TRANSITION FROM GALACTIC TO EXTRAGALACTIC COSMIC RAYS

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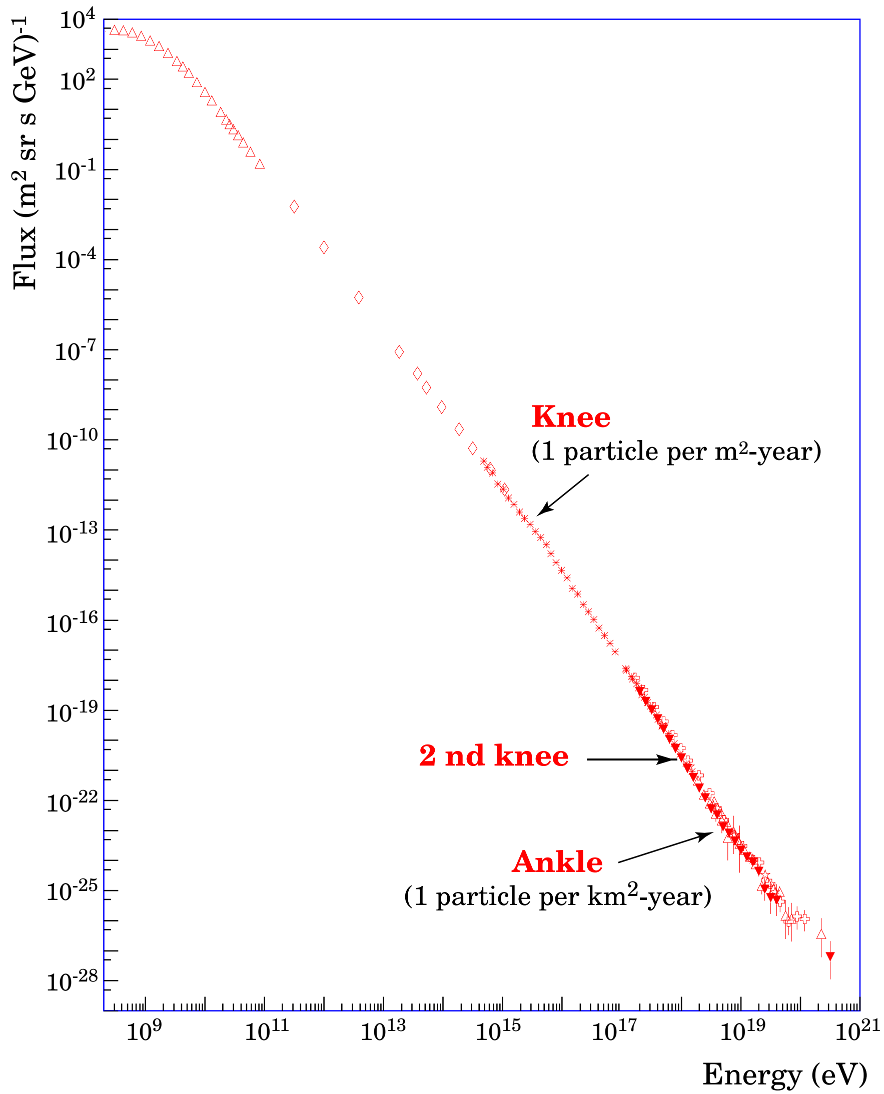
OBSERVED CR SPECTRUM



I. TOWARDS THE END OF GALACTIC CR

SUPERNOVA-REMNANT PARADIGM:

"Standard Model" for galactic cosmic rays

- **sources:** **supernova remnant**
- **acceleration:** **SNR shock acceleration**
- **chemical composition:** **rigidity-dependent injection**
- **propagation:** **diffusive propagation in magnetic fields**

DIFFUSIVE SHOCK-ACCELERATION:

- **spectrum:**
  At fixed SNR age the spectrum of escaped particles is close to δ-function. but time-averaged spectrum is $\propto E^{-2}$ or flatter at highest energies (Ptuskin, Zirakashvili 2006).

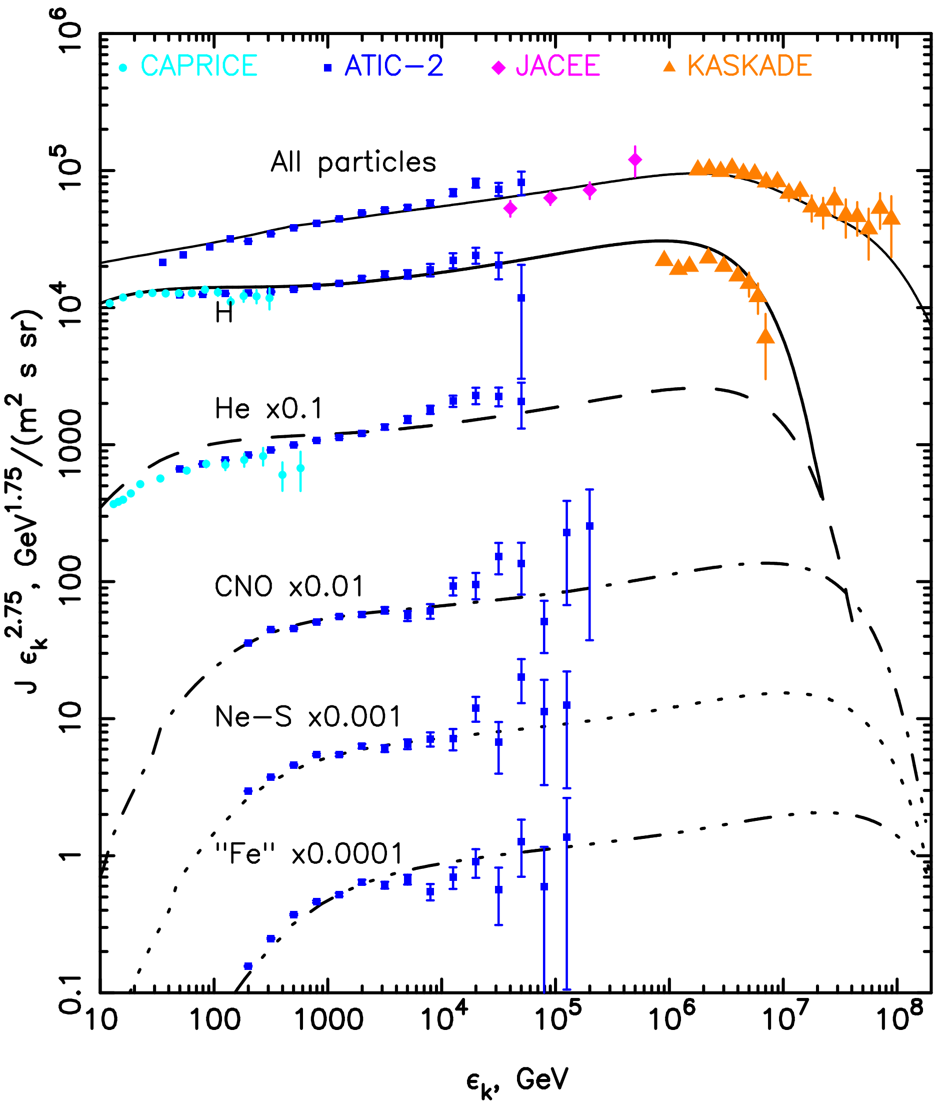
- **$E_{\rm max}$:**
  Acceleration to the highest energies occurs at the beginning of Sedov phase. Non-linear amplification of turbulent magnetic field in the shock precursor due to streaming instability of CR produces magnetic field with strength $\delta B \sim B \sim 10^{-4}$ G **(Bell and Lucek).**

$$\mathbf{E}_{\rm max} = \mathbf{4 \times 10^{15} Z} \frac{\mathbf{B}}{\mathbf{10^{-4}}\mathrm{G}} \left(\frac{\mathbf{W_{51}}}{\mathbf{n_g}/\mathrm{cm}^{\mathbf{3}}} \right)^{\mathbf{2/5}} \ \mathrm{eV}$$

$$\mathbf{E}_{\mathbf{p}}^{\rm max} = \mathbf{4 \times 10^{15} B_{-4}} \ \mathrm{eV}, \qquad \mathbf{E}_{\rm Fe}^{\rm max} = \mathbf{1 \times 10^{17} B_{-4}} \ \mathrm{eV}$$

