UHECR: Acceleration and Propagation

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ACCELERATION

UHE particles with energies observed up to $E \sim 3 \times 10^{20}$ eV can be in principle accelerated e.g. by shocks, unipolar induction and strong electromagnetic waves. Large $E_{\rm max}$ combined with large luminosity is a very limiting factor for shock acceleration above 10^{19} eV. However, AGN remain most promising candidates.

$E_{\max}$ for non-relativistic jets in AGN

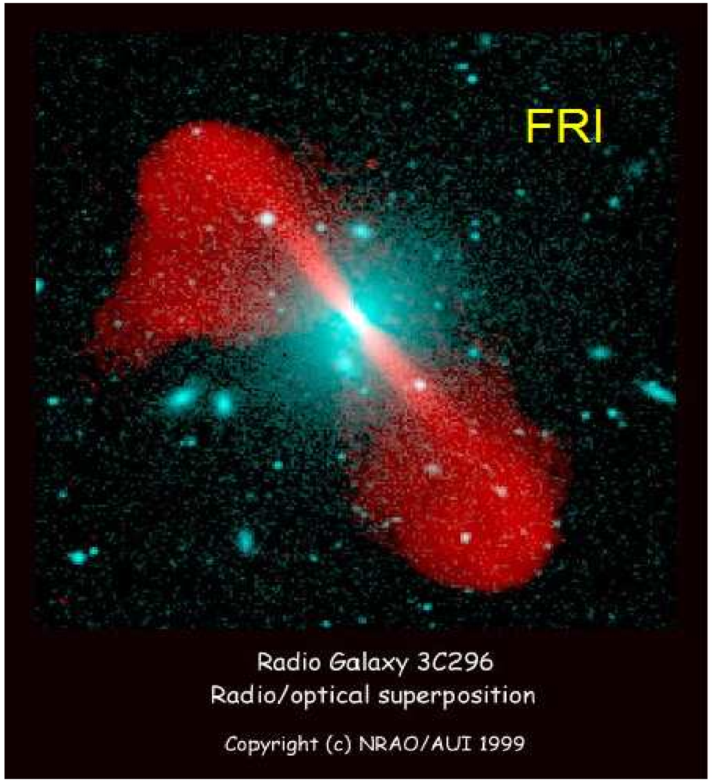
Biermann and Strittmatter 1987, Norman, Melrose, Achtenberg 1995, Ptuskin, Rogovaya, Zirakashvili, 2013

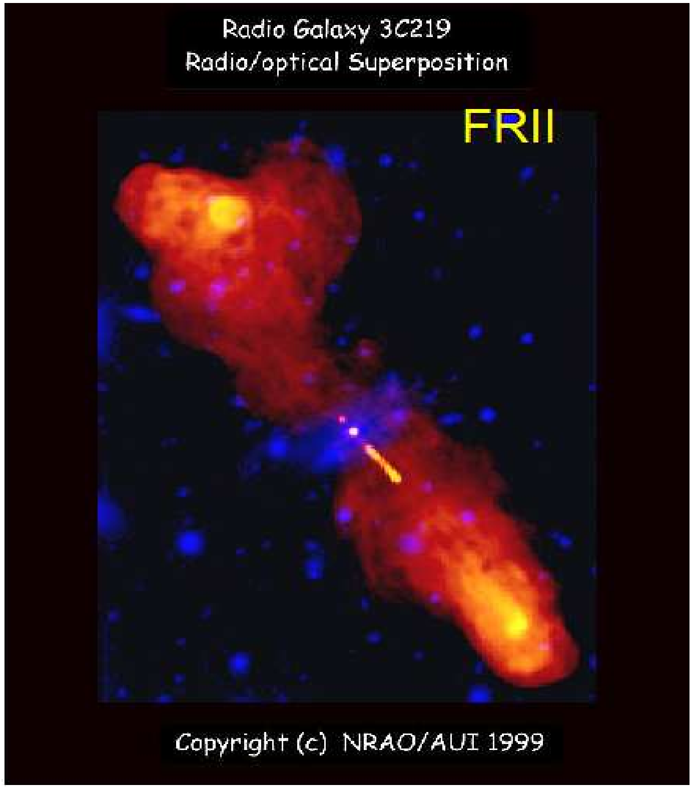
$E_{\max}$ from two conditions:
$E_{\max} = ZeB\beta_s R_s$ (Hillas criterion) and
$B^2/8\pi = \omega_{\rm part}$ or $B^2/8\pi \approx L/\pi R_s^2 c\beta$ (equipartition), results in

$$E_{\max} \sim Ze\beta_s(8L/c)^{1/2} \sim 6\times 10^{19} Z\beta_s L_{45}^{1/2}\ \mathrm{eV} \qquad (1)$$

Eq. (1) does not depend on $r_{\rm sh}$ and R_s.
Problem: At $\Gamma_j \lesssim 4$ jets are short, and HE protons are absorbed due to $p\gamma$ interaction.

Fanaroff-Riley I and II radio-galaxies



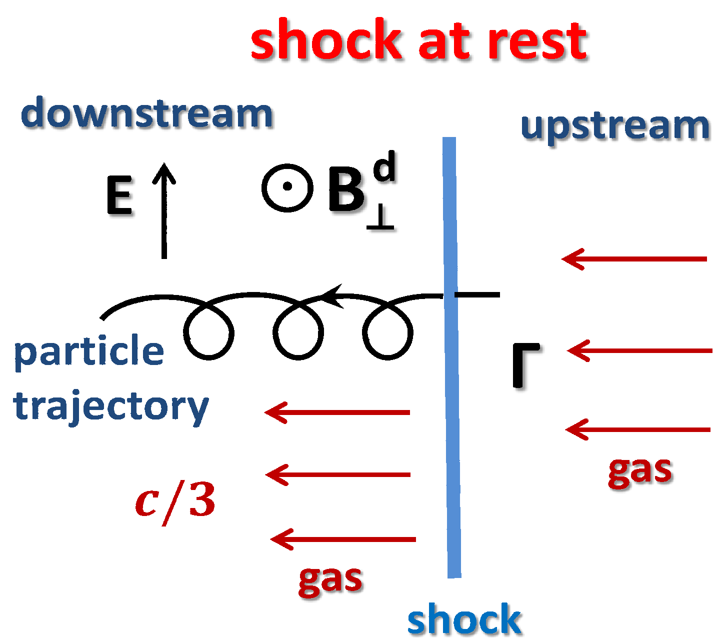


ACCELERATION IN RELATIVISTIC SHOCKS

is very promising because at single reflection a particle obtains $E \sim \Gamma_{\rm sh}^2 E_i$

Capturing of particles downstream:

- Perpendicular **large-scale** magnetic field $B_\perp^d$ is assumed.
- $B_\perp^d = \Gamma_s B_\perp^u$, $\vec{E}$ is induced.
- Drag of particles downstream by flow of the gas.
- Particles cannot return to upstream region.



Recent progress

Based on PIC simulations (Spitkovsky 2008, Sironi and Spitkovsky 2011) the small-scale microturbulence produced due to self-generated streaming instability results in repeating scattering between upstream and downstream (Fermi process) and in acceleration of particles (Lemoine and Pelletier 2010 - 2014, Bykov et al 2012, Reville and Bell 2014).

