Status of the GZK cut-off in Ultra High Energy Cosmic Rays

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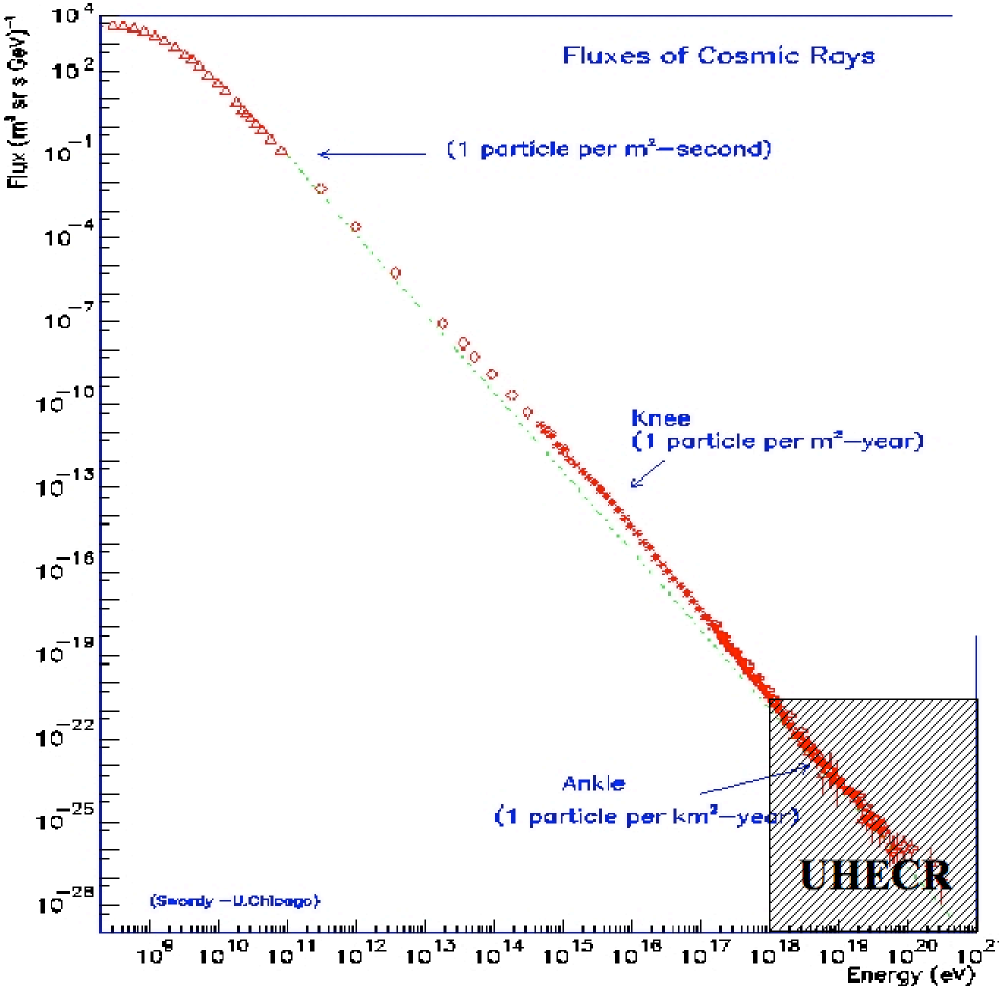
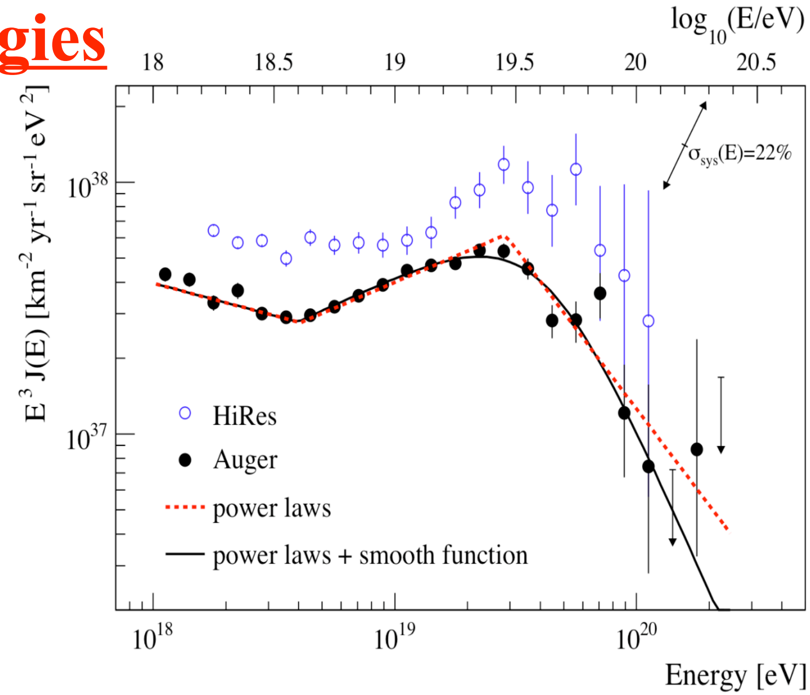
CR spectrum at Ultra High Energies





the observation of the GZK cut-off gives important hints about the spectrum and chemical composition of UHECR

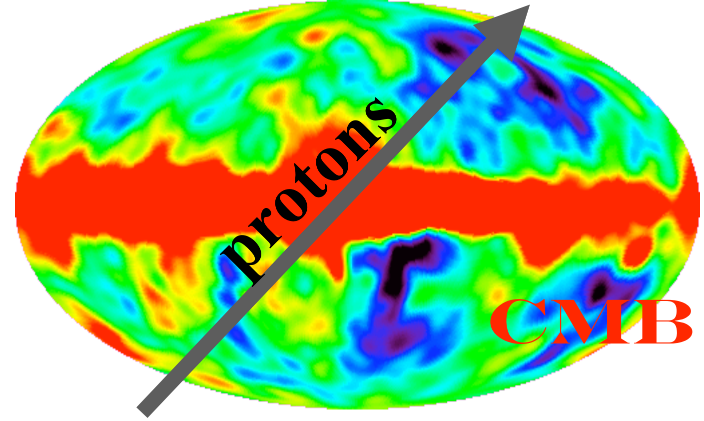
The observations on Earth are the result of the acceleration at the source (injection) and the propagation of particles in the background radiation (CMB & IR) (we will not discuss here magnetic fields, see Takami talk) .

