Baryogenesis via leptogensis from asymmetric dark matter and radiatively generated neutrino mass.

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Contents:

Results known so far:

- Dark matter relics $\Omega_{\rm DM}{\rm h}^2 = 0.1199 \pm 0.0027$
- Baryonic matter relics $\Omega_{\rm B}{\rm h}^2 = 0.02225 \pm 0.00016$
- Baryon asymmetry $5.8 \times 10^{-8} < \eta < 6.6 \times 10^{-10}$ where $\eta = \frac{\rm n_B}{\rm n_\gamma}$
- $\frac{\Omega_{DM}}{\Omega_B} \sim 5$

Planck Collaboration arXiv:1502.01589 [astro-ph.CO]

Asymmetric dark matter(ADM) framwork

- DM carries a conserved quantum number, e.g. $U(1)_B$, $U(1)_L$, $U(1)_{B-L}$
- An asymmetry is generated in the early universe, $n_{\Delta\chi} = n_\chi - n_{\bar{\chi}} > 0$ or $n_{\Delta L} = n_L - n_{\bar{L}} > 0$
- Transfer the asymmetry from one sector to other. $\mathrm{DM} \to \mathrm{SM}$ or $\mathrm{SM} \to \mathrm{DM}$
- If the asymmetry is in the leptonic sector then electroweak sphaleron process converted it into baryon asymmetry.
- The symmetric component is annihilated away, $\chi + \bar{\chi} \to a + b$

$$\sigma > \sigma_0 = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$

Now the abundance is set by $n_{\Delta\chi}$ instead of σ
if $n_{\Delta\chi} \sim n_B$ then $\Omega_{DM} \sim \Omega_B$ for $m_\chi \sim m_p \sim \mathrm{GeV}$
S. Nussinov 1985, D.B. Kaplan 1992, D.E. Kaplan, M.Luty and K.Zurek 2009

Model

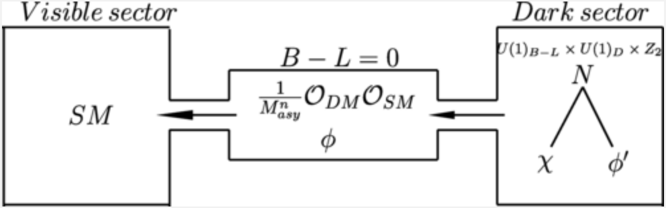
Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{(B-L)}$	$U(1)_D$	Z_2
N_R	**1**	**1**	0	-1	1	-
χ	**1**	**1**	0	-1	$\frac{1}{3}$	-
ϕ	**1**	**1**	0	0	0	$+$
$\phi^{'}$	**1**	**1**	0	0	$\frac{2}{3}$	$+$
ϕ_{B-L}	**1**	**1**	0	$+2$	-2	$+$

$$
\begin{aligned}
\mathcal{L} \supset \; & \overline{N_{Rj}} i\gamma^{\mu} D_{\mu} N_{Rj} + \overline{\chi} i\gamma^{\mu} D_{\mu}\chi + \frac{1}{2}(\partial_{\mu}\phi)(\partial^{\mu}\phi) \\
+ \; & (\partial_{\mu}\phi')^{\dagger}(\partial^{\mu}\phi') + (D_{\mu}\phi_{B-L})^{\dagger}(D^{\mu}\phi_{B-L}) \\
+ \; & M_{\chi}\overline{\chi}\chi + \lambda_{B-L}\phi_{B-L}\overline{(N_{Ri})^c}N_{Rj} + \lambda_{\rm DM}\overline{\chi}\chi\phi \\
+ \; & y_i \overline{N_{Ri}}\chi\phi' + h.c. - V(H,\phi,\phi')
\end{aligned} \tag{1}
$$

N.Narendra, S.Patra, N.Sahu and S.S. Phys.Rev.D98(2018)

