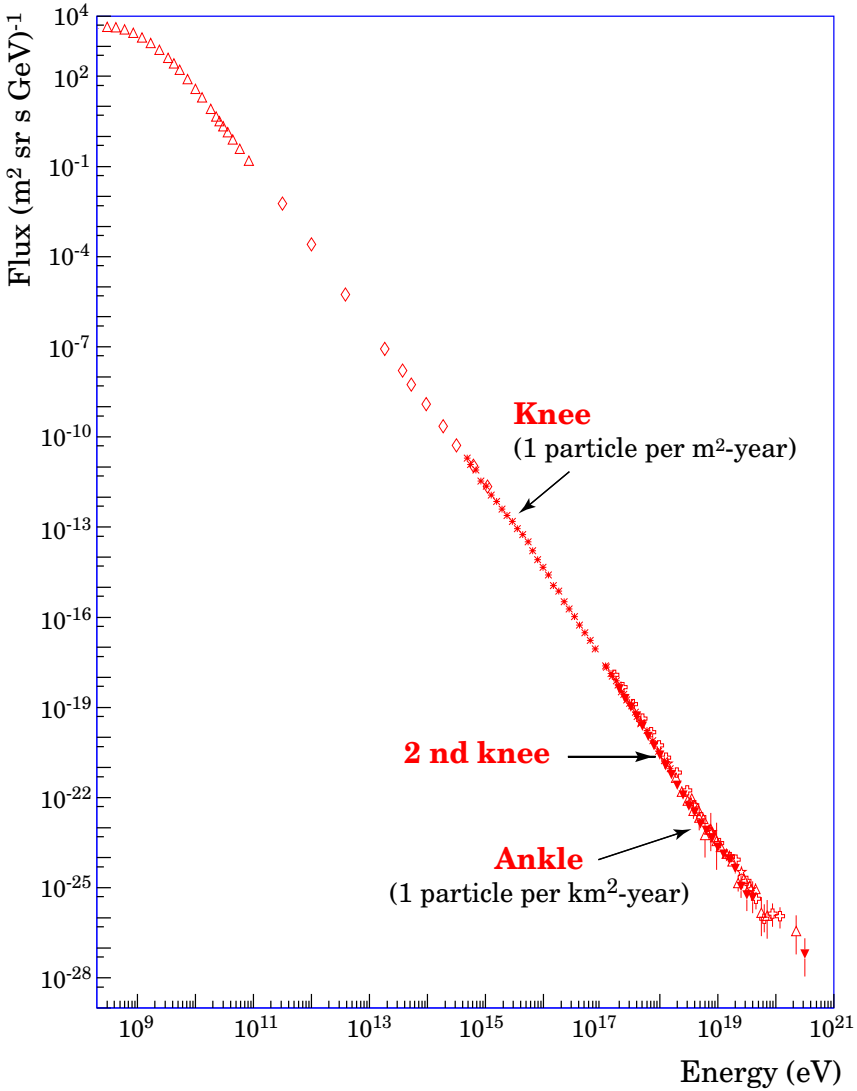
STATUS of ANKLE in UHECR

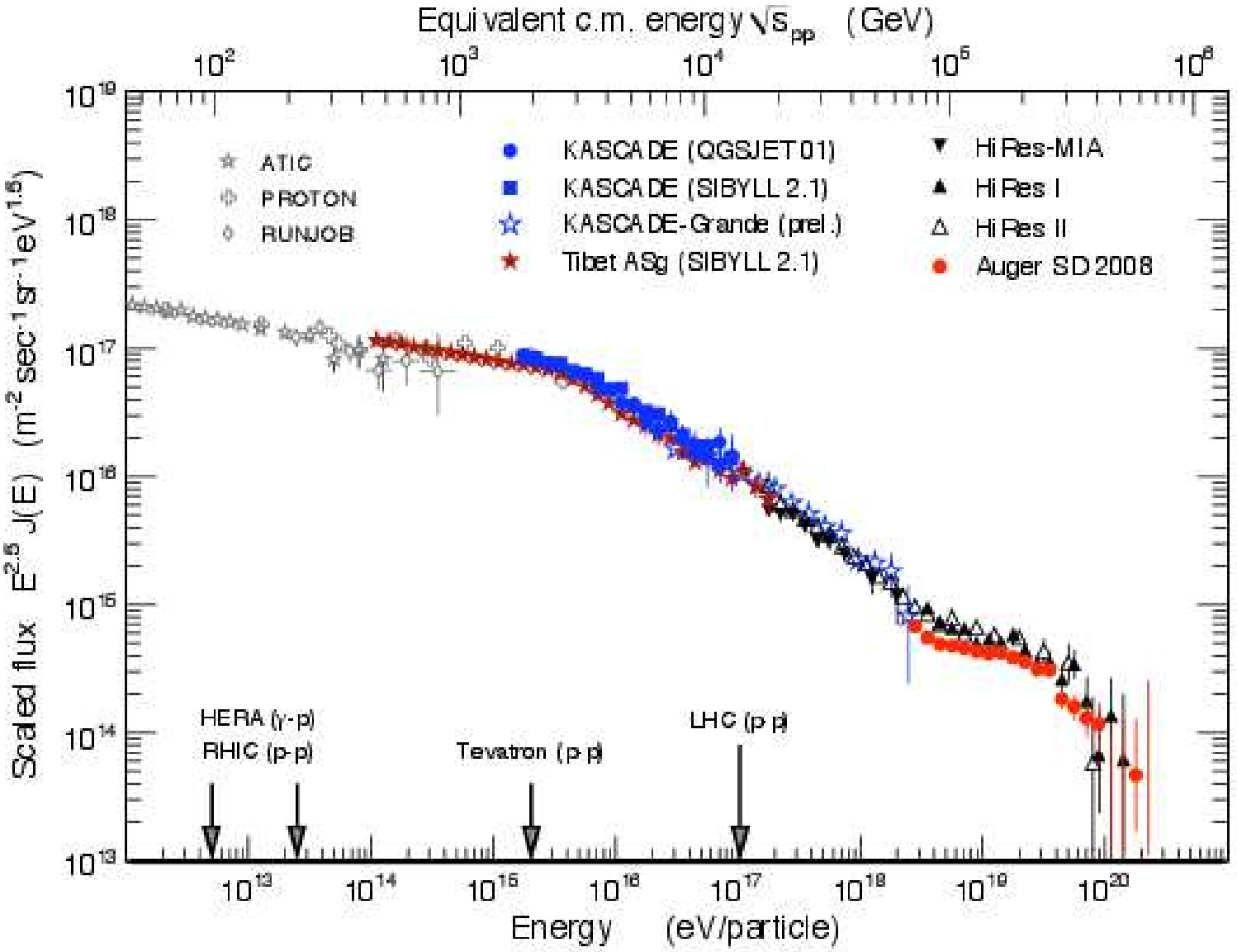
V. Berezinsky

INFN, Laboratori Nazionali del Gran Sasso, Italy

Total CR spectrum and features



SPECTRA and EXPERIMENTS



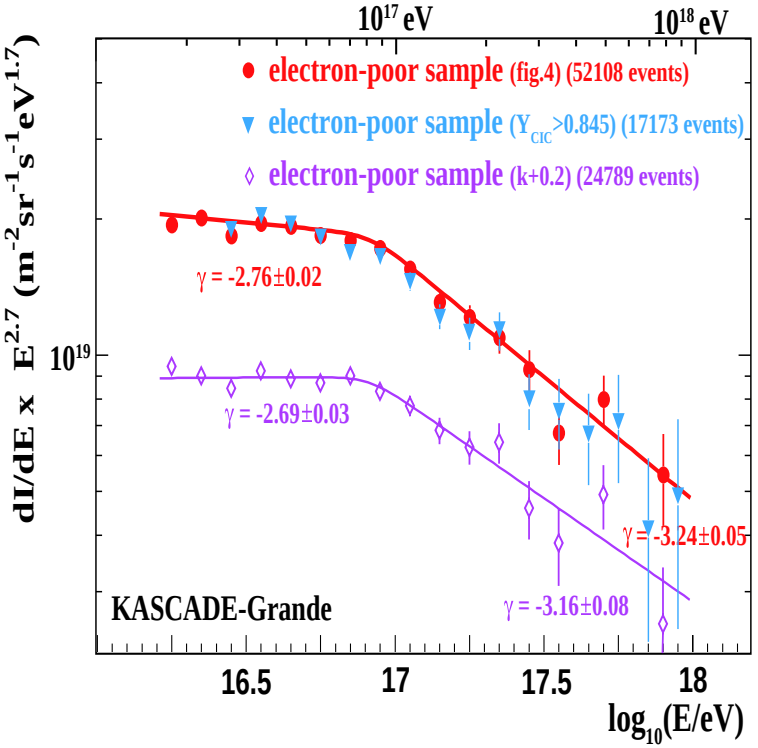
OBSERVED CR FEATURES

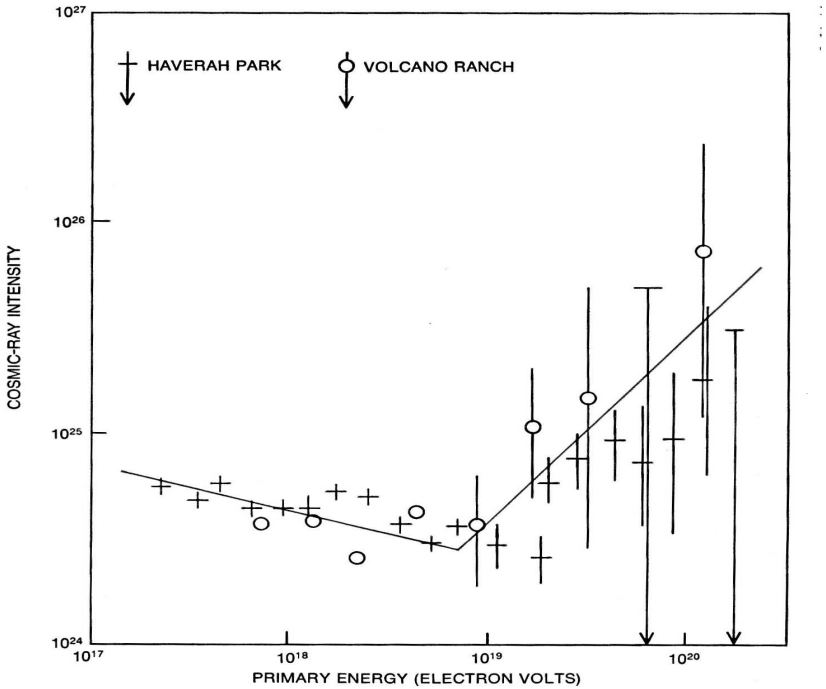
- **Knees**

  Proton knee: MSU, Khristiansen and Kulikov 1958 $E_p \sim (2-3)$ PeV.

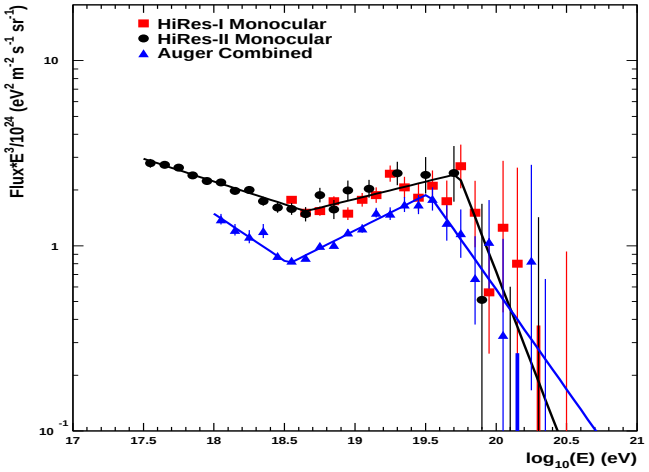
  Iron knee: KASCADE grande 2012 $E_{\rm Fe} = ZE_p \approx 80$ PeV.

- **Ankle:** Volcano Ranch, Linsley 1963, $E_a \approx 10$ **EeV.**





OBSERVED CR FEATURES (continued)



Observed ankle in power-law approximation

