UHE Nuclei Propagation and the Spectrum of UHECR

Roberto Aloisio

INAF – Osservatorio Astrofisico Arcetri

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General Framework for Nuclei Propagation

✓ Continuous Energy Losses

Particles survive the interaction process losing energy continuously.

✓ Kinetic Equation

UHE nuclei propagation is described by a kinetic equation

$$\frac{\partial n(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[b(\Gamma,t)n(\Gamma,t)\right] + \frac{n(\Gamma,t)}{\tau_{disi}} = Q(\Gamma,t)$$

✓ Nuclei photo-disintegration

The photo-disintegration process is treated as a ”decaying” process
That simply depletes the flux of the considered nuclei specie

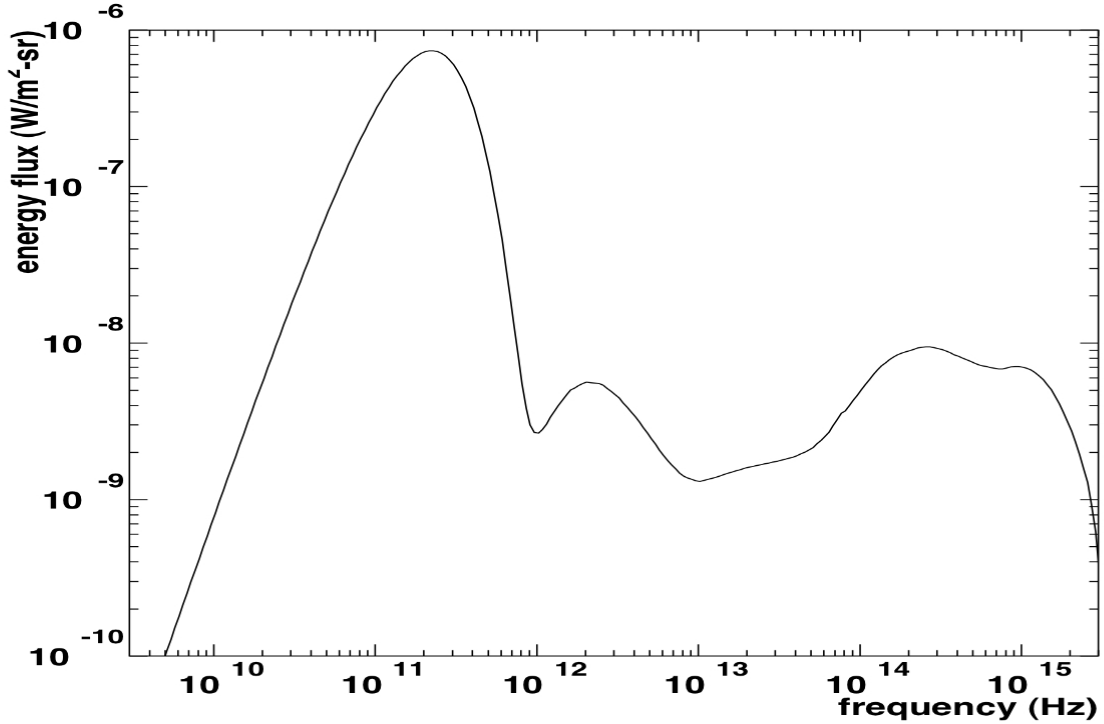
✓ Homogeneous Sources

Sources are homogeneously distributed over the all Universe.

Ultra High Energy Nuclei

✓ **Interaction with Astrophysical Backgrounds**

Cosmic Microwave Background
(CMB) Infra Red-Visible-Ultra Violet
(Extragalactic Background Light, EBL)



$$\lambda^{-1} = \frac{1}{2\Gamma^2}\int_{\epsilon_0(A)}^{\infty} d\epsilon_r \sigma(\epsilon_r, A)\nu(\epsilon_r)\epsilon_r \int_{\epsilon_r/(2\Gamma)} d\epsilon \frac{n_{bcgr}(\epsilon)}{\epsilon^2}$$

✓ **Pair-Production**

Only the Cosmic Microwave Background is relevant
Conservation of the nuclei specie

$A\,\gamma \rightarrow A\, e^+ e^-$ $\quad (\lambda^{-1}_{pair})_A = \frac{Z^2}{A}(\lambda^{-1}_{pair})_p$

✓ **Photo-Disintegration**

Also the Extragalactic Background Light (EBL) is relevant
Conservation of the nuclei Lorentz factor (no nuclear recoil)

$A\,\gamma \rightarrow (A-1) + N$

most relevant process
one nucleon emission
(giant dipole resonance)

