Effects of new long-range interaction: Recombination of relic Heavy neutrinos and antineutrinos

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Abstract

If stable Heavy neutrinos of 4th generation possess their own Coulomb-like interaction, recombination of pairs of Heavy neutrinos and antineutrinos can play important role in their cosmological evolution and lead to observable consequences. In particular, effect of this new interaction in the annihilation of neutrino-antineutrino pairs can account for $\gamma$-flux observed by EGRET.

1 Introduction

This work begins systematic study of model of subdominant component of dark matter in form of Heavy neutrinos in the special case when this component possesses its own long range interaction. It is supposed that new interaction is Coulomb-like, being described with unbroken $U(1)$-gauge group. We call it y-interaction. Its massless gauge boson and charge are called y-photon and y-charge, respectively. The existence of this interaction as well as of 4th generation (and 4th neutrinos), possessing it, can naturally follow from superstring inspired phenomenology. It is assumed according to that Heavy neutrino ($N$) belongs to new (4th) generation of fermions, that the electroweak and strong charges of 4th generation quarks and leptons are attributed analogously to other three Standard Model generations and that mass of 4th neutrino lies in range about $m = 45 - 80$ GeV. Strict conservation of y-charge implies the lightest fermion of 4th generation (4th neutrino) to be absolutely stable. Due to y-charge 4th neutrino cannot have Majorana mass, while its Dirac mass is of the order of other fermions of 4th generation. Thus y-interaction provides natural basis for the hypothesis of massive stable 4th neutrino. y-charge neutrality implies neutrinos to be accompanied by the same amount of antineutrinos.

In the early Universe effects of new interaction can influence the freezing out of y-charged 4th neutrinos. The existence of y-photons implies y-radiation background (y-background), interacting with y-charged neutrinos.

After decoupling from plasma and y-background 4th neutrinos and antineutrinos due to their long-range y-interaction can form bound systems. These bound systems annihilate rather quickly. Therefore such "recombination" of 4th neutrinos and antineutrinos (N-recombination) reduces their relic density and can lead to observable effects.
In the Galaxy, 4th neutrino pairs, being strongly subdominant component of Dark Matter (DM), can enter the clumps, formed by the dominant DM component and the enhancement of N-recombination in such clumps can lead to $\gamma$-flux, saturating high energy diffuse $\gamma$-background, observed by EGRET.

The existence of sufficiently longliving $y$-charged quarks of 4th generation \[3\] would add new element to the evolution of 4th neutrinos and the self-consistent picture for cosmological multi-component $y$-plasma requires separate consideration. Therefore we consider below the evolution and observable effects of 4th neutrinos and $y$-background only.

## 2 \ $y$-plasma and $y$-radiation in early Universe

In the early Universe at the temperature\(^1\) $T > m$ 4th neutrino pairs were in equilibrium with cosmological plasma, what lead to exponential decrease of their equilibrium concentration at $T < m$. When the annihilation rate became less than the rate of expansion (at $T_f \approx m/30$) 4th neutrino pairs were frozen out and their amount in the co-moving volume did not change essentially in the course of subsequent expansion. However, at lower temperatures, after decoupling of the frozen out $y$-charged 4th neutrinos from $y$-background, formation of bound systems neutrino-antineutrino (N-recombination) was possible.

Annihilation timescale of systems with the size $a_b$ bound due to interaction with the fine-structure constant $\alpha_y$ is given by

$$\tau_{ann} \sim \frac{m^2 a_b^3}{\alpha_y^2}$$

and it is quite short. Therefore such recombination is in fact equivalent to effective annihilation of neutrino pairs and it should reduce the number density of primordial 4th neutrinos.

Let us first consider the influence of $y$-interaction on the process of freezing out (at $T \sim m/30$) of 4th neutrinos. New interaction opens new channel of 4th neutrinos annihilation, which is analogous to $2\gamma$-annihilation of $e^+e^-$

$$N\bar{N} \rightarrow yy.$$  \hspace{1cm} (2)\hspace{1cm}

Furthermore for slow 4th neutrinos and antineutrinos (with relative velocity $v < 2\pi\alpha_y$) it leads to the increase of cross section of all their annihilation channels, including one via intermediate $Z$-boson ($N\bar{N} \rightarrow Z \rightarrow ...$), due to Coulomb-like factor of Sakharov enhancement

$$C = \frac{C_0}{1 - e^{-C_0 v}}$$

where $C_0 = \frac{2\pi\alpha_y}{v}$. \hspace{1cm} (3)\hspace{1cm}

At neutrino mass of interest ($m \sim 50$ GeV) channel $N\bar{N} \rightarrow Z \rightarrow ...$ is close to resonance ($m_{res} = m_Z/2 \approx 46$ GeV). Therefore the effect of channel (2), being suppressed near $m_{res}$, grows with the deviation of $m$ from $m_{res}$.