In the recent work by Reville and Bell (2014) the new element was included, the growth-rate time of instability. This rate is found to be very low and it strongly limits $E_{\max}$.

Cosmic-ray induced instabilities result in amplification of magnetic field on the scale of giroradius. As particles are accelerated the small-scale effects become insufficient and the mean large-scale magnetic field becomes the main effect. As was explained above accelerated particles are dragged by flow of the gas further downstream where particles are captured. $E_{\max}$ is detrmined by condition that isotropisation time reaches the Larmor time $r_L(E_{\max})/c$ (see next page).

B. Reville and A.R. Bell 2014

$$E_{\max} \approx \left(\frac{\Gamma_{\rm sh}}{100}\right)^2 \left(\frac{\lambda_d}{10c/\omega_{\rm pp}}\right) \left(\frac{\sigma_d}{10^{-2}}\right) \left(\frac{\sigma_u}{10^{-8}}\right)^{-1/2} \ {\rm PeV}$$

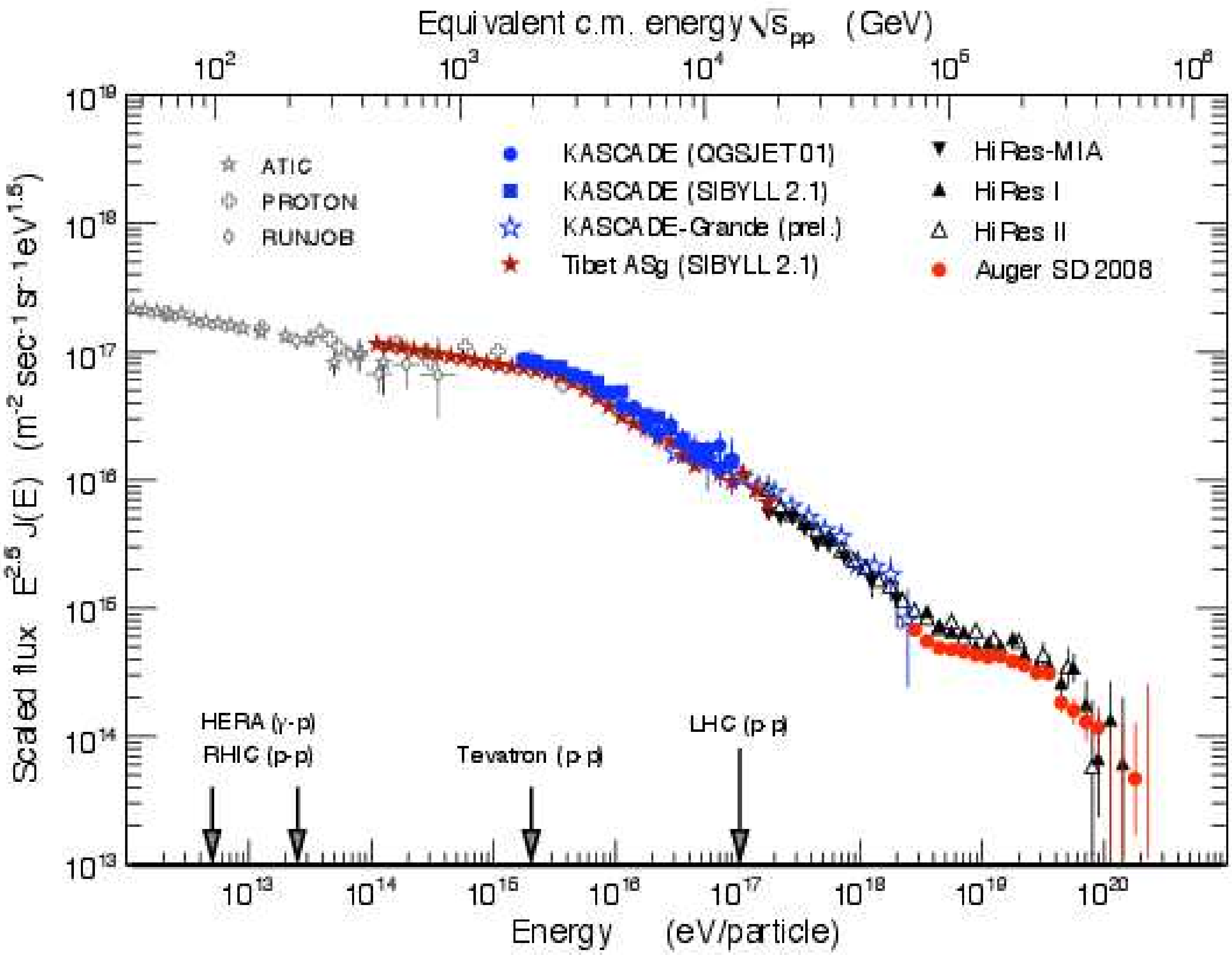
“The calculated growth-rates (of plasma instability) have insufficient time to modify the scattering, the acceleration to higher energies is ruled out.”

“Ultra-relativistic shocks are disfavoured as sources of high energy particles, in general.”

“.. this paper is not the first to suggest that GRBs are not the sources of UHECRs, but we gone one step further ..”

UHECR: propagation, signatures and mass composition

Spectrum and Features



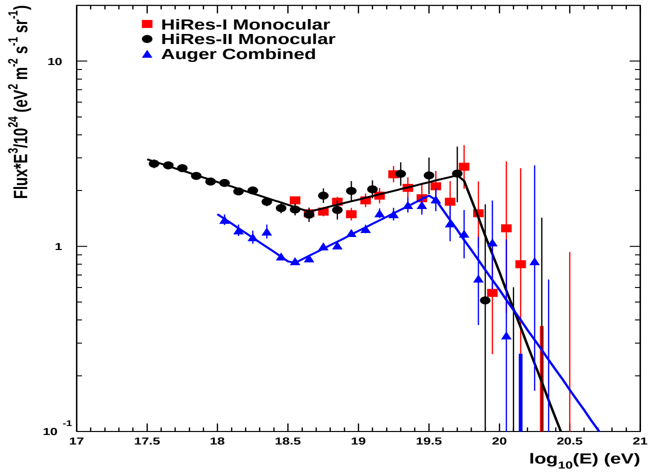
STATUS of ANKLE

In power-law approximation:

HiRes : $E_a = 4.5 \pm 0.5$ EeV

TA : $E_a = 4.9 \pm 0.3$ EeV

Auger : $E_a = 5.3 \pm 0.4$ EeV



Ankle can be explained as:

- **Transition** from galactic to extragalactic CRs
- intrinsic feature of **pair-production dip**

