Resolution to neutrino masses, baryon asymmetry in leptogenesis and cosmic-ray anomalies

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Abstract

By extending the lepton sector of standard model to include one sterile neutrino and two sets of new Higgs doublets and right-handed neutrinos, denoted by $(\eta_1, N_1, N_3)$ and $(\eta_2, N_2, N_4)$, with two $Z_2$ symmetries, the puzzles of neutrino masses, matter-antimatter asymmetry and cosmic-ray excess observed by Fermi-LAT and PAMELA can be resolved simultaneously. The characters of the model are: (a) neutrino masses arise from type-I and radiative seesaw mechanisms; (b) leptogenesis leading to baryon asymmetry at the energy scale of $O(1-10\text{TeV})$ could be realized through soft $Z_2$ symmetry breaking effects; and (c) the conditions of small couplings for a long-lived dark matter could be achieved naturally through loop corrections due to the same soft symmetry breaking effects. The candidate for dark matter in leptophilic decays could fit the Fermi-LAT and PAMELA data well.

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One of the strongest motivations for new physics is due to the unsolvable problems in the standard model (SM), such as the origin of neutrino masses, matter-antimatter asymmetry and dark matter, which are the phenomena observed well, but less understood. Recently, three astonishing experiments PAMELA [1], ATIC [2] and Fermi-LAT [3] in cosmic-ray measurements reheated the issue of the unknown stuff, in which the first one indicates anomaly in positron flux ratio while the later two observe excess in electron+positron ($e^+e^-$) flux. Although Fermi-LAT’s results don’t display the bump as shown at ATIC in the $e^-e^+$ flux, a clear excess at Fermi with high precision can not be denied. Promptly, it is proposed that one of possible resources for generating the exotic events in the flux of electrons and positrons is ascribed to the dark matter annihilations and/or decays [4, 5, 6].

PAMELA observes not only on the positron flux ratio but also on the antiproton flux ratio, however, the resulting evidences show no significant excess on the latter. Accordingly, if the excess observed at Fermi and PAMELA stems from the dark matter, the dark stuff should presumably be leptophilic. Furthermore, if the matter-antimatter asymmetry arises from the so-called leptogenesis where the baryon asymmetry originates from the lepton asymmetry [7], the issues of neutrino masses, baryon asymmetry and Fermi/PAMELA puzzles intriguingly are all related to the lepton sector. Based on this inference, it is interesting to investigate how these unsolved problems can be explained within a simple model uniformly.

Although dark matter annihilations could provide the source for the Fermi/PAMELA anomalies, it is inevitable that an enhanced boost factor of a few orders of magnitude, such as Sommerfeld enhancement [8], near-threshold resonances and dark-onium formation [9], has to be introduced. To evade of introducing unnecessary effects, we will focus on the mechanism of dark matter decays. Moreover, to get a long-lived dark matter, say $O(10^{26}\text{ s})$, usually we have to fine-tune either the new couplings to be tiny or the new scale in intermediated state to be as large as the scale of grand unified theories (GUTs). Hence, in order to fulfill our purpose, the subject we face is not only how the model provides a new CP violating (CPV) mechanism in the lepton sector so that lepton number asymmetry could be converted to the baryon asymmetry by the nonperturbative sphalerons [10], but also how a long-lived dark matter exists naturally while solving Fermi/PAMELA anomalies.

