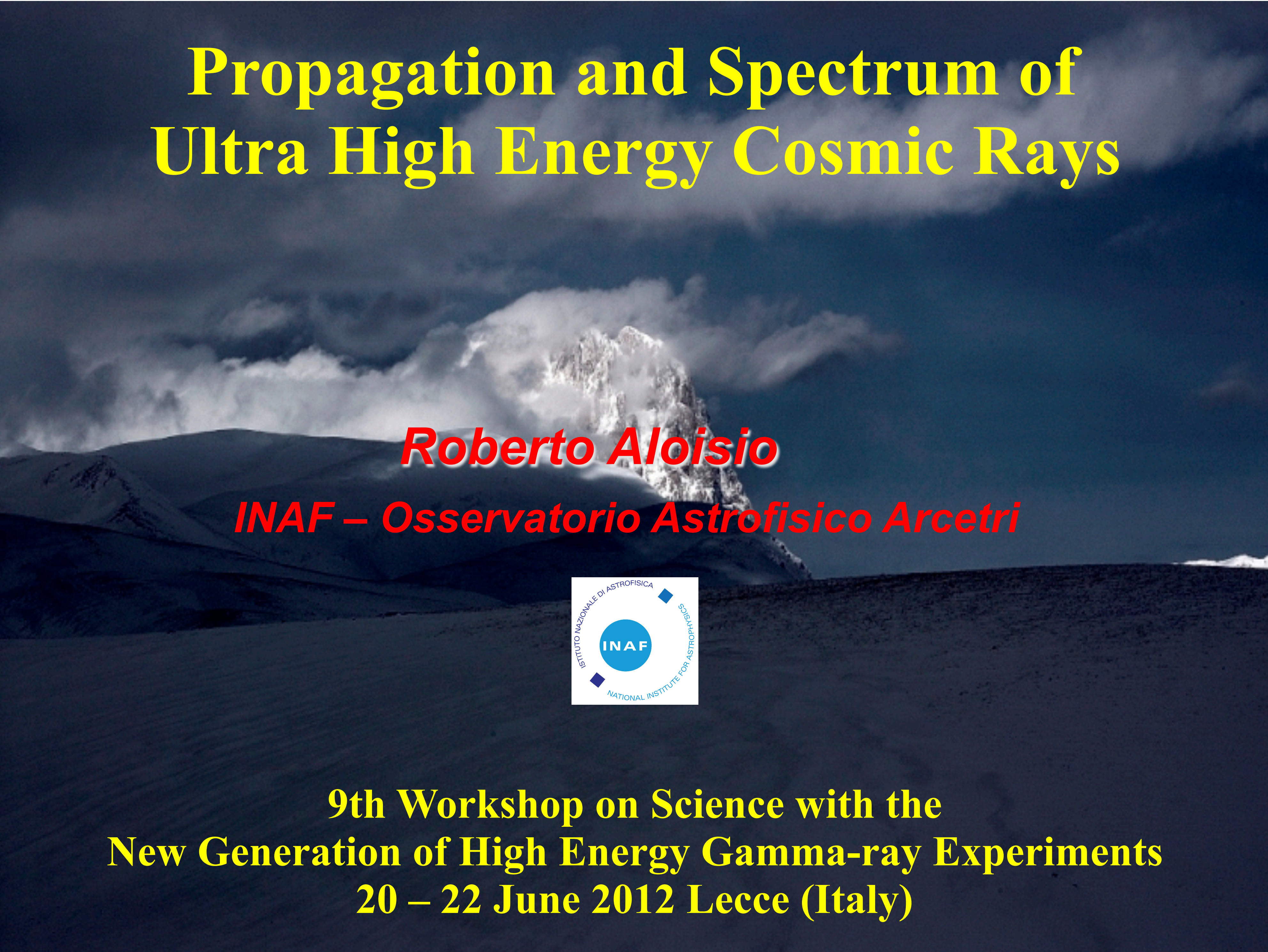


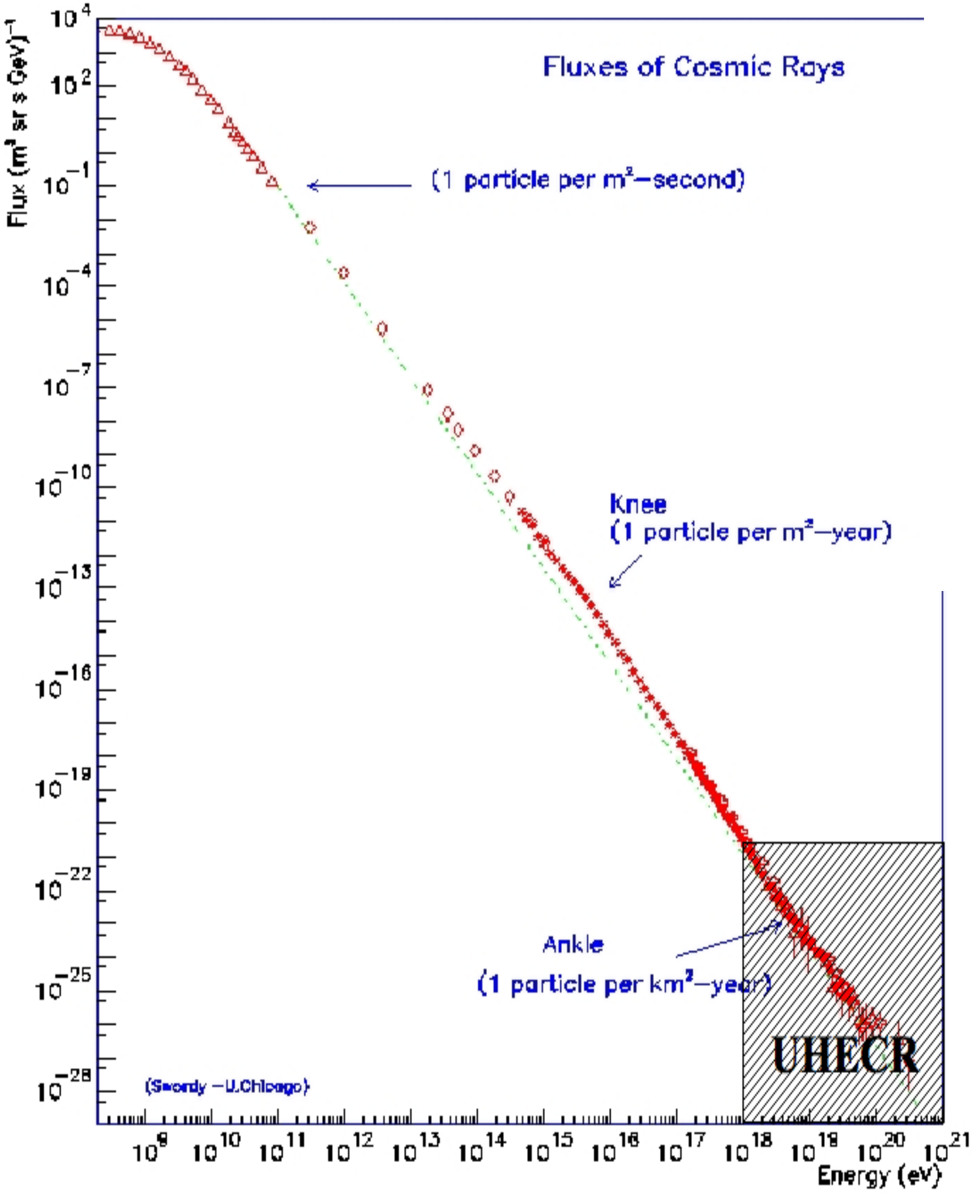
Propagation and Spectrum of Ultra High Energy Cosmic Rays

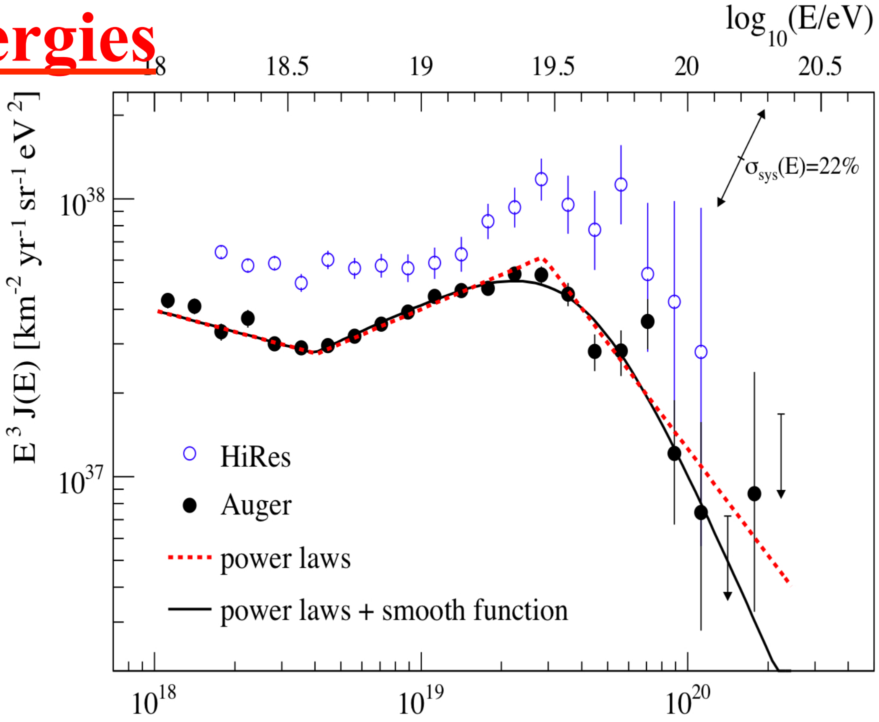
Roberto Aloisio

INAF – Osservatorio Astrofisico Arcetri

9th Workshop on Science with the
New Generation of High Energy Gamma-ray Experiments
20 – 22 June 2012 Lecce (Italy)

CR spectrum at Ultra High Energies

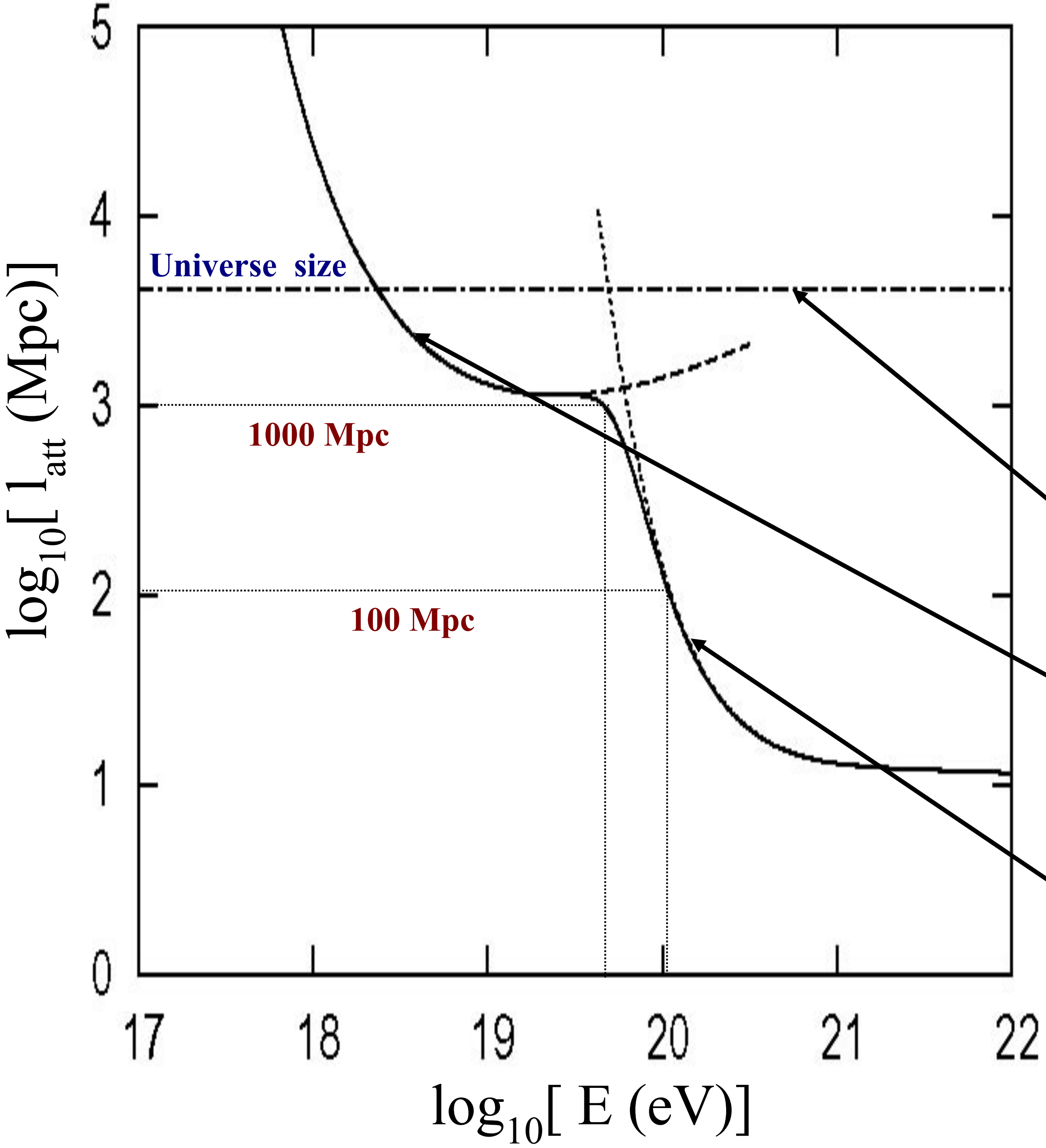


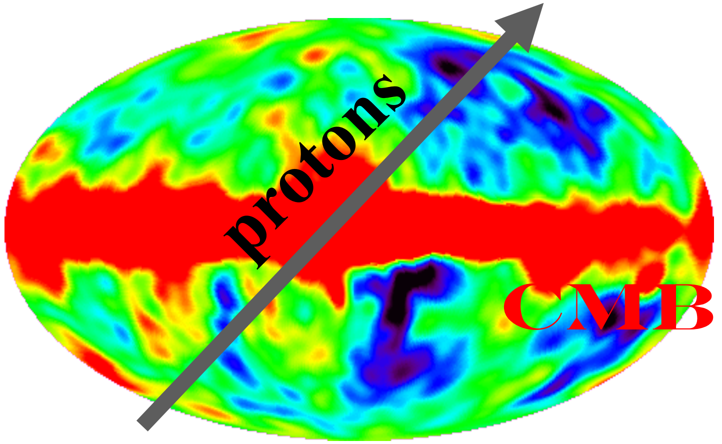


The observations on Earth are the result of the acceleration at the source (injection) and the propagation of particles in the background radiation (CMB & EBL) and possible intergalactic magnetic fields (IMF)

- ✓ **Spectrum**
- ✓ **Chemical Composition**
- ✓ **Anisotropy** (astronomy?)