Model

$$
\begin{aligned}
V(H,\phi,\phi') &= -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \frac{1}{2} M_\phi^2 \phi^2 \\
&+ \frac{1}{4}\lambda_\phi \phi^4 + M_{\phi'}^2 \phi'^\dagger \phi' + \lambda_{\phi'} (\phi'^\dagger \phi')^2 \\
&+ \frac{1}{2}\lambda_{H\phi}(H^\dagger H)\phi^2 + \mu_\phi \phi (H^\dagger H) + \mu'_\phi \phi (\phi'^\dagger \phi') \\
&+ \lambda_{H\phi'}(H^\dagger H)(\phi'^\dagger \phi') + \frac{\lambda_{\phi\phi'}}{2}\phi^2 (\phi'^\dagger \phi') \,. \qquad (2)
\end{aligned}
$$

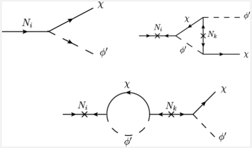


Asymmetric dark matter: generation of asymmetry

$$\epsilon_\chi = \frac{\Gamma(N_1 \to \chi_j \phi) - \Gamma(N_1 \to \bar{\chi}_j \phi)}{\Gamma_{N_1}}$$

$$\simeq -\frac{3}{8\pi}\left(\frac{M_1}{M_2}\right)\frac{\mathrm{Im}\left[(y^\dagger y)^2\right]_{12}}{(y^\dagger y)_{11}}. \quad (3)$$

$$(n_{\rm B-L})_{\rm total} = \frac{n^{eq}_{N_1}(T \to \infty)}{s} \times \epsilon_\chi \kappa s. \quad (4)$$

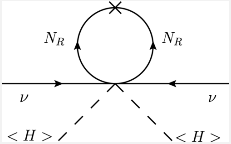


Neutrino Mass:

The lepton number is violated by the Majorana mass term of the heavy right handed neutrinos. Note that the term: $\overline{N_R}\tilde{H}^\dagger L$ is not allowed as N_R is odd under the Z_2 symmetry.

$$\mathcal{O}_\nu = \frac{(\overline{N_R}\tilde{H}^\dagger L)^2}{\Lambda^4}$$

$$\Lambda \approx 7.66 \times 10^{11} GeV \left(\frac{0.1eV}{M_\nu}\right)\left(\frac{M_N/\Lambda}{0.1}\right). \quad (5)$$



Transfer of asymmetry from dark sector to visible sector.

$$\mathcal{O}_8 = \frac{1}{M_{asy}^4}\overline{\chi}^2(LH)^2. \tag{6}$$

$$\Gamma_{\rm D} \simeq \left(\frac{T_D^4}{M_{\rm asy}^4}\right)^2 T_D\,, \tag{7}$$

$$M_{asy}^8 > M_{Pl}\,T_D^7\,. \tag{8}$$

- Here we consider that $T_D \gtrsim T_{\rm sph}$, where T_{sph} is the sphaleron decoupling temperature.
- For Higgs mass $M_h = 125\,\mathrm{GeV}$, the sphaleron decoupling temperature $T_{sph} > M_W$.
- $M_{asy} > 0.9 \times 10^4\,\mathrm{GeV}$

Standard equilibrium method:

The asymmetry in the equilibrium number densities of particle n_i and anti-particle $\bar{n}_i$ is,

$$n_i - \overline{n_i} = \frac{g_i}{2\pi^2}\int_0^\infty dq q^2 \left[\frac{1}{e^{\frac{E_i(q)-\mu_i}{T}} \pm 1} - \frac{1}{e^{\frac{E_i(q)+\mu_i}{T}} \pm 1}\right] \tag{9}$$

In the approximation of a weakly interacting plasma, $\beta\mu_i << 1$,

$$\begin{aligned} n_i - \overline{n_i} &\sim \frac{g_i T^3}{6} \times [2\beta\mu_i + \mathcal{O}((\beta\mu_i)^3) \text{ bosons} \\ &\sim \frac{g_i T^3}{6} \times [\beta\mu_i + \mathcal{O}((\beta\mu_i)^3) \text{ fermions}\,. \end{aligned} \tag{10}$$