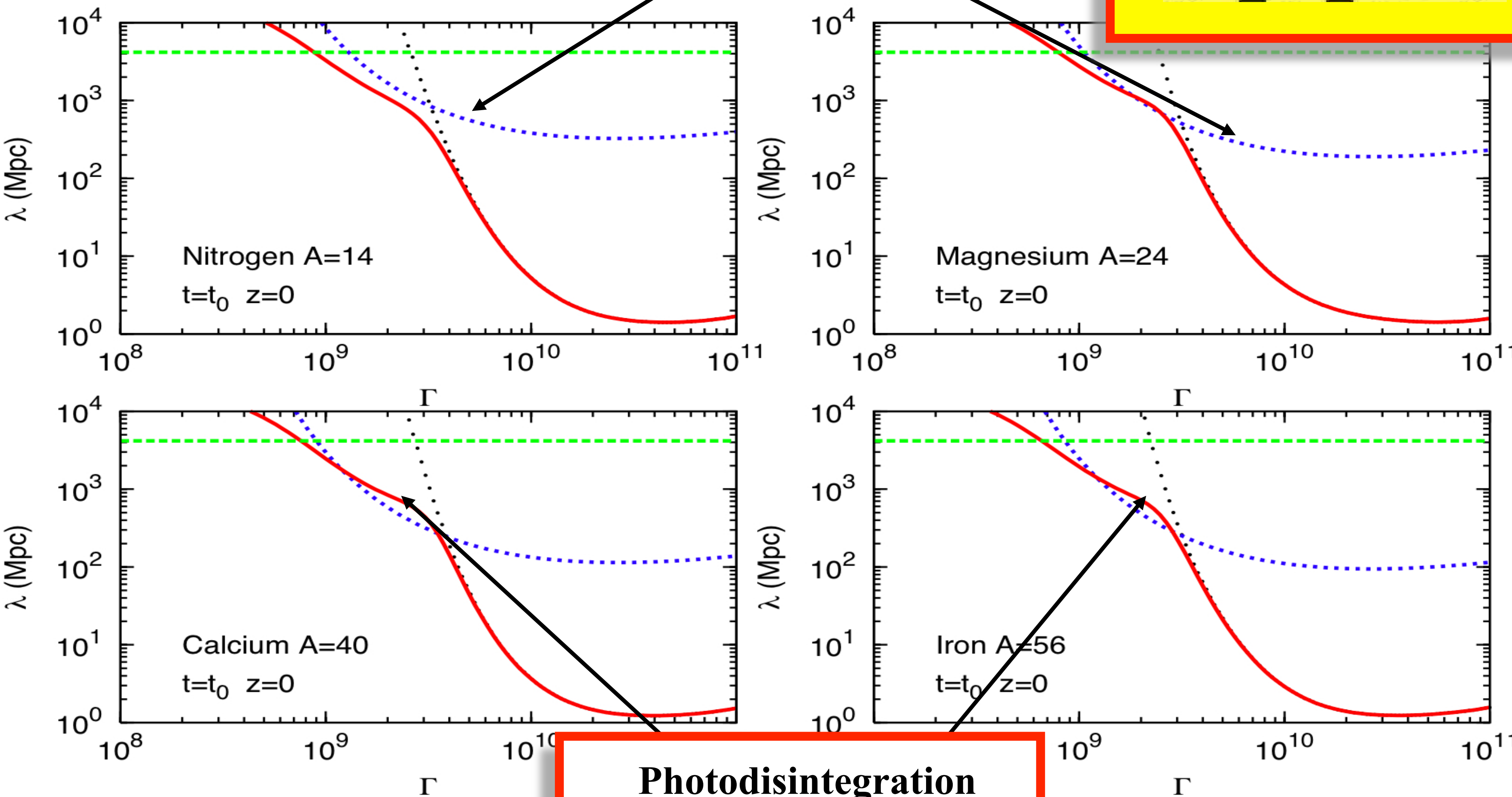
UHE Nuclei loss length

Pair production (CMB)

$A\gamma \rightarrow A e^+ e^-$

EBL effect only for photo-disintegration in the range

$10^8 \leq \Gamma \leq 2\times 10^9$



Photodisintegration (CMB+IR/V/UV)

$A\gamma \rightarrow (A\text{-}1) + N$

RA, Berezinsky, Grigorieva (2010)

Photo-Disintegration “life time”

Photo-disintegration is interpreted as a decaying process that simply depletes the flux of the considered particle

photo-disintegration

$$\frac{1}{\tau_A} = \frac{c}{2\Gamma^2}\int_{\epsilon_0(A)}^{\infty} d\epsilon_r \sigma(\epsilon_r, A)\nu(\epsilon_r)\epsilon_r \int_{\epsilon_r/(2\Gamma)} d\epsilon \frac{n_{bcgr}(\epsilon)}{\epsilon^2}$$

$\sigma(\epsilon_r, A)$ $\nu(\epsilon_r)$ as in Malkan and Stecker 1999

A univocally tags the nuclei specie, radioactive decay time much shorter than the typical photodisintegration time, (appreciable effects only at very high energy E>3x10^{20} eV)

red-shift evolution

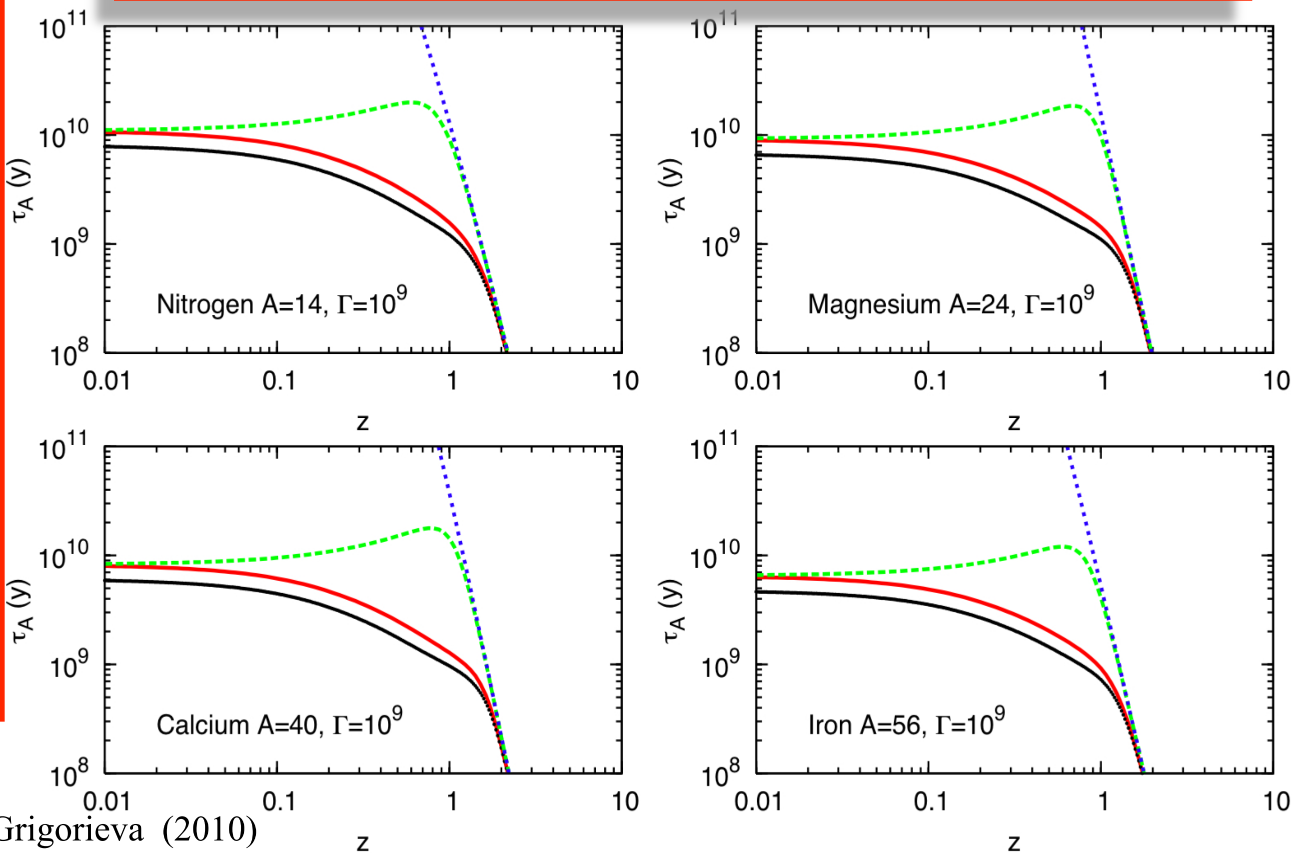
$$\frac{1}{\tau_A(\Gamma,z)} = \frac{1}{\tau^A_{CMB}(\Gamma,z)} + \frac{1}{\tau^A_{EBL}(\Gamma,z)}$$

CMB

$$n_z(\epsilon) = (1+z)^3 n_0((1+z)\epsilon_0)$$

EBL Malkan, Stecker, Scully (2006)

$$n_z(\epsilon)\begin{cases}\text{baseline evolution}\\ \text{fast evolution}\\ (1+z)^{-3/2}n_0(\epsilon)\end{cases}$$



RA, Berezinsky, Grigorieva (2010)

