High-scale Baryogenesis with Low-energy Observables

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- Matter-antimatter asymmetry
- Neutrino mass
- Dark matter
- Inflation
- Strong CP problem
- ...
- Proton decay
- Neutron-antineutron oscillation

Outline

- Introduction
- High-scale leptogenesis with testable neutrino mass generation and dark matter
- High-scale baryogenesis with testable neutron-antineutron oscillation and dark matter
- Summary

Introduction

‡ No primordial antimatter significantly exists in the present universe.

‡ All particles should come in particle-antiparticle pairs.

‡ An initial matter-antimatter asymmetry cannot survive after inflation.

We need a dynamical baryogenesis mechanism!

If CPT (C – charge conjugation, P – parity, T – time reversal.) is invariant, any successful baryogenesis mechanisms should satisfy the Sakharov conditions (Sakharov 67’):

‡ baryon number nonconservation,

‡ C and CP violation,

‡ departure from equilibrium.

$$\left.\begin{array}{l} B \xrightarrow{C} -B \ \text{ for } \ q_{L(R)} \xrightarrow{C} q^c_{L(R)} \\ B \xrightarrow{CP} -B \ \text{ for } \ q_L \xrightarrow{CP} q^c_R \end{array}\right\} \Longrightarrow n_B \equiv n_b - n_{\bar{b}} = \frac{1}{3}(n_{q_L} - n_{\bar{q}_L} + n_{q_R} - n_{\bar{q}_R}) \xrightarrow{C,CP} 0\,.$$

$$\langle B \rangle = \mathrm{Tr}(e^{-\frac{H}{T}} B) = \mathrm{Tr}[e^{-\frac{H}{T}} (CPT)^{-1} B (CPT)] = \mathrm{Tr}[e^{-\frac{H}{T}} (-B)] = -\langle B \rangle \Rightarrow \langle B \rangle = 0\,.$$

Both of the baryon (B) and lepton (L) numbers are violated by quantum effects in the standard model ('t Hooft, 76'.). The transition of the baryon and lepton numbers from one vacuum to the next vacuum is

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = N_f \frac{g_2^2}{32\pi^2}\epsilon_{\mu\nu\rho\sigma}\mathrm{Tr}\,(W^{\mu\nu}W^{\rho\sigma}) \Rightarrow \Delta B = \Delta L = N_f\,, \;\; \Delta(B-L) = 0\,.$$

At zero temperature, the baryon and lepton number violating processes via a tunneling between the topologically distinct vacua are highly suppressed. However, such sphaleron processes could become efficient during the temperatures near and above the electroweak phase transition (Kuzmin, Rubakov, Shaposhnikov, 85'.),

$$100\,\mathrm{GeV} < T < 10^{12}\,\mathrm{GeV}\,.$$

In the standard model, the sphaleron processes, the CKM phase and the electroweak phase transition can fulfill all of the three Sakharov conditions to realize an electroweak baryogenesis scenario (e.g. Morrissey, Ramsey-Musolf, 12'.).

Unfortunately, the baryon asymmetry induced by the electroweak baryogenesis in the standard model is too small to explain the observed value.

‡ The electroweak phase transition should be strongly first-order to avoid the washout of the induced baryon asymmetry. This requires the Higgs boson lighter than about $m_H < 40$ GeV, which is much lower than the experimental value $m_H = 125$ GeV.

‡ Even if the electroweak phase transition is strongly first-order, the induced baryon asymmetry can only arrive at the order of $\eta_B = \mathcal{O}(10^{-20})$.

We need a baryogenesis beyond the standard model!

The seesaw extension of the standard model is very attractive since it can provide a natural way to suppress the neutrino masses, meanwhile, accommodate a leptogenesis mechanism to generate the cosmic baryon asymmetry. In the usual seesaw-leptogenesis scenarios, the generating scales of the neutrino masses and the baryon asymmetry are determined by the masses of same particles. In other words, a high-scale leptogenesis will not allow a low-scale neutrino mass generation.

M. Fukugita and T. Yanagida, Phys. Lett. B **174**, 45 (1986).

The existence of non-baryonic dark matter poses another challenge to particle physics and cosmology. The dark matter particle may also play an essential role in the generation of the neutrino masses and even the production of the baryon asymmetry

L.M. Krauss, S. Nasri, and M. Trodden, Phys. Rev. D **67**, 085002 (2003).

E. Ma, Phys. Rev. D **73**, 077301 (2006).

In this talk I will show

- A high-scale leptogenesis can be allowed even if we expect to realize a neutrino mass generation at the TeV scale. In this scenario the dark matter particle plays an essential role.

- This idea can be modified to accommodate a high-scale baryogenesis with an observable neutron-antineutron oscillation and a testable dark matter.

- An inflationary baryogenesis/leptogenesis can be achieved.

High-scale leptogenesis with testable neutrino mass generation and dark matter

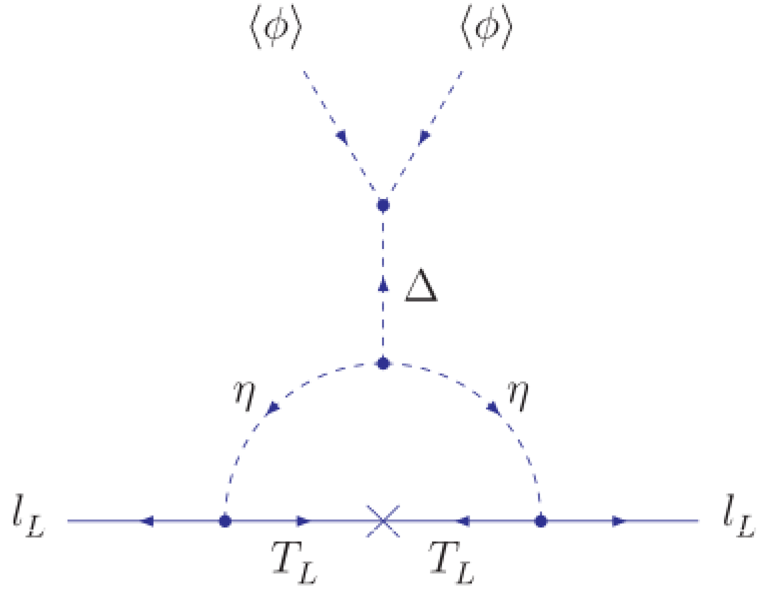
- A model for one-loop neutrino mass and dark matter
- A model for three-loop neutrino mass and dark matter
- A model for radiative type-II seesaw and minimal inelastic dark matter

A model for one-loop neutrino mass and dark matter

$$\phi(1,2,-\frac{1}{2})(0) = \begin{bmatrix} \phi^0 \\ \phi^- \end{bmatrix}, \quad l_L(1,2,-\frac{1}{2})(+1) = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}.$$

$$\begin{aligned}
\eta(1,2,-\tfrac{1}{2})(+1) &= \begin{bmatrix} \eta^0 \\ \eta^- \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{2}}(\eta_R^0 + i\eta_I^0) \\ \eta^- \end{bmatrix}, \\
\Delta_i(1,3,1)(0) &= \begin{bmatrix} \delta_i^+/\sqrt{2} & \delta_i^{++} \\ \delta_i^0 & -\delta_i^+/\sqrt{2} \end{bmatrix} \quad (i=1,2), \\
T_{Li}(1,3,0)(0) &= \begin{bmatrix} T_{Li}^0/\sqrt{2} & T_{Li}^+ \\ T_{Li}^- & -T_{Li}^0/\sqrt{2} \end{bmatrix} \quad (i=1,2,...).
\end{aligned}$$

$$(\mathrm{SM}\,,\ \Delta) \xrightarrow{Z_2} (\mathrm{SM}\,,\ \Delta)\,, \quad (T_L\,,\ \eta) \xrightarrow{Z_2} -(T_L\,,\ \eta)\,.$$



$$m^2_{\eta^0_R} = m^2_{\eta^0} + \sqrt{2}[\mu_{\Delta_1\eta}v_{\Delta_1} + \mu_{\Delta_2\eta}v_{\Delta_2}\cos\delta]\,,$$
$$m^2_{\eta^0_I} = m^2_{\eta^0} - \sqrt{2}[\mu_{\Delta_1\eta}v_{\Delta_1} + \mu_{\Delta_2\eta}v_{\Delta_2}\cos\delta]\,,$$
$$m^2_{RI} = -\sqrt{2}\,\mu_{\Delta_2\eta}v_{\Delta_2}\sin\delta\,.$$

