1807.06582 with Ryuichiro Kitano, and Yuta Hamada

KAIST

Baryogenesis via active neutrino oscillation

Wen Yin, KAIST in Korea

comic by Yuki Akimoto, higgstan.com

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1. Introduction

How to generate the baryon asymmetry?

Sakharov's conditions

**Baryon/Lepton number violation*

**C and CP violation*

**Out of thermal equilibrium*

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***Baryon/Lepton number violation ✓**

***C and CP violation ✓**

Neutrino oscillation can provide CP violation. Observed at 2sigma level.

***Out of thermal equilibrium**

T2K Collaboration, 1701.00432

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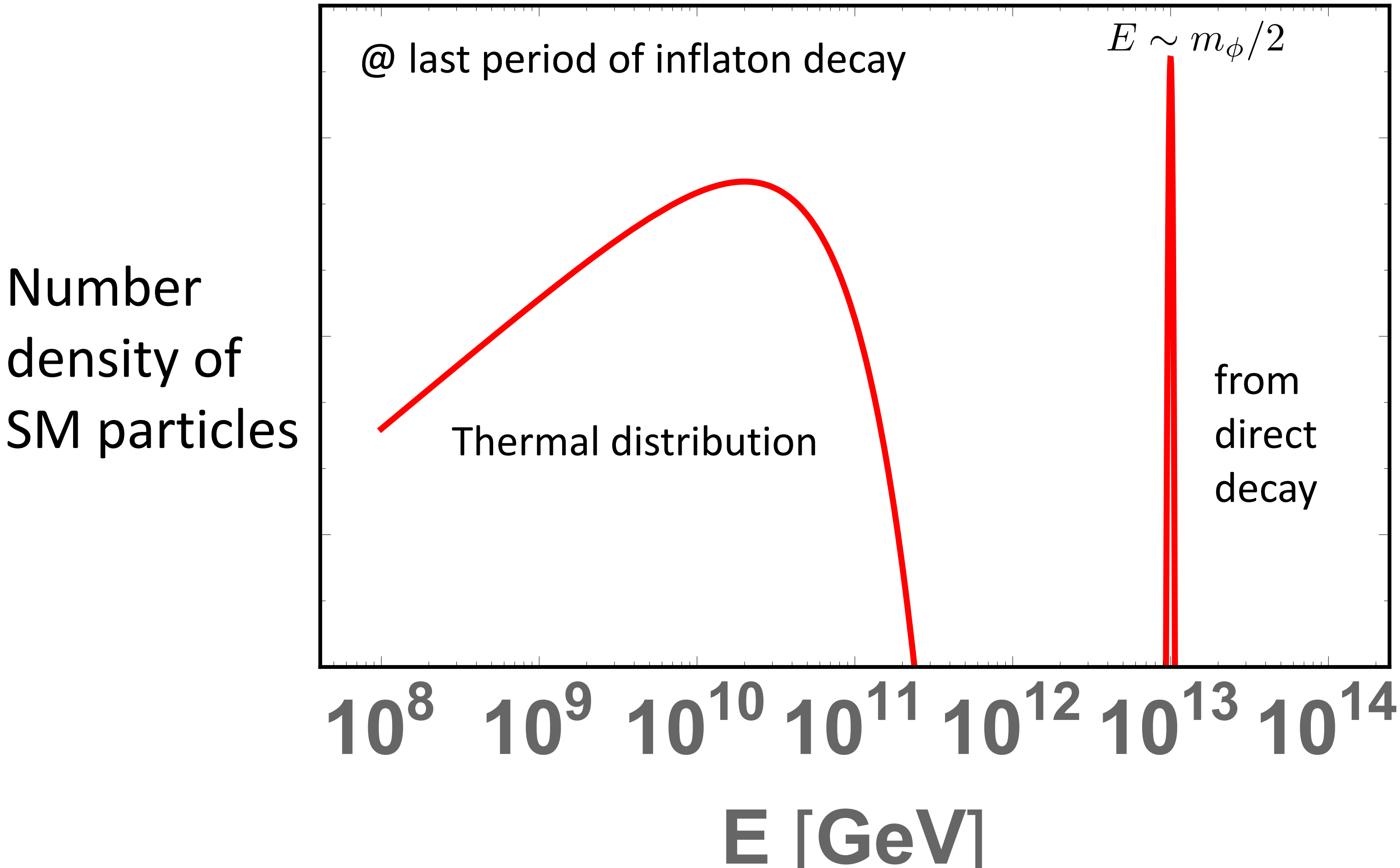
Big bang is a one way process

Inflaton decay: $\phi \to \text{SM particles}$



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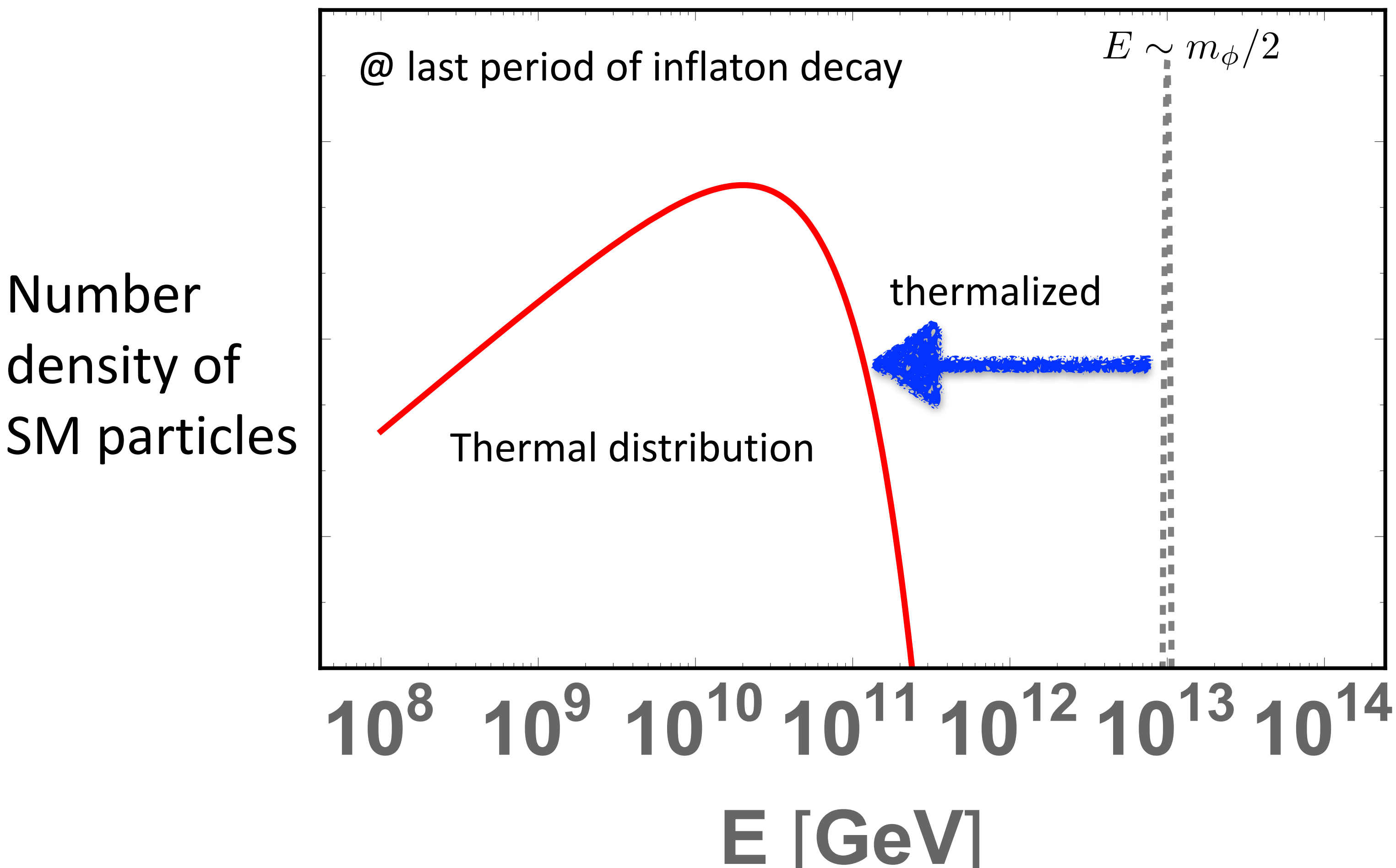
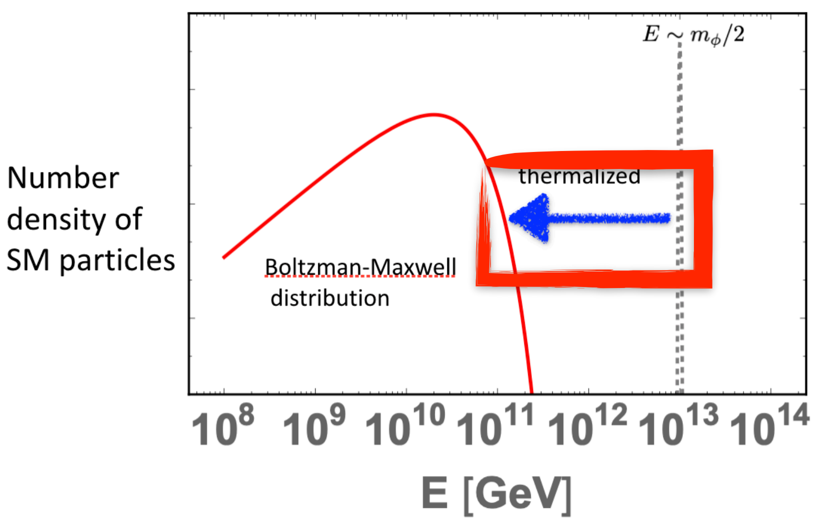


What I will show

Setup:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{\kappa_{ij}}{2}(\bar{l}_i^c P_L l_j) H H + \text{h.c.}$$

Baryogengesis due to active neutrino oscillation during the reheating/thermalization.



