Galactic Gamma halo by heavy neutrino annihilations?

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Abstract

The diffused gamma halo around our Galaxy recently discovered by EGRET could be produced by annihilations of heavy relic neutrinos $N$ (of fourth generation), whose mass is within a narrow range $(M_Z/2 < m_N < M_Z)$. Neutrino annihilation in the halo may lead to either ultrarelativistic electron pairs whose Inverse Compton Scattering on infrared and optical galactic photons could be the source of observed GeV gamma rays, or prompt 100 MeV - 1 GeV photons (due to neutral pion secondaries) born by $N\bar{N} \rightarrow Z \rightarrow q\bar{q}$ reactions. The consequent gamma flux ($10^{-7} - 10^{-6} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$) is well comparable to the EGRET observed one, and it is also compatible with the narrow window of neutrino mass $45 \text{GeV} < m_N < 50 \text{GeV}$, recently required to explain the underground DAMA signals. The presence of heavy neutrinos of fourth generation do not contribute much to solve the dark matter problem of the Universe, but may be easily detectable by outcoming LEP II data.

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1 Introduction

The surprising recent discovery of a diffused galactic gamma halo [1] could be explained by the presence at high galactic latitudes either of a diffused high energy cosmic ray sources (for instance fast running pulsars "Geminga" like [2]), or by the presence of neutral molecular clouds [3,4] at large galactic latitude, where high energy protons (tens of GeV) collide. However these two (ad hoc) solutions are not widely accepted and are not the unique ones.

The presence of heavy relic neutrinos of new fourth generation in the galactic halo and their annihilations may offer an elegant solution to the gamma ray halo origin.

Actually a fashionable candidate of a cold dark matter scenario is the neutralino, the lightest stable supersymmetric particle in the Minimal Supersymmetric Standard Model. However it doesn’t seem that neutralino could be in general an acceptable candidate as a source of gamma rays in the halo [1], mostly because its annihilations in light fermion pairs, due to its Majorana nature, are required to be in the \( p \) wave, as a consequence of Fermi statistics. At low energy the cross section is suppressed by a factor \( \beta^2 \) (\( \beta \) is neutralino velocity in the Galaxy), in comparison with \( s \) wave, and the resulting gamma flux could not be comparable with observations (below several order of magnitude) unless we introduce a model of a clumpy galactic halo, whose clustering processes is arbitrary and mysterious.

However being \( \sigma \sim m_\chi^2 [\beta^2 + (m_f/m_\chi)^2] \), annihilations in heavy fermions (\( c\bar{c}, b\bar{b}, t\bar{t} \) and the channels \( W^+W^-, ZZ, gg \)) are not \( \beta^2 \) suppressed, but the resulting gamma flux (obtained by Monte Carlo simulations) would still be less than \( 10^{-8} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \) in the range of masses with \( 0.025 < \Omega_\chi < 0.5 \) [5].

On the contrary heavy Dirac neutrino of a fourth generation, at masses \( m_N > M_Z/2 \), while not being able to solve all the dark matter problem in the galactic halo, could annihilate (more easily than neutralino) into fermions by \( s \) wave channel (with no \( \beta^2 \) suppression). Their relics produce either directly gammas by neutral secondary pions, or gamma rays by ICS of relativistic electrons (primaries or as secondary decay products of heavier leptons in the annihilation chains \( N\bar{N} \rightarrow l\bar{l} \rightarrow e^+e^- \)) onto thermal photons (\( IR, optical \)) near and above the galactic plane.
The estimated flux we derived here is roughly close to EGRET results in the hypothesis of a smooth and homogeneous galactic halo. Moreover heavy neutrino annihilations may also produce long life antiprotons (as well as unstable antineutrons), whose further annihilations on common protons (gas, plasma, molecular clouds), may also produce hundreds MeV neutral pions and secondary gamma photons. Anyway this additional possibility would require both neutrino solution and baryons in the halo, and it might be less plausible.

