ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Fermion number violating effects in low scale leptogenesis

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Based on :

SE and M. Shaposhnikov, PLB 771 (2017) 288-296

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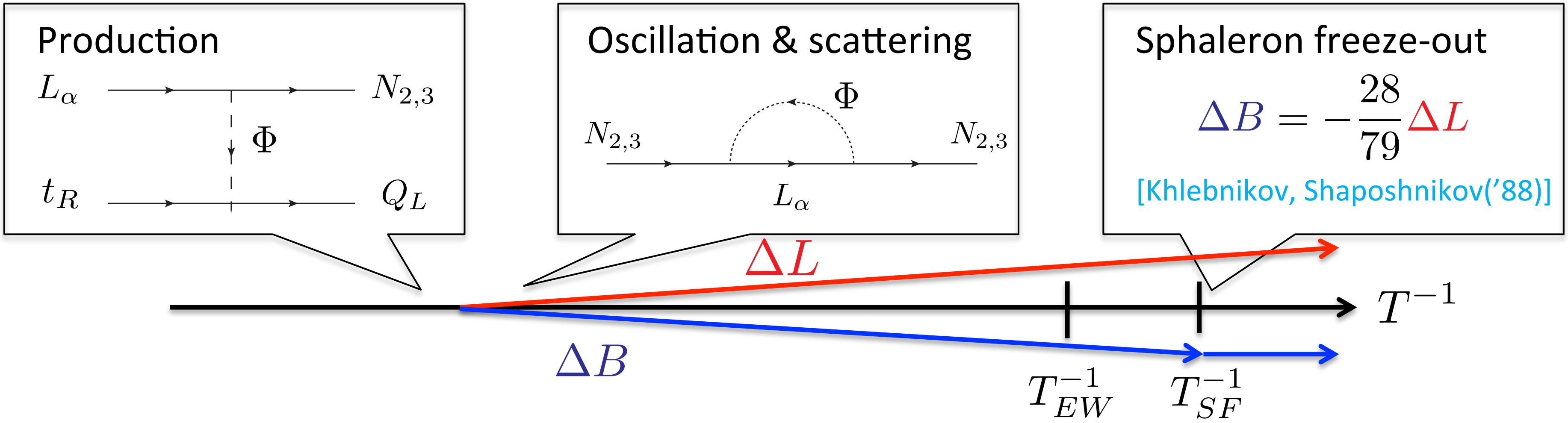
Baryogenesis via neutrino oscillation

[Akhemedov, Rubakov, Smirnov('98)] [Asaka, Shaposhnikov('05)]

Heavy Neutral Leptons (HNLs) : Right-handed neutrinos with $M < T_{\rm EW}$

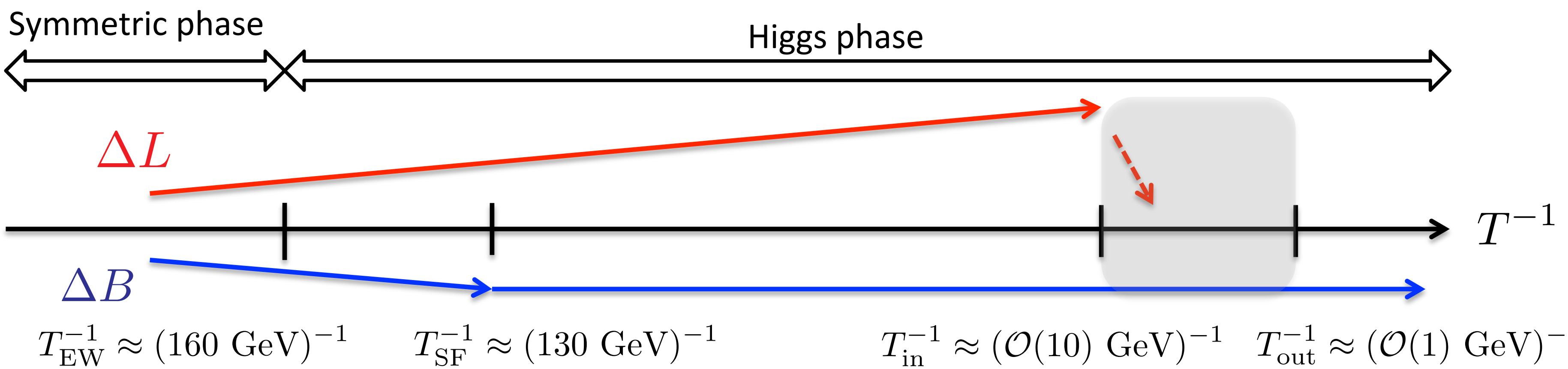
From $M \ll T$

- Source of lepton asymmetry production is HNL oscillation instead of the decays.
- Effective lepton number conservation $\to \Delta L \approx -\Delta N$



