May Heavy neutrinos solve underground and cosmic ray puzzles?

K. Belotsky$^{a,b}$, D. Fargion$^{c,d}$, M. Khlopov$^{a,b,c}$, R.V. Konoplch$^{c,e}$

$^a$ Moscow Engineering Physics Institute, Moscow, Russia
$^b$ Center for Cosmoparticle Physics "Cosmion" of Keldysh Institute of Applied Mathematics, Moscow, Russia
$^c$ Universita’ di Roma ”La Sapienza” and INFN, Rome, Italy
$^d$ INFN Section Roma1, Rome, Italy
$^e$ Department of Physics, New York University, New York, NY 10003, USA
Department of Physics, Manhattan College, Riverdale, New York, NY 10471, USA

Abstract

Primordial Heavy neutrinos of 4th generation might explain different astrophysical puzzles: indeed the simplest 4th neutrino scenario may be still consistent with known 4th neutrino physics, cosmic ray anti-matter and gamma fluxes and signals in underground detectors for a very narrow neutrino mass windows (46 – 47 GeV). We have analyzed extended Heavy neutrino models related to the clumpiness of neutrino density, new interactions in Heavy neutrino annihilation, neutrino asymmetry, neutrino decay. We found that in these models the underground signals maybe better combined with the cosmic ray imprint leading to a wider windows for neutrino mass (46 – 75 GeV) coinciding with the whole range allowed from uncertainties of electro-weak parameters.

1 Introduction

The problem of dark matter (DM) of the Universe was revealed about 70 years ago. Several possible physical candidates were suggested since that time and several approaches to probe these candidates appeared. However, observed phenomena, which have unclear nature yet, could not be decisively matched with expected effects caused by existing candidates.

An important step in exploration of DM problem was a development of direct searches for Weakly Interacting Massive Particles (WIMP). Underground detectors were created in which effects of nucleus recoil induced by interaction of cosmic WIMP with nucleus were searched for. A positive result at 6.3 sigma C.L. was obtained in the DAMA/NaI underground set-up at the Gran Sasso National Laboratory of I.N.F.N. by exploiting the distinctive WIMP annual modulation signature \( \Xi \). Being model independent this positive result cannot be directly compared with the single model-dependent negative results of other groups, which have also used
different target-nuclei, different experimental strategies, different set-ups and all assumptions fixed at a single set \([1]\). Moreover, it can be shown \([1]\) that these negative results are actually not incompatible with the positive signal by DAMA/NaI.

On the other hand, an indirect probing of DM can be based on cosmic ray (CR) data. The presence of DM in Galaxy in form of WIMPs can cause an appearance of cosmic particles of high energy due to an annihilation or decay of the WIMPs. An implication of these annihilation (decay) sources of cosmic rays could remove possible contradiction between observed cosmic ray fluxes and their predictions on the base of standard cosmic ray model.

The result of DAMA/NaI is a challenge for DM studies, expected to shed a light on the origin of DM. In fact, the existing physical candidates of dominant DM can hardly or not at all provide an explanation of the result of DAMA/NaI. WIMP candidates such as neutralino, axion, gravitino, sterile neutrino, axino, mirror (shadow) matter are able to compose all the required missing mass of the Universe, however, all these candidates, except neutralino, are virtually sterile particles in respect to their interactions with an ordinary matter. Therefore, it looks like the measurements of DAMA/NaI as well as anomalies observed in cosmic rays spectra require a non-sterile DM which, in particular, could be a non-dominant DM component in the form of Heavy neutrinos of the 4th generation \([2]\).

A possibility to explain the DAMA/NaI result within the framework of Standard Model extended to the 4th generation of fermions, revealed in \([2]\), is the subject of current consideration.

The Heavy neutrino \((N)\) is supposed to be a neutral fermion of a new 4th generation possessing the standard weak interaction. According to recent analysis of precision electroweak data\([4]\), where possible virtual contributions of 4th generation particles were taken into account, a fit is compatible with the 4th neutrino, being Dirac and (quasi-)stable, in a mass range about 50 GeV (47-50 GeV is \(1\sigma\) interval, 46.3-75 GeV is \(2\sigma\) interval) \([4]\) and other 4th generation particles satisfying their direct experimental constraints (above 80-130 GeV). In the following we will assume that the 4th neutrino mass is about 50 GeV.

If the fourth neutrino is sufficiently long living or absolutely stable, its primordial gas from the early Universe can survive to the present time and concentrate in the Galaxy. In the case of charge symmetry of 4th generation particles the primordial 4th neutrinos can not account for a bulk of missing mass in the present Universe. In the mass range about 50 – 80 GeV the 4th neutrinos can make up \(10^{-5} – 10^{-2}\) of total density of the Universe, being a non-dominant DM component. This leads to a scenario of multi component dark matter consisting of a subdominant Heavy neutrino component and a sterile dominant component. A complex analysis of astrophysical effects induced by a presence of Heavy neutrino (non-sterile) DM component is the purpose of present paper.

It is worth noting that the 4th generation of quarks and leptons, considered here and neutralino, which is widely considered as the candidate for WIMPs, are naturally incorporated in the framework of heterotic string phenomenology. \(^1\) It appeals to future multi-component dark matter analysis of the results of direct and indirect WIMP searches. However, the astrophysical uncertainties revealed below even for the model of 4th generation neutrino, which is the simplest physical model and implies the minimal amount of parameters, demonstrate all the complications to be expected in such multi-component dark matter approach.

