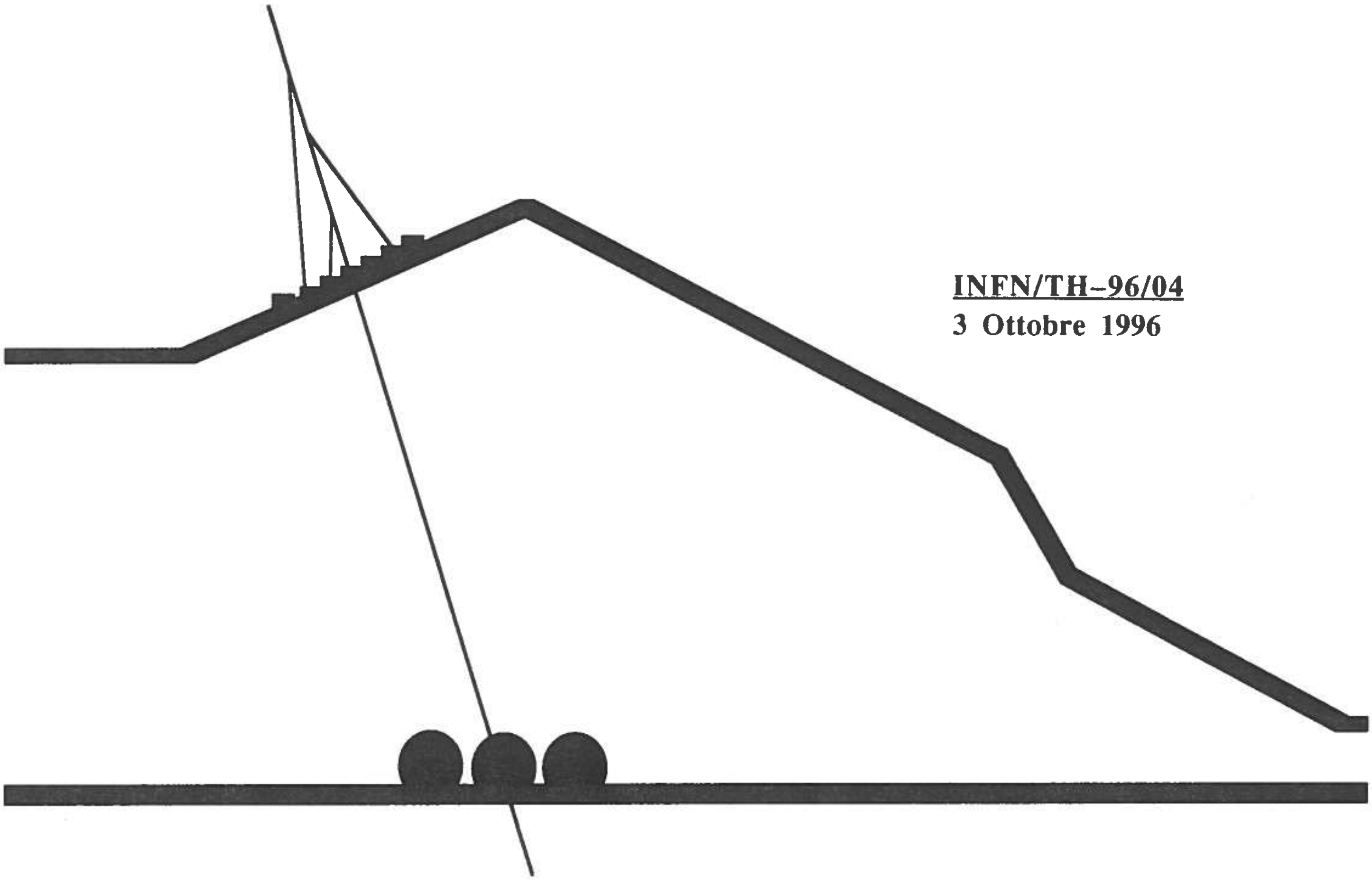

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CLUSTER OF GALAXIES AS A STORAGE ROOM FOR COSMIC RAYS

V.S. Berezinsky[1], P. Blasi[1,2] and V.S.Ptuskin[3]

ABSTRACT

It is demonstrated that clusters of galaxies are able to keep cosmic rays for a time exceeding the age of the Universe. This phenomenon reveals itself by the production of the diffuse flux of high energy gamma and neutrino radiation due to the interaction of the cosmic rays with the intracluster gas. The produced flux is determined by the cosmological density of baryons, Ω_b, if a large part of this density is provided by the intracluster gas. The signal from relic cosmic rays has to be compared with the flux produced by the late sources, which can be considered as a background in the search

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for cosmic ray production in the past. We calculate this flux considering the normal galaxies and AGN in the clusters as the sources of cosmic rays. Another potential cosmic ray source is the shock in the gas accreting to a cluster. We found that this background is relatively high: the diffuse fluxes produced by relic cosmic rays are of the same order of magnitude which can be expected from AGN in the clusters. In all cases the predicted diffuse gamma-ray flux is smaller than the observed one and the diffuse neutrino flux can be seen as the small bump at $E \sim 10^6\ GeV$ over the atmospheric neutrino flux. A bright phase in the galaxy evolution can be a source of the relic cosmic rays in clusters, revealing itself by diffuse gamma and neutrino radiations. We found that the observation of a signal from the bright phase is better for an individual cluster.

Subject headings: Cosmic Rays: diffusion,confinement - clusters of galaxies - radiation: diffuse, gamma, neutrinos

1. Introduction

The observations of X-ray radiation from the clusters of galaxies evidence that a large fraction of the cosmological baryonic density, ρ_b^{cos} is given by the intracluster gas (White and Frenk 1991, White 1993, White and Fabian 1995) . More specifically the cosmological density provided by the mass of the intracluster gas, Ω_b^{cl} is close to that derived from nucleosynthesis Ω_b^{ns}. If $\Omega_0 = 1$ one finds from the references above $\Omega_b^{clust} h^{3/2} \approx 0.05$ to be compared with the nucleosynthesis value $0.009 \leq \Omega_b h^2 \leq 0.024$ (Copi, Schramm and Turner 1995).

