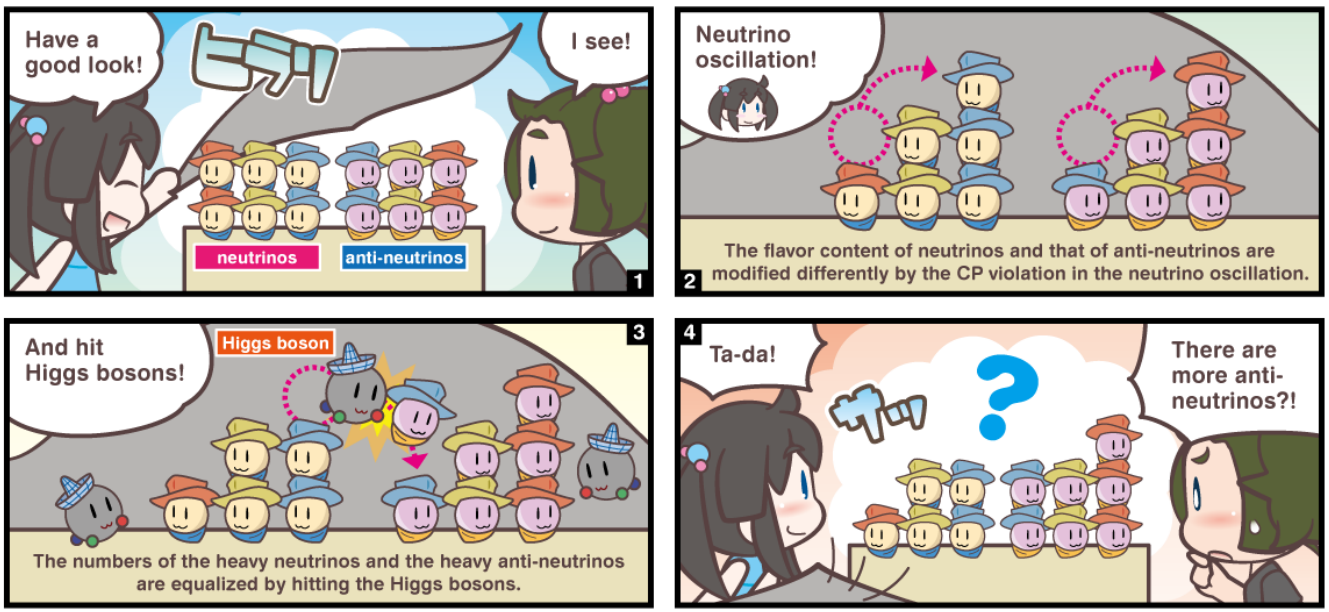
1807.06582 with Ryuichiro Kitano, Yuta Hamada
(See also 1908.11864 with Shintaro Eijima, Ryuichiro Kitano and Eijima's talk.)

Leptogenesis via active neutrino oscillation

Wen Yin, KAIST in Korea



comic
by Yuki Akimoto,
higgstan.com

International Joint Work Shop on the Standard Model and beyond, Oct. 15, 2019 Beijing, China

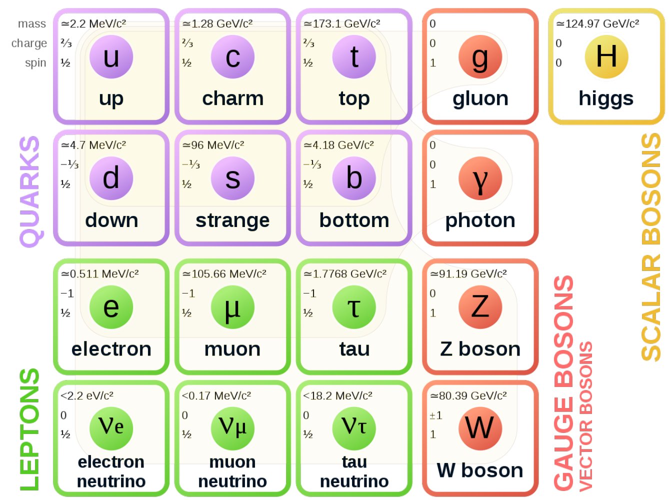
Contents

1. Introduction

The mysteries of particle physics and particle cosmology.

- Inflation
- Matter-antimatter asymmetry (Baryon asymmetry)
- Neutrino oscillation
- …

Standard model of particle theory(SM)



wikipedia, Kawasaki et al, 1709.01211

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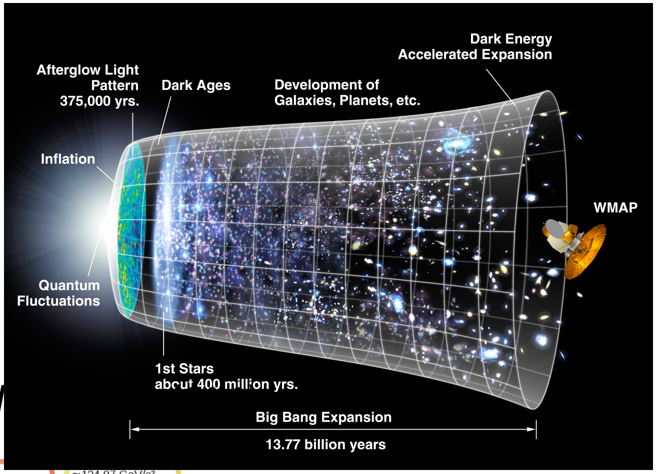
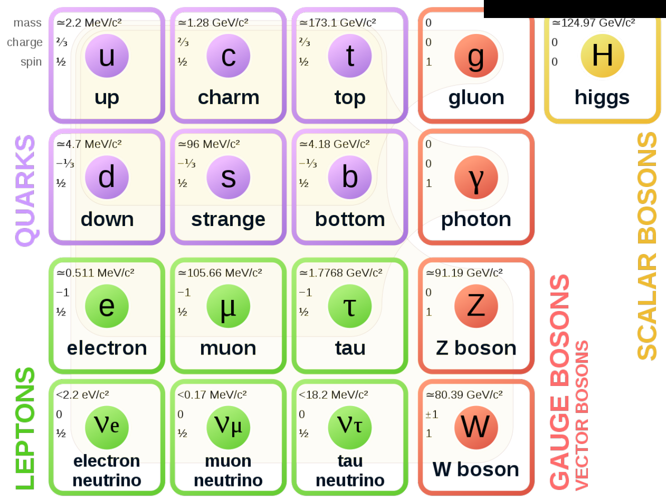


Standard model of particl



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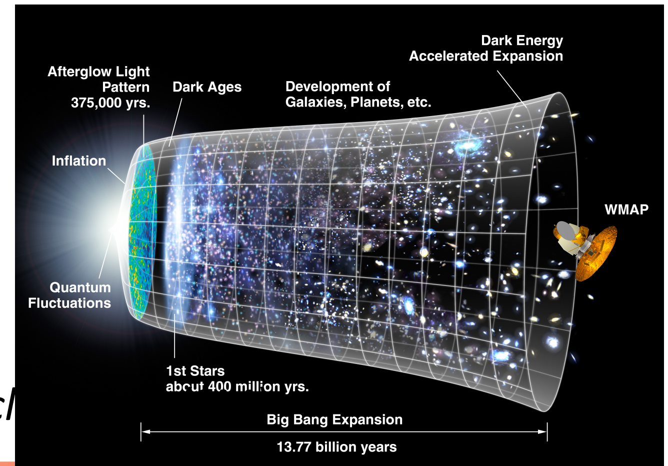