ANKLE is not a feature of transition

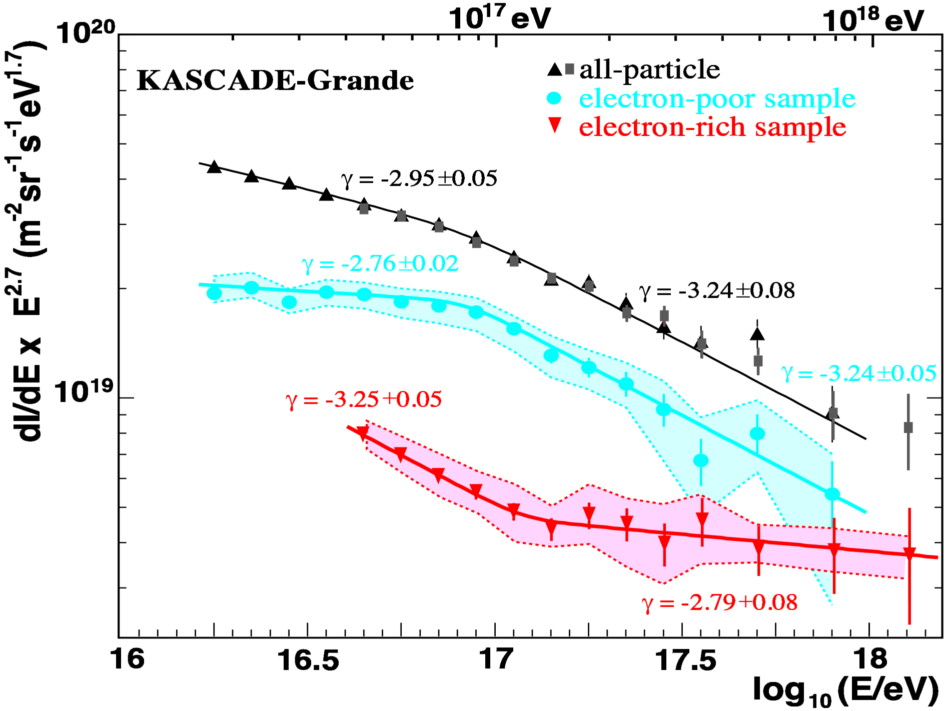
- At $1 - 4$ EeV, i.e. below the ankle, the mass composition according to all three detectors, Auger, TA and HiRes, is presented by protons (p) or **p + He**.
- In ankle model these particle are galactic.
- The measured anisotropy (Auger 2011) and MC simulations allows less than 10% of protons below the ankle, in contradiction with the ankle model.

Where is the transition ?

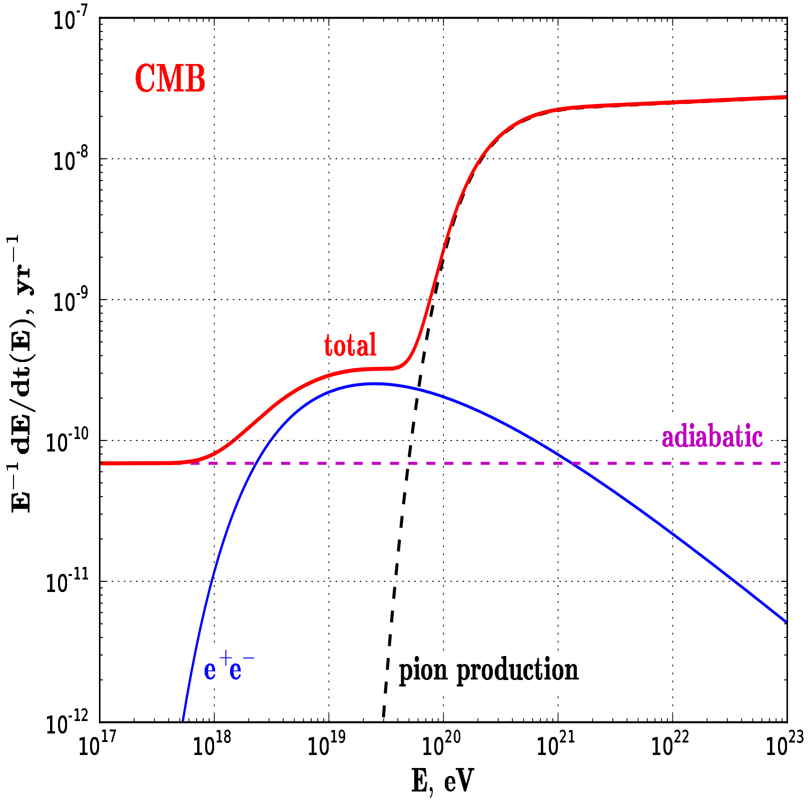
KASCADE-Grande found the light component with the following properties:

- p+He component at 0.1 - 1.0 EeV separated as 'electron-rich'
- extragalactic, otherwise anisotropy at $E \sim 1$ EeV.
- flat spectrum $\gamma = 2.79 \pm 0.08$, cf $\gamma = 3.24 \pm 0.08$ for total.

Hidden ankle transition

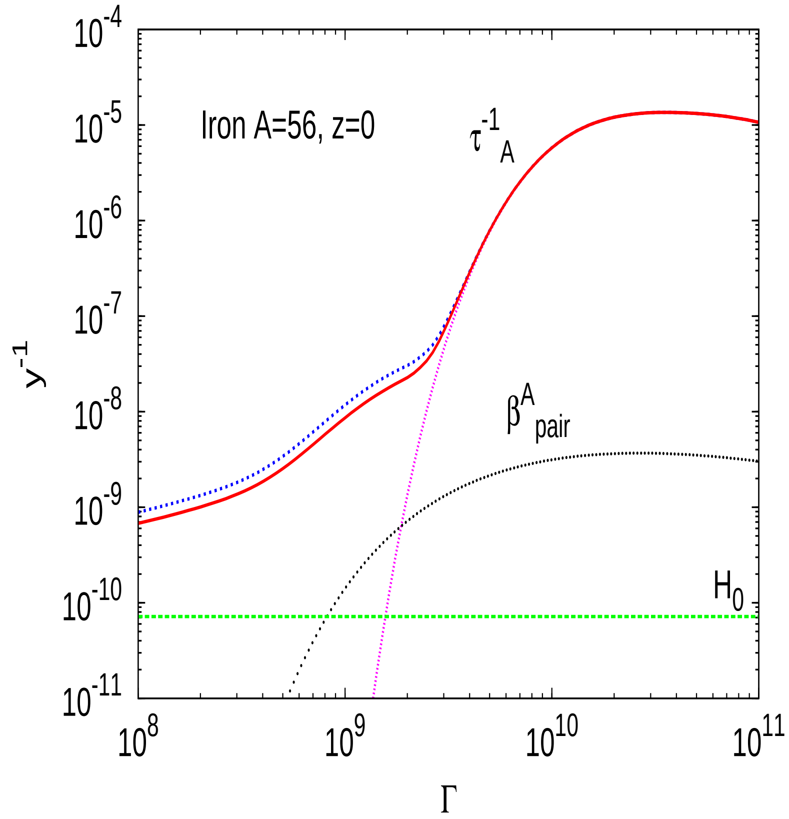


Signatures of particle propagation through CMB and EBL



$$E_{\mathrm{eq1}} = 2.4 \times 10^{18}\ \mathrm{eV}, \quad E_{\mathrm{eq2}} = 6.1 \times 10^{19}\ \mathrm{eV}$$

Pair-production dip and GZK cutoff.



Nuclei photo-dissociation: GR cutoff 1961.

$$\tau_A^{\mathrm{ebl}}(\Gamma_c) = \tau_A^{\mathrm{cmb}}(\Gamma_c)$$

UHE protons

INTERACTION SIGNATURES AND MODEL-DEPENDENT SIGNATURES

We want to see **observational signatures of interaction**, but in our calculations **model-dependent quantities** also appear, such as **distances** between sources, their cosmological **evolution**, modes of **propagation** (from rectilinear to diffusion), local source **overdensity** or **deficit** etc.