Primary Nuclei

the role of EBL consists in a suppression of the flux in the range

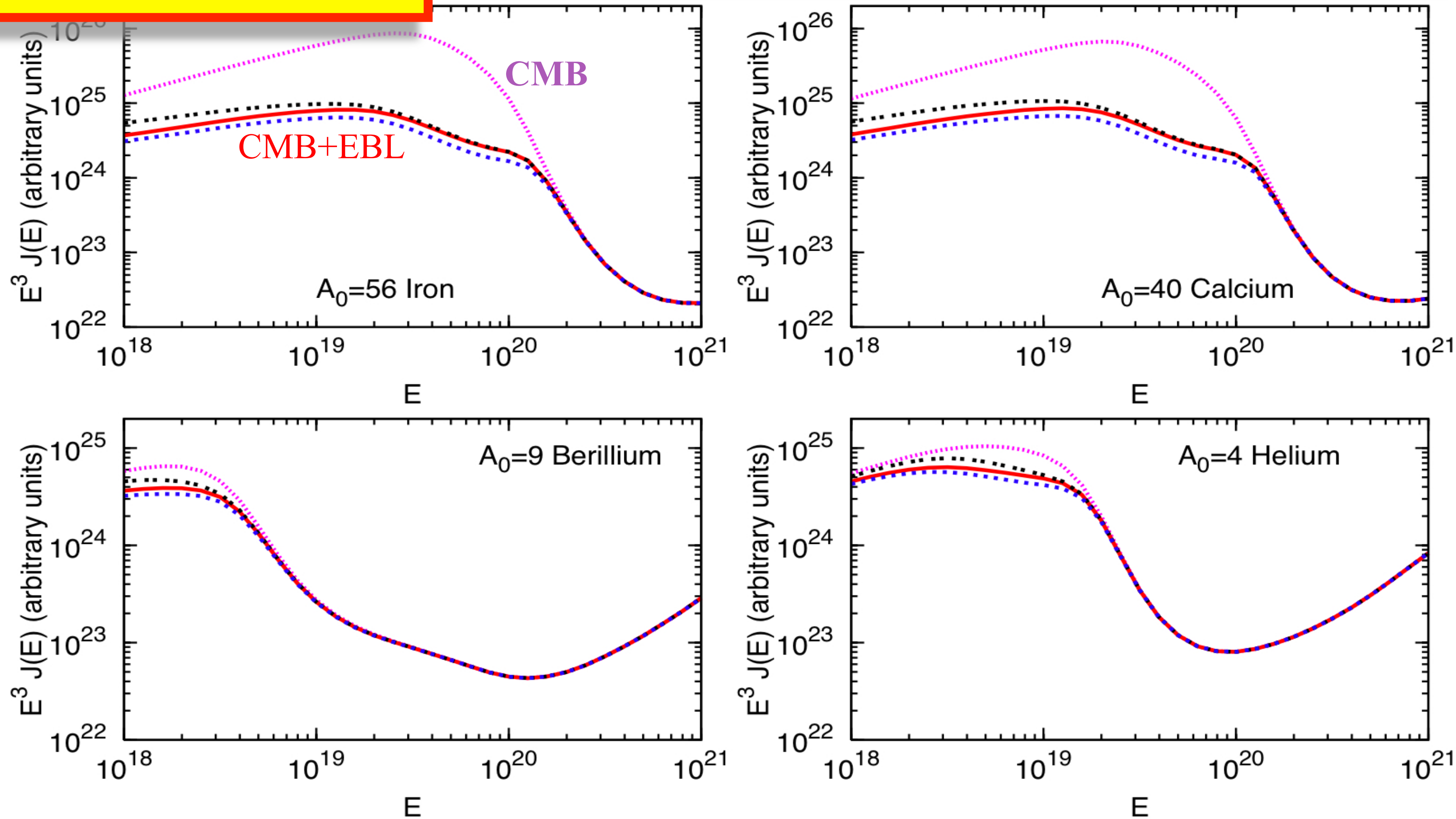
$$10^8 \leq \Gamma \leq 2 \times 10^9$$

Injection at the source

Assuming the injection of only one kind of nucleus A_0, with an homogenous distribution of sources.

$$Q_{A_0}(\Gamma, z) = \frac{(\gamma_g - 2)\mathcal{L}_0}{m_N A_0}\Gamma^{-\gamma_g}$$

$$\gamma_g = 2.3$$



RA, Berezinsky, Grigorieva (2010)

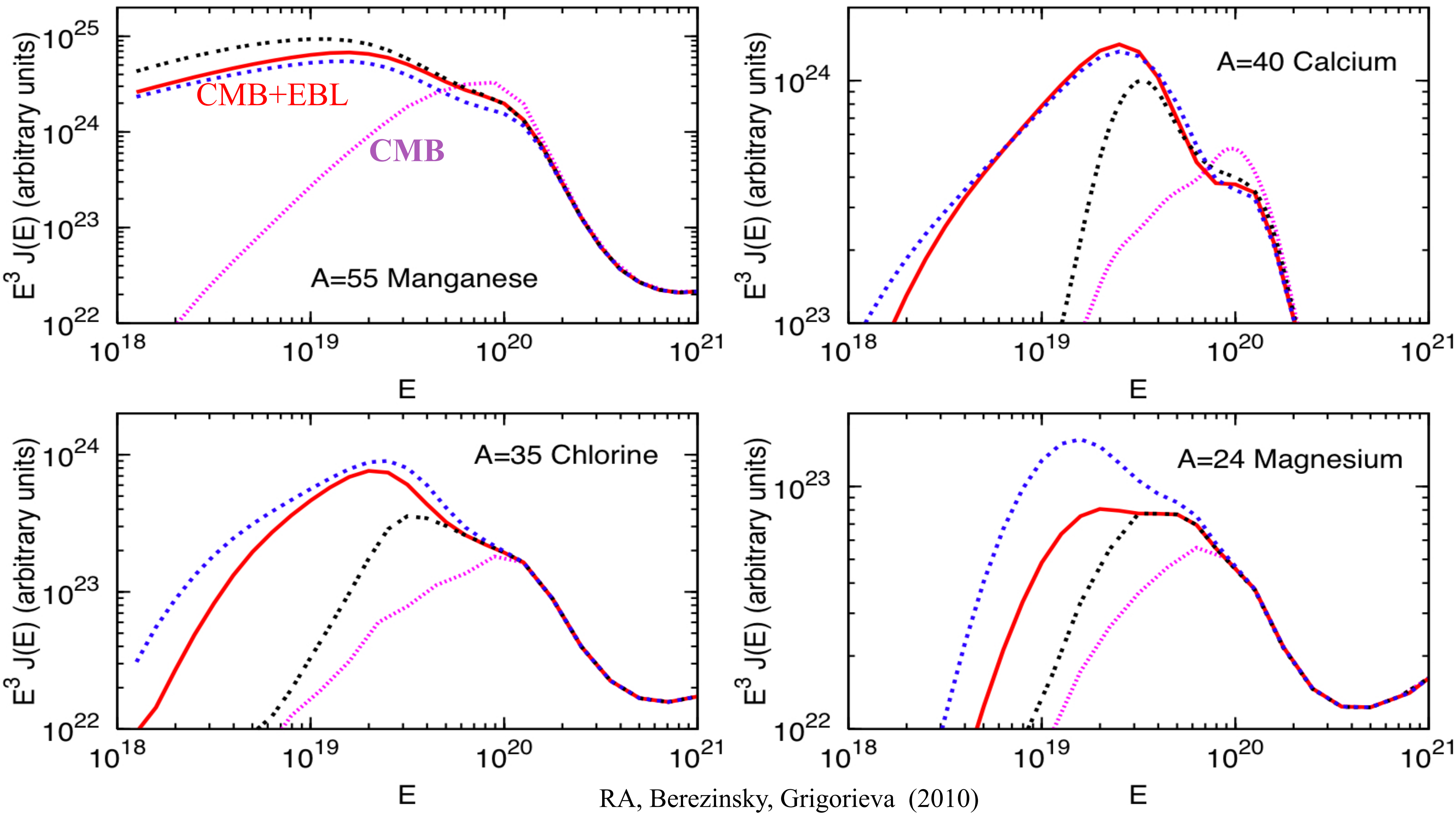
Secondary Nuclei

Dominant process: one nucleon emission Aγ→(A-1) + N

$$Q_A(\Gamma, z) = \frac{n_{A+1}(\Gamma, z)}{\tau_{A+1}(\Gamma, z)}$$

The EBL role consists in a flux regeneration of secondary in the range $10^8 \leq \Gamma \leq 2 \times 10^9$

