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SMR.1508 - 33

SUMMER SCHOOL ON PARTICLE PHYSICS

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ASTROPARTICLE PHYSICS

Lecture II

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UHECR PROBLEM:
STATUS OF ASTROPHYS. SOLUTION

UHECR PROBLEM

$E \gtrsim 10^{19}$ — EXTRAGALACTIC ORIGIN

GZK CUTOFF:

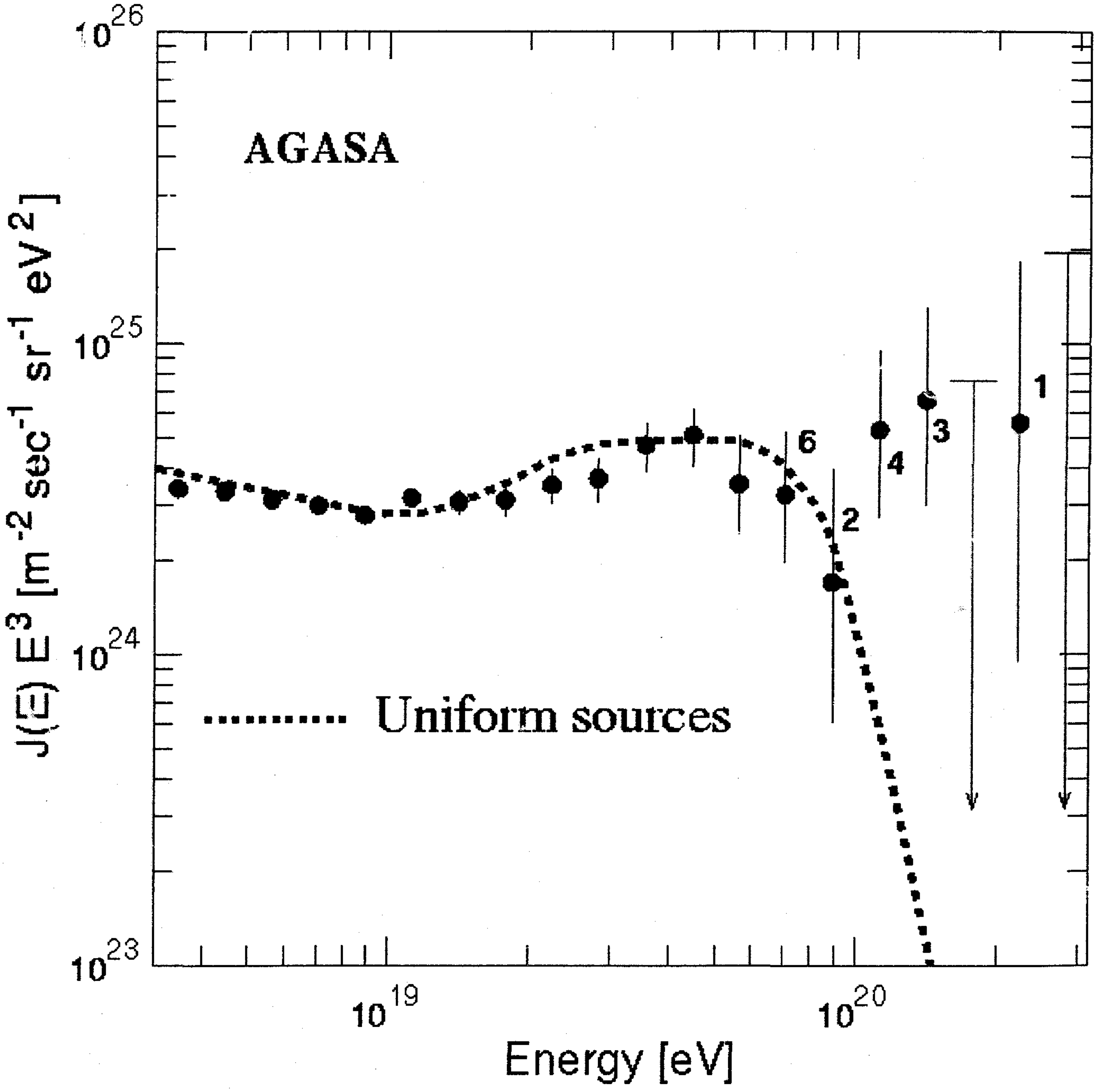
ENERGY LOSSES OF UHE PROTONS ON CMBR

$$p + \gamma_{CMBR} \to p + e^+ + e^-$$

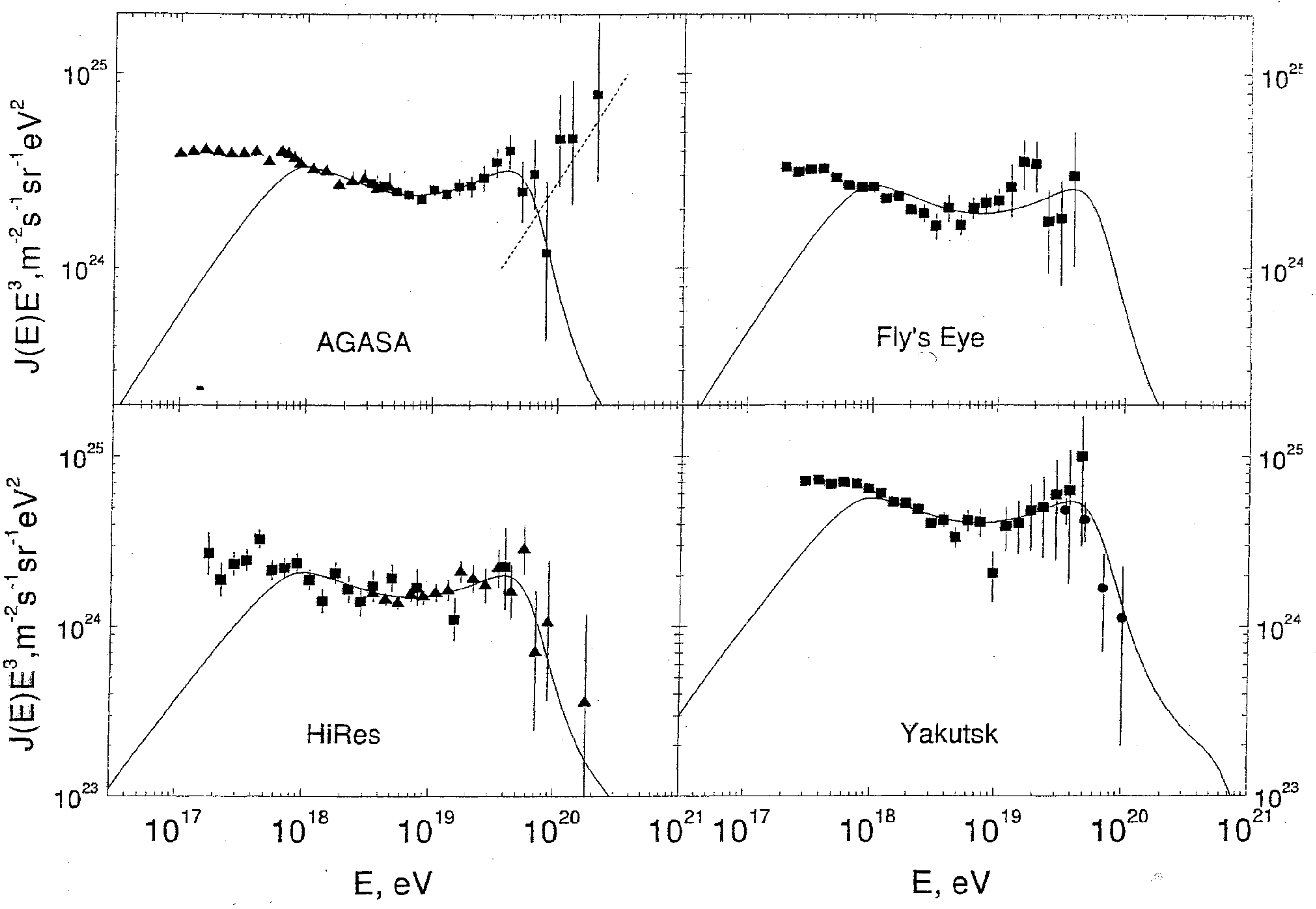
$$p + \gamma_{CMBR} \to N + \text{pions}$$

