Weakly Interacting Dark Matter and Baryogenesis

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PHG, Manfred Lindner, Utpal Sarkar, and Xinmin Zhang, 1009.1690.

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Outline

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Introduction

- Cosmological observations have precisely measured the fractions of the visible and dark matter in the present universe (e.g. Dunkley *et al.*, 08'),

$$\Omega_B h^2 = 0.02273 \pm 0.00062\,,$$
$$\Omega_\chi h^2 = 0.1099 \pm 0.0062\,.$$

It is surprised that the visible and dark matter contribute comparable energy densities to the present universe, i.e.

$$\Omega_\chi : \Omega_B \simeq 5\,,$$

although their properties are very different.

- The visible matter exists in the present universe as a matter–antimatter asymmetry, which is the same as the baryon asymmetry.

  If CPT is invariant, any successful baryogenesis mechanisms for generating a baryon asymmetry should fulfill the Sakharov cnditions (Sakharov 67').

  (1) Baryon number nonconservation.

  (2) C and CP violation.

$$n_B = \frac{1}{3}\Big(\underbrace{n_{q_L} - n_{\bar{q}_L}}_{SU(2)\,\text{doublets}} + \underbrace{n_{q_R} - n_{\bar{q}_R}}_{SU(2)\,\text{singlets}} \Big) \Rightarrow \begin{cases} C: & q_L \leftrightarrow \bar{q}_L\,, \quad B \leftrightarrow -B\,; \\ CP: & q_L \leftrightarrow \bar{q}_R\,, \quad B \leftrightarrow -B\,. \end{cases}$$

  (3) Departure from equilibrium.

$$\begin{aligned} \langle B \rangle &= \mathrm{Tr}\left(e^{-\frac{H}{T}} B\right) = \mathrm{Tr}\left[(CPT)(CPT)^{-1} e^{-\frac{H}{T}} B\right] \\ &= \mathrm{Tr}\left[e^{-\frac{H}{T}} (CPT)^{-1} B (CPT)\right] = \mathrm{Tr}\left[e^{-\frac{H}{T}} (-B)\right] = -\langle B \rangle\,. \end{aligned}$$

- Because the sphaleron (Kuzmin, Rubakov, Shaposhnikov, 85') process, which keeps active at temperatures,

$$100\,\mathrm{GeV} \sim T_{\mathrm{EW}} < T < T_{\mathrm{sph}} \sim 10^{12}\,\mathrm{GeV}\,,$$

exactly conserves the $(B-L)$–number while explicitly violates the $(B+L)$–number, any baryogenesis mechanisms above the electroweak scale should produce a $B-L$ asymmetry. Subsequently the sphaleron process will partially transfer the produced $B-L$ asymmetry to a baryon asymmetry. For example, in the SM framework, we have

$$B = \frac{28}{79}(B-L)\,.$$

The popular leptogenesis (Fukugita, Yanagida, 86') scenario where some lepton number violating interactions for realizing the seesaw (Minkowski, 77'; Yanagida, 79'; Gell-Mann, Ramond, Slansky, 79'; Glashow, 80'; Mohapatra, Senjanović, 80') can generate a lepton asymmetry (Fukugita, Yanagida, 86'; Langacker, Peccei, Yanagida, 86'; Luty, 91'; Zhang, Mohapatra, 92'; Flanz, Paschos, Sarkar, 95'; Flanz, Paschos, Sarkar, Weiss, 96'; Covi, Roulet, Vissani, 96'; Pilaftsis, 97'; Ma, Sarkar, 98'; Davidson, Ibarra, 02'; Buchmüller, Di Bari, Plümacher, 02'; Hambye, Senjanović, 02'; Bi, PHG, Wang, Zhang, 03'; PHG, Bi, 04'; Antusch, King, 04';...). The produced lepton asymmetry can result in a $B - L = -L$ asymmetry.

The lepton number violating interactions can also help us to resurrect the GUT-baryogenesis, which generates a baryon asymmetry and an equal lepton asymmetry, if they partly wash out the lepton asymmetry or the baryon asymmetry or their combination (Fukugita, Yanagida, 00'; PHG, Sarkar, 07').

- We can also consider the baryogenesis mechanisms below the electroweak scale (but before the BBN) for generating a baryon asymmetry (Babu, Mohapatra, Nasri, 06'; PHG, 07').
- In the above mentioned baryogenesis models, the baryon and/or lepton number should be explicitly violated. More specifically, we need break the baryon and/or lepton number in our visible world. This means that the baryon and/or lepton number in a bigger context including the visible sector and some hidden sector could be conserved. For example, in the leptogenesis with Dirac neutrinos (Dick, Lindner, Ratz, Wright, 99'; Murayama, Pierce; 02'; Cerdeno, Dedes, Underwood, 06'; PHG, He, 06'; PHG, He, Sarkar, 07'), a lepton asymmetry in the SM leptons and an equal but opposite lepton asymmetry in the right-handed neutrinos are simultaneously produced in the decays of some heavy particles. However, only the lepton asymmetry in the SM leptons can be partially converted to the baryon asymmetry by the sphaleron process since the Yukawa interactions of the light Dirac neutrinos are too weak to go into equilibrium before the electroweak phase transition.

