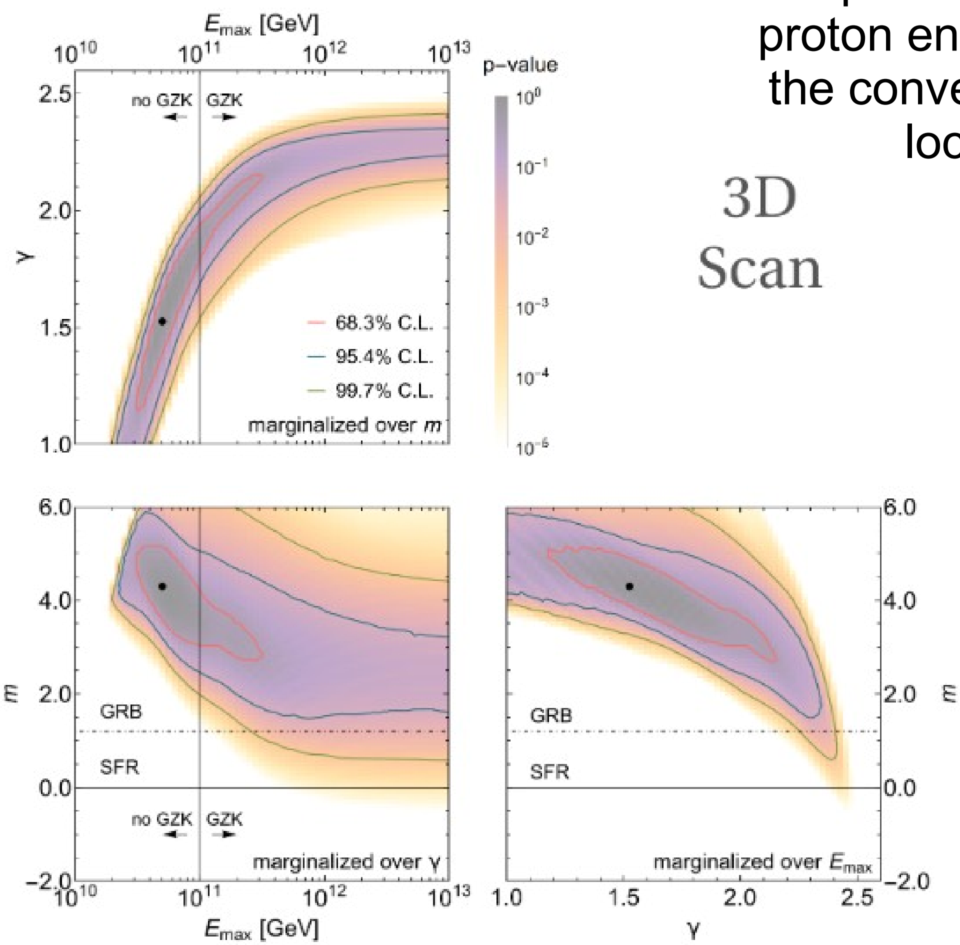
$$H(z) = (1+z)^m \times \begin{cases} (1+z)^{3.4}, & z < 1 \\ 2^{3.7}(1+z)^{-0.3}, & 1 \leq z < 4 \\ 2^{3.7} 5^{3.2} (1+z)^{-3.5}, & z > 4 \end{cases}$$

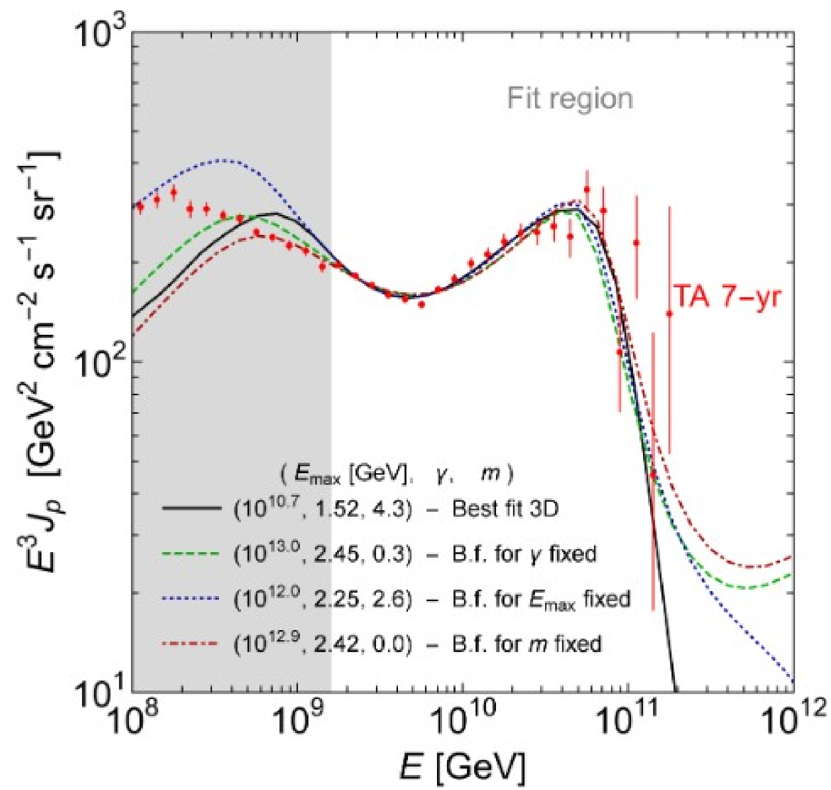
- See J. Heinze, DB, M. Bustamante and W. Winter, arXiv:1512.05988 [astro-ph] for details

Simulation of UHECR propagation and fit - protons

- Hard spectra, strong source evolution and low maximal proton energy at the source are slightly favored over the conventional GZK scenario → but a depletion of local sources has not been investigated here

