Leptogenesis via Neutrino Oscillation

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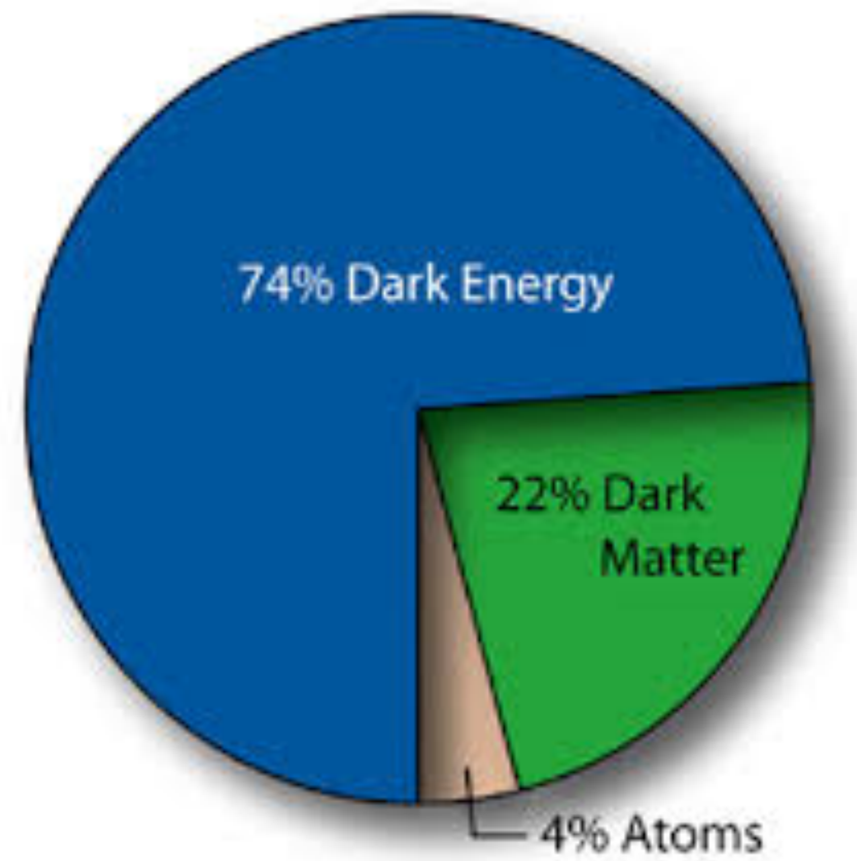
Baryogenesis

- There remains mystery in particle physics.
- We do not understand
  - Dark energy
  - Dark matter
  - Large energy density of atom



$$\frac{n_B}{s} \simeq (8.68 \pm 0.05) \times 10^{-11}$$

Sakharov’s three conditions

1. Violation of baryon number

2. Violation of C and CP

3. Out of thermal equilibrium

Conditions in SM

1. Violation of baryon number
   - Sphaleron process breaks B+L number. Yes
2. Violation of C and CP
   - CKM phase. Yes, but small
3. Out of thermal equilibrium
   - EWPT is crossover. No (w/ observed Higgs mass)

Conditions in SM

1. Violation of baryon number
   - Sphaleron process breaks B+L number. Yes
2. Violation of C and CP
   - CKM phase. Yes, but small
3. Out of thermal equilibrium — Physics beyond SM is needed.
   - EWPT is crossover. No (w/ observed Higgs mass)

New CP violating phase

- Now we know that neutrino is massive.

- Flavor and mass eigenstates of neutrino are different.

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \times \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})\ .$$

3 mixing angles and 3 CP phases (PMNS phase).

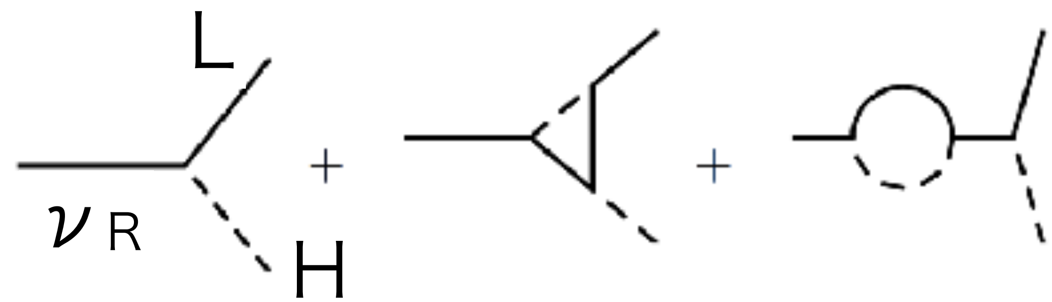
Leptogenesis

- One of simplest scenarios : Leptogenesis

[Fukugida-Yanagida '86]

Lepton asymmetry is generated by

decay of ν_R



- ν_R is produced in thermal plasma for $T_R \gtrsim M_{\nu R}$

by inflaton decay for $M_\Phi \gtrsim M_{\nu R}$

Our work [YH-Kitano '16, YH-Kitano-Yin '18]

Asymmetry by neutrino oscillation at reheating era.

