ULTRA HIGH ENERGY COSMIC RAYS: SIGNATURES and OBSERVATIONS

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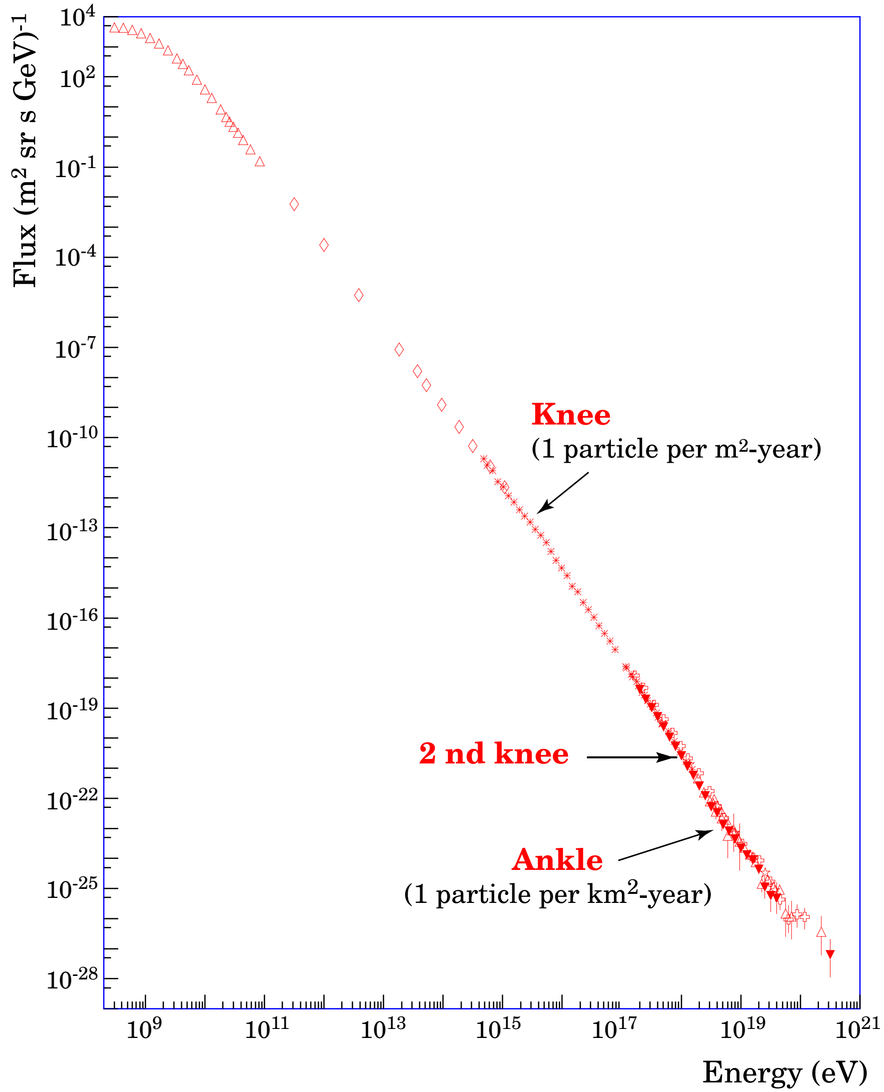
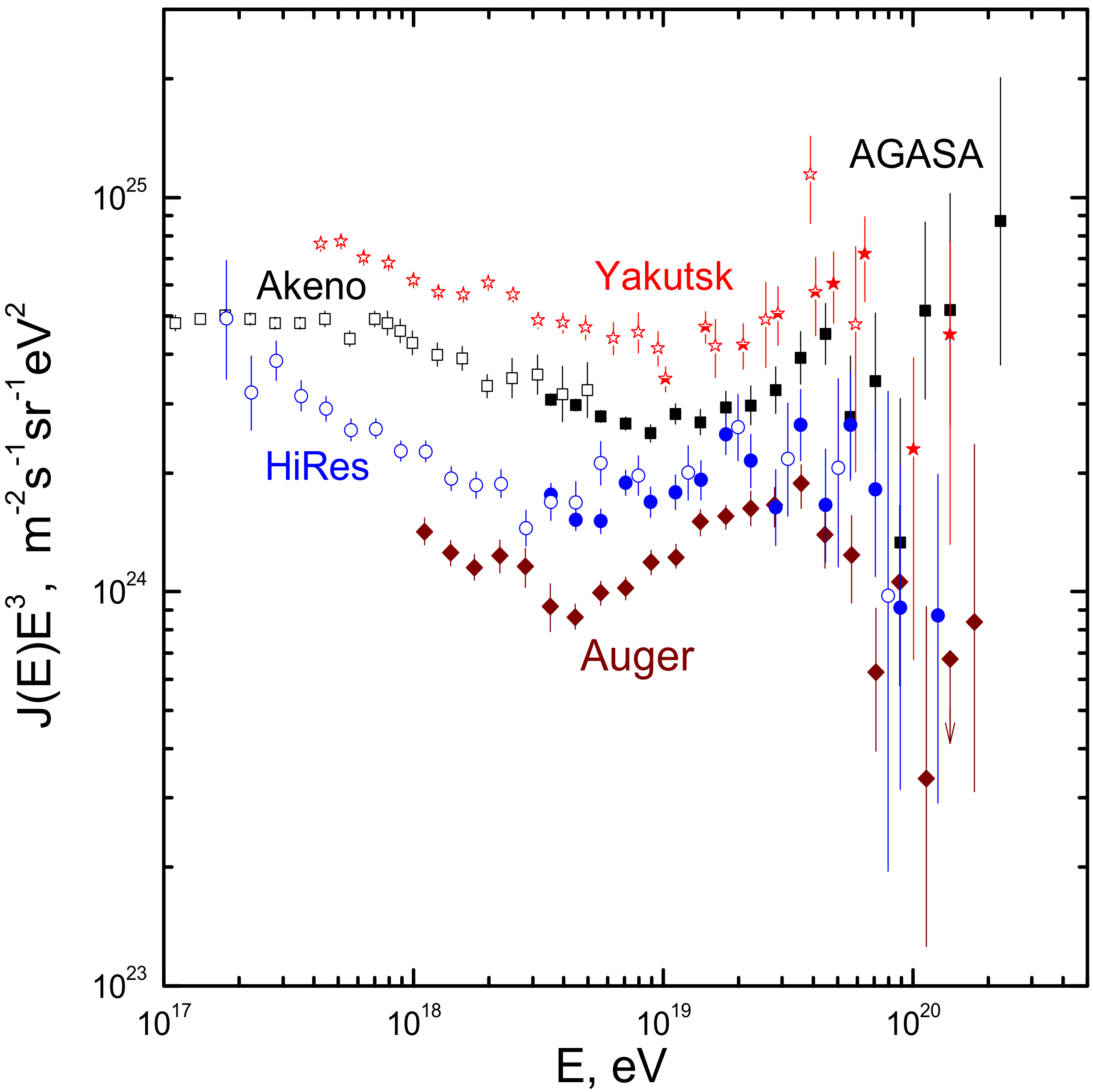
OBSERVED CR SPECTRUM