3D Scan



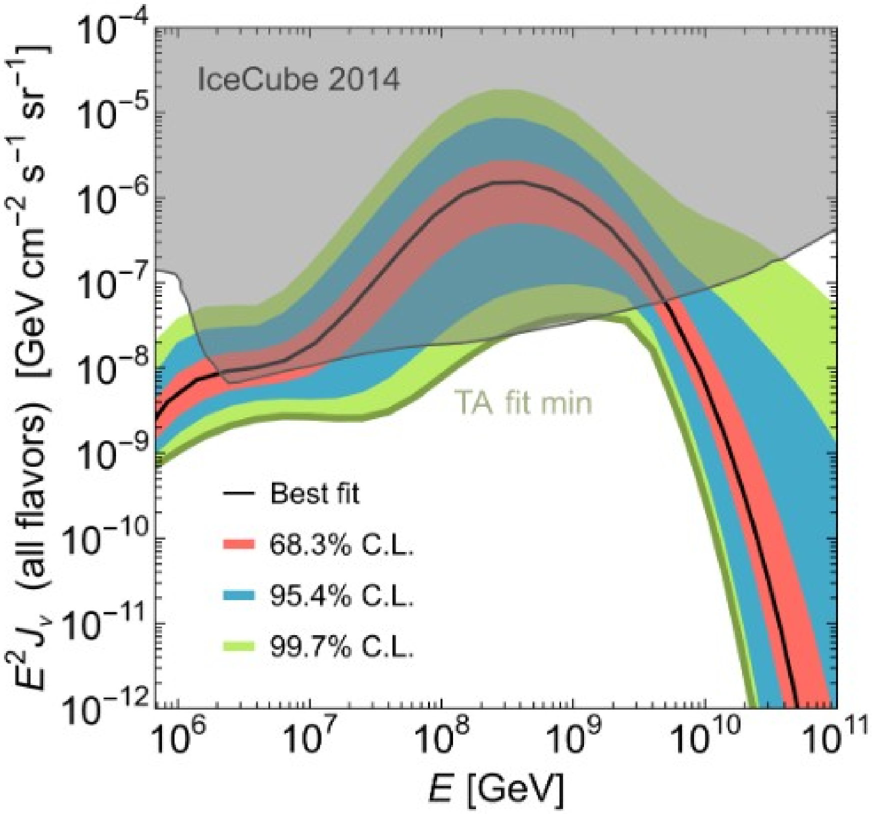


- To test the validity of the assumption of the “proton dip model” we use the associated neutrino flux

UHECR propagation and neutrino flux

- Taking into account the neutrino flux associated to the proton spectrum, the "degeneracy" of the proton parameters is reduced

- The proton dip model is challenged!



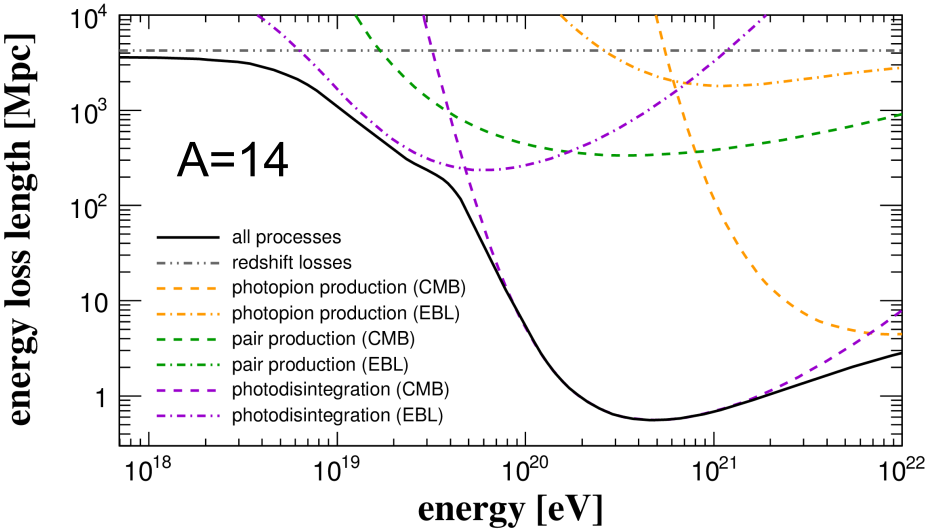
→ Other options to be explored:
- the "ankle model" cannot be excluded with the current procedure restricted to higher energies
- the **mixed composition** → to be tested with composition observables