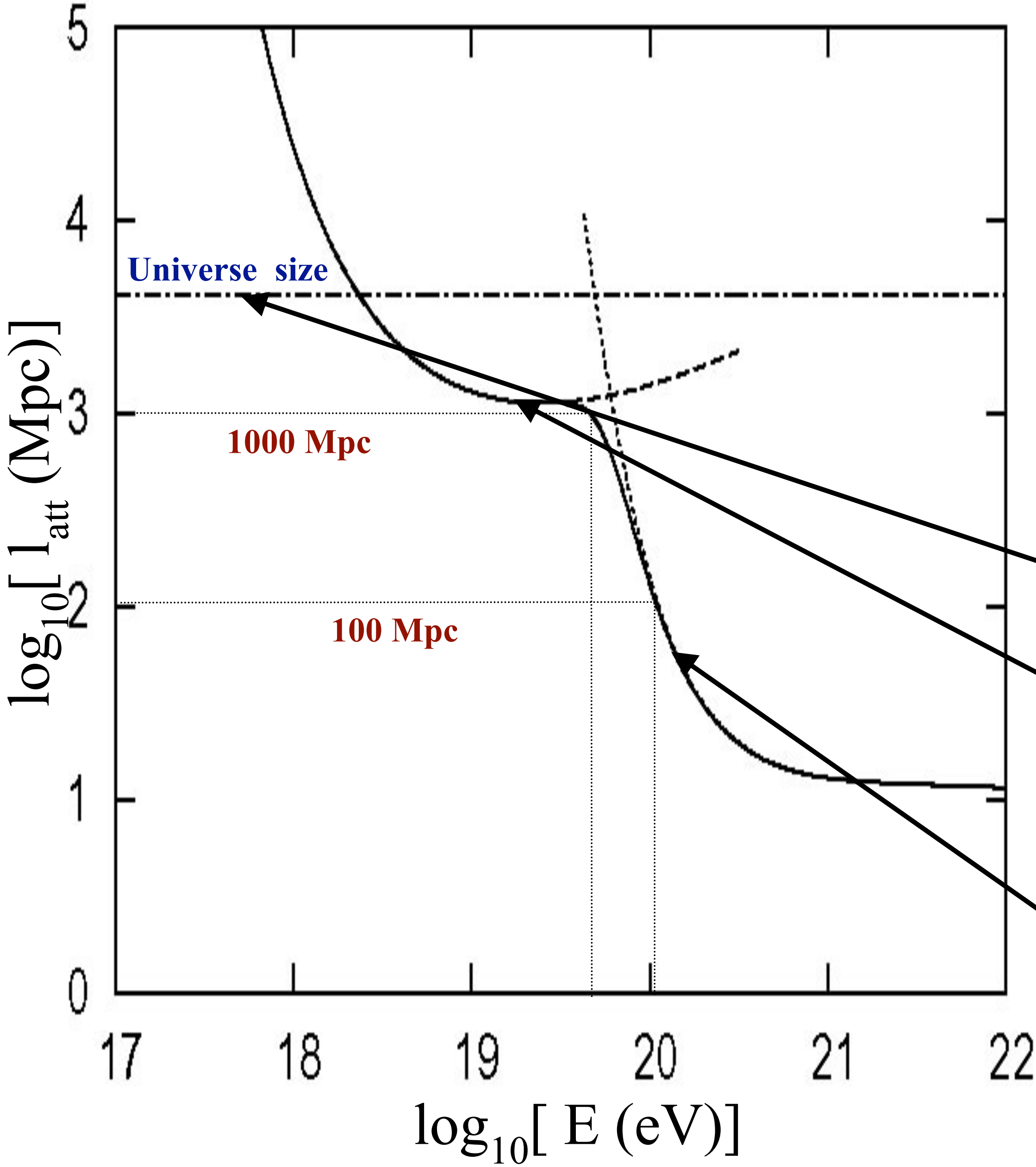
Spectrum

Chemical Composition

Anisotropy (correlations)

UHE Protons loss length





proton propagation is affected only by CMB

Adiabatic losses
Universe expansion

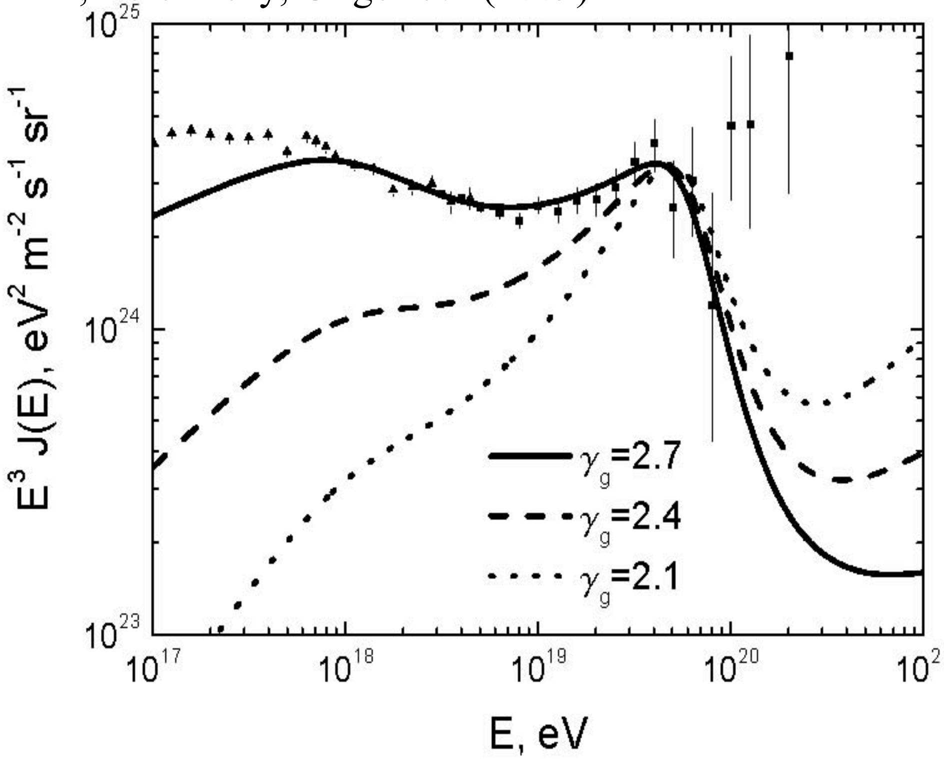
Pair production
$p\,\gamma \rightarrow p\, e^+ e^-$