$$\tan 2\beta = \frac{2\,m^2_{RI}}{m^2_{\eta^0_R} - m^2_{\eta^0_I}}\,.$$

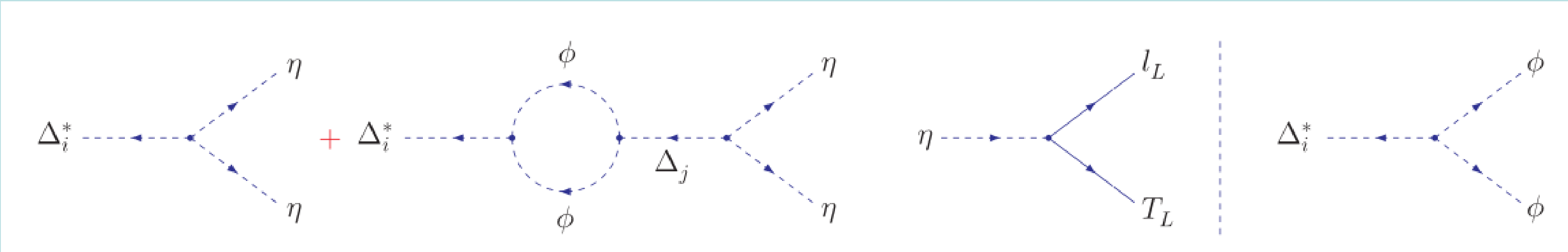
$$(m_\nu)_{\alpha\beta} = \frac{(\cos\beta - i\sin\beta)^2}{32\pi^2}\sum_i y_{\alpha i}y_{\beta i}M_{T_i}\left[\frac{m^2_{\hat\eta^0_R}}{m^2_{\hat\eta^0_R} - M^2_{T_i}}\ln\left(\frac{m^2_{\hat\eta^0_R}}{M^2_{T_i}}\right) - \frac{m^2_{\hat\eta^0_I}}{m^2_{\hat\eta^0_I} - M^2_{T_i}}\ln\left(\frac{m^2_{\hat\eta^0_I}}{M^2_{T_i}}\right)\right]\,.$$

$$m_\nu \simeq \frac{\sqrt{2}\sum_i \mu_{\Delta_i\eta}v_{\Delta_i}}{16\pi^2 m^2_{\eta^0}}yM_Ty^T \quad \text{for} \quad M^2_{T_i}\,,\ \mu_{\Delta_i\eta}v_{\Delta_i} \ll m^2_{\eta^0}\,.$$

Ma model

E. Ma, Phys. Rev. D **73**, 077301 (2006).

$$\mathcal{L} \supset -\lambda''_{\phi\eta}(\eta^\dagger\phi)^2 + \text{H.c.} \quad \text{with} \quad \lambda''_{\phi\eta} \simeq -\frac{\mu^*_{\Delta_i\eta}\mu_{\Delta_i\phi}}{M^2_{\Delta_i}} \simeq \frac{\sqrt{2}\mu_{\Delta_i\eta}v_{\Delta_i}}{v^2_\phi} \simeq \frac{\sqrt{2}\mu_{\Delta_i\eta}v_{\Delta_i}}{v^2}\,.$$



$$\Gamma_{\Delta_i} = \Gamma(\Delta_i^* \to \eta + \eta) + \Gamma(\Delta_i^* \to \phi + \phi) = \frac{1}{16\pi} \frac{|\mu_{\Delta_i \eta}|^2 + |\mu_{\Delta_i \phi}|^2}{M_{\Delta_i}} .$$

$$\varepsilon_{\Delta_i} = \frac{\Gamma(\Delta_i^* \to \eta + \eta) - \Gamma(\Delta_i \to \eta^* + \eta^*)}{\Gamma_{\Delta_i}} = \frac{1}{4\pi} \frac{\mathrm{Im}(\mu^*_{\Delta_i \phi} \mu_{\Delta_j \phi} \mu_{\Delta_i \eta} \mu^*_{\Delta_j \eta})}{\mu^2_{\Delta_i \eta} + \mu^2_{\Delta_i \phi}} \frac{1}{M^2_{\Delta_j} - M^2_{\Delta_i}} .$$

$$K = \frac{\Gamma_{\sigma_1}}{2H(T)} \Big|_{T=M_{\sigma_1}} . \qquad H = \left(\frac{8\pi^3 g_*}{90} \right)^{\frac{1}{2}} \frac{T^2}{M_{\mathrm{Pl}}} .$$

$$\eta_B = \frac{n_B}{s} \simeq -\frac{28}{79} \times \frac{\varepsilon_{\Delta_1}}{g_*} \times 3 \quad \text{for} \quad K \ll 1 .$$

$$M_{\Delta_1} = 100\,\mu_{\Delta_1\phi} = 100\,\mu_{\Delta_1\eta} = 10^{14}\,\mathrm{GeV}\,,$$
$$M_{\Delta_2} = 100\,\mu_{\Delta_2\phi} = 100\,\mu_{\Delta_2\eta} = 10^{15}\,\mathrm{GeV}\,,$$
$$\sin\delta = 0.016\,.$$

$$\varepsilon_{\Delta_1} = 6\times 10^{-8}\,, \quad K = 0.015\,, \quad \eta_B = 6.1\times 10^{-10}\,.$$

$$m_\nu \;=\; 0.1\,\mathrm{eV}\left(\frac{3\,\mathrm{TeV}}{m_{\eta^0}}\right)^2\left(\frac{y}{10^{-3}}\right)\left(\frac{M_T}{2.4\,\mathrm{TeV}}\right)\left(\frac{y^T}{10^{-3}}\right)\,.$$

DM mass: $M_T = 2.4\,\mathrm{TeV}$.

DM-nucleon scattering cross section: $\sigma_{\rm SI} = 1.3\times 10^{-45}\,\mathrm{cm}^2$.

M. Cirelli, N. Fornengo, and A. Strumia, Nucl. Phys. B **753**, 178 (2006).

A model for three-loop neutrino mass and dark matter

$$\phi(1,2,+\frac{1}{2})(0) = \begin{bmatrix} \phi^+ \\ \phi^0 \end{bmatrix},$$

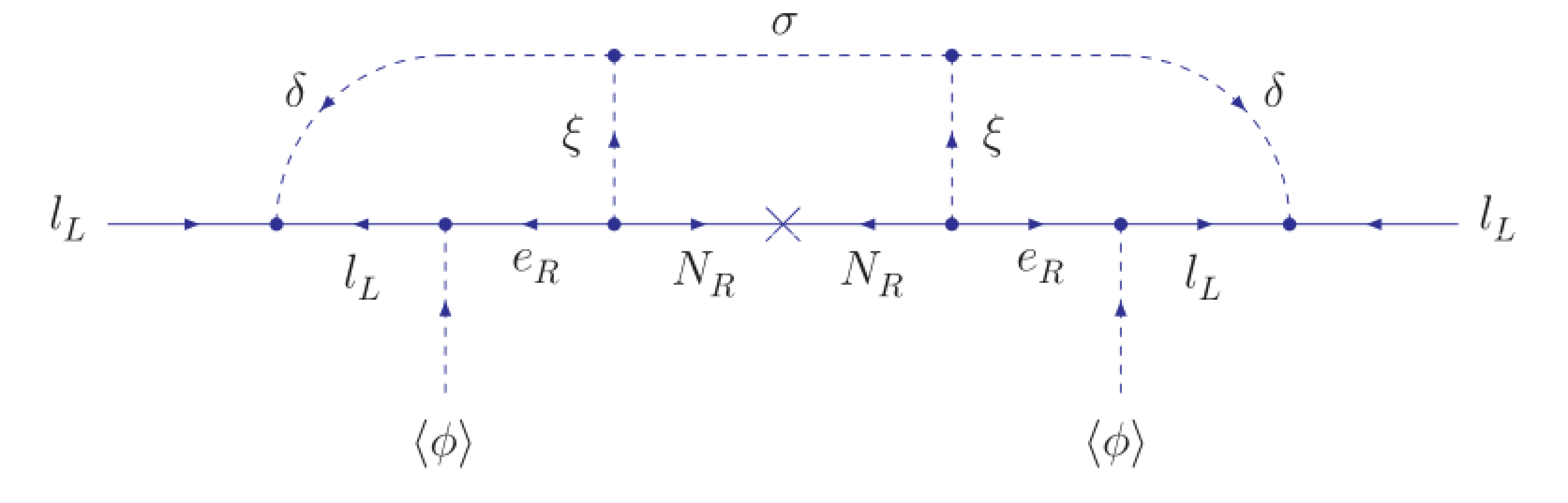
$$l_L(1,2,-\frac{1}{2})(+1) = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix},$$

$$e_R(1,1,-1)(+1)\,.$$

$$N_R(1,1,0)(0)\,, \quad \delta(1,1,+1)(-2)\,,$$

$$\xi(1,1,+1)(-1)\,, \quad \sigma(1,1,0)(0)\,.$$

$$(\mathrm{SM}\,,\,\delta) \xrightarrow{Z_2} (\mathrm{SM}\,,\,\delta)\,,\ (N_R\,,\,\xi\,,\,\sigma) \xrightarrow{Z_2} -(N_R\,,\,\xi\,,\,\sigma)\,.$$



