ULTRA HIGH ENERGY COSMIC RAYS

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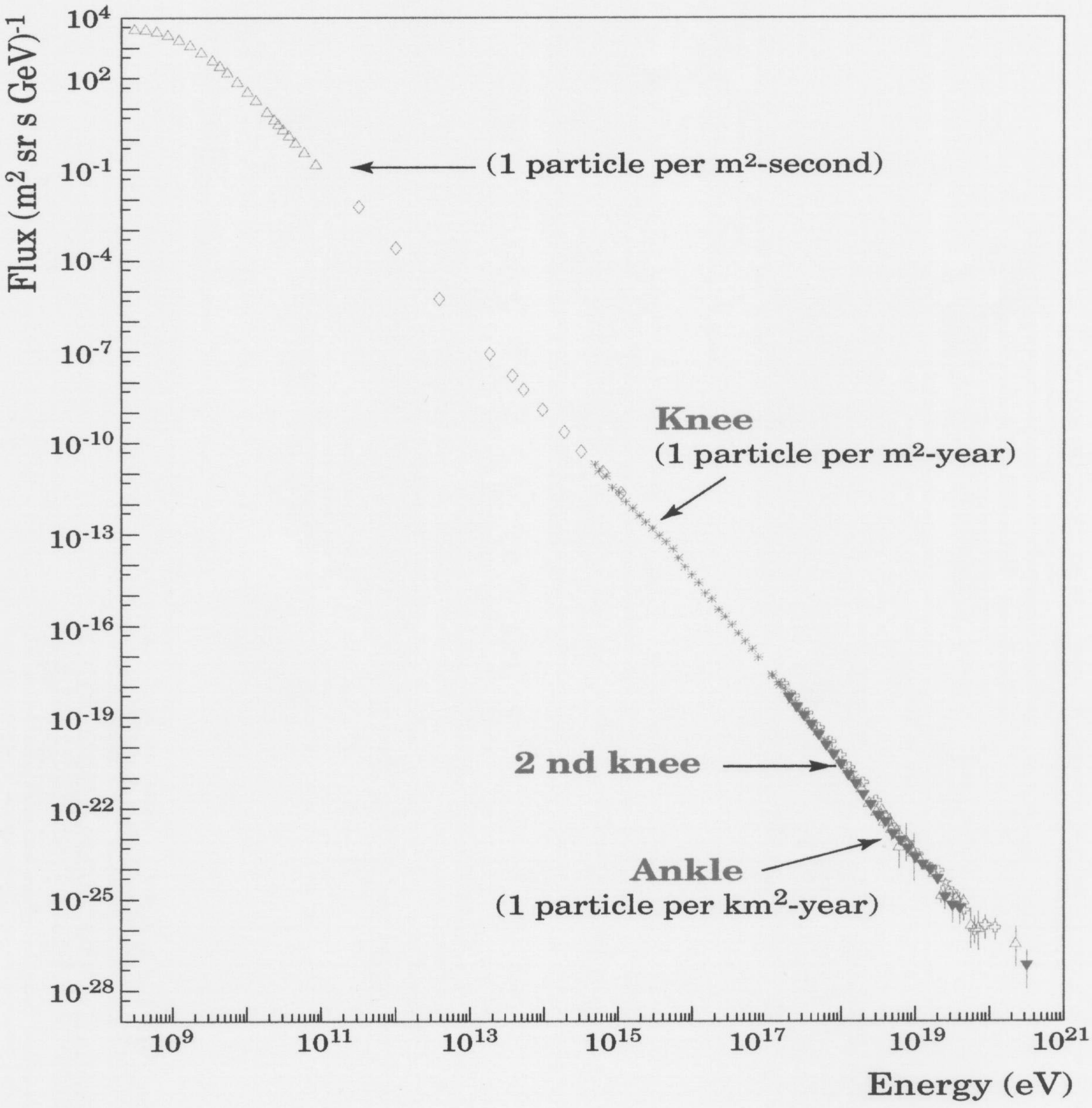
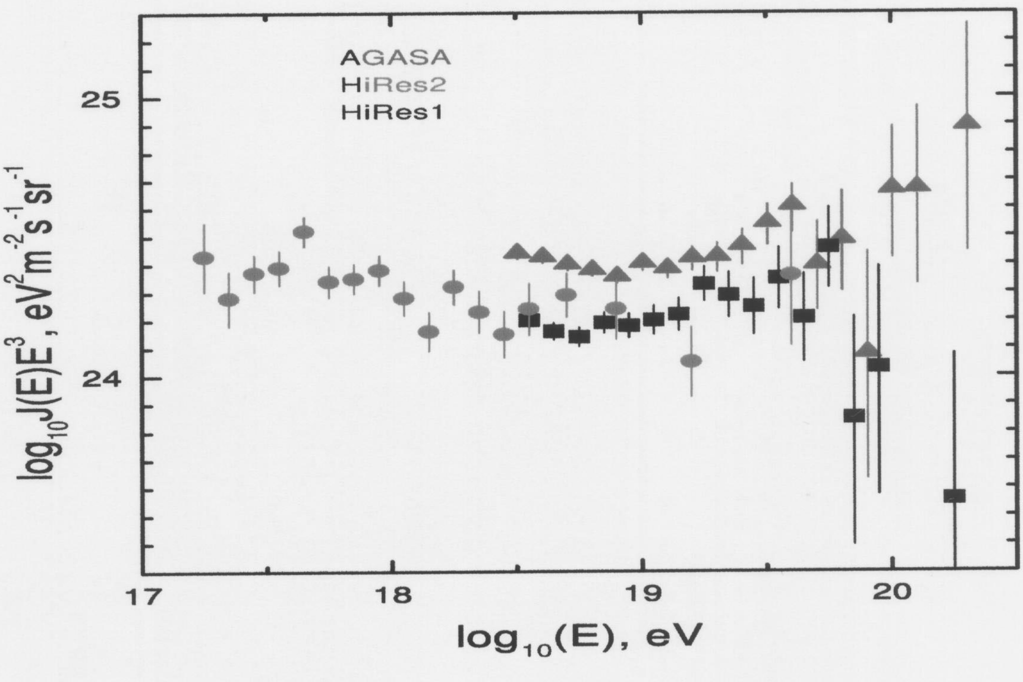
- **Astrophysical Solution to UHECR Problem**
- **Solutions with New Physics**

OBSERVATIONAL DATA

SPECTRUM OF COSMIC RAYS

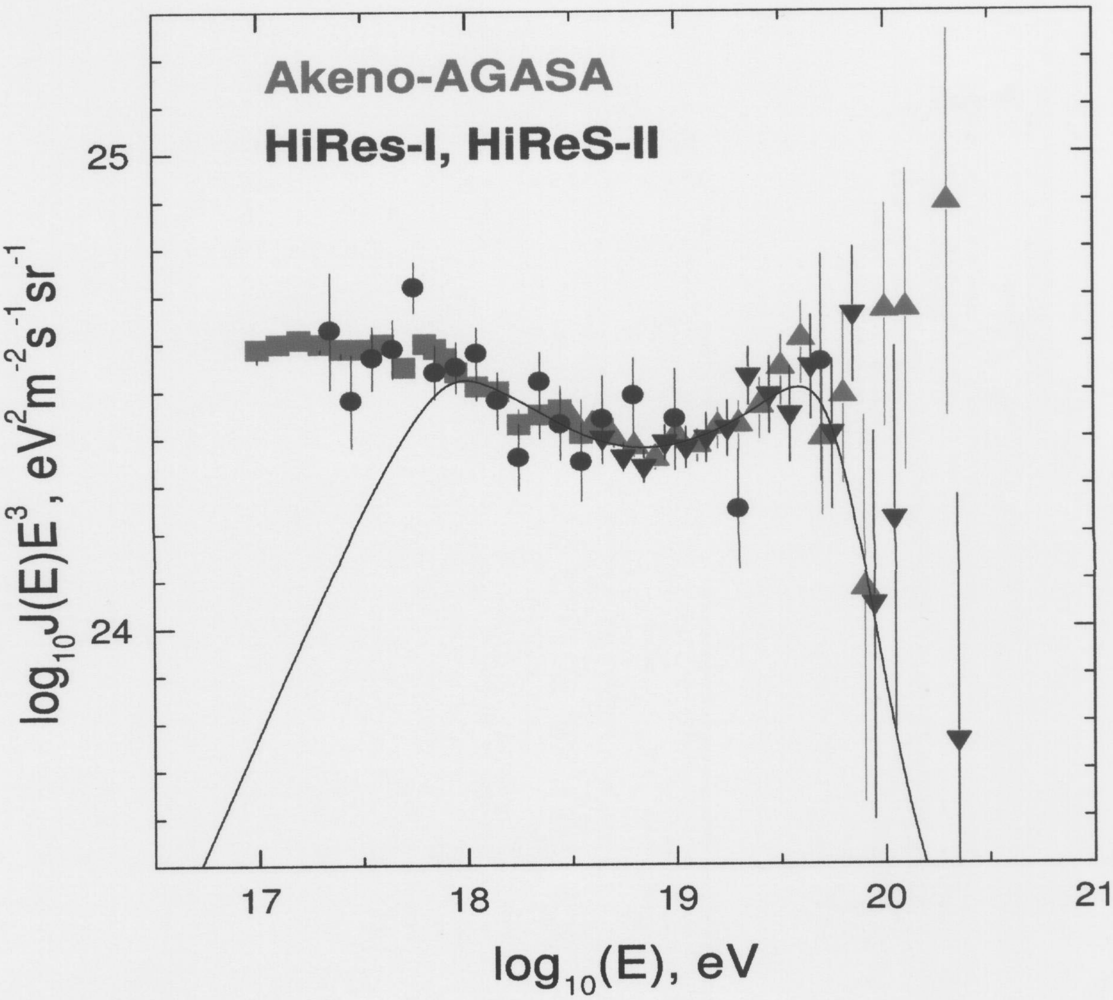


AGASA AND HiRes UHECR SPECTRA



AGASA and HiRes data shifted in energies:

$$\lambda_{agasa} = 0.9, \quad \lambda_{hires} = 1.26$$



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.**

World data (2000) $E \geq 4 \times 10^{19}$ **eV:**
5 doublets + 1 triplet within 3.0° **from** $N_{\rm tot} = 92$**.**
chance probability $< 0.3\%$**.**

HiRes data (2004): no clustering

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}**).**

(see criticism by Evans, Ferrer and Sarkar 2002 and reply by Tinyakov and Tkachev 2003.