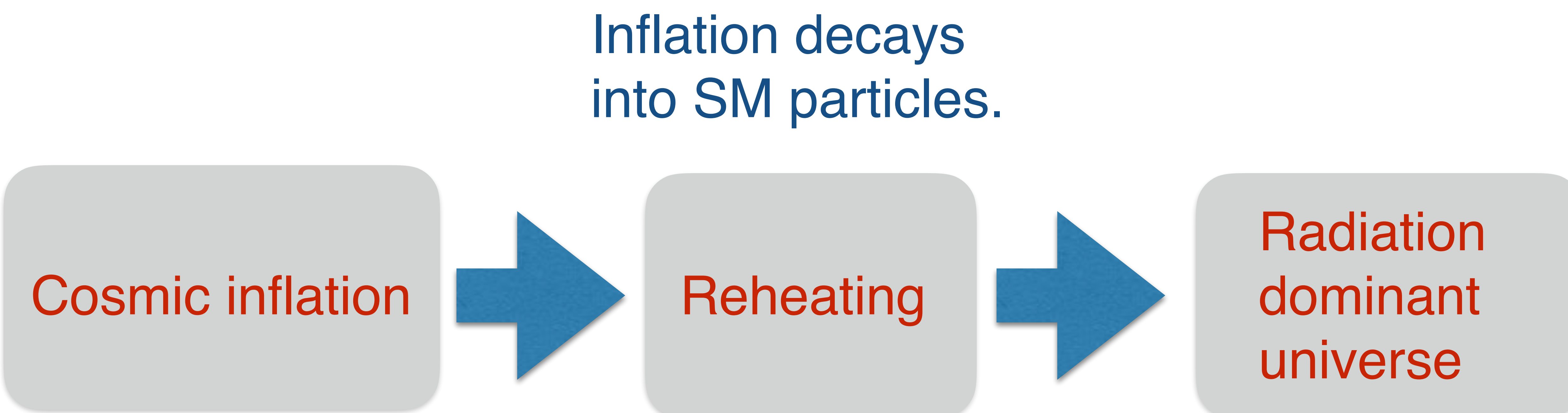
Message

- We propose new scenario of baryogengesis where the baryon number is generated during the era of reheating.
- Even if $T_R < M_{\nu R}$ and $M_\Phi < M_{\nu R}$, successful baryogenesis is realized.

[YH-Kitano ’16, YH-Kitano-Yin ’18]

Reheating era baryogenesis

- Standard inflationary cosmology



[YH-Kitano '16, YH-Kitano-Yin '18]

Reheating era baryogenesis

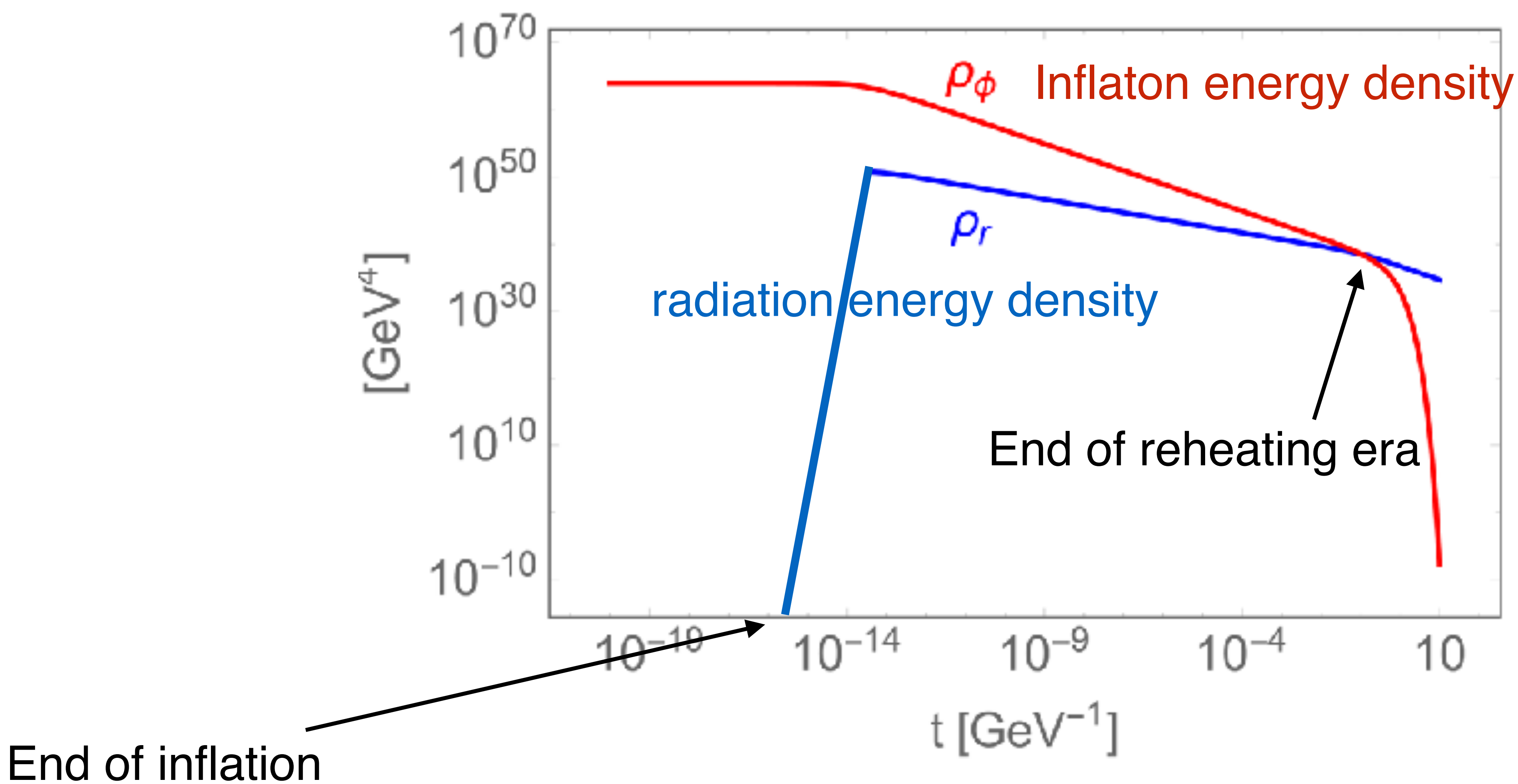
- Standard inflationary cosmology

Inflation decays
into SM particles.

far from thermal equilibrium.
good for baryogenesis.

History of universe

- Φ: inflaton, r: radiation.



Setup

- Simple model:

  Standard model

  w/ Majorana left handed neutrino+ (inflaton sector)

$$\mathcal{L} = \mathcal{L}_{SM} + \kappa llHH + \ldots \qquad \kappa\langle H\rangle^2 = U^* m_\nu U^\dagger$$

- Inflaton sector is characterized by m_Φ and T_R.

- Origin of llHH operator is not specified.

- Assume EFT description is valid. $\frac{\max[m_\nu]}{16\pi^2\langle H\rangle^2}E \lesssim 1$

Three conditions

- Baryon number violation.

  Combination of sphaleron & llHH op.

- C&CP violation.