To solve the mentioned problems, we extend the SM by including two extra Higgs doublets $\eta_i^T = (\eta_i^0, \eta_i^-) \ (i=1,2)$ with hypercharge $Y = -1$ and five right-handed neutrinos denoted by $N_{1-4}$ and $N$. Besides, we introduce two $Z_2$ discrete symmetries so that $\eta_1$ and $N_{1,3}$ are
transformed by
\[ \eta_1 \to -\eta_1, \quad N_{1,3} \to -N_{1,3}, \quad (1) \]
while \( \eta_2 \) and \( N_{2,4} \) follow
\[ \eta_2 \to -\eta_2, \quad N_{2,4} \to -N_{2,4} \quad (2) \]
under the first and second \( Z_2 \) symmetry, respectively. The unmentioned fields in above
equations denote invariance in each transformation. In addition, \( \eta_{1,2} \) do not have vacuum
expectation values (VEVs) when the discrete symmetries are exact. Accordingly, the Yukawa
sector could be found as
\[ -L_Y = \bar{L}_i Y_{ij} E_j \bar{H}_{jR} + \bar{L}_j Y_{jN} H N + \bar{L}_i y_{\alpha \beta} \eta_1 N_\alpha \]
\[ + \bar{L}_i y_{i\beta} \eta_2 N_\beta + \frac{m_N}{2} N^T C N \]
\[ + \sum_{k=1}^4 \frac{m_{N_k}}{2} N_k^T C N_k + H.c., \quad (3) \]
where \( L^T = (\nu_\ell, \ell)_L \) denotes the \( SU(2)_L \) doublet leptons, \( H^T = (H^0, H^-) \) is the SM Higgs
doublet, \( Y_{ij}^E, Y_{jN} \) and \( y_{\alpha \beta} \) with \( i, j = 1 - 3 \) and \( \alpha = 1, 3 (2, 4) \) stand for the Yukawa
couplings. For simplicity, we have chosen \( N_i \) as the diagonalized states before the electroweak
symmetry breaking (EWSB). Since the right-handed neutrino \( N \) directly couples to the SM
Higgs and ordinary leptons, the masses of neutrinos could be induced after the EWSB.
Therefore, \( N \) could lead to non-zero neutrino masses by the type-I seesaw mechanism, i.e.,
we have to set \( m_N \gg m_{N_i} \). Moreover, because of interactions associated with charged
leptons being \( \bar{\ell}_L N_i \eta_i^+ \), in order to explain the Fermi/PAMELA data, the decaying dark
matter should be the fermionic particle. Here, we take \( N_2 \) as the candidate. Thus, the mass
relations are required to obey \( m_{\eta_2(2)} > m_{N_{1,3}(2)} \) and \( m_{N_2} > m_{N_1} \). We will see clearly later
that if \( m_{N_4} \gg m_{N_3} > m_{\eta_2} \), the role of \( N_3 \) is responsible to the leptonic CP asymmetry
(CPA) in leptogenesis.

Since \( N_2 \) is protected by the \( Z_2 \)-symmetry and the decay is forbidden by kinematics, so
far it is still a stable particle. We note that \( N_3 \) and \( N_4 \) are allowed kinematically to decay
through the channels \( N_3 \to N_2 \ell^+ \ell^- \) and \( N_4 \to \ell \eta_2 \), respectively. In order to make the dark
matter unstable, we ascribe that the origin of the unstable dark matter is from the \( Z_2 \) soft
breaking terms, given by
\[ -L_{\text{soft}} = \mu_{34} N_3^T C N_4 + H.c. \quad (4) \]
Due to the soft breaking effects being associated with heavier right-handed neutrinos, it is clear that although $Z_2$ symmetries have been broken, the breaking effects will not open a sizable decaying channel for $N_2$. Hence, the unstable dark matter could be a long-lived one.

We now start to discuss in turn how the puzzles of small neutrino masses, baryon asymmetry and Fermi-LAT/PAMELA are solved in this model.