Kinetic equations for the Higgs phase

We derived the exact kinetic equations for $T < T_{\rm EW}$ (Higgs phase).



[D'Onofrio, Rummukainen ('16)] [D'Onofrio, Rummukainen, Tranberg ('14)] [Shaposhnikov ('08)]

- Fermion number violating effects to the baryon asymmetry of the universe (BAU)

- Large lepton asymmetries at $T < T_{\rm out}$ required from the resonant production in the νMSM [Asaka, Shaposhnikov ('05)] [Asaka, Blanchet, Shaposhnikov ('05)]

HNL oscillations and decays at $T < T_{\rm out}$ [Canetti, Drewes, Frossard, Shaposhnikov ('13)]

We found another possibility!

Kinetic equations for the Higgs phase

The density matrix can treat coherent and incoherent processes simultaneously.

$$\rho_N = \begin{pmatrix} \mathrm{Tr}[a_+^\dagger(k)a_+(k)\rho] & \mathrm{Tr}[a_+^\dagger(k)b_-(k)\rho] \\ \mathrm{Tr}[b_-^\dagger(k)a_+(k)\rho] & \mathrm{Tr}[b_-^\dagger(k)b_-(k)\rho] \end{pmatrix} - \rho_N^{eq}\mathbf{1},$$

ρ : density matrix operator of complete system

HNL field $\Psi = N_2 + N_3^c$

$$\Psi = \int \frac{d^3k}{(2\pi)^3}\frac{1}{\sqrt{2k_0}}\sum_\sigma \left[a_\sigma(k)u_\sigma(k)e^{-ik\cdot x} + b_\sigma^\dagger(k)v_\sigma(k)e^{ik\cdot x}\right],$$

Fermion numbers of creation operators.

plus, particles	minus, anti-particles
$a_+^\dagger(k),\ b_-^\dagger(k)$	$a_-^\dagger(k),\ b_+^\dagger(k)$

Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \overline{\Psi}i\partial_\mu\gamma^\mu\Psi - M\overline{\Psi}\Psi + \mathcal{L}_{int},$$

$$\mathcal{L}_{int} = -\frac{\Delta M}{2}(\overline{\Psi}\Psi^c + \overline{\Psi^c}\Psi) - (h_{\alpha 2}\langle\Phi\rangle\overline{\nu_{L\alpha}}\Psi + h_{\alpha 3}\langle\Phi\rangle\overline{\nu_{L\alpha}}\Psi^c + h.c.),$$

Kinetic equations of density matrix

$$i\dot{q}_i^0 = \mathrm{Tr}\left([\mathbf{H}, Q_i^0]\rho\right),$$

Number density : $q_i^0 = \mathrm{Tr}[Q_i^0\rho]$

Number density operator : Q_i^0

Total Hamiltonian : $\mathbf{H}$

We derived kinetic equations in the second order in yukawa couplings and first order in ΔM .

Kinetic equations for the Higgs phase

For leptonic numbers $\Delta_\alpha = \Delta L_\alpha - \Delta B/3$

$$i\frac{d\Delta_\alpha}{dt} = -i\left[\frac{12}{T^3}\int\frac{d^3k}{(2\pi)^3}\Gamma_{\nu_\alpha} f_f(1-f_f)\right]\omega_{\alpha\beta}\Delta_\beta + i\int\frac{d^3k}{(2\pi)^3}\left[\mathrm{Tr}[\tilde{\Gamma}_{\nu_\alpha}\rho_{\bar{N}}] - \mathrm{Tr}[\tilde{\Gamma}^*_{\nu_\alpha}\rho_N]\right],$$