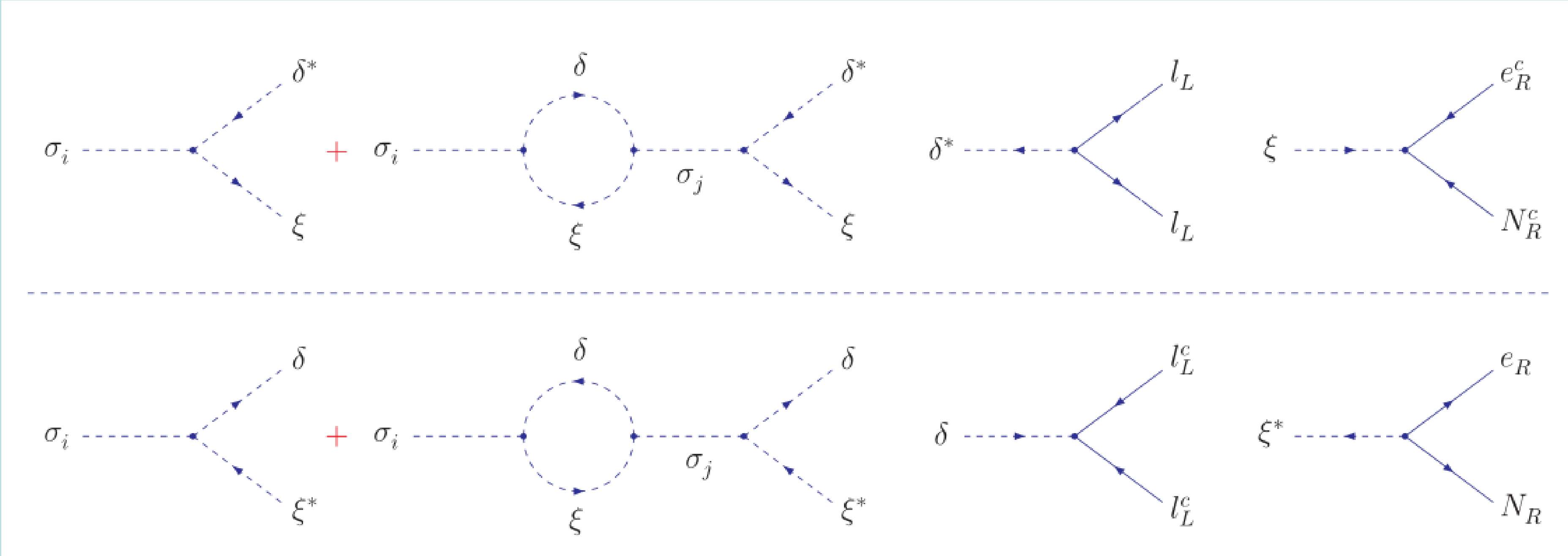
$$\mathcal{L} \supset -\kappa(\delta^\dagger\xi)^2 + \mathrm{H.c.} \quad \text{with} \quad \kappa = \sum_i \frac{\rho_i^2}{M_{\sigma_i}^2}\,.$$

Krauss-Nasri-Trodden model

L.M. Krauss, S. Nasri, and M. Trodden, Phys. Rev. D **67**, 085002 (2003).

The neutrinos can obtain their Majorana masses at three-loop level.

The lightest one of the Majorana fermions N_i can be a stable dark matter particle.



$$\Gamma_{\sigma_i} = \Gamma(\sigma_i \to \delta^* + \xi) + \Gamma(\sigma_i \to \delta + \xi^*) = \frac{1}{8\pi}\frac{|\rho_i|^2}{M_{\sigma_i}}\,.$$

$$\varepsilon_{\sigma_i} \;=\; \frac{\Gamma(\sigma_i \to \delta^* + \xi) - \Gamma(\sigma_i \to \delta + \xi^*)}{\Gamma_{\sigma_i}} = \frac{1}{8\pi}\frac{\mathrm{Im}(\rho_i^{*2}\rho_j^2)}{|\rho_i|^2}\frac{1}{M_{\sigma_j}^2 - M_{\sigma_i}^2}\,.$$

A model for radiative type-II seesaw and minimal inelastic dark matter

$$\phi(1,2,-\frac{1}{2})(0) = \begin{bmatrix} \phi^0 \\ \phi^- \end{bmatrix}, \quad l_L(1,2,-\frac{1}{2})(+1) = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}.$$

$$\begin{aligned}
\sigma_i(1,1,0)(-1) &= \frac{1}{\sqrt{2}}(\sigma_{iR} + i\sigma_{iI}) \quad (i = 1,2)\,, \\
\psi_L(1,2,+\tfrac{1}{2})(0) &= \begin{bmatrix} \xi_L^+ \\ \chi_L \end{bmatrix}, \quad \psi_L'(1,2,-\tfrac{1}{2})(0) = \begin{bmatrix} \chi_L' \\ \xi_L'^- \end{bmatrix}, \\
\Delta(1,3,-1)(0) &= \begin{bmatrix} \delta^-/\sqrt{2} & \delta^0 \\ \delta^{--} & -\delta^-/\sqrt{2} \end{bmatrix}.
\end{aligned}$$

$$(\mathrm{SM}\,,\ \Delta) \xrightarrow{Z_2} (\mathrm{SM}\,,\ \Delta)\,, \quad (\sigma\,,\ \psi_L\,,\ \psi_L') \xrightarrow{Z_2} -(\sigma\,,\ \psi_L\,,\ \psi_L')\,.$$

$$
\begin{aligned}
\mathcal{L} \;=\;& \mathrm{Tr}[(D_\mu\Delta)^\dagger D^\mu\Delta] - M_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) - \lambda_\Delta[\mathrm{Tr}(\Delta^\dagger\Delta)]^2 \\
& -\lambda'_\Delta \mathrm{Tr}[(\Delta^\dagger\Delta)^2] - \lambda_{\phi\Delta}\phi^\dagger\phi\mathrm{Tr}(\Delta^\dagger\Delta) \\
& -\lambda'_{\phi\Delta}\phi^\dagger\Delta^\dagger\Delta\phi - \mu_{\Delta\phi}(\phi^T i\tau_2\Delta\phi + \mathrm{H.c.}) \\
& +(\partial_\mu\sigma)^\dagger\partial^\mu\sigma - M_\sigma^2\sigma^\dagger\sigma - \frac{1}{2}(\tilde{M}_\sigma^2\sigma^2 + \mathrm{H.c.}) \\
& -\lambda_\sigma\sigma^\dagger\sigma\sigma^\dagger\sigma - \lambda_{\phi\sigma}\sigma^\dagger\sigma\phi^\dagger\phi - \lambda_{\Delta\sigma}\sigma^\dagger\sigma\mathrm{Tr}(\Delta^\dagger\Delta) \\
& +i\bar{\psi}_L\gamma^\mu D_\mu\psi_L + i\bar{\psi}'_L\gamma^\mu D_\mu\psi'_L - M_\psi(\bar{\psi}^c_L i\tau_2\psi'_L \\
& +\mathrm{H.c.}) + \frac{1}{2}(f\bar{\psi}^c_L i\tau_2\Delta\psi_L + f'\bar{\psi}'^c_L i\tau_2\Delta^\dagger\psi'_L + \mathrm{H.c.}) \\
& -(y\sigma\bar{l}^c_L i\tau_2\psi_L + \mathrm{H.c.}) + \mathcal{L}_{\mathrm{SM}} \quad \text{with}
\end{aligned}
$$

$$
\begin{aligned}
D_\mu\Delta &= \partial_\mu\Delta - ig\left[\frac{\tau_a}{2}W^a_\mu, \Delta\right] + ig'B_\mu\Delta\,, \\
D_\mu\psi_L &= \partial_\mu\psi_L - i\frac{1}{2}g\tau_a W^a_\mu\psi_L - i\frac{1}{2}g'B_\mu\psi_L\,, \\
D_\mu\psi'_L &= \partial_\mu\psi'_L - i\frac{1}{2}g\tau_a W^a_\mu\psi'_L + i\frac{1}{2}g'B_\mu\psi'_L\,.
\end{aligned}
$$

$$
\begin{aligned}
v &\equiv \sqrt{v_\phi^2 + 2v_\Delta^2} = 246\,\mathrm{GeV}\,, \\
\rho &= \frac{v_\phi^2 + 2v_\Delta^2}{v_\phi^2 + 4v_\Delta^2} = 1.00040 \pm 0.00024\,.
\end{aligned}
$$