- A dark matter candidate must satisfy several conditions: keep stable on the cosmological time scale, interact very weakly with electromagnetic radiation, and have the right relic density. However, the true identity of the dark matter still remains a mystery.

  In most models of dark matter, the dark matter is assumed to be a particle without any quantum number. The dark antimatter is identified to the dark matter.

  The relic density of the neutral dark matter can be thermally produced by the dark matter annihilation into other light species. The neutral dark matter can be scalar bosons (Silveira, Zee, 85'; Ma, 06';...), vector bosons (Hambye, 08'; PHG, He, Sarkar, Zhang, 09'), fermions (Ma, 06'; PHG, 07'; PHG, Hirsch, Sarkar, Valle, 08'; Bi, PHG, Li, Zhang, 09'; Bi, He, Ma, Zhang, 09';...). For example, a real scalar singlet as the simplest dark matter candidate (Silveira, Zee, 85'; McDonald, '94; Burgess, Pospelov, ter Veldhuis, 00'; Andreas, Hambye, Tytgat, 08'; He, Li, Li, Tsai, 10'; Farina, Pappadopulo, Strumia, 10'; Asano, Kitano, 10'; Guo, Wu, 10';...) can obtain a desired relic density through its quartic coupling with the SM Higgs doublet.

- There is another possibility that the dark matter carries certain quantum number(s) and hence the dark antimatter does exist. The excess of the dark matter over the dark antimatter can determine the amount of the dark matter relic density if the dark matter and antimatter have a fast annihilation.

  The dark matter asymmetry can be determined by the baryon asymmetry in some baryogenesis models (Kuzmin, 97'; Kitano, Low, 04'; Kaplan, Luty, Zurek, 09'; PHG, Sarkar, Zhang, 09'; PHG, Sarkar, 09'; An, Chen, Mohapatra, Zhang, 09'; McDonald, 10'; Hall, March-Russell, West, 10',...). In this scenario, the dark matter mass is not arbitrary but predictive since the nucleon mass has been well known. In these models, the dark matter mass is expected to be at the GeV scale unless we abandon the requirement of determining the dark matter asymmetry in terms of the baryon asymmetry (PHG, Sarkar, Zhang, 09'; PHG, Sarkar, 09').

- Recently, it has been pointed out that the asymmetric dark matter can have a mass at the TeV scale even if the dark matter asymmetry is fully determined by the baryon asymmetry (M.R. Buckley and L. Randall, 1009.0270; PHG, M. Lindner, U. Sarkar, and X. Zhang, 1009.1690).
- In the following, I shall introduce our work (PHG, M. Lindner, U. Sarkar, and X. Zhang, 1009.1690) in details.

The Models

- Baryon number conserving models.

$$q_L(\mathbf{3},\mathbf{2},\tfrac{1}{6})\,,\quad u_R(\mathbf{3},\mathbf{1},\tfrac{2}{3})\,,\quad d_R(\mathbf{3},\mathbf{1},-\tfrac{1}{3})\,,$$

$$\delta(\mathbf{3},\mathbf{1},-\tfrac{1}{3})\,,\quad \omega(\mathbf{3},\mathbf{1},\tfrac{2}{3})\,,\quad X_k(\mathbf{1},\mathbf{1},0)\,,\quad \chi(\mathbf{1},\mathbf{1},0)\,.$$

$$\mathcal{L} \supset -f_\delta \delta \bar{q}_L^c i\tau_2 q_L - f'_\delta \delta \bar{u}_R^c d_R - f_\omega \omega \bar{d}_R^c d_R + \text{H.c.}\,.$$

$$\mathcal{L} \supset -\kappa_1 X_1 \omega \delta^2 - \sum_{i=2}^{n} \kappa_i X_i^* X_{i-1}^{a_{i-1}} + \text{H.c.} \quad (a_{i-1} = 2 \text{ or } 3)\,.$$

$$\mathcal{L} \supset \begin{cases} -\gamma_1 X_1^* \chi^b + \text{H.c. with } b = 2 \text{ or } 3\,, \\ \\ -\gamma_n X_n^* \chi^b + \text{H.c. with } b = 2 \text{ or } 3 \text{ but } b \neq a_{n-1}\,. \end{cases}$$

Note that the choice $b \neq a_{n-1}$ is to forbid the couplings

$$-\alpha\chi^* X_{n-1} - \beta(\chi^* X_{n-1})^2 + \text{H.c.}\,.$$

The neutral scalars X_k and χ will not develop any vacuum expectation values to break the baryon number.