MEASURED FLUXES OF UHECR



PROPAGATION OF UHECR THROUGH CMB

INTERACTIONS

Protons

$$p + \gamma_{\rm CMB} \rightarrow p + e^+ + e^-$$

$$p + \gamma_{\rm CMB} \rightarrow N + \text{pions}$$

Nuclei

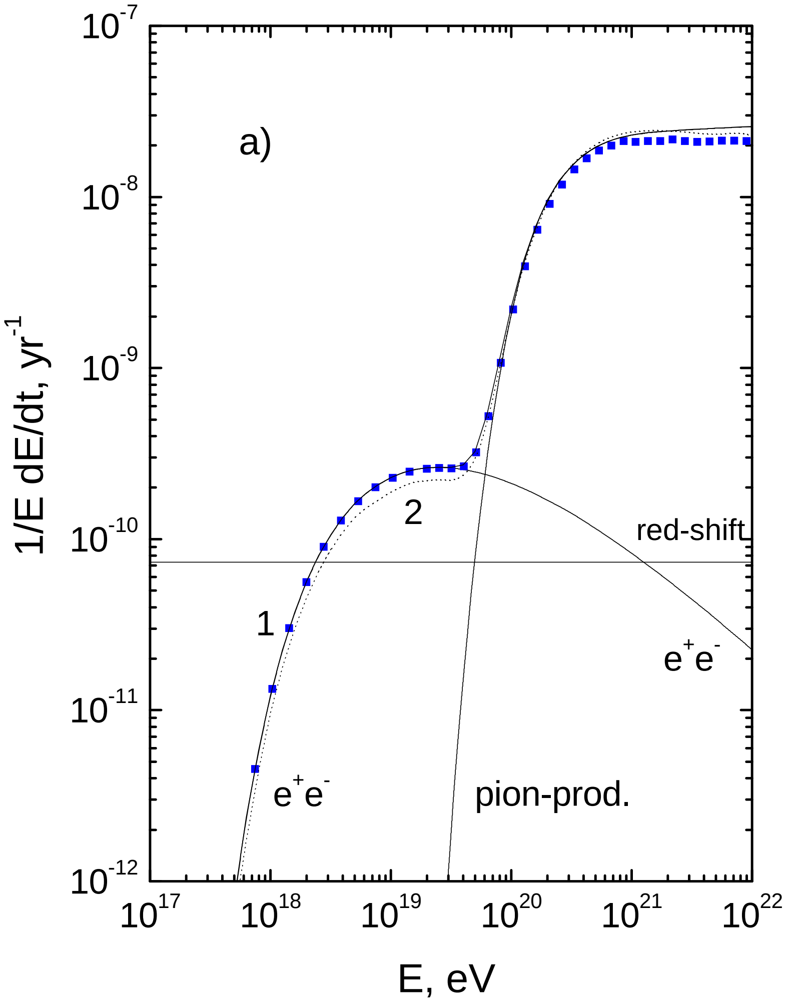
$$Z + \gamma_{\rm CMB} \rightarrow Z + e^+ + e^-$$

$$A + \gamma_{\rm CMB} \rightarrow (A-1) + N$$

$$A + \gamma_{\rm CMB} \rightarrow A' + N + \text{pions}$$

Photons

$$\gamma + \gamma_{\rm bcgr} \rightarrow e^+ + e^-$$



PROPAGATION SIGNATURES

Propagation of **protons** in intergalactic space leaves the imprints on the spectrum most notably in the form:

GZK cutoff and pair-production dip

These signatures might depend on the distribution of sources and way of propagation.

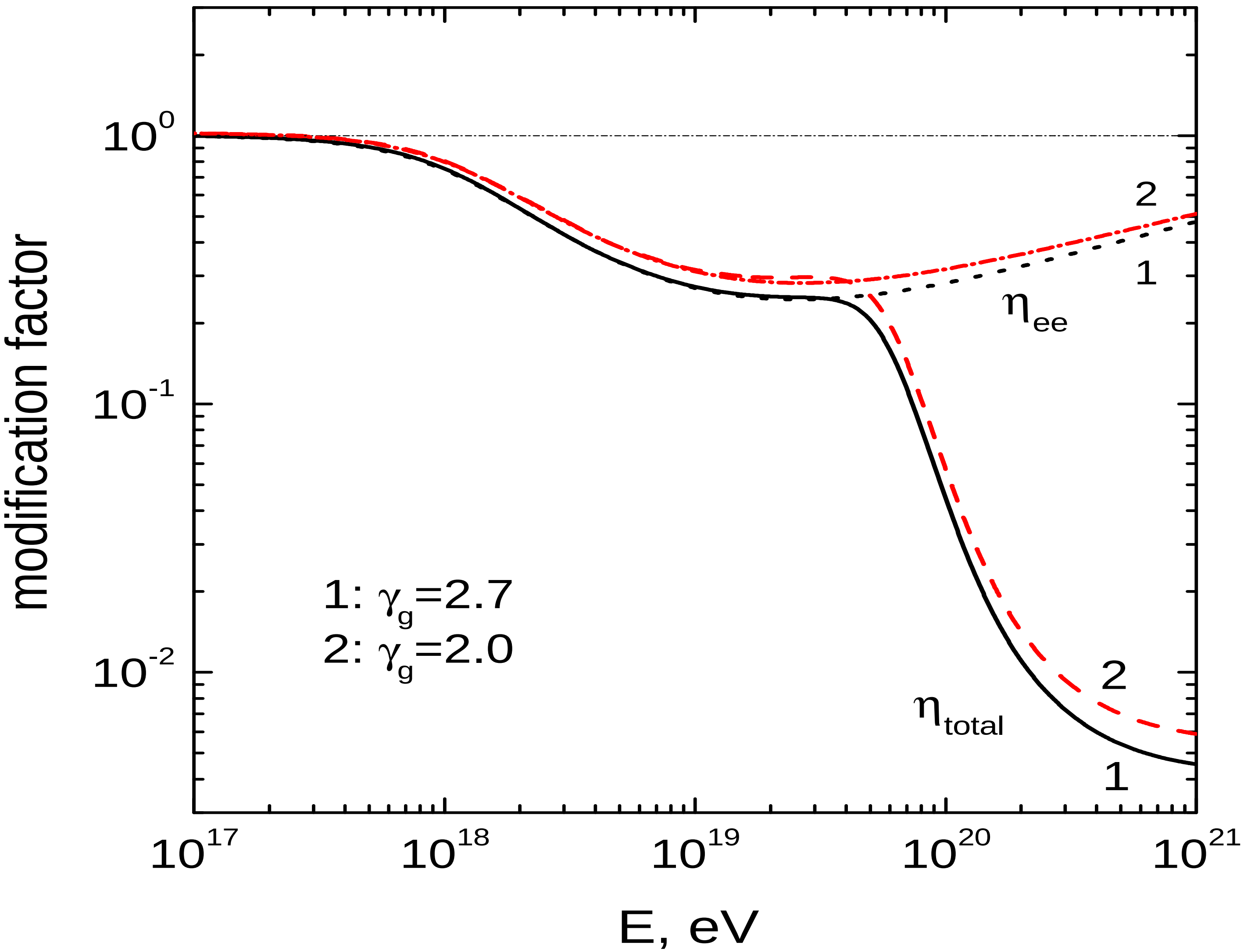
MODIFICATION FACTOR

(normalized theoretical energy spectrum)