PROPAGATION OF UHECR THROUGH CMB

INTERACTIONS

PROTONS

$$p + \gamma_{\mathrm{CMB}} \to p + e^+ + e^-$$

$$p + \gamma_{\mathrm{CMB}} \to N + \text{pions}$$

NUCLEI

$$Z + \gamma_{\mathrm{CMB}} \to Z + e^+ + e^-$$

$$A + \gamma_{\mathrm{CMB}} \to (A-1) + N$$

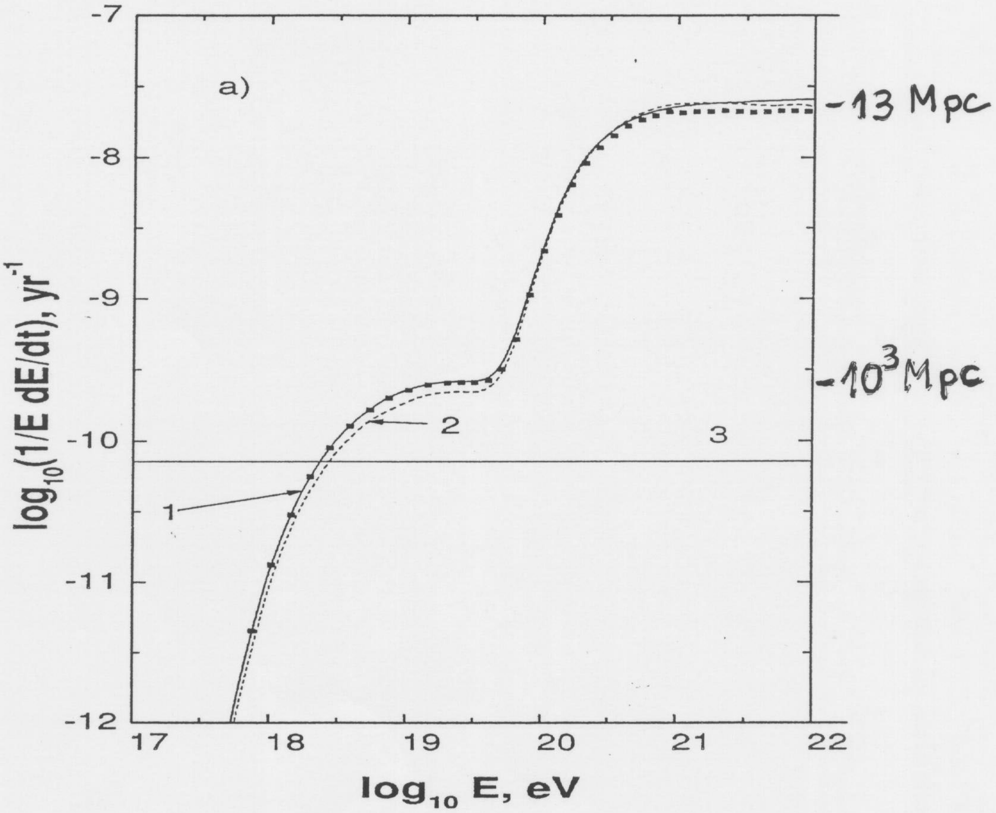
$$A + \gamma_{\mathrm{CMB}} \to A' + N + \text{pions}$$

PHOTONS

$$\gamma + \gamma_{\mathrm{bcgr}} \to e^+ + e^-$$

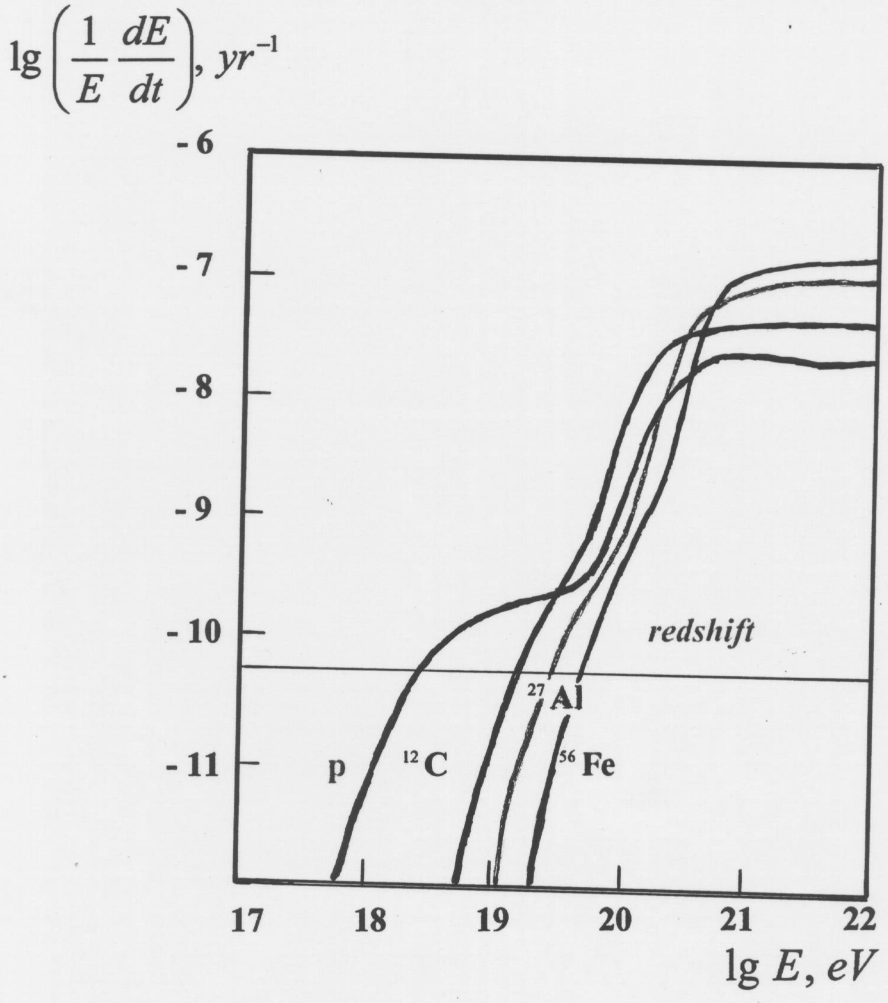
V.B., S. GRIGORIEVA, A. GAZIZOV
2001

ENERGY LOSSES OF UHE PROTONS

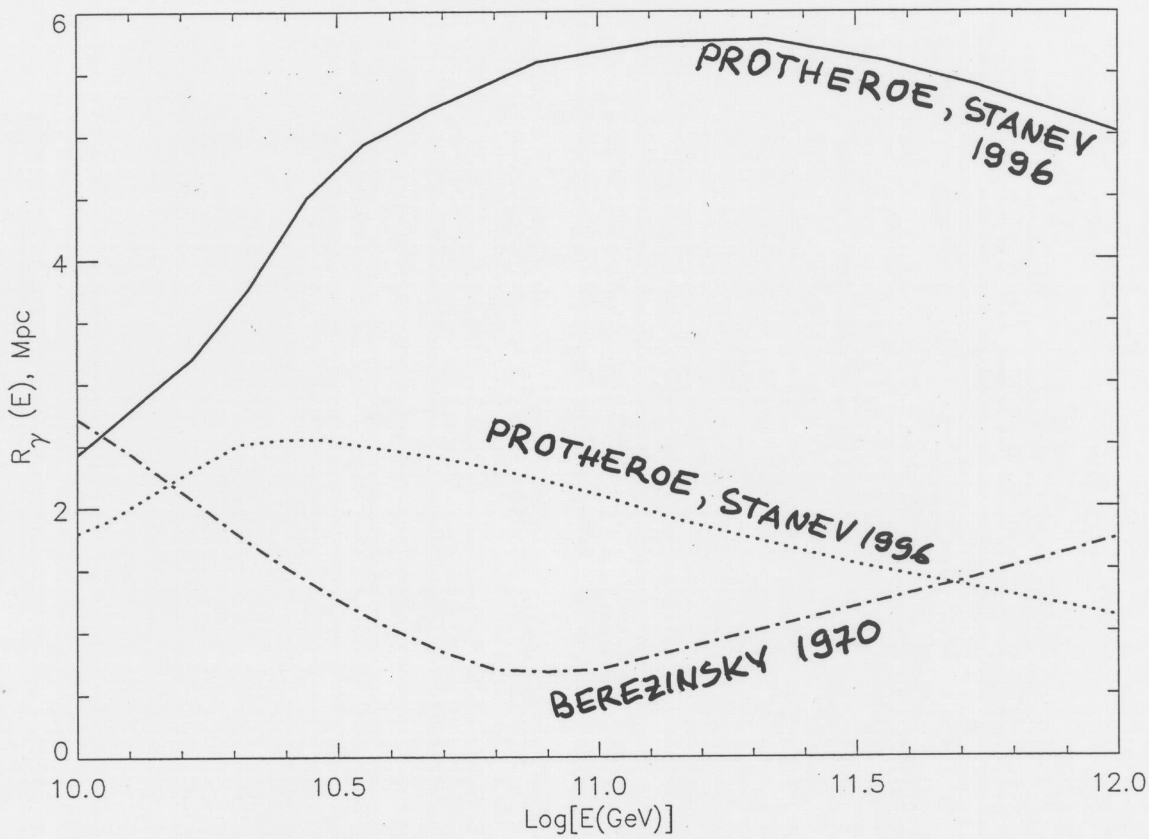


V.B., S. Grigorieva, G. Zatsepin, 1975

ENERGY LOSSES ON MICROWAVE RADIATION



ABSORPTION OF UHE GAMMAS ON RADIO BACKGROUND



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.

Magnetic fields might change the spectrum.

