Propagation of UHECR Nuclei through CMB and IR radiation Analytic Solution

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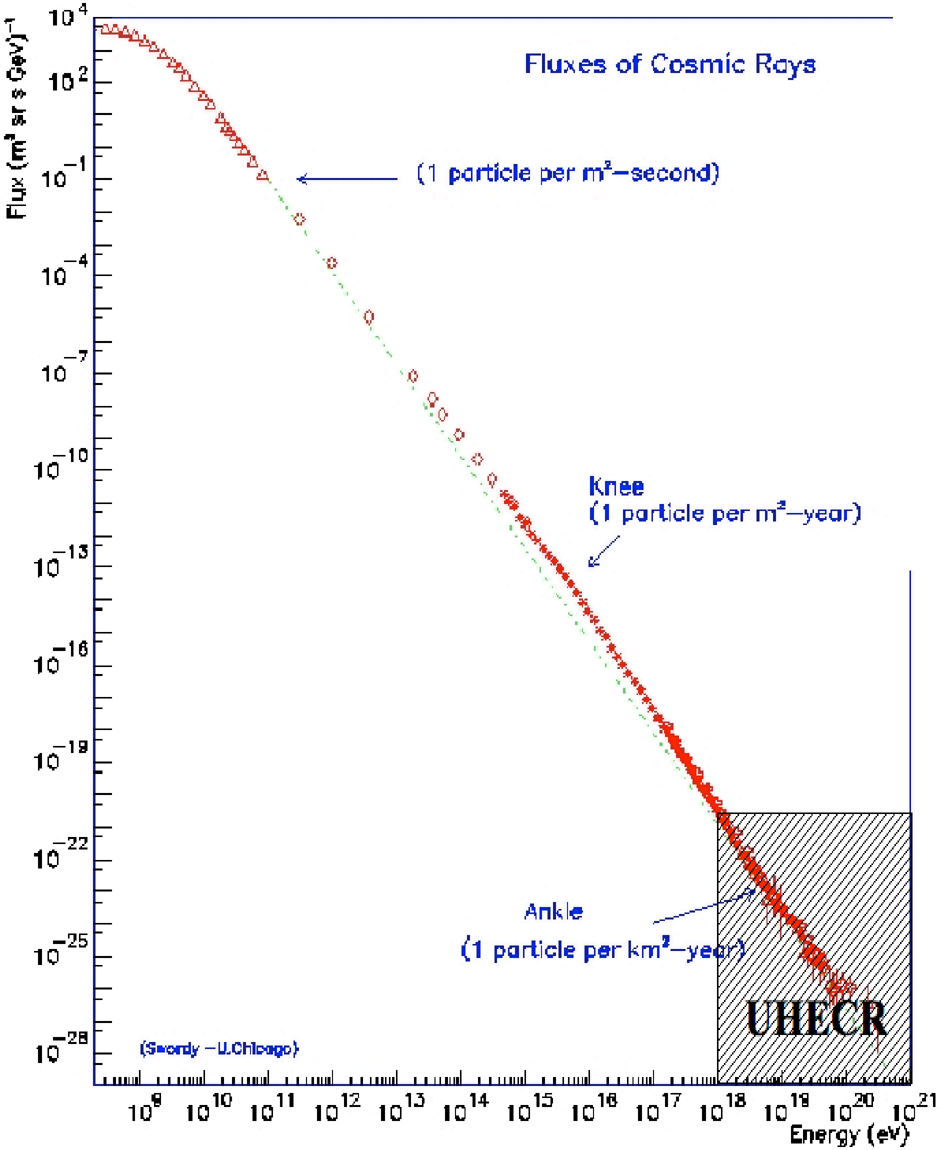
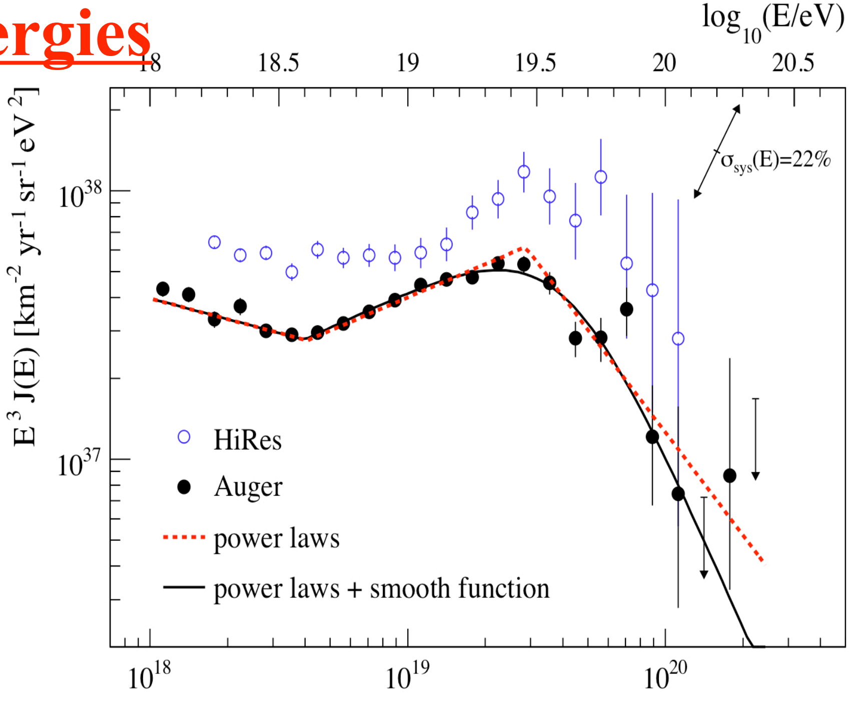
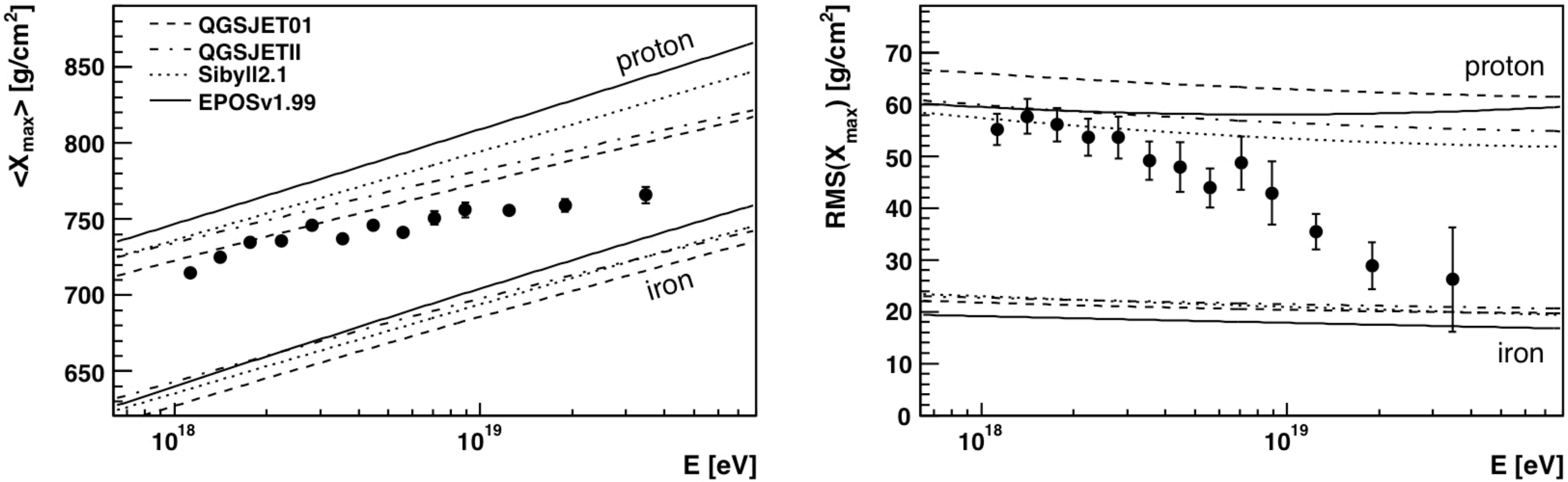
CR spectrum at Ultra High Energies