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

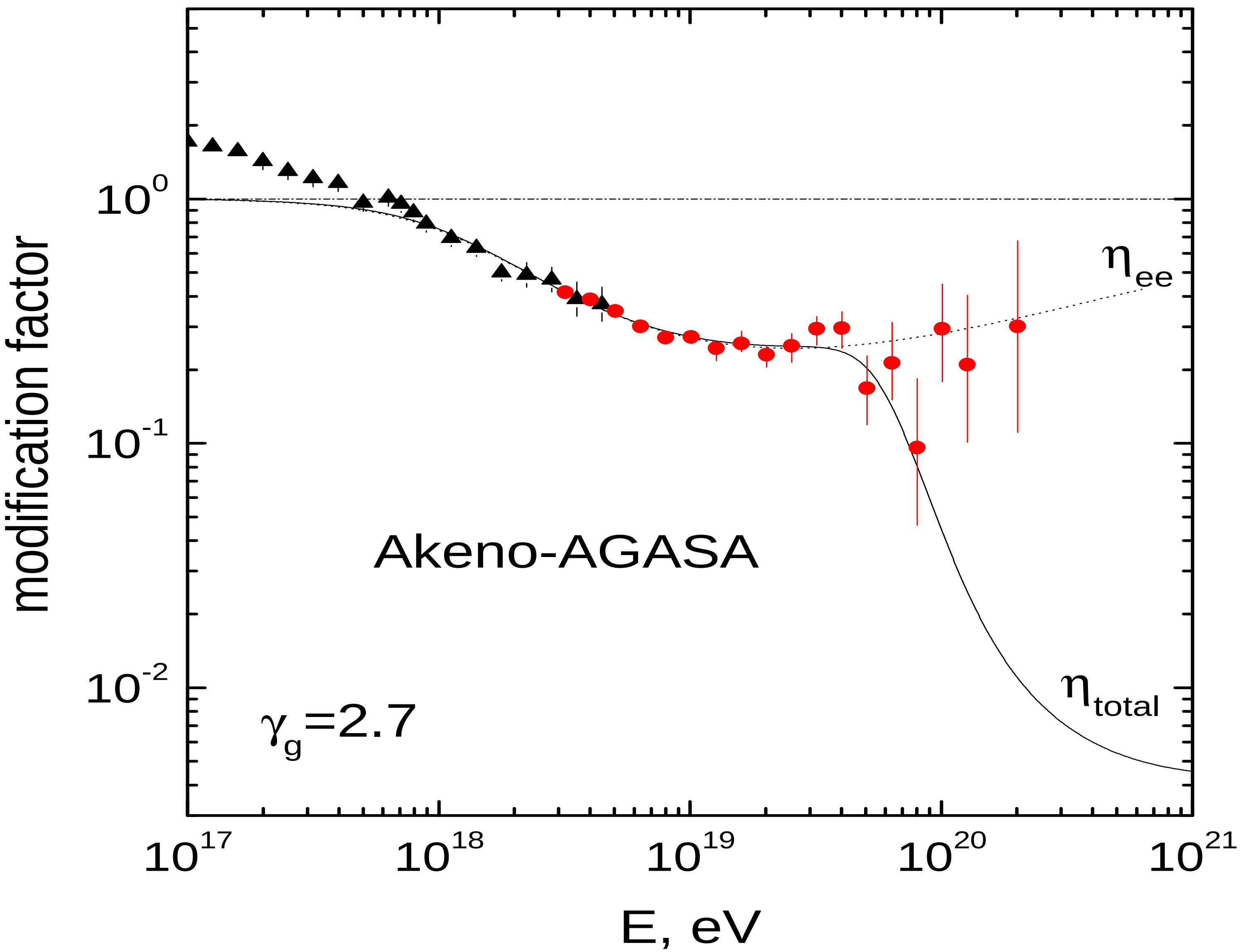
where $J_p^{\rm unm}(E)$ includes only adiabatic energy losses (redshift) and $J_p(E)$ includes total energy losses, $\eta_{\rm tot}(E)$ or adiabatic, e^+e^- energy losses, $\eta_{ee}(E)$.

DIP AND GZK CUTOFF IN DIFFUSE SPECTRA

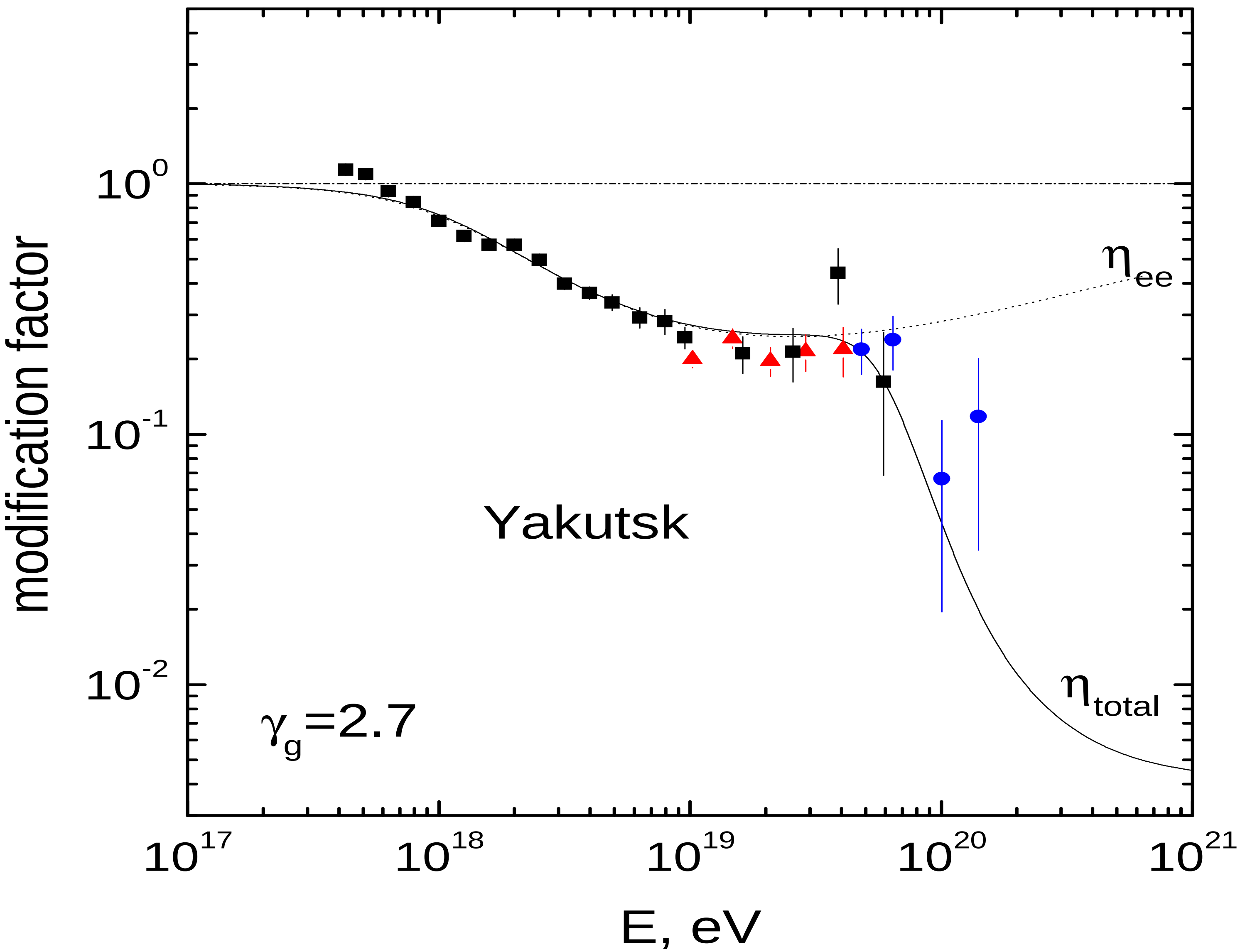


The dotted curve shows η_{ee}, when only adiabatic and pair-production energy losses are included. The solid and dashed curves include also the pion-production losses.