We should remark that even if in principle the UHE Neutrino of fourth family might produce a very exciting scattering with relic Heavy neutrino (a Heavy-Z-Boson Burst) nevertheless the cosmic relic \(N\) are too diluted and poor in number to be anyway competitive with the much more abundant (by 13 order of magnitude) and effective light neutrino \([\mathcal{G}]\) scattering. So there is little consequence of any Heavy-Z-Boson Burst model interactions. The eventuality for a UHE Neutrino (produced, for instance in Top-Down models as \([7]\)) to be a source of amplified resonant interaction with electron or quark (as for SUSY UHE neutralino scattering into s-electron and s-quark channels \([\mathcal{S}]\) is absent: there are not s-channel interaction able to overcome the electroweak cross-sections but only much less effective t-channel processes. Finally, the UHE \(N\) created by Top-Down models may nevertheless induce charged and neutral current interactions in Neutrino Detectors (SK,UNO,\(km^3\)) almost un-distinguishable from lighter UHE neutrino scattering in matter. This effect has just the ability to increase by a small factor \((\sim 25\%)\) the event rate in \(km^3\) or EUSO neutrino induced events if Top-Down mechanism is the main source of UHECR.

\(^1\)Mirror(shadow) matter, also naturally follows from heterotic string phenomenology. It is usually considered as sterile but its WIMP effects may play a role. \([\mathcal{K}]\)
Figure 1: Plot of DAMA favorable region (between upper and lower solid lines) for Heavy neutrinos of the 4th generation. A dashed line shows the fraction corresponding to a contribution of the Heavy neutrinos to CDM of the Universe.

2 Estimation of local Heavy neutrino density from DAMA/NaI experiment

A contribution of Heavy neutrinos $\rho_{loc,N}$ to the total local density $\rho_{loc}$ is given by a ratio

$$\xi_{loc} = \frac{\rho_{loc,N}}{\rho_{loc}}$$  \hspace{1cm} (1)

Approximately this parameter can be estimated as $\Omega_N/\Omega_{CDM}$ by assuming a dominance of Cold Dark Matter (CDM) in the Galaxy and by choosing the local fraction of relic Heavy neutrinos equal to their contribution to the cosmological density of CDM.

The results of DAMA/NaI, based on measurements of an "active" DM component, i.e. in our assumptions on cosmic Heavy neutrinos, give the fraction $\xi_{loc}$ of Heavy neutrinos in the local galactic density. Heavy neutrinos interact with nuclei ($^{23}$Na, $^{127}$I) of DAMA/NaI detector through the spin-independent coherent vector weak coupling. A spin-dependent axial weak coupling of neutrino and nuclei would contribute significantly within the considered mass range only if the corresponding WIMP-nucleon cross section exceeds the spin-independent one by several orders of magnitude, what in general is not the case for the 4th neutrino. The value $\xi_{loc}$ for Heavy neutrinos is deduced from the result of DAMA/NaI in term of $\xi_{loc}\sigma_{SI}$, where $\sigma_{SI}$ is the effective spin-independent WIMP-nucleon cross-section

$$\sigma_{SI} = \frac{G_F^2\mu^2}{8\pi} \frac{\beta_{Na} + \beta_{I}}{V_{Na}^2\beta_{Na} + V_{I}^{-2}\beta_{I}}$$ \hspace{1cm} (2)

Here $G_F$ is the Fermi constant, $\mu = mm_{nucl}/(m + m_{nucl})$ is the reduced mass of neutrino $m$ and nucleon ($m_{nucl} = 0.94$ GeV), $\beta_i = 4mm_i/(m + m_i)^2$, $V_i = 1 - (2 - 4\sin^2\theta_W)Z_i/A_i$ with $Z_i$ and $A_i$ being numbers of protons and nucleons in nucleus respectively, $\theta_W$ is the Weinberg angle.

Figure 1 shows a favorable region for Heavy neutrinos of the 4th generation measured by DAMA and the fraction corresponding to a Heavy neutrinos contribution to a local galactic density. The result of DAMA/NaI takes into account existing uncertainties in DM distribution parameters, in form-factor of nuclei, and in the other experimental parameters [1]. The fraction corresponding to a Heavy neutrinos contribution was estimated by taking $\Omega_{CDM} = 0.3$.

Note that the present work is based on the essentially updated DAMA/NaI results in comparison with the previous works [2, 3].
3 Shadows of Heavy neutrino annihilations in cosmic rays

Due to a concentration in Galaxy Heavy neutrinos can annihilate. The products of such annihilation contribute in cosmic ray fluxes and cosmic gamma radiation. Observational data on cosmic positrons, antiprotons and gamma-radiation are sensitive to this contribution.

An analysis of cosmic rays is complicated because a description of CR production and propagation contains significant uncertainties. Observational data do not allow to choose parameters of physical models of CR in a unique way for CR origin (injection spectra of each CR species) and CR propagation (diffusion coefficients and their energy dependence, parameters of convection, re-acceleration, magnetic halo parameters, matter distribution in Galaxy, model of solar modulation etc.). Recently a detailed study of CR models was performed in [9], [10], [11].

In order to study effects of possible DM annihilation in Galaxy, it is reasonable to accept the most conservative CR model. Eligible models should reproduce possible CR data which are the least sensitive to effects of WIMP annihilation (data on nuclear component of CR, its isotope composition). "Conventional model (C)" in [10] and "diffusion re-acceleration model (DR)" in [11] are the most suitable. We will use in our consideration fluxes of secondary positrons, antiprotons and gamma-radiation predicted in these models as a "background". Dark matter annihilation sources will be included in these models to reproduce DM effects.

An uncertainty in our analysis comes also from unknown distribution of subdominant Heavy neutrino DM in the Galaxy. There are many models of distribution of CDM in Galaxy. We will use models for dominant DM, re-scaling a dark matter density in an appropriate way for a non-dominant Heavy neutrino DM component. By fixing the density distribution of DM component in Galaxy we relate the result of DAMA, sensitive to local density of DM, with results of CR analysis, sensitive to DM density distribution in Solar neighborhood.