**Neutrino Masses**: By the first term of Eq. (3), the neutrino mass matrix could be expressed by

$$\left( m_\nu \right)_{ij}^{\text{Type-I}} \approx -m_D m_N^{-1} m_D^†,$$

where we have made the expansion in terms of $m_D / m_N$ and used $\langle H \rangle = v / \sqrt{2}$ as the vacuum expectation value (VEV) of the Higgs field. To explain the neutrino masses, with $Y_{i(j)}^N \sim O(1)$ we see that $m_N \sim 3 \times 10^{15}$ GeV/(1 eV) as expected by the conventional seesaw model. Besides the type-I seesaw mechanism, the masses of neutrinos could be also induced by radiative corrections in which the corresponding Feynman diagram is illustrated in Fig. 3(a). With the relevant quartic term in the Higgs potential, written by $\lambda_5 / 2 \left( H^\dagger \eta_{1,2} \right)^2$, the mass matrix through one-loop is given by

$$\left( m_\nu \right)_{ij}^{\text{rad}} \approx \frac{\lambda_5 v^2}{8\pi^2} \left( \frac{y_{i1} y_{j1} m_{N_1}}{m_{\eta_1}^2} + \frac{y_{i3} y_{j3} m_{N_3}}{m_{\eta_2}^2} \right),$$

where we have adopted $m_{\eta_{1(2)}} > m_{N_{1(2)}}$. Because $N_4$ is much heavier than other particles, we have ignored its contributions. With $m_{\eta_1} \sim 8$ TeV, $m_{\eta_2} \sim m_{N_3} \sim 4$ TeV, $m_{N_1} \sim m_{N_2} \sim O(1$ TeV), $\lambda_5 \sim O(10^{-4})$ and $y_{i3} \sim O(10^{-2})$, the neutrino mass by the dominant effects could be $O(1$ eV). Intriguingly, if we combine the type-I and radiative seesaw mechanisms together, it is found that some cancelations could occur between both. As a result, the constraint on the couplings of $\lambda_5$ and $y_{i1(2,3)}$ could be somewhat relaxed. Besides, the $m_\nu \sim 1$ eV resulted in each seesaw mechanism can be reduced to $O(0.01 - 0.1$ eV) by the cancelations.

**Leptogenesis**: Since $N_3$ plays the role of the lepton asymmetry at the energy scale of $O(1 - 10$ TeV), to satisfy the out-of-equilibrium condition, the decay rate of $N_3$ should be less than the Hubble constant $H$ at the temperature of $m_{N_3}$, given by

$$\Gamma_{N_3} < H(T = m_{N_3}) = \left( \frac{4\pi^3}{45} \right) \frac{T^2}{M_{\text{Planck}}} \bigg|_{T = m_{N_3}}.$$
where $g_\ast \approx 100$ denotes the number of active degrees of freedom and $M_{\text{Planck}} \sim 10^{19}$ GeV is the Planck scale. As mentioned early, $N_3$ could decay via the three-body channel of $N_3 \to N_1 \ell^+ \ell^-$. We check that by the phase space suppression and with $y_{i3}y_{i1} \sim 10^{-5}$, the rate for the three-body decay is around a factor of 5 smaller than Hubble constant. In addition, by the soft breaking effects of Eq. (4), $N_3$ will decay to $\ell \eta$ through the mixing with $N_4$, sketched by Fig. 1(b). The rate will depend on the parameters of $\mu_{34}$, $m_{N_4}$ and $y_{i4}$. By calculating the two-body decay rate of Fig. 1(b) and with $m_{N_3} = 4$ TeV, the constraint on the parameters is

$$\left| \frac{\mu_{34}}{m_{N_4}}y_{i4} \right| < 5 \times 10^{-7} \left( \frac{m_{N_3}}{4 \text{TeV}} \right).$$  \hspace{1cm} (8)$$

By employing small $\mu_{34}/m_{N_4}$, the decay rate less than the Hubble constant for $N_3$ of $O$(TeV) can be naturally accomplished.

