Baryogenesis and late-time lepton asymmetry via right-handed neutrino oscillations

Shintaro Eijima (KEK)

Based on: S.E. and M. Shaposhnikov, PLB 771 (2017) 288-296

S.E., M. Shaposhnikov and I. Timiryasov, JHEP 1907 (2019) 077

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Introduction

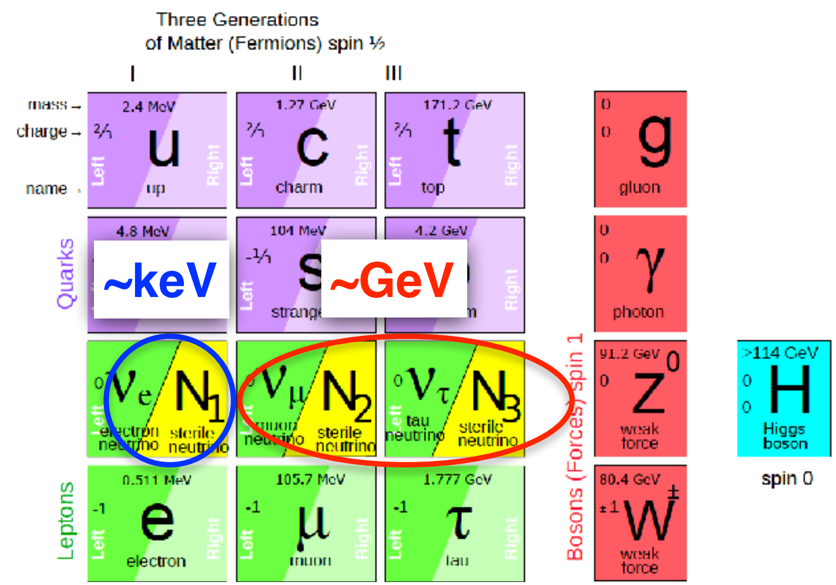
Observed phenomena beyond the SM;

- Neutrino oscillations
- Baryon Asymmetry of the Universe (BAU)
- Dark Matter (DM)

Seesaw mechanism
Leptogenesis
Sterile neutrino

νMSM (neutrino Minimal Standard Model) [Asaka, Shaposhnikov ('05)] [Asaka, Blanchet, Shaposhnikov ('05)]

SM + three right-handed neutrinos with masses below electroweak scale



$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{\nu}_{R_I}\gamma^\mu\partial_\mu\nu_{R_I} - F_{\alpha I}\bar{L}_\alpha\tilde{\Phi}\nu_{R_I} - \frac{M_{IJ}}{2}\bar{\nu}^c_{R_I}\nu_{R_J} + \text{h.c.}$$

Motivation

1. Parameter space for Baryogenesis

GeV-scale ν_R are testable in ground experiments!

Which parameter space is suggested from the successful Baryogenesis?

$$n_B \equiv \frac{n_b - n_{\bar{b}}}{s} \ \& \ n_B^{\rm obs} \simeq 8 \times 10^{-11}$$

Can be tested in near-future experiments?

2. Late-time Leptogenesis

Resonant production of sterile neutrino dark matter requires a large lepton asymmetry, 10^5 larger than BAU, at $T \sim 100\ \mathrm{MeV}$.

Can GeV-scale ν_R provide the asymmetry?

Necessary to investigate the mechanism generating asymmetry **via right-handed neutrino oscillations**

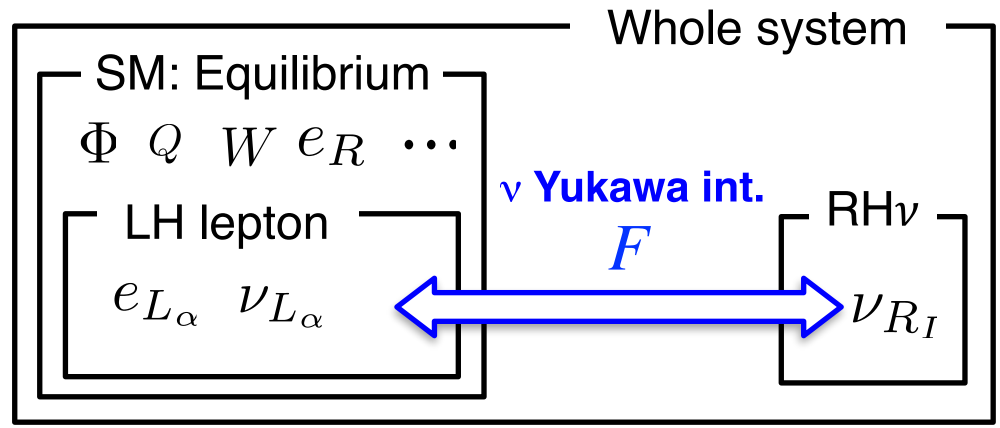
Baryogenesis via ν_R oscillation [1]

Mechanism

Yukawa coupling of $\nu_{R_{2,3}}$

$$|F_{2,3}| \sim 10^{-7,8}$$

- **Out-of-equilibrium process**
- **CP violation**



$$\nu_{RI} \quad \cdots\cdots\cdots \quad \nu_{RJ}$$

Coherent oscillations of ν_R

$$e^{-i\left(\frac{M_I^2 - M_J^2}{2p}\right)dt}$$

Baryogenesis via ν_R oscillation [1]

<u>Mechanism</u>

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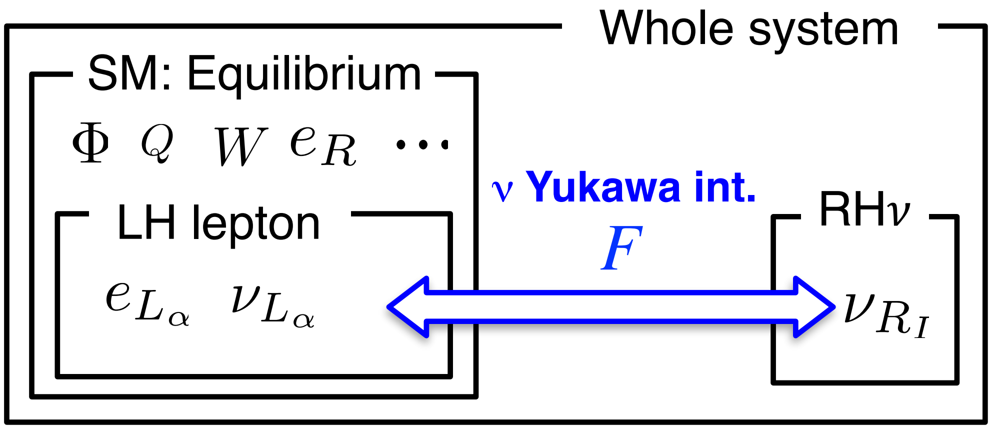
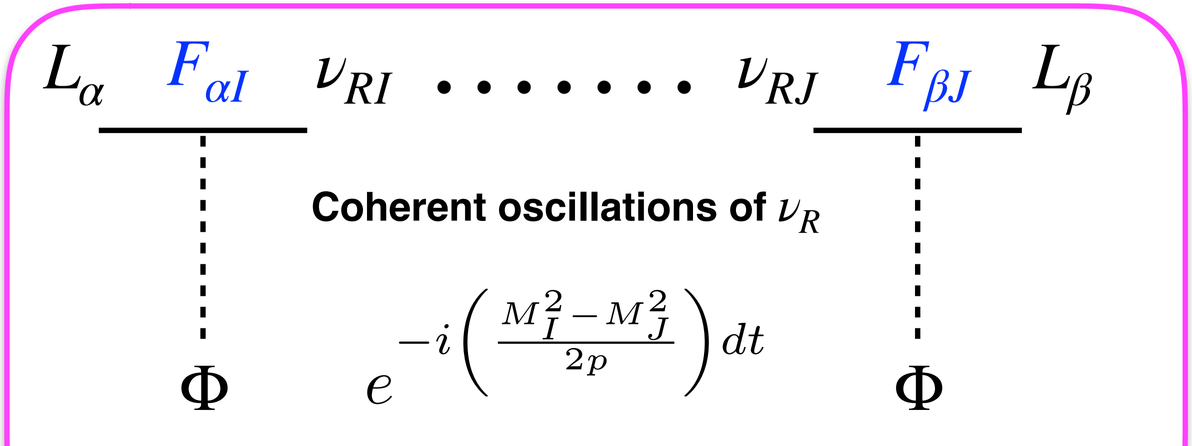