DIP AND BUMP IN THE DIFFUSE SPECTRUM

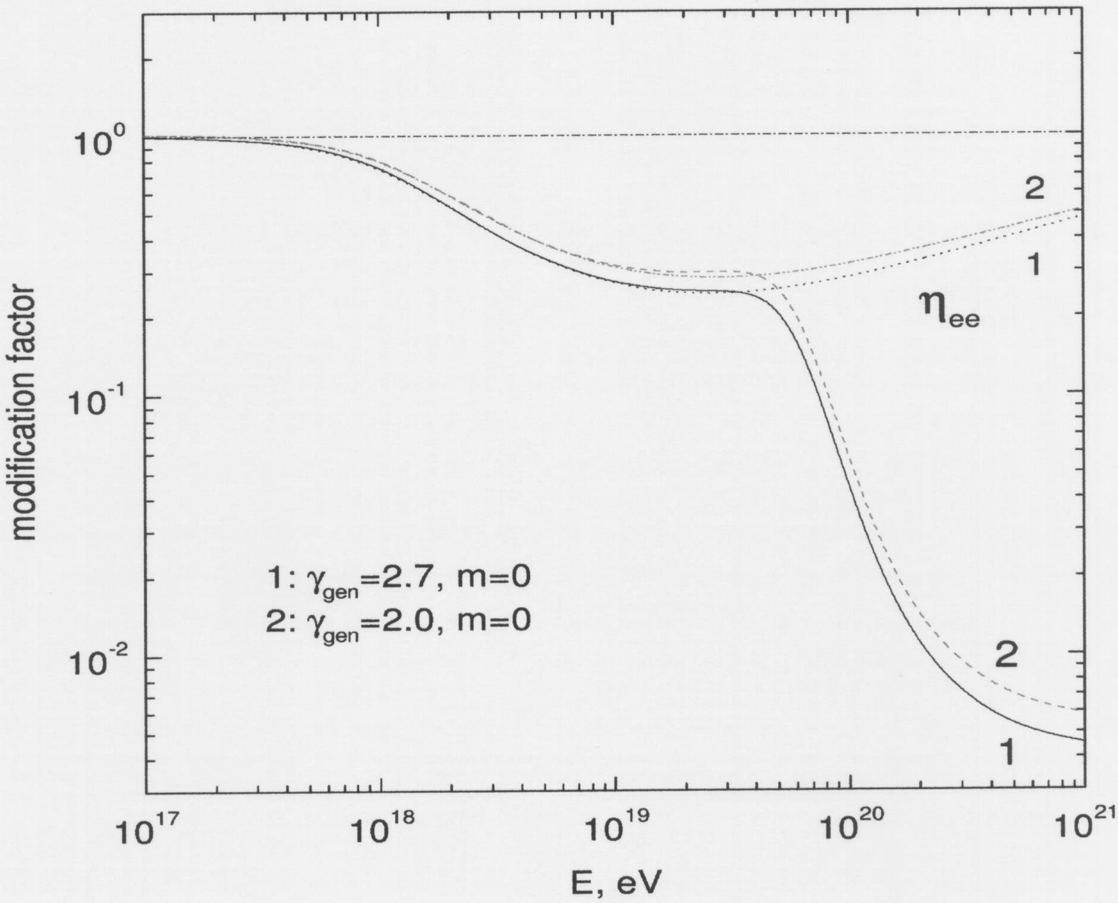
DEFINITION OF MODIFICATION FACTOR

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

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

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

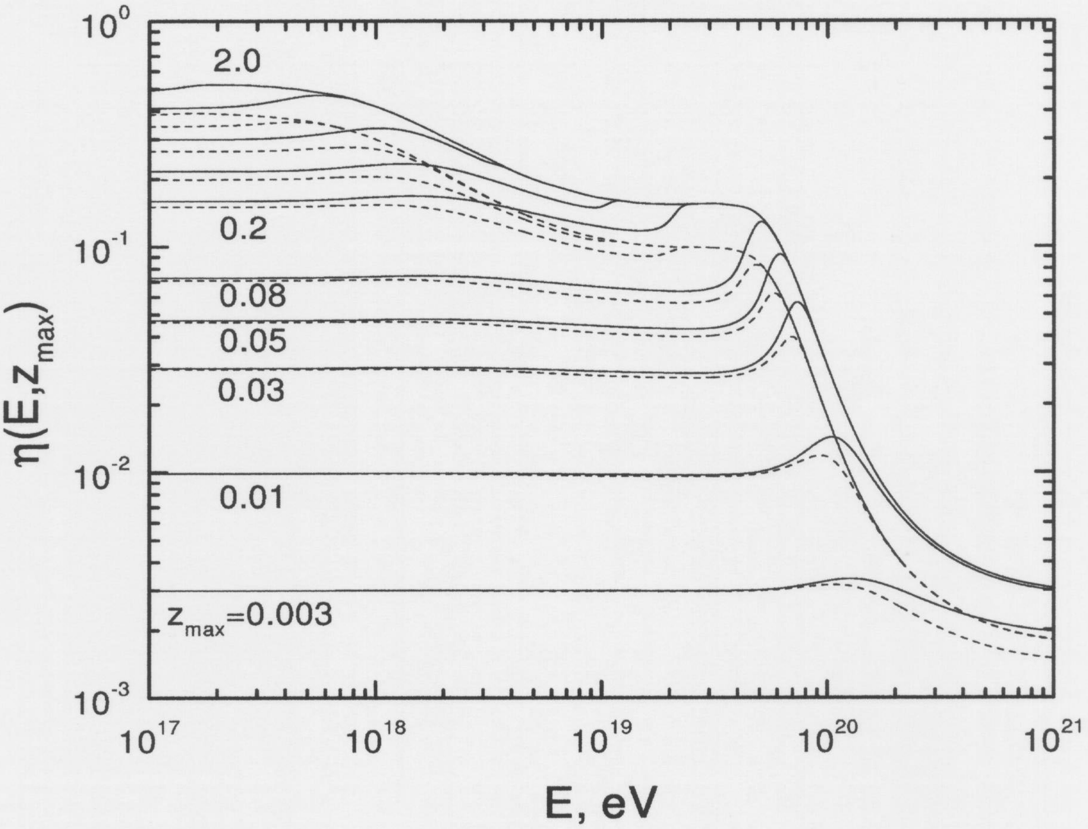
DIP AND BUMP IN DIFFUSE SPECTRA



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.

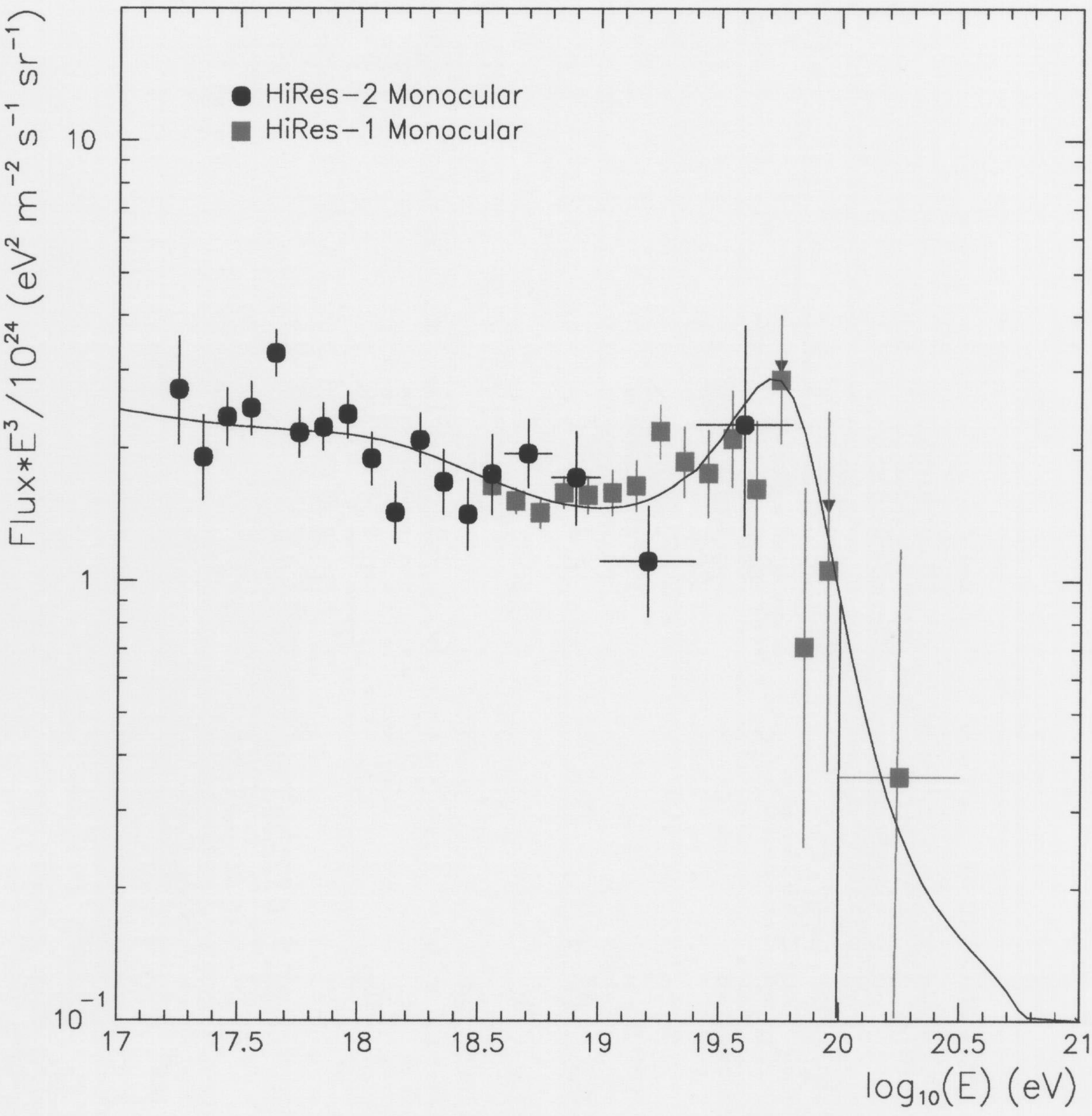
DISAPPEARANCE OF BUMPS IN DIFFUSE SPECTRA