Leptogenesis from active neutrino oscillation with two higher dimensional terms.
Kitano, Hamada 1609.05028.

c.f. Leptogenesis with light enough right-handed neutrinos.
Fukugida, Yanagida, 86; Pilaftsis, 97; Akhmedov et al, 98;

2. Neutrino Oscillation at big bang

$$\phi \to \nu_{\rm ini} + X, \bar{\nu}_{\rm ini} + \bar{X}$$

$\langle \nu_{\rm ini} |$

$$P_{{\rm ini}\to I} \simeq |\sum_{\alpha} \langle \nu_{\rm ini} | \nu_\alpha \rangle e^{it_{\rm MFP}(m^{\rm th}_{\nu_\alpha})^2/k} \langle \nu_\alpha | \nu_I \rangle|^2$$

c.f. $P_{e\to\mu} \simeq |\sum_{\alpha} \langle \nu_e | \nu_\alpha \rangle e^{itm^2_{\nu_\alpha}/k} \langle \nu_\alpha | \nu_\mu \rangle|^2$ @ vacuum

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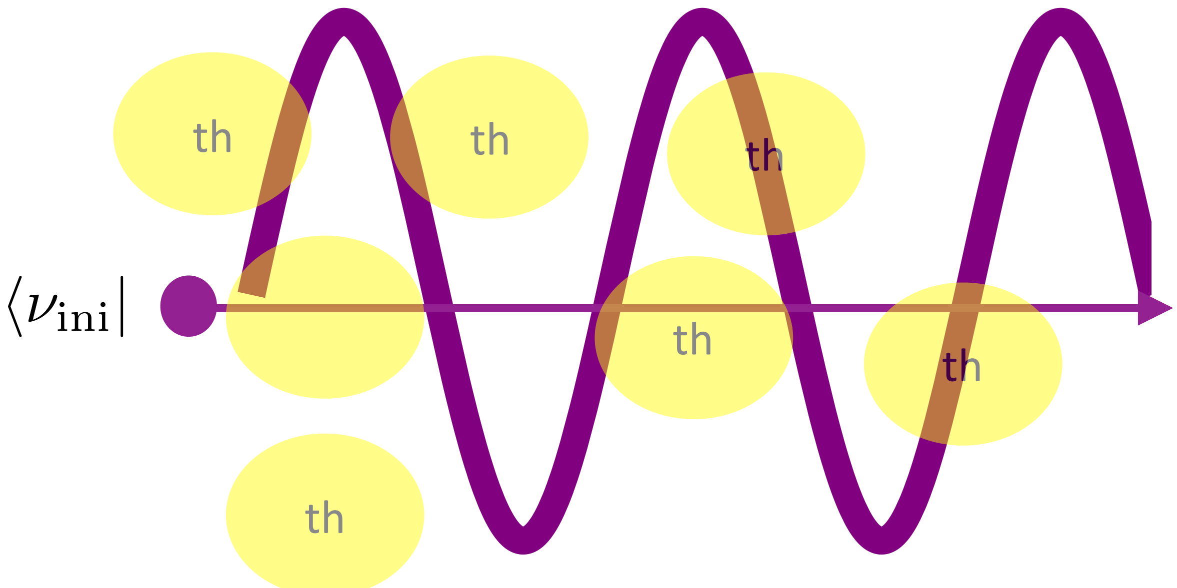

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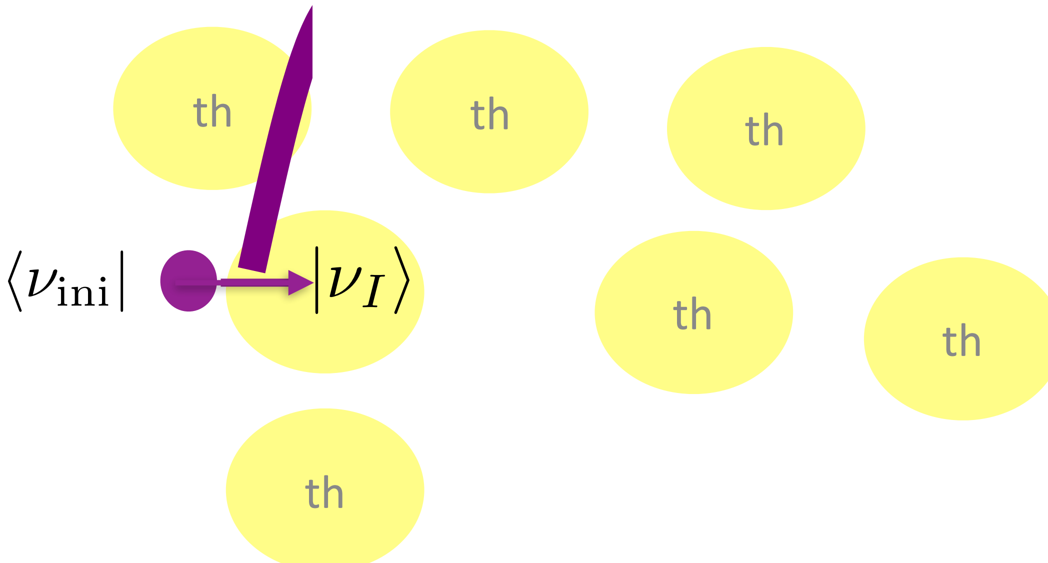

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Neutrino Oscillation provides CP violation

$$P_{\mathrm{ini}\to I} \simeq |\sum_\alpha \langle \nu_{\mathrm{ini}} | \nu_\alpha \rangle e^{i t_{\mathrm{MFP}} (m^{\mathrm{th}}_{\nu_\alpha})^2 / k} \langle \nu_\alpha | \nu_I \rangle |^2$$

$$t_{MFP} \sim \frac{1}{\alpha_2^2 T} \sqrt{\frac{k}{T}} \qquad (m^{\mathrm{th}}_{\nu,\alpha})^2 = \mathrm{eigen}[\frac{y_i^2 T^2}{16} \delta_{ij} + 0.046 (\kappa^* \kappa)_{ij} T^4] + C \delta_{ij}$$

$$P_{\mathrm{ini}\to I} - P_{\overline{\mathrm{ini}}\to \bar{I}} \propto \frac{\Delta (m^{\mathrm{th}}_\nu)^2}{k} t_{MFP} \sim 0.01 \sqrt{T/k}$$

c.f. $P_{e\to\mu} - P_{\bar{e}\to\bar{\mu}} \propto \sin[t \Delta m_\nu^2 / k]$ @vacuum

Oscillation phase is not too small at the reheating era.

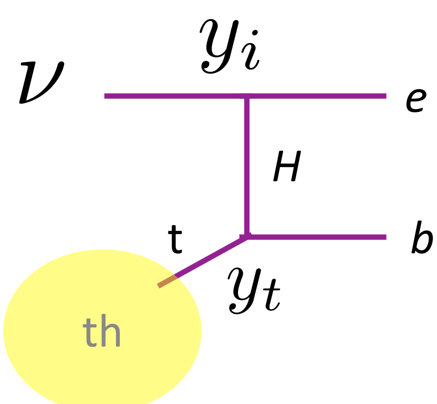
(In fact it is even larger than the naive estimate by factor $\sqrt{k/T}$)

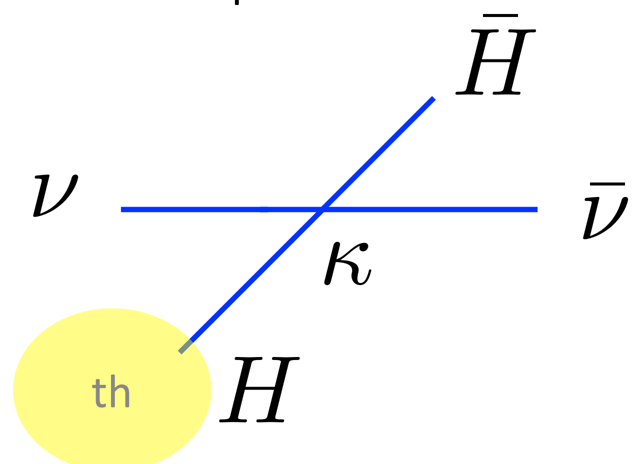
How to observe the “flavor”?

$$P_{\mathrm{ini}\to I} \simeq \left|\sum_{\alpha} \langle \nu_{\mathrm{ini}} | \nu_\alpha \rangle e^{i t_{\mathrm{MFP}} (m^{\mathrm{th}}_{\nu_\alpha})^2/k} \langle \nu_\alpha | \nu_I \rangle \right|^2$$

Only flavor dependent process can identify the flavor.

“Observation” is made due to the following interaction process.





$|\nu_I\rangle$ is the state defined by the interaction.

Lepton number violation happens through "observation".

$$P_{\mathrm{ini}\to I} \simeq |\sum_{\alpha} \langle \nu_{\mathrm{ini}}|\nu_\alpha\rangle e^{it_{\mathrm{MFP}}(m^{\mathrm{th}}_{\nu_\alpha})^2/k}\langle\nu_\alpha|\nu_I\rangle|^2$$

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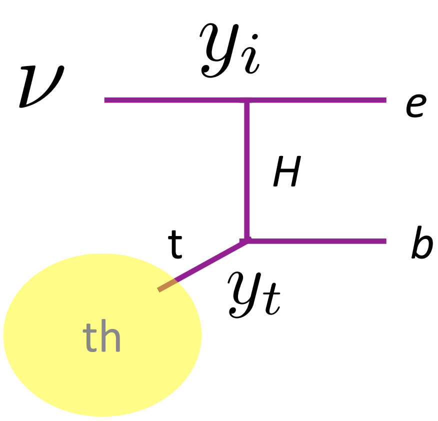
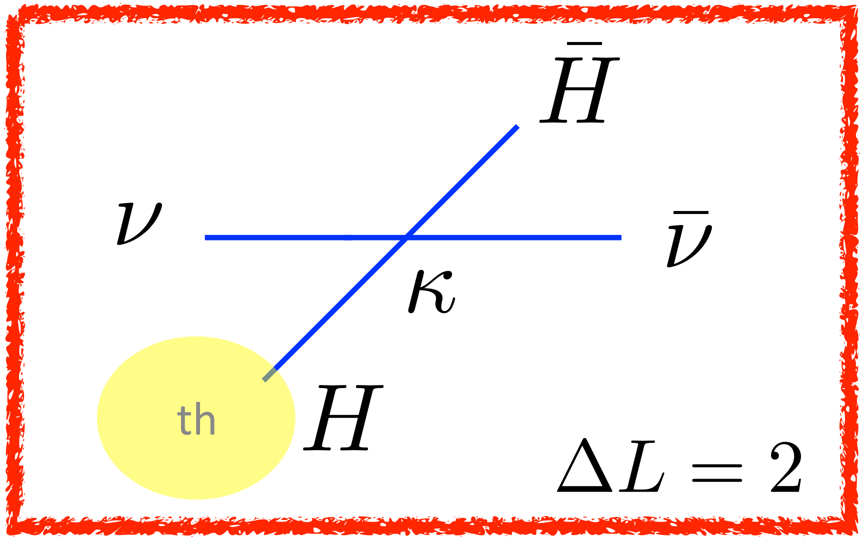




Lepton asymmetry can be made!