The ratio of cross sections of annihilation channels of (2) and through $Z$-boson in non-relativistic limit is independent of Coulomb factor and given by

$$\frac{\sigma_{yy}}{\sigma_Z} \approx 0.144 \left(\frac{\alpha_y}{1/30}\right)^2 \frac{P_Z(m)}{P_Z(50 \text{ GeV})},$$

where $m_Z$ and $\Gamma_Z$ are the mass and the width of $Z$-boson, $P_Z(50 \text{ GeV}) \approx 0.0289$. Effect of Coulomb factor also does not lead to the principle change, since at $T \sim m/30$ velocity of 4th neutrinos is still large.

Number density of 4th neutrinos $n$ can be expressed through its ratio $r$ to the entropy density $s$

$$n = rs = r \frac{2\pi^2 g_s T^4}{45},$$

where $g_s$ takes into account all the species of ultrarelativistic bosons and fermions and $T$ is the temperature of photons.

\(^1\)Throughout in the text the system of units $\hbar = c = k = 1$, where $k$ is the Boltzman constant, is used.
Figure 1: Number densities of 4th neutrinos frozen out at $T \sim m/30$ in units of entropy density for the cases without and with $y$-interaction with different magnitudes of its constant.

On the figure 1 the frozen out number density of 4th neutrinos ($r = \frac{2}{7}$) is presented. Both effects of channel (2) and Sakharov enhancement induce correction of density of 4th neutrinos within the factor 2-10.

After freezing out the gas of 4th neutrino pairs is for some period in thermal equilibrium with ambient ordinary matter and $y$-photon background.

$y$-background has direct thermal exchange with 4th neutrino pairs only and due to their small frozen out concentration it can not experience essential thermal exchange and be in thermal equilibrium with other matter (ordinary plasma and radiation) at $T < T_y$. In the course of successive evolution the number density of $y$-photons reduces relative to that of photons by a factor $\kappa < 1$. Due to entropy conservation, the less species remain in equilibrium with radiation, the smaller is the value of $\kappa$. In the period of Big bang nucleosynthesis (at $T \sim 1$ MeV) $\kappa \approx \frac{1}{6.5}$, and $y$-radiation can not influence significantly the predictions for light element abundance.

4th neutrinos interact with each other due to long-range $y$-interaction. This interaction with a large, Rutherford-like cross section provides their equilibrium (Maxwell) distribution, whatever energy losses or/and exchanges with other matter components they experience.

Before decoupling of 4th neutrinos from $y$-radiation their temperature $T_N$ was equal to that of $y$-photons, i.e. $T_N \approx \kappa^{1/3}T$. After decoupling of 4th neutrinos from $y$-background (at $T \ll T_{Ny}$) their temperature

$$T_N = \frac{T^2}{T_{Ny}}, \quad T_{Ny} \approx 22 \text{ keV} \left(\frac{m}{50 \text{ GeV}}\right)^{3/2} \frac{1/30}{\alpha_y}.$$  

The probability for 4th neutrinos and antineutrinos to form their bound states grows when particles slow down, so at $T \ll T_{Ny}$ the rate of this process increases. For estimation of this effect we will use classical approximation following [4]. $N$ and $\bar{N}$ moving towards each other due to $y$-attraction must experience dipole emission of $y$-radiation. If this radiative energy loss exceeds the initial energy of their relative motion, they become bound. The typical length for such energy loss is much less than the mean distance between 4th neutrinos ($a {\text{fortiori}} \text{Debye radius of } N\text{-plasma}$), and the timescale for this energy loss is much less than the timescale of N-N and N-$y$ interactions. It provides such binding to proceed freely, independent of other interaction processes. Cross section of bound system formation in this approach [5] is obtained to be

$$\sigma_b = \pi \rho_b^2(v) = \frac{(4\pi)^{7/5} \alpha_{cl}^2}{v^{14/5}},$$

where $\rho_b$ is the maximal impact parameter at which $N\bar{N}$ pair is bound due to $y$-radiative energy loss, $v$ is the initial $N\bar{N}$ relative velocity and $a_{cl} = \alpha_y/m$.

