Neutrinos from extragalactic cosmic ray interactions in the far infrared background

E. V. Bugaev,[1] A. Misaki,[2] and K. Mitsui[3]

[1] *INR, 60th October Anniversary Prospect 7a, 117312, Moscow, Russia*
[2] *Advanced Research, Institute for Science and Engineering, Waseda University, 169-0092, Tokyo, Japan*
[3] *Faculty of Management Information, Yamanashi Gakuin University, Kofu 400, Japan*

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Extragalactic background of high energy neutrinos arising from the interactions of cosmic ray protons with far-infrared extragalactic background radiation is calculated. The main assumption is that the cosmic ray spectrum at energies higher than $10^8 GeV$ has extragalactic origin and, therefore, is proton dominated. All calculations are performed with taking into account the possible cosmological evolution of extragalactic sources of cosmic ray protons as well as infrared-luminous galaxies.

I. INTRODUCTION

The extragalactic backround of high energy neutrinos studied in this paper arises from collisions of high energy cosmic ray (CR) protons emitted by local sources (e.g., by active galactic nuclei) in extragalactic space, with extragalactic photons. We will not consider here the more exotic sources of extragalactic neutrino bachground (ENB) such as annihilations of topological defects (e.g., cosmic strings) or decays of hypothetical relic supermassive particles. So, ENB studied here began to be produced in relatively late epochs (from cosmological point of view) of expansion when the galaxies of different types and, in particular, the sources of CR's already existed. The first calculations of ENB were performed about twenty years ago (Berezinsky 1978, Stecker 1978, 1979). Later, the detailed calculations of differential spectra of ENB were done in works of Hill and Schramm (1985), Bugaev and Osipova (1989,1990), Berezinsky et al (1991) and Yoshida and Teshima (1993). All these authors took into account the interactions of CR protons with relic photons ($T \cong 2.7K$) only.

In the present work we calculate ENB originating from interactions of CR protons with far-infrared radiation background (FIRB). The threshold of the corresponding photoproduction reaction is lower than in the case of relic photons, so the flux of resulting neutrinos may be not so small (depending, of course, on the intensity of FIRB). Technically, the problem of calculating the ENB from infrared photons is rather complicate because now the photon number density in extragalactic space is not given (in the previous case of relic photons this number is definitely known for all moments of time) and, therefore, must be calculated separately.

For the calculation of ENB one needs the following inputs.

1. The spectral energy distribution of the radiation from typical infrared-luminous galaxies. The theoretical studies of this value were carried out by many authors. For our aims the approach of Beichman and Helou (1991), who derived the synthetic spectral energy distributions for galaxies of different luminosities, appears to be most convenient.

2. The volume density of infrared-light galaxies (the luminosity function). This information is also available in many works and we use the data of Soifer et al (1987).

3. The parameters characterizing the density and luminosity evolution of the galaxies with look-back time (cosmological evolution parameters). Unfortunately, the parameters of evolution of infrared-bright galaxies are generally unknown. They can be determinated (constrained) only by comparison the results of theoretical calculation of infrared background with available experimental upper limits for FIRB. We will also follow this usual procedure.

4. Extragalactic CR spectrum and intensity and the corresponding evolution parameters for the sources of CR's. We do not know the extragalactic cosmic ray spectrum and, therefore, we are forced to use the crucial hypothesis about extragalactic origin of high energy CR's. Everywhere in our calculations we use the extragalactic model (the crossover energy $\sim 10^{17} eV$) and normalize our theoretical CR spectrum on experimental CR data.

The paper is organized as follows. In Sec.II we derive approximate expression for the extragalactic CR spectrum for nonzero redshifts using the continuous energy loss approximation. Sec.III is dedicated to calculation of far infrared photon background and to obtaining the constraints on parameters of cosmological evolution of this background. In Sec.IV we calculate the extragalactic neutrino spectrum (the main goal of the paper) using the inputs from Sec.II and Sec.III. The last section contains the result of the calculations.