COMPARISON WITH AKENO-AGASA DATA

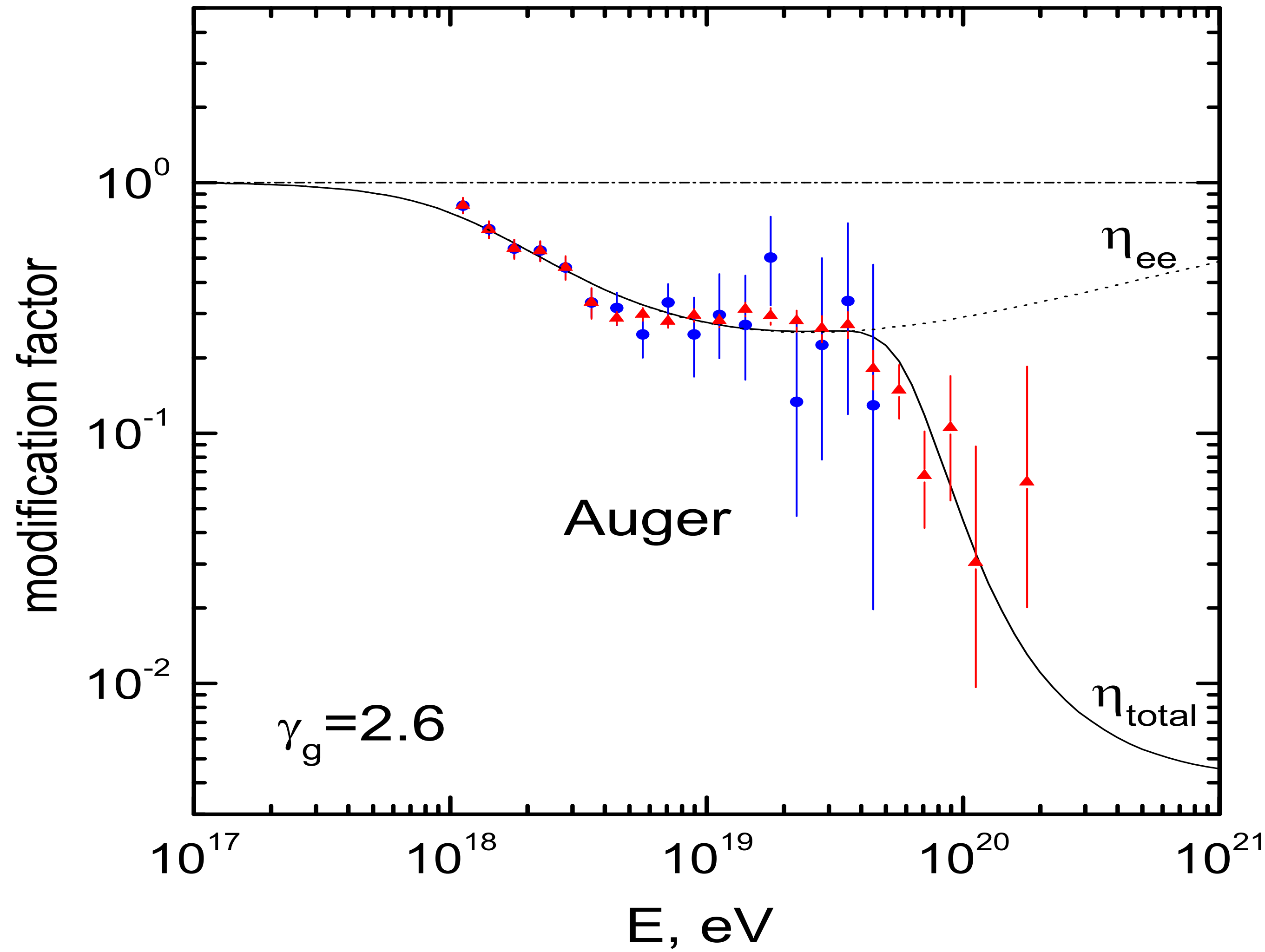


COMPARISON WITH YAKUTSK DATA

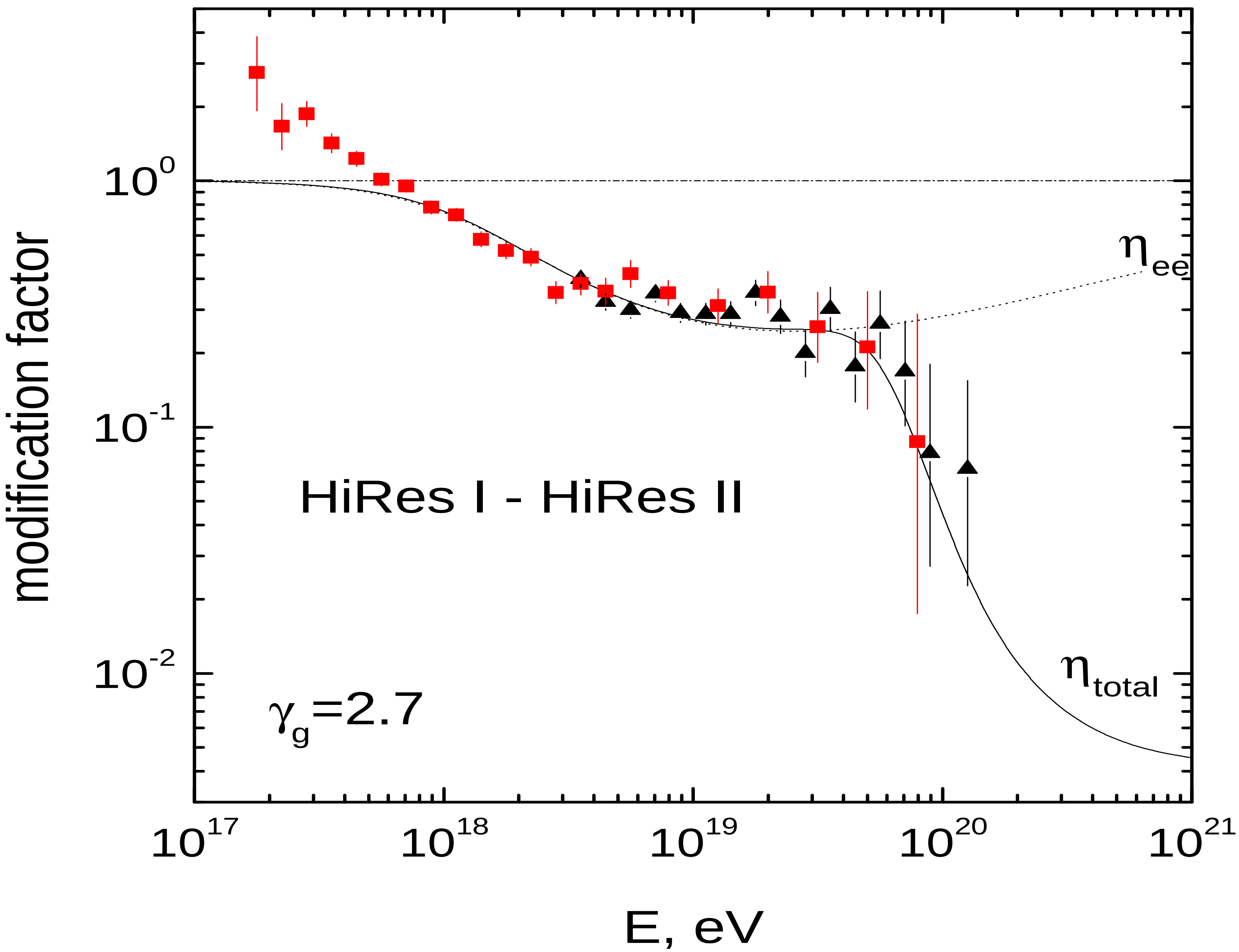


COMPARISON WITH AUGER DATA

(combined and hybrid events)