The rate of binding with cross section having the form $\sigma_b = \sigma_0/v^\beta$ for particles, distributed by Maxwell,
\[ \Gamma_{\text{rec}} = \langle \sigma b v \rangle n = \frac{4 \Gamma(2 - \frac{\beta}{2})}{2^{\beta \sqrt{\pi}}} \sigma_0 \left( \frac{m}{T_N} \right)^{\frac{\beta+1}{2}} r_s, \]  \tag{8}

After \( N - y \) decoupling \( \Gamma_{\text{rec}} \) exceeds the expansion rate \( H \) at \( T \) below

\[ T_{\text{rec}} \approx 15 \text{ keV} \left( \frac{m}{50 \text{ GeV}} \right)^{\frac{5}{18}} \left( \frac{\sigma_y}{1/30} \right)^{\frac{3}{2}} \left( \frac{r_{\text{rec}}}{1.22 \times 10^{-10}} \right)^{\frac{3}{2}} \]  \tag{9}

In this expression \( r_{\text{rec}} \) denotes the value of \( r(m, \sigma_y) \) before recombination starts, being determined by fig.1, and \( r(50 \text{ GeV}, 1/30) = 1.22 \times 10^{-15} \).

The most of created bound systems have typical size less than \( \rho_b \sim a_{\text{cl}}/\sqrt{7/15} \sim a_{\text{cl}}(m/T_N)^{7/10} \); and their annihilation timescale Eq.(1) turns out to be much less than the timescale of their destruction as well as than cosmological timescale.

During recombination, 4th neutrino gas will be effectively heated, since slow pairs recombine more effectively and disappear. From the other hand, due to dipole emission of \( N\bar{N} \) pairs scattered at \( \rho > \rho_b \) without binding, \( N\bar{N} \)-gas cools down. Evolution of 4th neutrino pairs with the account for the both thermal effects can be described by the system of equations

\[ \begin{cases} \frac{d\theta}{dt} = \langle \sigma_b v \rangle \frac{\theta^2}{m} \\ \frac{dT}{dt} = -\frac{\bar{\theta}}{4} \frac{\sigma}{T_N} \left( \frac{\frac{3}{2} T_N - E - \frac{1}{3} E_{\text{rel}} \sigma_b v}{T_N^2} \right) \frac{r_{\text{rec}}}{T_N} \end{cases} \]  \tag{10}

Here variable \( \theta \) shows deviation of neutrino temperature from Eq.(6) due to thermal effects, \( E \) and \( E_{\text{rel}} \) are the kinetic energy of a single neutrino (or antineutrino) and of relative motion in \( N\bar{N} \) pair, respectively.

\[ \langle \frac{3}{2} T_N - E - \frac{1}{3} E_{\text{rel}} \sigma_b v \rangle = \frac{3}{2} \gamma \langle \sigma_b v \rangle T_N, \]  \tag{11}

where \( \gamma = \frac{5\beta - 11}{18} = \frac{1}{6} \). Note that the terms \( \langle \frac{3}{2} T_N - E \sigma_b v \rangle \) and \( \langle -\frac{1}{3} E_{\text{rel}} \sigma_b v \rangle \) in Eqs.(10,11) describe thermal effects due to pair disappearance (heating at \( \beta > 1 \)) and due to dipole emission (cooling), respectively, and the first one prevails (\( \gamma > 0 \)). The system (10) can be solved by iterations (dividing the first equation by the second equation one gets \( \theta(\beta) = r_{\text{rec}} \theta^{-1/\gamma} \) and then substitutes this value into the system again). It gives for \( r \) at RD stage (at \( T > T_{\text{RM}} \approx 1 \text{ eV} \))

\[ r = \frac{r_{\text{rec}}}{\left[ 1 + F_R(T, T_{\text{rec}}) \right]^{1/\gamma}} \]  \tag{12}

and at MD stage (at \( T < T_{\text{RM}} \))

\[ r = \frac{r_{\text{rec}}}{\left[ 1 + F_R(T_{\text{RM}}, T_{\text{rec}}) + F_M(T, T_{\text{RM}}) \right]^{1/\gamma}} \]  \tag{13}

The functions \( F_{R,M} \) have the form

\[ F_{R,M}(T, T_0) = r_{\text{rec}} \frac{\bar{\gamma}}{\beta_{R,M}} D_{R,M} \left( \frac{1}{T_{\beta_{R,M}}} - \frac{1}{T_0^{\beta_{R,M}}} \right). \]  \tag{14}