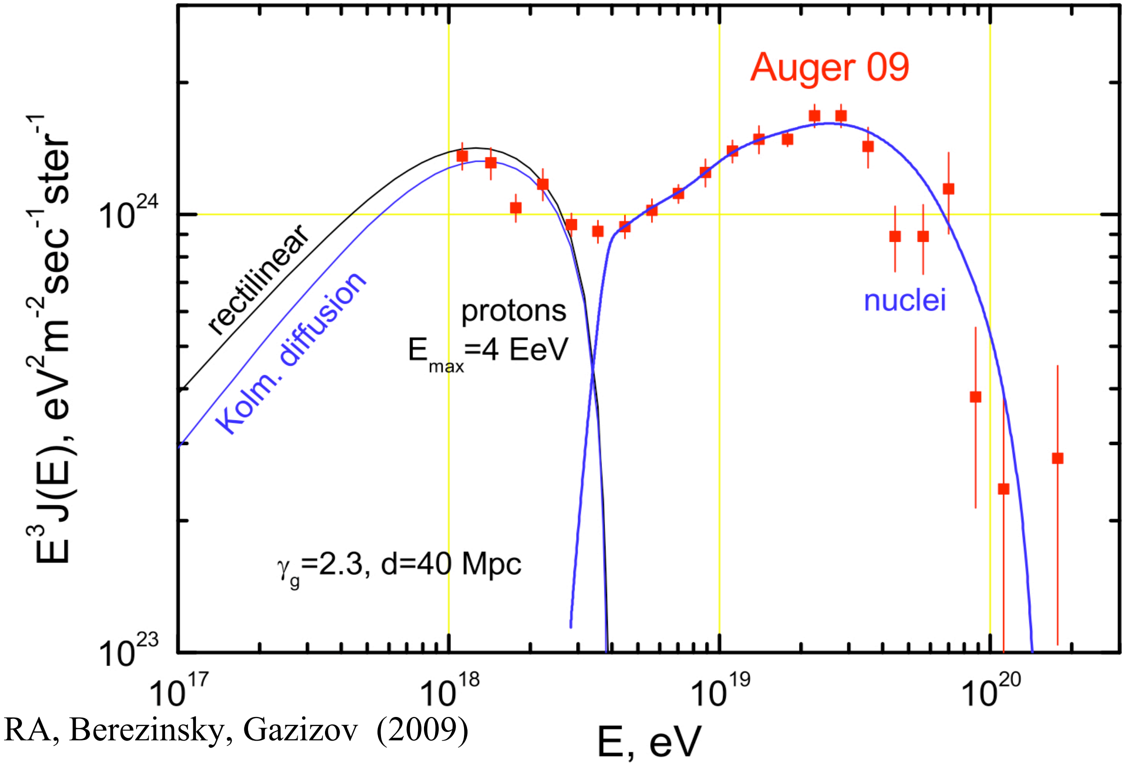




The observations on Earth are the result of the acceleration at the source (injection) and the propagation of particles in the background radiation (CMB & IR) (we will not discuss here magnetic fields) .