HiRes : $E_a = 4.5 \pm 0.5$ EeV

TA : $E_a = 4.9 \pm 0.3$ EeV

Auger : $E_a = 4.2 \pm 0.1$ EeV

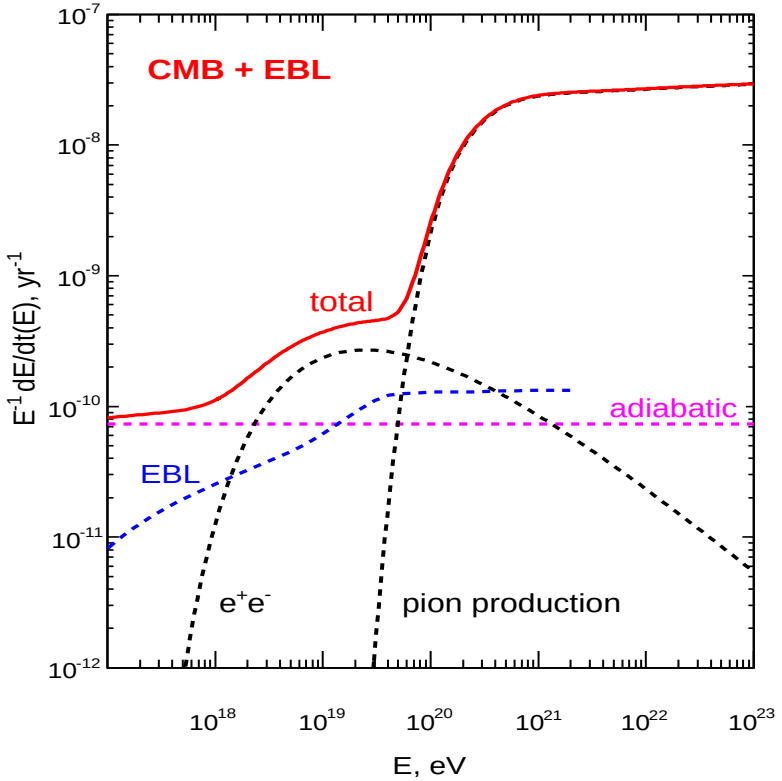
GZK cutoff : $p + \gamma \to N + \pi, \quad E_{\rm gzk} \approx 50$ EeV, $\quad E_{1/2} = 52.5$ EeV

HiRes : $E_{\rm gzk} = 56.2^{+5.4}_{-4.9}$ EeV $\qquad \log E_{1/2} = 19.73 \pm 0.07$

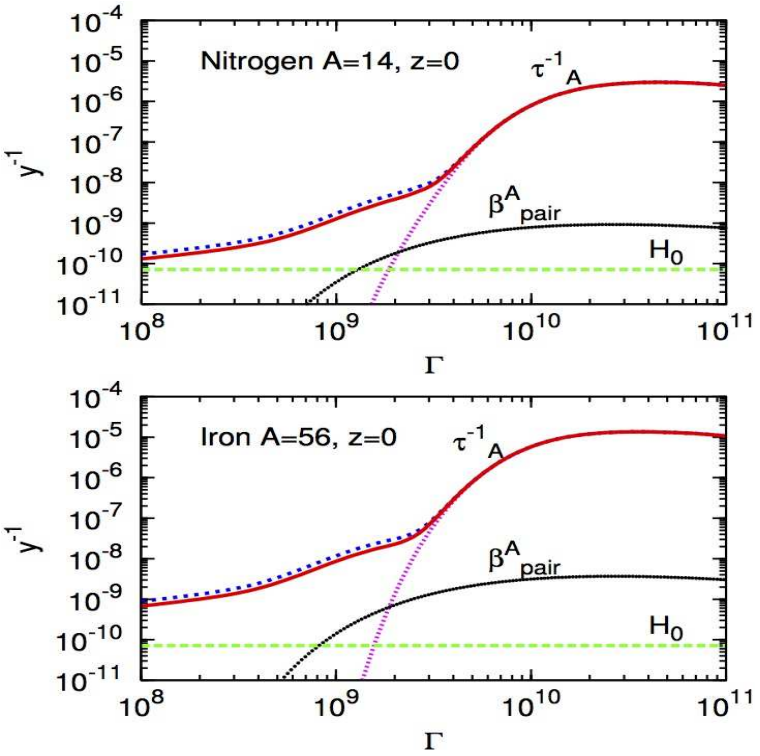
TA : $E_{\rm gzk} = 48 \pm 1.0$ EeV $\qquad \log E_{1/2} = 19.69 \pm 0.1$

Auger : $E_{\rm cut} = 25.7^{+1.1}_{-1.2}$. EeV $\qquad$ **theory BG 1988 :** $\log E_{1/2} = 19.72$

Signatures of particle propagation through CMB and EBL



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



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.