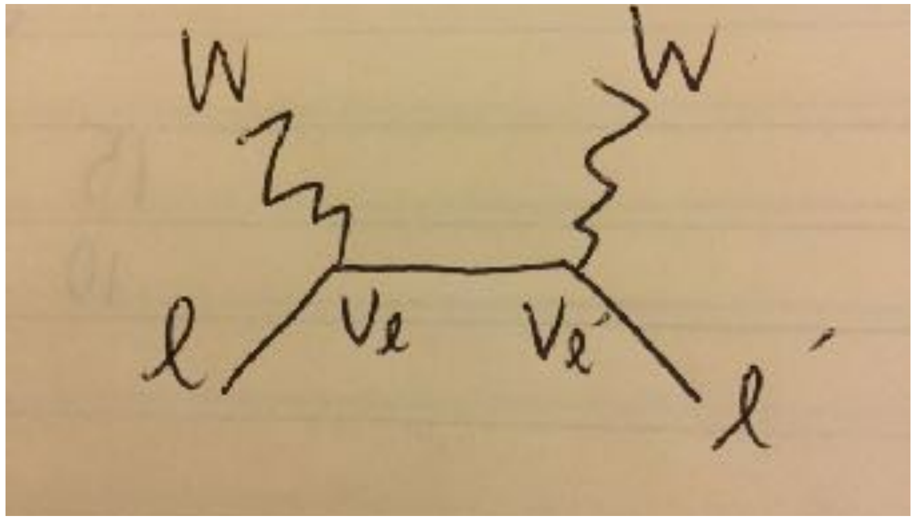
  PMNS phase in SM w/ massive neutrino.

- Away from equilibrium.

  By definition, reheating era satisfies condition.

Neutrino Oscillation

- External line is charged lepton.
- Propagator is not diagonalized by ν_l.



CP violating Neutrino Oscillation

- CP violating neutrino oscillation is relevant for our baryogengesis mechanism.

$$A_{\rm CP}^{(l'l)} \equiv P(\nu_l \to \nu_{l'}) - P(\bar{\nu}_l \to \bar{\nu}_{l'})$$

$$A_{\rm CP}^{(l'l)} = 4 \sum_{j>k} {\rm Im} \left(U_{l'j} U_{lj}^* U_{lk} U_{l'k}^* \right) \sin \frac{\Delta m_{jk}^2}{2p} L \,, \;\; l, l' = e, \mu, \tau \,.$$

Distance btw source&detector

Basic scenario

1: Left handed lepton from inflaton decay.

↓ CP violating neutrino oscillation

2: Flavor asymmetry appear (No net lepton asymmetry)

↓ Flavor dependent llHH washout

3: Net lepton asymmetry appears.

Basic scenario

1: Left handed lepton from inflaton decay.

2: Flavor asymmetry app

3: Net lepton asymmetry appears.

Origin

We consider two situations.

1. inflaton decays into leptons,
2. inflaton decays into Higgs, then Higgs→leptons by llHH.

Kinetic equation

- We numerically solve equations of motion for density matrix.

Scattering

$$i\frac{d\rho_{\mathbf{k}}}{dt} = [\Omega_{\mathbf{k}}, \rho_{\mathbf{k}}] - \frac{i}{2}\{\Gamma^d_{\mathbf{k}}, \rho_{\mathbf{k}}\},$$

Oscillation

$$i\frac{d\delta\rho_T}{dt} = [\Omega_T, \delta\rho_T] - \frac{i}{2}\{\Gamma^d_T, \delta\rho_T\} + i\delta\Gamma^p_T,$$

Because oscillation effect is important, kinetic eq. rather than Boltzmann eq. is used.

Two scale approximation: $p \sim m_\phi, p \sim T$

Initial condition

- Inflaton→leptons

Lepton state is parameterized as $|l_\phi\rangle = V_i |l_i\rangle$

$$\rho_{\mathbf{k}}|_{t=t_R} = \overline{\rho}_{\mathbf{k}}|_{t=t_R} = \mathcal{N} V_i V_j^*, \qquad \mathcal{N} = \frac{3}{4}\frac{T_R}{m_\phi} B,$$

- Inflaton→Higgs

initial lepton state is set by Yukawa/llHH

interaction.

Detail

Oscillation

$$\Omega_{ij}(\mathbf{p}) \simeq \frac{y_i^2 T^2}{16|\mathbf{p}|}\delta_{ij} + 0.046(\kappa^*\kappa)_{ij}\frac{T^4}{|\mathbf{p}|}, \quad \text{for } |\mathbf{p}| \gtrsim T.$$

$$\left(\Gamma^d_{\mathbf{k}}\right)_{ij} \simeq C\alpha_2^2 T\sqrt{\frac{T}{|\mathbf{k}|}}\delta_{ij} + \frac{9y_t^2}{64\pi^3|\mathbf{k}|}T^2(\delta_{i\tau}\delta_{\tau j}y_\tau^2 + \delta_{i\mu}\delta_{\mu j}y_\mu^2) + \frac{21\zeta(3)}{32\pi^3}(\kappa^*\cdot\kappa)_{ij}T^3,$$

Scattering

$$\left(\Gamma^d_T\right)_{ij} \simeq C'\alpha_2^2 T\delta_{ij} + \frac{9y_t^2}{64\pi^3}T(\delta_{i\tau}\delta_{\tau j}y_\tau^2 + \delta_{i\mu}\delta_{\mu j}y_\mu^2) + \frac{21\zeta(3)}{32\pi^3}(\kappa^*\cdot\kappa)_{ij}T^3,$$

$$\begin{aligned}(\delta\Gamma^p_T)_{ij} \simeq {} & C\alpha_2^2 T\sqrt{\frac{T}{|\mathbf{k}|}}\,(\rho_{\mathbf{k}})_{ij} - C'\alpha_2^2 T\,(\delta\overline{\rho}_T)_{ij} \\ & + \frac{3\zeta(3)}{8\pi^3}(\kappa^*\cdot(\overline{\rho}_{\mathbf{k}} - 3/4\rho_{\mathbf{k}})^t\cdot\kappa)_{ij}T^3 + \frac{3\zeta(3)}{8\pi^3}(\kappa^*\cdot(\delta\overline{\rho}_T - 3/4\delta\rho_T)^t\cdot\kappa)_{ij}T^3.\end{aligned}$$