Below electroweak phase transition, the Yukawa interactions can be given as:

$$\begin{aligned}\mathcal{L}_{Yukawa} &= g_{e_i}\bar{e}_{iL}he_{iR} + g_{u_i}\bar{u}_{iL}hu_{iR} \\ &+ g_{d_i}\bar{d}_{iL}hd_{iR} + h.c\,, \end{aligned} \quad (11)$$

which gives the following chemical potential condition,

$$0 = \mu_h = \mu_{u_L} - \mu_{u_R} = \mu_{d_L} - \mu_{d_R} = \mu_{e_{iL}} - \mu_{e_{iR}}\,. \quad (12)$$

Sphaleron condition($\prod_i Q_i Q_i Q_i L_i = 0$ conserve $B - L$ but violate $B + L$) are equilibrium above EW phase transition,

$$\mu_{u_L} + 2\mu_{d_L} + \mu_\nu = 0 \quad (13)$$

Charge neutrality of the universe gives,

$$Q = 4(\mu_{u_L} + \mu_{u_R}) + 6\mu_W - 3(\mu_{d_L} + \mu_{d_R}) - \sum_{i=1}^{3}(\mu_{e_{iL}} + \mu_{e_{iR}}) = 0\,. \quad (14)$$

Chemical equilibrium conditions:

The charge current interactions,

$$\mathcal{L}_{int}^{(W)} = gW_\mu^+ \bar{u}_L \gamma^\mu d_L + gW_\mu^+ e_{iL} \gamma^\mu \bar{\nu}_{e_{iL}} . \tag{15}$$

$$\mu_W = \mu_{u_L} - \mu_{d_L} , \tag{16}$$

$$\mu_W = \mu_\nu - \mu_{e_{iL}} , \forall i . \tag{17}$$

Solving above equations,

$$n_B = -\frac{90}{29}\mu_\nu \text{ and } n_L = \frac{201}{29}\mu_\nu . \tag{18}$$

Total baryon and lepton number densities in visible sector,

$$(n_{B-L})_{\rm vis} = -\frac{291}{29}\mu_\nu . \tag{19}$$

$$n_{\rm B} = \frac{30}{97}(n_{\rm B-L})_{\rm vis} \tag{20}$$

Chemical equilibrium conditions:

We assume that, the dark matter χ is also in thermal equilibrium with the visible sector via the dimension eight operator $\mathcal{O}_8$ until the sphaleron decoupling temperature $T_{\rm sph} > M_W$. This gives chemical equilibrium condition:

$$-\mu_\chi + \mu_\nu = 0 \tag{21}$$

we get the number density of χ asymmetry, which is also the $B - L$ number density in the dark sector:

$$n_\chi = (n_{\rm B-L})_{\rm dark} = -2\mu_\chi = \frac{58}{291}(n_{B-L})_{\rm vis}\,. \tag{22}$$

$$(n_{\rm B-L})_{\rm total} = \frac{349}{291}(n_{B-L})_{\rm vis}\,. \tag{23}$$

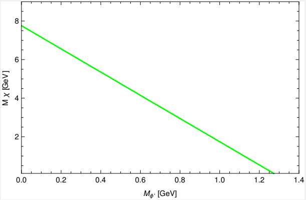
$$n_{\rm B} = \frac{90}{349}(n_{B-L})_{\rm total}\,. \quad (24)$$

$$n_{\chi} = \frac{58}{349}(n_{B-L})_{\rm total}\,. \quad (25)$$

$$n_{\phi'} = (n_{B-L})_{\rm total}\,. \quad (26)$$

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{\sum_{\rm i} {\rm n_{x_i}.m_{x_i}}}{B.m_B} \sim 5 \quad (27)$$

