UHECR: IS THERE STILL PLACE FOR UHE QCD

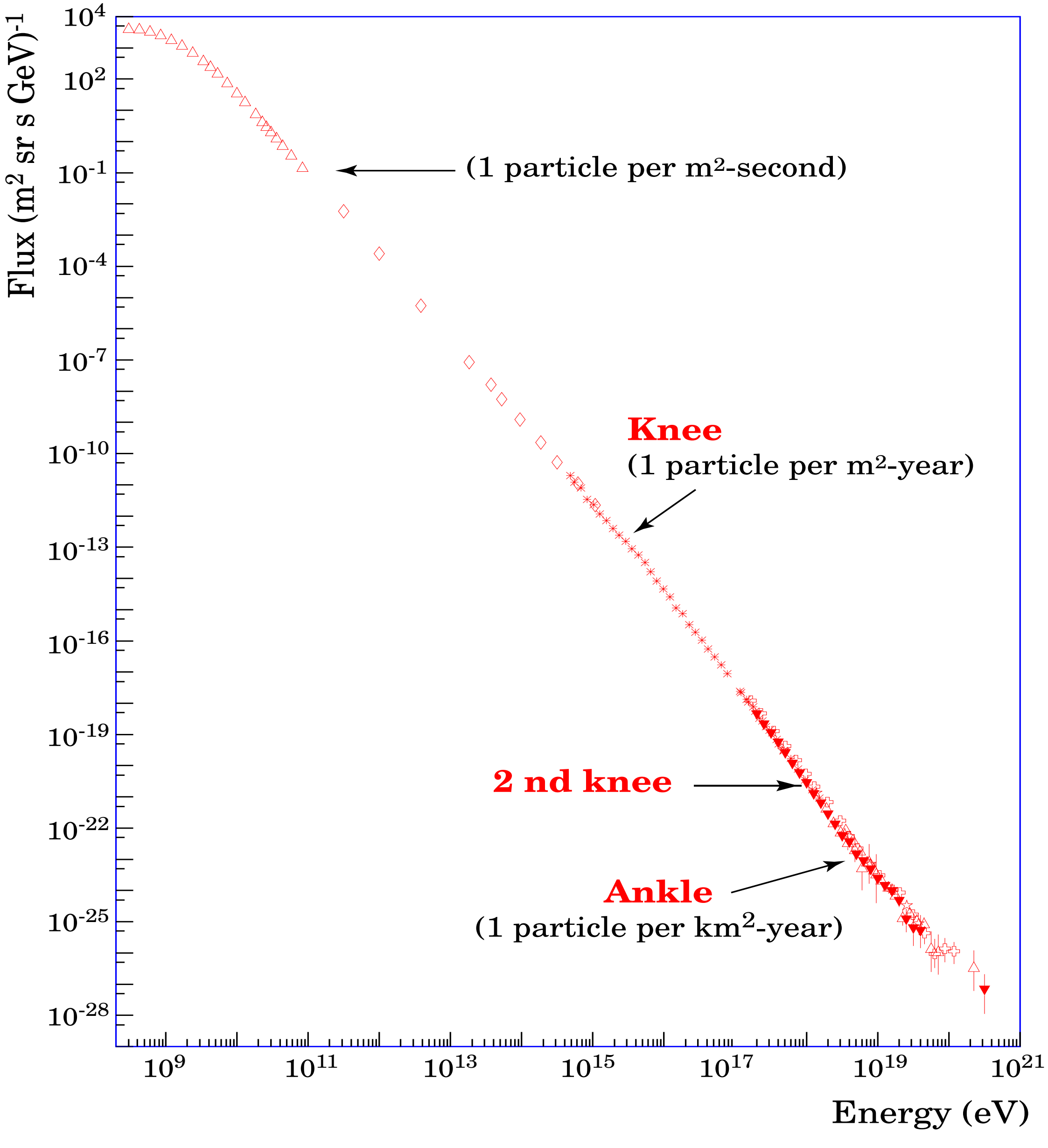
Astrophysical and New Physics Solutions

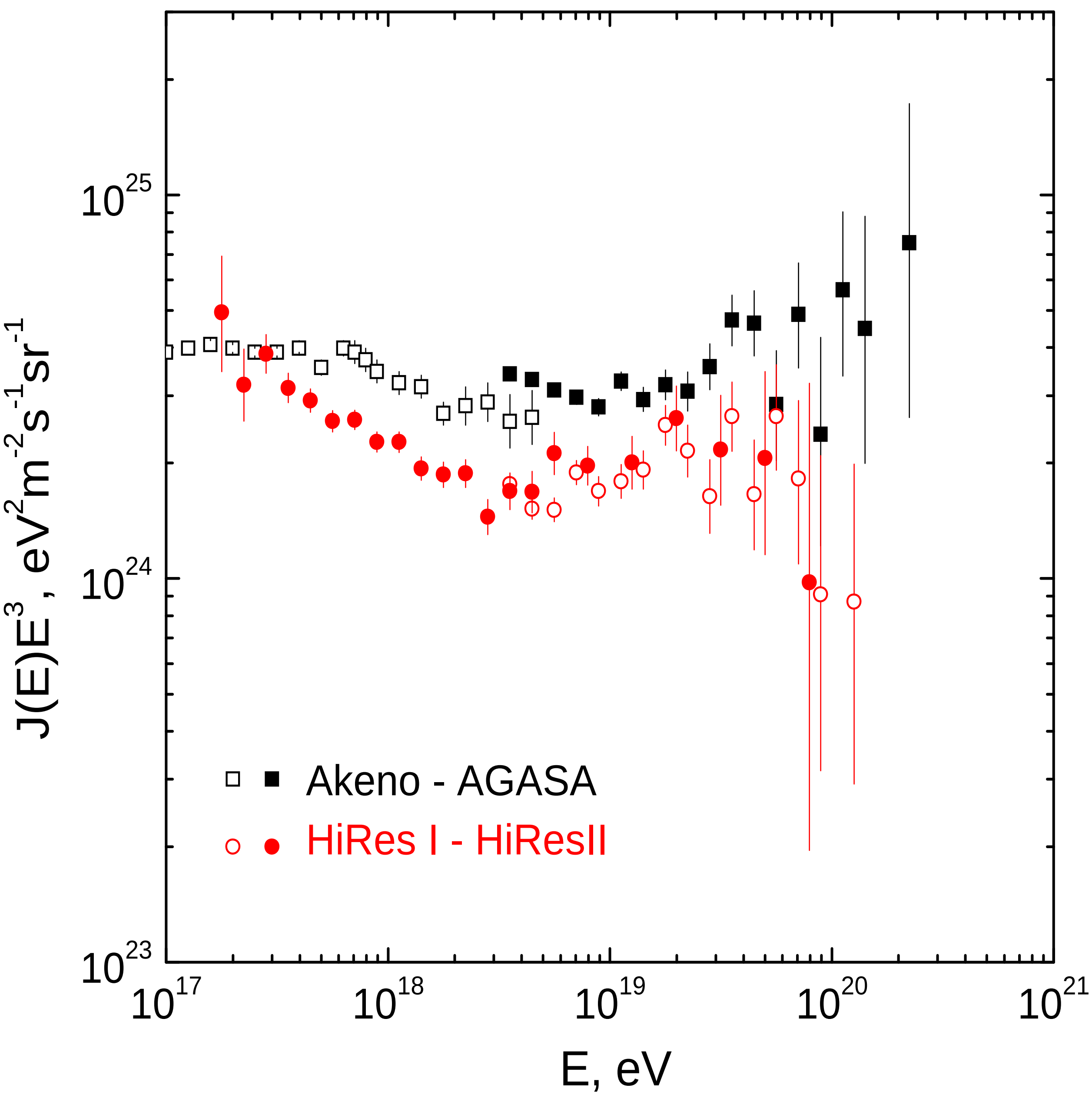
V. Berezinsky

INFN, Laboratori Nazionali del Gran Sasso, Italy

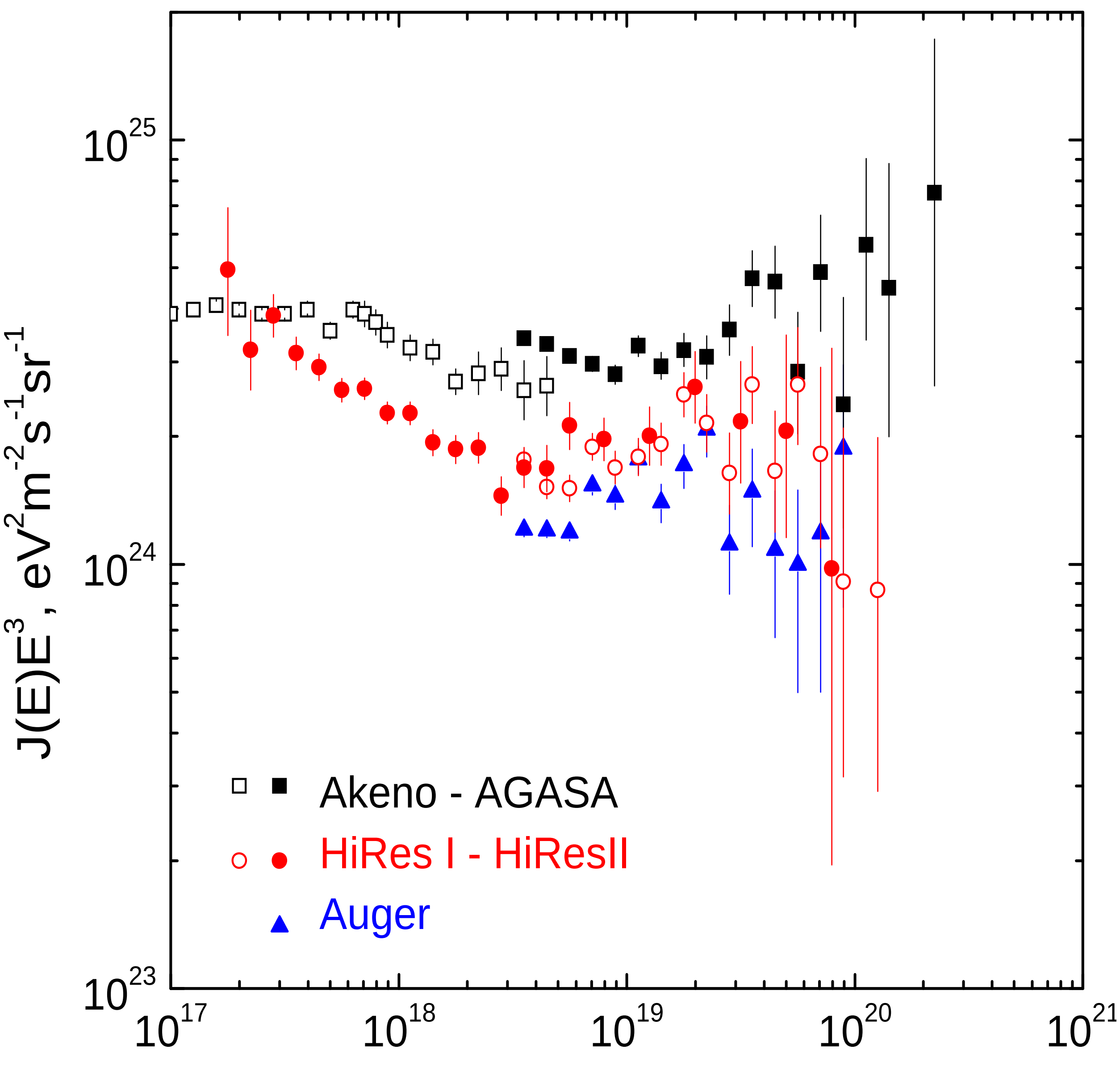
OBSERVATIONAL DATA

SPECTRUM OF COSMIC RAYS





J(E)E^3, eV^{2}m^{-2}s^{-1}sr^{-1}
10^{25}
10^{24}
10^{23}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
E, eV
Akeno - AGASA
HiRes I - HiResII



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J(E)E^3, eV^{2}m^{-2}s^{-1}sr^{-1}
E, eV
Akeno - AGASA
HiRes I - HiResII
Auger

SMALL-ANGLE CLUSTERING

AGASA data (2001) $E \geq 4 \times 10^{19}$ **eV:**
5 pairs (doublets)+ 1 triplet within 2.5° **from** $N_{\rm tot} = 59$**.**
5σ **excess over chance probability.**

HiRes data (2004): no clustering

INTERPRETATION

Dubovsky, Tinyakov and Tkachev (2000):

For rectilinear propagation of particles from the large number of sources, clustering is produced as a random appearance of pairs from a point-like source.

MC simulations can interpret this effect in terms of space density of the sources n_s (Blasi, De Marco 2003; Kachelriess, Semikoz 2004):

$$n_s = (1-3) \times 10^{-5}\ \mathrm{Mpc}^{-3}$$

CORRELATIONS WITH AGN (BL Lacs)

Tinyakov and Tkachev (2001):
AGASA and Yakutsk events at $4 \times 10^{19}\ eV \leq E \leq 8 \times 10^{19}$ eV correlate with BL Lacs (statistical significance 6×10^{-5}).

These correlations imply weak extragalactic magnetic fields. MHD simulations by Dolag et al 2003 favour the weak magnetic fields, of order of 0.1 nG in the filaments and 0.01 nG in voids.

BL Lacs are AGN with jets directed towards the observer. Correlations of UHE particles with BL Lacs imply acceleration in the direction of jet.

PROPAGATION OF UHECR THROUGH CMB

INTERACTIONS

Protons

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

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

Nuclei

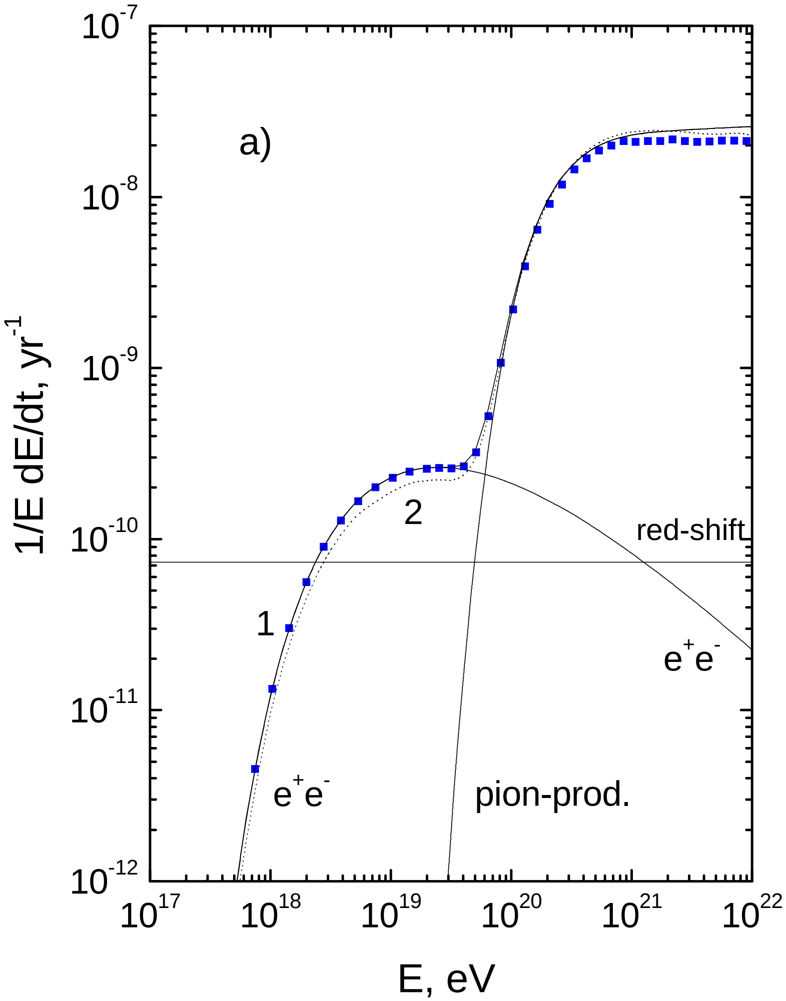
$$Z + \gamma_{\rm CMB} \rightarrow Z + e^+ + e^-$$