UHE Proton loss length





proton propagation is affected only by CMB

Adiabatic losses
Universe expansion

Pair production

$$p\,\gamma \rightarrow p\, e^{+} e^{-}$$

Photopion production

$$p\,\gamma \rightarrow p\,\pi^{0}$$
$$\rightarrow n\,\pi^{+}$$

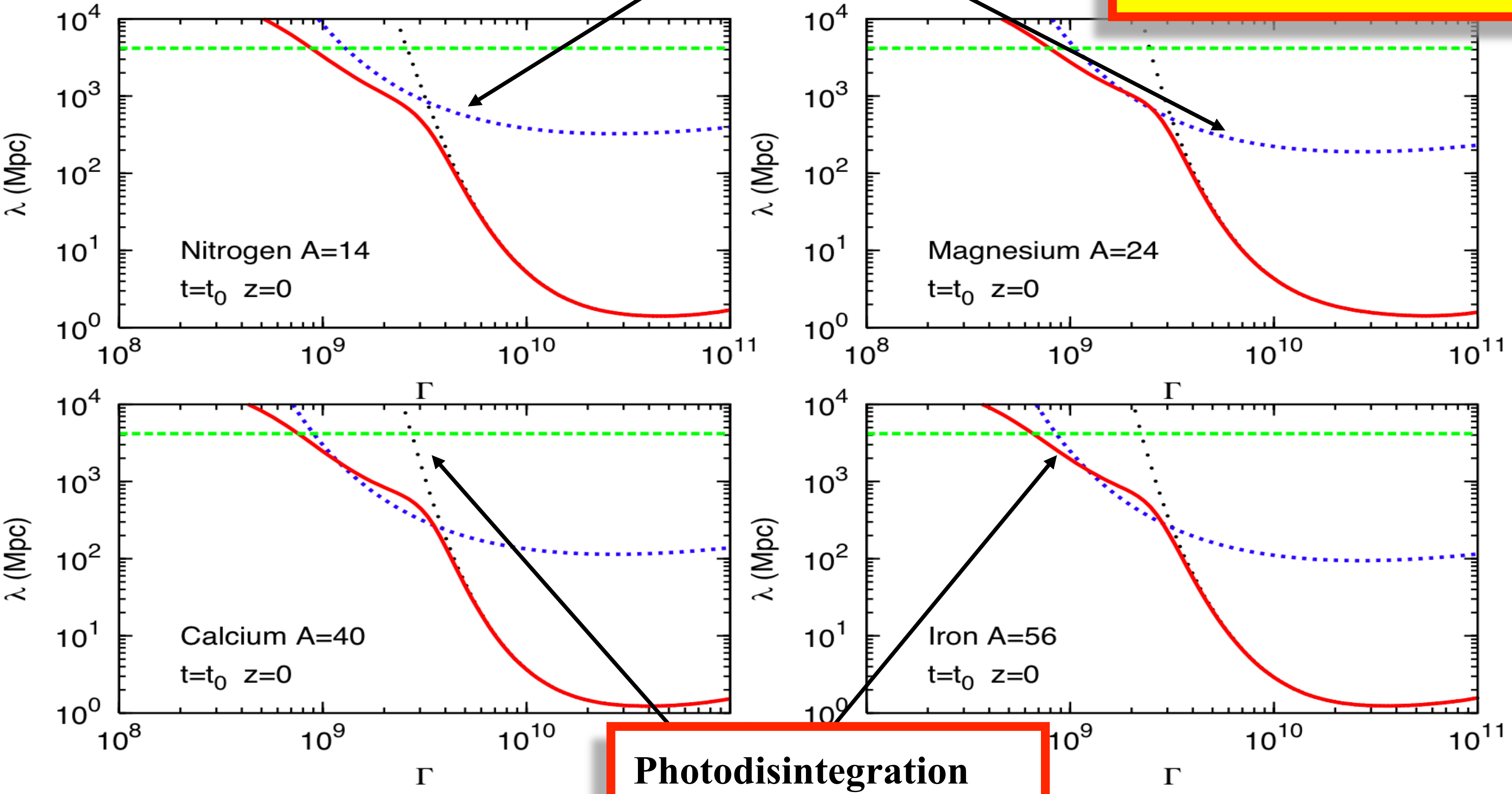
UHE Nuclei loss length

Pair production (CMB)

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

EBL effect only for photo-disintegration in the range

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



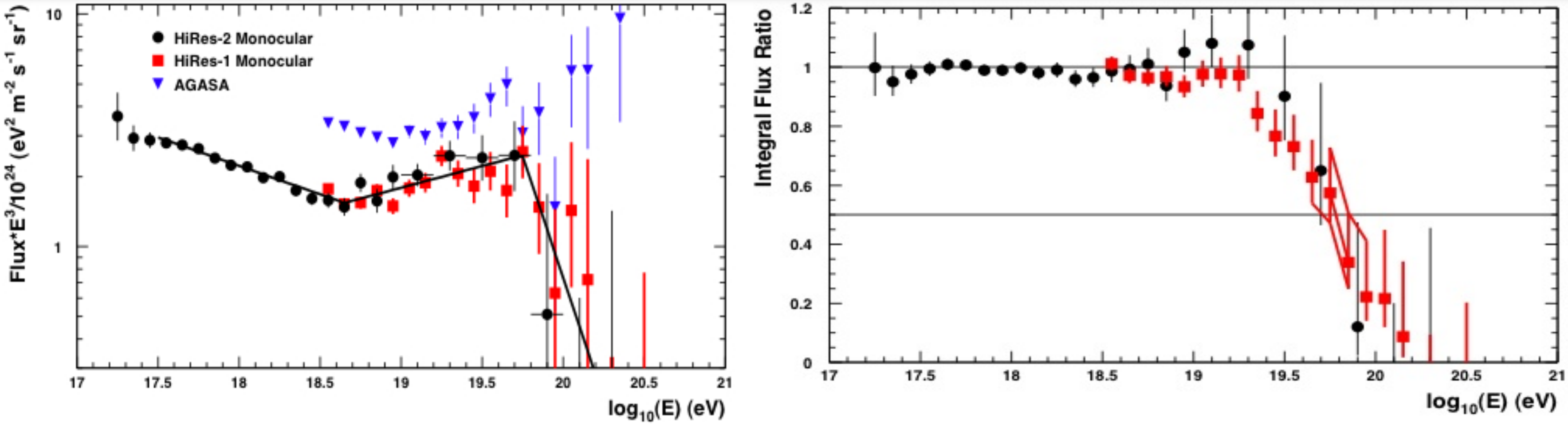
Photodisintegration (CMB+IR/V/UV)

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

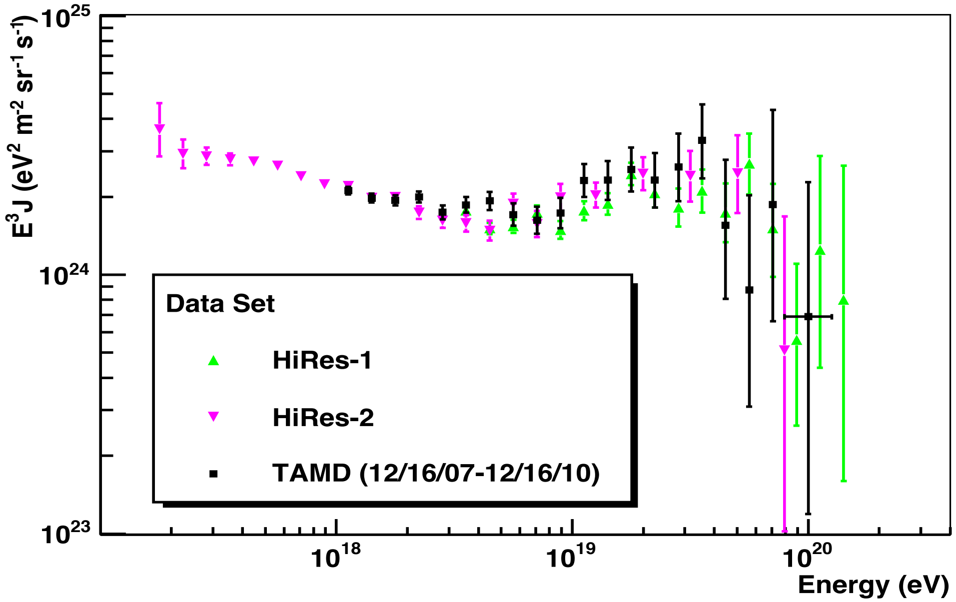
RA, Berezinsky, Grigorieva (2010)

HiRes & Telescope Array

The last HiReS analysis confirms the expected Greisen Zatzepin Kuzmin suppression for protons with $E_{1/2}=10^{19.73\pm0.07}$ eV in fairly good agreement with the theoretically predicted value $E_{1/2}=10^{19.72}$ eV.



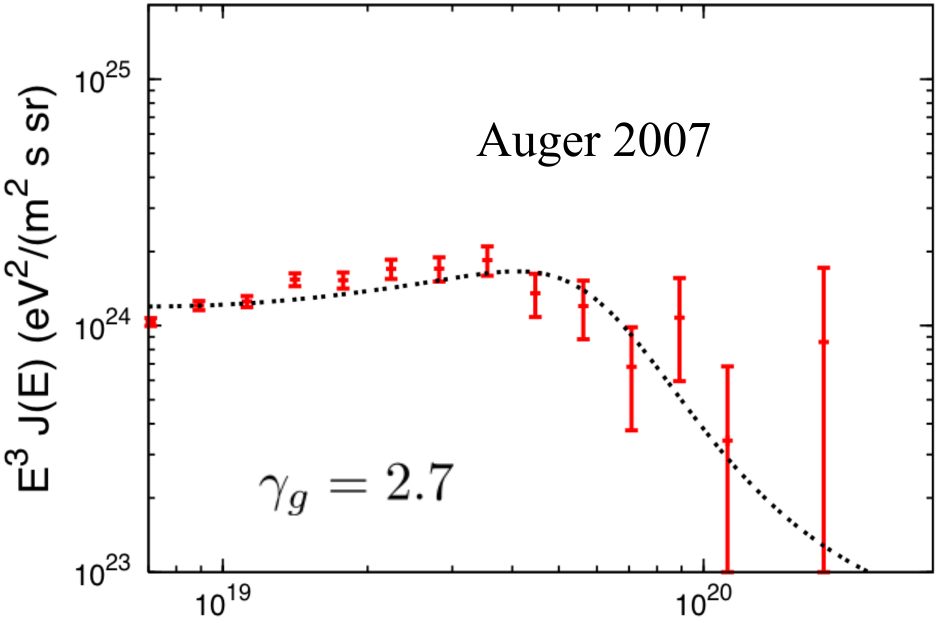
HiRes collaboration (2007)