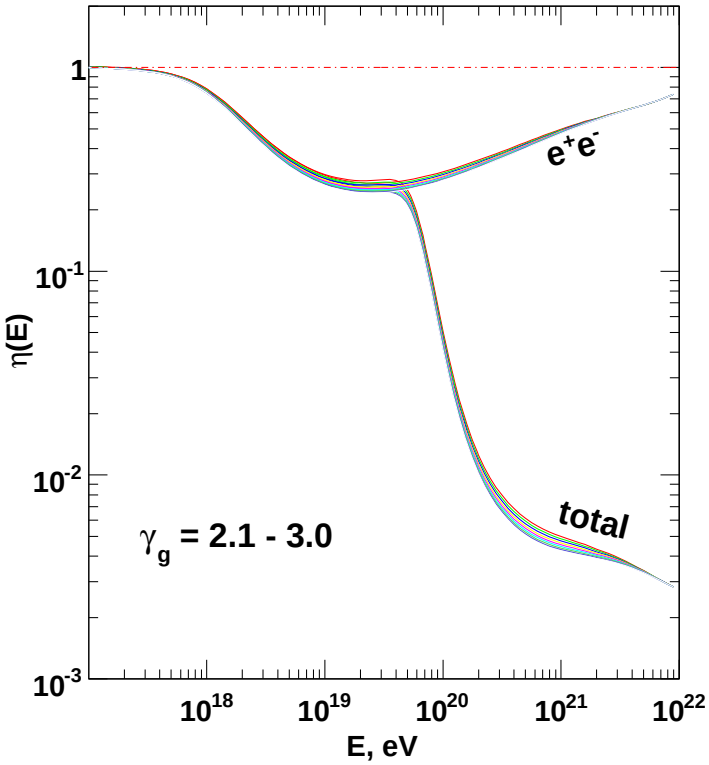
Energy spectrum in terms of **modification factor** characterizes well the **interaction signatures**.

MODIFICATION FACTOR

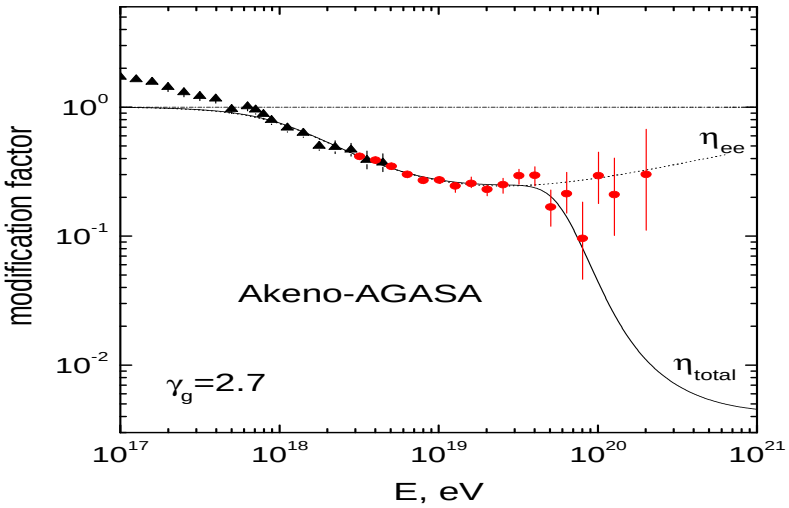
$$\eta(E) = \frac{J_p(E)}{J_p^{\rm unm}(E)}$$

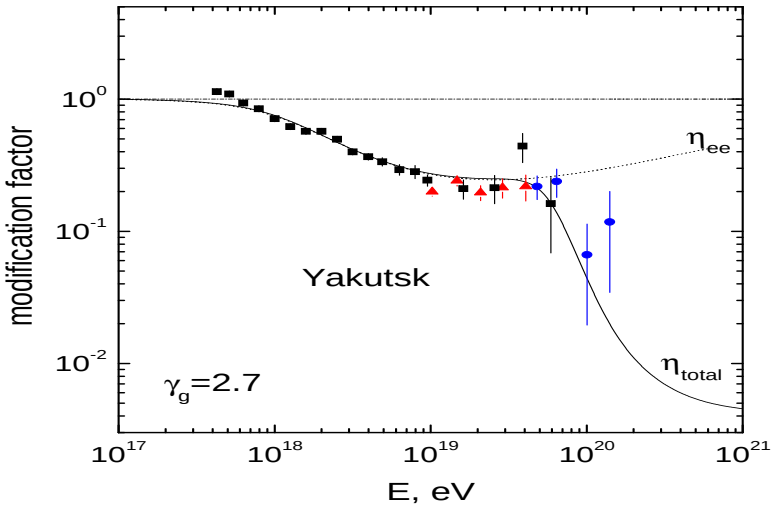
where $J_p^{\rm unm}(E) = KE^{-\gamma_g}$ includes only adiabatic energy losses.
Since many physical phenomena in numerator and denominator compensate or cancel each other, dip in terms of modification factor is less model-dependent than $J_p(E)$.

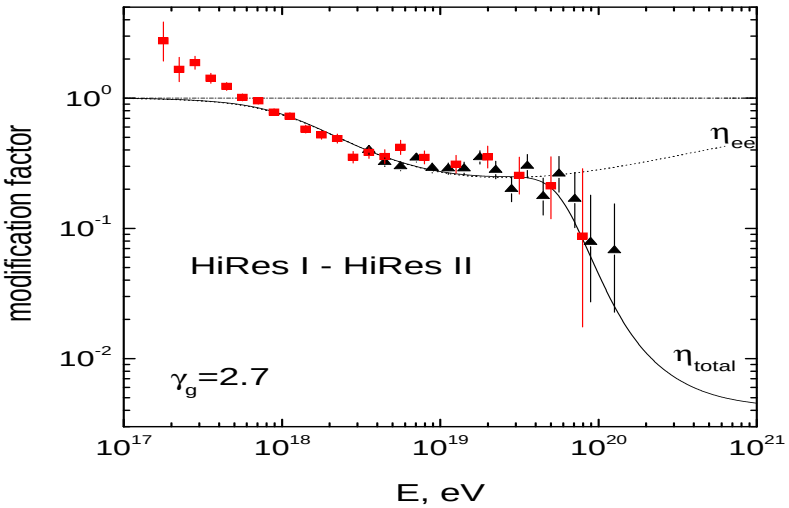
It depends very weakly on:
γ_g and $E_{\rm max}$,
modes of propagation (rect or diff),
large-scale source inhomogeneity,
source separation within 1-50 Mpc,
local source overdensity or deficit,..
It is modified by presence of nuclei
($\gtrsim 15\%$).
Experimental modification factor:
$\eta_{\rm exp}(E)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

