

# Visible and Dark Matter Genesis and Cosmic Positron/Electron Excesses

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Dark and baryonic matter contribute comparable energy density to the present Universe. The dark matter may also be responsible for the cosmic positron/electron excesses. We connect these phenomena with Dirac seesaw for neutrino masses. In our model (i) the dark matter relic density is a dark matter asymmetry generated simultaneously with the baryon asymmetry so that we can naturally understand the coincidence between the dark and baryonic matter; (ii) the dark matter mostly decays into the leptons so that its decay can interpret the anomalous cosmic rays with positron/electron excesses.

PACS numbers: 98.80.Cq, 95.35.+d, 14.60.Pq, 11.30.Fs

Precise cosmological observations indicate that dark and baryonic matter have different properties but contribute comparable energy density to the present Universe. This intriguing coincidence inspires us to propose a common origin for the creation and evolution of the dark and baryonic matter. Since the baryonic matter currently exists because of a matter-antimatter asymmetry, the dark matter relic density may also be an asymmetry between the dark matter and dark antimatter [1, 2, 3, 4]. The dark matter asymmetry and the baryon asymmetry may originate from decays of the same heavy particles, so that their coincidence is not surprising at all. On the other hand, recently cosmic-ray data [5, 6, 7, 8, 9] suggest [10] that (i) the dark matter should dominantly annihilate or decay into leptons with a large cross section or a long life time; (ii) the dark matter annihilation or decay should be consistent with the constraints from the observations on the gamma and neutrino fluxes. In this paper we explain these phenomena in a unified scenario where the neutrino masses originate through the Dirac seesaw mechanism [11].

We extend the standard model (SM) with a global  $U(1)_{lepton} \times U(1)_{dark}$  symmetry and include additional particles: singlet right-handed neutrino  $\nu_R(\mathbf{1}, \mathbf{1}, 0)(1, 1)$ , heavy doublet scalar  $\eta(\mathbf{1}, \mathbf{2}, -1/2)(0, -1)$ , charged singlet scalar  $\xi(\mathbf{1}, \mathbf{1}, 1)(-2, 0)$ , and neutral singlet scalars  $\sigma(\mathbf{1}, \mathbf{1}, 0)(0, -1)$  and  $\chi(\mathbf{1}, \mathbf{1}, 0)(-2, -1)$ , where the transformations are given under the SM gauge group  $SU(3)_c \times SU(2)_L \times U(1)_Y$  and the global symmetry  $U(1)_{lepton} \times U(1)_{dark}$ . For simplicity, we only present the relevant part of the Lagrangian for purpose of demonstration,

$$\begin{aligned} \mathcal{L} \supset & -y\overline{\psi}_L\eta\nu_R - f\xi\overline{\psi}_L^c i\tau_2\psi_L - \mu\sigma\eta^\dagger\phi - \kappa\chi^\dagger\xi\eta^T i\tau_2\phi \\ & + \text{H.c.} - M_\eta^2(\eta^\dagger\eta) - m_\xi^2(\xi^\dagger\xi) - m_\chi^2(\chi^\dagger\chi) \\ & - (\chi^\dagger\chi) [\alpha(\xi^\dagger\xi) + \beta(\phi^\dagger\phi) + \gamma(\sigma^\dagger\sigma)] \\ & - (\sigma^\dagger\sigma) [\zeta(\xi^\dagger\xi) + \epsilon(\phi^\dagger\phi) + \vartheta(\sigma^\dagger\sigma)]. \end{aligned} \quad (1)$$

Here  $\psi_L(\mathbf{1}, \mathbf{2}, -1/2)(1, 0)$  and  $\phi(\mathbf{1}, \mathbf{2}, -1/2)(0, 0)$ , respectively, are the SM lepton and Higgs doublets. The right-handed neutrinos neither have Yukawa couplings with the SM Higgs doublet nor have Majorana masses as a result of the  $U(1)_{lepton} \times U(1)_{dark}$  conservation. The global symmetry  $U(1)_{lepton}$  will be exactly conserved at any energy scales while the global symmetry  $U(1)_{dark}$  will be spontaneously broken above the weak scale.