In a similar fashion we could consider color-sextet and iso-singlet scalars to construct the models, i.e.

$$\begin{aligned} \delta(\mathbf{3},\mathbf{1},-\frac{1}{3}) &\Rightarrow \delta(\mathbf{6},\mathbf{1},-\frac{1}{3})\,,\\ \omega(\mathbf{3},\mathbf{1},\frac{2}{3}) &\Rightarrow \omega(\mathbf{6},\mathbf{1},\frac{2}{3})\,. \end{aligned}$$

- Lepton number conserving models.

$$l_L(\mathbf{1},\mathbf{2},-\tfrac{1}{2})\,,\quad \xi(\mathbf{1},\mathbf{3},1)\,,\quad X_k(\mathbf{1},\mathbf{1},0)\,,\quad \chi(\mathbf{1},\mathbf{1},0)\,.$$

$$\mathcal{L} \supset -f_\xi \overline{l}_L^c i\tau_2 \xi l_L + \text{H.c.}\,.$$

$$\mathcal{L} \supset -\kappa_1 X_1 \phi^T i\tau_2 \xi \phi - \sum_{i=2}^{n} \kappa_i X_i^* X_{i-1}^{a_{i-1}} + \text{H.c.} \quad (a_{i-1} = 2 \text{ or } 3)\,.$$

$$\mathcal{L} \supset \begin{cases} -\gamma_1 X_1^* \chi^b + \text{H.c. with } b = 2 \text{ or } 3\,, \\ \\ -\gamma_n X_n^* \chi^b + \text{H.c. with } b = 2 \text{ or } 3 \text{ but } b \neq a_{n-1}\,. \end{cases}$$

Again, the choice $b \neq a_{n-1}$ is to forbid the couplings

$$-\alpha\chi^* X_{n-1} - \beta(\chi^* X_{n-1})^2 + \mathrm{H.c.}\,.$$

The neutral scalars X_k and χ will not develop any vacuum expectation values to break the lepton number.

Alternatively, we could consider iso-singlet scalars to construct the models, i.e.

$$\mathcal{L} \supset -f_\zeta \zeta \bar{l}_L^c i\tau_2 l_L - f_\varrho \varrho \bar{e}_R^c e_R - \kappa_1 X_1 \varrho^* \zeta^2 + \mathrm{H.c.}\,,$$

with

$$e_R(\mathbf{1},\mathbf{1},-1)\,,\ \ \zeta(\mathbf{1},\mathbf{1},1)\,,\ \ \varrho(\mathbf{1},\mathbf{1},2)\,.$$

- The scalar singlet χ keeps stable so that it can contribute a relic density to the present universe.

  Consistency with the dark matter relic density?

  Explanation for the coincidence between the visible and dark matter?

  Implication on the dark matter detection?

Baryon Asymmetry and Dark Matter Asymmetry

- The decaying scalar singlet $X_k (k = 1 \text{ or } n \geq 2)$ can decay into: (1) two or three dark matter scalars; (2) a number of the SM quarks(leptons) through other on-shell and/or off-shell scalars.

  As long as the CP is not conserved, the above decays and their CP-conjugate can generate a baryon(lepton) asymmetry in the SM fields and a baryon(lepton) asymmetry in the dark matter scalar, respectively, after the decaying scalar X_k goes out of equilibrium,

$$\varepsilon_{\chi}^{B(L)} = \epsilon_{\chi}^{B(L)} \left(\frac{n_{X_k}}{s} \right) \Big|_{T_D} , \quad \varepsilon_{\text{SM}}^{B(L)} = \epsilon_{\text{SM}}^{B(L)} \left(\frac{n_{X_k}}{s} \right) \Big|_{T_D} .$$

  Here $\epsilon_{\chi}^{B(L)}$ and $\epsilon_{\text{SM}}^{B(L)}$ are the CP asymmetries, T_D is the decoupling temperature, s is the entropy density, n_{X_k} is the number density.