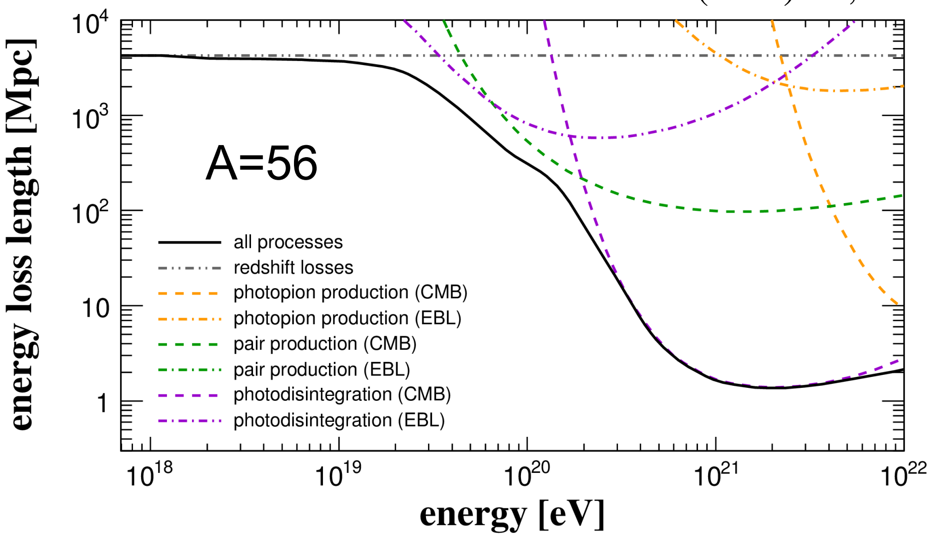
Hypothesis #2

- Testing the mixed composition at the source

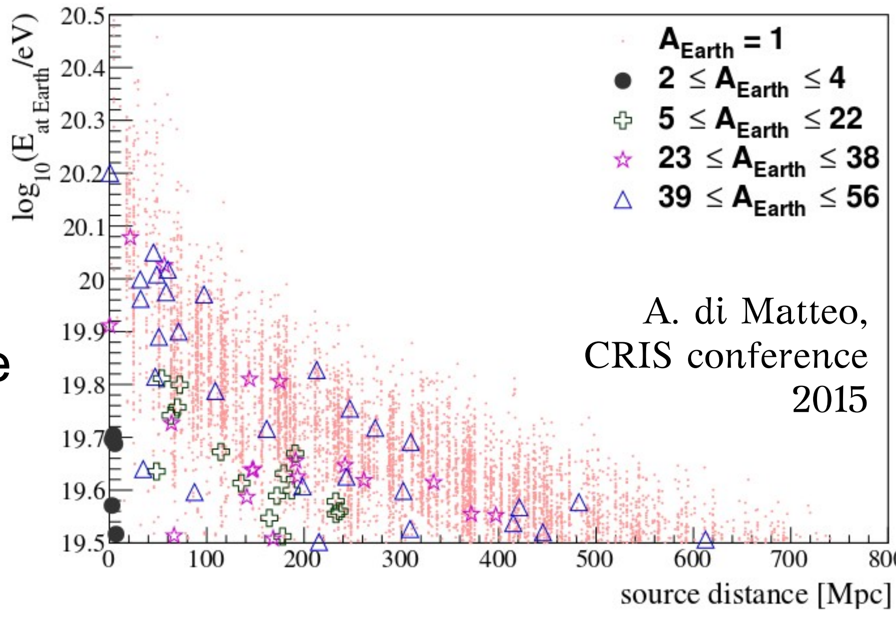
Interactions for nuclei

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



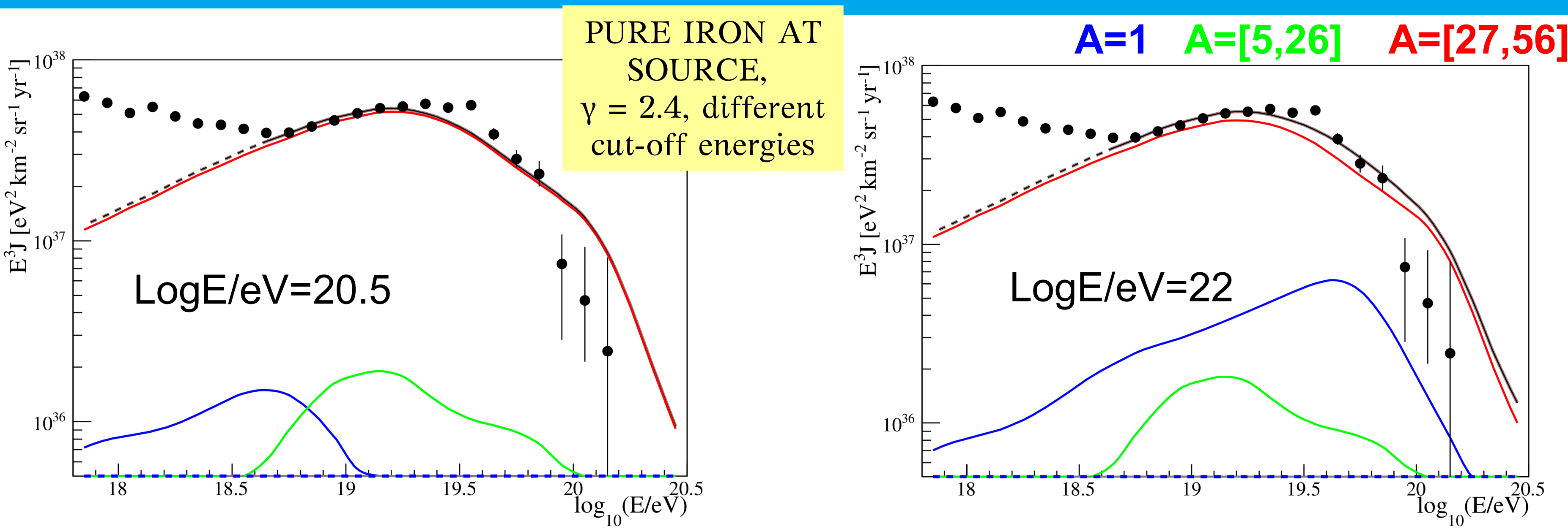


- Photopion production relevant for photons above 150 MeV in the NRF $\rightarrow \Gamma > 10^{11}$: if protons, $E > 6\,x\,10^{19}$ eV, if iron nuclei, $E > 3\,x\,10^{21}$ eV
- The suppression is mainly due to the photodisintegration of the nucleus due to interactions with background photons $\rightarrow$ the dominant process is the Giant Dipole Resonance



A. di Matteo, CRIS conference 2015

Propagated spectrum – pure iron nuclei at source

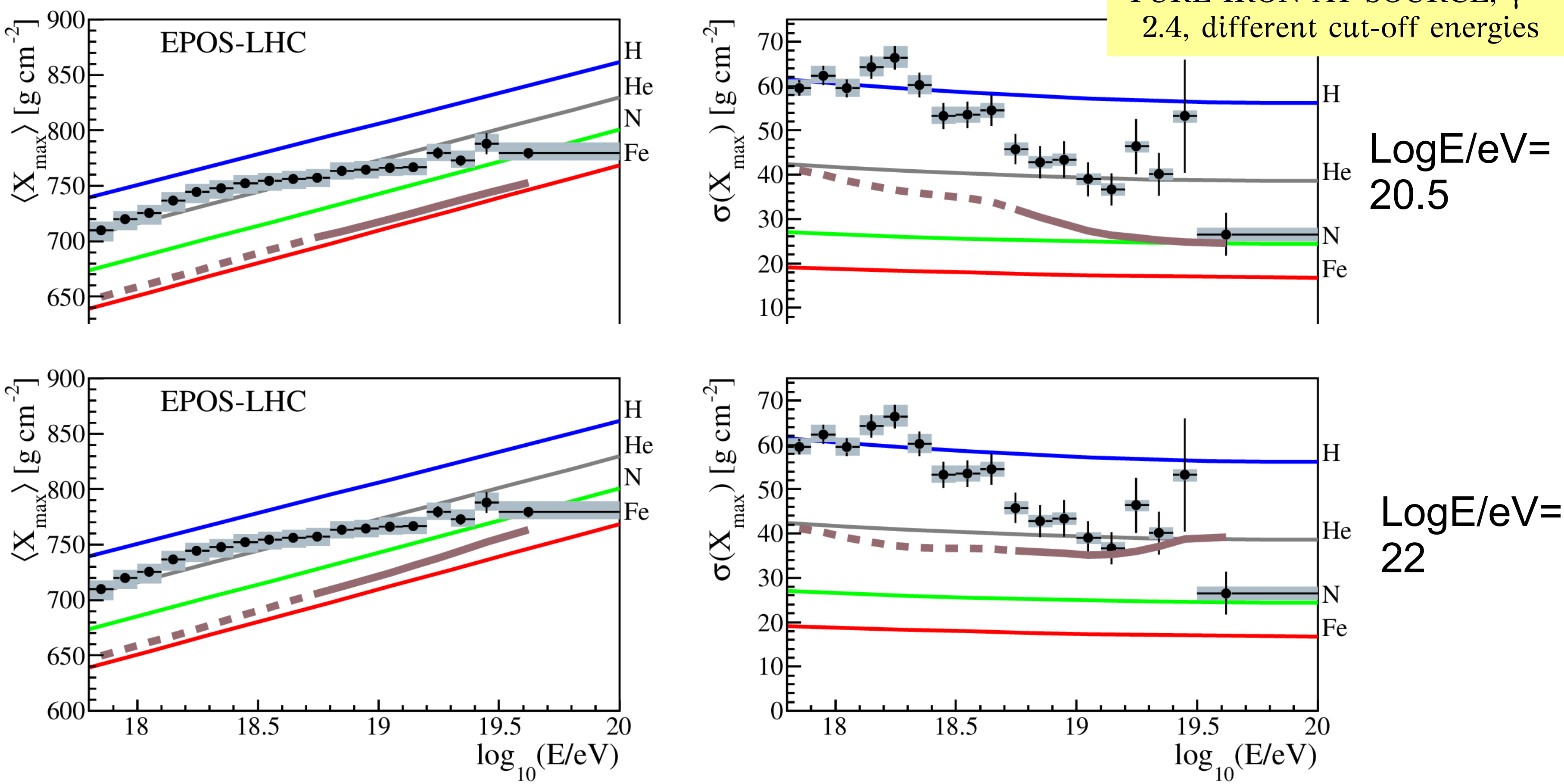


→ As for pure protons, <u>the spectrum has similar features with different hypotheses on the characteristics of the sources</u>