The singlet scalar  $\sigma$  acquires a vacuum expectation value (VEV) to break  $U(1)_{dark}$  and then induces a small VEV of the heavy doublet scalars  $\eta$  after the electroweak symmetry breaking by  $\langle\phi\rangle \simeq 174$  GeV,

$$\langle\eta\rangle \simeq -\frac{\mu\langle\sigma\rangle\langle\phi\rangle}{M_\eta^2} \quad \text{for } M_\eta \gtrsim \mu \gg \langle\sigma\rangle > \langle\phi\rangle. \quad (2)$$

Therefore through the Dirac seesaw mechanism [11], the neutrinos obtain very small Dirac masses naturally through their Yukawa couplings to the heavy doublet,

$$m_\nu = y\langle\eta\rangle. \quad (3)$$

In our model, the heavy doublet scalar  $\eta$  has three lepton number conserving decay channels:

$$\eta \rightarrow \psi_L\nu_R^c, \quad \eta \rightarrow \phi^*\xi^*\chi, \quad \eta \rightarrow \phi\sigma. \quad (4)$$

We consider two heavy scalars  $\eta_{1,2}$  to incorporate CP violation. These decays of  $\eta_{1,2}$  at loop orders (as shown in Fig. 1) can interfere to generate three types of lepton asymmetries after  $\eta_{1,2}$  go out of equilibrium: the first one (including that transferred from the charged singlet scalar  $\xi$ ) is stored in the left-handed lepton doublets  $\psi_L$ ; the second one is stored in the singlet right-handed neutrinos  $\nu_R$ ; and the third one is stored in the neutral singlet  $\chi$ , although the total lepton asymmetry vanishes as the lepton number is exactly conserved.

The effective Yukawa couplings of the left-handed lepton doublets to the SM Higgs doublet and the right-handed neutrinos are extremely weak, so that they can

not go into equilibrium until the temperature falls well below the electroweak scale. This will prevent the  $\nu_R$  asymmetry to cancel the  $\psi_L$  asymmetry before the sphaleron transitions are over. Thus, before the electroweak phase transition, the sphaleron [12] action will partially convert the lepton asymmetry stored in the left-handed lepton doublets to the baryon asymmetry in the Universe. Therefore, we can make use of the leptogenesis [13] via neutrino genesis [14] mechanism to understand the baryon asymmetry in the Universe. On the other hand, the asymmetry between the neutral singlet  $\chi$  and its CP-conjugate will always survive after it is produced because there are no other processes breaking the lepton number stored in  $\chi$ . We will show later that this  $\chi$  asymmetry corresponds to an amount of energy density, equal to the dark matter relic density, so that  $\chi$  becomes the dark matter candidate.

For an estimate of the amount of CP asymmetry, we work in the basis, in which the  $\eta_{1,2}$  mass matrix is real and diagonal:  $M_\eta^2 = \text{diag}(M_{\eta_1}^2, M_{\eta_2}^2)$ . We also assume  $M_{\eta_2} \gg M_{\eta_1}$ , so that the final lepton asymmetry stored in the left-handed lepton doublets  $\psi_L$  and the dark matter asymmetry stored in the neutral singlet  $\chi$  should mainly come from the decays of the lighter  $\eta_1$ :