- The CP asymmetries and then the baryon(lepton) asymmetries in the two sectors should be equal but opposite,

$$\epsilon_{\chi}^{B(L)} = -\epsilon_{\text{SM}}^{B(L)} \Rightarrow \varepsilon_{\chi}^{B(L)} = -\varepsilon_{\text{SM}}^{B(L)}.$$

i.e. the total baryon(lepton) asymmetry is zero, as a result of the exactly conserved baryon(lepton) number. For example, in the case of $k = n \geq 2$, we have

$$\epsilon_{\chi}^{B(L)} = \frac{\Gamma_{X_k \to (\chi)^b} - \Gamma_{X_k^* \to (\chi^*)^b}}{\Gamma_{X_k \to (\chi)^b} + \Gamma_{X_k \to (X_{k-1})^{a_{k-1}}}},$$

$$\epsilon_{\text{SM}}^{B(L)} = \frac{\Gamma_{X_k \to (X_{k-1})^{a_{k-1}}} - \Gamma_{X_k^* \to (X_{k-1}^*)^{a_{k-1}}}}{\Gamma_{X_k \to (\chi)^b} + \Gamma_{X_k \to (X_{k-1})^{a_{k-1}}}},$$

with

$$\begin{aligned}\Gamma_{X_k} &= \Gamma_{X_k \to (\chi)^b} + \Gamma_{X_k \to (X_{k-1})^{a_{k-1}}} \\ &= \Gamma_{X_k^* \to (\chi^*)^b} + \Gamma_{X_k^* \to (X_{k-1}^*)^{a_{k-1}}}.\end{aligned}$$

- We need at least two decaying scalar singlets X_k to generate the CP asymmetry at one-loop order. For example, let's consider the possible decays of $X_n (n \geq 2)$, as shown in FIG. 1.

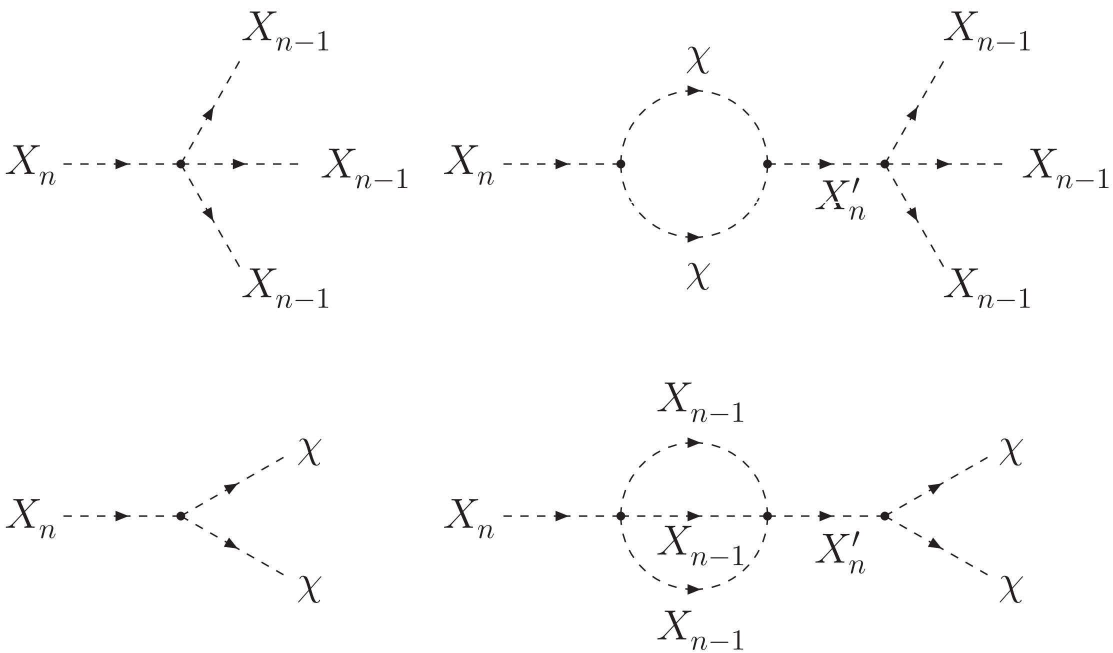

FIG. 1: The decays of X_n for generating the baryon(lepton) asymmetries in the subsequently decaying scalar X_{n-1} and in the dark matter scalar χ. The virtual X'_n carries the same quantum numbers with the decaying X_n.

- For successfully generating an asymmetry, the decaying particles X_k should go out of equilibrium. In the weak washout regime, the out-of-equilibrium condition can be described by

$$K = \frac{\Gamma_{X_n}}{2H(T)}\Big|_{T=m_{X_n}} < 1\,,$$

with

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

being the Hubble constant. Here $M_{\textrm{Pl}} \simeq 1.22 \times 10^{19}\,\textrm{GeV}$ is the Planck mass. As for g_*, it is the relativistic degrees of freedom. For example, in the case of $n = 6$, we have $g_* = 106.75 + 24 = 130.75$ (the SM species plus two color-triplet and iso-singlet scalars, five subsequently decaying singlet scalars and one dark matter scalar).