Here \( \beta_R = \beta - 2 = \frac{5}{6}, \beta_M = \beta - \frac{5}{2} = \frac{3}{10}, \bar{\gamma} = 1 + \gamma \frac{\beta - 1}{2} = \frac{23}{20} \),

\[ D_R = D_M \sqrt{T_{\text{RM}}} = \langle \sigma_b v \rangle \left( \frac{\theta T^3}{H_R} \right)^{\frac{\beta - 1}{2}} \approx 1.6 \times 10^{13} \text{ eV}^\frac{1}{2} \left( \frac{m}{50 \text{ GeV}} \right)^{\frac{1}{2}} \left( \frac{\sigma_y}{1/30} \right)^{\frac{3}{2}} \].  \tag{15}

Hubble constants on RD and MD stages are related as

\[ H_R = H_M \sqrt{\frac{T}{T_{\text{RM}}}} = \sqrt{\frac{4\pi^3 g_{\text{eff}} T^2}{45}}, \]

where \( g_{\text{eff}} \) takes into account contribution into energy density of all ultrarelativistic species. At \( T \ll T_0 \) the term \( 1/T_0^{\beta_{R,M}} \) in Eq.(14) can be neglected. Also \( 1 + F_R \) can be neglected in Eq.(13). Note that without the account for thermal effects \( (\theta - 1) \bar{\gamma} = 1 \).
Figure 2: Relic densities of 4th neutrinos in units of critical density for the cases with recombination, without it and without $\gamma$-interaction at all. $\alpha_y = 1/30, 1/60$ were taken.

In the period of galaxy formation gas of 4th neutrino pairs becomes strongly nonhomogeneous. Since the contribution of 4th neutrinos into the total density is negligible, they cannot play dynamically important role and follow the dominant component of dark matter in the process of development of gravitational instability. That is why evolution of 4th neutrinos in this period strongly depends on the model of galaxy formation. According to CDM model of galaxy formation at $z \sim 10 - 20$ the distribution of Dark matter becomes strongly non-homogeneous at small scales. Such structure can not appear in the model of Hot Dark Matter, which is however strongly disfavoured by the observational data.

In the course of development of gravitational instability the fraction of particles, which remain outside the structure of nonhomogeneities decreases with time. Therefore N-recombination in homogeneous gas of 4th neutrino turns out to be suppressed, when galaxies began to form at $T = T_{fin} = 10 T_{mod}$, where $T_{mod} = 2.7$ K. Recombination of 4th neutrinos in Galaxy with the account for small scale nonhomogeneity (clumpiness) of their distribution is considered in Section 4.

On Figure 2 the relic densities of 4th neutrinos are shown in units of critical density for $\alpha_y = 1/30$ and $1/60$. For comparison such densities without effects of recombination and without $\gamma$-interaction at all are put on Fig.2.

If (meta-)stable quarks of 4th generation (Q) exist and possess $\gamma$-charge, they represent another component of $\gamma$-plasma, and joint evolution of $\gamma$-charged N and Q should be studied. However, preliminary analysis indicates that there is a range of Q-gas parameters, at which presence of Q-component does not influence significantly the main features of N-recombination in early Universe.

### 3 $\gamma$-emission from recombination of primordial 4th neutrinos

Among the products of N-recombination (and annihilation) on RD stage only ordinary (light) neutrinos can survive to the present time. Their maximal modern energy, being red-shifted from the period of such early N-recombination, does not exceed few MeV. It makes their relatively small flux hardly detectable in neutrino observatories.

Hadronic and electromagnetic cascades induced by N-recombination interact with the ordinary plasma and radiation. The energy, realized in such interaction leads to distortion of CMB spectrum. If energy release in a unit volume exceeded $10^{-4}\varepsilon_{\gamma}$ and took place later than at $T \approx 5$ keV [9], it would be observed in CMB spectral measurements. Total energy realized in the result of recombination at $T < 5$ keV is given by

$$\frac{\delta\varepsilon}{\varepsilon_{\gamma}} < \frac{2ms(5\text{ keV})r(5\text{ keV})}{\varepsilon_{\gamma}(5\text{ keV})} \approx 2.5 \cdot 10^{-8} \left(\frac{5\text{ keV}}{T}\right)^{7\gamma} \left(\frac{r_{rec}}{1.22 \cdot 10^{-18}}\right)^{7\gamma} \left(\frac{50\text{ GeV}}{m}\right)^{5\gamma} \left(\frac{1/30}{\alpha_y}\right)^{2\gamma}. \tag{16}$$

This estimation makes annihilation effects be hardly constrained by the data on CMB.
If N-recombination proceeds on MD stage, \( \gamma \)-radiation induced by annihilation in this period will contribute into extragalactic \( \gamma \)-emission in the energy range measured by EGRET.