This observation was recently used by Dar and Shaviv (Dar and Shaviv 1995a, Dar and Shaviv 1995b) for calculating high energy gamma and neutrino radiations from clusters of galaxies (see references therein for the earlier works). In contrast to their calculations, where some ad hoc assumptions were made (most notably one about universality of cosmic ray flux in the galaxies and clusters), we shall use here a standard picture of production and propagation of cosmic rays (CR). This approach results in a lower flux and a different spectral index of radiation at high energy as compared with the calculations by Dar and Shaviv. Our conclusion about this low flux is valid for all present-day sources of cosmic rays considered in the literature, namely, normal galaxies and AGN in clusters, intracluster and accretion shocks.

However, as we shall show here, the clusters of galaxies are able to keep the accelerated particles for cosmologically long times and thus the production of gamma and neutrino radiations at present epochs can be due to these particles. The effective confinement of cosmic rays in the clusters was recently recognized by Volk, Aharonian and Breitschwerdt (1996) . They considered the cosmic rays in the clusters from the starburst galaxies in the past and TeV gamma radiation produced at present.

A powerful source of CR production can be the bright phase in the evolution of galaxies. The idea of bright phase was first put forward by Partridge and Peebles (1967) and was further developed in many works (see e.g. (Schwartz, Ostriker and Yahil 1975, Ostriker and Cowie 1981, Thompson 1989, Ozernoy and Chrnomordik 1976)). The bright phase is basically connected with the fast evolution of the massive stars (Zeldovich and Novikov 1971, Tinsley 1980). This process should result in explosions and shocks in young galaxies and clusters, and thus in acceleration of CR. One particular mechanism, convenient for calculations, is SN explosions. This was studied by Schwartz, Ostriker and Yahil (1975), Ostriker and Cowie (1981)) and most recently, in connection with cluster of galaxies, by Volk et al. (1996).

Clusters of galaxies are suitable for observations of bright phase in case it occures late, at redshifts $z \sim 1-2$ when the clusters were formed. These observations can include a search for young galaxies due to blue-enhanced radiation and in particular due to gamma and neutrino radiation produced by CR in clusters.

The plan of our paper is the following. In Section 2 we discuss the propagation of cosmic rays and their maximum energy. In Section 3 the confusing problem of the spectrum of produced radiation will be considered. The calculations of diffuse fluxes of gamma and neutrino radiation due to normal galaxies are presented in Section 4. In Section 5 we discuss the other sources of cosmic rays in a cluster, namely accretion shocks and AGN. Finally, in Section 6 we shall consider the bright phase of galaxy evolution relevant to radiation from clusters.

We shall finish this Introduction by a short summary of the properties of galaxy clusters relevant for our calculations.

A fundamental value which characterizes a cluster is the richness, or number of galaxies, N_g, in a group or cluster. This value typically varies from 10 to several hundreds. The clusters with $N_g > 100$ are defined as rich ones.

The total mass of a cluster, determined from the virial theorem, is called *gravitational* mass, M_{grav}. The cluster gravitational-mass distribution is given, according to Bahcall and Cen (1993), as

$$n(>M) = 4 \cdot 10^{-5} (\frac{M}{M_*})^{-1} exp(-\frac{M}{M_*})\ h^3\ Mpc^{-3} \tag{1}$$

where M is the total (gravitational) mass of a cluster within $1.5h^{-1}$ Mpc and $M_* = (1.8 \pm 0.3) \cdot 10^{14} h^{-1} M_\odot$. Further on we shall refer to the cluster with mass M_* as the *representative* cluster. The fraction of the gas mass in a cluster (relative to the gravitational mass) is commonly estimated as $(0.05-0.1)h^{-1.5}$ (see (Böringer 1995, Bahcall 1995)). In a recent work (White and Fabian 1995) this fraction is found for a sample of 13 clusters to be between 10 and 22 per cent.

The distribution (1) covers the range from $M_{grav} \sim 10^{12}h^{-1}M_\odot$ (small groups) to $5 \cdot 10^{15}h^{-1}M_\odot$. The representative mass of a cluster, according to distribution (1) is $M_* = 1.8 \cdot 10^{14}h^{-1}M_\odot$. The space density of clusters with $M > M_*$ is $\sim 1.4 \cdot 10^{-5}$ Mpc^{-3}.

Most of the cluster mass is in the form of dark matter. The fraction of gas is about $(0.05 - 0.1)h^{-1.5}$ relative to the gravitational mass (Böringer 1995, Bahcall 1995),.

The size of a cluster, R_{cl}, is defined as the distance at which a galaxy is gravitationally confined. Thus, the size is determined by the velocity dispersion as $R_{cl} = 2GM_{grav}/ < v^2 >$ and is typically $1.5h^{-1}$ Mpc, or roughly between $2 - 3$ Mpc.

Clusters of galaxies are powerful sources of X-ray radiation ($L_X \sim 10^{42} - 10^{44}$ erg/s). This radiation is interpreted as bremsstrahlung radiation of hot ($T \sim (3 - 10) \times 10^7$ K) intracluster gas. The observed temperature is close to the equilibrium temperature of the electron gas $T_e = m_p\sigma^2/6k$, where $\sigma =< v^2 >\sim (10^8$ $cm/s)^2$ is the velocity dispersion and k is the Boltzmann constant. At much lower temperature the electron gas condences to the cluster center, at much higher - it flows away.

Both spiral and elliptical galaxies are observed in the clusters. The spiral rich clusters have more than 50% of spirals, while the spiral poor clusters - - only 30% (Gorbatskii 1988) (see also (Dressler 1980))

More than $10 - 20\%$ of clusters have in the center a bright powerful cD galaxy with an absolute magnitude $M_V < -20^m$. This galaxy usually provides a large part of radio emission of a cluster. Other radiogalaxies are also observed in clusters. Thus, one can assume the presence of AGN's in clusters.

2. Propagation of cosmic rays and maximum energy

In the sections 2-4 we shall limit ourselves only to cosmic rays produced by normal galaxies in a cluster. This gives a conservative estimate of the produced flux, which can be considered as the lower limit, and also gives *reference calculations*: using them we shall discuss possible contributions of other CR sources.

Our consideration is based on two main observations.

- The diffuse flux is directly connected with the cosmological density of baryons and not with the gas density in a cluster.
- The spectrum of radiation is determined by the *production spectrum* of CR in the sources and not by the equlibrium spectrum of CR in a cluster.