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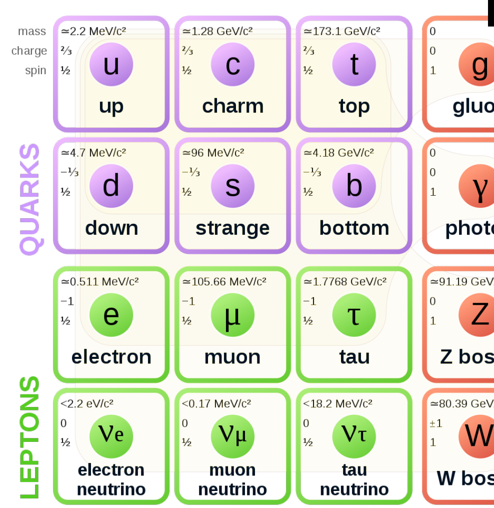

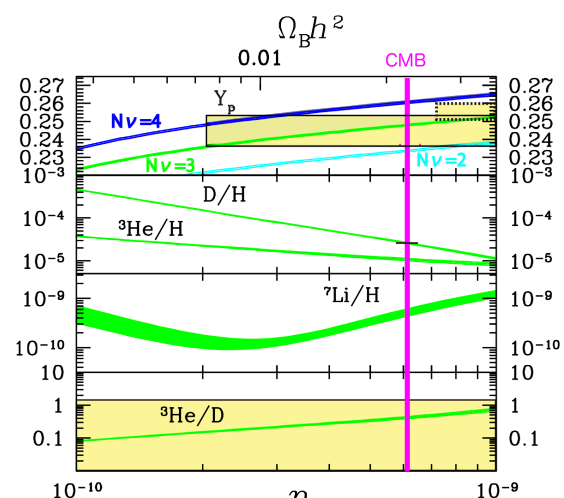

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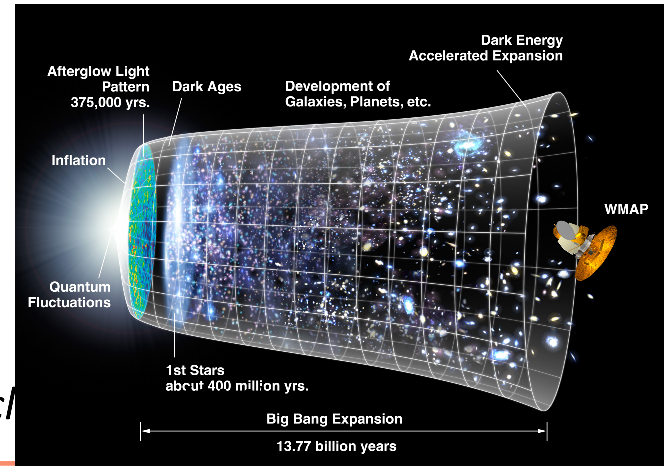

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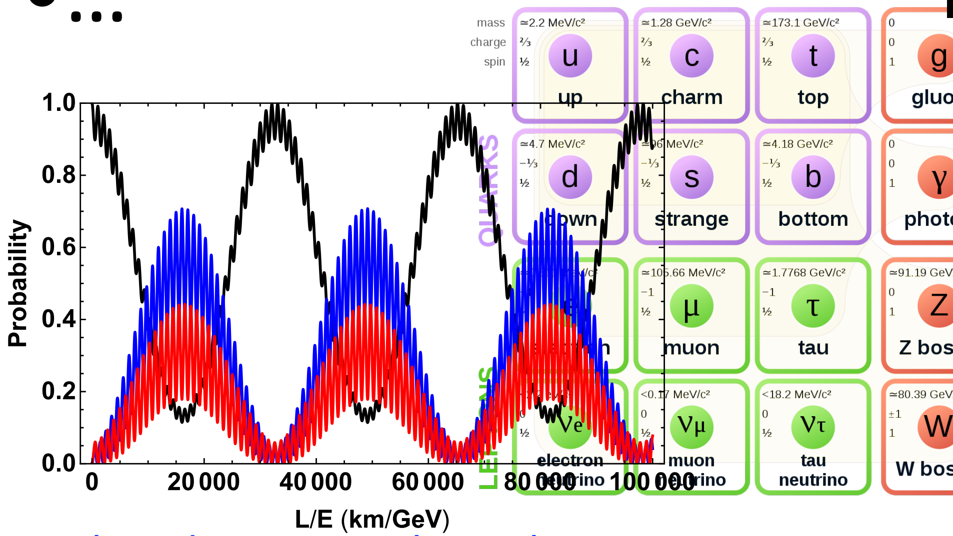

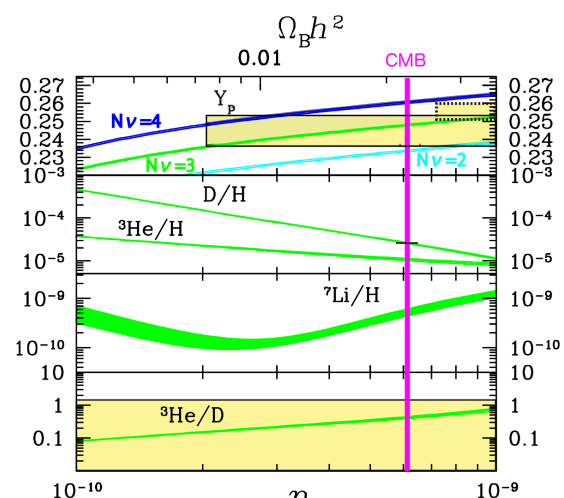

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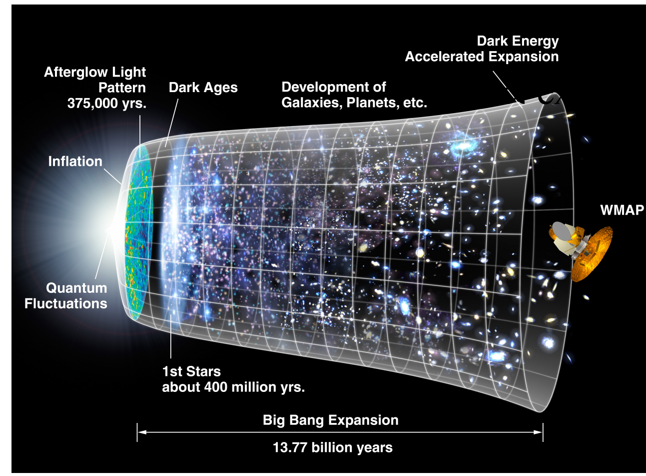
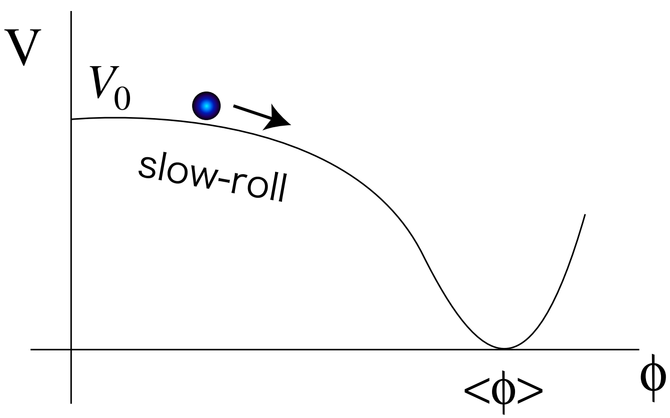
New physics: inflation

A.Guth, 1980; K.Sato, 1980; A.Starobinsky, 1980; Kazanas, 1980; A.Linde, 1981; Albrecht, Steinhardt, 1981;

The Universe experienced an exponential expansion.