$$\begin{aligned} \varepsilon_{\eta_1}^{\psi_L} &\equiv \frac{\Gamma(\eta_1 \rightarrow \psi_L \nu_R^c) - \Gamma(\eta_1^* \rightarrow \psi_L^c \nu_R)}{\Gamma_{\eta_1}} \\ &+ 2 \frac{\Gamma(\eta_1 \rightarrow \phi^* \xi^* \chi) - \Gamma(\eta_1^* \rightarrow \phi \xi \chi^*)}{\Gamma_{\eta_1}} \\ &= \frac{1}{4\pi} \frac{\text{Im} \left[ \text{Tr} \left( y_1^\dagger y_2 \right) \left( \frac{\mu_1^* \mu_2}{M_{\eta_2}^2} - \frac{1}{32\pi^2} \kappa_1 \kappa_2^* \frac{M_{\eta_1}^2}{M_{\eta_2}^2} \right) \right]}{\text{Tr} \left( y_1^\dagger y_1 \right) + \frac{1}{32\pi^2} |\kappa_1|^2 + \frac{|\mu_1|^2}{M_{\eta_1}^2}} \\ &- \frac{1}{64\pi^3} \frac{\text{Im} \left\{ \kappa_1^* \kappa_2 \left[ \frac{\mu_1^* \mu_2}{M_{\eta_2}^2} + \text{Tr} \left( y_2^\dagger y_1 \right) \frac{M_{\eta_1}^2}{M_{\eta_2}^2} \right] \right\}}{\text{Tr} \left( y_1^\dagger y_1 \right) + \frac{1}{32\pi^2} |\kappa_1|^2 + \frac{|\mu_1|^2}{M_{\eta_1}^2}}, \quad (5) \end{aligned}$$

$$\begin{aligned} \varepsilon_{\eta_1}^\chi &\equiv \frac{\Gamma(\eta_1 \rightarrow \phi^* \xi^* \chi) - \Gamma(\eta_1^* \rightarrow \phi \xi \chi^*)}{\Gamma_{\eta_1}} \\ &= -\frac{1}{128\pi^3} \frac{\text{Im} \left\{ \kappa_1^* \kappa_2 \left[ \frac{\mu_1^* \mu_2}{M_{\eta_2}^2} + \text{Tr} \left( y_2^\dagger y_1 \right) \frac{M_{\eta_1}^2}{M_{\eta_2}^2} \right] \right\}}{\text{Tr} \left( y_1^\dagger y_1 \right) + \frac{1}{32\pi^2} |\kappa_1|^2 + \frac{|\mu_1|^2}{M_{\eta_1}^2}}. \quad (6) \end{aligned}$$

As the decays of  $\xi$  into two leptons  $\psi_L$  are in equilibrium, we included the lepton asymmetry in  $\xi$  for estimating the total lepton asymmetry involved in the sphaleron process.

Here  $\Gamma_{\eta_i}$  denotes the total decay width of  $\eta_i$  or  $\eta_i^*$ ,

$$\begin{aligned} \Gamma_{\eta_i} &\equiv \Gamma(\eta_i \rightarrow \psi_L \nu_R^c) + \Gamma(\eta_i \rightarrow \phi^* \xi^* \chi) + \Gamma(\eta_i \rightarrow \phi \sigma) \\ &= \frac{1}{16\pi} \left[ \text{Tr} \left( y_i^\dagger y_i \right) + \frac{1}{32\pi^2} |\kappa_i|^2 + \frac{|\mu_i|^2}{M_{\eta_i}^2} \right] M_{\eta_i}. \quad (7) \end{aligned}$$

The unitarity and the CPT conservation imply the total decay width of  $\eta_1$  and  $\eta_1^*$  to be the same  $\Gamma_{\eta_1} = \Gamma_{\eta_1^*}$ . For simplicity, we assume  $y_2 = y_1 e^{i\varphi}$ ,  $\kappa_2 = \kappa_1 e^{i\varphi}$ ,  $\mu_2 = \mu_1 e^{i(\delta-\varphi)}$  and then derive

$$\varepsilon_{\eta_1}^{\psi_L} = \frac{\sin \delta}{4\pi} \frac{\left[ \text{Tr} \left( y_1^\dagger y_1 \right) - \frac{1}{16\pi^2} |\kappa_1|^2 \right] \frac{|\mu_1|^2}{M_{\eta_2}^2}}{\text{Tr} \left( y_1^\dagger y_1 \right) + \frac{1}{32\pi^2} |\kappa_1|^2 + \frac{|\mu_1|^2}{M_{\eta_1}^2}}, \quad (8)$$

$$\varepsilon_{\eta_1}^\chi = -\frac{\sin \delta}{4\pi} \frac{\frac{1}{32\pi^2} |\kappa_1|^2 \frac{|\mu_1|^2}{M_{\eta_2}^2}}{\text{Tr} \left( y_1^\dagger y_1 \right) + \frac{1}{32\pi^2} |\kappa_1|^2 + \frac{|\mu_1|^2}{M_{\eta_1}^2}}. \quad (9)$$