As a result one can notice that the problem we study, is defined by a very restricted set of parameters, namely, by the cosmological parameter Ω_b, by the cluster richness N_g (number of galaxies), by the size and age of clusters R_{cl} and τ_{cl}, respectively, and by the generation function of CR in a typical galaxy, $Q^g_{CR}(E)$.

Using CR production in our Galaxy as a guide, we can assume the generation spectrum in a galaxy to be $Q^g_p(E) = A(E+E_0)^{-\gamma_g}$ with $E_0 \sim 1\ GeV$. For $E \gg 1\ GeV$ one then obtains

$$Q^{gal}_p(E) = (\gamma_g - 1)(\gamma_g - 2)\frac{L_p}{E_0^2}(\frac{E}{E_0})^{-\gamma_g} \qquad (2)$$

where $L_p \sim 3 \cdot 10^{40}\ erg/s$ and $2.1 \leq \gamma_g \leq 2.4$ (Berezinsky et al. 1990). Note, that using our Galaxy as a reference source in a cluster results in a somewhat overestimated diffuse flux from the clusters. As it will be understood from the following consideration, we do not need the detailed picture of CR propagation in a cluster for the calculation of fluxes. It is only important for us to demonstrate that the escape time of CR out of a cluster is larger than the age of the cluster, i.e. that the particles injected by galaxies are confined within the cluster during its age. For the relevant estimates we shall use a simple model of diffusion propagation.

The radio observations show the presence of tangled magnetic fields in the clusters with strength $H \sim 1 - 3\ \mu G$ and with principal linear scale of homogeneity $l \sim 20\ pc$ (Jaffe 1980). For particles with the Larmor radius $r_H < l$, i.e. with energies $E < E_0 \approx 2 \cdot 10^7\ GeV$ (for $H = 1\mu G$), the diffusion coefficient can be estimated as $D_0 \approx cl/3 \approx 6 \cdot 10^{29}\ cm^2/s$. At $E > E_0$ the diffusion coefficient is $D(E) = D_0(E/E_0)^2$. The escape time of protons with energies $E < E_0$ from a cluster,

$$\tau \approx \frac{R_{cl}^2}{6D_0} = 3.0 \cdot 10^{11}\ yr, \tag{3}$$

is greater that the age of the cluster τ_{cl}, for which we shall use here and everywhere else the age of Universe $t_0 = 0.82 \cdot 10^{10} h_{0.8}^{-1}\ yr$.

Starting with energy $E_c \sim 1 \cdot 10^8\ GeV$ the escape time becomes less that the age of a cluster, $\tau_{cl} \approx t_0$, and production of the secondaries becomes less effective.

If we use another extreme picture for CR propagation, the Bohm diffusion, then the diffusion coefficient can be estimated as $D \sim cr_H$. The real value should be limited as $cr_H < D < cl/3$, where l is the inhomogeneity scale for the magnetic field. However, with the Bohm diffusion coefficient we obtain from Eq.(3) that the maximum energy for confinement in the cluster is $E_{max} \sim 2 \cdot 10^8\ GeV$, approximately as before.

The effective confinement of CR in a cluster was also recognized by Volk et al. (1996).

Another reason for the diminishing of the effectivity of gamma and neutrino production at very high energies can be connected with the maximum energy reachable by acceleration E_{max}. For the diffusive acceleration at SN shock fronts this energy is known to be $\sim 10^5 - 10^6\ GeV$.

E_{max} can be one-two orders of magnitude larger in the regions near to a SN filled by the presupernova stellar wind (Volk and Biermann 1988). In this case one can expect $E_{max} \sim 10^{16} - 10^{17}\ eV$.

On the other hand, from phenomenological considerations (Berezinsky et al. 1990) we know that particles with energies up to $\sim 10^{10}\ GeV$ are most probably of galactic origin, and the generation spectrum can have a power-law form up to this energy.

As a conservative approach we shall use $E_{max} \sim 1 \cdot 10^{8}\ GeV$, either due to inefficiency of confinement or acceleration.

3. Spectrum of radiation

This Section is just a note clarifying the difference in the radiation spectrum for the cases $\tau_{esc} > \tau_{cl}$ and $\tau_{esc} < \tau_{cl}$.

Let us consider a nuclear-thin object in which high energy protons diffuse from a central source. The generation function of the source is $Q_p \propto E^{-\gamma_g}$ and the diffusion coefficient $D(E) \propto E^{\eta}$.

The number of secondary particles $i = \gamma, \nu$ produced per unit time and unit volume for the power-law spectra of CR nucleons can be given in terms of the *production yields* Y_i (Berezinsky et al. 1990) as

$$q_i(E,r) = Y_i \sigma_{pp} n_H c n_p(E,r) \tag{4}$$

where $\sigma_{pp} = 3.2 \times 10^{-26}\ cm^2$ is the normalizing cross section for high energy pp scattering, n_H is the number density of gas in the cluster and $n_p(E,r)$ is the number density of protons with energy E at a distance r from the source. This density $n_p(E,r)$ can be found from the diffusion equation as

$$n_p(E,r) = \frac{1}{4\pi r}\frac{Q_p(E)}{D(E)} \tag{5}$$

The flux from the whole source can be found by integrating (4) over the volume

$$Q_i(E) = \int q_i(E,r) 4\pi r^2 dr \tag{6}$$

For the case $\tau_{esc} > \tau_{cl}$ the integration is limited by the upper limit

$$r_{max} = \sqrt{6D(E)\tau_{cl}} \tag{7}$$

and one obtains

$$Q_i(E) = Y_i Q_p(E) \sigma_{pp} n_H c \tau_{cl} \sim E^{-\gamma_g} \tag{8}$$

The physical meaning of this formula is straightforward: each high energy proton emitted by a source has the same probability of interaction, equal to $\sigma_{pp} n_H c \tau_{cl}$. This result is exact and can be obtained in the accurate theory of the diffusion.

For the other case $\tau_{dif} < \tau_{cl}$, $r_{max} = R_{cl}$ and

$$Q_i(E) = Y_i Q_p(E) \sigma_{pp} n_H c \frac{R_{cl}^2}{6D(E)} \sim E^{-(\gamma_g+\eta)} \tag{9}$$

The physical meaning of this formula is also evident: the probability of interaction depends on the escape time , $R_{cl}^2/D(E)$, and thus on the energy of the particles.