Inflation solves horizon and flatness problems.





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Quantum fluctuation for anisotropy of the Universe which has been observed in CMB.

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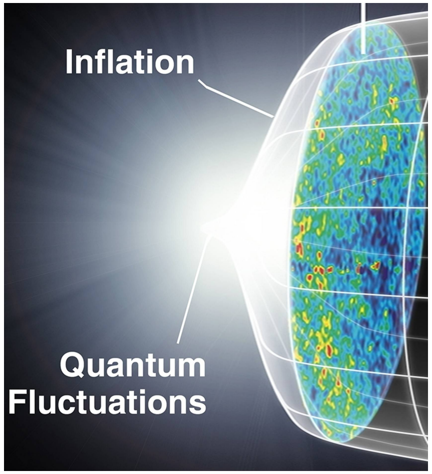

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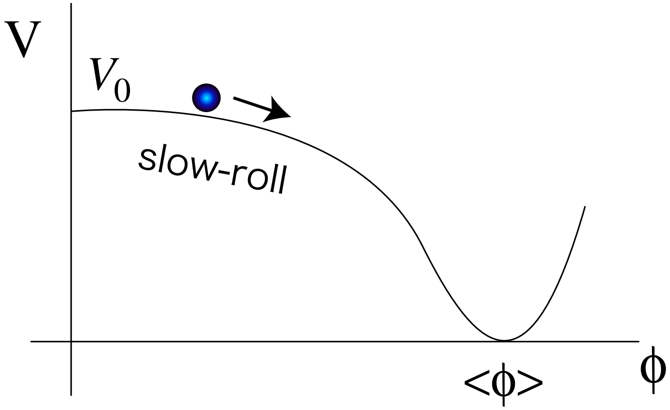

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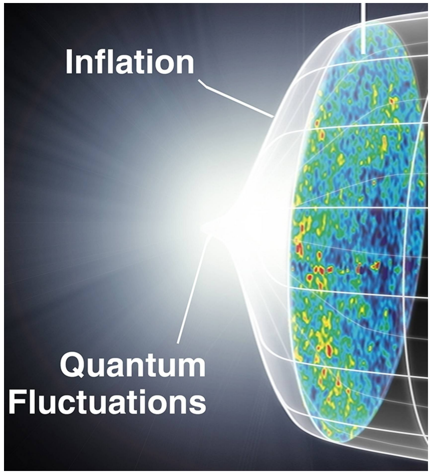

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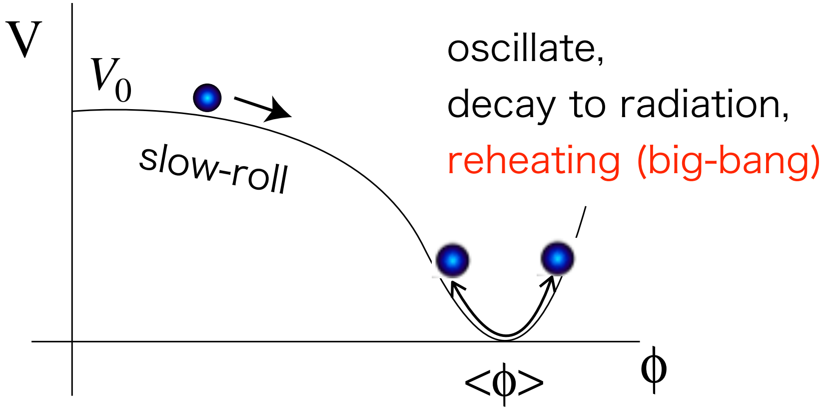

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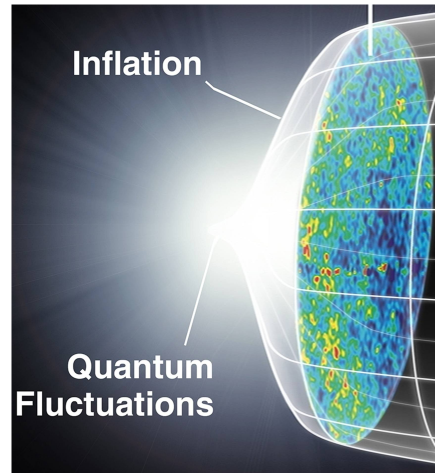

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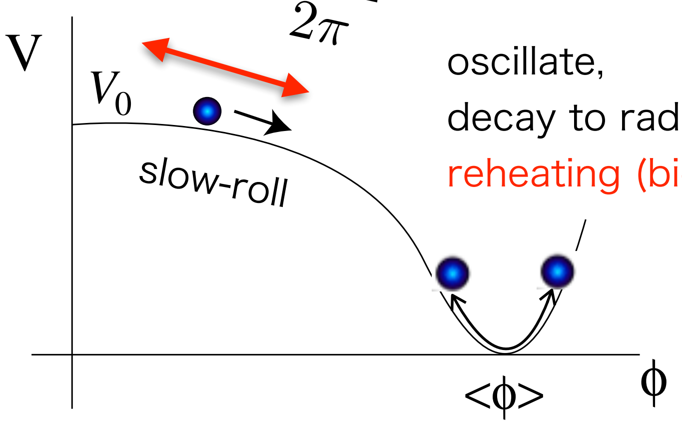

oscillate,
decay to radiation,
reheating (big-bang)

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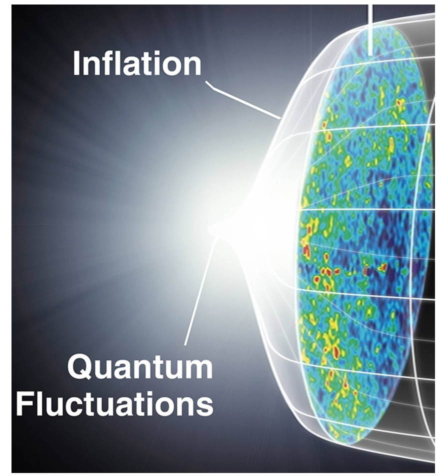

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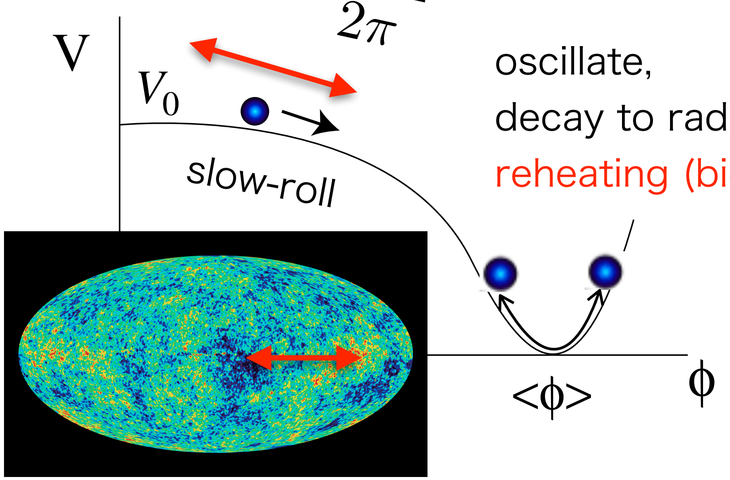