A_0=56 Iron γ_g=2.3



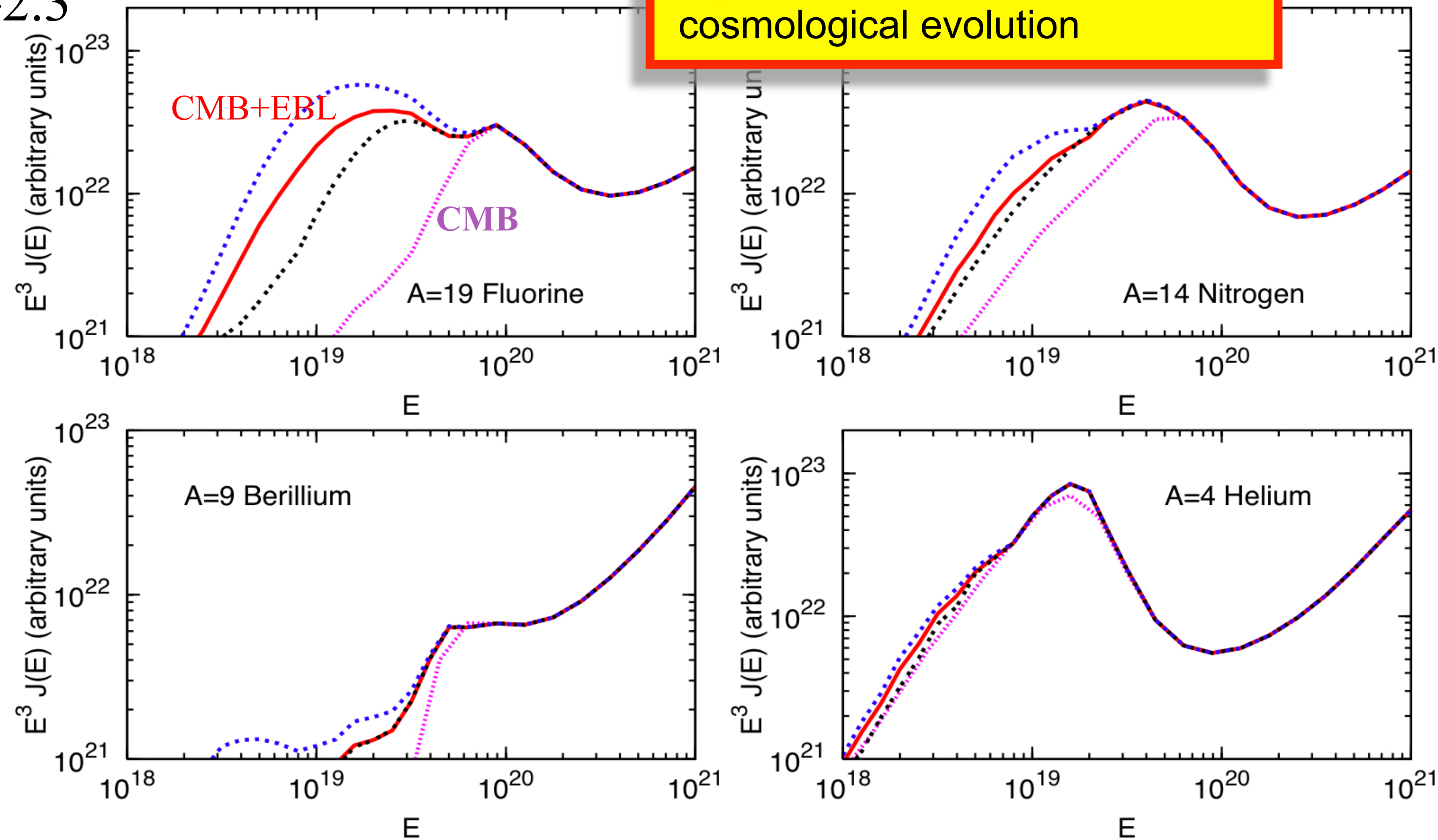
RA, Berezinsky, Grigorieva (2010)

starting from primary Iron the photodisintegration chain produces all kinds of secondary $A<A_0$. The lowest mass secondary are produced by the highest energies primaries, the fluxes are less sensitive to the EBL effect (CMB only).

$A_0=56$ Iron

$\gamma_g=2.3$

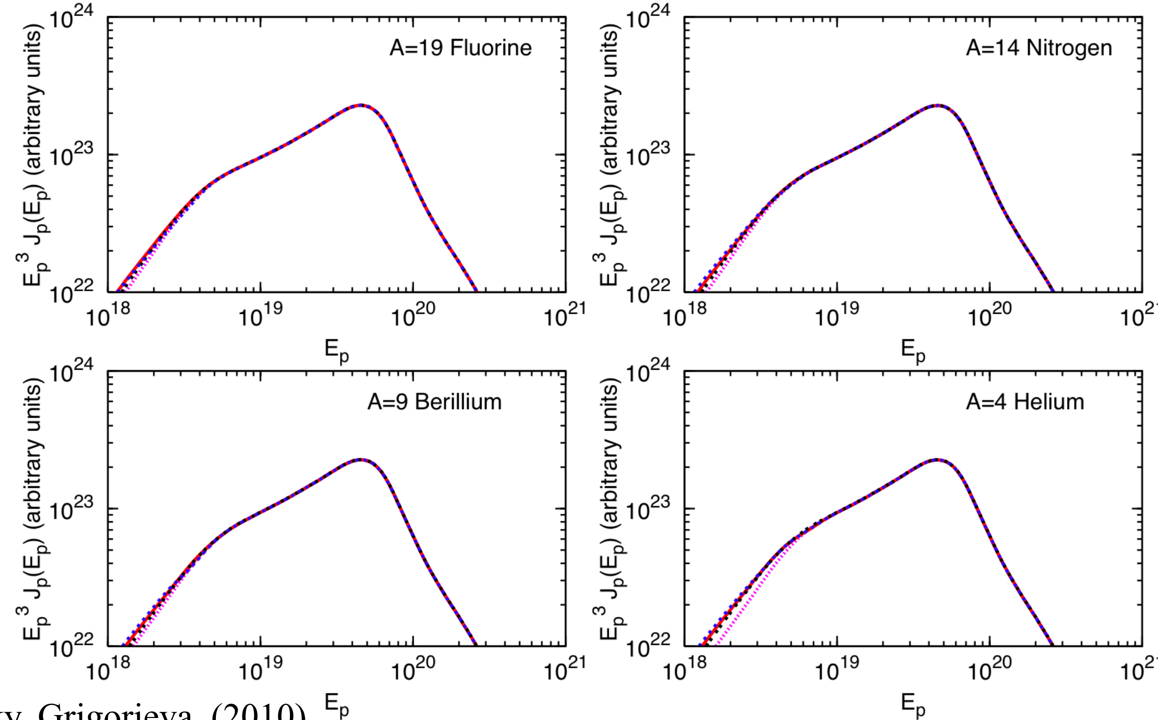
high A dependence on the EBL cosmological evolution