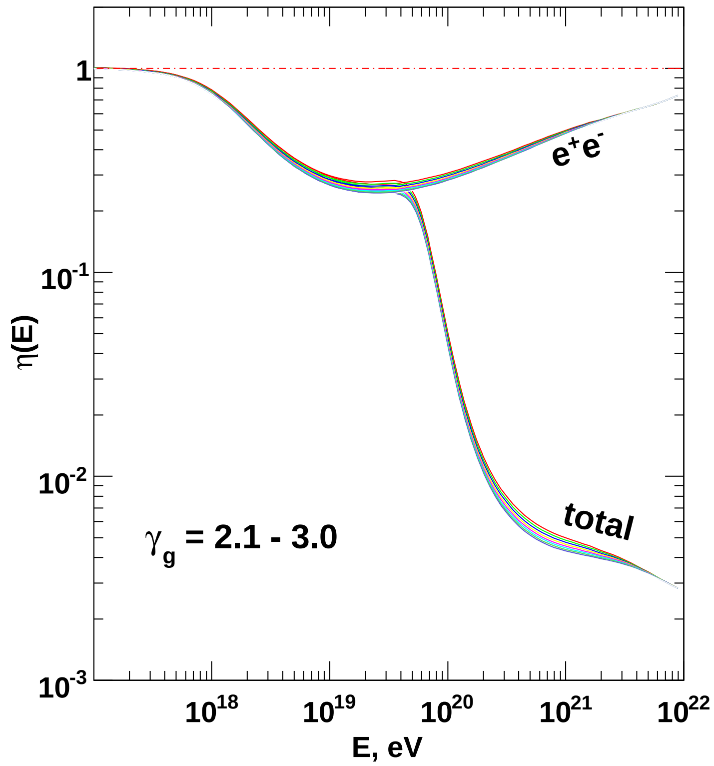
Energy spectrum in terms of **modification factor** characterizes well the **interaction signatures**.

MODIFICATION FACTOR

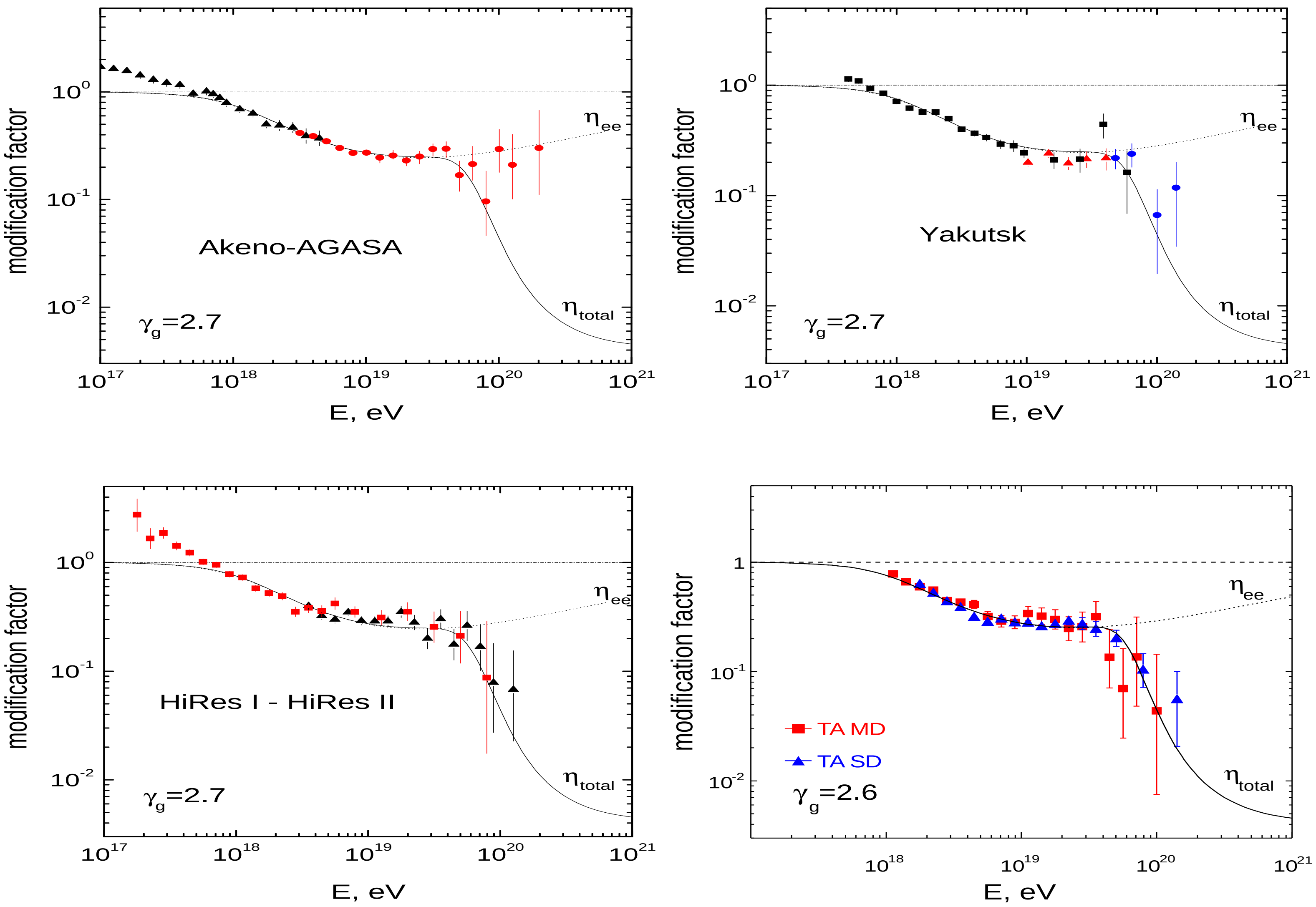
$$\eta(E) = \frac{J_p(E)}{J_p^{\rm unm}(E)}$$

where $J_p^{\rm unm}(E) = KE^{-\gamma_g}$ includes only adiabatic energy losses. Since many physical phenomena in numerator and denominator compensate or cancel each other, dip in terms of modification factor is less model-dependent than $J_p(E)$.