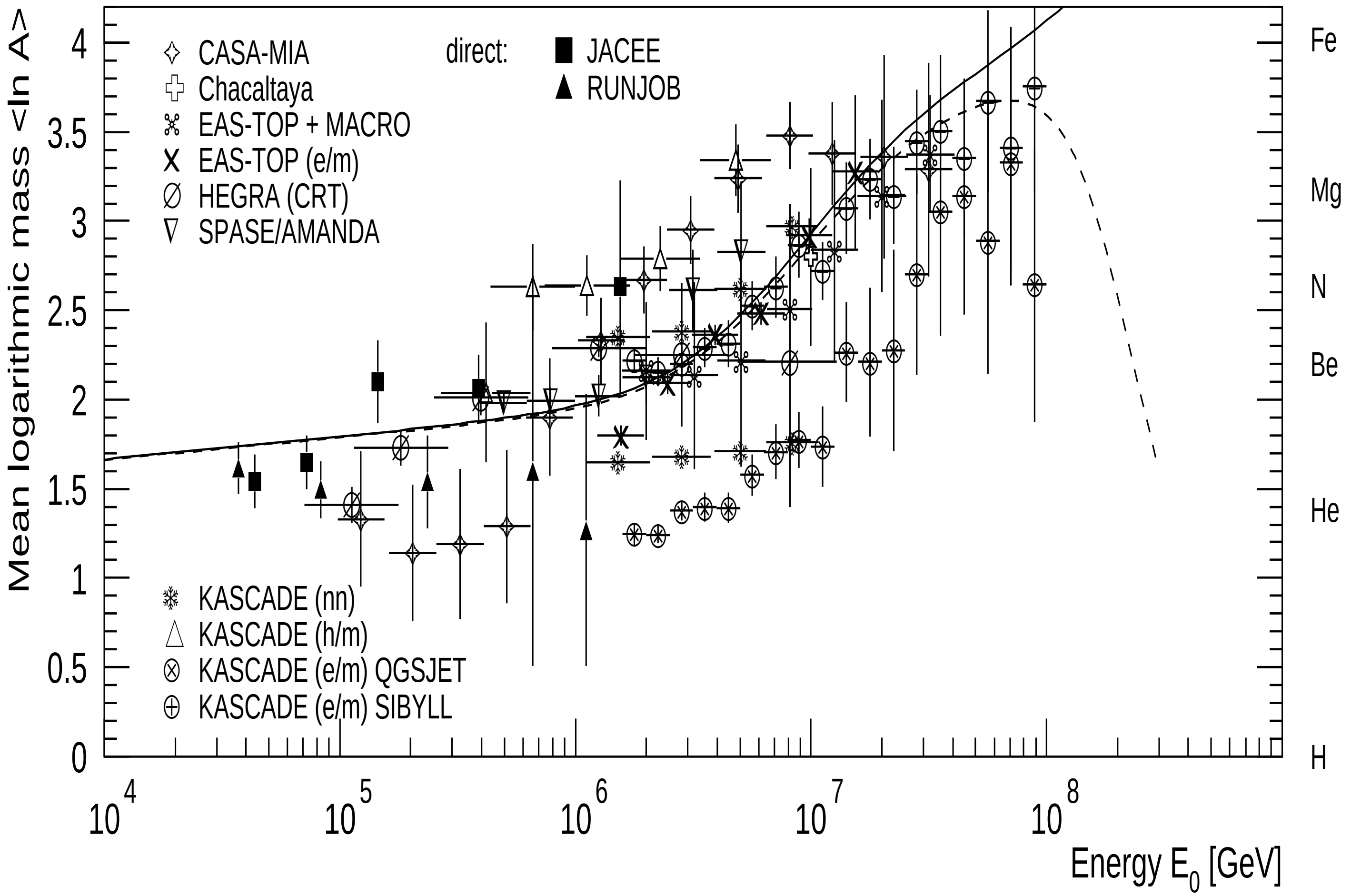
SM : GALACTIC SPECTRA AND KNEES

Berezhko and Völk 2007



MASS COMPOSITION VS ENERGY

Compilation of Hörandel 2005



CONCLUSION NEEDED FOR ANALYSIS OF TRANSITION

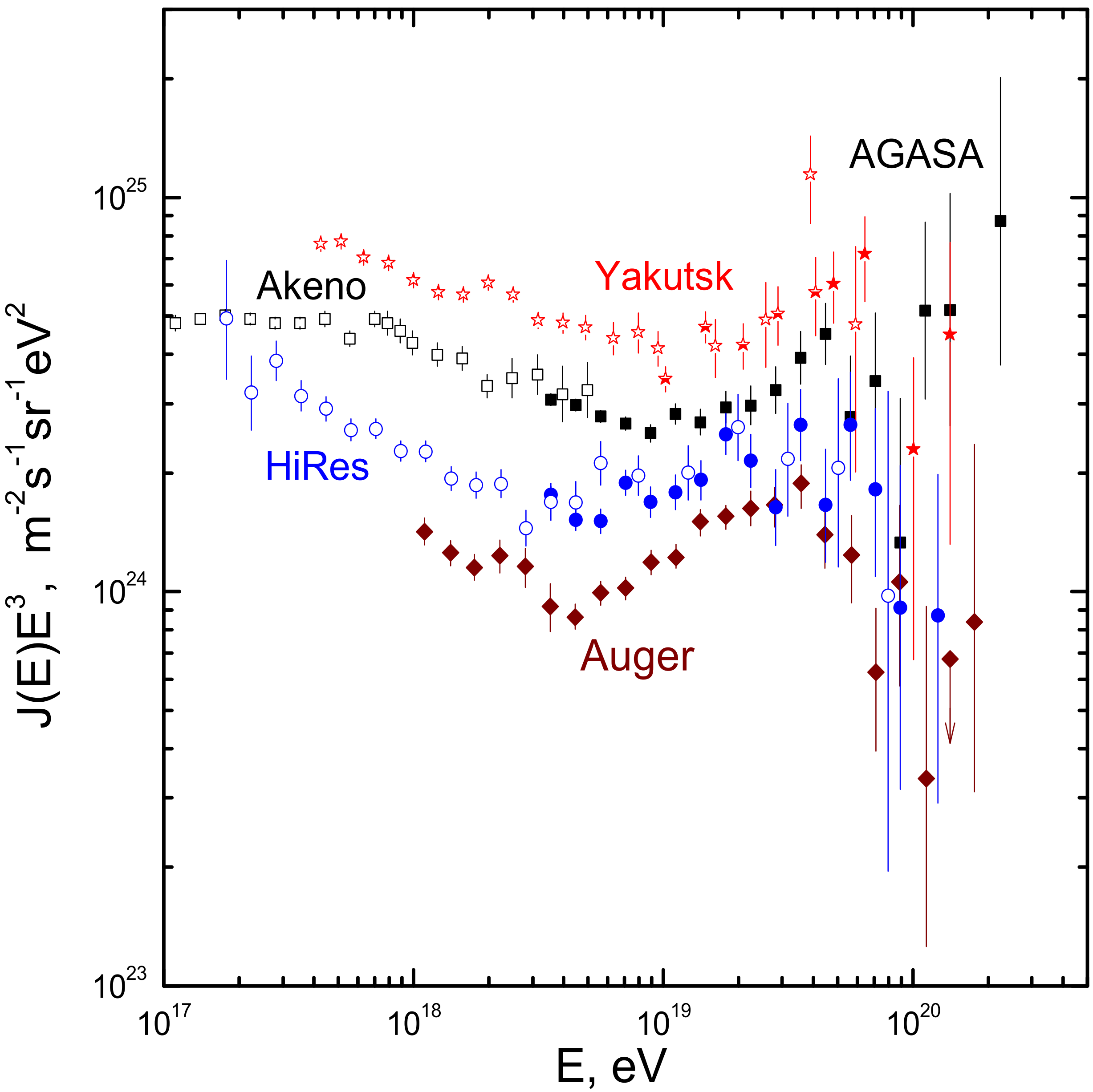
In "standard model" the end of Galactic cosmic rays starts at iron knee

$$\mathbf{E}_{\rm Fe}^{\rm knee} = \mathbf{Z}\mathbf{E}_{\mathbf{p}}^{\rm knee} \sim \mathbf{1} \times \mathbf{10}^{\mathbf{17}}\,{\rm eV}$$

Spectrum of Fe-nuclei at $E > E_{\rm Fe}^{\rm knee}$ is steep and it inevitably intersects somewhere the more flat extragalactic spectrum .

II. FROM UHECR TOWARDS THE KNEE

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

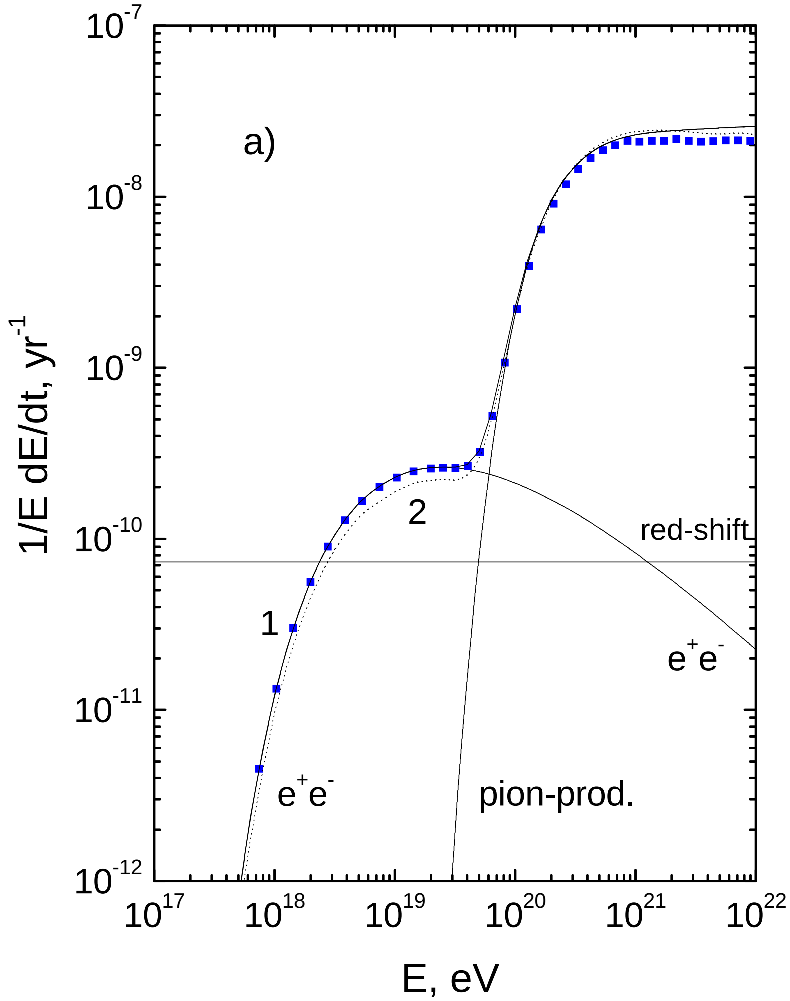
$$Z + \gamma_{\rm CMB} \rightarrow Z + e^{+} + e^{-}$$