- ✓ **Spectrum**
- ✓ **Chemical Composition**
- ✓ **Anisotropy** (correlations)





RA, Berezinsky, Gazizov (2009)

The latest Auger results on spectrum and chemical composition favor a nuclei dominated flux at the highest energies

UHE protons could show a correlation with sources

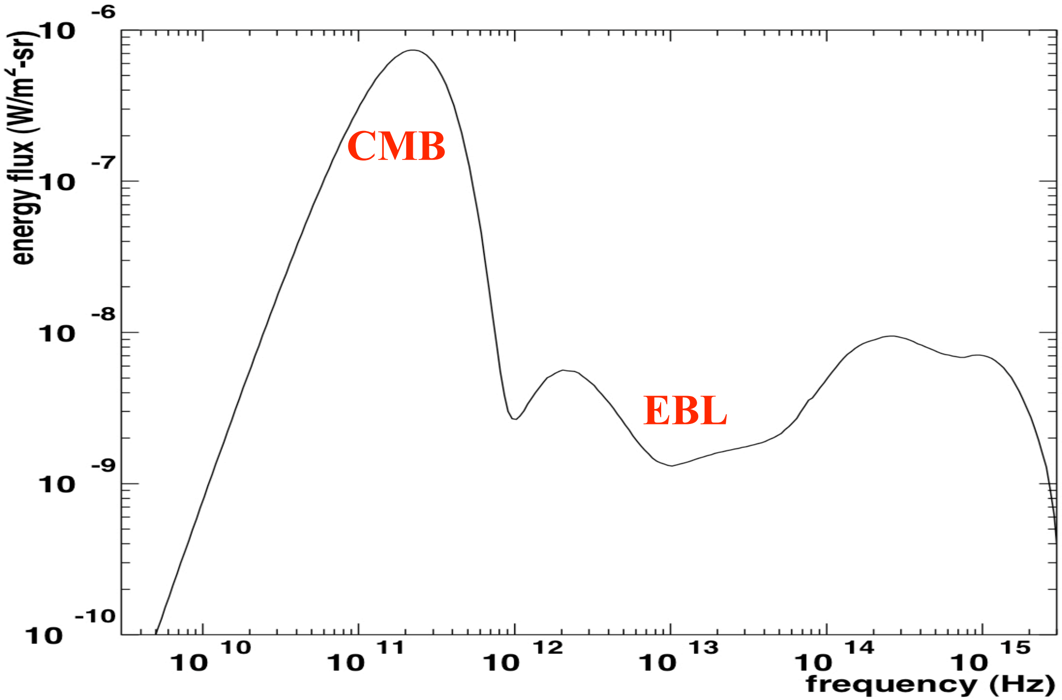
UHE nuclei couldn't

(deflection by galactic magnetic field)

Ultra High Energy Nuclei

✓ Interaction with Astrophysical Backgrounds

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



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

✓ Pair-Production

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

A γ → A $e^+ e^-$

$$(\lambda_{pair}^{-1})_A = \frac{Z^2}{A} (\lambda_{pair}^{-1})_p$$

✓ Photo-Disintegration

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

A γ → (A-1) + N

most relevant process
one nucleon emission
(giant dipole resonance)

