ON THE HEAVY RELIC NEUTRINO - GALACTIC GAMMA
HALO CONNECTION

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Abstract
A halo model with heavy relic neutrinos $N$ belonging to a fourth
generation and their annihilations in galactic halo may explain the recent
evidence of diffused gamma (GeV) radiation around galactic plane. We
considered a neutrino mass in the narrow range ($M_Z/2 < m_N < M_Z$)
and two main processes as source of gamma rays. A first one is ICS
of ultrarelativistic electron pair on IR and optical galactic photons and a
second due to prompt gammas by $\pi^0$ decay, leading to a gamma flux
($10^{-7} - 10^{-6}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$) comparable to EGRET detection. Our
predictions are also compatible with the narrow window of neutrino mass
45 GeV < $m_N$ < 60 GeV, required to explain the recent underground
DAMA positive signals.

1 Introduction
The recent observations of EGRET telescope show a diffuse $\gamma$ - ray emission
in the halo of our galaxy [1]. Actually models trying to explain a gamma halo
range between
a) a high galactic latitude distribution of high energy cosmic ray sources (fast
running pulsar "Geminga" like) [1][2],
b) collisions of high energy protons (tens of GeV) in molecular clouds (mostly
$H_2$), whose formation is favored in galactic halos [3],
c) a cold dark matter scenario with neutralino, the lightest supersymmetric
particle in the minimal SUSY model, whose annihilations in heavy fermions
($c\bar{c}, bb, t\bar{t}$) and bosons ($W^+W^-, ZZ, gg$) could lead to gamma secondaries
emission [4],
d) Inverse Compton Scattering (ICS) of interstellar photons off cosmic ray
electrons with a spectra harder than previous predictions [5].
A heavy Dirac neutrino of a fourth generation in a Cold Dark Matter (CDM)
model, at masses $m_N > M_Z/2$, may offer an elegant solution to the gamma
ray signal detected, though it can not solve all the dark matter problem in the
Neutrino annihilations at high galactic latitude could produce 1) \( \gamma \) rays by ICS of relativistic electrons (primaries or as secondary decay products of heavier leptons in the annihilation chains \( N \bar{N} \rightarrow l^+ l^- \rightarrow e^+ e^- \)) onto thermal photons (\( IR, \) optical) near and above the galactic plane, 2) direct gammas by neutral secondary pions decay. The estimated flux we derived here is roughly close to EGRET results in the hypothesis of a smooth and homogeneous galactic halo.

2 The heavy neutrino model

LEP I has fixed severe constrains on the number of "light" \( (m_{\nu} \ll M_Z/2) \) neutrino families from Z width data. However there is no experimental prohibition on the existence of an additional heavy neutral lepton with mass \( M_N > M_Z/2 \). Such a heavy stable neutrino belonging to a fourth fermion family was introduced nearly 20 years ago as a CDM candidate [6],[7]. An apparently simple fourth generation model is not so easy to build. Anyway models predicting a fourth heavy stable neutrino can be found in [8],[9],[10]. In an expanding universe scenario heavy neutrinos decouple from a thermal equilibrium condition when global temperature drops below their rest mass energy \( (T < m_N) \) and weak interactions become too slow to keep neutrinos in equilibrium with the cosmological fluid. From this moment the only change in neutrino density is due to cosmic expansion. The relic abundance is given by [11]

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

where \( g^* = N_{bos} + \frac{7}{8} N_{ferm} \) 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, \( (\overline{\sigma \beta})_f \) is the thermally averaged annihilation cross section at freeze out, \( n_\gamma = 0.24 T^3 \) is the cosmic photon number density.

Annihilations of heavy neutrinos in the universe happen through two main channels

**channel 1**) \( N \bar{N} \rightarrow f \bar{f} \) 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 \( m_N \)

**channel 2**) \( N \bar{N} \rightarrow W^+ W^- \) if \( m_N > m_W \)
with a cross section growing like \( m_N^2 \) for increasing \( m_N \) [12]. As \( \rho_N \propto \sigma^{-1} \), neutrino relic density exhibits a maximum (with \( \rho_{\text{max}}/\rho_c \approx \)

\[2\]
10^{-2} h^{-2}) near m_N \sim M_W and then starts to decrease as m_{N}^{-2} in the mass range m_N > m_W, without reaching the critical value \( \Omega = 1 \), at least in the mass range where Standard Model may be applied (m_N < 1 TeV).

Clustering during galactic structure formation determine an increase in neutrino density [13],[14],[15] that in the central part of the galaxy could be as large as 5 ÷ 7 orders of magnitude (the exact value depends on the other CDM, HDM densities and masses).