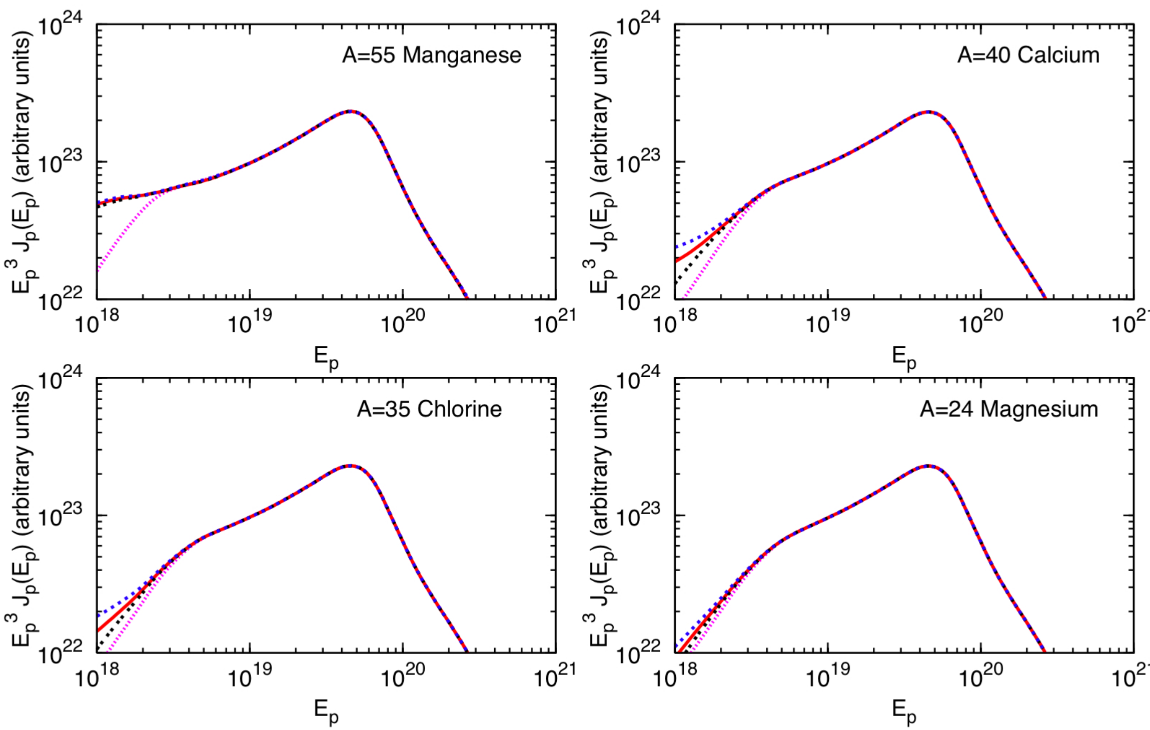
RA, Berezinsky, Grigorieva (2010)

Secondary Nucleons

the effect of EBL on secondary nucleons is marginal and related only to the lowest energies.



RA, Berezinsky, Grigorieva (2010)



the EBL role consists in a small flux regeneration in the energy range

$$10^{17}\ eV \leq E \leq 2 \times 10^{18}\ eV$$

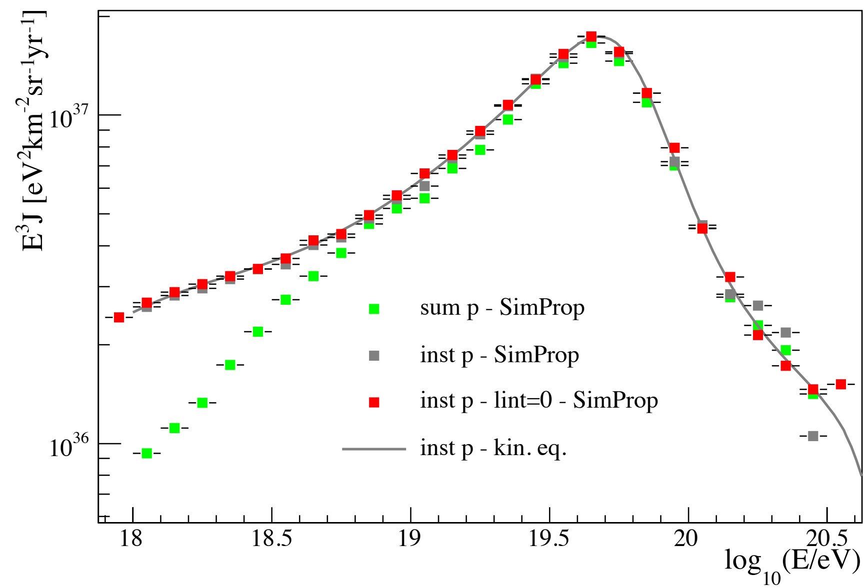
As for secondary nuclei (same injection) this effect is related to an increase in the injection efficiency (photo-disintegration).