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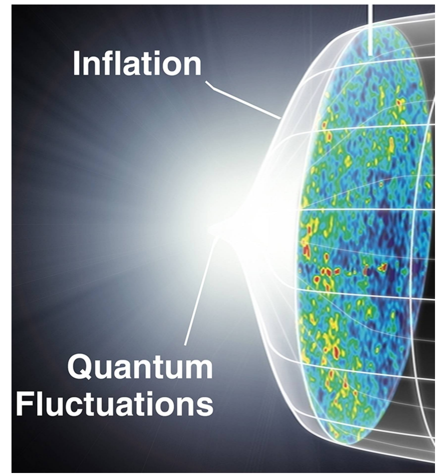

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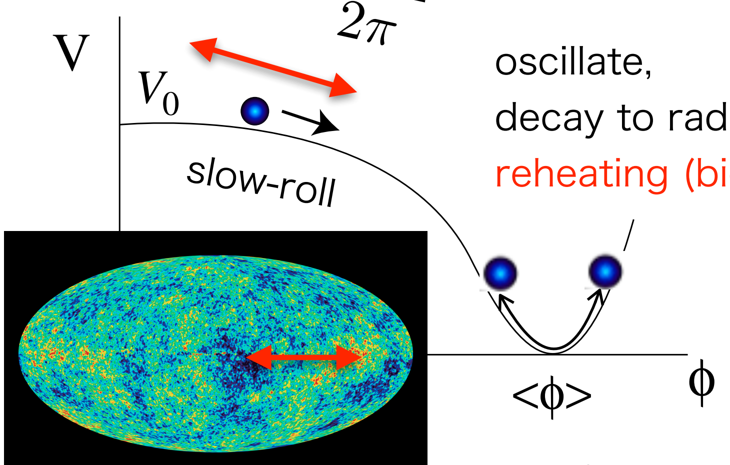

oscillate,
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Inflaton ϕ:

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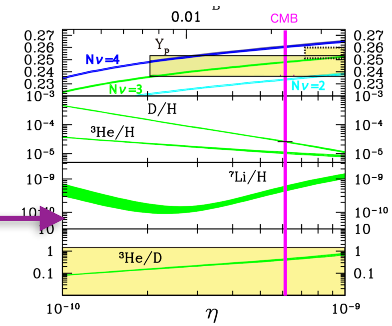
Existence of inflaton and inflation is very rigid!

New physics: baryogenesis

Baryogenesis happens

$$\frac{\Delta n_B}{s} \simeq 0$$



Inflation ends

reheating (big bang)

BBN, CMB (recombination)

t

To generate the baryon asymmetry of our universe <u>*Sakharov's conditions*</u> should be satisfied:

**Baryon/Lepton number violation* *with sphaleron*

**C and CP violation*

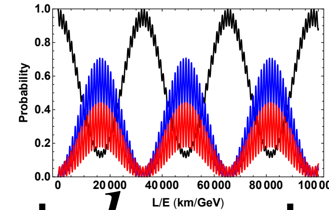
**Out of thermal equilibrium*

Unfortunately, the SM of the particle theory does not sufficiently satisfy them… <u>***New physics is needed for baryogenesis!***</u>

New physics: neutrino oscillation

A simple explanation:

the SM is a non-renormalizable effective theory
i.e. Majorana neutrino



$$\mathscr{L}_{SM} = \mathscr{L}_{SM}^{d\leq 4} - \frac{\kappa_{ij}}{2}\bar{L}^{c}{}_{i}\hat{P}_{L}L_{j}HH + h.c + \cdots$$

$$\ni \frac{m_{\nu ij}}{2}\bar{\nu}_i^c \hat{P}_L \nu_j$$

Possible origins of the LLHH term

UV completed by heavy particles.
e.g.

seesaw mechanism

Yanagida 79; Gell-Mann, et al 79;Minkowski, 77;

High scale R-parity violating SUSY?
See Prof Liu's talk slide,
See also WY, 1808.00440 in the context of charge quantization.

Just exist as it is valid up to 10^{17} GeV

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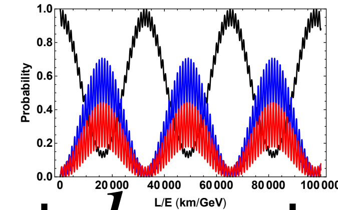

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Baryon asymmetry of universe with Majorana neutrino

- Baryogenesis with right-handed neutrinos
  M. Fukugita, T. Yanagida 1986; Pilaftsis 1997; Buchmuller Plumacher, 1998;
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- Baryogenesis with the LLHH interaction term Hamada, Kitano, WY, 2018;

See also Hamada, Kawana 2015; Takahashi, Yamada 2015; Hamada Kitano 2016, with LLHH + other higher dimensional terms.

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  Today's topic

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I will be talking about

Setup:

$$\mathscr{L} = \mathscr{L}_{SM}^{d\leq 4} - \frac{\kappa_{ij}}{2} \bar{L^c}_i \hat{P}_L L_j HH + h.c.$$

At ***around the reheating (big-bang)***, ***neutrino flavor oscillation*** can generate baryon asymmetry with ***LLHH scattering process***.