The (naive) estimation of lepton asymmetry

$m_\phi \sim T \ll 10^{12} GeV$ with certain CP phase

$$\frac{\Delta n_L}{s} \propto Br_{\phi \to \nu_{\rm ini} + X / \overline{\nu_{\rm ini}} + \overline{X}} \times t_{MFP} \frac{\Delta m_\nu^2}{T} \times \frac{\sigma^{\rm th}_{llHH}}{\sigma^{\rm th}_{\rm yukawa}}$$

CP violation (blue underline: $t_{MFP} \frac{\Delta m_\nu^2}{T}$)

lepton # violation (red underline: $\frac{\sigma^{\rm th}_{llHH}}{\sigma^{\rm th}_{\rm yukawa}}$)

Blue line: Flavor dependent asymmetry of order $\frac{\Delta m_{\rm th}^2}{T} \frac{1}{\Gamma_{\rm th}} \sim 0.01$

Red line: How frequently the flavor is observed by the llHH interaction.

$$\frac{\sigma^{th}_{llHH}}{\sigma^{th}_{\rm yukawa}} \sim \frac{\Delta m_\nu^2 / v^4 T^2}{y_\tau^2 y_t^2}$$

The (naive) estimation of lepton asymmetry

$m_\phi \sim T \ll 10^{12} GeV$

$$\frac{\Delta n_L}{s} \propto Br_{\phi \to \nu_{\rm ini} + X / \bar{\nu}_{\rm ini} + \bar{X}} \times 10^{-9} \left(\frac{T_R}{10^9 GeV} \right)^2$$

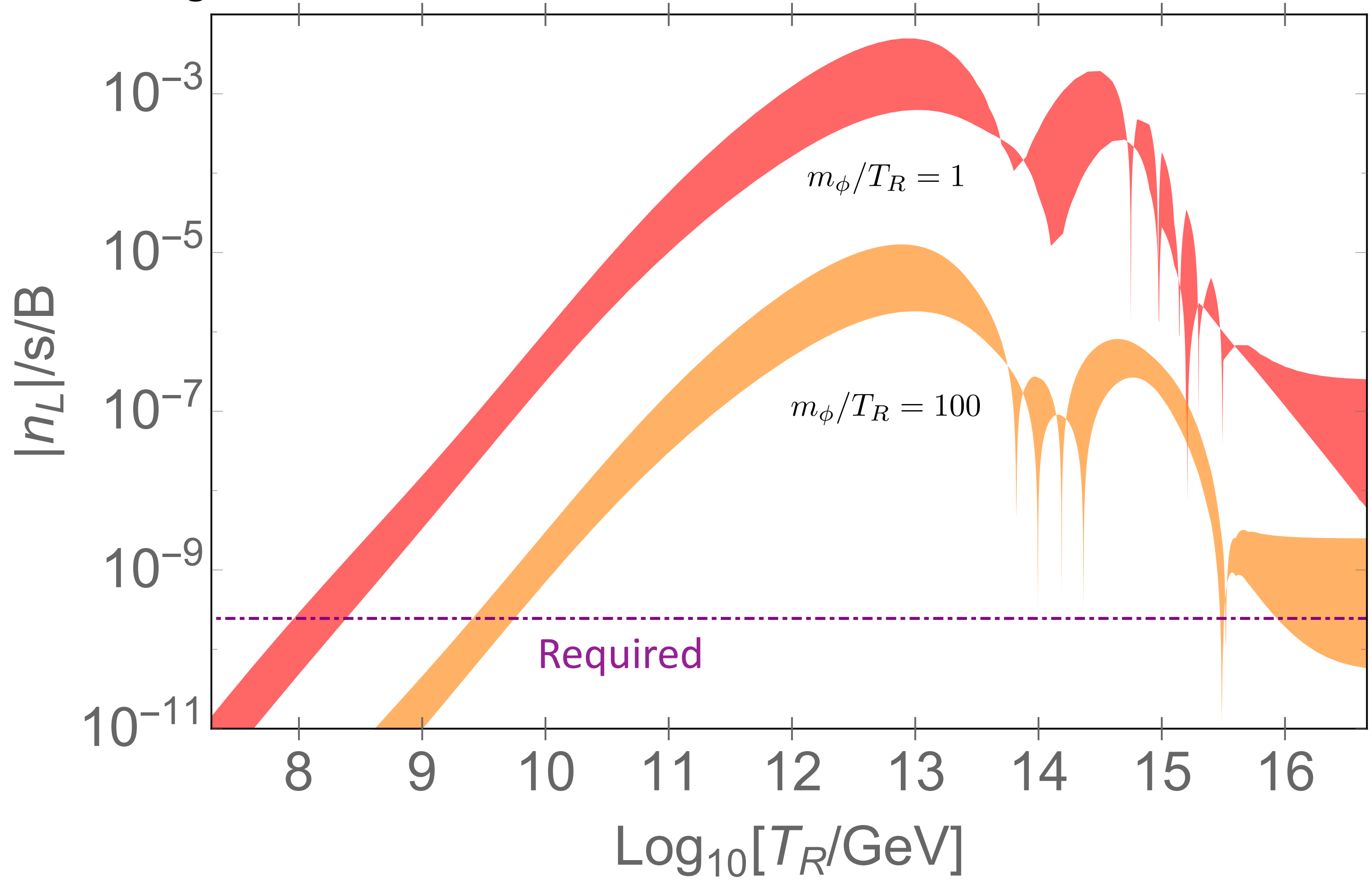
c.f. required asymmetry $$|\Delta n_L / s| \sim 10^{-10}$$

Enough asymmetry can be made for sufficiently high reheat temperature.

For a precise prediction or more complicated processes,
we need a systematic approach.

3. Numerical result (Normal Hierarchy)

By solving kinetic equations, Sigl, Raffelt, 1993
we get



Dirac phase=-pi/2,
Majorana phase=0.3
V∝{1,1,1}

Assumption:
1. Flavor dependent coupling ϕ to ν.
2. Preexisting thermal plasma of all SM particles.

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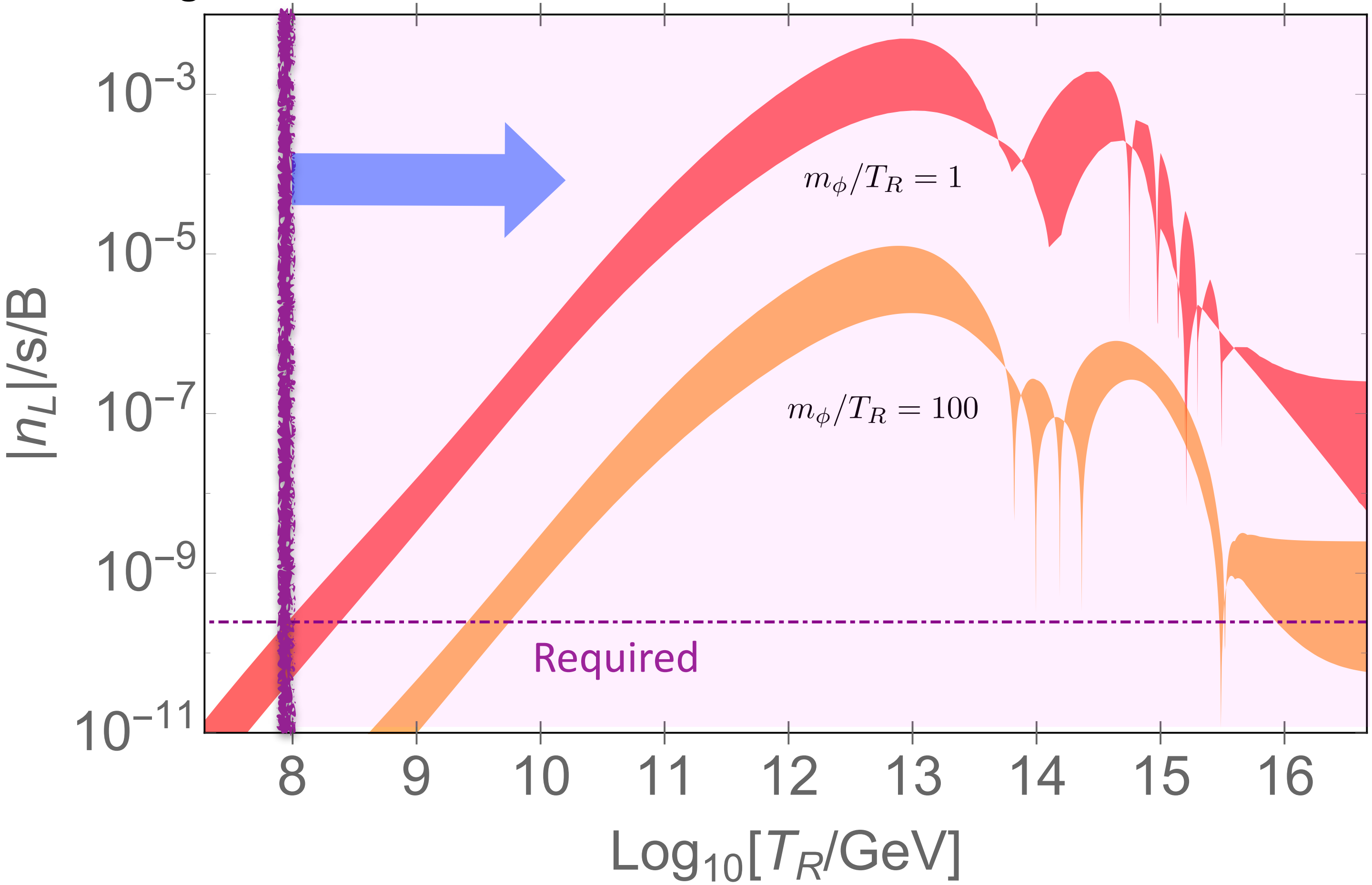

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Assumption:
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2. Preexisting thermal plasma of all SM particles.

Baryogenesis can be successful for $T_R \gtrsim 10^8\, GeV$ ***due to active ν oscillation during thermalization.***

Summary

Kitano, Hamada, WY 1807.06582

Baryon asymmetry explained within SM with

$$-\frac{\kappa_{ij}}{2}(\bar{l}_i^c P_L l_j) H H + \text{h.c.}$$

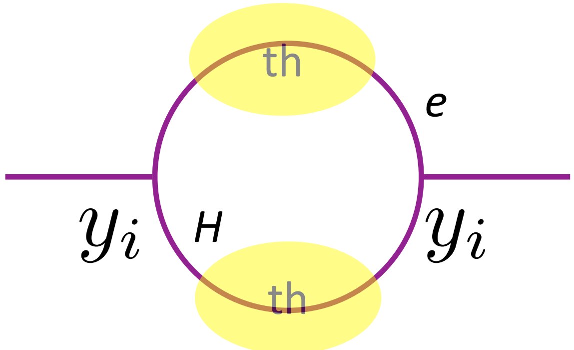
- Required reheat temperature $> 10^8\ GeV$.

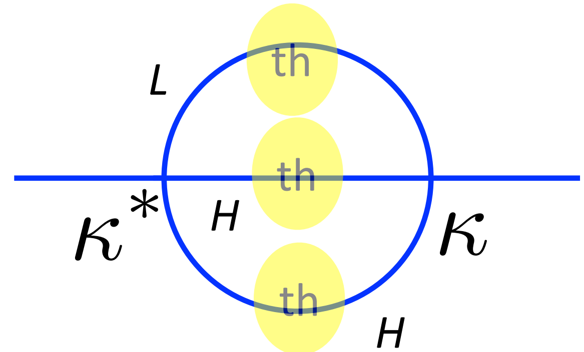
- The scenario can be tested in future neutrino exps, such as neutrinoless double beta decay exps, especially for inflaton dominantly decays to Higgs. (given in our paper.)

Backups

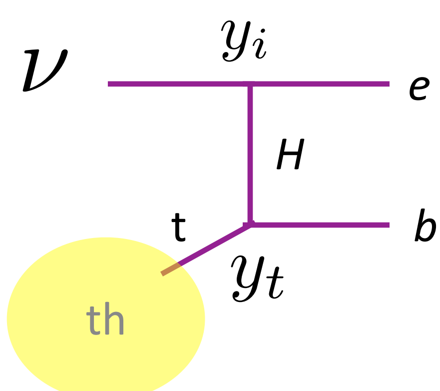
Mass basis $\neq$ interaction basis!