Our heavy neutrino candidate is not an ad hoc model; its unique free parameter, the neutrino mass, is already constrained by cosmological data (no high pollution of $e^+e^-$ cosmic rays in the range $M_Z < m_N < 300 GeV$ is observed), while recent early data from underground detector of WIMP could be attributed to heavy neutrinos, streaming in DAMA detector at a very narrow and defined mass window $45 GeV < m_N < 50 GeV$ [6].

## 2 Heavy neutrino cosmological evolution

The early Universe provide a unique laboratory to test elementary particles which are produced in the cosmic thermal bath at huge rate and at highest energies. The number of known lepton families known is actually fixed at three. Their cosmic relics, namely the tiny survived fraction of baryons (over antibaryons) and the corresponding tiny fraction of leptons (electrons) over antileptons are a minor trace with respect to the huge number density of massless gauge boson relics, the 2.75 BBR photons, whose number density is comparable with the expected electron, muon and tau neutrinos. These ”light” neutrinos in thermal equilibrium at very early stages of Universe evolution, may share a small mass, as last experimental evidences from Superkamiokande (atmospheric neutrino) recently suggest, making ”light” neutrinos a preferable candidate for hot dark matter in the Universe.

Recently it has been suggested that light $\nu$ presence in galactic halo might be already probed by the survival of ultrahigh cosmic rays originated at high cosmic distances (above GZK cut off), whose only explanation may be indebted to UHE neutrino - relic galactic neutrino interactions [7, 8]. Cosmological nucleosynthesis arguments bounds the total flavour number of light neutrinos to three or four, while terrestrial data on the Z width at LEP infer severe constrains on any further ”light” ($m_\nu \ll M_Z/2$) weakly interact-
ing neutrino families detectable from boson gauge decay.

Anyway, a fourth lepton family above \( \frac{M_Z}{2} \) masses is not experimentally forbidden. A similar ”heavy” stable neutrino has been proposed nearly 20 years ago as a Cold Dark Matter candidate, able to reach the critical mass density at GeV masses (the Lee - Weinberg - Dolgov suggestion now in disagreement with LEP limits on Z width [9]) and at TeV masses [10].

Let us remind that the residual cosmological abundance of heavy neutrinos in the Universe depends on the conditions of ”freeze out”, when they decouple from a state of thermal equilibrium with other particle species during the primordial stages of Universe evolution. At high temperatures \( (T \gg m_N) \) heavy neutrino concentration is comparable with that of photons. When the temperature drops below neutrino mass \( (T \approx m_N) \), due to Universe expansion, neutrino are still in thermal equilibrium but relic concentration decreases like \( n_N \propto \text{exp}(-m_N/T) \) until the decoupling. At this moment the weak interactions rate becomes comparable with cosmic expansion, and too slow to keep neutrinos in equilibrium with other particles. The knowledge of these processes cross sections is essential in order to calculate the neutrino density today.

According to the Standard Model, neutrino relic abundance is given by [14]

\[
n_N \simeq \frac{2 \times 10^{-18}}{g_s^{1/2} M_p m_N (\sigma \beta)_f} \left[ 40 + \ln \left( \frac{g_s}{g_s^{1/2}} M_p m_N (\sigma \beta)_f \right) \right] n_\gamma (T), \quad (1)
\]

\(^1\text{An apparently simple electroweak model with a fourth heavy neutrino is not so easy to define. First of all it has to be included an additional quark pair in order to cancel anomalies, and assured the stability of the lightest particle of the family (heavy N). In a SU(5) model the dimension five operators appearing in the lagrangian density lead to the neutral fermion decay with a lifetime shorter than the age of the Universe (\( \tau \sim M_{pL}^2/m_N^3 \sim M_{pL}^2/M_0^3 \sim 10^8 \text{s} < H_0^{-1} \sim 3 \cdot 10^{17} \text{s} \)). Theoretical models predicting four fermion families which exclude these operators contribution can be found in Ref [11-13]. In Ref. [11] for example it is shown that a non Abelian horizontal symmetry, broken at some high scale can guarantee the replica of a fourth fermion generation with a heavy stable neutrino, leaving global U(1) (related to lepton number conservation) unbroken. New fermion masses are constrained in the range [11]

\[ M_N \sim 50 \text{GeV}, \quad M_L > 80 \text{GeV}, \quad M_{B'} \sim 100 \text{GeV}, \quad M_{T'} > 150 \text{GeV}. \]
where \( g^* = N_{\text{bos}} + \frac{7}{8} N_{\text{ferm}} \) is the number of effective degrees of freedom at temperature \( T \), \( g_s \) is the number of particle spin states \( M_p \) is the proton mass, \( \langle \sigma \beta \rangle_f \) is the thermally averaged annihilation cross section at freeze out, \( n_\gamma = 0.24T^3 \) is the cosmic photon number density.