As a basic model for our estimations we select Evan’s halo model, which in [11] was named as C2. The values of parameters in this model are \( v_0 = 170 \text{ km/sec}, \rho_{\text{loc}} = 0.67 \text{ GeV/cm}^3 \). Density distribution of DM in Galaxy is given by Eq(41) of [1] or Eq(34) of [12] with the parameters \( q = 1/\sqrt{2} \) and \( R_c = 5 \text{ kpc} \)

\[
\rho(R, z) = \text{const} \frac{2R^2 + R^2}{(R_c^2 + R^2 + 2z^2)^2},
\]

where \( R \) and \( z \) are the radius in the galactic plane and the cylindrical coordinate axis perpendicular to it, \( \text{const} \) is defined from a condition \( \rho(R = R_0 = 8.5 \text{kpc}, z = 0) = \rho_{\text{loc}} \).

It is worth to note the chosen DM distribution is smooth and does not have a sharp profile near the Galactic center (GC).

Also, to illustrate a dependence on a halo model choice, we will consider an isothermal halo model with a sharp behavior of density near GC. Density distribution of the isothermal halo is given by

\[
\rho(R) = \rho_{\text{loc}} \frac{R^2 + R_c^2}{R^2 + R_c^2},
\]

with \( R_c = 1 \text{ kpc} \), where \( R \) is the distance from GC.

Note that the use of cuspy halo model, like Navarro-Frank-White model [13], leads to intermediate results.

3.1 Signature of Heavy neutrinos annihilation in cosmic gamma fluxes

An excess of cosmic gamma-radiation observed by EGRET over predicted galactic \( \gamma \)-emission, often called "extragalactic" \( \gamma \)-background, can be considered as a possible effect of dark matter sources. A flux of cosmic gamma-radiation near the Earth from annihilation of relic Heavy neutrinos is defined by

\[
I = \frac{dN_\gamma}{dtdSdtdE} = \frac{1}{4\pi} \frac{1}{4} \sigma v \int_0^\infty n^2 dl \frac{dN_\gamma E}{dE}.
\]
Figure 2: Cosmic gamma-radiation from galactic center (0.5° < l < 30.0°, 330.0° < l < 359.0°): EGRET data, predicted background (dot-dashed line), and the best-fit contribution from 47-80 GeV neutrino DM for Evan’s halo model. The set of dashed lines corresponds to pure annihilation gamma-fluxes, the set of solid lines is the sum of background and annihilation fluxes.

Here <σv> is the product of cross section of N̅N annihilation and a relative velocity of neutrinos averaged over velocity distribution, \( n = \rho/m \) is the number density of neutrinos in Galaxy. An integration is performed along the line of sight with formally infinite upper limit, \( dN/E/dE \) is the mean multiplicity of photons created in an act of annihilation for \( E - (E + dE) \) energy interval. The factor 1/4 comes from the fact that the number densities of neutrinos and antineutrinos are equal to a half of their total number density \( n \). To obtain a distribution \( dN/E/dE \) a code PYTHIA 6.2 was used.

Figures 2 and 3 show \( \gamma \)-fluxes at the Earth from two directions: from the Galactic center (Fig.2) and from a halo in the direction of Galactic zenith (Fig.3). Corrected EGRET data for the halo were taken from [14], where EGRET data were re-analyzed in an advanced approach in which the galactic contribution was subtracted giving pure isotropic "extragalactic" \( \gamma \)-radiation. Dashed/solid lines in these figures show annihilation/annihilation plus background \( \gamma \)-fluxes for neutrino mass ranging 47-80 GeV. The annihilation \( \gamma \)-fluxes were obtained selecting density parameter \( \xi_{loc} \) at given (Evan’s) density distribution to fit in the best way the observation data for the accepted value of neutrino mass. In a fitting procedure \( \chi^2 \) criterion was used by fixing the Galactic contribution (background) and changing the annihilation flux by the \( \xi_{loc} \)-parameter. Neutrino masses were chosen as 47, 50, 55, 60, 65, 70, 75, 80 GeV.

The low energy part of \( \gamma \)-spectrum from halo (Fig.3) is not reproduced by annihilation of Heavy neutrinos in the halo. However this low energy part can be explained by extragalactic emission based on a blazar population [14, 15]. This emission is expected with a similar slope in spectra as data points exhibit. Extraction of pure "extragalactic" \( \gamma \)-flux in direction of Galactic center (GC) is more complicated problem. We used observational data and a prediction of galactic contribution for \( \gamma \)-flux from GC [10] in accordance with model "C". The galactic contribution (referred to as a background) is shown in Fig.2 by dot-dashed line.

All \( \xi_{loc} \)-parameters, fitting in the best way the predicted annihilation with background fluxes to observational data, will be presented in a figure below.

3.2 Signature of Heavy neutrinos annihilation in cosmic \( e^+ \) and \( p \) fluxes

The flux of charged particles from annihilation of Heavy neutrinos in Galaxy near the Earth is defined by a diffusion of particles from \( N \bar{N} \) annihilation to the region around the Earth of the size as large as the characteristic diffusion length. For antiprotons, which do not experience significant energy loss, this region is determined by
Figure 3: Cosmic gamma-radiation from zenith galactic direction: EGRET data and the best-fit gamma-flux from 47-80 GeV neutrino DM annihilation (the set of lines) for Evan’s halo model.

the size of halo where they are trapped by magnetic field. For positrons the size of region of dark matter annihilation sources contributing to a flux near the Earth depends on energy loss of positrons. This does not allow positrons, created with an energy $E_0$, to come with energy $E$ from distance strongly exceeding

$$\lambda(E, E_0) = \left( \int_{E_0}^{E} \frac{D(E')}{b(E')} dE' \right)^{1/2}.$$  \hfill (6)