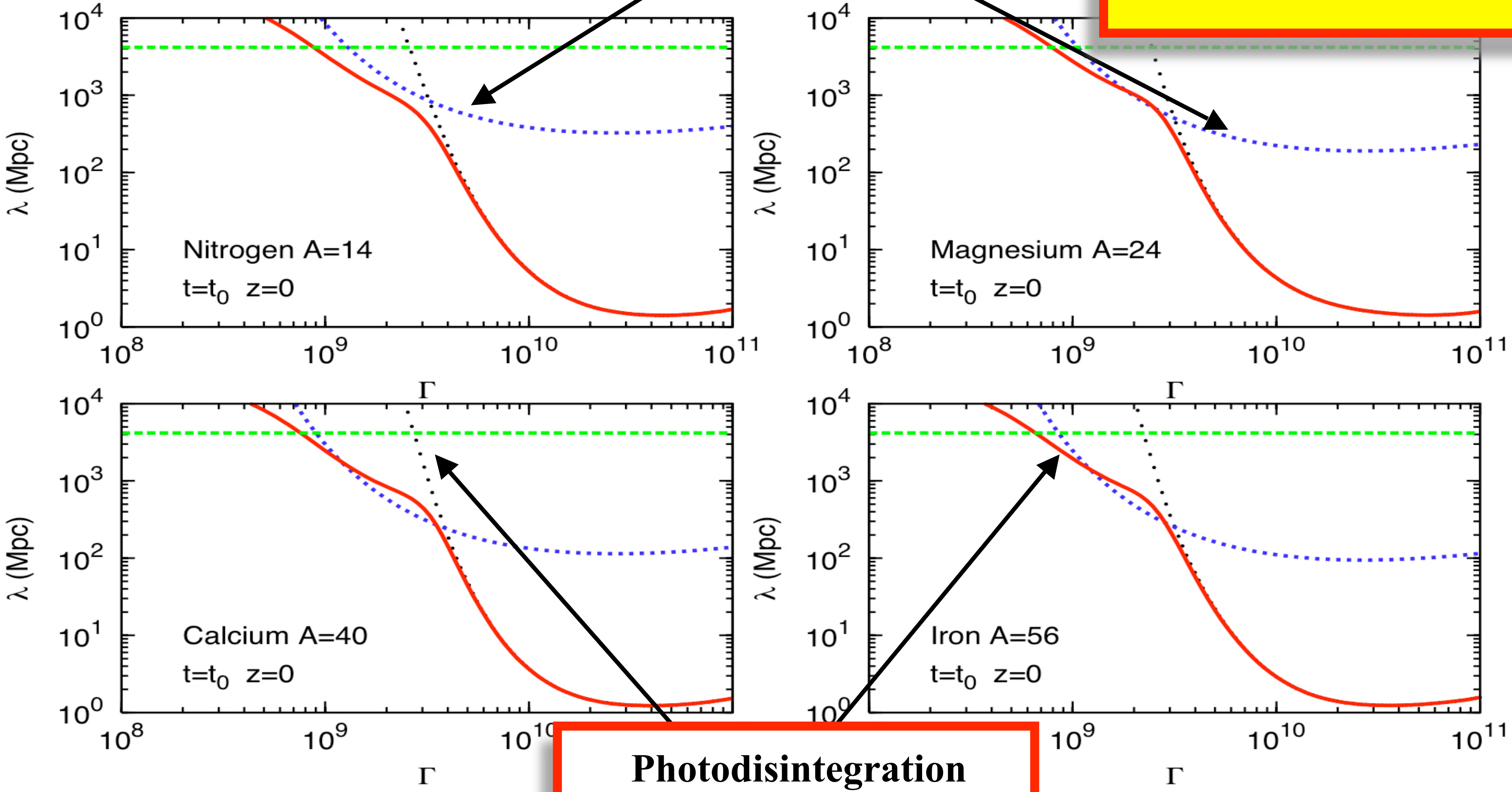
UHE Nuclei loss length

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)

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

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

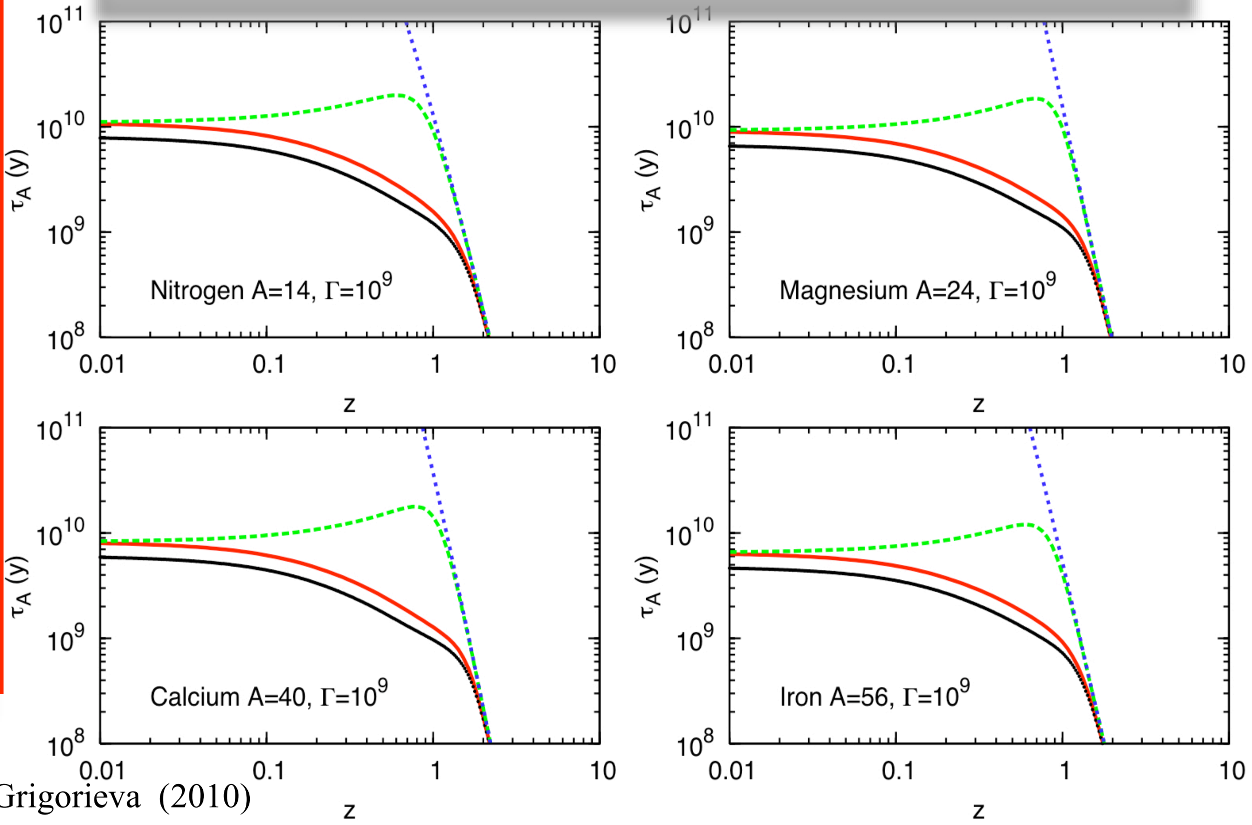
$$\frac{1}{\tau_A(\Gamma, z)} = \frac{1}{\tau^A_{CMB}(\Gamma, z)} + \frac{1}{\tau^A_{EBL}(\Gamma, z)}$$

CMB

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

EBL Malkan, Secker, Scully (2006)

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



RA, Berezinsky, Grigorieva (2010)

UHE Nuclei kinetic equation

$$\frac{\partial n_A(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[b_A(\Gamma,t) n_A(\Gamma,t)\right] + \frac{n_A(\Gamma,t)}{\tau_A(\Gamma,t)} = Q_A(\Gamma,t)$$

Lorentz factor variation rate

photo-disintegration “decay”

Injection:
primary nuclei
secondary nuclei

$$b_A(\Gamma,z) = \Gamma \frac{Z^2}{A}\beta^p_{pair}(\Gamma,z) + \Gamma H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}$$

nuclei kinetic equation solution

$$n_A(\Gamma, z=0) = \int_0 dz \left|\frac{dt}{dz}\right| Q_A\left[\Gamma'(\Gamma,z)\right]\frac{d\Gamma'}{d\Gamma}e^{-\eta(\Gamma',z)}$$

