Theoretical Models for the Propagation of Ultra High Energy Cosmic Rays and the Auger observations.

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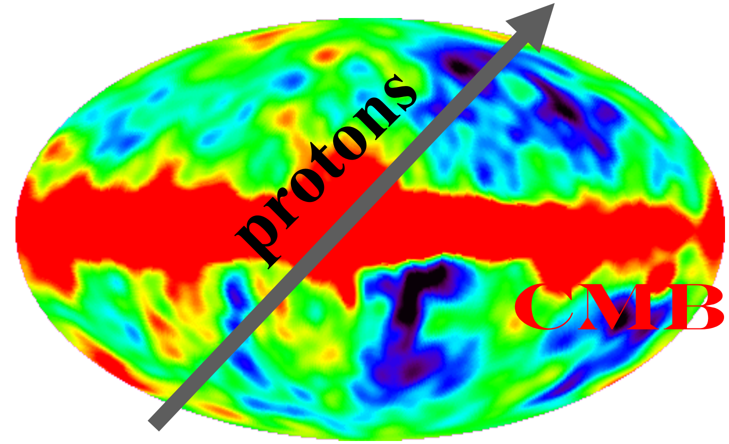
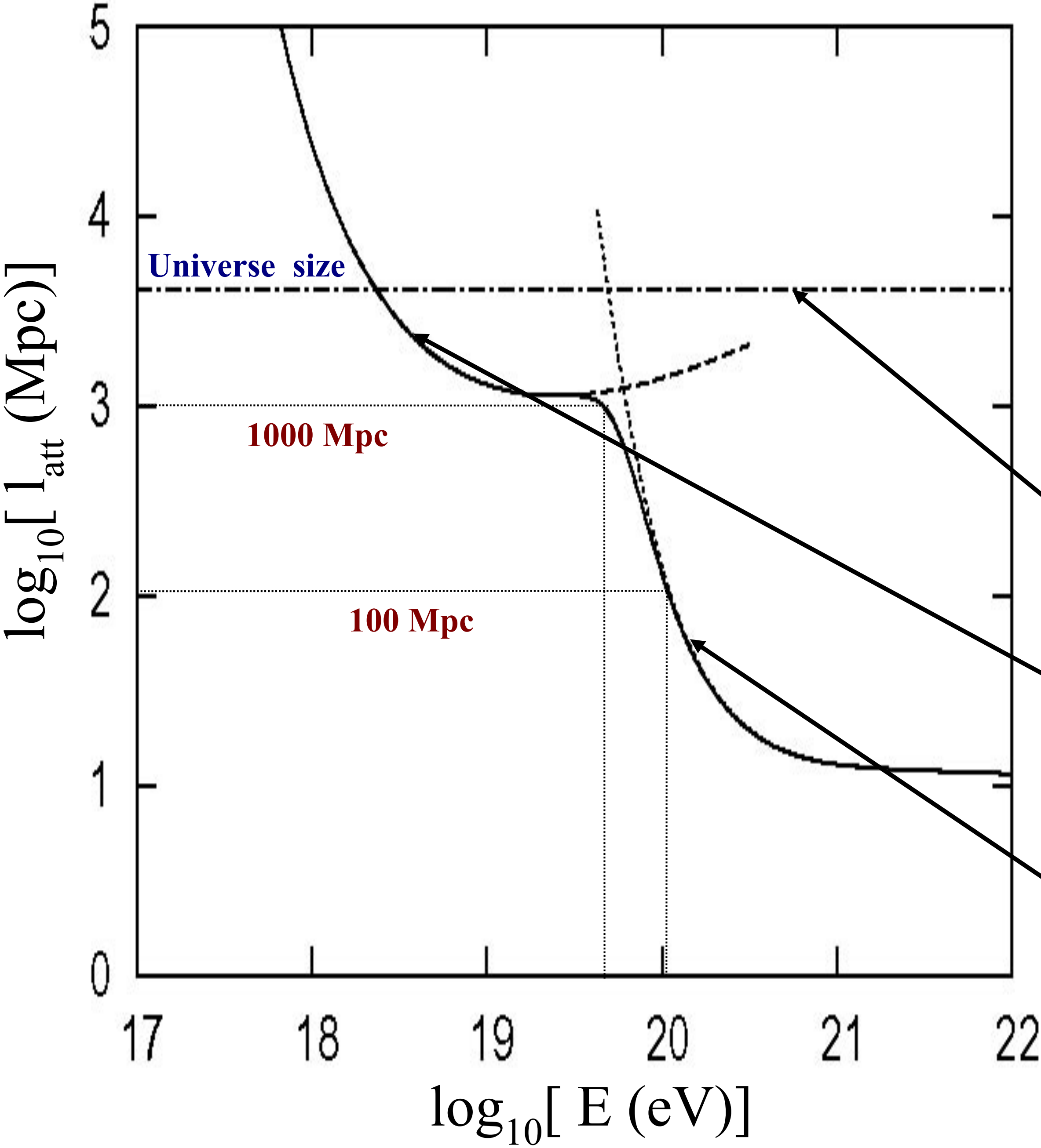
Vulcano Workshop 2012
Frontier Objects in Astrphysics and Particle Physics

UHE Proton loss length



proton propagation is affected only by CMB

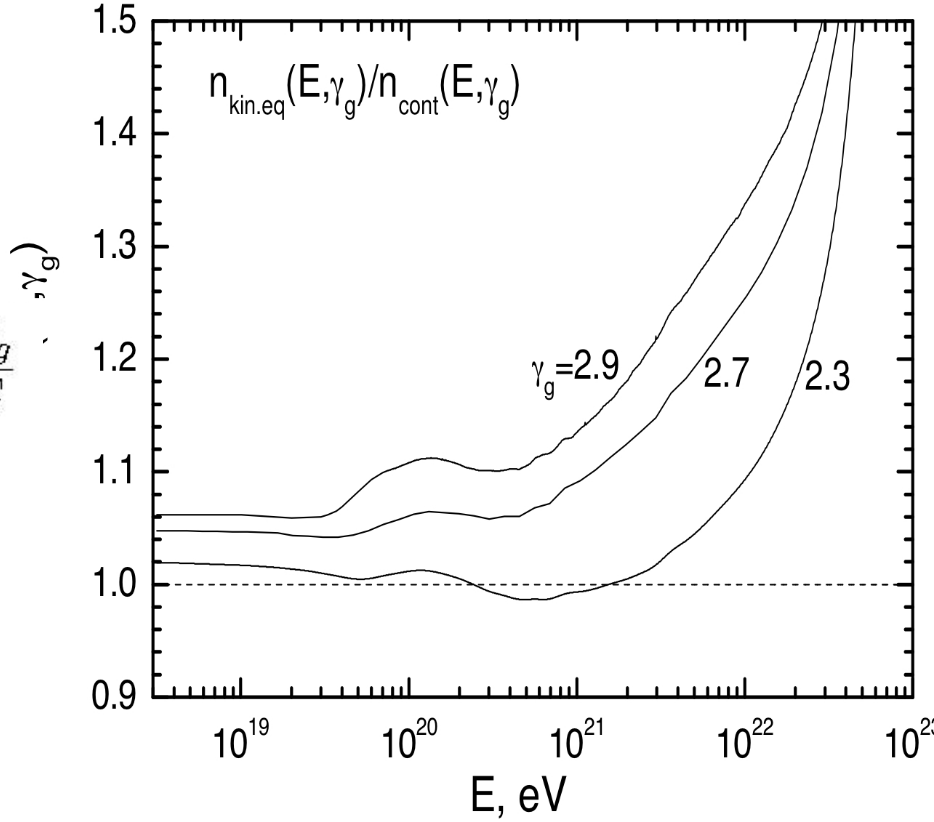


Protons propagation in Intergalactic Space

Continuum Energy Losses

Protons lose energy but do not disappear. Fluctuations in the pγ interaction start to be important only at $E>5\times10^{19}$ eV.

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



Berezinsky, Grigorieva, Gazizov (2006)

Uniform distribution of sources

the UHECR sources are continuously distributed with a density n_s.

$$J(E) = \frac{c}{4\pi} n_s \int_0^{z_{max}} dz \left|\frac{dt}{dz}\right| Q_{inj}(E_g(E,z)) \frac{dE_g}{dE}$$

Discrete sources

the UHECR sources are discretely distributed with a spacing d.

$$J(E) = \frac{1}{4\pi}\sum_i \frac{Q_{inj}(E_g(E,z_i))}{r_i^2(1+z_i)} \frac{dE_g(E,z_i)}{dE}$$

Injection spectrum number of particles injected at the source per unit time and energy