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

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

Photons

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



PROPAGATION SIGNATURES

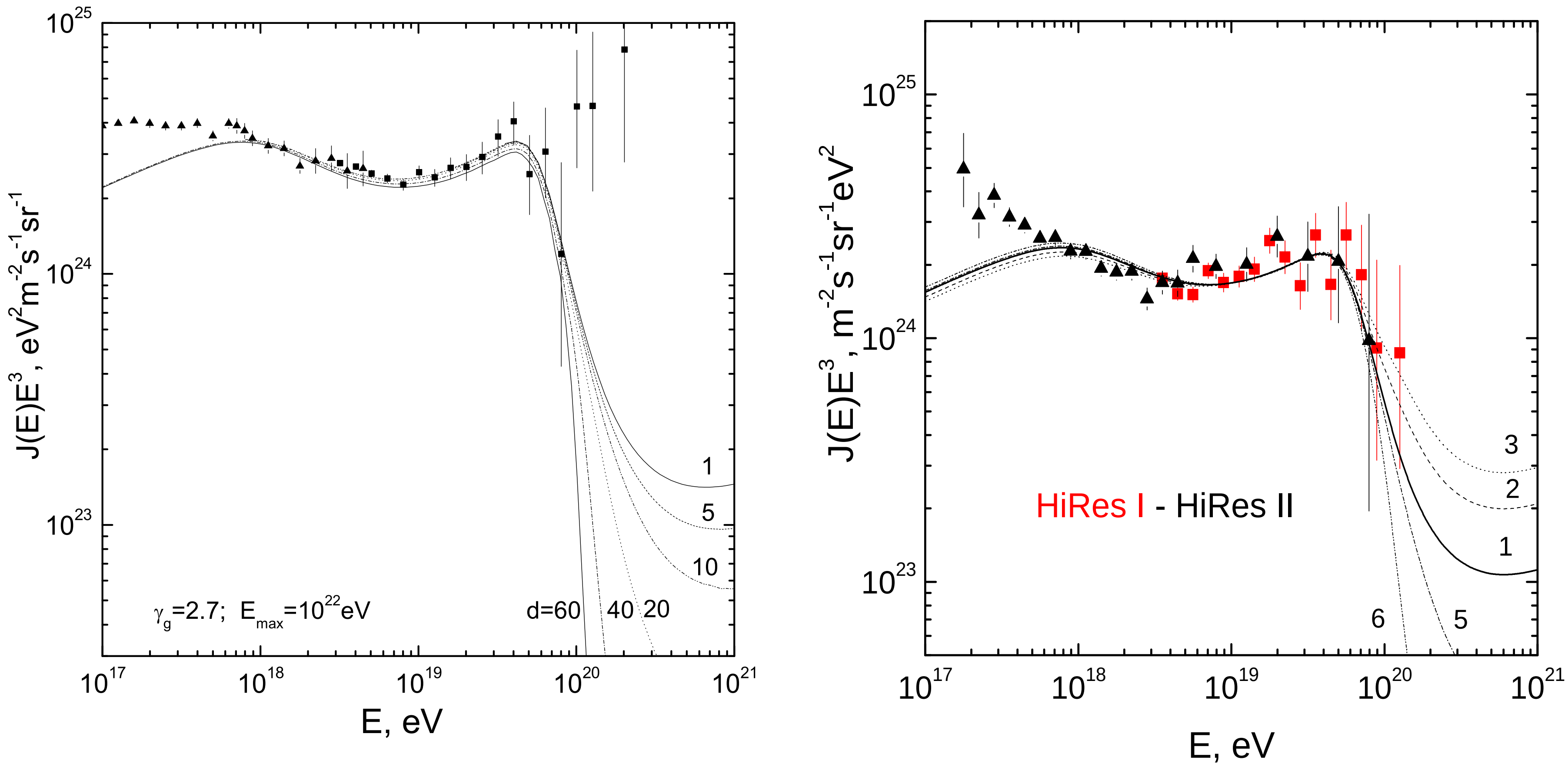
Propagation of **protons** in intergalactic space leaves the imprints on the spectrum most notably in the form:

GZK cutoff and pair-production dip

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

GZK CUTOFF

GZK cutoff is modified by **discreteness** in source distribution and by source local **overdensity/deficit** and by different values of $\mathbf{E}_{\max}$.



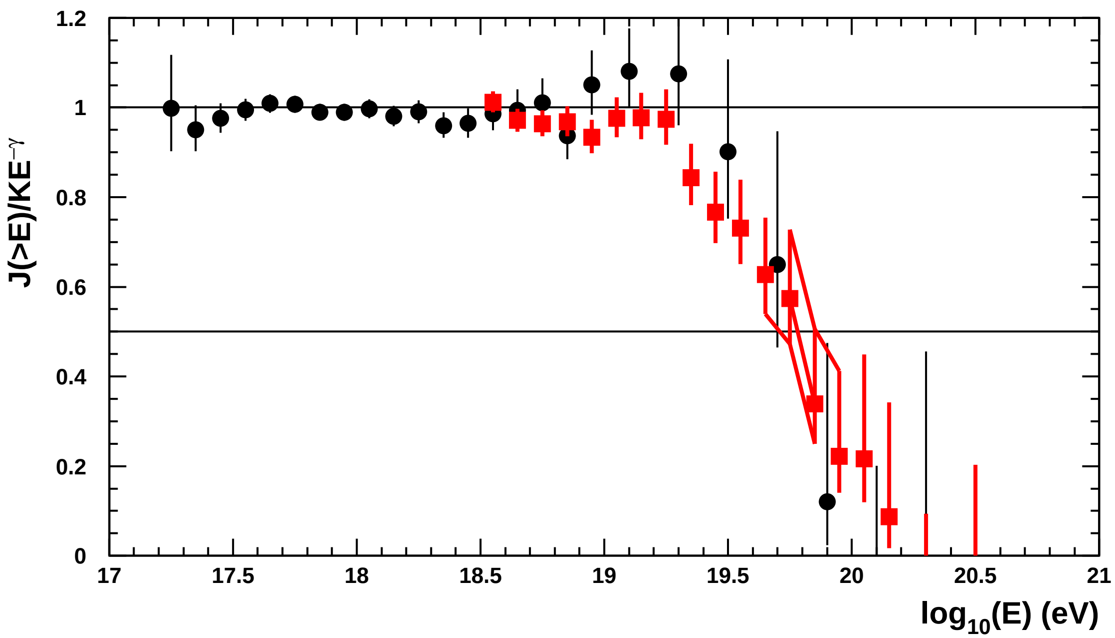
GZK CUTOFF IN HiRes DATA

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

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

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

$$\mathrm{E}_{1/2} = 10^{19.73 \pm 0.07}\ \mathrm{eV}$$



PAIR-PRODUCTION DIP IN THE DIFFUSE SPECTRUM

VB, Grigorieva 1988; Aloisio, VB, Blasi, Gazizov, Grigorieva (2004 - 2007).

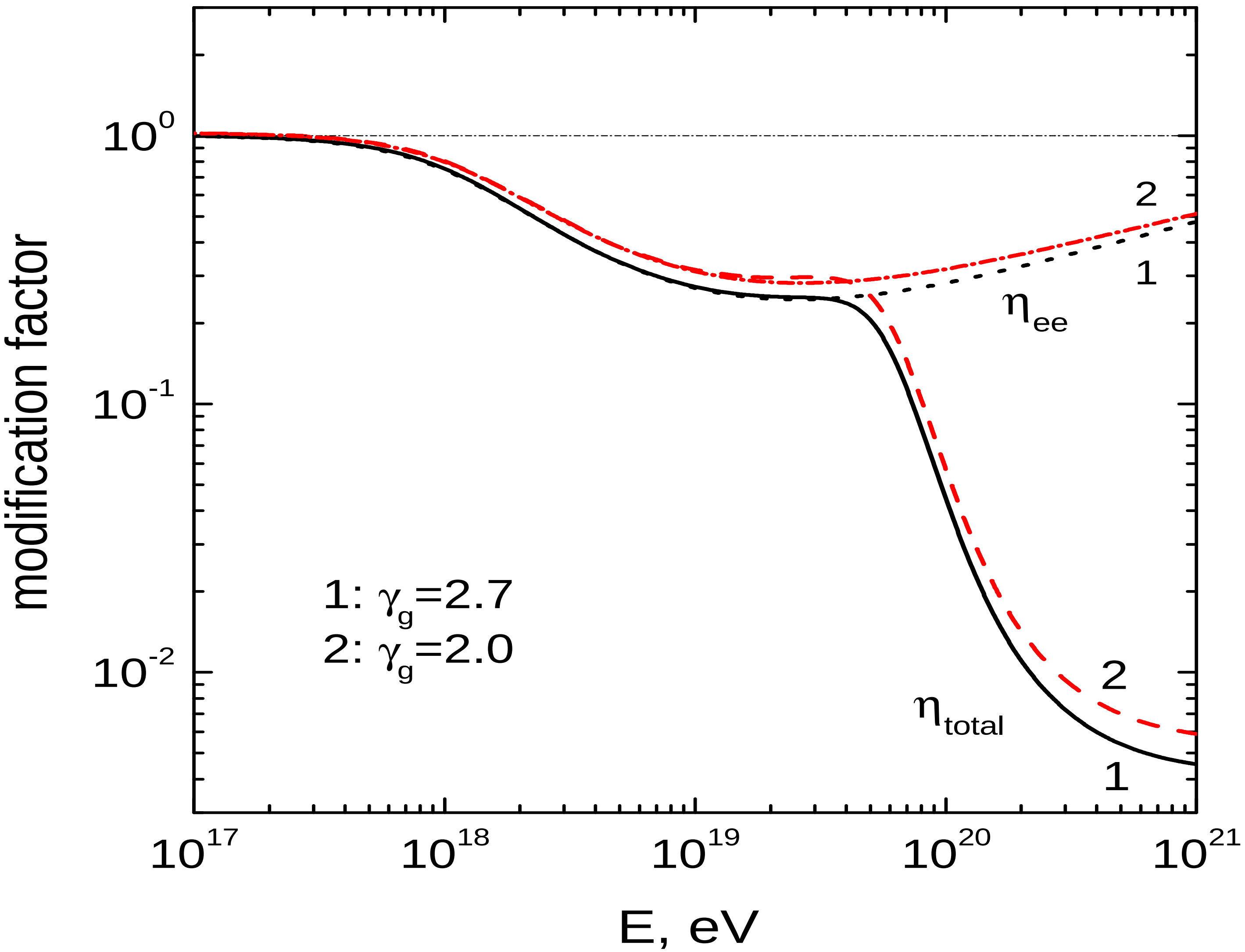
DEFINITION OF MODIFICATION FACTOR

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

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, $\eta_{ee}(E)$.