Another necessary condition to achieve baryon asymmetry is the CPA, defined by

$$A_{CP} = \frac{\Gamma(N_3 \to \ell \eta_1) - \Gamma(N_3 \to \ell \eta_2)}{\Gamma(N_3 \to \ell \eta_1) + \Gamma(N_3 \to \ell \eta_2)}. \hspace{1cm} (9)$$

A nonzero direct CPA should involve CPV and CP conserving (CPC) phases simultaneously. Here, the complex Yukawa couplings $y_{i\alpha}$ can provide the new CPV source. Therefore, we need a new mechanism to generate the physical CPC phase. It has been well known that one-loop effects could produce the CPC phase when the on-shell condition of particle in the internal loop is satisfied. In the model the CPC phases could be induced via self-energy \cite{14} and vertex corrections \cite{7} illustrated in Fig. 1(c) and (d). Therefore, the CPAs via

\begin{align*}
\text{(b)} & \quad N_3 \xrightarrow{\ell} N_4 \xrightarrow{\ell} \eta_2 \\
\text{(c)} & \quad N_3 \xrightarrow{\ell} N_1 \xrightarrow{\ell} N_2 \xrightarrow{\ell} \eta_2 \\
\text{(d)} & \quad N_3 \xrightarrow{\ell} N_1 \xrightarrow{\ell} N_4 \xrightarrow{\ell} \eta_2
\end{align*}

FIG. 1: Feynman diagrams of (a) Neutrino masses by radiative corrections and (b), (c) and (d) the $N_3 \to \ell \eta_2$ decay at tree and loop levels.
self-energy (S) and vertex (V) diagrams are respectively found to be [15]

\[ A_{CP}^{S}(N_3) \approx -\frac{1}{8\pi} r_Y^2 \sin\delta \frac{\sqrt{x_2}}{x_2 - 1}, \]
\[ A_{CP}^{V}(N_3) \approx -\frac{1}{8\pi} r_Y^2 \sin\delta \times \sqrt{x_2} [(1 + x_2) \log(1 + 1/x_2) - 1] \]  

(10)

with \( x_2 = (m_{N_2}/m_{N_3})^2 \) and \( r_Y^2 \sin\delta = \text{Im}(y_{i4}^* y_{i2})^2/|y_{i4}|^2 \). \( \delta \) is taken as the CPV phase and the repeating index \( i \) stands for the summation in lepton flavors. Following the relation of the observed baryon asymmetry and the lepton asymmetry, formulated by [16]

\[ \left( \frac{n_B}{s} \right)_{\text{obs}} = \frac{28 n_B - n_L}{79 s}, \quad \frac{n_L}{s} \approx \frac{n_\gamma}{2s} A_{CP} \]  

(11)

where \( s \) and \( n_{B(L,\gamma)} \) are the entropy and baryon (lepton,\( \gamma \)) density of the universe, respectively, we obtain

\[ \left( \frac{n_B}{s} \right)_{\text{obs}} \approx -\frac{1}{12g_*} [A_{CP}^{S}(N_3) + A_{CP}^{V}(N_3)] \]  

(12)

where we have used \( s = g_* T^3 (2\pi^2/45) \) and \( n_\gamma = 2T^3/\pi^2 \). With \( |\sin\delta| = 0.3 \), the baryon asymmetry as a function of \( r_Y \) is presented in Fig. 2 where the solid, dashed, dotted and dash-dotted lines represent \( N_2 = 2, 2.5, 3.0 \) and \( 3.5 \) TeV, respectively, with \( N_3 = 4 \) TeV.

According to the results, \( r_Y \sim |y_{i2}| \sim O(10^{-3}) \) not only satisfies the criterion for radiative neutrino masses but also explains the baryon asymmetry in leptogenesis.

**Fermi-LAT/PAMELA**: Due to \( N_{3,4} \) being heavier than other particles, the soft breaking interactions introduced in Eq. (4) cannot directly lead to \( N_2 \) decays. However, by combining the soft breaking effects with Yukawa couplings, we find that a finite dimension-4
hard operator for the mixture of \( \eta_1 \) and \( \eta_2 \) could be induced at one-loop level, sketched in Fig. 3. The resultant contributions to the scalar potential is given by

\[
d\delta V_{\text{hard}} = C_h \left( \eta_1^\dagger H \right) \left( \eta_2^\dagger H \right) + H.c., \tag{13}
\]