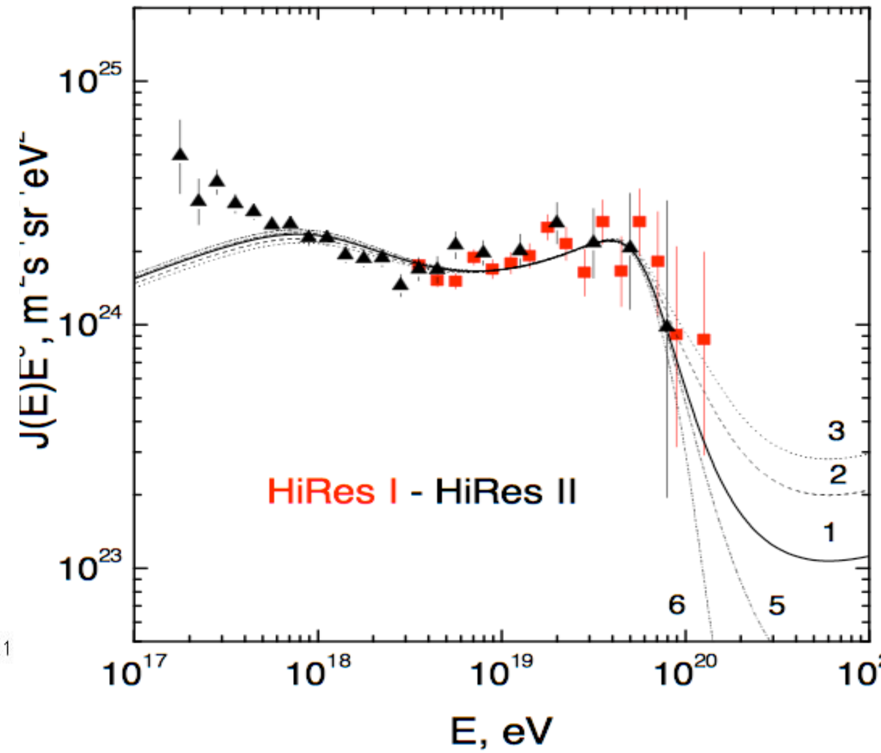
Photopion production
$p\,\gamma \rightarrow p\,\pi^0$
$\rightarrow n\,\pi^+$

The End of the CR Spectrum?

The Greisen Zatzepin Kuzmin suppression in the flux is an effect of the interaction of protons with the CMB field it starts at $E_{GZK} \approx 5\text{x}10^{19}$ eV due to the photopion production process: $p\ \gamma \rightarrow\ p\ \pi$

RA, Berezinsky, Grigorieva (2009)



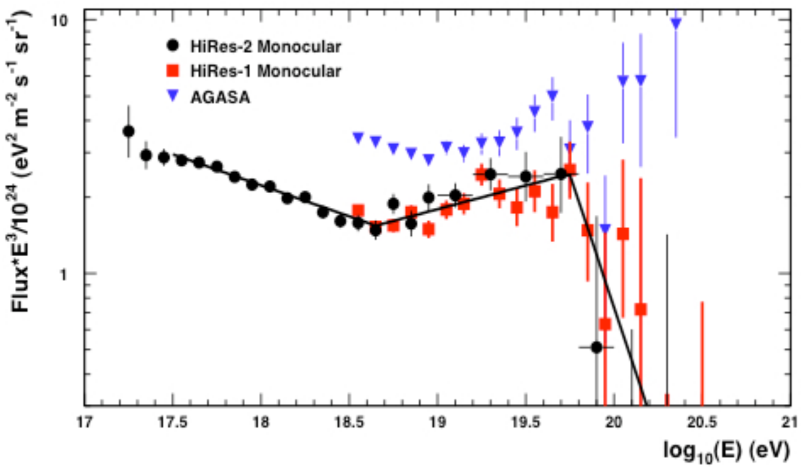


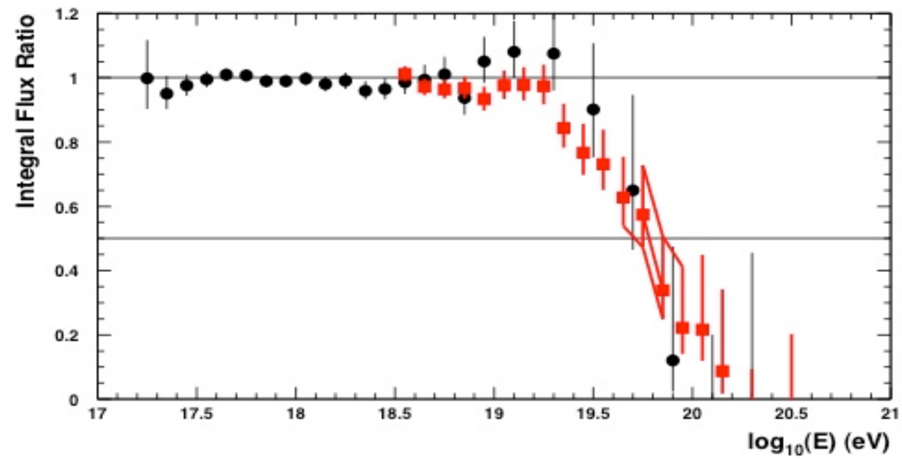
Berezinsky et al. (2002)

GZK feature is quite independent of the source characteristics and it is theoretically well defined through $E_{1/2}=10^{19.72}$ (Berezinsky & Grigorieva 1988)

HiRes & Telescope Array

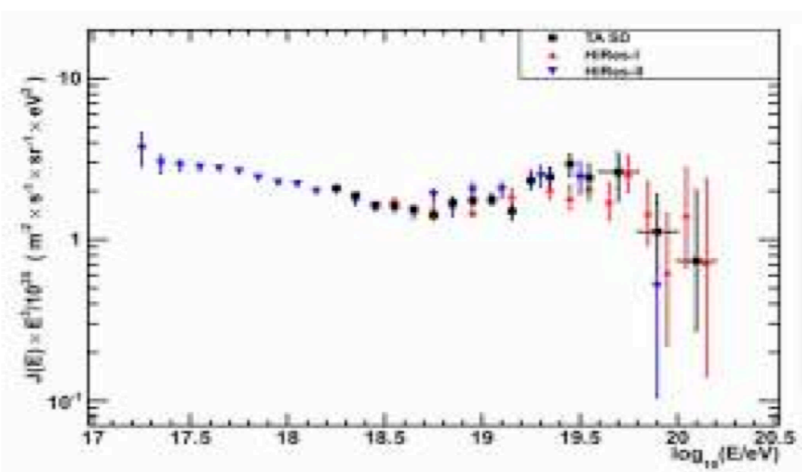
The last HiReS analysis confirms the expected Greisen Zatzepin Kuzmin suppression in the flux with $E_{1/2}=10^{19.73\pm0.07}$ eV in fairly good agreement with the theoretically predicted value (more in the Thomson talk of Friday)