$$
|v_\Delta| = \sqrt{\frac{1-\rho}{2\rho}}\,v \lesssim 2.2\,\mathrm{GeV} \quad \text{for} \quad \rho \lesssim 1.00112\,.
$$

$$
M_\sigma^2 = \mathrm{diag}\{M_{\sigma_1}^2\,,\; M_{\sigma_2}^2\}\,, \quad \tilde{M}_\sigma^2 = \mathrm{diag}\{\tilde{M}_{\sigma_1}^2\,,\; \tilde{M}_{\sigma_2}^2\}\,.
$$

$$
M_{\sigma_{iR}}^2 = M_{\sigma_i}^2 + \tilde{M}_{\sigma_i}^2\,, \quad M_{\sigma_{iI}}^2 = M_{\sigma_i}^2 - \tilde{M}_{\sigma_i}^2\,.
$$

$$
f = f^*\,, \quad f' = f'^*\,.
$$

Minimal inelastic dark matter

$$\mathcal{L} \supset -M_\psi(\overline{\xi_L^{+c}}\xi_L'^- + \text{H.c.}) + M_\psi(\overline{\chi_L^c}\chi_L' + \text{H.c.}) + \frac{v_\Delta}{2\sqrt{2}}[f(\overline{\chi_L^c}\chi_L + \text{H.c.}) - f'(\overline{\chi_L'^c}\chi_L' + \text{H.c.})]\,.$$

$$\xi^- = (\xi_L^+)^c + \xi_L'^-\,, \quad \xi^+ = \xi_L^+ + (\xi_L'^-)^c\,, \quad \xi^- = (\xi^+)^c \quad \text{with} \quad M_\xi = M_\psi\,.$$

$$\chi_1 = -(\chi_L + \chi_L^c)\sin\beta + (\chi_L' + \chi_L'^c)\cos\beta = \chi_1^c \quad \text{with}$$

$$M_{\chi_1} = \sqrt{M_\psi^2 + \frac{1}{8}(f+f')^2 v_\Delta^2} - \frac{1}{2\sqrt{2}}(f-f')v_\Delta\,,$$

$$\chi_2 = i[(\chi_L - \chi_L^c)\cos\beta + (\chi_L' - \chi_L'^c)\sin\beta] = \chi_2^c \quad \text{with}$$

$$M_{\chi_2} = \sqrt{M_\psi^2 + \frac{1}{8}(f+f')^2 v_\Delta^2} + \frac{1}{2\sqrt{2}}(f-f')v_\Delta\,.$$

$$\tan 2\beta = \frac{2\sqrt{2}M_\chi}{(f+f')v_\Delta}\,.$$

$$\mathcal{L} \supset i\overline{\xi^+}\gamma^\mu\partial_\mu\xi^+ - M_\xi\overline{\xi^+}\xi^+ + \frac{i}{2}\overline{\chi_1}\gamma^\mu\partial_\mu\chi_1 - \frac{1}{2}M_{\chi_1}\overline{\chi_1}\chi_1 + \frac{i}{2}\overline{\chi_2}\gamma^\mu\partial_\mu\chi_2 - \frac{1}{2}M_{\chi_2}\overline{\chi_2}\chi_2$$
$$+e\overline{\xi^+}\gamma^\mu\xi^+A_\mu + \frac{g\cos 2\theta_W}{2\cos\theta_W}\overline{\xi^+}\gamma^\mu\xi^+Z_\mu + \frac{g\cos 2\beta}{4\cos\theta_W}(\overline{\chi_1}\gamma_5\gamma^\mu\chi_1 - \overline{\chi_2}\gamma_5\gamma^\mu\chi_2)Z_\mu$$
$$+i\frac{g\sin 2\beta}{2\cos\theta_W}\overline{\chi_1}\gamma^\mu\chi_2 Z_\mu - \frac{g}{\sqrt{2}}\overline{\chi_1}\gamma^\mu(P_L\sin\beta + P_R\cos\beta)\xi^+W_\mu^-$$
$$-i\frac{g}{\sqrt{2}}\overline{\chi_2}\gamma^\mu(P_L\sin\beta + P_R\cos\beta)\xi^+W_\mu^- + \text{H.c.}\,.$$

$$\mathcal{L} \supset i\overline{\xi^+}\gamma^\mu\partial_\mu\xi^+ - M_\xi\overline{\xi^+}\xi^+ + \frac{i}{2}\overline{\chi_1}\gamma^\mu\partial_\mu\chi_1 - \frac{1}{2}M_{\chi_1}\overline{\chi_1}\chi_1 + \frac{i}{2}\overline{\chi_2}\gamma^\mu\partial_\mu\chi_2 - \frac{1}{2}M_{\chi_2}\overline{\chi_2}\chi_2$$
$$+e\overline{\xi^+}\gamma^\mu\xi^+A_\mu + \frac{g\cos 2\theta_W}{2\cos\theta_W}\overline{\xi^+}\gamma^\mu\xi^+Z_\mu + i\frac{g}{2\cos\theta_W}\overline{\chi_1}\gamma^\mu\chi_2 Z_\mu - \frac{g}{2}\overline{\chi_1}\gamma^\mu\xi^+W_\mu^-$$
$$-i\frac{g}{2}\overline{\chi_2}\gamma^\mu\xi^+W_\mu^- + \text{H.c.} \quad \text{for} \quad \beta \simeq \frac{\pi}{4}\,.$$

$$\Delta M_\chi \;=\; M_{\chi_2} - M_{\chi_1} = \frac{1}{\sqrt{2}}(f - f')v_\Delta = 12.1\,\mathrm{GeV}\left(\frac{f-f'}{2\sqrt{4\pi}}\right)\left(\frac{v_\Delta}{2.2\,\mathrm{GeV}}\right) < 12.1\,\mathrm{GeV}\,.$$

$$\Delta M_\chi \lesssim 550\,\mathrm{keV}\ \text{ for }\ f, f' < \sqrt{4\pi}\,,\ v_\Delta \lesssim 10^{-4}\,\mathrm{GeV}\,.$$

$$\Delta M \;=\; M_{\xi^\pm} - M_{\chi_{1,2}} \;=\frac{g^2\sin^2\theta_W}{16\pi^2}M_\psi f\left(\frac{m_Z}{M_\psi}\right) \simeq \frac{1}{2}\alpha m_Z = 332\,\mathrm{MeV}\,.$$

$$f(r) = \begin{cases} r^4\ln r - r^2 - r(r^2-4)^{\frac{1}{2}}(r^2+2)\ln\frac{r+\sqrt{r^2-4}}{2} & \text{for }\ r \geq 2\,, \\ r^4\ln r - r^2 + r(4-r^2)^{\frac{1}{2}}(r^2+2)\arctan\frac{\sqrt{4-r^2}}{r} & \text{for }\ r \leq 2\,. \end{cases}$$

The lighter Majorana fermion χ_1 can keep stable to leave a relic density in the present universe. Since the charged fermion $\xi^{\pm}$ and the Majorana fermions $\chi_{1,2}$ are highly quasi-degenerate, not only the annihilations of the lightest χ_1 but also the annihilations and co-annihilations involving the heavier $\xi^{\pm}$ and χ_2 should be taken into account to calculate the relic density.

In the case the gauge interactions dominate the annihilations and co-annihilations, ones find the stable χ_1 can serve as the DM particle if its mass has a fixed value,

$$M_{\chi_1} = 1.2\,\mathrm{TeV}\,.$$

This can be achieved by assuming that the Higgs triplet Δ has a mass close to or heavier than the DM mass so that its contributions to the DM annihilations and co-annihilations are highly suppressed. Clearly, this is the case of the minimal DM scenario.

