Common Origin of Visible and Dark Universe

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Motivation

- Cosmological observations indicate that dark energy, dark matter and visible matter contribute comparable energy density to the present Universe (e.g. Spergel *et al.*, 06'.),

$$\rho_{\rm DE} : \rho_{\rm DM} : \rho_{\rm B} \simeq 74\% : 21.6\% : 4.4\% \,. \tag{1}$$

The evolution of the dark and visible Universe is different. How to understand this coincidence?

- The visible matter exists in the present Universe as a matter–antimatter asymmetry, which is the same as the baryon asymmetry. If the amount of baryon and antibaryon were the same, they would have annihilated and we could not have existed.

  The most promising mechanism for generating a baryon asymmetry is leptogenesis (Fukugita, Yanagida, 86'.). In the leptogenesis scenario, a lepton asymmetry is first produced, which is then partially converted to a baryon asymmetry by the sphaleron (Kuzmin, Rubakov, Shaposhnikov, 85'.) process before the electroweak phase transition.

  The leptogenesis can connect the baryon asymmetry to the small neutrino masses through seesaw (Minkowski, 77'; Yanagida, 79'; Gell-Mann, Ramond, Slansky, 79'; Glashow ,79'; Mohapatra, Senjanović, 79'.).

- Since 1998, atmospheric, solar, reactor and accelerator neutrino oscillation experiments have confirmed the nonzero neutrino masses (e.g. Schwetz, Tortola, Valle, 08'.),

$$\left|\Delta m^2_{\mathrm{atm}}\right| = 2.4^{+0.12}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2\,, \tag{2}$$

$$\Delta m^2_{\mathrm{sol}} = 7.65^{+0.23}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2\,. \tag{3}$$

On the other hand, the cosmological observations give an upper bound on the neutrino masses (e.g. Spergel *et al.*, 06'.),

$$\Sigma_i m_{\nu_i} < \mathcal{O}(1\,\mathrm{eV})\,. \tag{4}$$

So, the neutrino mass scale should be of the order of

$$m_\nu \sim \mathcal{O}(0.01 - 1\,\mathrm{eV})\,. \tag{5}$$

- The true identity of the dark matter remains a mystery so far. Understanding the nature of the dark matter is one of the most challenging problems in particle physics and cosmology. Candidates for the dark matter must satisfy several conditions: keep stable on the cosmological time scale, interact very weakly with electromagnetic radiation, and have the right relic density.

  In most models of dark matter, ones assume the dark matter to be neutral particles without any quantum number, and then adjust its decay or annihilation rate to give a required relic density.

  There is another possibility that the dark matter actually carries some $U(1)$ quantum number so that the dark antimatter also exists. The excess of dark matter over dark antimatter could determine the amount of dark matter relic density if the dark matter and dark antimatter have very fast annihilation rate.

  The dark matter asymmetry can be produced simultaneously with the baryon asymmetry from leptogenesis (Kuzmin, 97'; Kitano, Low, 04'; Kaplan, Luty, Zurek, 09'; PHG, Sarkar, Zhang, 09'.).

- Currently our Universe is accelerating due to the existence of dark energy (e.g. Spergel *et al.*, 06'.),

$$\rho_{\mathrm{DE}} \equiv \left(\Lambda_{\mathrm{DE}}\right)^4 \simeq (2 \times 10^{-3}\,\mathrm{eV})^4 \,. \tag{6}$$

An interesting possibility for dark energy is quintessence (Wetterich, 88'; Peebles, Ratra, 88'.) with an extremely flat potential. It has been proposed (Weiss 87'; Frieman, Hill, Stebbins, Waga, 97'.) that pseudo-Nambu-Goldstone boson (pNGB) arising from spontaneous breaking of certain global symmetry near the Planck scale can provide an attractive realization of the quintessence dark energy.

- It is striking that the energy scale of dark energy is far lower than any known scales in particle physics but close to that of neutrino masses,

$$\Lambda_{\mathrm{DE}} \sim m_\nu \,. \tag{7}$$

This coincidence between neutrino masses and dark energy inspires us to consider them in a unified scenario, i.e., neutrino dark energy model which usually predicts mass varying neutrinos (PG, Wang, Zhang, hep-ph/0307148; Fardon, Nelson, Weiner, hep-ph/0309800.).

- The neutrino dark energy could have implications on leptogenesis (PG, Wang, Zhang, 03'; Bi, PG, Wang, Zhang, 03'; PG, Bi, 04'.).

  pNGB from spontaneous breaking of certain global symmetry in the type-I seesaw models for the neutrino masses (Barbieri, Hall, Oliver, Strumia, 05'; Hill, Mocioiu, Paschos, Sarkar, 06'.) could be the quintessence dark energy.

  Leptogenesis and pNGB quintessence could be unified in the type-II Majorana or Dirac seesaw models for the neutrino masses (PHG, He, Sarkar, 07'; PHG, 07'.).

I. Dark matter, baryonic matter and dark energy have different properties but contribute comparable energy density to the present Universe.

II. The dark energy has a scale far lower than all known scales in particle physics but very close to the neutrino masses.