COMPARISON WITH HIRES DATA



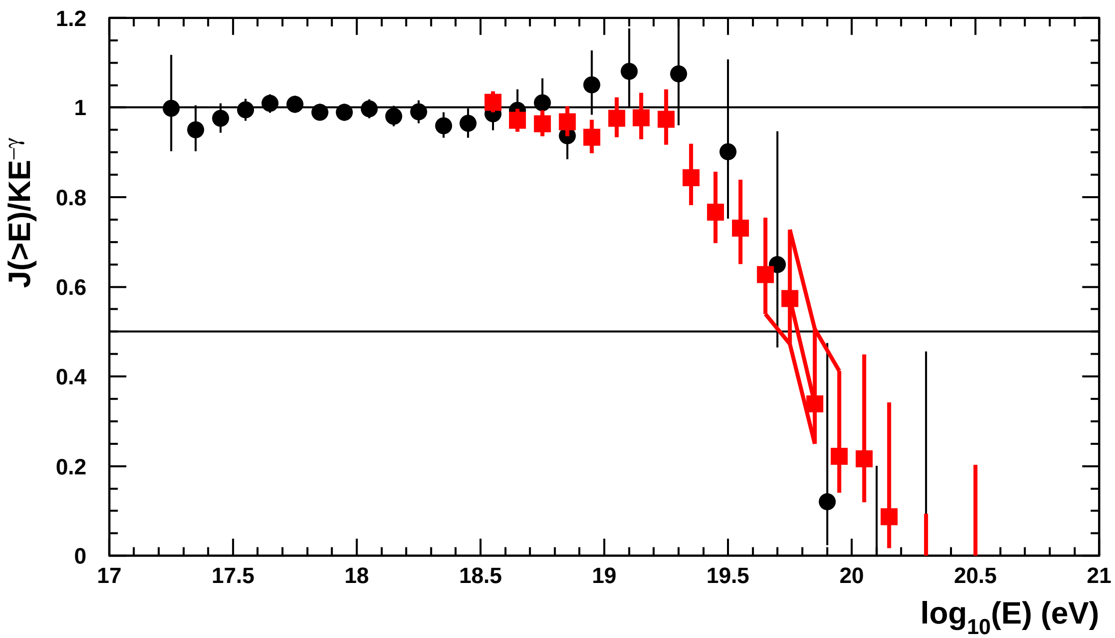
GZK CUTOFF IN HiRes DATA

In the integral spectrum GZK cutoff is numerically characterized by energy $E_{1/2}$ where the calculated spectrum $J(>E)$ becomes half of power-law extrapolation spectrum $KE^{-\gamma}$ at low energies. As calculations (V.B.&Grigorieva 1988) show

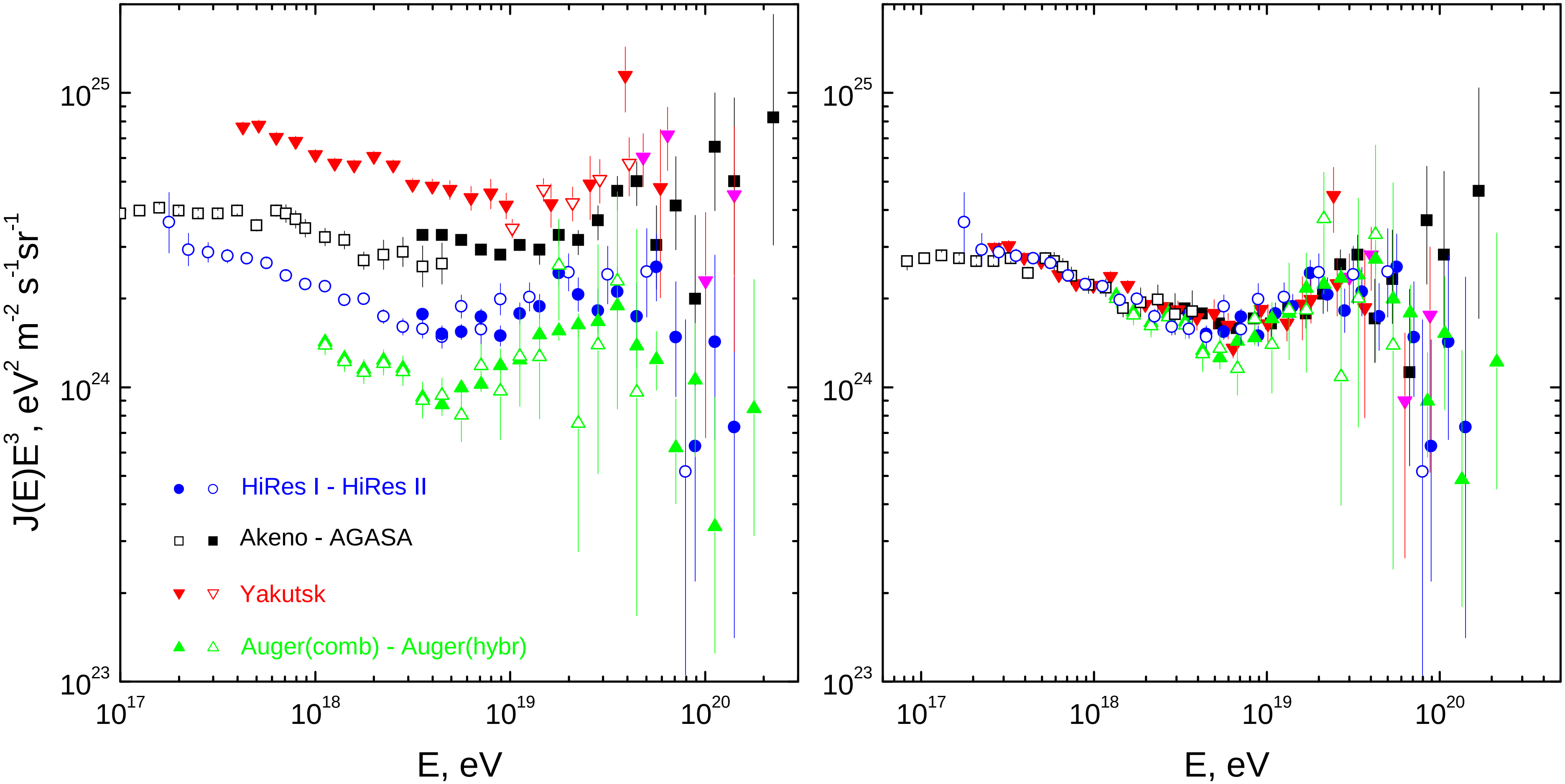
$$\mathrm{E}_{\mathbf{1/2}} = \mathbf{10^{19.72}}\ \mathrm{eV}$$

valid for a wide range of generation indices from 2.1 to 2.8. HiRes obtained:

$$\mathrm{E}_{\mathbf{1/2}} = \mathbf{10^{19.73\pm0.07}}\ \mathrm{eV}$$



CALIBRATION by DIP and BEGINNING of GZK CUTOFF



Energy shift: $\lambda = 1$ **for HiRes,** $\lambda = 1.2$ **for Auger,** $\lambda = 0.75$ **for AGASA,** $\lambda = 0.83$ **for Akeno and** $\lambda = 0.625$ **for Yakutsk.**

THREE MODELS FOR UHECR:

DIP, ANKLE, and MIXED-COMPOSITION MODELS

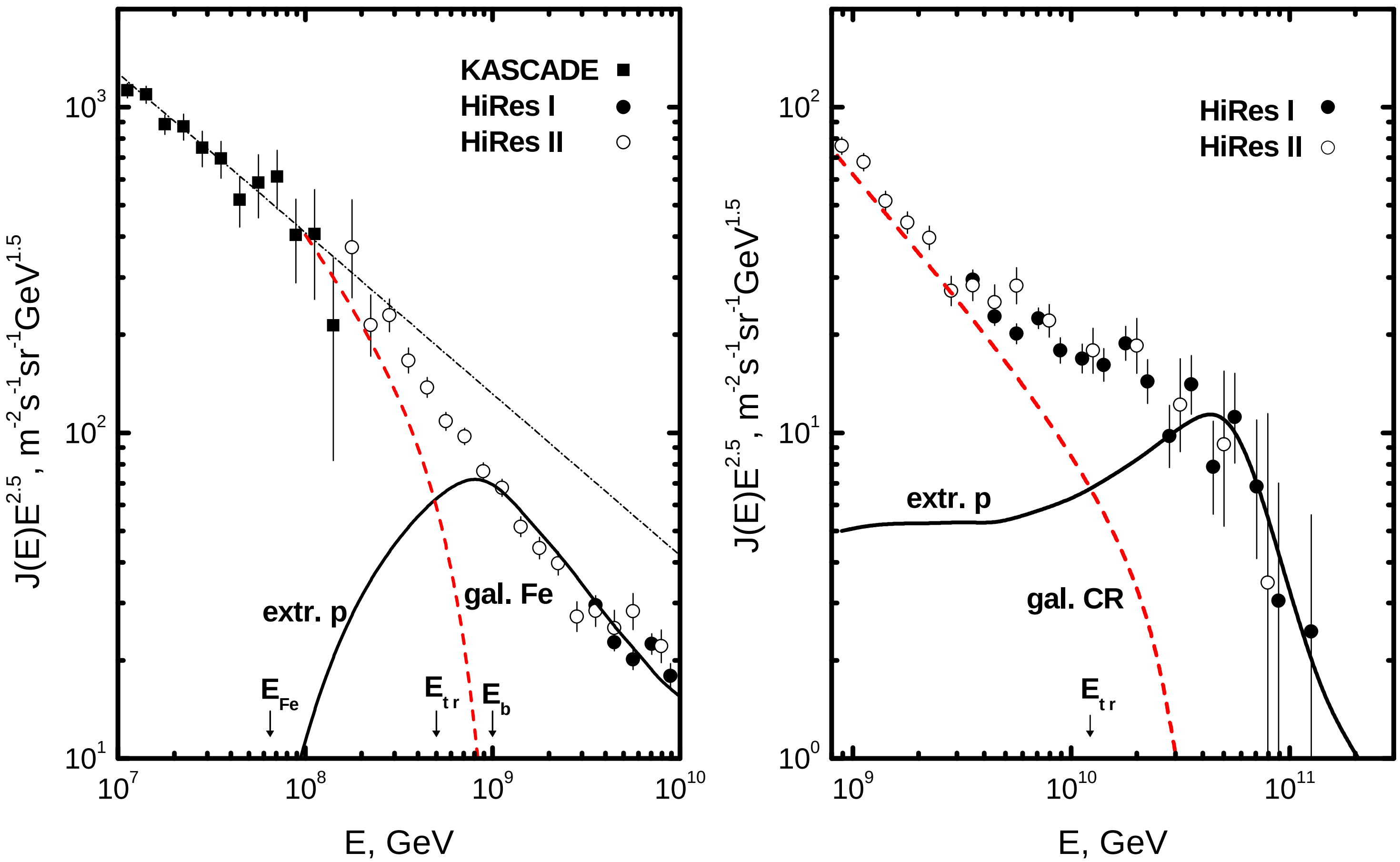
(for description of spectra, mass composition and transition)

- **Dip model, which automatically automatically includes ankle (protons).**
- **Ankle model, at $E_a \sim 1 \times 10^{19}$ equal fluxes $\mathrm{J}_{\mathrm{gal}} = \mathrm{J}_{\mathrm{extr}}$ (protons).**
- **Mixed composition model, $\mathrm{E}_a \sim 3 \times 10^{18}$ eV is the end of transition.**

THE DIP and ANKLE MODELS

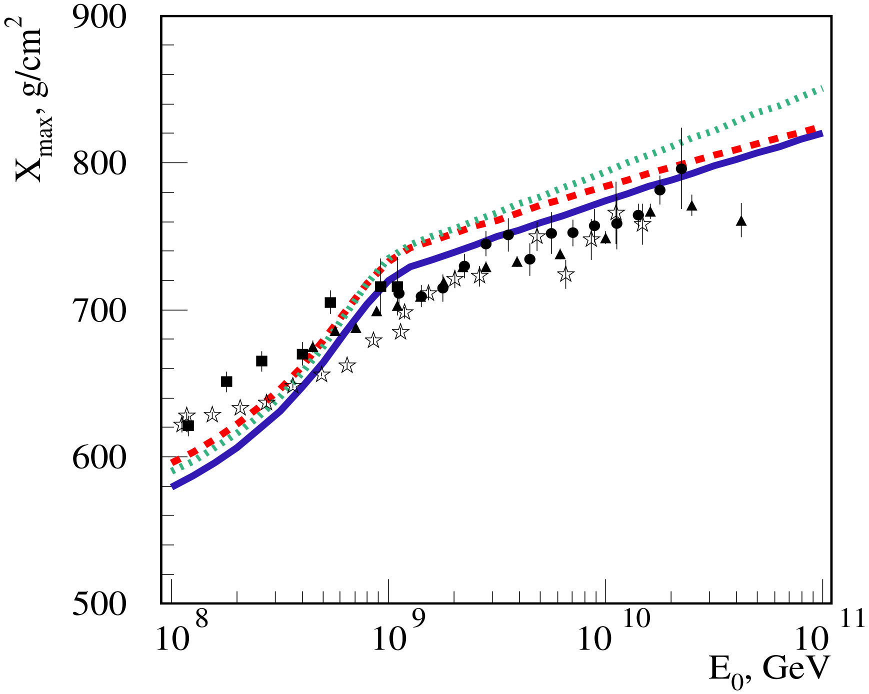
In the dip model transition occurs at $E_{\rm tr} < E_b = 1 \times 10^{18}$ eV, i.e. at second knee. This transition agrees perfectly with the standard galactic model.

In the ankle model transition occurs at $E_a = 1 \times 10^{19}$ eV and the galactic flux at this energy is half of the total in contradiction with standard galactic model.