HiRes collaboration (2007)

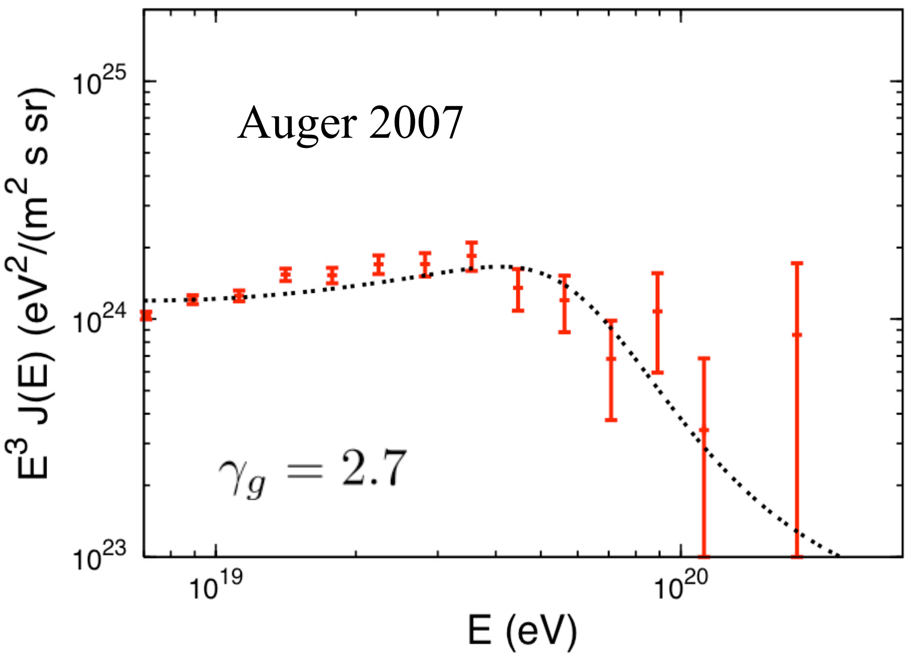
TA collaboration (2010)

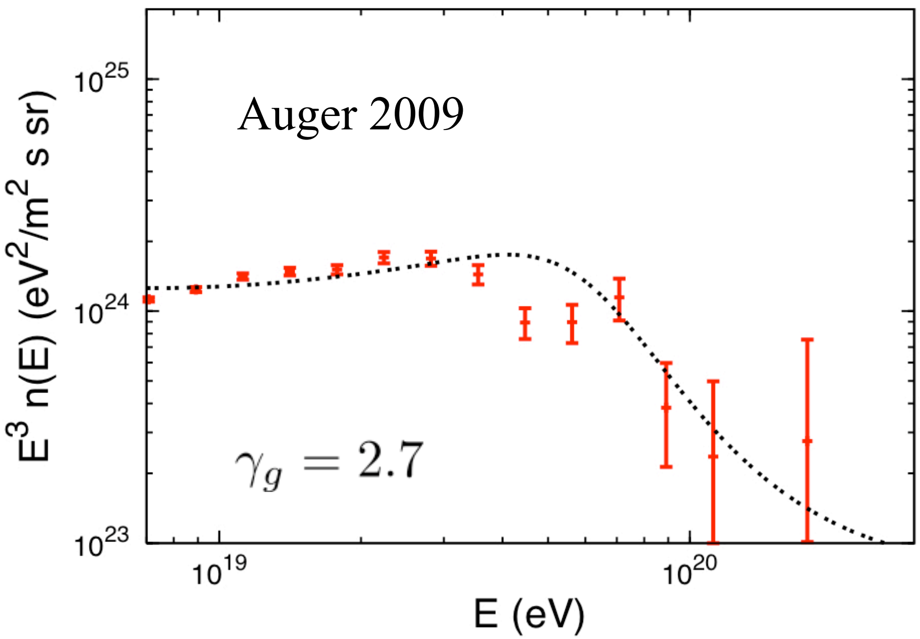


The new Telescope Array results, in agreement with HiReS, show a suppression in the spectrum compatible with the GZK feature (more in the Stokes talk).

Auger Observatory

The last Auger data on flux show a suppression roughly at the expected GZK energy, even if the comparison of 2007 and 2009 data seem to weaken the agreement with the expected GZK behavior.