III. The excess matter over antimatter in the baryonic sector is probably related to the neutrino masses through leptogenesis in seesaw models.

In our work we consider a common origin of dark and visible Universe in a variant of seesaw model, where

(1) the dark matter relic density is a dark matter asymmetry emerged with the baryon asymmetry from leptogenesis;

(2) the dark energy is due to a pNGB associated with the neutrino mass-generation.

Outline

- 1. The Simple Model
- 2. Neutrino Masses
- 3. Visible and Dark Matter Asymmetry
- 4. Dark Matter Detection
- 5. Dark Energy in the Completed Model
- 6. Conclusion

1. The Simple Model

Fields	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$U(1)_{lepton}$	Z_3
q_L	$(\mathbf{3}, \mathbf{2}, +\frac{1}{6})$	0	1
d_R	$(\mathbf{3}, \mathbf{2}, -\frac{1}{3})$	0	1
u_R	$(\mathbf{3}, \mathbf{2}, +\frac{2}{3})$	0	1
ψ_L	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	+1	1
ℓ_R	$(\mathbf{1}, \mathbf{1}, -1)$	+1	1
ϕ	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	0	1
ξ	$(\mathbf{1}, \mathbf{3}, +1)$	−2	1
η	$(\mathbf{1}, \mathbf{1}, 0)$	+2	1
σ	$(\mathbf{1}, \mathbf{1}, 0)$	−1	1
χ	$(\mathbf{1}, \mathbf{1}, 0)$	$-\frac{2}{3}$	ω

$$\mathcal{L}_{\mathrm{Y}} \supset -\frac{1}{2} y \, \overline{\psi_L^c} \, i \, \tau_2 \, \xi \, \psi_L + \mathrm{H.c.}\,, \tag{8}$$

$$\begin{aligned} V \supset \; & M_\eta^2 \left(\eta^\dagger \eta\right) + \left(\kappa \, \eta \, \phi^T \, i \, \tau_2 \, \xi \, \phi + \lambda \, \eta \, \chi^3 + \rho \, \eta \, \sigma^2 + \mathrm{H.c}\right) \\ & + \left(\chi^\dagger \chi\right) \left[\alpha \, \mathrm{Tr}\left(\xi^\dagger \xi\right) + \beta \left(\phi^\dagger \phi\right) + \gamma \left(\sigma^\dagger \sigma\right)\right] \\ & + \left(\sigma^\dagger \sigma\right) \left[\zeta \, \mathrm{Tr}\left(\xi^\dagger \xi\right) + \epsilon \left(\phi^\dagger \phi\right) + \vartheta \left(\sigma^\dagger \sigma\right)\right] . \end{aligned} \tag{9}$$

2. Neutrino Masses

- The singlet scalar σ is expected to develop a VEV of the order of TeV to drive the spontaneous symmetry breaking of the global lepton number,

$$\langle \sigma \rangle = \mathcal{O}\left(\mathrm{TeV}\right) , \tag{10}$$

Consequently, the heavy singlet η will pick up a small VEV,

$$\langle \eta \rangle \simeq -\frac{\rho \langle \sigma \rangle^2}{M_\eta^2} \qquad \left(M_\eta > \rho \quad \text{and} \quad M_\eta \gg \langle \sigma \rangle \right) . \tag{11}$$

- This small VEV $\langle \eta \rangle$ will induce a suppressed trilinear coupling of the Higgs triplet ξ to the Higgs doublet ϕ,

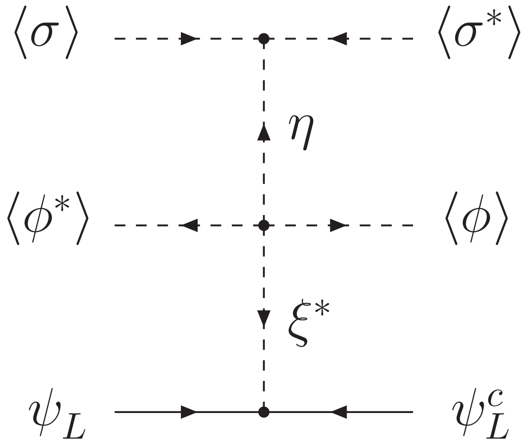
$$\mathcal{L} \supset -\mu\phi^T i\tau_2 \xi \phi + \text{H.c.} \qquad \left(\mu = \kappa \langle \eta \rangle \simeq -\kappa \frac{\rho \langle \sigma \rangle^2}{M_\eta^2}\right) . \qquad (12)$$

The Higgs triplet will obtain a small VEV after the electroweak symmetry is spontaneously broken by the VEV $\langle \phi \rangle \simeq 174\,\text{GeV}$,

$$\langle \xi \rangle \simeq -\frac{\mu \langle \phi \rangle^2}{m_\xi^2} \quad \left(\mu \ll m_\xi\right) . \qquad (13)$$

- The neutrinos hence obtain their small Majorana masses through the Yukawa couplings of the Higgs triplet to the lepton doublets,

$$m_\nu \;=\; y\,\langle\xi\rangle\,. \tag{14}$$



"Double Type-II Seesaw" (PHG, He, Sarkar, Zhang, 09'.).