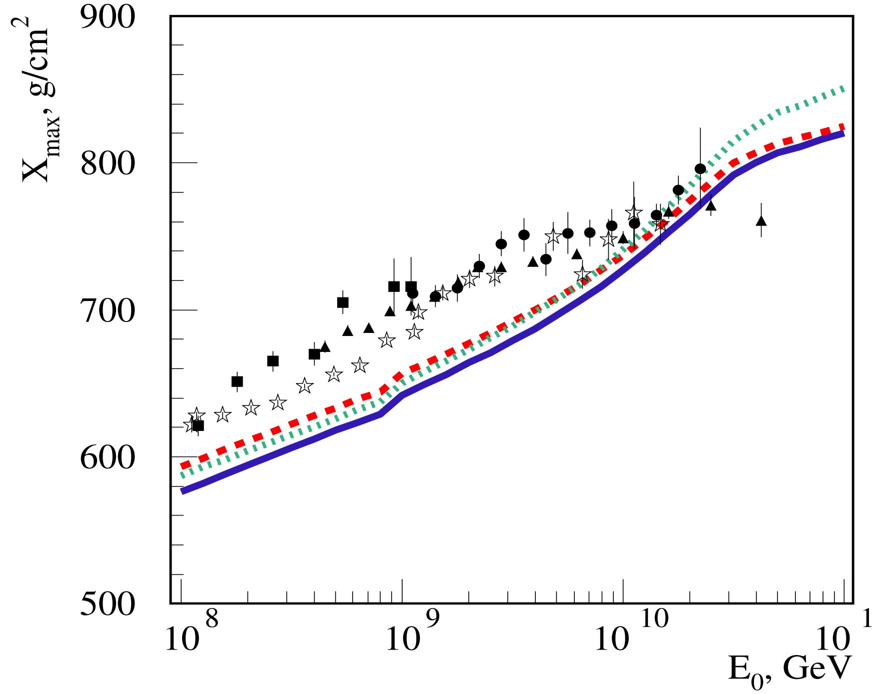


THE DIP and ANKLE MODELS: MASS COMPOSITION

In the dip model transition to proton-dominated component is completed at 1×10^{18} eV, while in the ankle model at 1×10^{19} eV. In the range 1 - 10 EeV ankle model predicts iron or mixed composition, while dip model - proton-dominated composition.
The elongation rate is most sensitive tool of chemical composition.



$X_{\max}(E)$ **in the dip model.**

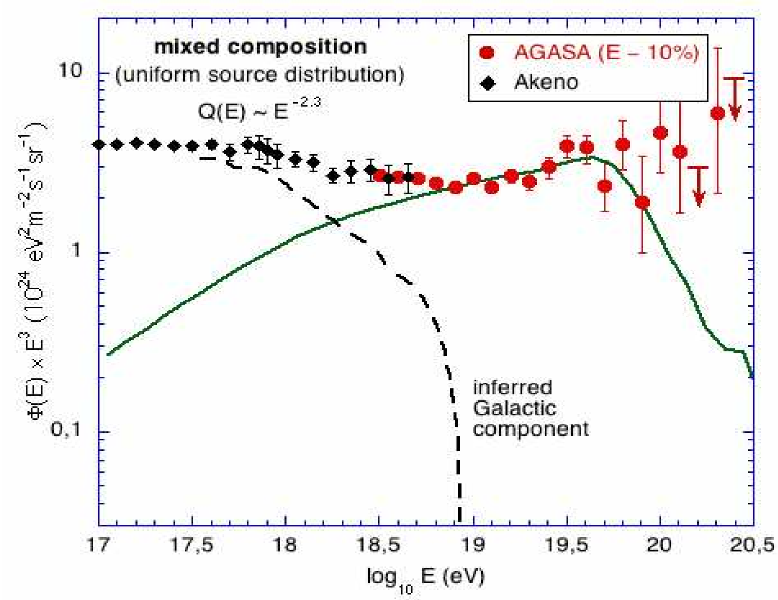


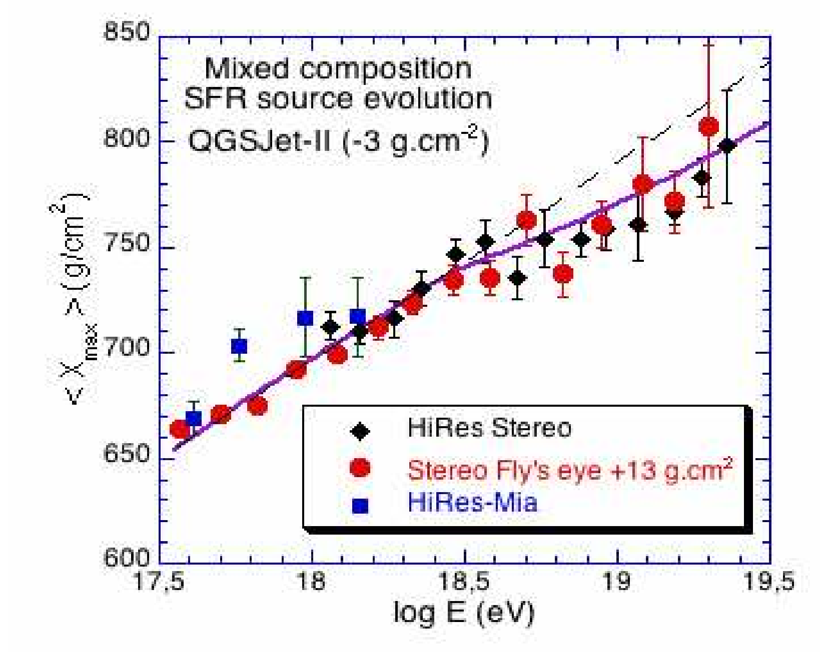
$X_{\max}(E)$ **in the ankle model.**

MIXED COMPOSITION MODEL

Allard, Parizot and Olinto (2005 - 2007)

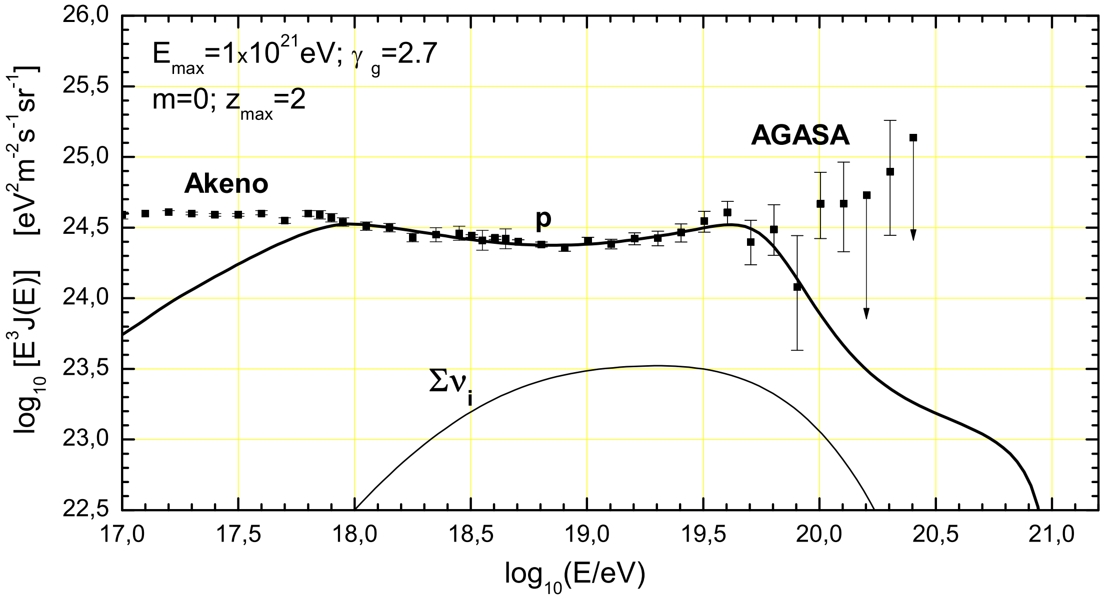
- **generation spectrum with $\gamma_g = 2.1 - 2.3$.**
- **mixed composition at generation.**
- **end of transition at $E \sim 3 \times 10^{18}$ eV .**