→ 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



- 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)

Simulation of UHECR propagation - Nuclei

- Monte Carlo codes for the propagation of UHECRs in the extragalactic space takink into account:

  - adiabatic energy losses due to the expansion of the Universe

  - pair production

  - photodisintegration

  - photopion production

Uncertaities in inputs from physics and astrophysics more important than in the case of pure protons

- ***SimProp***, simprop-dev@aquila.infn.it

Last release: v2r3, R. Aloisio, DB, A. di Matteo, A.F. Grillo, S. Petrera, F. Salamida, arXiv:1602.01239

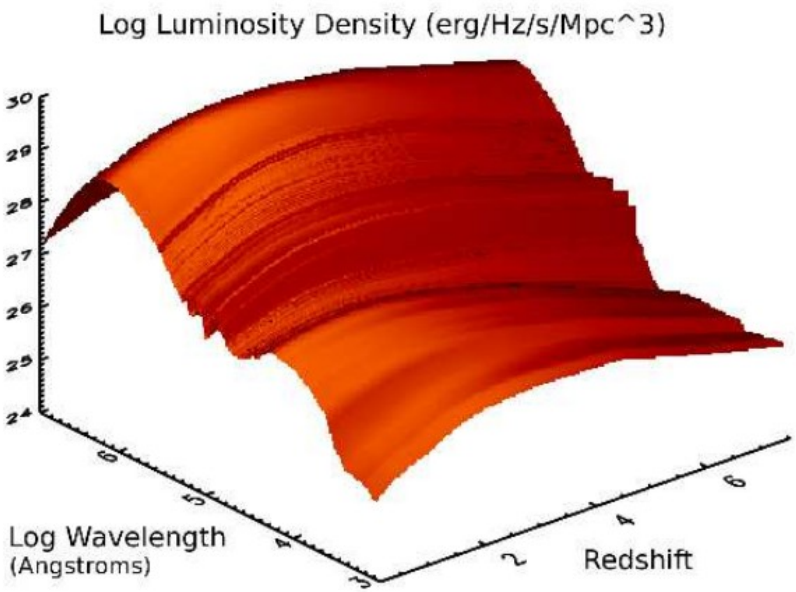
- **CRPropa**, http://crpropa.desy.de

- See R.Alves Batista, DB, A. di Matteo, A. van Vliet and D. Walz, JCAP 1510 (2015) 10, 063 for a detailed comparison of these MC codes

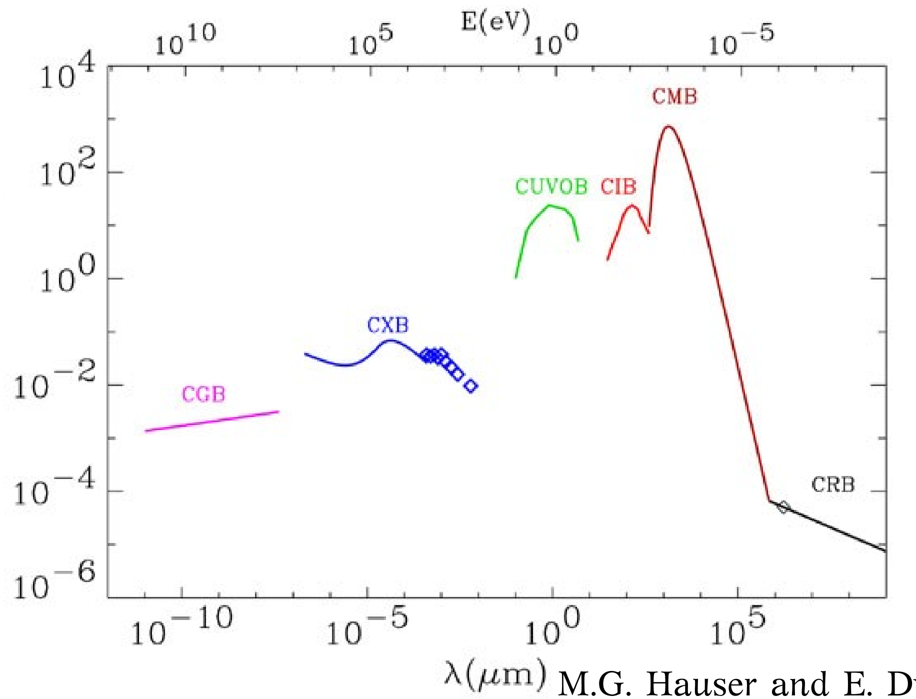
Uncertainties: the extragalactic background light

- 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



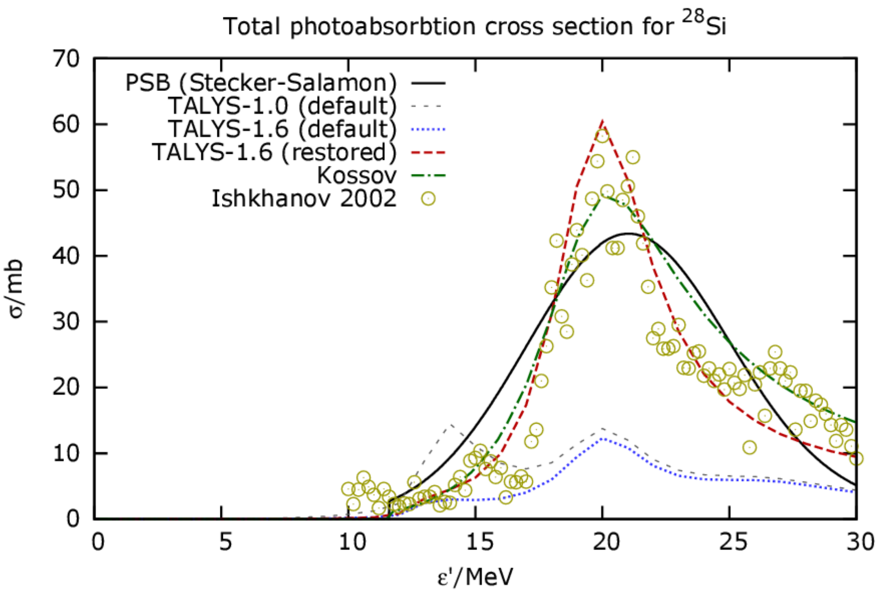
Gilmore et al. Mon.Not.Roy.Astron.Soc. 422 (2012) 3189