with

\[
C_h = \frac{1}{16\pi^2} \left( y_{i3}^* Y^N_i \right) \left( y_{j4}^* Y_j^N \right) \frac{\mu_{34}}{m_N}, \tag{14}
\]

where we have neglected the terms associated with \( m_{N_3,4}/m_N \) and used the Einstein summation convention for the indices \( i \) and \( j \). If we simply ignore the summation in indices \( i \) and \( j \), by combining with Eq. (5), the mixing effect of \( \eta_1 \) and \( \eta_2 \), denoted by \( \mu_{12}^2 \), could be simplified to be

\[
\mu_{12}^2 \sim \frac{1}{16\pi^2} (m_\nu)_{ij} y_{i3}^* y_{j4}^* \mu_{34}.
\]

With using \( y_{i3} \sim 10^{-2} \) and \( m_{N_3} = 5 \times 10^4 \) TeV and following Eqs. (8) and (15), we immediately have \( \mu_{12}^2 < 1.5 \times 10^{-12} \text{GeV}^2 \). Since \( Z_2 \) symmetries will be restored while \( \mu_{34} \) vanishes, the smallness of \( \mu_{12}^2 \) is still nature in technique. Consequently, the lifetime for \( N_2 \) dictated by \( N_2 \to N_1 \ell\ell \) can be found by

\[
\tau_{N_2} \simeq \frac{2^9 \pi^3}{3 |y_{i2} y_{j1}^*|^2} \frac{m_{N_3}^5}{m_{N_2}^5} \left( \frac{m_{N_1}^2}{m_{N_2}^2} \right)^2 \left( 1 - \frac{m_{N_1}^2}{m_{N_2}^2} \right)^4. \tag{16}
\]

Adopting \( m_{\eta_{1(2)}} = 8(4) \) TeV, \( m_{N_{1(2)}} = 0.5(2) \) TeV, \( y_{i1} y_{j2} \sim 7.5 \times 10^{-6} \) and the obtained upper value of \( \mu_{12}^2 \), we get \( \tau_{N_2} \approx 2.5 \times 10^{26} \) s. Clearly, the values of the parameters in the model could be compatible with the phenomena of neutrino masses, leptogenesis and long-lived dark matter.
Since the long-lived dark matter could only decay in leptophilic, for illustration, we simply consider the electron-positron pair and one electron (positron) and antimuon (muon) as the possible final states, in which antimuon (muon) will further decay to positron (electron) by SM weak interactions. Due to three possible channels involved, where the associated parameters are proportional to $|y_{e2}y_{e1}^*|^2$, $|y_{e2}y_{e1}^*|^2$ and $|y_{\mu2}y_{\mu1}^*|^2$, the energy spectrum for electron (positron) can be formulated by

$$\frac{dN_{e^\pm}}{dE} = \frac{1}{N} \left( c_\alpha^2 \frac{d\Gamma_{ee}}{dE} + c_\beta^2 \frac{d\Gamma_{e\mu}}{dE} + c_\gamma^2 \frac{d\Gamma_{\mu e}}{dE} \right),$$

(17)

with

$$\frac{d\Gamma_{ee}}{dE} = E^2 \left( \frac{3}{2} \Delta m_{21}^2 - \frac{8}{3} m_{N_2} E \right),$$
$$\frac{d\Gamma_{e\mu}}{dE} = F_{e\mu}(E) + \int_{m_{\mu}}^{m_{N_2}/2} dE_\mu F_{\mu e}(E_\mu) \frac{d|M_{\mu}|^2(E_\mu, E)}{dE},$$
$$\frac{d\Gamma_{\mu e}}{dE} = F_{\mu e}(E) + \int_{m_{\mu}}^{m_{N_2}/2} dE_\mu F_{e\mu}(E_\mu) \frac{d|M_{\mu}|^2(E_\mu, E)}{dE},$$