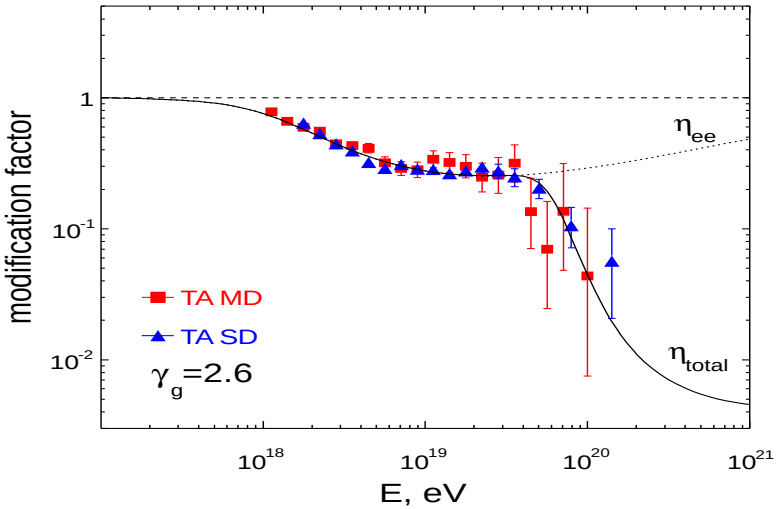


Comparison of pair-production dip with observations



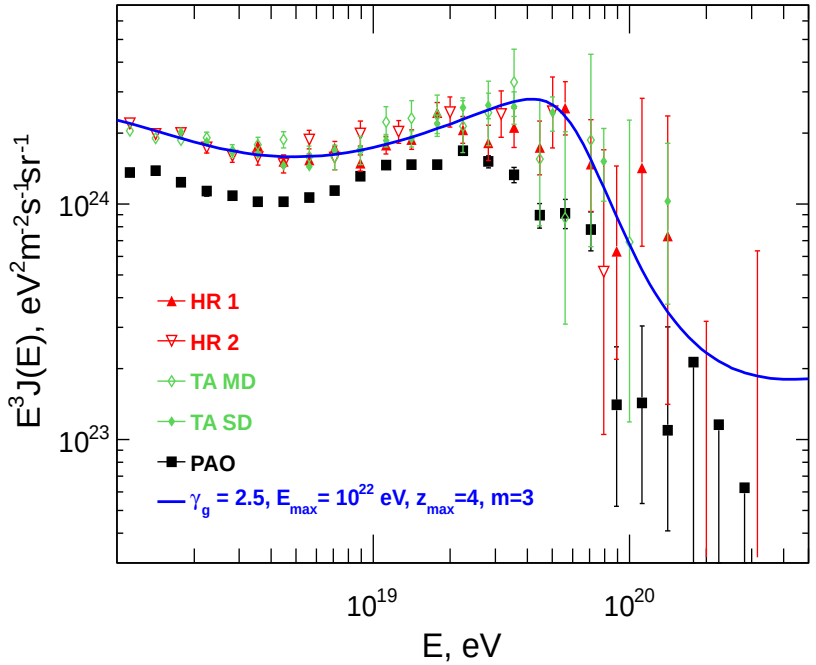


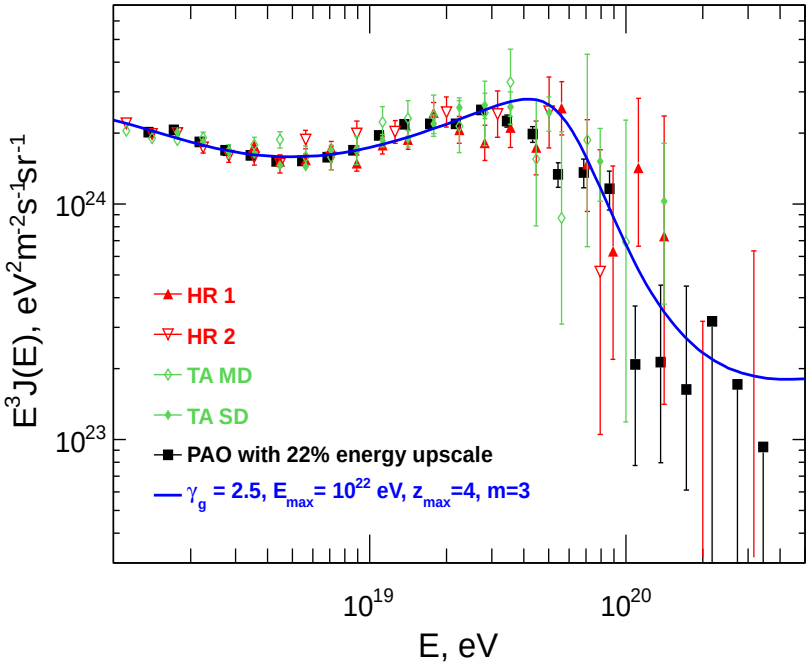




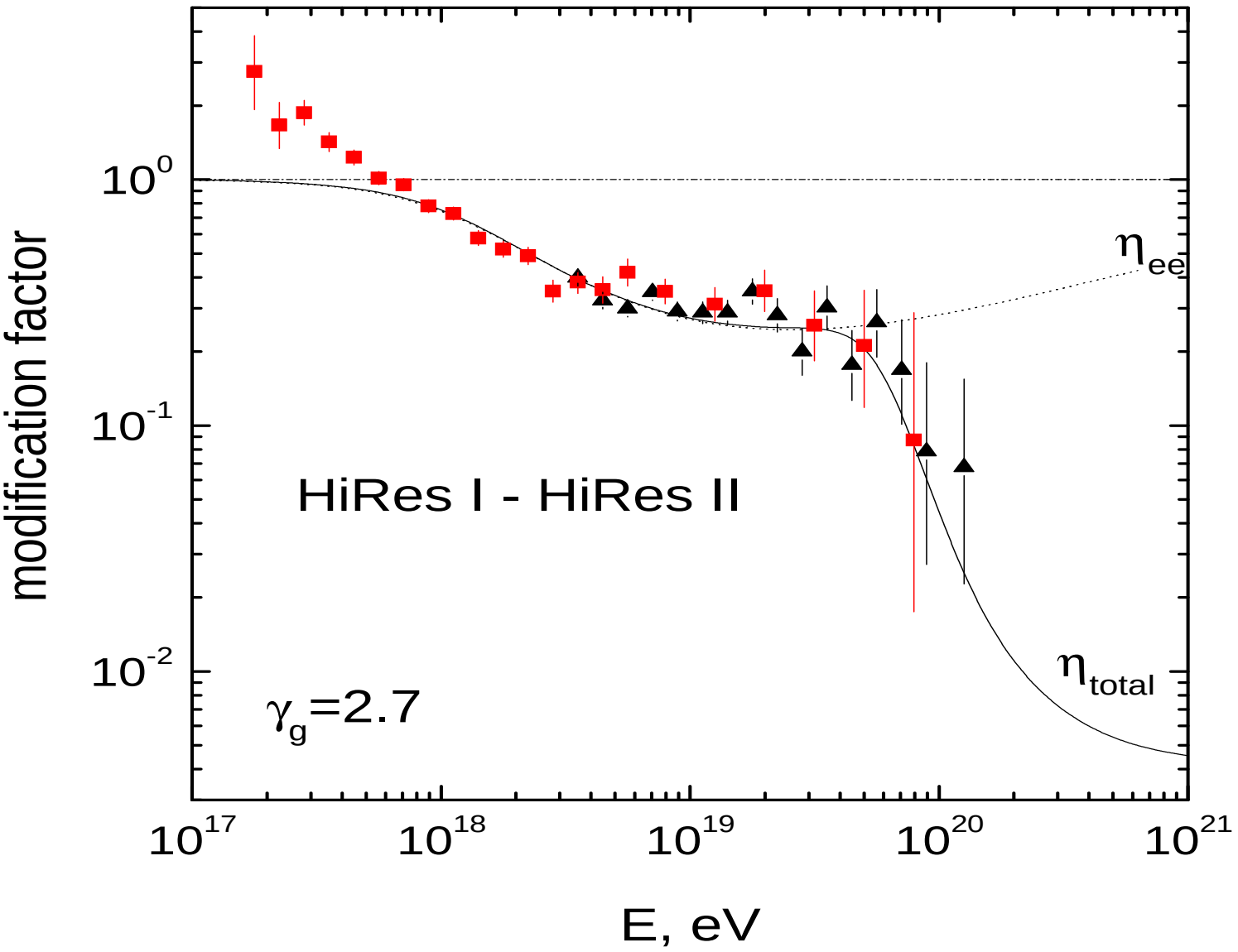
DIP in AUGER 2011 DATA

In modification factor presentation 2011 χ^2 is large. $\chi^2_{\min}$ can be reached in model-dependent presentation in terms of natural spectrum $E^3 J(E)$, using energy shift $\lambda = 1.22$ and cosmological evolution. As a result of χ^2-minimization absolute Auger flux coincides with HiRes and TA.

