SuperGZK NEUTRINOS: TESTING PHYSICS BEYOND SM

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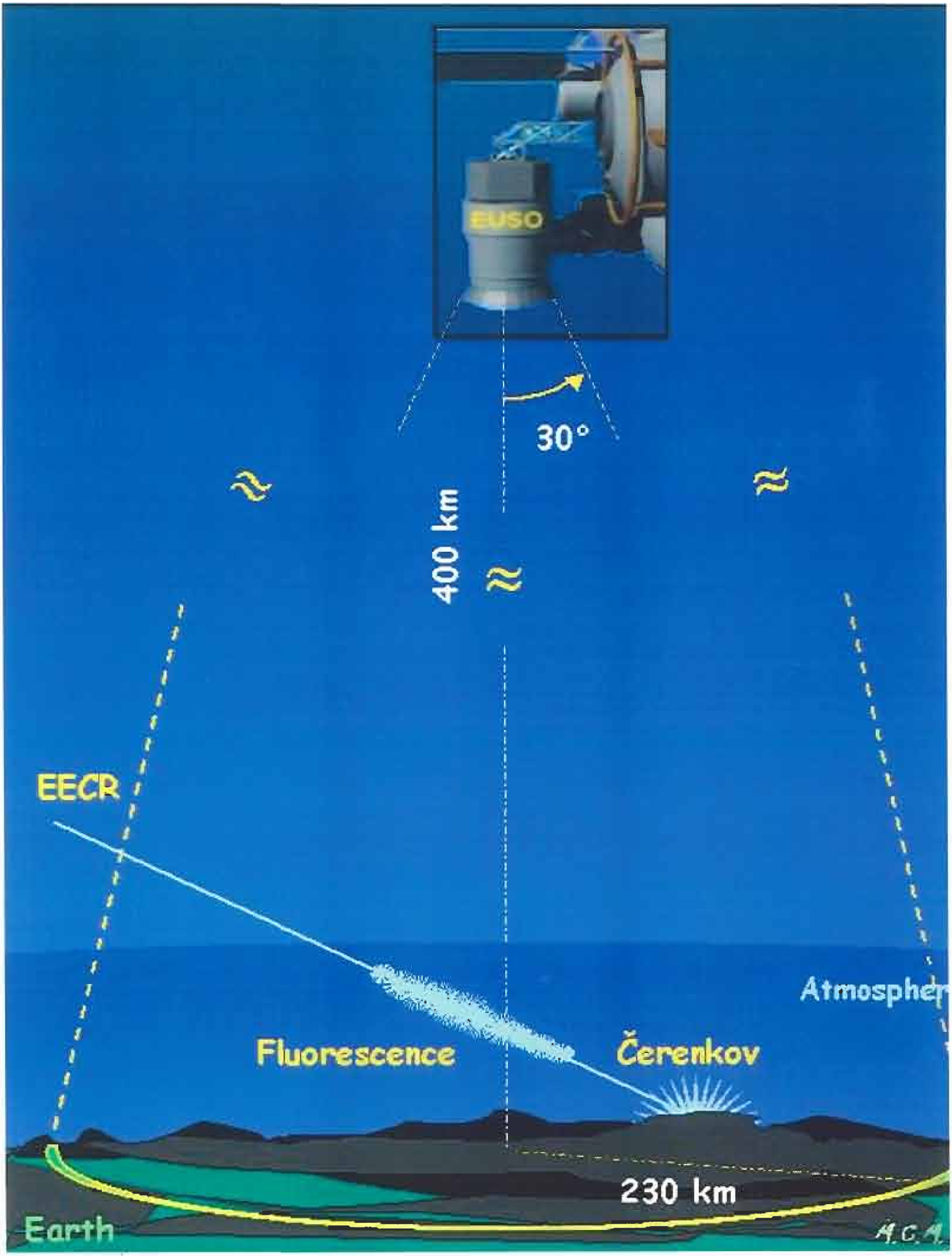


EUSO
30°
400 km
EECR
Atmospher
Fluorescence
Čerenkov
230 km
Earth
A.C.A.

GENERATION of NEUTRINOS with $E_\nu > 10^{20}$ eV

- ACCELERATION TO $E \gg 10^{20}$ eV

  Γ^2-MECHANISM

  PROBLEM: capturing behind the shock

  (Gallant, Achterberg: $E_{\rm max} \leq 10^{20}$ eV)

  UNCONVENTIONAL MECHANISMS: acceleration by strong e-m waves, plasma mechanisms (Tsytovich; Sagdeev; Takahashi)

- DECAY OF SUPERHEAVY PARTICLES (DM and TD)

$$E_\nu \leq 0.1 m_X$$

- ANNIHILATION OF MONOPOLES

  in monopoles connected by strings, e.g. necklaces

  VB, Vilenkin 1997

$$M + \bar{M} \to A_\mu, H \to \text{pions} \to \text{neutrinos}$$

  Neutrino energy $E_\nu \leq 0.1 m_M$

- RADIATION BY MONOPOLES

  Monopoles connected by strings,

  VB, Martin, Vilenkin 1997

  Emission of gauge bosons by accelerated monopoles.

  The neutrino energy $E \sim \Gamma a$, can reach $M_{\rm Pl}$

COSMOGENIC NEUTRINOS

$$p + \gamma_{\mathrm{CMB}} \rightarrow \pi + all$$

Neutrino fluxes are connected with the observed UHECR flux

SuperGZK neutrino flux can be higher than proton flux.

COSMIC RAYS AT ULTRA HIGH ENERGIES (NEUTRINO?)

V. S. BERESINSKY and G. T. ZATSEPIN
Academy of Sciences of the USSR. Physical Institute. Moscow

Received 8 November 1968

The neutrino spectrum produced by protons on microwave photons is calculated. A spectrum of extensive air shower primaries can have no cut-off at an energy $E > 3 \times 10^{19}$ eV, if the neutrino-nucleon total cross-section rises up to the geometrical one of a nucleon.

Greisen [1] and then Zatsepin and Kusmin [2] have predicted a rapid cut-off in the energy spectrum of cosmic ray protons near $E \sim 3 \times 10^{19}$ eV because of pion production on 2.7° black body radiation. Detailed calculations of the spectrum were made by Hillas [3]. Recently there were observed [4] three extremely energetic extensive air showers with an energy of primary particles exceeding 5×10^{19} eV. The flux of these particles turned out ot be 10 times greater than according to Hillas' calculations.

In the light of this it seems to be of some interest to consider the possibilities of absence of rapid (or any) fall in the energy spectrum of showerproducing particles. A hypothetic possibility we shall discuss* consists of neutrinos being the showerproducing particles at $E > 3 \times 10^{19}$ eV due to which the energy spectrum of shower producing particles cannot only have any fall but even some flattening.

The neutrinos under consideration are originated in decays of pions, which are generated in collisions of cosmic ray protons with microwave photons. When calculating the neutrino spectrum the same assumptions were made as by Hillas [3]:

(1) The protons of high and extremely high energies are of extragalactic origin with an output of generation varying with time as t^{-s} after a certain starting time t_0**,

(2) The integral energy spectrum of generated protons is of the form $E^{-\gamma}$ up to an energy not less than 10^{22} eV.