V.B., Grigorieva 1988

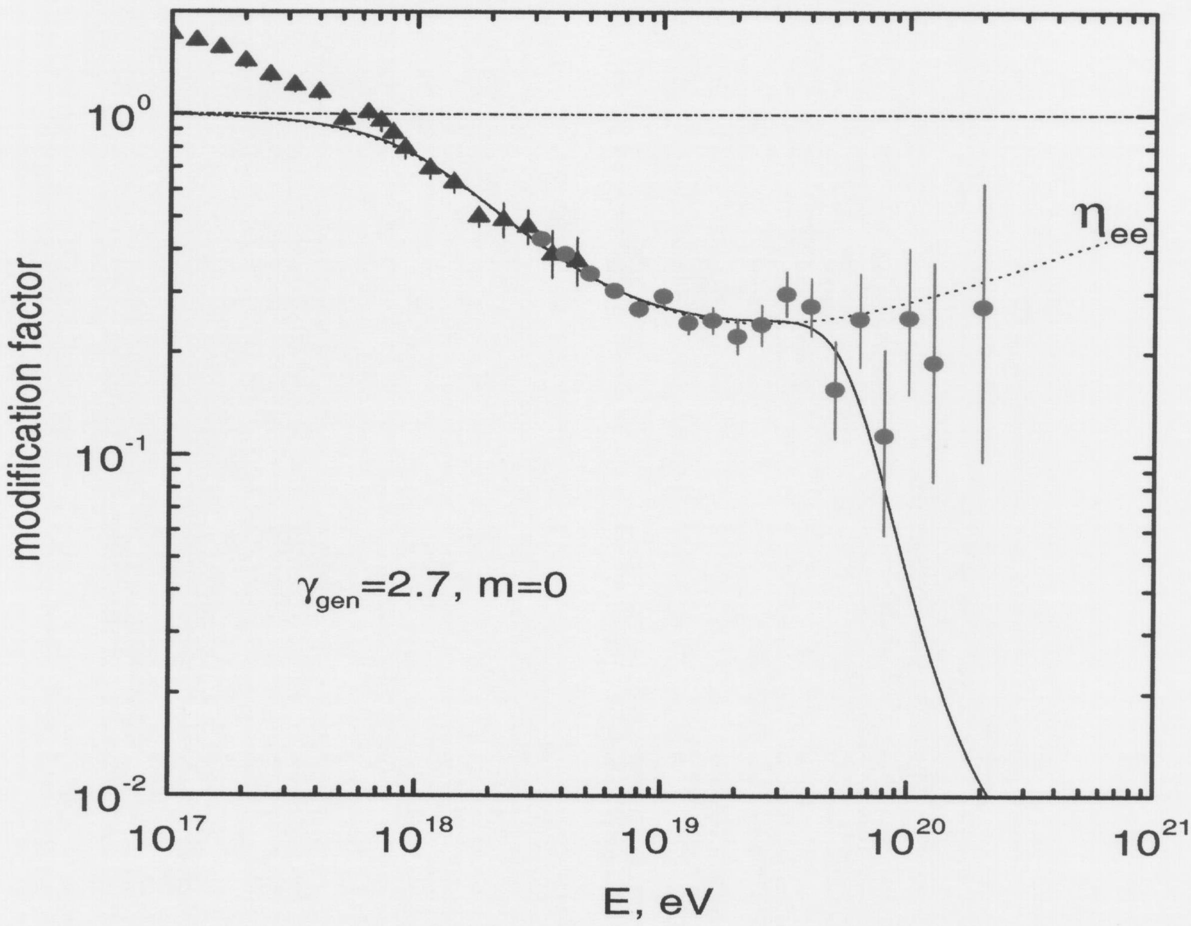


The solid curves are for $\gamma_g = 2.0$, and dashed curves – for $\gamma_g = 2.7$. The curves between $z_{\rm max} = 0.2$ and $z_{\rm max} = 2.0$ have $z_{\rm max} = 0.3,\ 0.5,\ 1.0$.

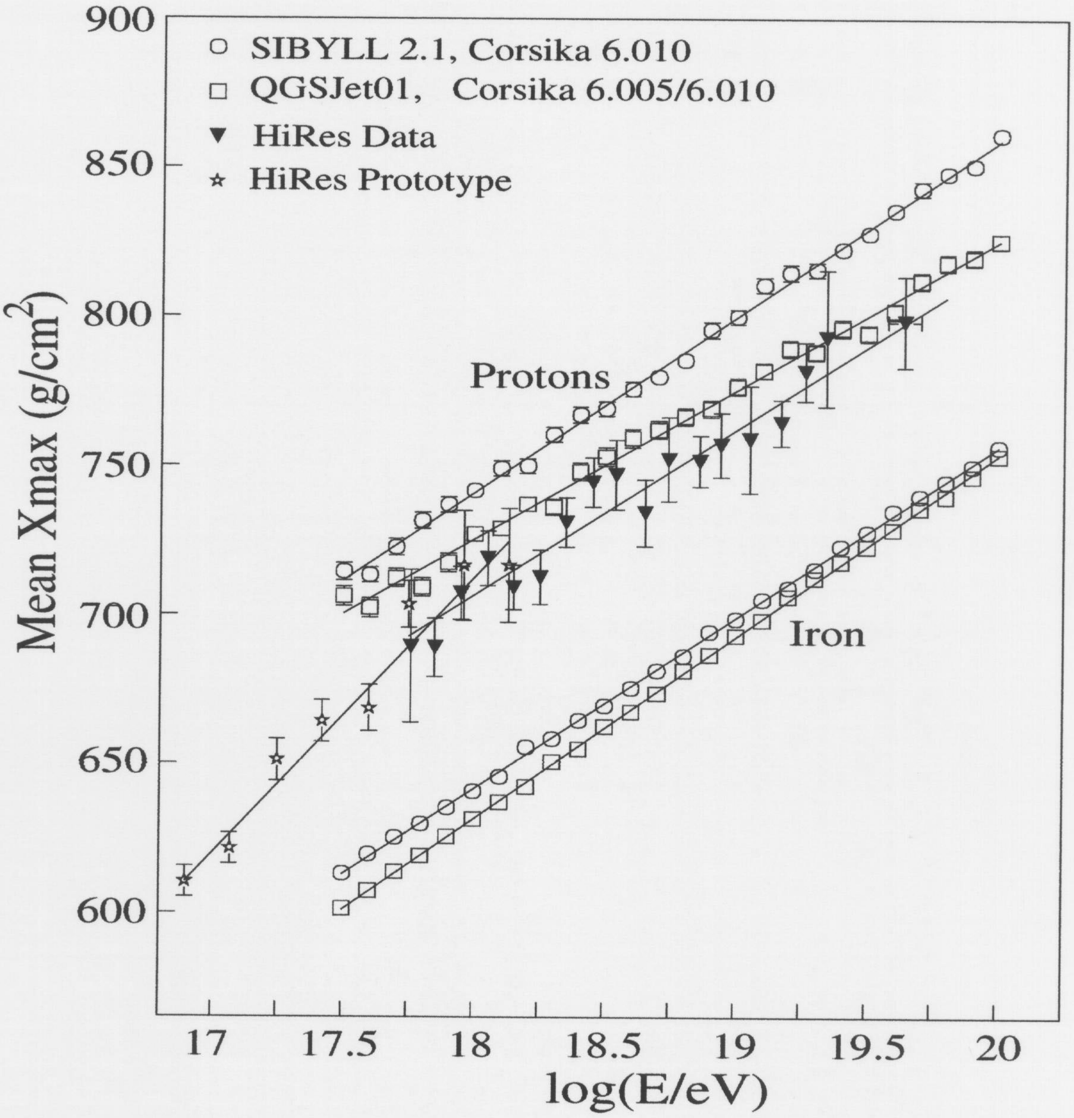
PSEUDO-BUMP IN EXPERIMENTAL DATA



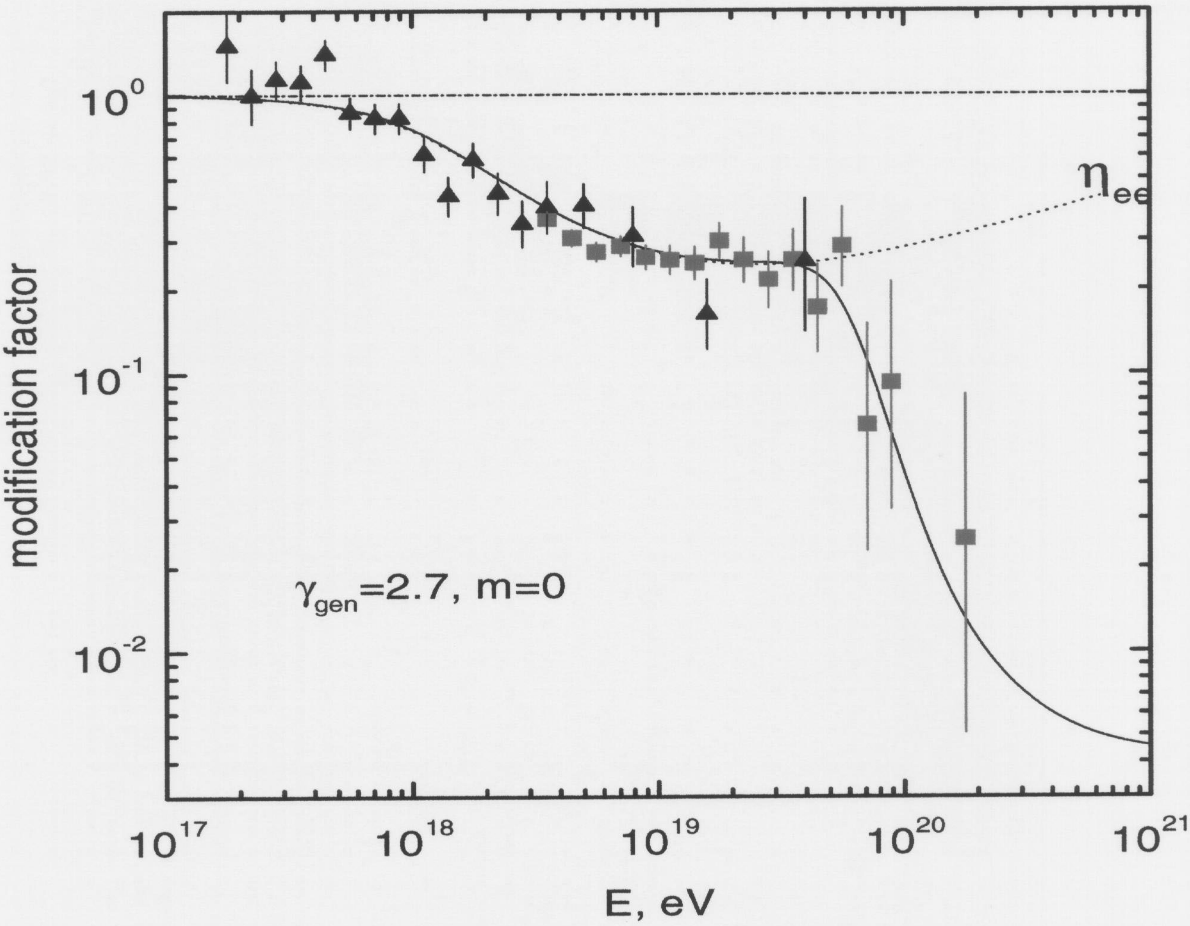
DIP IN COMPARISON WITH AKENO-AGASA DATA



HiRes data on mass composition



DIP IN COMPARISON WITH HIRES DATA



INTERPRETATION OF SMALL-ANGLE CLUSTERING

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.**
Number of sources:

$$N_s^* \sim \bar{N}_{\rm tot}^3/\bar{N}_{\rm cl}^2.$$

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

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

CORRELATIONS WITH BL Lacs

In case of protons as primaries, 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 (simulations by Sigl et al favour stronger fields). With field by Dolag et all protons with $E \geq 4 \times 10^{19}$ **eV propagate quasi-rectilinearly.**

