HOT PROBLEMS in UHECR

V. Berezinsky

INFN, Gran Sasso Science Institute and Laboratori Nazionali del Gran Sasso, Italy

- **acceleration**
- **propagation and spectra**
- **protons: interaction signatures**
- **mass composition**

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 topological defects. 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

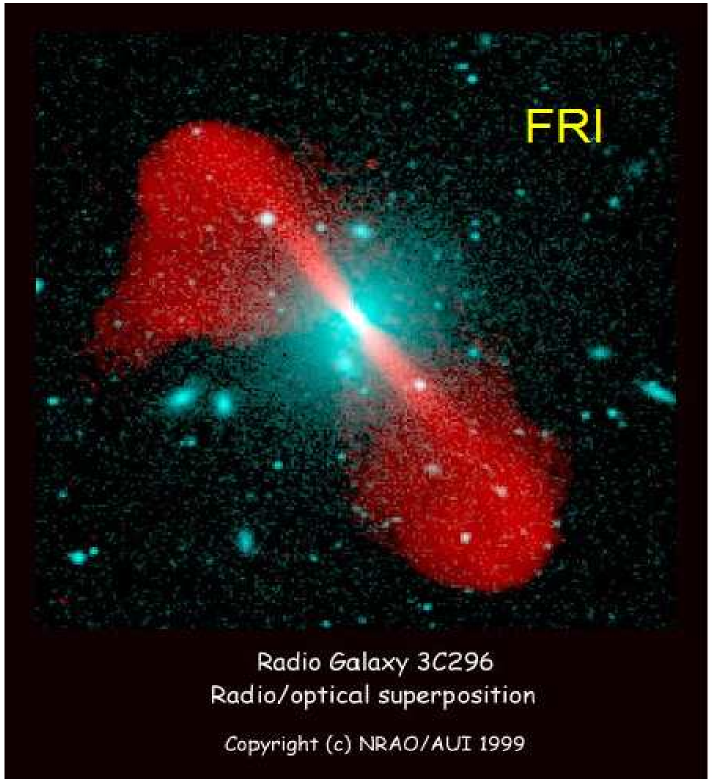
Biermann and Strittmatter 1987, Norman, Melrose, Achtenberg 1995, Ptuskin, Rogovaya, Zirakashvili, 2013

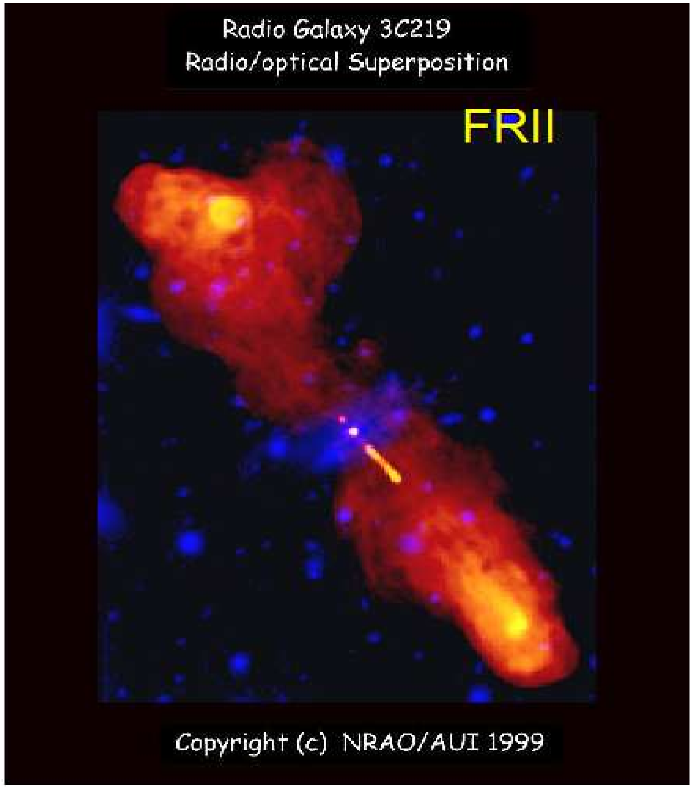
$E_{\max}$ from two conditions:
$E_{\max} = ZeB\beta_s R_s$ (Hillas criterion) and
$B^2/8\pi = \omega_{\rm part}$ or $B^2/8\pi \approx L/\pi R_s^2 c\beta$ (equipartition), results in

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

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

Detective story in five acts

act 1

GREAT EXCITEMENT

In a single reflection particle obtains

$$E \propto \Gamma_{\rm sh}^2 \, E_i$$

act 2

Efficiency in further crossings is low

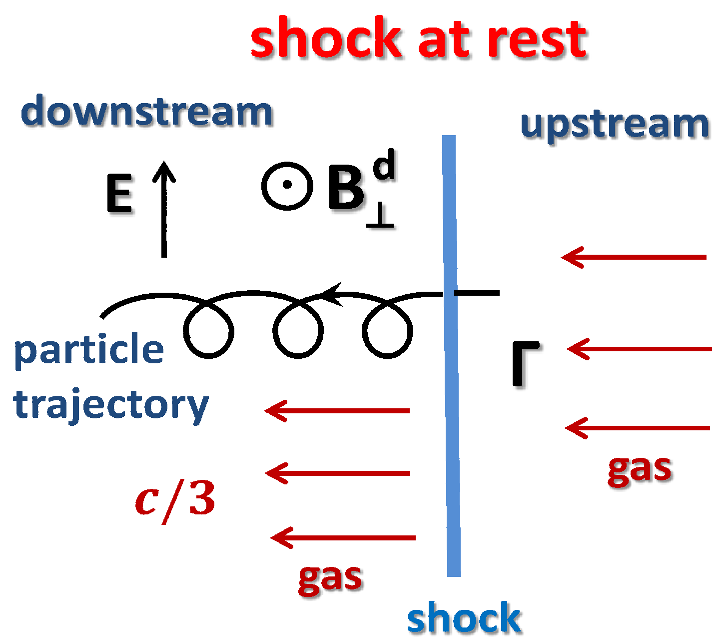
$$E \sim \Gamma_{\rm sh}^2 \xi^n \ E_i \quad \text{with} \quad \xi \approx 1.7$$

act 3

full disaster !!

Capturing of particles downstream

- Perpendicular **large-scale** magnetic field $B_{\perp}^{d}$.
- $B_{\perp}^{d} = \Gamma_s B_{\perp}^{u}, \quad \vec{E}$ is induced.
- Drag of particles downstream by flow of gas (**quasi-helical orbits**).
- **Particles cannot return to up-stream region.**



act 4

Γ^2-Acceleration Renaissance 2011

Sironi and Spitkovsky (2011) found in low-magnetised plasma

$$\sigma = \frac{B^2}{4\pi n m_p c^2} \ll 1,$$

streaming (Weibel) instability which results in production of small-scale turbulence with size

$$\lambda \sim c/\omega_{pp} \sim 10.$$

Scattering of particles on these micro-turbulences results in repeating transition between downstream and upstream regions and thus in Fermi regime of acceleration. (Lemoine and Pelletier 2010 -2014, Bykov et al 2012, Reville and Bell 2014).

act 5

Epilogue 2015

Reville and Bell 2014 included in calculations the new element, the growth time of instability. There are two competing processes: isotropisation of particles due to scattering and drift of particles downstream, with characteristic times D_θ^{-1} and R_L/c, respectively. Acceleration occurs when $D_\theta^{-1} < R_L/c$, and Emax of acceleration is determined by equality of these quantities.