3. Visible and Dark Matter Asymmetry

- The heavy singlet η has three decay channels:

$$\eta \rightarrow \xi^* \phi^* \phi^* , \quad \eta \rightarrow \chi^* \chi^* \chi^* , \quad \eta \rightarrow \sigma^* \sigma^* . \tag{15}$$

If the CP is not conserved, the above decays and their CP-conjugate can generate a lepton asymmetry stored in the Higgs triplet ξ, in the light singlet χ and in the light singlet σ, respectively, after the heavy singlet η goes out of equilibrium.

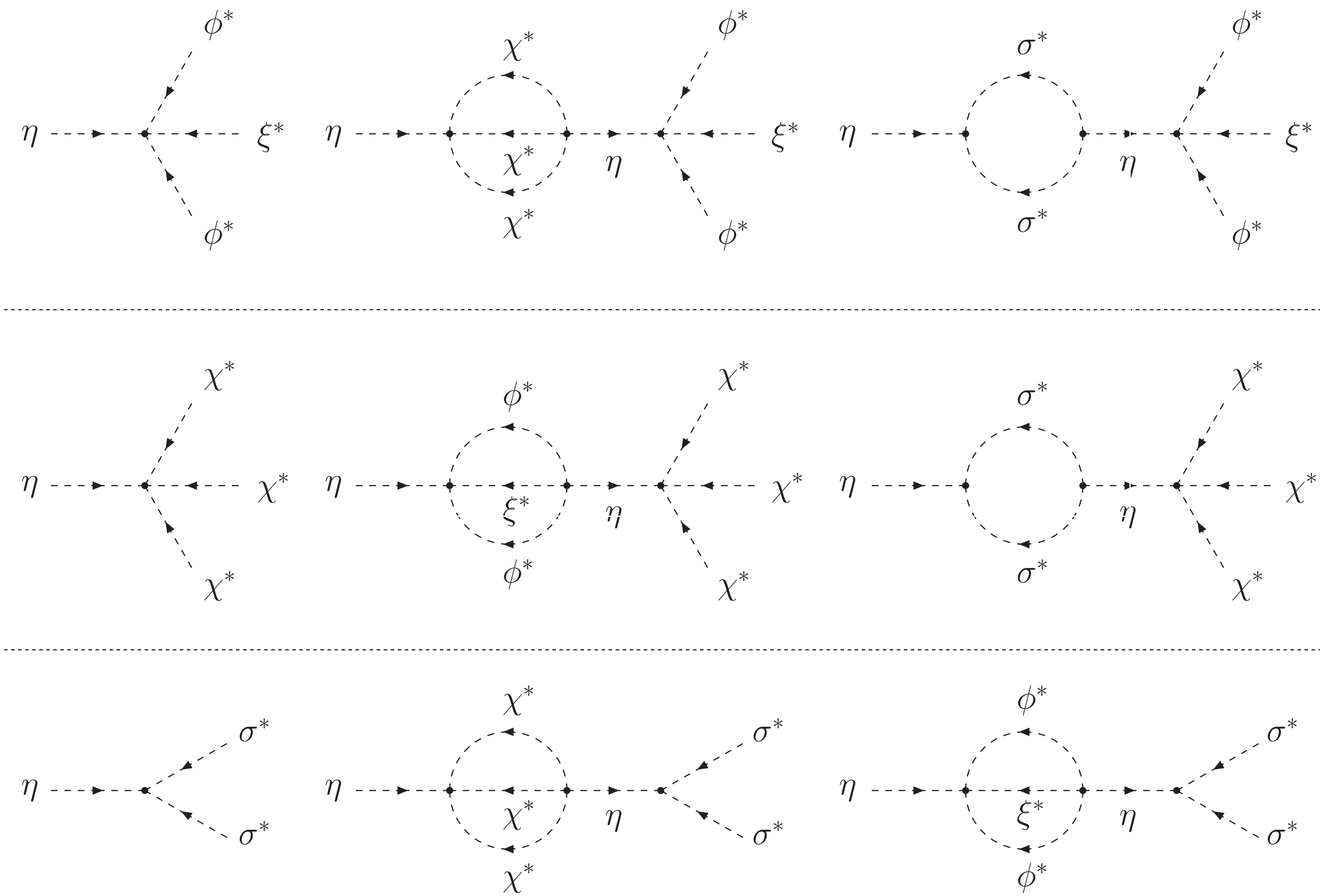
As the fields ξ, χ and σ carry lepton numbers, these fields would store different types of lepton asymmetry. The three types of lepton asymmetry would decouple from each other as they are produced, although the total lepton asymmetry is zero as a result of the exactly lepton number conservation.

1. The lepton asymmetry stored in the light singlet χ will survive since χ is not related to other lepton number violating interactions. We will show later this asymmetry can serve as the dark matter asymmetry to give a desired dark matter relic density.