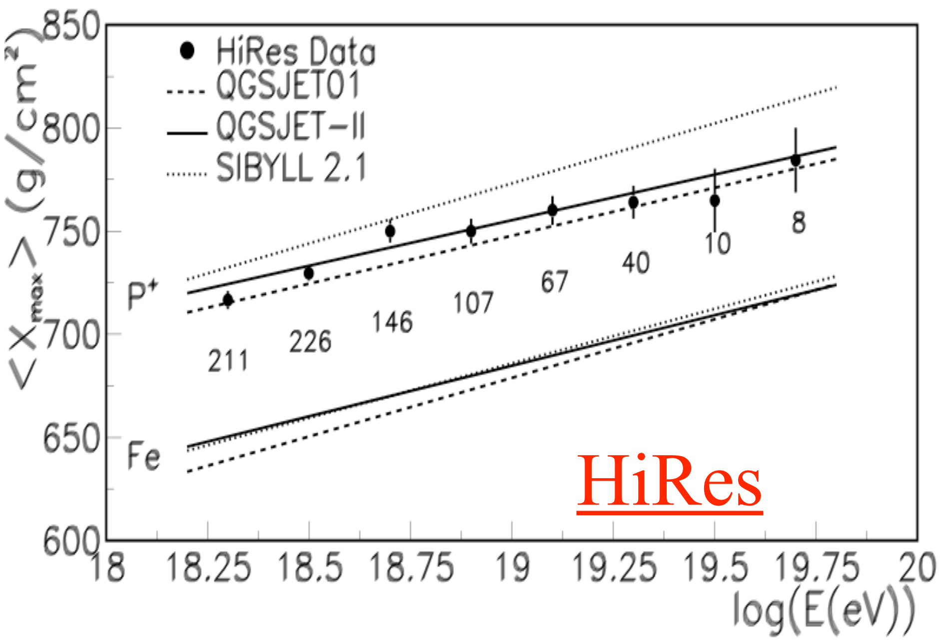


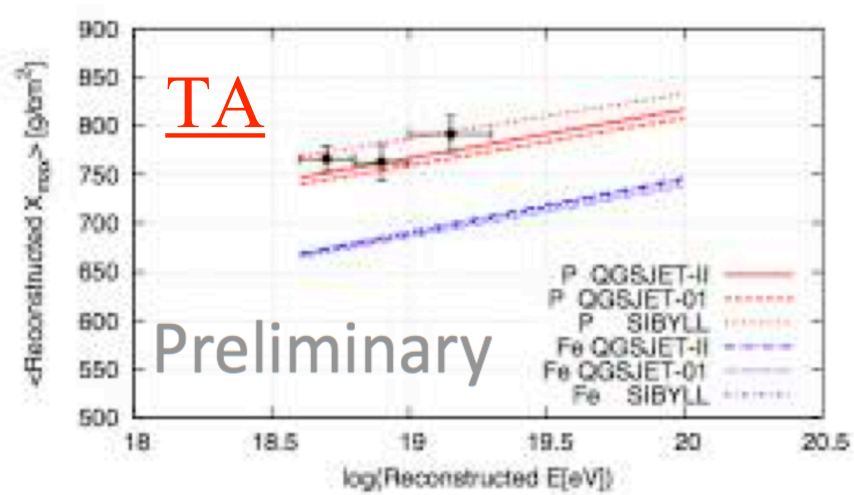


Chemical Composition

The GZK feature is nothing but a signature of a proton dominated spectrum. On chemical composition different experiments show different results

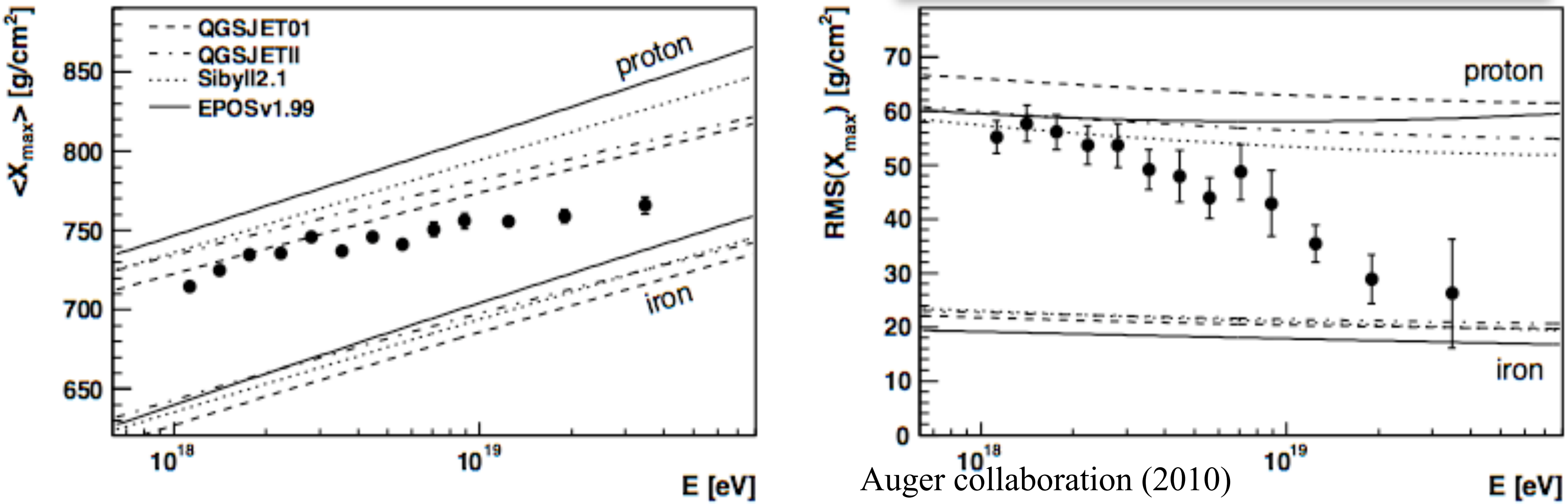
HiRes and Telescope Array favor a proton dominated spectrum at $E>10^{18}$ eV.





Auger chemical composition

The latest Auger results on chemical composition show the tendency for a nuclei dominated flux at the highest energies



Auger collaboration (2010)

In any case one should note that at the GZK energies ($E>5\times10^{19}$ eV) chemical composition is poorly known with no published data by Auger and very low statistics (only 8 events!) by HiRes.