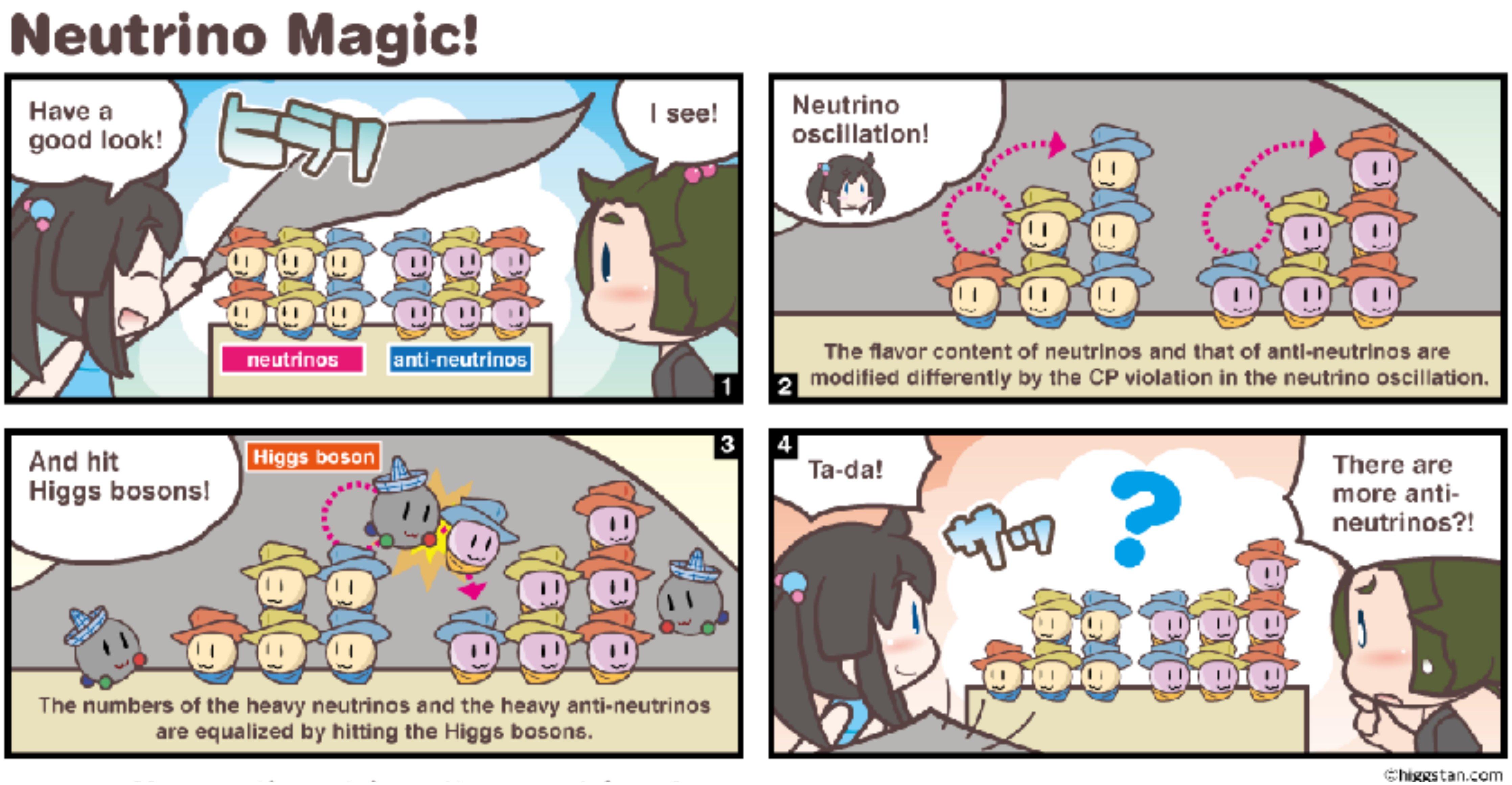
Some formula are in Akhmedov,et al. '98; Abada, et al. '06; Asaka, et al. 11.

Comment

- If inflaton dominant decay mode is Higgs, then sign of asymmetry only depends on Dirac&Majorana phase.

- Unknown CP phase in UV does not affect !

Comic



comic by Yuki Yamamoto,
higgstan.com

Analytic solution

Perturbation

- The kinetic eq. can be solved perturbatively.

$$i\frac{d}{dt}\tilde{\Delta}^{\mathrm{mass}} \simeq [\Omega^{\mathrm{mass}}, \rho^{\mathrm{mass}} + \bar{\rho}^{\mathrm{mass}}] + P(t)\cdot\tilde{\Delta}^{\mathrm{mass}},$$

Oscillation

(density matrix of particle)-(density matrix of anti-particle)

Scattering

Scattering stops Oscillation.

Approximately

$$i\frac{d}{dt}\tilde{\Delta}^{\mathrm{mass}} \simeq [\Omega^{\mathrm{mass}}, \rho^{\mathrm{mass}} + \bar{\rho}^{\mathrm{mass}}] \qquad (t_{\mathrm{ini}} \lesssim t \lesssim t_{\mathrm{cut}})$$

$$i\frac{d}{dt}\tilde{\Delta}^{\mathrm{mass}} \simeq P(t)\cdot\tilde{\Delta}^{\mathrm{mass}}, \qquad (t_{\mathrm{cut}} \lesssim t \lesssim t_{\mathrm{end}})$$

Analytic solution

$$\tilde{\Delta}^{\text{mass}}(t_{\text{end}}) = \mathcal{T}\left(e^{-i\int_{t_{\text{ini}}+t_{\text{pair}}}^{t_{\text{end}}} dt' P(t')}\right)\tilde{\Delta}^{(0)}$$