Γ’ solution of the
energy losses equation

$$\frac{d\Gamma}{dt} = b_A(\Gamma,t)$$

dΓ’/dΓ as in
RA, Berezinsky,
Grigorieva 2010

photo-disintegration “life-time”

$$\eta(\Gamma',z) = \int_0^z dz' \left|\frac{dt}{dz'}\right| \frac{1}{\tau_A(\Gamma',z')}$$

Primary Nuclei

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

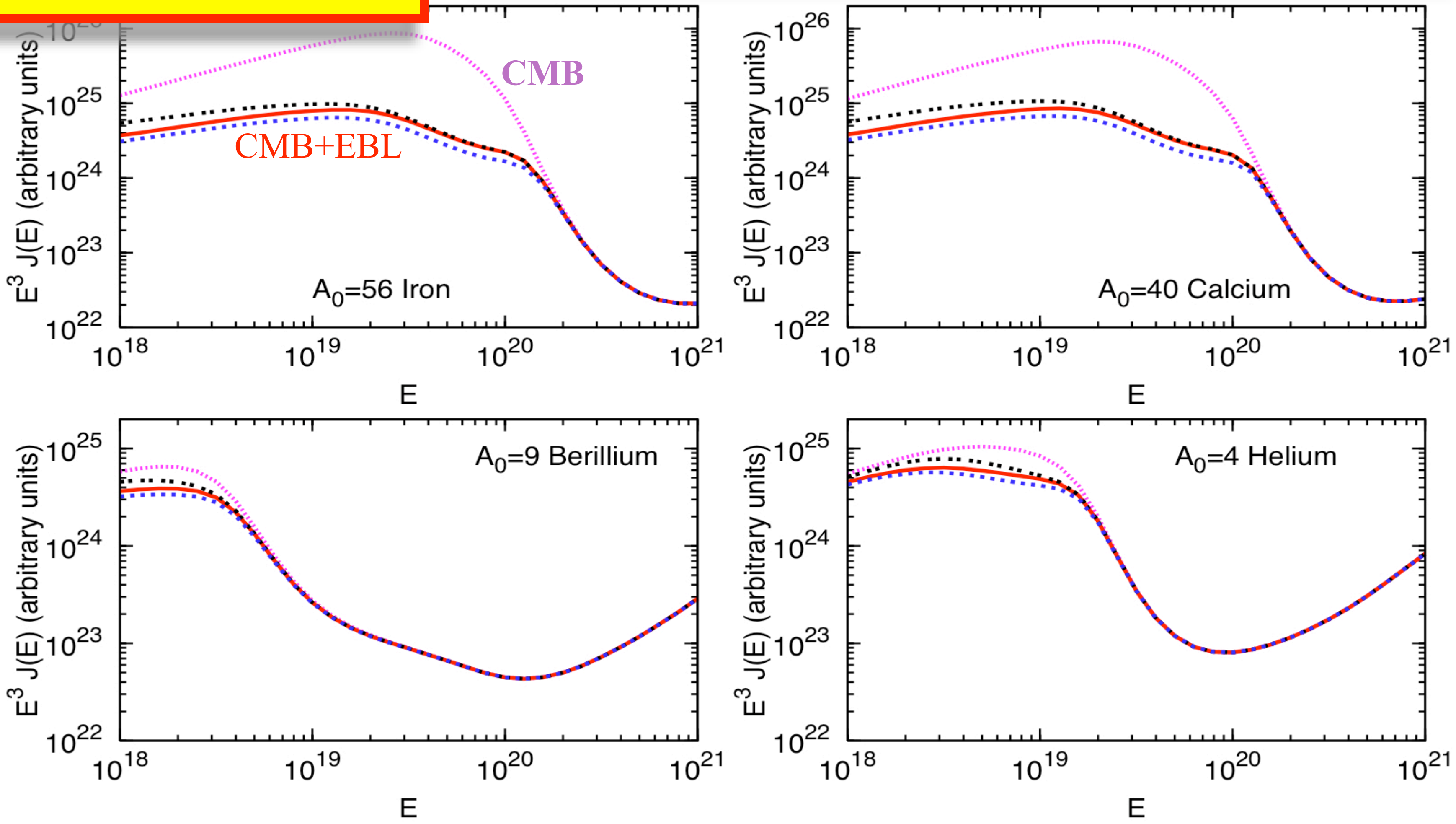
$$10^8 \leq \Gamma \leq 2 \times 10^9$$

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

Secondary nuclei injection

dominant process: one nucleon emission Aγ→(A-1) N.
Conservation of the Lorentz factor.

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

The flux of any secondary A can be determined solving the system (chain) of kinetic equations till the fixed A.

$$\begin{aligned}
\frac{\partial n_{A_0}(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[n_{A_0}(\Gamma,t) b_{A_0}(\Gamma,t)\right] + \frac{n_{A_0}(\Gamma,t)}{\tau_{A_0}(\Gamma,t)} &= Q_{A_0}(\Gamma,t) \\
\frac{\partial n_{A_0-1}(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[n_{A_0-1}(\Gamma,t) b_{A_0-1}(\Gamma,t)\right] + \frac{n_{A_0-1}(\Gamma,t)}{\tau_{A_0-1}(\Gamma,t)} &= \frac{n_{A_0}(\Gamma,t)}{\tau_{A_0}(\Gamma,t)} \\
&\vdots \\
\frac{\partial n_{A}(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[n_{A}(\Gamma,t) b_{A}(\Gamma,t)\right] + \frac{n_{A}(\Gamma,t)}{\tau_{A}(\Gamma,t)} &= \frac{n_{A+1}(\Gamma,t)}{\tau_{A+1}(\Gamma,t)}
\end{aligned}$$