For the matrix density of HNLs

$$i\frac{d\rho_N}{dt} = [H_N, \rho_N] - \frac{i}{2}\{\Gamma_N, \rho_N\} - \frac{i}{2}\sum_\alpha \tilde{\Gamma}^\alpha_N \omega_{\alpha\beta}\left[\frac{12\Delta_\beta}{T^3} f_f(1-f_f)\right],$$

For the matrix density of anti-HNLs

$$i\frac{d\rho_{\bar{N}}}{dt} = [H^*_N, \rho_{\bar{N}}] - \frac{i}{2}\{\Gamma^*_N, \rho_{\bar{N}}\} + \frac{i}{2}\sum_\alpha (\tilde{\Gamma}^\alpha_N)^* \omega_{\alpha\beta}\left[\frac{12\Delta_\beta}{T^3} f_f(1-f_f)\right],$$

$\omega_{\alpha\beta}$: susceptibility matrix describing the distribution of asymmetries in plasma

- The structure of kinetic equations is exactly the same as those in previous works
- **All the terms are expressed explicitly through parameters of the theory**

Kinetic equations for the Higgs phase

Effective Hamiltonian

$$H_N = H_0 + H_I,$$

$$H_0 = -\frac{\Delta M M}{E_N}\sigma_1$$

$$H_I = h_+ \sum_\alpha Y^N_{+,\alpha} + h_- \sum_\alpha Y^N_{-,\alpha},$$

Production rates

$$\Gamma_N = \Gamma_+ + \Gamma_-,$$

$$\Gamma_+ = \gamma_+ \sum_\alpha Y^N_{+,\alpha},$$

$$\Gamma_- = \gamma_- \sum_\alpha Y^N_{-,\alpha},$$

$$\tilde{\Gamma}^\alpha_N = -\gamma_+ Y^N_{+,\alpha} + \gamma_- Y^N_{-,\alpha},$$

$$\Gamma_{\nu_\alpha} = (\gamma_+ + \gamma_-) \sum_I h_{\alpha I} h^*_{\alpha I},$$

$$\tilde{\Gamma}_{\nu_\alpha} = -\gamma^\nu_{+,\alpha} Y^\nu_{+,\alpha} + \gamma^\nu_{-,\alpha} Y^\nu_{-,\alpha}.$$

Coefficients

$$h_+ = \frac{2\langle\Phi\rangle^2 E_\nu (E_N + k)(E_N + E_\nu)}{k E_N (4(E_N + E_\nu)^2 + \gamma_\nu^2)},$$

$$h_- = \frac{2\langle\Phi\rangle^2 E_\nu (E_N - k)(E_N - E_\nu)}{k E_N (4(E_N - E_\nu)^2 + \gamma_\nu^2)},$$

$$\gamma_+ = \frac{2\langle\Phi\rangle^2 E_\nu (E_N + k)\gamma_\nu}{k E_N (4(E_N + E_\nu)^2 + \gamma_\nu^2)},$$

$$\gamma_- = \frac{2\langle\Phi\rangle^2 E_\nu (E_N - k)\gamma_\nu}{k E_N (4(E_N - E_\nu)^2 + \gamma_\nu^2)},$$

$$E_N = \sqrt{k^2 + M^2} \qquad E_\nu = k - b_L$$

Matrices of yukawa couplings

$$Y^N_{+,\alpha} = \begin{pmatrix} h_{\alpha 3} h^*_{\alpha 3} & -h_{\alpha 3} h^*_{\alpha 2} \\ -h_{\alpha 2} h^*_{\alpha 3} & h_{\alpha 2} h^*_{\alpha 2} \end{pmatrix},$$

$$Y^N_{-,\alpha} = \begin{pmatrix} h_{\alpha 2} h^*_{\alpha 2} & -h_{\alpha 3} h^*_{\alpha 2} \\ -h_{\alpha 2} h^*_{\alpha 3} & h_{\alpha 3} h^*_{\alpha 3} \end{pmatrix},$$

$$Y^\nu_{+,\alpha} = \begin{pmatrix} h_{\alpha 3} h^*_{\alpha 3} & -h_{\alpha 2} h^*_{\alpha 3} \\ -h_{\alpha 3} h^*_{\alpha 2} & h_{\alpha 2} h^*_{\alpha 2} \end{pmatrix},$$

$$Y^\nu_{-,\alpha} = \begin{pmatrix} h_{\alpha 2} h^*_{\alpha 2} & -h_{\alpha 2} h^*_{\alpha 3} \\ -h_{\alpha 3} h^*_{\alpha 2} & h_{\alpha 3} h^*_{\alpha 3} \end{pmatrix},$$