SPACE DENSITY OF THE SOURCES

BL Lacs are FR radiogalaxies with jets directed towards us. Then the density of BL Lacs is

$$n_s^* = n_{\mathrm{FR}} \frac{\Omega_b}{4\pi}$$

The density $n_s^* = 1 \times 10^{-5}\ \mathrm{Mpc}^{-3}$ **implies too high space density of FR radiogalaxies.**

THE BGG MODEL

- **source generation spectrum**

$$Q_{\text{gen}}(E_g) = \begin{cases} \propto 1/E_g^2 & \text{at } E_g \le E_c \\ \propto E_g^{-2.7} & \text{at } E_g \ge E_c \end{cases}$$

with $E_c \sim 1 \times 10^{18}$ **eV inspired by HiRes and analysis of the modification factor.**

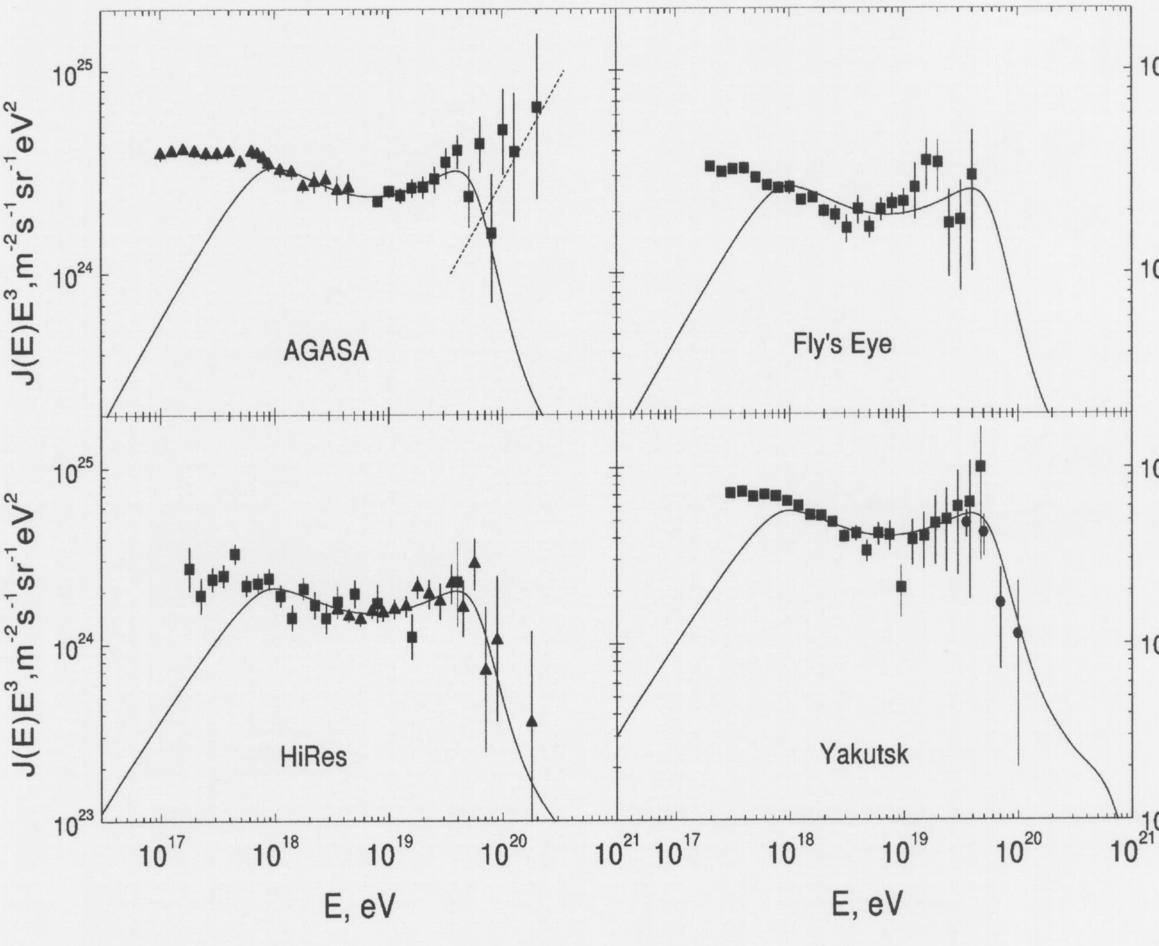
- $E_{\text{max}} = 1 \times 10^{21}$ **eV**
- **no source evolution:** $m = 0$
- $\mathcal{L}_0 \sim 3 \times 10^{46}$ **erg/Mpc^3 yr**
- **magnetic field according to Dolag et al, with clustering and correlations with BL Lacs due to rectilinear propagation of protons with energies** $E \ge 4 \times 10^{19}$ **eV.**
- **correlations with BL Lacs imply jet acceleration. e.g. pinch acceleration in jets by Trubnikov 1987**

$$Q(E) \propto E^{-\gamma_g}, \;\; \gamma_g = 1 + \sqrt{3} = 2.73.$$

- **Luminosity of a source (FR radiogalaxy)**

$$L_p \sim \frac{\mathcal{L}_0}{n_s^*} \frac{\Omega_b}{4\pi} \sim 1 \times 10^{44} \frac{\Omega_b}{4\pi} \text{ erg/s.}$$

Comparison of calculated spectra with data

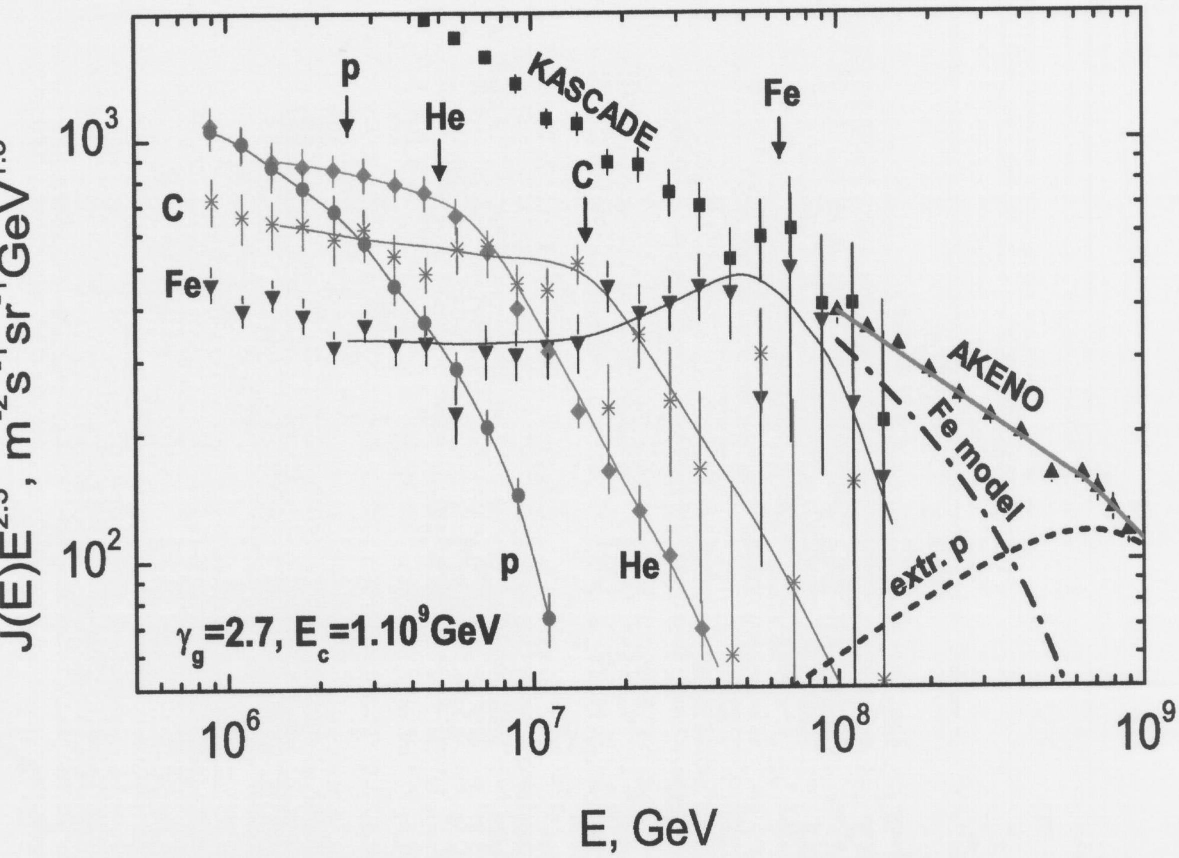


LOW-ENERGY PREDICTIONS OF THE MODEL

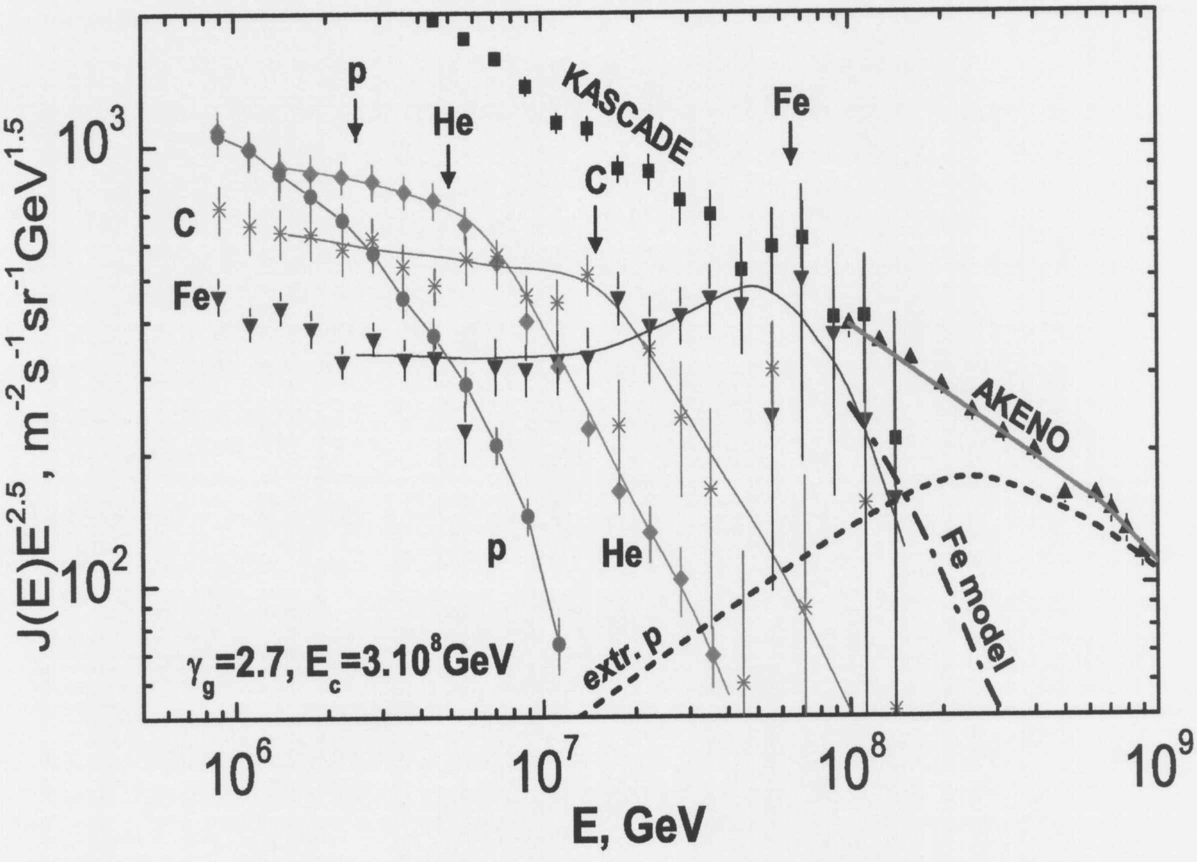
HOW UHE PROTON SPECTRUM IS CONNECTED WITH GALACTIC CR SPECTRUM?