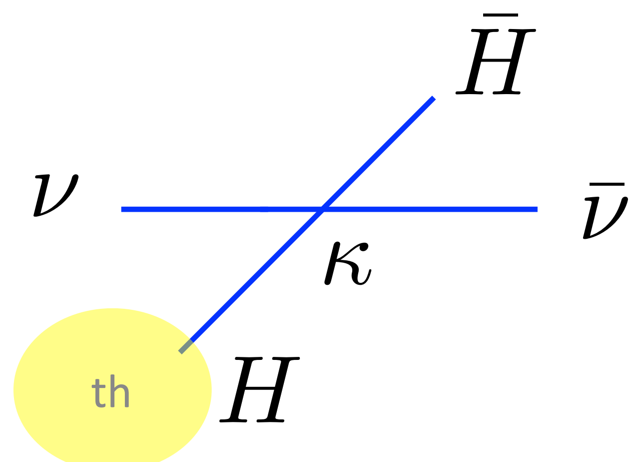
Mass:





Interaction:



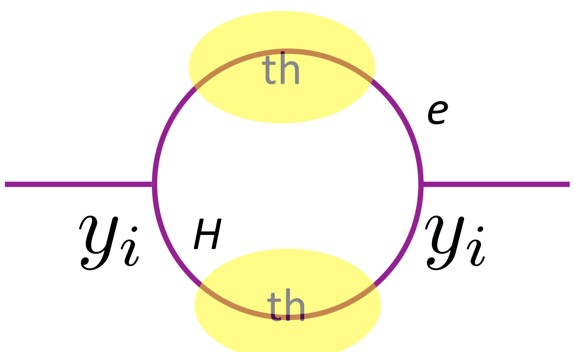


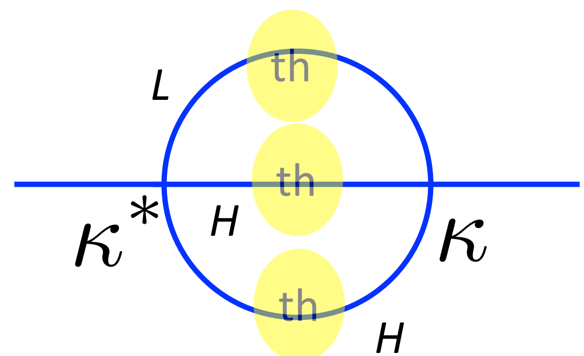
CP violation can take place!

Oscillating frequency during reheating.

$$P_{\mathrm{ini}\to I} \simeq \left| \sum_{\alpha} \langle \nu_{\mathrm{ini}} | \nu_\alpha \rangle e^{i t_{\mathrm{MFP}} (m^{\mathrm{th}}_{\nu_\alpha})^2 / k} \langle \nu_\alpha | \nu_I \rangle \right|^2$$

$$(m^{\mathrm{th}}_{\nu,\alpha})^2 = \mathrm{eigen}\left[\frac{y_i^2 T^2}{16}\delta_{ij} + 0.046(\kappa^*\kappa)_{ij} T^4\right] + C\delta_{ij}$$





$|\nu_\alpha\rangle$ is the mass eigen state.

Kinetic Equation (Extended Boltzmann Eqs)

density matrix for left-handed leptons $\rho(\mathbf{p}) \equiv \rho_{ij}(\mathbf{p})$ $i, j = e, \mu, \tau$

$$i\frac{d\rho(\mathbf{p})}{dt} = [\Omega(\mathbf{p}), \rho(\mathbf{p})] - \frac{i}{2}\{\Gamma^d_{\mathbf{p}}, \rho(\mathbf{p})\} + \frac{i}{2}\{\Gamma^p_{\mathbf{p}}, 1 - \rho(\mathbf{p})\},$$

Oscillation term Interaction terms (with CP phase)

$$\left(i\frac{d\overline{\rho}(\mathbf{p})}{dt} = - [\Omega(\mathbf{p}), \bar{\rho}(\mathbf{p})] - \frac{i}{2}\{\Gamma^d_{\mathbf{p}}, \overline{\rho}(\mathbf{p})\} + \frac{i}{2}\{\Gamma^p_{\mathbf{p}}, 1 - \overline{\rho}(\mathbf{p})\}, \right)^*$$

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

This is absent in ordinary Boltzmann eqs.

$\mathrm{tr}[\Omega, \rho] = 0$ $\mathrm{tr}\,[\rho - \bar{\rho}]$

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Different ↕ Interaction terms (with CP phase)

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strong phase

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This is absent in ordinary Boltzmann eqs.

Oscillation term generates flavor dependent lepton asymmetry,
but $\mathrm{tr}[\Omega, \rho] = 0$ means total asymmetry $\mathrm{tr}\,[\rho - \bar{\rho}]$ is not generated.

Two scales approximation

Two scales approximation, $p \sim m_\phi, p \sim T$

$$(\rho_{\mathbf{k}})_{ij} = \int_{|\mathbf{p}|\sim m_\phi} \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{\rho_{ij}(\mathbf{p},t)}{s},$$

$$(\delta\rho_T)_{ij} = \int_{|\mathbf{p}|\sim T} \frac{d^3\mathbf{p}}{(2\pi)^3} \left(\frac{\rho_{ij}(\mathbf{p})}{s} - \frac{\rho^{\rm eq}_{ij}(\mathbf{p})}{s}\right),$$

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

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

Equations to be solved

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

+ eqs of right-handed/anti leptons

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

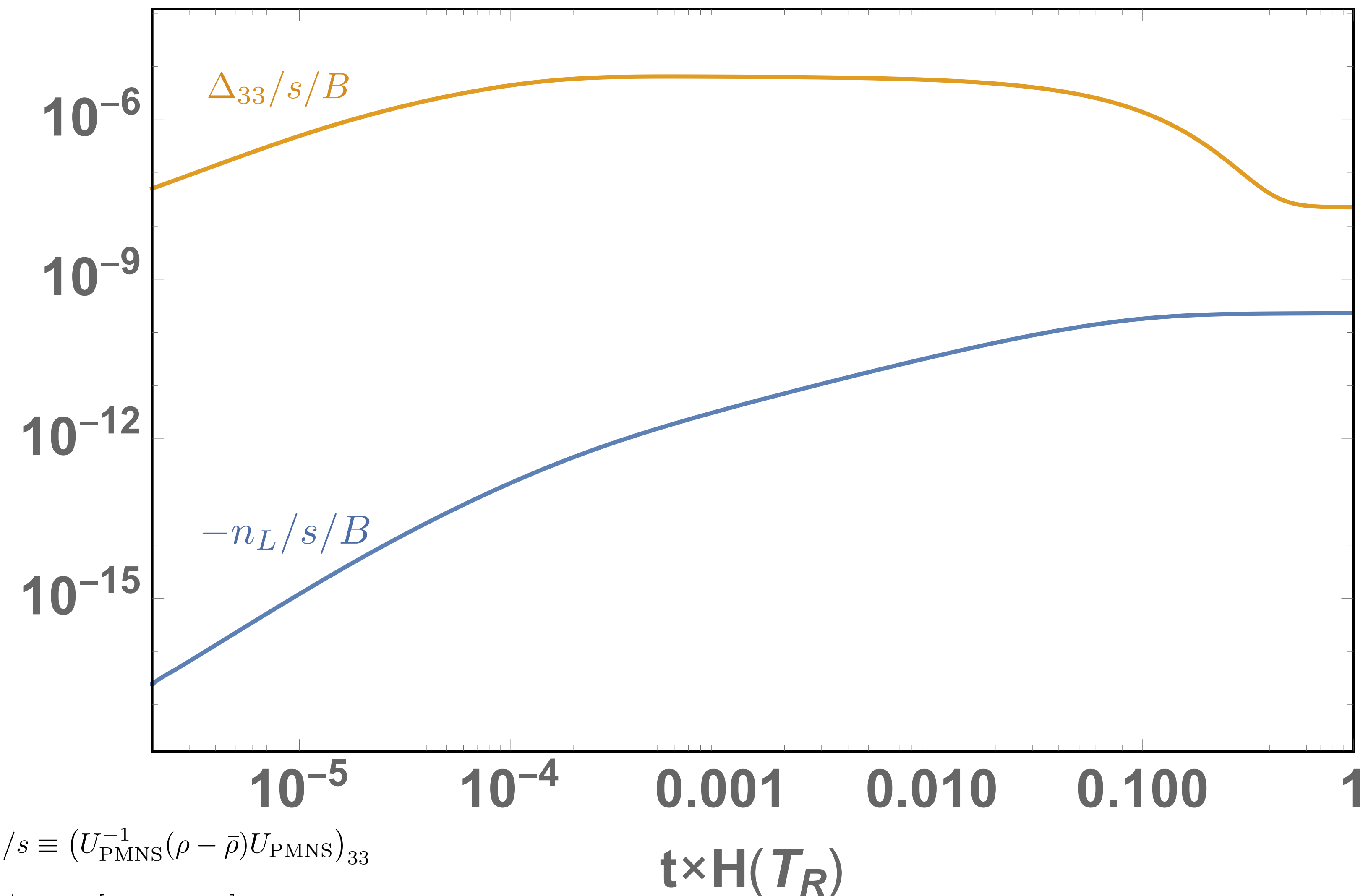
$$\Omega_k = \frac{y_i^2 T^2}{16 m_\phi}\delta_{ij} + 0.046(\kappa^*\kappa)_{ij}\frac{T^4}{m_\phi} \qquad \Omega_T = \frac{y_i^2 T}{16}\delta_{ij} + 0.046(\kappa^*\kappa)_{ij}T^3$$

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

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

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

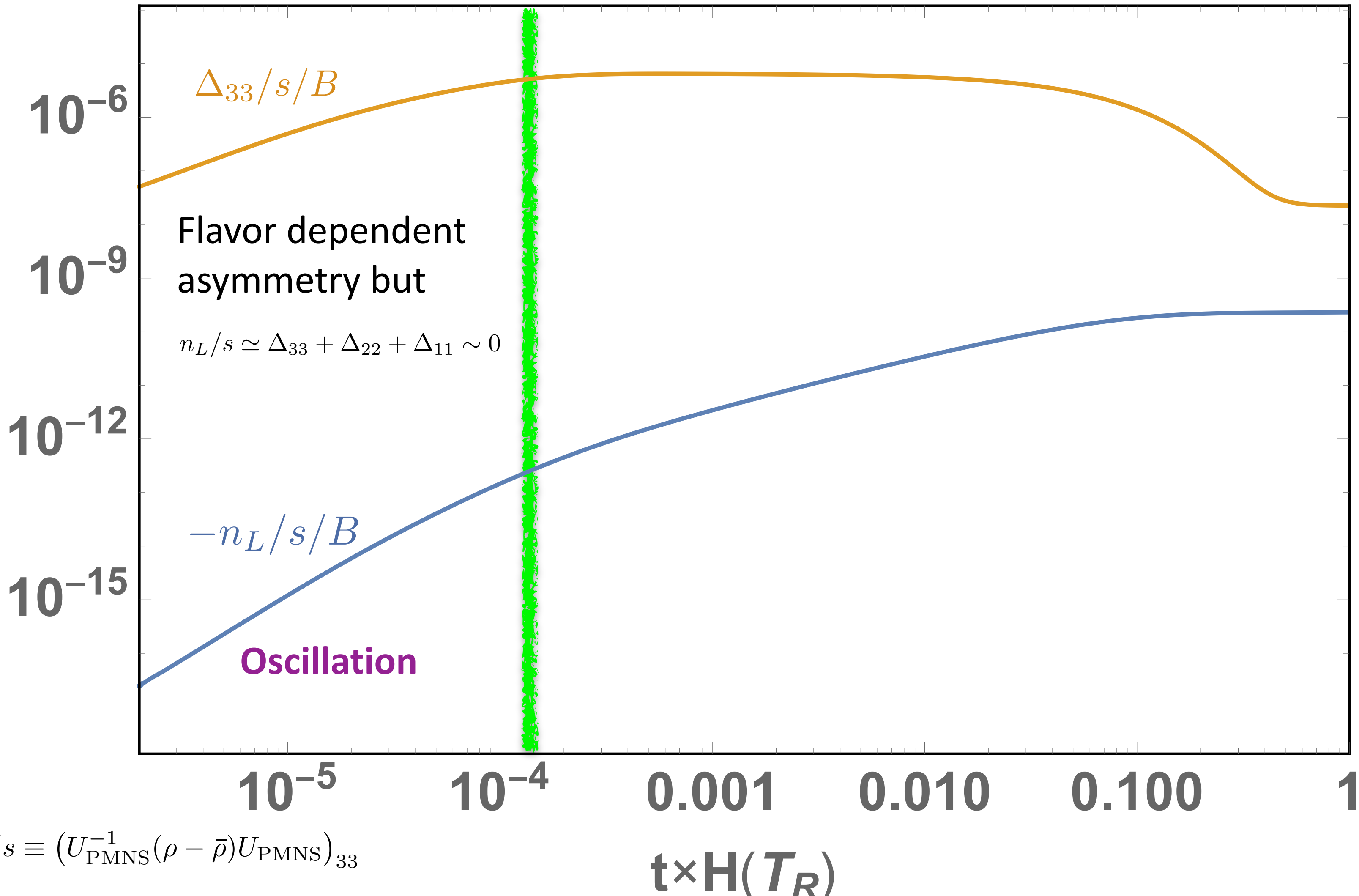
Some formula can be also found in Akhmedov,et al. 9803255; Abada, et al. 0601083.; Asaka, et al. 1112.5565.
See Refs. [Landau and Pomeranchuk 1953; Migdal 1956] for LPM effect.