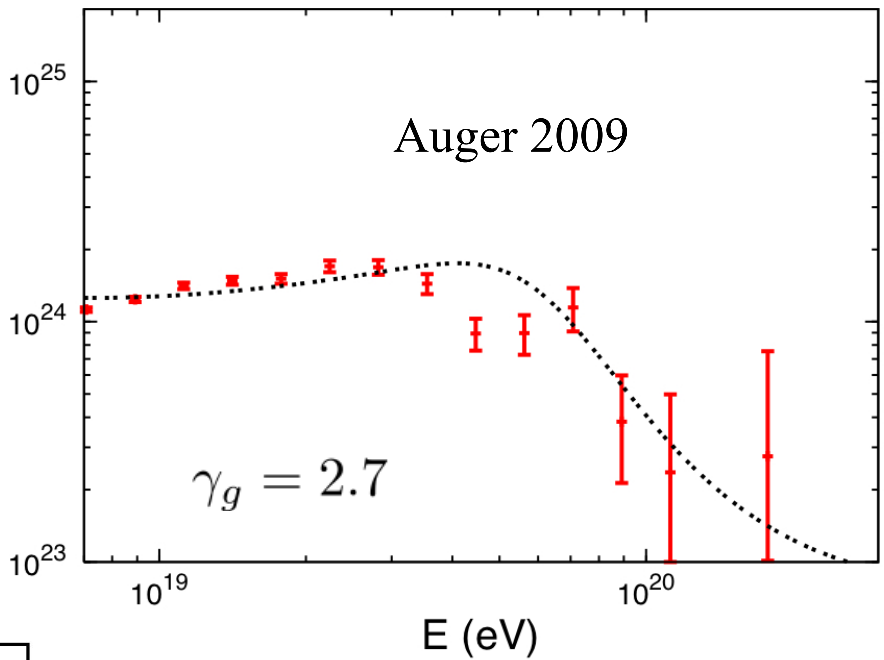


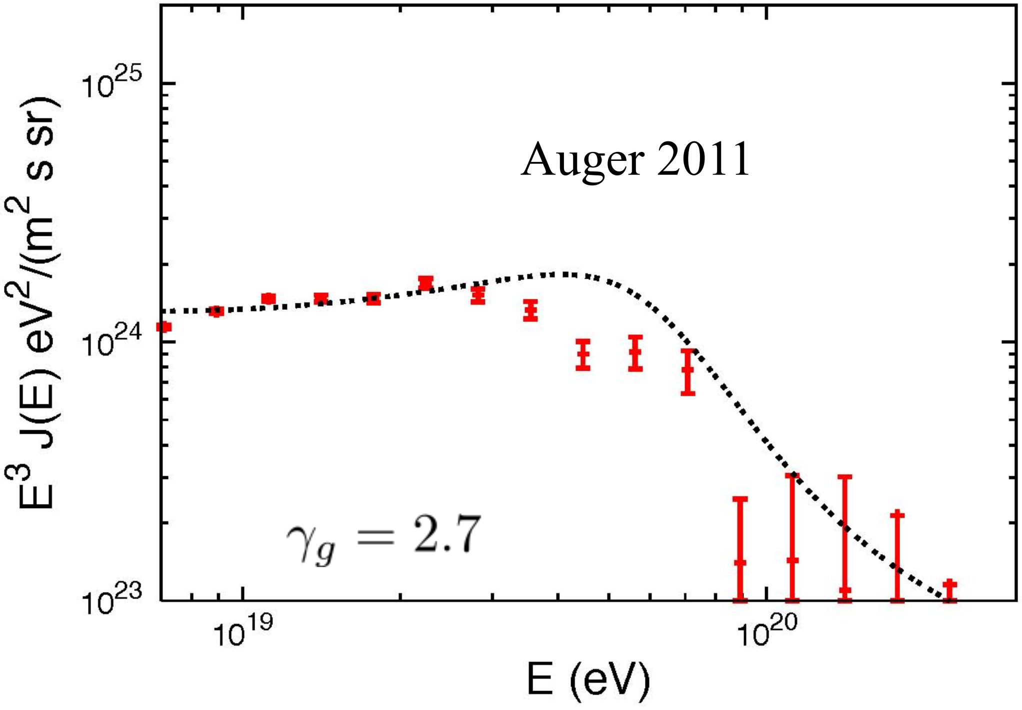
TA collaboration (2012)

The new Telescope Array results, in agreement with HiReS, show a suppression in the spectrum compatible with the GZK feature

Auger Observatory







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 weakens the agreement with the expected protons GZK behavior (hints of an heavier composition at the highest energies? See later.)

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>5×10^{19} eV.

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

Uniform distribution of sources

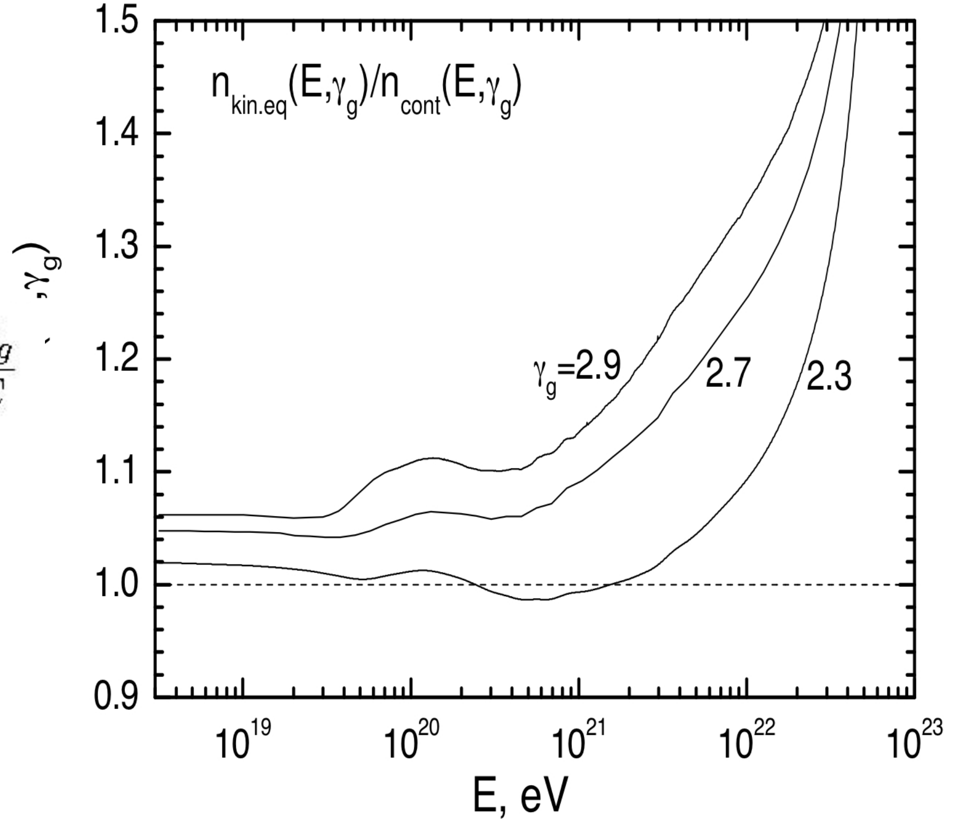
the UHECR sources are continuously distributed with a density n_s.

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

Discrete sources

the UHECR sources are discretely distributed with a spacing d.

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



Berezinsky, Grigorieva, Gazizov (2006)

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

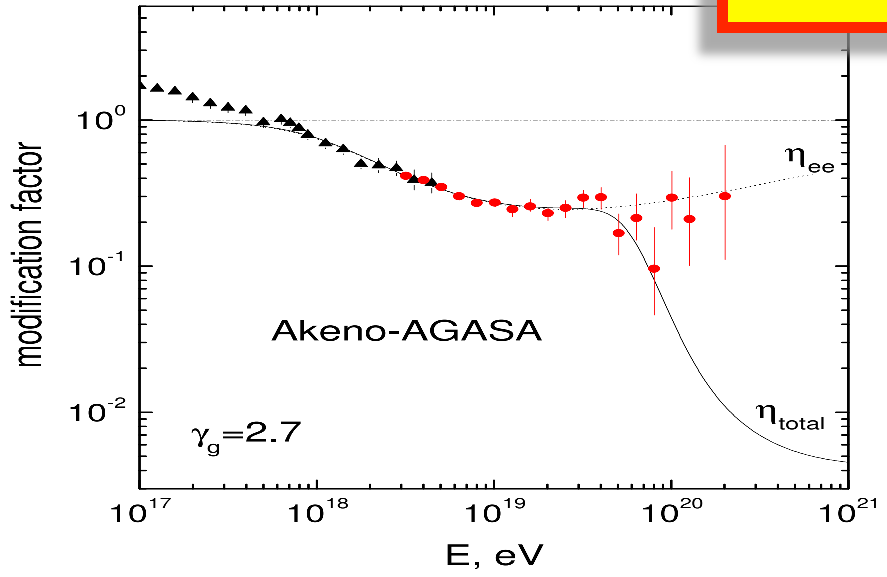
$$Q_{inj} = \frac{L_p(\gamma-2)}{E_C^2}\left(\frac{E}{E_C}\right)^{-\gamma}$$

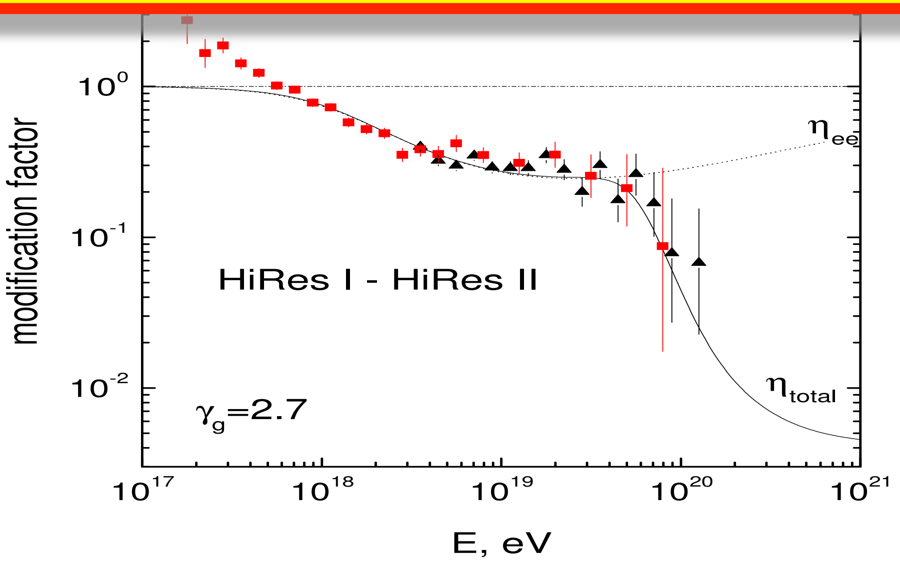
$\gamma > 2$ injection power law

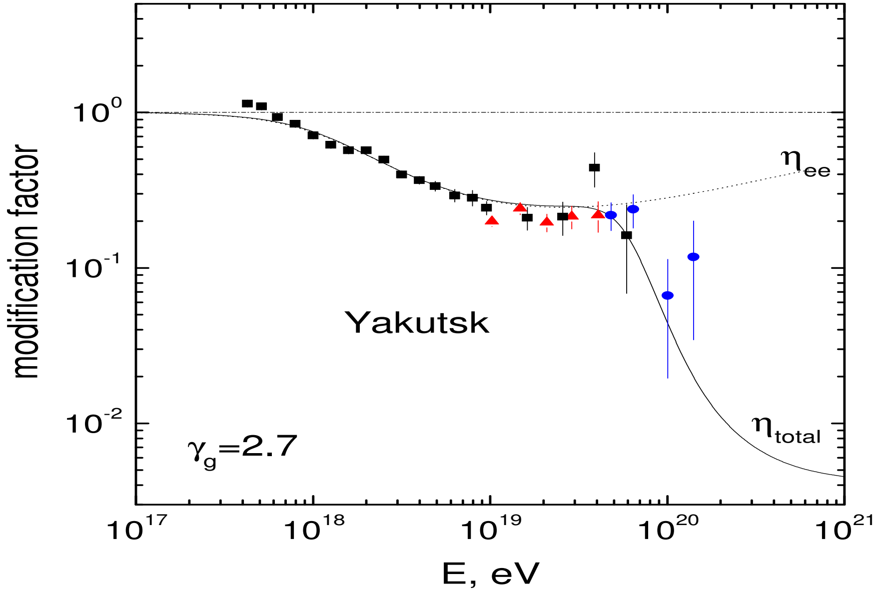
$J_p = L_p\, n_S$ source emissivity

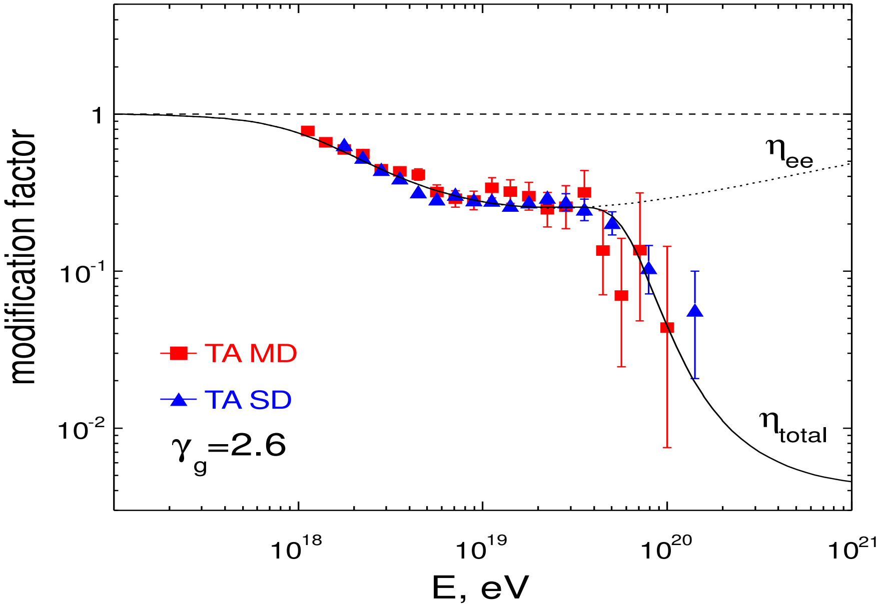
Dip Model

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.