FOR HOMOGENEOUS DISTRIBUTION OF SOURCES THE SPECTRUM STEEPENS AT $E_{1/2} = 5.3 \cdot 10^{19}$ eV

GZK CUTOFF IS NOT OBSERVED ?



AGASA
Uniform sources
J(E) E³ [m⁻² sec⁻¹ sr⁻¹ eV²]
Energy [eV]
10^26
10^25
10^24
10^23
10^19
10^20
1
2
3
4
6



J(E)E^3,m^-2s^-1sr^-1eV^2
AGASA
Fly's Eye
HiRes
Yakutsk
E, eV
E, eV

ENERGY LOSSES AND THEIR SIGNATURES

PROTONS

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

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

NUCLEI

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

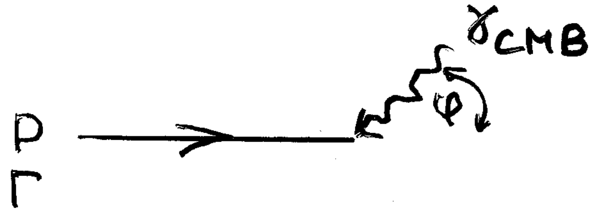
$$A + \gamma_{CMB} \rightarrow (A-1) + N$$

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

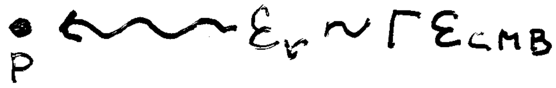
PHOTONS

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

CALCULATIONS



lab syst (l.s.)



p-rest syst (r.s.)

$(Kp) = E_p \varepsilon_{CMB} (1+\cos\varphi)$

$(Kp) = \varepsilon_r m_p$

$$\frac{1}{E}\frac{dE}{dt} =$$

$$\frac{cT}{2\pi^2\Gamma^2}\int_{\varepsilon_{th}}^{\infty} d\varepsilon_r\, \sigma(\varepsilon_r) f(\varepsilon_r)\, \varepsilon_r \left\{-\ln\left[1-\exp\left(-\frac{\varepsilon_r}{2\Gamma kT}\right)\right]\right\}$$

ε_r IS ENERGY OF γ IN r.s.