Here $D$ is the diffusion coefficient which is energy (rigidity) dependent, $b(E)$ is the rate of energy loss defined as

$$\frac{dE}{dt} = -b(E).$$  \hfill (7)

Charged cosmic particles experience a solar modulation. To take into account this effect we will use force-field model [16]. In this approximation the intensity measured at the top of the Earth’s atmosphere (inner heliosphere) at the energy $E_{\text{Earth}}$ corresponds to a local interstellar (LIS) intensity (outer heliosphere) through the relation

$$I_{\text{LIS}}(E = E_{\text{Earth}} + \Phi(t)) = \left( \frac{E_{\text{Earth}} + \Phi(t)}{E_{\text{Earth}}^2 - m_p^2} \right)^2 I_{\text{Earth}}(E_{\text{Earth}}, t).$$  \hfill (8)

Here $m_p$ is the mass of cosmic particle, $\Phi(t)$ is the energy lost by the cosmic particles during their travel in the heliosphere. $\Phi(t)$ is the parameter of the model which can be derived from an observation of appropriate period of Solar activity. A dependence of solar modulation of CR on the sign of particle charge appears at low energy (at LIS energy, less than 1-2 GeV). It is shown in [17] this dependence during nineties (positive half-cycle of the Sun) broke the force-field approximation for description of data on negatively charged particles (electrons, antiprotons) in low energy range. Whereas positively charged particles were well described by the force-field model in that period. We will use data on cosmic positrons and antiprotons transformed into LIS by Eq(8), what will lead to some underestimation of LIS antiproton flux at low energy. Note that the energy scale of modulation is determined by $\Phi(t)$, being around 1GeV, and for $E >> 1$ GeV effect of modulation is negligible.

For an estimation of positron flux from $N\bar{N}$ annihilation we adopted the diffusion approximation of positron propagation in Galaxy without inclusion of the effect of diffusion zone boundaries [18]. It is well-known that a strong energy loss of high energy cosmic $e^{\pm}$ makes their spectra dependent on the space distribution of density of $e^{\pm}$-sources. It disfavors the use of ”leaky-box” model for a quantitative estimation of the effects of tangled, diffusion propagation of $e^{\pm}$ in Galaxy. A diffusion coefficient and energy loss parameter were chosen following
"DR" model \[11\]

\[
D(E) = 6.1 \times 10^{28} \left( \frac{E}{4 \text{ GeV}} \right)^{0.33} \text{ cm}^2 \text{s}^{-1},
\]
\[
b(E) = \beta E^2, \quad \beta = 1.52 \times 10^{-9} (0.5 + 0.5(H/3 \mu G)^2) \text{ yr}^{-1} \text{ GeV}^{-1},
\]

Here in the expression for \(\beta\) the dependence on the averaged galactic magnetic field \(H\) and its value 3 \(\mu\) G are taken in accordance with \[19\]. Such parameters (Eq(9-10)) allow positrons originated as far as at GC to contribute to the flux near the Earth. A background (secondary) positron flux was taken as predicted in "DR" model keeping accordance with the choice of parameters (Eq(9-10)). "DR" model takes into account effect of boundaries and effect of re-acceleration, acceleration of cosmic particles (initially accelerated in their sources) during their propagation in interstellar medium. A disagreement between our estimation of annihilation flux and the used prediction of background is not significant. An effect of boundaries of diffusion zone is not very important for Evan’s DM halo model as it is seen from \[20\].

The decrease of halo size \(z_h\) leads to the de-population of distribution of positrons with \(\lambda > z_h\) (Eq(6)) because they escape the diffusion zone more intensively than at larger \(z_h\) and also because a contribution from dark matter annihilation sources situated outside the diffusion zone is not taken into account. The escape from the diffusion zone leads to diminishing relative contribution of annihilation positrons from GC with a decreasing halo size, what is more marked effect for halo models with a sharp density profile near GC. The use of Evan’s halo model with its smoothed density distribution provides better accuracy for the used approximation than other models with sharper profiles. Also to reduce a deviation of annihilation fluxes obtained in our approximation from that one which would be predicted in "DR" model, induced by the neglecting of the boundaries, we excluded a contribution from dark matter annihilation sources situated outside the diffusion zone of \(z_h = 4\) kpc. Effect of re-acceleration appears below 5 GeV in positron spectra \[20\] (or the right part of Fig.5 in the ref. \[21\]), where the role of secondary positrons shades the possible dark matter annihilation sources contribution.

In Fig.4 the predicted LIS positron fluxes as compared to observational data of HEAT \[22\] are presented. There are the secondary positron flux (dot-dashed line), the sum of secondary and the best-fit annihilation fluxes (the set of solid lines) and separately the last ones (the set of dashed lines), obtained for the range of neutrino mass 47-80 GeV. Note, that the curves corresponding to the annihilation fluxes are extended up to the energy equal to \(m\) of neutrino, above this energy the predicted total fluxes (secondary plus annihilation positrons) are the same as the secondary flux at \(E > m\). HEAT data were "demodulated" taking \(\Phi = 664\) MeV, derived from data of CAPRICE \[17\]. A fitting was performed in the same way as described above for gamma-radiation. First point of HEAT (slightly below 2 GeV in Fig.4) was omitted in the procedure of fitting. This point is apparently inconsistent even with the predicted secondary positron flux and also inconsistent with the other measurements of cosmic positrons \[17\]. Note that the low energy range should be considered cautiously, because predictions in this range depend on possible effects of re-acceleration.