UHE Nuclei path length

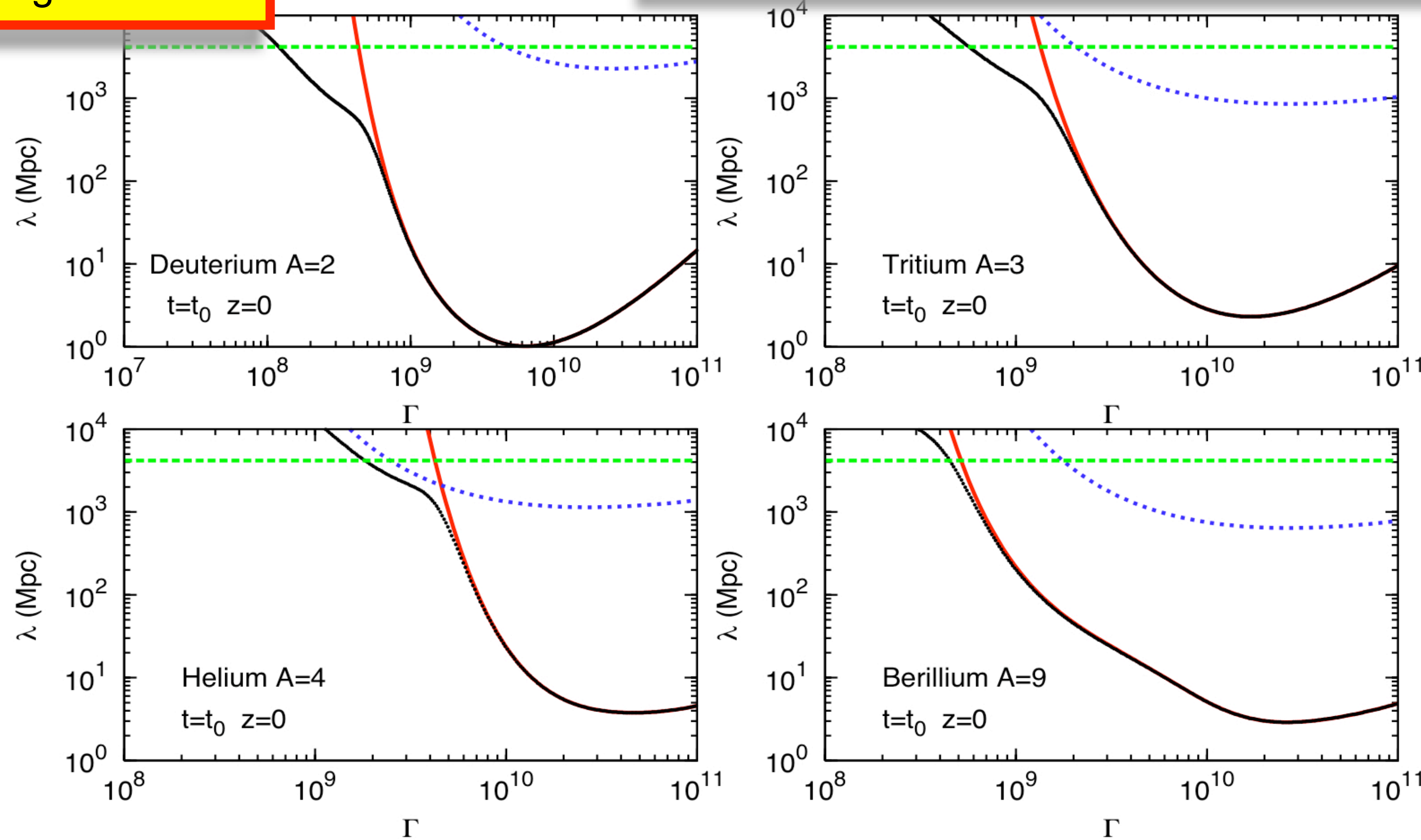
$$E = m_N A\Gamma$$

$$\left(\frac{1}{E}\frac{dE}{dt}\right) = \left(\frac{1}{A}\frac{dA}{dt}\right) + \left(\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right)$$

$\left(\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right)$ **Pair production (CMB)** $A\gamma \rightarrow A e^{+} e^{-}$ **conserves A**

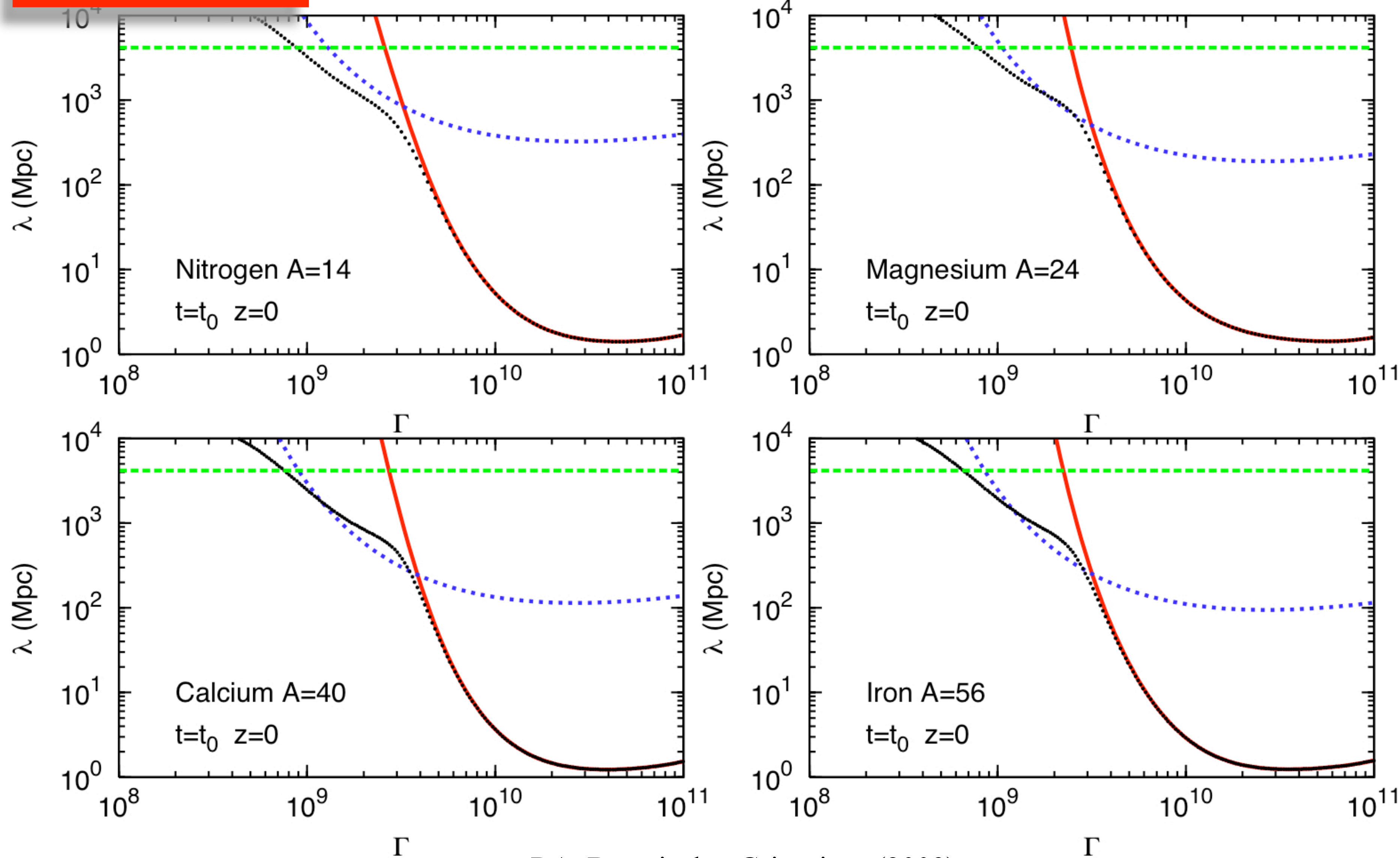
$\left(\frac{1}{A}\frac{dA}{dt}\right)$ **Photodisintegration (CMB+IR/V/UV)** $A\gamma \rightarrow (A-1) + N$ **conserves Γ**

Light Nuclei



RA, Berezinsky, Grigorieva (2009)