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

The allowed Emax is too small.

B. Reville and A.R. Bell 2014

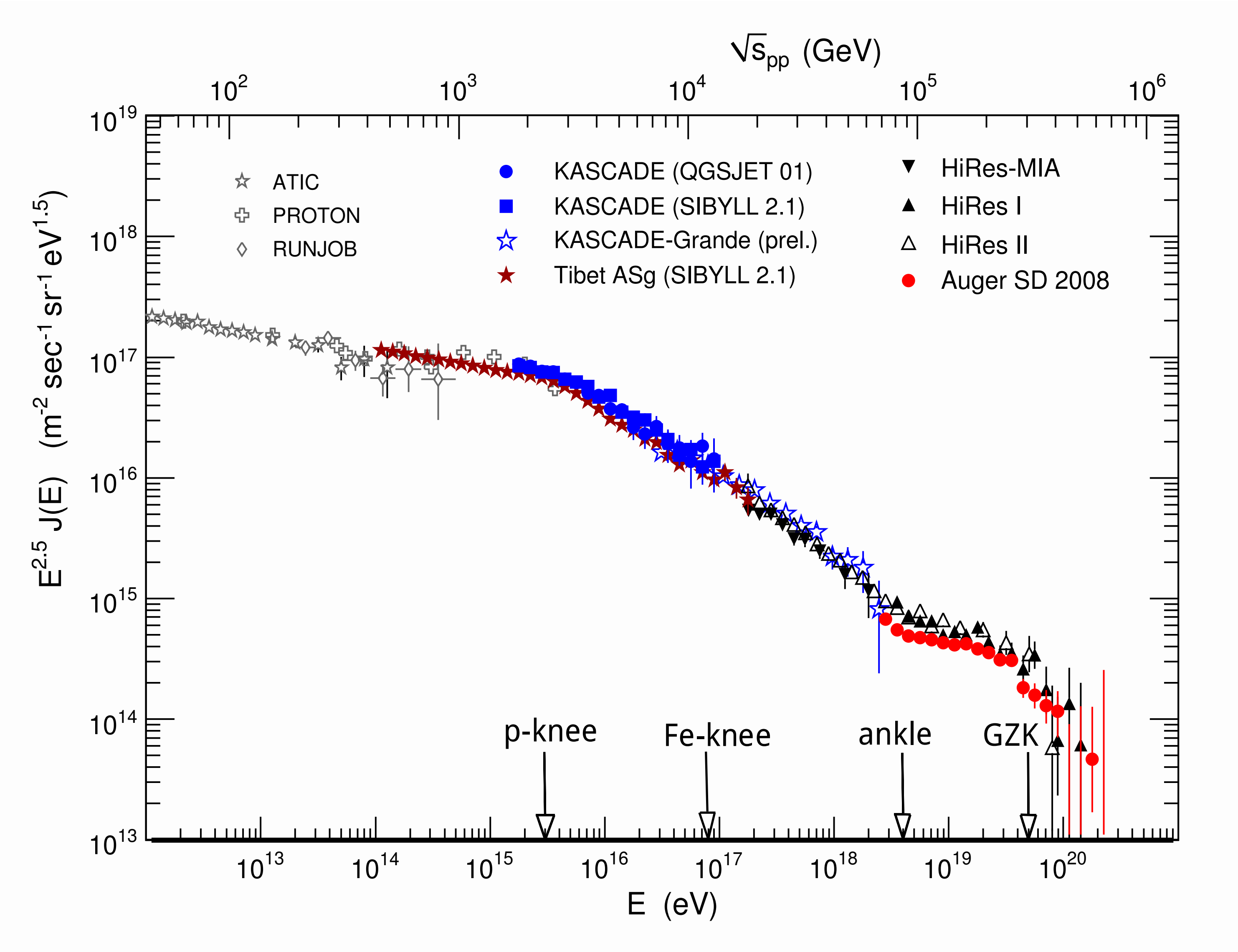
“The calculated growth-rates (of plasma instability) have insufficient time to modify the scattering, the acceleration to higher energies is ruled out.”

“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 and its signatures

Spectrum and Spectral Features

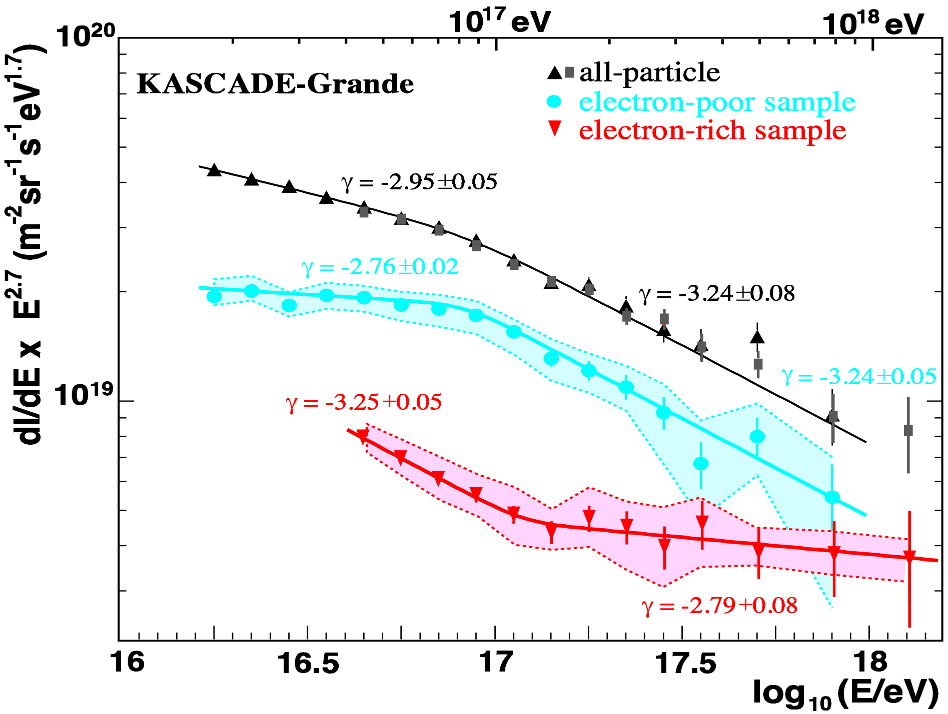


Where is the transition ?