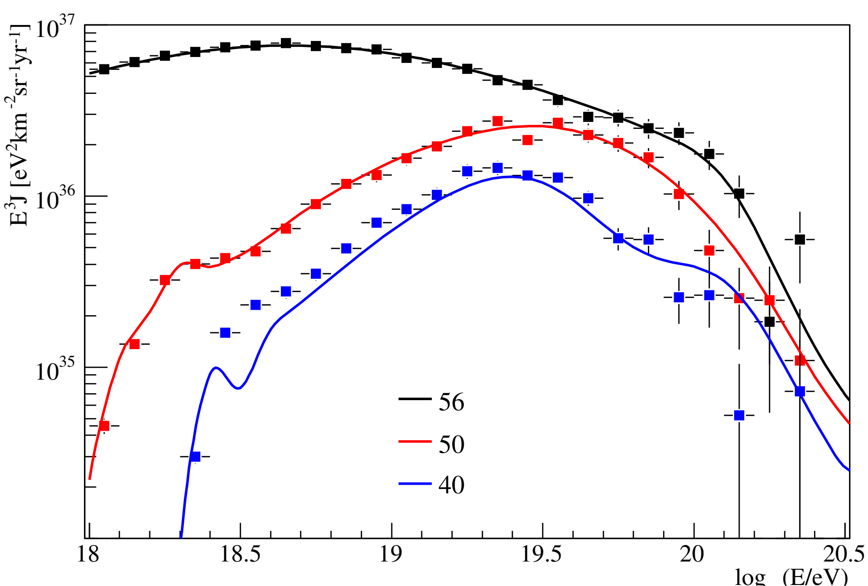
SimProp: MC for UHECR propagation

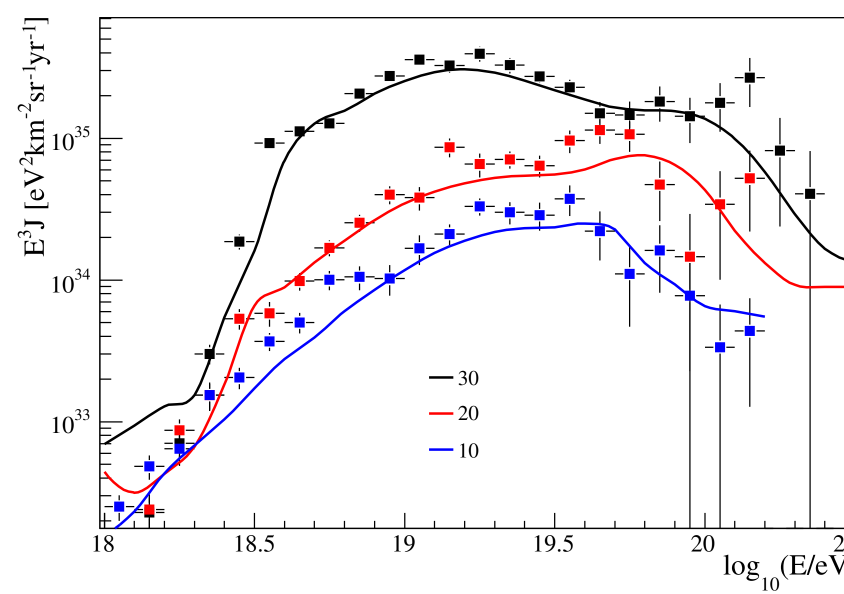
- ✓ Photo-disintegration process treated in the MC approach

$$P(\Gamma, z) = exp\left(-\int_z \frac{1}{\tau_{A,i}(\Gamma, z')}\left|\frac{dt}{dz'}\right| dz'\right)$$

- ✓ Good agreement with the fluxes computed in the kinetic approach

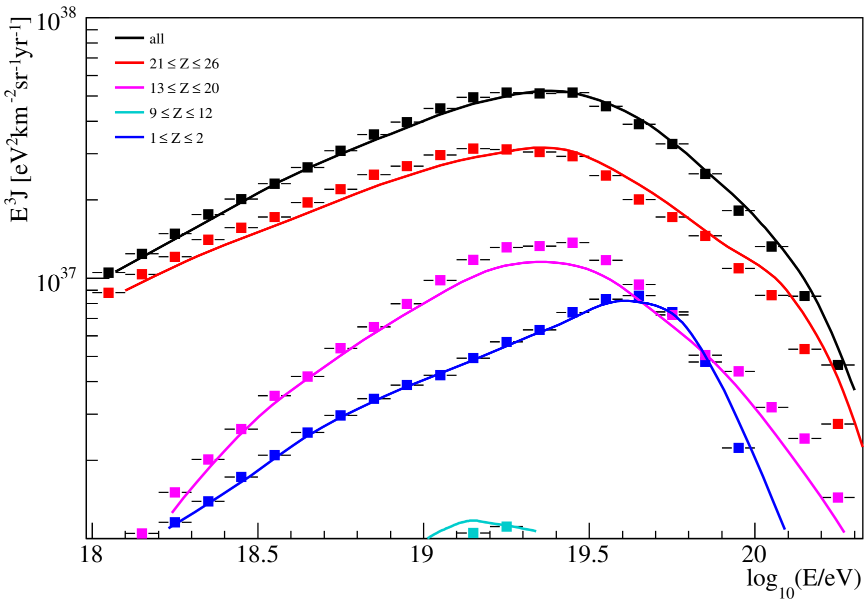


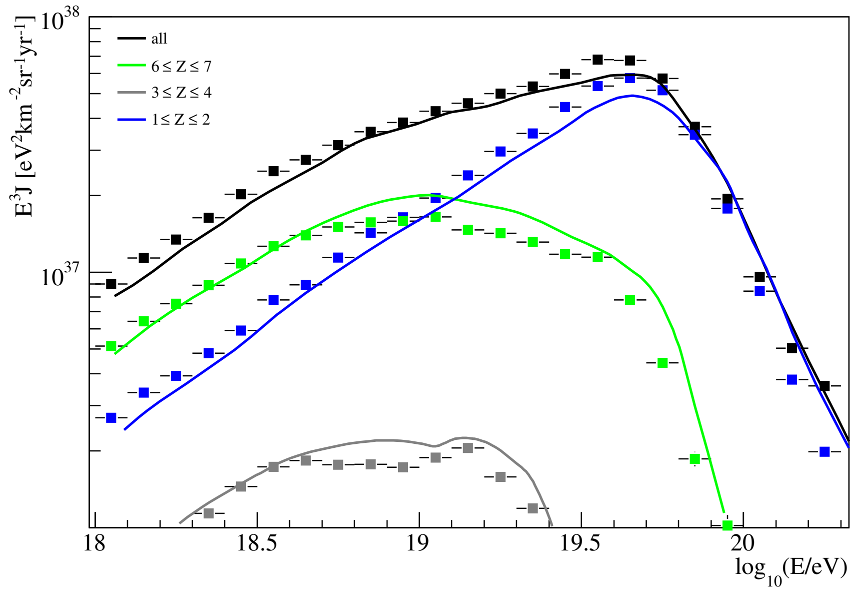




RA, D. Boncioli, A.F. Grillo, S. Petrera and F. Salamida (2012)

✓ Good agreement also with fluxes computed in a different MC approach (Allard et al. 2008)





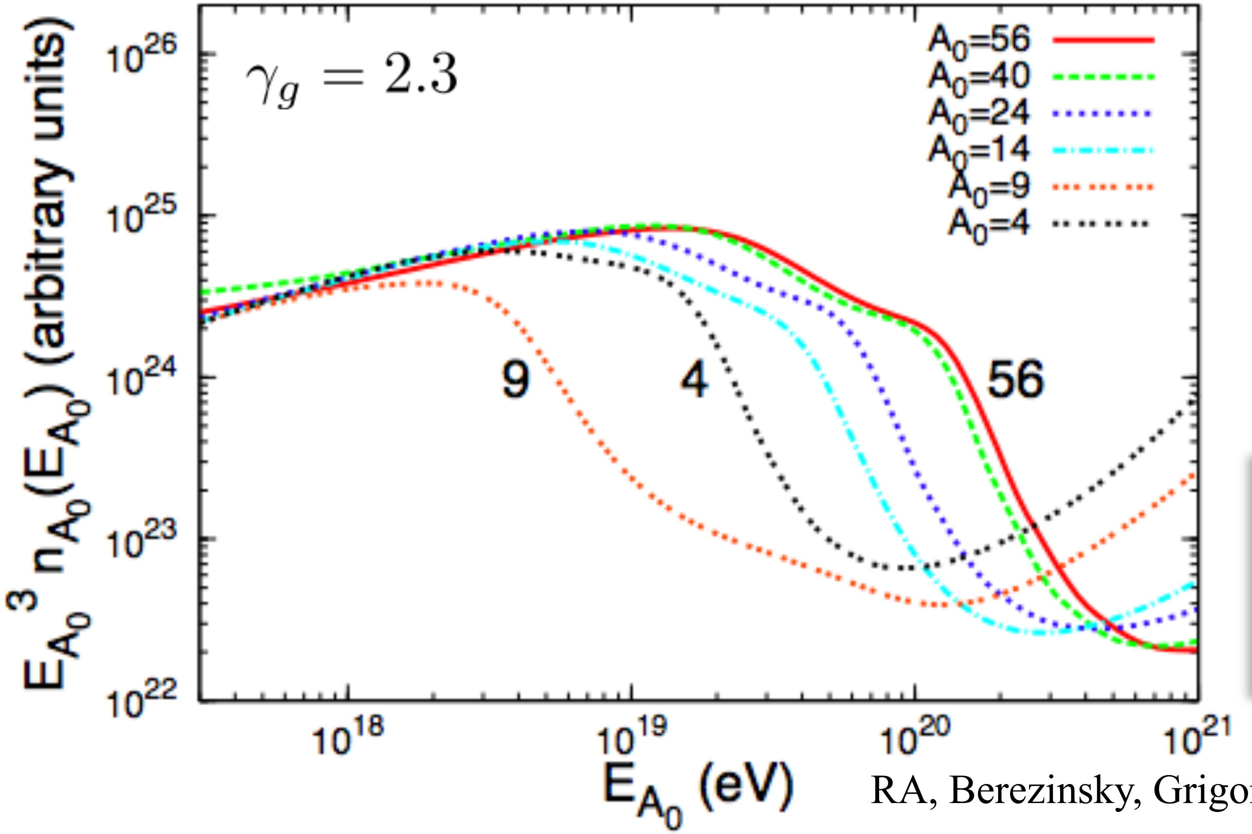
RA, D. Boncioli, A.F. Grillo, S. Petrera and F. Salamida (2012)