$$\Delta_{33}/s \equiv \left(U^{-1}_{\rm PMNS}(\rho-\bar{\rho})U_{\rm PMNS}\right)_{33}$$

$$n_L/s \equiv {\rm Tr}[\rho-\bar{\rho}+...]$$

★



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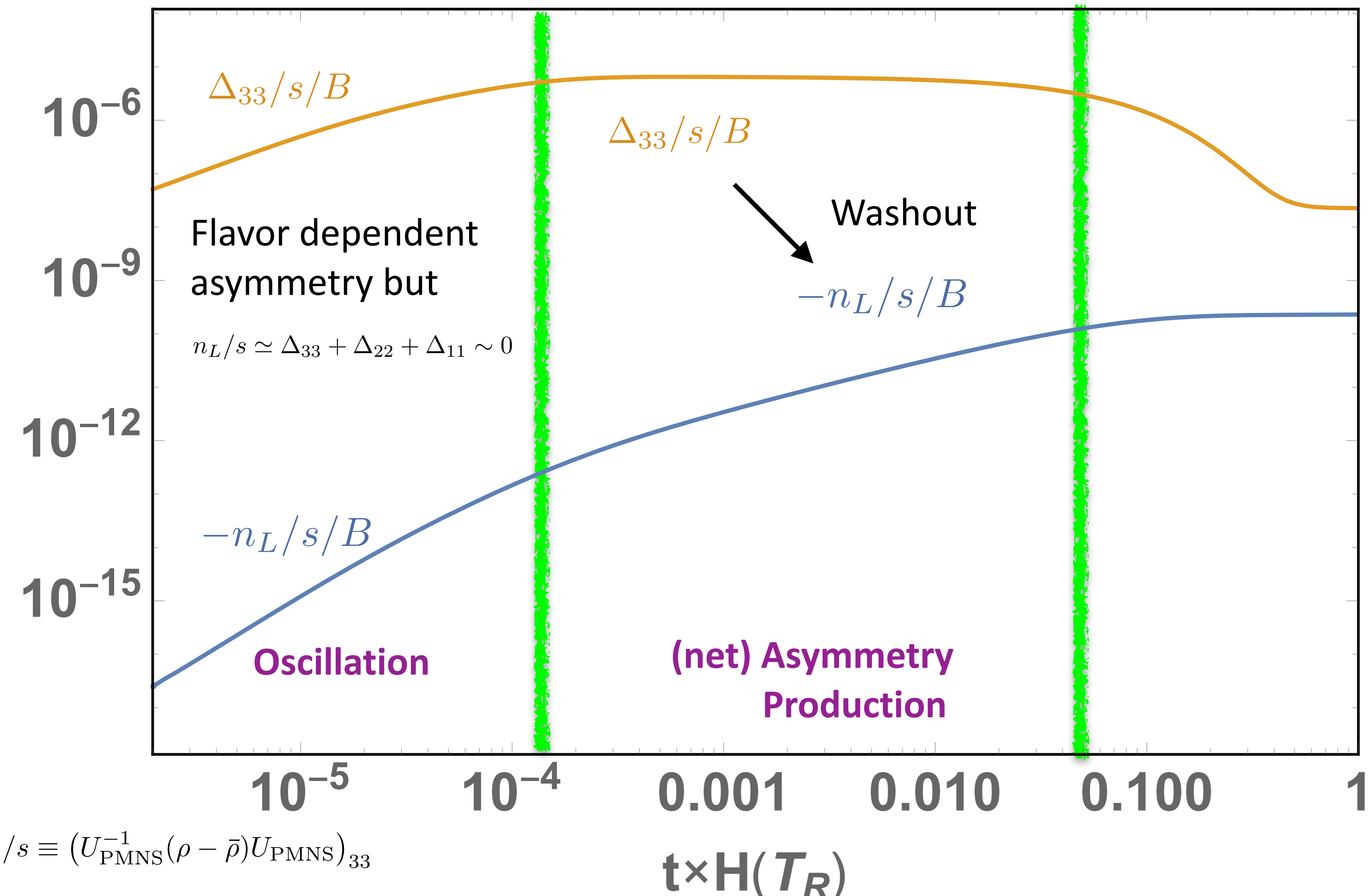
★ $(\Gamma_{wo})_\alpha \propto m_{\nu_\alpha}^2$

Normal hierarchy: $(\Gamma_{wo})_3$ is largest.



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★ $(\Gamma_{wo})_\alpha \propto m^2_{\nu_\alpha}$

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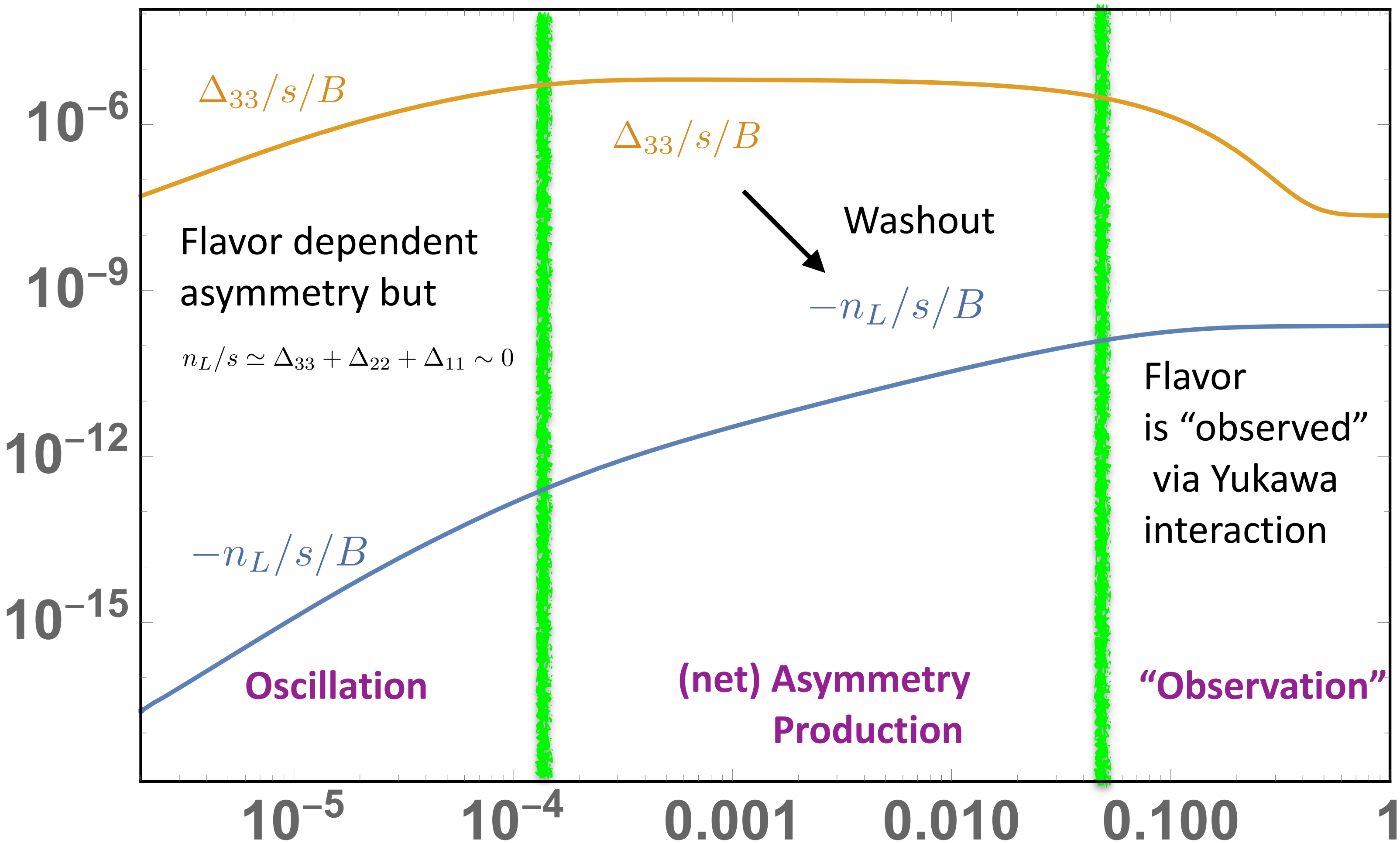