Heavy Nuclei



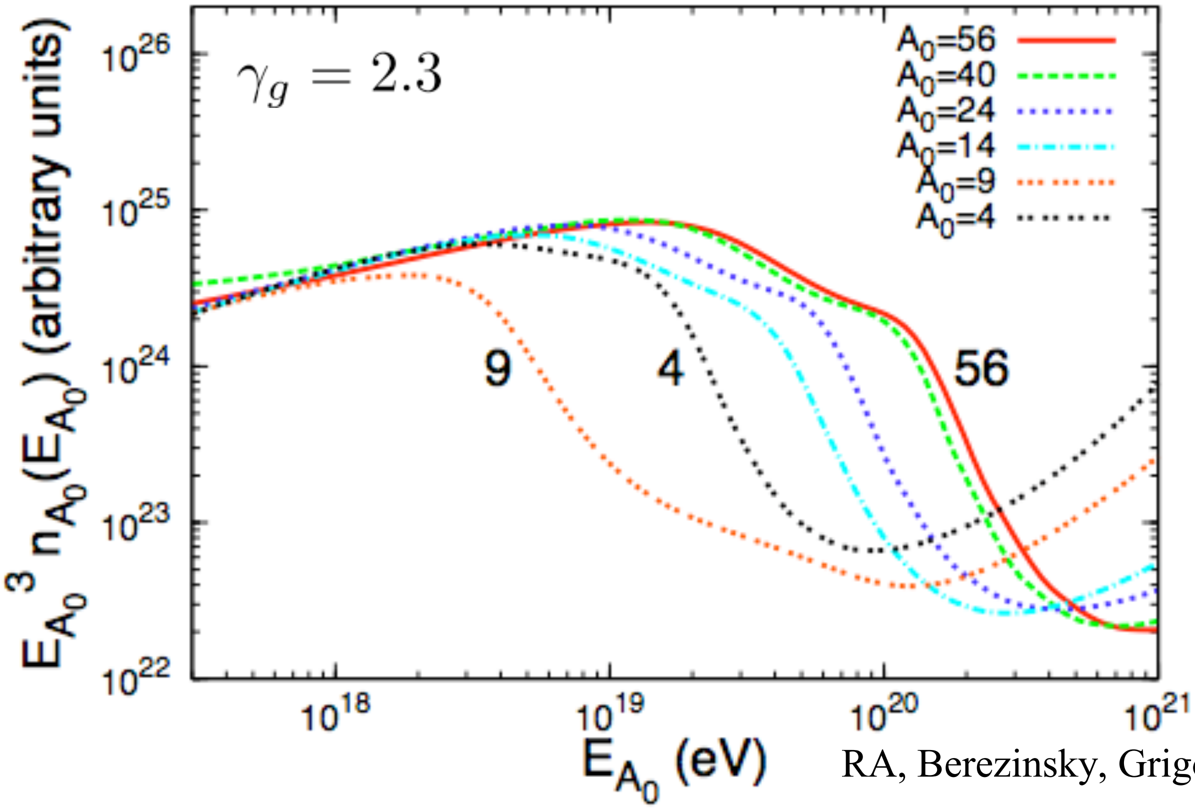
RA, Berezinsky, Grigorieva (2009)

Nuclei GZK-like behavior

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

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

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)

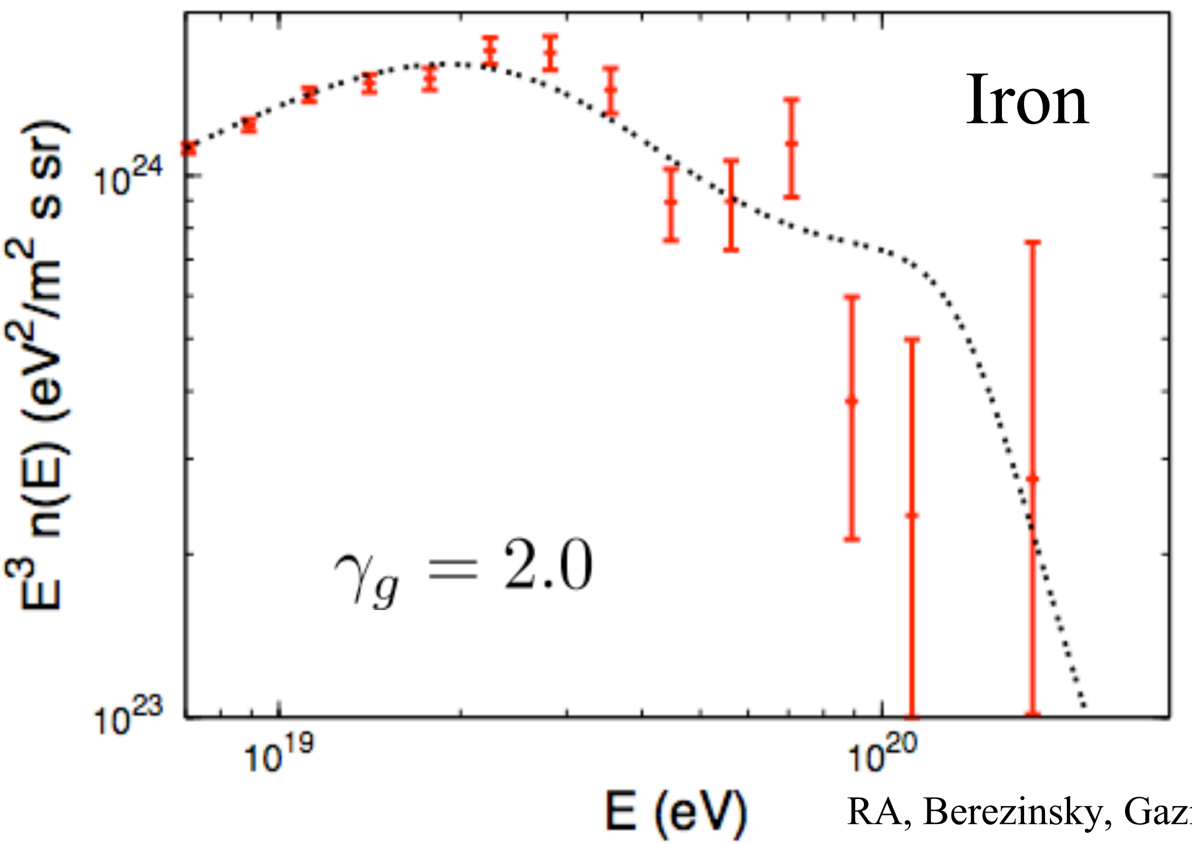
$$E_{cut}(A) = A m_N \Gamma_c$$

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

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

The high energy suppression observed in the Auger spectrum can be also compatible with a dominance of heavy nuclei in composition.