$$Q_{inj} = \frac{L_p(\gamma-2)}{E_c^2}\left(\frac{E}{E_c}\right)^{-\gamma}$$

$\gamma > 2$ injection power law

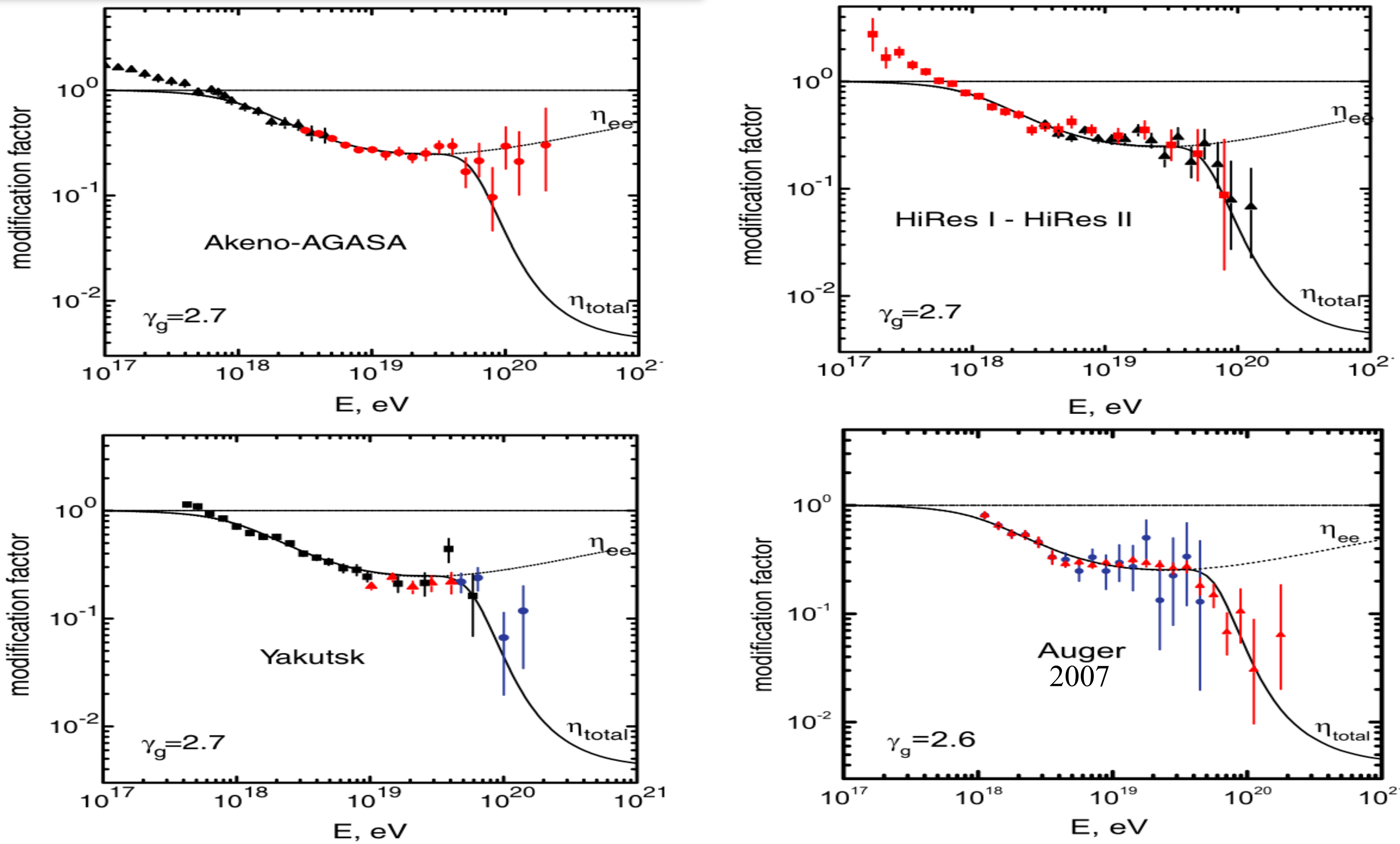
$J_p = L_p\, n_S$ source emissivity

Dip Model

In the energy range 10^{18} - 5×10^{19} eV the spectrum behavior is a signature of the pair production process of UHE protons on the CMB radiation field.

Best fit values

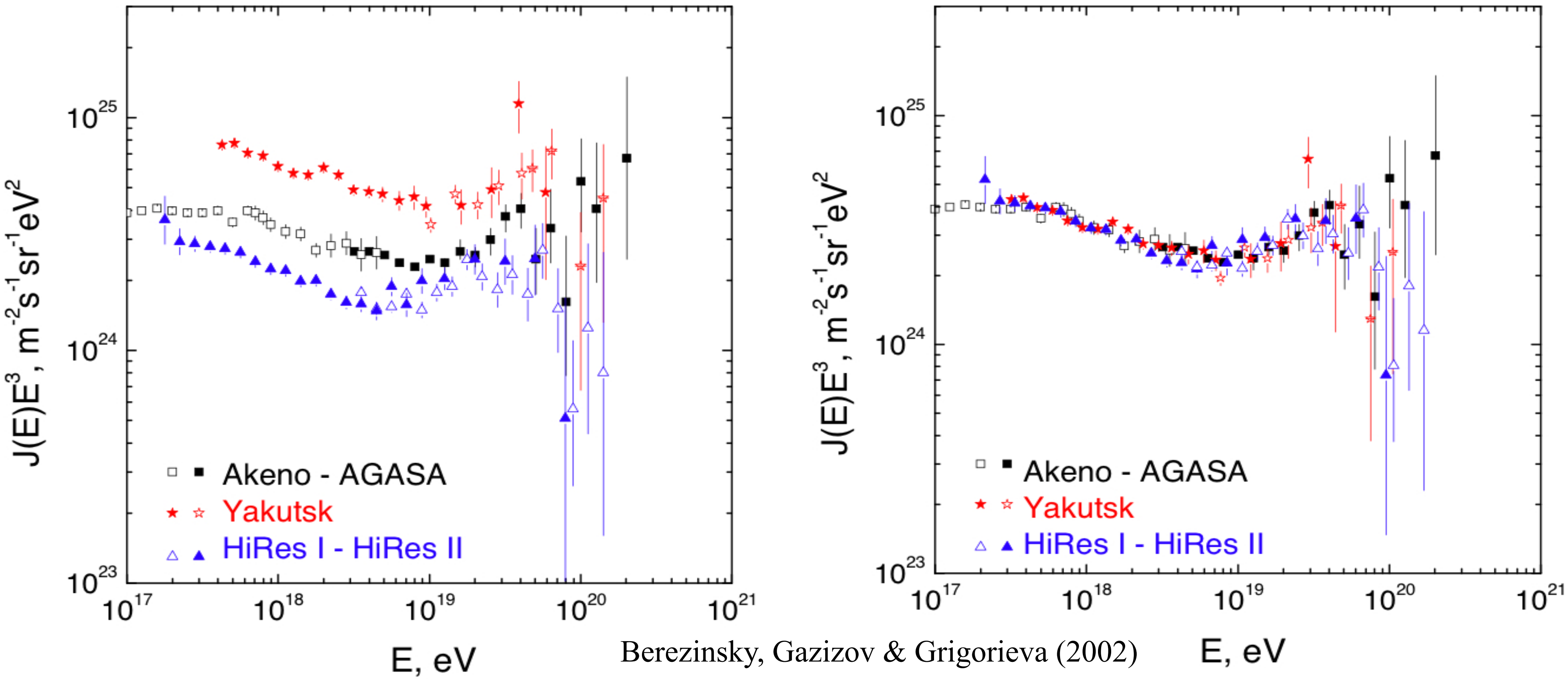
$\gamma = 2.7 \quad J_p = O(10^{40})$ erg $s^{-1}Mpc^{-3}$



RA et al. (2007) - Berezinsky et al (2002)

Energy calibration by the Dip

Different experiments show different systematic in energy determination



Berezinsky, Gazizov & Grigorieva (2002)

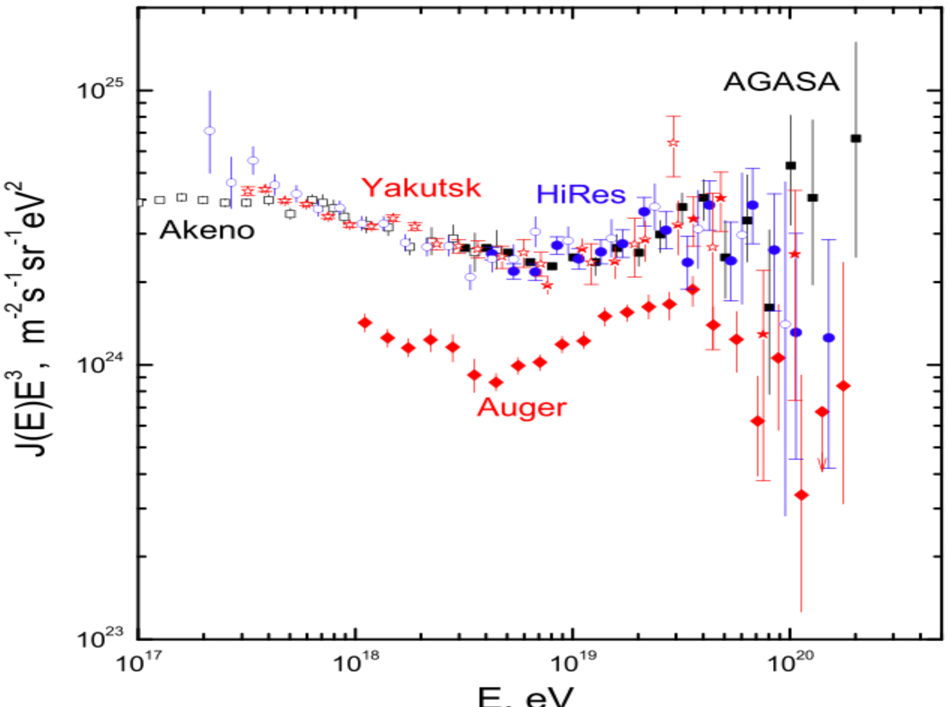
Calibrating the energy through the Dip gives an energy shift $E \rightarrow \lambda E$
(with λ fixed by minimum χ^2)

$$\lambda_{AGASA} = 0.90 \qquad \lambda_{HiRes} = 1.21 \qquad \lambda_{Yakutsk} = 0.75$$

NOTE: $\lambda<1$ for on-ground detectors and $\lambda>1$ for fluorescence detectors

(these shifts are all inside the systematic errors of the experiments)

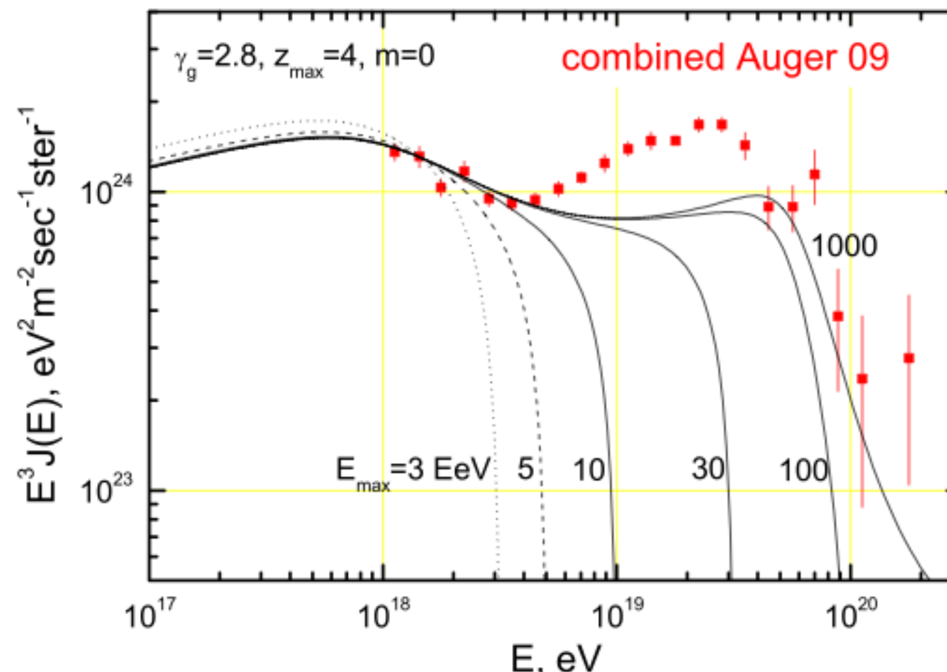
The very good agreement obtained among different measurements (apart Auger) calibrating the energy by the dip represents a strong indication in favor of an UHECR proton dominated spectrum