$$\Gamma(L_\alpha \to L_\beta) \neq \Gamma(\bar{L}_\alpha \to \bar{L}_\beta)$$

$$\longrightarrow \quad n_{L_e} \neq 0,\ n_{L_\mu} \neq 0,\ n_{L_\tau} \neq 0$$

$$n_{L_e} + n_{L_\mu} + n_{L_\tau} = 0$$

Baryogenesis via ν_R oscillation [1]

<u>Mechanism</u>

Yukawa coupling of $\nu_{R_{2,3}}$

$$|F_{2,3}| \sim 10^{-7,8}$$

- **Out-of-equilibrium process**
- **CP violation**

Whole system

SM: Equilibrium

$\Phi \quad Q \quad W \quad e_R \quad \cdots$

LH lepton

$e_{L_\alpha} \quad \nu_{L_\alpha}$

ν Yukawa int.

F

RHν

ν_{R_I}

$L_\alpha \quad F_{\alpha I} \quad \nu_{RI} \quad \cdots\cdots\cdots \quad \nu_{RJ} \quad F_{\beta J} \quad L_\beta$

Coherent oscillations of ν_R

$$e^{-i\left(\frac{M_I^2 - M_J^2}{2p}\right)dt}$$

$\Phi \qquad \Phi$

$$\Gamma(L_\alpha \to L_\beta) \neq \Gamma(\bar{L}_\alpha \to \bar{L}_\beta)$$

$$\to \quad n_{L_e} \neq 0,\ n_{L_\mu} \neq 0,\ n_{L_\tau} \neq 0$$

$$n_{L_e} + n_{L_\mu} + n_{L_\tau} = 0$$

Evolution

$L_\beta \quad F_{\beta I} \quad \nu_{RI}$

Φ

$$n_L = \sum_\alpha n_{L_\alpha} \neq 0$$

$n_B(T_{\rm SF}) = -\frac{28}{79} n_L(T_{\rm SF})$ at $T_{\rm SF} \simeq 130\,\mathrm{GeV}$

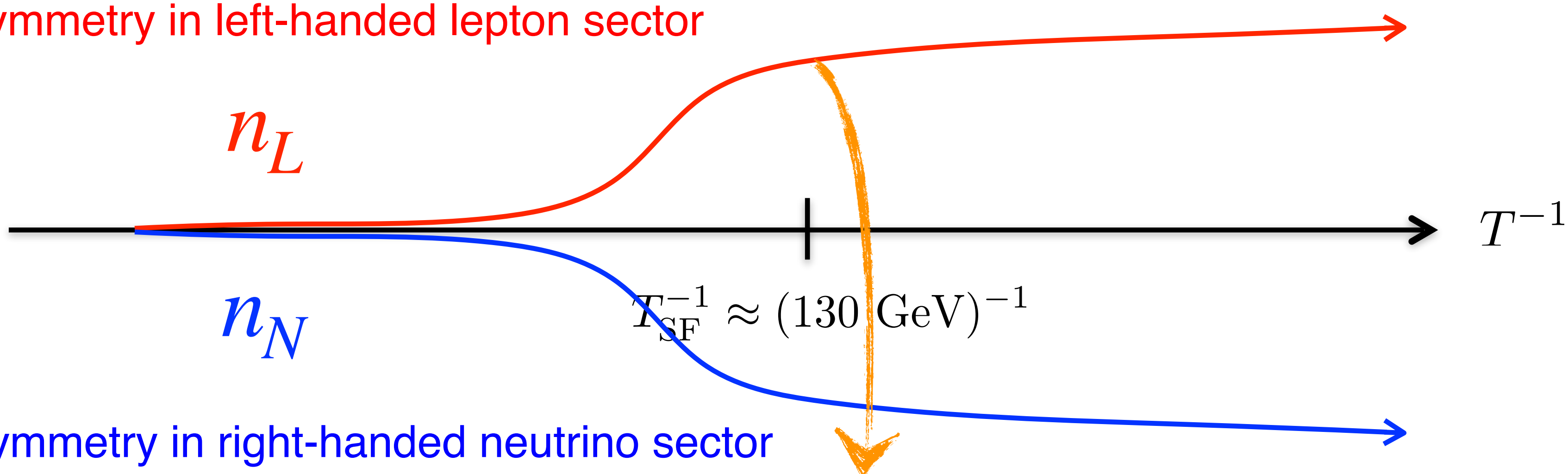
Baryogenesis via ν_R oscillation [2]

Key features

1. Effective lepton number conservation due to $M \ll T$

$$n_L \approx -n_N$$

Asymmetry in left-handed lepton sector



Asymmetry in right-handed neutrino sector

$$n_B(T_{\rm SF}) = -\frac{28}{79} n_L(T_{\rm SF}) \ \&\ n_B^{\rm obs} \simeq 8 \times 10^{-11}$$

n_L generation continues even after $T_{\rm SF}$ until ν_R are thermalized

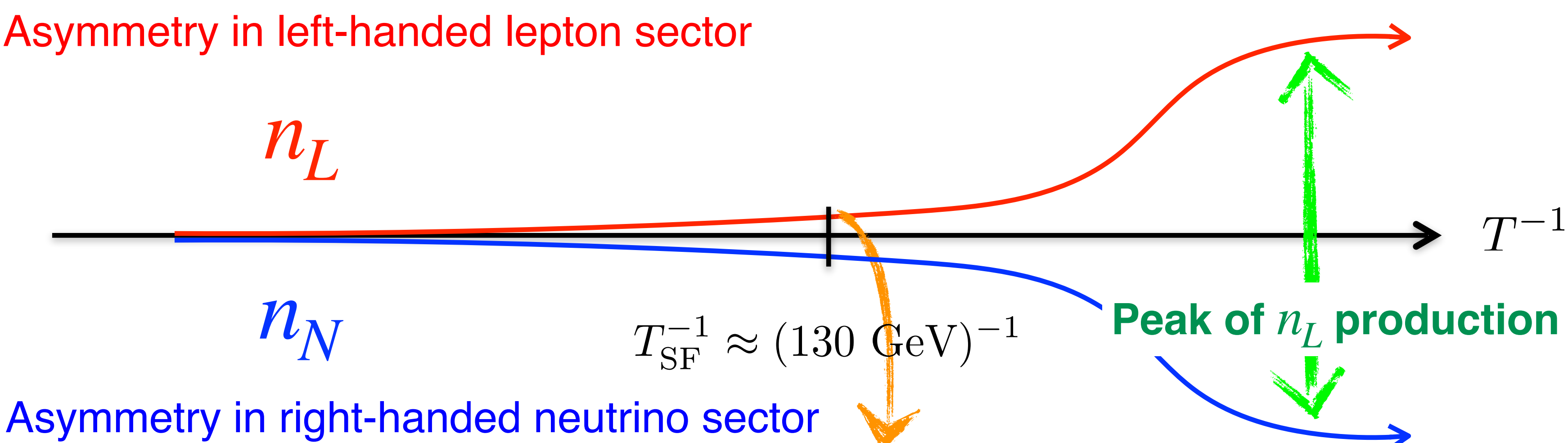
Baryogenesis via ν_R oscillation [3]