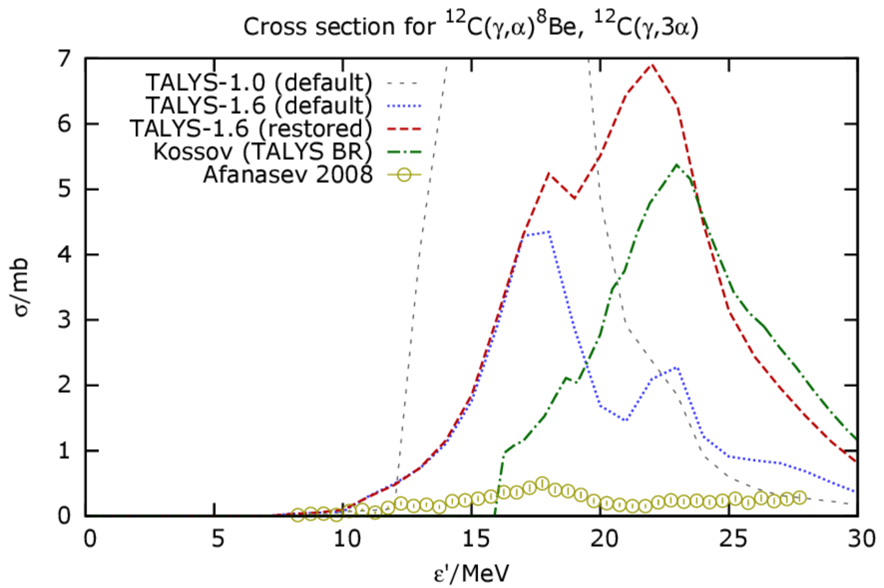
M.G. Hauser and E. Dwek, Ann. Rev. Astron. Astrop. 39 (2001) 249

Uncertainties: photodisintegration cross sections

- Several measurements of photoabsorption cross sections are available
- Phenomenological models in reasonable agreement with them



- Exclusive channels for charged ejectiles are hard to measure (ejectiles multiply scattered in the target)
- Phenomenological models do not agree with the (few) available measurements

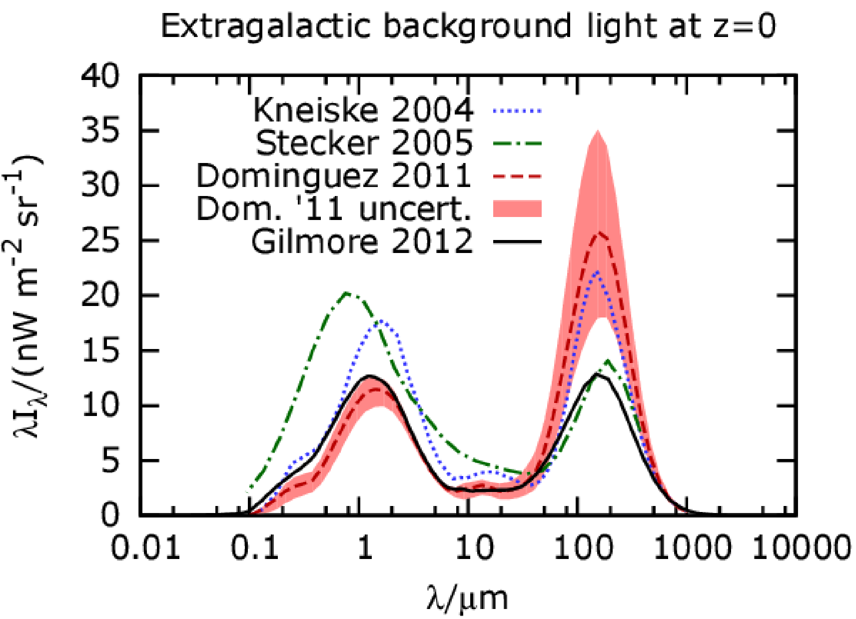


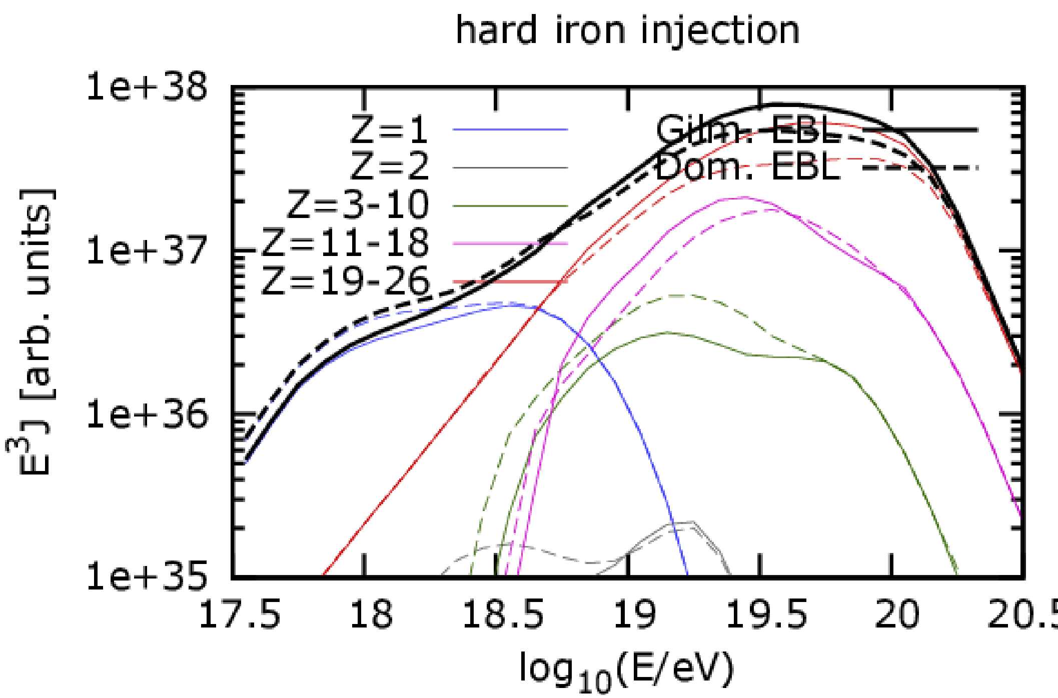
- PSB model as used in *SimProp*: cross sections from Puget, Stecker and Bredekamp, Astrophys.J. (1976) 638-654, energy threshold from Stecker and Salamon, Astrophys.J (1999) 521-526
- TALYS, www.talys.eu