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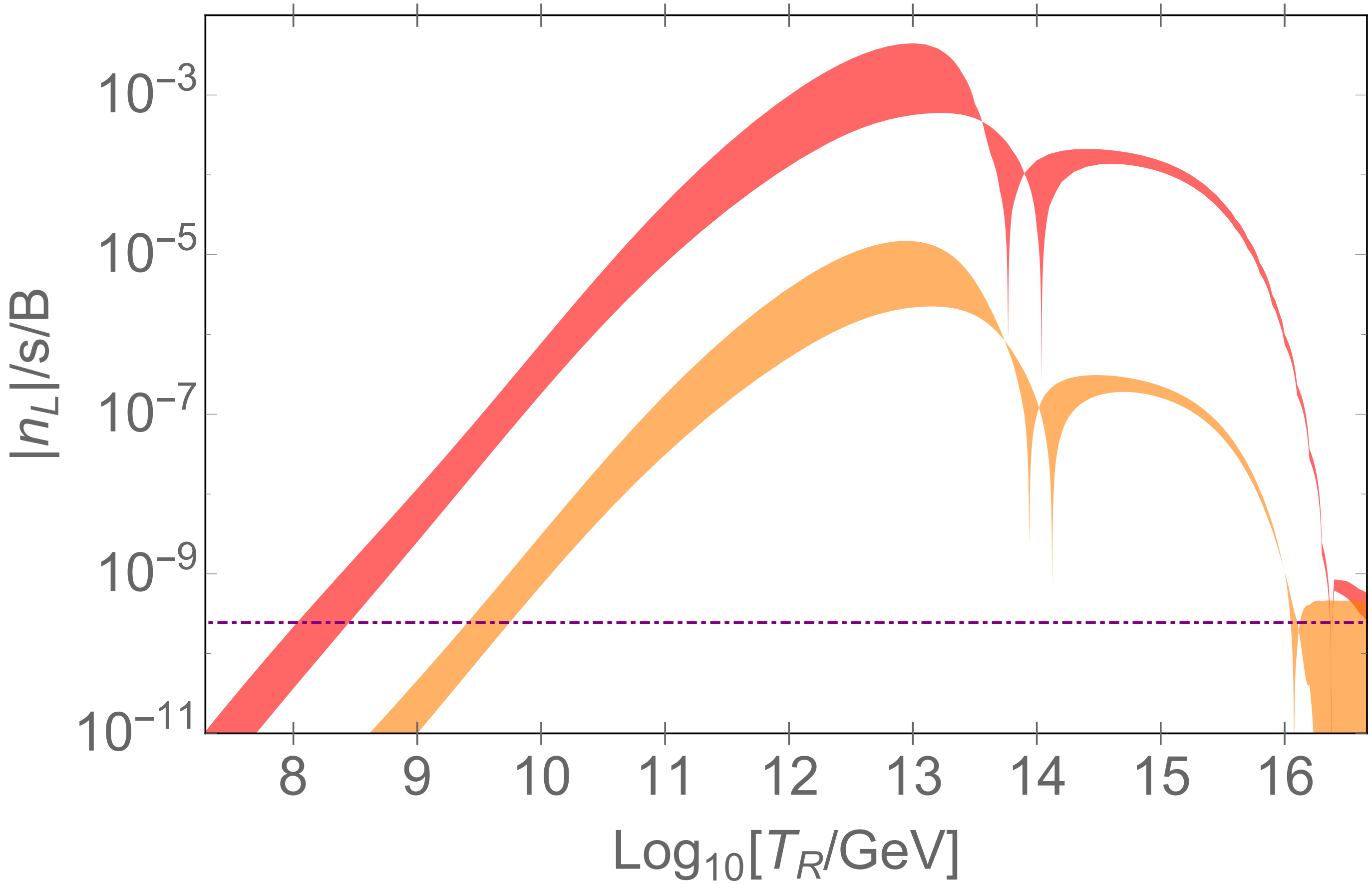
FIGURES FOR INFLATON->LEPTON

Inverted hierarchy one massless neutrino.
Other parameters are same as the main part one.



normal order degenerate mass. mnulightest=0.07eV
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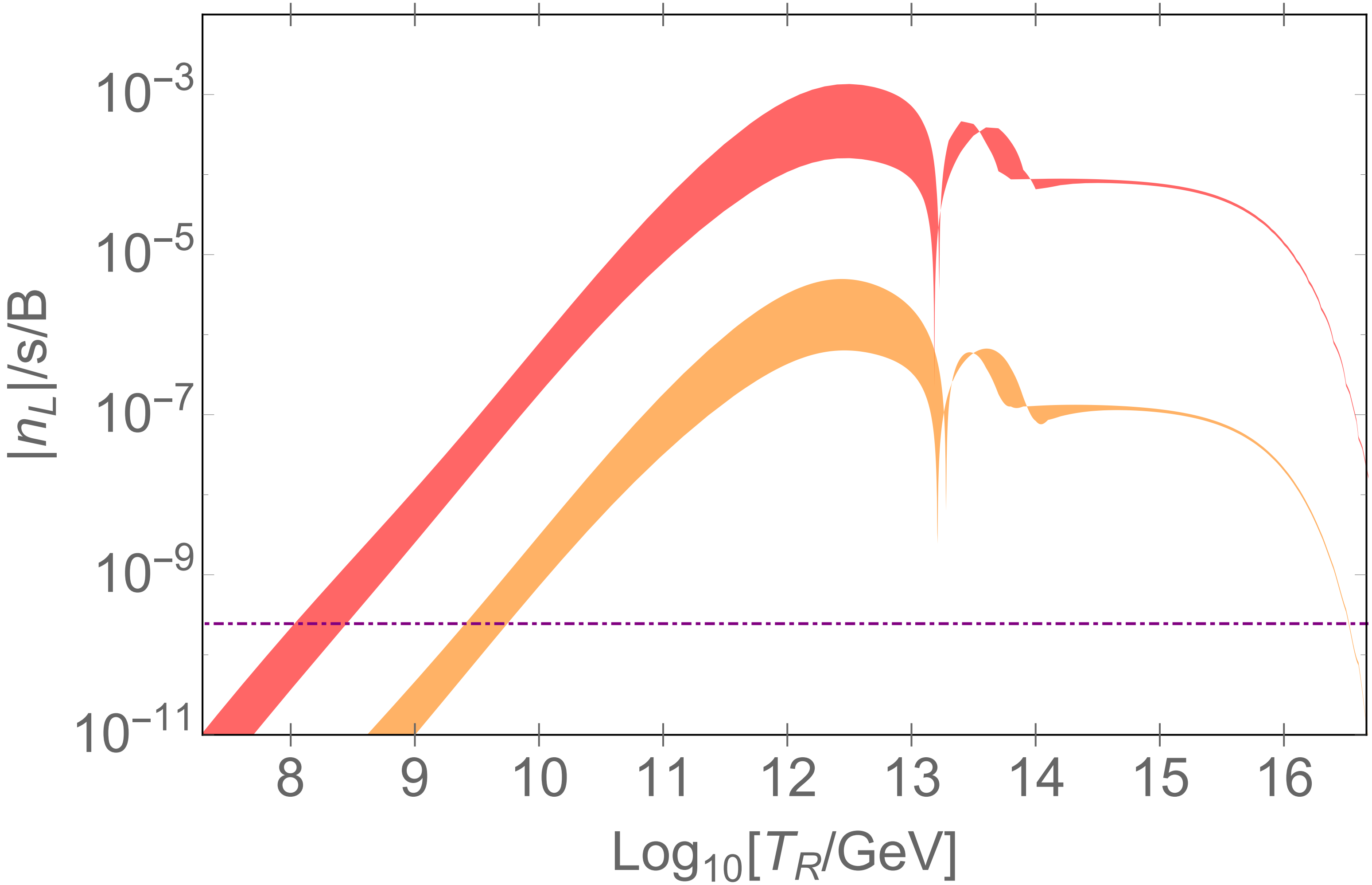

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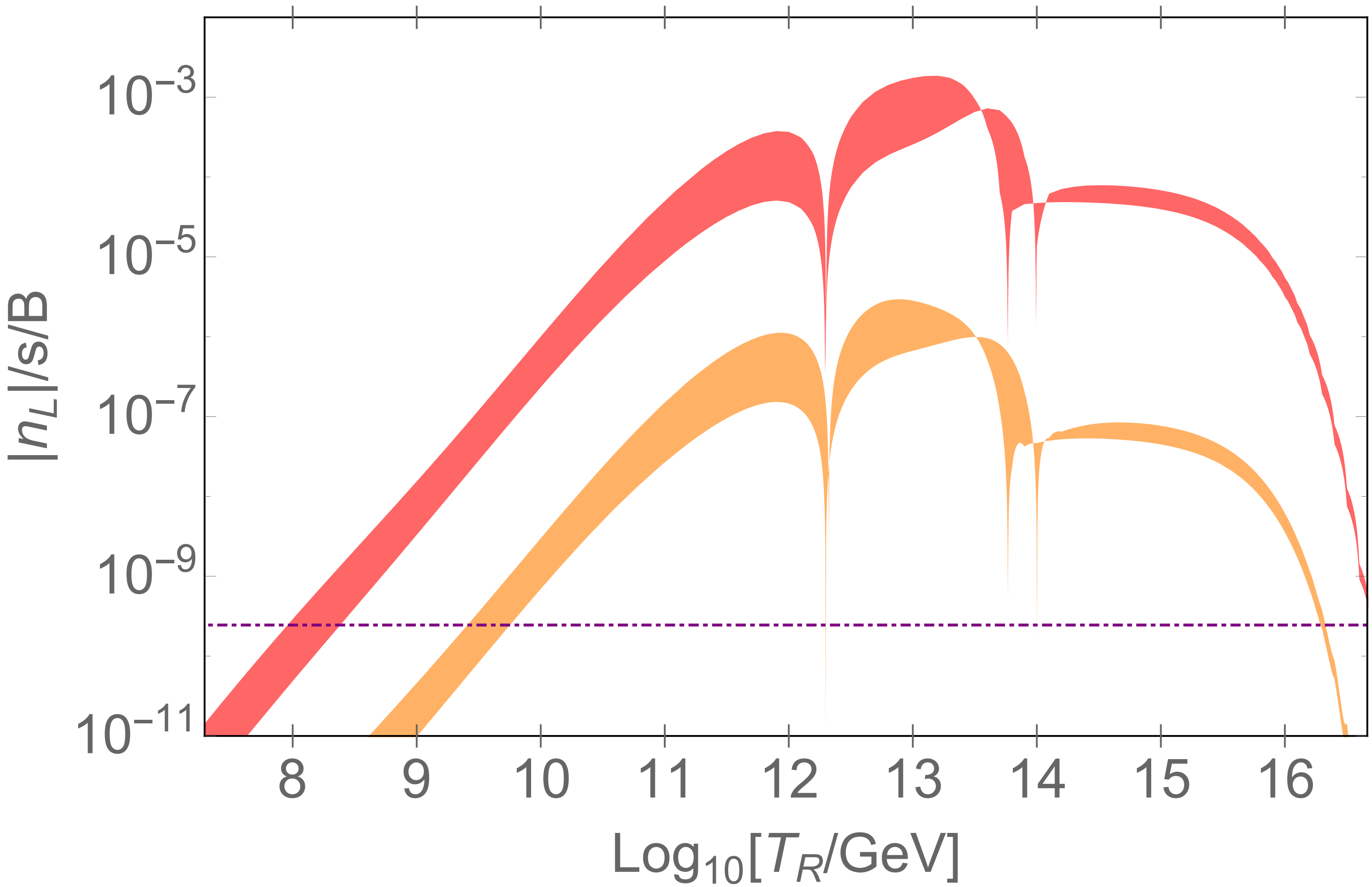
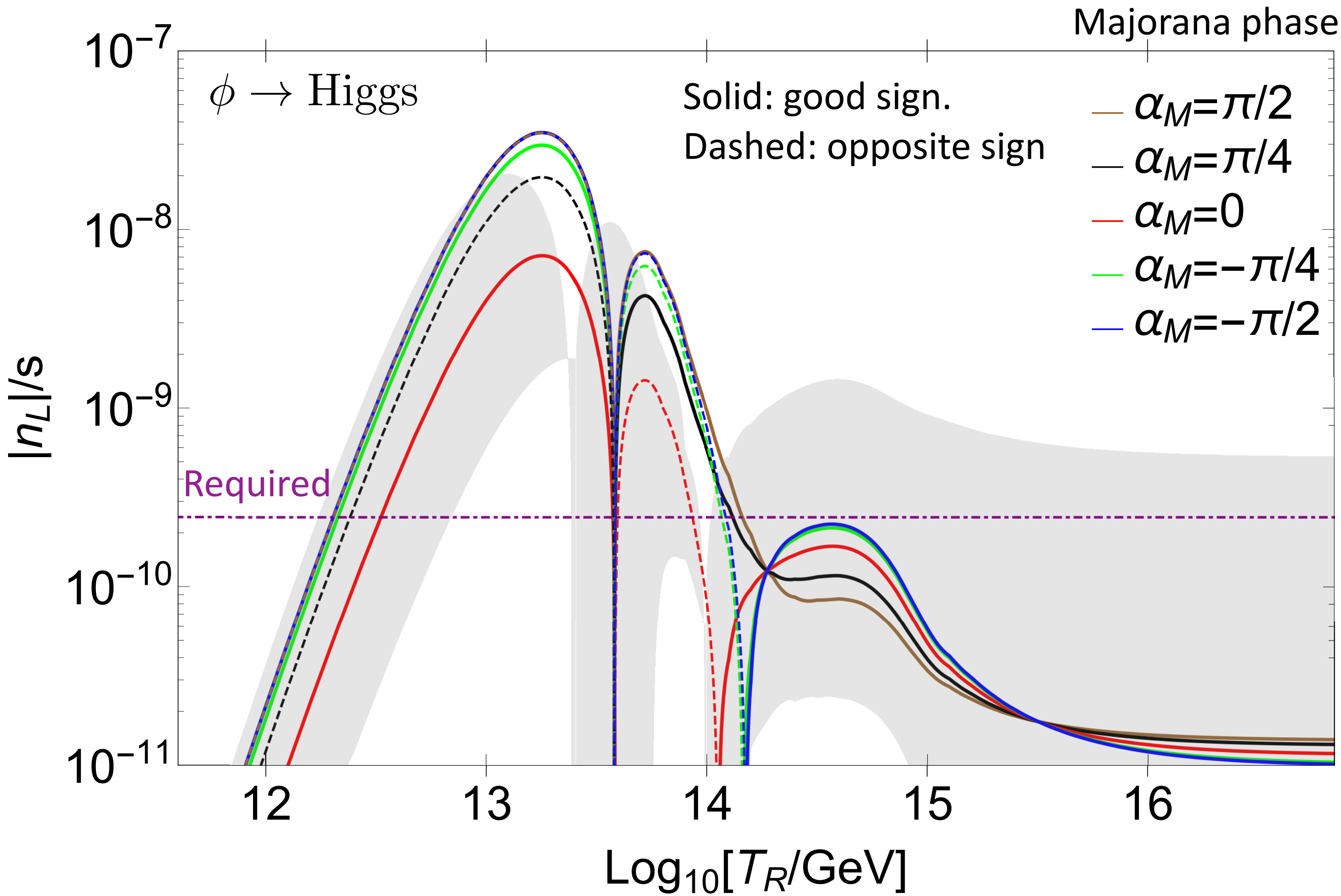