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

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

Photons

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



PROPAGATION SIGNATURES

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

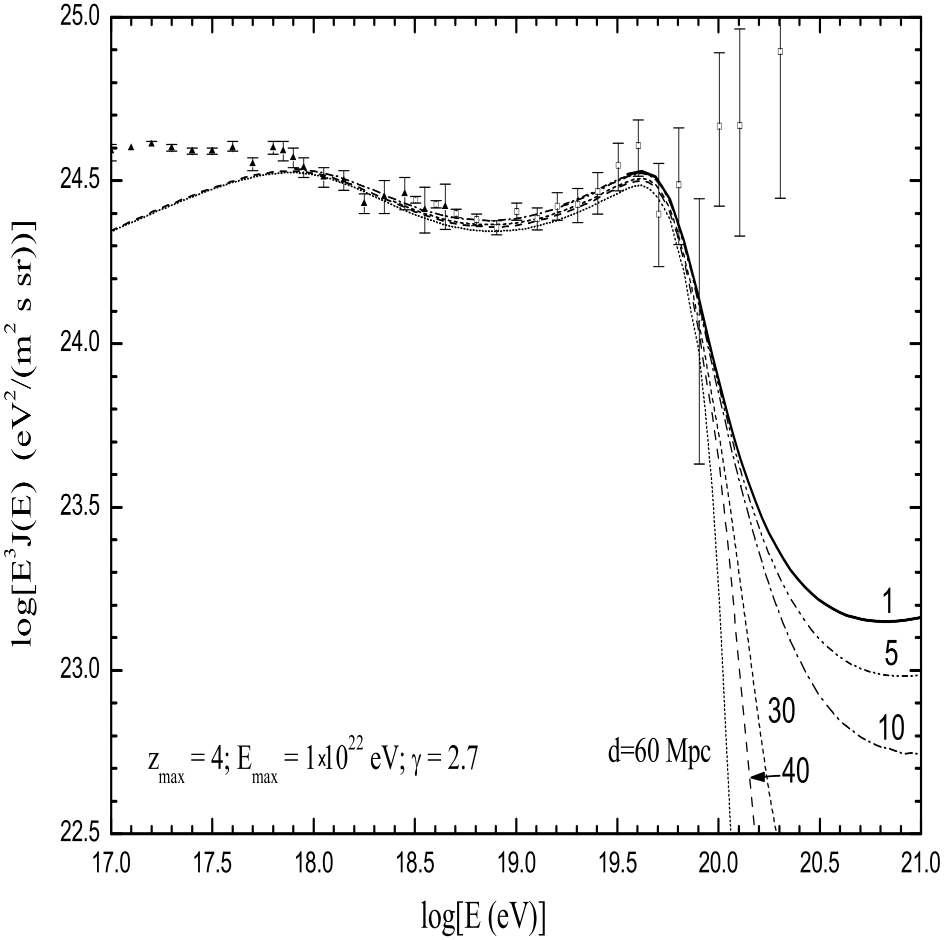
GZK cutoff, bump, dip

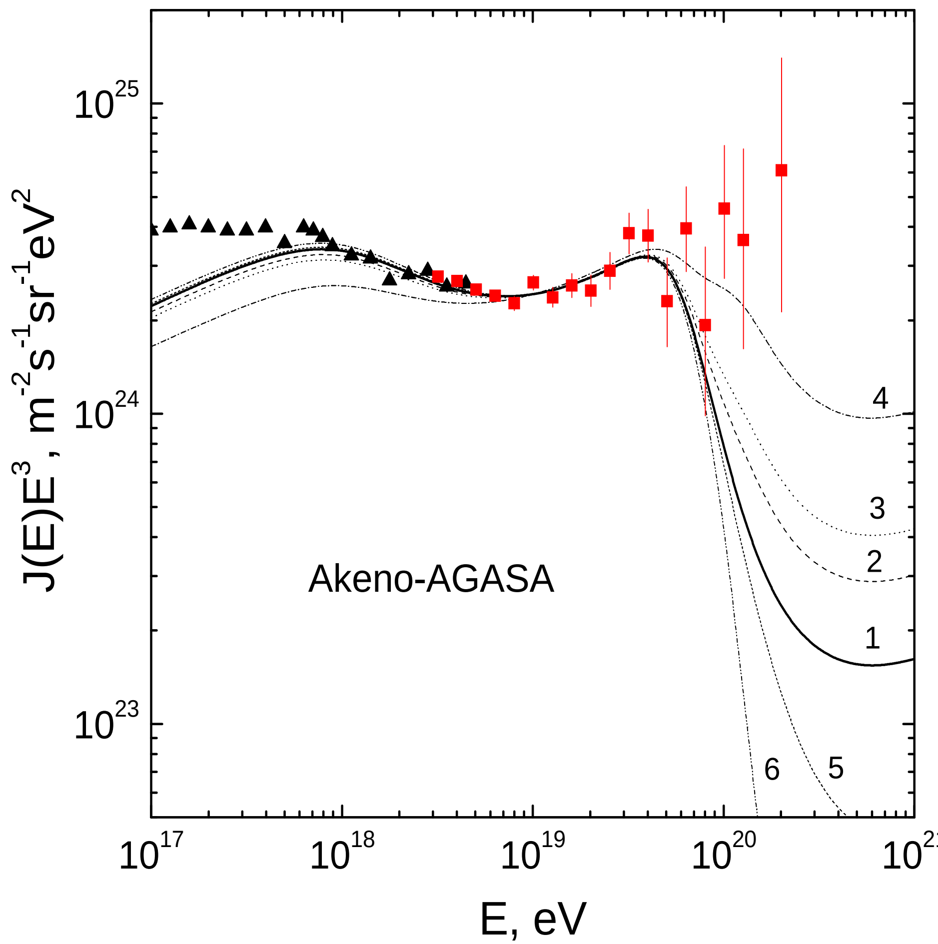
These signatures might depend on the distribution of sources and way of propagation.

GZK cutoff can be less sharp in case of local overdensity of the sources, or more sharp in case of their local deficit.

GZK CUTOFF

GZK cutoff is modified by **discreteness** in source distribution and by source local **overdensity/deficit**





Due to these uncertainties, GZK cutoff, if found, would be difficult to distinguish from **acceleration cutoff**

DIP IN THE DIFFUSE SPECTRUM

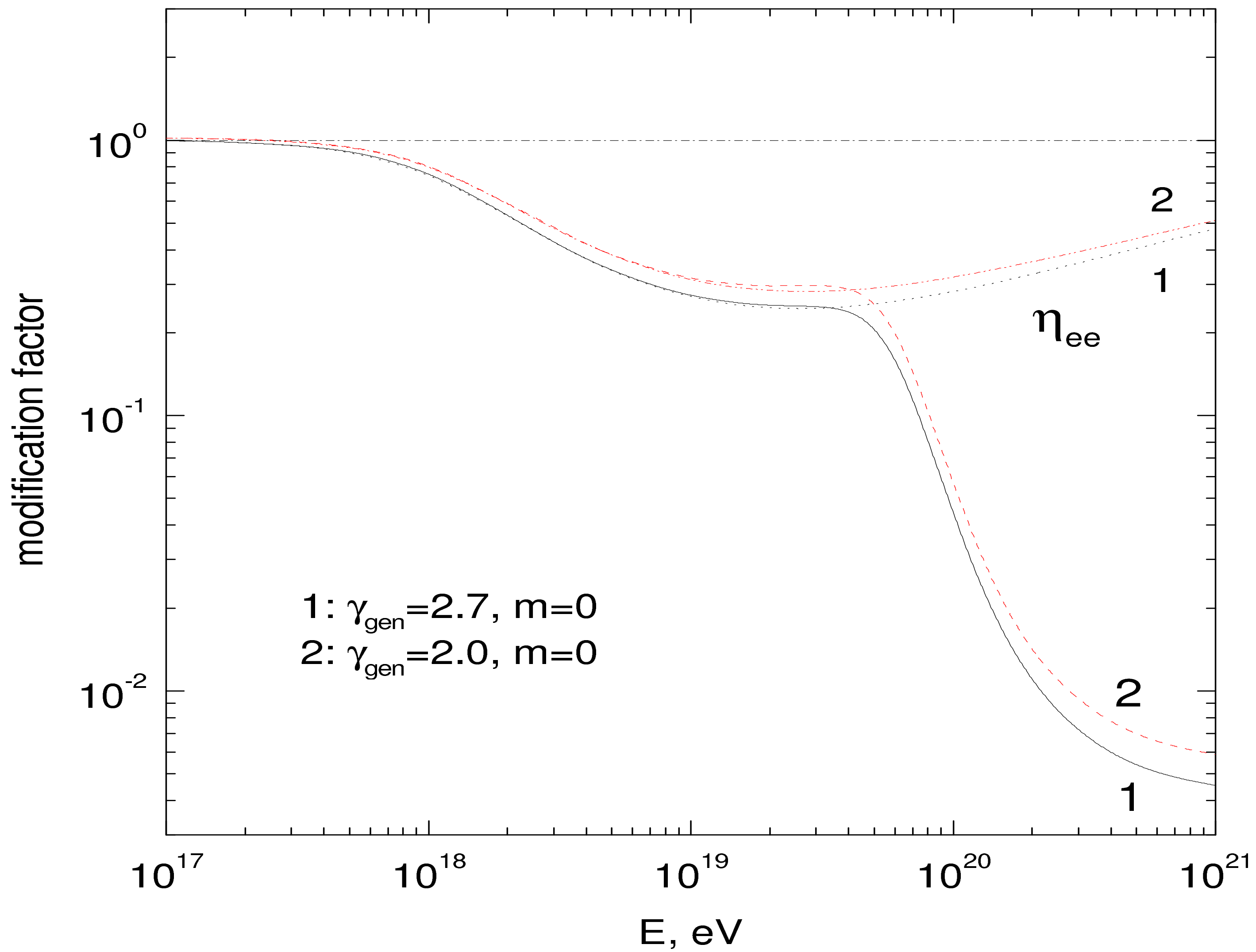
DEFINITION OF MODIFICATION FACTOR

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

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

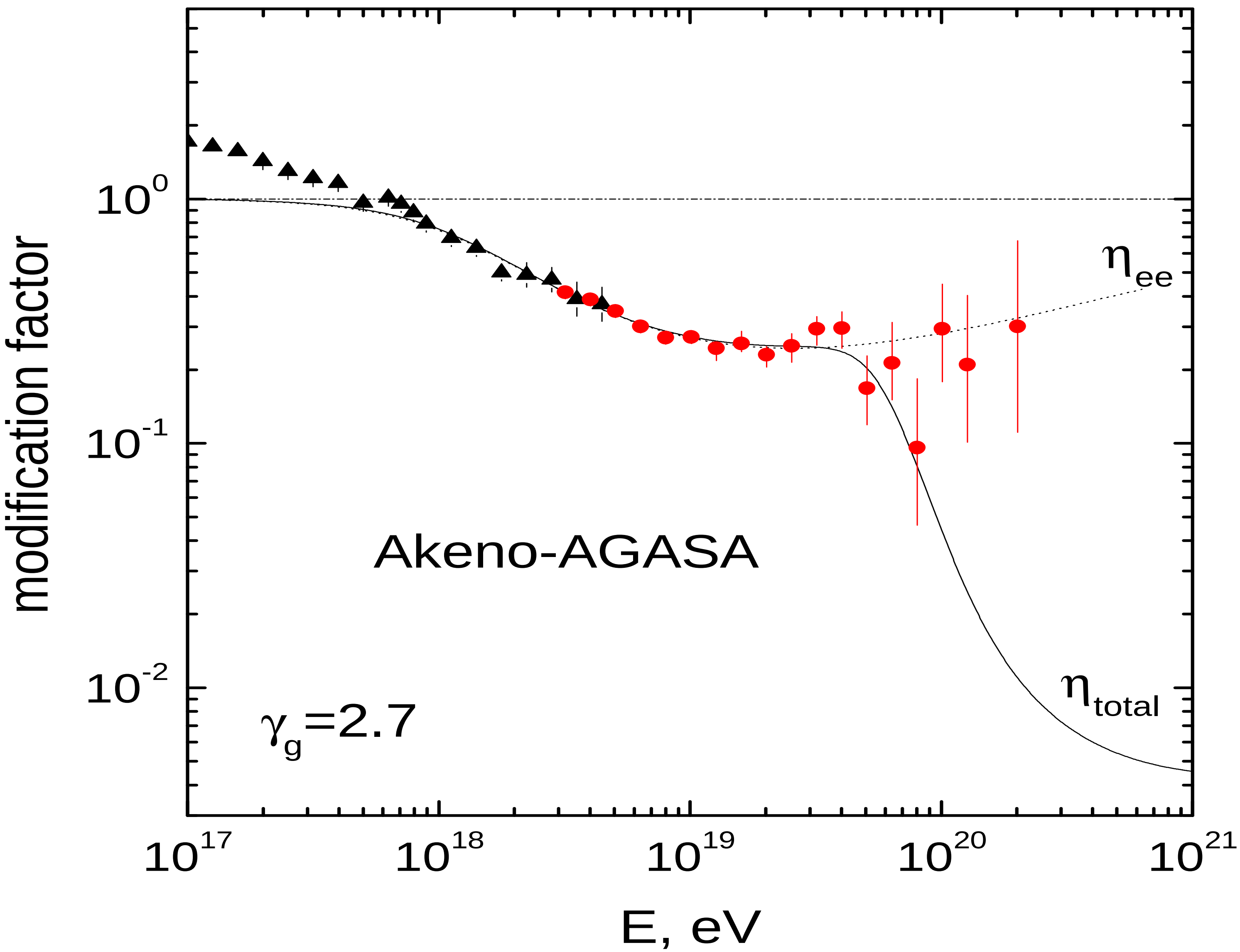
Since both $J_p^{\rm unm}(E)$ and $J_p(E)$ include factor $E^{-\gamma_g}$, $\eta(E)$ depends weakly on γ_g.