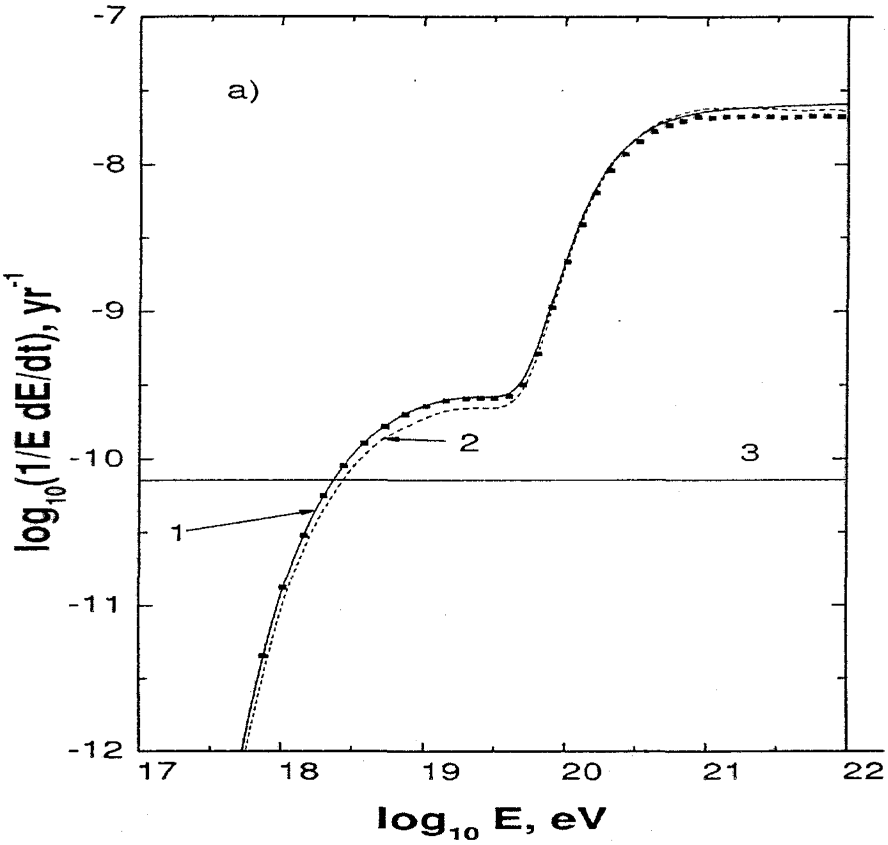
Γ IS PROTON LORENTZ FACTOR

$f(\varepsilon_r)$ IS FRACTION OF ENERGY LOST

$T = 2.725$ K

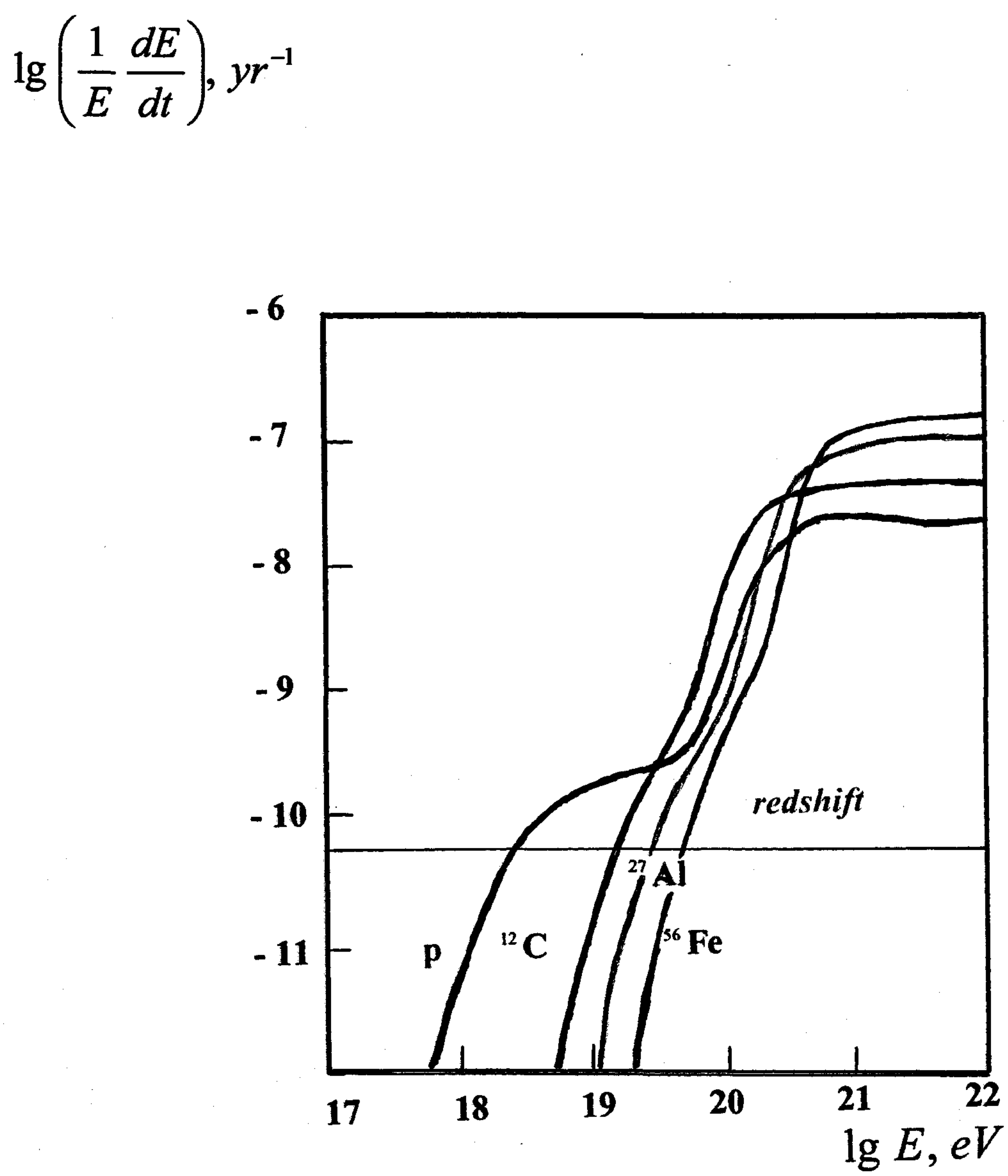
V.B., S. GRIGORIEVA, A. GAZIZOV
2001

ENERGY LOSSES OF UHE PROTONS

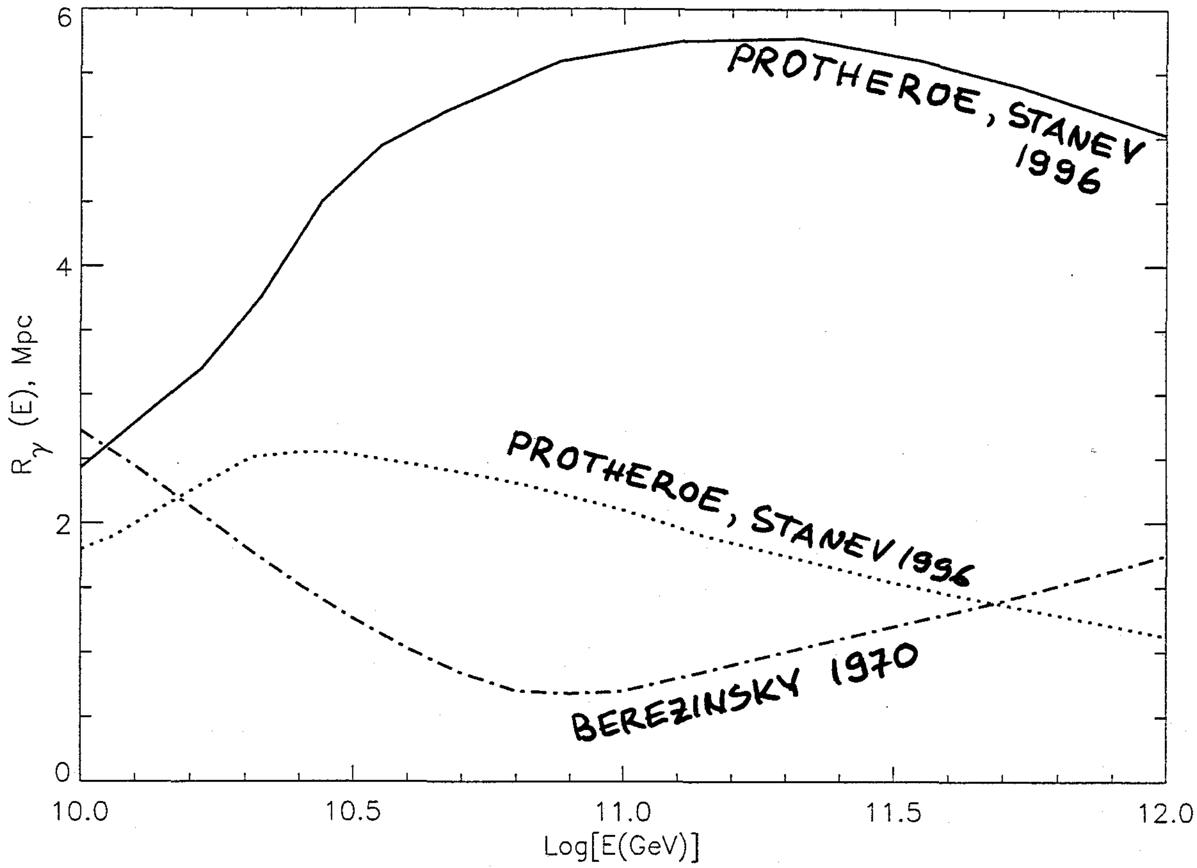


V.B., S. Grigorieva, G. Zatsepin, 1975

ENERGY LOSSES ON MICROWAVE RADIATION



ABSORPTION OF UHE GAMMAS ON RADIO BACKGROUND



PROPAGATION SIGNATURES OF UHE PROTONS

$E_{1/2}$ (GZK), BUMP (PILE-UP PROTONS), DIP

E1/2 AS NUMERICAL CHARACTERISTIC OF GZK CUTOFF

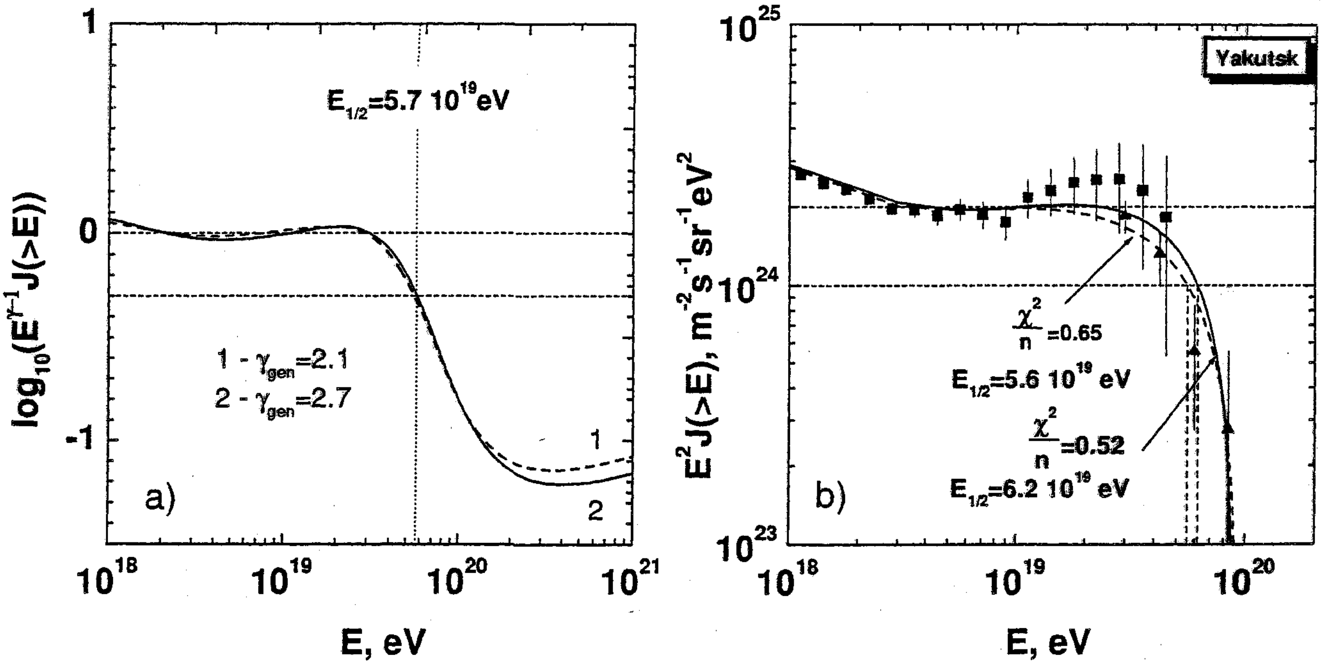


FIG. 4: *$E_{1/2}$ as numerical characteristic of the GZK cutoff. In panel a) $E_{1/2}$ for different γ_g are presented. In panel b) $E_{1/2}$ is found from the integral spectrum of the Yakutsk array using two fits of the integral spectrum.*