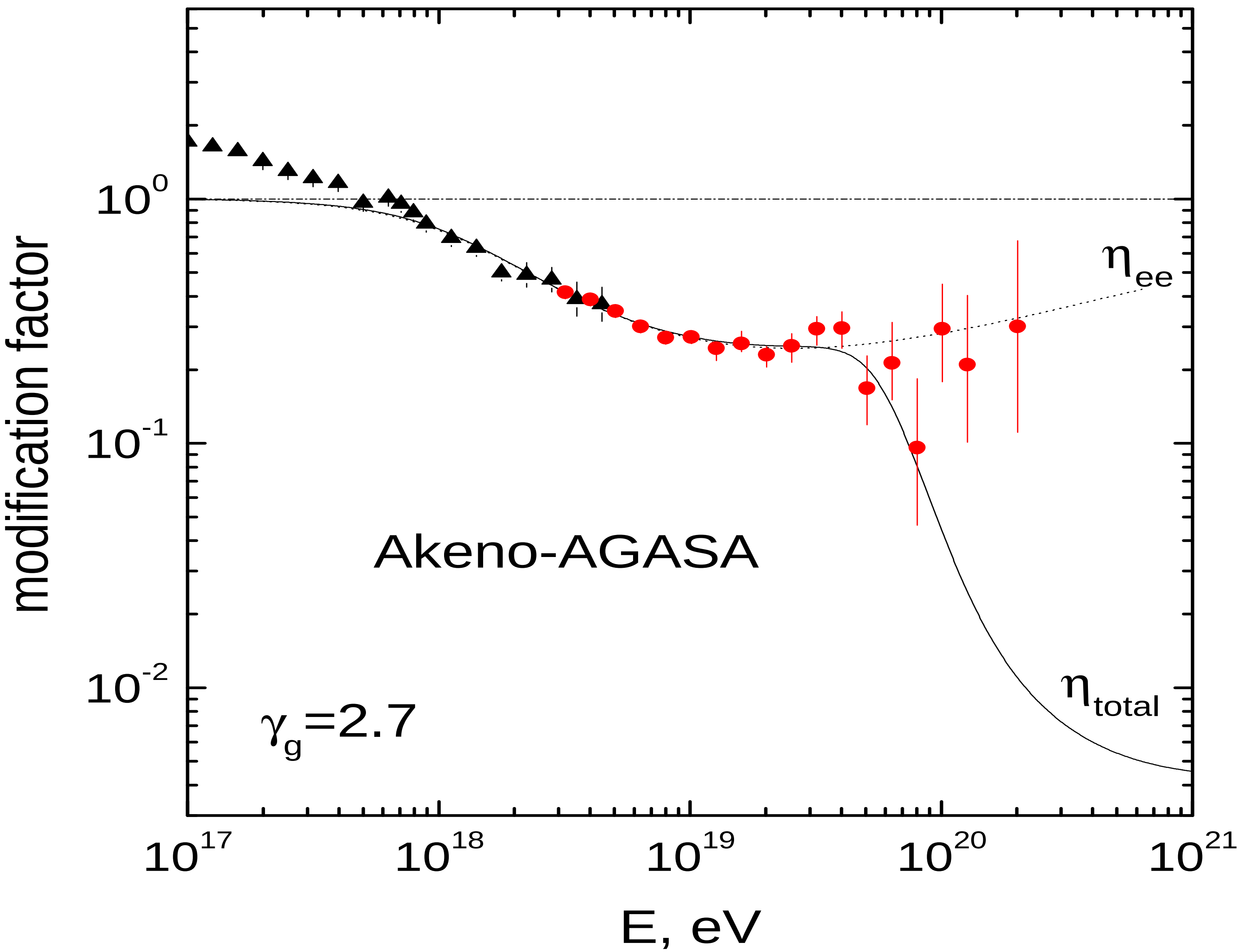
Since both $J_p^{\rm unm}(E)$ and $J_p(E)$ include factor $E^{-\gamma_g}$, $\eta(E)$ depends weakly on γ_g.

DIP IN DIFFUSE SPECTRA

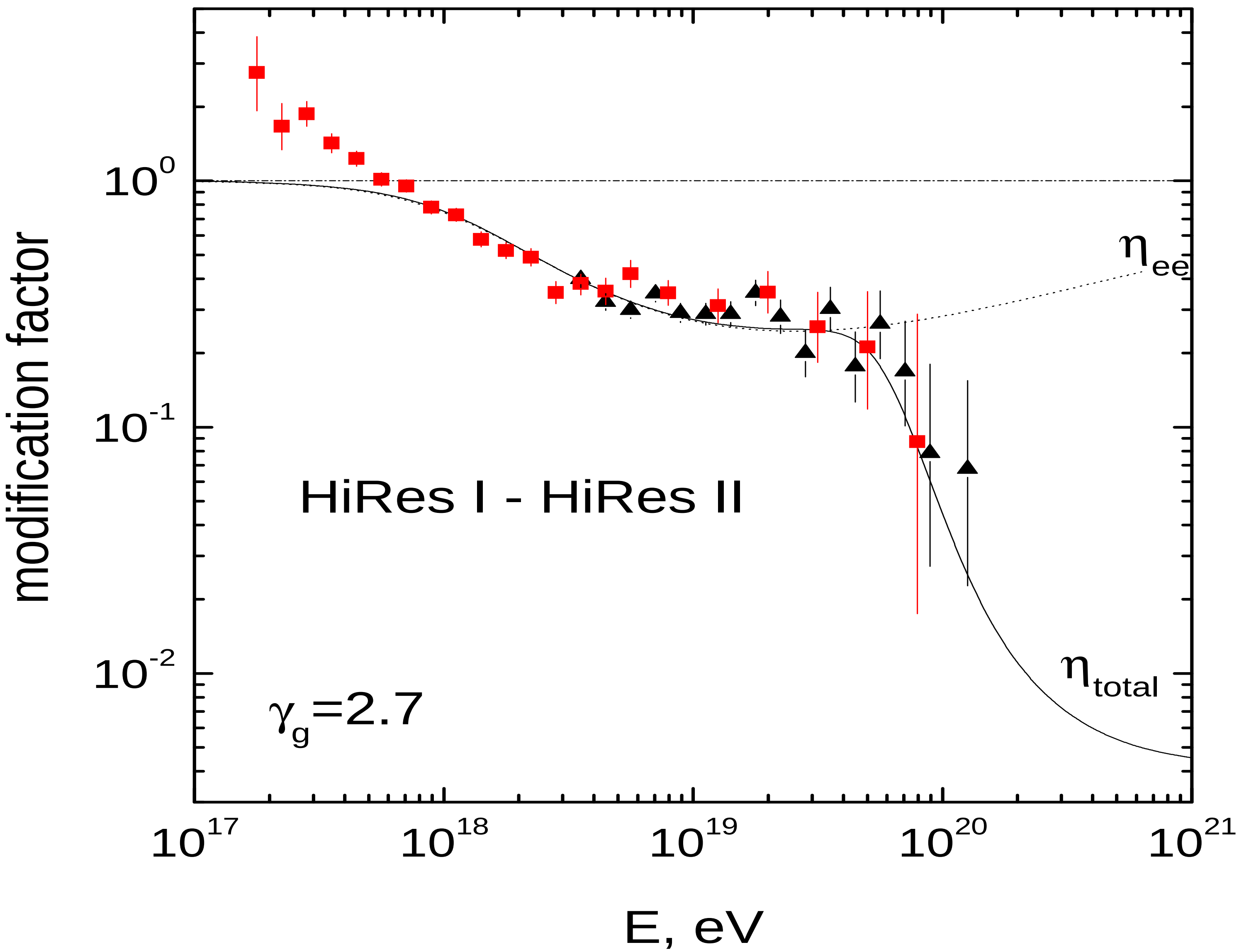


The dotted curve shows η_{ee}, when only adiabatic and pair-production energy losses are included. The solid and dashed curves include also the pion-production losses.