DIP IN DIFFUSE SPECTRA

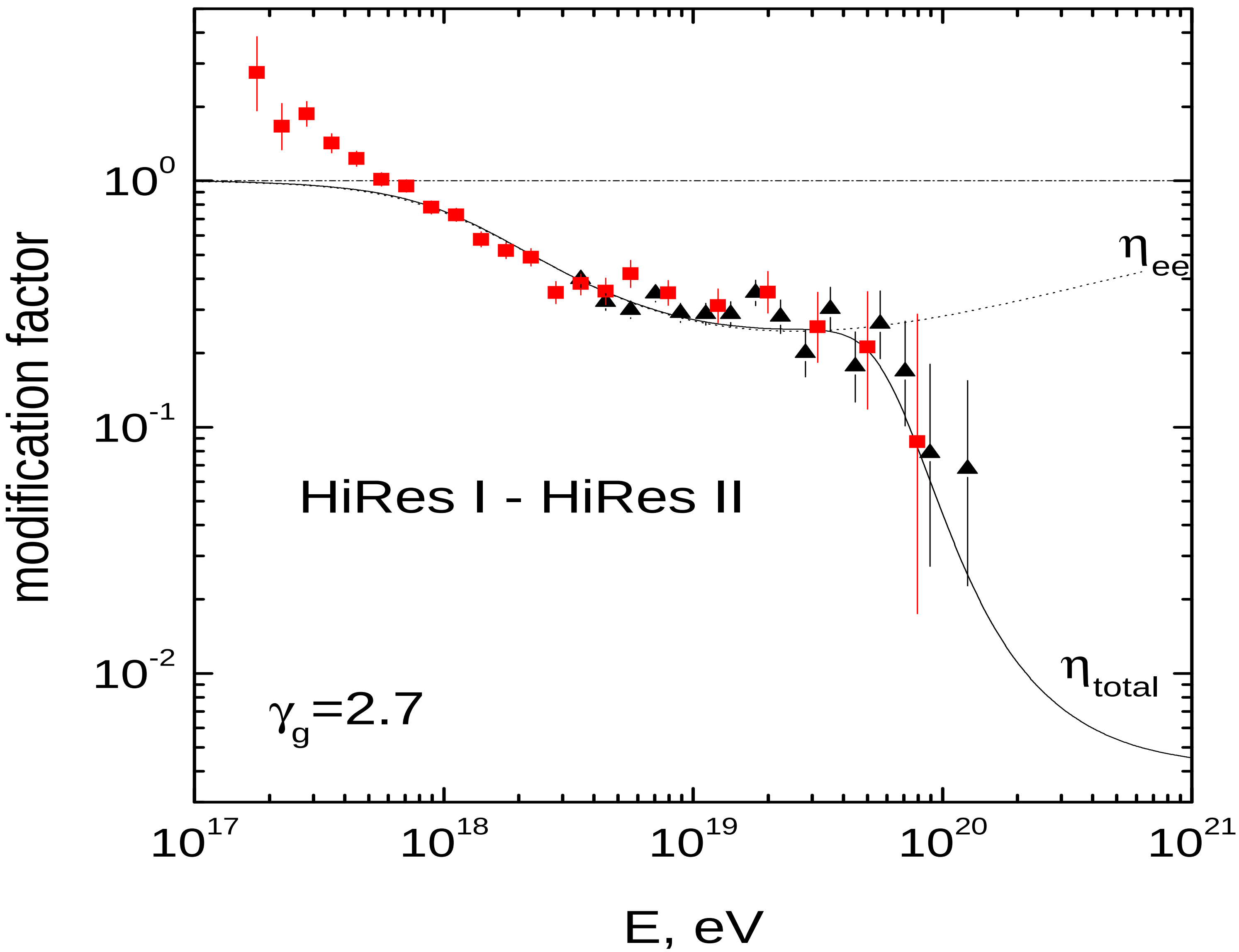


The dotted curve shows η_{ee}, when only adiabatic and pair-production energy losses are included. The solid and dashed curves include also the pion-production losses.