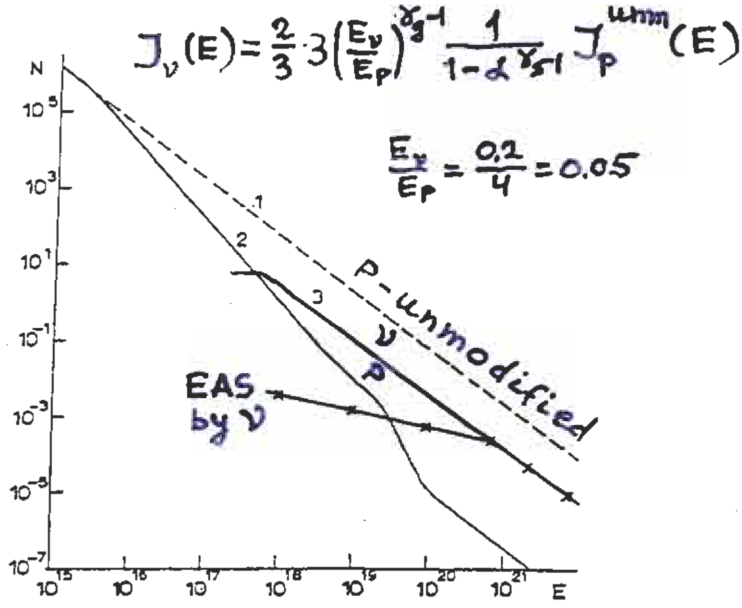


Fig. 1.

The calculated neutrino spectrum is represented by curve 3. It has the same spectrum exponent as the spectrum of generated protons. The calculations were made assuming that the pion originating in nucleon-microwave photon collision takes in average near 20% proton energy and the value $\gamma = 1.5$ was used. The calculated ratio of the neutrino intensity to that of the unmodified spectrum of protons (curve 1) at the same energy is $\sim 6 \times 10^{-2}$. We call "unmodified" a proton spectrum at present in the case when a red shift is the only kind of energy losses. The mentioned ratio does not depend on evolution of proton sources and the cosmological model. The proton spectrum at present is shown by curve 2. The curves 1 and 2 were obtained by Hillas using

* Cocconi was the first, who supposed that ultra high energy extensive air showers can be caused by neutrinos [5].

** The Hillas' assumptions about evolution of proton sources are based on Longairs [6] assumptions for evolution of radiogalactics, the latter chosen to fit experimental data.

RECENT CALCULATIONS

Engel, Seckel, Stanev   Phys. Rev. D 64 (2001) 093010

Kalashev et al,   Phys, Rev, D 66 (2002) 063004

Fodor, Katz, Ringwald, Tu   hep-ph/0309171

COSMOGENIC NEUTRINOS FROM THE OBSERVED UHECR FLUX

V. Berezinsky, A. Gazizov, S. Grigorieva 2003

Kinetic equation for UHE proton density $n_p(E,t)$

$$\frac{\partial n_p(E,t)}{\partial t} = -2H(t)n_p(E,t) + H(t)E\frac{\partial n_p(E,t)}{\partial E}$$
$$- \frac{\partial}{\partial E}\left[b_{pair}(E,t)n_p(E,t)\right]$$
$$- P(E,t)n_p(E,t) + \int_E^{E_{max}} dE' \frac{dP(E',E,t)}{dE'} n_p(E',t)$$
$$+ Q_p(E,t) \quad (1)$$

Source production:

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

$$q_{\rm gen}(E_g) = \begin{cases} 1/E_g^2 & \text{at } E_g \le E_c \\ E_c^{-2}(E_g/E_c)^{-\gamma_g} & \text{at } E_g \ge E_c \end{cases}$$

where $\mathcal{L}_p(z) = (1+z)^m \mathcal{L}_0$ is UHECR emissivity.

$$\mathcal{L} = n_s L_p$$

Parameters γ_g, $\mathcal{L}_0$, E_c are fixed by observations.

no-evolution case ($m = 0$):

$\gamma_g = 2.7, E_c = 1 \times 10^{18}, \mathcal{L}_0 = 3.5 \times 10^{46}$ erg/Mpc^3 yr

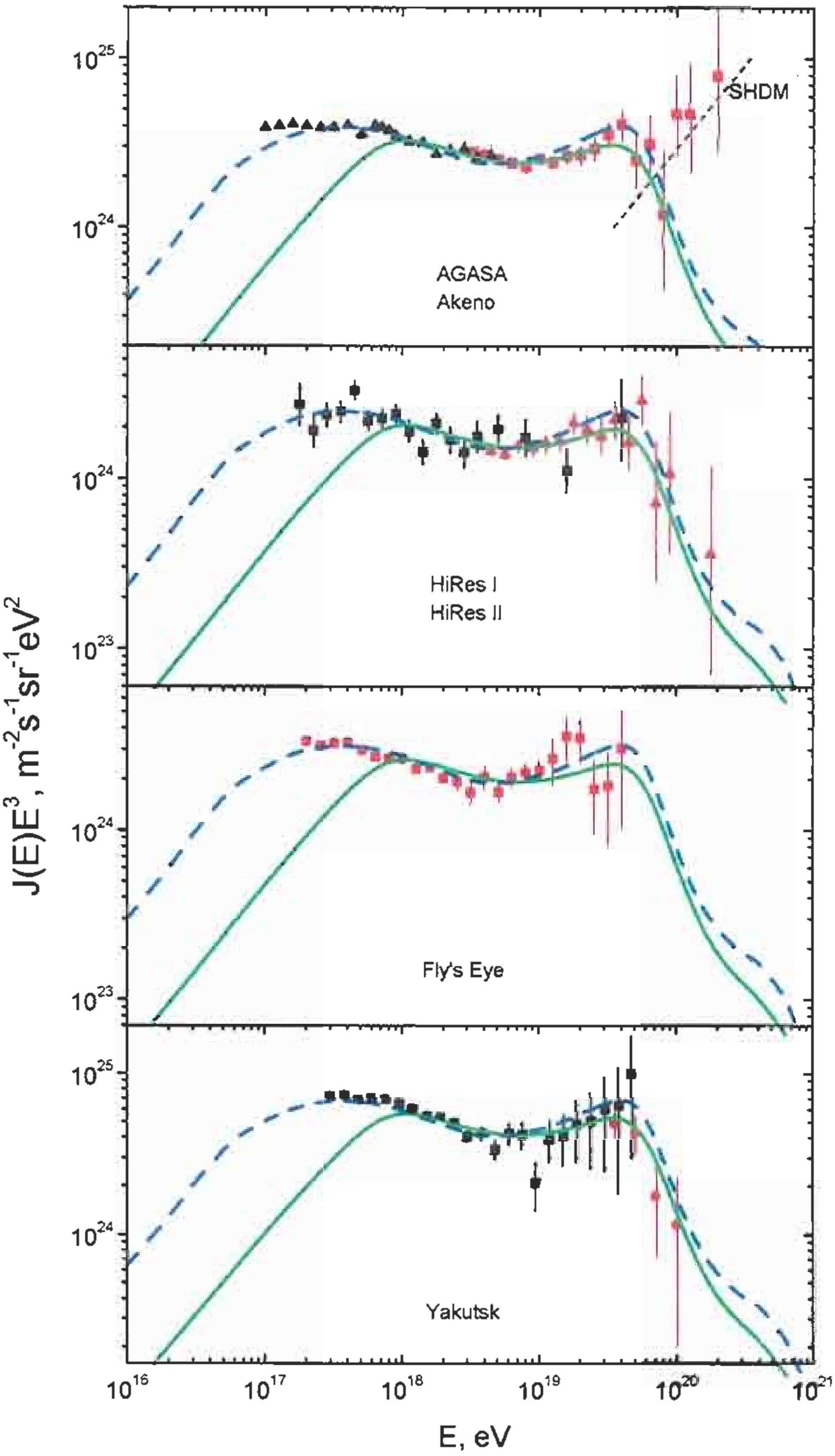
evolutionary case $m = 4$:

$\gamma_g = 2.45, \quad \mathcal{L}_0 = 2.5 \times 10^{46}$ erg/Mpc^{3}yr

Parameters not fixed by UHECR observations,

$E_{\rm max}$ and $z_{\rm max}$ (in non-evolutionary case)

affect neutrino spectrum



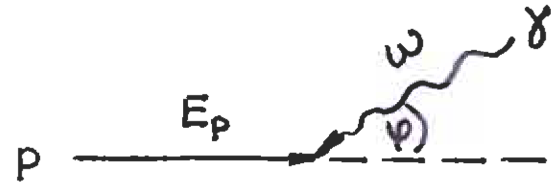
10^{25}
10^{24}
SHDM
AGASA
Akeno
10^{24}
10^{23}
HiRes I
HiRes II
10^{24}
10^{23}
Fly's Eye
10^{25}
10^{24}
Yakutsk
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
E, eV
$J(E)E^3$, $m^{-2}s^{-1}sr^{-1}eV^2$

CALCULATIONS OF NEUTRINO FLUX

based on VB and Gazizov Phys. Rev. D47, 1217, 1993

$$p + \gamma \rightarrow a + X$$

$$a = \pi^{\pm},\ K^{\pm},\ \rho,\ \Delta^{+},\ \Delta^{++}$$



From experimental data combined with calculations:

$$\frac{d\sigma_a}{dx_a}(E_c, x_a), \quad (x_a = E_a/E_p)$$

$$a \rightarrow \nu + X$$

$$\frac{d\sigma_\nu}{dx_\nu}(E_c, x_\nu) = \sum_a \int_{x_{\min}}^{x_{\max}} \frac{dx_a}{x_a}\frac{d\sigma_a}{dx_a}(E_c, x_a) B_a(x_\nu/x_a)$$

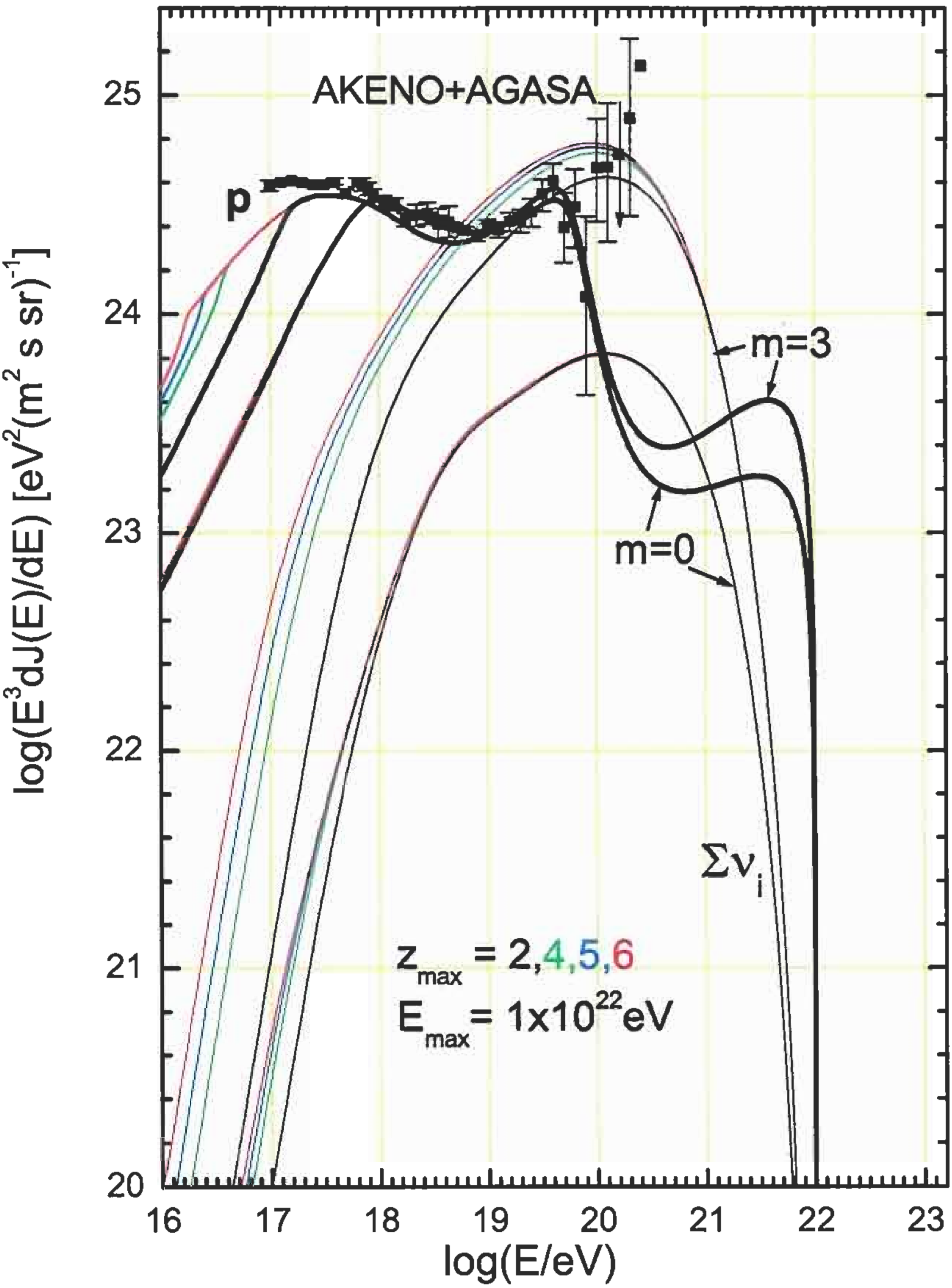
$\frac{d\sigma_\nu}{dx_\nu}(E_c, x_\nu)$ are given in PR D47, 1217, 1993.

Neutrino generation rate:

$$Q_\nu(E_{\nu,t}) = 2\pi c \int dE_p n_p(E_p, t) \int d\omega \int d\cos\phi$$

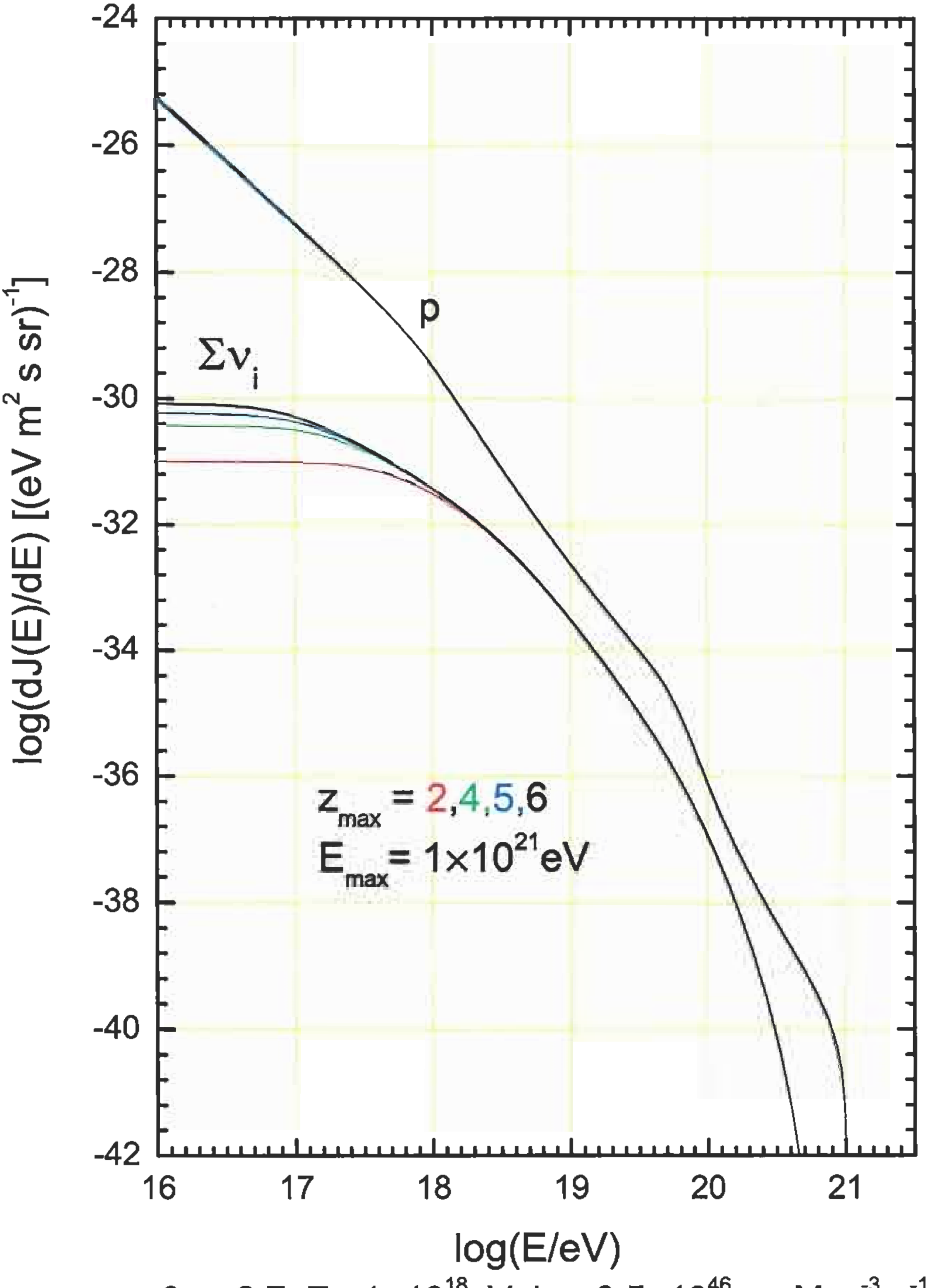
$$n_\gamma(\omega, \phi)(1 + \cos\phi)\frac{d\sigma_\nu}{dE_\nu}(E_\nu, E_p, \omega, \phi)$$

(2)