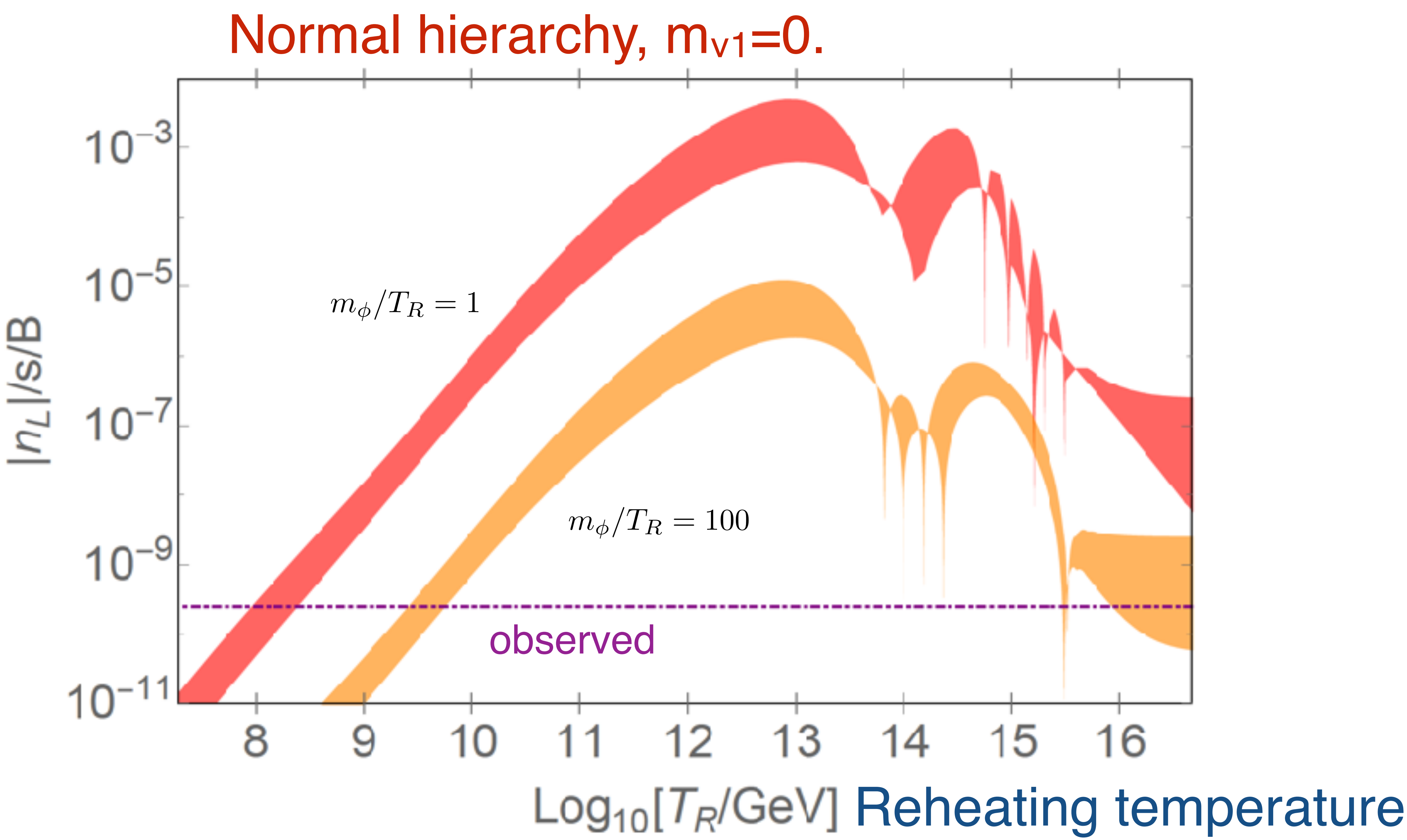
$$\tilde{\Delta}^{(0)} \simeq -i\left[\Omega^{\text{mass}}, \rho^{\text{mass}} + \bar{\rho}^{\text{mass}}\right] t_{\text{pair}}$$

This reproduces numerical result very well.

Numerical Result

[YH-Kitano-Yin '18]