M. Cirelli, N. Fornengo, and A. Strumia, Nucl. Phys. B **753**, 178 (2006).

Due to the small VEV $v_\Delta \leq 2.2\,\mathrm{GeV}$ and then the specific rotation angle $\beta \simeq \pi/4$, the spin-dependent and elastic scattering of the DM particle χ_1 off the nucleon will be far below the experimental sensitivities. As for the spin-independent and elastic scattering, its cross section can be computed at one-loop level,

$$\sigma_{\mathrm{SI}} \simeq 3 \times 10^{-46}\,\mathrm{cm}^2\,.$$

M. Cirelli, N. Fornengo, and A. Strumia, Nucl. Phys. B **753**, 178 (2006).

Furthermore, the DM particle χ_1 and its heavier partner χ_2 now have a spin-independent and inelastic scattering off the nucleon at tree level. When the $\chi_1 - \chi_2$ mass split disappears, the cross section can arrive at

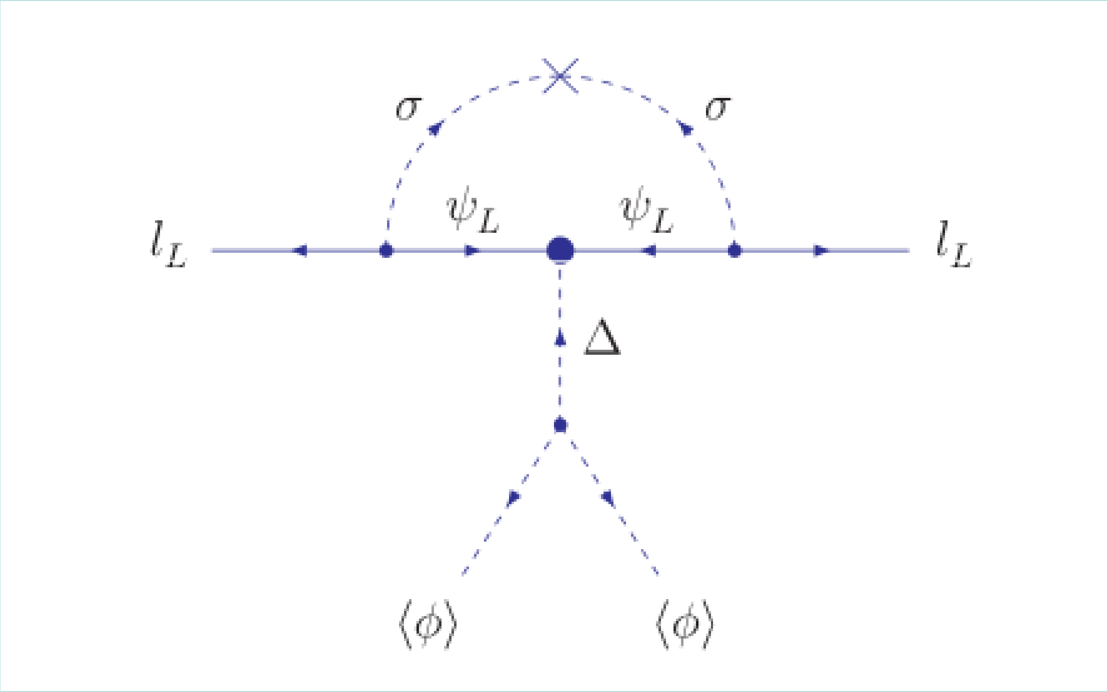
$$\begin{aligned}\sigma_0 &= \frac{m_p^2 G_F^2}{128\pi}\left[\frac{(A-Z)-(1-4\sin^2\theta_W)Z}{A}\right]^2\\ &= 1.16\times 10^{-40}\,\mathrm{cm}^2\left[\frac{(A-Z)-(1-4\sin^2\theta_W)Z}{A}\right]^2\,.\end{aligned}$$

$$M_{\chi_1}\,,\quad \Delta M_\chi\,,\quad \sigma_0\,.$$

D. Tucker-Smith and N. Weiner, Phys. Rev. D **64**, 043502 (2001).

G. Jungman, M. Kamionkowskib, and K. Griestd, Phys. Rept. **267**, 195 (1996).

Radiative type-II seesaw



$$(m_\nu)_{\alpha\beta} = \frac{M_{\chi_1}}{16\pi^2}\sum_i y_{\alpha i} y_{\beta i}\left[\frac{M^2_{\sigma_{iR}}}{M^2_{\sigma_{iR}} - M^2_{\chi_1}}\ln\left(\frac{M^2_{\sigma_{iR}}}{M^2_{\chi_1}}\right) - \frac{M^2_{\sigma_{iI}}}{M^2_{\sigma_{iI}} - M^2_{\chi_1}}\ln\left(\frac{M^2_{\sigma_{iI}}}{M^2_{\chi_1}}\right)\right] - \frac{M_{\chi_2}}{16\pi^2}\sum_i y_{\alpha i} y_{\beta i}\left[\frac{M^2_{\sigma_{iR}}}{M^2_{\sigma_{iR}} - M^2_{\chi_2}}\ln\left(\frac{M^2_{\sigma_{iR}}}{M^2_{\chi_2}}\right) - \frac{M^2_{\sigma_{iI}}}{M^2_{\sigma_{iI}} - M^2_{\chi_2}}\ln\left(\frac{M^2_{\sigma_{iI}}}{M^2_{\chi_2}}\right)\right] .$$

$$L \supset -\frac{1}{2} f_{\rm eff} \bar{l}^c_L i\tau_2 \Delta^\dagger l_L + {\rm H.c.} \quad \text{with}$$

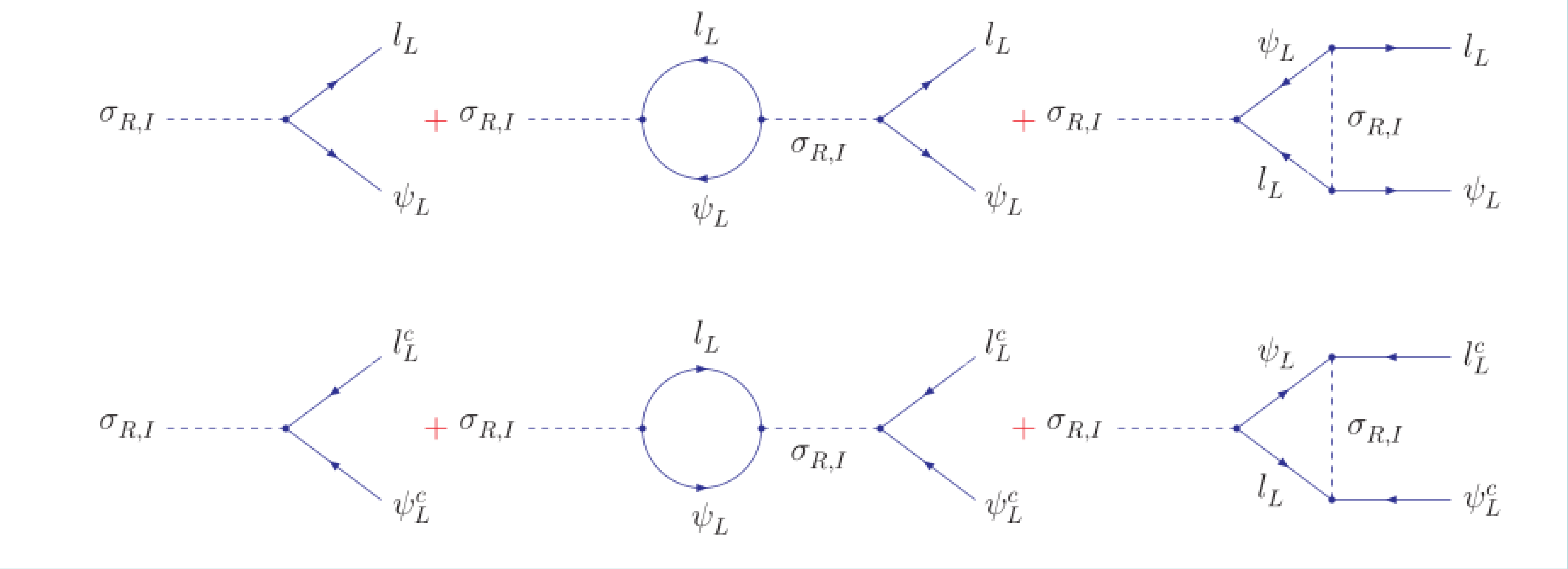
$$(f_{\rm eff})_{\alpha\beta} = \frac{(f - f')}{16\pi^2}\sum_i y_{\alpha i} y_{\beta i} \ln\left(\frac{M^2_{\sigma_{iR}}}{M^2_{\sigma_{iI}}}\right)$$

$$\text{for} \quad M_\Delta < 2\, M_{\chi_{1,2}} \ll M_{\sigma_{iR}} \neq M_{\sigma_{iI}} .$$

A type-II seesaw can be tested at the LHC if the related Higgs triplet has a small VEV $v_\Delta \lesssim 10^{-4}$ GeV.