Fermion number violating effects

Coefficients

$$h_+ = \frac{2\langle\Phi\rangle^2 E_\nu (E_N + k)(E_N + E_\nu)}{k E_N (4(E_N + E_\nu)^2 + \gamma_\nu^2)},$$

$$h_- = \frac{2\langle\Phi\rangle^2 E_\nu (E_N - k)(E_N - E_\nu)}{k E_N (4(E_N - E_\nu)^2 + \gamma_\nu^2)},$$

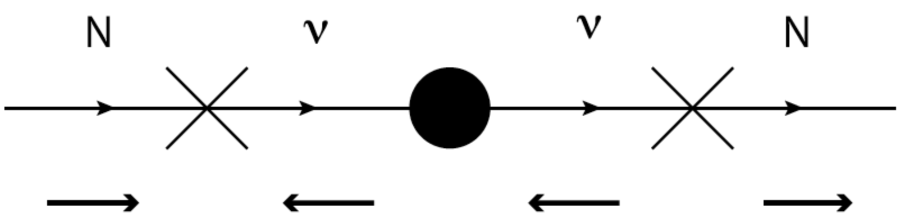
$$\gamma_+ = \frac{2\langle\Phi\rangle^2 E_\nu (E_N + k)\gamma_\nu}{k E_N (4(E_N + E_\nu)^2 + \gamma_\nu^2)},$$

$$\gamma_- = \frac{2\langle\Phi\rangle^2 E_\nu (E_N - k)\gamma_\nu}{k E_N (4(E_N - E_\nu)^2 + \gamma_\nu^2)},$$

"+" processes

$$h_{\alpha 2}\, a_+(k)\, b_\nu(-k)\, e^{-i(E_N+E_\nu)t},$$

$$h_{\alpha 2}^*\, b_\nu^\dagger(-k)\, a_+^\dagger(k)\, e^{i(E_N+E_\nu)t},$$

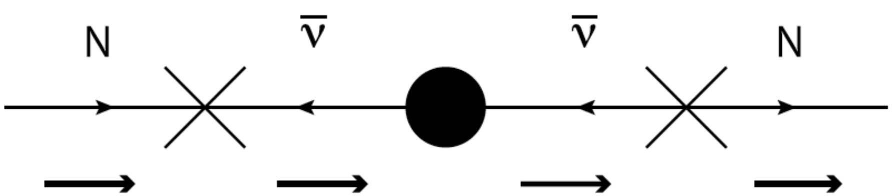


(a) Fermion number conserving process

"-" processes

$$h_{\alpha 3}^*\, a_+(k)\, b_\nu(k)^\dagger\, e^{-i(E_N-E_\nu)t},$$

$$h_{\alpha 3}\, b_\nu(k)\, a_+^\dagger(k)\, e^{i(E_N-E_\nu)t}.$$



(b) Fermion number violating process

Fermion number violating effects are taken into account automatically.

Improved kinetic equations

To make more realistically the coefficients are modified.

Higgs phase → Symmetric phase

$$h_+ = \mathcal{K}(m_h)\frac{T^2}{8k} + \frac{2\langle\Phi\rangle^2 E_\nu (E_N + k)(E_N + E_\nu)}{kE_N(4(E_N+E_\nu)^2 + \gamma_\nu^2)}, \longrightarrow h_+ = \frac{T^2}{8k},$$

$$\gamma_+ = \gamma_+^{\text{direct}} + \frac{2\langle\Phi\rangle^2 E_\nu (E_N + k)\gamma_\nu}{kE_N(4(E_N+E_\nu)^2 + \gamma_\nu^2)}, \longrightarrow \gamma_+ = \frac{1}{E_N}\mathrm{Im}\,\Pi_R,$$

$$\gamma_+^{\text{direct}} = \mathcal{K}(m_h)\frac{1}{E_N}\mathrm{Im}\,\Pi_R + \gamma_{ph},$$

$$\mathcal{K}(m_h) = \frac{3}{\pi^2 T^3}\int_0^\infty dp\, p^2 f_b(E_h)(1 + f_b(E_h)),$$

$$\gamma_{ph} = \frac{1}{E_N}\frac{m_h^2 T}{32\pi k}\ln\left\{\frac{1+e^{-\frac{m_h^2}{4kT}}}{1-e^{-\frac{1}{T}(k+\frac{m_h^2}{4k})}}\right\},$$