II. EXTRAGALACTIC CR PROTON SPECTRA FOR DIFFERENT Z

To obtain the expressions for the spectra and intensity of CR protons in extragalactic space we will use the transport equation without integral term, i.e., we will work in the continious energy loss approximation introduced by Berezinsky and Grigor'eva (1988). The validity of this approximation was studied in lates work of Yoshida and Teshima (1993). It was shown that this approximation is not very good only for spectra from local sources (in particular, the spikes near the cut off is more sharply expressed then in exact Monte-Carlo calculations). But in the case of diffuse spectra (i.e., the spectra integrated over redshift) which is of interest for us in this paper, the continious energy loss approximation works rather well: it predicts the characteristic dip-bump structure, at least in the case of not very strong cosmological evolution.

The cosmological transport equation for extragalactic CR protons is (Blumental, 1970)

$$\frac{\partial n(E,z)}{\partial z} + \frac{\partial}{\partial E}\left[\beta(E,z)n(E,z)\right] - \frac{3n(E,z)}{1+z} = g(E,z). \tag{2.1}$$

Here, $n(E,z)$ is the differential number density having the dimension (unit volume)$^{-1}$ $\cdot$ (unit of energy)$^{-1}$, i.e., $n(E,z)dE$ is the number of protons with given red shift z in energy interval dE near E. The function $\beta(E,z)$ is the change (loss) of proton energy on unit interval of z:

$$\beta(E,z) = \frac{dE}{dz} = \frac{E}{1+z} + \frac{b(E\cdot(1+z))}{H_0\sqrt{1+z}} \quad ; \quad b(E) = -\frac{dE}{dt}. \tag{2.2}$$

Here, H_0 is the Hubble constant, $b(E)$ is the well known function describing the proton energy losses per unit of time spent in the extragalactic space filled by relic photon gas.

The source function $g(E,z)$ in Eq.(2.1) can be written in the form:

$$g(E,z) = \rho(z)\eta(z)f(E)\frac{dt}{dz}. \tag{2.3}$$

Here, $\rho(z)$ is the number density of local CR sources (e.g., AGNs),

$$\rho(z) = \rho_0(1+z)^3, \tag{2.4}$$

$\eta(z)$ is the activity of each local source (the integrated number of produced particles per second),

$$\eta(z) = (1+z)^m\eta_0\theta(z_{max}-z). \tag{2.5}$$

Wrighting Eq.(2.5) we assume that the cosmological evolution can be parametrized by power law and by the sharp cut off at some value z_{max} (m and z_{max} are considered as parameters of a model of the source). The function $f(E)$ in Eq.(2.3) describes the form of differential energy spectrum of the source and has the simple normalization:

$$\int_{E_0}^{\infty} f(E)dE = 1. \tag{2.6}$$

For the connection of dt and dz we use the simple formula

$$\frac{dt}{dz} = -\frac{1}{H_0\sqrt{1+2q_0z}(1+z)^2} \tag{2.7}$$

following from the Einstein-de Sitter model. We will adopt everywhere below the following values of q_0 and H_0:

$$q_0 = \frac{1}{2} \quad ; \quad H_0 = 75\frac{km}{s\cdot Mps}. \tag{2.8}$$

In order to obtain the simple analytic formulae for the spectrum the two additional approximations are used in the following: i) photon energy losses in infrared photon gas are ignored (so, only energy losses due to relic photons are taken into account) and ii) the function $b(E)$ is approximated by the following simple expressions:

$$\begin{aligned} b(E) &= \beta_0 E \quad ; \quad 3\cdot 10^9 GeV < E < 10^{11} GeV, \\ b(E) &= \beta_0' E \quad ; \quad E > 10^{11} GeV \end{aligned} \tag{2.9}$$

and $b(E) = 0$ for $E < 3 \cdot 10^9 GeV$. β_0 and β_0' are constants:

$$\beta_0' = 2 \cdot 10^{-8} year^{-1} \quad ; \quad \beta_0 = 2.5 \cdot 10^{-10} year^{-1}.$$

We assume the power law for the injection spectrum from the extragalactic source:

$$J_{inj}(E) = \frac{\gamma - 1}{E_0} \left(\frac{E}{E_0} \right)^{-\gamma} (GeV^{-1}). \tag{2.10}$$

In the following we will assume also that the extragalactic spectrum has the cut off from below at energy $E_0 = 10^8 GeV$.