P. Fileviez Perez, T. Han, G. Huang, T. Li, and K. Wang, Phys. Rev. D **78**, 015018 (2008).

Leptogenesis



$$\begin{aligned}\Gamma_{\sigma_{iR}} &\equiv \sum_{\alpha}[\Gamma(\sigma_{iR} \to l_{L\alpha} + \psi_L) + \Gamma(\sigma_{iR} \to l^c_{L\alpha} + \psi^c_L)] \\ &= \frac{1}{8\pi}(y^\dagger y)_{ii} M_{\sigma_{iR}}\,,\end{aligned}$$

$$\begin{aligned}\varepsilon_{\sigma_{iR}} &\equiv \frac{\sum_\alpha[\Gamma(\sigma_{iR} \to l_{L\alpha} + \psi_L) - \Gamma(\sigma_{iR} \to l^c_{L\alpha} + \psi^c_L)]}{\Gamma_{\sigma_{iR}}} \\ &= \frac{1}{24\pi}\frac{\mathrm{Im}\{[(y^\dagger y)_{ij}]^2\}}{(y^\dagger y)_{ii}}\left\{\left[S\left(\frac{M^2_{\sigma_{jR}}}{M^2_{\sigma_{iR}}}\right) + V\left(\frac{M^2_{\sigma_{jR}}}{M^2_{\sigma_{iR}}}\right)\right]\right. \\ &\quad \left. - \left[S\left(\frac{M^2_{\sigma_{jI}}}{M^2_{\sigma_{iR}}}\right) + V\left(\frac{M^2_{\sigma_{jI}}}{M^2_{\sigma_{iR}}}\right)\right]\right\}.\end{aligned}$$

$$\begin{aligned}S(x) &= \frac{2}{x-1}\,, \\ V(x) &= (1+2x)\left[2 + (1+2x)\ln\left(\frac{x}{1+x}\right)\right].\end{aligned}$$

$$
\begin{aligned}
\Gamma_{\sigma_{iI}} &\equiv \sum_{\alpha}[\Gamma(\sigma_{iI} \to l_{L\alpha} + \psi_L) + \Gamma(\sigma_{iI} \to l^c_{L\alpha} + \psi^c_L)] \\
&= \frac{1}{8\pi}(y^\dagger y)_{ii} M_{\sigma_{iI}} ,
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon_{\sigma_{iI}} &\equiv \frac{\sum_\alpha[\Gamma(\sigma_{iI} \to l_{L\alpha} + \psi_L) - \Gamma(\sigma_{iI} \to l^c_{L\alpha} + \psi^c_L)]}{\Gamma_{\sigma_{iI}}} \\
&= -\frac{1}{24\pi}\sum_{j\neq i}\frac{\mathrm{Im}\{[(y^\dagger y)_{ij}]^2\}}{(y^\dagger y)_{ii}}\left\{\left[S\left(\frac{M^2_{\sigma_{jR}}}{M^2_{\sigma_{iI}}}\right) + V\left(\frac{M^2_{\sigma_{jR}}}{M^2_{\sigma_{iI}}}\right)\right]\right. \\
&\quad \left. - \left[S\left(\frac{M^2_{\sigma_{jI}}}{M^2_{\sigma_{iI}}}\right) + V\left(\frac{M^2_{\sigma_{jI}}}{M^2_{\sigma_{iI}}}\right)\right]\right\} .
\end{aligned}
$$

$$
\begin{aligned}
S(x) &= \frac{2}{x-1} , \\
V(x) &= (1+2x)\left[2 + (1+2x)\ln\left(\frac{x}{1+x}\right)\right] .
\end{aligned}
$$

Thermal leptogenesis

$$M^2_{\sigma_{1I}} \ll M^2_{\sigma_{1R}} \ll M^2_{\sigma_{2I}} \ll M^2_{\sigma_{2R}} \,.$$

$$\varepsilon_{\sigma_{1I}} \simeq \frac{1}{8\pi} \frac{\mathrm{Im}\{[(y^\dagger y)_{12}]^2\}}{(y^\dagger y)_{11}} \frac{M^2_{\sigma_{1I}}}{M^2_{\sigma_{2I}}} \,.$$

$$K = \frac{\Gamma_{\sigma_{1I}}}{2H(T)}\bigg|_{T=M_{\sigma_{1I}}} \,, \qquad H = \left(\frac{8\pi^3 g_*}{90}\right)^{\frac{1}{2}} \frac{T^2}{M_{\rm Pl}} \,.$$

$$\eta_B = \frac{n_B}{s} \simeq -\frac{28}{79} \times \frac{\varepsilon_{\sigma_{1I}}}{g_*}$$

$$\text{for} \quad K \ll 1 \,.$$

$$M_{\sigma_{1I}} = 10^{-1}\, M_{\sigma_{2I}} = 1.5 \times 10^{13}\,\mathrm{GeV} \,,$$
$$M_{\sigma_{1R}} = 10^{-1}\, M_{\sigma_{2R}} = 7.5 \times 10^{13}\,\mathrm{GeV} \,,$$
$$\Delta M = 550\,\mathrm{keV} \,, \quad y = \mathcal{O}(10^{-2}) \,.$$

$$\varepsilon_{\sigma_{1I}} = \mathcal{O}(10^{-7}) \,, \qquad K = \mathcal{O}(0.1) \,, \qquad \eta_B = \mathcal{O}(10^{-10}) \,.$$

Inflationary leptogenesis

The real scalar σ_{1I} can realize an inflation.

R. Kallosh, A. Linde, and A. Westphal, Phys. Rev. D **90**, 023534 (2014).

$$\eta_B = -\frac{28}{79}\varepsilon_{\sigma_{1I}} T_{\rm RH}/M_{\sigma_{1I}}\,.$$

$$\begin{aligned} T_{\rm RH} &\equiv T(t=\Gamma_{\sigma_{1I}}^{-1}) \\ &= \left(\frac{90}{8\pi^3 g_*}\right)^{\frac{1}{4}} \sqrt{\frac{(y^\dagger y)_{11} M_{\rm Pl} M_{\sigma_{1I}}}{16\pi}}\,. \end{aligned}$$

$$\begin{aligned} &M_{\sigma_{1I}} = 10^{-1}\, M_{\sigma_{2I}} = 1.5\times 10^{13}\,{\rm GeV}\,, \\ &M_{\sigma_{1R}} = 10^{-1}\, M_{\sigma_{2R}} = 7.5\times 10^{14}\,{\rm GeV}\,, \\ &\Delta M = 550\,{\rm keV}\,, \quad y = \mathcal{O}(10^{-2})\,. \end{aligned}$$

$$\varepsilon_{\sigma_{1I}} = \mathcal{O}(10^{-9})\,, \qquad T_{\rm RH} = \mathcal{O}(10^{12}\,{\rm GeV})\,, \qquad \eta_B = \mathcal{O}(10^{-10})\,.$$

High-scale Baryogenesis with Testable Neutron-antineutron Oscillation and Dark Matter

- A model for one-loop neutron-antineutron oscillation and dark matter

A model for one-loop neutron-antineutron oscillation and dark matter

$$d_R(3,2,-\tfrac{1}{3})(+\tfrac{1}{3})\,, \quad u_R(3,2,+\tfrac{2}{3})(+\tfrac{1}{3})\,,$$

$$q_L(3,2,+\tfrac{1}{6})(+\tfrac{1}{3}) = \begin{bmatrix} u_L \\ d_L \end{bmatrix}\,,$$

$$\phi(1,2,+\tfrac{1}{2})(0) = \begin{bmatrix} \phi^+ \\ \phi^0 \end{bmatrix}\,.$$

$$\chi_R(1,1,0)(0)\,, \quad \delta(3,1,-\tfrac{1}{3})(-\tfrac{2}{3})\,, \quad \xi(3,1,-\tfrac{1}{3})(-\tfrac{1}{3})\,,$$
$$\sigma_a(1,1,0)(0) \quad (a=1,2)\,.$$

$$(\mathrm{SM}\,,\,\delta) \xrightarrow{Z_2} (\mathrm{SM}\,,\,\delta)\,,\ (\chi_R\,,\,\xi\,,\,\sigma) \xrightarrow{Z_2} -(\chi_R\,,\,\xi\,,\,\sigma)\,.$$

$$\mathcal{L} \supset -\frac{1}{2}M_\sigma^2\sigma^2 - (\mu_\delta^2 + \lambda_{\delta\phi}\phi^\dagger\phi)\delta^\dagger\delta - (\mu_\xi^2 + \lambda_{\xi\phi}\phi^\dagger\phi)\xi^\dagger\xi$$
$$- \left[\frac{1}{2}m_\chi\bar{\chi}_R\chi_R^c + \rho\sigma\delta^\dagger\xi + y\xi^\dagger\bar{d}_R^c\chi_R + f\delta\bar{d}_R^c u_R\right.$$
$$\left. + \frac{1}{2}h\delta\bar{q}_L^c i\tau_2 q_L + \text{H.c.}\right].$$

$$m_\delta^2 = \mu_\delta^2 + \lambda_{\delta\phi}\langle\phi\rangle^2 > 0\,, \quad m_\xi^2 = \mu_\xi^2 + \lambda_{\xi\phi}\langle\phi\rangle^2 > 0\,.$$

$$\chi = \chi_R + \chi_R^c = \chi^c \quad \text{for} \quad m_\chi = m_\chi^*\,.$$

$$\alpha = \arg\left(\frac{\rho_2}{\rho_1}\right) \neq 0\,.$$

$$h = h^T$$

Dark Matter

$$\mathcal{L} \supset \frac{y_i y_j^*}{m_\xi^2} \bar{d}_{Ri} \chi_R^c \bar{\chi}_R^c d_{Rj} = \frac{y_i y_j^*}{8 m_\xi^2} \bar{d}_i \gamma^\mu (1 - \gamma_5) d_j \bar{\chi} \gamma_\mu \gamma_5 \chi \,.$$

$$\langle \sigma v_{\rm rel} \rangle = \frac{\sum_{i,j=d,s,b} |y_i|^2 |y_j|^2}{4\pi} \frac{m_\chi^2}{m_\xi^4} v_{\rm rel}^2 \,.$$

$$m_\chi = 100\,\mathrm{GeV}\,, \quad m_\xi = 1\,\mathrm{TeV}\,, \quad y_d = 1 \gg y_{s,b}$$

$$\Rightarrow \langle \sigma v_{\rm rel} \rangle = 0.1\,\mathrm{pb}\,.$$

$$\mathcal{L} \supset \frac{y_i y_j^*}{m_\xi^2} \bar{d}_{Ri} \chi_R^c \bar{\chi}_R^c d_{Rj} = \frac{y_i y_j^*}{8 m_\xi^2} \bar{d}_i \gamma^\mu (1 - \gamma_5) d_j \bar{\chi} \gamma_\mu \gamma_5 \chi \,.$$