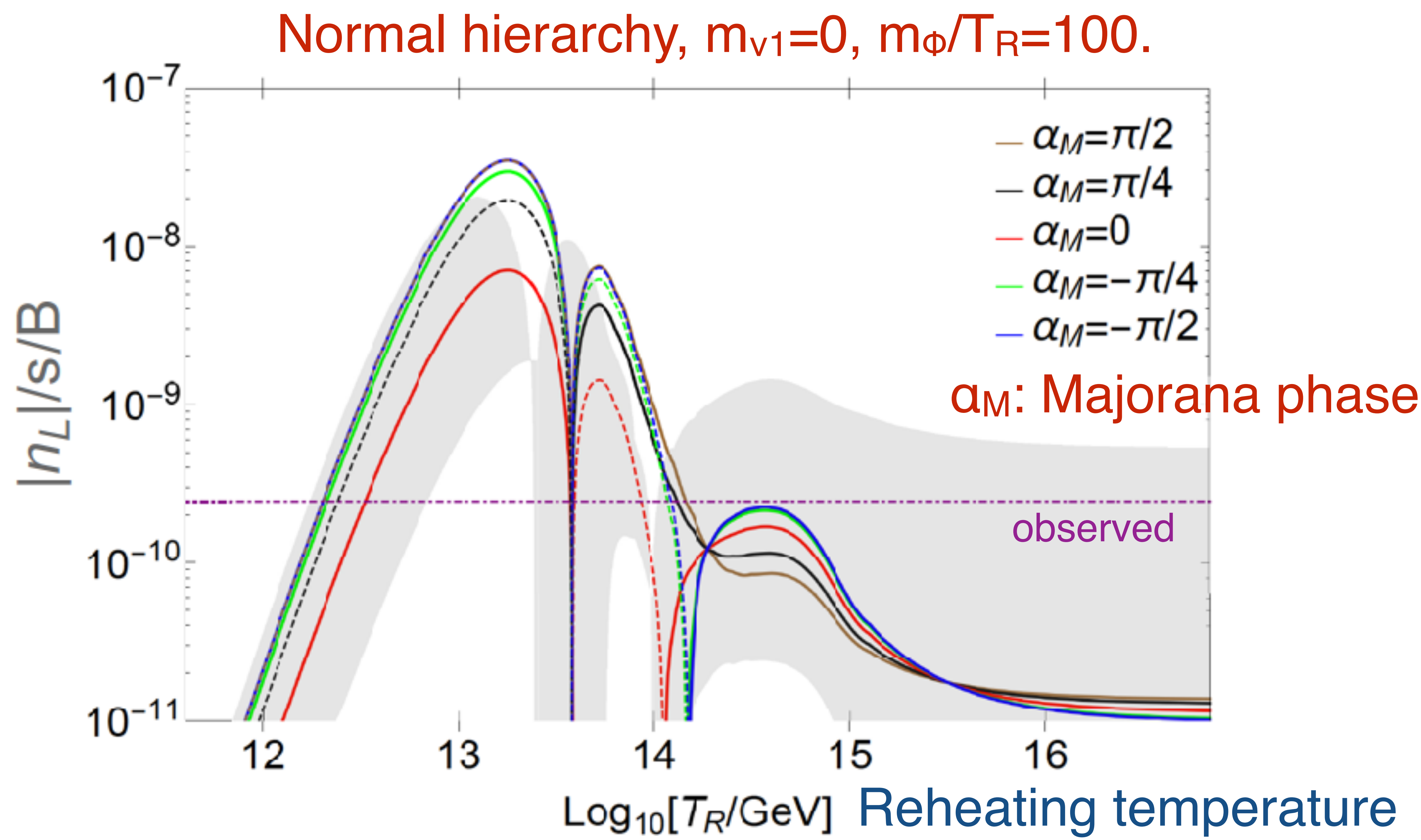
Inflaton Φ → leptons



Band: uncertainty of LPM effect. $T_R > 10^{15}$GeV is not trustable.

[YH-Kitano-Yin '18]

Inflaton $\Phi \to$ Higgs



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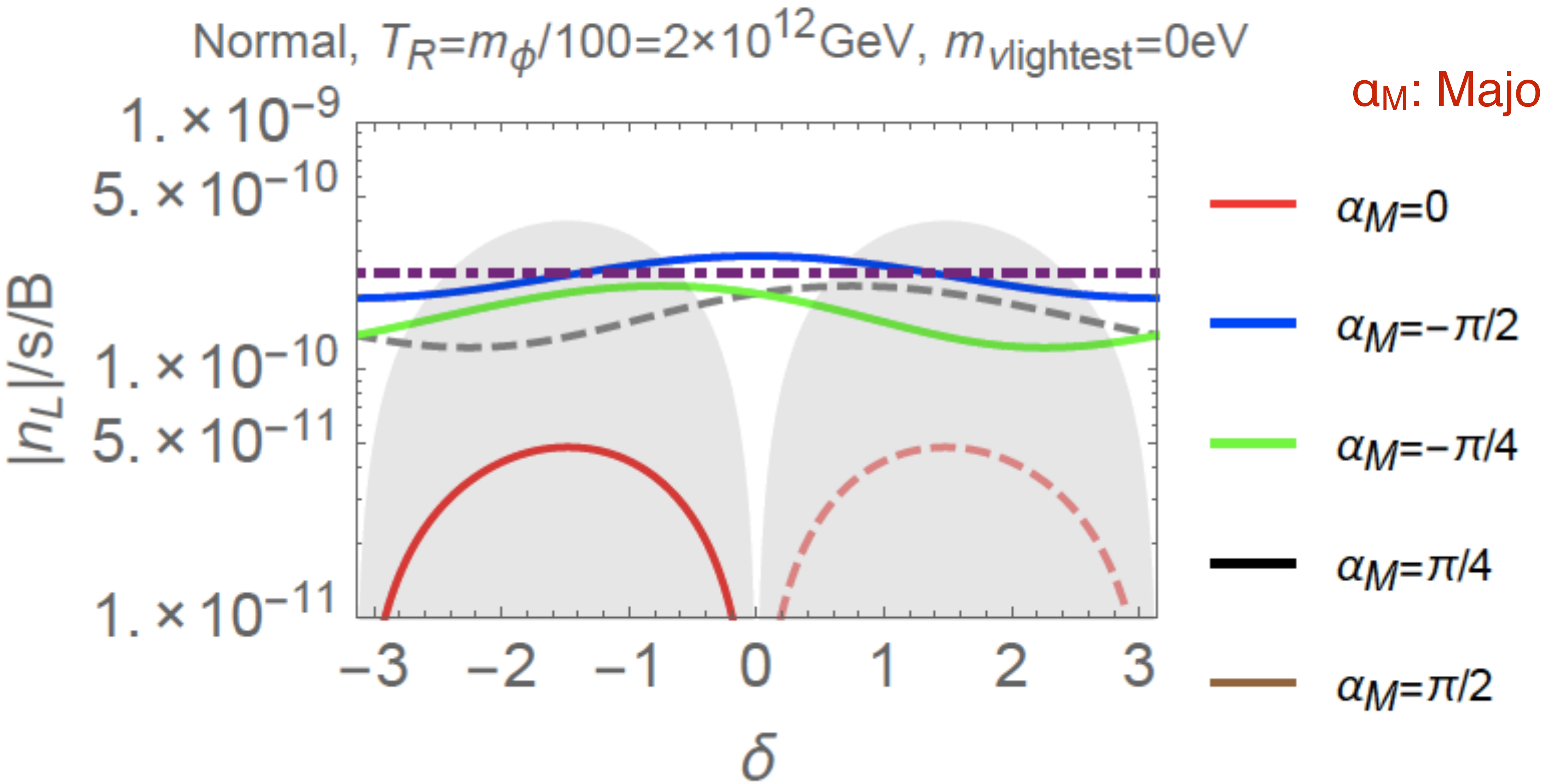
[YH-Kitano-Yin ’18]

Phase Dependence

α_M: Majorana phase



Dirac phase

Solid: correct sign ($n_B > 0$).
Dashed: wrong sign ($n_B < 0$)

Parameter dependence

- Inflaton→leptons

B: branching ratio, Lightest neutrino is massless.