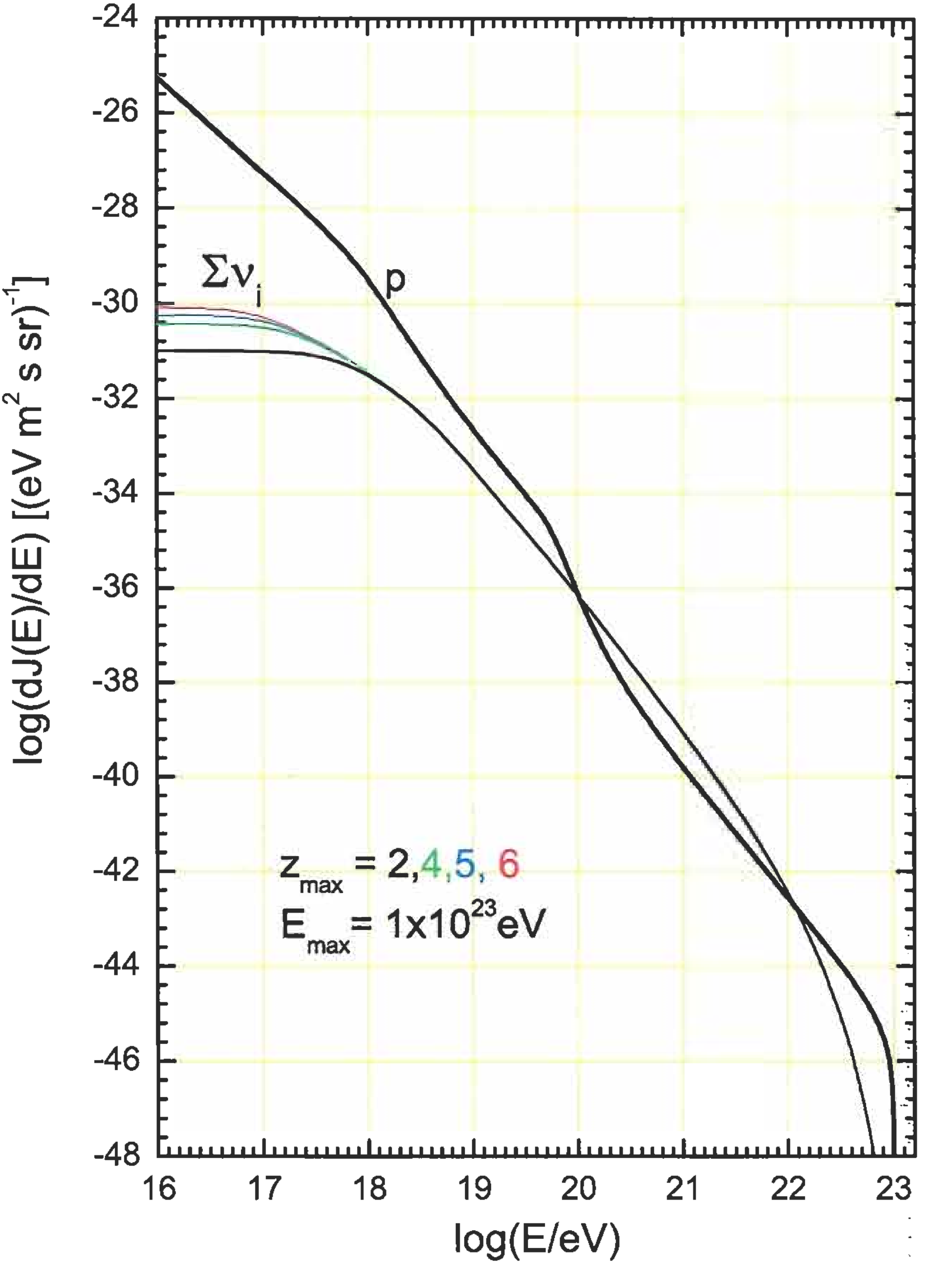


m=0: γ=2.7; E_c=1x10^{18}eV; L_0= 3.5x10^{46}erg $Mpc^{-3}yr^{-1}$

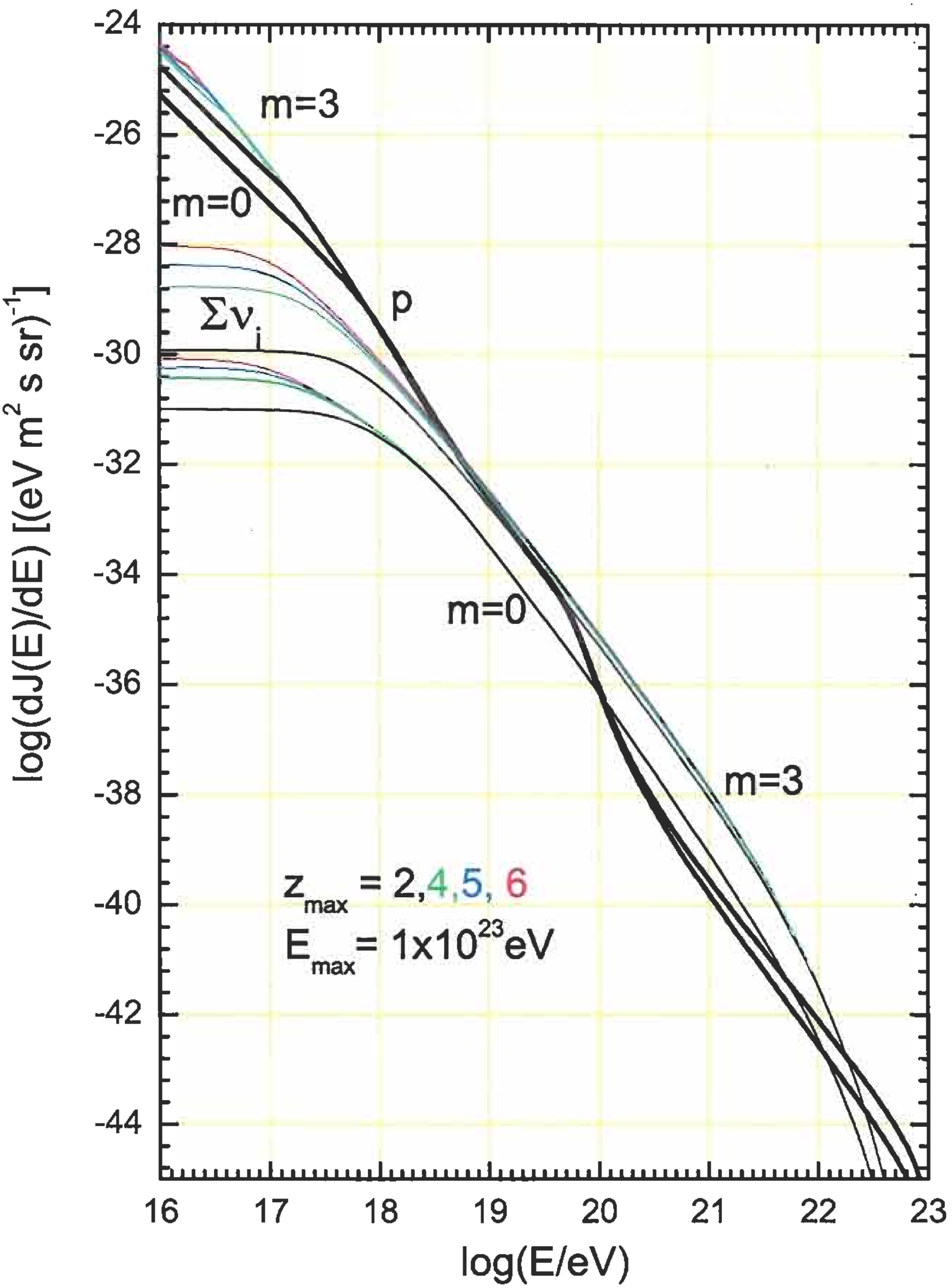
m=3: γ=2.5; E_c=3x10^{17}eV; L_0= 2.5x10^{46}erg $Mpc^{-3}yr^{-1}$



m=0; γ=2.7; $E_c=1\times10^{18}$eV; $L_0= 3.5\times10^{46}$erg $Mpc^{-3}yr^{-1}$



m=0: γ=2.7; E_c=1x10^{18}eV; L_0= 3.5x10^{46}erg Mpc^{-3}yr^{-1}



m=0: γ=2.7; E_c=1x10^{18}eV; L_0= 3.5x10^{46}erg Mpc^{-3}yr^{-1}

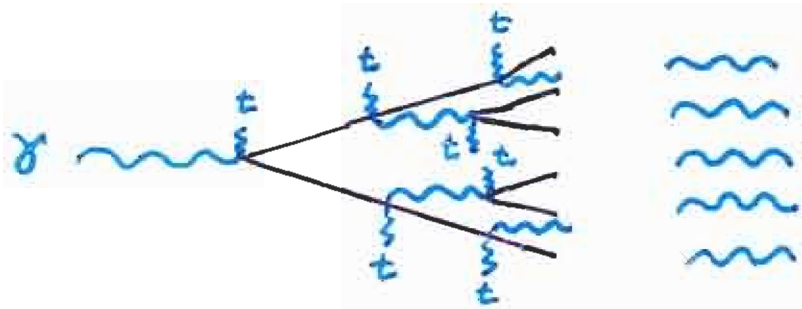
m=3: γ=2.5; E_c=3x10^{17}eV; L_0= 2.5x10^{46}erg Mpc^{-3}yr^{-1}

CASCADE UPPER LIMIT (VB 1977)

e-m cascade on target photons

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

$$e + \gamma_{tar} \rightarrow e' + \gamma'$$



diffuse
extragalactic gamma
0.01 – 100 GeV

$$E^2 I_\nu(E) \leq \frac{c}{4\pi} \omega_{cas}$$

$$\omega_{cas} \leq 2 \times 10^{-6} \frac{eV}{cm^3}$$ (EGRET)

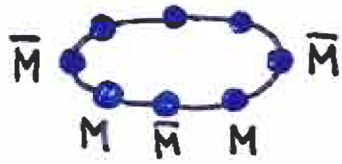
$$I_\nu(>E) \leq 10 \times E_{20}^{-1} Km^{-2} yr^{-1} sr^{-1}$$

TOPOLOGICAL DEFECTS

- SYMMETRY BREAKING IN EARLY UNIVERSE RESULTS IN PHASE TRANSITIONS (D.A. KIRZHNITZ 1972). THEY ARE ACCOMPANIED BY TOPOLOGICAL DEFECTS.
- DEPENDING ON SYMMETRY BREAKING, DEFECTS CAN BE IN FORM OF SURFACES (DOMAIN WALLS), LINES (STRINGS), AND POINTS (MONOPOLES).

TD OF INTEREST FOR UHECR

- MONOPOLES: $G \to H \times U(1)$
- ORDINARY STRINGS: $U(1)$ BREAKING
- MONOPOLES CONNECTED BY STRINGS: $G \to H \times U(1) \to H \times Z_n$
  e.g. NECKLACES $Z_n = Z_2$
- SUPERCONDUCTING STRINGS



PRODUCTION OF UHECR

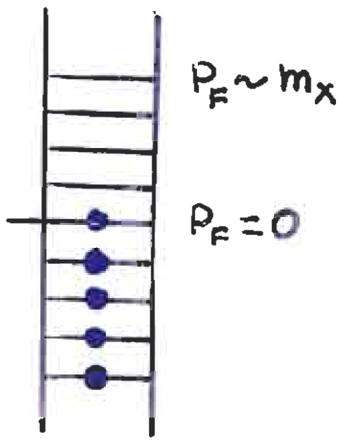
- ANNIHILATION OF MONOPOLES

$M + \bar{M} \to$ PARTON CASCADE $\to$ PIONS $\to$ PHOTONS + NEUTRINOS

- SUPERCONDUCTING STRINGS

$$\frac{dp}{dt} = e\mathcal{E} \; \begin{cases} p = e\mathcal{E}t & p \sim m_X \\ J = e^2\mathcal{E}t & J \sim e m_X \end{cases}$$

$X \to$ PARTON CASCADE $\to$ PIONS $\to \gamma + \nu$



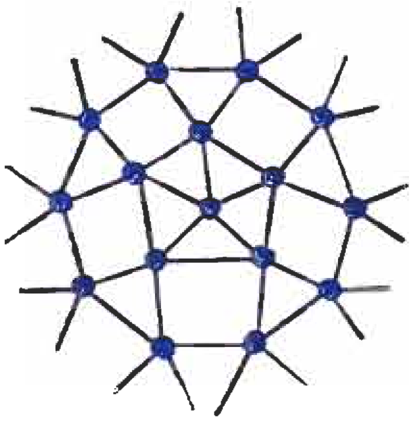
MONOPOLES CONNECTED BY STRINGS

V.B., X.Martin, A.Vilenkin, PR D56, 2024, 1997

$$G \underset{\eta_m}{\rightarrow} H \times U(1) \underset{\eta_s}{\rightarrow} H \times Z_N$$

mass of monopole: $m = 4\pi\eta_m/e$, tension: $\mu = 2\pi\eta_s^2$

MS NETWORK



Due to cosmological evolution momopoles become relativistic at $t \sim t_0$: $v_0 \sim c$, $\Gamma_0 \gg 1$.