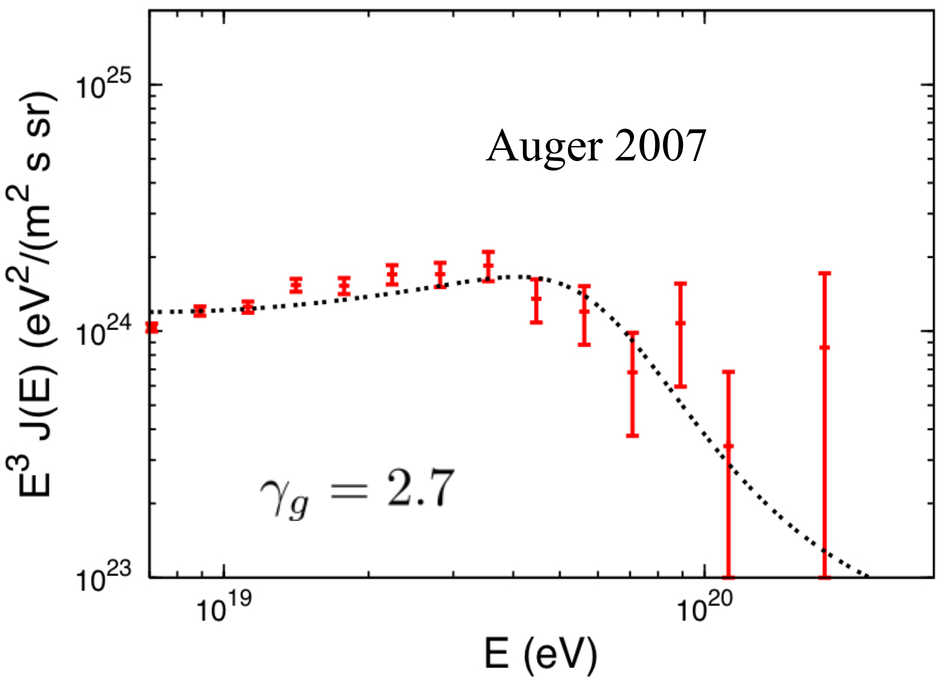
RA et al. (2007)

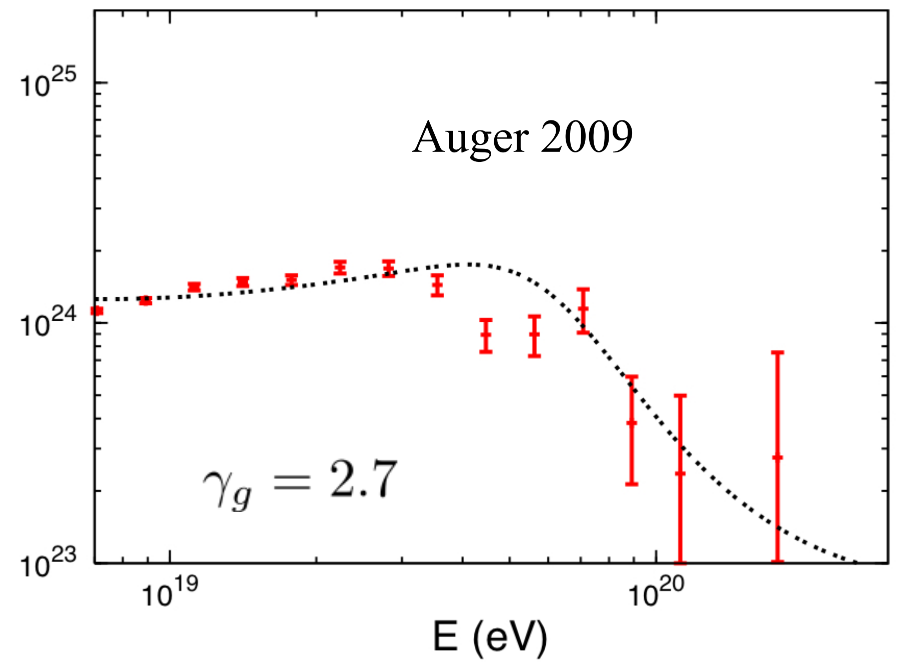
the calibration of 2007 Auger data requires a large energy shift of about 50% (outside the experimental systematics) signal of deviation from the dip behavior

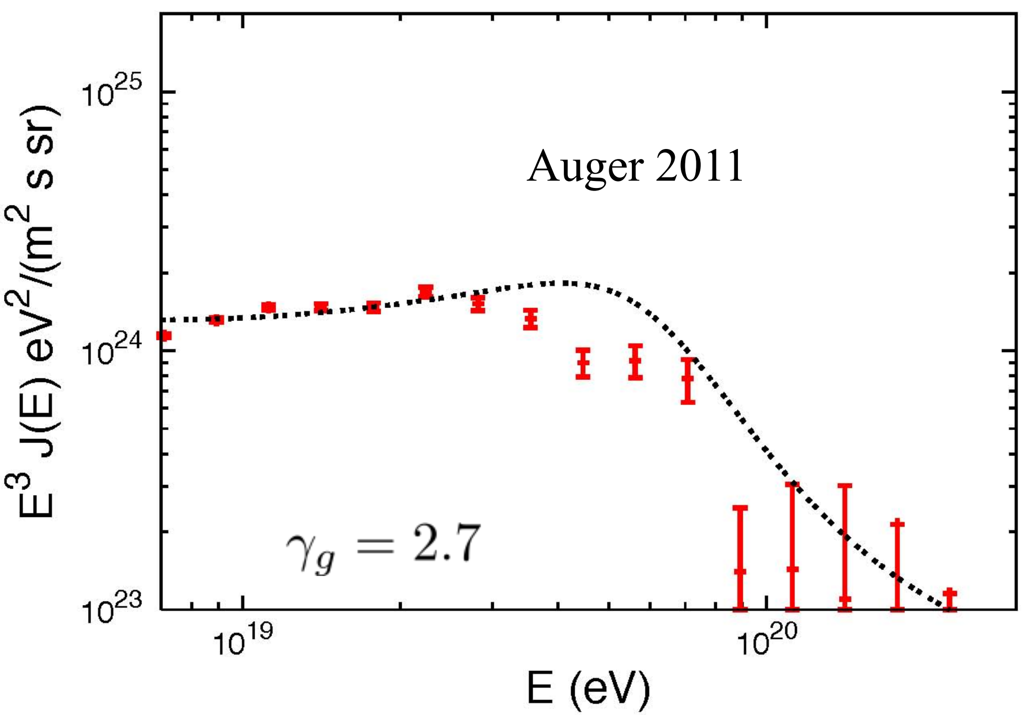
If compared with the 2009 Auger data the agreement with the dip behavior becomes worse.



RA, Berezinsky, Gazizov (2011)