Therefore, spectra (8) and (9) are different. This difference often causes confusion. In particular, Dar and Shaviv (1995a) took the spectrum index of gamma-radiation equal to that of the equilibrium spectrum of the protons in our galaxy (i.e. Eq.(9)), while in fact it is equal to the index of the generation spectrum of protons (Eq.(8)).

To generalize this note, we mention that the absorption time of protons (or electrons), when essential, can play the role of age.

4. Diffuse fluxes of high energy gammas and neutrinos due to normal galaxies

We consider *pp*-production of high energy gamma and neutrino radiation. The number of gamma's or neutrinos produced by one cluster at time t during the interval dt can be given in terms of the *production yields* Y_i (see (Berezinsky et al. 1990) and Table 1) as

$$N_i(E,t)dt = Y_i Q_i^{gal}(E) N_g t \sigma_{pp} n_H c dt, \quad (10)$$

where $i = \gamma, \nu$, Q_p^{gal} is given by Eq.(2) and for other notations see Section 3. The values of the yields are reported in Table 1. Note that due to the definition of the yields, Y_i and Q_i are taken at the same energy E.

Integrating over time and summing the contribution of all clusters one finds the diffuse flux:

$$I_i(E) = \frac{3}{32\pi^2} Y_i \frac{\sigma_{pp}(ct_0)^2}{m_H R_{cl}^3} Q_p^{gal}(E) N_g \xi \Omega_b \rho_{cr}, \quad (11)$$

where we used $n_{cl} M_{gas}^{cl} = \xi \Omega_b \rho_{cr}$.

From Eq's(11) and (2) one can see that the diffuse flux is determined by the cosmological density of baryons Ω_b, the cluster parameters N_g and R_{cl} and the galactic quantity $Q_p^{gal}(E)$.

We can now compare the calculated gamma-ray flux (11) with the one extracted from the EGRET observations at $10 - 50$ GeV (Osborne et al. 1994):

$$I_\gamma^{obs}(E) = 9.6 \cdot 10^{-7} E_{GeV}^{-2.11} \; cm^{-2} s^{-1} sr^{-1} GeV^{-1}. \quad (12)$$

To fit the data we choose $\gamma_g = 2.11$, which is in the allowed range of the generation spectrum index. Using $\xi = 1/2$, $N_g = 100$, $Y_\gamma = 0.116$ and $R_{cl} = 1.5 h^{-1}$ Mpc we obtain:

$$I_\gamma(E) = 3.4 \times 10^{-10} \; E^{-2.11} h_{80} \frac{\Omega_b h^2}{0.025} \; cm^{-2} s^{-1} sr^{-1} GeV^{-1}. \quad (13)$$

The calculated flux is only $\sim 3 \cdot 10^{-4}$ of that observed experimentally. Notice that one cannot diminish arbitrarily the radius of clusters, R_{cl}, because the mass inside a smaller radius cannot provide $\Omega_b h^2 = 0.02$.

This result is not surprising, because the column density CR traversed in the intracluster gas, $x \sim c\rho_g t_0$ is of order $0.5 - 1\ g/cm^2$, i.e. of the same order as in a galaxy. It means that fluxes of gamma-radiation produced by CR in the parent galaxy and in a cluster are of the same order of magnitude. It is known that normal galaxies cannot produce the observed diffuse flux at energies $100\ MeV - 10\ GeV$. Cluster production of neutrinos with the highest possible energies is of greater interest, because the galactic grammage $x_{gal}(E)$ diminishes as E increases, while grammage in a cluster does not depend on energy up to $E_p \sim 10^8\ GeV$.

The duffuse neutrino flux calculated with the help of Eq.(11) is shown in Fig.1 together with vertical atmospheric neutrino fluxes. For the prompt atmospheric neutrinos we took the calculations of Gondolo, Ingelman and Thunman (1995) (see also references therein). For the calculated flux from clusters we used the same parameters as above and neutrino yields from Table 1. One can see that for the case of normal galaxies, as CR sources, the predicted neutrino flux is practically undetectable.

The upper limit on the neutrino flux shown in Fig.1 is obtained from the condition that the diffuse gamma-ray flux observed at $10 - 50\ GeV$ (12) is produced by clusters. It results in

$$I^{max}_{\nu_\mu+\bar{\nu}_\mu}(E) = \frac{Y_{\nu_\mu+\bar{\nu}_\mu}}{Y_\gamma} I^{obs}_\gamma(E).$$

5. Other sources: AGN's and shocks

In this section we shall discuss the other sources of CR in the clusters, namely AGN's, shocks inside the clusters and the accretion shocks.

5.1.. Active Galactic Nuclei

Since about 1% of galaxies have an AGN, we can expect one AGN per cluster with richness $N_g = 100$. In particular, roughly 1% of spirals are Seyfert galaxies with luminosity $10^{44} - 10^{45}$ erg/s (Weedman 1977). About 5% of elliptical galaxies are radiogalaxies (Schmidt 1978). A very powerful source of CR's can be the cD-galaxy often observed in the center of clusters.

There are no well elaborated mechanisms of particle acceleration in AGN's. When particles are accelerated diffusively by the accretion shocks in the vicinity of the black hole, they are dragged by the flow of gas onto the black hole. A plausible mechanism of acceleration is due to unipolar induction in the accretion disc around the black hole (Blandford 1976) or acceleration in jets (Biermann and Streitmatter 1987, Quenby and Lieu 1989). It can be expected that up to 10% of the total energy release is transferred to accelerated particles.

However, even assuming one AGN with total luminosity $L_{tot} \sim 10^{45}$ erg/s, we arrive at $L_{CR} \sim 10^{44}$ erg/s, to be compared with the total CR luminosity of normal galaxies $N_g L^g_{CR} \sim 3 \cdot 10^{42}$ erg/s. The gain factor, 30, is still not enough to reconcile the Eq.s (12) and (13). In the case of high energy neutrino radiation, this factor is important: the neutrino flux from clusters can produce a bump over the atmospheric neutrino flux at $E \sim 10^6$ GeV (see Fig. 1).