- Since the baryon(lepton) asymmetry in the dark matter scalar has no effect on the sphaleron processes, the baryon(lepton) asymmetry in the SM quarks(leptons) can be partially converted to the final baryon asymmetry, (Kuzmin, Rubakov, Shaposhnikov, 85'),

$$\eta_B = \frac{28}{79}\varepsilon^B_{\mathrm{SM}} \ \text{or} \ \eta_B = -\frac{28}{79}\varepsilon^L_{\mathrm{SM}} \,.$$

  This is like the leptogenesis (Fukugita, Yanagida, 86'). Note for the baryon number conserving models, the coefficient $\frac{28}{79}$ should be absent if the baryon asymmetry is produced after the electroweak phase transition.

  As for the dark matter asymmetry, it is the ratio of the baryon(lepton) asymmetry in the dark matter scalar over the baryon(lepton) number of the dark matter scalar,

$$\eta_\chi = \begin{cases} \pm\frac{b}{2}\varepsilon^{B(L)}_{\chi} & \text{for} \quad k = 1\,, \\ \pm\frac{b}{2a_1 a_2 \ldots a_{n-1}}\varepsilon^{B(L)}_{\chi} & \text{for} \quad k = n\,. \end{cases}$$

- We now consider the case of $n = 6$ to indicate that the induced baryon asymmetry can explain the observation. For this purpose, we calculate the CP asymmetry,

$$\epsilon_X^{B(L)} = -\epsilon_{\mathrm{SM}}^{B(L)} = \frac{1}{128\pi^3}\frac{\mathrm{Im}(\gamma_6'\gamma_6^*\kappa_6'^*\kappa_6)}{\frac{|\gamma_6|^2}{m_{X_6}^2}+\frac{1}{32\pi^2}|\kappa_6|^2}\frac{1}{m_{X_6'}^2 - m_{X_6}^2},$$

and the decay width,

$$\Gamma_{X_6} = \frac{1}{16\pi}\left(\frac{|\gamma_6|^2}{m_{X_6}^2}+\frac{1}{32\pi^2}|\kappa_6|^2\right)m_{X_6}.$$

We take

$$m_{X_6'} = 3.5 \times 10^{12}\,\mathrm{GeV}\,,$$
$$m_{X_6} = 10^{12}\,\mathrm{GeV}\,,$$
$$\frac{|\gamma_6'|}{m_{X_6'}} = \frac{|\gamma_6|}{m_{X_6}} = 0.006\,,$$
$$|\kappa_6'| = |\kappa_6| = 0.1\,,$$
$$\sin\left(\frac{\gamma_6'\gamma_6^*\kappa_6'^*\kappa_6}{|\gamma_6'\gamma_6\kappa_6'\kappa_6|}\right) = -0.27\,,$$

to determine

$$\epsilon_{\mathrm{SM}}^{B} = 3.22 \times 10^{-8}\,, \quad K = \frac{\Gamma_{X_6}}{2H(T)}\Big|_{T=m_{X_6}} \simeq 0.43\,.$$

The final baryon asymmetry can be approximately calculated by (Kolb, Turner, 90'),

$$\eta_B \simeq \frac{28}{79} \times \frac{\epsilon^B_{\mathbf{SM}}}{g_*} = 0.873 \times 10^{-10}\,,$$

which is well consistent with the observation (Dunkley *et al.*, 08'),

$$\begin{aligned}\eta_B &= \frac{1}{7.04} \times (6.225 \pm 0.170) \times 10^{-10} \\ &= (0.884 \pm 0.024) \times 10^{-10}\,.\end{aligned}$$

The other interactions violate the SM baryon and/or lepton number should decouple before the above baryogenesis epoch. Otherwise, they will wash out the induced baryon asymmetry. For example, we check the case that the neutrinos obtain their Majorana masses through the seesaw mechanism (Minkowski, 77'; Yanagida, 79'; Gell-Mann, Ramond, Slansky, 79'; Glashow, 80'; Mohapatra, Senjanović, 80'). Below the seesaw scale, the induced lepton number violating interactions should have the following rate (Fukugita, Yanagida, 90'),

$$\Gamma_A = \frac{1}{\pi^3}\frac{\mathrm{Tr}(m_\nu^\dagger m_\nu)}{v^4}T^3 = \frac{1}{\pi^3}\frac{\sum_i m_i^2}{\langle\phi\rangle^4}T^3 \,,$$

where m_ν is the neutrino mass matrix. For our parameter choice, the above rate is smaller than the Hubble constant at the baryogenesis epoch. This means the lepton number violation for generating the neutrino masses will not affect the induced baryon asymmetry.

- In the above numerical estimation, we have assumed the decaying scalars are thermally produced by their interactions with other fields. This is the thermal baryogenesis scenario. Alternatively, we can consider the nonthermal baryogenesis, where the decaying scalars are responsible for the chaotic inflation (Linde, 83').