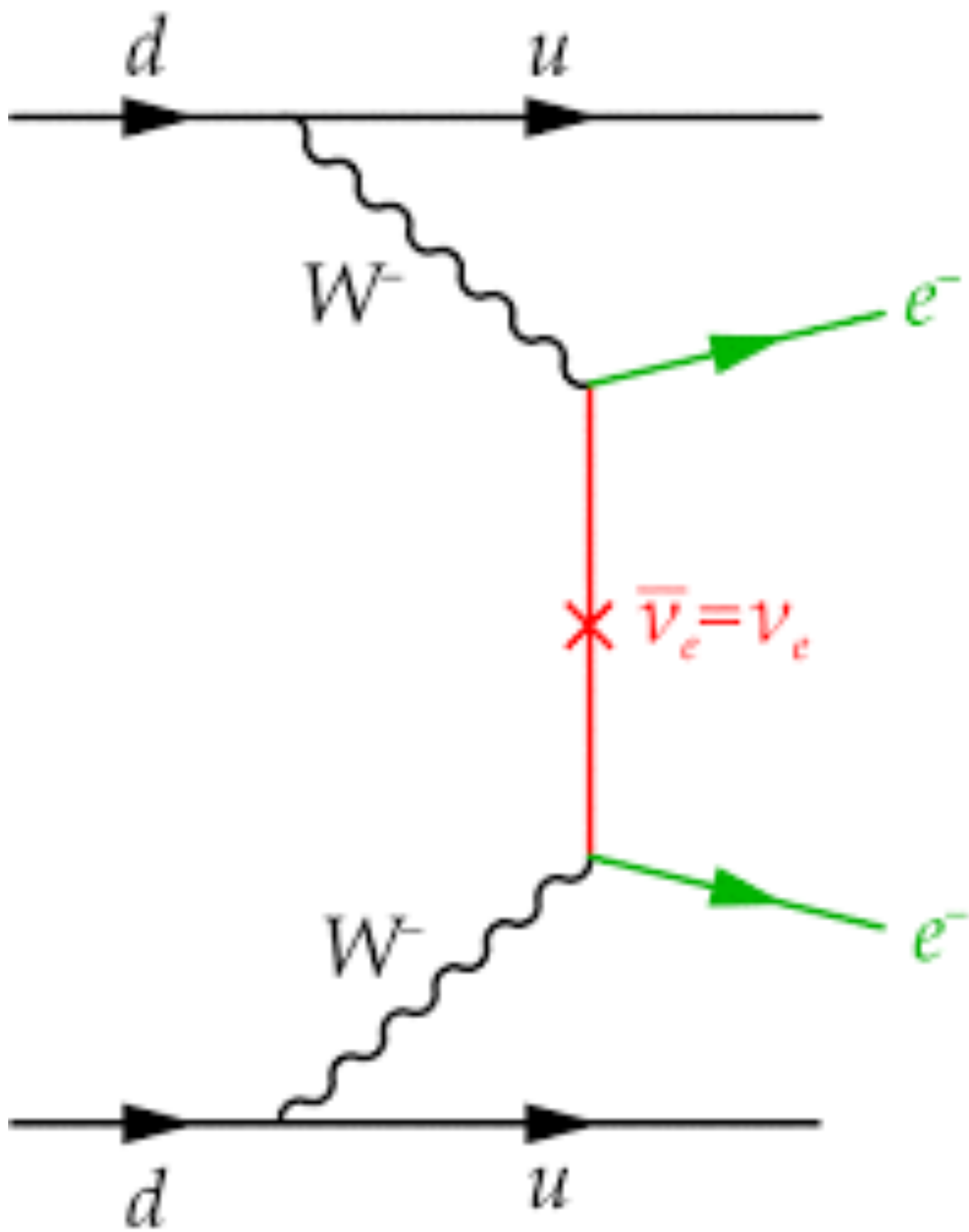
$$\frac{n_L}{s} \sim -2 \times 10^{-6} \cdot \xi_{CP} \cdot B \cdot \left(\frac{T_R}{10^{11}\ \mathrm{GeV}} \right)^3 \left(\frac{m_\phi}{10^{13}\ \mathrm{GeV}} \right)^{-1}$$

- Inflaton→Higgs

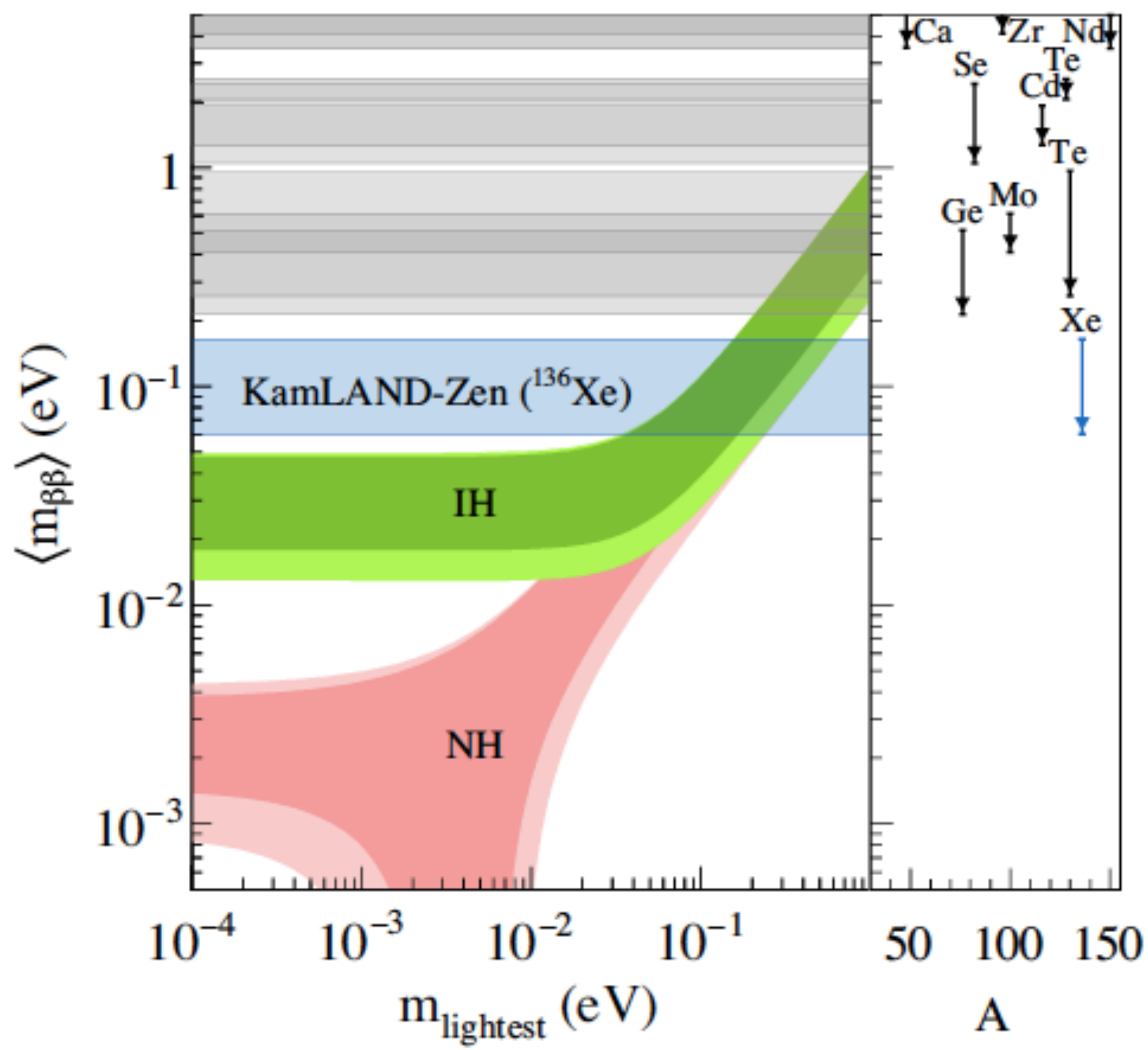
$$\frac{n_L}{s} \sim 4 \times 10^{-9} B \cdot \overline{\xi_{CP}} \left(\frac{T_R/m_\phi}{0.01} \right)^{1/2} \left(\frac{T_R}{10^{13}\ \mathrm{GeV}} \right)^3$$