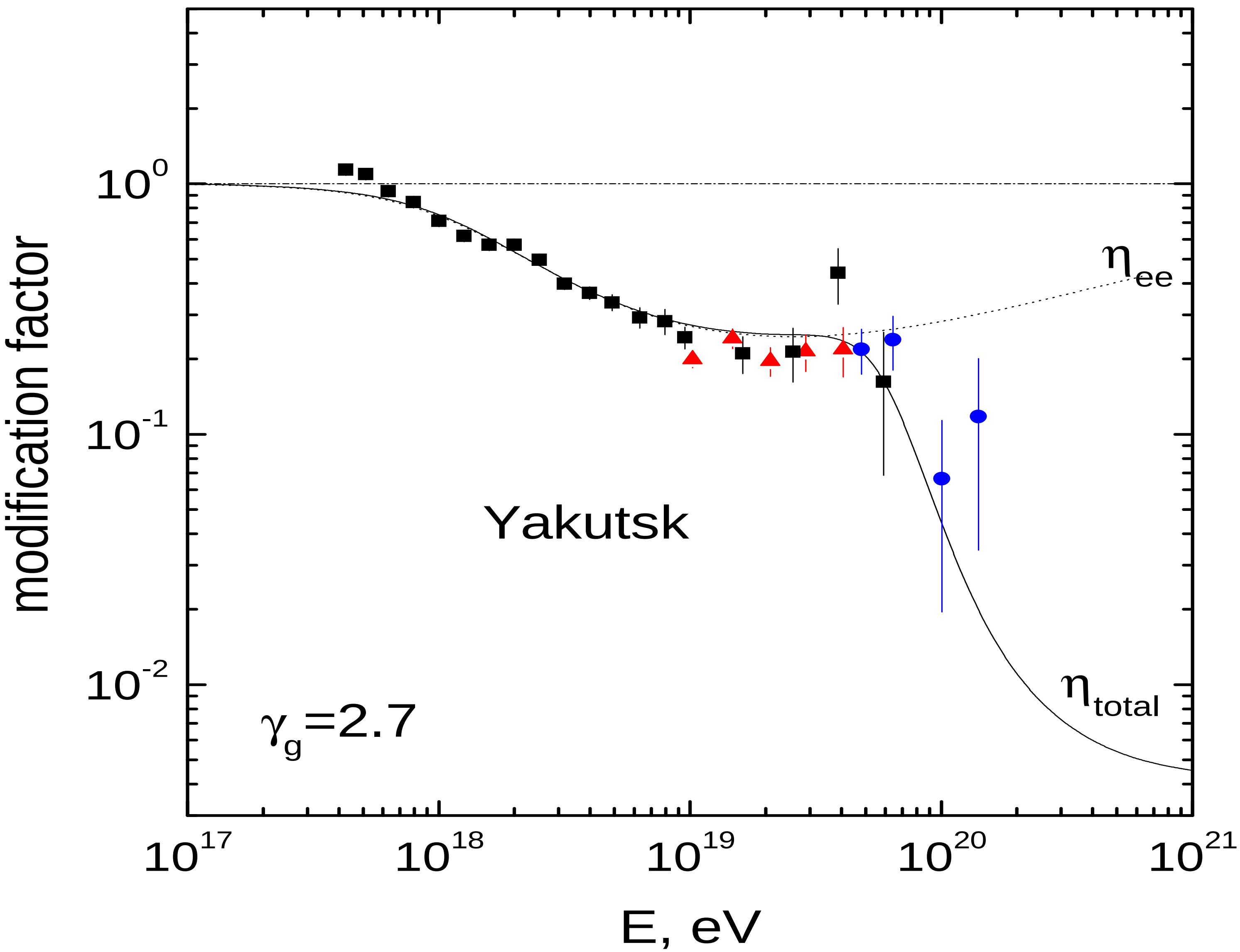
DIP IN COMPARISON WITH AKENO-AGASA DATA



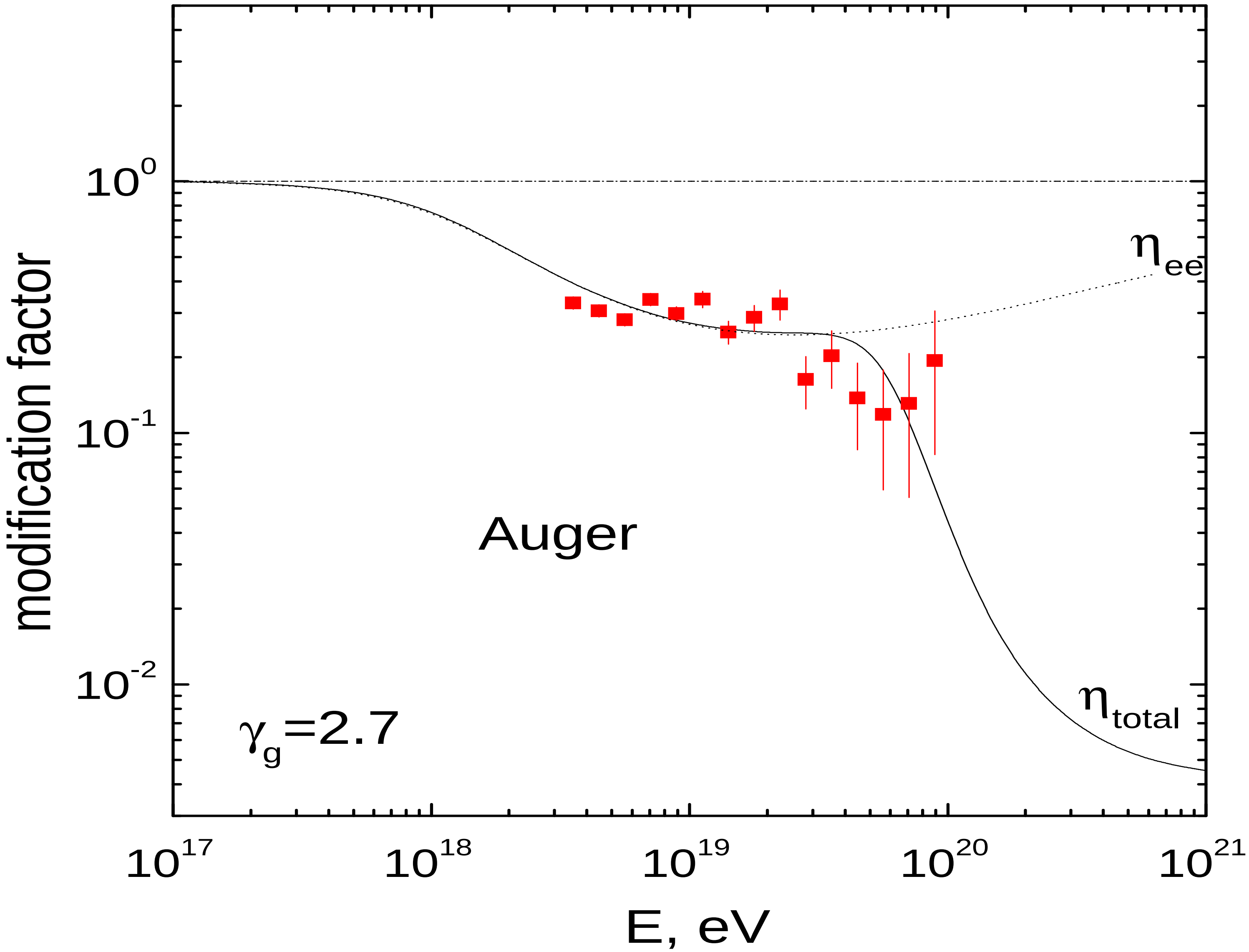
DIP IN COMPARISON WITH HIRES DATA



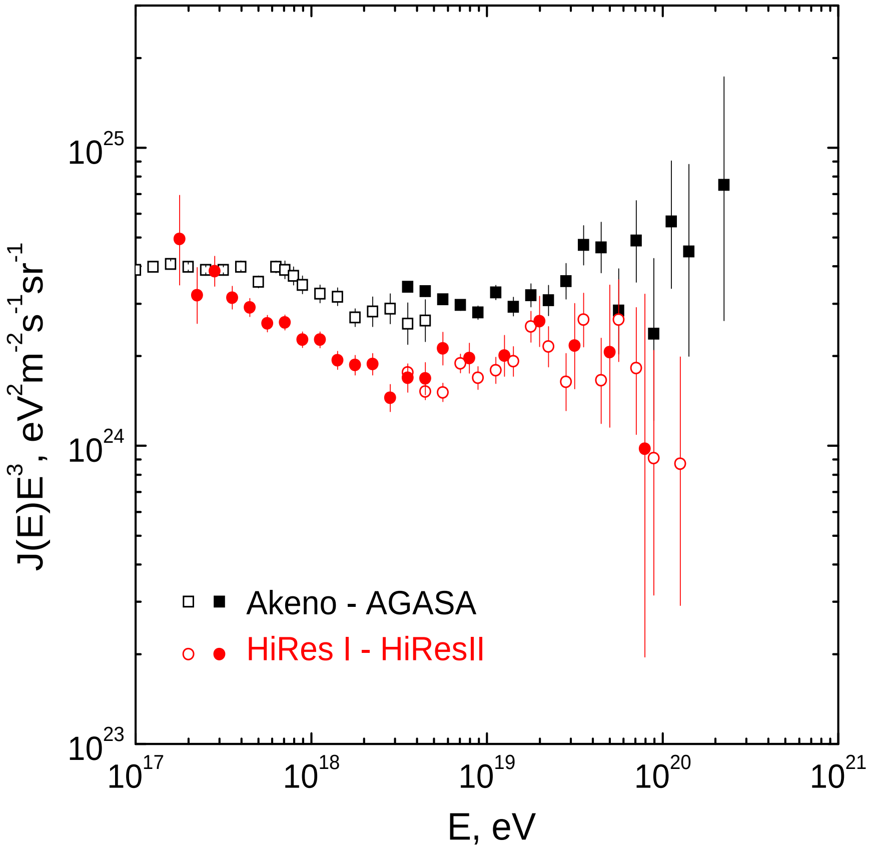
DIP IN COMPARISON WITH YAKUTSK DATA

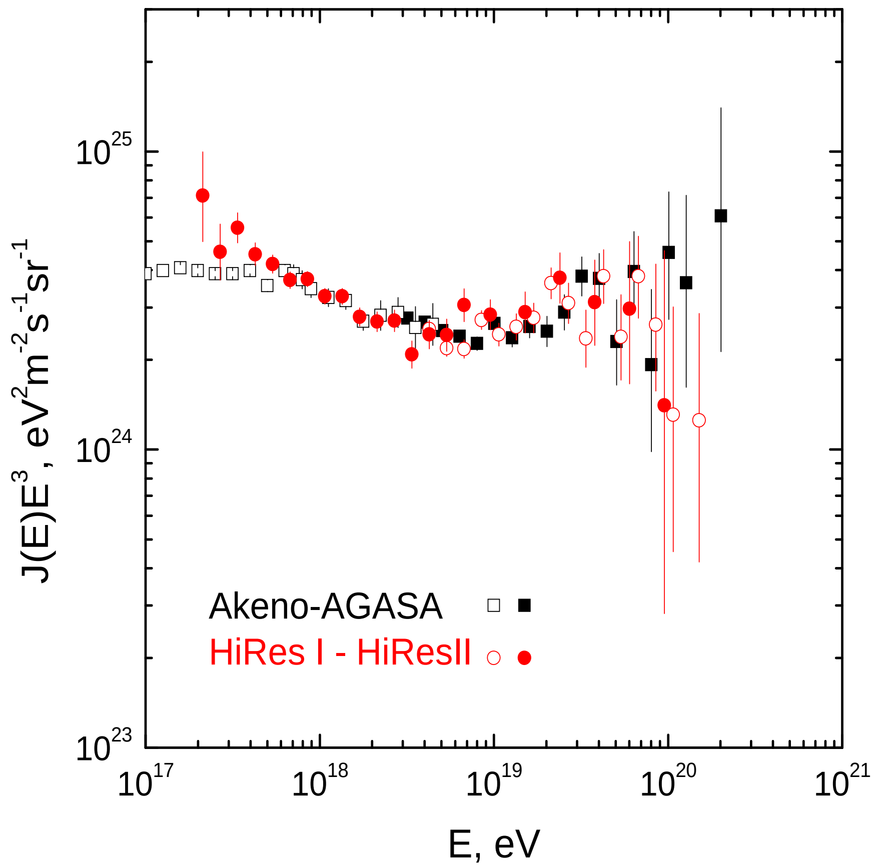


DIP IN COMPARISON WITH AUGER DATA



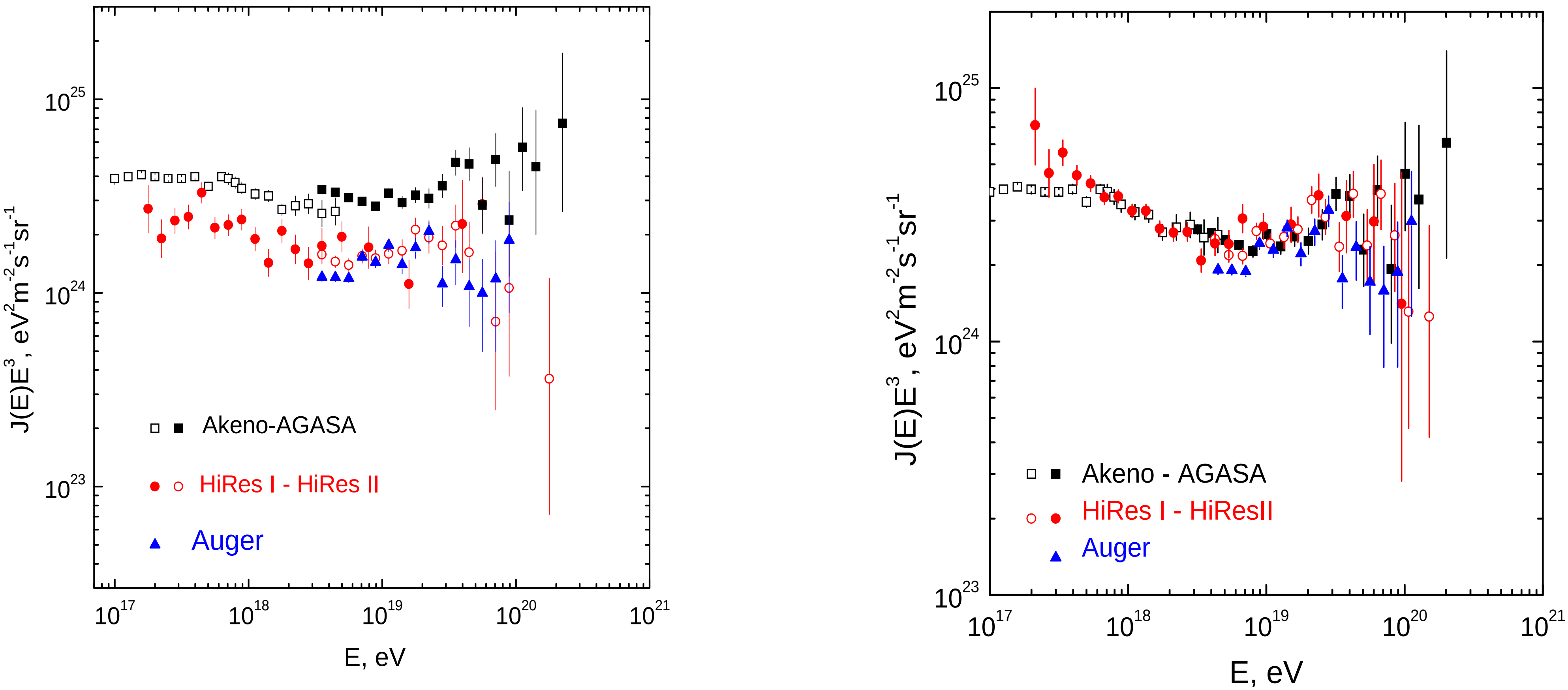
DIP AND AGASA-HIRES DISCREPANCY





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

AGASA-HIRES-AUGER DATA

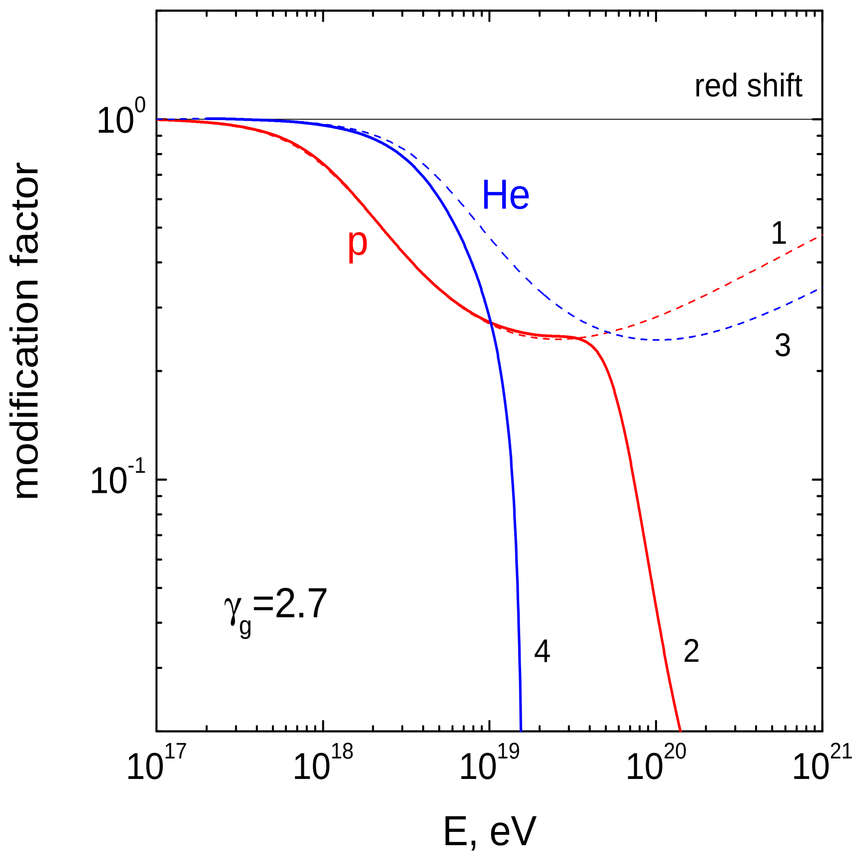


AGASA, HiRes and Auger data (left panel) and AGASA, HiRes and Auger data with energy shift $\lambda_{\mathrm{AGASA}} = 0.9$, $\lambda_{\mathrm{HiRes}} = 1.2$ and $\lambda_{\mathrm{Auger}} = 1.26$.