  It is also possible to make use of the resonant effect to enhance the CP asymmetry, like the resonant leptogenesis (Flanz, Paschos, Sarkar, 95'; Flanz, Paschos, Sarkar, Weiss, 96'; Covi, Roulet, Vissani, 96'; Pilaftsis, 97'). In this case, the decaying scalars can be at a low scale such as the TeV scale.

  The required scalar bilinears could be verified at colliders such as the LHC or the ILC.

Predictive Dark Matter Mass

- If the dark matter asymmetry is responsible for the dark matter relic density, we can read

$$\Omega_B : \Omega_\chi = \eta_B m_N : \eta_\chi m_\chi \,,$$

where m_N is the nucleon mass and will be taken to be $m_N = \frac{1}{2}(m_p + m_n) = 939\,\mathrm{MeV}$ by ignoring the tiny difference between the proton and neutron masses. Since the fractions of the visible and dark matter in the present universe has been precisely measured (Dunkley *et al.*, 08'),

$$\begin{aligned} \Omega_B h^2 &= 0.02273 \pm 0.00062 \,, \\ \Omega_\chi h^2 &= 0.1099 \pm 0.0062 \,, \end{aligned}$$

we can predict the dark matter mass by

$$m_\chi = \frac{\Omega_\chi}{\Omega_B}\frac{\eta_B}{\eta_\chi} m_N \,.$$

The ratio between the baryon asymmetry and the dark matter asymmetry, i.e. $\frac{\eta_B}{\eta_\chi}$, can be well determined once we fix the baryon(lepton) numbers of the decaying neutral scalars and the dark matter scalar.

We thus can predict the dark matter mass. For example, in the case with $k = 1$, we read

$$m_\chi = \begin{cases} 1.07\,\mathrm{GeV} & \text{for} \quad b = 3\,, \\ 1.61\,\mathrm{GeV} & \text{for} \quad b = 2\,. \end{cases}$$

For a bigger baryon(lepton) number of the dark matter scalar, the dark matter mass can become heavier. For example, by taking $a_1 = ... = a_{n-1} = 3$ and $b = 2$, we read

$$m_\chi = \begin{cases} 4.83\,\mathrm{GeV} & \text{for} \quad n = 2\,, \\ 14.5\,\mathrm{GeV} & \text{for} \quad n = 3\,, \\ 43.4\,\mathrm{GeV} & \text{for} \quad n = 4\,, \\ 130\,\mathrm{GeV} & \text{for} \quad n = 5\,, \\ 391\,\mathrm{GeV} & \text{for} \quad n = 6\,, \\ 1.17\,\mathrm{TeV} & \text{for} \quad n = 7\,. \end{cases}$$

- Since the dark matter asymmetry is expected to account for the dark matter relic density, it is necessary for a fast annihilation between the dark matter and antimatter to dilute the thermally produced dark matter relic density. For a dark matter candidate with a mass from a few GeV to a few TeV, its thermally relic density can be determined by

$$\Omega_\chi h^2 \simeq \frac{0.1\,\mathrm{pb}}{\langle \sigma v \rangle}\,.$$

  Therefore, the annihilation cross section between the dark matter and antimatter should be much bigger than the typical value $\sim 1\,\mathrm{pb}$ for thermally generating the dark matter relic density.

We check for a dark matter mass above a few hundred GeV, the dark matter scalar can annihilate very fast into the SM fields through its quartic coupling with the SM Higgs doublet,

$$\begin{aligned}\mathcal{L} &\supset -\lambda_{\chi\phi}\chi^*\chi\phi^\dagger\phi \\ &\Rightarrow -\lambda_{\chi\phi}vh\chi^*\chi - \frac{1}{2}\lambda_{\chi\phi}h^2\chi^*\chi \ \text{ with } \ \phi = \left[\begin{array}{c}\frac{1}{\sqrt{2}}(v+h)\\ 0\end{array}\right].\end{aligned}$$

For example, we have

$$\langle\sigma v\rangle = \frac{\lambda_{\chi\phi}^2}{16\pi m_\chi^2} = \begin{cases}\frac{\lambda_{\chi\phi}^2}{1}\cdot 50.7\,\text{pb} & \text{for} \quad m_\chi = \ 391\,\text{GeV}\,,\\ \frac{\lambda_{\chi\phi}^2}{5}\cdot 28.3\,\text{pb} & \text{for} \quad m_\chi = 1.17\,\text{TeV}\,.\end{cases}$$

As for the case with a dark matter mass around or below the SM Higgs mass, the dark matter annihilation into the SM fields should be suppressed by the Yukawa couplings of the SM fermions. In this case, we need to introduce other fields to enhance the annihilation between the dark matter and anti-matter. For example, we can consider a Higgs singlet $\sigma(\mathbf{1},\mathbf{1},0)$ to break a global symmetry at the electroweak scale, i.e.