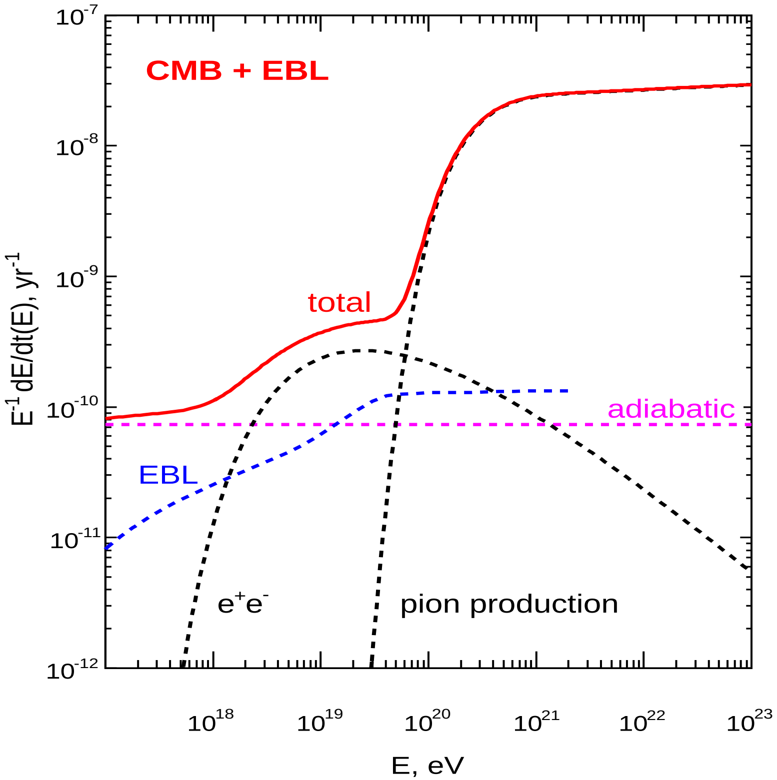
KASCADE-Grande found the light component with the following properties:

- **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

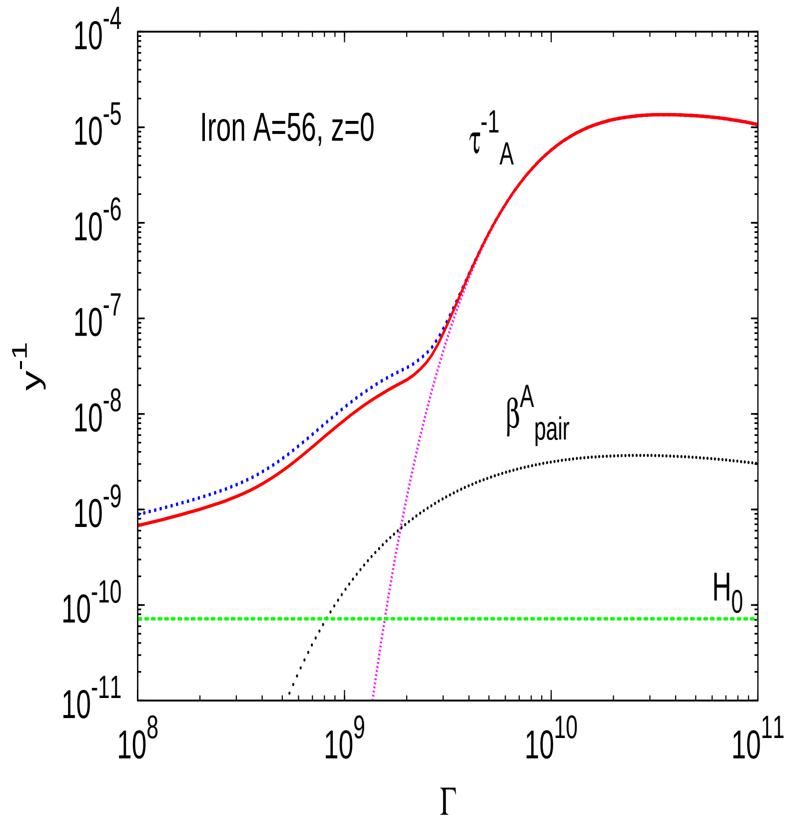


Signatures of particle propagation through CMB and EBL



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

Pair-production dip and GZK cutoff.



Nuclei photo-dissociation: GR cutoff 1961.

$$\tau_A^{\rm ebl}(\Gamma_c) = \tau_A^{\rm cmb}(\Gamma_c)$$
$$\Gamma_c = 3.2 \times 10^9, \quad E_c = 1.8 \times 10^{20}\ \textbf{eV}$$

•

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.

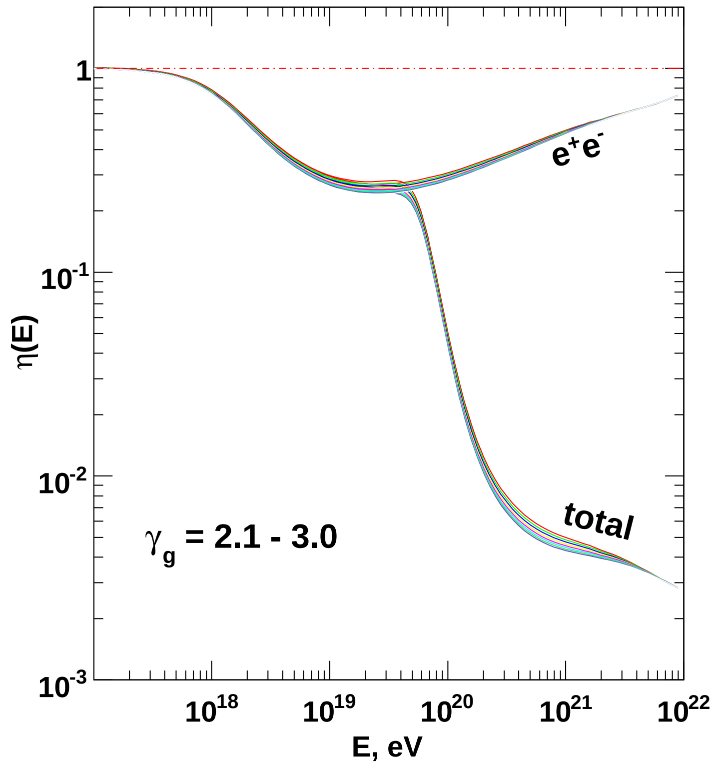
Energy spectrum in terms of modification factor characterizes well the interaction signatures.