Nuclei Suppression at HE

Critical Lorentz factor $\Gamma_c(A,t)$

$$\beta^A_{e^+e^-}(\Gamma,t) + H_0(t) = \beta^\Gamma_{dis}(A,t)$$

The critical Lorentz factor fixes the scale at which photo-disintegration becomes relevant, for heavy nuclei it is almost independent of the nuclei specie



RA, Berezinsky, Grigorieva (2009)

$$E_{cut}(A) = A m_N \Gamma_c$$

$$\Gamma_c \simeq 2 \times 10^9$$

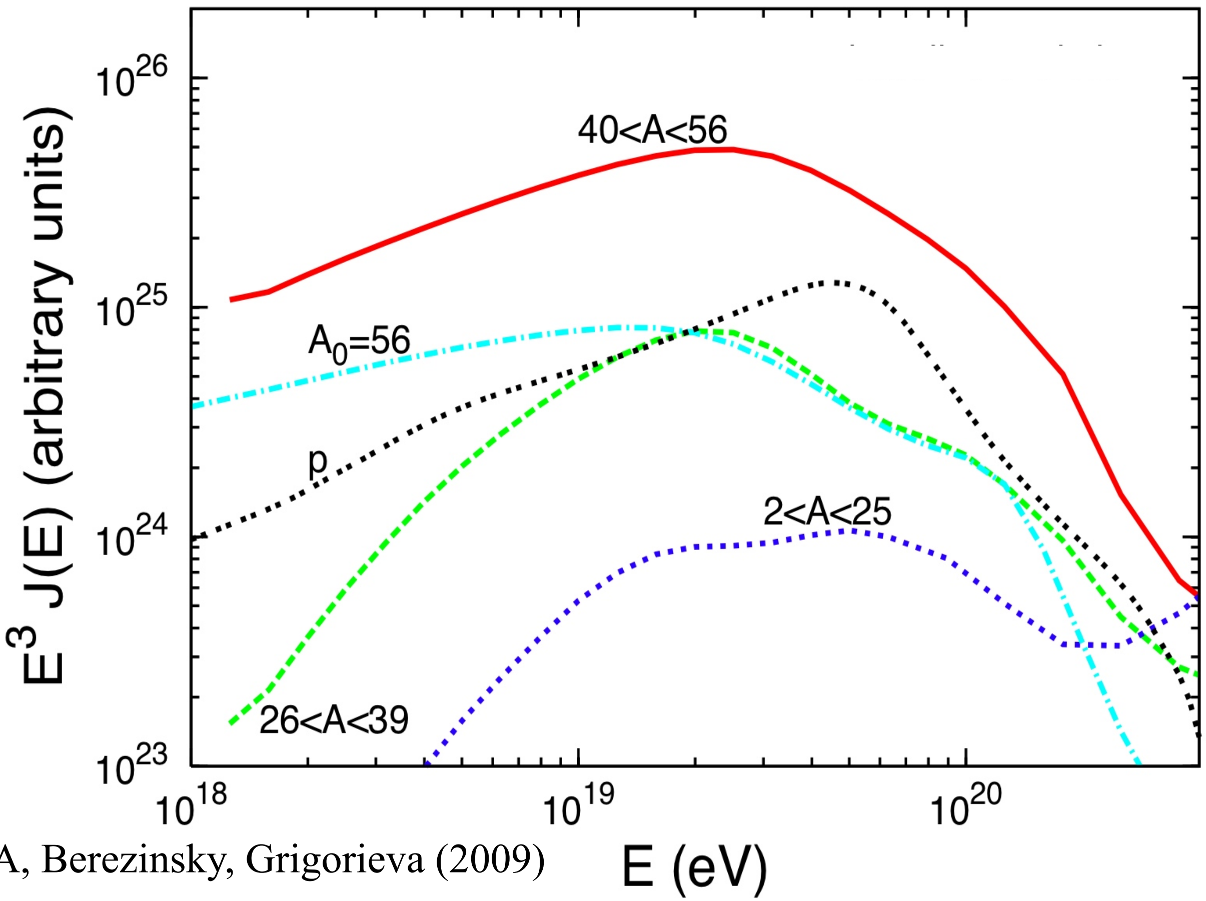
note that the cut-off energy is proportional to the atomic mass-number A of nuclei

Caveat

It is impossible to observe on earth a pure heavy nuclei spectrum, even if sources inject only heavy nuclei of a fixed specie on earth we will observe all secondary (protons too) produced by photo-disintegration.

this fact is coherent with the Auger result on X_{max}, that shows a mixed composition at the highest energies.

anisotropy study is a key ingredient to disentangle the proton component in the spectrum