5.2. Shocks inside clusters

These shocks can be produced by galactic winds. Even if this phenomenon occurs, it is energetically provided by SN induced shocks from the galaxies . CR accelerated in a galaxy obtain a total energy which is about the same order of magnitude as one carried away by the galactic wind. Actually the situation is even worse: as was pointed out by Breitschwerdt, McKenzie and Volk (1991) and Breitschwerdt, McKenzie and Volk (1993),the intracluster pressure is so large that the winds from the galaxies do not develop, except in the case of the starburst phase.

5.3. Accretion shock

In this work we assume that a large fraction of cosmologically produced baryons are concentrated in the clusters of galaxies. It implies a large rate of accretion of baryonic gas to the clusters. This rate averaged over the age of Universe can be roughly estimated as

$$< \dot{M} > \sim M_{gas}/t_0 \tag{14}$$

where M_{gas} is the mass of the gas in a cluster.

We imploy in this section the calculations of Bertschinger (1985) for spherically symmetric accretion of a mixture of non-dissipative gas (dark matter with a critical density) and a dissipative (baryonic) gas. The process of fluctuation growth in both linear and non-linear regimes is dominated by the non-dissipative component, while baryonic gas moves in the gravitational potential produced by dark matter. However, as demonstrated by Bertschinger (1985) both components have the same density distribution $\rho \propto r^{-9/4}$ and actually the independent solutions for dissipative gas with adiabatic index $\gamma = 5/3$, and non-dissipative gas are very similar. The main difference is the existence of a shock in baryonic gas. The shock originates because of the collision of the flow with the dense self-produced core. It propagates outward according to $R_{sh} \sim t^{8/9}$, where R_{sh} is the shock radius. At present, $t = t_0$, for intervals of time $\tau \ll t_0$ we can consider the shock as a stationary one.

The basic parameter in this theory is the turnaround radius R_{ta}.

The formation of a cluster takes place in the background of the expansion of the Universe. R_{ta} can be defined approximately as the distance where the free-fall velocity $v_{ff} = \sqrt{2GM/r}$ is equal to the Hubble velocity $v_H = H_0 r$. As an order of magnitude this condition gives $R_{ta}^3 \sim GM/H_0^2$, where M is the total mass inside the turn-around radius R_{ta}. In our calculations we shall use a more accurate expression from (Gunn and Gott 1972, Bertschinger 1985):

$$R_{ta} = (8GMt_0^2/\pi^2)^{1/3}. \tag{15}$$

The solutions of Bertschinger are scaling ones which are presented in terms of dimensionless quantities. As a dimension parameter for our case we can take the turnaround radius with value $R_{ta} = 5\ Mpc$. It gives the gravitational mass inside $R_{cl} = 2\ Mpc$,

$$M_{cl}^{grav} = \frac{4}{3}\pi \rho_{cr} R_{ta}^3 M(\lambda_{cl}) = 3.1 \cdot 10^{14} M_\odot,$$

where ρ_{cr} is the critical cosmological density, $\lambda = r/R_{ta}$ is the dimensionless distance and $M(\lambda)$ is the scaling mass given by Bertschinger (1985) (we use in this Section $h = 0.75$). According to Eq.(1) this mass corresponds to a representative cluster for our consideration.

The shock radius is found by Bertschinger to be $R_{sh} = 0.347 R_{ta}$. Normalizing the density of baryonic gas by the condition $M_{cl}^{gas}/M_{cl}^{grav} = 0.1$ one can find the gas density at $R = R_{sh}$ as $\rho_{gas} = 2.2 \cdot 10^{-29}\ g/cm^3$. The radial velocity of gas at the position of the shock is, according to (Bertschinger 1985), $v_r = 1.5 R_{ta}/t_0 = 8.4 \cdot 10^7\ cm/s$. Now we can calculate the CR luminosity due to shock acceleration assuming that 10% of the kinetic energy of the infalling gas is transferred to accelerated particles:

$$L_{CR} = 0.2\pi \rho_{gas}(R_{sh}) R_{sh}^2 v_r^3 = 2.3 \cdot 10^{44}\ erg/s. \tag{16}$$

The maximum energy of accelerated particles estimated in an usual way from equality of acceleration and diffusion time is

$$E_{eV}^{max} \sim 300 \frac{u_r(R_{sh})}{c} H_G R_{sh} \approx$$
$$9.3 \cdot 10^{17} (H/1\mu G)(R_{sh}/3\ Mpc)(u_r/10^7\ cm/s)\ eV \tag{17}$$

The alternative solution for gas accretion to the cluster is given by the pancake model (Zeldovich 1970). The shock is also produced in this model. The results of numerical calculations for the cluster-size pancake are given by Doroshkevich, Zeldovich and Sunyaev (1976). The distance to the shock in this simulation is about 0.6 Mpc for a typical size of a cluster 2 Mpc. The gas velocity at the position of the shock is $1.5 \cdot 10^7$ cm/s. The CR luminosity can be estimated very roughly for the given parameters and geometry as $\sim 10^{43}$ erg/s.

6. Bright Phase

The first-generation stars were produced due to non-linear growth of the fluctuations in the baryonic gas. Their mass spectrum was strongly dominated by the large masses with a fundamental scale given by the Jeans mass $M_J \sim 10^5 M_\odot$. The fragmentation of these massive protostars results in the formation of the initial mass function (IMF), being strongly enhanced by massive short-lived first-generation stars. Most of these massive stars finish their evolution as SNII. The explosions and stellar winds enrich the interstellar gas by heavy elements and this composition is seen in metal deficient population II stars. The duration of the longest phase in the heavy-star evolution, the main sequence stage, can be estimated as the ratio of the thermonuclear production of energy, $\epsilon M c^2$, to the luminosity L, or

$$\tau_{MS} \sim \frac{\epsilon M c^2}{(1.3 \times 10^{38} M/M_\odot)} (L/L_{Edd})^{-1} \sim 5 \times 10^5 \frac{L_{Edd}}{L} \ yr,$$

where the conversion coefficient ϵ is taken as the representative value 1×10^{-3}. Thus, the typical duration of the bright phase is $10^7 - 10^8$ years. Partridge and Peebles (1967) in their pioneering work assumed the duration as 3×10^7 yr.