2. The lepton asymmetry stored in the Higgs triplet ξ can be rapidly transferred to a lepton asymmetry in the lepton doublets ψ_L, as the lepton number conserving decay of ξ into two ψ_L is in equilibrium at this time. Although the lepton number is spontaneously broken at the TeV scale, the lepton number violating coupling of the Higgs triplet to the Higgs doublet is highly suppressed so that the induced lepton number violating processes will not go into equilibrium until the temperature is well below the electroweak scale. Therefore the lepton asymmetry stored in ψ_L will be partially converted to a baryon asymmetry by the sphaleron action.

3. The lepton asymmetry stored in the light singlet σ will not affect the baryon asymmetry of the Universe as σ does not take part in the sphaleron process.

- For realizing a CP violation in the decays of the heavy singlet η, it is necessary that the tree-level diagrams interfere with the self-energy loop diagrams.



- We thus need at least two heavy singlets η to generate the CP asymmetry. Here we minimally introduce two heavy singlets $\eta_{1,2}$.

  For convenience, in the scalar potential,

$$V \supset M_\eta^2 \left(\eta^\dagger \eta\right) + \left(\kappa\,\eta\,\phi^T\,i\,\tau_2\,\xi\,\phi + \lambda\,\eta\,\chi^3 + \rho\,\eta\,\sigma^2 + \mathrm{H.c}\right), \quad (16)$$

  we choose the base of $\eta_{1,2}$ to give a real and diagonal mass matrix $M_\eta^2 = \mathrm{diag}\left(M_{\eta_1}^2, M_{\eta_2}^2\right)$ and two real cubic couplings $\rho = (\rho_1, \rho_2)$ by a proper rotation. Consequently we only need to ensure the dimensionless parameters $\kappa = (\kappa_1, \kappa_2)$ and $\lambda = (\lambda_1, \lambda_2)$ to be complex.

- In the limiting case where the two heavy singlets $\eta_{1,2}$ have hierarchical masses, the final lepton asymmetry stored in the Higgs triplet ξ and the dark matter asymmetry stored in the light singlet χ should mainly come from the decays of the lighter one. For illustration, let us consider this hierarchical case. Without loss of generality we will refer to η_1 as the lighter heavy singlet and η_2 the heavier one.

- For simplicity, we assume

$$\frac{\kappa_i}{|\kappa_i|} \equiv \frac{\lambda_i}{|\lambda_i|} = e^{i\delta_i}\,, \tag{17}$$

and then calculate,

$$\begin{aligned}
\varepsilon^{\xi}_{\eta_1} &\equiv 2\frac{\Gamma(\eta_1 \to \xi^*\phi^*\phi^*) - \Gamma(\eta_1^* \to \xi\phi\phi)}{\Gamma_{\eta_1}} \\
&= \frac{\sin(\delta_2-\delta_1)}{2\pi}\left|\frac{\kappa_2}{\kappa_1}\right| \frac{\rho_1\rho_2}{M^2_{\eta_2}-M^2_{\eta_1}} \frac{\frac{3}{32\pi^2}|\kappa_1|^2}{\frac{\rho_1^2}{M^2_{\eta_1}} + \frac{3}{32\pi^2}\left(|\kappa_1|^2+|\lambda_1|^2\right)}\,,
\end{aligned} \tag{18}$$

$$\begin{aligned}
\varepsilon^{\chi}_{\eta_i} &\equiv 3\frac{\Gamma(\eta_1^* \to \chi\chi\chi) - \Gamma(\eta_1 \to \chi^*\chi^*\chi^*)}{\Gamma_{\eta_1}} \\
&= -\frac{3\sin(\delta_2-\delta_1)}{4\pi}\left|\frac{\lambda_2}{\lambda_1}\right| \frac{\rho_1\rho_2}{M^2_{\eta_2}-M^2_{\eta_1}} \frac{\frac{3}{32\pi^2}|\lambda_1|^2}{\frac{\rho_1^2}{M^2_{\eta_1}} + \frac{3}{32\pi^2}\left(|\kappa_1|^2+|\lambda_1|^2\right)}\,.
\end{aligned} \tag{19}$$

Here Γ_{η_1} denotes the total decay width of η_1 or η_1^*,

$$\begin{aligned}
\Gamma_{\eta_1} &\equiv \Gamma(\eta_1 \to \xi^*\phi^*\phi^*) + \Gamma(\eta_1 \to \chi^*\chi^*\chi^*) + \Gamma(\eta_1 \to \sigma^*\sigma^*) \\
&\equiv \Gamma(\eta_1^* \to \xi\ \phi\ \phi\ ) + \Gamma(\eta_1^* \to \chi\ \chi\ \chi\ ) + \Gamma(\eta_1^* \to \sigma\ \sigma\ ) \\
&= \frac{1}{8\pi}\left[\frac{\rho_1^2}{M_{\eta_1}^2} + \frac{3}{32\pi^2}\left(|\kappa_1|^2 + |\lambda_1|^2\right)\right] M_{\eta_1}\,, \qquad (20)
\end{aligned}$$

The ratio between $\varepsilon_{\eta_1}^{\xi}$ and $\varepsilon_{\eta_1}^{\chi}$ is simple,

$$\varepsilon_{\eta_1}^{\xi} : \varepsilon_{\eta_1}^{\chi} = |\kappa_1\kappa_2| : -\frac{3}{2}|\lambda_1\lambda_2|\,. \qquad (21)$$

- For generating an asymmetry, the decaying particles η_1 and η_1^* should match the out-of-equilibrium condition. For simplicity, we will consider the weak washout regime where

$$\Gamma_{\eta_1} < H(T)\Big|_{T \simeq M_{\eta_1}} . \tag{22}$$

Here

$$H(T) = \left(\frac{8\pi^3 g_*}{90}\right)^{\frac{1}{2}} \frac{T^2}{M_{\mathrm{Pl}}} \tag{23}$$

is the Hubble constant with the relativistic degrees of freedom $g_* \simeq 100$ and the Planck mass $M_{\mathrm{Pl}} \simeq 10^{19}\,\mathrm{GeV}$.