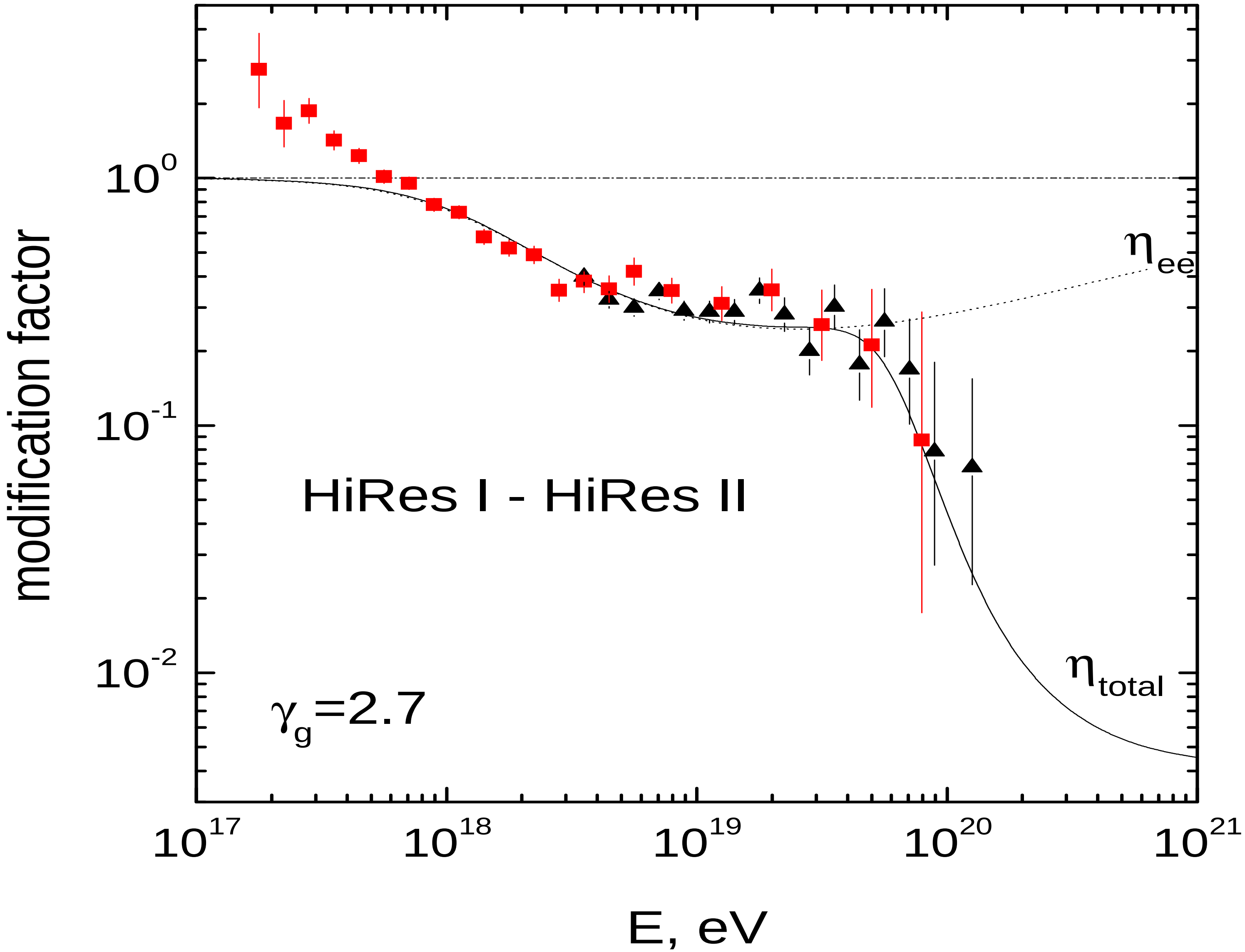
It depends very weakly on:
γ_g and $E_{\rm max}$,
modes of propagation (rect or diff),
large-scale source inhomogeneity,
source separation within 1-50 Mpc,
local source overdensity or deficit,..
It is modified by presence of nuclei ($\gtrsim 15\%$).
Experimental modification factor:
$\eta_{\rm exp}(E) = J_{\rm obs}(E)/KE^{-\gamma_g}$.



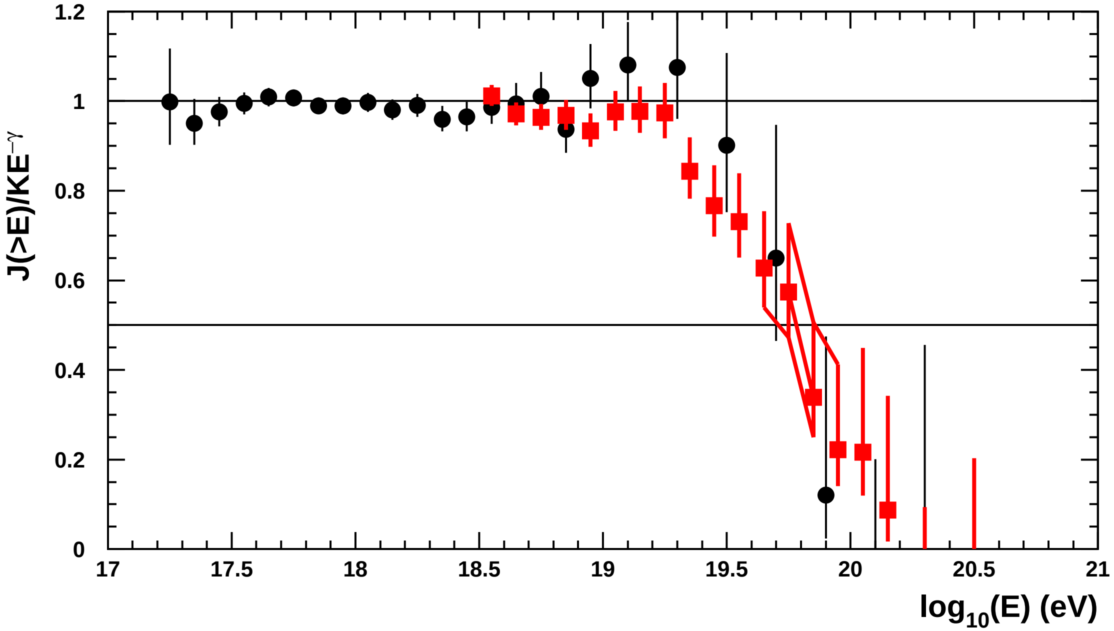
Comparison of pair-production dip with observations



GZK CUTOFF IN HiRes DIFFERENTIAL SPECTRUM



GZK CUTOFF IN HiRes INTEGRAL SPECTRUM



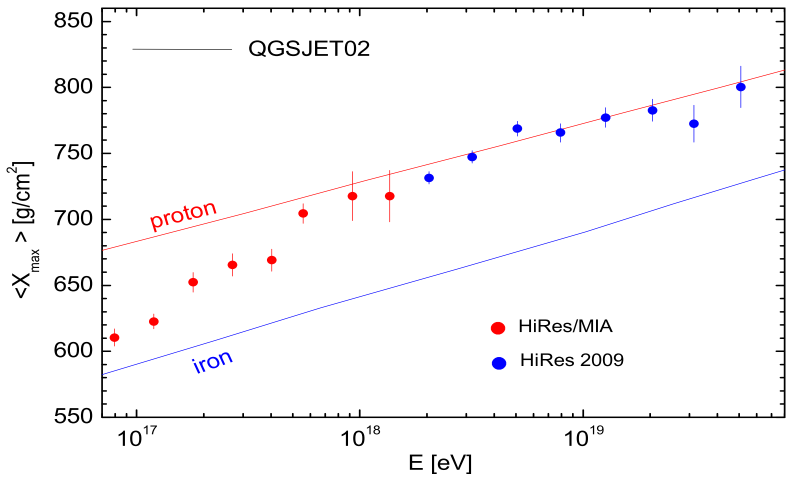
$E_{1/2}$ in HiRes **integral** spectrum confirms that steepening in the differential spectrum is the GZK cutoff:

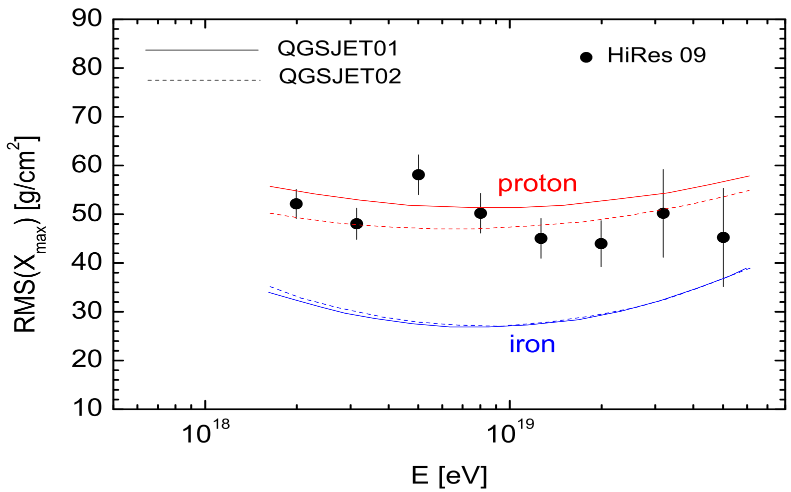
$$\mathrm{E}^{\mathrm{meas}}_{\mathbf{1/2}} = \mathbf{10^{19.73\pm0.07}}\ \mathrm{eV} \quad \mathrm{cf} \quad \mathrm{E}^{\mathrm{theor}}_{\mathbf{1/2}} = \mathbf{10^{19.72}}\ \mathrm{eV}$$

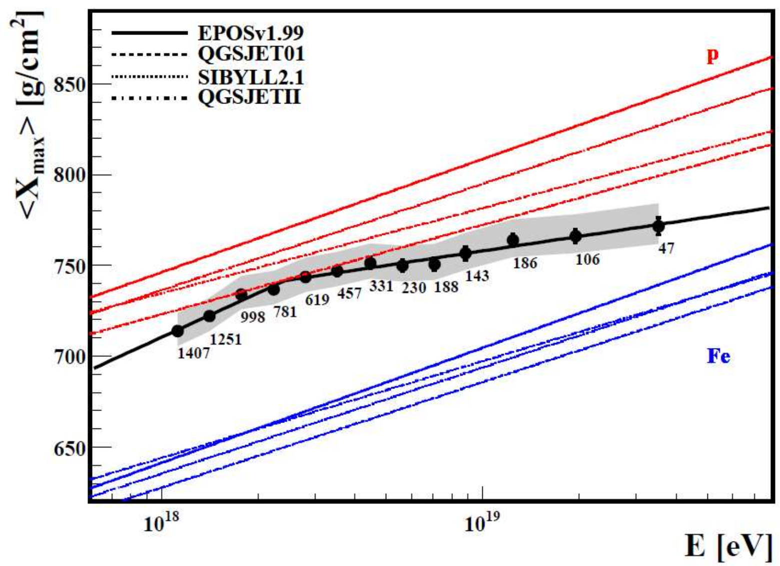
DIRECT MEASUREMENTS OF MASS COMPOSITION

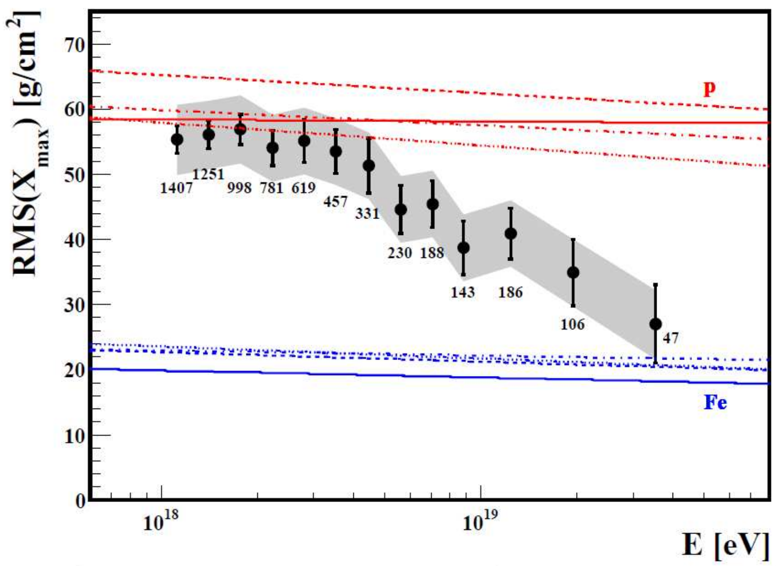
is a necessary component of consistent picture

MASS COMPOSITION: HIRES (top) vs AUGER (bottom)







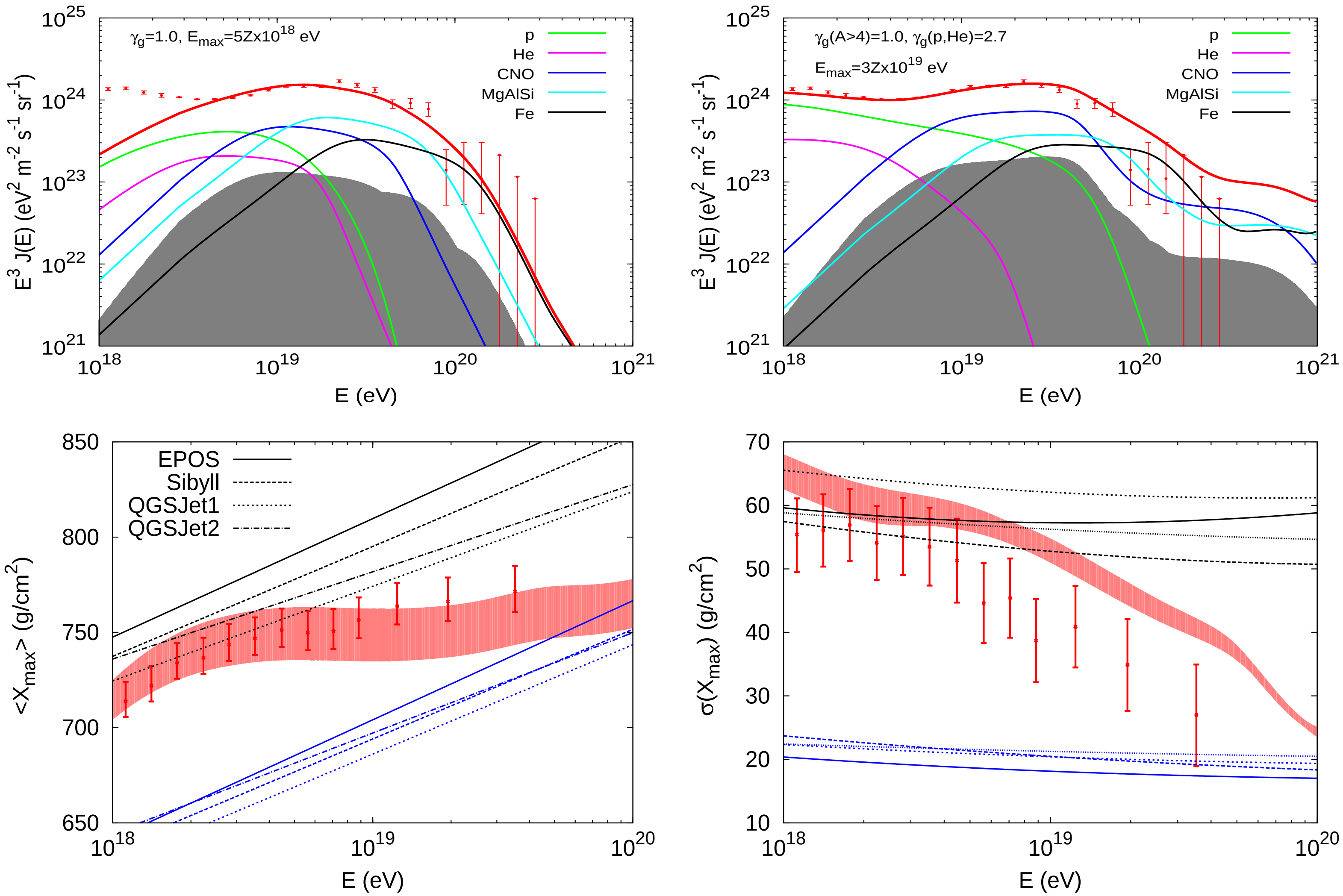


Interpretation of Auger spectrum and mass composition

Aloisio, V.B., Blasi (2013), see also Taylor, Ahlers, Aharonian (2012).