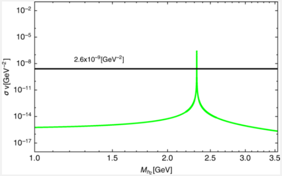
For $\frac{n_B}{s} \sim 6\times 10^{-10}$ the $\epsilon_\chi \sim 10^{-6}$
Dark matter mass $m_\chi \sim m_{\phi'} \sim 1 GeV$

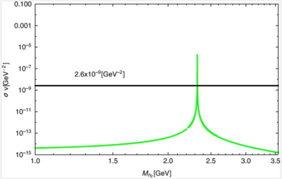


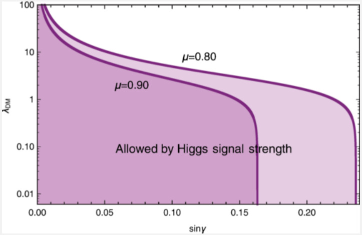
Annihilation of the symmetric component of DM:

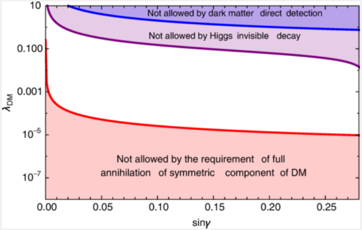
The annihilation cross-section for the process: $\overline{\chi}\chi \rightarrow \overline{f}f$ or $\overline{\phi'}\phi' \rightarrow \overline{f}f$ through $\phi - \mathrm{H}$ mixing is given by:

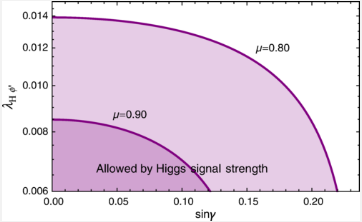
$$\begin{aligned}
\sigma v &= \frac{\sqrt{s - 4M_f^2}}{16\pi s\sqrt{s}} \\
&\times \frac{\lambda_{DM}^2 \lambda_f^2 cos^2\gamma sin^2\gamma}{\left[(s - M_{h_1}^2)^2 + \Gamma_{h_1}^2 M_{h_1}^2\right]\left[(s - M_{h_2}^2)^2 + \Gamma_{h_2}^2 M_{h_2}^2\right]} \\
&\times \{\left[2s - (M_{h_1}^2 + M_{h_2}^2)\right]^2 + \left[\Gamma_{h_1} M_{h_1} + \Gamma_{h_2} M_{h_2}\right]^2\} \\
&\times \{(s - 2M_\chi^2)(s - 2M_f^2) - 2M_f^2(s - 2M_\chi^2) \\
&- 2M_\chi^2(s - 2M_f^2) + 4M_\chi^2 M_f^2\}
\end{aligned} \tag{28}$$

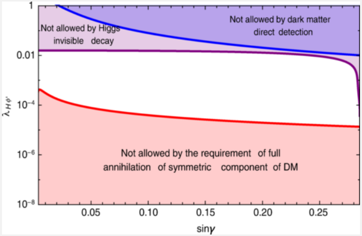





μ=0.80
μ=0.90
Allowed by Higgs signal strength
λ_DM
sinγ


Not allowed by dark matter direct detection
Not allowed by Higgs invisible decay
Not allowed by the requirement of full annihilation of symmetric component of DM
λ_DM
sinγ


μ=0.80
μ=0.90
Allowed by Higgs signal strength
λ_Hφ'
sinγ


Not allowed by Higgs invisible decay
Not allowed by dark matter direct detection
Not allowed by the requirement of full annihilation of symmetric component of DM
λ_Hφ'
sinγ

Conclusion:

- Asymmetric dark matter naturally explain the cosmic coincidence problem i.e. number density of baryonic matter and dark matter have of the same order.
- In our model fermionic and bosonic both are contributing to dark matter relics and both are asymmetric.
- At one loop level the active neutrinos accquired masses via a dimension eight operator.