Inspired by KASCADE date we assume that at $E > 1 \times 10^{17}$ eV galactic spectrum is dominated by iron nuclei.

The galactic iron flux is calculated by subtracting UHE proton spectrum of the BGG model from the observed all-particle spectrum.



KASCADE
p
He
C
Fe
C
Fe
AKENO
Fe model
extr. p
p
He
γ_g=2.7, E_c=1.10^{9}GeV
10^3
10^2
$J(E)E^{2.5}$, $m^{-2}s^{-1}sr^{-1}GeV^{1.5}$
10^6
10^7
10^8
10^9
E, GeV



KASCADE
p
He
C
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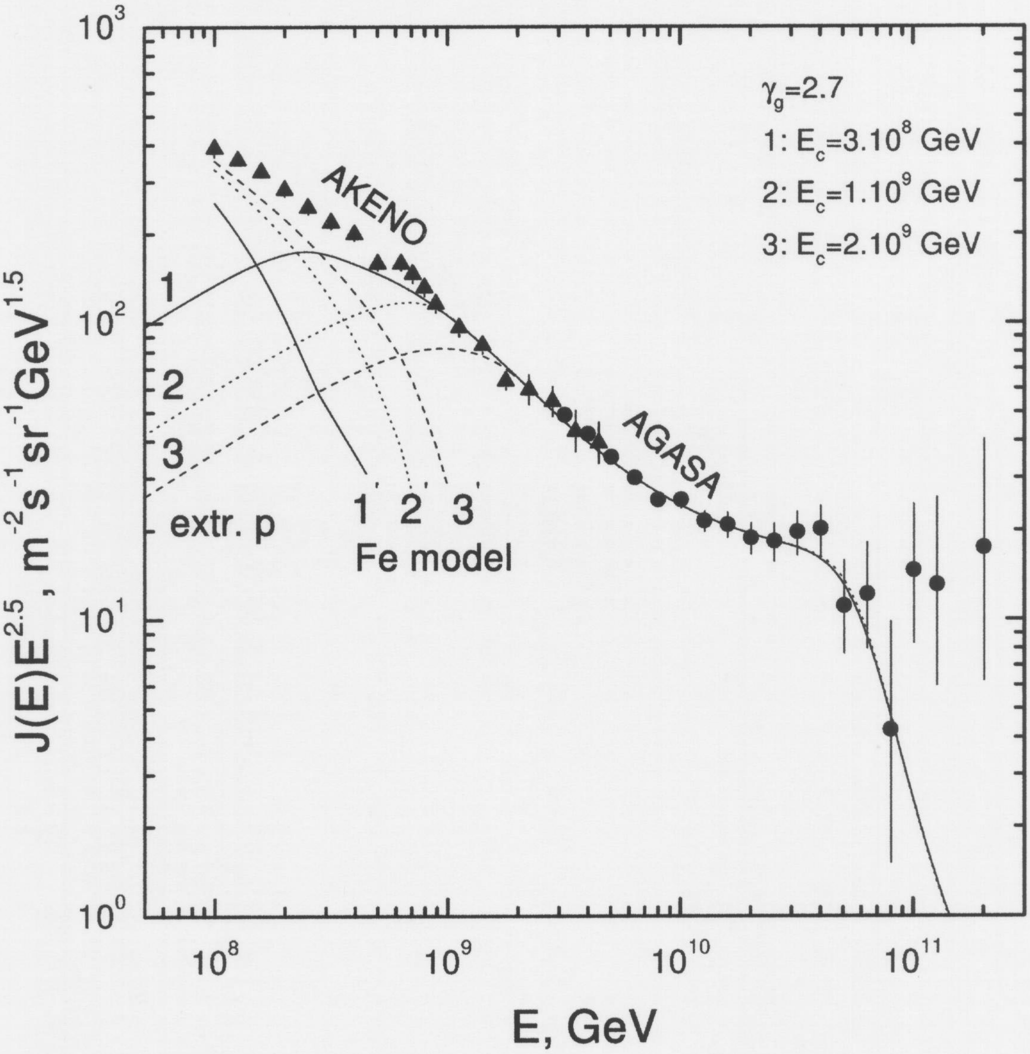
γ_g=2.7, E_c=3.10^{8}GeV
10^3
10^2
$J(E)E^{2.5}$, $m^{-2}s^{-1}sr^{-1}GeV^{1.5}$
10^6
10^7
10^8
10^9
E, GeV

TRANSITION FROM GALACTIC TO EXTRAGALACTIC COSMIC RAYS



Shape of the galactic (iron) spectrum at $E \geq 3 \times 10^8$ **GeV agrees with the Hall diffusion.**

PROPAGATION IN MAGNETIC FIELDS

According to numerical simulations, propagation in strong magnetic fields 10 - 100 nG results in small-angle clustering and weak GZK cutoff (Sigl et al 1999, Yoshiguchi et al 2003).

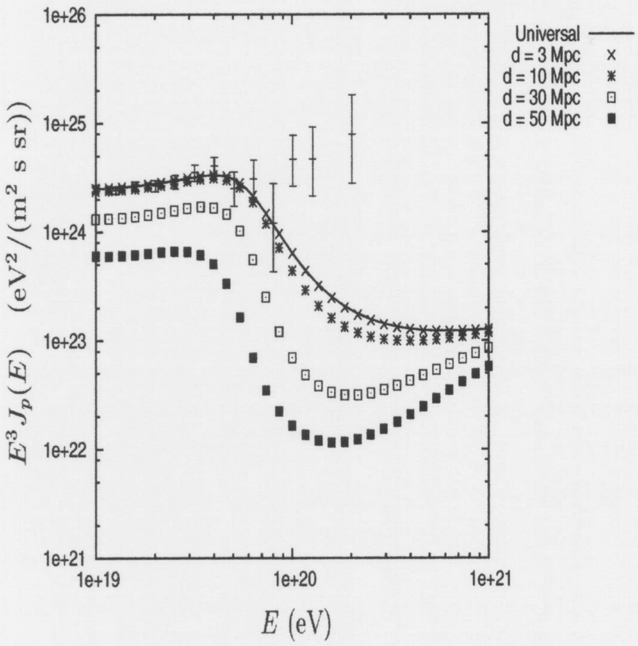
PROPAGATION THEOREM

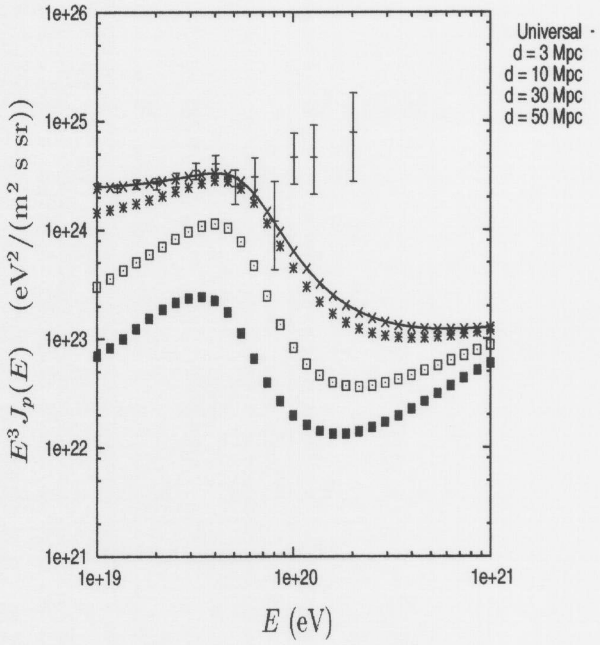
R. Aloisio, V.B. 2004

FOR UNIFORM DISTRIBUTION OF SOURCES WITH SEPARATION d MUCH LESS THAN CHARACTERISTIC LENGTHS OF PROPAGATION, SUCH AS $l_{\text{att}}(E)$ and $l_{\text{diff}}(E)$, THE DIFFUSE SPECTRUM OF UHECR HAS AN UNIVERSAL (STANDARD) FORM INDEPENDENT OF MODE OF PROPAGATION

The spectrum of the BGG model is the universal one, and it is valid for a wide range of magnetic fields $B \leq$ 10 nG and galactic separations d.

Convergence to universal spectrum





Convergence of the diffusion spectrum to the universal spectrum in the case of $D = const$ diffusion (left panel) and the Bohm diffusion (right panel), with magnetic configuration (B_0, l_c) =(100 nG, 1 Mpc).