A spherical halo around our galaxy made of heavy neutrinos is the model proposed in order to explain \( \gamma \) emission observed at high galactic latitude. In a galactic halo, neutrinos with a higher density distribution could annihilate again leading to a flux of ordinary particles beyond the galactic plane, potential sources of high energy radiation.

Constrains on neutrino mass come either from cosmological data (not too high pollution of \( e^+e^- \) cosmic rays is observed in the range \( M_Z < m_N < 300 GeV \) [11]) or DAMA detector, where recent signals could be attributed to heavy neutrino in the mass window \( 45 GeV < m_N < 50 GeV \).[15].

3 Neutrino annihilation products as gamma ray source

3.1 Relativistic electron pairs: ICS on the galactic interstellar radiation field(ISRF)

Heavy neutrinos could directly annihilate in relativistic electron pairs (either prompt ones or born through secondary decay processes of heavier particles \( \mu, \tau \), as in channel 1 way). Channel 2 leads to electron pairs through leptonic decay of W (\( N\bar{N} \rightarrow W^+W^- \rightarrow l^+l^- \)). Electron pairs may be generated even by W, Z hadronic decay through charged pions and neutrons production.

Electrons and positrons are trapped by galactic magnetic field, and propagating through the Galaxy loose either "memory" of their "place of birth" as well as energy for bremsstrahlung, synchrotron or ICS. These processes determine a broadening of different electron "lines" (\( N\bar{N} \rightarrow l^+l^- \rightarrow e^+e^- \)), so that \( e^- (e^+) \) spectra (even considering electrons and positrons that come from hadron decays) are at final stages described by the consequent approximated power law \( J = KE^{-\alpha} \) (where K is a normalization constant). Numerical simulation of \( N\bar{N} \) annihilation performed with the package PYTHIA 5.7 [16] 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 \( 45 GeV < m_N < M_Z \)). Such a cosmic ray input can not be used to confirm or refute heavy neutrino presence in galactic halo.

ICS of "soft" background photons (isotropic CBR or anisotropic infrared and optical interstellar radiation field) off relativistic electrons created out of the
galactic plane is a possible source of radiation. Energies order of magnitude is fixed by the ICS characteristic relation \( E_{\gamma} = \frac{4}{3} \epsilon_{ph} (E_e/m_e c^2)^2 \), where \( \epsilon_{ph} \) is the target photon energy.

We excluded here collisions with microwave photons which would require too large neutrino masses \((m_N > 1 \text{ TeV})\). No clear theory is still available for such a heavy particle. ICS on IR and optical photons needs respectively \( E_e \geq 50 \text{ GeV} \) and \( E_e \geq 10 \text{ GeV} \), and is more efficient in gamma ray production. The Galaxy is a disk-like radiative source of radius \( \sim 15 \text{ kpc} \), so the interstellar radiation field has a vertical extent of several kpc. We assumed this radiation to be represented by the obvious scaling law

\[
n_{ph}(r) = \frac{n_{ph}(0)}{1 + r^2/a_{\gamma}^2}.
\]  

(2)

where \( r \) is the distance from the galactic plane, and \( a_{\gamma} = 10 \text{ kpc} \) is the characteristic length of interstellar radiation distribution in the Galaxy. Photon density could be considered roughly constant in a region of radius \( a_{\gamma} \) [15].

An electron distribution \((KE^{-\alpha})\) interacting by ICS with photons at energy \( \epsilon_{ph} \) and density \( n_{ph} \) generate radiation whose intensity is [17]

\[
J_{\gamma}(E_{\gamma}) = \frac{2}{3} K a_{\gamma} n_{ph} \sigma_T \left( \frac{\epsilon_{ph}}{(m_e c^2)^2} \right)^{(\alpha-1)/2} E_{\gamma}^{-(\alpha+1)/2}
\]  

(3)

where \( n_{ph} \) is the target photon background density, \( \epsilon_{ph} \) its average energy and \( \sigma_T \) is the Thomson cross section.