The main events of heavy neutrinos annihilation in the Universe are

\[
N \bar{N} \to ff,
\]

if \( M_Z/2 < m_N < m_W \), where the cross section decreases as \( 4m_N^2/(4m_N^2 - M_Z^2)^2 \) for growing \( m_N \), and

\[
N \bar{N} \to W^+W^-
\]

if \( m_N > m_W \), where the cross section grows like \( m_N^2 \).

Because neutrino relic density \( \rho_N \propto \sigma^{-1} \) [9-10], it grows until a maximum value near \( m_N \sim M_W \) with \( \rho_{\text{max}}/\rho_c \approx 10^{-2} \), and it starts to decrease in the mass range \( m_N > m_W \), as Enquist showed in his work [15]. The Heavy neutrino can not reach the critical value \( \Omega = 1 \), at least below a few TeV energy mass, where the Standard Model may be applied.

The neutrino "fluid" decouples from thermal equilibrium (at \( T_f \approx m_N/30 \)) and starts to cluster, in matter dominated Universe, at earlier times (\( z \approx 10^5 \)) compared with the baryons which remain in equilibrium with photons until \( z \sim 1500 \). After recombination, baryonic matter is gravitationally captured by primordial neutrino seeds, while heavy neutrinos lose energy moving in the non static gravitational field of ordinary matter collapsing. This mechanism drives neutral lepton clustering in galactic dark halos as a consequence of gravitational interaction with baryons.

The neutrino density increase[6, 16-18] in the central part of the Galaxy may become \( 5 \div 7 \) orders of magnitude larger than its cosmological value \(^3\). For

\(^2\)We have to note that in a Cold Dark Matter scenario dominated by neutralino (\( \Omega_\chi \approx 1 \)), in the very particular case expecting that both \( \chi \) and \( N \) share comparable mass and very similar electroweak interactions, the mean galactic overdensity of our heavy neutrino should not exceed the value \( 3 \cdot 10^4 \rho_c \). In this case we can not explain naturally the DAMA signal and the gamma flux with no additional local clustering.

However for the most general case (\( \Omega_{DM} < 0.2 - 0.5 \), \( and/or m_\chi < m_N \), \( and/or \sigma_\chi > \sigma_N \)) the neutrino decoupling and clustering may occur in a separated way more efficiently than
this reason the heavy neutrinos $N$ may reannihilate (after the earliest epoch of Hot Universe) with antineutrinos in the halo leading to a flux of ordinary particles beyond the galactic plane, which may be more easily detectable. Contributing a small part of the total dark matter density and participating rarely to reannihilation, the primordial fourth generation neutrinos can cause significant effects by their annihilation processes. Electrons, positrons, nucleons (antinucleons) and gamma rays are possible final products of the annihilation chains. Relic leptons (namely electron pairs), interacting by ICS with soft interstellar radiation background, and gamma photons produced by $\pi^0$ decay could be the favorite sources of the GeV radiation observed in the galactic halo.

3 Neutrino annihilation in relativistic electron pairs: Inverse Compton scattering on the galactic interstellar radiation as a source of gamma rays.

Heavy neutrinos could directly annihilate in relativistic electron pairs ($N\bar{N} \rightarrow Z \rightarrow e^+e^-$) or through secondary decay processes of heavier particles as it is showed in Table 1, where we considered only the annihilations leading to most energetic electron pairs. We indicated with $\Phi$ the electron pair normalized probability production (through each Z decay) for each corresponding chain channels (direct $\phi_e$, or via $\mu$ or $\tau$ decays $\phi_{\mu e}$, $\phi_{\tau e}$, $\phi_{\tau\mu e}$). Charged pions and neutrons generated in jets by annihilation in quark - antiquark pairs through Z or W hadronic decay also give electrons as secondaries, but their energy is lower than one order of magnitude.