The approximation used for proton energy losses and given by Eq.(2.9), together with the expressions (2.3-2.5) for the source function $g(E, z)$, permit to obtain the analytical solution of the transport equation (2.1). The corresponding formulae for the CR spectrum $J(E, z)$ appear to be different in three energy regions:

1. $E < 3 \cdot 10^9/(1 + z)$
2. $3 \cdot 10^9/(1 + z) < E < 10^{11}/(1 + z)$
3. $E > 10^{11}/(1 + z)$.

In all final expressions for the spectrum there is the following common factor:

$$\Omega(E, z, \gamma, E_0) = \frac{c\rho_0\eta_0}{4\pi H_0} \cdot \frac{\gamma - 1}{E_0} (1 + z)^{\gamma+2} \cdot \left(\frac{E}{E_0} \right)^{-\gamma}. \tag{2.11}$$

In the region 3. one obtains

$$J(E, z) = \Omega \int_z^{z_{max}} dx (1 + x)^{m - \frac{3}{2} - \gamma} \exp \left[\left\{ 178(1 - \gamma) \left[(1 + x)^{3/2} - (1 + z)^{3/2} \right] \right\} \right]. \tag{2.12}$$

For the region 2. the formula for the spectrum is slightly more complicate:

$$J(E, z) = \Omega \int_z^{min(z_{max}, x_b)} dx (1 + x)^{m - \frac{3}{2} - \gamma} \exp \left[\left\{ 2.2 \left[(1 + x)^{3/2} - (1 + z)^{3/2} \right] \right\} \right] \tag{2.13}$$

and the value x_b is determined from the equation

$$\ln \frac{10^{11}(1 + z)}{E(1 + x_b)^2} = 2.2 \left[(1 + x_b)^{3/2} - (1 + z)^{3/2} \right]. \tag{2.14}$$

In region 1. there are two subregions:

1a. $x_{b_1} \equiv \sqrt{\frac{3 \cdot 10^9}{E}(1 + z)} - 1 > z_{max}$; $E > E_0$;

$$J(E, z) = \Omega \frac{1}{m - \frac{1}{2} - \gamma} \left[(1 + z_{max})^{m - \frac{1}{2} - \gamma} - (1 + z)^{m - \frac{1}{2} - \gamma} \right]; \tag{2.15}$$

1b. $x_{b_1} < z_{max}$;

$$J(E, z) = \Omega \left[\frac{1}{m - \frac{1}{2} - \gamma} \left[(1 + x_{b_1})^{m - \frac{1}{2} - \gamma} - (1 + z)^{m - \frac{1}{2} - \gamma} \right] \right. \\ \left. + \int_{x_{b_1}}^{min(z_{max}, x_{b_2})} dx (1 + x)^{m - \frac{3}{2} - \gamma} \exp \left[2.2(1 - \gamma) \left[(1 + x)^{3/2} - (1 + x_{b_1})^{3/2} \right] \right] \right] \tag{2.16}$$

and the value x_{b_2} is determined from the equation similar to Eq.(2.14):

$$\ln \frac{10^{11}(1 + z)}{E(1 + x_{b_2})^2} = 2.2 \left[(1 + x_{b_2})^{3/2} - (1 + x_{b_1})^{3/2} \right]. \tag{2.17}$$

Using these formulae one can calculate the CR proton spectra for different values of redshift z. The parameters are: m, z_{max}, γ and the product $(\rho_0\eta_0)$. Calculating $J(E,0)$ for fixed values of m, z_{max}, γ and normalizing it on the measured CR spectrum at energies $(10^{17} - 10^{19})GeV$ one can determine this product characterizing the CR source. After this procedure we obtain the CR spectrum for different z which can be used in section IV for the calculation of the ENB.

III. FAR INFRARED EXTRAGALACTIC BACKGROUND

The differential number density of infrared photons for different values of z, $N^{IR}(E_\gamma, z)$, can be calculated from the cosmological transport equation, which is similar with Eq.(2.1), but contains no energy loss term ($b(E) = 0$).