Let’s consider an effect of diffusion coefficient variation, or correspondingly (see Eq(6)) a variation of positron diffusion length. A decrease in \(D\) by a factor 10 modifies a little a slope (makes steeper) of spectra of annihilation positrons near the Earth and changes the best-fit \(\xi_{loc}\) parameter by less than 20\%. The further decrease in \(D\) causes no influence, because mean free path length \(\lambda\) becomes less than typical physical scales of the problem (the distance to the nearest boundary of diffusion zone or the length scale of variation in the DM density distribution).

To estimate the flux of antiprotons from \(N\tilde{N}\) annihilation near the Earth we accept a leaky-box model. In this model the intensity can be defined by a simple expression

\[
I = \frac{\nu_{\tilde{p}}}{4\pi} < \dot{n}_{\tilde{p}} > \tau_{conf}.
\]

Here \(\nu_{\tilde{p}}\) is the velocity of antiproton, \(< \dot{n}_{\tilde{p}} > = \frac{\int \frac{4}{\mu} n^2 c <\sigma v> dV}{\int \frac{4}{\mu} n^2 dV} \) is the mean number of antiprotons created in a unit volume per second per energy interval \(E - (E + dE)\), averaged over the volume of Galaxy, \(\tau_{conf}\) is the confinement time, the other notations are analogous to those introduced in Eq(5). Time \(\tau_{conf}\) is a parameter
of the model and it has the meaning of the time of $\bar{p}$ confinement in Galaxy. We chose $\tau_{con}$ to be $10^7$ years as in the early works [2]. The volume of Galaxy is supposed to be the volume of region where antiprotons are confined and this region is chosen in form of a disk with radius 25 kpc and semiheight $z_h = 4$ kpc, typical for CR models. Energy losses of antiprotons are neglected in Eq(11). Such simplification is justified by small mean matter column (5 g/cm$^2$) traveled by cosmic nuclei, which was deduced from CR analysis. A small fraction of antiprotons, which lose their energy in an inelastic scattering on protons of medium ("tertiary" component), appears in antiproton spectra at very low energy [11].

As a background the secondary antiprotons predicted in model "C" of [10] were used. For a comparison with observations the combined data of BESS’95 and ’97 were used [23], which were demodulated with parameter $\Phi = 540$ MeV, derived from BESS'95 [24]. Data BESS’98 belong to time of high solar activity what is less suitable from point of view of detection of possible dark matter annihilation sources [24]. Figure 5 shows a spectrum of cosmic antiprotons. Unlike the cases of gamma-radiation and positrons the spectra of antiprotons from $N\bar{N}$ annihilation for different values of Heavy neutrino mass coincide within an energy interval presented in Fig.5. A charge-sign dependence of solar modulation and an effect of re-acceleration are significant at low energy, making results in this energy range less certain.

An increase of parameter $\tau_{con}$ or/and a decrease of volume comprising $\bar{p}$ propagation zone in Galaxy lead to a decrease in the best-fit density parameter $\xi_{loc}$. Uncertainties in $\tau_{con}$ and $V_{Gal}$ lead to overall uncertainty of about a factor 2.

Note, that the analysis of CR carried out in this work differs from analogous analysis performed in the previous works [2], [25] by more refined consideration, in particular more realistic CR models and models of distribution of Heavy neutrinos in Galaxy.

### 4 Heavy neutrino in underground versus cosmic rays signals

As one can see from figures 2-5, the presence of dark matter annihilation sources in the form of Heavy neutrinos improves description of existing data on cosmic gamma-radiation, positrons, antiprotons with corresponding $\xi_{loc}$ selected in the best way from observational data. The annihilation fluxes in these figures were obtained for Evan’s halo model (Eq(3)) as described above. In the same manner as in case of Evan’s model the parameters $\xi_{loc}$, allowing to fit in the best way CR data, were obtained for isothermal halo model (Eq(4)). All these parameters for different values of neutrino mass are shown in Fig.6 in comparison with those preferable in
Figure 5: Cosmic antiprotons (LIS): BESS(95+97) data, predicted background (dot-dashed line), and the best-fit contribution from 47-80 GeV neutrino DM (the set of dashed lines is pure annihilation antiproton fluxes, the set of solid lines is the sum of background and annihilation fluxes) for Evan’s halo model. Note, that for the considered interval of neutrino masses the sets of dashed and solid lines are virtually reduced to single lines.

measurements of DAMA. There is the set of black lines in upper half of figure, starting at $m = 46$ GeV and ending at $m = 80$ GeV, which corresponds to $\xi_{loc}$ parameters, inferred from CR analysis. Pairs of solid (dot-dashed), dotted and dashed lines of this set are related with the best-fit $\xi_{loc}$ for gamma-radiation from halo (GC), for cosmic positrons and antiprotons respectively. Upper and lower lines of each pair correspond to Evan’s and isothermal halo models respectively. Solid and dashed grey lines, going across the picture, enclose favorable region of DAMA. For consistent comparison of $\xi_{loc}$, inferred from CR analysis using Evan’s halo model, the values of $\xi_{loc}$, derived from analysis of DAMA/NaI measurements based on the same Evan halo model, are shown by dashed grey lines.

All $\xi_{loc}$ parameters, obtained from CR analysis, define parameters favored by CR data as well as upper constraints imposed by CR data. So, given results allow to make a conclusion that CR data are consistent with measurements of DAMA/NaI in framework of hypothesis about the 4th generation neutrino.