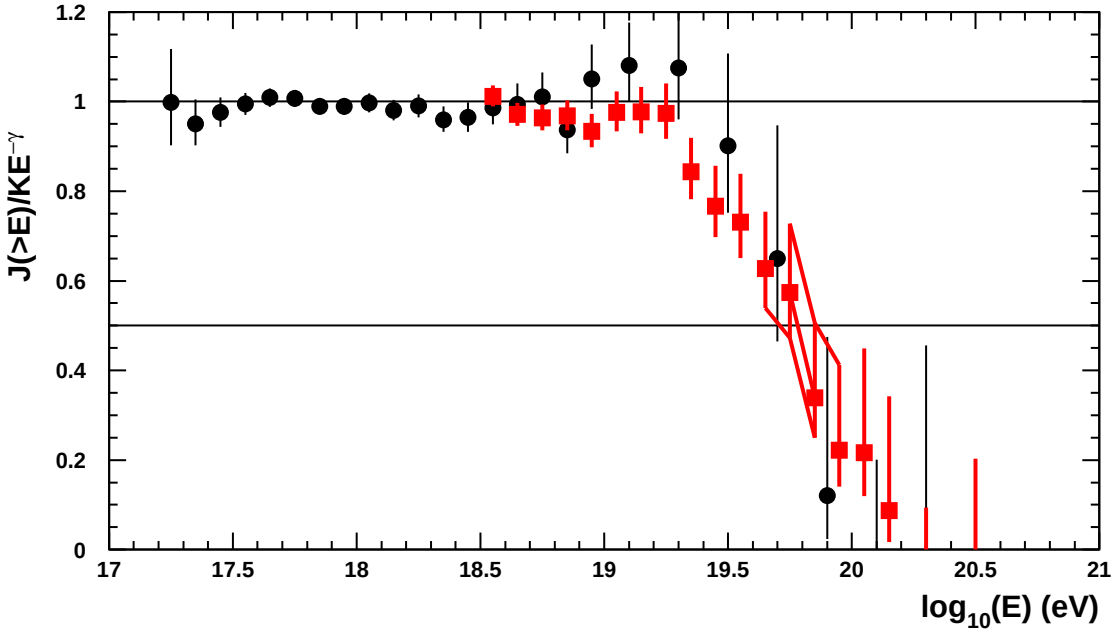




GZK CUTOFF IN HiRes DIFFERENTIAL SPECTRUM



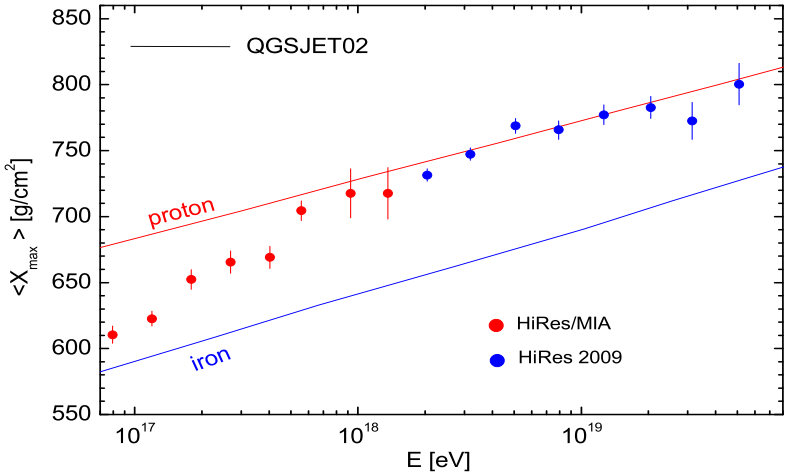
GZK CUTOFF IN HiRes INTEGRAL SPECTRUM

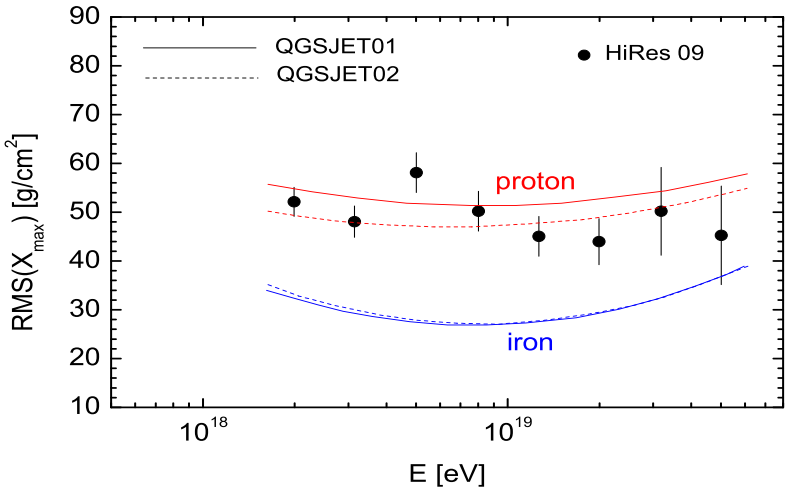


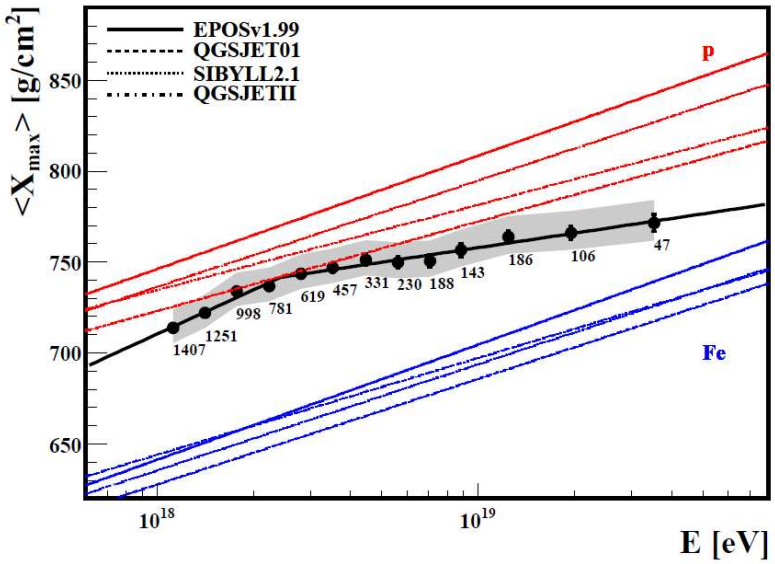
$E_{1/2}$ in HiRes integral spectrum confirms that steepening in the differential spectrum is the GZK cutoff:

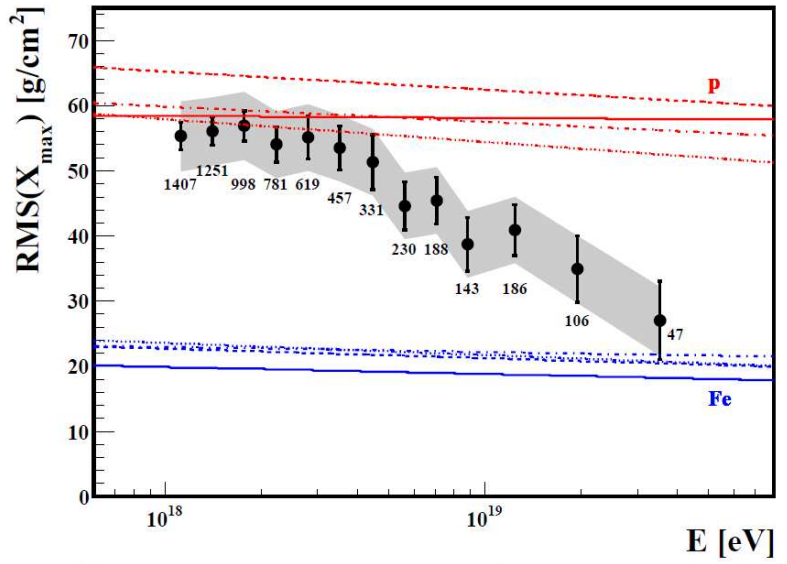
$$\mathrm{E}_{1/2}^{\mathrm{meas}} = 10^{19.73 \pm 0.07}\ \mathrm{eV} \quad \mathrm{cf} \quad \mathrm{E}_{1/2}^{\mathrm{theor}} = 10^{19.72}\ \mathrm{eV}$$

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









ANISOTROPY and ANKLE

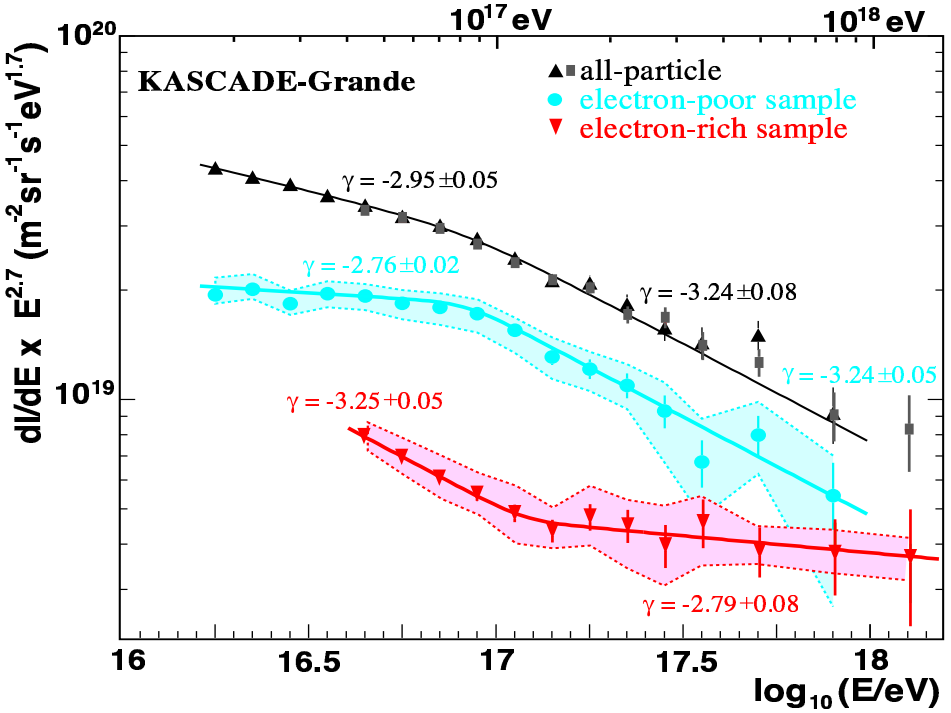
According to measurements of all three largest detectors, Auger, HiRes and Telescope Array, the mass composition at (1 - 3) EeV. i.e. below the ankle, is **proton-dominated**, or **p + He - dominated**. If galactic, such composition is excluded by recent measurements of anisotropy (Auger 2011 and 2012). Then ankle with $E_a \approx (4-5)$ EeV cannot be the feature of **transition from galactic to extragalactic** cosmic rays. Transition should occur at lower energy **in agreement with dip model.** Recent MC simulation for galactic particles (Giacinti et al 2012) confirms this conclusion

Thus ankle can be interpreted either as intrinsic property of pair-production dip or, in case of Auger results, like transition from extragalactic protons to extragalactic nuclei.