The complete reaction chains at lowest energies are not considered here, but other WIMP component [18]. In general there is no strong constraint for a neutrino density contrast with $\Omega_N \sim 10^{-3}$. Therefore the clustering of neutrino could not be bounded by a twin ghost WIMP candidate whose free parameters are totally unknown (mass, cross-section, helicity). Moreover there are real possibilities that baryonic dark matter (MACHOs, molecular clouds) constitutes a relevant component of galactic dark matter. In this scenario the density contrast $(\delta\rho/\rho)_{bar}$ in the galactic halo is much larger than $10^5 \div 10^7$, and the consequent neutrino clustering may easily reach or exceed the assumed one.
we use it as a first reference as well as the detailed Monte Carlo processes [19].

The presence of heavy neutrino would determine (as a consequence of occasional annihilations) a flux of cosmic rays in the halo of the Galaxy whose intensity should be in the range of actual detector sensibilities. Anyway it could be hardly distinguishable from the standard sources contribution (as supernova or supernova remnants) to the galactic background.

Electrons and positrons are trapped by magnetic fields, and propagating through the Galaxy they lose either "memory" of their "place of birth" or energy by bremsstrahlung, synchrotron or ICS. These processes determine a broadening of different electron "lines" \((N \bar{N} \rightarrow l \bar{l} \rightarrow e^+e^-)\), so that \(e^- (e^+)\) spectra (even considering electrons and positrons that come from hadron decays) are at final stages described by numerical spectra and consequent approximated power law \(E^{-\alpha}\) [19,20]. The numerical simulations of \(N \bar{N}\) annihilation performed with the package PYTHIA 5.7 [19] with suitable modifications to include a fourth generation of fermions, show that such \(N \bar{N}\) relic electron fluxes are considerably lower than observed neighbor galactic background (in the range of masses \(45 \text{GeV} < m_N < M_Z\)). Such cosmic ray input can not be used to confirm or refuse heavy neutrino presence in galactic halo. Recently the possible excess of positrons has been considered as a probe of heavy neutrino annihilations [20].

A gamma signal at high galactic latitudes detected by EGRET could be a test of neutrino annihilation in the Milky Way halo, because no standard gamma rays sources are known in these galactic regions (\(\gamma\)-rays can practically travel in straight paths through the Galaxy with no absorption because the mean \(\gamma - p\) free path length at typical interstellar density is about 20 Mpc [21]).

In the present section we consider as source of high energy radiation in the halo the Inverse Compton Scattering (ICS) of relativistic electrons (by \(N \bar{N}\) collisions) on "soft" radiative backgrounds diffused in the Galaxy, mainly Cosmic Background Radiation (CBR), and the Interstellar Radiation Field (infrared and optical photons). The electron energies, required by ICS mechanism in order to generate gamma radiation, are given by

\[
E_\gamma = \frac{4}{3} \epsilon_{ph} \left( \frac{E_e}{m_e c^2} \right)^2
\]  

(2)
with $\epsilon_{ph}$ the target photon energy.

The Compton scattering on cosmic microwave photons call for too large neutrino masses ($m_N > 1\, TeV$) in order to reach gamma GeV energies. In this range of $m_N$ masses perturbative theory could not be applied and neutrino interactions could not even be weak anymore. No clear study for $N\bar{N}$ annihilation is known above TeV energies. Therefore we excluded neutrinos with mass above 1 TeV from our consideration.

The ICS on IR and optical photons with respectively $E_e \geq 50\, GeV$ or $E_e \geq 10\, GeV$, is more efficient in gamma rays production. Indeed assuming interstellar radiation being represented by the following scaling law

$$n_{ph}(r) = \frac{n_{ph}(0)}{1 + r^2/a^2_\gamma}. \quad (3)$$

where $r$ is the distance from the galactic plane, and $a_\gamma = 10\, kpc$ is the characteristic length of interstellar radiation distribution in the Galaxy, the photon density could be considered roughly constant in a region of radius $a_\gamma$ [22].