MODIFICATION FACTOR

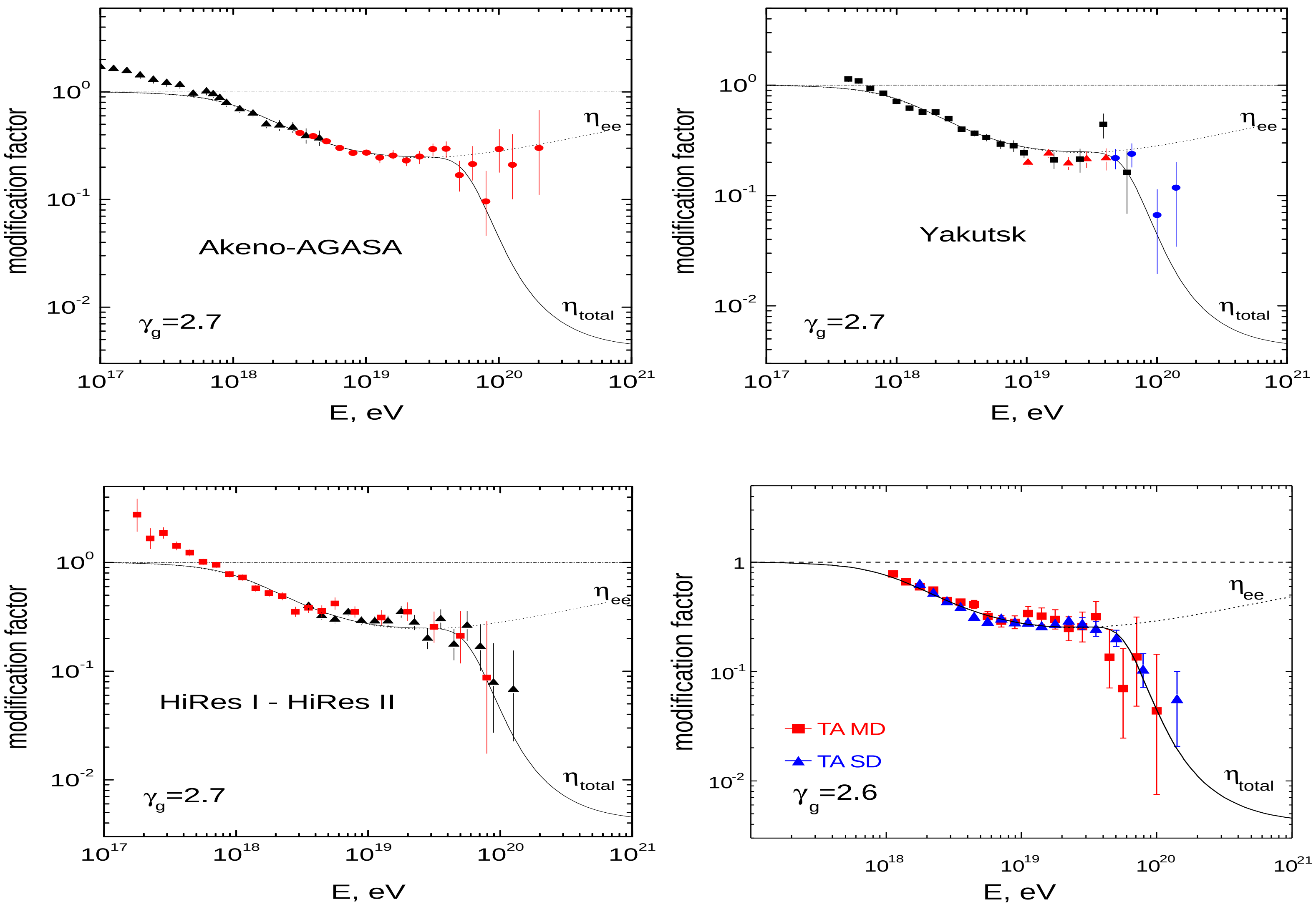
$$\eta(E) = \frac{J_p(E)}{J_p^{\rm unm}(E)}$$

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 $J_p(E)$.

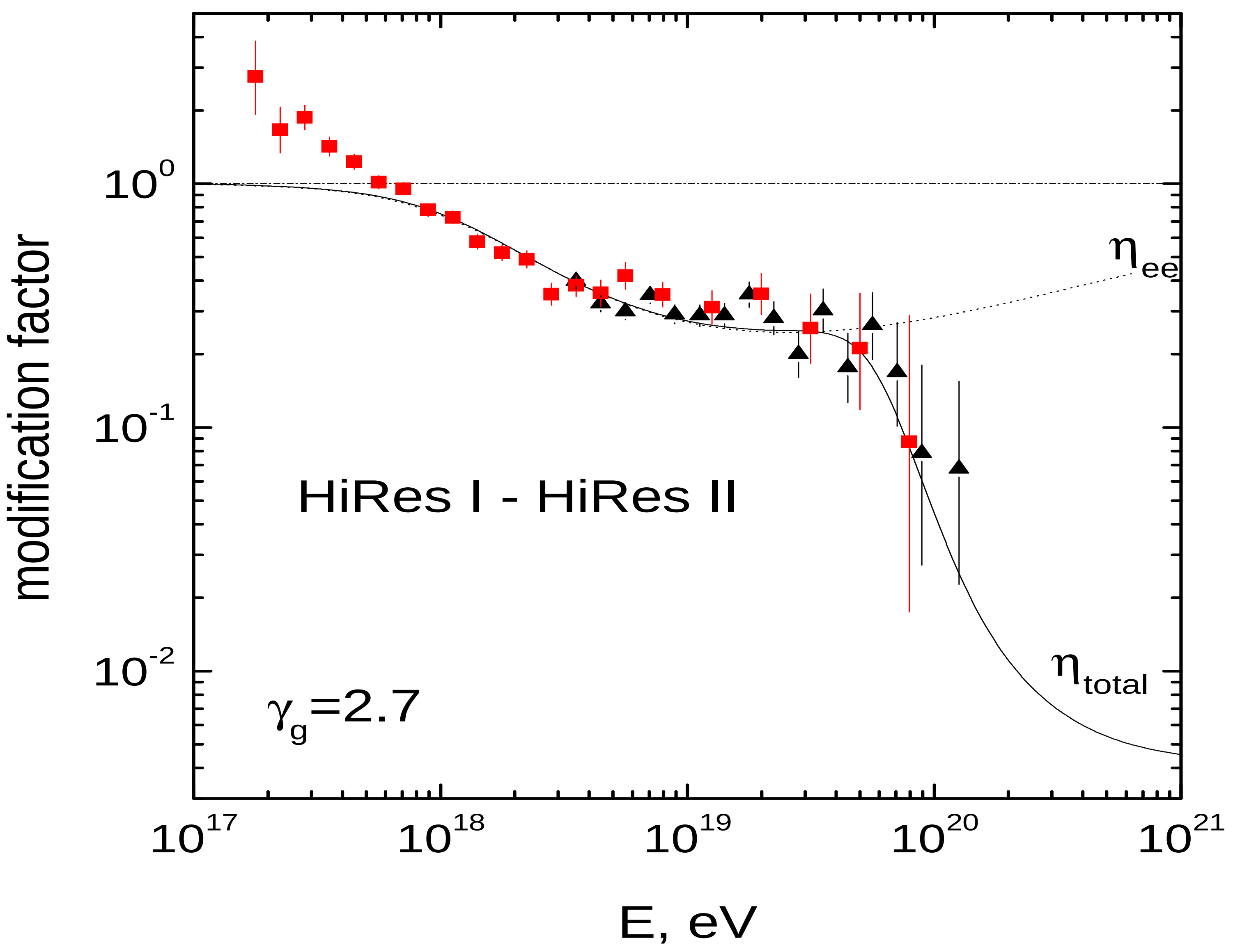
It depends very weakly on:
γ_g and $E_{\max}$,
modes of propagation (rect or diff),
large-scale source inhomogeneity,
source separation within 1-50 Mpc,
local source overdensity or deficit,..
It is modified by presence of nuclei ($\gtrsim 15\%$).
Experimental modification factor:
$\eta_{\rm exp}(E) =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