The total energy release during the bright phase is estimated from nuclear conversion. Partridge and Peebles (1967) found $W \sim 3 \times 10^{61}$ $ergs$ per galaxy; Schwartz, Ostriker and Yahil

(1975) estimated it as $W \sim 10^{61} - 10^{62}$ $ergs$. These authors considered this energy as being released in the form of kinetic energy of SN shells, which results in the shocks and acceleration of the particles (see also (Ostriker and Cowie 1981)). An emphasis was given to this processes in the clusters of galaxies. In the early works the bright phase was assumed to be at relatively large red shifts, e.g. $2 < z < 10$ in the work by Schwartz, Ostriker and Yahil (1975).

In the most recent calculations of Volk et al. (1996) the bright phase (starburst phase) was placed at relatively low red shift $z \sim 2 - 3$ and the total energy release was found from the iron abundance in the clusters. In the discussion below we shall follow this approach.

Finally we mention the detailed calculations by White and Frenk (1991) for the galactic evolution. These calculations start with the cosmological evolution of fluctuations described in the Cold Dark Matter cosmological model and proceed with the stellar evolution up to the present age of the Universe. The star formation in this model occurs late: half of the stars are born at the epoch with red shift $z < 1$. No bright phase is found. This result is not a surprise, because the authors use the mass function as it is observed now, while the main assumption which leads to the bright phase is the strong enhancement of the mass spectrum by supermassive short-lived stars.

How much can we increase the calculated diffuse fluxes taking into account the bright phase production?

The increase can be estimated as the ratio W_{CR}^{bp}/W_{CR}^{g}, where W_{CR}^{bp} and W_{CR}^{g} are the CR energy release during the bright phase and due to present-day galaxies, respectively. The value W_{CR}^{bp} is given by the product of N_{SN}, the total number of SN explosions during the bright phase and $W_{CR}^{SN} = 2.8 \times 10^{49}$ erg/s, the total energy of CR produced by one SN. The former can be found, following Volk et al. (1996), as $M_{Fe}/0.1M_{\odot}$, where M_{Fe} is the mass of iron in the intracluster gas and $0.1M_{\odot}$ is the mass of iron produced by one SNII explosion. Since the mass fraction of iron in a cluster is about $\epsilon_{Fe} \approx 7 \times 10^{-4}$ we obtain for our representative cluster with the mass of gas $M_*^{gas} = 1.8 \times 10^{13} h^{-1} M_\odot$:

$$W_{CR}^{bp} = \epsilon_{Fe} \frac{M_*^{gas}}{0.1 M_\odot} W_{CR}^{SN} = 4.4 \times 10^{60}\ erg/s. \qquad (18)$$

The value of W_{CR}^{g} is

$$W_{CR}^{g} = L_p t_0 N_g \approx 7.7 \times 10^{59}\ erg \qquad (19)$$

and thus the factor of the diffuse flux increase is rather small, about 6.

Note that the estimate for W_{CR}^{bp} estimated by Volk et al. (1996) is ~ 15 times larger than our value. The main reason for this descrepancy is in the value of W_{CR}^{SN}. Volk et al adopted it from theoretical considerations as $3 \times 10^{50}\ erg$. Our value is found from phenomenology of CR in our Galaxy. Namely it is given as L_P/ν_{SN}, where $\nu_{SN} \approx 1/30\ yr$ is the frequency of SN explosions in our Galaxy and L_P is the CR luminosity of our galaxy, given by Berezinsky et al. (1990)

$$L_P = \frac{c\omega_{CR} M_g}{x} \approx 3 \times 10^{40}\ erg/s, \qquad (20)$$

where $\omega_{CR} \approx 0.5\ eV/cm^3$ is the observed density of CR, $x \approx 5\ g/cm^2$ is the the grammage traversed by CR in the Galaxy and $M_g \approx 5 \times 10^{42}\ g$ is the total mass of the interstellar gas. As a result, our value of $W_{CR}^{SN} \approx 2.8 \times 10^{49}\ erg$ is 11 times less than that of Volk et al. (1996).

We conclude, therefore, that the increase of the diffuse flux due to bright phase as compared with normal galaxies is smaller than that due to AGN and accretion shocks.

7. Discussion and conclusions

We have calculated the diffuse fluxes of high energy gamma and neutrino radiation from clusters of galaxies. These radiations are produced in pp-interactions of high energy CR with intracluster gas. The basic assumption which we use is that a considerable part of the cosmologically produced baryons are concentrated inside the clusters. An interesting observation is that, with this assumption, a very restricted set of parameters enters the calculations. They are: the generation function of CR in the sources, $Q_{CR}(E)$, the cluster size R_{cl} and the richness N_g. The exact picture of propagation of CR in a cluster does not affect the produced flux of radiation, because the escape time of CR from a cluster is larger than the age of the cluster. For the same reason, the spectrum of the produced radiation is very flat. At high energy it reproduces the *production* spectrum of CR in the sources.

We made explicit calculations for CR produced by normal galaxies. In this case the generation function, $Q_{CR}(E)$, for a galaxy can be taken as that of our Galaxy. It gave us a reference case for calculations: for other sources the produced flux is scaled as the CR luminosity of a source L_{CR}.

What other possible sources could there be?

The general restriction is that they must be very powerful to exceed the total CR luminosity of normal galaxies in a representative cluster, $3 \cdot 10^{42}\ erg/s$.

The anticipated sources could be AGN's (including the central cD-galaxy in a cluster) and the shock in the accretion flow of the gas onto clusters. They can increas L_{CR} and thus the diffuse flux by factor ~ 30. According to our estimates the bright phase can increase W_{CR}, and thus the diffuse flux, only by factor 6 as compared with normal galaxies.

The normal galaxies in the cluster can provide neither the observed diffuse flux of gamma rays nor the detectable neutrino flux at any energy. The accretion shock acceleration and/or acceleration of particles in AGN's can result in the production of a detectable bump above the atmospheric neutrino flux at energy $E \sim 10^6\ GeV$, while the predicted $0.1 - 100\ GeV$ flux of gamma radiation remains one order of magnitude less than observed.

Our results differ from calculations of Dar and Shaviv (1995a, 1995b) : they are more pessimistic for gamma radiation and more optimistic for neutrino radiation.