We have already underlined that numerical simulation of electron pairs spectra from $N\bar{N}$ annihilation for different values of neutrino masses ($m_N = 45, 50, 100, 300\, GeV$) [19], could be approximated, in a reasonable energy windows, by a power law

$$J(E_e) = KE_e^{-\alpha}. \quad (4)$$

where $K$ is a normalization constant. An electron distribution with such a power law, interacting by ICS with photons at energy $\epsilon_{ph}$ and number density $n_{ph}$, generate radiation at higher energy whose intensity is given by [23-25]

$$J_\gamma(E_\gamma) = \int dr \int I(E_e)dE_e \int \sigma n_{ph}(\epsilon_{ph}, r)d\epsilon_{ph} \quad (5)$$

Estimates of the power index $\alpha$ lead to the determination of gamma intensities by ICS, leading to the following power law:

$$J_\gamma(E_\gamma) = \frac{2}{3} K a_\gamma n_{ph} \sigma_T \left( \frac{\epsilon_{ph}}{(mc^2)^2} \right)^{(\alpha-1)/2} E_\gamma^{-(\alpha+1)/2} \quad (6)$$
where $n_f$ is the target photon background density, $\bar{\epsilon}_{ph}$ its average energy and $\sigma_T$ is the Thomson cross section.

Gamma intensity has been calculated for $m_N = 45, 50, 100, 300\, GeV$. The largest fluxes have been obtained for ICS on optical photons. Assuming an average $N\bar{N}$ clustering $\rho_N^{gal}/\rho_N^{cosm} = 10^7$, for a neutrino mass $m_N = 50\, GeV$, we found a gamma flux

$$
\frac{dN_\gamma}{dS\,dt\,d\Omega\,dE_\gamma} \simeq 2 \cdot 10^{-7} A(\psi) \left( \frac{E_\gamma}{GeV} \right)^{-1.55} \left( \frac{a_\gamma}{10\, kpc} \right) \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}
$$

(7)

and for $m_N = 100\, GeV$ one finds

$$
\frac{dN_\gamma}{dS\,dt\,d\Omega\,dE_\gamma} \simeq 3 \cdot 10^{-7} A(\psi) \left( \frac{E_\gamma}{GeV} \right)^{-1.5} \left( \frac{a_\gamma}{10\, kpc} \right) \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}.
$$

(8)

The flux depends on the angular coordinate $\psi$ which is the angle between the line of sight $L$ and the direction of the galactic center, related to galactic coordinates $l, b$ by $\cos \psi = \cos l \cos b$.

$A(\psi)$ is an adimensional integral of interstellar photon density along the corresponding line of sight, and has been defined as

$$
A(\psi) = \frac{1}{a_\gamma} \int_{\text{line of sight}} \frac{dr(\psi)}{1 + r(\psi)^2/a_\gamma^2}
$$

(9)

At high galactic latitudes $A(\psi) \geq 1$.

Gamma intensity due to infrared background is less abundant than optical photons as a consequence of the spectral power law $E^{-\alpha}$.

Our integral flux is comparable with EGRET observed one, whose value at high galactic latitudes is:

$$
\Phi_\gamma(E > 1\, GeV) \simeq 8 \cdot 10^{-7} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}.
$$

We found that gamma flux due to ICS is

$$
\Phi_\gamma(E > 1\, GeV) \simeq 4 \cdot 10^{-7} A(\psi) \left( \frac{a_\gamma}{10\, kpc} \right) \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}.
$$
with $m_N \simeq 50\, GeV$, and
\[
\Phi_\gamma(E > 1\, GeV) \simeq 6 \cdot 10^{-7} A(\psi) \left( \frac{a_\gamma}{10\, kpc} \right) cm^{-2}\, s^{-1}\, sr^{-1}
\]
with $m_N \sim 100\, GeV$.