Key features

2. **Scale of asymmetry generation can be controlled**

$$\int_{t_i}^{t} \frac{M_i^2 - M_j^2}{2p} dt' \approx 1 \longrightarrow \text{Oscillation temperature: } T_{\rm osc} \simeq (\Delta M\, M\, M_0)^{\frac{1}{3}}$$

$$M = \frac{M_3 + M_2}{2},\ \Delta M = \frac{M_3 - M_2}{2},\ M_0 \simeq 7 \times 10^{17} \mathrm{GeV}$$



$$n_B(T_{\rm SF}) = -\frac{28}{79} n_L(T_{\rm SF})\ \&\ n_B^{\rm obs} \simeq 8 \times 10^{-11}$$

Possibility to explain BAU and late-time asymmetry simultaneously

Kinetic equations for Baryogenesis

To treat coherent and incoherent processes at the same time

Matrix of density : $\rho = \begin{pmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{pmatrix}$ $\left\{ \begin{array}{l} \text{Diagonal elements : occupation numbers} \\ \text{Off-diagonal elements : correlations} \end{array} \right.$

For ν_R and anti-ν_R (2x2 matrix)

$$\frac{d\rho_N}{dt} = -i\left[H_N, \rho_N\right] - \frac{1}{2}\{\Gamma_N, \rho_N - \rho_N^{\text{eq}}\} - \frac{1}{2}\sum_\alpha \left[\tilde{\Gamma}_N^\alpha \Delta\rho_{\nu_\alpha}\right]$$

Oscillation — Production and Destruction — Communication (back-reaction)

$$\frac{d\rho_{\bar{N}}}{dt} = -i\left[H_N^*, \rho_{\bar{N}}\right] - \frac{1}{2}\{\Gamma_N^*, \rho_{\bar{N}} - \rho_N^{\text{eq}}\} + \frac{1}{2}\sum_\alpha \left[\left(\tilde{\Gamma}_N^\alpha\right)^* \Delta\rho_{\nu_\alpha}\right]$$

For lepton asymmetries $\Delta\rho_{\nu_\alpha}$ $(\alpha = e, \nu, \tau)$

Damping — Communication (back-reaction)

$$\frac{d\Delta\rho_{\nu_\alpha}}{dt} = -\Gamma_{\nu_\alpha}\Delta\rho_{\nu_\alpha} + \mathrm{Tr}[\tilde{\Gamma}_{\nu_\alpha}\rho_{\bar{N}}] - \mathrm{Tr}[\tilde{\Gamma}_{\nu_\alpha}^*\rho_N]$$

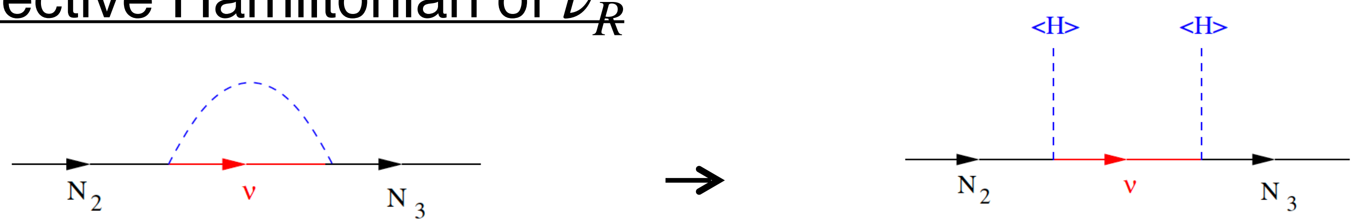
$$H_N = H_0 + H_I$$

$$H_I, \Gamma \propto F^2$$

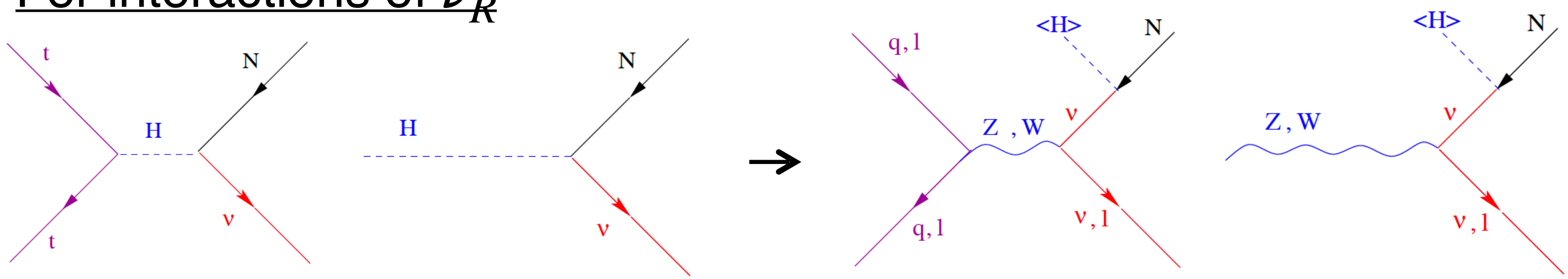
Our work [1]

Derive kinetic equations in the Higgs phase $(T < T_{\mathrm{EW}})$

For effective Hamiltonian of ν_R



For interactions of ν_R



Lepton number conserving and violating contributions

$$\Gamma = \Gamma_+ + \Gamma_- \qquad \Gamma_+, H_+ \propto T \qquad \text{; Lepton \# conserving}$$

$$H = H_+ + H_- \qquad \Gamma_-, H_- \propto (M/T)^2 T \qquad \text{; Lepton \# violating}$$

Our work [2]

Impacts on our purposes

1. Parameter space for Baryogenesis

Baryogenesis needs information in the Higgs phase

$$T_{\mathrm{SF}} \simeq 130 \text{ GeV} < T_{\mathrm{EW}} \simeq 160 \text{ GeV}$$

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

Perform comprehensive numerical analysis of Baryogenesis taking LNV corrections, plasma neutrality and exact sphaleron treatment into account additionally

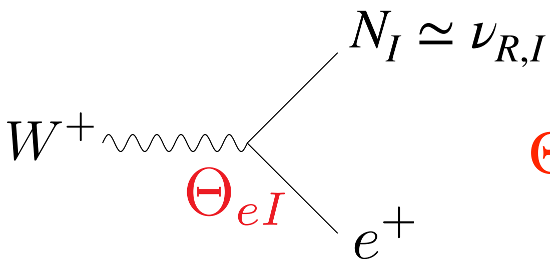
[Ghiglieri, Laine ('16, '17)] [Drewes, Garbrecht, Gueter, Klaric ('16)] [SE, Shaposhnikov, Timiryasov ('17)]
[Hernamdez, Kekic, Lopez-Pavon, Racker, Salvado ('16)] [Hambye, Teresi ('17)]
[Antusch, Cazzato, Drewes, Fischer, Garbrecht, Gueter, Klaric ('17)] …