During N-recombination, within interval, when Universe temperature falls down on \( dT \), \( s \cdot dr \) pairs of \( N\bar{N} \) in unit volume annihilate, where \( dr \) is given by Eq. (10).

Let \( B_Z = \frac{1}{1 + \sigma_{yy}} \) be fraction of annihilation acts going through the channel \( N\bar{N} \to Z \to \ldots \), being determined with the help of Eq. (5), and \( dN_\gamma(E_0) = f_\gamma(E_0)dE_0 \) be averaged multiplicity of created \( \gamma \) in this channel within energy interval \( E_0 \ldots E_0 + dE_0 \). Due to redshift modern energy \( E \ldots E + dE \) of photons emitted at the temperature \( T \) (redshift \( z \)) is given by

\[
E_0 = (z + 1)E = \frac{T}{T_{mod}}E,
\]

Taking into account that number density evolves as \( \propto s \), for modern number density of \( \gamma \) products of early \( N\bar{N} \) annihilation we have

\[
dn_\gamma(E) = B_Z \cdot dN_\gamma(E_0) \cdot s(T_{mod}) \cdot dr(T) = B_Z s_{mod} \cdot f_\gamma(E_0(T, E)) \frac{T}{T_{mod}}dE \cdot r'_TdT,
\]

where \( r'_T = \frac{dT}{dT} \), \( s_{mod} = s(T_{mod}) \approx 3 \times 10^3 \text{ cm}^{-3} \). One can pass from integration \( dT \) to \( dE_0 \). For intensity from Eq. (18) we have

\[
I_\gamma(E) = \frac{c}{4\pi} \frac{dn_\gamma}{dE} = \frac{B_Z s_{mod} C T_{mod}}{4\pi E^2} \int_{T_{mod}E_0}^{E_{0\max}} f_\gamma(E_0) \cdot r'_T(T(E, E_0)) \cdot E_0dE_0.
\]

Here \( E_{0\max} \) is the upper limit of annihilation \( \gamma \)-spectrum, \( c \) is the light speed. The relationship between \( E_0 \), \( E \), \( T \) is given by Eq. (17).

Using results of previous section one obtains intensity of \( \gamma \)-radiation from primordial 4th neutrino recombination given on Figure 3 for different values of \( m \) and \( \alpha_y \). EGRET data on extragalactic \( \gamma \)-radiation are shown for comparison. Spectra \( f_\gamma(E_0) \) had been obtained with the help of code PYTHIA 6.2.

Effect of \( T_N \) variation (growth) due to disappearance of slow pairs and to dipole emission was taken into account here. This effect raises the predicted \( \gamma \)-flux by factor 2-3.

The growth of \( T_N \) reduces \( \langle \sigma \phi \rangle \), what seem to contradict the mentioned increase in the predicted \( \gamma \)-flux. The fact is that we are interested in annihilation effects produced on the late stages of N-recombination. Indeed, since the maximal energy of the created \( \gamma \) is equal to the mass of 4th neutrino, annihilation photons, born in period \( T < 2000 \text{K} \), contribute to the energy range of EGRET. To this period the bulk of the primordial 4th neutrinos had been annihilated, so the net effect in the interested range is proportional integrally not to the initial \( r_{rec} \), but to their residual number density, which is in the inverse dependence on
\( \sigma_b v \). By the same reason the inverse dependence of predicted \( \gamma \)-flux on \( \alpha_y \) is explained, being explicitly given by \( I_{\gamma}(\alpha_y) \propto r_{\gamma}^2(\alpha_y)B_Z(\alpha_y) \propto \alpha_y^{-2} \gamma r_{\gamma\gamma}(\alpha_y)B_Z(\alpha_y) \).

Comparison with EGRET data restricts the allowed values of \( \alpha_y \) as \( \alpha_y > 1/137 \) for \( m = 50 \text{ GeV} \). This constraint becomes slightly more severe for larger \( m \).

Note that the products of N-recombination at \( T < 2000 \text{ K} \) can provide early ionisation of neutral matter gas, which is favoured by WMAP data.