The expression for the source function of the transport equation is

$$g^{IR}(E_\gamma, z) = \int \frac{dL}{L}\rho(z,L)S^{IR}(E_\gamma, L)\frac{1}{E_\gamma}\cdot\frac{dt}{dz}. \tag{3.1}$$

Here, the function S^{IR} is the differential luminosity of a typical infrared-luminous galaxy. We determined S^{IR} from the synthetic spectral energy distributions $F(E_\gamma, L)$ for galaxies with given total luminosities L (in far-infrared region) obtained by Beichman and Helou (1991):

$$S^{IR}(E_\gamma, L) \cong 2\cdot 10^{53}F(E_\gamma, L). \tag{3.2}$$

In this formula the functions S^{IR} and F are measured in (sec^{-1}) and (Jy), respectively. The functions F were calculated for a distance $1Mpc$ from the galaxy and S^{IR} is normalized by the relation

$$\int_{E_{\gamma min}}^{E_\gamma^{max}} S^{IR}(E_\gamma, L)dE_\gamma = L, \tag{3.3}$$

where

$$E_\gamma^{min} = 1.243\cdot 10^{-3}eV \quad (\lambda = 10^3\mu m) \quad ; \quad E_\gamma^{max} = 0,393eV \quad (\lambda = 10^{0.5}\mu m) \tag{3.4}$$

The theoretical spectral energy distributions $F(E_\gamma, L)$ include a number of components, the main of which is a "cirrus" component (emission from a dust heated by the interstellar radiation field) and a hot starburst component (Beichman and Helou, 1991).

The volume density of galaxies $\rho(z, L)$ is connected with the local luminosity function $\rho(0, L)$ by the relation

$$\rho(z, L) = \rho(0, \frac{L}{(1+z)^{\gamma_e}})(1+z)^{3+\gamma_d}. \tag{3.5}$$

Here, γ_d and γ_e are parameters characterizing, correspondingly, the density and the luminosity cosmological evolution of the infrared-bright galaxies. For $\rho(0, L)$ we will use the analytic fit to data of Soifer et al (1987) which is presented in Beichman and Helou (1991):

$$\begin{aligned} \rho(0, L) &= 10^{-2.07}\cdot L^{-2.31} \quad , \quad L \geq 10^{0,4} \\ \rho(0, L) &= 10^{-2.73}\cdot L^{-0.65} \quad , \quad L < 10^{0.4}. \end{aligned} \tag{3.6}$$

In Eq.(3.6) the total luminosity L is measured in units of $(10^{10}L_{Sun})$ and $\rho(0, L)$ is in $(Mpc)^{-3}(mag)^{-1}$ (i.e., $\rho(0, L) \approx dn_G/d\ln L$; $dn_G = \rho(0, L)dL/L$). The interval of modelling was (Soifer et al 1987)

$$10^{-1.8} < L < 10^3,$$

but we will use in the following the more narrow interval,

$$1 < L < 10^3.$$

Now, using Eqs.(3.1) and (2.7), we obtain the following expression for the differential number density of infrared photons

$$N^{IR}(E_\gamma, z) = \int\limits_{z'_{max}}^{z} dx \left(\frac{1+z}{1+x}\right)^2 \int \frac{dL}{L}\rho(x, L)S^{IR}(\xi_\gamma(x), L)\frac{1}{\xi_\gamma(x)} \cdot \left(-\frac{1}{H_0(1+x)^{2.5}}\right) \quad . \tag{3.7}$$

Eq.(3.7) was obtained using the connection between the values of energies at redshifts x and z:

$$\xi_\gamma(x) = \xi_\gamma(z)\frac{1+x}{1+z} \quad ; \quad \xi_\gamma(z) = E_\gamma.$$

The function $N^{IR}(E_\gamma, z)$ is measured in $(cm^{-3}eV^{-1})$ if E_γ is substituted in (eV), ρ in $(Mpc)^{-3}(mag)^{-1}$ and $F(E_\gamma, L)$ in (Jy).

Calculating $N^{IR}(E_\gamma, z)$ for the particular case $z = 0$ we obtain the differential number density of infrared photons for our epoch. Multiplying it on E_γ (and on the factor $\frac{c}{4\pi}$) we obtain the FIRB intensity $I(E_\gamma)$,

$$I(E_\gamma) = \frac{c}{4\pi}E_\gamma N^{IR}(E_\gamma, 0) \quad (cm^{-2}sec^{-1}sr^{-1}), \tag{3.8}$$

which can be compared with experimental data.