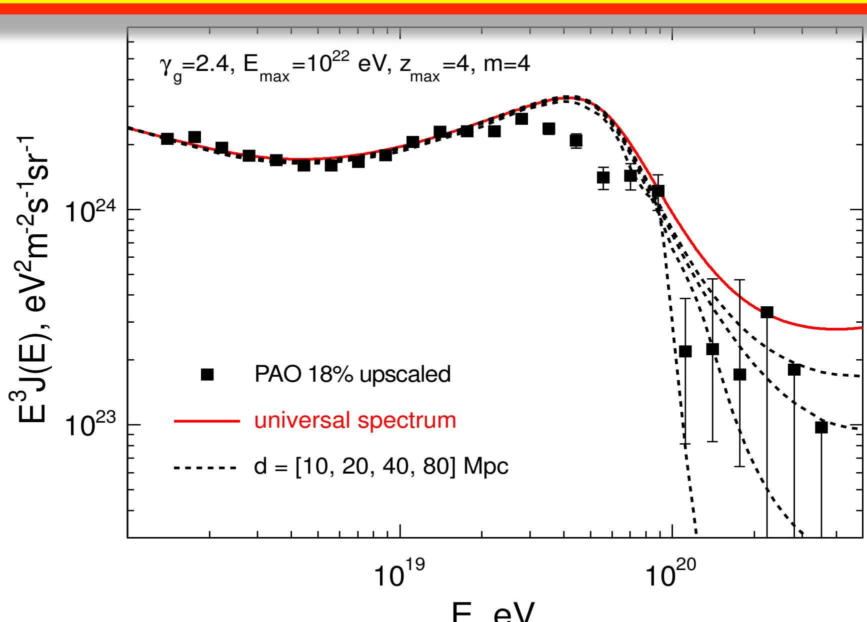


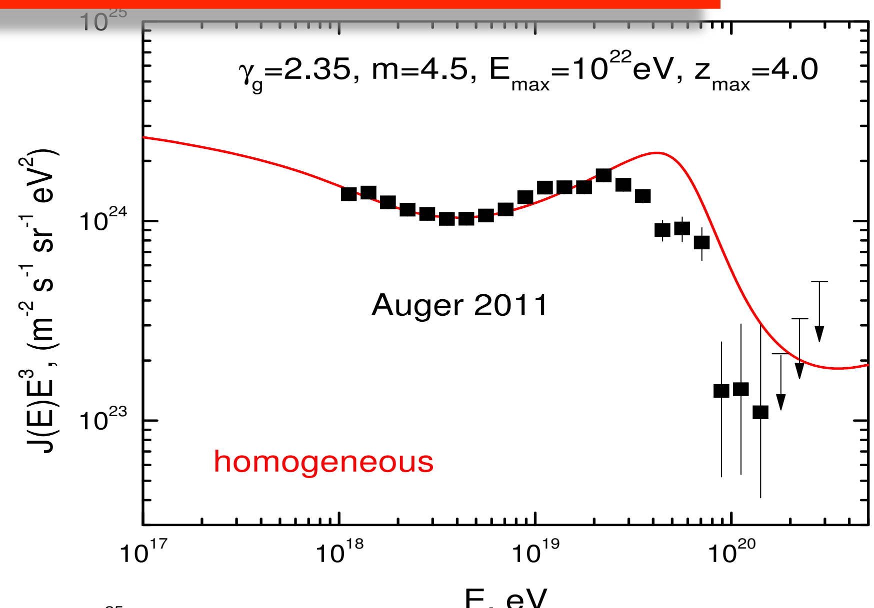


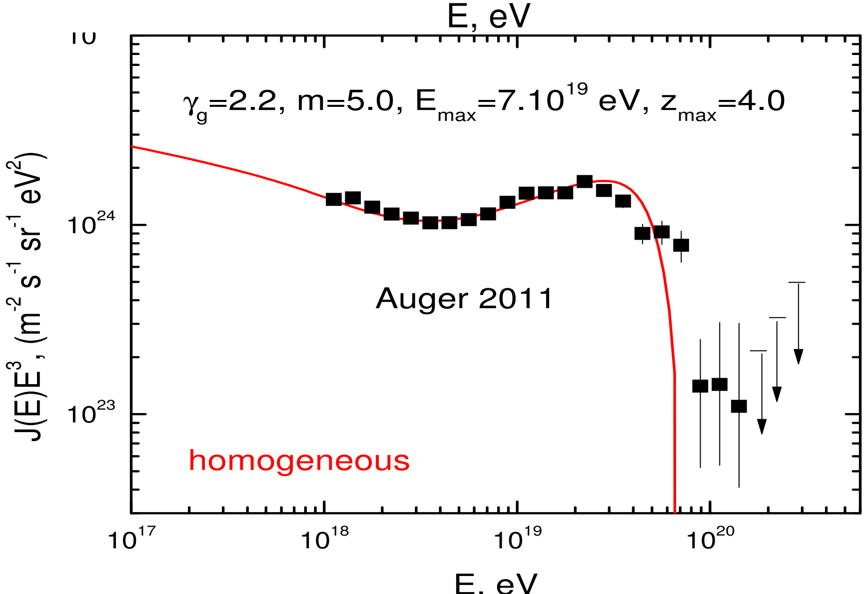


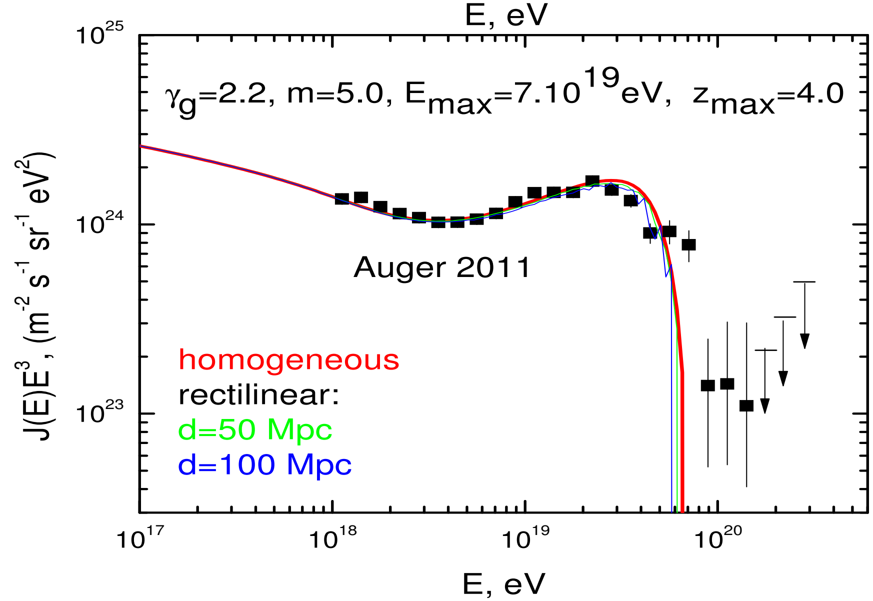
The last Auger data on flux show a suppression roughly at the expected GZK energy for protons, even if the comparison of 2007, 2009 and 2011 data seem to weaken the agreement with the expected protons GZK behavior (for a detailed review of the latest Auger data please refer to the Grillo's talk.)

Taking the latest Auger (2011) data it is very difficult to explain the observed flux at all energies in the framework of a pure proton composition. <u>Signal of heavy nuclei</u>. <u>Failure of the dip model</u>.









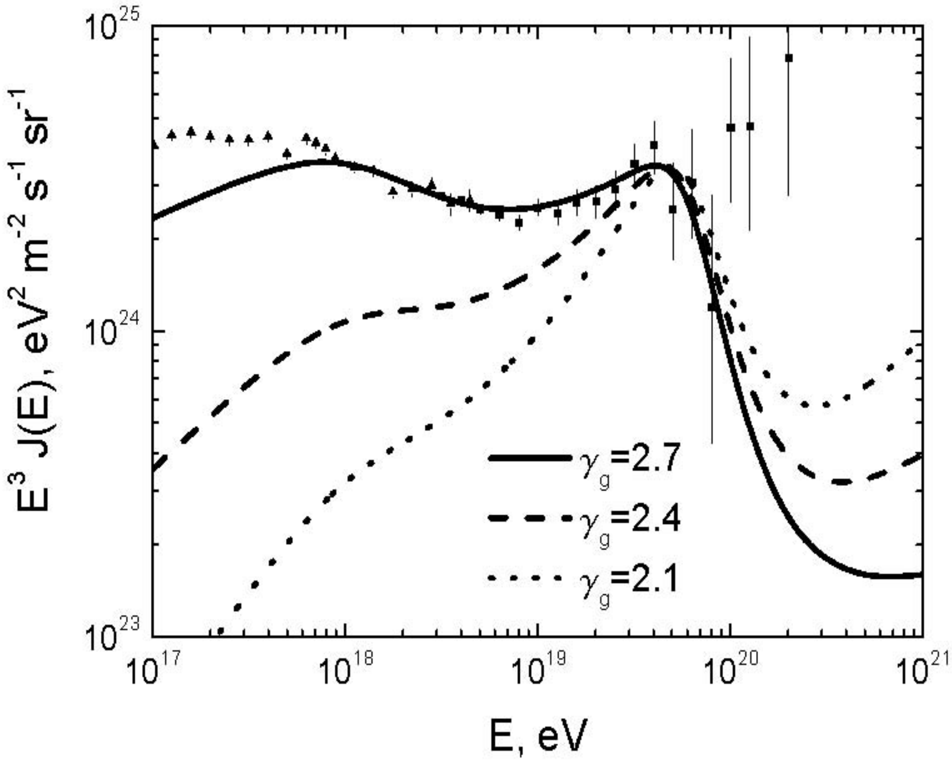
Caveats

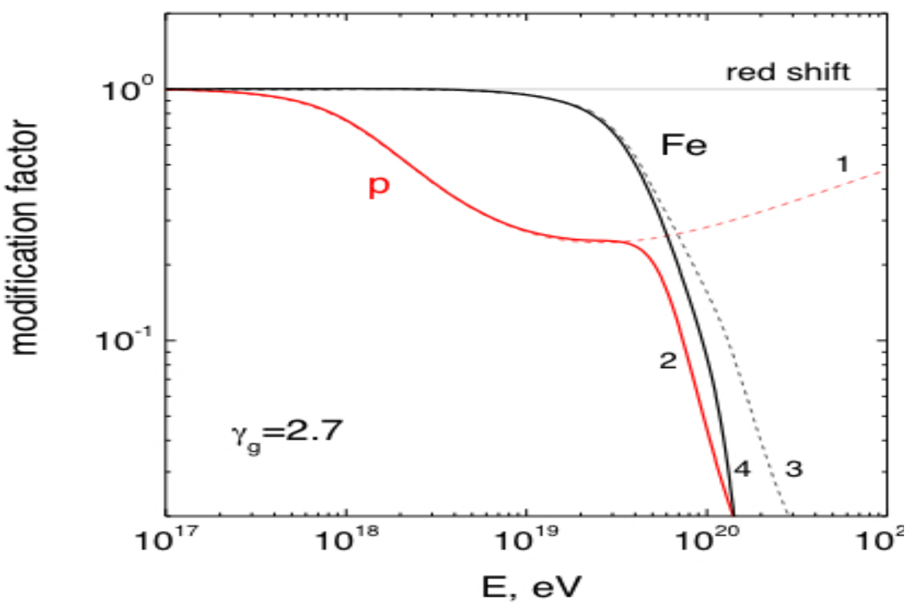
The interpretation of the observed spectrum in terms of protons pair-production losses FAILS if:

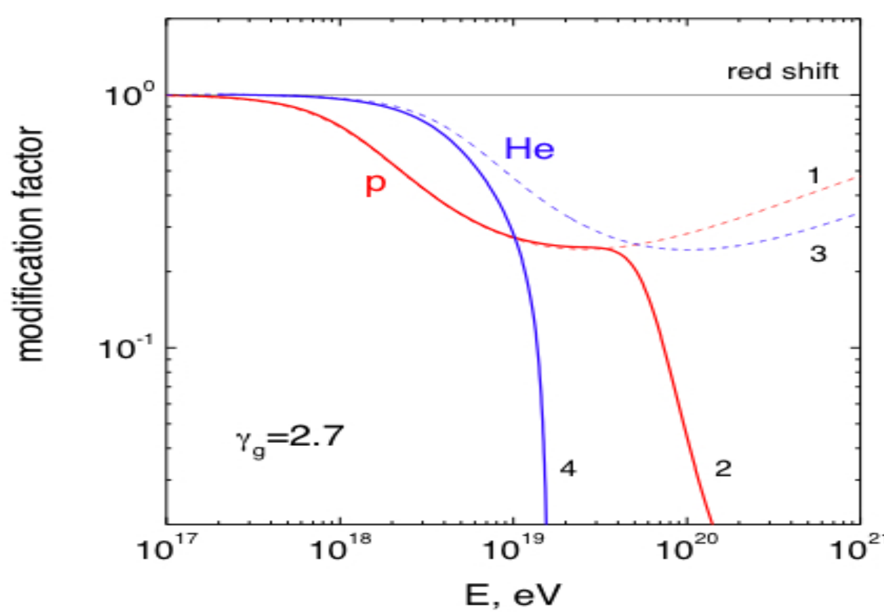
- ✓ the injection spectrum has $\gamma < 2.4$
- ✓ heavy nuclei fraction injected $E>10^{18}$ eV larger than 15%