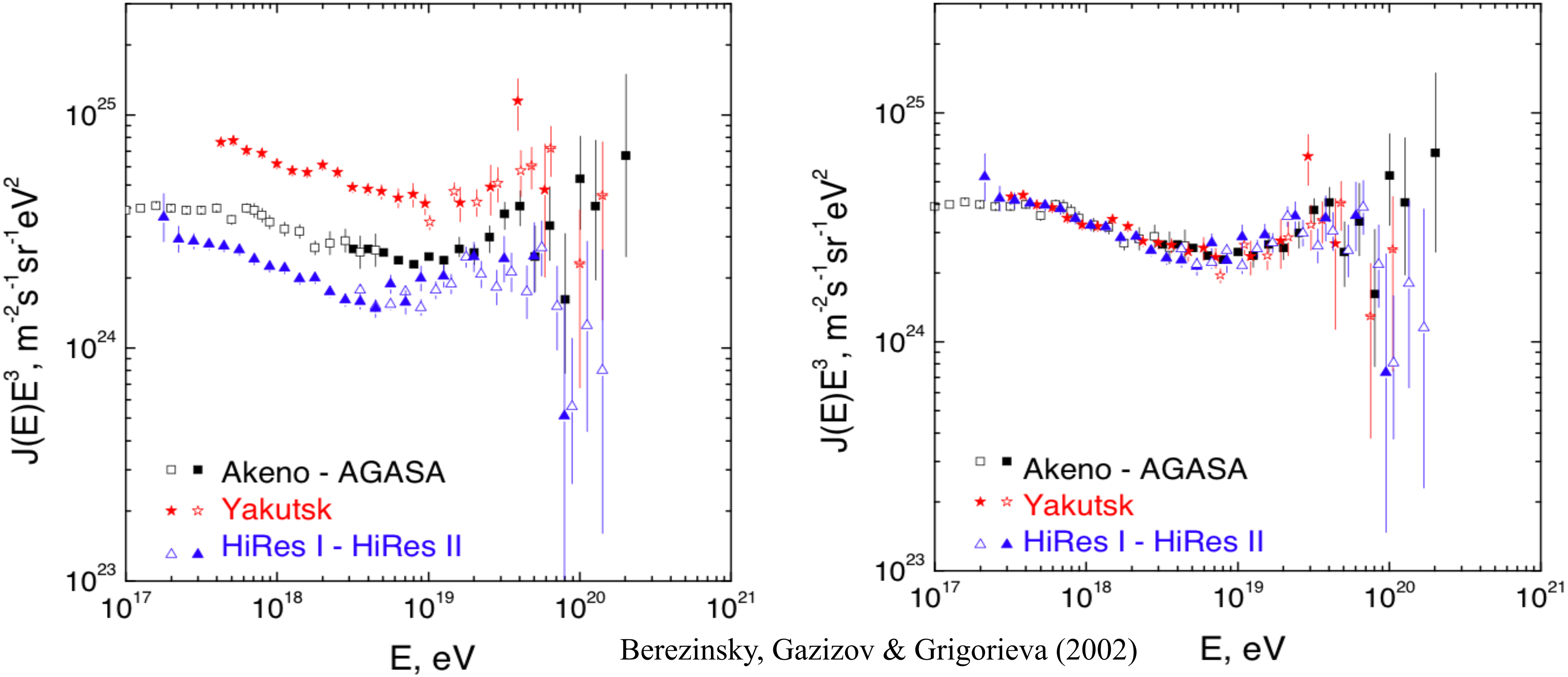




RA et al. (2007-2012)- Berezinsky et al (2002)

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 $E \longrightarrow \lambda E$

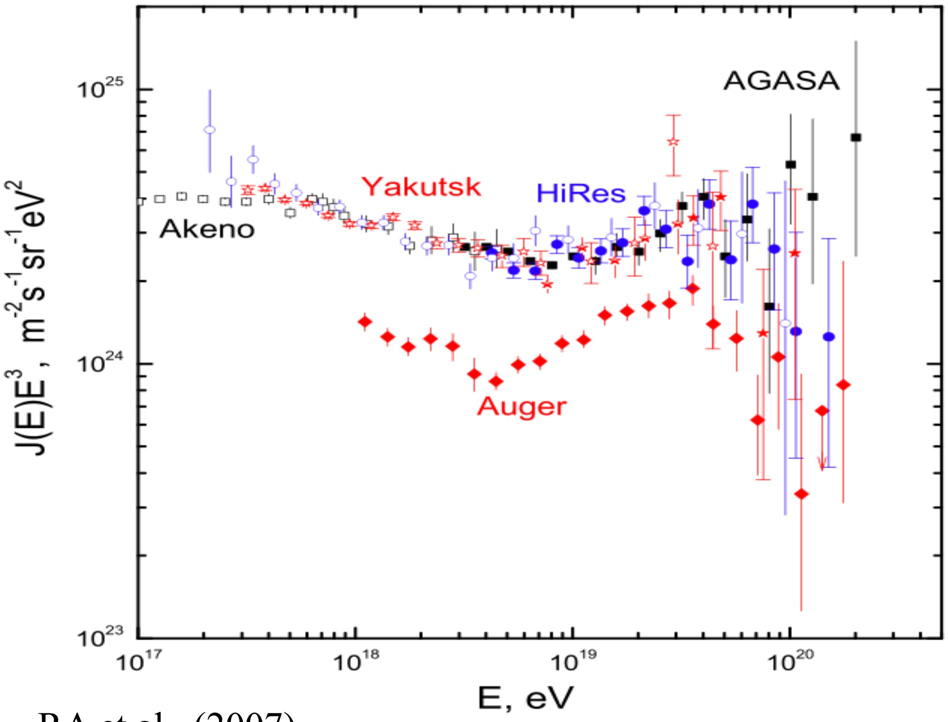
(with λ fixed by minimum χ^2)

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

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

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

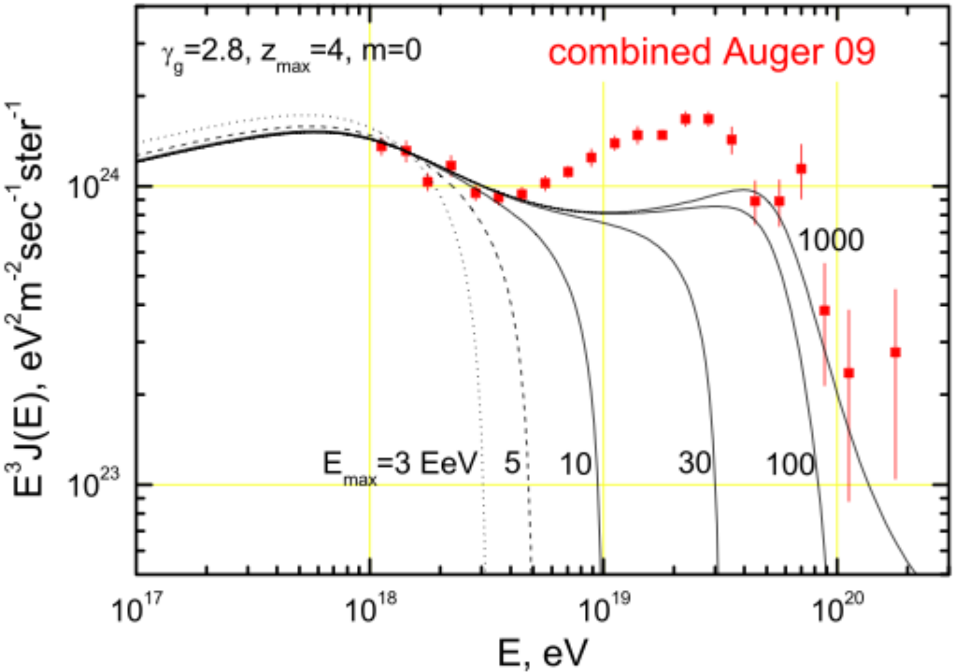
The very good agreement obtained among different measurements (apart Auger) calibrating the energy by the dip represents a strong indication in favor of an UHECR proton dominated spectrum



RA et al. (2007)

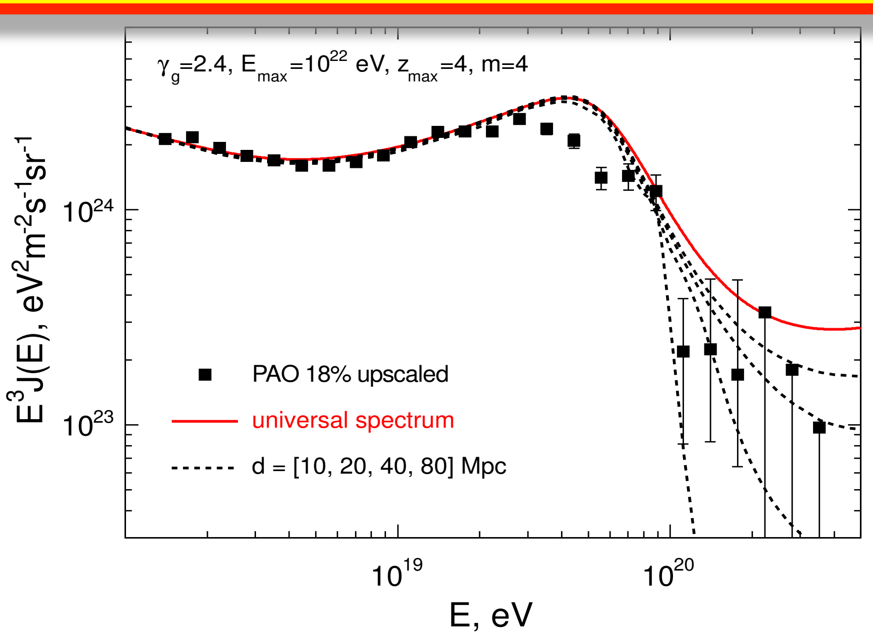
the calibration of 2007 Auger data requires a large energy shift of about 50% (outside the experimental systematics) signal of deviation from the dip behavior

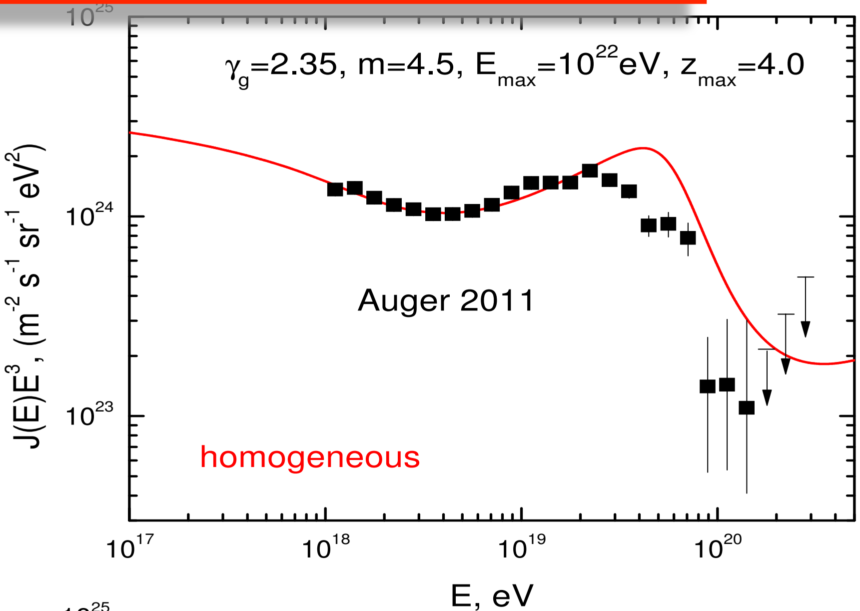
If compared with 2009 and 2011 Auger data the agreement with the dip behavior becomes worse.

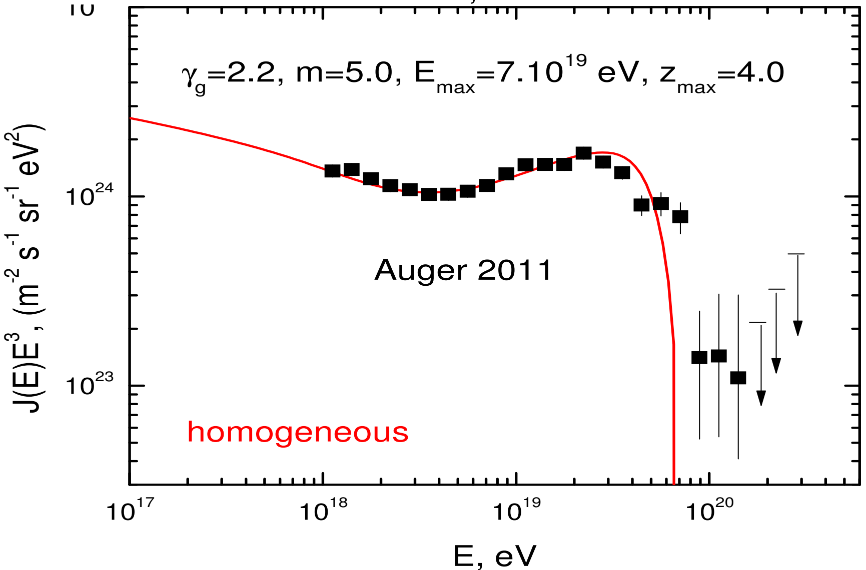


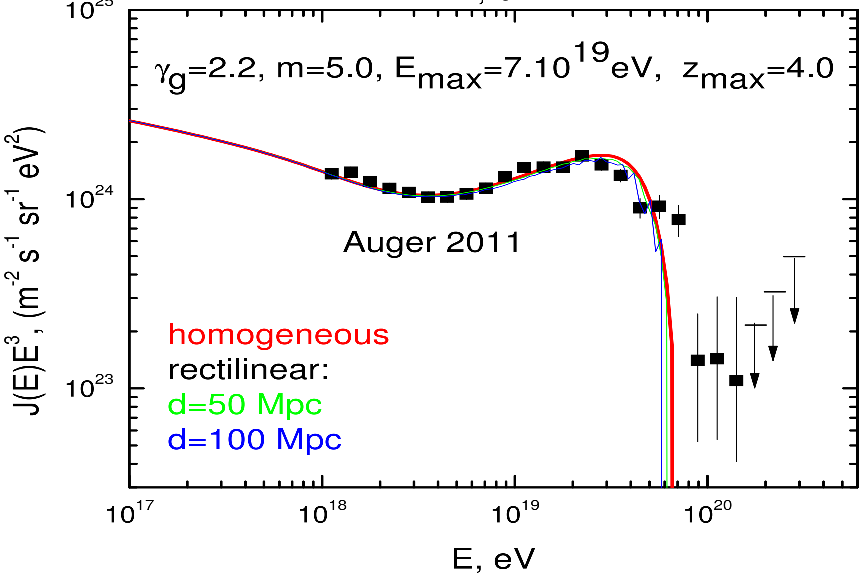
RA, Berezinsky, Gazizov (2011)

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. Signal of heavy nuclei. Failure of the dip model.