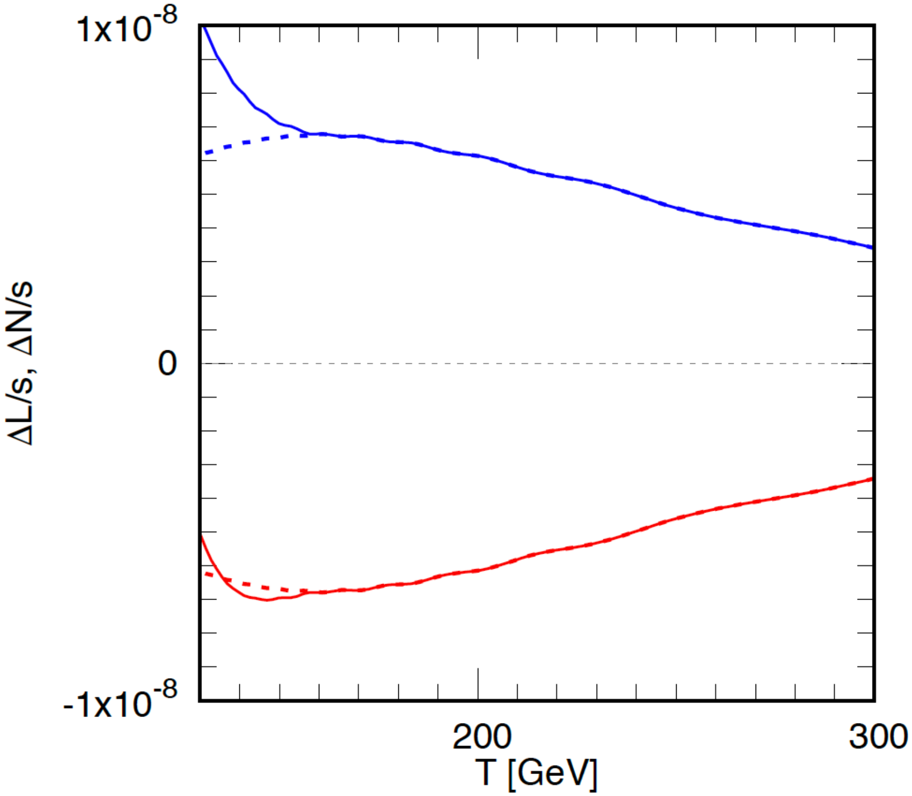
[Ghiglieri, Laine ('16)]

$$h_- = \frac{2\langle\Phi\rangle^2 E_\nu (E_N - k)(E_N - E_\nu)}{kE_N(4(E_N-E_\nu)^2 + \gamma_\nu^2)}, \longrightarrow h_- = 0,$$

$$\gamma_- = \frac{2\langle\Phi\rangle^2 E_\nu (E_N - k)\gamma_\nu}{kE_N(4(E_N-E_\nu)^2 + \gamma_\nu^2)}, \longrightarrow \gamma_- = 0,$$

Fermion number violation on baryogenesis

Comparison between lepton asymmetries generated by the improved kinetic equations (solid line) and those only with expressions in symmetric phase (dotted line).



NH, $M = 10$ GeV, $\Delta M = 10^{-10}$ GeV, $X_\omega = 1$

- The total lepton asymmetry in the whole system violates.
- The contribution in the Higgs phase gives a correction to the baryon asymmetry abundance.