$y_d = 1 \gg y_{s,b}$

$$\sigma_0 = \frac{4|y_d|^4}{\pi} \frac{\mu_A^2}{m_\xi^4} [\Delta d^{(p)} \langle S_p \rangle + \Delta d^{(n)} \langle S_n \rangle]^2 \frac{J+1}{J} \,.$$

$$\mu_A \;=\; m_A m_\xi / (m_A + m_\xi)$$

$\Delta d^{(p)} [\Delta d^{(n)}]$ is the down-quark matrix element in a proton(neutron).

$\langle S_p \rangle (\langle S_n \rangle)$ is the expectation value of the spin content of the proton group in the nucleus.

J is the total nucleus spin.

$$\sigma_N \;=\; \sigma_0 \mu_N^2 / \mu_A^2$$

$$\mu_N = m_N m_\xi / (m_N + m_\xi)$$

$$\Delta d^{(p)} = -0.38,\ \Delta d^{(n)} = 0.77.$$

$$\langle S_p \rangle = 0.010,\ \langle S_n \rangle = 0.329,\ J = 1/2 \text{ for } {}^{129}\text{Xe}.$$

$$\langle S_p \rangle = -0.009,\ \langle S_n \rangle = -0.272,\ J = 3/2 \text{ for } {}^{131}\text{Xe}.$$

$$\sigma_0 = 1.5 \times 10^{-36}\,\text{cm}^2\,, \quad \sigma_N = 8 \times 10^{-41}\,\text{cm}^2 \text{ for } {}^{129}\text{Xe}.$$

$$\sigma_0 = 6.0 \times 10^{-37}\,\text{cm}^2\,, \quad \sigma_N = 3 \times 10^{-41}\,\text{cm}^2 \text{ for } {}^{131}\text{Xe}.$$

Neutron-antineutron Oscillation

$$\mathcal{L} \supset -\frac{\kappa}{\Lambda_R^5}\bar{d}_R^c d_R \bar{u}_R^c d_R \bar{u}_R^c d_R - \frac{\kappa}{\Lambda_L^5}\bar{d}_R^c d_R \bar{u}_L^c d_L \bar{u}_L^c d_L$$

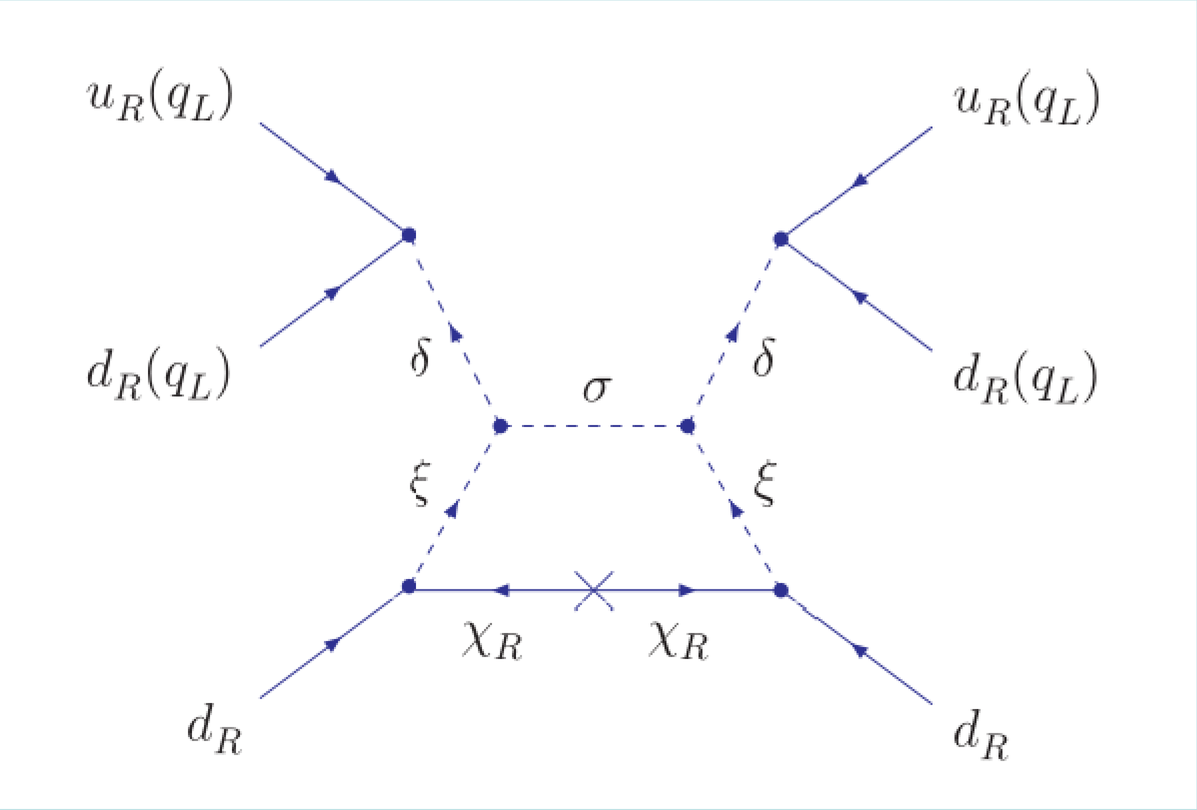
$$+\text{H.c.} \quad \text{with}$$

$$\frac{\kappa_{ijklmn}}{\Lambda_R^5} = \frac{y_i y_j f_{kl} f_{mn}}{4\pi^2} \frac{\rho_a^2 m_\chi \left[1 - \frac{m_\chi^2}{m_\xi^2 - m_\chi^2} \ln\left(\frac{m_\xi^2}{m_\chi^2}\right)\right]}{M_{\sigma_a}^2 m_\delta^4 (m_\xi^2 - m_\chi^2)}$$

$$\simeq \frac{y_i y_j f_{kl} f_{mn}}{4\pi^2} \frac{\rho_a^2 m_\chi}{M_{\sigma_a}^2 m_\xi^2 m_\delta^4} \quad \text{for} \quad m_\xi^2 \gg m_\chi^2 \,,$$

$$\frac{\kappa_{ijklmn}}{\Lambda_L^5} = \frac{y_i y_j h_{kl} h_{mn}}{4\pi^2} \frac{\rho_a^2 m_\chi \left[1 - \frac{m_\chi^2}{m_\xi^2 - m_\chi^2} \ln\left(\frac{m_\xi^2}{m_\chi^2}\right)\right]}{M_{\sigma_a}^2 m_\delta^4 (m_\xi^2 - m_\chi^2)}$$

$$\simeq \frac{y_i y_j h_{kl} h_{mn}}{4\pi^2} \frac{\rho_a^2 m_\chi}{M_{\sigma_a}^2 m_\xi^2 m_\delta^4} \quad \text{for} \quad m_\xi^2 \gg m_\chi^2 \,.$$


$u_R(q_L)$
$d_R(q_L)$
δ
σ
ξ
χ_R
χ_R
d_R
$u_R(q_L)$
$d_R(q_L)$
δ
ξ
d_R

$$\delta m_{n-\bar{n}} \sim \Lambda^6_{\rm QCD} G_{n-\bar{n}}$$

$$= 3.4 \times 10^{-5}\,{\rm GeV} \left(\frac{\Lambda_{\rm QCD}}{180\,{\rm MeV}}\right)^6 \left(\frac{G_{n-\bar{n}}}{{\rm GeV}^{-5}}\right) .$$

$$\tau_{n-\bar{n}} = \frac{1}{\delta m_{n-\bar{n}}} \approx 2 \times 10^8\,{\rm sec} \left(\frac{10^{-28}\,{\rm GeV}^{-5}}{G_{n-\bar{n}}}\right) .$$