Dar and Shaviv assumed that CR density in clusters is the same as in our Galaxy. We cannot reproduce their assumption studying all possible sources of CR in the cluster. For the CR production by the normal galaxies the energy density of CR in a cluster is

$$\omega_{CR}^{cl} = \frac{3L_P N_g t_0}{4\pi R_{cl}^3} = 9.3 \cdot 10^{-4} h^2 \ eV/cm^3$$

to be compared with the galactic value 0.5 eV/cm^3. Here $L_P = 3 \cdot 10^{40}$ erg/s is the CR luminosity of our Galaxy and $N_g = 100$ is the richness of a typical cluster. Increasing the CR luminosity of a cluster up to 10^{44} erg/s, due to accretion shock or AGN, we are still left with more than one order of magnitude deficit.

The bright phase deserves a special discussion. If SNe are the main sources of CR, the bright phase gives the increased flux described as compared to normal galaxies by a factor n_{SN}^{bp}/n_{SN}^{ng}, where n_{SN}^{bp} and N_{SN}^{ng} are the SN space density due to bright phase and normal galaxies, respectively. They can be found as

$$n_{SN}^{bp} = \frac{\epsilon_{Fe}}{0.1 M_\odot} \int_{M_{min}}^{\infty} n(M) M_{gas} dM$$

and

$$n_{SN}^{ng} = \nu_{SN} t_0 \int_{M_{min}}^{\infty} n(M) N_g(M) dM$$

where $n(M)$ is obtained by differentiating eq. (1), M is the gravitational mass and $M_{gas} \sim 0.1\ M$ is the gas mass in a cluster; $N_g(M)$ is the number of galaxies in a cluster with mass M, and ν_{SN} is the SN frequency in a normal galaxy. The ratio n_{SN}^{bp}/n_{SN}^{ng} is about 8, i.e. practically the same as the previously estimated value assuming all clusters having the characteristic mass M_*.

As we demonstrated the spectrum of high energy radiation coincides with the production spectrum of CR. That is why our spectrum can be as flat as $E^{-2.1}$, while Dar and Shaviv explicitly state that their spectrum is $E^{-2.7}$. This is the reason that our flux of neutrino radiation is higher for the same CR luminosity.

The bright phase can give a much more pronounced effect for the case of *individual* cluster. In particular for the Perseus cluster, discussed by Volk et al, the mass of the gas is very large $M \approx 4 \times 10^{14} M_{\odot}$ for the given richness $N \approx 500$, and therefore the total number of SN is very large as compared with with the number of SN produced by galaxies during their normal evolution. Such galaxies are the best candidates for both gamma ray observations and blue-shifted young galaxies.

Finally, we shall discuss the possibility of gamma-ray detection from the nearest Virgo cluster (19 Mpc).

The EGRET observations (Fichtel et al. 1994) give the upper limit for 100 MeV gamma-ray flux $F_{\gamma}(> 100 MeV) < 0.5 \times 10^{-7}\ cm^{-2}\ s^{-1}$, which is actually valid only for the central source $M87$. In the models considered here the flux from the extended region occupied by the whole cluster can be considerably larger. Using the richness N=2500 and mass of the gas $M \approx 1 \times 10^{14} M_{\odot}$ we obtain the flux at $E_{\gamma} > 100\ MeV \sim 5 \times 10^{-9} cm^{-2} s^{-1}$ both for normal galaxies and bright phase. The gain factor predicted in general is lost for the Virgo cluster due to the huge number of galaxies in comparison with the gas mass. Unfortunatelly this flux is undetectable for the existing instruments.

Table 1: The values of the yields

γ	2.1	2.2	2.3	2.4	2.5	2.6	2.7
$\gamma - rays$	116	88.8	69.0	54.2	43.0	34.5	
$\nu_\mu + \bar{\nu}_\mu$	126.2	94.6	69.8	51.9	39.1	29.7	22.8
$\nu_e + \bar{\nu}_e$	58.7	44	32.3	23.81	17.87	13.46	10.25

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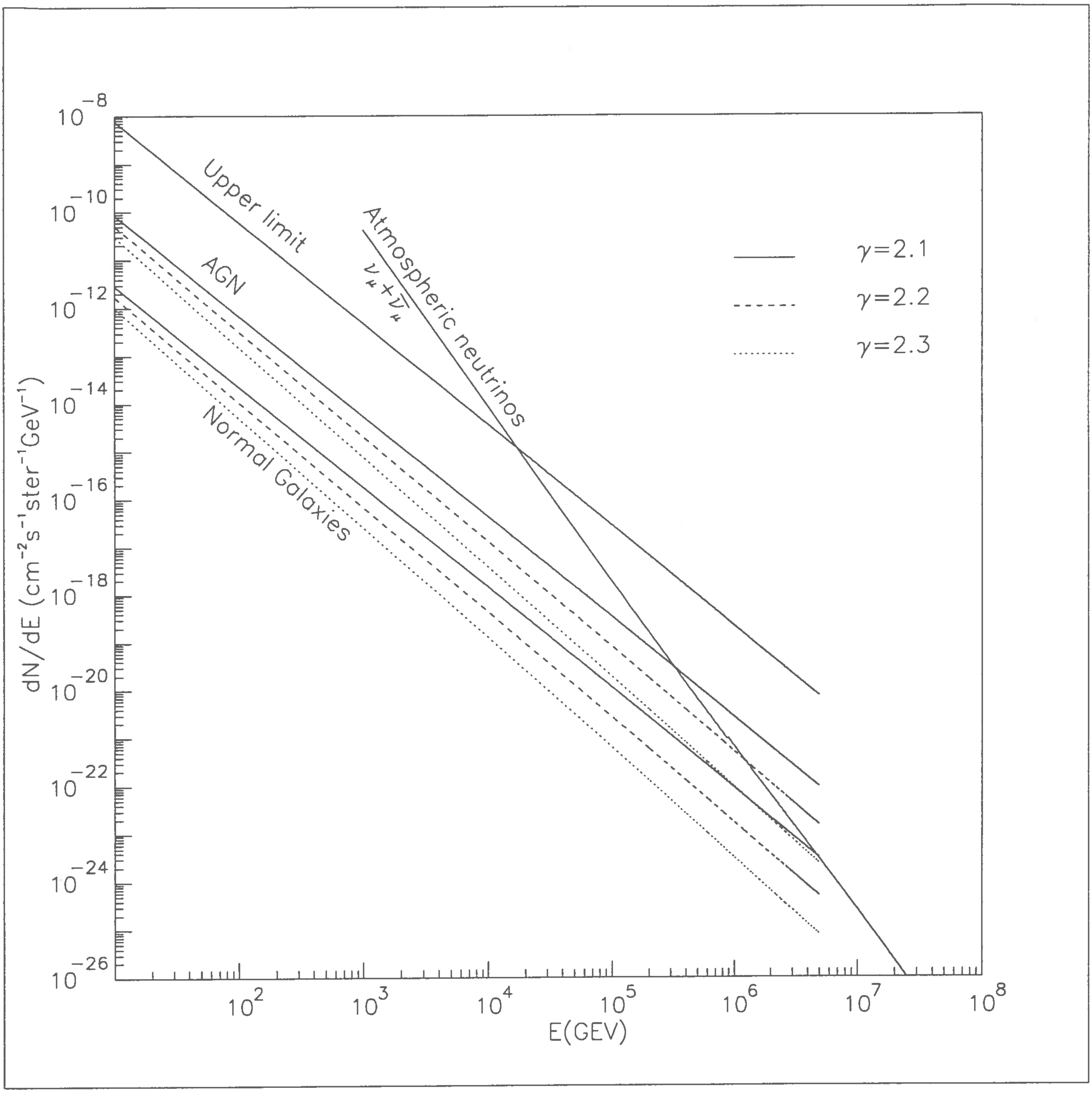
Fig. 1.— The diffuse neutrino flux due to the interactions of the CR produced by Normal Galaxies and AGN with the intracluster gas. The upper limit refers to the maximum neutrino flux correspondent to the observed diffuse gamma ray flux as produced in clusters. As a comparison the atmospheric neutrino flux is plotted with the prompt neutrinos taken into account.