Conserved quantum number

We can address approximate conserved quantum numbers as combinations of asymmetries for HNLs and active flavors,

$$L_\pm = \Delta_N \mp \sum_\alpha \Delta_\alpha \,, \quad \text{where} \quad \Delta_N = \left[\int \frac{d^3k}{(2\pi)^3} \mathrm{Tr}(\rho_N - \rho_{\bar{N}}) \right].$$

[Shaposhnikov ('08)]

$$\begin{aligned}\frac{d}{dt}L_- = -2 \int \frac{d^3k}{(2\pi)^3} \gamma_- \sum_\alpha \Big[& h_{\alpha 2} h^*_{\alpha 2} (\rho_{N,11} - \rho_{\bar{N},11}) \\ & + h_{\alpha 3} h^*_{\alpha 3} (\rho_{N,22} - \rho_{\bar{N},22}) \\ & - 2\mathrm{Re}(h_{\alpha 2} h^*_{\alpha 3})(\mathrm{Re}\,\rho_{N,12} - \mathrm{Re}\,\rho_{\bar{N},12}) \\ & + 2\mathrm{Im}(h_{\alpha 2} h^*_{\alpha 3})(\mathrm{Im}\,\rho_{N,12} + \mathrm{Im}\,\rho_{\bar{N},12}) \\ & + (h_{\alpha 2} h^*_{\alpha 2} + h_{\alpha 3} h^*_{\alpha 3})\, \omega_{\alpha\beta} \left[\frac{12\Delta_\beta}{T^3} f_f (1 - f_f) \right] \Big],\end{aligned}$$

$$\begin{aligned}\frac{d}{dt}L_+ = -2 \int \frac{d^3k}{(2\pi)^3} \gamma_+ \sum_\alpha \Big[& h_{\alpha 2} h^*_{\alpha 2} (\rho_{N,11} - \rho_{\bar{N},11}) \\ & + h_{\alpha 3} h^*_{\alpha 3} (\rho_{N,22} - \rho_{\bar{N},22}) \\ & - 2\mathrm{Re}(h_{\alpha 2} h^*_{\alpha 3})(\mathrm{Re}\,\rho_{N,12} - \mathrm{Re}\,\rho_{\bar{N},12}) \\ & + 2\mathrm{Im}(h_{\alpha 2} h^*_{\alpha 3})(\mathrm{Im}\,\rho_{N,12} + \mathrm{Im}\,\rho_{\bar{N},12}) \\ & - (h_{\alpha 2} h^*_{\alpha 2} + h_{\alpha 3} h^*_{\alpha 3})\, \omega_{\alpha\beta} \left[\frac{12\Delta_\beta}{T^3} f_f (1 - f_f) \right] \Big].\end{aligned}$$

If Γ_+ (Γ_-) doesn't come into thermal equilibrium, the system has an effectively conserved L_+ (L_-) .

In such a case generated asymmetries can potentially survive from the wash-out up to smaller temperatures even if HNLs are equilibrated.

Eigen-values of Γ_+ (solid lines) and Γ_-(dashed lines) divided by H

The interesting parameter range for the large lepton asymmetry production at smaller temperatures is $M \lesssim 2\ \mathrm{GeV}$ and $X_\omega \sim 1$.