UNIVERSAL SPECTRUM

Conservation of number of particles in comoving volume:

$$n_p(E)dE = \int_0^{t_0} dt\, Q_{\rm gen}(E_g, t)\, dE_g$$

$$E_g = E_g(E, t)$$

$Q(E_g, t)$ **is generation rate per comoving volume.**

$$Q_{\rm gen}(E_g, t) = \mathcal{L}_0 (1+z)^m K q_{\rm gen}(E_g)$$

$q_{\rm gen}(E_g) = E_g^{-\gamma_g}$, **with** $K = \gamma_g - 2$ **for** $\gamma_g > 2$.

$$dt = \frac{dz}{H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}},$$

$$J_p(E) = \frac{c}{4\pi}\, \mathcal{L}_0\, K \times$$

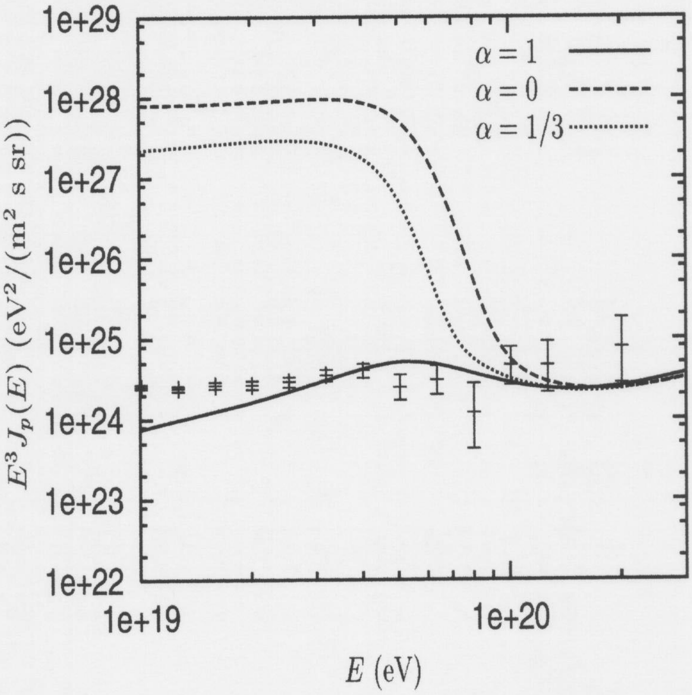
$$\int_0^{z_{max}} dz \frac{dt}{dz}(1+z)^m q_{\rm gen}\left(E_g(z, E)\right) \frac{dE_g}{dE}$$

$$\frac{dE_g(z_g)}{dE} = (1+z_g) \exp\left[\int_0^{z_g} dt (1+z)^3 \left(\frac{db_0(E')}{dE'}\right)\right]$$

where $E' = (1+z)E_g(E, z)$ **and** $b_0(E) = (dE/dt)_{\rm CMB}$

WHY GZK CUTOFF IS ABSENT IN STRONG MAGNETIC FIELDS?

The flux at $E > 5 \times 10^{19}$ eV is suppressed due to large energy losses. In strong magnetic fields the flux at lower energies is equally suppressed because of longer travel time from a source, $t \sim r^2/D(E)$, in spite of smaller dE/dt.



Diffuse fluxes from lattice-distributed sources with $d = 30$ Mpc and for magnetic configuration (1000 nG, 1 Mpc). $\alpha = 1$ corresponds to Bohm diffusion with $D(E) \propto E$, $\alpha = 0$ and 1/3 correspond to $D = const$ and the Kolmogorov diffusion, respectively. Luminosity of a source is $L_p = 1.5 \times 10^{47}$ erg/s.

THREE PROBLEMS OF ASTROPHYSICAL SOLUTION

Highest energy events $E > 1 \times 10^{20}$ eV

AGASA excess needs another component of UHECR.

The problem exists for other detectors. There are 5 events with $E \geq 1 \times 10^{20}$ eV (FE, HiRes, Yakutsk). Distance to the sources cannot exceed 20 - 30 Mpc. **No sources are seen in these directions.**

Low energy problem

If transition from galactic to extragalactic CR occurs at ankle $E \sim 1 \times 10^{19}$ eV, and iron knee is located at $E_{\rm Fe} \approx 6.5 \times 10^{16}$ eV (KASCADE), **how the gap between 1×10^{17} and 1×10^{19} is filled?**

The BGG model solves this problem assuming the transition at the position of the second knee $E_c \sim 1 \times 10^{18}$ eV.

Acceleration to $E_{\rm max} \geq 1 \times 10^{21}$ eV

SOLUTIONS WITH NEW PHYSICS

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

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

  No radically new physics involved, **fits the data**

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

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

  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 $\tilde{g}g$): **not excluded.**

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

SUPERHEAVY DARK MATTER (SHDM)

- **PRODUCTION: many efficient mechanisms at post-inflationary epochs, most attractive one is production in time-varying gravitational field. Creation occurs when $H(t) \sim m_X$. Since $H(t) \leq m_\phi \sim 10^{13}$ GeV,**

$$m_X \sim 10^{13}\ \text{GeV}.$$

(e.g. $m_X \sim 3 \times 10^{13}$ GeV results in $\Omega_X h^2 \sim 0.1$).

- **LONGEVITY OF SHDM PARTICLES.**
Discrete gauge symmetry protection, like R-parity for neutralino. Decay is provided by superweak effects: warmhole, high dimension operators etc.

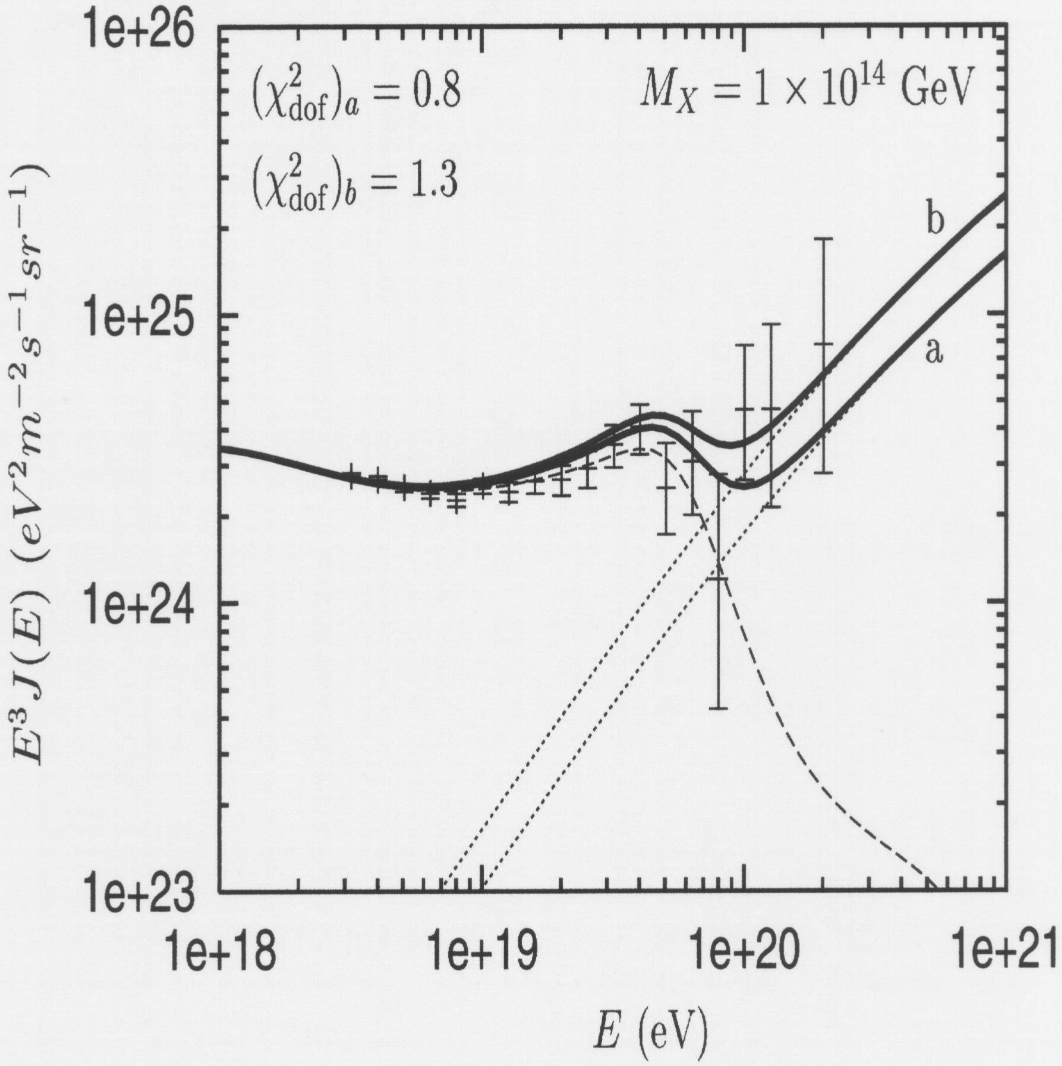
- **ACCUMULATION IN THE GALACTIC HALO.**
Like for any DM, overdensity=2.1$\times 10^5$.

- **X-PARTICLE DECAY.**
Photon dominance $\gamma/p \approx 2 - 3$.
Energy spectrum:

$$J_{\text{SHDM}}(E) \propto E^{-\gamma_g}, \ \text{with} \ \gamma_g \approx 1.94$$

This spectral index excludes SHDM as explanation of observed spectrum at $E < 1 \times 10^{20}$ eV. Only AGASA excess can be explained.

AGASA EXCESS from SUPERHEAVY DARK MATTER



RESONANT NEUTRINOS (Z-BURSTS)

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

Elementary-particle physics is standard.

$$E_0 = \frac{m_Z^2}{2m_\nu} \geq 1.8 \times 10^{22} \left(\frac{0.23\ \mathrm{eV}}{m_\nu}\right)\ \mathrm{eV}$$

$$E_p \geq 1.8 \times 10^{23}\ \mathrm{eV}$$

For $m_\nu < 0.23$ eV, spectrum (p+γ) has a noticeable GZK cutoff.