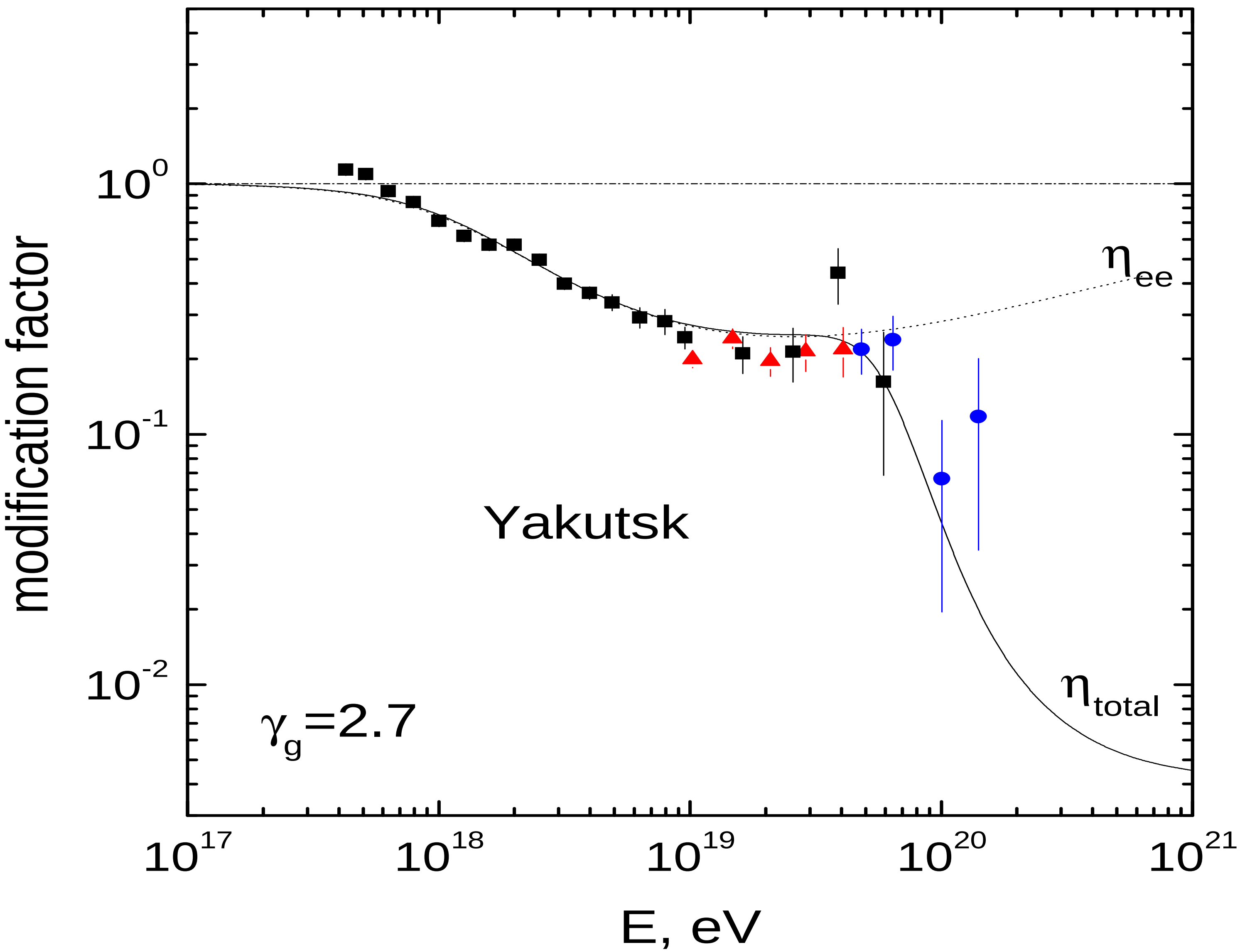
DIP IN COMPARISON WITH AKENO-AGASA DATA



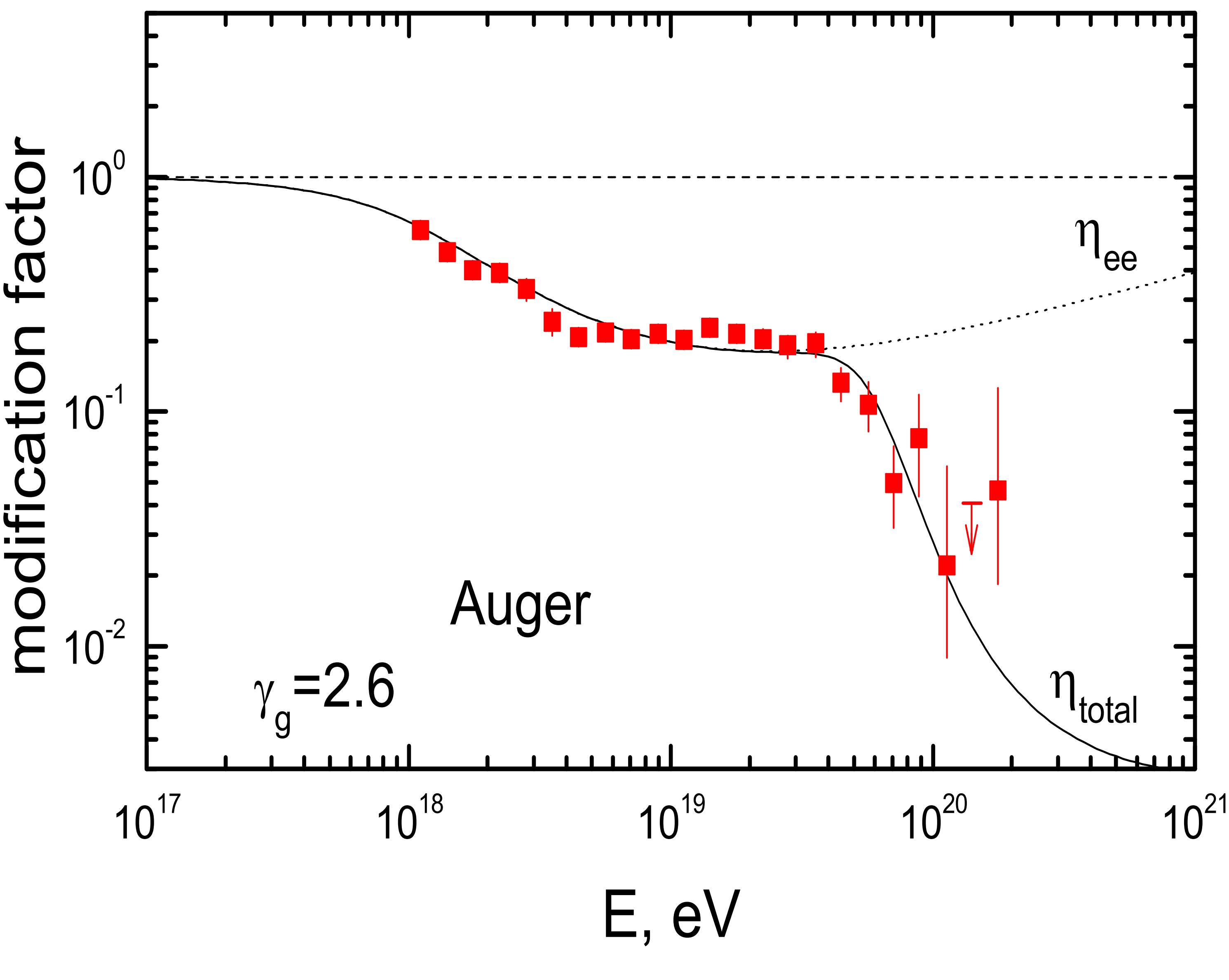
DIP IN COMPARISON WITH HIRES DATA



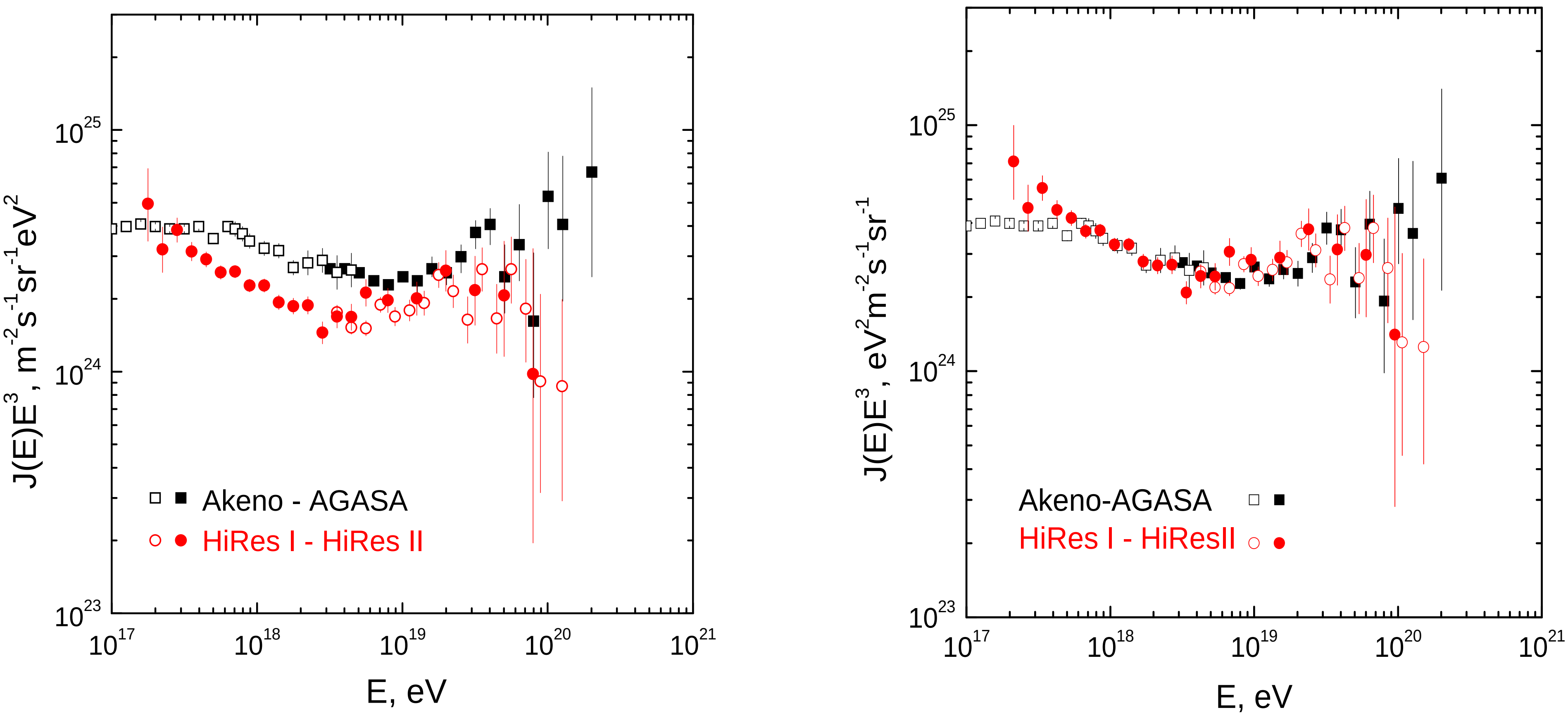
DIP IN COMPARISON WITH YAKUTSK DATA



DIP IN COMPARISON WITH AUGER DATA

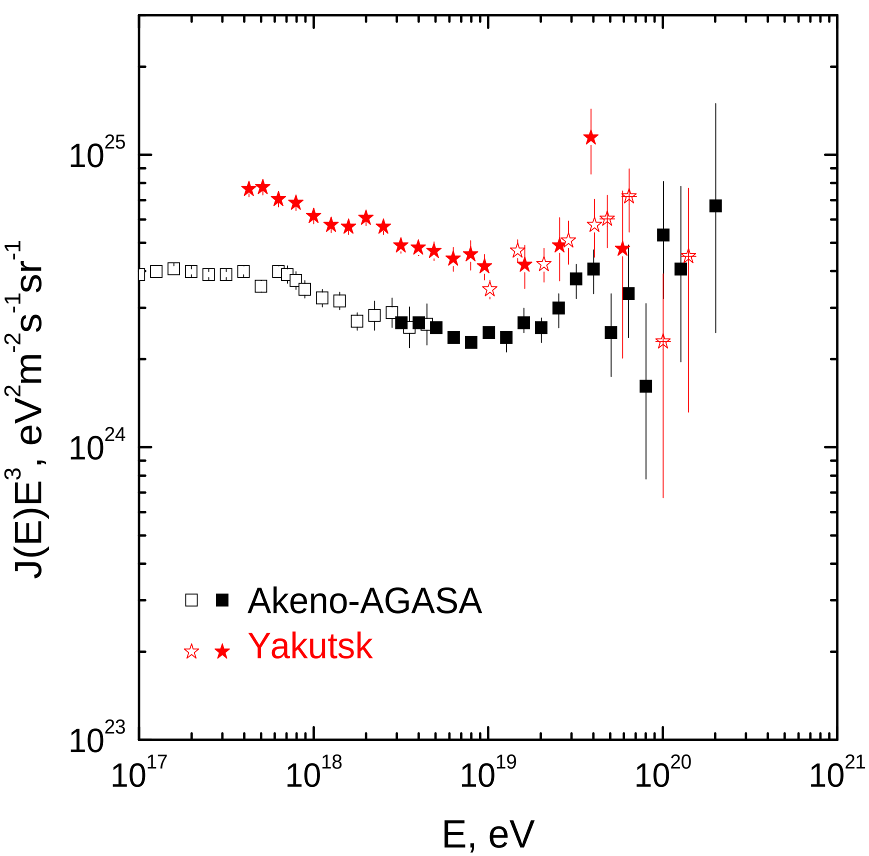


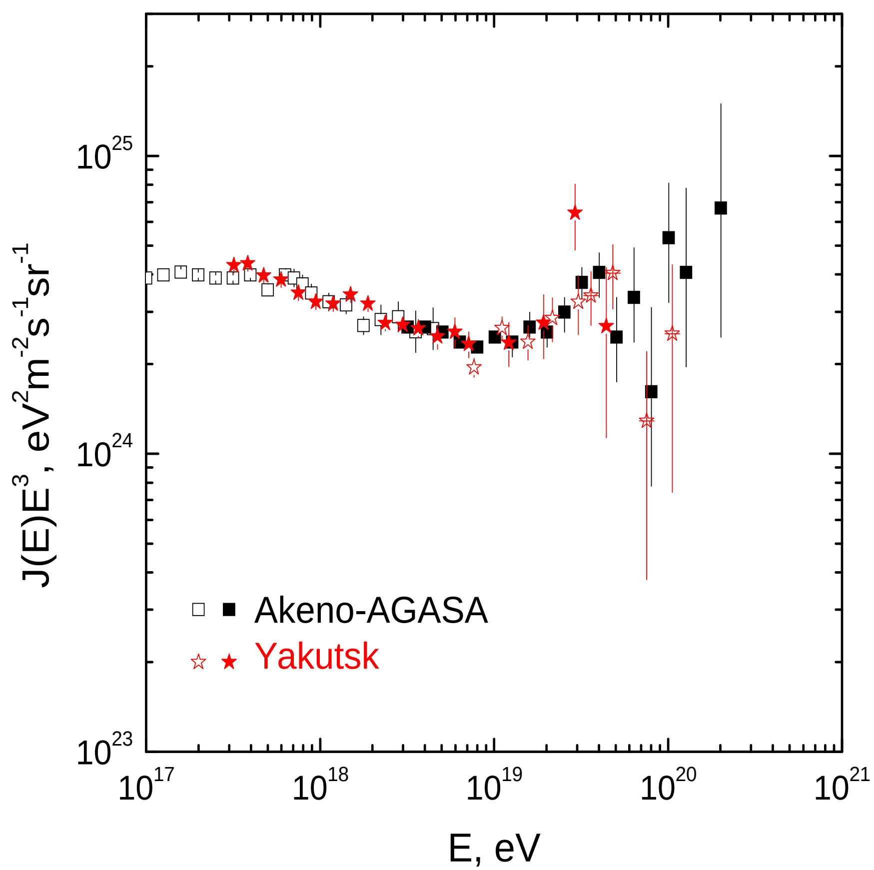
ENERGY CALIBRATION BY DIP : AGASA-HIRES DISCREPANCY