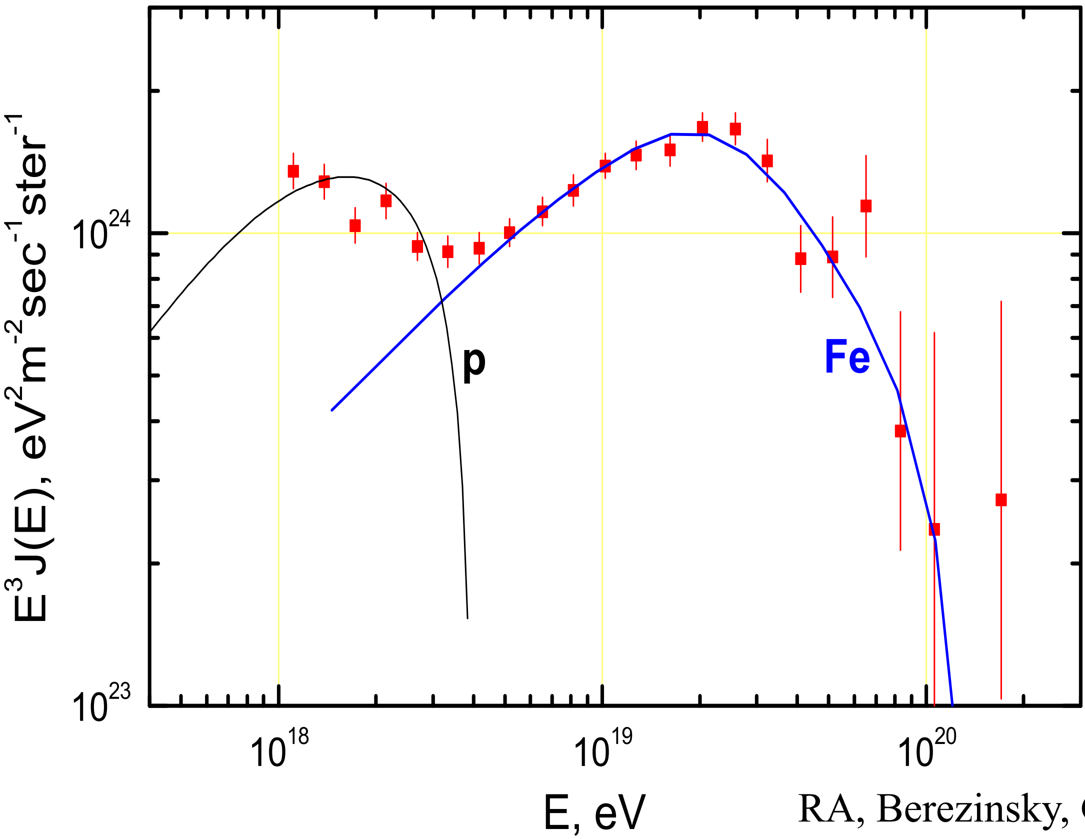


RA, Berezinsky, Grigorieva (2009)

Interaction vs maximum energy

GZK cut-off for protons as well as photo-disintegration cut-off for nuclei are consequences of particle interaction with backgrounds. The observed flux suppression at high energy can be also connected with the maximum energy that sources can provide.

$$E_{max}(Z) = Z E^p_{max}$$



RA, Berezinsky, Gazizov (2009)

$$E^p_{max} = 4 \times 10^{18}\ eV$$

$$E^{Fe}_{max} \simeq 10^{20}\ eV$$

analogy with the galactic CR behavior: protons dominate at the lowest energies and nuclei dominate at the highest.

Disappointing Model

If nuclei dominate at the highest energies:

✓ **no correlation with sources**

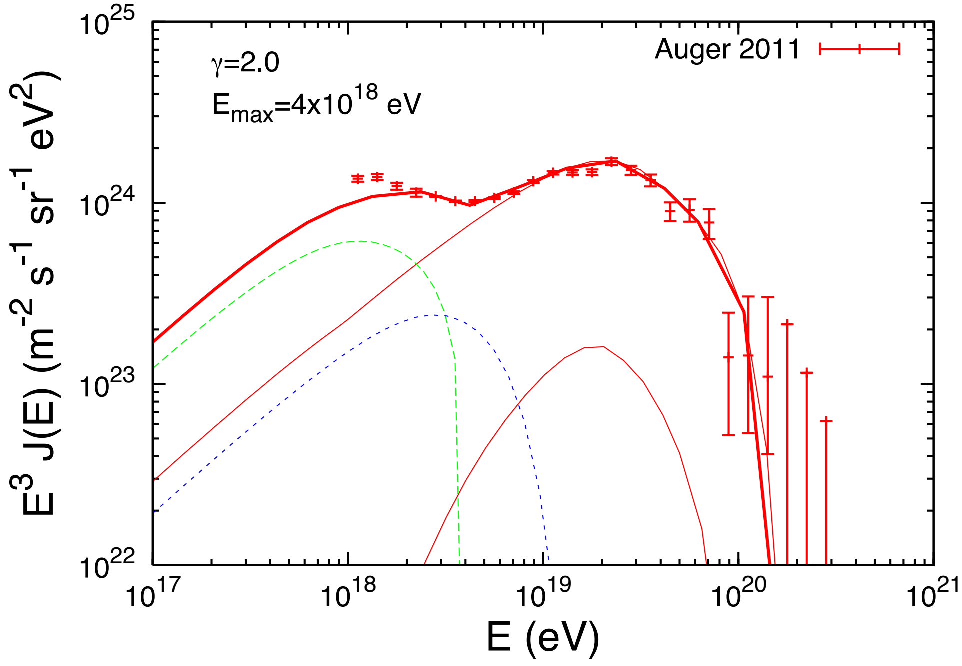
The μG galactic magnetic field substantially deviates particles trajectories:

$$\theta = \frac{Z}{2\pi} \frac{l_{Kpc} B_{\mu}}{E_{20}}$$

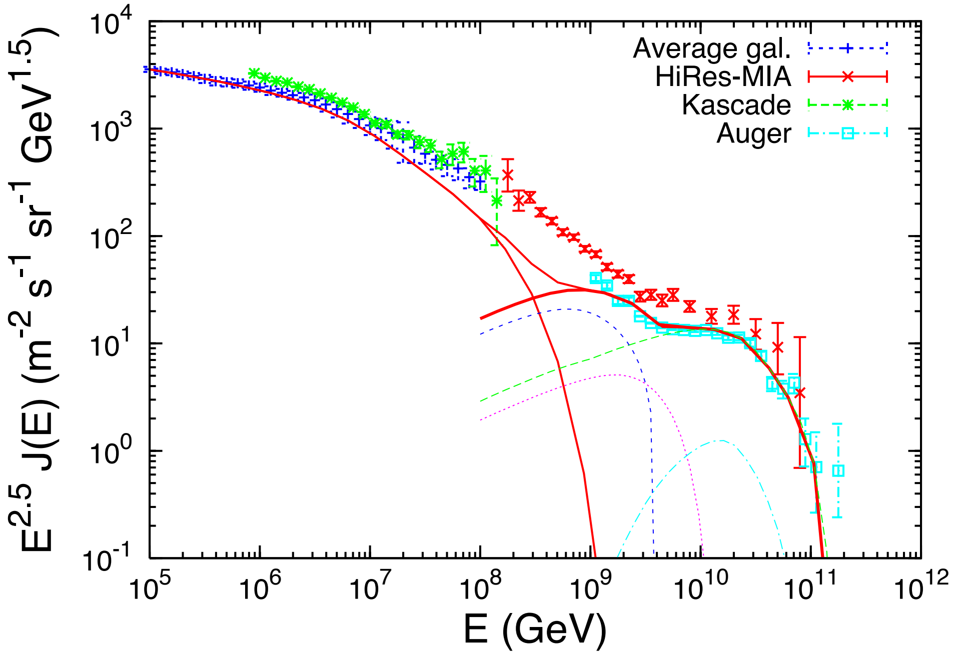
✓ **no production of ν and γ**

Nuclei interacting with CMB and EBL just photo-disintegrate no production of secondary neutrinos nor gamma-rays.

really a disappointing scenario



RA et al. (2012)



Conclusions

- ✓ The experimental observation of the UHECR chemical composition has a paramount importance in choosing among different source models.

- ✓ Observations of UHECR are still unclear, with different experiments claiming different results. A renewed experimental effort is needed in order to asses the nature of UHECR.

- ✓ The solution of this puzzle is fundamental in establishing the future directions of this field of research.

- ✓ Computational schemes, both analytical and MC, aiming to describe the propagation of UHE particles have been reached a good level of refinement (see also Taylor talk today) and can be used as a powerful tool to interpret the experimental observations, unveiling the nature of UHECR and their sources.