$$\sigma = \frac{1}{\sqrt{2}}(v' + h')e^{i\frac{\rho}{v'}}\,.$$

The dark matter scalar χ has a quartic coupling with σ,

$$\mathcal{L} \;\supset\; -\lambda_{\chi\sigma}\chi^*\chi\sigma^*\sigma\,,$$

so that it can significantly annihilate into the massless Goldstone ρ. For example, by fixing $m_{h'} = 70\,\mathrm{GeV}$, we have

$$\langle\sigma v\rangle = \frac{\lambda^2_{\chi\sigma}m^2_\chi}{4\pi m^4_{h'}} = \begin{cases} \frac{\lambda^2_{\chi\sigma}}{10}\cdot 14.8\,\mathrm{pb} & \mathrm{for} \quad m_\chi = 1.07\,\mathrm{GeV}\,, \\ \frac{\lambda^2_{\chi\sigma}}{5}\cdot 16.7\,\mathrm{pb} & \mathrm{for} \quad m_\chi = 1.61\,\mathrm{GeV} \\ \frac{\lambda^2_{\chi\sigma}}{1}\cdot 30.1\,\mathrm{pb} & \mathrm{for} \quad m_\chi = 4.83\,\mathrm{GeV}\,. \end{cases}$$

If the mixing between the SM Higgs boson h and the non-SM one h', which is from the quartic coupling,

$$\mathcal{L} \supset -\lambda_{\sigma\phi}\sigma^*\sigma\phi^\dagger\phi\,,$$

is taken into account, the SM Higgs boson could mostly decay into the massless Goldstone boson. This will result in an interesting implication on the Higgs searches at the colliders (Jungman, Luty, 91'; Dedes, Figy, Hoche, Krauss, Underwood, 08';...)

The global symmetry breaking may be related to the Dirac seesaw mechanism (Roncadelli, Wyler, 83'; Roy, Shanker, 84'; PHG, He, 06') for generating the small Dirac neutrino masses. For example, we consider (PHG, He, 06')

$$\mathcal{L} \supset -y_\nu \bar{l}_L \eta \nu_R - \mu \sigma^* \eta^\dagger \phi + \text{H.c.}\,,$$

where $\nu_R(\mathbf{1}, \mathbf{1}, 0)$ denotes the right-handed neutrinos and $\eta(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ is a new Higgs doublet. As shown in FIG. 2, we can obtain the desired neutrino masses for $y_\nu = \mathcal{O}(1)$ and $\mu < m_\eta = \mathcal{O}(10^{14}\,\text{GeV})$ for $\langle\sigma\rangle \sim \langle\phi\rangle$.

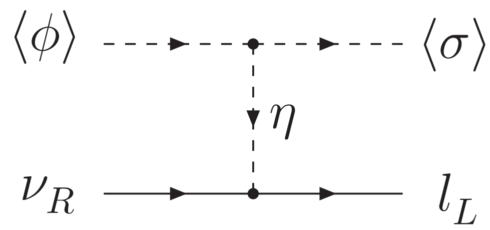

FIG. 2: Seesaw for light Dirac neutrinos.

Dark Matter Detection

- As a main consequence of the models with the asymmetric dark matter relic density, the current universe will have abundant dark matter and rare dark antimatter.

  With the rare dark antimatter, it is difficult to detect the annihilation between the dark matter and antimatter in the present universe although the cross section is sizable.

  The dark matter scalar also has no decay modes.

  Therefore, our models have no implications on dark matter indirect detection experiments. Fortunately, they are possible to verify by dark mater direct detection experiments and at colliders, as I will show later.

- The t-channel exchange of the SM Higgs boson h will result in an elastic scattering of the dark matter χ on the nucleon N to open a window for the dark matter direct detection experiments.

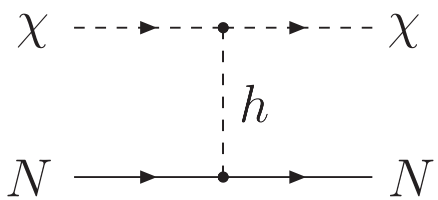

FIG. 3: The Higgs mediates the scattering of dark matter on nucleon.

The cross section should be

$$\sigma_{\chi N \to \chi N} = \frac{\lambda_{\chi\phi}^2}{4\pi} \frac{f^2 m_N^2 \mu_r^2}{m_h^4 m_\chi^2},$$

where $\mu_r = m_\chi m_N/(m_\chi + m_N)$ is the reduced mass, the factor f, which has a central value $f = 0.30$ and varies in a rather wide range $0.14 < f < 0.66$ (Koch, 82'; Gasser, Leutwyler, Sainio, 91'; Bottino, Donato, Fornengo, Scopel, 00'; Pavan, Arndt, Strakovski, Workman, 02'), parametrizes the coupling of the Higgs to the nucleons from the trace anomaly, i.e. $f m_N = \langle N | \sum_q m_q \bar{q} q | N \rangle$.