(primordial He has $n_{He}/n_H \approx 0.08$)

Berezinsky et al. (2004) Allard et al. (2005) RA et al. (2006)



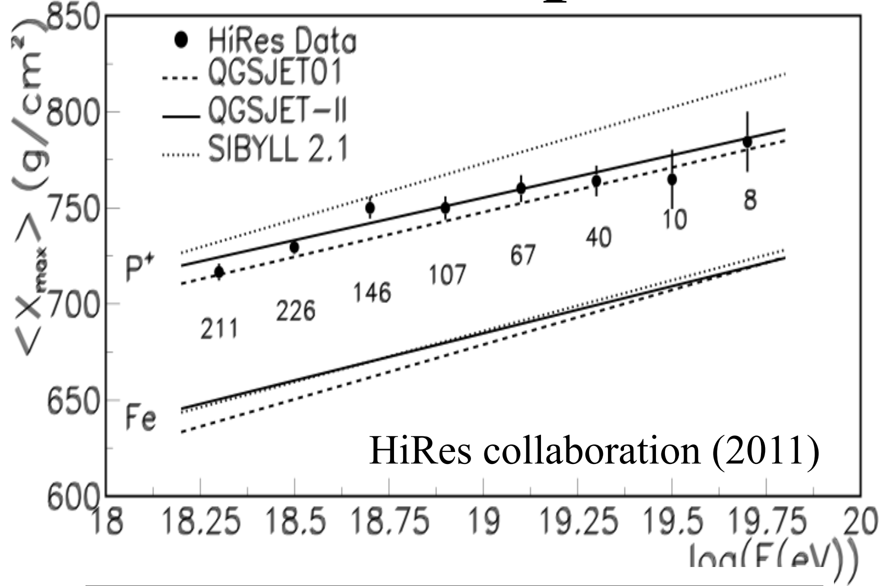


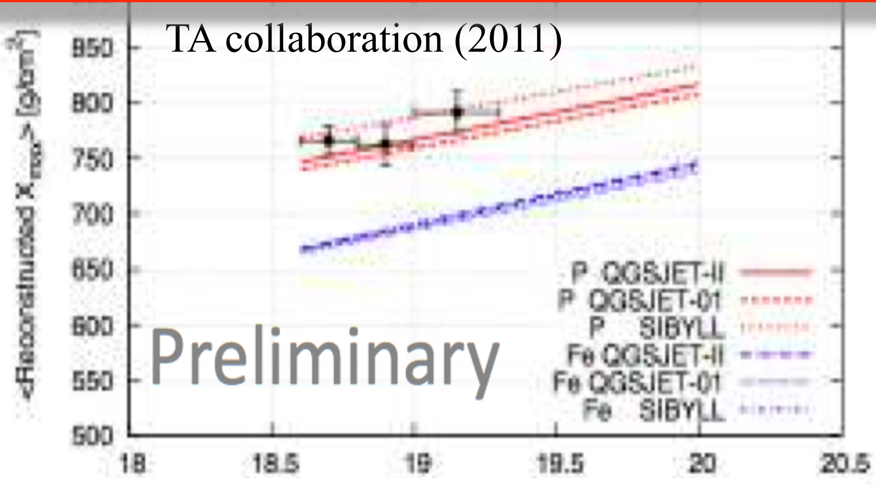


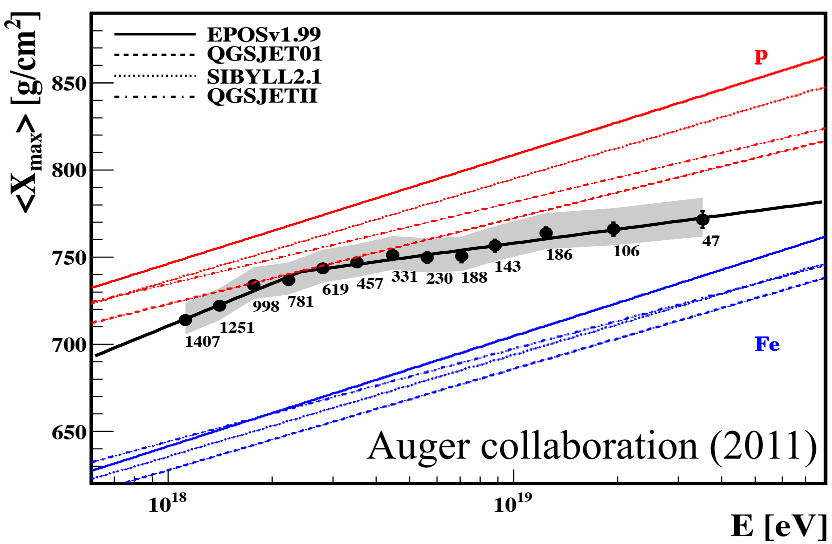
RA, Berezinsky, Grigorieva (2008)

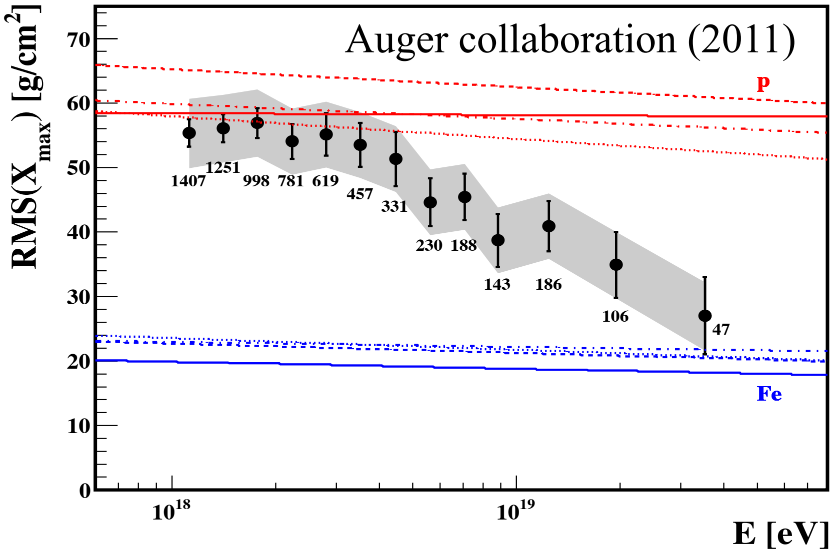
Chemical Composition

The resuts of HiRes and TA are consistent with a proton dominated flux









As discussed in the Grillo's talk, the latest Auger results on chemical composition show the tendency for a nuclei dominated flux at the highest energies.

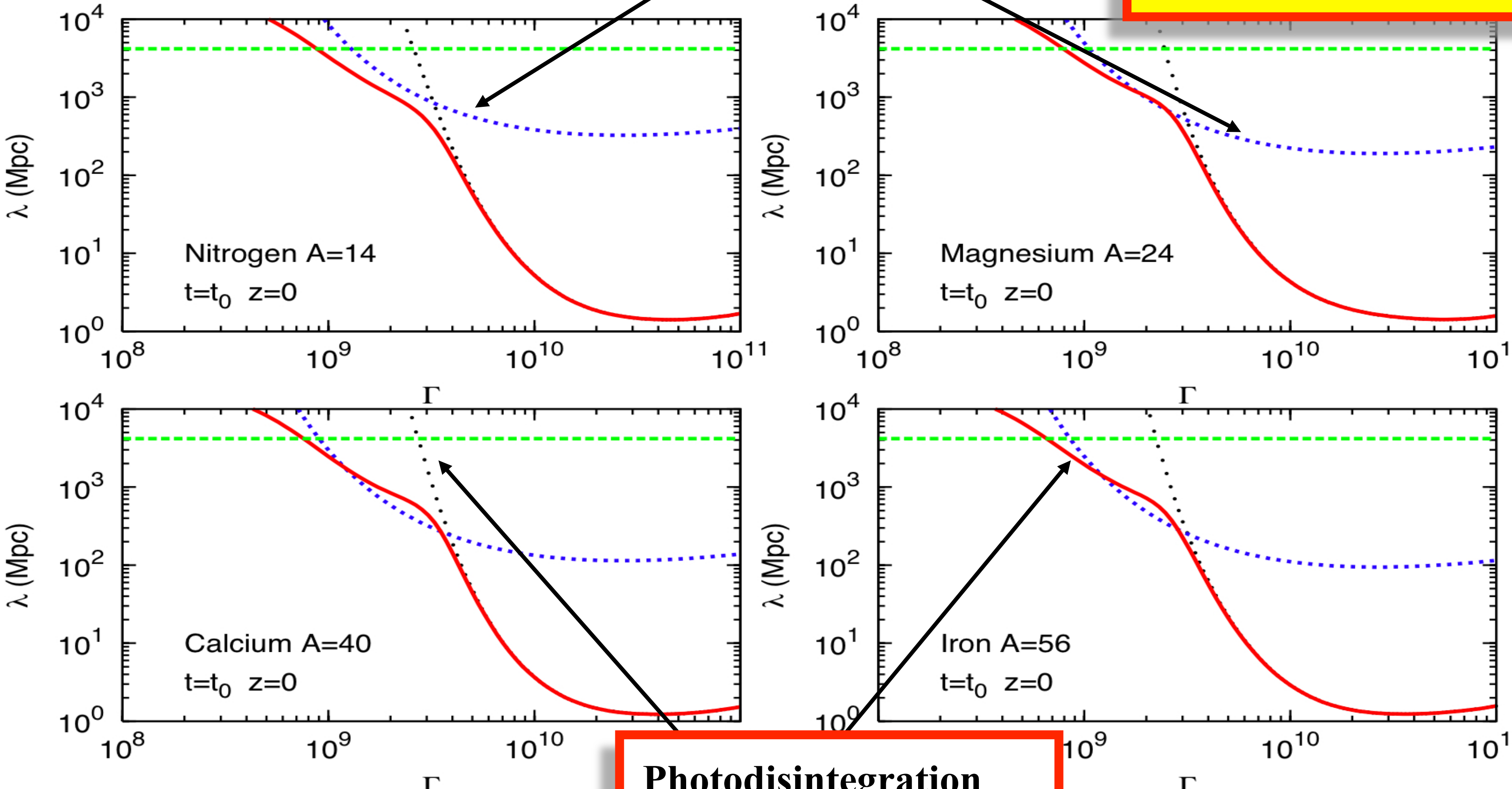
UHE Nuclei loss length

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)