$G_{n-\bar{n}} = G_R + G_L$ with

$$G_R = \frac{\kappa_{ddudud}}{\Lambda_R^5} = \frac{y_d^2 f_{ud}^2}{4\pi^2} \frac{m_\chi}{m_\xi^2 m_\delta^4} \sum_a \frac{\rho_a^2}{M_{\sigma_a}^2}$$

$$= 10^{-28}\,{\rm GeV}^{-5} \times \left(\frac{y_d}{1}\right)^2 \left(\frac{f_{ud}}{4.5 \times 10^{-3}}\right)^2$$

$$\times \left(\frac{m_\chi}{100\,{\rm GeV}}\right) \left(\frac{1\,{\rm TeV}}{m_\xi}\right)^2 \left(\frac{1\,{\rm TeV}}{m_\delta}\right)^4$$

$$\times \sum_a \left(\frac{\rho_a/M_{\sigma_a}}{10^{-3}}\right)^2 ,$$

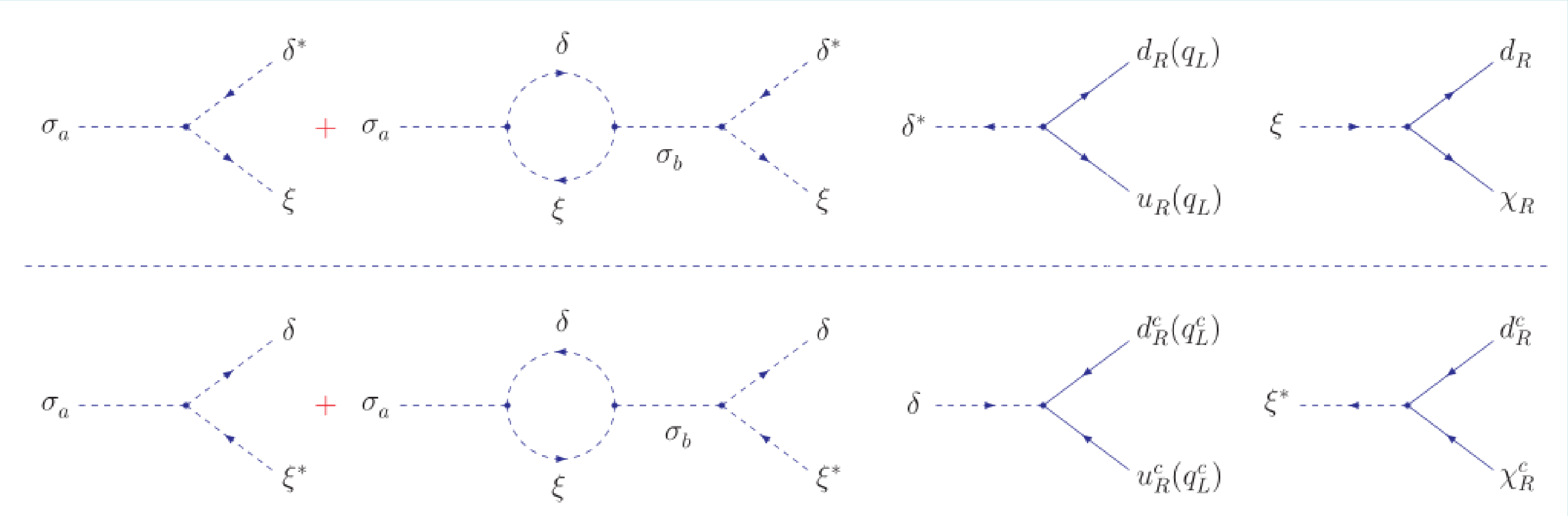
$$G_L = \frac{\kappa_{ddudud}}{\Lambda_L^5} = \frac{y_d^2 h_{ud}^2}{4\pi^2} \frac{m_\chi}{m_\xi^2 m_\delta^4} \sum_a \frac{\rho_a^2}{M_{\sigma_a}^2}$$

$$= 10^{-28}\,{\rm GeV}^{-5} \times \left(\frac{y_d}{1}\right)^2 \left(\frac{h_{ud}}{4.5 \times 10^{-3}}\right)^2$$

$$\times \left(\frac{m_\chi}{100\,{\rm GeV}}\right) \left(\frac{1\,{\rm TeV}}{m_\xi}\right)^2 \left(\frac{1\,{\rm TeV}}{m_\delta}\right)^4$$

$$\times \sum_a \left(\frac{\rho_a/M_{\sigma_a}}{10^{-3}}\right)^2 .$$

Baryogenesis



$$\Gamma_{\sigma_a} = \Gamma(\sigma_a \to \delta^* + \xi) + \Gamma(\sigma_a \to \delta + \xi^*) = \frac{3}{8\pi} \frac{|\rho_a|^2}{M_{\sigma_a}} .$$

$$\varepsilon_{\sigma_a} = \frac{\Gamma(\sigma_a \to \delta^* + \xi) - \Gamma(\sigma_a \to \delta + \xi^*)}{\Gamma_{\sigma_a}} = \frac{3}{8\pi} \frac{\mathrm{Im}(\rho_a^2 \rho_b^{*2})}{|\rho_a|^2} \frac{1}{M_{\sigma_b}^2 - M_{\sigma_a}^2} .$$

In the Majorana neutrino case, we assume the baryon asymmetry will be produced after the lepton-number-violating interactions for generating the neutrino mass matrix m_ν decouple at a very high temperature, M. Fukugita, T. Yanagida, Phys. Rev. D **42**, 1285 (1990).

$$T = 10^{12}\,\mathrm{GeV}\left[\frac{0.04\,\mathrm{eV}^2}{\mathrm{Tr}(m_\nu^\dagger m_\nu)}\right] .$$

For the Dirac neutrinos, their mass generation conserves the lepton number so that it will not affect the produced baryon asymmetry at all.

Thermal baryogenesis

$$K = \frac{\Gamma_{\sigma_1}}{2H(T)}\Big|_{T=M_{\sigma_1}} . \qquad H = \left(\frac{8\pi^3 g_*}{90}\right)^{\frac{1}{2}} \frac{T^2}{M_{\rm Pl}} .$$

$$\eta_B = \frac{n_B}{s} \simeq \frac{28}{79} \times \frac{\varepsilon_{\sigma_1}}{g_*} \quad \text{for} \quad K \ll 1 .$$

$$M_{\sigma_1} = 10^3\,|\rho_1| = 10^{12}\,\text{GeV} ,$$
$$M_{\sigma_2} = 10^3\,|\rho_2| = 10^{13}\,\text{GeV} ,$$

$$\Rightarrow$$

$$K = 0.04 , \quad \varepsilon_{\sigma_1} = 3.3 \times 10^{-8} \left(\frac{\sin 2\alpha}{0.28}\right) .$$

$$\Downarrow$$

$$\eta_B = 10^{-10} \left(\frac{\sin 2\alpha}{0.28}\right) .$$

Inflationary baryogenesis

The real scalar σ_1 can realize a inflation.

R. Kallosh, A. Linde, and A. Westphal, Phys. Rev. D **90**, 023534 (2014).

$$\eta_B = \frac{28}{79}\varepsilon_{\sigma_1} T_{\rm RH}/M_{\sigma_1} \,.$$

$$T_{\rm RH} \equiv T(t = \Gamma_{\sigma_1}^{-1}) = \left(\frac{90}{8\pi^3 g_*}\right)^{\frac{1}{4}} \sqrt{\frac{3M_{\rm Pl}|\rho_1|^2}{16\pi M_{\sigma_1}}} \,.$$

$$M_{\sigma_1} = 10^3\,|\rho_1| = 1.5\times 10^{13}\,{\rm GeV}\,,$$
$$M_{\sigma_2} = 10^3\,|\rho_2| = 1.5\times 10^{14}\,{\rm GeV}\,,$$

$$\Longrightarrow$$

$$T_{\rm RH} = 7.7\times 10^{11}\,{\rm GeV}\,,$$
$$\varepsilon_{\sigma_1} = 5.6\times 10^{-9}\left(\frac{\sin 2\alpha}{0.047}\right)\,,$$
$$\eta_B = 10^{-10}\left(\frac{\sin 2\alpha}{0.047}\right)\,.$$

Summary

- A successful leptogenesis can be realized at a very high scale even if the neutrino mass generation is expected to verify at colliders.
- An observable neutron-antineutron oscillation can allow a high-scale baryogenesis.
- In these scenarios, the dark matter particle plays an essential role.
- Such high-scale baryogenesis/leptogenesis can come from the inflaton decay.

Thank you very much!