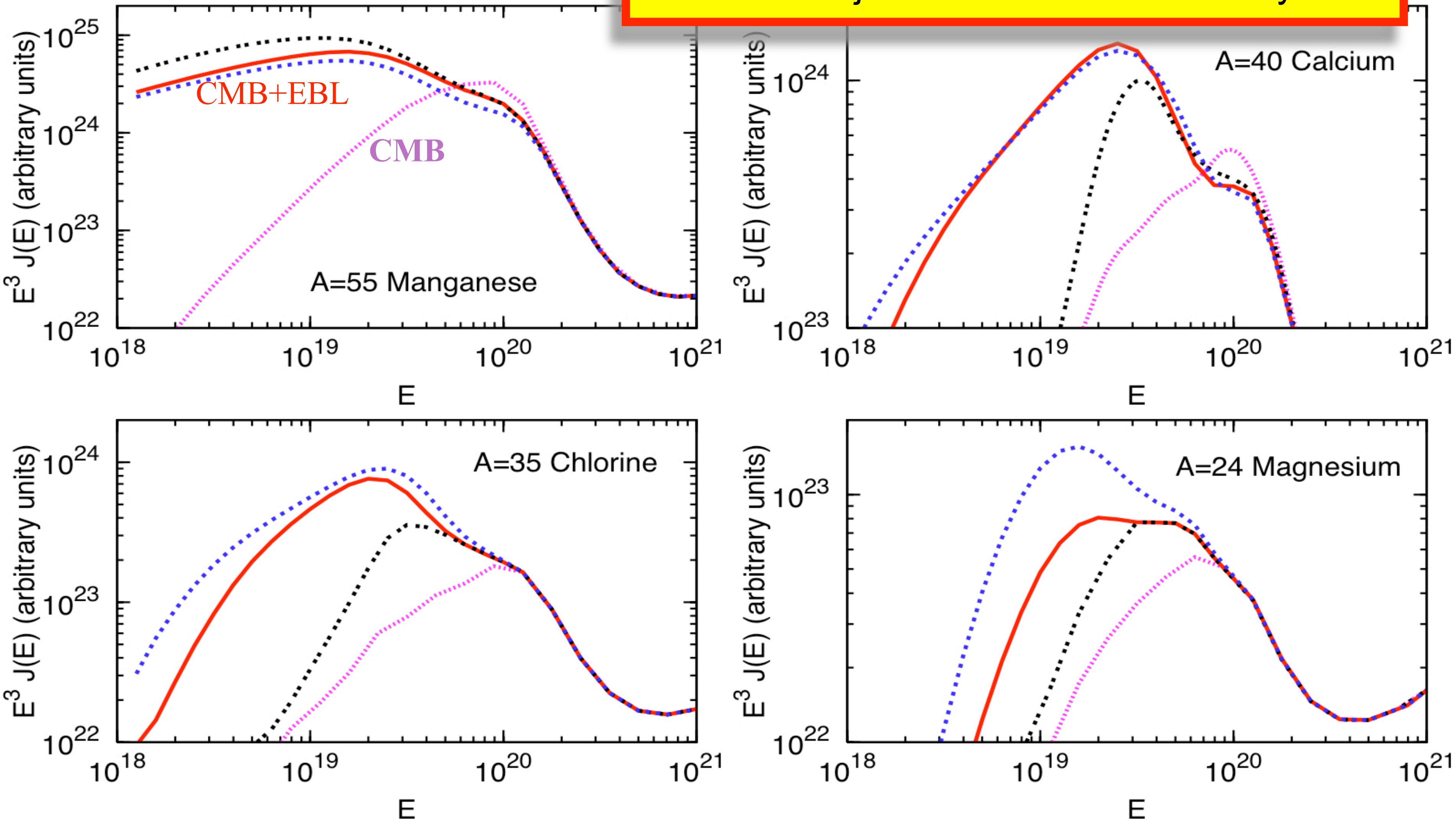
A_0=56 Iron
γ_g=2.3

RA, Berezinsky, Grigorieva (2010)