AGASA and HiRes spectra calibrated by the dip. The energy shift needed for $\chi^2_{\min}$ is $\lambda_{\rm AGASA} = 0.9$ and $\lambda_{\rm HiRes} = 1.2$. Both are allowed by systematic errors.

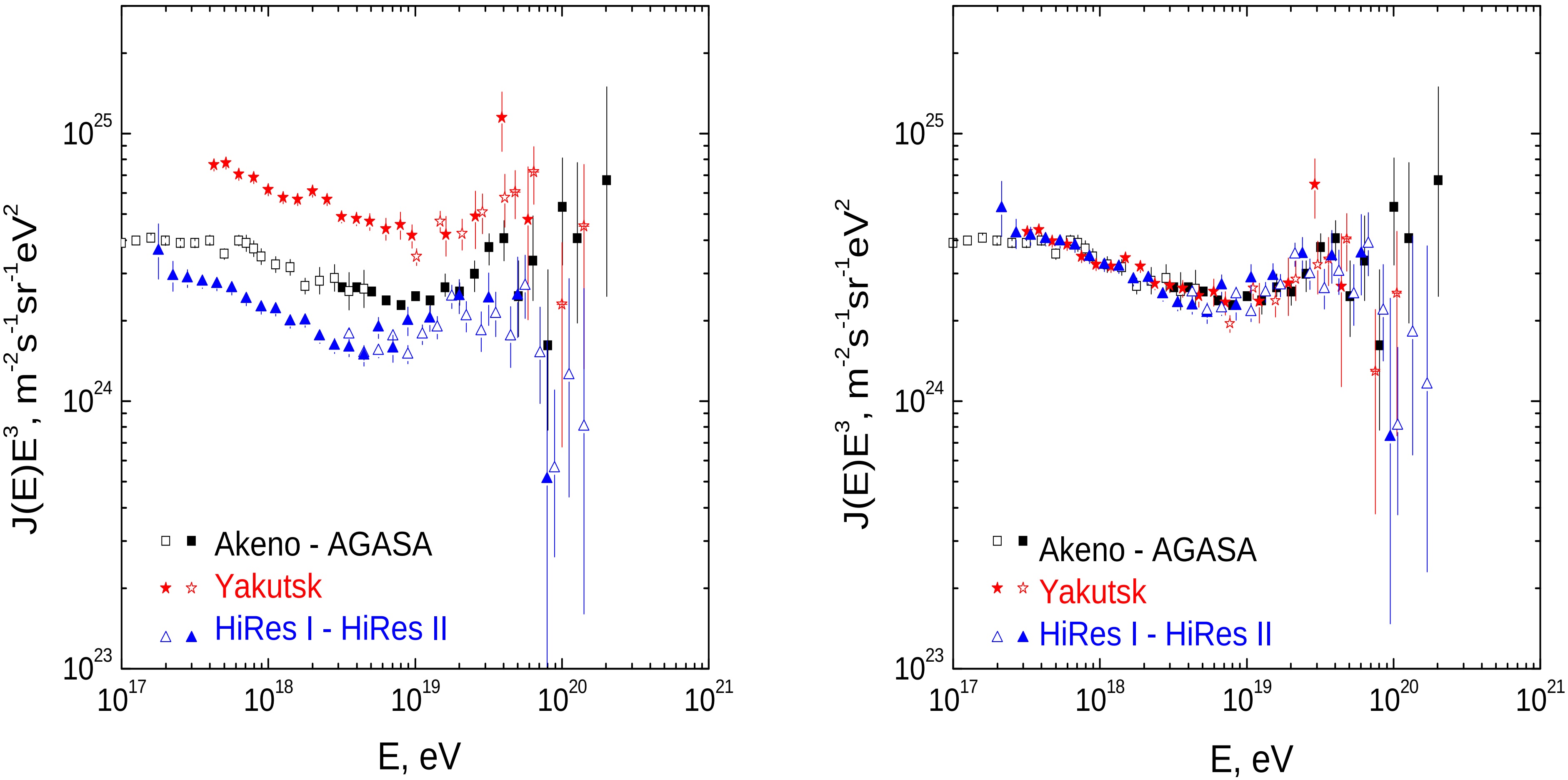
DIP AND AGASA-YAKUTSK DISCREPANCY





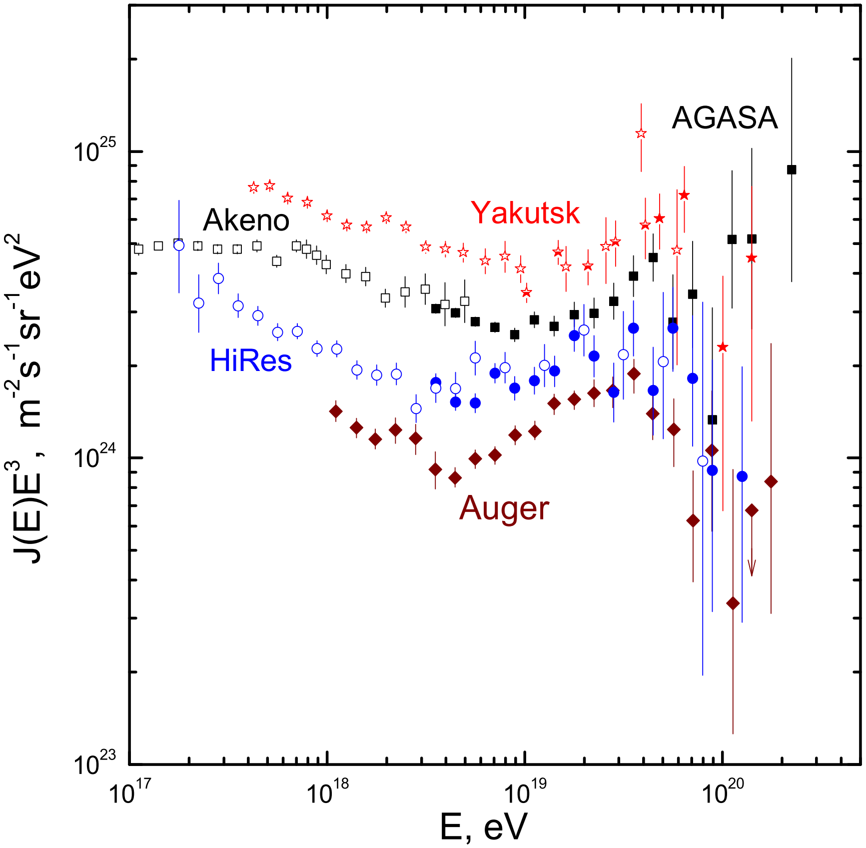
AGASA and Yakutsk spectra calibrated by the dip. The energy shift needed for $\chi^2_{\rm min}$ is $\lambda_{\rm AGASA} = 0.9$ and $\lambda_{\rm Yakutsk} = 0.75$. Both are allowed by systematic errors.