An additional source of information about possible existence of WIMPs is data from the search for light neutrino fluxes from annihilation of WIMPs accumulated inside the Earth and Sun. But existing data of underground measurements of neutrino fluxes exhibit, contrary to CR data, a lack of neutrinos as compared to predicted background (atmospheric neutrinos). New physics is possibly required here. An interpretation based on 3-flavor neutrino oscillations fails to reproduce all appropriate existing data without an introduction of a new sterile neutrino. An estimation of muon neutrino fluxes from annihilation of Heavy neutrinos inside the Earth gives a result comparable with the expected corresponding atmospheric neutrino flux in the energy range $> 3$ GeV for $m = 50$ GeV for acceptable parameters of Evan’s halo model. In this analysis the result depends also on WIMP velocity distribution which affects the capture rate of WIMPs by the Earth. This ratio is reduced by a few times if the velocity distribution given by Evan’s halo model (Eq(A1-A4) [12]) with velocity parameter $v_0 = 170$ km/sec is replaced by Maxwellian distribution with r.m.s. velocity $v_0 = 220$ km/sec. An analysis of underground measurements of upward-going muons (Super-Kamiokande, MACRO, Baksan), induced by neutrino fluxes, requires its further development.

A question about an agreement between all predicted parameters for the 4th generation neutrino, helping to improve description data of different species, is of greater interest. Striking is a relative closeness of $\xi_{loc}$ parameters preferable for different observations. Figure 6 shows that ”play” with the form of density distribution of Heavy neutrinos in Galaxy is able to change significantly $\xi_{loc}$ derived from different observations. An agreement between the considered data is possible. For the chosen isothermal model all $\xi_{loc}$ parameters (lower lines from pairs of lines of upper (black) lines in Fig.6) favored by CR data, a neutrino mass is close to its
Figure 6: DAMA favorable region (as in Fig.1) and the best-fit density parameters deduced from cosmic gamma-radiation (from halo and CG), positron and antiproton analysis. Horizontal grey dashed and solid lines enclose DAMA favorable region accepting Evan’s halo model and other halo models, respectively. The set of upper lines corresponds to the $\xi_{loc}$ parameters preferable for CR data. In this set of lines, upper and lower lines of the same type correspond to Evan’s halo model and to isothermal halo model, respectively. Vertical grey dashed and solid lines restrict 1$\sigma$ and 2$\sigma$ allowable range of the 4th neutrino mass deduced from the particle physics data analysis.

lower constraint, in the region of corresponding magnitudes, deduced from DAMA experiment accounting for different halo models.

In the case of isothermal model, the value of $\xi_{loc}$ parameter inferred from analysis of cosmic gamma-radiation from halo (solid line), differs from the other ones. This discrepancy can be due to a possible extragalactic $\gamma$-radiation (see Fig.3) the account for which can lead to better agreement. But, of course, results of indirect WIMP searches should be treated cautiously taking into account the low precision of the corresponding experimental data.

Given Evan’s halo model, predictions of $\xi_{loc}$ from the data on different CR species are differed by a factor of three. In a view of approximations in CR analysis described above it should not be considered as the principal discrepancy. An agreement achieved between predictions of parameters preferable for CR data and for measurement of DAMA would require reduction of parameter $\xi_{loc}$, preferred by CR data, by a factor a few - ten in the allowed range of neutrino mass below 50 GeV. Such a reduction corresponds to an amplification of the annihilation flux proportional to the square of that factor.

In other words, the results of DAMA/NaI experiment are compatible with indirect effects of 4th neutrino annihilation, but the observational indications to WIMP annihilation effects in cosmic rays and gamma radiation can be explained together with these results only for some models and for a very narrow interval of neutrino masses (46-47 GeV). To increase the range of neutrino masses, at which direct and indirect WIMP signals can find simultaneous explanation, the rate of 4th neutrino annihilation in Galaxy should be much larger.

5 Three ways to extend neutrino models and mass range

5.1 Amplification of neutrino annihilation due to clumpiness

There is a possibility to amplify CR flux created by dark matter annihilation sources maintaining local density and average density distribution of DM in Galaxy. This possibility is related with a clumpy DM distribution
in Galaxy ([20] and references therein). In particular we are considering local clustering in our galactic center and halo with no peculiar density enhancement for our neighborhood. The opposite situation (higher Solar and lower global galactic density) is a possibility much less probable and attractive.

CDM might form clumps on the stage of structure formation in the Universe. As it was shown in [20] a small fraction of total DM mass (a few×10⁻³) can survive to present time in form of clumps and it is enough to provide strong enhancement (up to a few orders of magnitude) of annihilation signal. Being a non-dominating DM component, Heavy neutrinos most likely do not form their own clumps. A formation of clumps should be governed by the dominating CDM component. Heavy neutrinos should subserve in such processes for values of the formed clump mass, \( M_{\text{clump}} \), exceeding some minimal one, \( M_{\text{N,min}} \). The last one is defined by the size of a proto-clump equal to free-streaming length of neutrinos, \( \lambda_{\text{fs}} \), when inhomogeneities start to grow. \( \lambda_{\text{fs}} \) depends on the moment of Heavy neutrinos decoupling from an ambient plasma. For 50 GeV neutrino the temperature of decoupling is estimated as \( T_d \sim 20 \text{ MeV} \), whereas the mass \( M_{\text{N,min}} \sim 0.6 \times 10^{-6} M_\odot \) (Eq(37) of [20]). Provide a dominant CDM component has a less free-streaming scale (that is, for instance, quite probable for neutralinos and heavy gravitinos), there would exist the clumps with masses in the range \( M_{\text{clump}} > M_{\text{min}} \) so that \( M_{\text{min}} < M_{\text{N,min}} \). For heavy neutrinos the ranges of clump masses are \( M_{\text{min}} < M_{\text{clump}} < M_{\text{N,min}} \), and \( M_{\text{clump}} > M_{\text{N,min}} \). Creation of clumps only of the second mass range is not expected to proceed with a separation of the dominant CDM component and Heavy neutrinos.

We will suppose a conservation of proportionality (ratio) between densities of dominant CDM component and Heavy neutrinos in such a clump creation. Clumps lighter than \( M_{\text{N,min}} \), if they are, can be populated by Heavy neutrinos in less degree in accordance with the mechanism of adiabatic loss of energy by collisionless particles (neutrinos) in an external variable gravitation field [27].