KASCADE-Grande: 2013 BREAK-THROUGH

'Small' 700×700 m^2 array with scintillation and muon detectors.
p+He component is separated by muon content with properties:

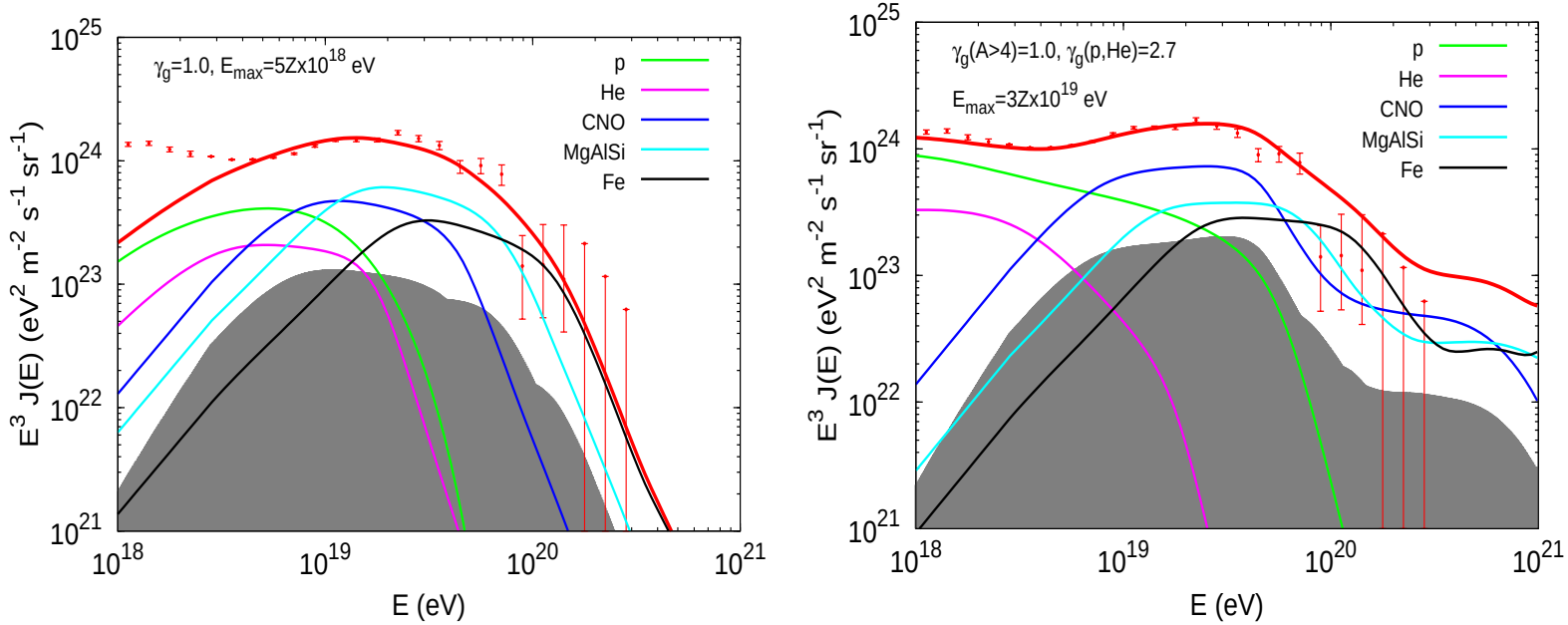
- p+He component at 0.1 - 1.0 EeV separated as 'electron-rich' using special event criteria, 6300 events.
- extragalactic, otherwise anisotropy at $E \sim 1$ EeV.
- flat spectrum $\gamma = 2.79 \pm 0.08$, cf $\gamma = 3.24 \pm 0.08$ for total.



Significance of Light-Kascade-Component

If this component is extragalactic, flat ($\gamma_g \approx 2.7$, cf $\gamma = 2.79 \pm 0.08$) and $E_{\rm max}$ is large ($E_{\rm max} \gtrsim 1 \times 10^{20}$ eV) one obtains dip model.

If $E_{\rm max}$ is low ($E_{\rm max} < 1 \times 10^{19}$) this component provides the necessary element to build the **Auger-based models** (Aloisio, VB, Blasi 2013):



SHORT CONCLUSIONS

Two models for **ankle** at $E_a \approx (4-5)$ EeV: (i) **transition** from galactic to extragalactic CRs and (ii) intrinsic feature of **pair-production dip**.

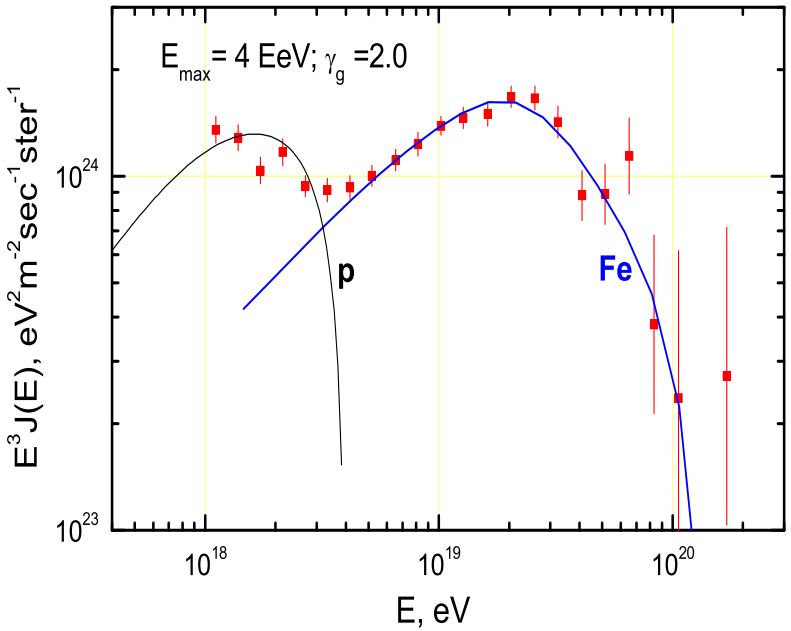
- **Ankle as transition** is **excluded** because of **anisotropy** of galactic component at $E < E_a$.
- The main problem at present is contradiction between HiRes/TA and PAO on mass composition at $E > (3-5)$ EeV :
- HiRes/TA observe proton dominance and signatures of proton interaction with CMB: pair-production dip and GZK cutoff in differential and integral spectra.
- PAO reports the nuclei composition steadily heavier with energy.
- The KASCADE observed ankle-like component at $0.1 \lesssim E \lesssim 1$ EeV automatically produces dip model in case $E_{\rm max} > 1 \times 10^{20}$ eV, and Auger-based model in case $E_{\rm max} < 1 \times 10^{19}$ eV.

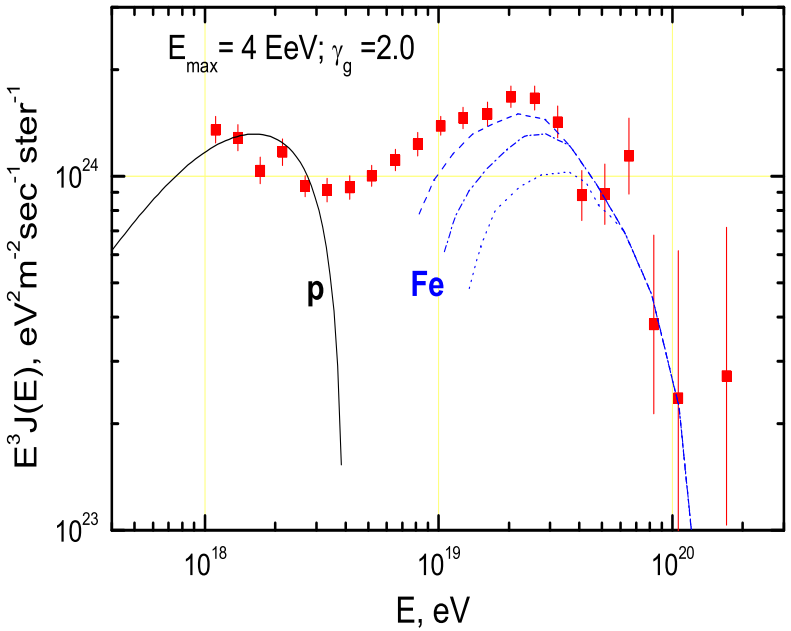
AUGER - BASED MODELS

- According Auger at $E > 3$ GeV Z steadily grows with E.
- At $1 \lesssim E \lesssim 3$ EeV data of Auger and HiRes agree with proton composition.
- If this component is extragalactic, then $E_p^{\max} \leq 4$ EeV, otherwise protons dominate at $E > 3$ EeV.