For this comparison we will use the constraints on FIRB from analyses of COBE/FIRAS data. The possible values of parameters γ_d, γ_e can be, in principle, determined by this way. Furthermore, one should also take into account the constraints on FIRB from the HEGRA experiment.

IV. EXTRAGALACTIC SPECTRA OF HIGH ENERGY NEUTRINOS

For simplicity we use in this work one-pion approximation, i.e., we assume that in $p\gamma$-reaction only two particles (neutron and pion) are produced. In this case, as is well known (see, e.g., Hill and Schramm (1985)) the pions have approximately isotropic distribution in the center of mass system and, as a consequance, the step-like energy spectra in the observer system.

The main photoproduction reaction,

$$p_{CR} + \gamma_{infrared} \to \pi^+ + n, \tag{4.1}$$

and subsequent decays

$$\pi^+ \to \mu^+ + \nu_\mu, \qquad \mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu \tag{4.2}$$

lead to production of ν_μ,$\tilde{\nu}_\mu$, ν_e. In the present work we will be interested only in $(\nu_\mu + \tilde{\nu}_\mu)$-flux. Therefore, we add together the neutrino from pion and muon decays.

The number of proton-photon collisions per second and per units of photon energy and $\cos\theta_\gamma$ is equal to (for a given z)

$$\frac{dn_{coll}}{dtdE_\gamma d\cos\theta_\gamma} = \frac{c}{2}\sigma(s)(1+\cos\theta_\gamma)N^{IR}(E_\gamma, z). \tag{4.3}$$

Here, $\sigma(s)$ is the total cross section of the reaction (4.1). Using the connection between E_γ and E_γ^{lab},

$$E_\gamma^{lab} = E_\gamma(1+\cos\theta_\gamma)\cdot\gamma_p, \tag{4.4}$$

one obtains

$$\frac{dn_{coll}}{dtdE_\gamma^{lab}d\cos\theta_\gamma} = \frac{c}{2\gamma_p}\sigma(E_\gamma^{lab})N^{IR}\left(\frac{E_\gamma^{lab}}{\gamma_p(1+\cos\theta_\gamma)}, z\right). \tag{4.5}$$

Evidently, n_{coll} is a function of E_p, E_γ^{lab}, $\cos\theta_\gamma$ and z. Differential neutrino production spectrum from the pion and muon decays is given by the following integral:

$$N_\nu^{prod}(E_\nu, z) = \frac{4\pi}{c}\int dE_p \int dE_\gamma^{lab} \int d\cos\theta_\gamma \frac{dn_{coll}}{dtdE_\gamma^{lab}d\cos\theta_\gamma}\cdot j_\nu(E_p, E_\gamma^{lab}, E_\nu)J(E_p, z), \tag{4.6}$$

where $J(E_p, z)$ is the extragalactic CR photon spectrum calculated in sec.II and $j_\nu(E_p, E_\gamma^{lab}, E_\nu)$ is the neutrino spectrum per one $p\gamma$ collision. The production spectrum is measured in $(cm^{-3}sec^{-1}GeV^{-1})$, and, as it should be, it is the number of neutrinos produced in unit volume per second and per unit interval of energy. So, this value has the same sense as the product $\rho(z)\eta(z)f(E)$ in the case of CR protons (see Eq.(2.3)).

The last step is the calculation of the neutrino extragalactic spectrum (or number density), i.e., the ENB by integration the N_ν^{prod} over all redshifts. The source function of the neutrino transport equation is

$$g_\nu(E_\nu, z) = N_\nu^{prod}(E_\nu, z)\frac{dt}{dz} \tag{4.7}$$

and the final result for the neutrino spectrum is

$$\begin{aligned} J_\nu(E_\gamma) &= \frac{c}{4\pi}\int\limits_{z_{max}}^{0}\frac{1}{(1+z)^2}g_\nu(E_\nu(1+z), z)dz = \\ &= \frac{c}{4\pi H_0}\int\limits_{0}^{z_{max}}\frac{1}{(1+z)^{4.5}}N_\nu^{prod}(E_\nu(1+z), z)dz. \end{aligned} \tag{4.8}$$