Upper limit
Atmospheric neutrinos
$\nu_\mu + \bar{\nu}_\mu$
AGN
Normal Galaxies
$\gamma=2.1$
$\gamma=2.2$
$\gamma=2.3$
dN/dE (cm^{-2}s^{-1}ster^{-1}GeV^{-1})
E(GEV)
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
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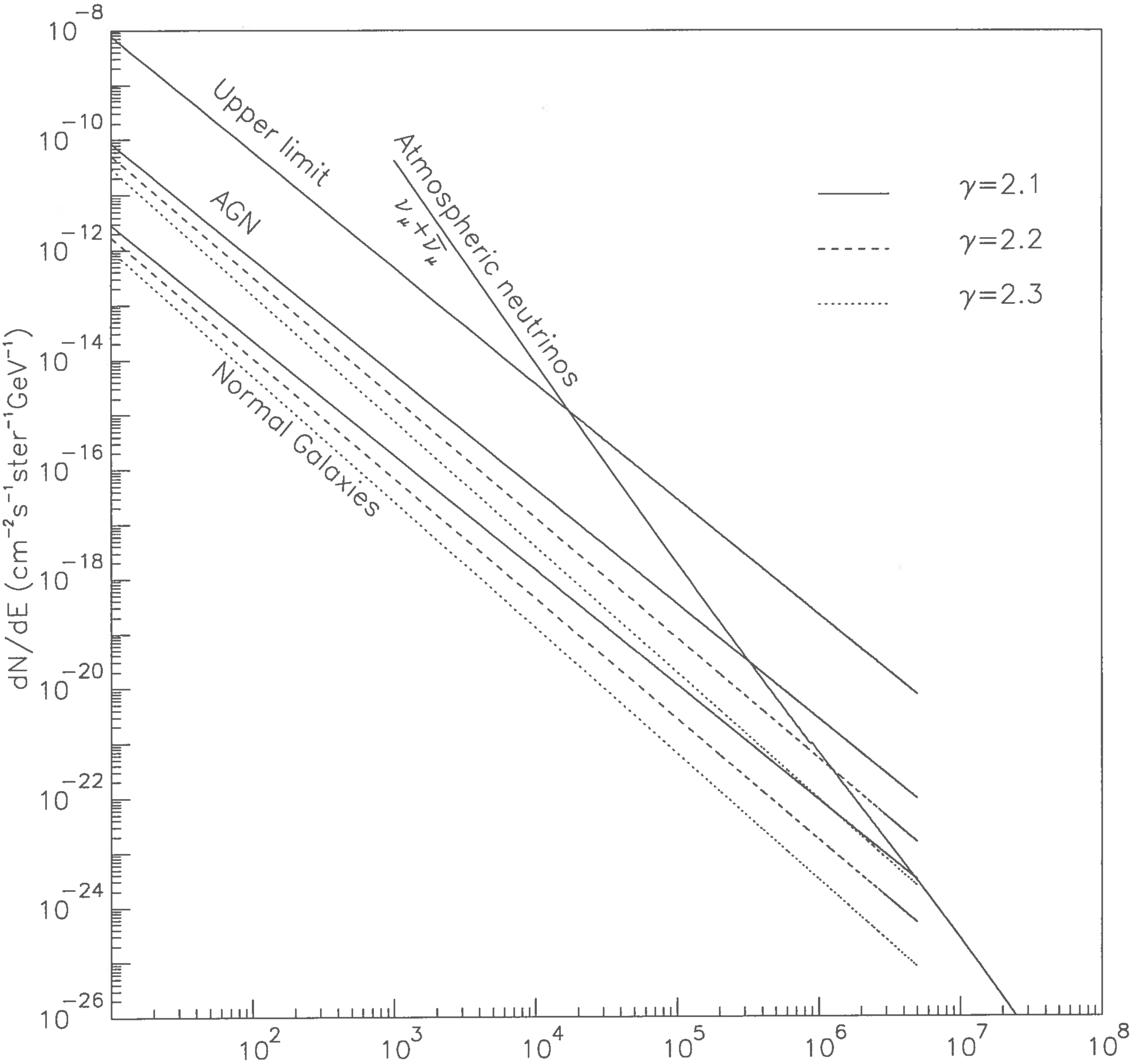
10^{7}
10^{8}



Upper limit
Atmospheric neutrinos
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γ=2.1
γ=2.2
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dN/dE (cm^{-2}s^{-1}ster^{-1}GeV^{-1})
E(GEV)
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{2}
10^{3}
10^{4}
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10^{7}
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