2. Late-time Leptogenesis

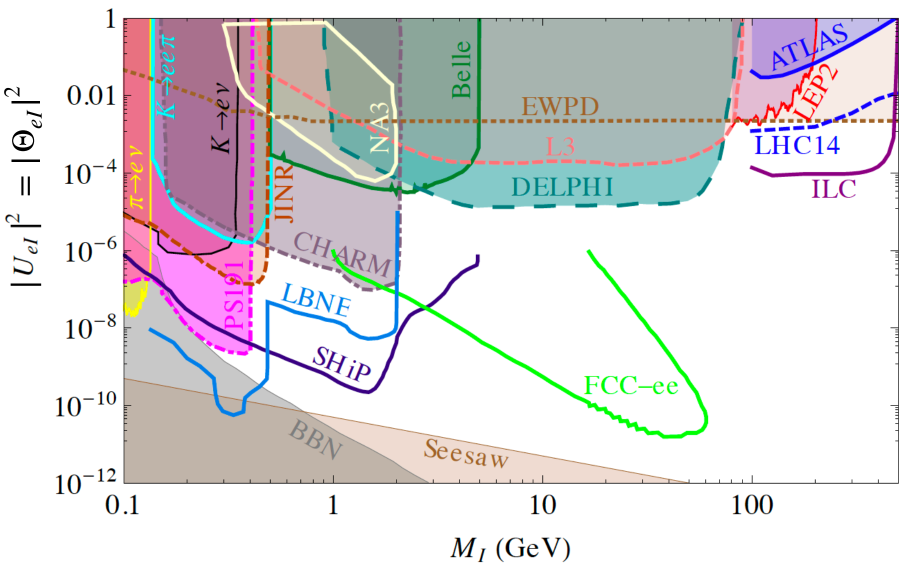
Study the asymmetry production at lower temperatures properly

Parameter space of Baryogenesis

Constraints



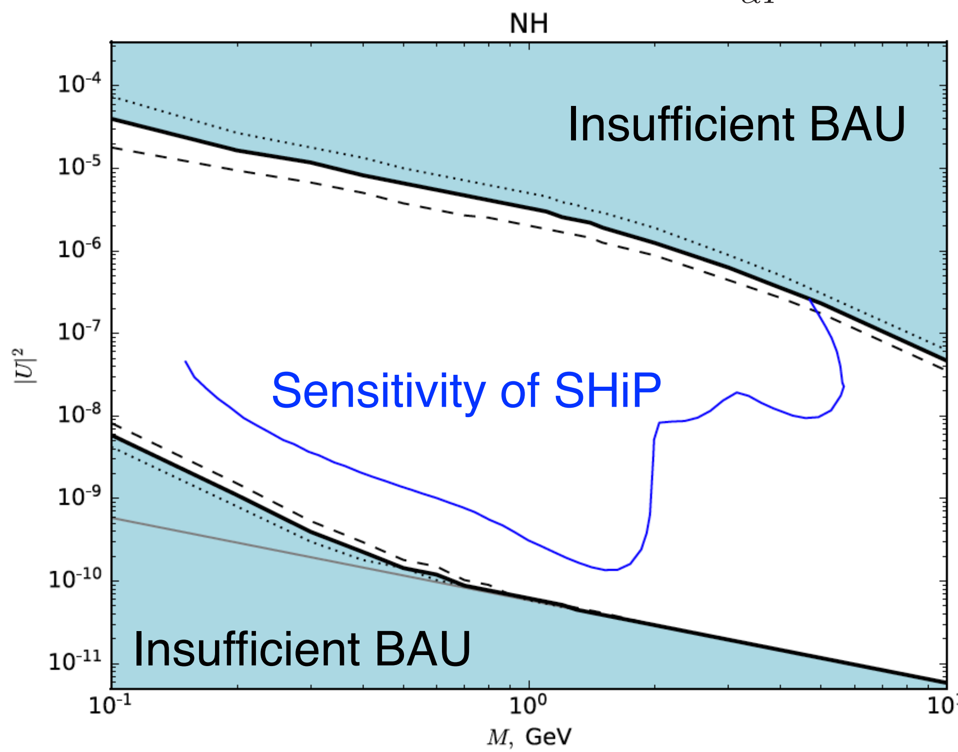
$$\Theta_{\alpha I} \equiv \frac{v F_{\alpha I}}{M_I}$$



[The SHiP collaboration ('15)]

Numerical result

Typical mixing of ν_R: $U^2 \equiv \sum_{\alpha I} |\Theta_{\alpha I}|^2$



[SE, Shaposhnikov, Timiryasov ('18)]

For GeV-scale mass the near-future experiment will probe the wide region in the suggested parameter space!

Issue of late-time leptogenesis

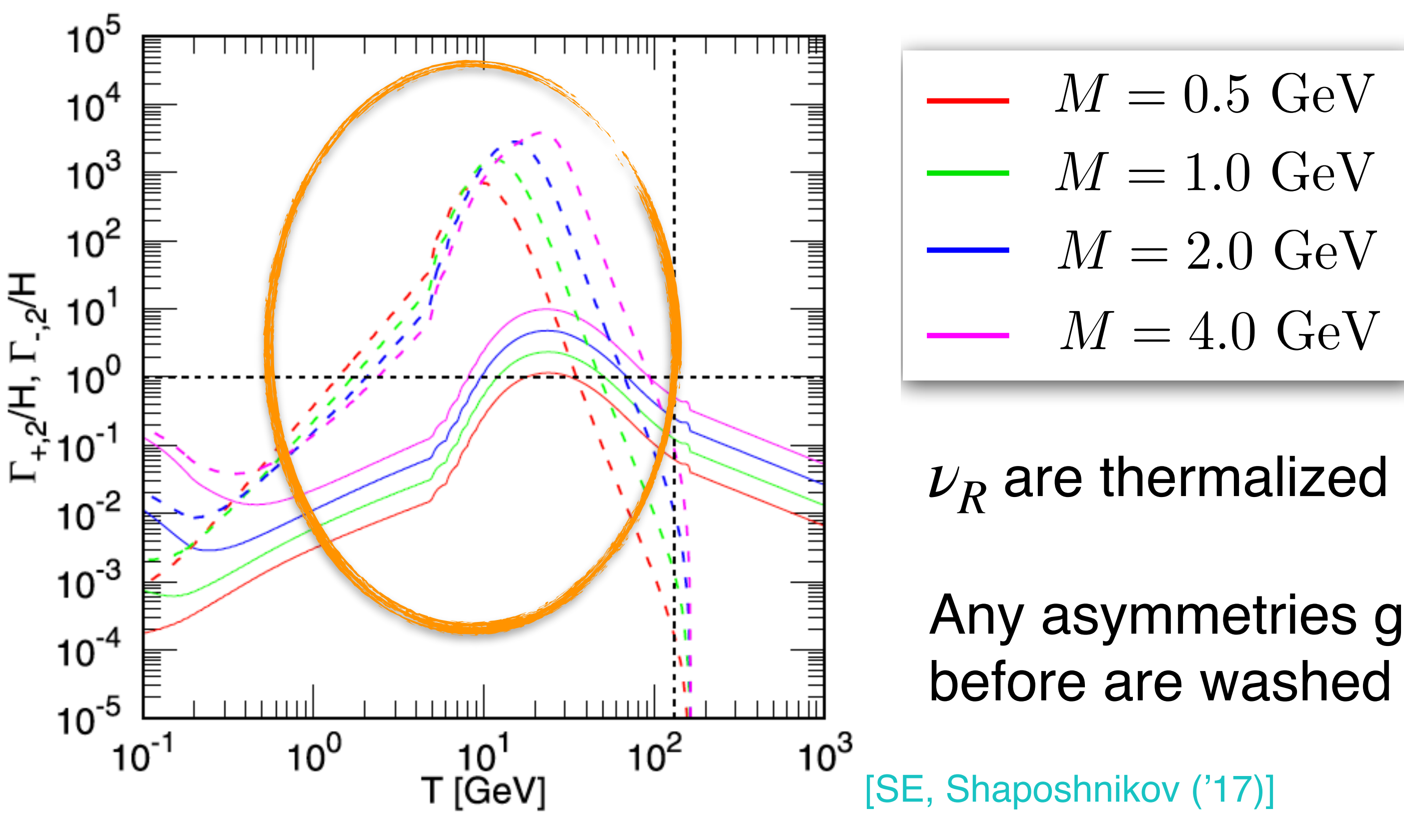
Thermalization

Interaction rate: $\Gamma_N = \Gamma_+ + \Gamma_-$

Γ_+ ; Lepton number conserving rate

Γ_- ; Lepton number violating rate

Largest eigenvalues of Γ_+ (solid lines) and Γ_- (dashed lines)