Gamma intensity has been calculated for \( m_N = 45, 50, 100, 300 \text{ GeV} \). The largest flux has been obtained for ICS on optical photons. For \( m_N = 50 \text{ GeV} \) the calculated flux is

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

(4)

and for \( m_N = 100 \text{ GeV} \) one finds

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

(5)

\( A(\psi) \) is the adimensional integral of interstellar photon density along the line of sight \( L \), defined by the angular coordinate \( \psi \) (angle between \( L \) and the direction of the galactic centre). \( A(\psi) \) is of few unities and corresponds to
\[ A(\psi) = \frac{1}{\alpha_{\gamma}} \int_{\text{line of sight}} \frac{dr(\psi)}{(1 + r(\psi)^2/a^2)} \]  \hspace{1cm} (6)

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

Assuming an average \( N\bar{N} \) clustering \( \rho_{\text{gal}}^{\bar{N}}/\rho_{\text{cosm}}^{\bar{N}} = 10^6 \), the flux obtained for two values of \( m_N \)

1) \( \Phi_\gamma(E > 1 \text{ GeV}) \simeq 4 \cdot 10^{-7} A(\psi) \left( \frac{\alpha_{\gamma}}{10 \text{ kpc}} \right) \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \quad (m_N \simeq 50 \text{ GeV}), \)

2) \( \Phi_\gamma(E > 1 \text{ GeV}) \simeq 6 \cdot 10^{-7} A(\psi) \left( \frac{\alpha_{\gamma}}{10 \text{ kpc}} \right) \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \quad (m_N \simeq 100 \text{ GeV}), \)

is comparable with EGRET observations:

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

Additional tests of this model could be obtained with the nearly detectable signal of hundreds KeV radiation in the halo with flux \( J_\gamma \simeq 10^{-2} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) at peak energy \( E_\gamma \sim 300 \text{KeV} \) as well as a flux \( J_X \simeq 0.3 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) at \( E_X \sim 3 \text{KeV} \) due to ICS of tens of GeV and GeV electrons with CBR. An additional parasite radio background arises at high galactic latitudes due to synchrotron losses of the same electrons at \( E_e \sim 10 \text{GeV} \), with typical density flux

\[ J_{\text{sync}} \sim 5 \cdot 10^4 \left( \frac{B}{1 \mu G} \right) \left( \frac{\gamma}{2 \cdot 10^4} \right)^{-2} \left( \frac{U_{\text{rad}}}{0.2 \text{eV cm}^{-3}} \right)^{-1} \text{Jy}. \]  \hspace{1cm} (7)

and average frequency

\[ \nu = \gamma^2 \left( \frac{eB}{2\pi m_e} \right) \sim 1 \text{GHz} \left( \frac{B}{1 \mu G} \right) \left( \frac{\gamma}{2 \cdot 10^4} \right)^2 \]  \hspace{1cm} (8)

where we used as characteristic scale for the magnetic field \( B = 1 \mu G \), and as optical background energy density \( U_{\text{rad}} = 0.2 \text{eV cm}^{-3} \).

### 3.2 Annihilations in gamma photons

Gamma radiation could also be produced in neutrino annihilations due to neutral pions secondaries in Z, W hadronic decay. This kind of emission does not need to introduce any kind of radiative background and is directly related to neutrino distribution in the halo.

Photon flux is described by the following expression:
\[ J_\gamma = \frac{1}{4\pi m_N^2} \sum_i \sigma_i \psi \frac{dN^i}{dE} \int_{\text{line of sight}} \rho^2(r) dr(\psi) \] (9)

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 \( \sum_i \sigma_i \psi \frac{dN^i}{dE} \) counts all possible final photon channels \( \frac{dN^i}{dE} \) which could contribute to gamma photons emission. The integral of neutrino density along the line of sight is:

\[ \frac{1}{(\xi_0)^\gamma[1 + (\xi_0)^\alpha]^{(\beta - \gamma)/\alpha}} \] (10)

The simplest density profile is described by an isothermal sphere with \( \alpha = 2, \beta = 0, \gamma = 0 \) and length scale \( a \geq 10 \text{kpc} \).

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.

Models with a singular behaviour towards the galactic center or which postulate a clumpy distribution of dark matter could contribute to enhance the total gamma flux in the halo, but we shall neglect them here.

Monte Carlo simulations of neutrino annihilations [16] have been also used to compare EGRET flux, showing that it is possible to extrapolate a power law for gamma spectrum.

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

\[ \Phi_\gamma > 6 \cdot 10^{-7} I(\psi) \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \] (11)

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

\[ \Phi_\gamma > 4 \cdot 10^{-7} I(\psi) \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \] (12)
In conclusion there are at least two independent processes able to solve the puzzle of a GeV gamma halo by the role of a cosmic relic DM made of fourth generation heavy neutrinos. The neutrino masses are constrained into a narrow energy window \((45 \text{GeV} < m_N < 60 \text{GeV})\), in order to combine at once the DAMA data and the other underground detector. This reality will be soon confirmed or excluded by LEP II search for \(e^-e^+ \rightarrow N\bar{N}\gamma\) events [19] in this energy band.

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