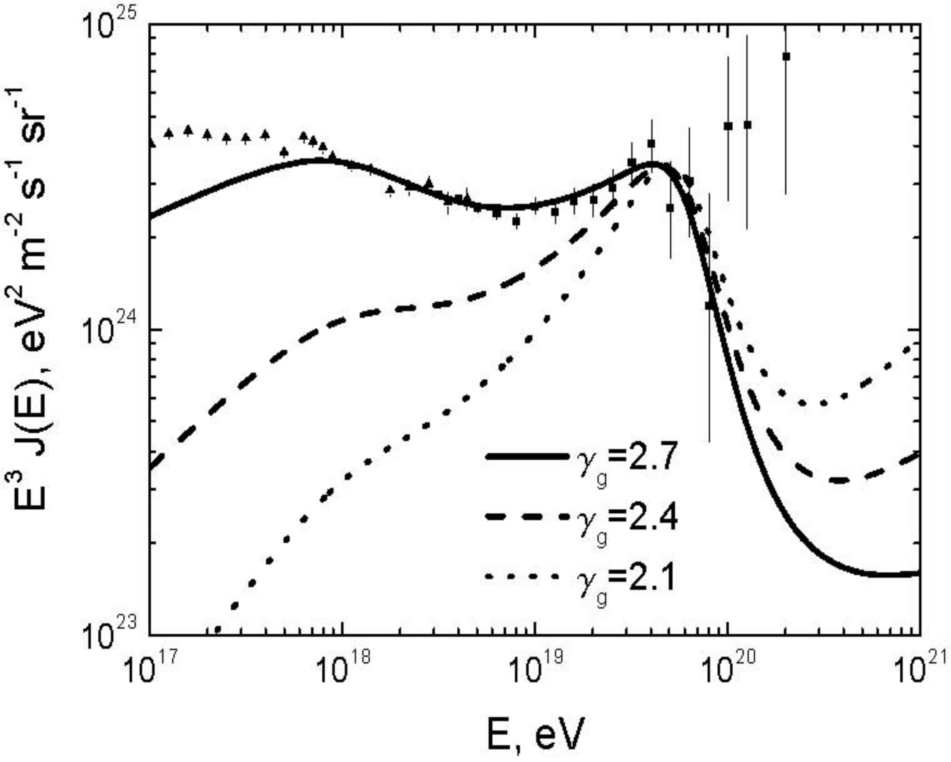
Caveats

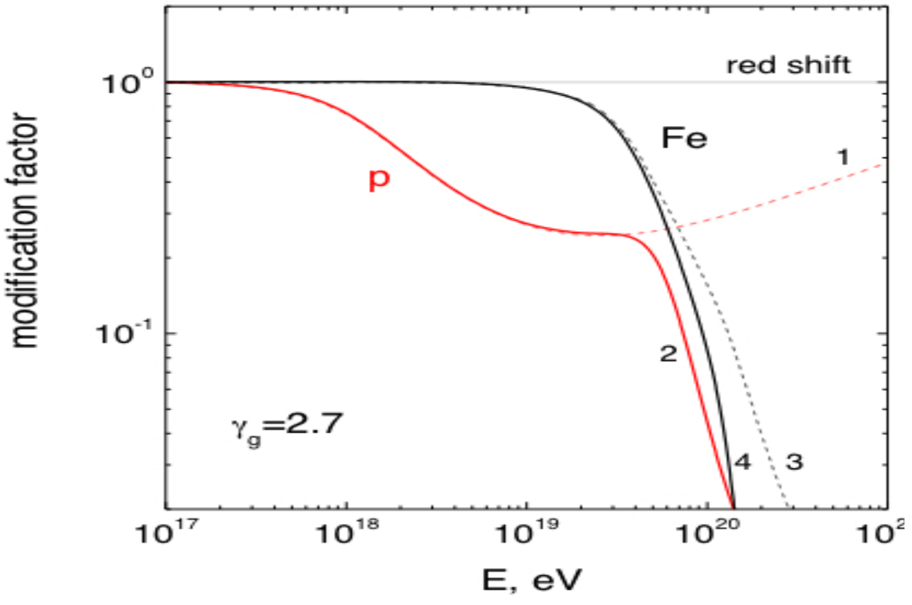
The interpretation of the observed spectrum in terms of protons pair-production losses FAILS if:

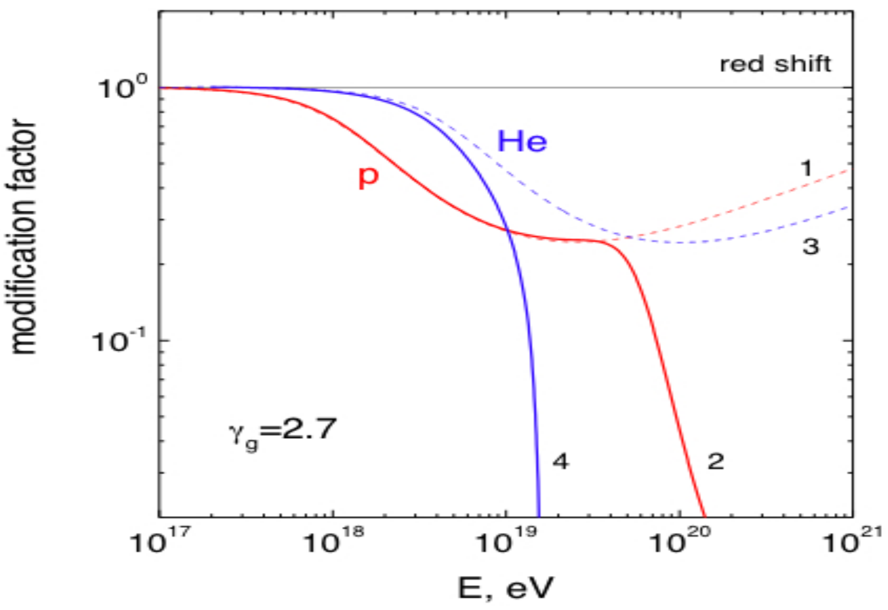
- ✓ the injection spectrum has $\gamma < 2.4$
- ✓ heavy nuclei fraction injected $E > 10^{18}$ eV larger than 15%

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

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





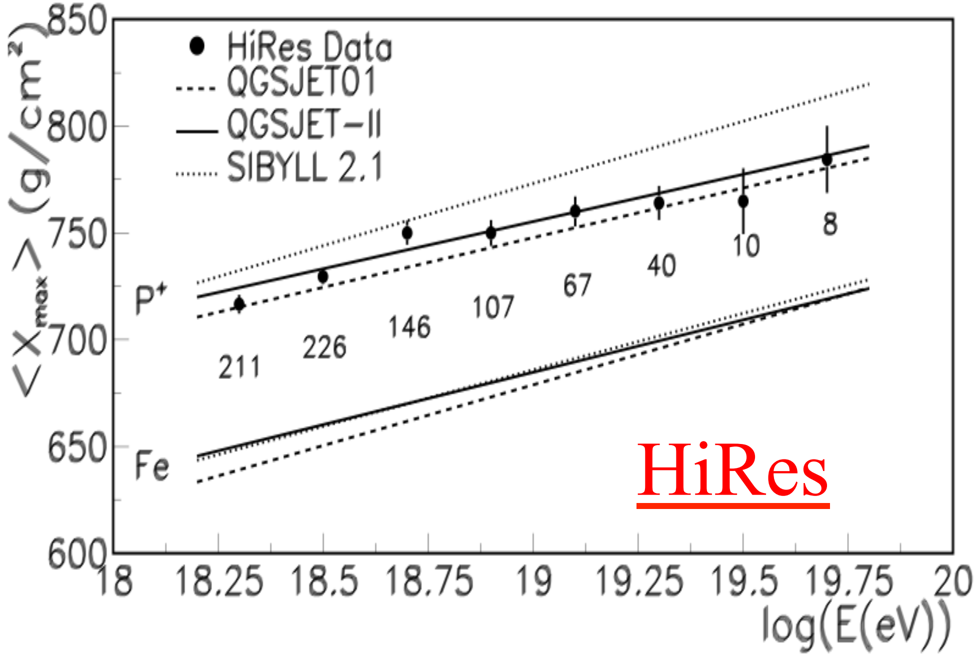


RA, Berezinsky, Grigorieva (2008)

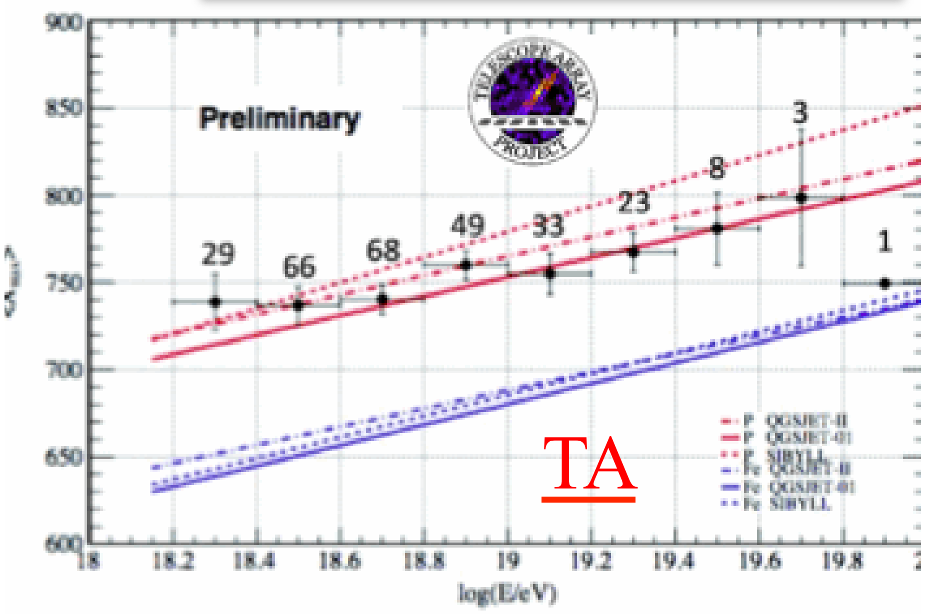
Chemical Composition

The GZK and dip features are nothing but a signature of a proton dominated spectrum. On chemical composition different experiments show different results

HiRes and Telescope Array favor a proton dominated spectrum at $E>10^{18}$ eV.

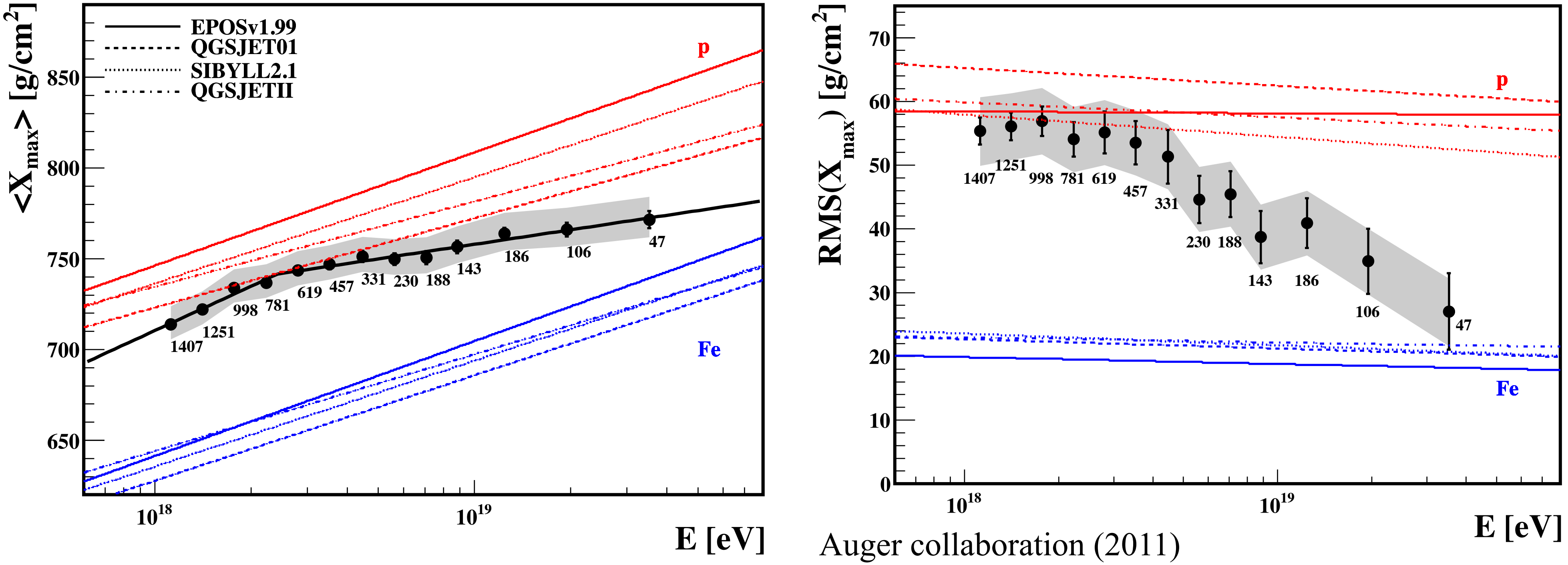


HiRes



TA

Auger chemical composition



Auger collaboration (2011)

The latest Auger results on chemical composition show the tendency for a nuclei dominated flux at the highest energies. The experimental result seems to show some inconsistency among different observable tagging the chemical composition of primary cosmic rays.