4 Effects of \( \gamma \)-charged 4th neutrinos in Galaxy

Due to their negligible contribution into the cosmological density (see Fig.2), 4th neutrino cannot play any significant role in the dynamics of galaxy formation. Their distribution in Galaxy will be governed by the dominant DM component, which we assume to be CDM, for definiteness. In the gravitational potential of Galaxy 4th neutrinos acquire large virial velocities \( u \sim 200 \text{ km/s} \). It strongly reduces the rate of their recombination so that the corresponding timescale highly exceeds the age of the Universe \( t_{\text{mod}} \). However, the typical lifetime of created bound systems in Galaxy is much less than \( t_{\text{mod}} \) and slow N-recombination can produce \( \gamma \)-flux, accessible to observations.

Assume that 4th neutrinos are distributed in Galaxy according to isothermal halo model with density profile

\[
\rho(R) = \rho_{\text{N loc}} \frac{(1 \text{kpc})^2 + (8.5 \text{kpc})^2}{(1 \text{kpc})^2 + R^2},
\]

where \( R \) is the distance to the galactic center, \( \rho_{\text{N loc}} = \xi \cdot 0.3 \text{ GeV/cm}^3 \). The distribution is determined by the dominant CDM component and the 4th neutrino density is taken to follow it, being proportional to the ratio \( \xi \) of 4th neutrino and dominant CDM densities. Velocity distribution is assumed to be Maxwellian with the maximal likelihood value \( u = 220 \text{ km/s} \). It turns out that the \( \gamma \)-flux, predicted for various halo models is rather weakly sensitive to their choice, varying within a factor 1-2.

The account for small scale inhomogeneity (clumps), of dominating Cold Dark Matter (CDM) strongly enhances the predicted \( \gamma \)-flux from N-recombination. The possibility of such a small scale structure and its survival to the present time is determined by primordial perturbation spectrum and on dynamics of galaxy formation. We will take into account by parameter \( \eta \) the enhancement of N-recombination (annihilation) rate due to clumpiness. In the case of 4th neutrinos such enhancement can be much larger, than for non-interacting DM particles, since 4th neutrino annihilation in clumps goes through N-recombination, which is enhanced not only due to increase of concentration, but also (and dominantly) owing to much smaller virial velocities of 4th neutrinos inside the clump, as compared with their averaged density and velocity distributions in the Galaxy.

The following effects are important in the estimation of parameter \( \eta \).

Since clumps are formed by the dominating CDM particles, the minimal mass of such clumps is determined by the ultraviolet cut in the spectrum of their density fluctuations, which is determined for weakly interacting particles by the scale of their free streaming. As in \( \Omega \) we’ll use the results of 7 in the description of such CDM clumps. The existence of the period of thermal equilibrium with ordinary matter and \( \gamma \)-radiation makes gas of 4th neutrino hotter, than ordinary CDM gas. It prevents 4th neutrinos from entering the smallest CDM clumps and there exists the minimal mass of CDM clump, in which the presence of 4th neutrinos is not suppressed. This critical minimal mass is estimated to be equal to

\[
M_{N \text{min}} \approx 10^{-2} M_\odot \left( \frac{50 \text{ GeV}}{m} \right)^{15/4} \left( \frac{\alpha_y}{1/30} \right)^{3/2}, \tag{21}
\]

where \( M_\odot \) is the solar mass. Following 11 we can suppose that 4th neutrino density distribution at scales larger than \( M_{N \text{min}} \) is proportional to that of CDM, so their relative contribution is \( \Omega_N = \Omega_{CDM} = 0.3 \). Radius of clump with \( M = M_{N \text{min}} \) is equal to

\[
R \approx 3 \cdot 10^{17} \text{ cm} \left( \frac{50 \text{ GeV}}{m} \right)^{5/4} \left( \frac{\alpha_y}{1/30} \right)^{1/2}. \tag{22}
\]
Typical velocity of particles inside the clump with $M = M_{N \text{min}}$ is determined by

$$u_{cl} = \sqrt{\frac{GM_{N \text{min}}}{R}} \approx 19 \text{ m/s.} \quad (23)$$

We will assume that this velocity parameter is constant over all the volume of clump. Here we do not consider the possibility for 4th neutrinos to enter the clumps of mass less than $M_{N \text{min}}$, which was considered in [1].

Clumps of mass around the minimal one give the main contribution into the annihilation enhancement effect. The shape of the number density distribution $n$ inside the clump determines the effect of annihilation by the factor

$$S = \frac{V}{N^2} \int n^2 dV, \quad (24)$$

where $V = \frac{4}{3} \pi R^3$, $N = \int n dV$ is the total amount of given particles inside the clump; $\bar{n} = \frac{N}{V}$ gives the mean number density.