Sakharov's conditions

**Baryon/Lepton # violation*

**C and CP violation*

**Out of equilibrium*

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**Out of equilibrium* ✓

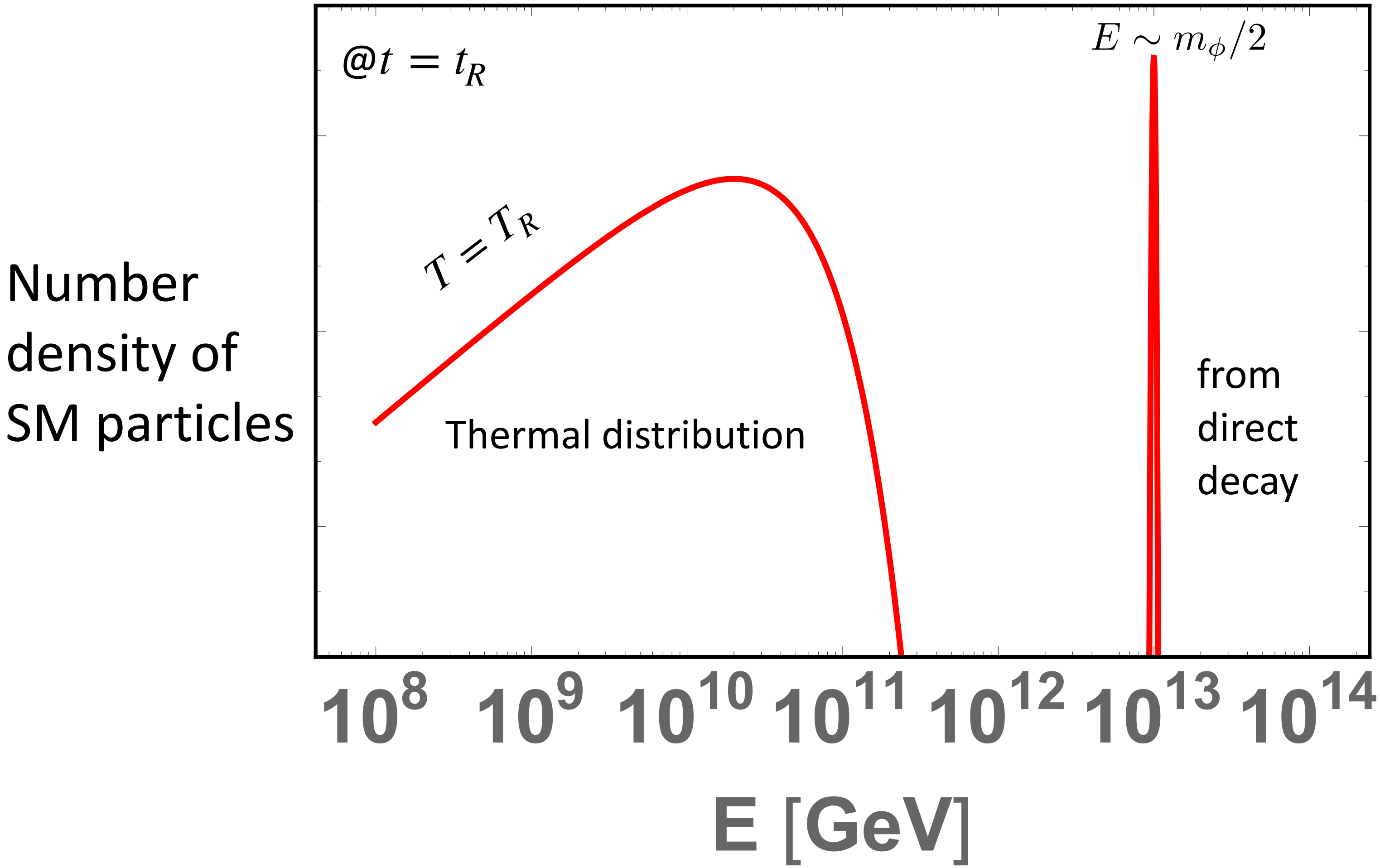
Thermalization around reheating

2. Baryogenesis via active neutrino oscillation

Kitano, Hamada, WY 1807.06582

Inflaton decay: $\phi \rightarrow \mathrm{SM\ particles}$ (2 body)