It has to be underlined that the same tens of $GeV$ electrons which collide with interstellar radiation could scatter on the microwave background, uniformly distributed in the Galaxy (even at high latitudes) and originate additional radiation at peak energy $E_\gamma \sim 300\, keV$ with a flux $J_\gamma \simeq 10^{-2}\, cm^{-2}\, s^{-1}\, sr^{-1}$ as well as ICS of $GeV$ electrons with a flux $J_\gamma \sim 0.3\, cm^{-2}\, s^{-1}\, sr^{-1}$ and peak energy $E_X \sim 3\, keV$. Actually this radiation could not be easily observable in this background radiation region by present detectors.

A further constraint on this model could be the detection of a radio background at high galactic latitudes due to synchrotron losses of tens GeV electrons. Because of the same dependence on the square of electron energy, it should be reasonable to admit that the same electrons generating gamma radiation could also interact with magnetic fields in the halo. Such a synchrotron emission would be characterized by an average frequency
\[
\nu = \gamma^2 \left( \frac{eB}{2\pi m_e} \right) \sim 1\, GHz \left( \frac{B}{1\mu G} \right) \left( \frac{\gamma}{2 \cdot 10^4} \right)^2
\]
(10)

with a characteristic scale for the magnetic field $B = 1\, \mu G$.

ICS and synchrotron luminosity are related by
\[
\frac{L_{sync}}{L_{IC}} \simeq \frac{U_{mag}}{U_{rad}}
\]
(11)

where $U_{mag}$ and $U_{rad}$ stand for the energy density of magnetic and interstellar radiation fields, so the typical density flux of synchrotron radiation would be
\[
J_{sync} \sim 5 \cdot 10^4 \left( \frac{B}{1\mu G} \right) \left( \frac{\gamma}{2 \cdot 10^4} \right)^{-2} \left( \frac{U_{rad}}{0.2\, eV\, cm^{-3}} \right)^{-1}\, Jy.
\]
(12)
considering an optical background energy density (due to standard sources in the Galaxy) comparable with microwave background in a sphere of radius $r = 10 \text{ kpc}$ at a characteristic value $U_{\text{rad}} = 0.2 \text{ eV cm}^{-3}$.

It is remarkable that recent model interpretations of gamma and radio backgrounds do indeed reach similar expectation fluxes comparable with the observed ones [26]. In a sentence radio-gamma halo association seems to be reliable and it confirms the peculiar role of ICS by ultrarelativistic electrons in a wide halo.

4 Gamma photons from heavy neutrino annihilations

A different route from neutrino annihilations in the halo could also originate a diffuse background of gamma radiation with a continuum energy spectrum. This main source of gamma production is the decay of $\pi^0$ mesons created in the fragmentation of quarks through the annihilation channels $N\bar{N} \rightarrow Z \rightarrow q\bar{q}$.

If $m_N > m_W$ a gamma spectrum is given by W decay, because the channel $N\bar{N} \rightarrow W^+W^-$ becomes dominant.

This mechanism of gamma emission depends only on neutrino distribution in the halo, with no need of introducing neither soft radiative backgrounds as for above ICS case, nor a molecular gas distribution beyond galactic plane which could interact with high energy cosmic rays (see De Paolis et al. hypothesis about MACHOs role as gamma halo source [3,4]).

In this way gamma radiation should preserve the memory of spatial distribution similar to dark matter in the Galaxy.

The photon flux is described by the following expression:

$$J_\gamma = \frac{1}{4\pi m_N^2} \sum_i \sigma_i v \frac{dN_i}{dE} \int_{\text{line of sight}} \rho^2 (r) dr (\psi)$$

(13)

where $\psi$ is the angle between the line of sight and the galactic center, $\rho (r)$ is heavy neutrino density as a function of galactocentric radius, and $\sum_i \sigma_i v \frac{dN_i}{dE}$ counts all possible final photon channels $\frac{dN}{dE}$ which could contribute to the gamma photons emission. The integral of neutrino density along the line of sight...
sight \( L \) depends on the halo model chosen for a dark matter distribution, which is generally described as
\[
\rho(r) \propto \frac{1}{(\frac{r}{a})^\gamma[1 + (\frac{r}{a})^\alpha(\beta-\gamma)/\alpha]}
\] (14)

Particular values of the parameters give models with a singular behaviour towards the galactic center, which could determine a strong enhancement of gamma flux in that direction. Other models postulate a clumped distribution of dark matter, with the density profile describing the average distribution of dark matter in the galactic halo. One can expect local enhancement of gamma radiation from those regions at higher neutrino densities.