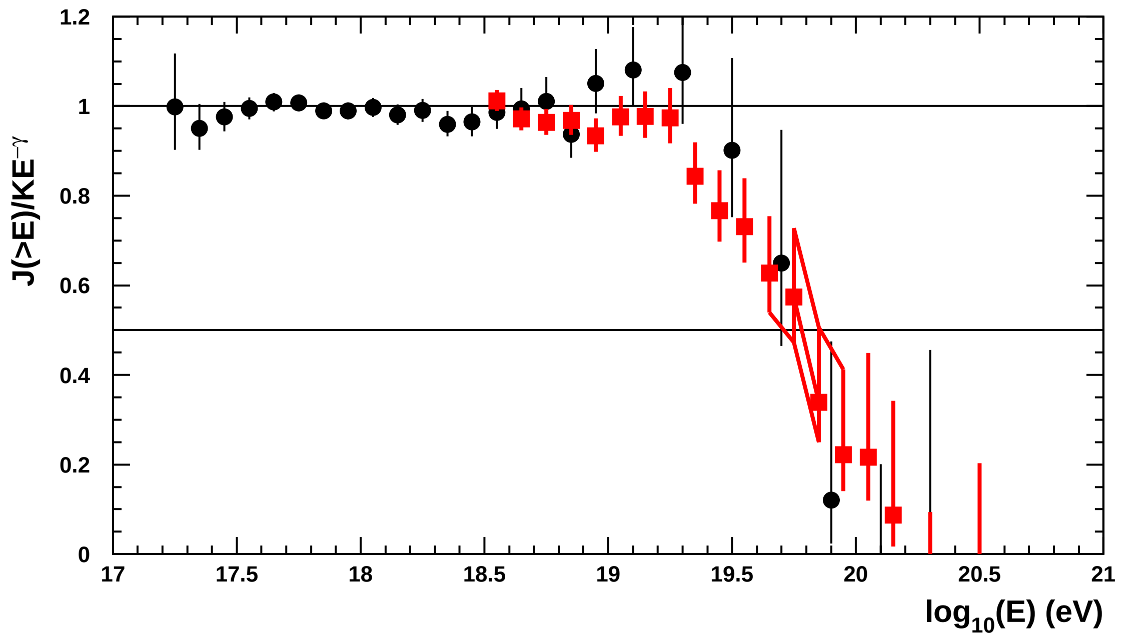
Comparison of pair-production dip with observations



GZK CUTOFF IN HiRes DIFFERENTIAL SPECTRUM



GZK CUTOFF IN HiRes INTEGRAL SPECTRUM



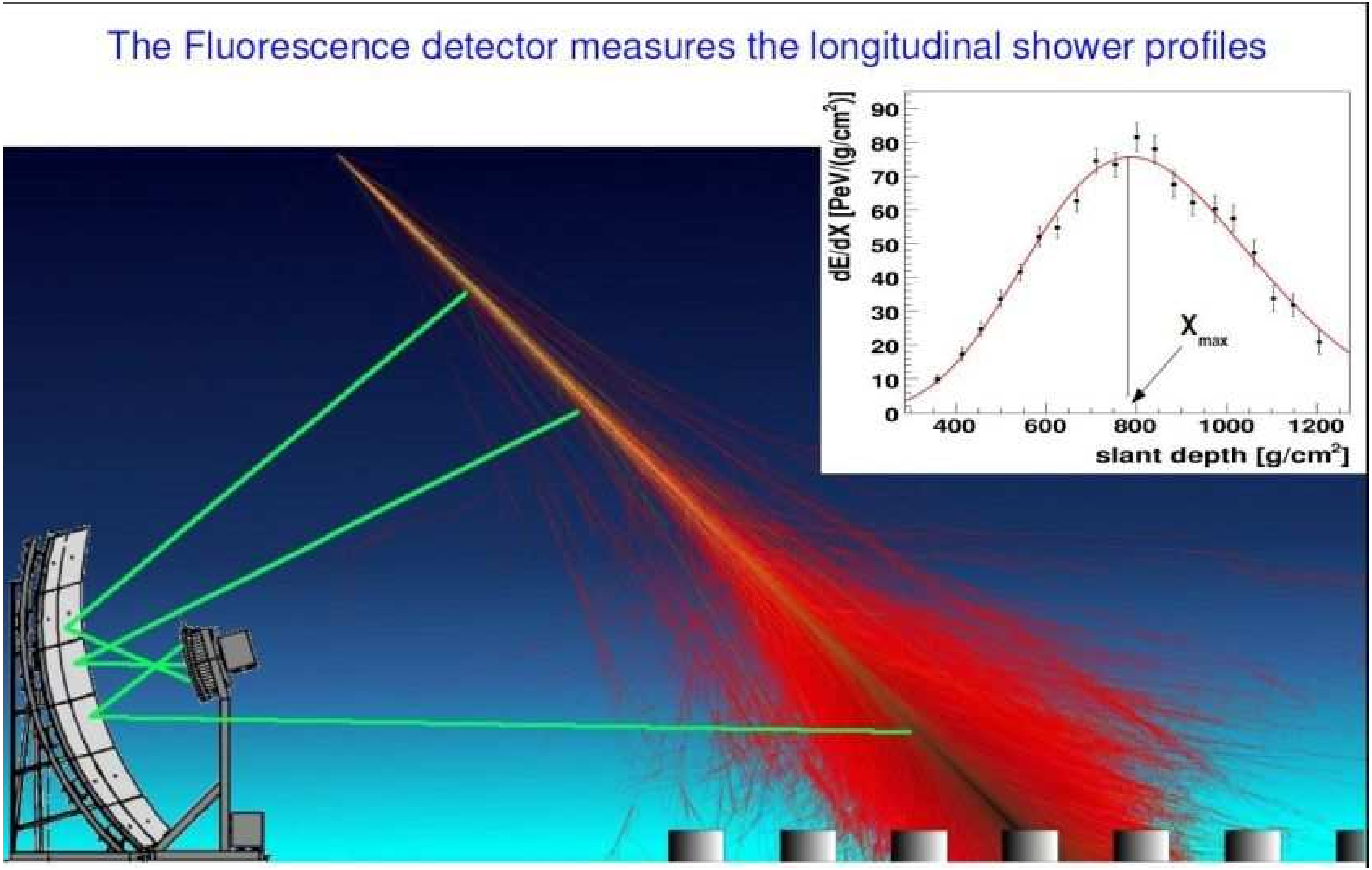
$E_{1/2}$ in HiRes integral spectrum confirms that steepening in the differential spectrum is the GZK cutoff:

$$E_{1/2}^{meas} = 10^{19.73 \pm 0.07}\ \mathrm{eV} \quad \mathrm{cf} \quad E_{1/2}^{theor} = 10^{19.72}\ \mathrm{eV}$$