Monopoles oscillate due to $f = \mu$ and obtain a proper acceleration $a \sim \mu$.

Harmonic oscillation: $x = x_0 \sin \Omega t$.

$$a_{\rm max} = \frac{2}{3\sqrt{3}}\Gamma_0^2\Omega$$

RADIATION OF MASSIVE GAUGE BOSONS

In case $a \gg M$ (M is the boson mass)

$$P = \frac{g^2}{16\sqrt{6}\pi^2}\Gamma_0^3\Omega^2,$$

$$E_{\max} = \Gamma_0 a_{\max} = \frac{\pi^2}{3}\Gamma_0^3\Omega$$

In case $a \ll M$

$$P = \sqrt{\frac{2\pi}{3}}\frac{g^2}{2\pi^2}\frac{\Gamma_0^2\Omega^2}{v_0^4}\sqrt{\frac{Mv_0}{a_{\max}}}\exp\left(-\frac{2}{3}\frac{Mv_0}{a_{\max}}\right)$$

$$E_{\max} \sim \Gamma_0 M$$

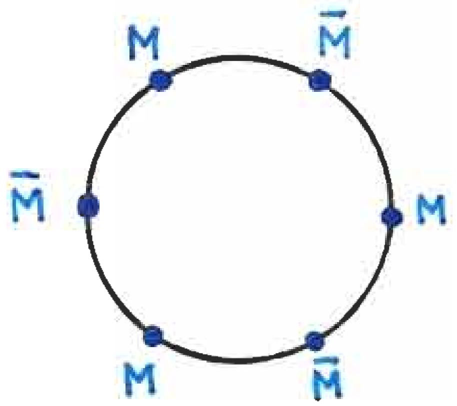
$E_{\max}$ REACHES THE PLANCKIAN SCALE

NECKLACES

V.B., A.Vilenkin, PRL 79, 5202, 1997

$$G \underset{\eta_m}{\rightarrow} H \times U(1) \rightarrow H \underset{\eta_s}{\times} Z_2$$

mass of monopole: $m = 4\pi\eta_m/e$, tension: $\mu = 2\pi\eta_s^2$



$$r = \frac{m}{\mu d}, \text{ production rate : } \dot{n}_X \sim \frac{r^2\mu}{t^3 m_X}$$

$$\text{produced energy density : } \omega \sim m_X \dot{n}_X t \sim r^2 \frac{\mu}{t^2}$$

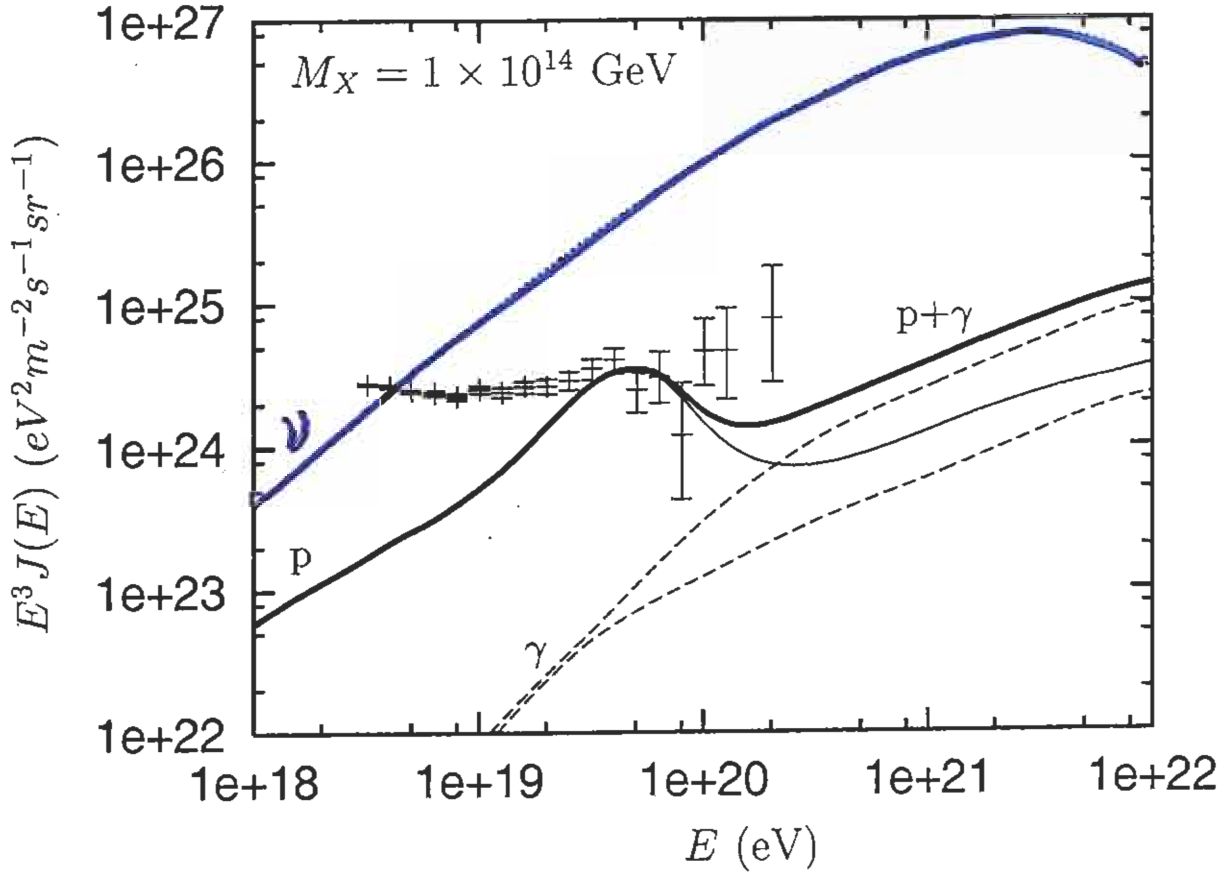
$$\omega_{\text{cas}} = \frac{3}{4} r^2 f_\pi \frac{\mu}{t_0} t_0 \leq 2 \cdot 10^{-6} \text{ eV/cm}^3 \quad \text{(EGRET)}$$

$$r^2\mu \leq 8.5 \times 10^{27} \text{ GeV}^2$$

Maximum neutrino energy:

$$E_\nu^{\text{max}} \sim 0.1 m_X \sim 10^{13} (m_X/10^{14}) \text{GeV}$$

SUPER GZK NEUTRINOS FROM NECKLACES



SUPERHEAVY DARK MATTER (SHDM)

1. PRODUCTION:

- In time varying gravitational field after inflation.
- No coupling with inflaton, X can be sterile.
- Creation occurs when $H(t) \sim m_X$
- Since $H(t) \leq m_{\rm infl} \sim 10^{13}$ GeV, $m_X \leq 10^{13}$ GeV
- $m_X \sim 10^{13}$ GeV results in $\Omega_X h^2 \sim 0.1$.