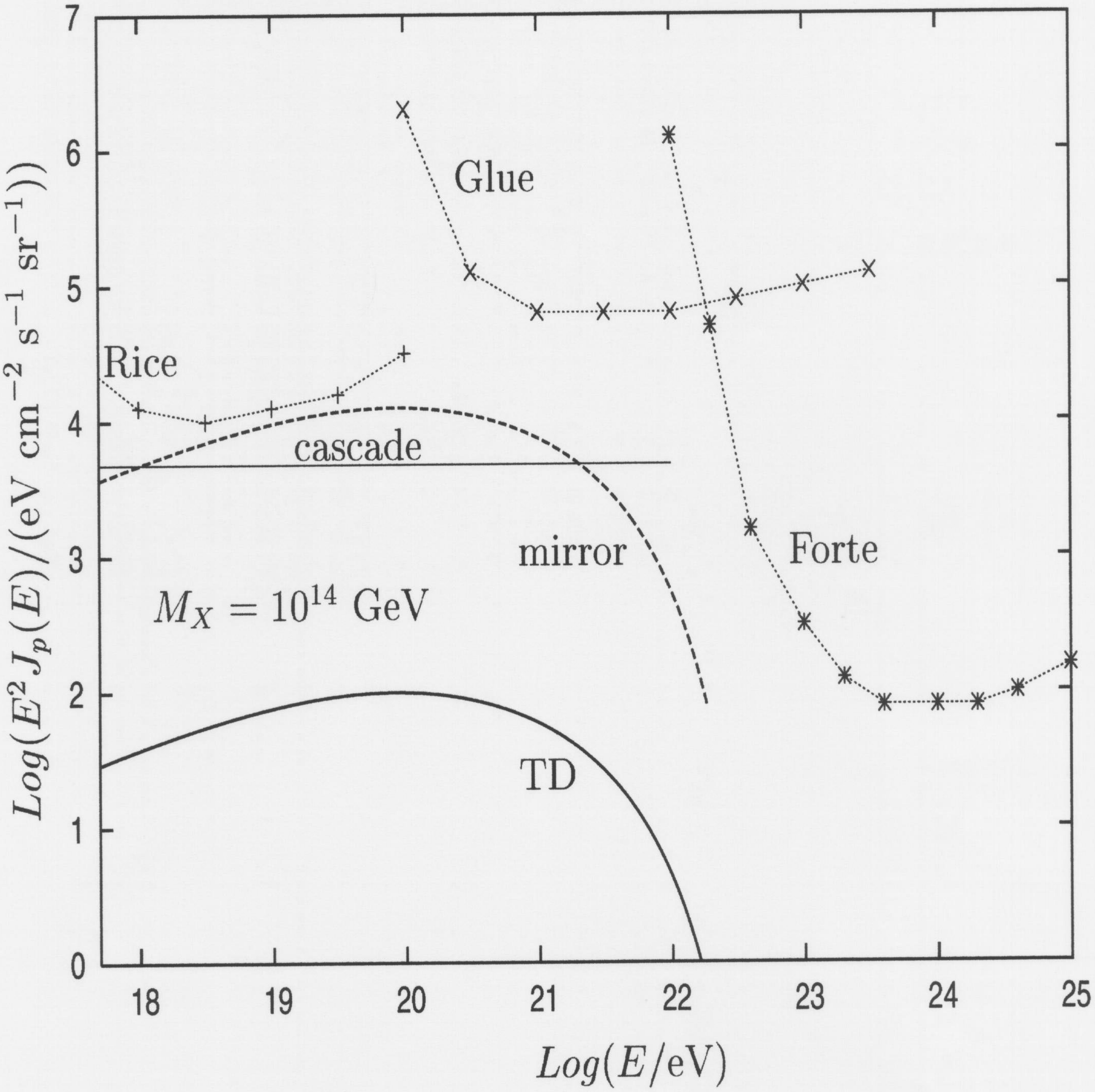
Cascade limit on neutrino flux,

$$J_\nu(E_0) < \frac{c}{4\pi} \frac{\omega_{\mathrm{cas}}}{E_0^2}$$

with $\omega_{\mathrm{cas}} \leq 3 \times 10^{-6}$ eV/cm^3 (EGRET), excludes accelerator sources, TDs and SHDM (even in case when $X \to \nu\bar{\nu}$).

Mirror neutrinos as primaries for Z-burst model are excluded by the radio-detection upper bounds, e.g. GLUE.

UHE NEUTRINOS FROM MIRROR TDs



TOPOLOGICAL DEFECTS

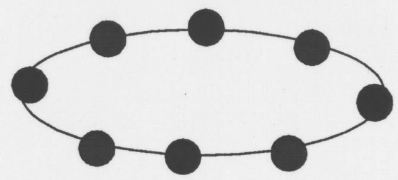
Symmetry breaking in early universe results in phase transitions (D. Kirzhnitz 1972), which are accompanied by topological defects.

Depending on symmetry breaking, defects can be in the form of surfaces (domain walls), lines (strings) or points (monopoles).

TD OF INTEREST FOR UHE NEUTRINOS

- ➜ MONOPOLES
- ➜ ORDINARY STRINGS
- ➜ MONOPOLES CONNECTED BY STRINGS

$G \to H \times U(1)$
U(1) breaking
$G \to H \times U(1) \to H \times Z_n$



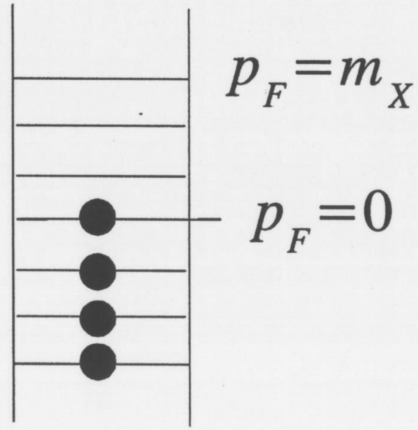
e.g. necklaces $Z_n = Z_2$
$M + \bar{M} \to$ parton cascade→pions→neutrinos
(monopolonia, necklaces)

- ➜ SUPERCONDUCTING STRINGS

$$\frac{dp}{dt} = eE \;\to\; p = eEt \qquad p \sim m_X$$

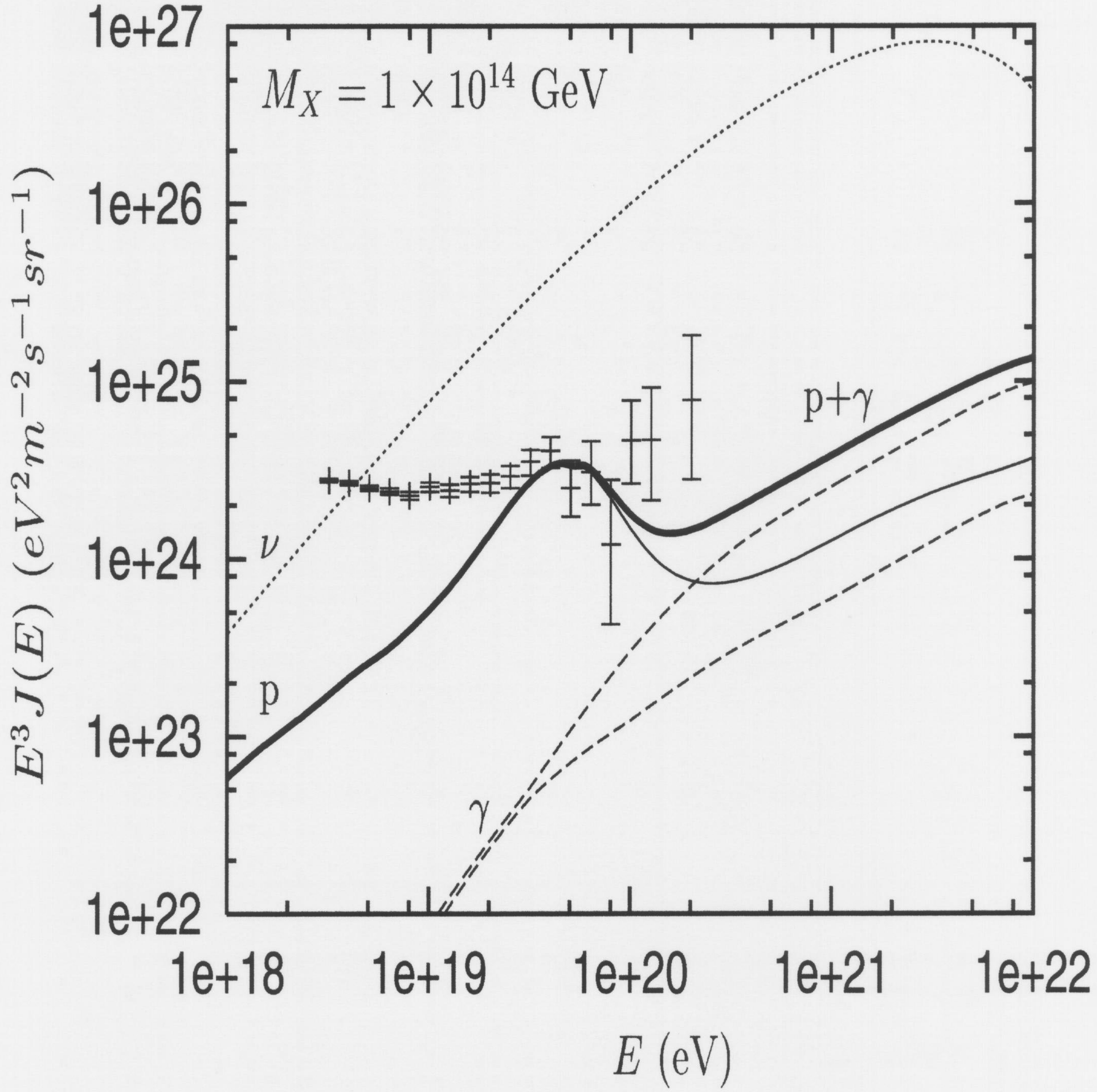
$$\frac{dp}{dt} = eE \;\to\; \frac{dJ}{dt} = e^2 E \qquad J = J_c \sim e\, m_X$$

X → parton cascade → pions → neutrinos



CUSPS: boosting by large Lorentz factor

UHECR FROM NECKLACES



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.
- Dip is confirmed by model-independent analysis with 2 free parameters, $\gamma_g = 2.7$ and $K_{\rm norm}$: $\chi^2 = 19.06$ for d.o.f.=17, χ^2/d.o.f.=1.12.
  This analysis implies transition from galactic to extragalactic CR at $E \sim 1 \times 10^{18}$ eV, i.e. at position of the second knee.
- Transition to the proton component at $E \sim 1 \times 10^{18}$ eV is confirmed by HiRes data.

2. The model with the source spectrum

$$Q_{\rm gen}(E_g) = \begin{cases} \propto 1/E_g^2 & \text{at } E_g \leq E_c \\ \propto E_g^{-2.7} & \text{at } E_g \geq E_c \end{cases}$$

predict the universal spectrum for strong enough magnetic fields $B <$ (a few) $\times\ 10$ nG with good agreement with observed spectrum at $E \leq 1 \times 10^{20}$ eV.

- $E_c \sim 1 \times 10^{18}$ **eV provides a smooth transition from galactic heavy nuclei at** $E \leq 1 \times 10^{17}$ **eV to extragalactic protons at** $E \geq 1 \times 10^{18}$ **eV.**

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

3. In astrophysical solution there is problem with superGZK particles $E > 1 \times 10^{20}$ **eV.**

- **AGASA excess,**

- **No visible sources in the direction of particles with** $E > 1 \times 10^{20}$ **eV for all detectors.**

POSSIBLE SOLUTIONS:

- **SHDM,**

- **New signal carriers (strongly interacting neutrino, light stable hadron),**

- **Lorentz-invariance violation.**

The Auger detector data (2005) will clarify the situation.