The ratio between  $\varepsilon_{\eta_1}^{\psi_L}$  and  $\varepsilon_{\eta_1}^\chi$  then becomes,

$$\varepsilon_{\eta_1}^{\psi_L} : \varepsilon_{\eta_1}^\chi = \text{Tr} \left( y_1^\dagger y_1 \right) - \frac{1}{16\pi^2} |\kappa_1|^2 : -\frac{1}{32\pi^2} |\kappa_1|^2. \quad (10)$$

The final baryon asymmetry and dark matter asymmetry would contribute energy density to the present Universe as below [15],

$$\begin{aligned} \rho_B^0 &= n_B^0 m_N = \frac{n_B^0}{s_0} m_N s_0 = -\frac{28}{79} \frac{n_{L_{SM}}}{s} \Big|_{T \simeq M_{\eta_1}} m_N s_0 \\ &\simeq -\frac{28}{79} \varepsilon_{\eta_1}^{\psi_L} \frac{n_{\eta_1}^{eq}}{s} \Big|_{T \simeq M_{\eta_1}} m_N s_0, \quad (11) \end{aligned}$$

$$\begin{aligned} \rho_\chi^0 &= n_\chi^0 m_\chi = \frac{n_\chi^0}{s_0} m_\chi s_0 = \frac{n_\chi}{s} \Big|_{T \simeq M_{\eta_1}} m_\chi s_0 \\ &\simeq \varepsilon_{\eta_1}^\chi \frac{n_{\eta_1}^{eq}}{s} \Big|_{T \simeq M_{\eta_1}} m_\chi s_0, \quad (12) \end{aligned}$$

where  $m_N \simeq 1 \text{ GeV}$  is the masses of the nucleons,  $s$  is the entropy density,  $n_B$  and  $n_\chi$ , respectively, are the number density of baryon and dark matter,  $n_{\eta_1}^{eq}$  is the equilibrium distribution of the heavy singlet  $\eta_1$ . The solutions (11) and (12) for the baryon and dark matter density are obtained, assuming that the decays of  $\eta_1$  satisfies the out-of-equilibrium condition,

$$\Gamma_{\eta_1} \lesssim H(T) \Big|_{T=M_{\eta_1}} = \left( \frac{8\pi^3 g_*}{90} \right)^{\frac{1}{2}} \frac{M_{\eta_1}^2}{M_{\text{Pl}}}, \quad (13)$$

where  $H(T)$  is the Hubble constant with relativistic degrees of freedom  $g_* \simeq 100$  and the Planck mass  $M_{\text{Pl}} \simeq 10^{19} \text{ GeV}$ . In the presence of the fast annihilation between the dark matter and dark antimatter, the dark matter asymmetry should be equivalent to the dark matter relic density. In this scenario, the contributions from