2. LONGEVITY PROBLEM $\tau_X > 10^{10}$ yr:

can be solved for particles protected by **discrete symmetry**, e.g. R-parity for neutralino.

3. DECAY:

- due to warmhole effects
- due to instanton effects
- due to higher Z_N operators

$$\tau_X \sim 10^{11} - 10^{12} \text{ yr}$$

4. EXPLICIT MODELS:

cryptons – confined states of fractionally cherged particles in superstring theory.

$$\tau_X \sim \frac{1}{m_X}\left(\frac{M_*}{m_X}\right)^{10}$$

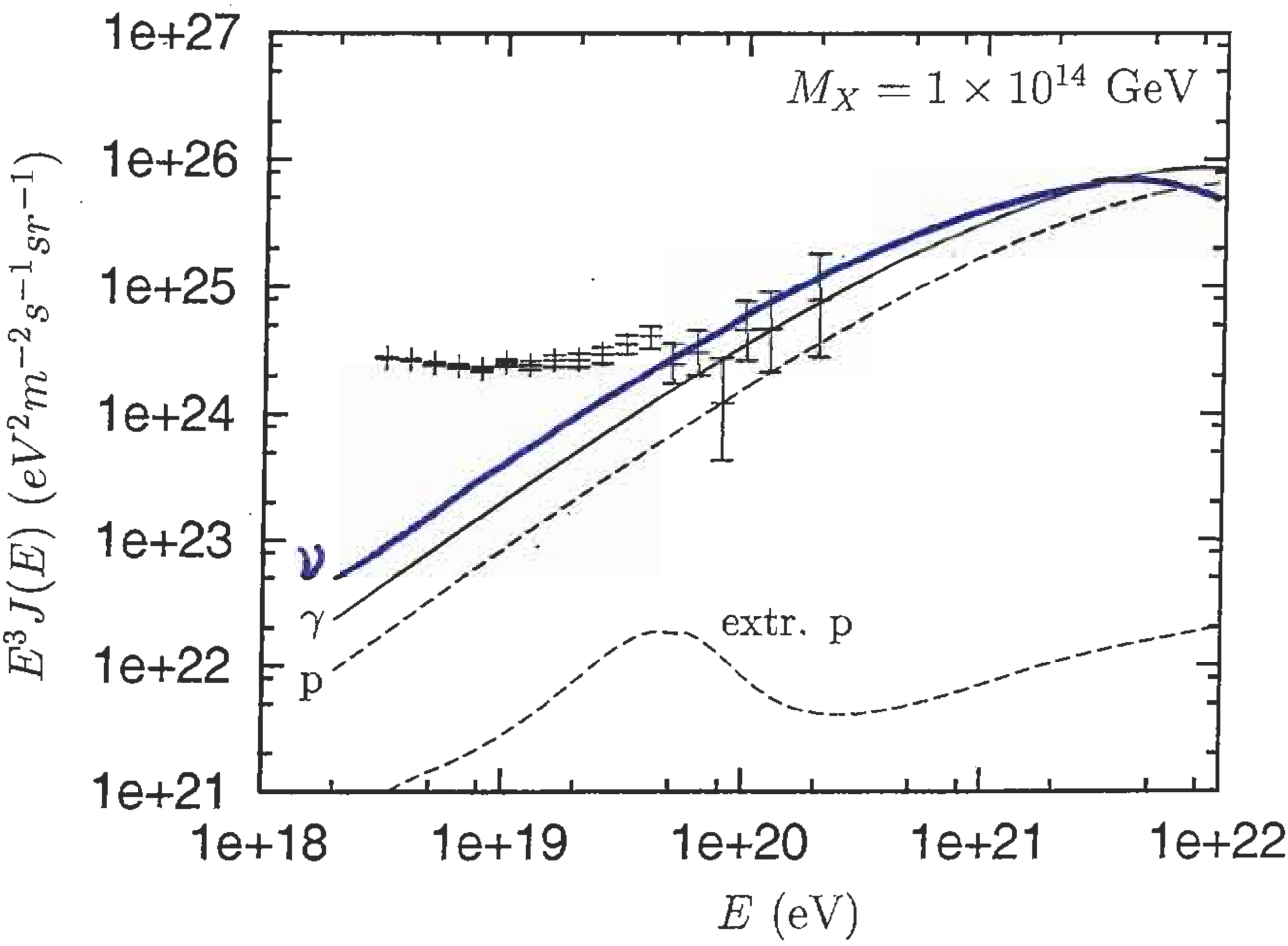
SUSY QCD SU(N_c) with $N_c \sim 6 - 10$.

4. ACCUMULATION IN THE HALO:

$$\delta = \frac{\rho_X^{\mathrm{halo}}}{\rho_X^{\mathrm{extr}}} = \frac{\rho_{\mathrm{DM}}^{\mathrm{halo}}}{\Omega_{\mathrm{CDM}}\rho_{\mathrm{cr}}} = 2.1 \times 10^5$$

Due to large overdensity – no GZK cutoff,

SUPERGZK NEUTRINOS FROM SHDM



MIRROR MATTER AS A HIDDEN NEUTRINO SOURCE

THEORETICAL CONCEPT OF MIRROR MATTER

Lee and Yang 1956, Landau 1957, Salam 1957, Kobzarev, Pomeranchuk and Okun 1966

assumption:

PARTICLE (HILBERT) SPACE IS A REPRESENTATION OF EXTENDED LORENTZ GROUP.

Extended Lorentz group includes reflection: $\vec{\mathbf{x}} \rightarrow -\vec{\mathbf{x}}$.
In particle space it corresponds to inversion operation I_r.
In empty space reflection $\vec{x} \rightarrow -\vec{x}$ and time shift $t \rightarrow t + \Delta t$ commute.
In the particle space the corresponding operators must commute, too:

$$[\mathcal{H}, I_r] = 0.$$

i.e. eigenvalues of operator I_r must be conserved.
$I_r = P$ (parity operator) is not conserved.
definition:

$$P\psi(x_\mu) = \gamma_0\psi(x_0, -\vec{x});$$
$$P\phi(x_\mu) = \pm\phi(x_0, -\vec{x}).$$

- Lee and Yang: $I_r = P \cdot R$, where R transfers particle to the new state (mirror particle).
- Landau: $I_r = CP$ where C transfers particle to antiparticle. This hypothesis has been dismissed by discovery of CP violation.

MIRROR PARTICLE SPACE is generated by R-transformation with the same particle content and interactiions (symmetries). Since $L \to R'$ and $R \to L'$, *e.g.* $I_r \psi_L(t, \vec{x}) \to \psi'_R(t, -\vec{x})$,
$SU_2(L) \times U(1) \to SU'_2(R) \times U'(1)$
with a new photon (γ') and new gauge bosons.

Kobzarev, Pomeranchuk, Okun suggested that ordinary and mirror sectors communicate only gravitationally. The mirror matter in the universe may exist as the mirror stars and mirror galaxies.

COMMUNICATION TERMS can be written as

$$\mathcal{L}_{\text{comm}} = \frac{1}{M_{\text{Pl}}} (\bar{\psi}_L \phi)(\psi'_R \phi') \tag{3}$$

where $\bar{\psi}_L = (\bar{l}_L, \ \bar{\nu}_L)$ and $\phi = (\phi_0^*, \ -\phi_+^*)$.

After SSB, Eq.(3) results in mixing of ordinary and mirror (sterile) neutrinos.

$$\frac{v_{\text{EW}}^2}{M_{\text{Pl}}} \bar{\nu}_L \nu'_R, \tag{4}$$

with $\mu \equiv v_{\text{EW}}^2 / M_{\text{Pl}} = 2.5 \cdot 10^{-6}$ eV.