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 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

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

Γ’ solution of the
energy losses equation

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

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

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

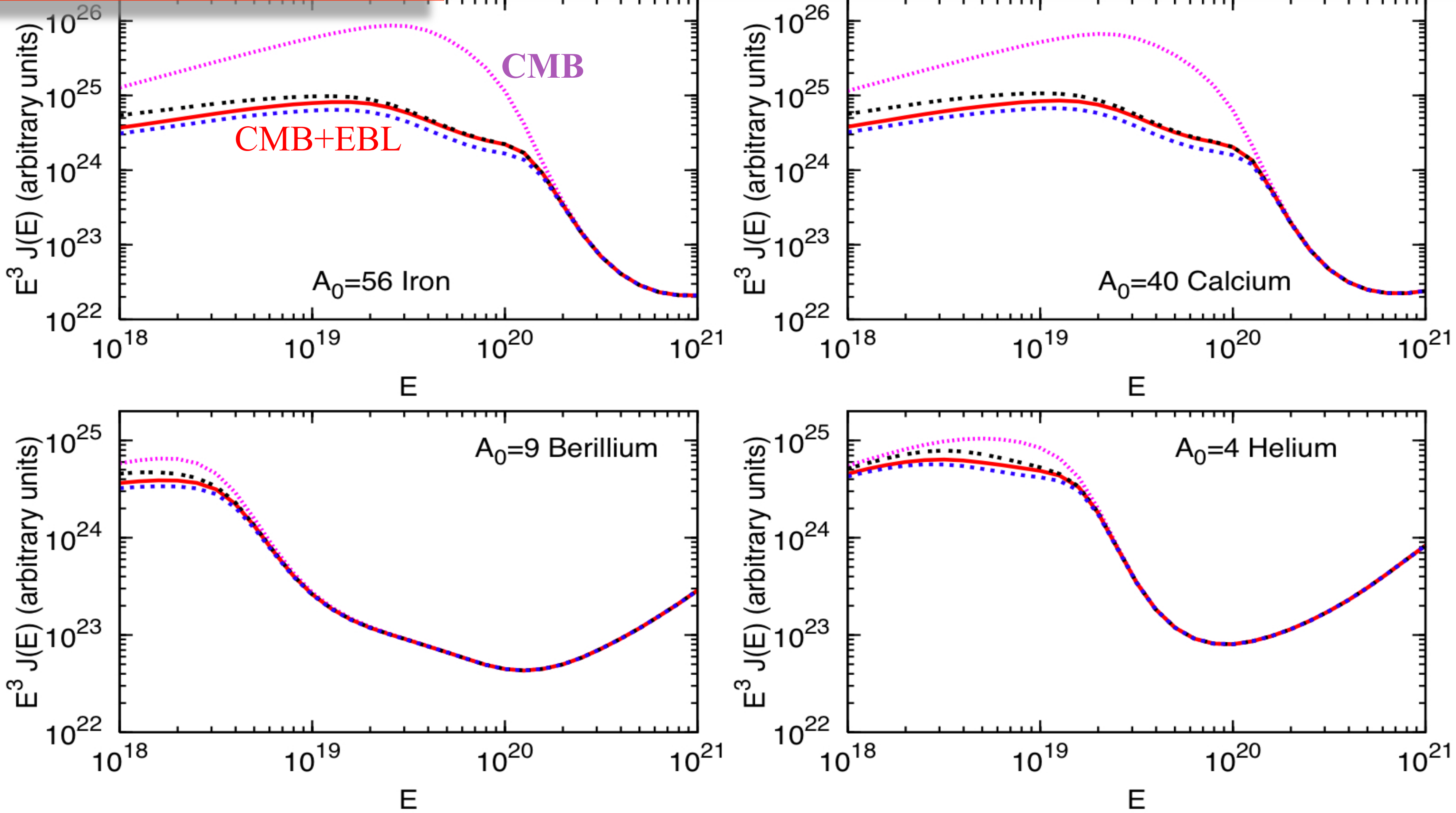
$$10^8 \leq \Gamma \leq 2 \times 10^9$$

Injection at 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)

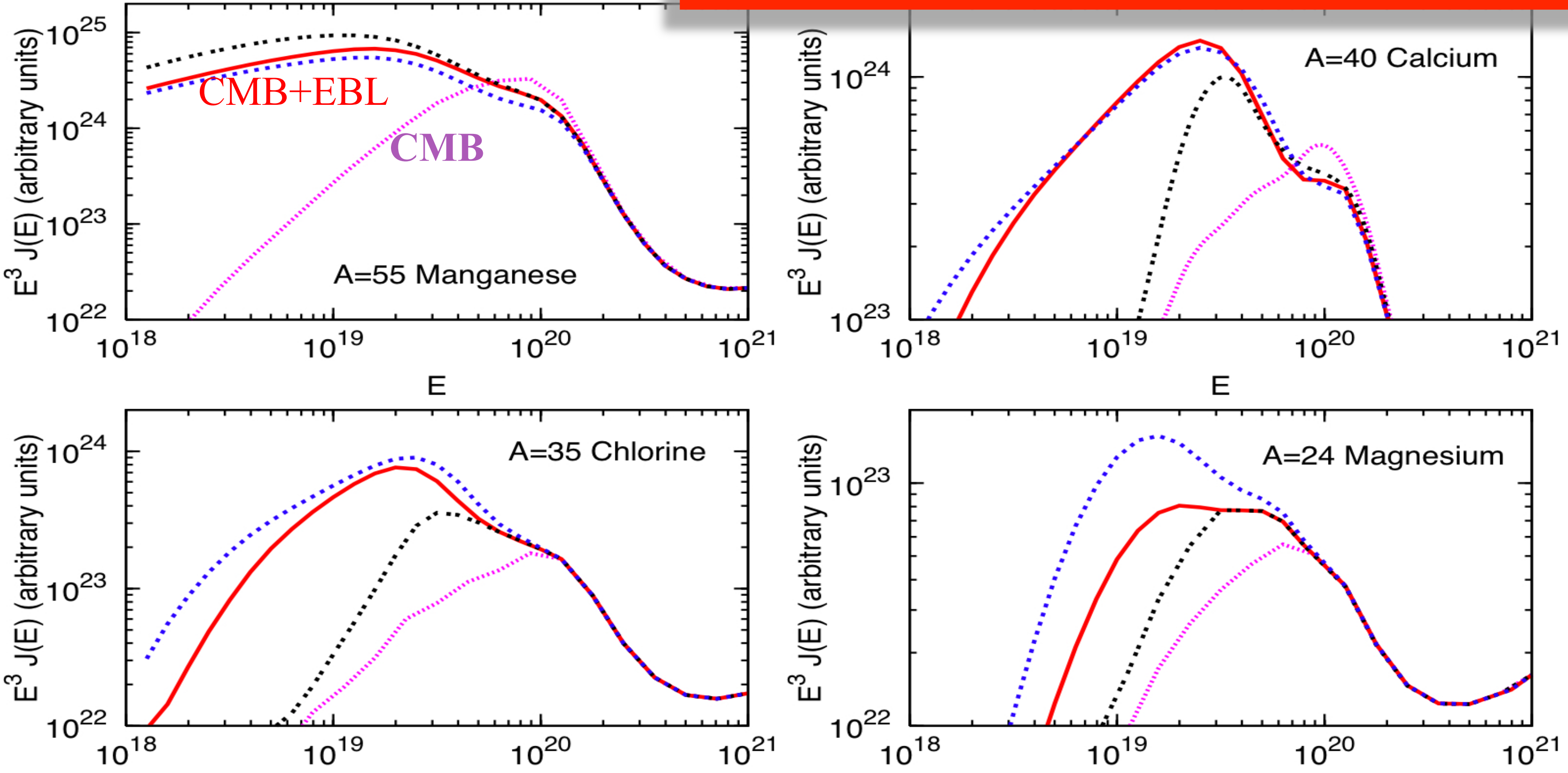
Secondary Nuclei

high A dependence on the EBL cosmological evolution

the EBL role consists in a flux regeneration in the range

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

due to an injection increased efficiency



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

RA, Berezinsky, Grigorieva (2010)

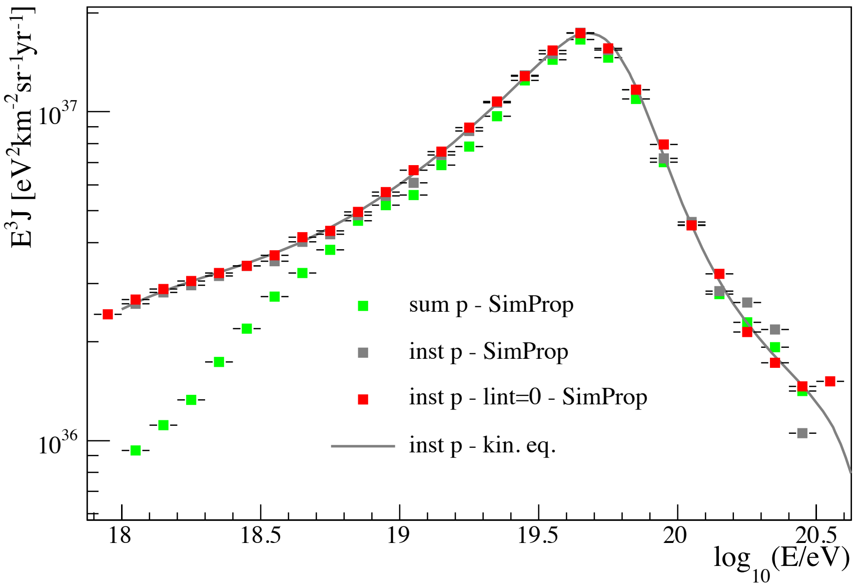
starting from primary Iron the photodisintegration chain produces all kinds of secondary $A<A_0$. The lowest mass secondary are produced by the highest energies primaries, the fluxes are less sensitive to the EBL effect (CMB only).

MC for UHECR nuclei propagation

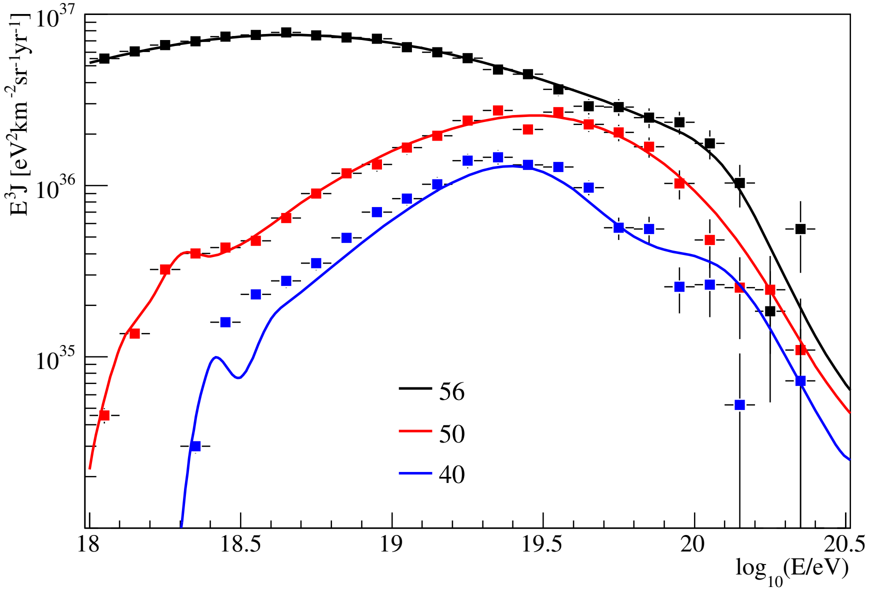
- ✓ Photo-disintegration process treated in the MC approach

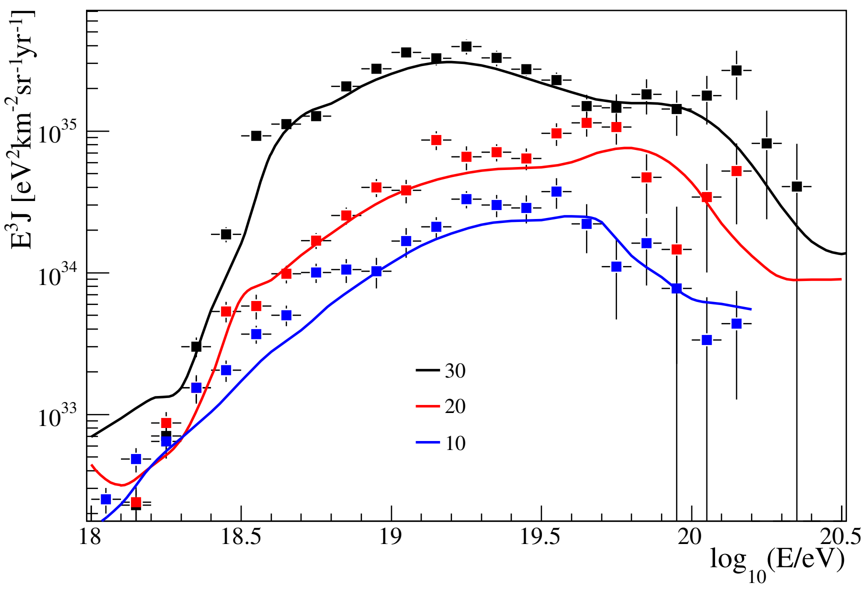
$$P(\Gamma, z) = exp\left(-\int_z \frac{1}{\tau_{A,i}(\Gamma, z')}\left|\frac{dt}{dz'}\right| dz'\right)$$