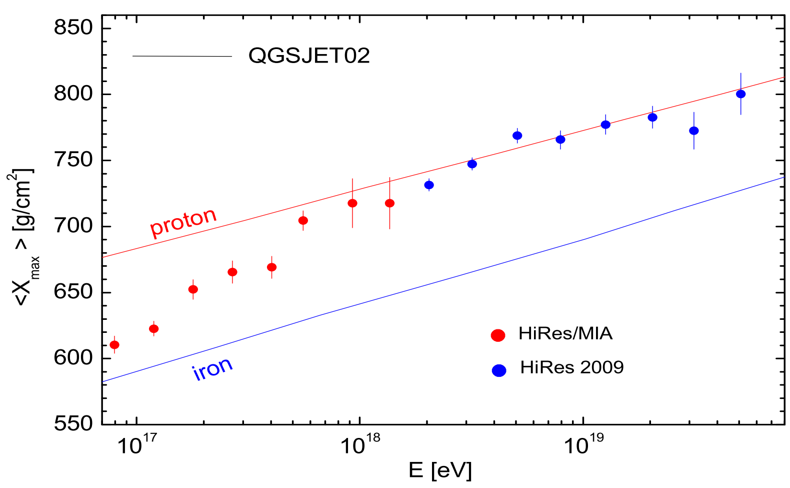
DIRECT MEASUREMENTS OF MASS COMPOSITION

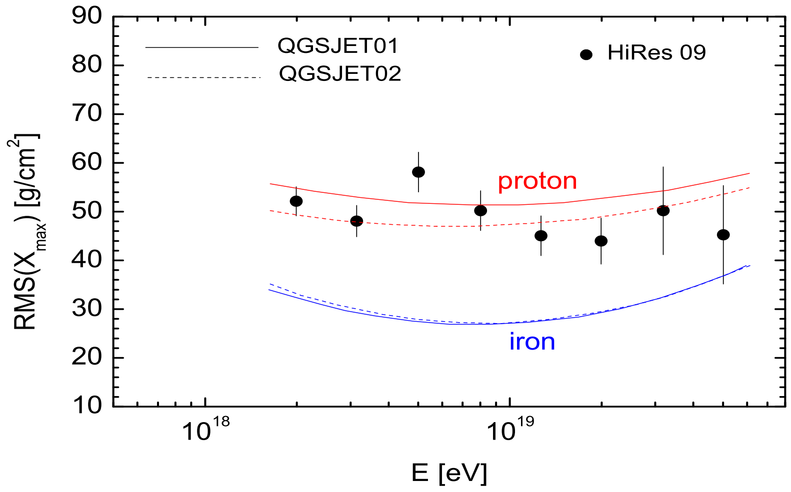
is a necessary component of consistent picture

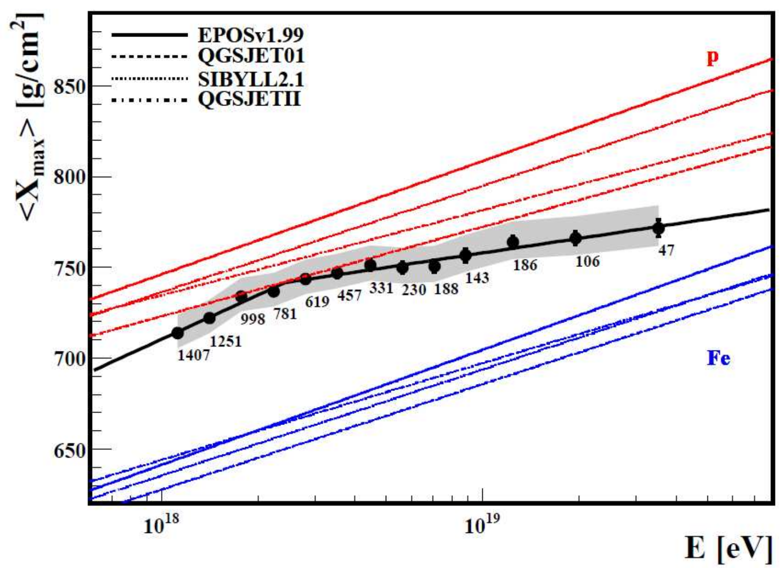
Calorimetric measurement of mass composition

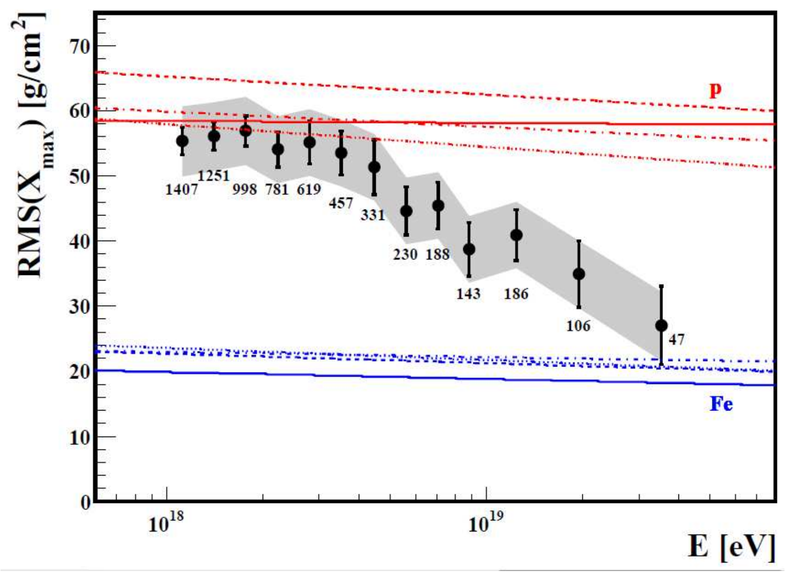


MASS COMPOSITION: HIRES (top) vs AUGER (bottom)