Eq.(4) implies oscillations between ν and ν'.

For other particles μ is too small in comparison with their masses.

UHE NEUTRINOS FROM MIRROR TDs

Calculation of mirror neutrino flux from mirror TDs is identical to that from ordinary TDs.

From all particles produced by mirror X-decays only neutrinos (due to $\nu_{\rm mirr} \to \nu_{\rm ord}$) are visible.

$$L_{\rm osc} \sim \frac{E}{\Delta m^2} \sim \frac{E}{4M_i\mu} \sim 10 \;\; \frac{E}{10^{20}\text{ eV}} \;\; \frac{7{\cdot}10^{-3}\text{ eV}}{M_\nu}\text{ kpc}$$

Probability of oscillation: $P_{\nu' \to \nu} = 1/2$

UPPER LIMIT ON MIRROR NEUTRINO FLUX

$$\nu + \bar{\nu}_{\rm DM} \to Z^0 \to hadrons \to \textbf{e-m cascade}$$

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

$$\dot{n}_Z = 4\pi \;\; \sigma_{tot} \;\; n_{\nu_i} \;\; I_\nu(E_0)\; E_0$$

$$\omega_{\rm cas} = 0.5 E_0\, \dot{n}_Z\, t_0\, f_h/f_{tot}, \quad f_h/f_{\rm tot} = 0.7.$$

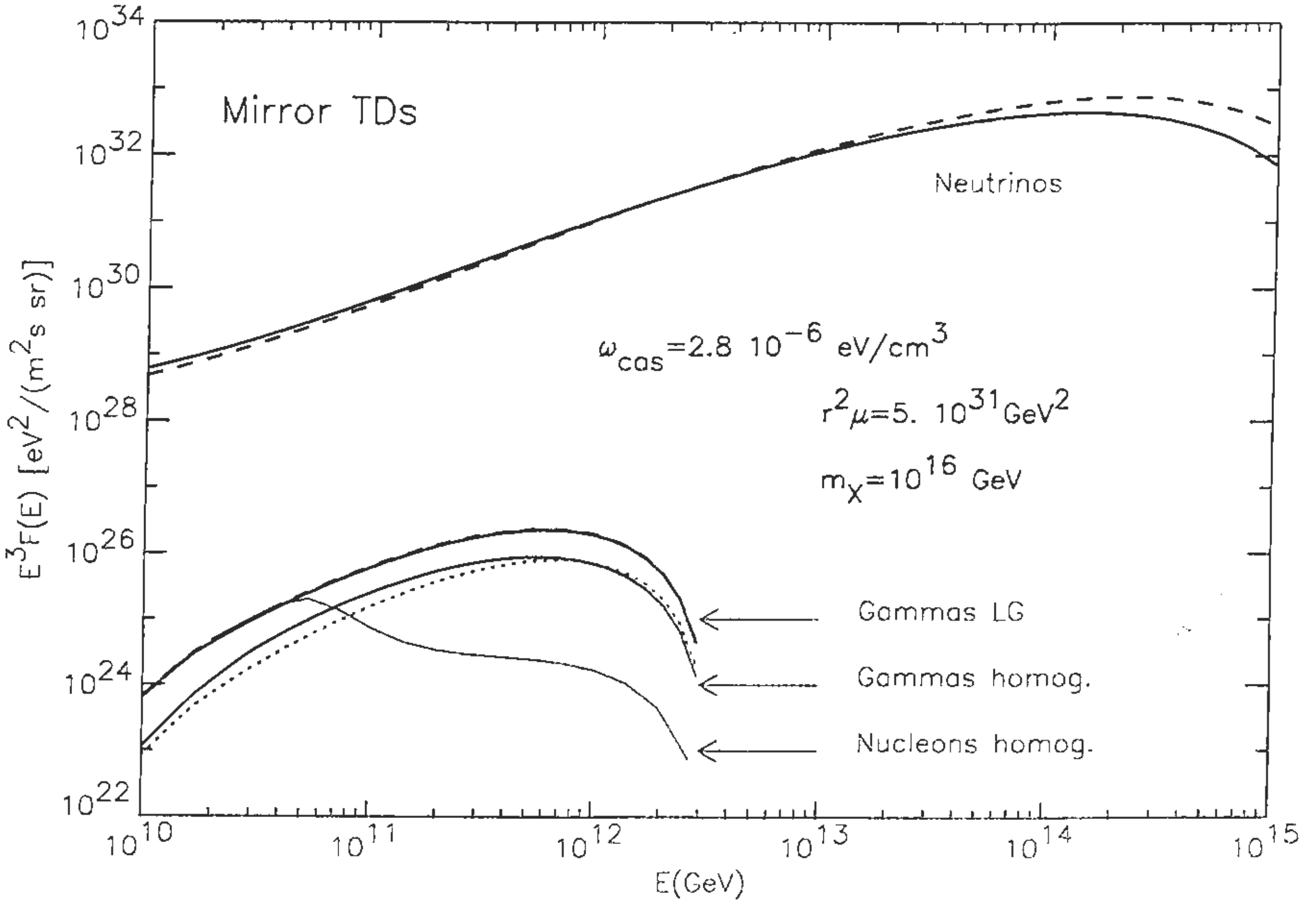
$$I_\nu(E_0) \le \frac{f_{\rm tot}}{f_h} \;\; \frac{\omega_{\rm cas}}{\sigma_{\rm tot}\, n_{\nu_i}\, t_0} \; \frac{{m_\nu}^2}{m_Z^4}.$$

The strongest limit is imposed by lightest neutrino, if corresponding $E_\nu = m_Z^2/2m_\nu$ is available.

Ratio of upper limits:

$$\frac{I_\nu^{mirr}(E_0)}{I_\nu^{cas}(E_0)} = 8\, \frac{f_{\rm tot}}{f_h} \; \frac{1}{\sigma_{tot}\, n_{\nu_i}\, t_0} = 1.3 \cdot 10^3.$$

SUPERGZK NEUTRINOS FROM MIRROR TD



CONCLUSIONS

- SuperGZK NEUTRINOS ($E_\nu > 1.10^{20}$ eV) are ONLY MARGINALLY PRODUCED BY ACCELERATOR SOURCES WITH $E_p^{max} > 2 \times 10^{21}$ eV.
IN CASE $E_p^{\rm max} = 1 \times 10^{22}$ NEUTRINO FLUX CAN BE DETECTABLE.
FLUX OF COSMOGENIC NEUTRINOS, WHICH ACCOMPANIES OBSERVED UHECR FLUX CAN BE CONSIDERED AS LOWER LIMIT.

- DETECTABLE FLUXES OF SuperGZK NEUTRINOS CAN BE PRODUCED BY SOURCES WITH PHYSICS BEYOND SM: TDs, SUPERHEAVY DM and MIRROR MATTER.

- CASCADE UPPER LIMIT:

$$I_\nu(E) \leq \frac{c}{4\pi}\frac{\omega_{\rm cas}}{E^2};$$

or $I_\nu(>E) \leq 10\ {\rm km}^{-2}{\rm yr}^{-1}{\rm sr}^{-1}E_{20}^{-1}$

- MIRROR NEUTRINOS OBEY WEAKER LIMIT:

$$I_\nu(E_0) \leq \frac{c}{2\pi}\frac{\omega_{\rm cas}}{E_0^2}\frac{1}{\sigma_t n_\nu t_0},$$

with $\sigma_t n_\nu t_0 \approx 0.01$

THESE CONCLUSIONS ARE MADE FOR CONSERVATIVE νN CROSS-SECTION.