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





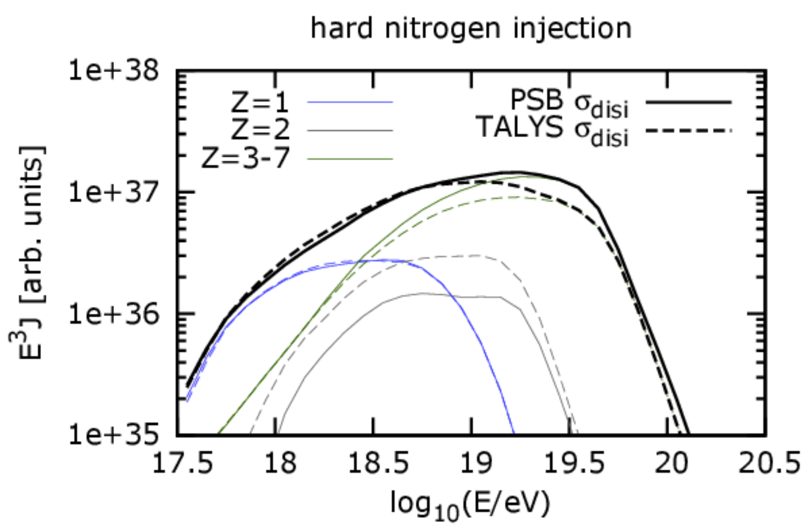
★ brighter EBL → softer spectrum at Earth and lighter composition

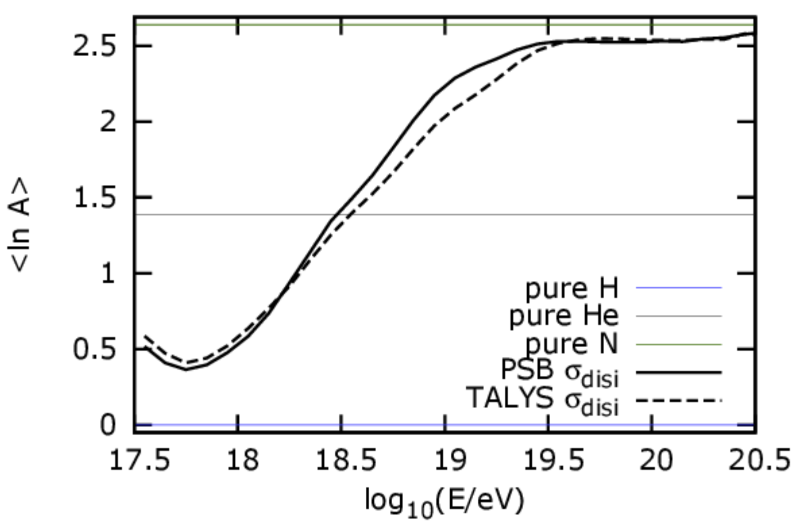
R. Alves Batista, DB, A. di Matteo, A. van Vliet and D. Walz, JCAP 1510 (2015) 10, 063

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

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

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

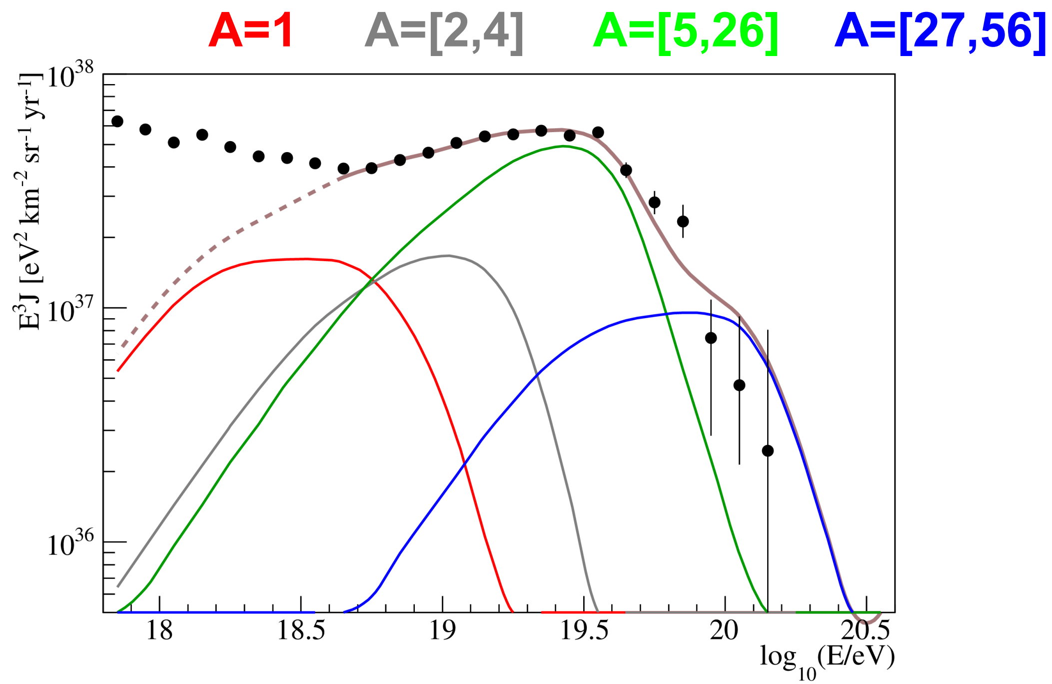
- Various models for propagation (*SimProp* and CRPropa propagation codes with different choices for cross sections and EBL models) and air interactions were used
- See A. di Matteo for the Pierre Auger Collaboration, PoS(ICRC2015)249 for details