$\gamma_g = 1.0, \;\; E_{\max} = 5Z$ EeV

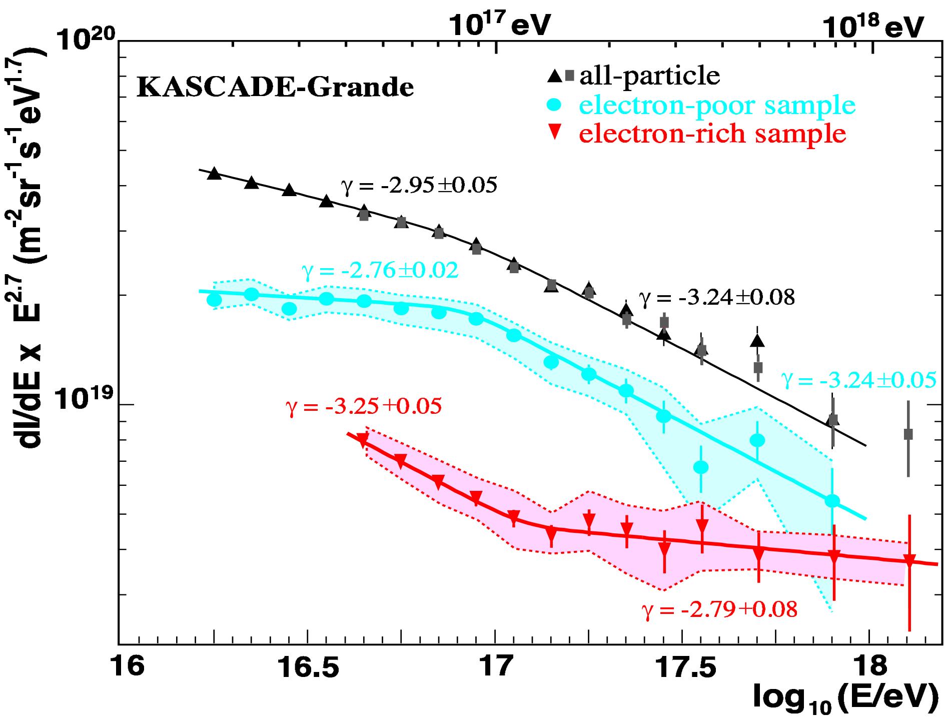
$\gamma_g(p, He) = 2.7$



Impact of KASCADE-Grande experiment

KASCADE-Grande found the light component with the following properties:

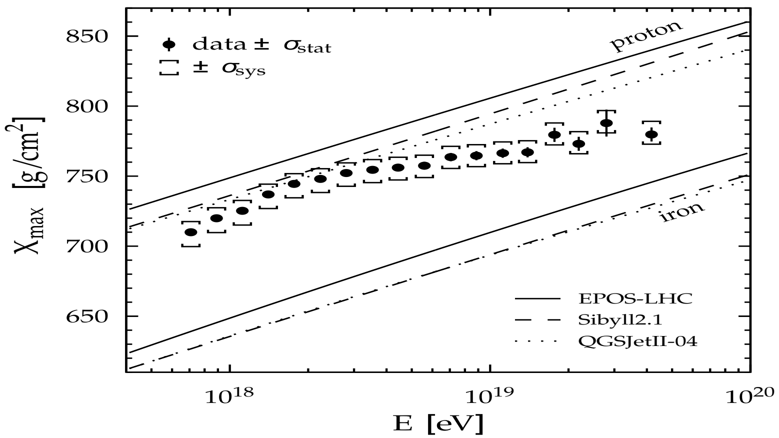
- p+He component at 0.1 - 1.0 EeV separated as 'electron-rich'
- extragalactic, otherwise anisotropy at $E \sim 1$ EeV.
- flat spectrum $\gamma = 2.79 \pm 0.08$, cf $\gamma = 3.24 \pm 0.08$ for total.
- p+Fe at $E \sim 1$ EeV with equal fractions contradict new Auger data.