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



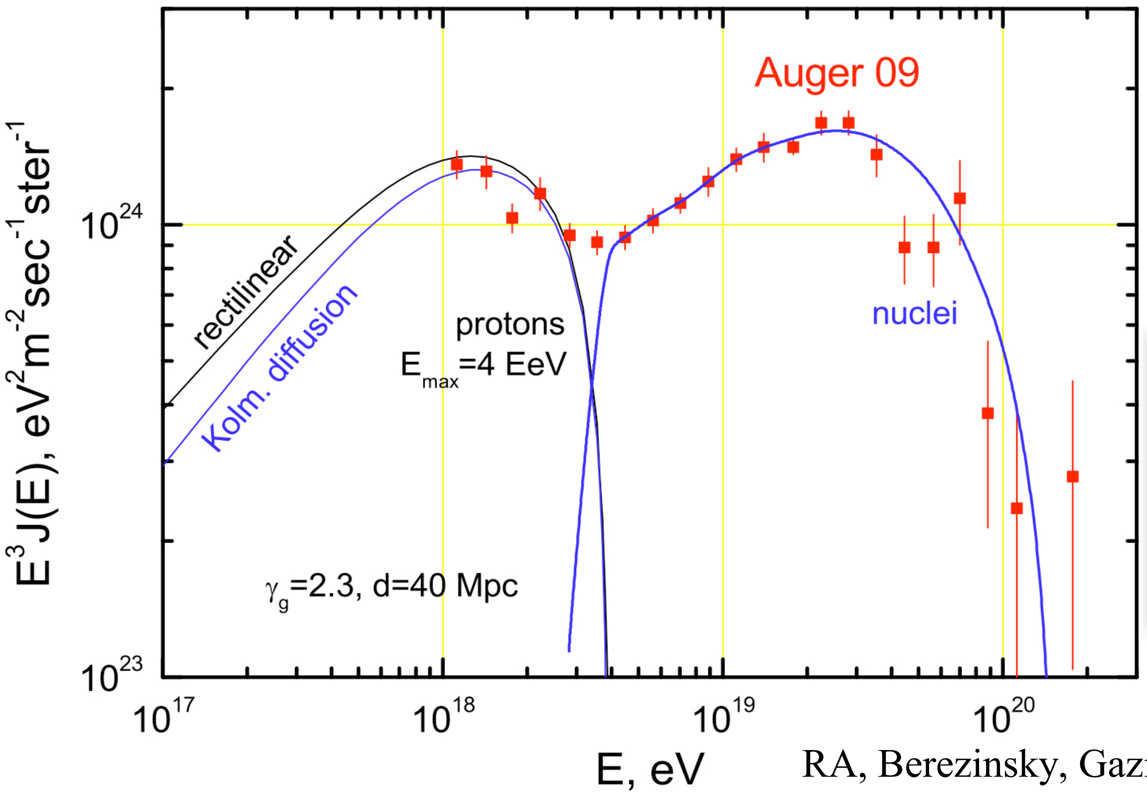
RA, Berezinsky, Gazizov (2010)

in this case we could not ascribe the Auger observed high energy suppression to the GZK effect

Interaction vs maximum energy

GZK cut-off for protons as well as photo-disintegration cut-off for nuclei are a consequence 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)

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

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

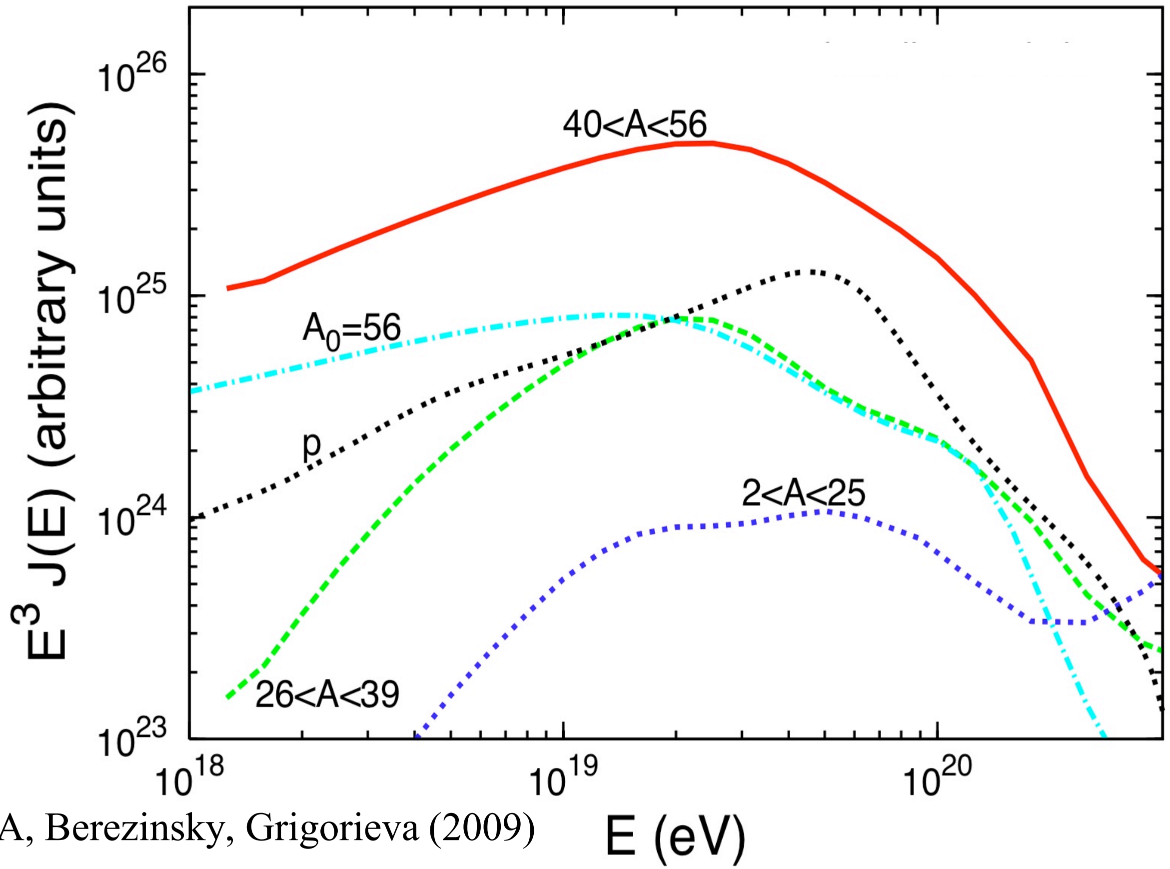
analogy with the galactic CR behavior: protons dominate at the lowest energies and nuclei dominate at the highest.

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 secondaries (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)

Conclusions

In the case of astrophysical origin of UHECR, independently of the sources and chemical composition, a suppression of the flux at the highest energies is expected. A clear characterization of such suppression gives us precious informations about the nature of UHECR.

Protons (GZK cut-off)

$$E_{cut} \simeq 5 \times 10^{19}\ eV \quad E_{1/2} = 10^{19.72}\ eV$$

Nuclei (photodisintegration cut-off)

$$E_{cut}(A) = A m_N \Gamma_c \quad \Gamma_c \simeq 2 \times 10^9$$

A firm experimental determination of the chemical composition at the highest energies is crucial in determining the nature of the observed suppression in the flux.

The study of anisotropy at the highest energies can be used to distinguish among protons and nuclei.