Aloisio, VB, Gazizov 2009: Disappointing model.

$$E_i^{\max} = Z_i E_p^{\max}, \quad \gamma_g = 2.0$$

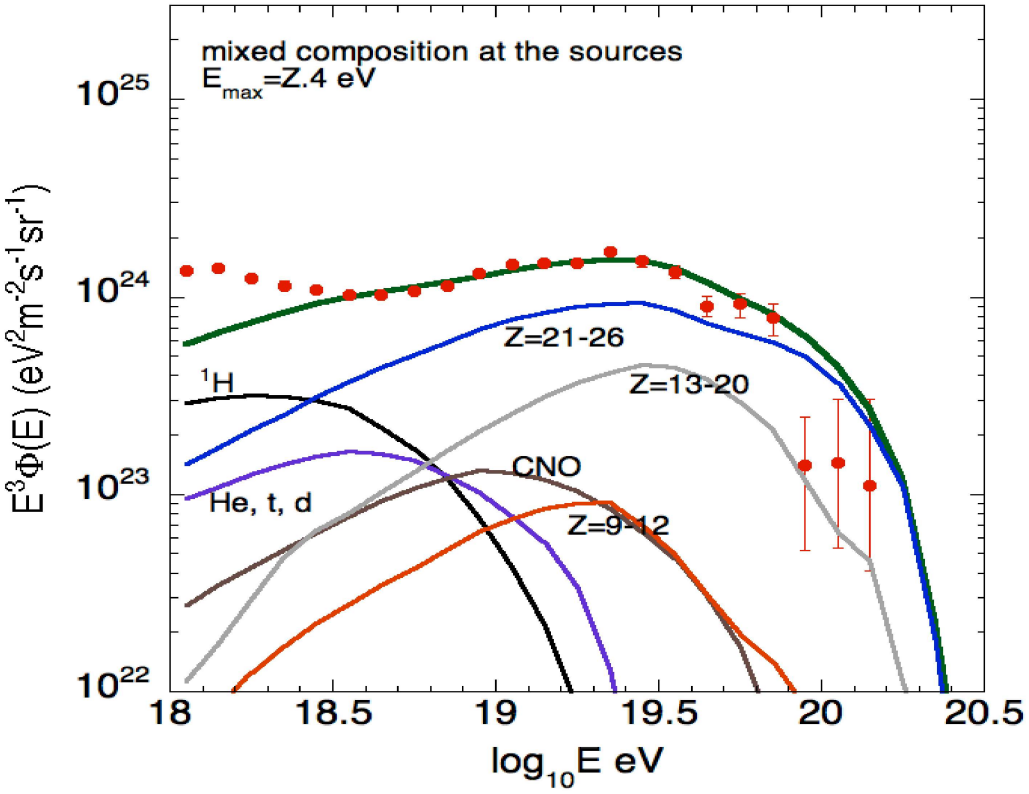




MIXED COMPOSITION MODEL

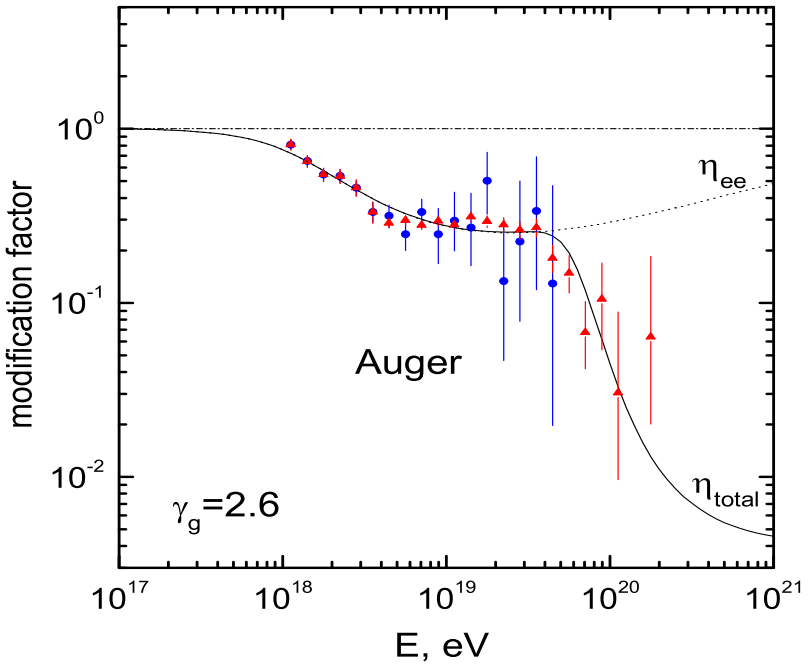
Allard 2011

Parameters: $E_i = Z_i E_p^{\max}$, $E_p^{\max} = 4$ EeV, $\gamma_g = 2.0$, enriched by heavy elements.

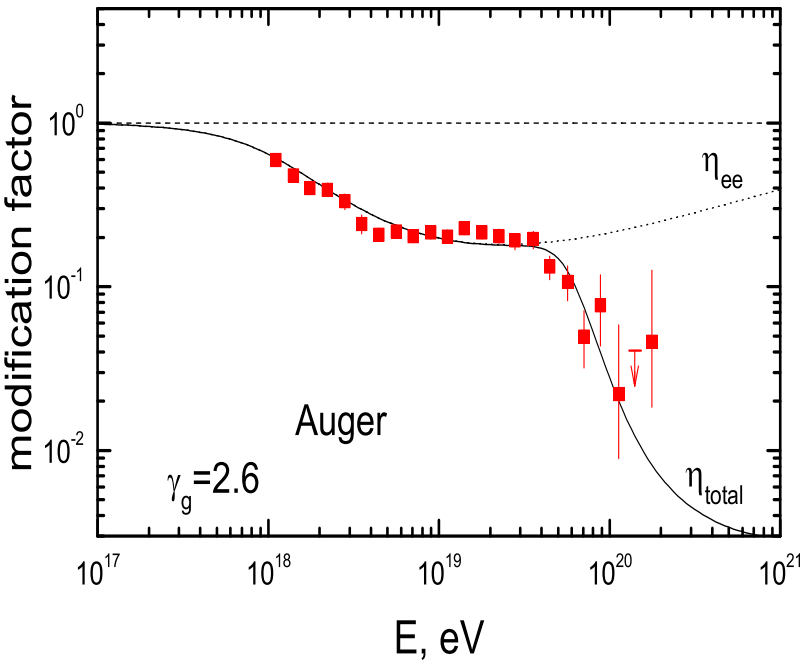


DIP in AUGER 2007 DATA

In 2007 Auger data agree reasonably well with the dip. Later, tremendously increasing statistics made error bars much smaller. Observational data include model-dependent effects (e.g. evolution), while theoretical modification factor does not.



Hybrid and combined events 2007



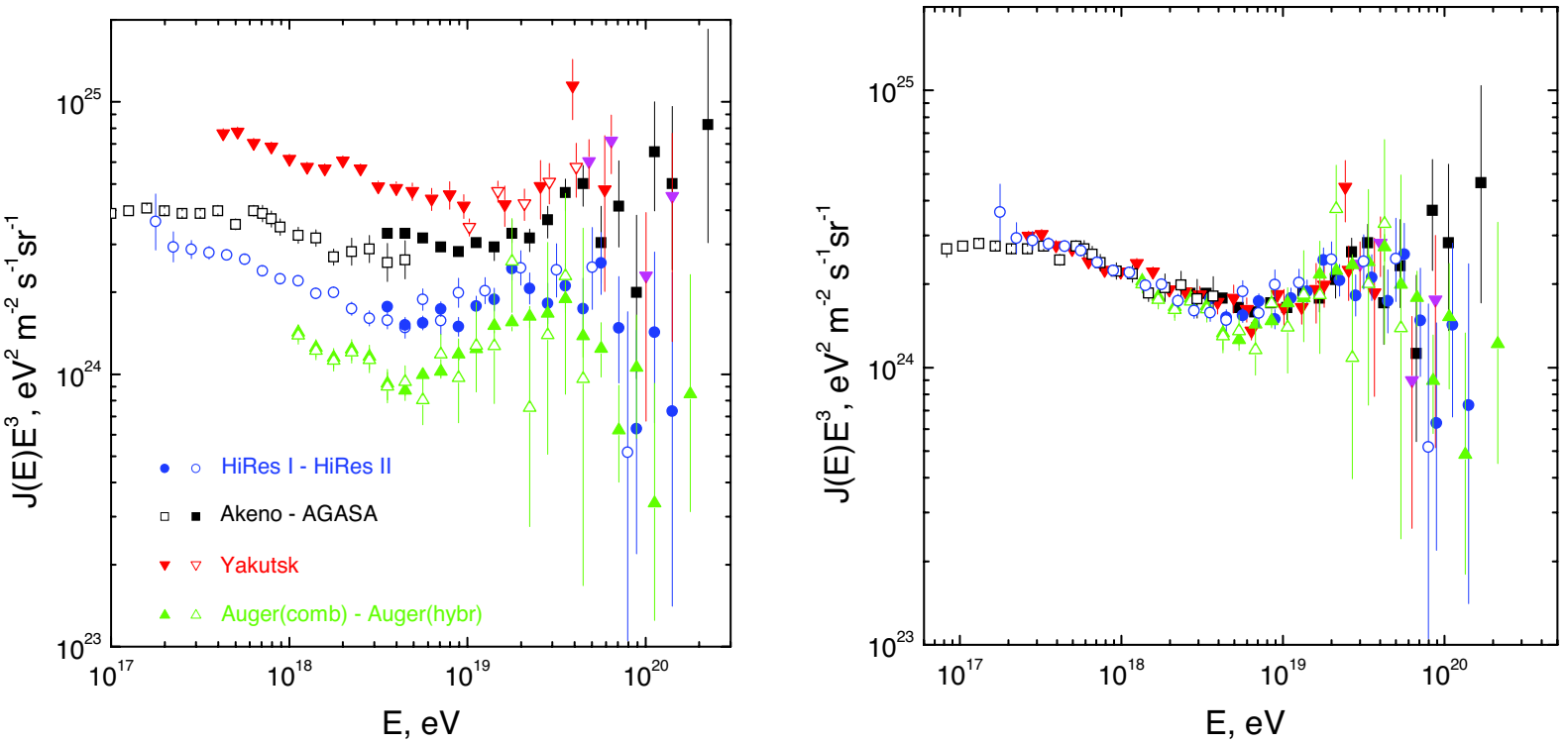
Combined events 2007,

PAIR-PRODUCTION DIP as ENERGY CALIBRATOR

Pair-production dip has a fixed energy position, serving as a standard candle.