FIGURES FOR INFLATON->HIGGS

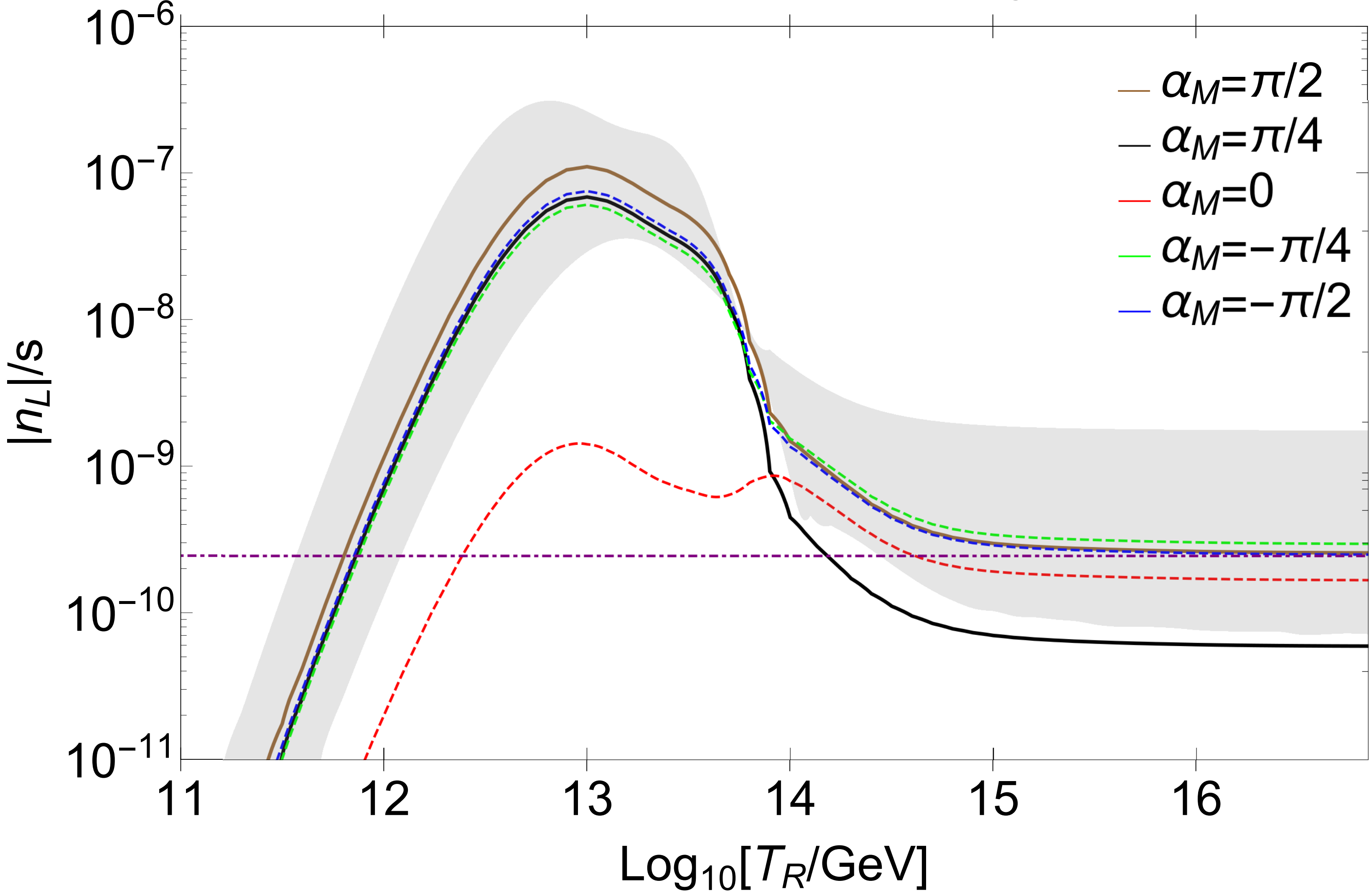
Solution (Normal Hierarchy)



Inflaton mass =100 T_R

Two massive neutrinos. Dirac Phase=-Pi/2

Inverted degenerate case.
mnulightest=0.07eV



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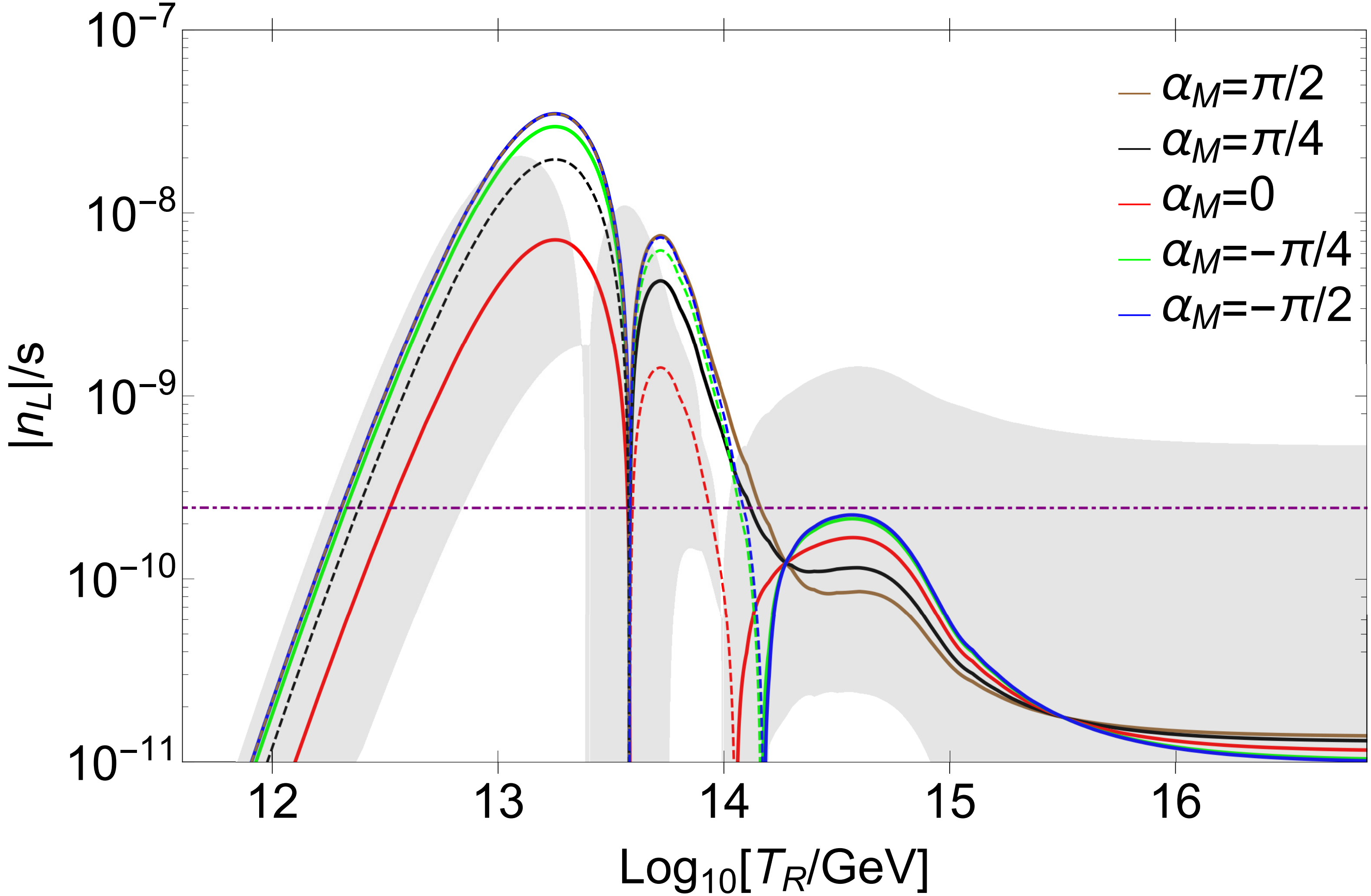