- There is a lepton number violating coupling of the Higgs triplet ξ to the Higgs doublet ϕ when the light singlet σ develops its VEV $\langle\sigma\rangle = \mathcal{O}(\mathrm{TeV})$.

  This cubic coupling μ between the Higgs scalars is highly suppressed, specifically is much smaller than the mass of the Higgs triplet ξ, i.e. $\mu \ll m_\xi$, we thus have

$$\Gamma(\xi \to \phi^*\phi^*) = \frac{1}{16\pi}\frac{|\mu|^2}{m_\xi} \ll H(T)\Big|_{T=m_\xi}\,, \qquad (24)$$

  so the induced lepton number violating processes can only go into equilibrium at a very low temperature and can not wash out the lepton asymmetry stored in the Higgs triplet ξ during the sphaleron epoch.

- The final baryon asymmetry and dark matter asymmetry would contribute energy density to the present Universe,

$$\begin{aligned}\rho_B^0 &= n_B^0 m_N = \frac{n_B^0}{s_0} m_N s_0 = -\frac{28}{79}\frac{n_{L_{SM}}}{s}\Big|_{T\simeq M_{\eta_1}} m_N s_0 \\ &\simeq -\frac{28}{79}\varepsilon_{\eta_1}^{\xi}\frac{n_{\eta_1}^{eq}}{s}\Big|_{T\simeq M_{\eta_1}} m_N s_0 \ , \end{aligned} \tag{25}$$

$$\begin{aligned}\rho_\chi^0 &= n_\chi^0 m_\chi = \frac{n_\chi^0}{s_0} m_\chi s_0 = \frac{n_\chi}{s}\Big|_{T\simeq M_{\eta_1}} m_\chi s_0 \\ &\simeq \varepsilon_{\eta_1}^{\chi}\frac{n_{\eta_1}^{eq}}{s}\Big|_{T\simeq M_{\eta_1}} m_\chi s_0 \ . \end{aligned} \tag{26}$$

Here $m_N \simeq 1\,\mathrm{GeV}$ is the masses of the nucleons, s is the entropy density, n_B and n_χ, respectively, are the number density of baryon and dark matter, $n_{\eta_1}^{eq}$ is the equilibrium distribution of η_1.

- In the presence of fast annihilation between the dark matter and dark anti-matter, the dark matter asymmetry should be equivalent to the dark matter relic density.

  In this scenario, the contributions from the baryonic and dark matter to the present Universe should have the following ratio,

$$\Omega_B : \Omega_\chi \equiv \rho_B^0 : \rho_\chi^0 = -\frac{28}{79}\varepsilon_{\eta_1}^{\xi} m_N : \varepsilon_{\eta_1}^{\chi} m_\chi \,, \tag{27}$$

  with

$$\varepsilon_{\eta_1}^{\xi} : \varepsilon_{\eta_1}^{\chi} = |\kappa_1 \kappa_2| : -\frac{3}{2}|\lambda_1 \lambda_2| \,. \tag{28}$$

- We take

$$
\begin{aligned}
M_{\eta_1} = 0.1 M_{\eta_2} = 4 \times 10^{13}\,\mathrm{GeV}\,, \;\; \rho_1 = \rho_2 = 1.5 \times 10^{12}\,\mathrm{GeV}\,, \\
\langle\sigma\rangle = 1\,\mathrm{TeV}\,, \;\; m_\xi = 540\,\mathrm{GeV}\,, \;\; m_\chi = 7\,\mathrm{GeV}\,, \\
|\kappa_1| = |\kappa_2| = 2.4|\lambda_1| = 2.4|\lambda_2| = 1\,, \\
y = \mathcal{O}(1)\,, \;\; \sin\left(\delta_2 - \delta_1\right) = -0.075\,,
\end{aligned} \tag{29}
$$

to output

$$
\begin{aligned}
\langle\chi\rangle \simeq -0.94\,\mathrm{eV}\,, \;\; \mu \simeq -0.94\,\mathrm{eV}\,, \;\; \langle\xi\rangle \simeq 0.1\,\mathrm{eV}\,, \\
\varepsilon^{\xi}_{\eta_1} \simeq -4\,\varepsilon^{\chi}_{\eta_1} \simeq -1.4 \times 10^{-7}\,,
\end{aligned} \tag{30}
$$

and then find

$$
m_\nu \sim 0.1\,\mathrm{eV}\,, \;\; \eta^0_B \simeq 6.2 \times 10^{-10}\,, \;\; \Omega_\chi : \Omega_B \simeq 5\,, \tag{31}
$$

which are well consistent with the experimental observations. Here

$$
\eta^0_B = \frac{n^0_B}{n^0_\gamma} \simeq 7.04 \times \frac{n^0_B}{s_0}\,, \tag{32}
$$