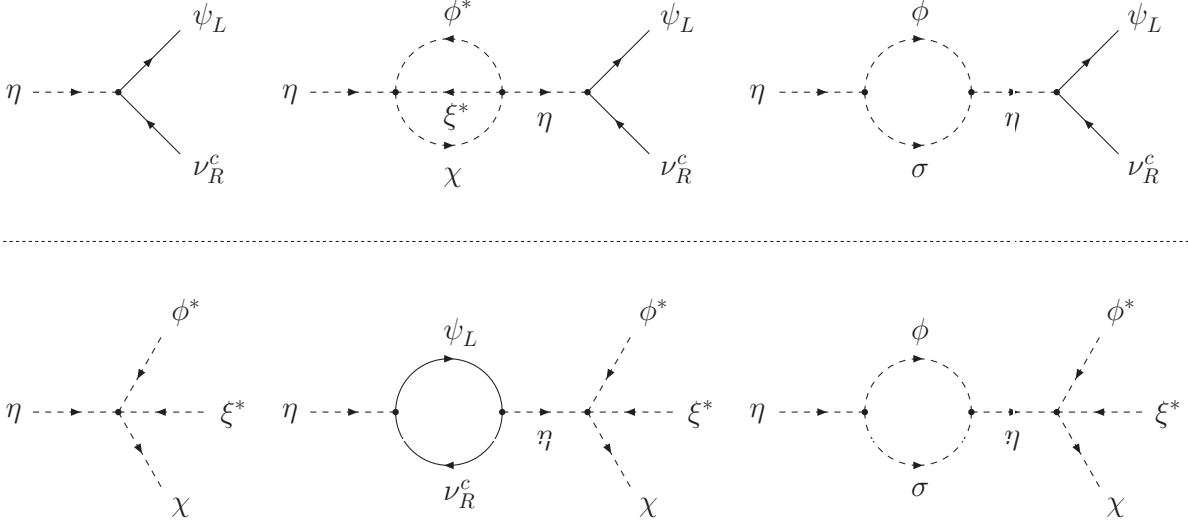


FIG. 1: The lepton number conserving decays for generating the desired lepton asymmetry and dark matter asymmetry.

the baryonic and dark matter to the present Universe should have the following ratio,

$$\Omega_B : \Omega_\chi \equiv \rho_B^0 : \rho_\chi^0 = -\frac{28}{79} \varepsilon_{\eta_1}^{\psi_L} m_N : \varepsilon_{\eta_1}^\chi m_\chi. \quad (14)$$

Conventionally, we define

$$\begin{aligned} \eta_B^0 &= \frac{n_B^0}{n_\gamma^0} \simeq 7.04 \times \left[ -\frac{28}{79} \varepsilon_{\eta_1}^{\psi_L} \frac{n_{\eta_1}^{eq}}{s} \Big|_{T \simeq M_{\eta_1}} \right] \\ &\simeq \frac{7.04 \varepsilon_{\eta_1}^{\psi_L}}{15 g_*}, \end{aligned} \quad (15)$$

to describe the current baryon asymmetry. Here  $n_\gamma$  is the number density of photon.

For giving a numerical example, we take  $M_{\eta_1} = 0.1 M_{\eta_2} = 5 \times 10^{13} \text{ GeV}$ ,  $|\mu_1| = |\mu_2| = 10^{12} \text{ GeV}$  and obtain  $\langle \eta_1 \rangle = 100 \langle \eta_2 \rangle \simeq 1 \text{ eV}$  for  $\langle \sigma \rangle = 1.5 \times 10^4 \text{ GeV}$ . Consequently the neutrino masses would be,

$$m_\nu \sim \mathcal{O}(0.01 \text{ eV}) \quad \text{for } y_1 = y_2 e^{-i\varphi} = \mathcal{O}(0.01). \quad (16)$$

We further input  $m_\chi = 4 \text{ TeV}$ ,  $|\kappa_1| = |\kappa_2| = 0.02$ ,  $\sin \delta = -0.5$  and  $\text{Tr}(m_\nu^\dagger m_\nu) = \text{Tr}(y_1^\dagger y_1) \langle \eta_1 \rangle^2 = 3 \times 10^{-3} \text{ eV}^2$  to obtain a lepton asymmetry

$$\varepsilon_{\eta_1}^{\psi_L} \simeq -2.3 \times 10^3 \varepsilon_{\eta_1}^\chi \simeq -1.4 \times 10^{-7}. \quad (17)$$

Eventually, we obtain the baryon asymmetry and the dark matter asymmetry as below

$$\eta_B^0 \simeq 6.2 \times 10^{-10}, \quad \Omega_\chi : \Omega_B \simeq 5, \quad (18)$$

which are fully consistent with the experimental observations [16].