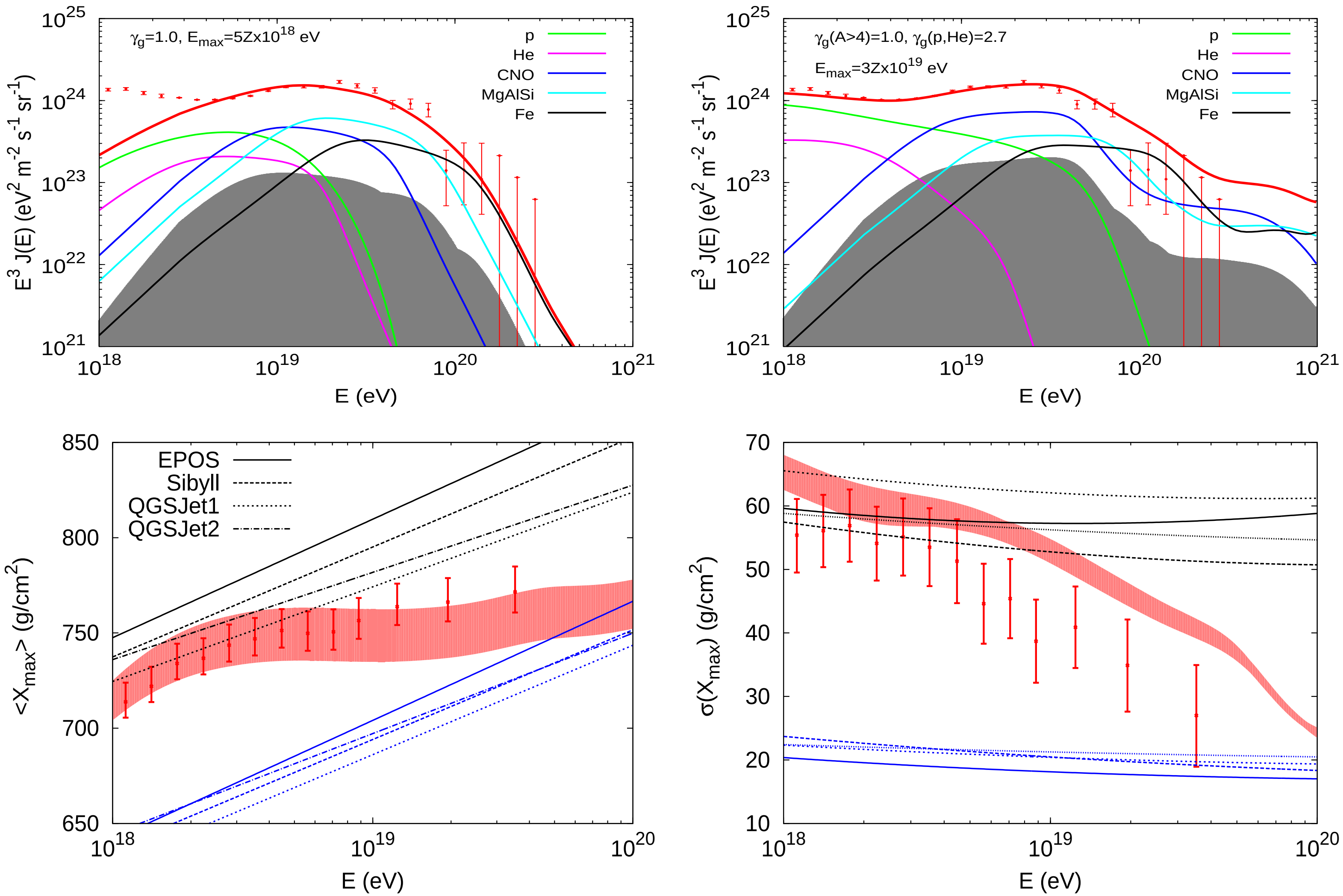




Interpretation of Auger spectrum and mass composition

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

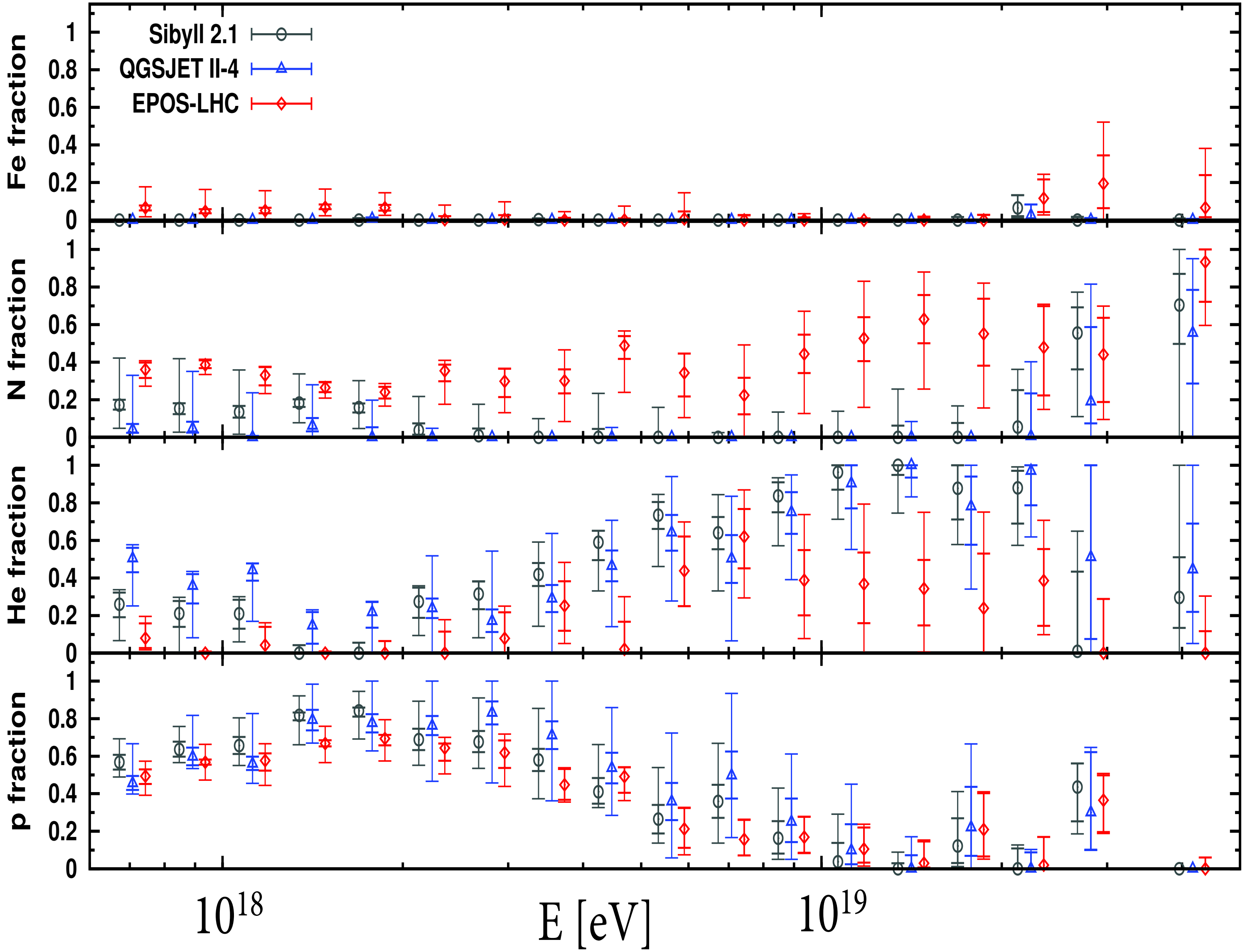
$\gamma_g = 1.0,\ E_{\max} = 5Z$ **EeV** $\qquad\qquad \gamma_g(p, He) = 2.7$