- We now check if the annihilation between the dark matter and dark anti-matter is so fast that the dark matter relic density can be determined by the dark matter asymmetry. By taking into account that $\langle\sigma\rangle = \mathcal{O}(\mathrm{TeV})$ and $\langle\phi\rangle \simeq 174\,\mathrm{GeV}$, the thermally averaged cross section in the non-relativistic limit is easy to read,

$$\begin{aligned}
\langle\sigma v\rangle &= \frac{1}{32\pi}\left[3\left(\alpha-\frac{\gamma\zeta}{2\vartheta}\right)^2+2\left(\beta-\frac{\gamma\epsilon}{2\vartheta}\right)^2\right]\frac{1}{m_\chi^2}\\
&\quad+\frac{1}{16\pi}\left(\frac{4}{9}-\frac{\gamma}{2\vartheta}\right)^2\frac{m_\chi^2}{\langle\sigma\rangle^4} \qquad \text{for } m_\chi=\mathcal{O}(\mathrm{TeV})\,, \\
\langle\sigma v\rangle &= \frac{\beta^2}{4\pi}\sum_f N_f^c\frac{m_f^2}{m_h^4}\left(\frac{m_\chi^2-m_f^2}{m_\chi^2}\right)^{\frac{3}{2}} \qquad \text{for } m_\chi=\mathcal{O}(\mathrm{GeV})\,.
\end{aligned} \tag{33}$$

Here f denotes the SM fermions with $m_f < m_\chi$, N_f^c is the number of colors of the f-fermion, h is the physical Higgs boson defined by $\phi = \frac{1}{\sqrt{2}}h + \langle\phi\rangle$.

By inputting $\alpha, \beta, \gamma, \zeta, \epsilon, \vartheta < \sqrt{4\pi}$, the thermally averaged cross section is flexible to reach a large value. For example, we obtain

$$\begin{aligned} \langle \sigma v \rangle &= 22\,\mathrm{pb} \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2 , \\ \langle \sigma v \rangle &= 20\,\mathrm{pb} \left(\frac{7\,\mathrm{GeV}}{m_\chi}\right)^2 \left(\frac{120\,\mathrm{GeV}}{m_h}\right)^4 . \end{aligned} \tag{34}$$

for $\alpha, \beta, \gamma = 2$ and $\zeta, \epsilon, \vartheta = 1$.

It is well known that the thermally produced dark matter with a mass from a few GeV to a few TeV should have a thermally averaged cross section slightly smaller than $1\,\mathrm{pb}$ to give a right relic density. If the thermally averaged cross section is too big, the relic density will be much below the desired value.

This means in the present model, the thermally produced relic density is negligible so that the dark matter asymmetry can naturally be a very good approximation of the total relic density.

4. Dark Matter Detection

- As a main consequence of the models with common origin of visible and dark matter through their asymmetries, our Universe will have mostly visible and dark matter and very little visible and dark antimatter.

  Due to the absence of the dark antimatter, the annihilation between the dark matter and dark antimatter can not leave any significant products although the cross section is very large.

- The dark matter scalar χ has a quartic coupling with the SM Higgs doublet ϕ, i.e. $\beta\left(\chi^{\dagger}\chi\right)\left(\phi^{\dagger}\phi\right)$. The induced cubic coupling is

$$V \supset \sqrt{2}\,\beta\,\langle\phi\rangle\,h\,\left(\chi^{\dagger}\chi\right)\,. \tag{35}$$

  Through the s-channel exchange of the physical Higgs boson, the dark matter is possible to find as a missing energy at colliders such as the CERN LHC (McDonald, '94; Burgess, Pospelov, ter Veldhuis, 00'.).

  The t-channel exchange of the physical Higgs boson will result in an elastic scattering of dark matter on nuclei and hence a nuclear recoil (McDonald, '94; Burgess, Pospelov, ter Veldhuis, 00'.).

- The spin-independent cross section of the dark-matter-nucleon elastic scattering would be (e.g. Andreas, Hambye, Tytgat, 08'.),

$$\sigma\left(\chi N \to \chi N\right) \;=\; \frac{\beta^2}{4\pi}\frac{\mu_r^2}{m_h^4 m_\chi^2} f^2 m_N^2\,, \tag{36}$$

where $\mu_r = m_\chi m_N/(m_\chi + m_N)$ is the nucleon-dark-matter reduced mass, m_h is the mass of the physical Higgs boson, the factor f in the range $0.14 < f < 0.66$ with a central value $f = 0.30$ parameterizes the Higgs to nucleon coupling, $f m_N \equiv \langle N|\sum_q m_q \bar{q} q|N\rangle$.