In the non-relativistic limit, the annihilation cross-section of dark matter and dark antimatter reads,

$$\langle \sigma v \rangle = \frac{1}{32\pi} \left[ \left( \alpha - \frac{\gamma\zeta}{2\vartheta} \right)^2 + 2 \left( \beta - \frac{\epsilon\zeta}{2\vartheta} \right)^2 + 2\gamma^2 \right] \frac{1}{m_\chi^2}, \quad (19)$$

which could be very high as  $\alpha, \beta, \gamma, \zeta, \epsilon, \vartheta < \sqrt{4\pi}$ . For example, we obtain  $\langle \sigma v \rangle = 18 \text{ pb}$   $(4 \text{ TeV}/m_\chi)^2$  for  $\alpha, \beta, \vartheta = 0.1$  and  $\gamma, \zeta, \epsilon = 1$ . The thermally produced dark matter, with the mass within the range of a few GeV to a few TeV, should have an annihilation cross section slightly smaller than 1 pb to give the desired relic density (18). If the cross section is much bigger than 1 pb, the thermally produced relic density should be negligible. Therefore the dark matter relic density can be well approximated by the dark matter asymmetry.

The recent cosmic-ray experiments [5, 6, 7, 8, 9] suggest [10] that (i) the TeV-scale dark matter should mostly annihilate or decay into the leptons with a large cross section or a long life time; (ii) the dark matter annihilation or decay should not result in overabundant gamma and neutrino fluxes. For demonstration, we take the rotation,

$$\begin{aligned} Z_1 [\langle \phi \rangle \phi + \langle \eta_1 \rangle \eta_1 + \langle \eta_2 \rangle \eta_2] &\rightarrow \phi = \begin{pmatrix} \frac{1}{\sqrt{2}} h + \langle \phi \rangle \\ 0 \end{pmatrix}, \\ Z_1 Z_2 [\langle \phi \rangle (\langle \eta_1 \rangle \eta_1 + \langle \eta_2 \rangle \eta_2) - (\langle \eta_1 \rangle^2 + \langle \eta_2 \rangle^2) \phi] &\rightarrow \eta_1, \\ Z_2 [\langle \eta_1 \rangle \eta_2 - \langle \eta_2 \rangle \eta_1] &\rightarrow \eta_2, \end{aligned} \quad (20)$$

where  $Z_1 = [\langle \phi \rangle^2 + \langle \eta_1 \rangle^2 + \langle \eta_2 \rangle^2]^{-\frac{1}{2}}$  and  $Z_2 = [\langle \eta_1 \rangle^2 + \langle \eta_2 \rangle^2]^{-\frac{1}{2}}$ . Clearly, the Yukawa couplings of the heavy doublet scalars to the quarks are highly suppressed by  $\mathcal{O}(\langle \eta \rangle / \langle \phi \rangle)$ . Therefore, the dark matter  $\chi$  should mostly decay into the charged singlet scalar  $\xi$ , the left-handed charged leptons  $\ell_L$ , the right-handed neutrinos  $\nu_R$  and

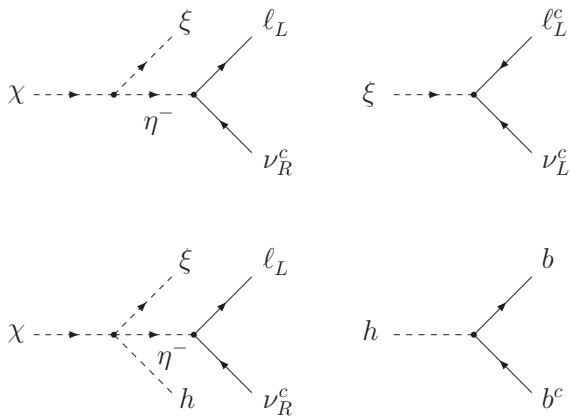


FIG. 2: The dark matter ( $\chi$ ) decays into the charged leptons ( $\ell$ ), the neutrinos ( $\nu$ ) and the bottoms ( $b$ ).