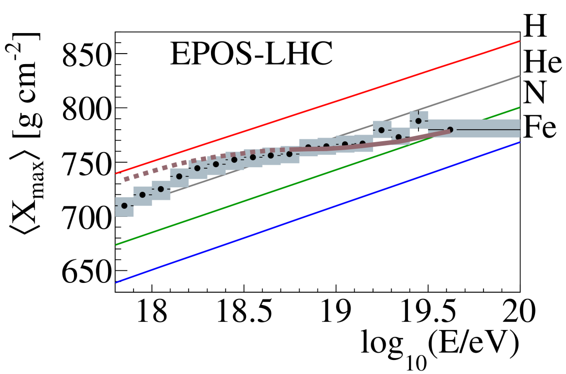
Fit results

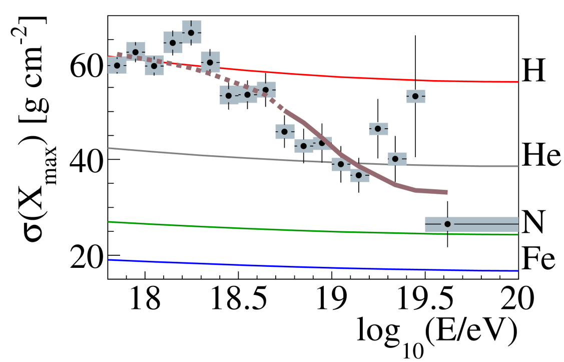
MODEL

- *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





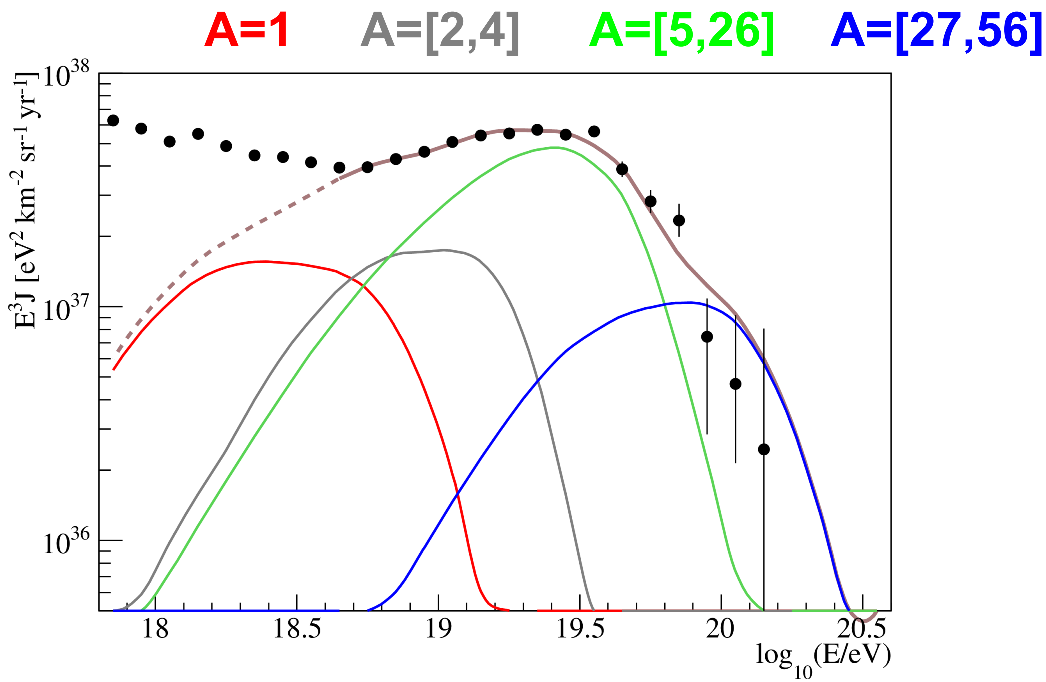


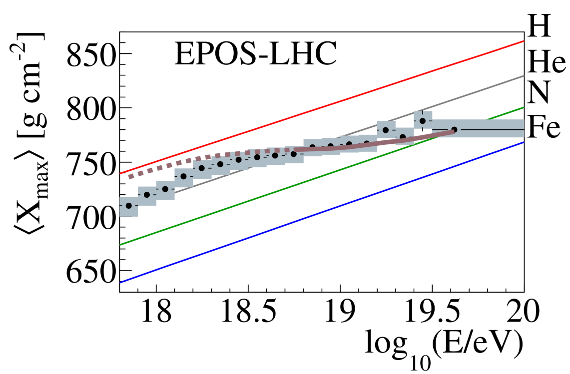
Fit results

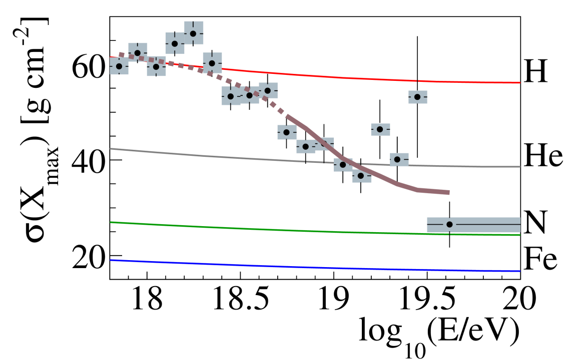
MODEL

- *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





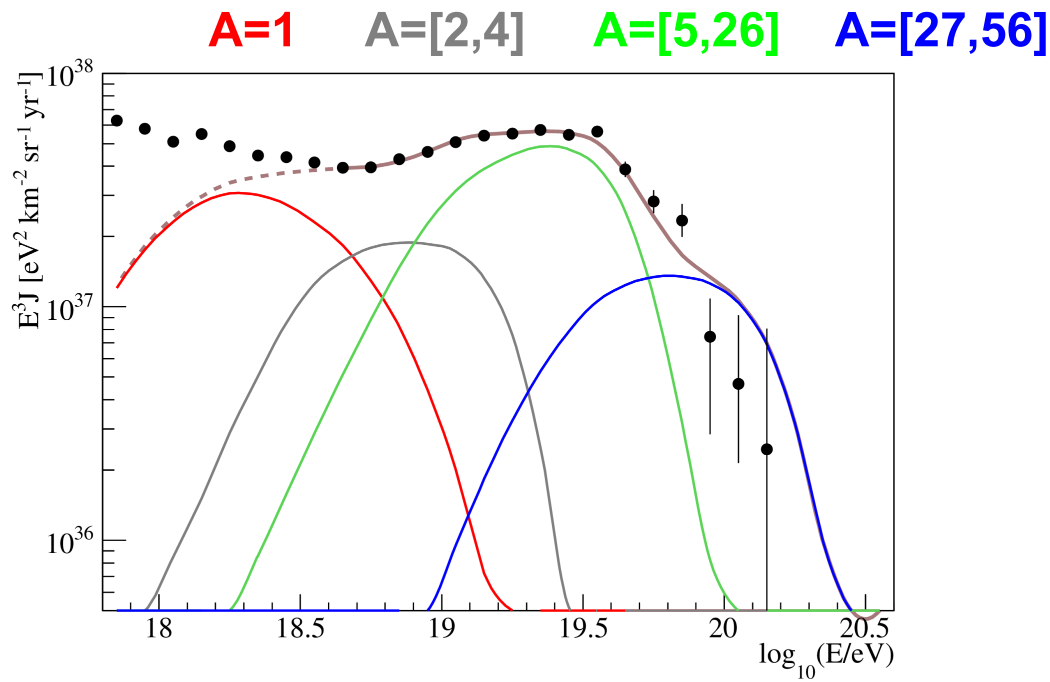


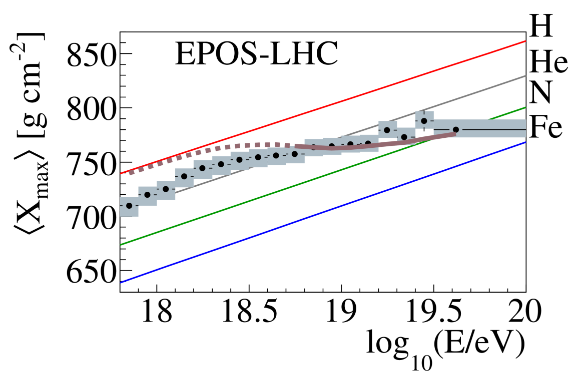
Fit results

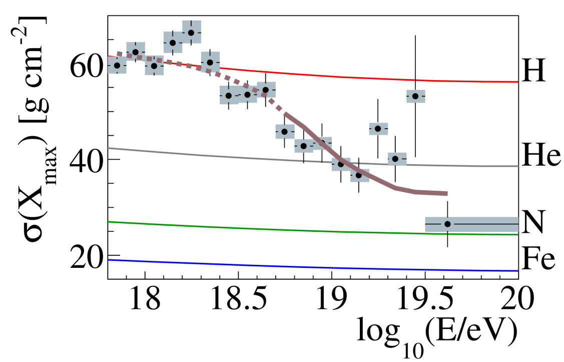
MODEL

- *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





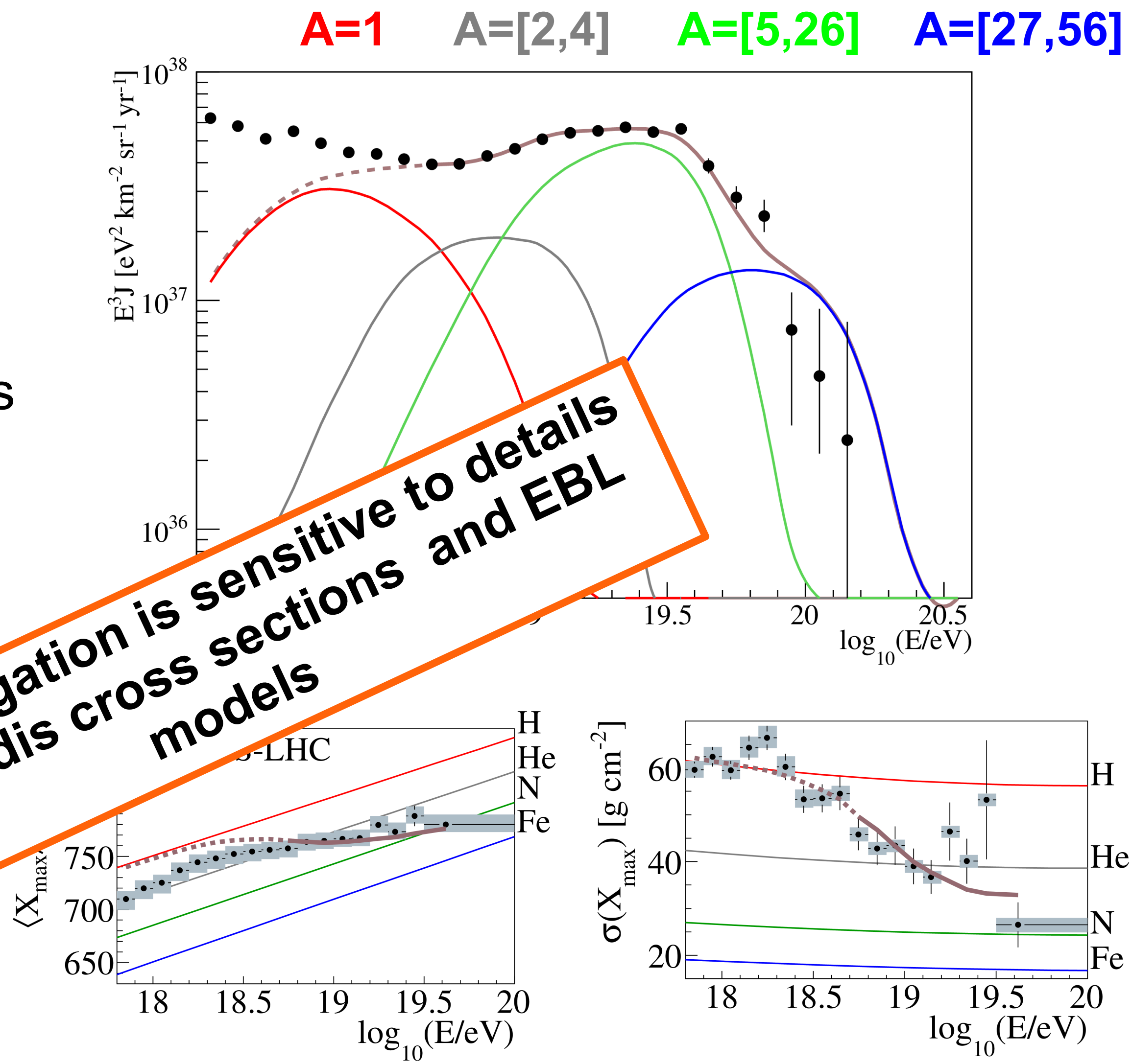


Fit results

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

Conclusions

- The UHECR spectrum presents some features due to interactions of particles during their travel from the source to the detection

The aim of the upgrade of the Auger Observatory, collectively dubbed AugerPrime, is to provide additional measurements of composition-sensitive observables to allow us to address the following questions: (i) Elucidate the mass composition and the origin of the flux suppression at the highest energies, i.e., the differentiation between the energy loss effects due to propagation, and the maximum energy of particles injected by astrophysical sources. (ii) Search for a flux contribution of protons up to the highest energies. We aim to reach a sensitivity to a contribution as small as 10% in the flux suppression region. The measurement of the fraction of protons is the decisive ingredient for estimating the physics potential of existing and future cosmic ray, neutrino, and gamma-ray detectors; thus prospects for proton astronomy with future