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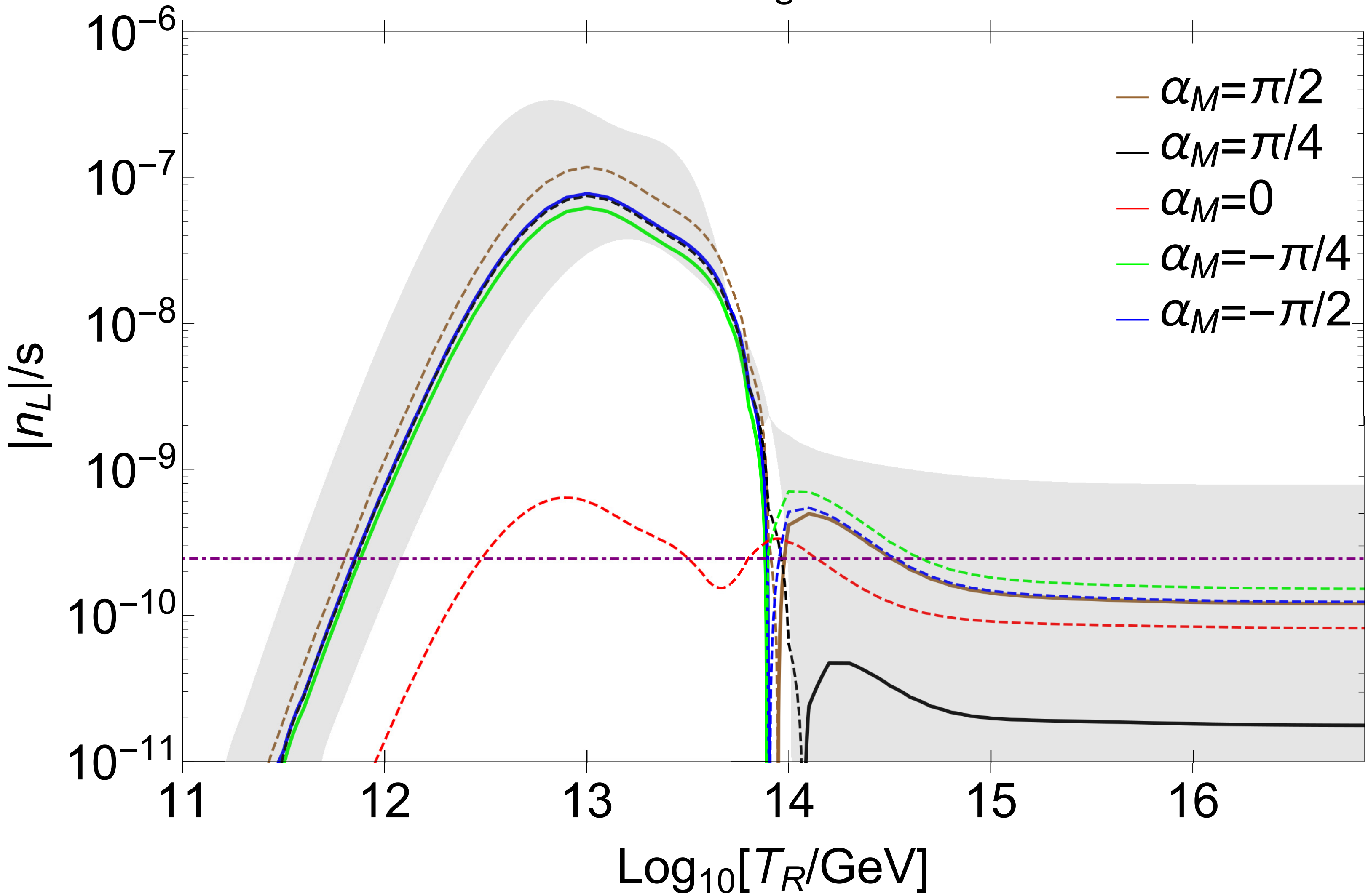
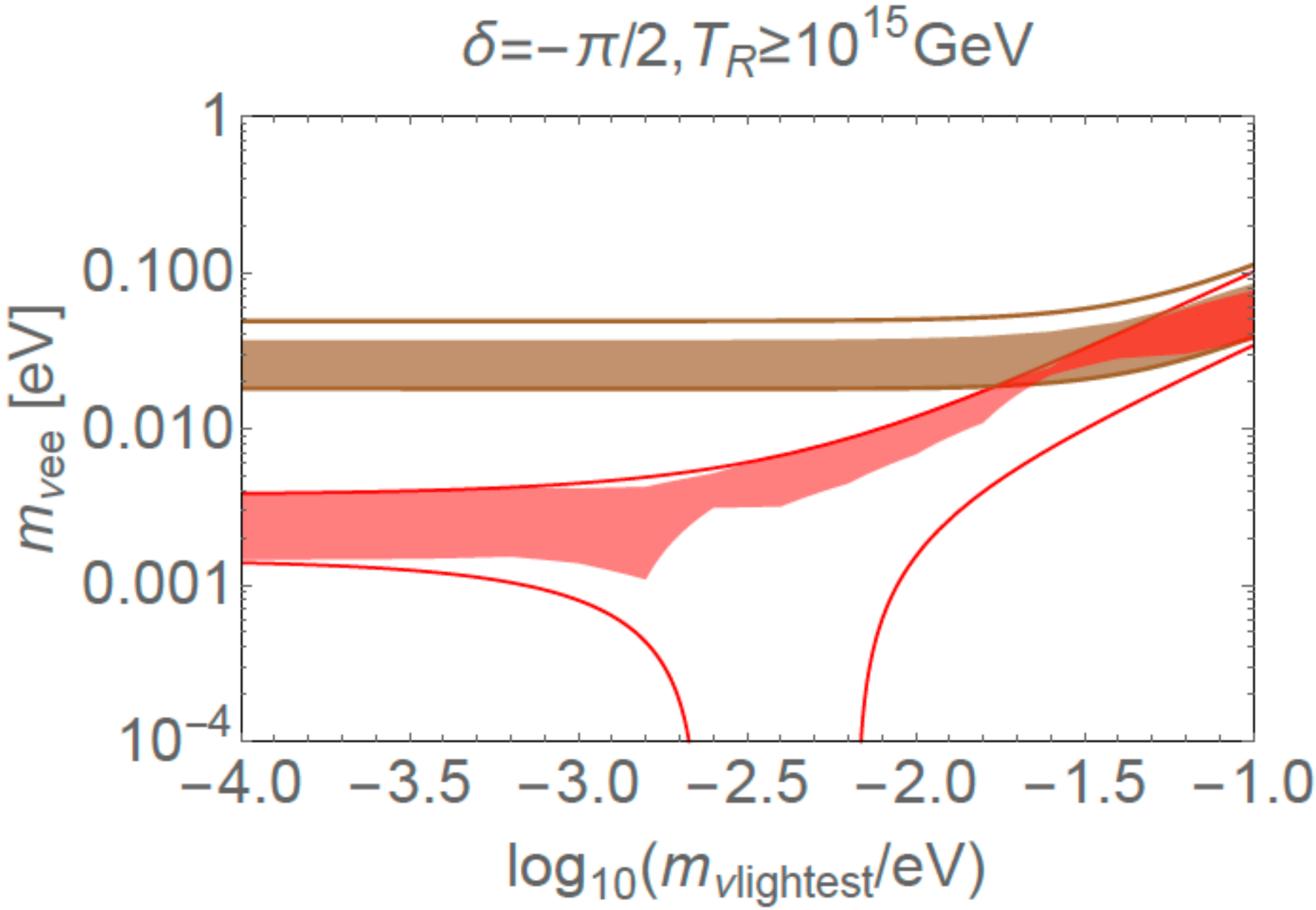
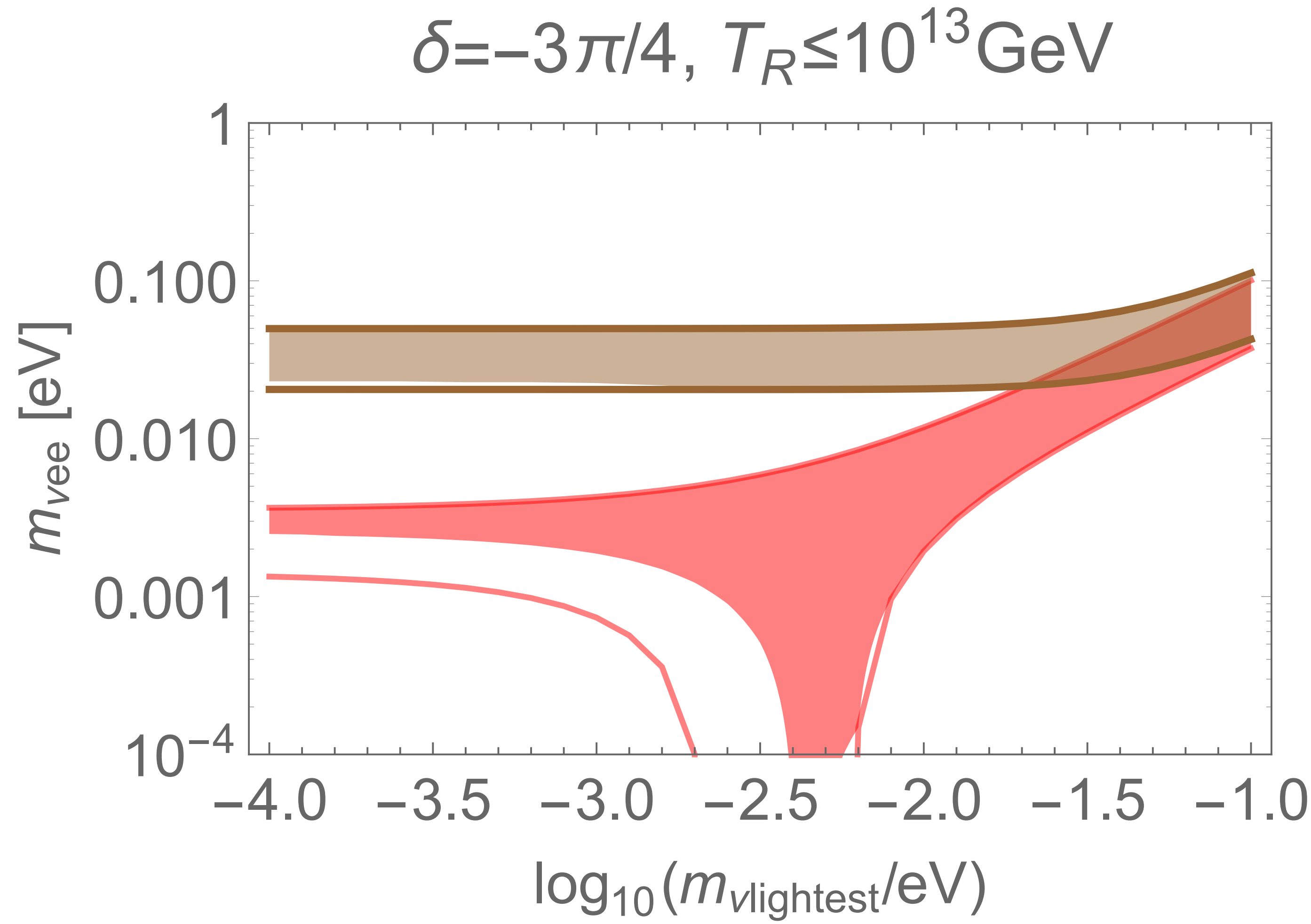


Neutrinoless double beta decay

The CP phase and neutrino mass can be tested from neutrino exps.





δ=−3π/4, T_R≤10^{13}GeV
1
0.100
0.010
0.001
10^{-4}
m_{vee} [eV]
−4.0
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
$\log_{10}(m_{\nu lightest}/eV)$