BUMP

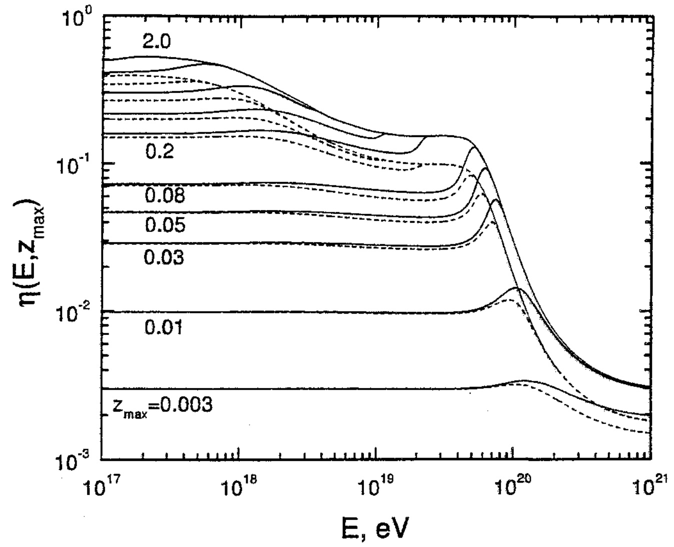


FIG. 6: Modification factors for diffuse spectra with different $z_{\max}$. The curves between $z_{\max} = 2.0$ and $z_{\max} = 0.2$ have $z_{\max} = 0.3$,0.5 and 1.0. The solid curves are for $\gamma_g = 2.0$ and dashed ones - for $\gamma_g = 2.7$. The pile-up peaks, clearly seen at small $z_{\max}$, disappear when summation of sources goes to large $z_{\max} > 1$ [4].

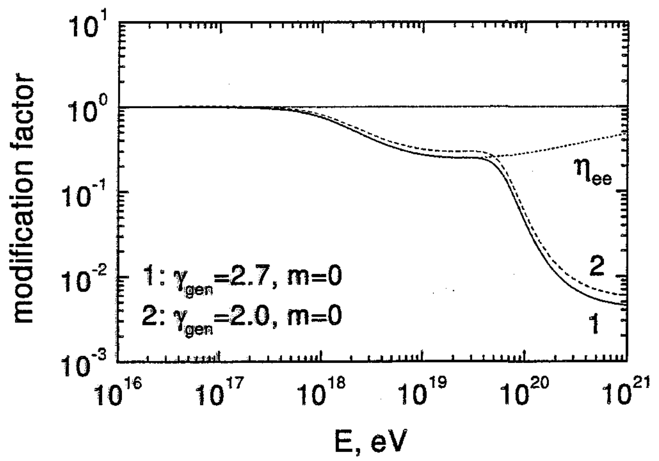


FIG. 7: Modification factor as characteristic of the dip and bump. The dotted curve show η_{ee}, when adiabatic and pair-production energy losses are included, for the case $\gamma_g = 2.7$. The solid and dashed curves include also the pion-production energy losses. The pile-up peaks are practically absent [4].