$$\overline{\xi_{CP}} \sim (\sin \alpha_M + 0.2 \sin(\alpha_M + \delta))$$

ν less double β decay



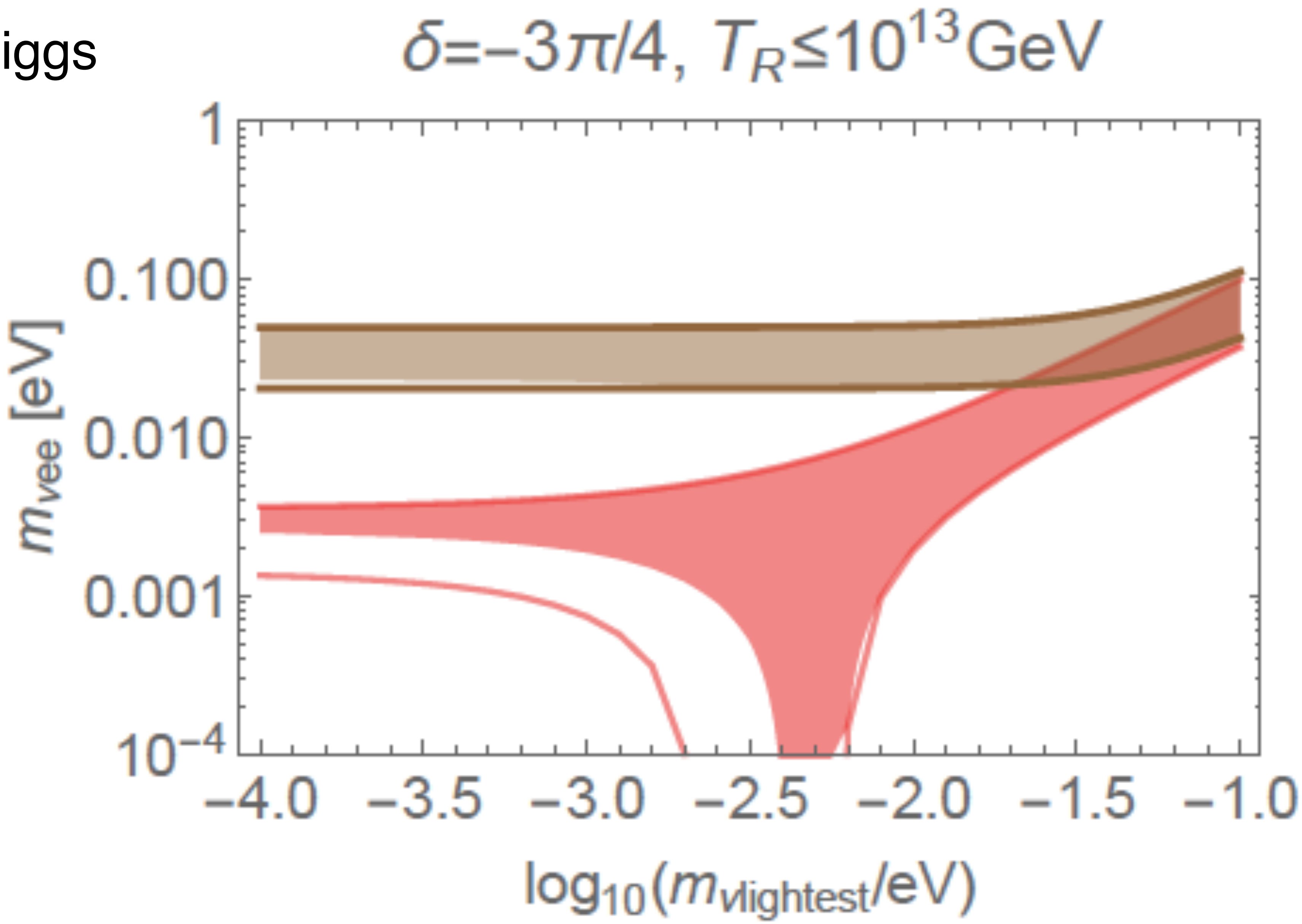
[KamLAND-Zen '16]



[YH-Kitano-Yin ’18]

Implication

Inflaton→Higgs



Summary

- We propose new scenario of baryogengesis where $T_R < M_{\nu R}$ and $M_\Phi < M_{\nu R}$.

- The oscillation of left handed lepton plays the crucial role.