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



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





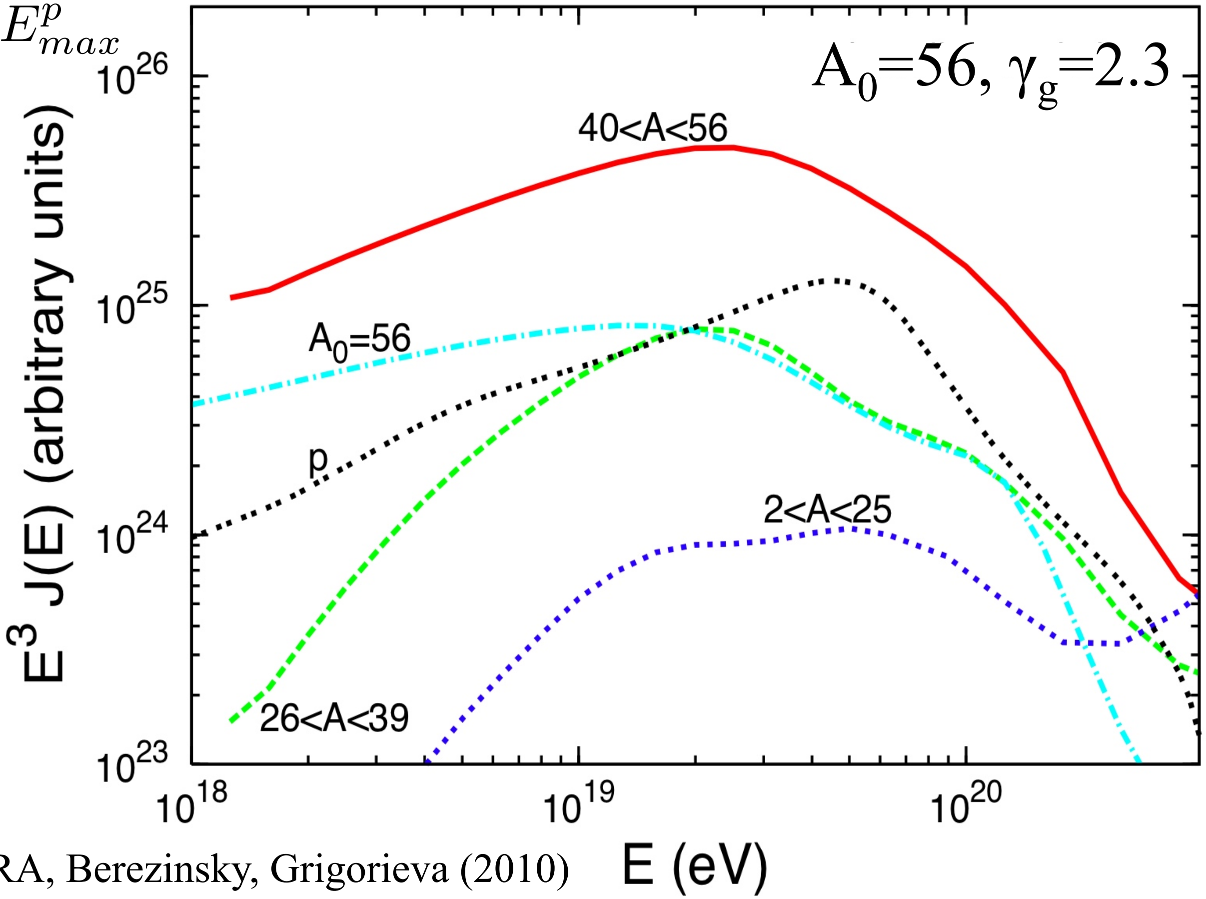
Caveat

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.

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

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

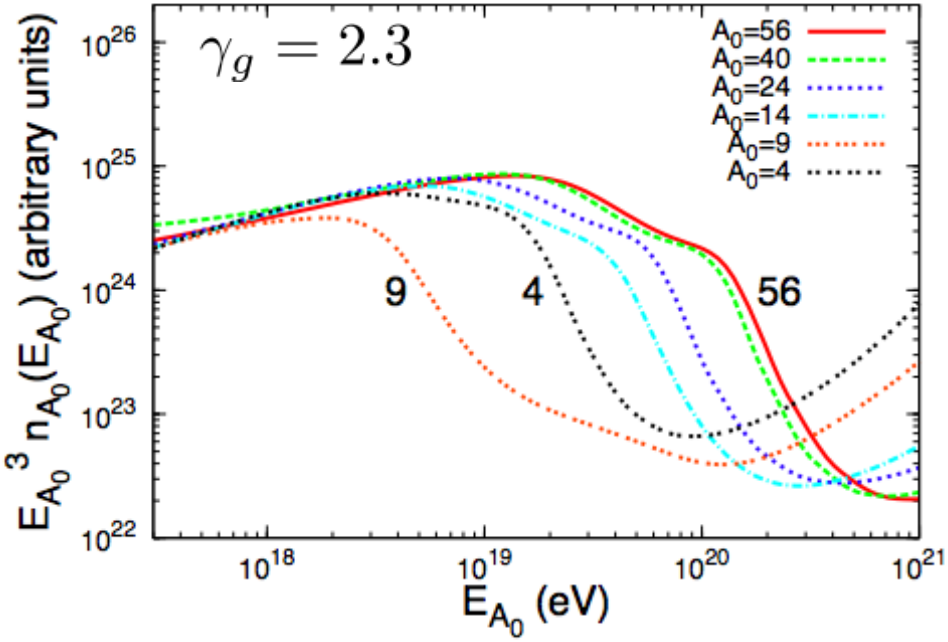
Critical Lorentz factor $\Gamma_c(A,\Gamma,t)$

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

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

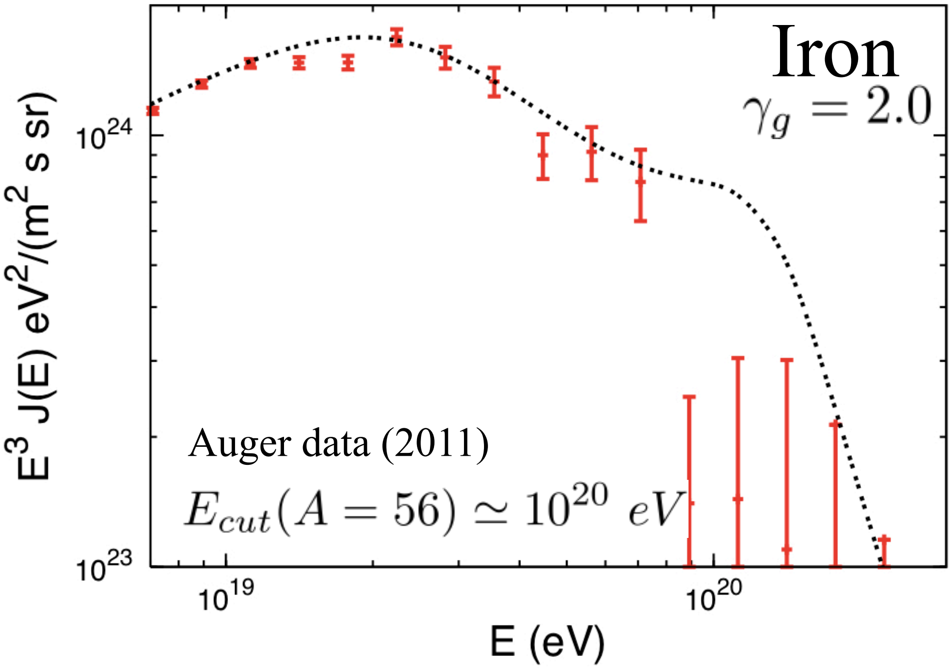
$$\Gamma_c\simeq 2\times 10^9$$

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



RA, Berezinsky, Grigorieva (2011)

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



Auger data (2011)

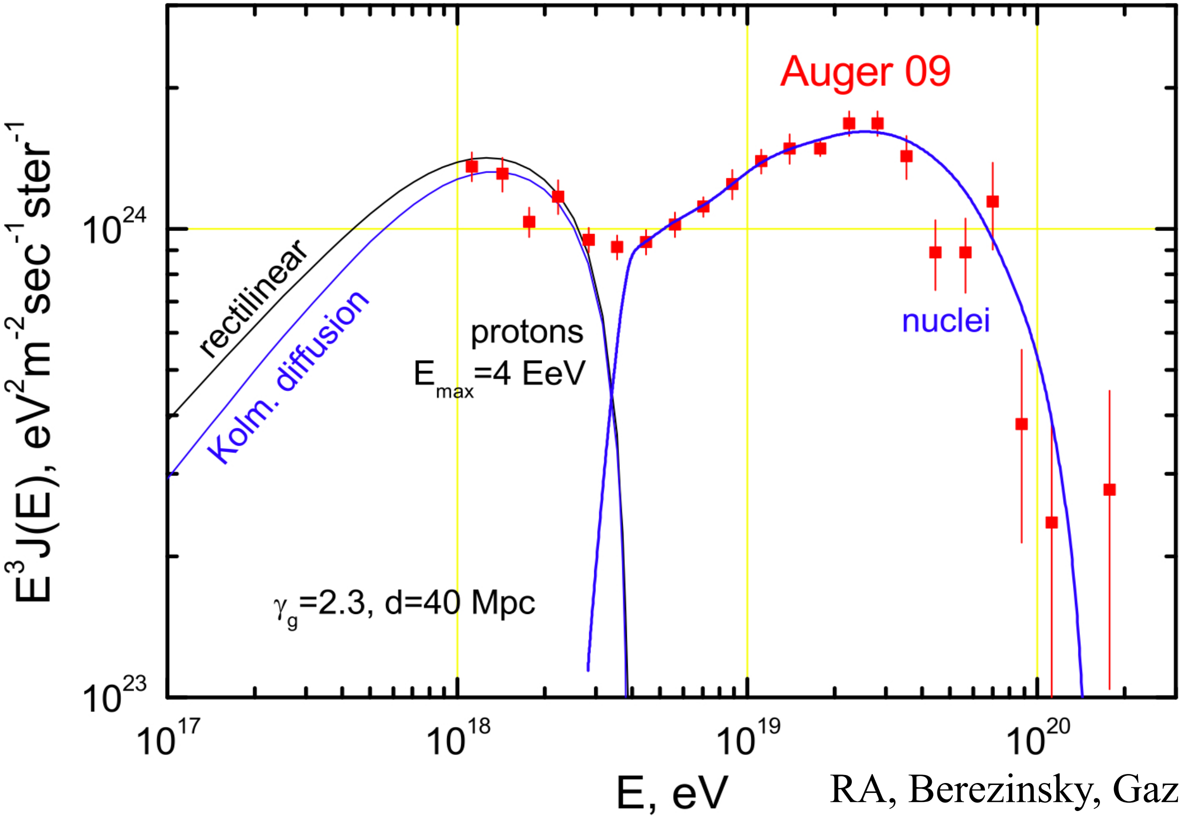
$E_{cut}(A=56)\simeq 10^{20}\ eV$

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.

$$E_{max}(Z) = ZE^{p}_{max}$$



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 Models

Models with an heavy nuclei dominance at the highest energies, constructed to fit the observations of Auger on chemical composition.

If nuclei dominate at the highest energies:

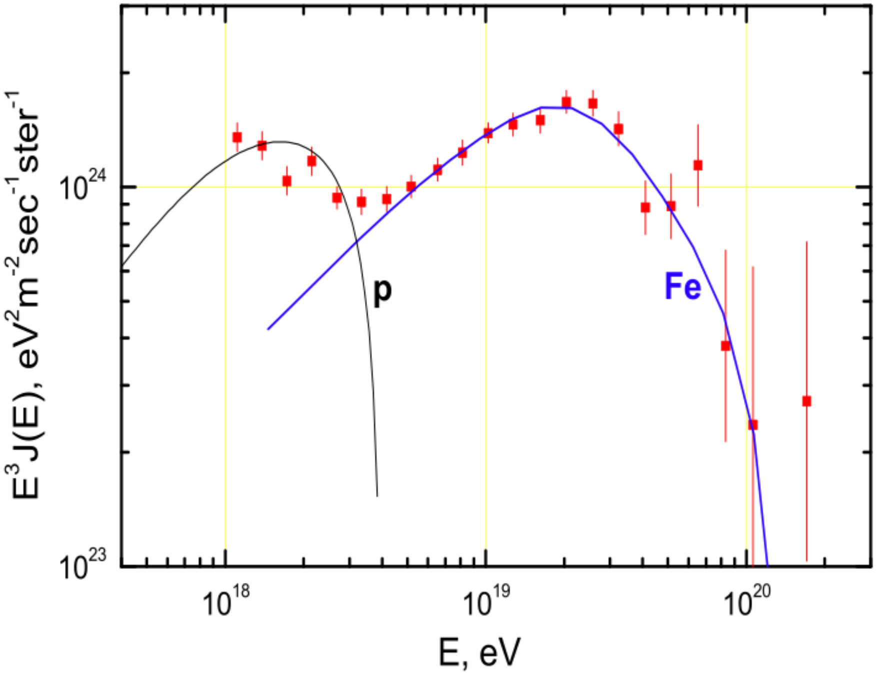
✓ **no correlation with sources**

The μG galactic magnetic field substantially deviates particles trajectories:

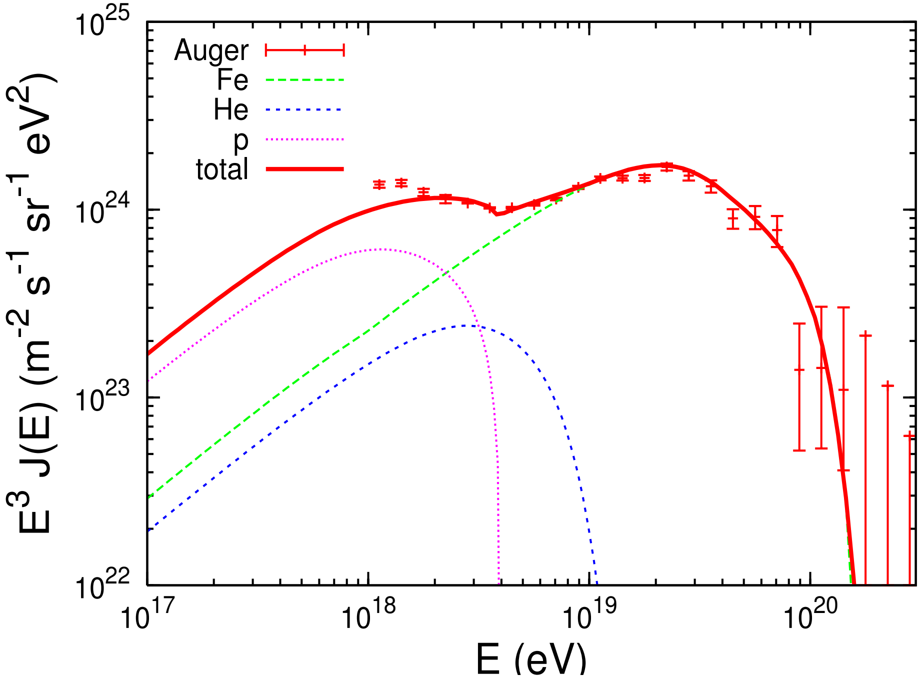
$$\theta = \frac{Z}{2\pi}\frac{l_{Kpc}B_{\mu}}{E_{20}}$$