the EBL role consists in a flux regeneration in the range

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

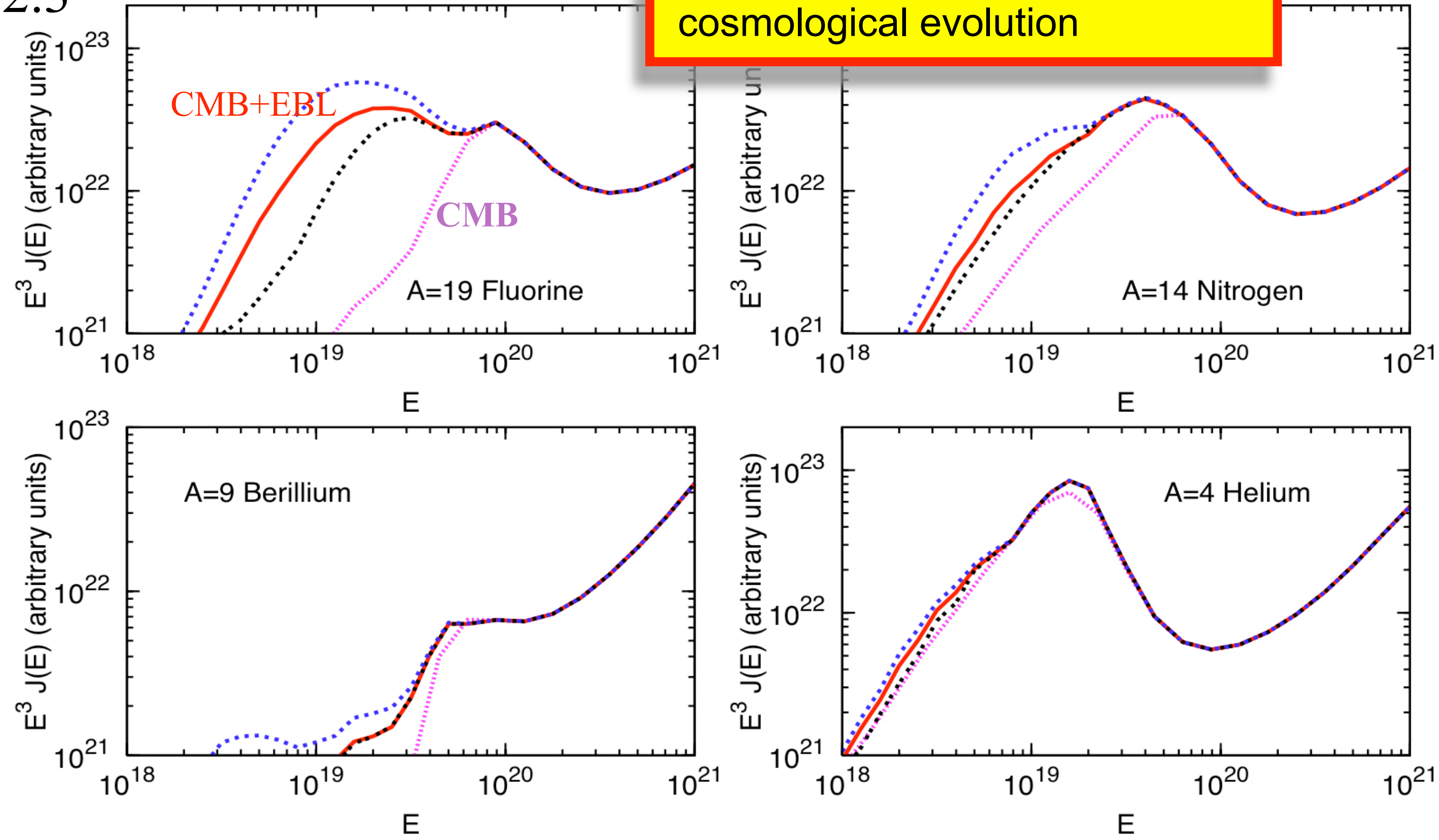
due to an injection increased efficiency



starting from primary Iron the photodisintegration chain produces all kind 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 kinetic equation

$$\frac{\partial n_p(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[b_p(\Gamma,t) n_p(\Gamma,t)\right] = Q_p^A(\Gamma,t)$$

each secondary nucleus
in the decay chain of A_0
produces almost one nucleon
$A\,\gamma \rightarrow (A\text{-}1)\ \ N$

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

Only CMB is relevant
pair and photo-pion production

$$b_p(\Gamma,z) = \Gamma[\beta^p_{pair}(\Gamma,z) + \beta^p_{pion}(\Gamma,z)] + \Gamma H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}$$

nucleons kinetic equation solution

$$n_p^A(\Gamma, z=0) = \int_0 dz \left|\frac{dt}{dz}\right| Q_p^A\left[\Gamma'(\Gamma,z)\right]\frac{d\Gamma'}{d\Gamma} \qquad n_p(\Gamma,z=0) = \sum_{A<A_0} n_p^A(\Gamma,z=0)$$

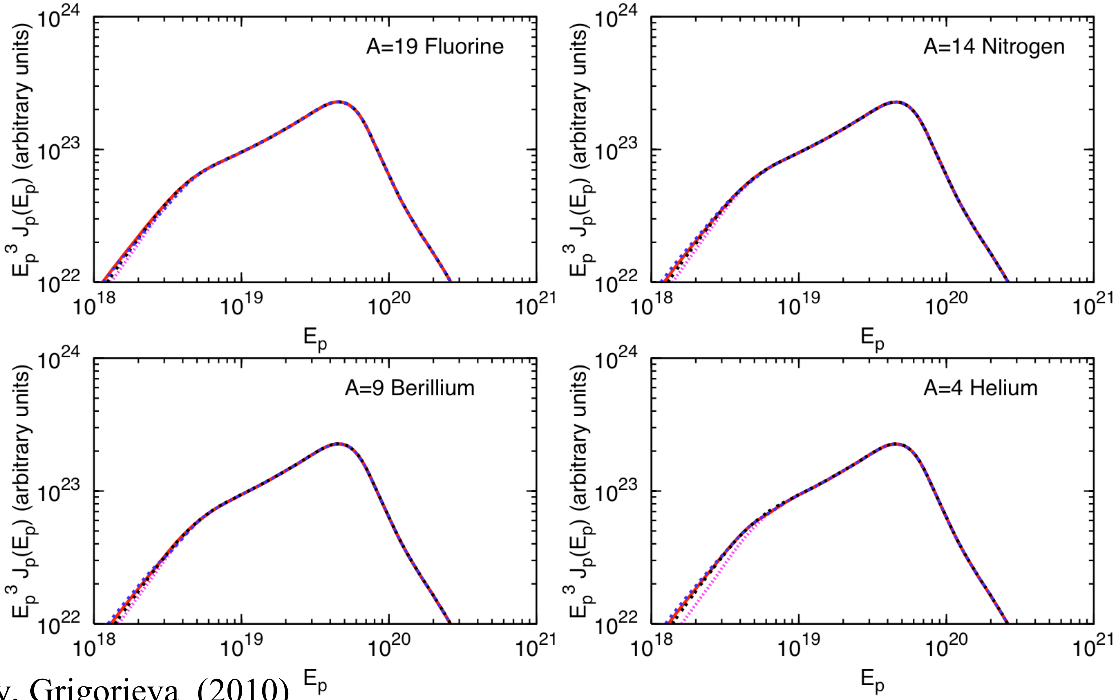
Γ’ solution of the energy losses equation