The simplest profile is described by an isothermal sphere for heavy neutrino clustering in a galactic halo with length scale \( a \geq 10 \text{ kpc} \), and mass density
\[
\rho = \frac{\rho_0}{1 + (r/a)^2}
\]
where \( \rho_0 \) is the central density of the halo.

In the spherical model the square density integral leads to an adimensional intensity \( I(\psi) \)
\[
I(\psi) = \int \frac{1}{(1 + (r/a)^2)^2} dr(\psi)/a;
\]
this intensity has a characteristic behaviour which is maximum in the direction of the galactic center \( (\psi = 0) \), and then decreases for \( 0 < \psi < \pi \), but it doesn’t vary more than a factor ten with the angular coordinate. At high latitudes \( I(\psi) \) is generally of order unity.

A rough way to calculate the photon flux by neutrino annihilation through the channel \( N\bar{N} \rightarrow q\bar{q} \) comes from the analysis of \( Z \) decay. The probability of a hadronic \( Z \) decay is 20 times greater than its decay in an electron pair \( (\Gamma(Z \rightarrow \text{hadrons})/\Gamma(Z \rightarrow e^-e^+) = 20.795 \pm 0.040 \ [27]) \), with an average production of \( < n_\pi > \sim 9 \) neutral pions. So the cross section of a hadronic \( N\bar{N} \) annihilation would roughly be \( (\sigma v)_{\text{hadr}} \sim 20(\sigma v)_{e^-e^+} \), where \( (\sigma v)_{e^-e^+} \) has been previously calculated [14]. Assuming that the fundamental contribution to the flux is given by a spherical region of radius \( a \), Eq. (13) becomes
\[ J_\gamma = 2 < n_\nu^0 > \frac{(\sigma v)_{\text{had}}}{4\pi} n_0^2 a I(\psi) \]  

(15)

where \( n_0 N = \rho_0 / m_N \) is neutrino central number density.

With a neutrino mass \( m_N = 50 \text{ GeV} \) a flux estimate gives

\[ J_\gamma \sim 1.2 \cdot 10^{-6} I(\psi) \left( \frac{\Omega_{\text{clust}}}{10^7} \right) \left( \frac{a}{30 \text{kpc}} \right) \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]  

(16)

where \( \Omega_{\text{clust}} = (\rho_G / \rho_b)^{3/4} \) (\( \rho_G \) is the average matter density in the Galaxy, while \( \rho_b \) is the cosmological baryonic matter density) describes the increase in neutrino density during the clustering in the galaxy. This result is comparable to EGRET measures (see previous section).

Monte Carlo simulations of neutrino annihilations [19] have been also used to compare EGRET flux, showing that it is possible to extrapolate a power law for the gamma spectrum.

An approximated integral flux for \( m_N = 50 \text{ GeV} \) and \( a \sim 10 \text{kpc} \) is roughly

\[ \Phi_\gamma > 6 \cdot 10^{-7} I(\psi) \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \]  

(17)

while for \( m_N = 100 \text{ GeV} \) at \( a \sim 10 \text{kpc} \)

\[ \Phi_\gamma > 4 \cdot 10^{-7} I(\psi) \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \]  

(18)

Finally we notice that due to the drastic increase of \( \sigma_{NN} \) at Z pole and the consequent suppression of \( NN \) relic number, the expected gamma flux at \( m_N \approx 45 \text{ GeV} \) is much smaller and negligible, with

\[ \Phi_\gamma > 2 \cdot 10^{-8} I(\psi) \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \]  

(19)

5 Conclusions

The role of a heavy neutrino as a non dominant cold dark matter component has been analyzed in order to explain the Gamma halo around our Galaxy.
We considered a narrow range of neutrino masses between the values $M_Z/2 < m_N < M_Z$. The lower part of this range has been fixed as a consequence of last results of DAMA experiment, that show a consistency of NaI detector signal with a heavy neutrino CDM candidate, having a mass $45 \, GeV < m_N \leq 50 \, GeV$ (with the upper limit only giving a relic neutrino density high enough to be cosmologically relevant).