the physical Higgs boson  $h$ . We show the dominant decay channels in Fig. 2. Here we have taken into account that (1)  $\xi$  can uniquely and rapidly decay into the left-handed leptons  $\ell_L$  and  $\nu_L$  through the Yukawa coupling  $f\xi\overline{\psi}_L^c i\tau_2\psi_L$ ; (2)  $h$  can dominantly decay into the bottom quarks. The decay width is given by

$$\Gamma_\chi = \frac{1}{192 \cdot (2\pi)^3} \sum_{i,j=1}^2 \kappa_i^* \kappa_j \text{Tr} \left( y_i y_j^\dagger \right) \frac{\langle \phi \rangle^2 m_\chi^3}{M_{\eta_i}^2 M_{\eta_j}^2} \times \left[ 1 + \frac{1}{96 \cdot (2\pi)^2} \frac{m_\chi^2}{\langle \phi \rangle^2} \right]. \quad (21)$$

For giving a numerical example, we choose the parameters considered before and then determine the life time,

$$\tau_\chi = \frac{1}{\Gamma_\chi} \simeq 0.74 \times 10^{26} \text{ sec}. \quad (22)$$

We notice that the SM Higgs boson and then the bottom quark appear in the final states of the dark matter decay. However, the branching ratio is small (less than 4%) for the present choice of the parameters. This means the dark matter mostly decays into the leptons. Compared with the good fitting in [10], we find that the dark matter decay in our model can induce the desired positron/electron excesses but avoid the overabundant gamma and neutrino fluxes.

The quartic coupling of the dark matter scalar  $\chi$  to the SM Higgs doublet  $\phi$ , i.e.  $\beta(\chi^\dagger\chi)(\phi^\dagger\phi)$ , will result in an elastic scattering of dark matter on nuclei and hence a nuclear recoil [17]. The spin-independent cross section of the dark-matter-nucleon elastic scattering would be,

$$\sigma(\chi N \rightarrow \chi N) = \frac{\beta^2}{4\pi} \frac{\mu_r^2}{m_h^4 m_\chi^2} f^2 m_N^2 \simeq 10^{-44} \text{ cm}^2 \times \frac{\beta^2}{4\pi} \left( \frac{f}{0.3} \right)^2 \left( \frac{120 \text{ GeV}}{m_h} \right)^4 \left( \frac{4 \text{ TeV}}{m_\chi} \right)^2, \quad (23)$$

which is below the current experimental limit [18, 19], however, reachable for the future experiments. Here  $\mu_r = m_\chi m_N / (m_\chi + m_N)$  is the nucleon-dark-matter reduced mass,  $m_h$  is the mass of the physical Higgs boson  $h$  (The mixing between  $h$  and  $h'$  (from  $\sigma$ ) is negligible for  $\langle \sigma \rangle \gg \langle \phi \rangle$ .), the factor  $f$  with a central value  $f = 0.30$  [17] parameterizes the Higgs to nucleons coupling from the trace anomaly,  $f m_N \equiv \langle N | \sum_q m_q \bar{q}q | N \rangle$ .

In this paper we connect the neutrino masses with the origin of the dark matter relic density and the baryon asymmetry in the present Universe. In our model, the dark matter relic density is a dark matter asymmetry because the thermal relic density of dark matter is negligible in the presence of the fast annihilation between the dark matter and dark antimatter. This dark matter asymmetry originate simultaneously with a lepton asymmetry, which can explain the baryon asymmetry via the sphaleron process, and given by the amount of CP violation in out-of-equilibrium decays of heavy scalars. The dark matter mostly decays into the leptons to generate the positron/electron excesses without the overabundant gamma and neutrino fluxes so that we can explain the results from the recent cosmic-ray experiments.

**Acknowledgement:** We thank Xiao-Jun Bi and Goran Senjanović for helpful discussions. US thanks the Department of Physics and the McDonnell Center for the Space Sciences at Washington University in St. Louis for inviting him as Clark Way Harrison visiting professor. XZ is supported in part by the National Natural Sciences Foundation of China under grants 10533010 and 10675136, and by the Chinese Academy of Sciences under grant KJCX3-SYW-N2.

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