The dark matter scattering cross section is strongly constrained by the dark matter direct detection experiments. We fix $m_h = 120\,\mathrm{GeV}$ and $f = 0.3$ and then read

$$\sigma_{\chi N\to\chi N} = \begin{cases} \frac{\lambda^2_{\chi\phi}}{1}\cdot 2.6\cdot 10^{-39}\,\mathrm{cm}^2 & \mathrm{for} \quad m_\chi = 1.07\,\mathrm{GeV}\,, \\ \frac{\lambda^2_{\chi\phi}}{1}\cdot 1.6\cdot 10^{-39}\,\mathrm{cm}^2 & \mathrm{for} \quad m_\chi = 1.61\,\mathrm{GeV}\,, \\ \frac{\lambda^2_{\chi\phi}}{1}\cdot 3.1\cdot 10^{-40}\,\mathrm{cm}^2 & \mathrm{for} \quad m_\chi = 4.83\,\mathrm{GeV}\,, \\ \frac{\lambda^2_{\chi\phi}}{0.1}\cdot 4.4\cdot 10^{-42}\,\mathrm{cm}^2 & \mathrm{for} \quad m_\chi = 14.5\,\mathrm{GeV}\,, \\ \frac{\lambda^2_{\chi\phi}}{0.01}\cdot 5.3\cdot 10^{-44}\,\mathrm{cm}^2 & \mathrm{for} \quad m_\chi = 43.4\,\mathrm{GeV}\,, \\ \frac{\lambda^2_{\chi\phi}}{0.05}\cdot 3.0\cdot 10^{-44}\,\mathrm{cm}^2 & \mathrm{for} \quad m_\chi = 130\,\mathrm{GeV}\,, \\ \frac{\lambda^2_{\chi\phi}}{1}\cdot 6.8\cdot 10^{-44}\,\mathrm{cm}^2 & \mathrm{for} \quad m_\chi = 391\,\mathrm{GeV}\,, \\ \frac{\lambda^2_{\chi\phi}}{5}\cdot 3.8\cdot 10^{-44}\,\mathrm{cm}^2 & \mathrm{for} \quad m_\chi = 1.17\,\mathrm{TeV}\,. \end{cases}$$

For the dark matter mass in the range from a few GeV to a few TeV, the dark matter scattering cross section can be below the experimental limits (e.g. Kopp, Schwetz, Zupan, 09') by choosing the dark-matter-Higgs coupling and the Higgs mass. For example, with $m_\chi = 391\,\mathrm{GeV}$, we can obtain $\sigma_{\chi N \to \chi N} = 6.8 \cdot 10^{-44}\,\mathrm{cm}^2$ and $\langle \sigma v \rangle = 50.7\,\mathrm{pb}$ by taking $\lambda_{\chi\phi} = 1$ and $m_h = 120\,\mathrm{GeV}$.

- Through the s-channel exchange of the SM Higgs boson, the dark matter scalar is possible to find as a missing energy at colliders such as the CERN LHC (Silveira, Zee, 85'; McDonald, '94; Burgess, Pospelov, ter Veldhuis, 00';...). For example, the SM Higgs boson could dominantly decay into the dark matter,

$$\frac{\Gamma_{h\to\chi^*\chi}}{\Gamma_{h\to\bar{b}b}} = \frac{\lambda_{\chi\phi}^2 v^4}{6 m_b^2 m_h^2}\sqrt{1-\frac{4m_\chi^2}{m_h^2}} \gg 1\,.$$

6. Conclusion

- Baryogenesis mechanism can simultaneously generate a baryon asymmetry and a dark matter asymmetry. The dark matter asymmetry can account for the dark matter relic density. This scenario can naturally explain the comparable energy densities of the baryonic and dark matter in the present universe.

- As the dark matter asymmetry is fixed by the baryon asymmetry, we can determine the dark matter mass. Specifically, the predictive dark matter mass is at the GeV scale in the usual models.

- We proposed a mechanism to predict the dark matter mass in the range from the GeV scale to the TeV scale. In our models, the dark matter asymmetry is the ratio of the baryon(lepton) asymmetry in the dark matter scalar over the baryon(lepton) number of the dark matter scalar. This means that the dark matter can have a heavier mass if it has a bigger baryon(lepton) number.

- Our dark matter scalar can have a sizable quartic coupling with the SM Higgs doublet. Therefore, it is possible to verify by dark matter direct detection experiments and at colliders.

Thanks!