$$\frac{d\Gamma}{dt} = b_p(\Gamma,t)$$

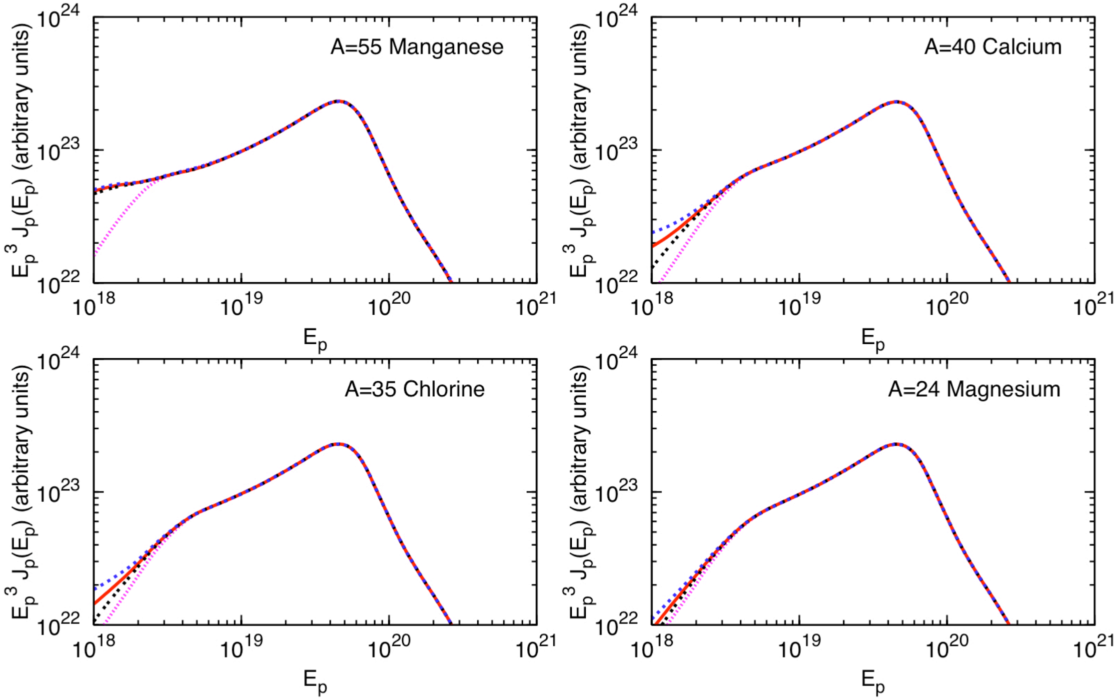
dΓ’/dΓ as in
Berezinsky and
Grigorieva 1988

Secondary Nucleons

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



RA, Berezinsky, Grigorieva (2010)



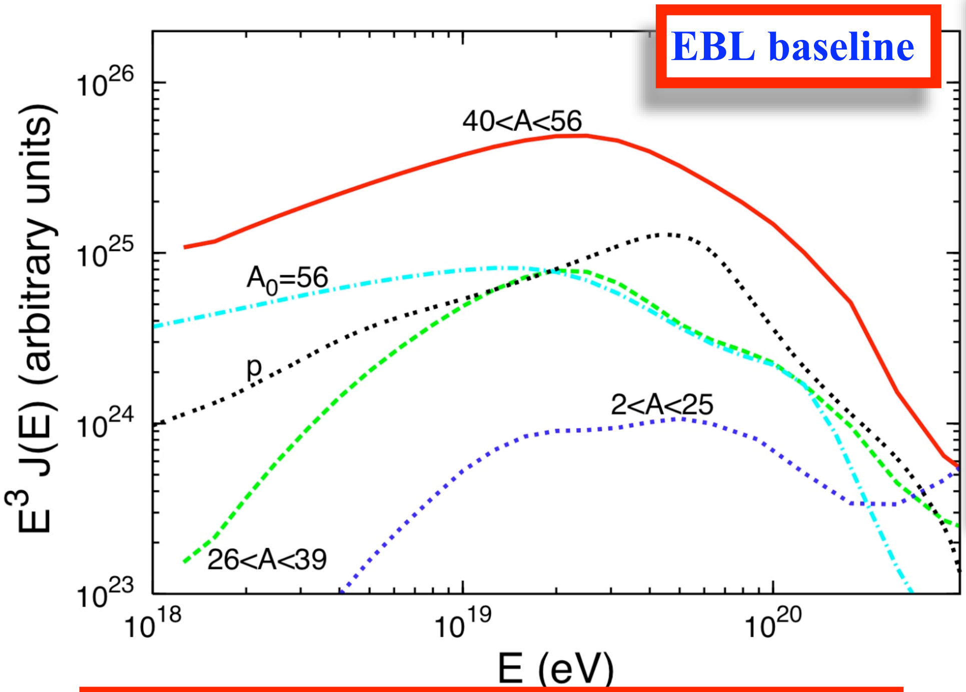
the EBL role consists in a small flux regeneration in the energy range

$$10^{17}\ eV \leq E \leq 2\times10^{18}\ eV$$

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

Conclusions

EBL baseline



✓ The effect of EBL is restricted to

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

at higher energies the CMB dominates.

✓ Differences in the EBL cosmological evolution regime affect mainly secondary nuclei.

✓ Heavy nuclei dominate (primary and secondary).

✓ Flux of secondary protons is subdominant, it comprises not more that 10% of the total flux.

✓ In any realistic model a primary proton component must be present, the proton fraction will be higher.

EBL fast evolution