where $N$ is the normalization, $c_\alpha^2 + c_\beta^2 + c_\gamma^2 = 1$, $\Delta m_{21}^2 = m_{N_2}^2 - m_{N_1}^2$, $F_{e\mu}(E) = E^2(\Delta m_{21}^2 - 2m_{N_2}E)$, $F_{\mu e}(E) = E^2(\Delta m_{21}^2/2 - 2/3m_{N_2}E)$ and

$$\frac{d|M_{\mu}|^2(E_\mu, E)}{dE} = \frac{G_F^2}{6\pi^3} \frac{1}{|\vec{p}_\mu|} \left\{ \frac{4}{3} \left[ E^3 (E_\mu - |\vec{p}_\mu|)^3 - \left( \frac{m_{\mu}^2}{2} \right)^3 \right] \right. - \left. \frac{3}{2} m_{\mu}^2 \left[ E^2 (E_\mu - |\vec{p}_\mu|)^2 - \left( \frac{m_{\mu}^2}{2} \right)^2 \right] \right\}. \quad (18)$$

For $d\Gamma_{e\mu}/dE$ and $d\Gamma_{\mu e}/dE$, the allowed energy range for muon and electron are found to be $m_{\mu} \leq E_\mu \leq m_\chi/2$ and $0 \leq E \leq m_{\mu}^2/2(E_\mu - |\vec{p}_\mu|)$, respectively. Since the experiments measure the flux of cosmic-rays, the used formalism to estimate the flux from the new source is given by

$$\Phi_{e^\pm}^{N_2} = \frac{c}{4\pi} \frac{1}{m_{N_2}^4 \tau_{N_2}} \int_0^{m_{N_2}/2} dE' G(E, E') \frac{dN_{e^\pm}}{dE'},$$

(19)

with $c$ being the speed of light. For numerical estimations, we adopt the result parametrized by [17]

$$G(E, E') \simeq \frac{10^{16}}{E^2} \exp[a + b(E^{6-1} - E'^{6-1})] \theta(E' - E) \quad [\text{cm}^{-3}\text{s}] \quad (20)$$
with \( a = -0.9809, b = -1.1456 \) and \( \delta = 0.46 \).

For including the primary and secondary electrons and secondary positrons, we use the parametrizations, given by [18, 19]

\[
\Phi_{e^-}(E) = \frac{0.16E^{-1.1}}{1 + 11E^{0.9} + 3.2E^{2.15}} \text{[GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}],
\]

\[
\Phi_{e^+}(E) = \frac{0.7E^{0.7}}{1 + 110E^{1.5} + 600E^{2.9} + 580E^{4.2}} \text{[GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}],
\]

\[
\Phi_{e^+}(E) = \frac{4.5E^{0.7}}{1 + 650E^{2.3} + 1500E^{4.2}} \text{[GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}].
\]

(21)

where \( \Phi_{\text{prim(sec)}} \) denotes the primary (secondary) cosmic ray. Accordingly, the total electron and positron fluxes are defined by

\[
\Phi_{e^-} = \kappa \Phi_{e^-}^{\text{prim}} + \Phi_{e^-}^{\text{sec}} + \Phi_{e^-}^{N2},
\]

\[
\Phi_{e^+} = \Phi_{e^+}^{\text{sec}} + \Phi_{e^+}^{N2}.
\]

(22)

Here, according to Refs. [19] and [20], we have regarded the normalization of the primary electron flux to be undetermined and parametrized by the parameter of \( \kappa \). The value of \( \kappa \) is chosen to fit the data. Before introducing the source of the primary positron, \( \kappa \) is set to be 0.8. Taking \( m_{N_2(1)} = 2(0.2) \text{ TeV} \) and \( \kappa = 0.65 \), we present the \( e^- e^+ \) flux and ratio of fluxes \( e^+/(e^- + e^+) \) by \( N_2 \) decays in Fig. 4 in which the thick solid, dashed and dash-dotted lines stand for \((\alpha, \beta, \gamma) = (1, 0, 0), (0, 1, 0) \) and \((0, 0, 1)\), respectively. Obviously, with proper