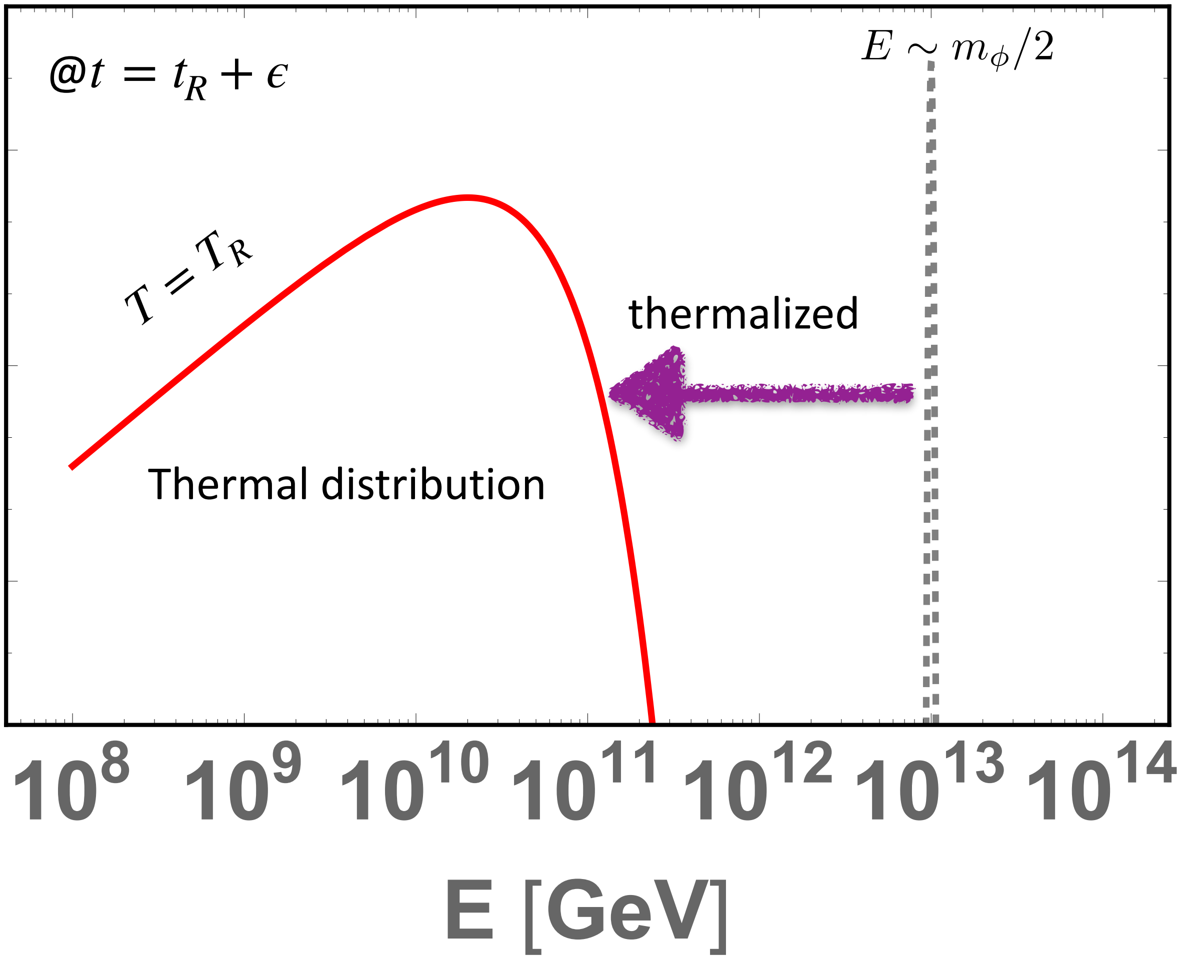
at the moment of an inflaton decay



Thermalization during reheating

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

Number density of SM particles



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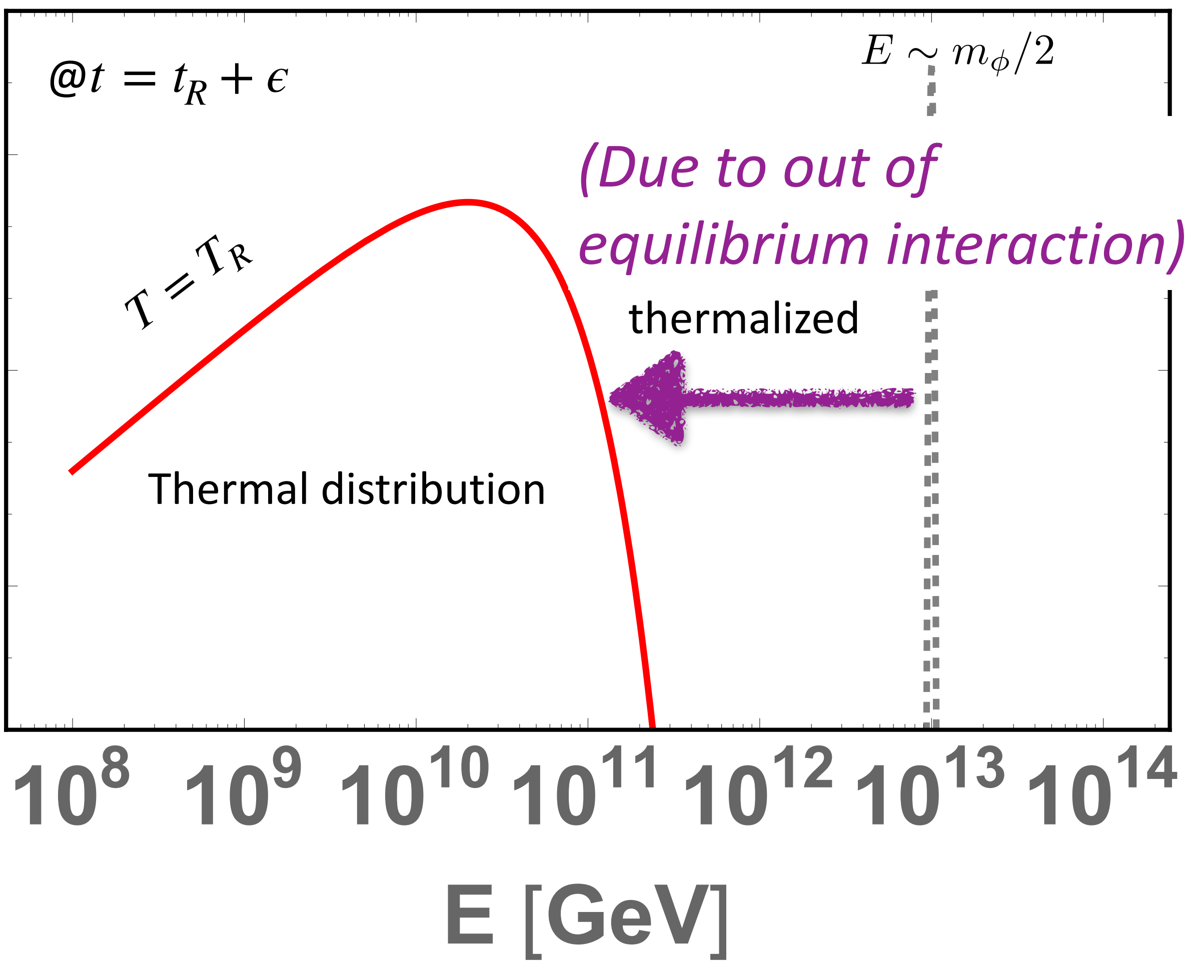
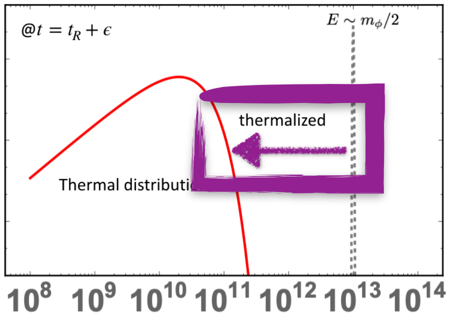


Neutrino oscillation during thermalization



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

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

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

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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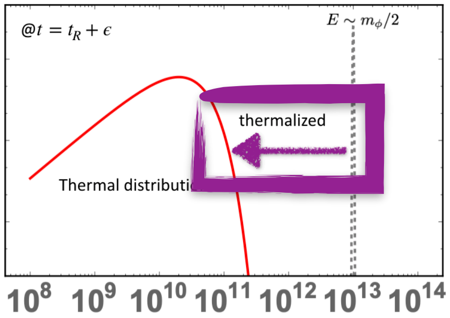

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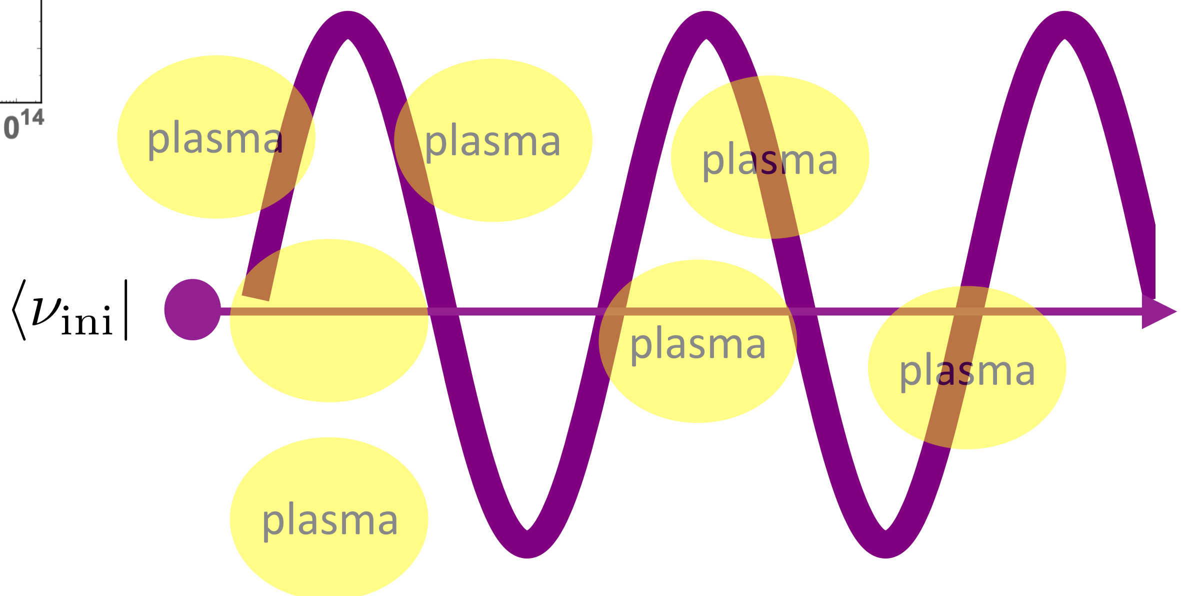

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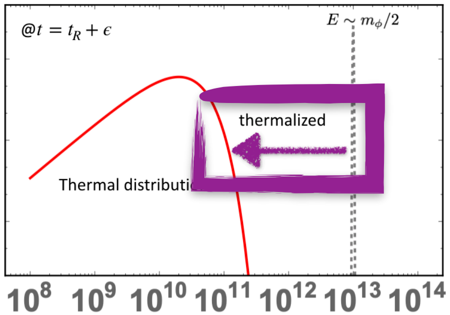

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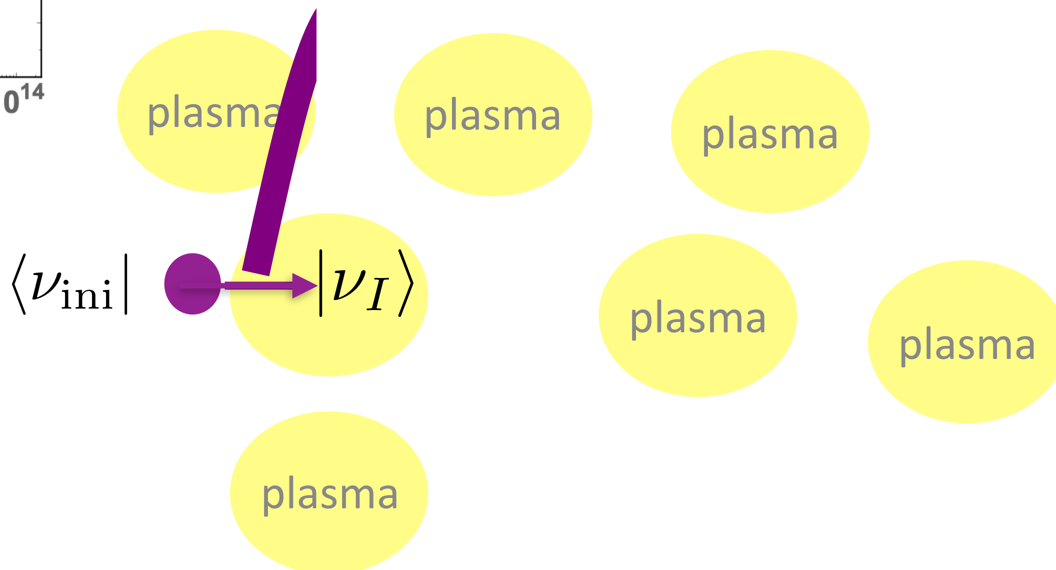