UHE Nuclei kinetic equation

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

Lorentz factor variation rate

photo-disintegration "decay"

Injection: primary nuclei, secondary nucleons/nuclei

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

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

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

nuclei kinetic equation solution

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

Γ' solution of the energy losses equation

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

$$\frac{d\Gamma'}{d\Gamma} = \frac{1+z'}{1+z} exp\left[\frac{Z^2}{A}\int_z^{z'} dz'' \frac{(1+z'')^2}{H(z'')} \left(\frac{db_0^p(\tilde{\Gamma})}{d\tilde{\Gamma}}\right)_{\tilde{\Gamma}=(1+z'')\Gamma''}\right]$$

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

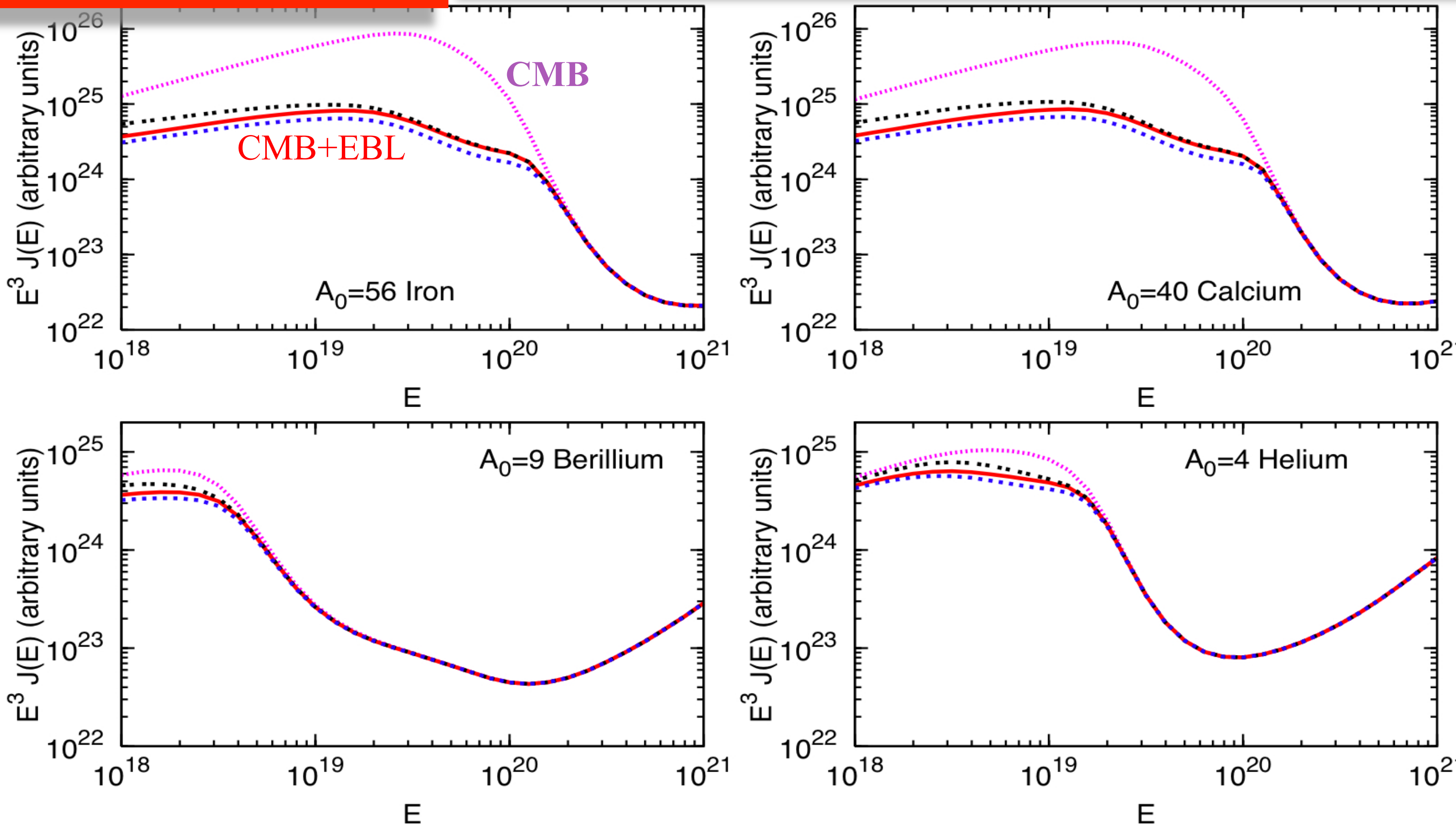
$$10^8 \leq \Gamma \leq 2 \times 10^9$$

Injection at thesource

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

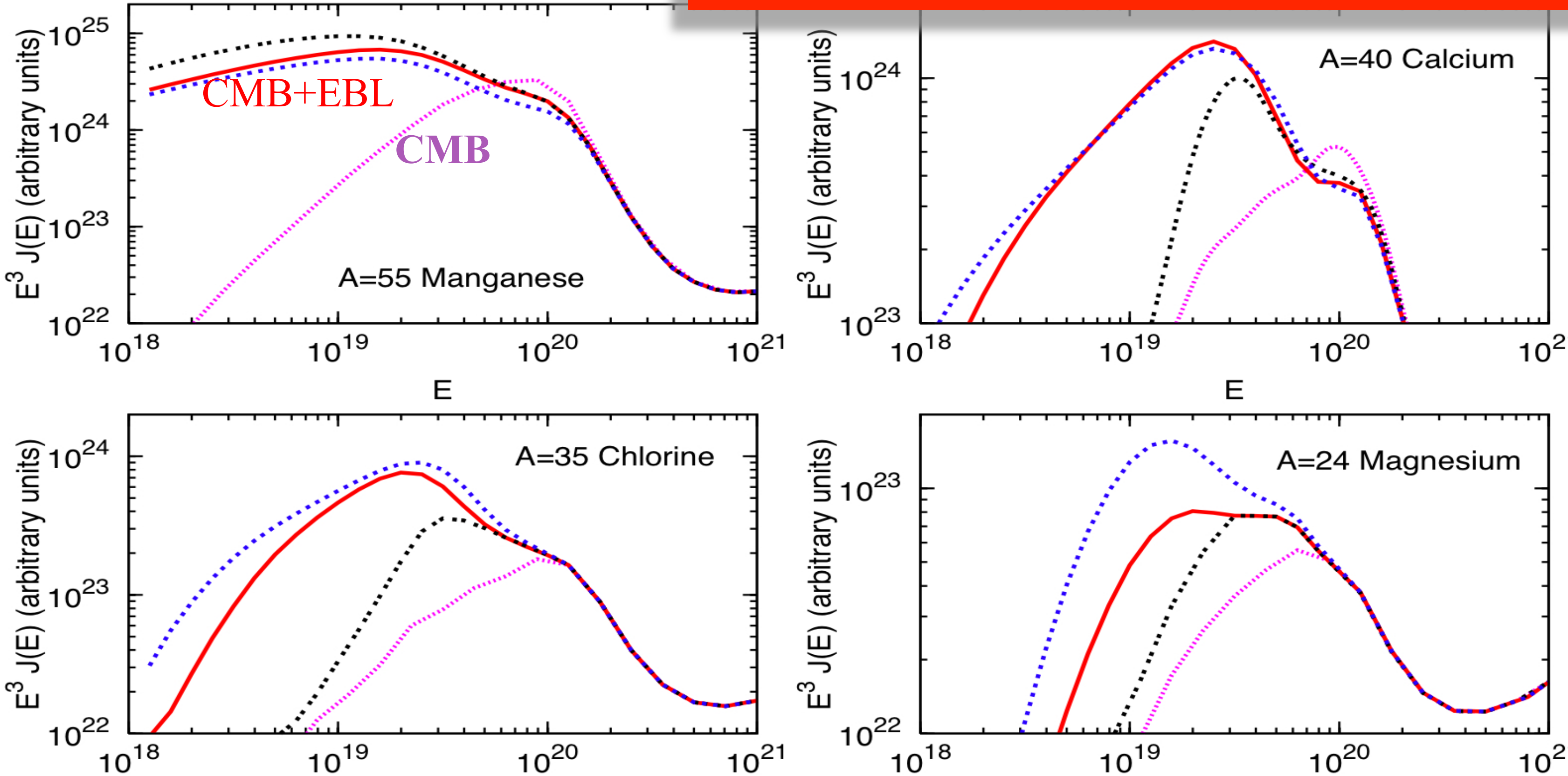
high A dependence on the EBL cosmological evolution

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

$A_0=56$ Iron $\gamma_g=2.3$



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).