![Graphs showing electron and positron fluxes](image)

FIG. 4: electron+positron flux (left) and the ratio of positron flux to electron+positron flux (right), where the thick solid, dashed and dash-dotted lines represent \((\alpha, \beta, \gamma) = (1, 0, 0), (0, 1, 0) \) and \((0, 0, 1)\), respectively.

values for the parameters, the decaying dark matter could fit the Fermi-LAT and PAMELA data well simultaneously.
Inspired by the recent data measured by Fermi-LAT and PAMELA, we have found that the puzzles of small neutrino masses and baryon asymmetry as well as dark matter can be solved uniformly by extending the lepton sector of the SM with two $Z_2$ symmetries. In the proposed model, the conventional type-I and radiative corrections seesaw mechanisms coexist to generate the masses of neutrinos. The matter-antimatter asymmetry originated from leptogenesis could be accomplished by the introduced new stuff associated with soft $Z_2$ breaking terms. With the same soft breaking effects, the condition of small couplings for a long-lived decaying dark matter can be realized naturally through radiative corrections.

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[1] O. Adriani et al. [PAMELA Collaboration], Nature 458, 607 (2009). [arXiv:0810.4995 [astro-ph]].
[2] J. Chang et al. [ATIC Collaboration], Nature 456, 362 (2008).
[3] A. A. Abdo et al. [Fermi LAT Collaboration], arXiv:0905.0025 [astro-ph.HE].
[4] L. Bergstrom, T. Bringmann and J. Edsjo, Phys. Rev. D77, 103520 (2008); M. Cirelli et al., arXiv:0808.3867 [astro-ph]; 0809.2409 [hep-ph]; V. Barger et al., Phys. Lett. B672,141 (2009); J. Liu, P. f. Yin and S. h. Zhu, arXiv:0812.0964 [astro-ph]; D. Hooper, A. Stebbins and K. M. Zurek, arXiv:0812.3202 [hep-ph]. X. J. Bi, P. H. Gu, T. Li and X. Zhang, JHEP 0904, 103 (2009); D. Hooper and K. M. Zurek, arXiv:0902.0593 [hep-ph]; K. Cheung, P. Y. Tseng and T. C. Yuan, arXiv:0902.4035 [hep-ph]; X. J. Bi, X. G. He and Q. Yuan, arXiv:0903.0122 [hep-ph]; D. S. M. Alves et al., arXiv:0903.3945 [hep-ph]; A. A. E. Zant, S. Khalil and H. Okada, arXiv:0903.5083 [hep-ph]; J. McDonald, arXiv:0904.0969 [hep-ph]; M. Kuhlen and D. Malyshev, arXiv:0904.3378 [hep-ph]; F. Y. Cyr-Racine, S. Profumo and K. Sigurdson, arXiv:0904.3933 [astro-ph.CO]; L. Bergstrom, J. Edsjo and G. Zaharijas, arXiv:0905.0333 [astro-ph.HE]; X. J. Bi et al arXiv:0905.1253 [hep-ph].
[5] C. R. Chen, F. Takahashi and T. T. Yanagida, Phys. Lett. B671, 71 (2009); Phys. Lett. B673, 255 (2009); C. R. Chen and F. Takahashi, JCAP 0902, 004 (2009); P. F. Yin et al., Phys. Rev. D79, 023512 (2009); K. Hamaguchi, E. Nakamura, S. Shirai, T. T. Yanagida, arXiv:0811.0737 [hep-ph]; A. Ibarra and D. Tran, JCAP 0902, 021 (2009) arXiv:0811.1555 [hep-ph]; C. R. Chen, M. M. Nojiri, F. Takahashi and T. T. Yanagida, arXiv:0811.3357 [astro-ph]; E. Nardi, F. Sannino and A. Strumia, JCAP 0901, 043 (2009) arXiv:0811.4153 [hep-ph]; A. Arvanitaki et al., arXiv:0812.2075 [hep-ph]; K. Hamaguchi, S. Shirai and T. Yanagida, Phys. Lett. B673, 247 (2009) arXiv:0812.2374 [hep-ph]; K. Hamaguchi, F. Takahashi and T. T. Yanagida, arXiv:0901.2168 [hep-ph]; K. Ishiwata, S. Matsumoto and T. Moroi, arXiv:0811.0250 [hep-ph]; 0903.0242 [hep-ph]; 0903.3125 [hep-ph]; S. L. Chen, R. N. Mohapatra, S. Nussinov and Y. Zhang, arXiv:0903.2562 [hep-ph]; A. Arvanitaki et al., arXiv:0904.2789 [hep-ph]; S. Shirai, F. Takahashi and T. T. Yanagida, arXiv:0905.0388 [hep-ph]; K. Kohri, J. McDonald and N. Sahu, arXiv:0905.1312 [hep-ph]; K. Hamaguchi, K. Nakaji and E. Nakamura, arXiv:0905.1574 [hep-ph]; N. Okada and T. Yamada, arXiv:0905.2801 [hep-ph].