$$I(E) = I_{unm}(E)\,\eta(E, z_{max})$$

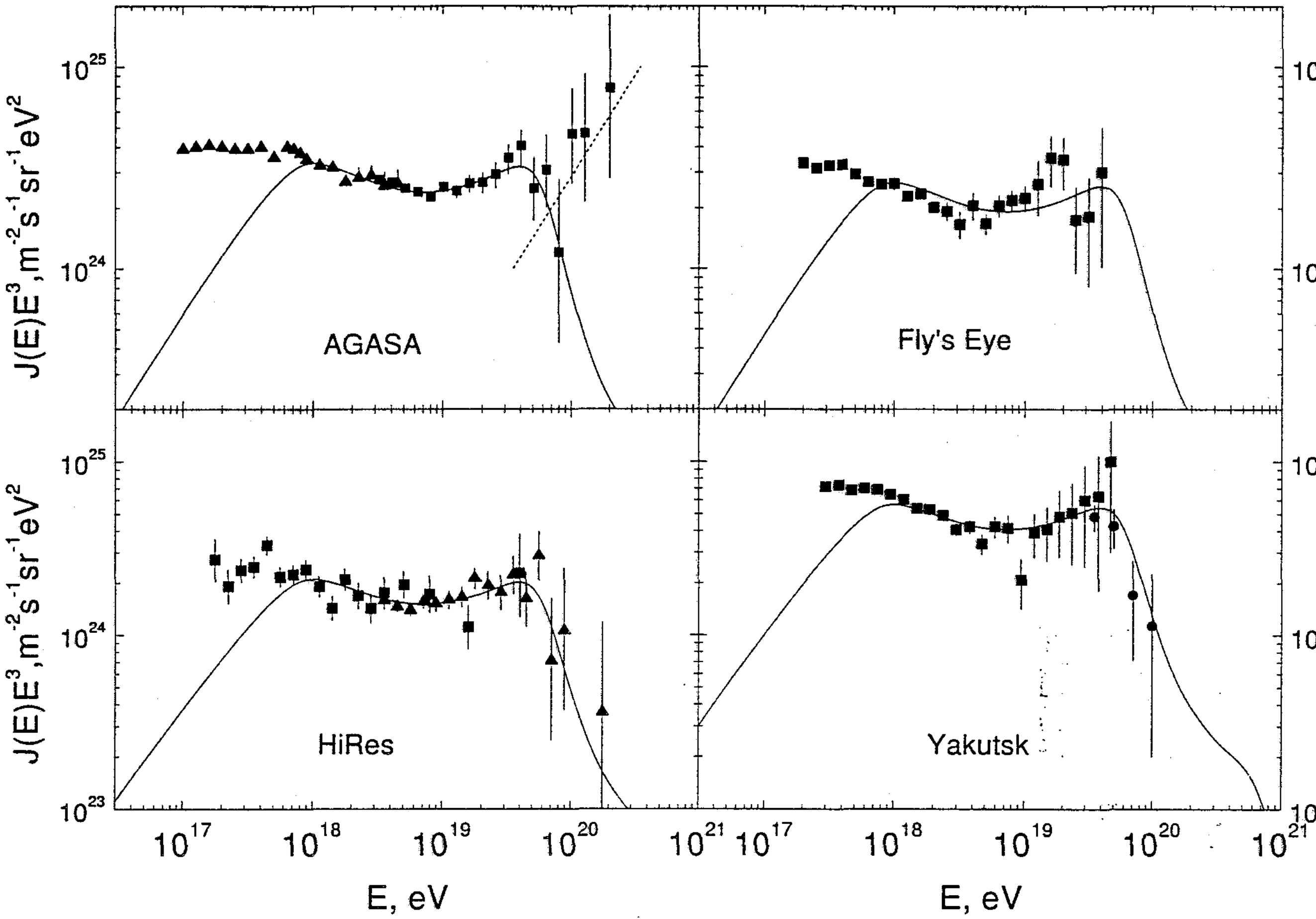
$$I_{unm}(E) = \frac{c}{4\pi}(\gamma_g - 2)\,\frac{\mathcal{L}_0}{H_0}\,E^{-\gamma_g}$$

$$\eta(E, z_{max}) = dz\,\frac{\lambda^{-\gamma_g}(E,z)}{(1+z)\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}}\,\frac{dE_g}{dE}$$

$$\lambda(E,z) = E_g(E,z)/E$$

DIP IN UHECR

V.B., GRIGORIEVA, GAZIZOV 2002



$\gamma_{gen} = 2.7$ EMISSIVITY $\mathcal{L}_0 = 3.0 \cdot 10^{46}$ erg/Mpc^{3}yr

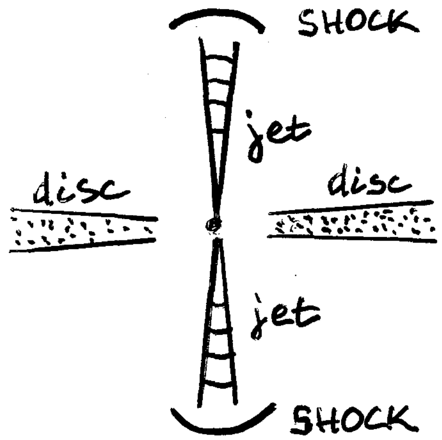
SOURCES AND ACCELERATION

SOURCES MUST BE POWERFUL $\mathcal{L}_0 \sim 10^{46}$ erg/Mpc^{3}yr
AND ACCELERATE PARTICLES UP TO $E_{max} \sim 10^{21}$ eV

CANDIDATES: AGN and GRBs

ACCELERATION IN AGN

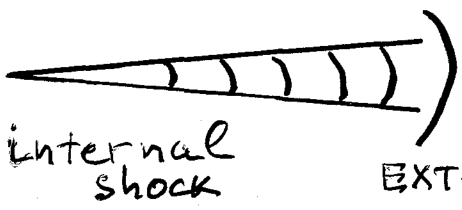
(JETS AND SHOCKS, Biermann, Racken 1993)



$$E_{max} \sim 10^{21} B_{-4} \left(\frac{R_j}{1\,\mathrm{Kpc}}\right) \frac{V_j}{c} \ \mathrm{eV}$$

UNIPOLAR INDUCTION IN ACCRETION DISC

ACCELERATION IN GRB



EXTERNAL SHOCK $\Gamma_{sh} \sim 300$

ARE THERE OBSERVATIONAL INDICATIONS TO THE SOURCES ?