Higher mass values are excluded by the analysis of experimental data up to $300 \, GeV$ [6,14].

Two different emission mechanism have been analyzed and compared: ICS of relativistic electrons (originated in $N\bar{N}$ annihilations) on optic background photons, and direct neutrino annihilation in high energy photons.

Both processes determine a radiation flux close to experimental results, but distinguish themselves for a different galactic distribution of the radiation produced.

1. A spherical symmetry in the case of prompt gamma photons by $N\bar{N}$ annihilations close to neutrino profile (assuming the smooth model) in the halo.

2. A spherical (neutrino) with a spheroidal (photon) distribution recalling more the luminous structure of the visible part of the Galaxy if gamma rays are generated by ICS.

The profile of photon flux showed by Dixon et al. indicates a different morphology of gamma halo at different energy ranges, with the evidence of a halo excess not correlated with a component on the galactic plane for $300 \, MeV < E < 1 \, GeV$, while for $E > 1 \, GeV$ a planar gamma component is clearly detected.

Actually it is not possible to determine which is the real process source of this high energy photons (ICS or pion decay), but neutrino annihilations could describe more easily than other models the presence of a high galactic latitude emission recently discovered.

In conclusion the possibility to solve at once the DAMA signals and the gamma halo at GeV with a unique fourth neutrino generation is fascinating: near forthcoming Lep II data analysis of $e^+e^- \rightarrow N\bar{N}\gamma$ events [28] may confirm or exclude this new physics window.
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TABLE 1

Main $N\bar{N}$ annihilations for final electron production.

| Reaction | Energy ($E_e$) | Normalized probability ($\Phi_e$) |
|----------|----------------|----------------------------------|
| a) $N\bar{N} \rightarrow Z \rightarrow f \bar{f}$ | $m_N$ | $1^a$ |
| $N\bar{N} \rightarrow \mu^+\mu^-$ | $m_N$ | $\Phi_{\mu\mu} = 1$ |
| $\mu^\pm \rightarrow e^\pm + X$ | $m_N$ | $\Phi_{\mu e} = 0.18$ |
| $N\bar{N} \rightarrow \tau^+\tau^-$ | $m_N$ | $\Phi_{\tau\tau} = 0.18$ |
| $\tau^\pm \rightarrow e^\pm + X$ | $m_N$ | $\Phi_{\tau\mu e} = 0.11$ |
| $N\bar{N} \rightarrow \tau^+\tau^-$ | $0.13 m_N$ | $\Phi_{\tau\pi\mu e} = 0.11$ |
| b) $N\bar{N} \rightarrow W^+W^-$ | $m_N$ | $1^b$ |
| $W^\pm \rightarrow \mu^\pm + \nu_{\mu}(\bar{\nu}_{\mu})$ | $m_N$ | $\Phi_{\mu\mu} = 1$ |
| $W^\pm \rightarrow \tau^\pm + \nu_{\tau}(\bar{\nu}_{\tau})$ | $m_N$ | $\Phi_{\mu e} = 0.18$ |
| $\mu^\pm \rightarrow e^\pm + X$ | $m_N$ | $\Phi_{\mu\mu} = 0.18$ |
| $W^\pm \rightarrow \tau^\pm + \nu_{\tau}(\bar{\nu}_{\tau})$ | $0.06 m_N$ | $\Phi_{\tau\pi\mu e} = 0.11$ |

$^a N\bar{N} \rightarrow Z \rightarrow f \bar{f}$, net probability $\approx 3.3\%$.

$^b N\bar{N} \rightarrow W^+W^- \rightarrow f \bar{f}$, net probability $\approx 10.7\%$.