In case of 4th neutrinos, annihilation rate strongly increases due to its velocity dependence so their number in clump can experience essential change. In our study of evolution of 4th neutrinos in the clump we will take into account effects of heating due to slow pairs disappearance and of dissipation due to dipole emission (the latter turns to be less important, than the former). Parameter Eq. (23) is connected with the initial temperature of N: $T_{N0} = \frac{m_N^2}{2\pi}$. Any decrease of the total number of 4th neutrinos in the clump does not affect its gravitational potential and mass, being determined by dominant DM component. We will assume that the shape of distribution of 4th neutrinos inside the clump does not alter with time, and that the value of the factor (24) for 4th neutrinos can be taken the same as for non-interacting DM, which was estimated in [7] to be $S \approx 5$. Then for total amount of 4th neutrinos inside the clump one has

$$\begin{aligned}
\dot{N}_{\text{ann}} &= \int \left\{ \frac{dN}{dt} = -\langle \sigma v \rangle N^2 \right\}^2 dV, \\
\frac{3}{2} dN_{\text{ann}} &= \langle (\frac{3}{2}T_N - E - \frac{1}{5}E_{\text{rec}}) \sigma_b v \rangle N S, \\
\end{aligned} \quad (25)$$

Solution of this system is analogous to that of Eqs. (11) and yields

$$N = N_0 \left( \frac{T_{N0}}{T_N} \right)^{\frac{3}{2}}, \quad T_N = T_{N0} \left( 1 + \frac{t - t_0}{\tau} \right)^{1 + \frac{3}{\gamma}}, \quad \tau = \frac{1}{\gamma \langle \sigma_b v \rangle_0 \bar{n}_0 S}. \quad (26)$$

Here $\dot{N}_{\text{ann}}$ means the total annihilation rate given by first equation of system (25). Index "0" corresponds to the initial moment $T_N = T_{N0}$. The mean number density of 4th neutrinos in the clump and characteristic time of recombination in it $\tau$ are estimated as

$$\bar{n}_0 \approx 1.8 \cdot 10^{-8} \text{ cm}^{-3} \frac{\xi}{230} \left( \frac{50 \text{ GeV}}{m} \right)^{\frac{3}{2}}, \quad \tau \approx 0.20 \text{ Gyr} \left( \frac{m}{50 \text{ GeV}} \right)^{\frac{3}{2}} \left( \frac{1/30}{\alpha_y} \right)^{\frac{11}{10}}, \quad (27)$$

where $\xi(m = 50 \text{ GeV}, \alpha_y = 1/30) = 2.3 \cdot 10^{-8}$ was used; note that $\xi(50, 1/137) = 1.1 \cdot 10^{-7}$. Neglecting the dependence of $\tau$ on $r_{\text{rec}}$, one obtains $\xi \propto m^{18/23} \alpha_y^{22/23}$, so $\tau$ is almost independent of $m$ and $\alpha_y$.

The obtained value of $\tau$ exceeds the clump dynamical timescale $\sim R/u_{cl} \approx 0.005$ Gyr what provides the shape of 4th neutrinos distribution to follow the "equilibrium" form inside the clump. However, the temperature $T_N$ during $t - t_0 \approx 10$ Gyr becomes 2 times larger. It implies that for the "equilibrium" form of N distribution the effect of N evaporation can be important. It can lead to the slowing down of annihilation rate in the clump as compared with the above estimation.

Enhancement factor $\eta$ for 4th neutrinos, corresponding to the present moment may be estimated as

$$\eta = \eta_0 \left( \frac{u_{cl}}{u_{cl}} \right)^{9/5} \left( \frac{\tau}{t - t_0} \right)^{1 + \frac{3}{\gamma}} \left( \frac{m}{50 \text{ GeV}} \right)^{9/4} \left( \frac{1/30}{\alpha_y} \right)^{9/10}. \quad (28)$$

Here the factor $\eta_0 \propto \bar{n}_{cl}^2/\bar{n}_{Gal}^2$ (i.e. proportional to the ratio of averaged squared number densities of DM particles inside the clumps and steeply distributed in Galaxy) denotes the enhancement of annihilation of
Figure 4: $\gamma$-fluxes from recombination of 4th neutrinos in early Universe and in Galaxy with enhancement factor 200 in comparison with EGRET data for $\alpha_y = 1/137$ and $m = 50$ GeV.

non-interacting DM in clumps. From figures 3-5 of [7] one obtains its value in the range $1 \leq \eta_0 \leq 5$ for $M_{min} = M_{N_{min}}$.