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Neutrino oscillation provides CP violation

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

$$t_{MFP} \sim \frac{1}{\alpha_2^2 T}\sqrt{\frac{k}{T}}$$

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

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

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

<u>Oscillation phase is not too small at thermalization around the reheating.</u>

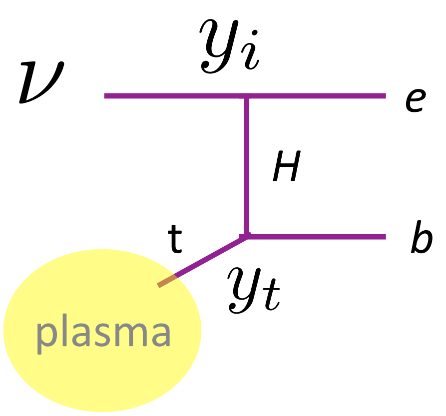
Hamada Kitano 2016

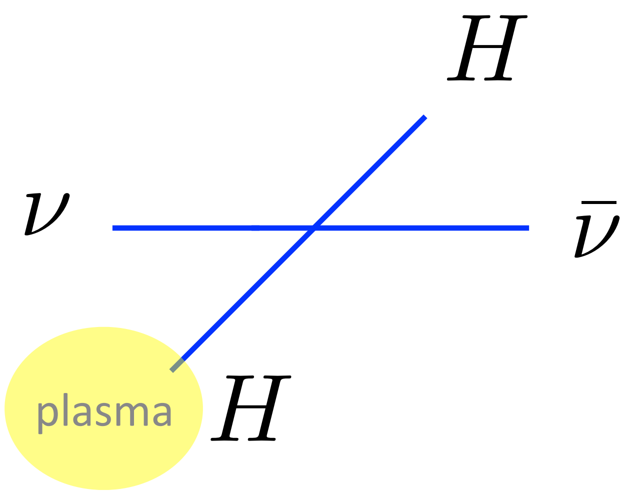
How to observe "flavor"?

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

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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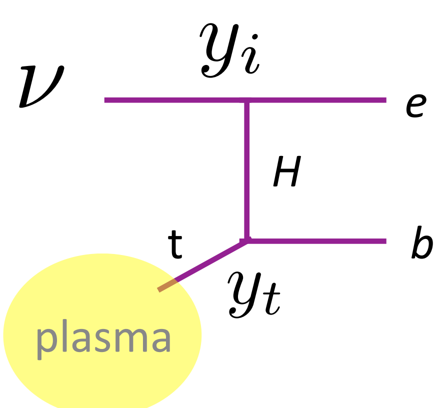

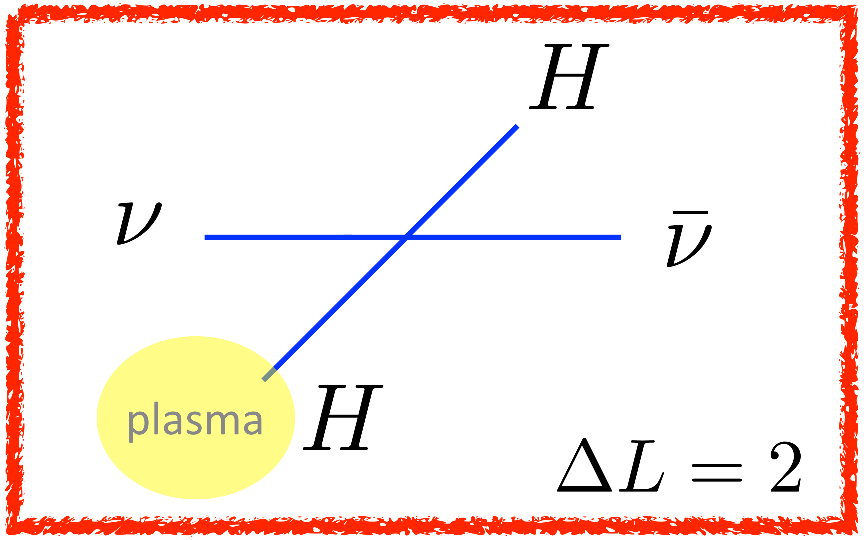

Lepton asymmetry can be made!

The (naive) estimation of lepton asymmetry

$m_\phi \sim T \ll 10^{12} GeV$ with O(1) CP phase, general flavor structure

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

Lepton asymmetry | Branching ratio | CP violation | Lepton # violation

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

How frequently the flavor is observed by the llHH interaction.

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

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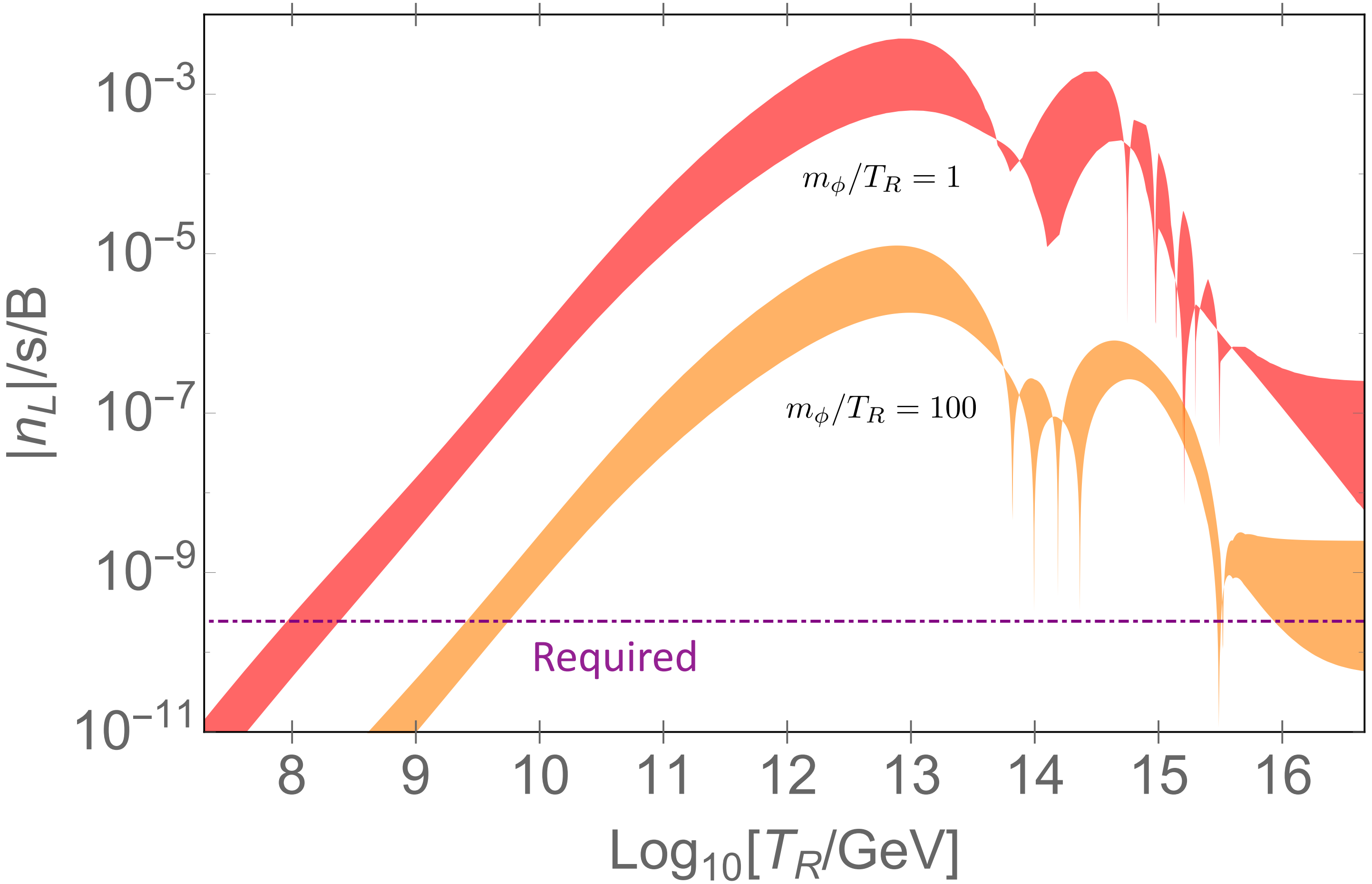
$$\frac{\Delta n_L}{s} \propto B_{\phi \to \nu_{\rm ini} + X / \bar{\nu}_{\rm ini} + \bar{X}} \times 10^{-9} \left(\frac{T_R}{10^9 GeV} \right)^2$$