[6] C. H. Chen, C. Q. Geng and D. Zhuridov, Phys. Lett. B675, 77 (2009); arXiv:0905.0652.

[7] M. Fukugita and T. Yanagida, Phys. Lett. B174, 45 (1986).

[8] J. Hisano, S. Matsumoto and M. M. Nojiri, Phys. Rev. Lett. 92, 031303 (2004; N. Arkani-Hamed et al., Phys. Rev. D79, 015014 (2009).

[9] M. Pospelov and A. Ritz, Phys. Rev. D78, 055003 (2008); D. Feldman, Z. Liu and P. Nath, Phys. Rev. D79, 063509 (2009); J. D. March-Russell and S. M. West, arXiv:0812.0559 [astro-ph].

[10] V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B155, 36 (1985).

[11] P. Minkowski, Phys. Lett. B 67, 421 (1977); T. Yanagida, Proceedings of the Workshop on Unified Theories and Baryon Number in the Universe, edited by A. Sawada and A. Sugamoto, (KEK Report No. 79-18, 1979); S. Glashow, in Quarks and Leptons, Cargese, 1979, edited by M. Lévy et al. (Plenum, New York, 1980); M. Gell-Mann, P. Ramond, and R. Slansky, Proceedings of the Supergravity Stony Brook Workshop, New York, edited by P. Van Nieuwenhuizen and D. Freedman (North-Holland, Amsterdam, 1979); R. N. Mohapatra and G. Senjanović, Phys. Rev. Lett. 44, 912 (1980).

[12] E. Ma, Phys. Rev. D73, 077301 (2006).

[13] A. D. Sakharov, JETP Lett. 24 (1967).
[14] M. Flanz, E. A. Paschos and U. Sarkar, Phys. Lett. B345, 248 (1995); M. Flanz et al., Phys. Lett. B389, 693 (1996).
[15] T. Hambye, Nucl. Phys. B633, 171 (2002).
[16] S. Yu. Khlebnikov and M. E. Shaposhnikov, Nucl. Phys. B308, 885 (1988); T. A. Harvey and M. S. Turner, Phys. Rev. D42, 3344 (1990).
[17] A. Ibarra and D. Tran, JCAP 0807, 002 (2008) [arXiv:0804.4596 [hep-ph]].
[18] E. A. Baltz and J. Edsjo, Phys. Rev. D59, 023511 (1999) [arXiv:astro-ph/9808243].
[19] I. Moskalenko and A. Strong, Astrophys. J.493, 694 (1998) [arXiv:astro-ph/9710124].
[20] E. A. Baltz et al., Phys. Rev. D65, 063511 (2002) [arXiv:astro-ph/0109318].