Estimations of [20] for the enhancement factor of dominant DM annihilation flux due to the presence of clumps can be applied to Heavy neutrinos. This factor is defined as

\[
\eta = \frac{I_{\text{clump}} + I_{\text{hom}}}{I_{\text{hom}}}
\]  

(12)

where \( I_{\text{clump}} \) and \( I_{\text{hom}} \) are the intensities of annihilation fluxes from clumps of DM and homogeneously distributed DM. It crucially depends on minimal mass of clumps, \( \eta(M_{\text{min}}) \), the lightest clumps give the main contribution into an annihilation rate. Under assumption on proportionality between densities the predictions for enhancement factor can be referred to non-dominating Heavy neutrinos DM assuming the minimal clump mass to be \( M_{\text{N,min}} \)

\[
\eta_N = \eta(M_{\text{N,min}}). \tag{13}
\]

Note, that Fig.1 implies some deviation from such proportionality within a factor 1-100 at \( m = 50 \text{ GeV} \) for an average local density (which is deduced from dynamical observation to be within 0.17-1.7 GeV/cm³), if real local density (in vicinity of the Earth) does not differ significantly from the average one.

Additional contribution into an enhancement of the neutrino annihilation rate will result from the clumps with a mass in the range \( M_{\text{min}} - M_{\text{N,min}} \). The enhancement from these clumps can be roughly estimated as a corresponding estimation in [26] for \( M_{\text{min}} \) reduced with respect to smaller relative compression of Heavy neutrino density inside the given clumps as compared to that of dominant DM. In each such clump the relative compression of neutrino density, i.e. the ratio of densities inside a clump and outside it (of homogeneous component near the clump), should be smaller than that of dominant component of matter (CDM) in accordance with [27]

\[
\frac{\rho_N}{\rho_N} \frac{\rho_{\text{CDM clump}}}{\rho_{\text{CDM hom}}} = \left( \frac{\rho_{\text{CDM clump}}}{\rho_{\text{CDM hom}}} \right)^{3/4}. \tag{14}
\]

As a first approximation we neglect details (differences) of density distributions of dominant component and Heavy neutrinos inside these clumps. So, the factor \( \eta \) is determined by squared ratio of densities above both for Heavy neutrinos and for CDM. The enhancement factor for Heavy neutrinos for a clump mass between \( M_{\text{min}} \) and \( M_{\text{N,min}} \) can be estimated as

\[
\eta_{N \text{add}} = \eta(M_{\text{min}})^{3/4}, \tag{15}
\]

where \( \eta(M_{\text{min}}) \) is the enhancement factor as predicted in [20] (for dominant DM component).
Factor $\eta$ increases with a decrease of clump mass \cite{20}, so a contribution from the clumps of mass $M_{min} < M_{clump} < M_{N\ min}$, which are relatively less populated by Heavy neutrinos, can be comparable with those of mass $M_{clump} > M_{N\ min}$. For instance, for an index of primeval perturbation spectrum $n_p = 1.05$, index of power-like density distribution inside the clump $\beta = 1.8$ at $M_{N\ min} = 0.6 \times 10^{-6} M_\odot$ we have $\eta_N \approx 20$ (see Fig.5 of \cite{20}), and assuming $M_{min} = 10^{-8} M_\odot$ we obtain $\eta_{N\ add} \approx (30)^{3/4} \approx 13$. For essentially smaller values of $M_{min}$ the contribution from clumps with $M_{min} < M_{clump} < M_{N\ min}$ is turned out to prevail.

A density parameter $\xi_{loc}$ should decrease as a square root of enhancement factor $\eta_N$, so in example above we get $\xi_{loc}$ by a factor 5 less at 50 GeV than it is in Fig.6. For other values of neutrino mass of interest the result is virtually the same. An agreement between measurement of DAMA/NaI and CR observation data is possible for the hypothesis of 4th neutrino with Evan’s halo model within allowed neutrino mass range below 50 GeV (see Fig.7).

Note that in our approximation we did not pay attention to a correction for given quantitative estimations of an effect of clumps due to a different DM density distribution in Galaxy (Evan’s) than it was supposed in \cite{20}. Also note, that a destruction of clumps near GC \cite{20} should partially decrease the enhancement of annihilation $\gamma$-flux from GC due to clumps. This may improve agreement between results for photons from GC and the halo.

In the case if a minimal possible DM clump mass, $M_{min}$, is greater than $M_{N\ min}$ (there is only a unique mass range), then the enhancement factor would be given by Eq(13) with $M_{min}$ instead of $M_{N\ min}$.

5.2 Amplification of neutrino annihilation due to new Coulomb-like interaction

An annihilation signal as a signature of existence of DM particles like Heavy neutrinos implies a condition of the presence of both particles and antiparticles. The case considered in the present article was based on an assumption of charge symmetry of 4th generation particles, i.e. an equality between the numbers of primordial 4th neutrinos and antineutrinos. Such a statement can find physical foundation in superstring models. New charge(s) is(are) predicted there which, being strictly conserved, can be ascribed only to 4th generation particles \cite{28}. It accounts for absolute stability of the lightest particle bearing this charge (assumed to be the 4th neutrino) and an equality between particles and antiparticles of a new generation.

An important consequence of a new charge is an effect of new interaction. In a wide class of models this charge is $U(1)$-gauge charge which leads to existence of corresponding massless gauge bosons ($y$-photons) and to a Coulomb-like interaction of 4th neutrinos. It was revealed in \cite{29}, that this new interaction does not influence
The account for this new Coulomb-like interaction, possessed by 4th neutrinos, extends the possibility of unified explanation of CR and DAMA/NaI data in the framework of 4th neutrino hypothesis for the most part of considered interval of neutrino masses. Figure 8 corresponds to the case of $\alpha_y = 1/30$, which is the most natural value for this coupling constant.