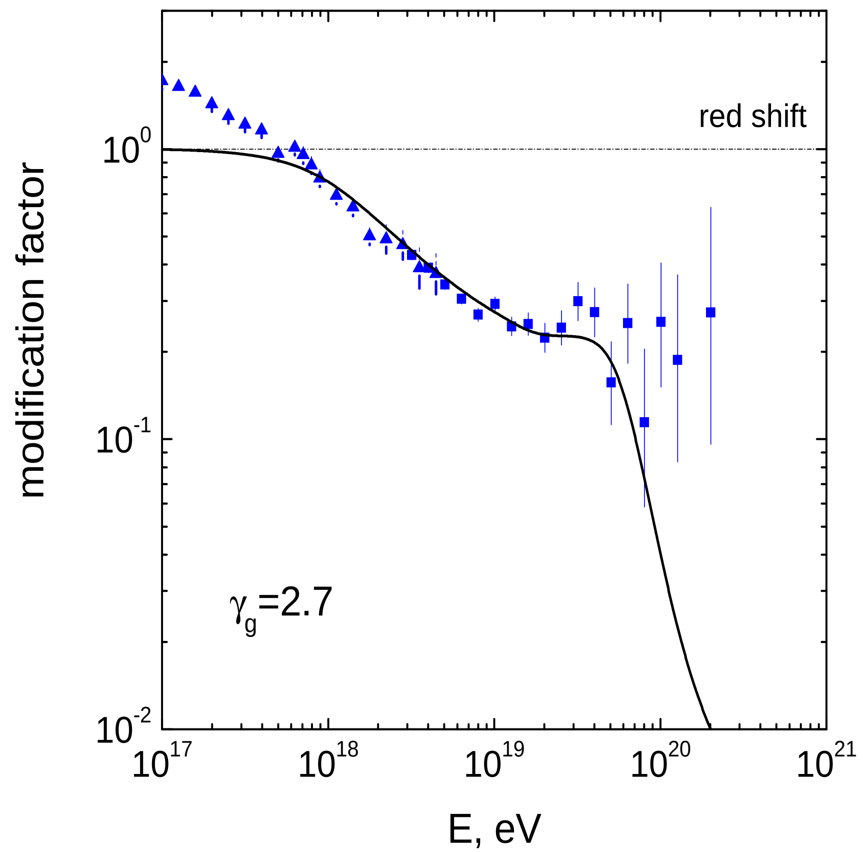
DIP: ROBUSTNESS and CAVEATS

Dip is stable relative to discreteness in source distribution, mode of propagation, local source overdensity and deficit, acceleration $E_{\max}$ etc.

Dip is modified by presence of UHE nuclei in primary flux

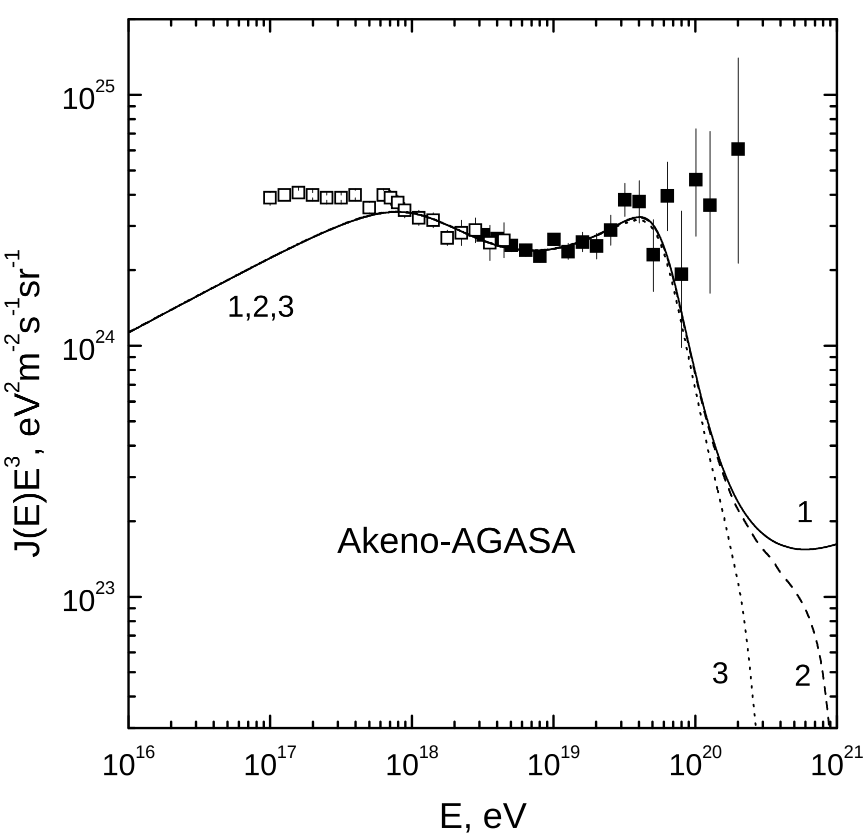


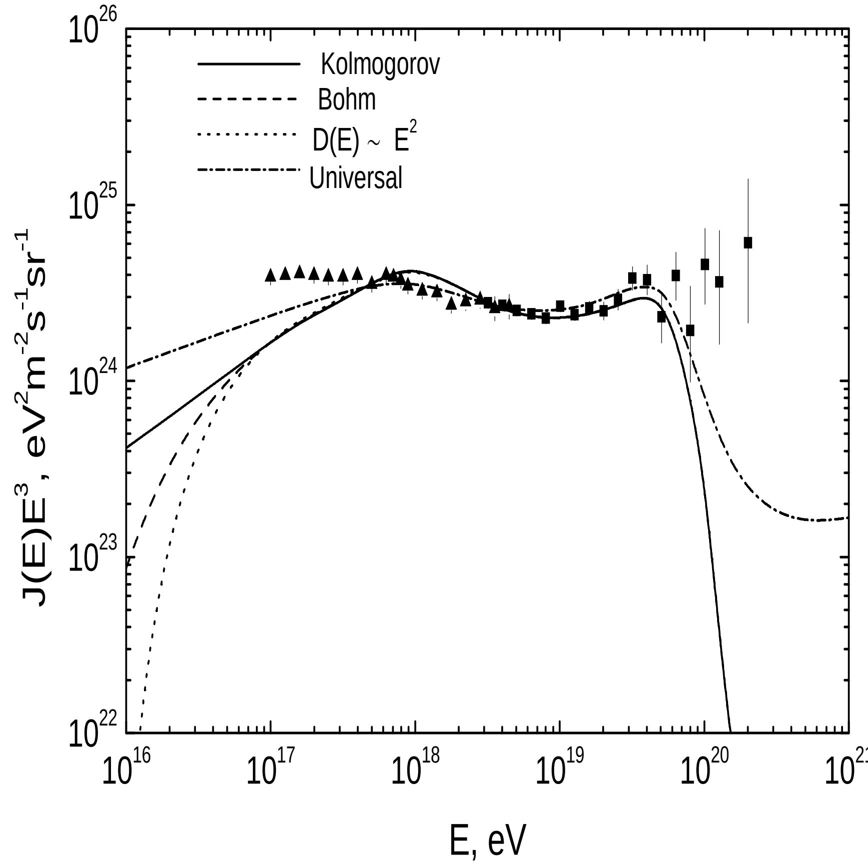
Modification factors for He and protons.



Modification factor for mixed composition with $n_{\rm He}/n_{\rm H} = 0.1$.

TRANSITION from EXTRAGALACTIC to GALACTIC CR





. **rectilinear propagation** **diffusive propagation**

The transition starts at $E_c = 1 \times 10^{18}$ eV. It is determined by fundamental energy $E_{\rm eq} = 2 \times 10^{18}$ eV, where pair-production and adiabatic energy losses become equal. Observed transition must occur at smaller energy $E < E_c$, and thus it coincides with position of the second knee.

TRANSITION at the ANKLE

Best fit of data with help of galactic+extragalactic components

$$Q_p^{\rm gen} = \mathcal{L}_p(\gamma_g - 2)E^{-\gamma_g}, \quad \text{with} \;\; \gamma_g = 2.2$$

$$J_{\rm gal}(E) = K_{\rm gal}E^{-\alpha}\frac{1}{1+\exp(E/E_{\rm max})}$$

with $\alpha = 3.3$ and $E_{\rm max} = 1 \times 10^{19}$ eV.