- For the dark matter mass within the range of 10 GeV to 1 TeV, we have

$$\sigma\left(\chi N \to \chi N\right) \simeq \left[1.2 \times 10^{-39}\left(\frac{10\,\mathrm{GeV}}{m_\chi}\right)^2 - 1.7 \times 10^{-43}\left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2\right]\mathrm{cm}^2 \times \frac{\beta^2}{4\pi} \times \left(\frac{f}{0.3}\right)^2 \times \left(\frac{120\,\mathrm{GeV}}{m_h}\right)^4, \qquad (37)$$

which could be naturally below the current experimental limit (Angle *et al.*, 07'; Ahmed *et al.*, 08'.) and testable in the future experiments.

- If the recent DAMA signal (Bernabei *et al.*, 08'.) is confirmed, it should be induced by the scattering of the dark matter particles from the galactic halo on the target nuclei in the detectors.

  The good fitting (Petriello, Zurek, 08'.) on the DAMA data and the null results from other direct dark matter detection experiments (Angle *et al.*, 07'; Ahmed *et al.*, 08'.) opens a small window for the dark-matter-nucleon elastic scattering with the spin-independent cross section and the dark matter mass as below,

$$3 \times 10^{-41}\,\mathrm{cm}^2 < \sigma < 5 \times 10^{-39}\,\mathrm{cm}^2\,, \tag{38}$$

$$3\,\mathrm{GeV} < m < 8\,\mathrm{GeV}\,. \tag{39}$$

  In our model, this can be easily matched by inputting $\beta = \mathcal{O}(0.1 - 1)$, $0.14 < f < 0.66$ and $m_h = 120\,\mathrm{GeV}$.

5. Dark Energy in the Completed Model

- We suppose three families of leptons have independent phase transformations. We thus need six Higgs triplets

$$\xi_{ij} = \xi_{ji} (i, j = 1, 2, 3) \tag{40}$$

to give the Yukawa couplings for generating the neutrino masses,

$$\mathcal{L} \supset - \sum_{i,j=1}^{3} \left[\frac{1}{2} y_{ij} \overline{\psi_{L_i}^c} i\tau_2 \xi_{ij} \psi_{L_j} + \mathrm{H.c.} \right] . \tag{41}$$

- For one Higgs doublet ϕ, we further need six heavy singlets

$$\eta_{ij} = \eta_{ji} (i, j = 1, 2, 3) \tag{42}$$

to generate the cubic coupling of the Higgs triplets to the Higgs doublet,

$$\mathcal{L} \;\supset\; -\sum_{i,j=1}^{3} \left[\kappa_{ij}\eta_{ij}\phi^T i\tau_2 \xi_{ij}\phi + \mathrm{H.c.}\right] . \tag{43}$$

- Moreover, we replace the one light singlet χ by six ones, i.e.

$$\chi_{ij} = \chi_{ji} (i, j = 1, 2, 3) \tag{44}$$

so that the following interaction is allowed,

$$\mathcal{L} \supset -\sum_{i,j=1}^{3} \left[\lambda_{ij} \eta_{ij} \chi_{ij}^{3} + \mathrm{H.c.} \right] . \tag{45}$$

- Finally, we introduce six singlets

$$\zeta_{ij} = \zeta_{ji} (i, j = 1, 2, 3) \tag{46}$$

to construct the couplings of the heavy singlets η_{ij} to the light singlet σ,

$$\mathcal{L} \ \supset \ -\sum_{i,j=1}^{3} \left[\omega_{ij}\zeta_{ij}\eta_{ij}\sigma^2 + \mathrm{H.c}\right] \, . \tag{47}$$

- The couplings relevant for our discussions are then given by,

$$\begin{aligned}\mathcal{L} \;\supset\; & -\sum_{i,j,k,\ell=1}^{3}\Big[\frac{1}{2}y_{ij}\overline{\psi^{c}_{L_i}}i\tau_2\xi_{ij}\psi_{L_j}+\kappa_{ij}\eta_{ij}\phi^{T}i\tau_2\xi_{ij}\phi\\ & +\lambda_{ij}\eta_{ij}\chi^{3}_{ij}+\omega_{ij}\zeta_{ij}\eta_{ij}\sigma^{2}+\varsigma_{ijk\ell}\left(\zeta^{\dagger}_{ij}\zeta_{k\ell}\right)\left(\eta^{\dagger}_{ij}\eta_{k\ell}\right)\\ & +\mathrm{H.c}\Big]\,. \end{aligned} \tag{48}$$

- There is a $U(1)^6$ global symmetry generated by the independent phase transformations of each singlet $\zeta_{ij} = \zeta_{ji}(i,j = 1,2,3)$. However, this $U(1)^6$ will be explicitly broken down to its subgroup $U(1)^3$ due to the Yukawa couplings of the Higgs triplets $\xi_{ij} = \xi_{ji}(i,j = 1,2,3)$ to the lepton doublets $\psi_{L_i}(i = 1,2,3)$.

- After the singlets ζ_{ij} get their VEVs $\langle\zeta_{ij}\rangle \equiv \frac{1}{\sqrt{2}} f_{ij}$, we have

$$\chi_{ij} = \frac{1}{\sqrt{2}} \left(f_{ij} + \varpi_{ij} \right) e^{i \frac{\varphi_{ij}}{f_{ij}}} , \tag{49}$$

where $\varpi_{ij}(i,j = 1,2,3.)$ and $\varphi_{ij} = \varphi_{ij}(i,j = 1,2,3.)$ are the neutral bosons and the Nambu-Goldstone bosons (NGBs), respectively.