V. RESULTS AND DISCUSSION

The numerical calculations of the far infrared background $N^{IR}(E_\gamma, z)$ had been performed for several sets of parameters. For the calculations of this background we used the following set:

$$\gamma_d = 4 \quad , \quad \gamma_e = 0.2 \quad , \quad z'_{max} = 1. \tag{5.1}$$

The FIRB function $I(E_\gamma)$ obtained with this set appears to be close to the experimental data (see, e.g., Dwek et al, 1998). In particular, the maximum value of $\nu I(\nu)$ (at $\lambda \sim 300\mu m$) is about $10(nW\ m^{-2}sr^{-1})$, in agreement with the data.

For the calculation at the CR spectrum of different values of the redshift z we used the analytical formulae derived in Sec.II, with the parameters

$$\gamma = 2.5 \quad ; \quad m = 3.5 \quad , \quad z_{max} = 5. \tag{5.2}$$

The normalization of the theoretical CR spectrum at $z = 0$ to the experimental data at $E \sim 10^8 \sim 10^{10}\ GeV$ gives

$$\rho_0\eta_0 \cong 10^{-41}(cm^{-3}sec^{-1}). \tag{5.3}$$

The resulting curve of the muon neutrino background from interactions of CRs with FIRB is shown at Fig.1. On the same figure we show, for comparison, the muon neutrino spectrum from π, k decays in atmosphere (for horizontal direction) and the spectrum of atmospheric prompt muon neutrinos.

The neutrino background from interactions of extragalactic cosmic rays with relic photons ("cosmogenic neutrino flux") is determined, evidently, by the same parameters γ, m, z_{max}. As an illustration, we show at Fig.1 the result of the estimate of this flux (dot-dashed curve). This estimate was obtained using the approximate formula derived in Bugaev and Osipova (1989):

$$\begin{aligned} J_\nu(E_\nu) = \frac{c}{4\pi H_0}\rho_0\eta_0\frac{\xi(\gamma)}{E_{max}}\Bigg\{&\theta\left[E_{max} - E_\nu(1+z_{max})^2\right]\cdot\frac{(1+z_{max})^{m-\frac{1}{2}+\gamma} - 1}{m - \frac{1}{2} + \gamma} \\ &+\theta(E_{max} - E_\nu)\theta\left[E_\nu(1+z_{max})^2 - E_{max}\right]\cdot\frac{\left(\frac{E_{max}}{E_\nu}\right)^{\frac{1}{2}(m-\frac{1}{2}+\gamma)} - 1}{m - \frac{1}{2} + \gamma}\Bigg\}. \end{aligned} \tag{5.4}$$

Here, E_{max} is equal to

$$E_{max} = \bar{E}_\pi (1 - \frac{m_\mu^2}{m_\pi^2}) \tag{5.5}$$

and $\bar{E}_\pi$ is the mean energy of pions produced by protons of the local source, $\bar{E}_\pi = 2.5 \cdot 10^{19} eV$. The value $\xi(\gamma)$ is the mean number of neutrinos produced by one proton,

$$\xi(\gamma = 2.5) \approx 0.7 \cdot 10^{-4} \quad ; \quad \xi(\gamma = 2) \approx 3.5 \cdot 10^{-3}. \tag{5.6}$$

One can see from figure that the neutrino flux from the interactions of CRs with the infrared background may be essential and should be taken into account in calculations of statistics of neutrino events in large neutrino telescopes. Unfortunately, the predictions of this neutrino flux are strongly model dependent. It is evident from the results of the paper that the measurements with high precision of the infrared background radiation will be not enough for such predictions if the parameters describing the cosmological evolution of infrared-bright galaxies and CR sources will be badly known.

Note added. After this paper had been finished, the paper by T. S. Stanev (*astro-ph*/0404535, 27 April 2004) on the same subject has appeared. In this paper the results very similar to those presented in the present paper were obtained.