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Landau theorem

A model with more than three parameters can explain any experimental data.

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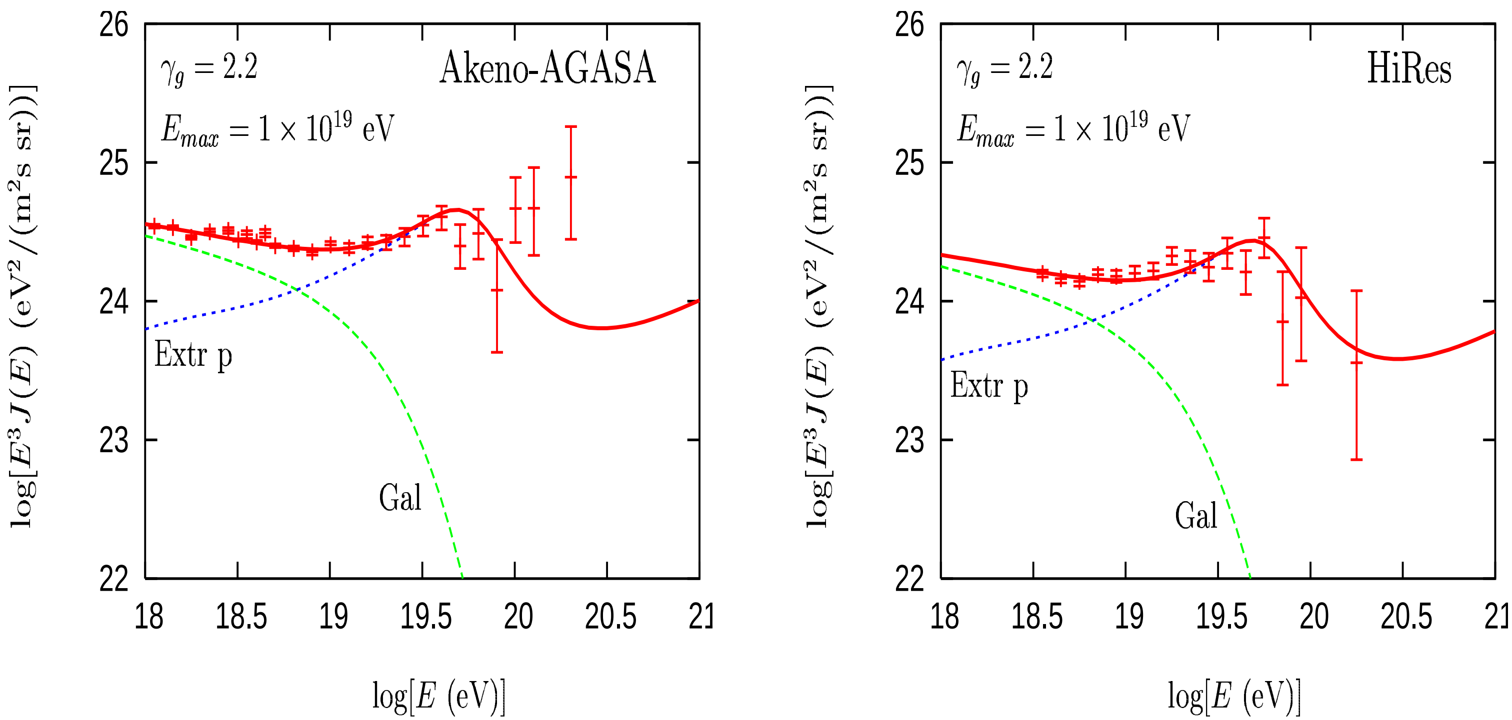
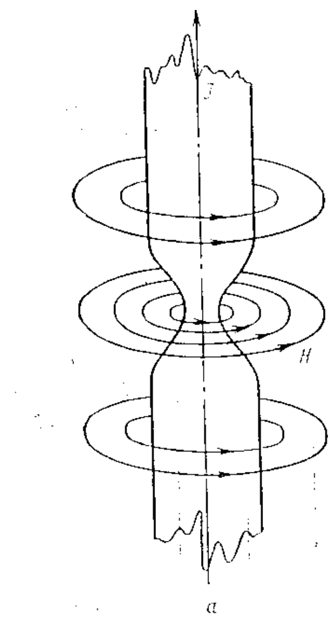


AGN MODEL

Acceleration



Pinch mecanism in jets: B.A.Trubnikov et al. 1990

$$q_{gen}(E) \sim E^{-\gamma_g}, \qquad \gamma_g = 1 + \sqrt{3} = 2.73$$

$$E_{\max} > 1 \times 10^{22}\ eV.$$

We assume: $E_{\max} = 1 \times 10^{21}$ eV.

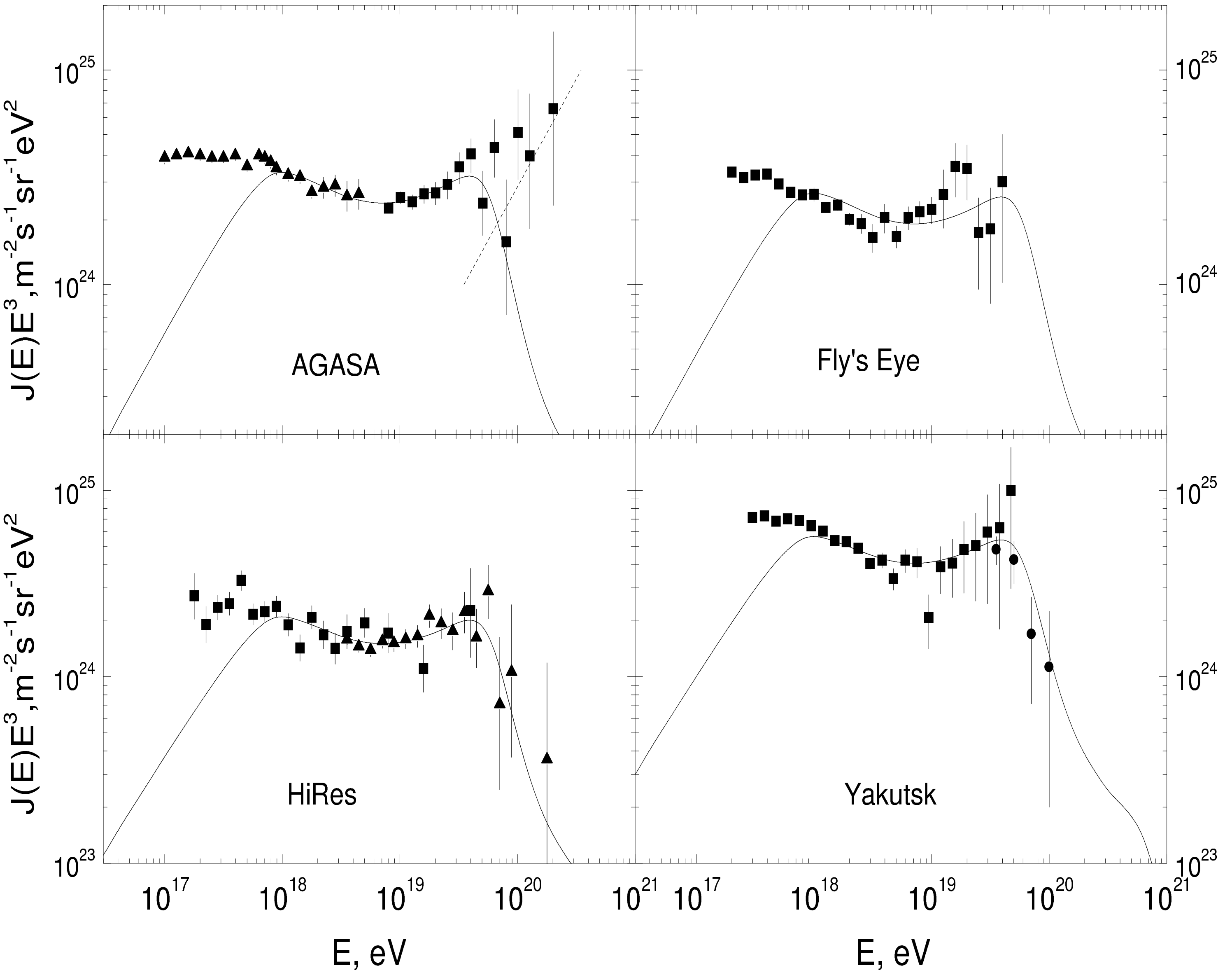
generation spectrum for quasi-rectilinear propagation:

$$q_{\rm gen}(E) \propto \begin{cases} E_g^{-2} & \text{at } E_g \le E_c \\ E_g^{-2.7} & \text{at } E_g \ge E_c \end{cases} \qquad (1)$$