AUGER MASS COMPOSITION, September 2014

Phys. Rev. D 90 (2014) 122005

Iron and Proton fractions



Auger 2014: summary

- p+He is dominant composition up to 10 EeV with 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 models.
- Since protons below 40 EeV are extragalactic, ankle as transition from galactic to extragalactic CRs is excluded.
- Iron fraction is very small at all energies

CONCLUSIONS

- **The propagation signatures for protons are pair-production dip ($p+\gamma_{\rm cmb} \to p+e^{+}+e^{-}$) and GZK cutoff ($p+\gamma_{\rm cmb} \to N+\pi$).**

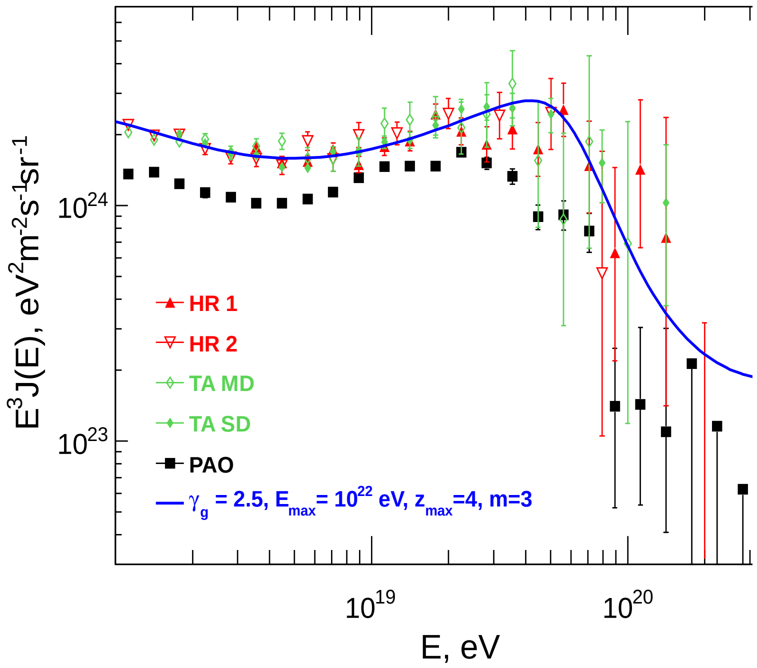
- **The propagation signature for nuclei is GR cutoff with $\Gamma_c \approx (3-4)\times 10^9$ for all nuclei, and $E_{\rm GR} \approx A\Gamma_c m_N \approx (3-4)A \times 10^{18}$ eV.**
- **HiRes and TA observed the the proton signatures further confirmed by proton-dominated mass composition.**

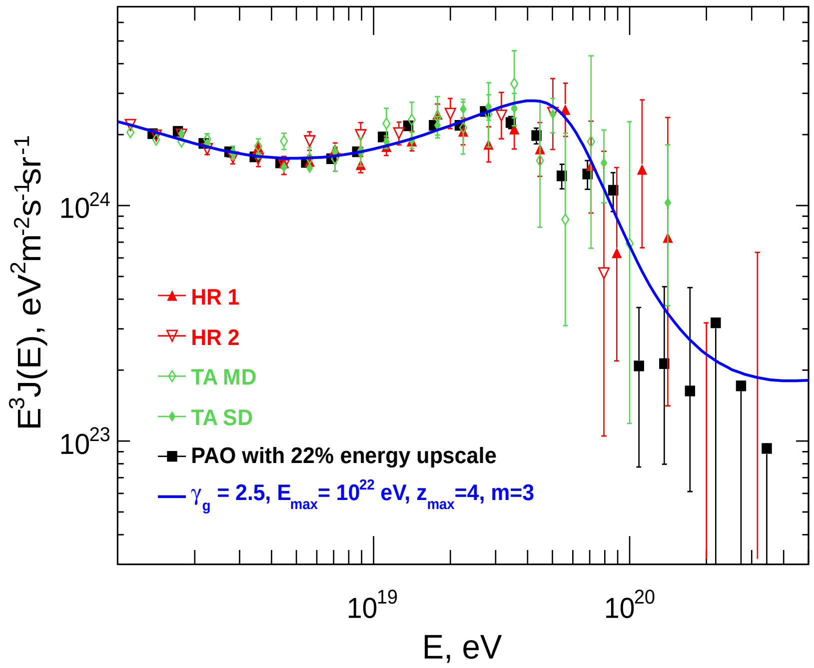
- **Auger (2013) reports the nuclei composition steadily heavier with increasing energy. The models which explain simultaneously the Auger energy spectrum, $X_{\rm max}(E)$ and RMS (dispersion) must have very flat generation spectrum $\gamma_g < 1.6$ and additional EeV proton+He component with steep spectrum.**

THANK YOU !!

PAIR-PRODUCTION DIP in Auger data

Energy scale of each detector has to be shifted by factor λ to minimize χ^2. For HiRes and TA $\lambda \approx 1$. To reach $\chi^2_{\rm min}$ for PAO $\lambda = 1.22$ is needed. Equality of fluxes after recalibration is confirmation of pair-production nature of the dip.



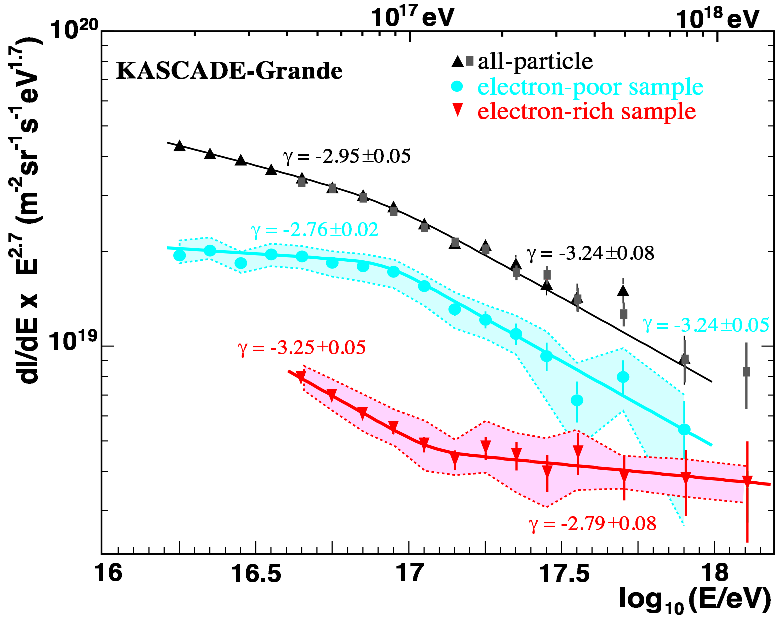


STATUS of ANKLE

Two competitive scenarios:
ankle as transition and ankle as intrinsic feature of the dip.
Auger, HiRes, TA: $E_a = (4-5)$ **EeV and at** $E < E_a$**: light nuclei**

Ankle as transition

Where is the transition ?



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.**