✓ **no production of ν and γ**

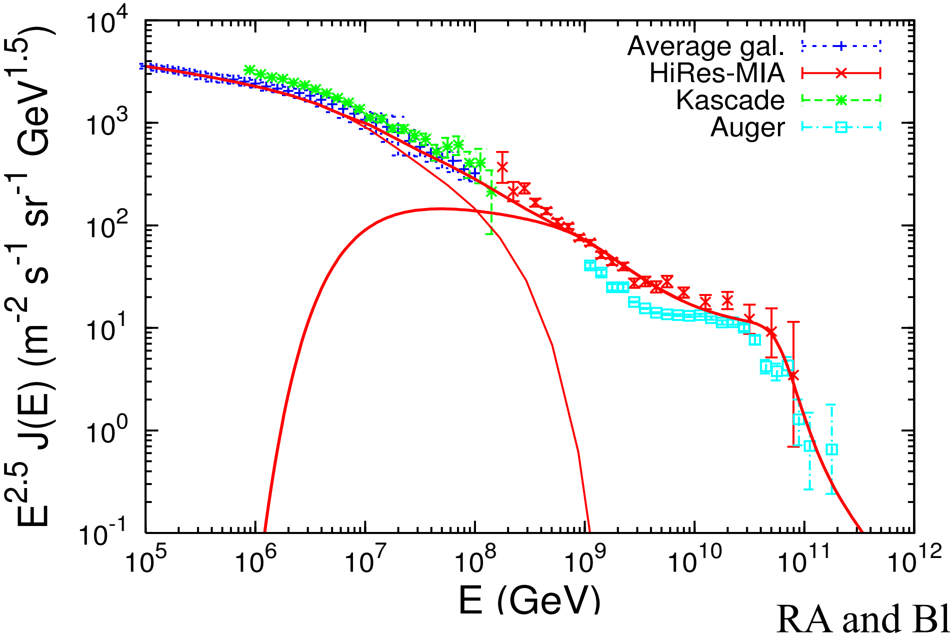
Nuclei interacting with CMB and EBL just photo-disintegrate no production of secondary neutrinos and gamma-rays.

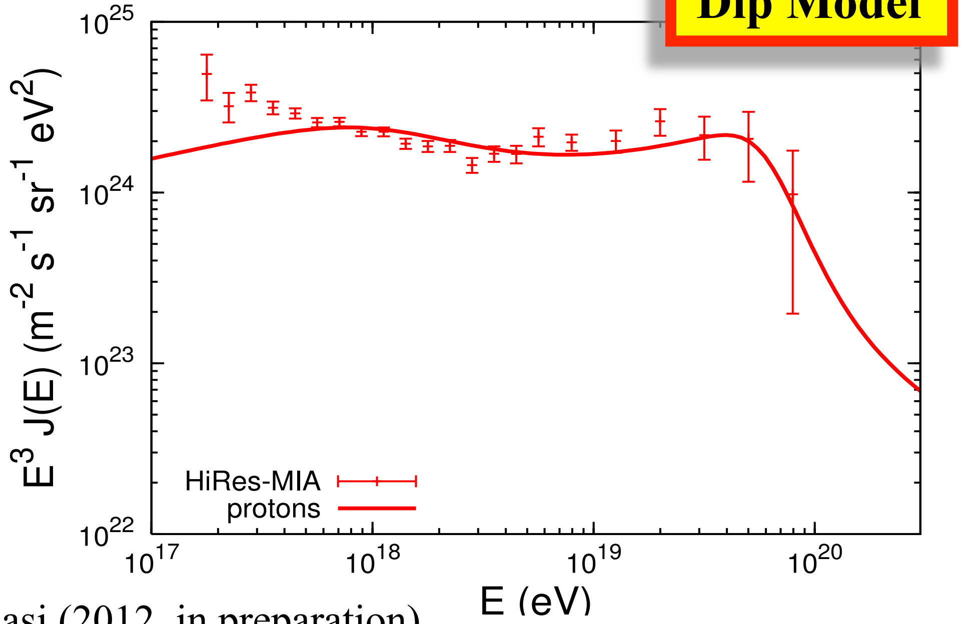


RA, Berezinsky, Gazizov (2010)



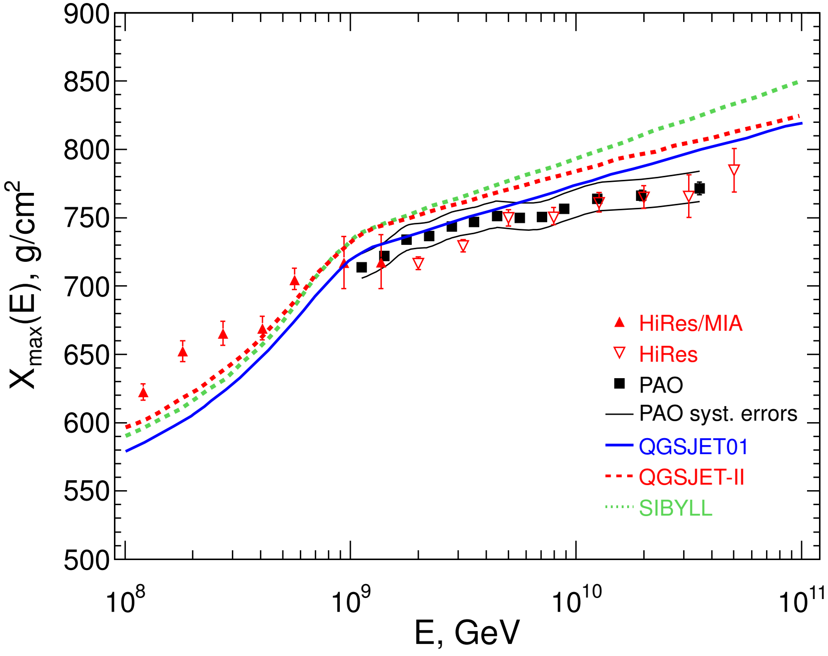
Galactic and ExtraGalactic CR





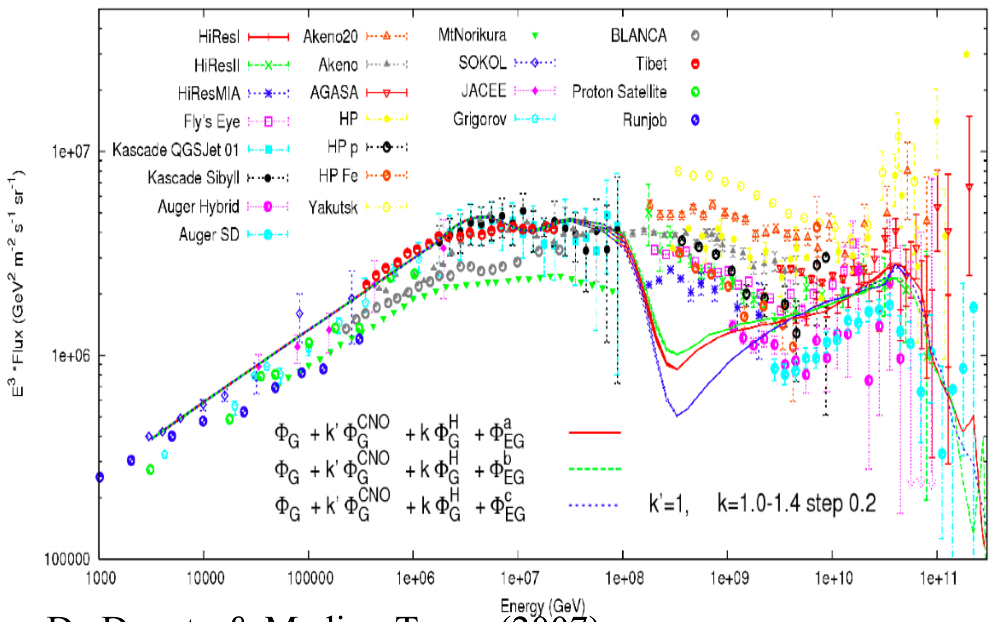
Dip Model

RA and Blasi (2012, in preparation)

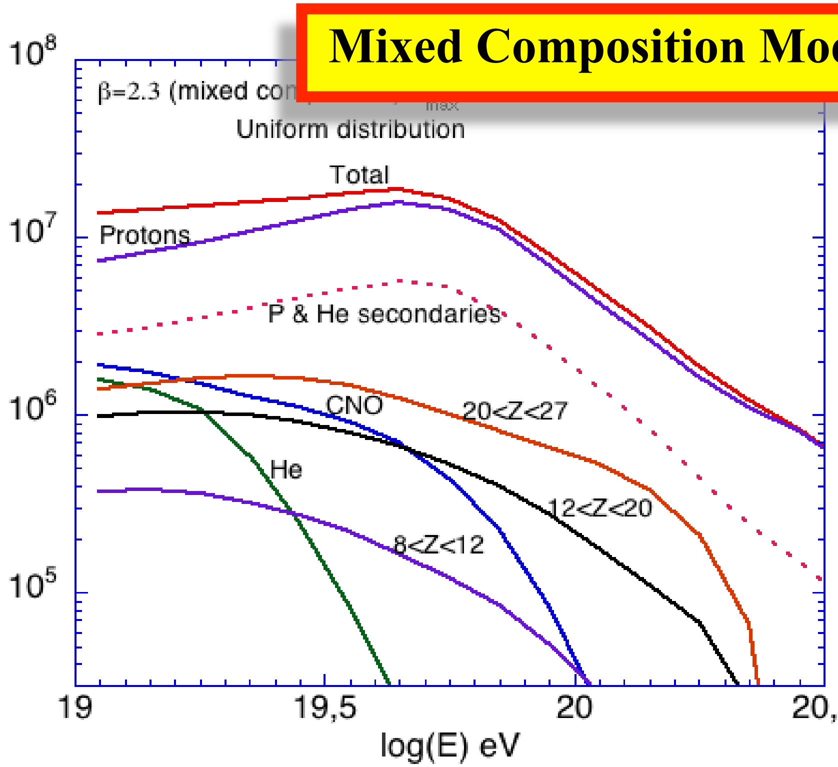


- The Galactic CR spectrum ends in the energy range 10^{17} eV, 10^{18} eV.
- 2^{nd} Knee appears naturally as the steepening energy corresponding to the transition from adiabatic to pair production energy losses $E_{2K} \approx 10^{18}$ eV.

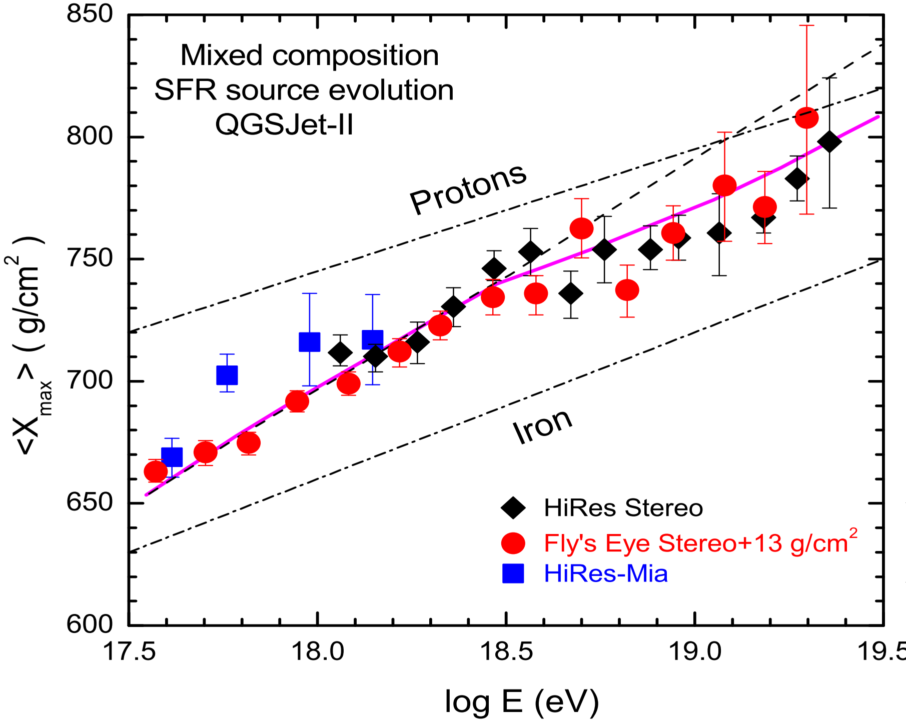
Mixed Composition Model



De Donato & Medina-Tanco (2007)



Allard, Parizot, Olinto (2005)



Allard, Parizot, Olinto (2005)

- The Galactic CR spectrum ends at energies larger than 10^{18} eV ($E_{tr} \approx 3\times10^{18}$ eV).
- Composition dominated by Galactic nuclei below E_{tr}, and Extra-Galactic nuclei above E_{tr} (difficult to detect).

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 $E<10^{18}$ 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 $E>4x10^{18}$ eV

✓Transition Galactic/ExtraGalactic CR at $E>10^{18}$ 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