The estimation (28) does not take into account the mass spectrum of clumps. The latter is predicted to start from the minimal value $M = M_{min}$ and to fall down with the increase of $M$. The account for this mass distribution of clumps will slightly decrease the value of $\eta$. Indeed, in Eq.(28) the $u_{cl}$ dependence on $M$ gives additional suppression $\propto M^{-3/5}$.

Active annihilation of 4th neutrinos inside the clumps after they separate from the cosmological expansion at $z \sim 10 - 20$ contributes into the intergalactic $\gamma$-background. However, in the period of clump formation, when the density inside the clumps is of the same order as the average density ($\delta \rho/\rho \sim 1$), this contribution cannot exceed the effect of N-recombination by homogeneously distributed 4th neutrinos. During the successive periods of galaxy formation the amount of neutrinos inside the clumps decreases due to their annihilation, while homogeneously distributed neutrinos enter the inhomogeneities and their fraction reduces with time. It leads to the suppression of extra-galactic contribution into the high energy part of gamma background as compared with the local effect of N-recombination in clumps of the halo of our Galaxy.

Intensity of the modern $\gamma$ radiation from annihilation of 4th neutrinos in the direction $\vec{l}$ to halo of Galaxy is determined by

$$I(E) = \eta \cdot \frac{B_Z(\alpha_y)}{4\pi} f_\gamma(E) \int_0^\infty \left( \frac{\rho}{m} \right)^2 dl.$$  

For $m = 50$ GeV, $\alpha_y = 1/137$ with factor $\eta \approx 200$ one obtains $\gamma$-flux shown on Figure 4.

To saturate the high energy part of EGRET data at larger values of $\alpha_y$, a slightly larger factor $\eta$ is required. For instance, if $\alpha_y = 1/30$ (at $m = 50$ GeV), $\eta \approx 240$. Such a weak sensitivity of the predicted galactic $\gamma$-flux to the value of $\alpha_y$ follows from the fact that this flux depends on $\alpha_y$ virtually only through such dependence of $B_Z$. The latter is weak for the values of $m$ close Z-boson resonance. It strongly differs from the case of primordial recombination, where in addition neutrino velocity depends on $\alpha_y$ through $T_{Ny}$. That is why a slight change of the factor $\eta$ can easily compensate the decrease of $B_Z(\alpha_y)$ for larger $\alpha_y$.

5 Discussion

The existence of new long range interaction would lead to new forms of matter, such as $y$-plasma and to a set of new phenomena, in which N-recombination, considered in the present paper plays important role.

In the considered case of $y$-charged 4th neutrinos N-recombination suppresses strongly the pre-galactic density of this subdominant component of Dark Matter, but appears possible to explain all the data on extragalactic $\gamma$-emission observed by EGRET by the effect of N-recombination for $m \approx 50$ GeV and $\alpha_y \approx 1/100$. 

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It should be noted that in the framework of Grand Unification (GUT) models the value of $\alpha_y$ can hardly be less than $\alpha_{em} = 1/137$. Moreover, such a small value of $\alpha_y$ implies rather specific requirements for GUT model, which embeds $y$-interaction. Indeed, $y$-interaction, being possessed by 4th generation fermions only, should be unified with other interactions at large energy scale. Therefore one can expect that it should have constant at low energies greater than electromagnetic one, since the last is reduced from the unified (GUT) constant due to screening by virtual particles of all the four generations.

The future theoretical model, which will embed the considered here new long range U(1) interaction, should satisfy a set of necessary conditions, such as anomaly freedom of $y$-interaction. The $y$-charge assignment $e_y$ of 4th generation particles (N, E, U, D) like $e_yN = e_yE = -e_yU/3 = -e_yD/3$ would avoid triangle anomalies within Standard Model field content extended to four generations. However, triangle anomaly problem, as well as the possible effects of $y$-$\gamma$, $y$-$Z$ mixings should be considered within a unified framework. To avoid theoretical inconsistencies such framework can involve possible extension of particle content (SUSY partners, exotics of $E_6$ superstring inspired GUT model, etc.), what requires separate study.

Taking into account these theoretical problems, the present analysis has no aim to give any final conclusion. It just opens the room for the systematic search for WIMPs, possessing new long range forces. One can apply to these searches the methods, developed in this work. One can hardly imagine the impact of the existence of such particles. Reminding Zeldovich, we can only repeat his words: "Though the probability for these phenomena is small, their expectation value is great!"

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