$F_{2,3} \simeq F_{2,3}^{\min}$

ν_R are thermalized

Any asymmetries generated before are washed out…

[SE, Shaposhnikov ('17)]

Protection by conservation law

Combinations of leptonic asymmetries for ν_R and active flavors

[Shaposhnikov ('08)]

$$L_\pm \equiv n_N \mp n_L$$

When total lepton number is conserved $n_L \approx -n_N$

$$\rightarrow L_+ \approx -2n_L,\ L_- \approx 0$$

From the derived kinetic equations

$$\frac{dL_+}{dt} \propto \gamma_+$$; Lepton # conserving

$$\frac{dL_-}{dt} \propto \gamma_-$$; Lepton # violating

$$\left[\ \Gamma_N = \Gamma_+ + \Gamma_- \qquad \begin{array}{l} \gamma_+ \sim \Gamma_+/F^2 \\ \gamma_- \sim \Gamma_-/F^2 \end{array}\ \right]$$

If Γ_+ (Γ_-) doesn't come into equilibrium, $L_+(L_-)$ is a **conserved number**

Generated asymmetries associated with $L_+(L_-)$ can potentially be protected from the wash-out down to lower temperatures!

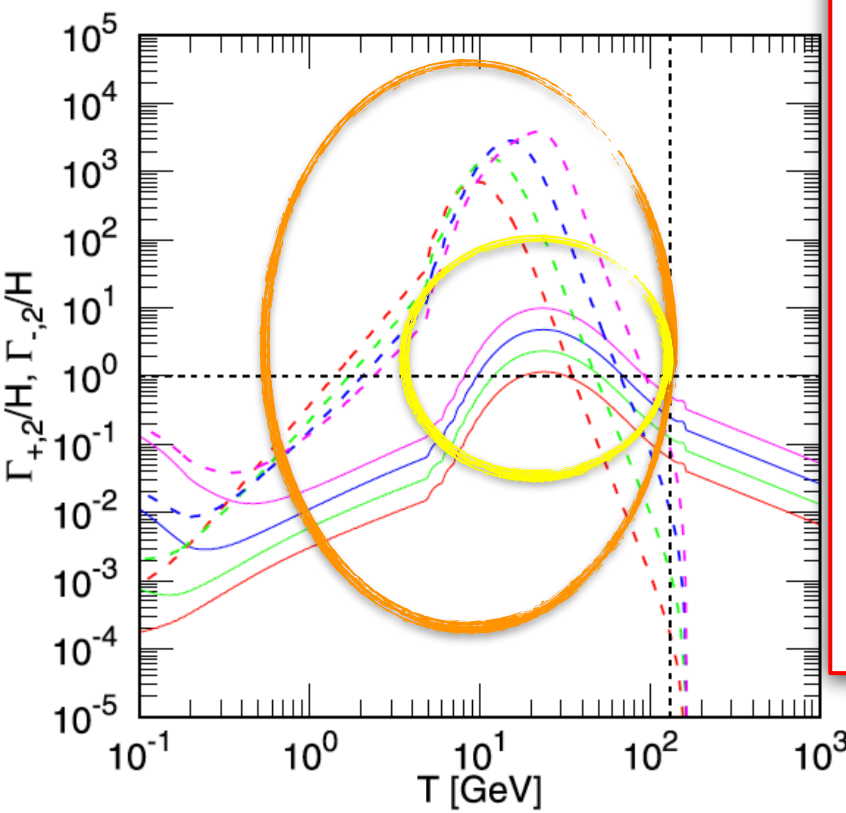
Survival from wash-out

$\Gamma_- / H \gg 1$

ν_R must be thermalized

No conservation of L_-

Largest eigenvalues of Γ_+ (solid



$\Gamma_+ / H \lesssim \mathcal{O}(1)$ for $M \lesssim 2$ GeV

Effective conservation of L_+

Just before thermal-in

$$L_+ = n_N - n_L \approx -2n_L$$

This conservation law can potentially solve the issue in the resonant DM production!

before are washed out…

[SE, Shaposhnikov ('17)]

Summary

Taking into account recent improvements in the Baryogenesis we carried out the comprehensive numerical analysis. The results show that near future experiments would probe origins of neutrino masses and baryon asymmetry of the universe.

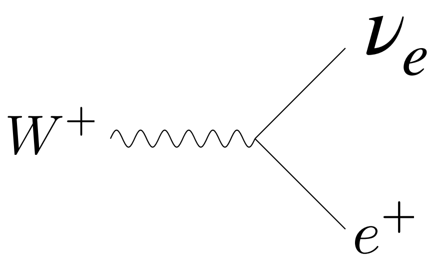
To extend the kinetic equations into the Higgs phase enables to study the late-time Leptogenesis in details. The asymmetry protection due to the conservation law could potentially encourage the resonant production of sterile neutrino dark matter. The numerical computation is now in progress.

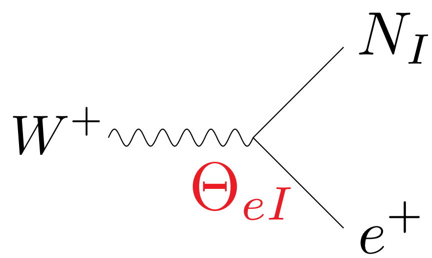
Backup slides

Search for GeV-scale RHν

Weak interaction through neutrino mixing; $\nu_{L\alpha} = U_{\alpha i}\nu_i + \Theta_{\alpha I} N_I^c$

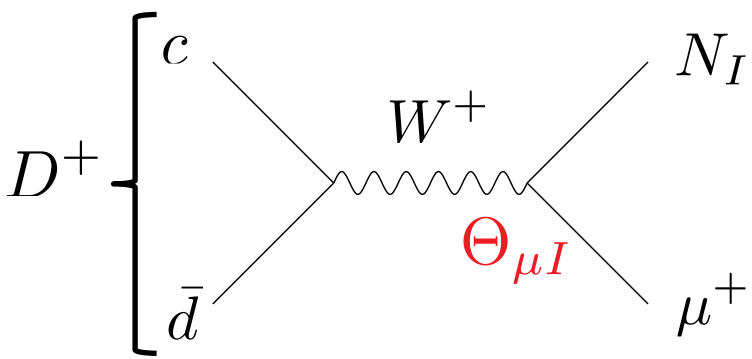
$(\nu_{R\,I} \simeq N_I)$



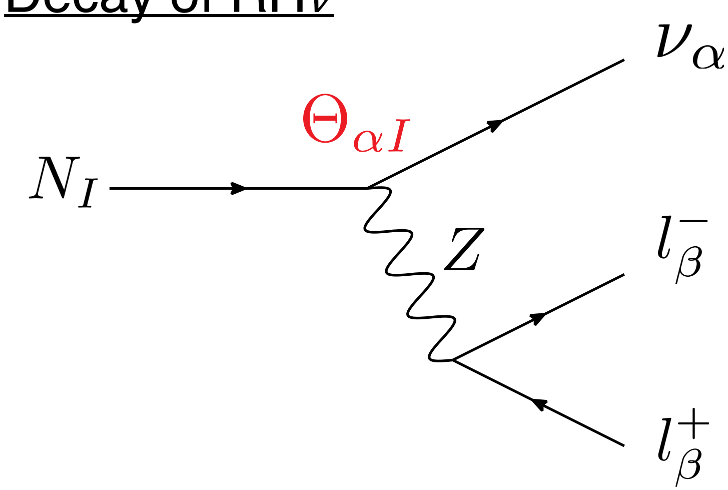


$$\Theta_{\alpha I} \equiv \frac{(M_D)_{\alpha I}}{M_I} = \frac{vF_{\alpha I}}{M_I} \ll 1$$