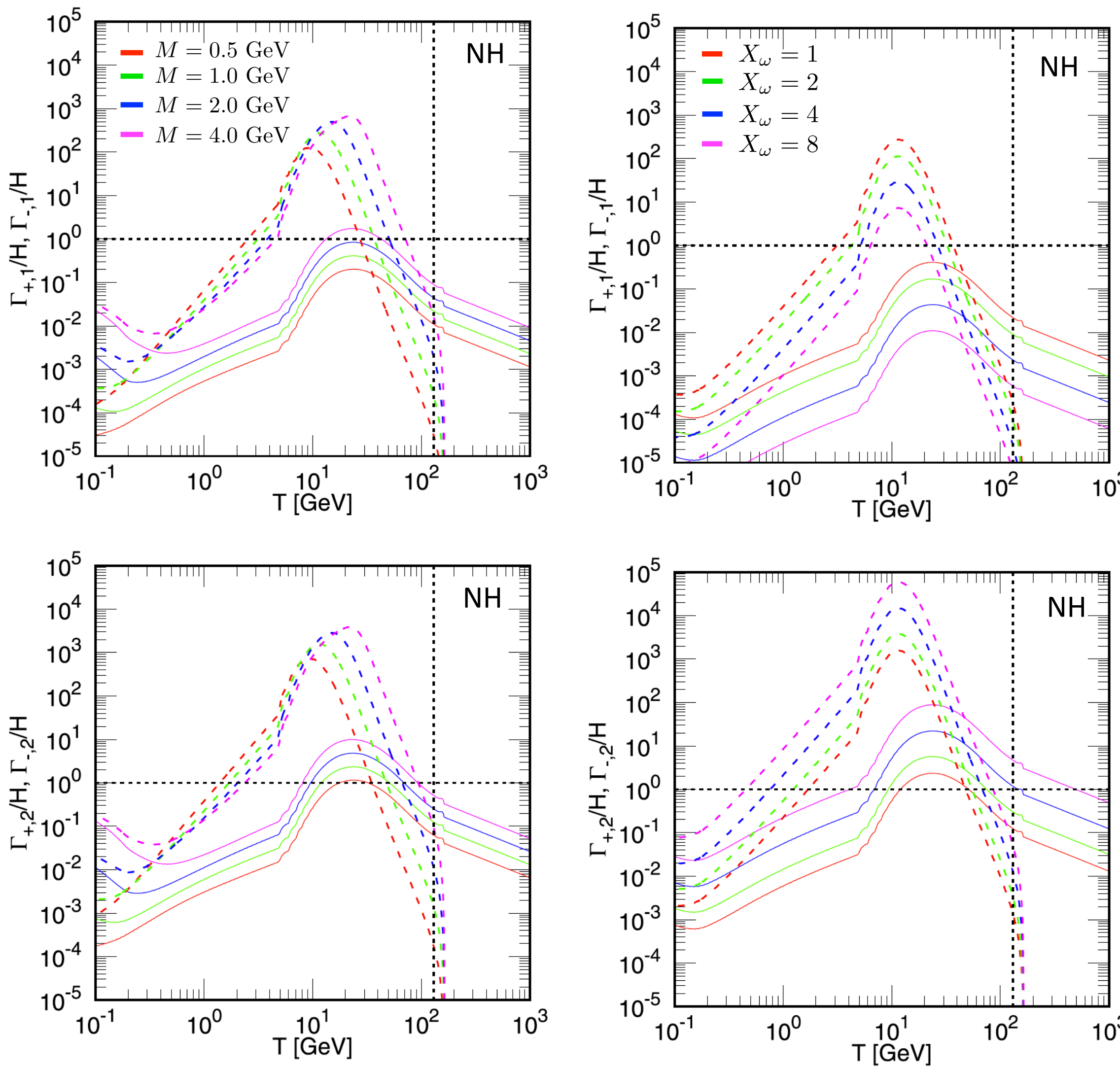
- Large asymmetry in L_+
- Protection from wash-out

Under an equilibrium which is led from Γ_- but has an effective L_+ conservation,

$$\frac{\Delta_N}{\sum_\alpha \Delta_\alpha} \approx -\frac{22}{69}\,.$$

For several M ($X_\omega = 1$)

For several X_ω ($M = 1.0\ \mathrm{GeV}$)



Summary

We improved the kinetic equations for baryogenesis via neutrino oscillations by deriving those in the Higgs phase with fermion number violating effects.

We found HNLs with small mixing and relatively small mass can potentially generate large lepton asymmetries for small temperatures required from the resonant production of sterile neutrino dark matter. It is a consequence of the protection of asymmetries from wash-out due to a conservation of lepton number.
The parameter space of HNLs suggested by this mechanism can be probed at SHiP or SHiP-like experiments with the highest possible sensitivity.

For both baryogenesis and leptogenesis complete parameter scanning will be performed in a future work.