The case of clumpiness of Heavy neutrinos with new interaction, while being possible, is more complex and involves both factors ($\eta$ and $\alpha_y$). Its combined role will offer more tunable scenarios; however for sake of simplicity we will not take it into account here.

On the first sight Sakharov’s enhancement does not influence the annihilation rate of accumulated 4th neutrinos inside the Earth and Sun, which is defined by their capture rate. However, the existence of stable quark of 4th generation can make the picture more complicated. Being compatible with the constraints on the abundance of anomalous isotopes, the presence of small amount of anomalous hadrons, containing this quark (or antiquark) and possessing the $U(1)$-gauge charge can cause asymmetry in capture rates for 4th neutrino and antineutrino and thus influence their annihilation rate in Earth and Sun. A role of this gauge interaction, its charges and field in effects of Heavy neutrinos as well as the account of possible existence of stable 4th generation hadrons requires a separate discussion.
5.3 The role of Heavy neutrino asymmetry and decays

If neutrinos of 4th generation do not possess new $U(1)$-gauge charge, there does not appear any fundamental reason for their absolute stability as well as for their strict charge symmetry. If charge symmetry is absent, which is the case for baryons in the Universe, the 4th neutrinos would prevail over their antineutrinos (or vice versa) and they could decay. A magnitude of this asymmetry, being defined as the ratio of difference of present number densities of 4th neutrinos and 4th antineutrinos ($\delta n$) and present relic photon number density, is an additional parameter of the problem. This parameter should be much less than that of baryons in order not to exceed an essentially relative contribution of 4th neutrino into the density of CDM derived from measurements of DAMA (Fig.1). A difference $\delta n \sim \text{a few} \times n_{\text{sym}}$, where $n_{\text{sym}}$ is the relic Heavy neutrino density in the case of charge symmetry, leads to an increase of relic 4th neutrino density by a few times and to an exponential decrease of density of relic 4th antineutrinos by a few orders of magnitude. As seen in Fig.1 this would be especially favored for neutrino mass around 50 GeV. If relic neutrinos survive to present time, their annihilation signals from Galaxy and from the Earth and Sun weaken by a few orders of magnitude as compared to the symmetric case.

However, in the asymmetric case another signature of 4th neutrino DM in CR is possible. Neutrinos of 4th generation are unstable in this case and their decays in the galactic halo can lead to effects similar to the ones from stable neutrino annihilation. In this case CR data can be reproduced, if 4th neutrino decay lifetime is, for Evan’s density distribution, $\tau \approx \xi_{\text{loc}} \cdot (0.2 - 2) \times 10^{19} \text{years} \frac{50 \text{GeV}}{m}$. (18)

Here $\xi_{\text{loc}}$ is the local density fraction of neutrinos in charge asymmetric case. The value of the decay rate preferable for CR data changes weakly with variation of neutrino mass (since it is defined by the observed CR fluxes), so uncertainty 0.2-2 in estimation (18) is mainly induced by uncertainty of best-fit $\xi_{\text{loc}}$ parameters deduced from data of different CR species (for Evan’s halo model). Note that there is a difference by a factor 2 in energy release for annihilation reaction and decay process. But in the numerical estimations for the effects of decay the predictions for CR fluxes, induced by neutrino annihilation, can be used without significant change with only proper account for the change in the energy release, provided that hadron modes are present in decay with sufficient probability. Parameter $\xi_{\text{loc}} \approx 0.01 - 0.001$ would provide for neutrino of mass about 47-70 GeV with the lifetime given above an agreement between the measurement of DAMA/NaI and CR data. So, preferable lifetime of 4th neutrino is $\tau \sim (2 \times 10^{15} - 2 \times 10^{17})$ years. Note, that clumpiness does not affect the fluxes of products of Heavy neutrino decay in the Galaxy. Also note, that the annihilation rate of neutrinos accumulated inside the Earth and Sun in the symmetric case corresponds to a timescale less than the age of Solar system (much less in case of the Sun). So the decay rate with the lifetime above (18) is strongly suppressed as compared to a corresponding annihilation rate for the symmetric case.

6 Conclusions

In the present work it was shown that the positive result at 6.3 sigma C.L. obtained in DAMA/NaI and observed possible excesses in cosmic gamma-radiation, positrons and antiprotons can be in agreement within the framework of hypothesis of a 4th neutrino mass hidden nearby half the Z-boson mass. The evident advantage of this hypothesis is the minimal number of physical parameters. In the simplest case it is only the mass of neutrino (to be compared with minimally 5 parameters in the case of SUSY dark matter).

But even in this simplest case we have revealed the complex model dependence on the galactic mass distribution and cosmic ray diffusion. We have shown its compatibility within realistic values of Heavy neutrino mass. The model may be naturally extended in the case of in-homogeneous (clumpy) galactic halo, new Heavy neutrino Interactions related to its necessary stability, relic neutrino asymmetry and it consequent unstability and decay. In those models there are room for better agreement between underground and cosmic rays signals.

\footnote{In the case of light neutrinos, which decouple in the conditions of thermodynamical equilibrium, such asymmetry would determine their chemical potential (see review in [31]).}
The lightest neutrino masses (∼ 50 GeV) might be searched inside the old LEP data regarding electron pair annihilations into one photon with missing energy \[32\]; the largest ones (∼ 57 – 75 GeV) might be discovered by near future LHC search of invisible Higgs boson decay \[33\]. Additional satellites and antimatere search in Space might define the exact parameter range for this extension of the lepton sector, whose existence might be tested also in the search for a novel pair of 4th quark family\[34\].

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