- SMALL-SCALE ANGULAR CLUSTERING:

  FROM 92 EVENTS THERE ARE 5 DOUBLETS AND 1 TRIPLET WITHIN 2.5°

  THRESHOLD OF EFFECT: $E \geq 4 \cdot 10^{19}$ eV

  CHANCE PROBABILITY $< 1 \cdot 10^{-3}$

  INTERPRETATION:

  - COMPACT SOURCES

    NUMBER OF SOURCES WITHIN 25 Mpc IS

    $N_s = 220^{+207}_{-100}$. DENSITY $\sim 5 \cdot 10^{-76}$ cm^{-3}

  - NEUTRAL PRIMARIES OR VERY WEAK MAGN FIELD

- CORRELATION WITH BL Lacs AT $E \sim 4-8 \cdot 10^{19}$ eV

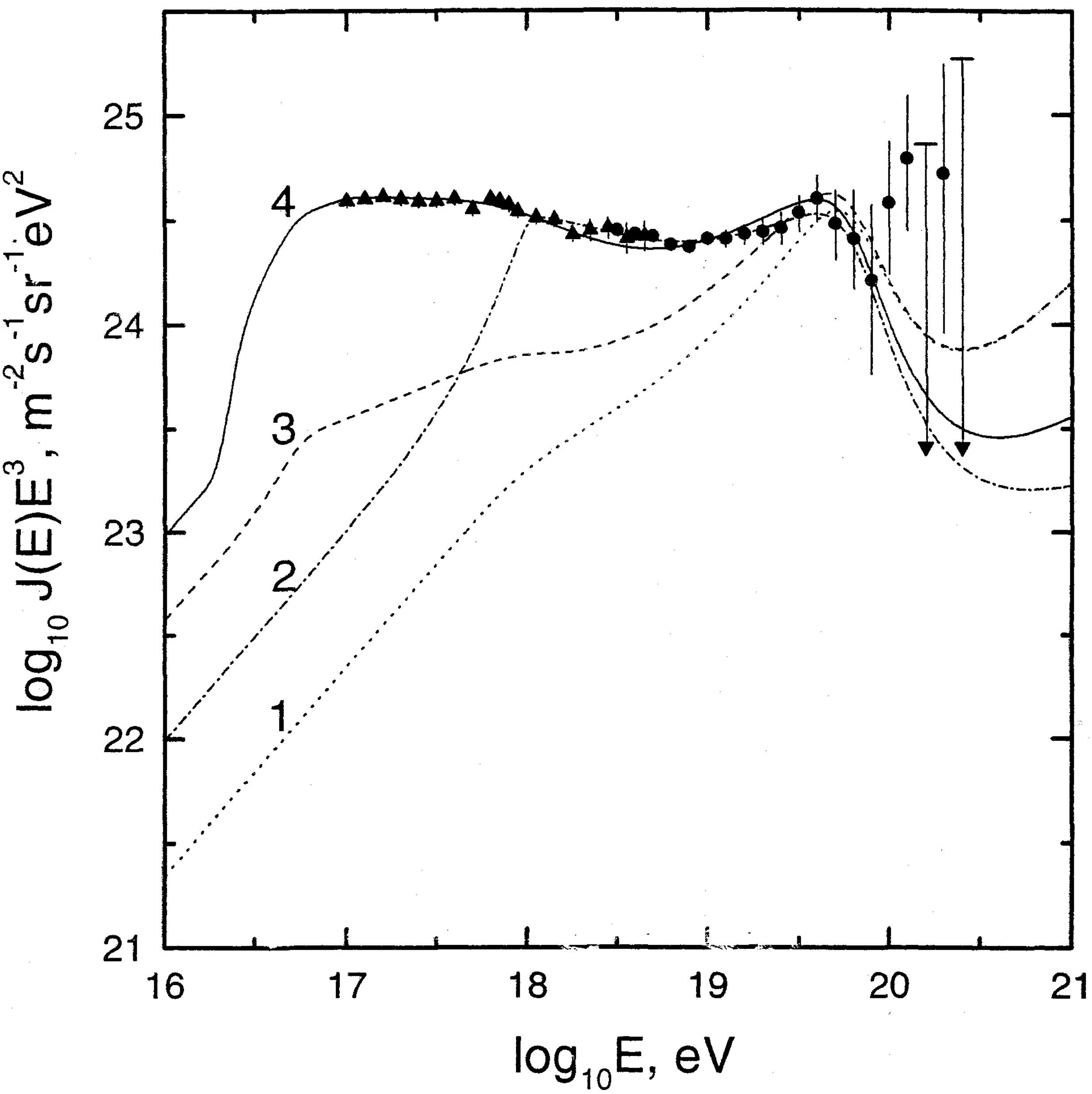
  Tinyakov, Tkachev 2001

  INTERPRETATION:

  RECTILINEAR PROPAGATION OF PROTONS (WEAK MAGN FIELD) OR NEUTRAL PARTICLES

UHECR FROM GRBs

hep-ph/0107306



1: E^{-2} SPECTRUM, NO EVOLUTION, $\mathcal{L}_{CR} = 2\cdot 10^{45}$ erg/Mpc^{3}yr

3: E^{-2} SPECTRUM, EVOLUTION, $\mathcal{L}_{CR} = 2\cdot 10^{45}$ erg/Mpc^{3}yr

2: $\begin{cases} E^{-2} \text{ AT } E \le E_c \\ E^{-\gamma_g} \text{ AT } E \ge E_c \end{cases}$ NO EVOLUTION $\mathcal{L}_{CR} = 3.7\cdot 10^{46}$ erg/Mpc^{3}yr

4: — " — EVOLUTION $\mathcal{L}_{CR} = 3.1\cdot 10^{46}$ erg/Mpc^{3}yr

$\mathcal{E}_{GRB} = 1\cdot 10^{43}$ erg/Mpc^{3}yr M. Schmidt 1999

AGN AS UHECR SOURCES

- SPECTRUM

$$Q_g(E_g, z) = \frac{L_p(z)}{\ln \frac{E_c}{E_{min}} + \frac{1}{\gamma_g - 2}} \, q_{gen}(E_g)$$

$$q_{gen}(E_g) = \begin{cases} 1/E_g^2 & \text{AT } E_g \leq E_c \\ E_c^{-2}(E_g/E_c)^{-\gamma_g} & \text{AT } E_g \geq E_c \end{cases}$$

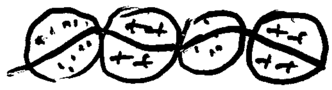
$$J_p(E) = \frac{c}{4\pi} \frac{\mathcal{L}_0}{\ln \frac{E_c}{E_{min}} + \frac{1}{\gamma_g - 2}} \int_0^{z_{max}} dt \, (1+z)^m q_{gen}(E_g, E) \frac{dE_g}{dE}$$

NO-EVOLUTION CASE: $m = 0$, $\gamma_g = 2.7$, $E_c = 1 \cdot 10^{18}$ eV

$\mathcal{L}_0 = L_p n_{AGN}$. AT $n_{AGN} \sim 10^{-76}\, cm^{-3}$, $L_p \simeq 4 \cdot 10^{41}$ erg/s