<u>Production from meson decays</u>



<u>Decay of RHν</u>



$$N \to \nu\nu\bar{\nu}\,,\; N \to \nu l\bar{l}\,,\; N \to l^+ M^- \ldots$$

Yukawa coupling constants

In the minimal (two RHνs) case $\boldsymbol{F = (i/\langle\Phi\rangle) U\, D_\nu^{\frac{1}{2}}\, \Omega\, D_N^{\frac{1}{2}}}$ (3x2 matrix)

[Casas, Ibarra ('01)]

U : PMNS matrix; $\theta_{12}, \theta_{13}, \theta_{23}$, CP phases

$$D_\nu^{\frac{1}{2}} = \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3})$$
$$D_N^{\frac{1}{2}} = \mathrm{diag}(\sqrt{M_1}, \sqrt{M_2}) = \mathrm{diag}(\sqrt{\bar{M} - \Delta M}, \sqrt{\bar{M} + \Delta M})$$

Ω : A orthogonal matrix; A complex mixing angle $\omega \to \mathrm{Re}\omega + i\mathrm{Im}\omega$

$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\xi\sin\omega & \xi\cos\omega \end{pmatrix}_{\text{(NH)}}$$

$$\cos(i\mathrm{Im}\,\omega) = \cosh(\mathrm{Im}\,\omega) = (e^{\mathrm{Im}\,\omega} + e^{-\mathrm{Im}\,\omega})/2$$
$$\sin(i\mathrm{Im}\,\omega) = i\sinh(\mathrm{Im}\,\omega) = i(e^{\mathrm{Im}\,\omega} - e^{-\mathrm{Im}\,\omega})/2$$

For large $|\mathrm{Im}\,\omega|$ $F \propto \exp(|\mathrm{Im}\,\omega|)$, BUT neutrino oscillation data can be always explained!

cf.) $\hat{M}_\nu = -v^2 F M_M^{-1} F^T$

H and Γ

Effective Hamiltonian

$$H_N = H_0 + H_I,$$

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

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

Production and back-reaction rates

$$\Gamma_N = \boxed{\gamma_+}\boxed{\sum_\alpha Y^N_{+,\alpha}} + \boxed{\gamma_-}\boxed{\sum_\alpha Y^N_{-,\alpha}}$$

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

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

$$\tilde{\Gamma}_{\nu_\alpha} = -\boxed{\gamma_+}\boxed{Y^\nu_{+,\alpha}} + \boxed{\gamma_-}\boxed{Y^\nu_{-,\alpha}}$$

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

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

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

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

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H and Γ

Effective Hamiltonian

$$H_N = H_0 + H_I,$$

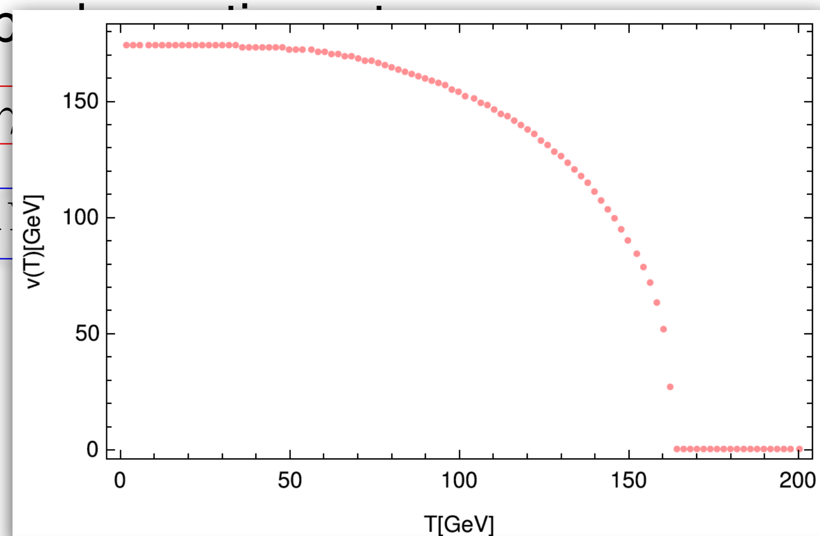
$$H_0 = -\frac{\Delta M M}{E_N}\sigma_1$$

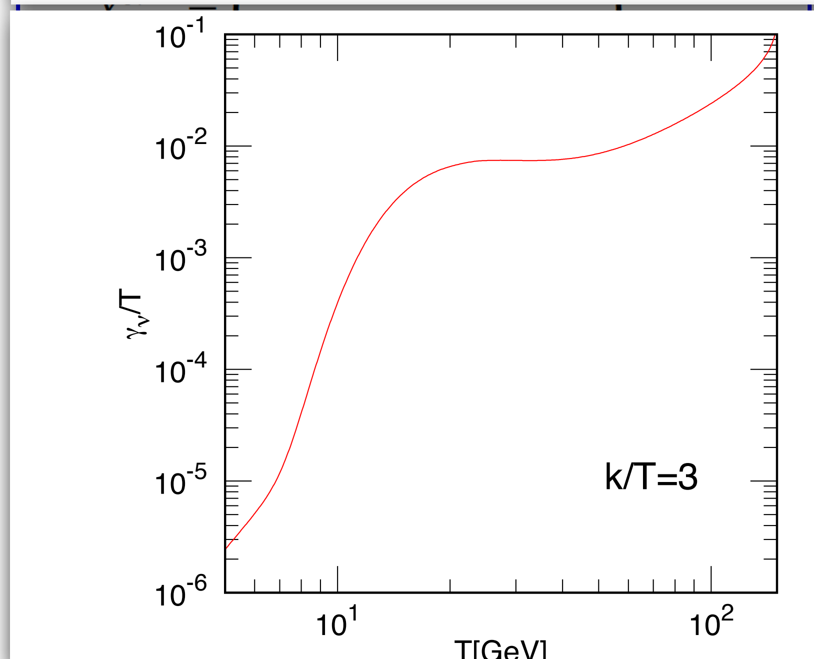
$$H_I = \boxed{h_+}\boxed{\sum_\alpha Y^N_{+,\alpha}} + \boxed{h_-}\boxed{\sum_\alpha Y^N_{-,\alpha},}$$

Production and b

$$\Gamma_N = \boxed{\gamma_+}\boxed{\sum_\alpha Y^N_{+,\alpha}} + \gamma$$

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





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

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

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

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

H and Γ

Higgs phase

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

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

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

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

$$\gamma_{ph} = \frac{1}{E_N}\frac{m_h^2 T}{32\pi k}\ln\left\{\frac{1 + e^{-\frac{m_h^2}{4kT}}}{1 - e^{-\frac{1}{T}\left(k + \frac{m_h^2}{4k}\right)}}\right\},$$ [Ghiglieri, Laine ('16)]