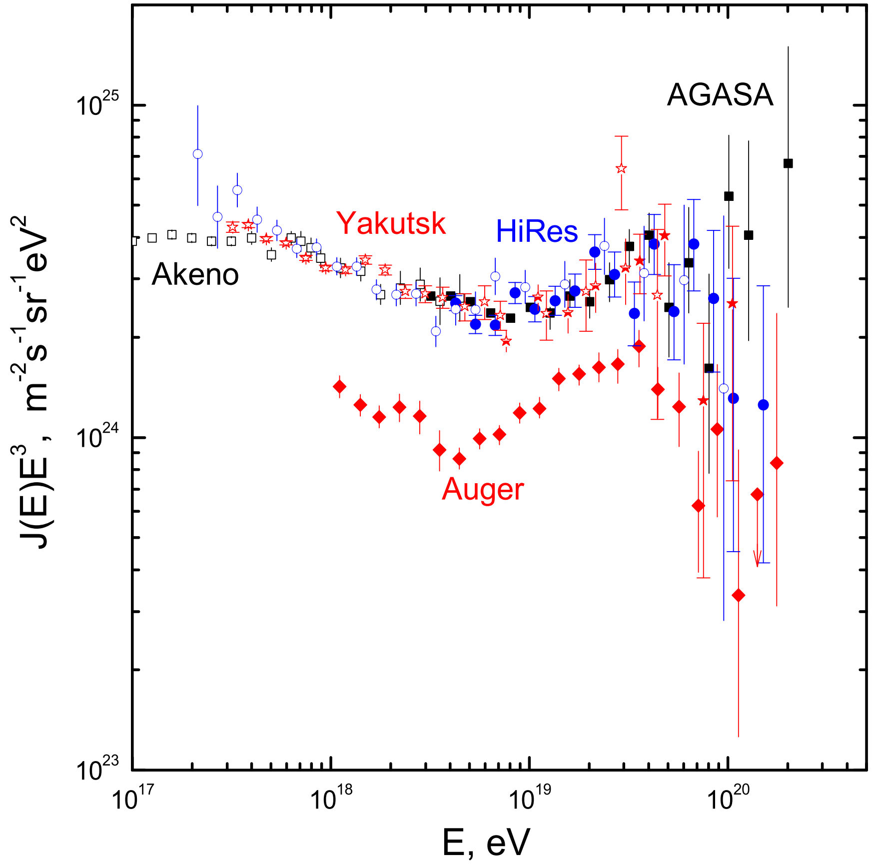
AGASA-HIRES-YAKUTSK DISCREPANCY



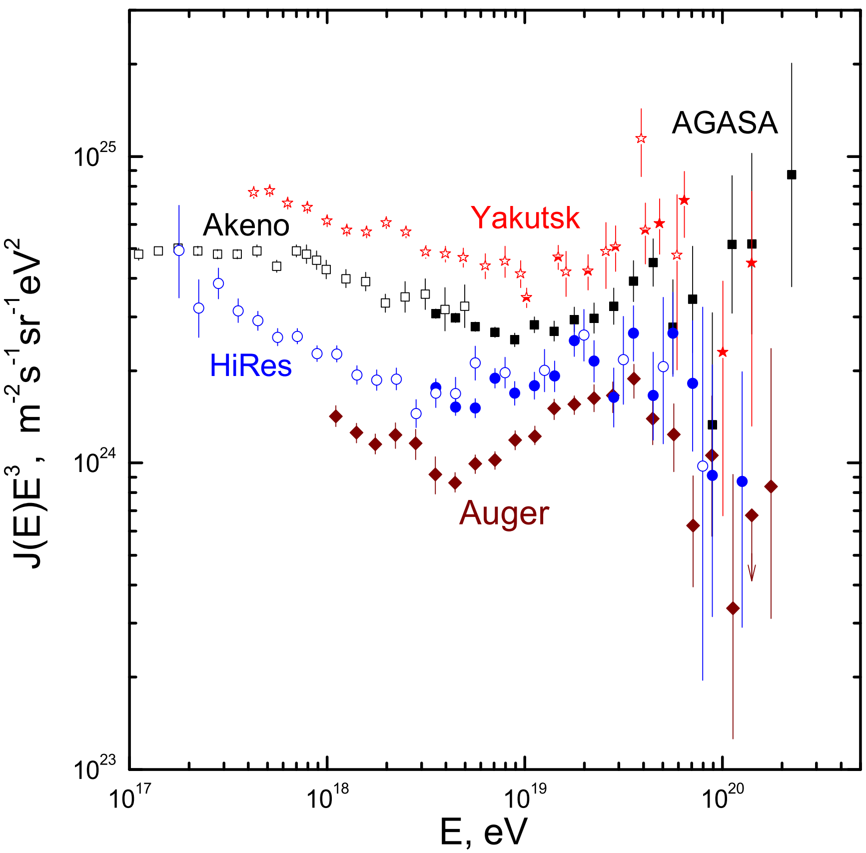
AGASA, Hires and Yakutsk spectra calibrated by the dip.

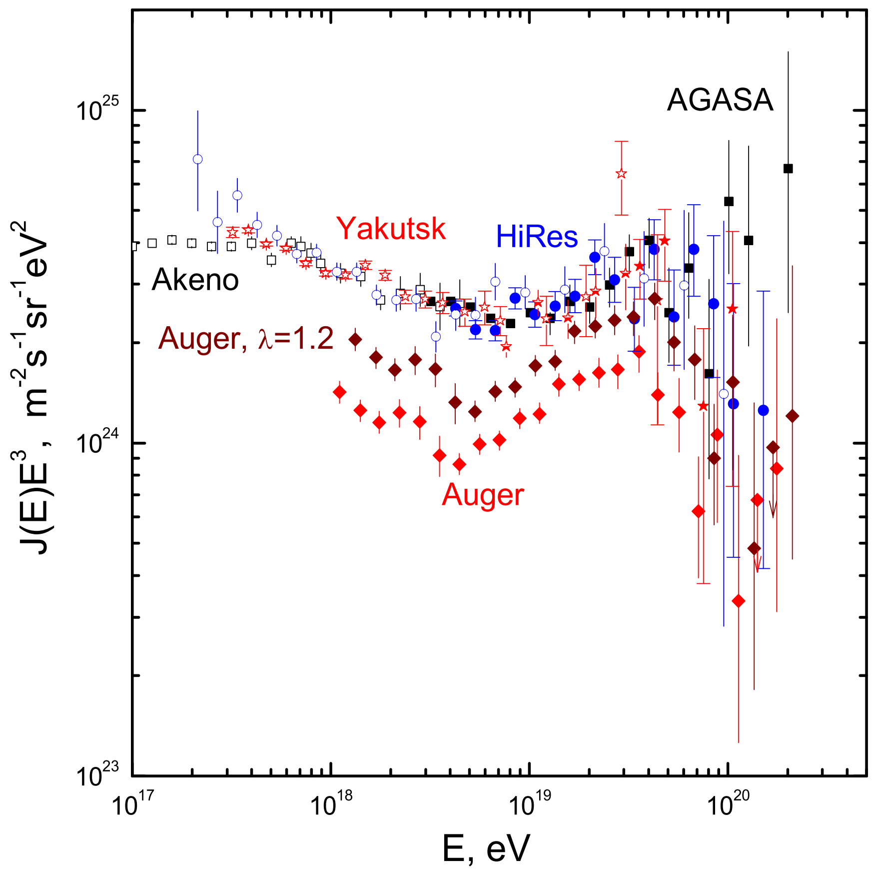
COMPARISON OF AUGER WITH CALIBRATED DATA





COMPARISON OF AUGER WITH CALIBRATED DATA





CONCLUSIONS NEEDED FOR ANALYSIS OF TRANSITION

- **Very good agreement of the predicted dip energy-shape with the data of all detectors demonstrates that large fraction of particles observed at $1 \times 10^{18} - 4 \times 10^{19}$ eV are extragalactic protons propagating through CMB.**

- **The numerical agreement of HiRes data with GZK cutoff implies that at energy $E \geq 5 \times 10^{19}$ eV protons dominate, too.**

III. TRANSITION

THREE MODELS OF TRANSITION:

DIP, ANKLE, and MIXED-COMPOSITION MODELS

- **In the dip model, dip automatically includes ankle.**
- **In ankle model,** $E_a \sim 1 \times 10^{19}$ **corresponds to equal fluxes** $\mathrm{J_{gal}} = \mathrm{J_{extr}}$.
- **In the mixed model,** $\mathrm{E}_a \sim 3 \times 10^{18}$ **eV is the end of transition.**

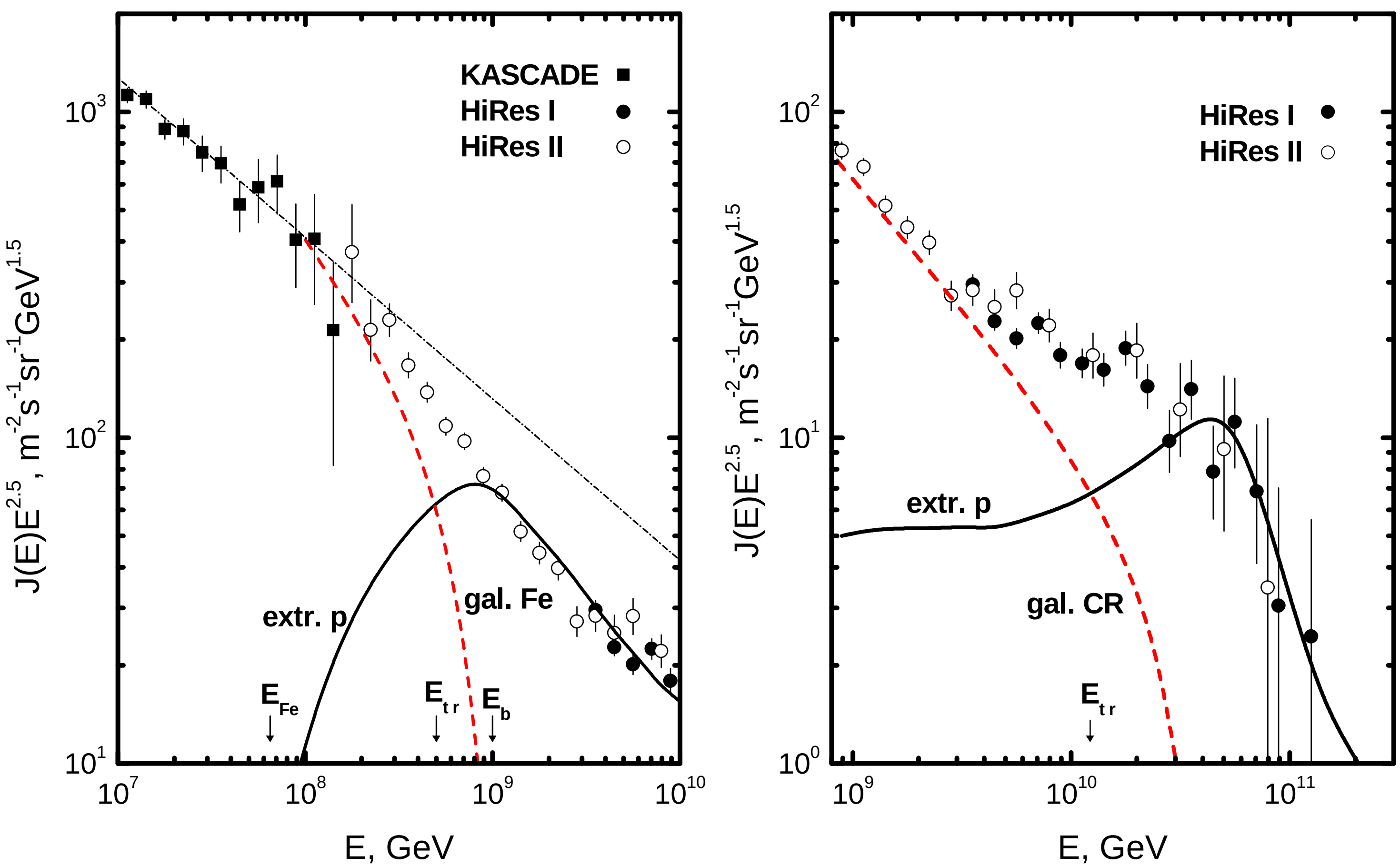
Necessary assumption for ankle and mixed models:

AGREEMENT OF DATA WITH PAIR-PRODUCTION DIP IS ACCIDENTAL

THE DIP and ANKLE TRANSITIONS

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.