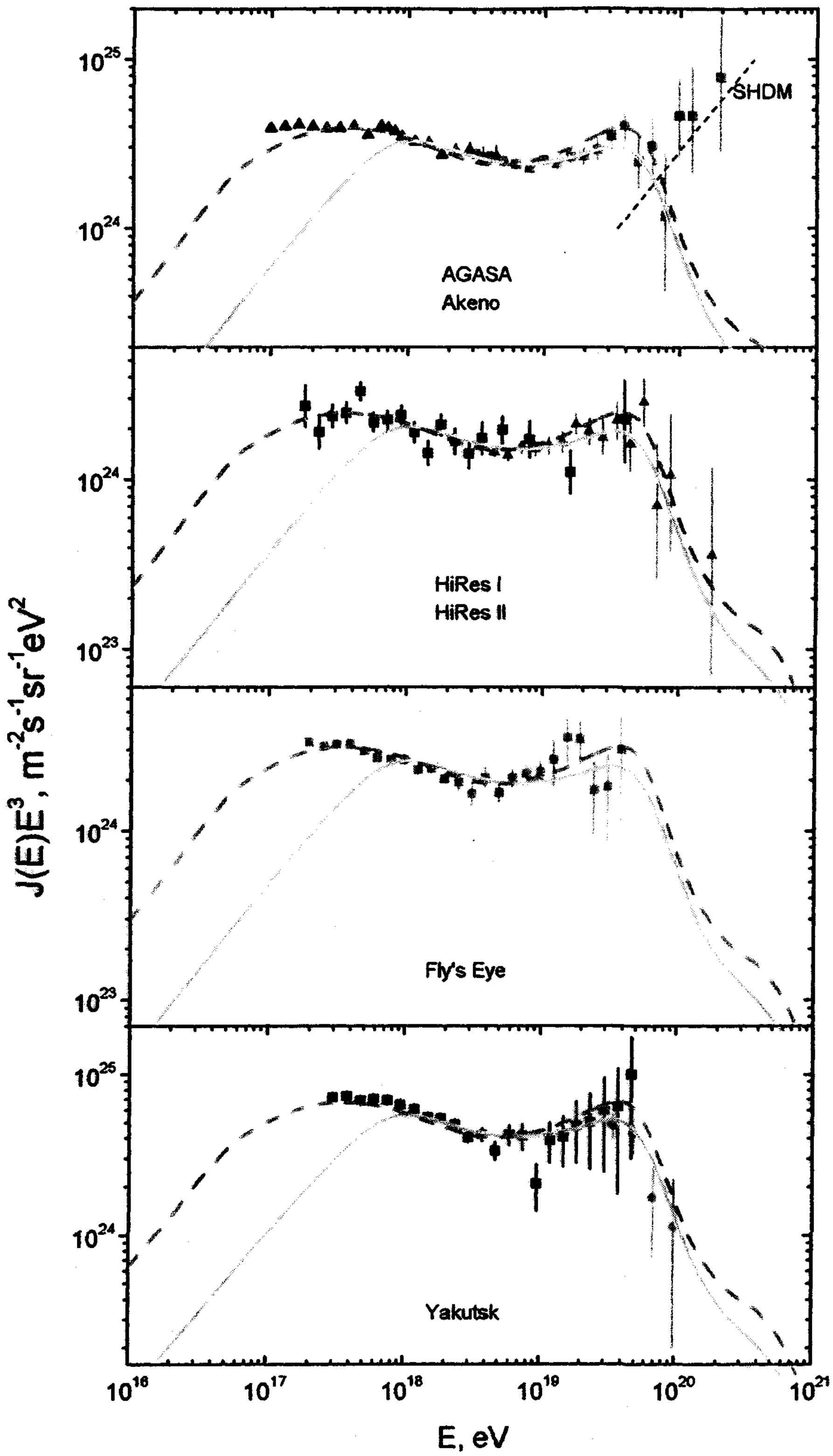
- EXTRAGALACTIC MAGNETIC FIELD

FOR MULTIPLE SCATTERING IN SPACE-REVERSAL FIELD



$$B \leq \frac{E\,\theta_{res}}{e\sqrt{l_{att}\, l_{hom}}} \sim \begin{cases} 6 \cdot 10^{-10}\, G & \text{AT } l_{hom} \sim 10\, kpc \\ 6 \cdot 10^{-11}\, G & \text{AT } l_{hom} \sim 1\, Mpc \end{cases}$$

- GZK CUTOFF IS PRESENT

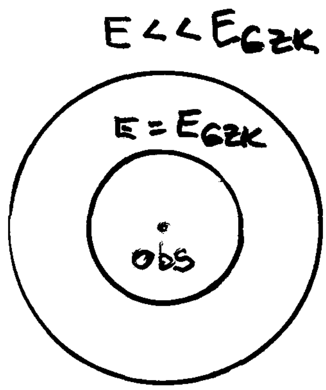


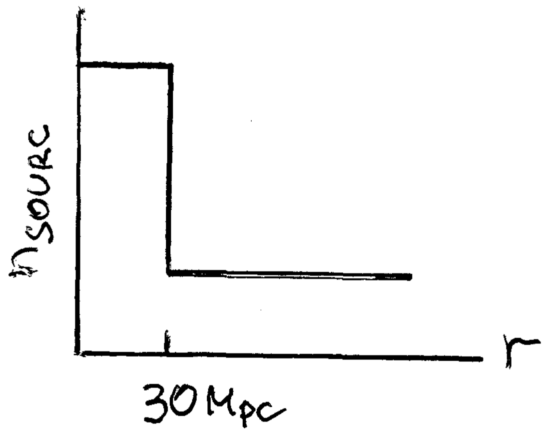
SHDM
AGASA
Akeno
HiRes I
HiRes II
Fly's Eye
Yakutsk
J(E)E^3, m^-2s^-1sr^-1eV^2
E, eV