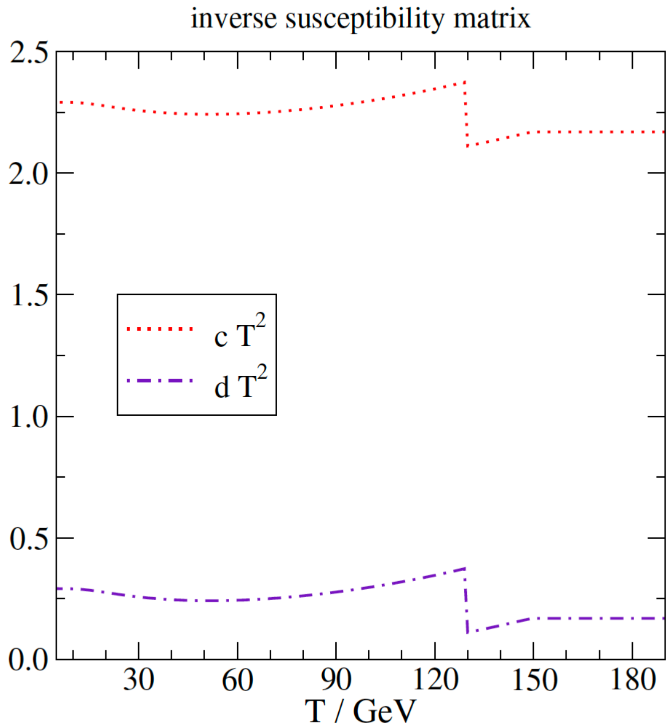
backup

Temperature−depending parameters

Susceptibility matrix

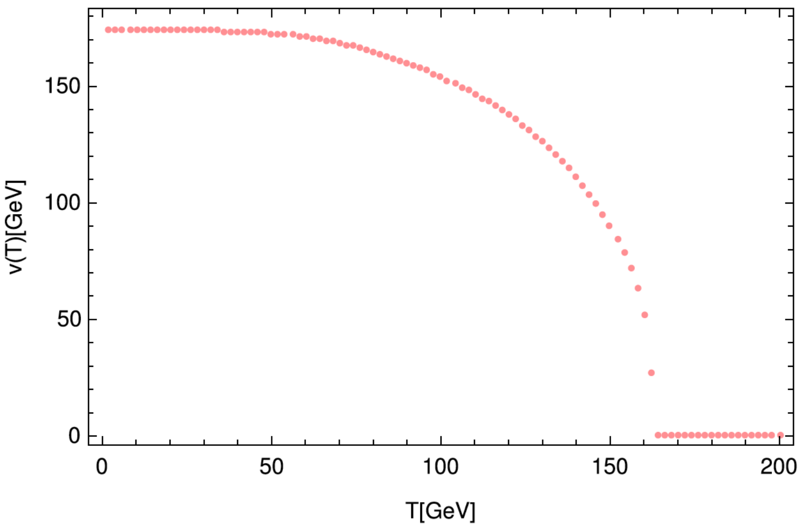
$$\omega_{\alpha\beta} = \frac{1}{6T^2}\Xi^{-1}_{\alpha\beta}$$

$$\Xi^{-1} = \begin{pmatrix} c & d & d \\ d & c & d \\ d & d & c \end{pmatrix}$$



[Ghiglieri, Laine ('16)]

Higgs vacuum expectation value



[Drewes, SE ('16)]

Yukawa coupling constants from seesaw

From the seesaw mass matrix $M_\nu = -\langle\Phi\rangle^2 F\, M_M^{-1}\, F^T$, the yukawa coupling constants in mass basis are

$$F = (i/\langle\Phi\rangle) U\, D_\nu^{\frac{1}{2}}\, \Omega\, D_N^{\frac{1}{2}}$$ (3x2 matrix) [Casas, Ibarra ('01)]

- $D_\nu^{\frac{1}{2}} = \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3})$
- $D_N^{\frac{1}{2}} = \mathrm{diag}(\sqrt{M_1}, \sqrt{M_2}) = \mathrm{diag}(\sqrt{M_N - \Delta M}, \sqrt{M_N + \Delta M})$
- $$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\eta} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$
- $$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\xi\sin\omega & \xi\cos\omega \end{pmatrix}$$ (*e.g.* NH)

ω :complex parameter $\xi = \pm 1$

For large $\mathrm{Im}\,\omega$

$$F \propto \exp(\mathrm{Im}\,\omega) \equiv X_\omega$$

For small $\mathrm{Im}\,\omega$

$$F \propto \exp(-\mathrm{Im}\,\omega) \equiv X_\omega^{-1}$$

ν osc. is guaranteed as long as this parameterization is relevant.