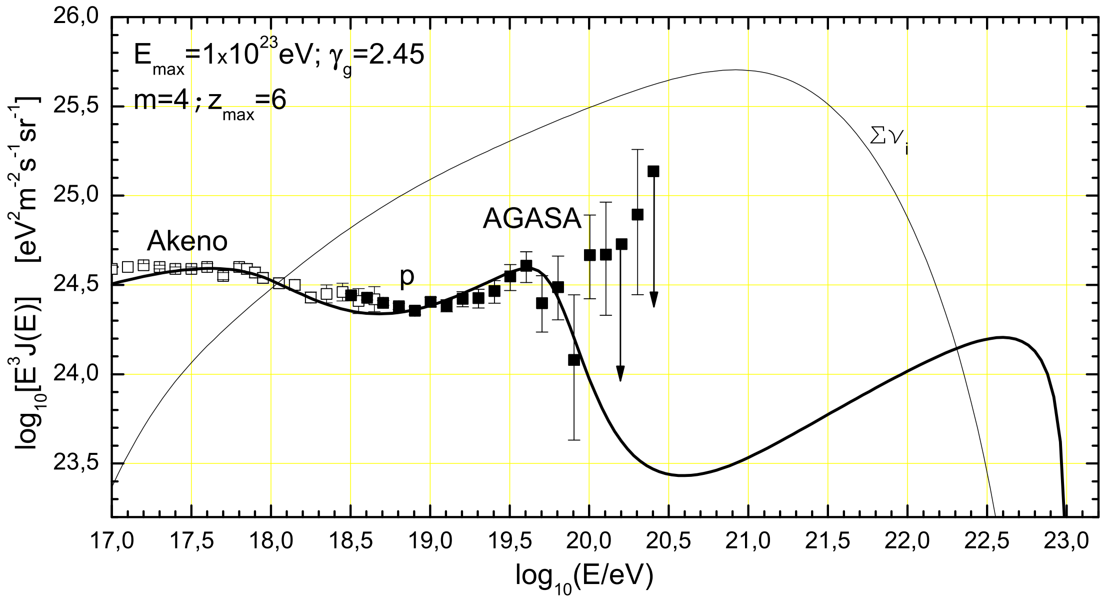




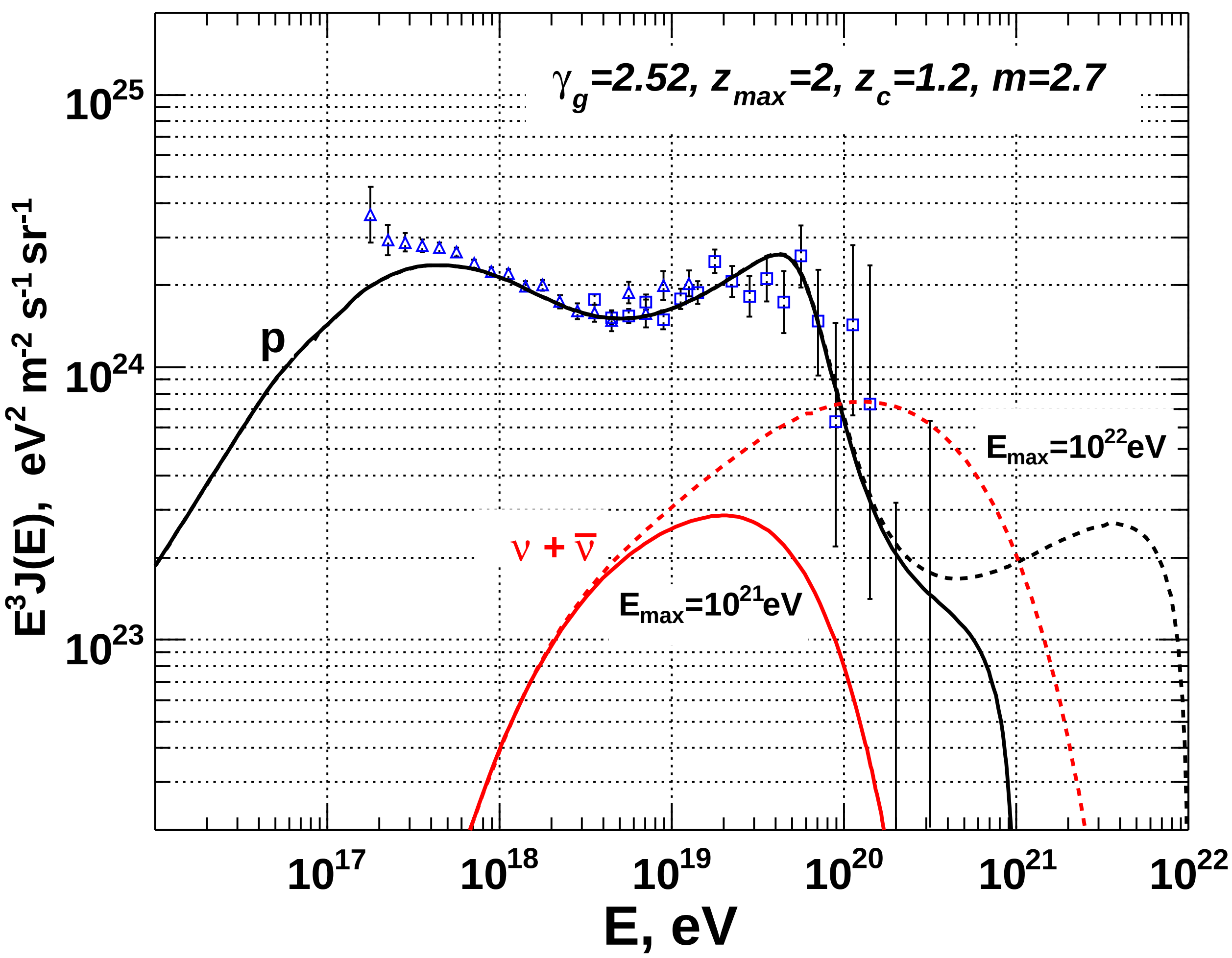
Energy spectrum in the mixed model. $X_{\max}(E)$ **in the mixed model.**

COSMOGENIC NEUTRINO FLUXES IN THE DIP MODEL





COSMOGENIC NEUTRINO FLUXES FROM AGN



CONCLUSIONS

- **The peculiar shape of pair-production dip at $1 \times 10^{18} \leq \mathrm{E} \leq 4 \times 10^{19}$ eV is well seen by all existing UHECR detectors.**

- **HiRes and Auger detectors found the steepening of the spectrum consistent with GZK cutoff. $E_{1/2}$ measured by HiRes, confirms quantitatively that this steepening is the GZK cutoff.**

- **The observed dip and GZK cutoff are signatures of protons. They evidence for proton dominance at energies $1 \times 10^{18} - 1 \times 10^{20}$ eV.**

- **The elongation rate $X_{\max}(E)$ as direct measurement of mass composition is contradictory:**

  HiRes: proton-dominated composition.
  Auger: mixed composition.

- **UHE neutrino radiation can discriminate between dip and mixed composition models. Neutrino flux lower than the minimum flux in the dip model favours presence of nuclei as primaries.**

- **There are three phenomenological models for UHECR : dip, ankle and mixed composition models. The last two models must assume the agreement of the pair-production dip with observations as accidental. The precise measurement of the mass composition is needed to discriminate between these models.**

- **The energies $10^{17} - 10^{18}$ eV look like the key region for cosmic ray origin. More precise measurements of X_{max}(E) at these energies will be obtained in the nearest future by TALE detector (Utah) and FDs with high elevation angles at Auger detector. They will shed more light not only on transition problem, but also on origin of galactic and extragalactic CR.**