ABSENCE OF GZK CUTOFF IN ASTROPHYSICAL MODELS

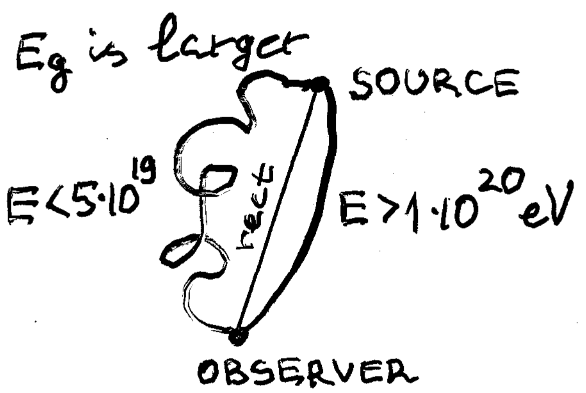
- LOCAL OVERDENSITY

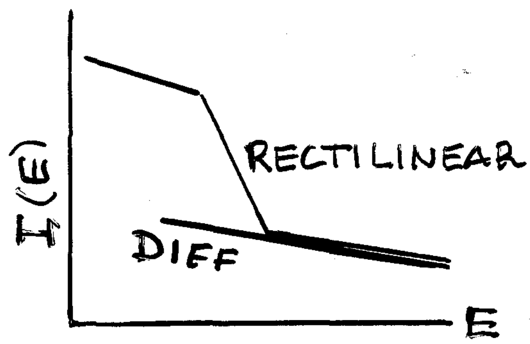
$F(E) \sim r_{max}(E)$





- STRONG EXTRAGALACTIC MAGN FIELD

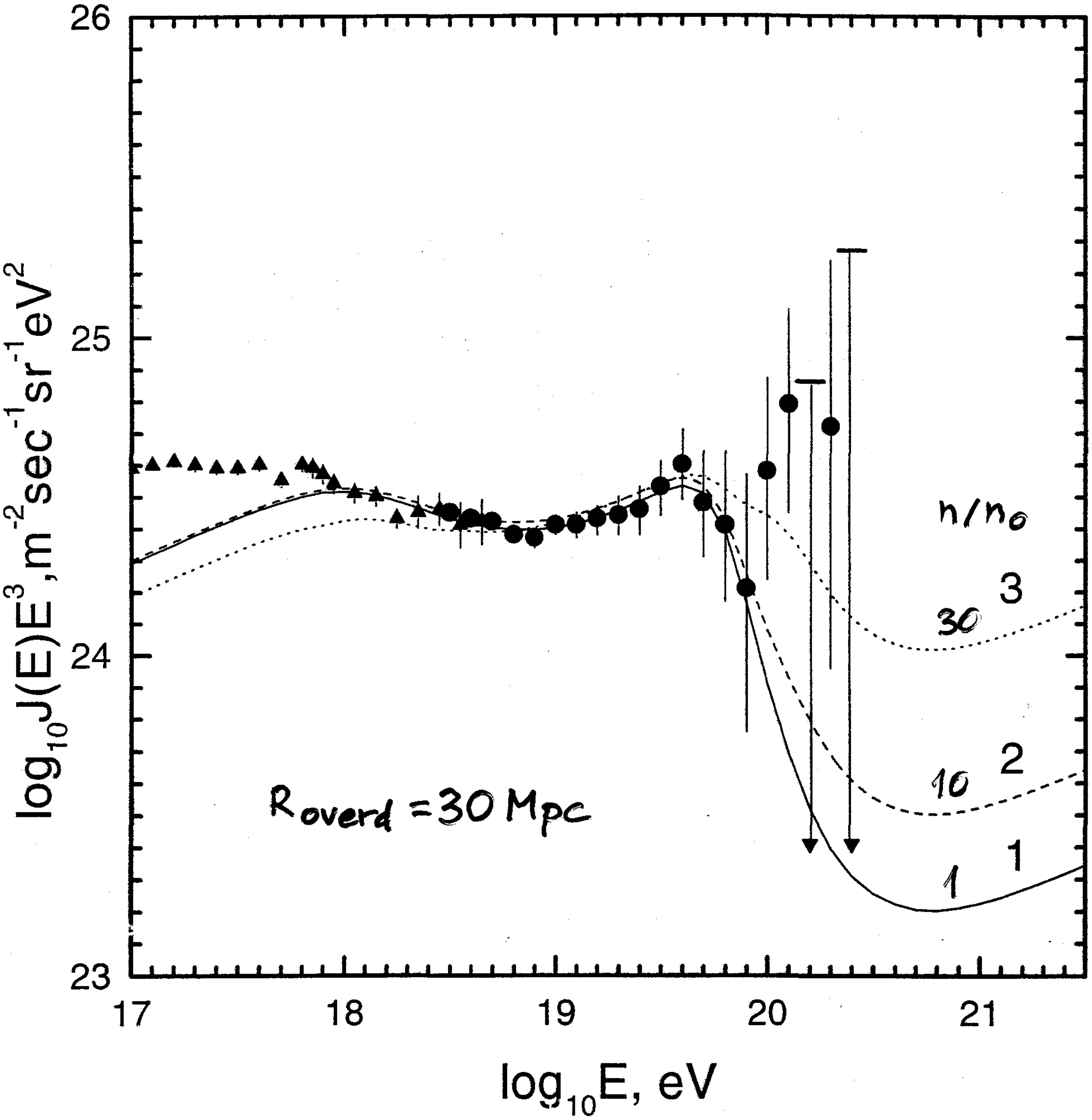




CORRELATION WITH BL Lacs MUST BE IGNORED

UHECR FROM SOURCES WITH LOCAL OVERDENSITY

hep-ph/0107306



PROBLEM WITH ASTROPHYSICAL SCENARIO AT $E > 1 \cdot 10^{20}$ eV

ATTENUATION LENGTH AT $E = 2 \cdot 10^{20}$ eV IS $l_{att} \sim 30$ Mpc

IN THE DIRECTION OF PARTICLES WITH MAX ENERGY $2-3 \cdot 10^{20}$ eV MUST BE SEEN THE SOURCE (AGASA, FE AND HiRes EVENTS)

- THIS PROBLEM IS UNAVOIDABLE IN CASE OF CORRELATION WITH BL Lacs
- THIS PROBLEM IS AMELIORATED FOR MODELS WITH STRONG MAGNETIC FIELD
  e.g. FOR $E = 2 \cdot 10^{20}$ eV:

$$l_{att} \approx 30 \text{ Mpc} \qquad r_H = 20 \text{ Mpc}\, E_{20} \frac{B}{10\,\text{nG}}$$

CONCLUSIONS

- RECENT HiRes DATA AGREE WITH PRESENCE OF GZK CUTOFF, WHILE AGASA DATA SHOW EXCESS OVER GZK PREDICTION (11 EVENTS WITH $E > 1 \cdot 10^{20}$ eV).

- THERE IS THE UHECR PROBLEM EVEN WITHOUT AGASA EVENTS: 3 HIGHEST ENERGY EVENTS (FE, HiRes, Yakutsk) AT $E > 1 \cdot 10^{20}$ eV (FE EVENT AT $E \approx 3 \cdot 10^{20}$ eV) DO NOT HAVE SOURCES IN THEIR DIRECTIONS.

- OBSERVED SPECTRA HAVE A SIGNATURE OF INTERACTION OF PROTONS WITH CMB IN THE FORM OF THE DIP AND $E_{1/2}$ (YAKUTSK DATA). HiRes DATA CONFIRM PROTON COMPOSITION AT $E > 1 \cdot 10^{18}$ eV.

- UHECR WITH AGN AS THE SOURCES EXPLAIN WELL AT $1 \cdot 10^{18} \leq E \leq 8 \cdot 10^{19}$ eV
  - SPECTRA
  - SMALL-SCALE ANGULAR CLUSTERING AND
  - CORRELATIONS WITH BL Lacs.

  THE SMALL EXTRAGALACTIC MAGNETIC FIELD IS REQUIRED IN THIS MODEL

- EVENTS WITH $E > 1 \cdot 10^{20}$ eV REMAIN THE PROBLEM