detectors will be clarified. Moreover, the flux of secondary gamma rays and neutrinos due to proton energy loss processes will be predicted. (iii) Study extensive air showers and hadronic multiparticle production. This will include the exploration of fundamental particle physics at energies beyond those accessible at terrestrial accelerators, and the derivation of constraints on new physics phenomena, such as Lorentz invariance violation or extra dimensions.

Auger Upgrade, ICRC 2015

- A well-established feature is the <u>suppression of the flux at the highest energies</u>, which interpretation changes if different assumptions on composition and distribution of sources are taken into account

- Understanding the origin of the suppression of the flux at the highest energies is not possible without

  - a multimessenger approach, taking into account the neutrino flux → that has the power to challenge conventional UHECR models

  - a combination of UHECR results, including composition, which is affected by uncertainties in the physics and astrophysics assumptions

- From the experimental point of view, <u>an increased sensitivity to the composition at the highest energies is strongly needed</u> in order to elucidate the spectrum features, in particular the origin of the suppression

Outlook

- Assumptions on nuclei species accelerated at the source → arbitrary
- How heavier nuclei can be accelerated in the source and escape without disintegrating into the source?
- What are the consequences for neutrinos fluxes and cosmic ray composition?

- Detailed study about mechanisms occurring *inside* the source are needed → photodisintegration, photomeson production...