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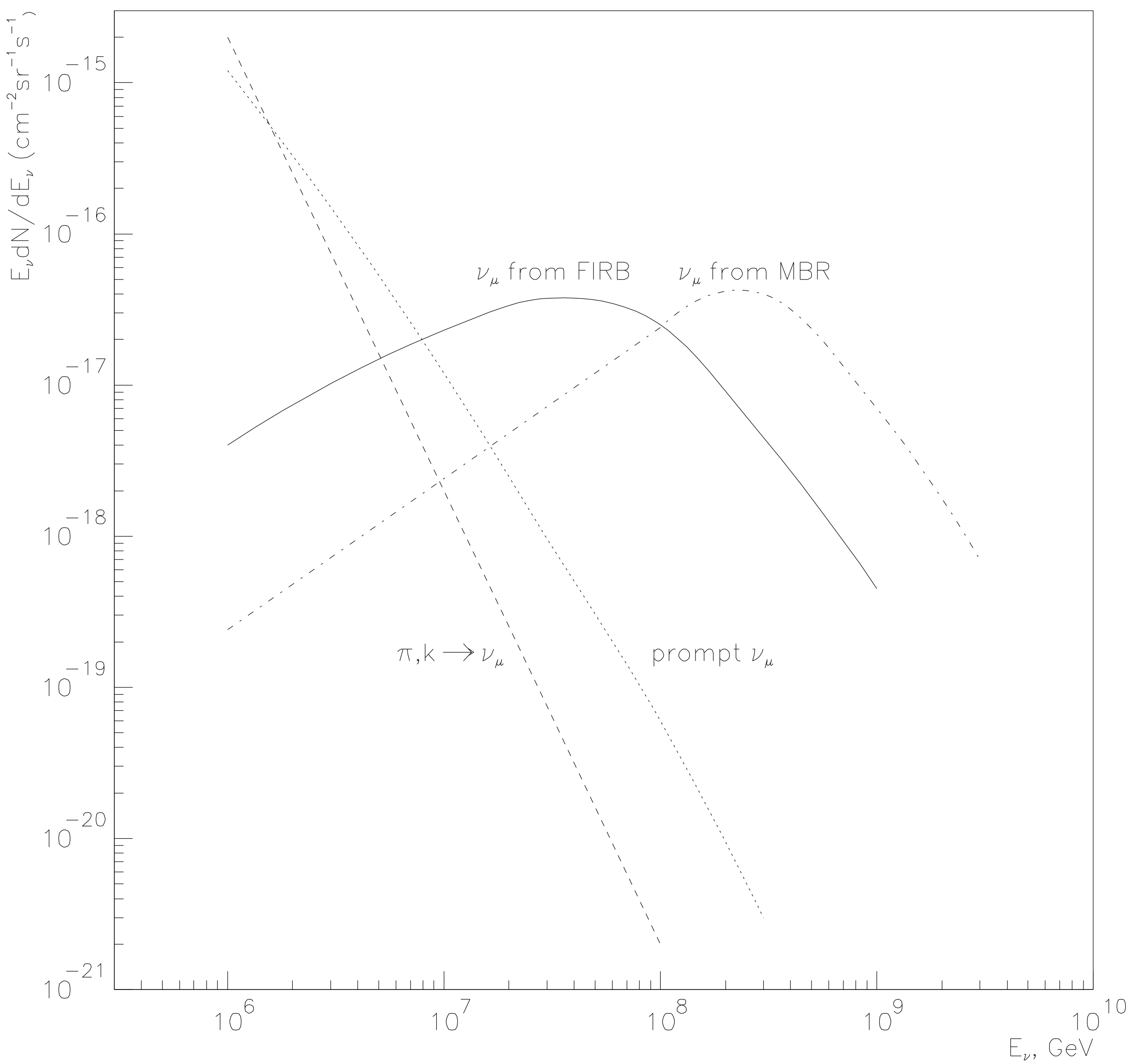

FIG. 1. Extragalactic neutrino spectra from interactions of cosmic rays with far infrared radiation background (solid line) and with relic photons (dot-dashed line). Cosmological model parameters used in the calculations are given in the text. For comparison, the horizontal neutrino spectrum from π, k decays in atmosphere (dashed line) and the spectrum of prompt atmospheric neutrinos (dotted line) are shown.