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

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

Ultra-relativistic limit

$$\langle\Phi\rangle \to 0$$

Symmetric phase

$$h_+ = \frac{T^2}{8k},$$

$$\gamma_+ = \frac{1}{E_N}\mathrm{Im}\,\Pi_R,$$

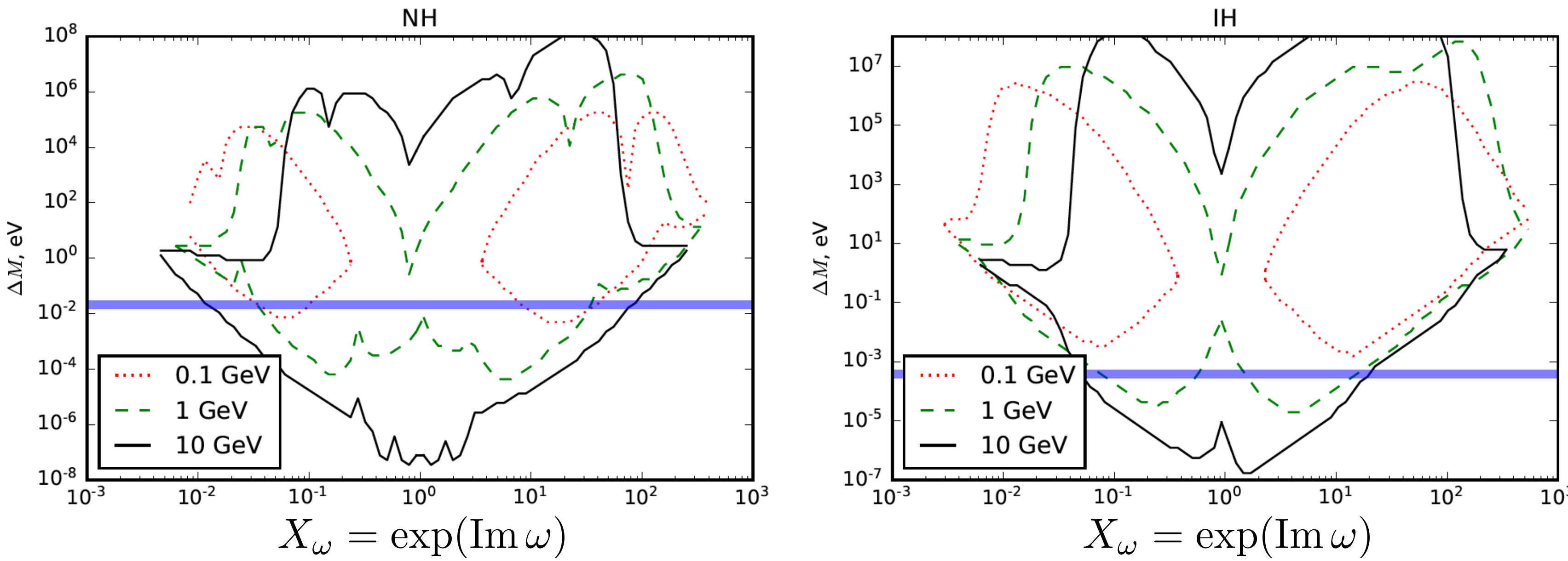
$$h_- = 0,$$

$$\gamma_- = 0,$$

Parameter dependence of Baryogenesis

$$\text{NH:} \quad \delta = \pi, \quad \eta = 3\pi/2, \quad \mathrm{Re}\,\omega = \pi/4,$$
$$\text{IH:} \quad \delta = 0, \quad \eta = \pi/2, \quad \mathrm{Re}\,\omega = \pi/4.$$

Mass dependence in the baryogenesis

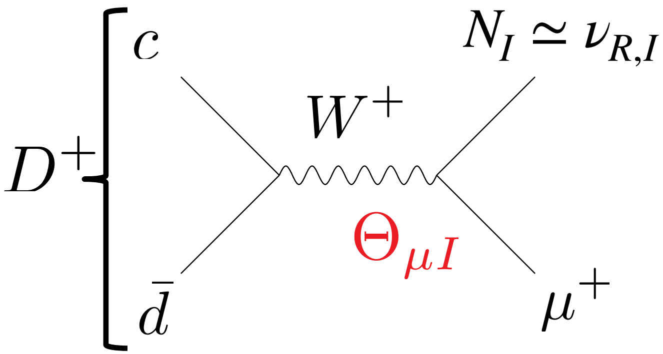


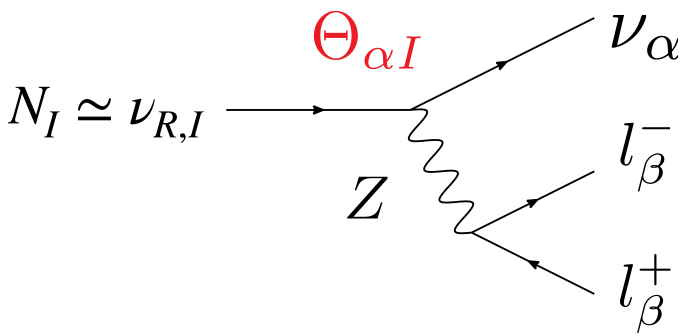
[SE, Shaposhnikov, Timiryasov ('18)]

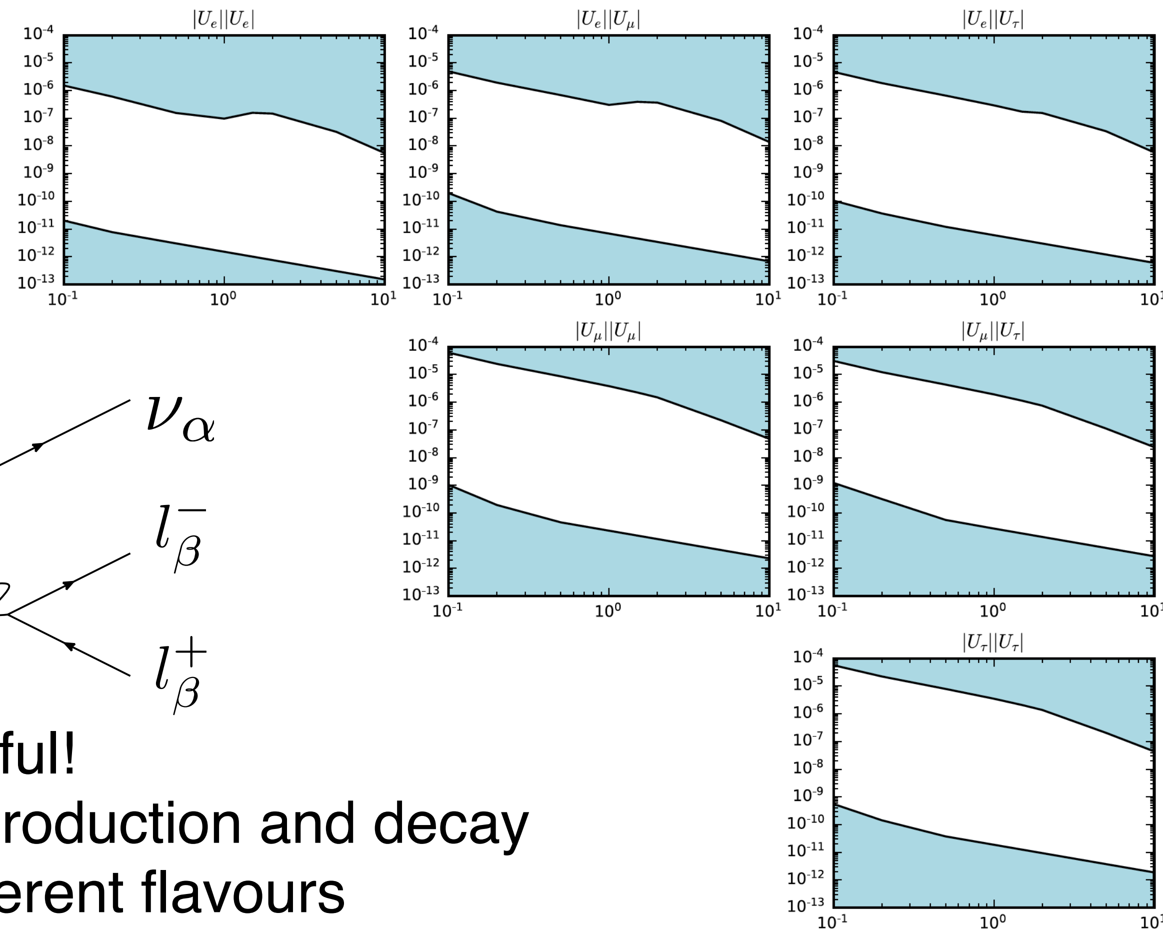
Parameter space of Baryogenesis [2]