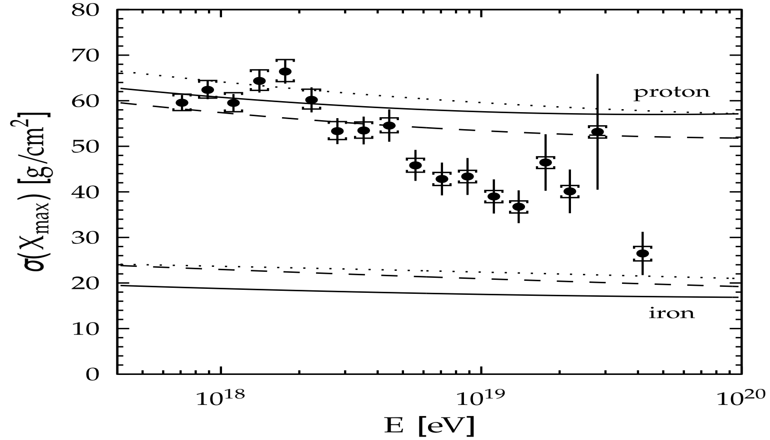


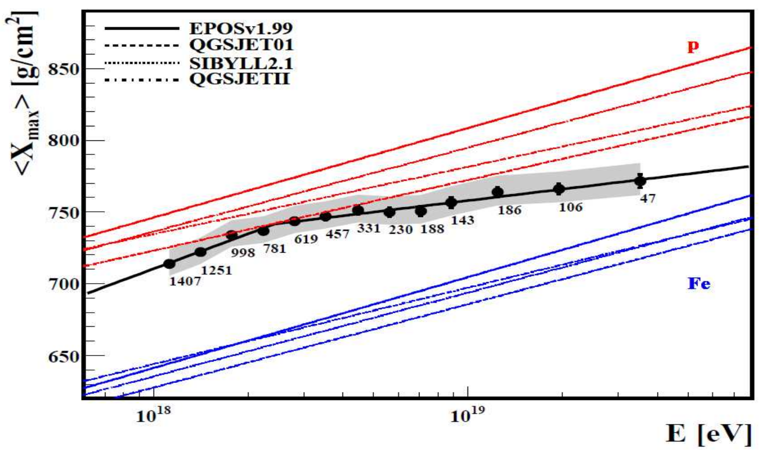
AUGER MASS COMPOSITION, September 2014

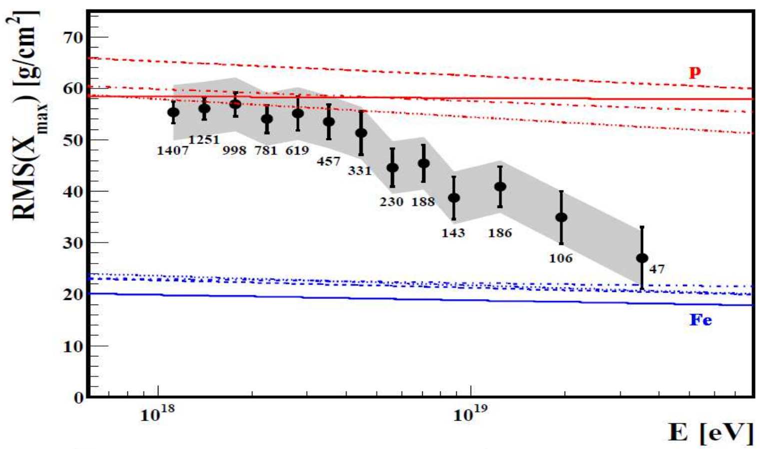
important step further with a new method of determination of fraction of nuclei !!!

Xmax and RMS Sept. 2014



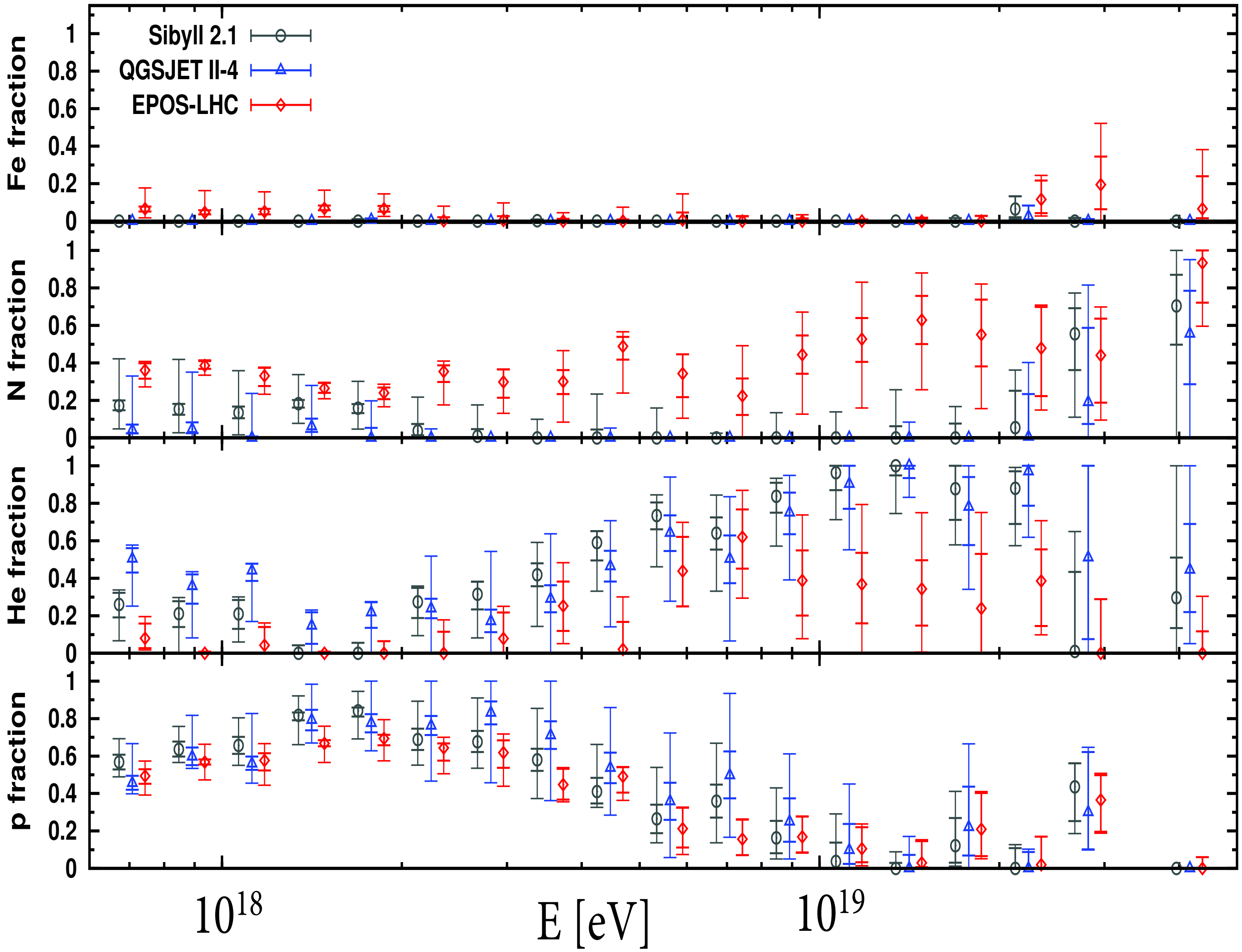






RMS at 35 EeV needs a large fraction of Fe (see next page).

Iron and Proton fractions



New Auger results and conclusions

- **p+He is dominant composition up to 10 EeV with a small fraction of intermediate nuclei increasing up to highest energies.**
- **Proton fraction is observed at all energies. It is dominant (60 - 80)% up to 2 EeV, falling down at 4 EeV, with minimum at (10-20) EeV and with resurgence at higher energies.**
- **The presence of proton component at all energies excludes rigidity-dependent $E_{\rm max}$ with $E_p^{\rm max}$ around (4 - 5) EeV, widely used in most astrophysical models.**
- **Since protons below 40 EeV are extragalactic, ankle as transition from galactic to extragalactic CRs is excluded.**
- **Iron fraction is consistent with zero at all energies in contradiction with RMS at 35 EeV.**

CONCLUSIONS

- **The propagation signatures for protons are pair-production dip ($p+\gamma_{\rm cmb} \to p+e^{+}+e^{-}$) and GZK cutoff ($p+\gamma_{\rm cmb} \to N+\pi$).**
- **The propagation signature for nuclei is GR cutoff with $\Gamma_c \approx (3-4)\times 10^{9}$ for all nuclei, and $E_{\rm GR} \approx A\Gamma_c m_N \approx (3-4)A \times 10^{18}$ eV.**
- **HiRes and TA observed the the proton signatures further confirmed by proton-dominated mass composition.**
- **Until 2014 Auger reported the nuclei composition steadily heavier with increasing energy. The models which explain simultaneously the Auger energy spectrum, $X_{\rm max}(E)$ and RMS (dispersion) must have very flat generation spectrum $\gamma_g < 1.6$ and additional EeV proton+He component with steep spectrum.**

- **The main problem of UHECR at present is contradiction between HiRes/TA and PAO data on mass composition at $E > 4$ EeV which is less pronounced now with the new 2014 Auger data. Dominance of p+He composition at all energies may be a compromise between TA and Auger data.**

- **Detection of nearby sources at distance 60 - 80 Mpc (Taylor, Ahlers, Aharonian 2011) may solve the UHECR puzzle. The sources are characterised by combination of high $E_{\max}$ and L. AGN satisfy this criterion, GRB - not.**