Among these NGBs, three of them will acquire nonzero masses via the Coleman-Weinberg potential (due to the explicit breaking of global symmetries $(U(1)^6 \to U(1)^3)$ and thus become pNGBs. The other three remain massless as the result of spontaneous breaking of the subgroup $U(1)^3$.

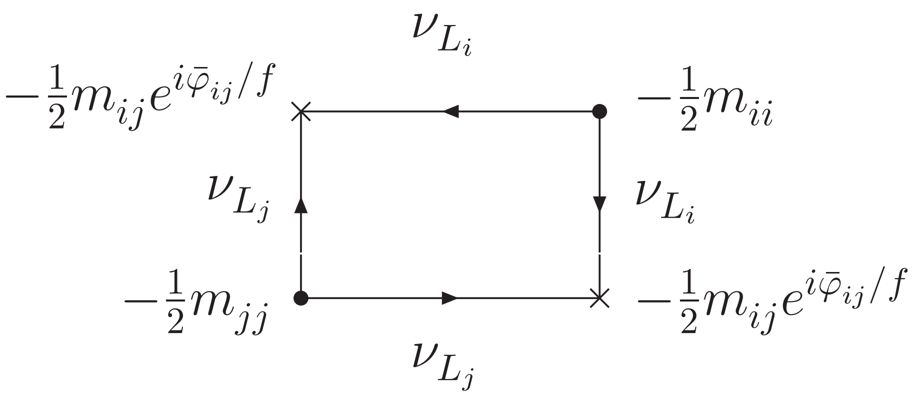
- For demonstration, we obtain by proper phase rotation, which is without loss of generality,

$$\mathcal{L} \supset -\sum_i \frac{1}{2} y_{ii} \overline{\psi^c_{L_i}} i\tau_2 \xi_{ii} \psi_{L_i} - \sum_{i \neq j} \frac{1}{2} y_{ij} e^{i\frac{\bar{\varphi}_{ij}}{f}} \overline{\psi^c_{L_i}} i\tau_2 \xi_{ij} \psi_{L_j} \, , \tag{50}$$

where

$$\frac{\bar{\varphi}_{ij}}{f} = -\frac{\varphi_{ij}}{f_{ij}} + \frac{\varphi_{ii}}{2f_{ii}} + \frac{\varphi_{jj}}{2f_{jj}} \, . \tag{51}$$

It is impossible to remove $\bar{\varphi}_{ij}$ $(i \neq j)$ by any further transformations.



$$m_{ij} = y_{ij}\langle\xi_{ij}\rangle$$

$$m_{ii} = y_{ii}\langle\xi_{ii}\rangle$$

- The leading loop diagram will contribute a Coleman-Weinberg effective potential for $\bar{\varphi}_{ij}$,

$$V(\bar{\varphi}_{12}, \bar{\varphi}_{23}, \bar{\varphi}_{31}) = -\frac{1}{32\pi^2}\sum_{k=1}^{3} m_k^4 \ln\frac{m_k^2}{\Lambda^2}, \qquad (52)$$

where m_k as a function of $\bar{\varphi}_{ij}$ is the k-th eigenvalue of the neutrino mass matrix m_ν and Λ is the ultraviolet cutoff.

- A typical term in V that contributes to the potential of a pNGB field Q has the form,

$$V(Q) \simeq V_0 \cos\left(\frac{Q}{f}\right) , \tag{53}$$

with $V_0 = \mathcal{O}(m_\nu^4)$. It is well known that with f of the order of Planck mass $M_{\rm Pl}$, the pNGB Q will acquire a mass of the order of $\mathcal{O}(m_\nu^2/M_{\rm Pl})$ and thus provides a consistent candidate for the quintessence dark energy.

6. Conclusion

We proposed a variant of seesaw model that provides a common origin of the visible and dark matter and relates the dark energy to the neutrino masses:

I. There is a dark matter asymmetry produced together with a lepton asymmetry that explains the baryon asymmetry via the sphaleron process.

   This dark matter asymmetry can account for the dark matter relic density because the annihilation between the dark matter and dark antimatter is so fast that the thermally produced relic density should be negligible.

II. The dark matter scalar has a quartic coupling with the SM Higgs doublet so that it is expected to produce at the colliders and/or detect by the direct dark matter detection experiments.

   For example, the induced dark-matter-nucleon elastic scattering can explain the DAMA signal and the null results from other direct dark matter detection experiments.

III. The pNGB associated with the neutrino mass-generation can be the quintessence field and thus provide a consistent candidate for the dark energy. the neutrino masses are functions of the dark energy field, which will evolute with time and/or in space. In consequence, the neutrino masses are variable, rather than constant.

The prediction of the mass varying neutrinos might be verified in the experiments, such as the short gamma ray burst, the cosmic microwave background, the large scale structures and the neutrino oscillations.

Thank You