Full parameter scanning

Individual mixings of HNLs: $\sum_{I,J=2,3} |\Theta_{I\alpha}|^2 \cdot |\Theta_{J\beta}|^2 = |U_\alpha|^2 \cdot |U_\beta|^2$





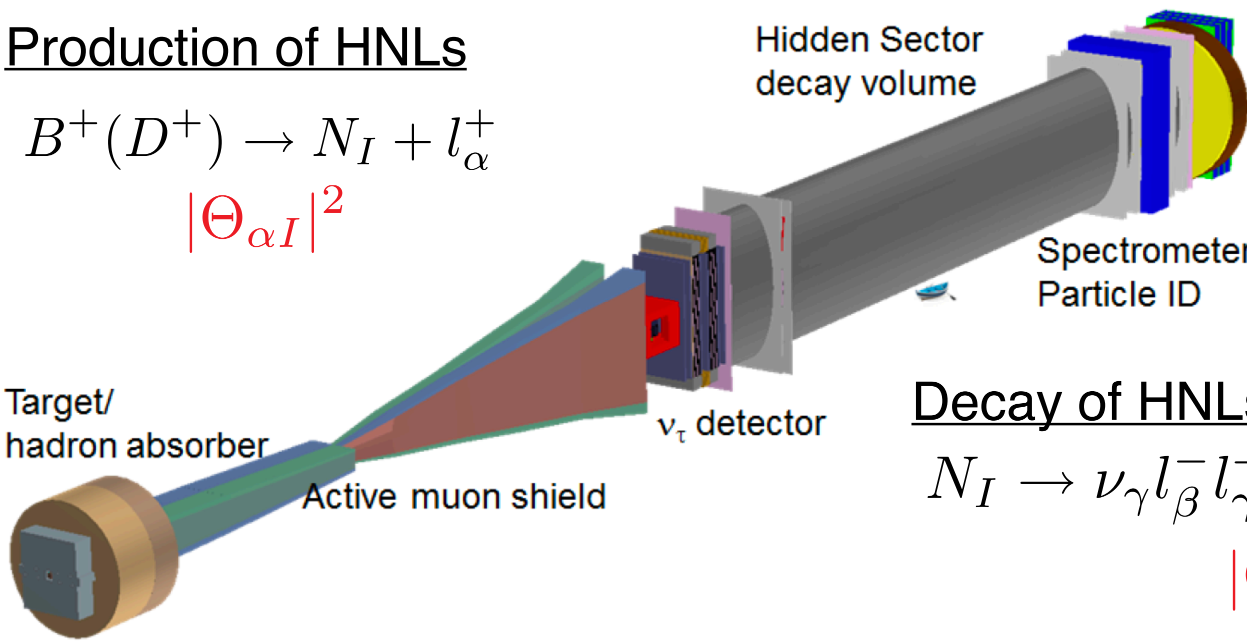


Practically more useful!
In experiments the production and decay can happen with different flavours

SHiP experiment

Search for **Hi**dden **P**article (**SHiP**) is a proposed beam-dump experiment by using the SPS in CERN.

SHiP
Search for Hidden Particles



[The SHiP collaboration ('15)]

Production of HNLs

$$B^+(D^+) \to N_I + l_\alpha^+$$

$$|\Theta_{\alpha I}|^2$$

Decay of HNLs

$$N_I \to \nu_\gamma l_\beta^- l_\gamma^+ \qquad N_I \to l_\beta^- M^+$$

$$|\Theta_{\beta I}|^2$$

Individual flavor mixings are also important information for the search!

In this method relevant mixings are $\sum_{I,J=1,2} |\Theta_{\alpha I}|^2 |\Theta_{\beta J}|^2 = |U_\alpha|^2 |U_\beta|^2$.

Resonant production of sterile ν DM

Production with lepton asymmetries

$$\Gamma_N \sim \Theta_M^2(T)\Gamma_\nu \sim \Theta_M^2(T) G_F^2 T^5$$

$$\Theta_M^2(T) \simeq \frac{\Theta_1^2}{\left(1 + \frac{2p}{M_1^2}(b(p,T) \pm c(T))\right)^2 + \Theta_1^2}$$

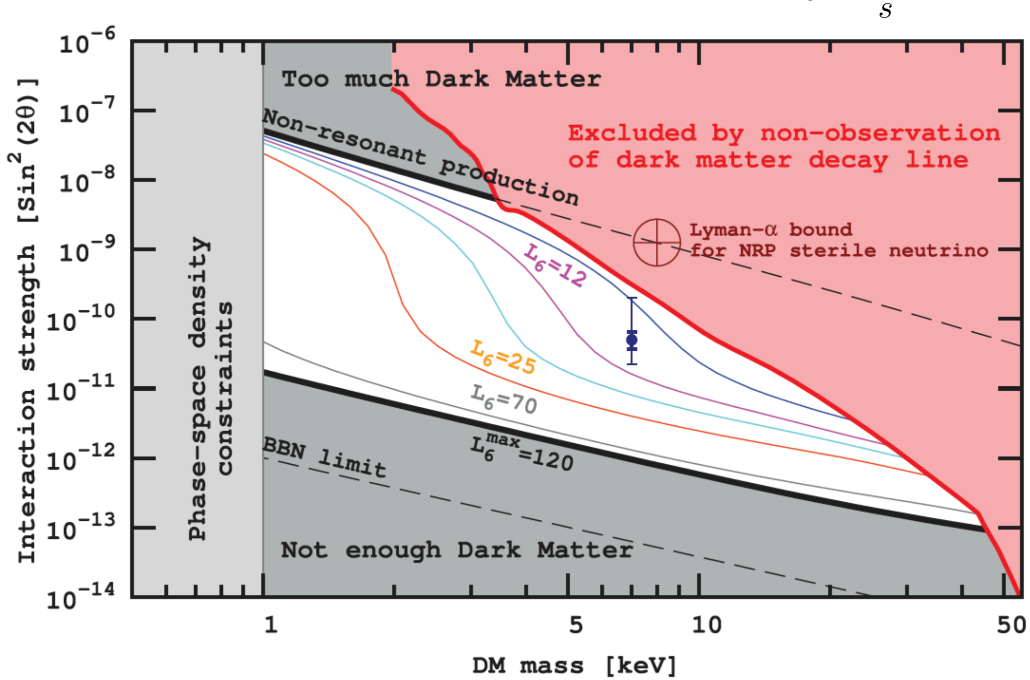
$$\begin{cases} b(p,T) = \dfrac{16 G_F^2}{\pi \alpha_W} p (2 + \cos^2\theta_W) \dfrac{7\pi^2 T^4}{360} \\ c(T) = 3\sqrt{2} G_F (1 + 4\sin^2\theta_W)(n_{\nu_e} - n_{\bar{\nu}_e}) \end{cases}$$

When $\left[1 + \frac{2p}{M_1^2}(b(p,T) \pm c(T))\right] \simeq 0$
the mixing is enhanced

$n_{\nu_\alpha}/s \gtrsim 10^{-5}$ is necessary

($\sum_\alpha n_{\nu_\alpha}/s \simeq 10^{-10}$ for the BAU)

$$L_6 = \frac{n_L}{s} \times 10^6$$



[Boyarsky, Ruchayskiy, Shaposhnikov ('09)]