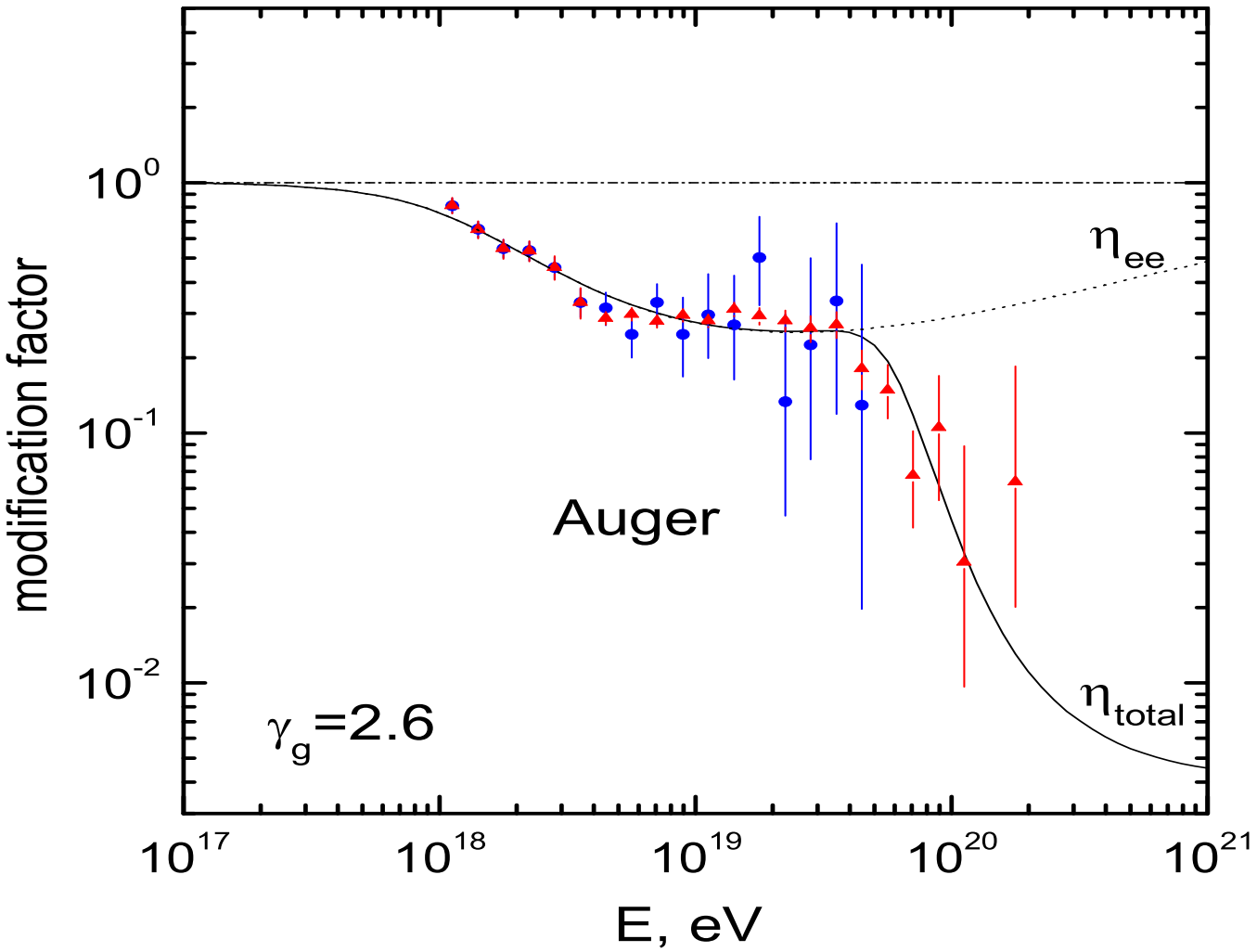
Energy scale of each detector has to be shifted by factor λ to minimize χ^2. Equality of fluxes after recalibration is confirmation of pair-production nature of the dip.

V. Berezinsky, A. Gazizov, S. Grigorieva 2006



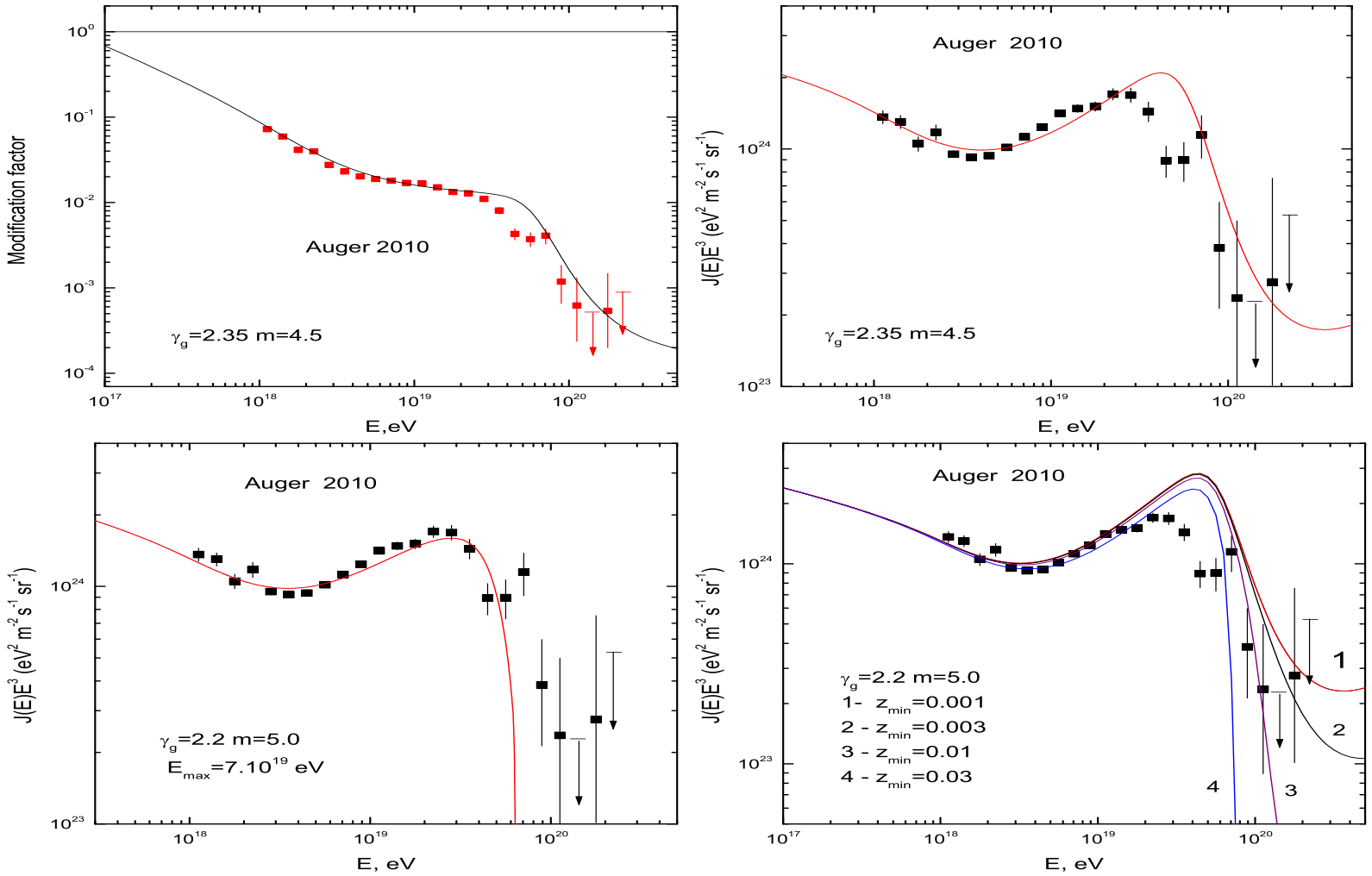
GZK CUTOFF IN AUGER SPECTRUM 2007

(combined and hybrid events)



GZK CUTOFF IN AUGER SPECTRUM 2010

S. Grigorieva



GZK CUTOFF IN AUGER SPECTRUM 2011

S. Grigorieva