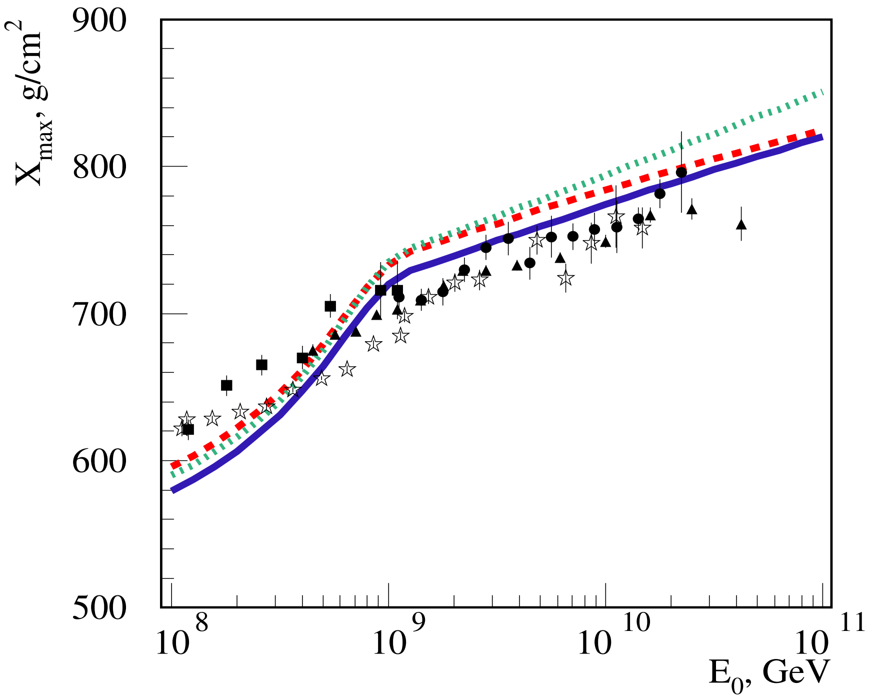
In the ankle model transition occurs at $E_a = 1 \times 10^{19}$ eV and the galactic flux at this energy is half of the total in contradiction with standard galactic model.



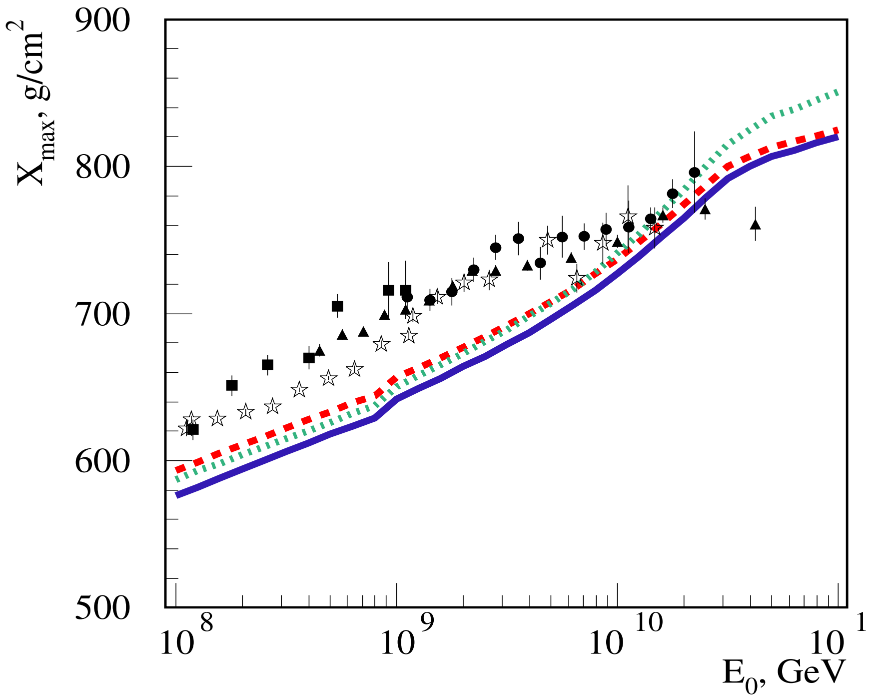
THE DIP and ANKLE TRANSITIONS: MASS COMPOSITION

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.**

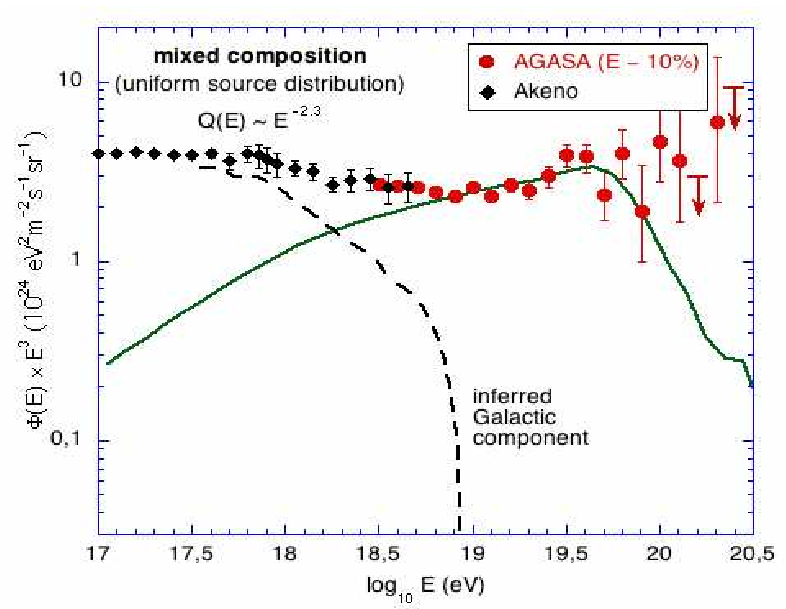


$X_{\max}(E)$ **in the ankle model.**

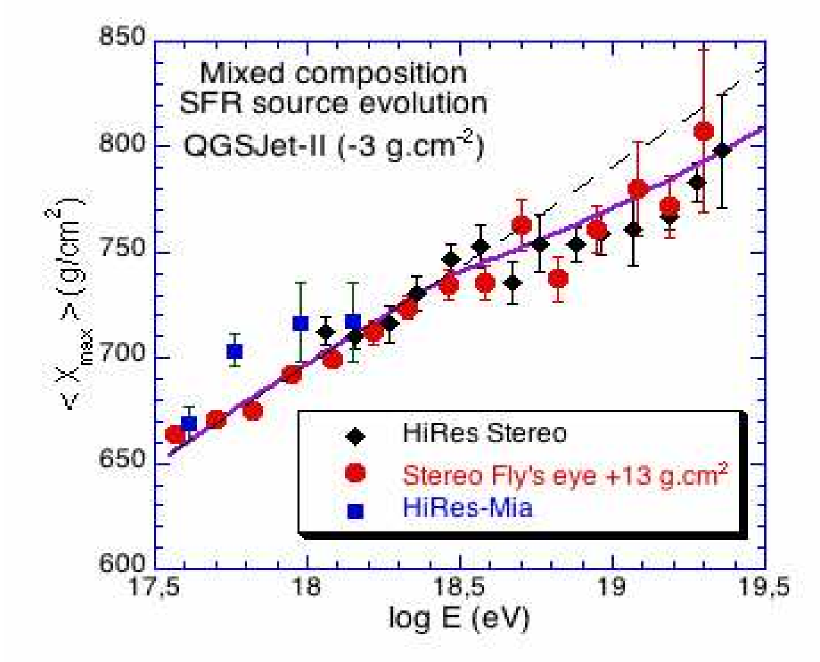
MIXED COMPOSITION MODEL

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.

CONCLUSIONS

- **The galactic CR are well described by the "standard model" with SNR as the sources and with diffusive propagation of CR in the Galaxy. The end of galactic CR corresponds to iron knee** $E_{Fe}^{max} \sim 1 \times 10^{17}$ **eV, with a sharp steepening above this energy.**

- **The pair-production dip for extragalactic CR at** $1 \times 10^{18} \leq E \leq 4 \times 10^{19}$ **eV is well confirmed by all existing UHECR detectors and it demonstrates that most of observed particles are extragalactic protons propagating through CMB. Energy calibration of detectors confirms this conclusion.**

- **The dip model of transition is based on proximity of the end of galactic CR** $E_{Fe}^{max} \sim 1 \times 10^{17}$ **eV and the beginning of the dip** $E_b \approx 1 \times 10^{18}$ **eV, where transition is completed. The predicted transition from galactic iron to extragalactic protons is very sharp. Observationally transition occurs at the second dip.**

- **The two other models of transition assume agreement of the pair-production dip (VB & Grigorieva 1988) with the observed dip as incidental and use the two-component dip model by Hill & Schramm 1985.**

- **The traditional ankle model assumes transition at $\mathrm{E}_a \sim 1 \times 10^{19}$ eV with extragalactic generation spectrum $\propto E^{-2}$. It needs another component of galactic CR beyond $\mathrm{E}_{\mathrm{Fe}}^{\mathrm{max}} \approx 1 \times 10^{17}$ eV.**
- **The mixed composition model assumes production of extragalactic CR with flat generation spectrum $\gamma_g = 2.1 - 2.3$. The transition is completed at $\mathrm{E} \approx 3 \times 10^{18}$ eV and the model marginally agrees with "standard model". The spectral agreement at the dip $1 \times 10^{18} - 4 \times 10^{19}$ eV is reached using the subtraction procedure and the choice of nuclear composition.**
- **The transition is accompanied by a change in chemical composition, described by elongation rate $\mathrm{X}_{\mathrm{max}}$(E). The dip model predicts fast growth of $\mathrm{X}_{\mathrm{max}}$(E), while the mixed model - the smooth behaviour. The dip model marginally agrees with the data, while the mixed model gives a good fit.**
- **The energies $10^{17} - 10^{18}$ eV look like the key region for cosmic ray origin. More precise measurements of $\mathrm{X}_{\mathrm{max}}$(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.**