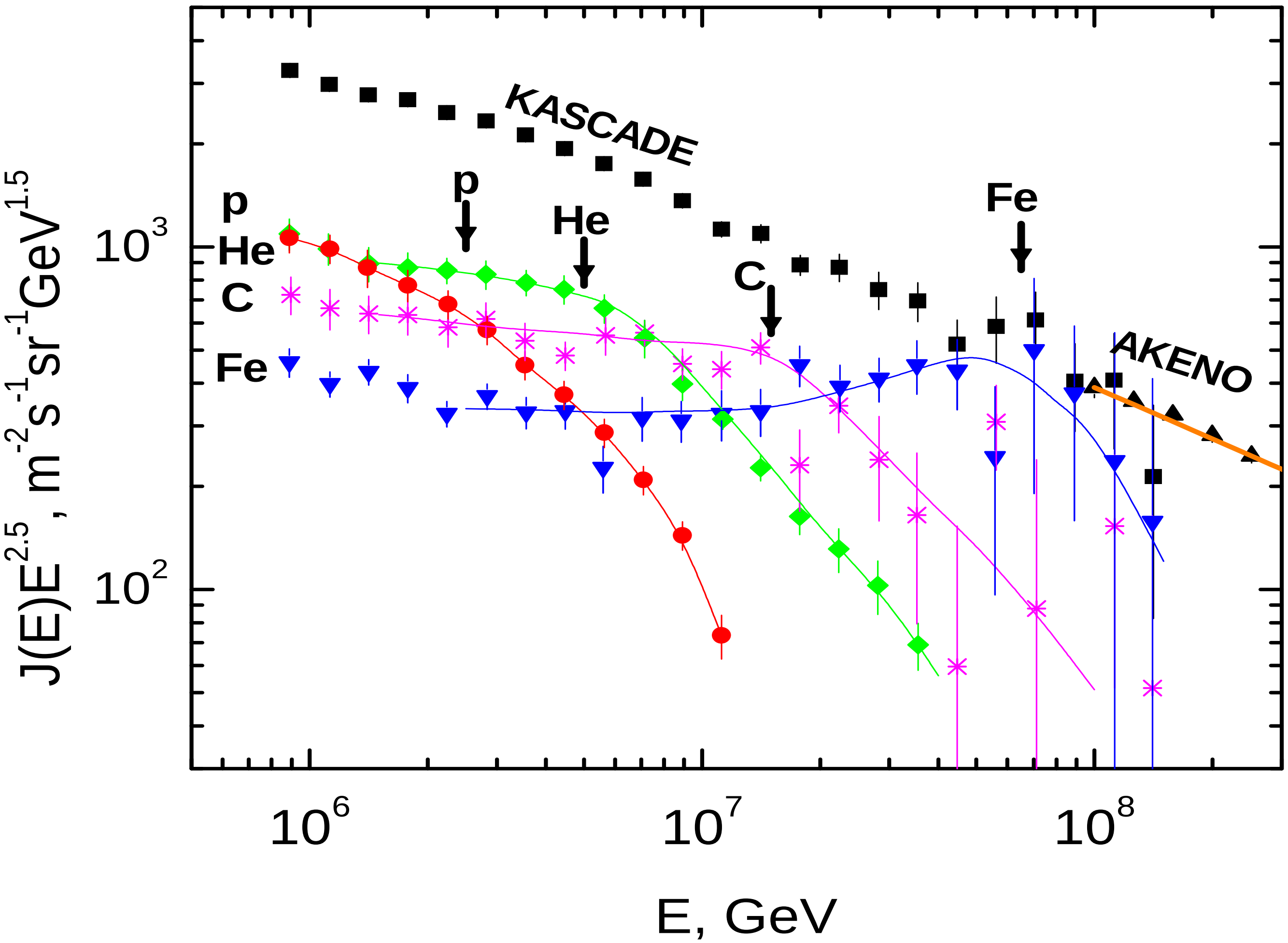
emissivity: $\mathcal{L}_0 = 3.5 \times 10^{46}$ erg/yr Mpc^3

source luminosity: $L_p = 3.7 \times 10^{43}$ erg/s for $n_s = 3 \times 10^{-5}$ Mpc^{-3}.

Comparison of calculated spectra with data



TRANSITION from GALACTIC to EXTRAGALACTIC CR

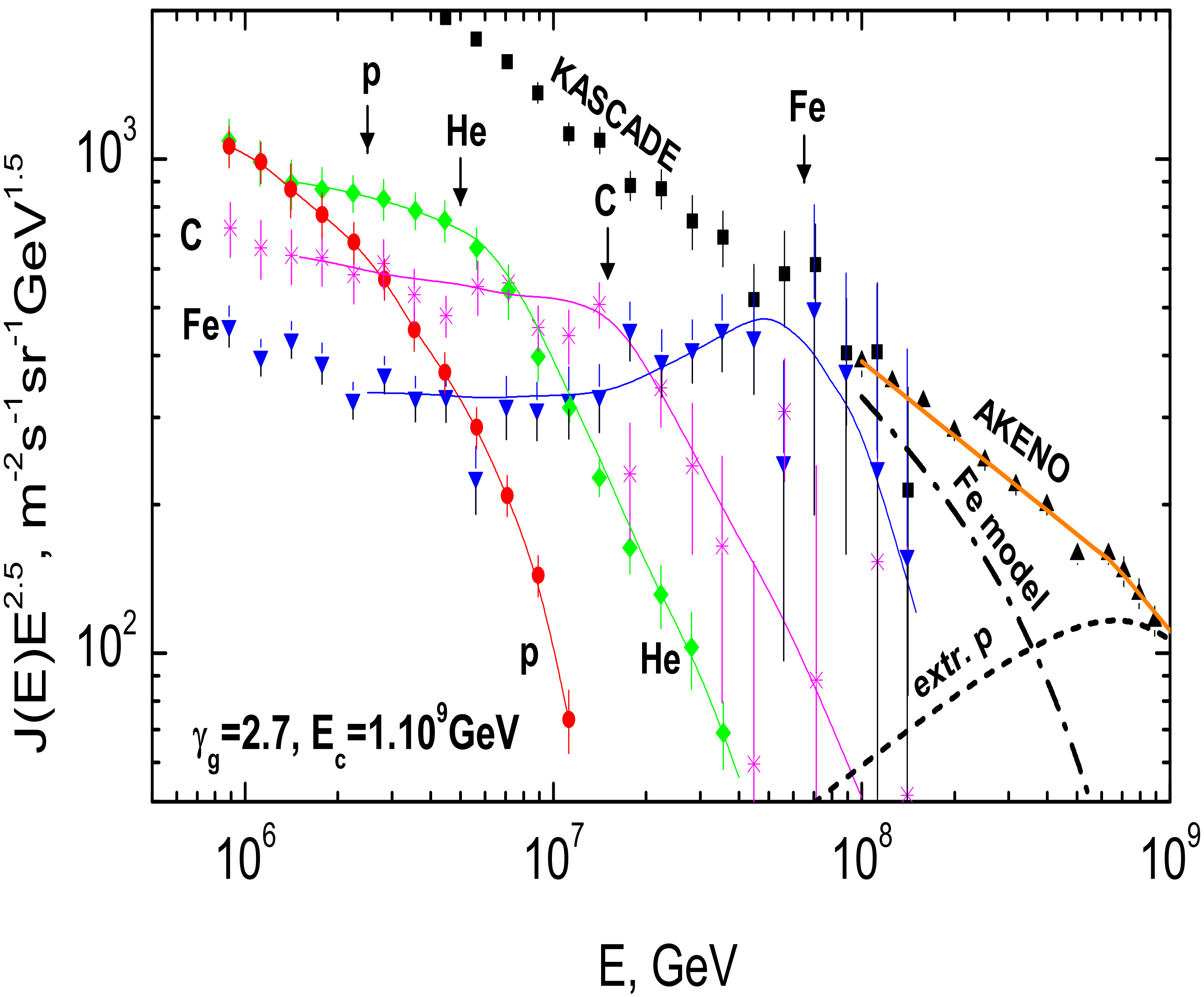


If transition from galactic to extragalactic CR occurs at **ankle**, $E_a \approx 1 \times 10^{19}$ eV, then there are two problems:

1. UHE iron nuclei start to disappear from Galaxy at $E_{\rm Fe} \approx 6.5 \times 10^{16}$ eV. How the gap between 1×10^{17} eV and 1×10^{19} eV is filled?

2. UHE protons start to disappear from Galaxy at $E_p \approx 2.5 \times 10^{15}$ eV. Then how they appear again in the Akeno experiment (fraction $f > 10\%$) at $E > 1 \times 10^{17}$ eV?

TRANSITION from GALACTIC to EXTRAGALACTIC CR in AGN MODEL



DOES UHECR PROBLEM STILL EXIST?

1. AGASA EXCESS?

- **Auger does not observe it.**
- **There is no discrepancy between AGASA and HiRes after energy calibration by dip.**
- **AGASA excess may have statistical origin.**
- **If AGASA excess is real it needs another CR component, most probably connected with new physics.**

2. NO SOURCES ARE SEEN IN DIRECTIONS OF PARTICLES WITH $E > 1 \times 10^{20}$ eV.

e.g. for golden Fly's Eye event with $E = 3 \times 10^{20}$ eV : $\ell_{\rm att} = 21$ Mpc.

SOLUTIONS WITH NEW PHYSICS

motivated by AGASA excess at $E \geq 1 \times 10^{20}$ eV

- **SUPERHEAVY DARK MATTER ($X \to$ hadrons)**

$$M_X > 10^{12}\ \mathrm{GeV}, \ \ \tau_X > 10^{10}\ \mathrm{yr}$$

No radically new physics involved, fits the data

- **RESONANT NEUTRINOS (Z-BURSTS)**

$$\nu + \bar{\nu}_{\mathrm{DM}} \to Z^0 \to \mathrm{hadrons}$$

Excluded: too high flux of neutrinos required

- **TOPOLOGICAL DEFECTS**
  Reliable physics, weak GZK cutoff, disfavoured.

- **NEW PARTICLES**
  Strongly interacting neutrino, light (quasi)stable hadron (e.g. glueballino $\tilde{g}g$), mirror neutrons: not excluded.

- **LORENTZ INVARIANCE VIOLATION**
  Most radical proposal: fits the data.

CONCLUSIONS

1. Extragalactic UHE protons have propagation signatures in the form of GZK cutoff and dip.

- **Presence of GZK cutoff is questioned by AGASA data, though it can have the statistical origin.**

- **Dip is confirmed by model-independent analysis with good agreement with spectra shapes measured by AGASA, HiRes, Fly's Eye, Yakutsk detectors.**

- **This analysis implies transition from extragalactic to galactic CR at $E_c \sim 1 \times 10^{18}$ eV, i.e. at position of the second knee. E_c is determined by fundamental energy of proton interaction with CMB $E_{\rm eq} = 2 \times 10^{18}$ eV.**

- **Transition to the proton component at $E \sim 1 \times 10^{18}$ eV is confirmed by measurement of mass composition by HiRes, HiRes-MIA, Yakutsk, it does not contradict to Haverah Park, and it contradicts to Akeno and Fly's Eye data.**

- **Transition at the ankle remains an alternative.**

2. **In case of weak magnetic field $B < 1 - 10$ nG quasi-rectilinear propagation of protons with $E > 4 \times 10^{19}$ eV explains clustering and correlations with AGN.**

3. **The jet AGN model with the pinch acceleration explains $E_{\max} = 1 \times 10^{21}$ eV and $\gamma_g = 2.7$, provides the smooth transition to the galactic CR and predicts the galactic iron spectrum at $E < 1 \times 10^{18}$ eV in agreement with the Hall diffusion. It explains small-angle clustering and correlations with BL Lacs.**