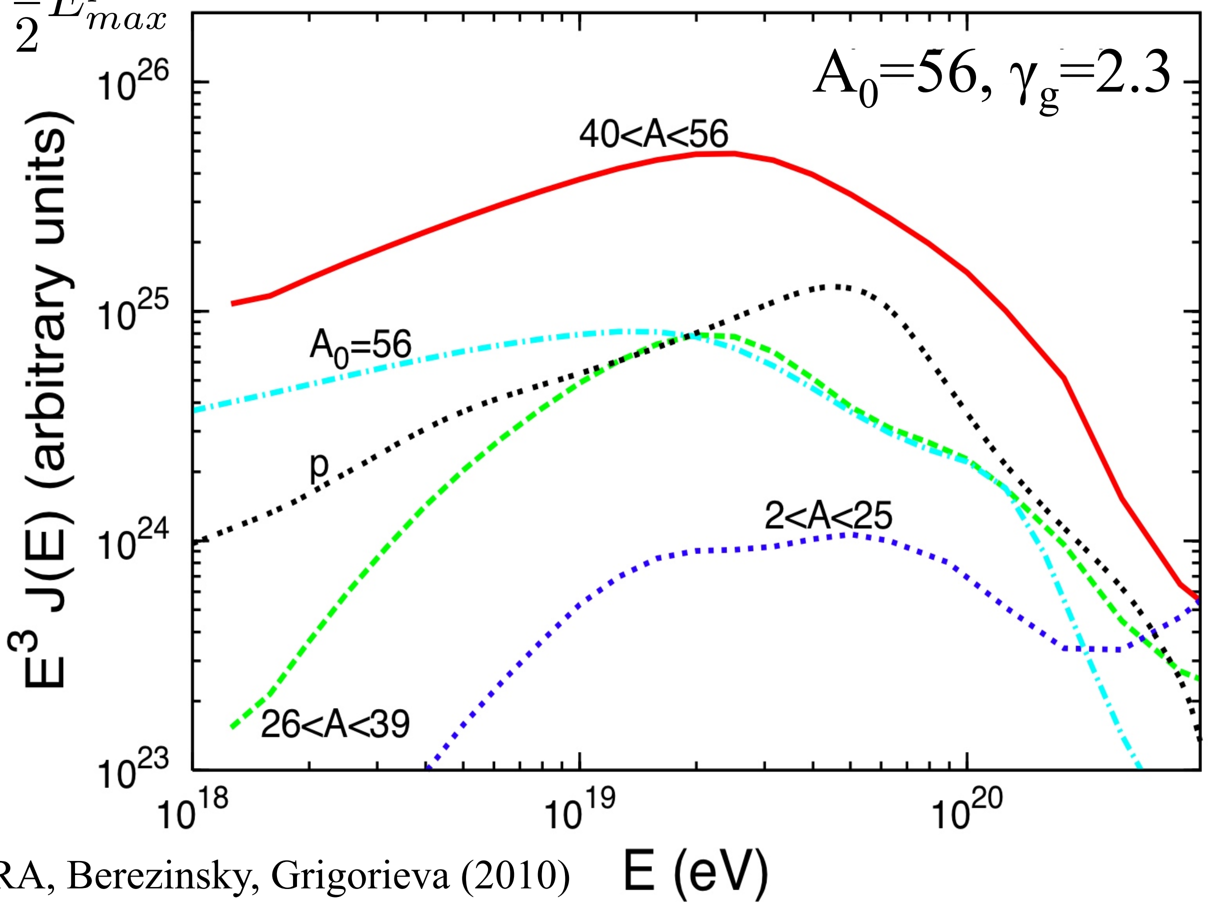
Caveat

If the maximum energy for protons is high enough ($E_{max}>10^{20}$ eV), 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.

$$E_{max}^{p,sec} = \frac{E_{max}^{A_0}}{A_0} = \frac{Z_0 E_{max}^{p}}{A_0} \simeq \frac{1}{2} E_{max}^{p}$$

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

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



RA, Berezinsky, Grigorieva (2010)

Nuclei GZK-like behavior

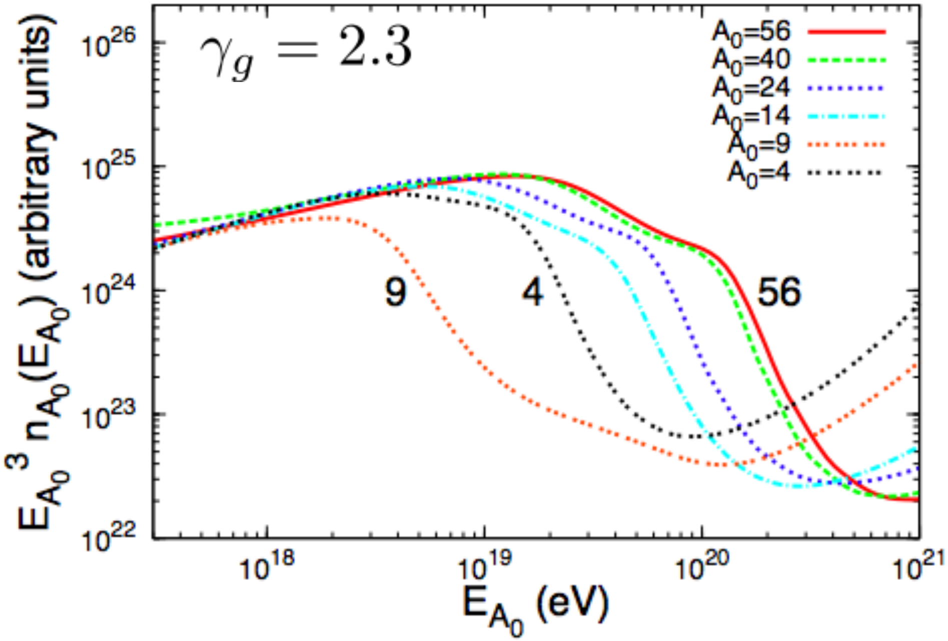
Critical Lorentz factor $\Gamma_c(A,\Gamma,t)$

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

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

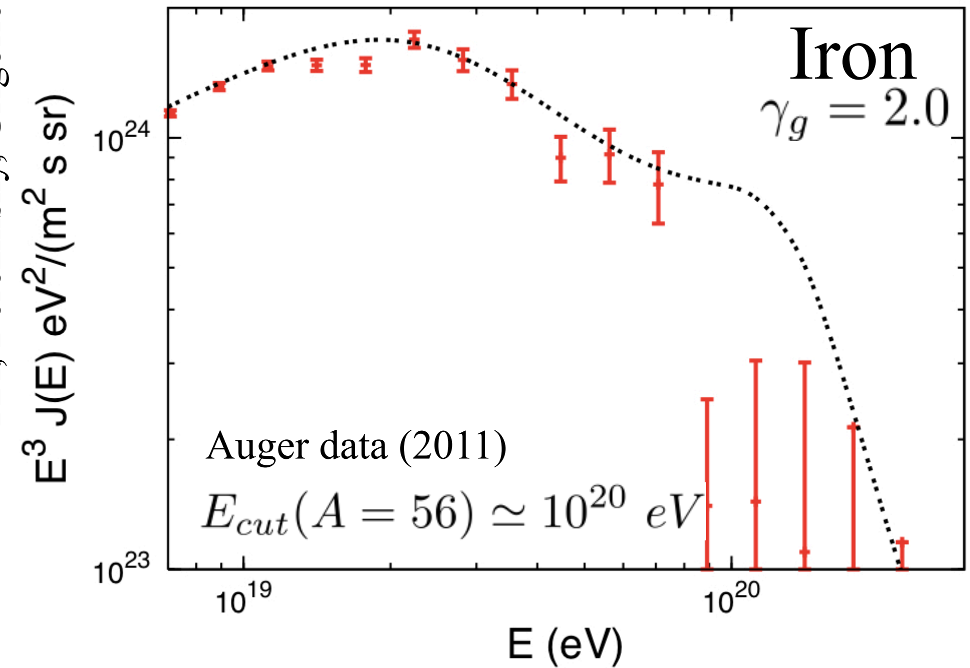
$$\Gamma_c\simeq 2\times 10^9$$

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



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

RA, Berezinsky, Grigorieva (2011)

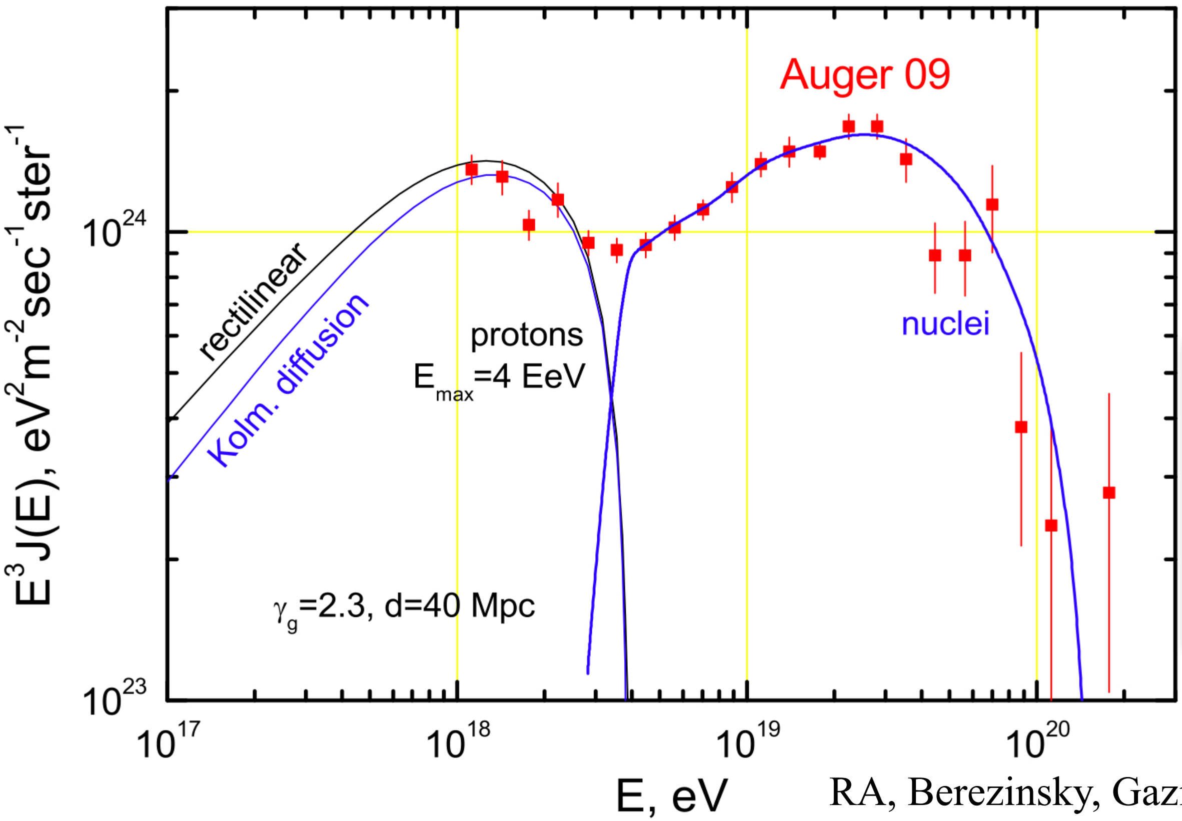


in this case we could not ascribe the Auger observed high energy suppression to a proton interaction effect (Greisen Zatsepin Kuzmin)

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 (2010)

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

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

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:

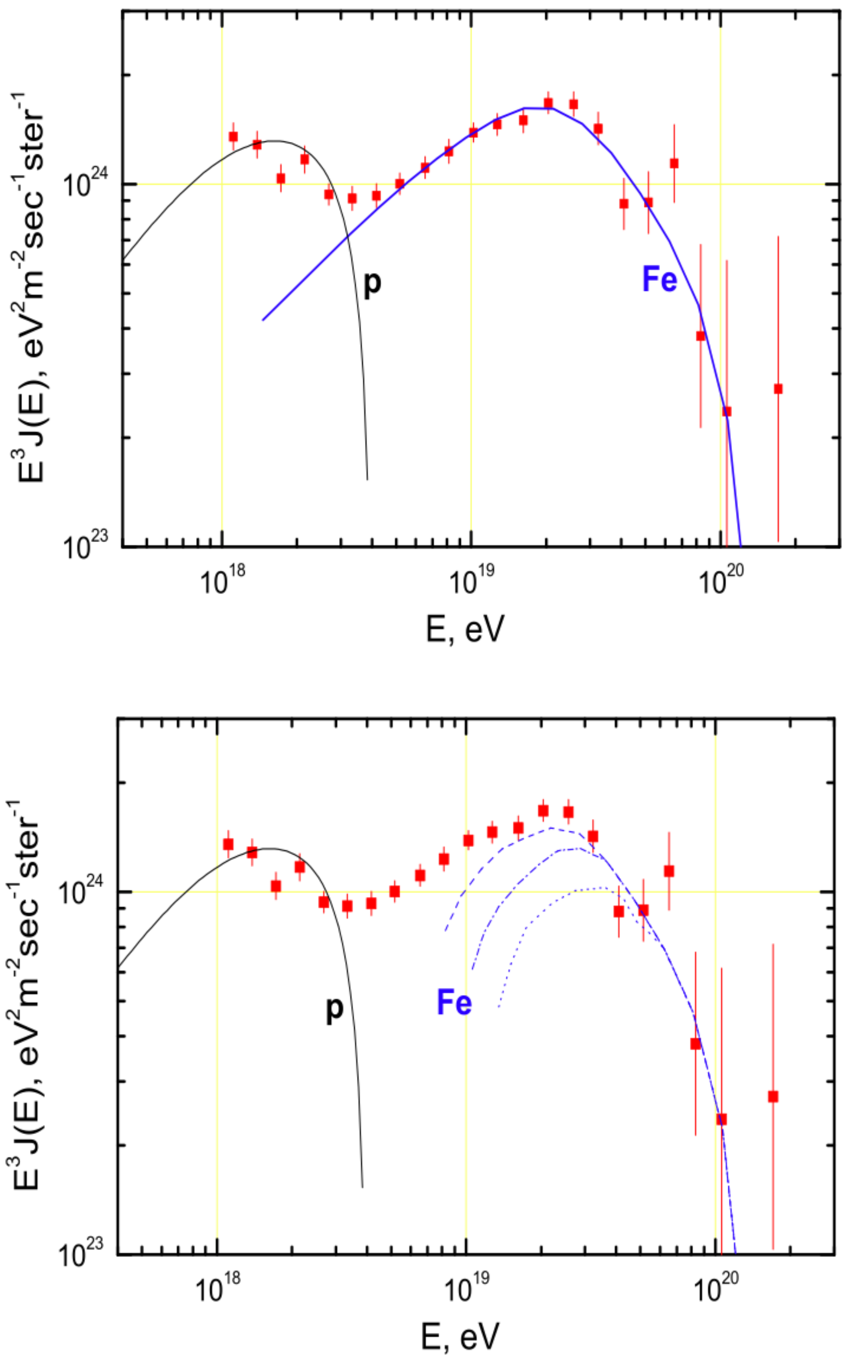
✓ **no correlation with sources**

The μG galactic magnetic field substantially deviates particles trajectories:

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

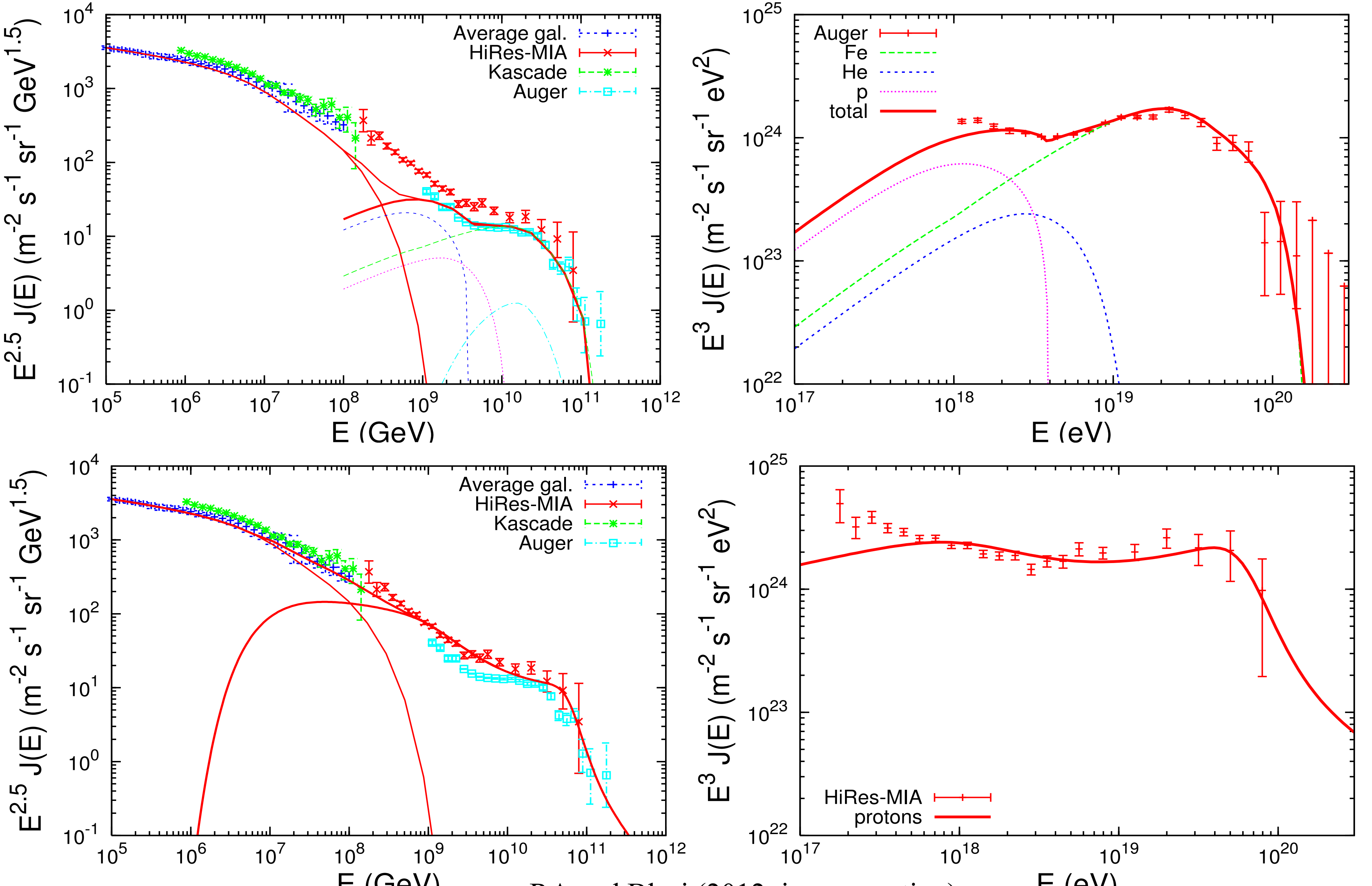
✓ **no production of ν and γ**

Nuclei interacting with CMB and EBL just photo-disintegrate no production of secondary neutrinos and gamma-rays.



RA, Berezinsky, Gazizov (2010)

Galactic and ExtraGalactic CR



RA and Blasi (2012, in preparation)

Conclusions

If compared with theoretical models a very puzzling scenario emerges from HiRes and Auger data:

HiRes

- ✓Protons dominate the UHECR flux
- ✓Transition Galactic/ExtraGalactic CR at 10^{18} eV
- ✓Steep injection spectra at the sources $\gamma_g > 2.5$
- ✓High maximum energy at the source $E_{max} > 10^{20}$ eV
- ✓Correlation with sources (UHECR astronomy is feasible)
- ✓Production of secondary ν and γ

Auger

- ✓Heavy nuclei dominate the UHECR flux at $E > 4 \times 10^{18}$ eV
- ✓Flat injection spectra at the sources $\gamma_g < 2.3$
- ✓Low maximum energy for protons at the source $E_{max} < 10^{19}$ eV
- ✓No correlation with sources (deflections due to galactic magnetic field)
- ✓No production of ν and γ only secondary nuclei/nucleons (photo-disintegration)

the experimental observation of the UHECR chemical composition at the highest energies has a paramount importance in choosing among the two alternative scenarios depicted.

The solution of this puzzle is fundamental in establishing the future directions of this field of research. Observations at the highest energies are still affected by poor statistics and a renewed experimental effort is needed in order to choose among the two alternatives presented here.

The analytical computation scheme based on the kinetic equation is a unique and fast powerful tool to interpret the experimental observations, unveiling the nature of UHECR and their sources.

Thank you