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

Enough asymmetry can be generated with sufficiently high reheating temperature.

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:
Preexisting thermal plasma of all the SM particles.

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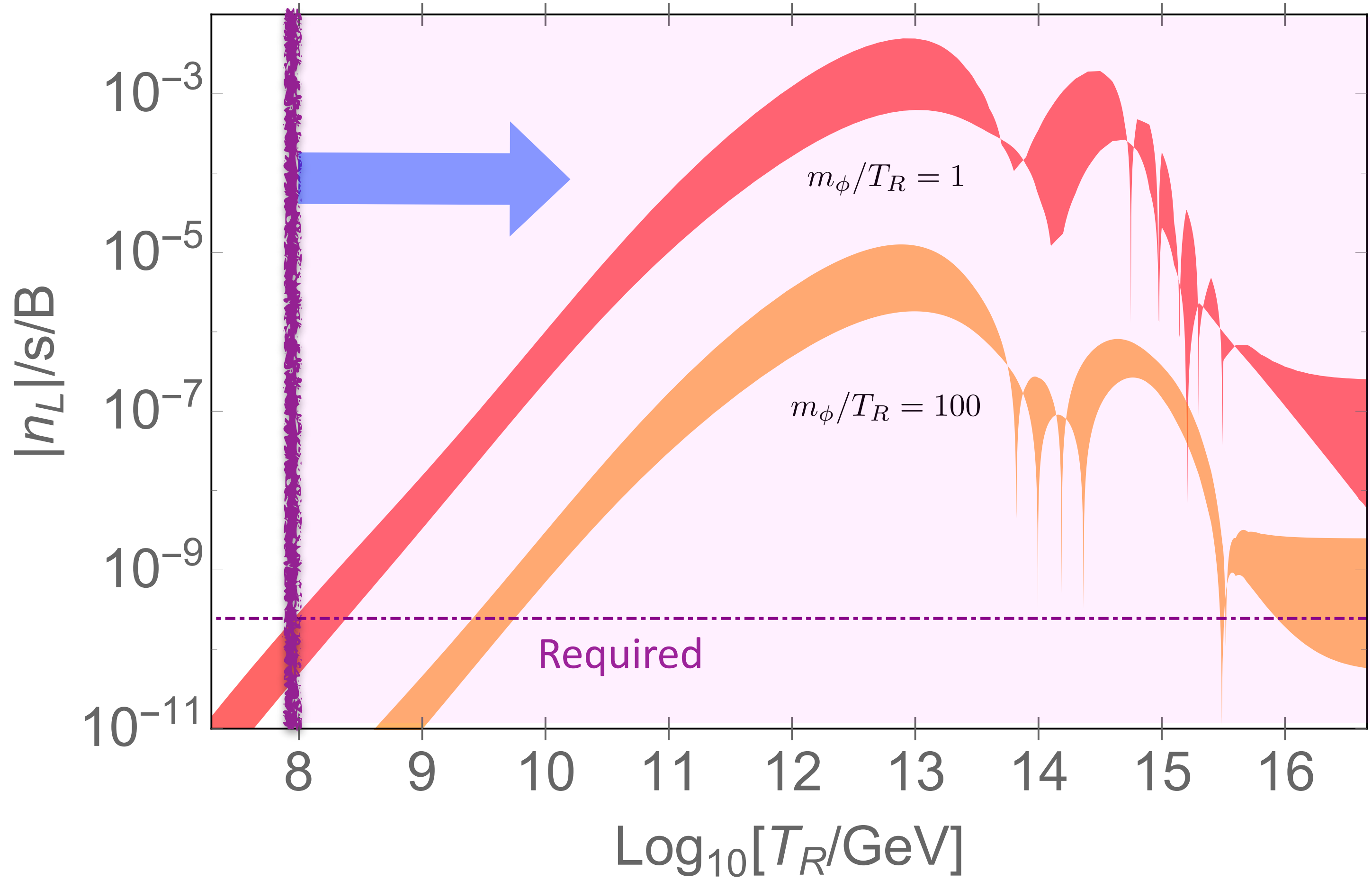


Dirac phase=-pi/2,
Majorana phase=0.3
V∝{1,1,1}

Assumption:
Preexisting thermal plasma of
all the SM particles.

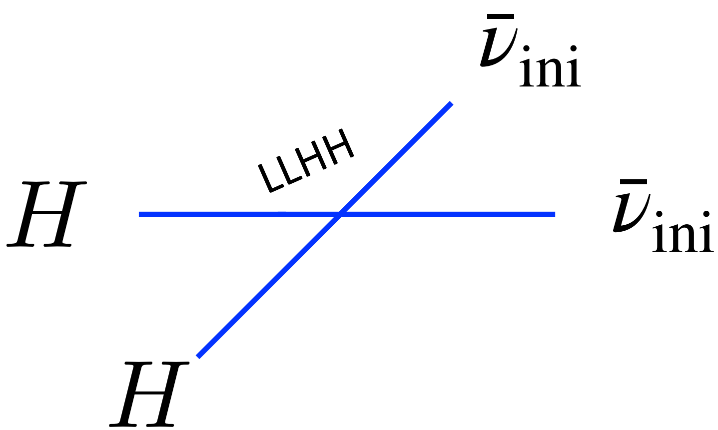
Baryogenesis can be successful for $T_R \gtrsim 10^8\, GeV$ ***due to active neutrino oscillation during thermalization.***

3. Baryogenesis from PMNS matrix

Let us consider the renormalizable inflaton coupling to the SM

$$\mathscr{L} \supset -A\phi|H|^2 - \lambda_\phi \phi^2 |H|^2 \qquad A, \lambda_\phi\text{: real parameters}$$

$$\phi \to HH^*$$



$\longrightarrow$ *Neutrino flavor oscillation!*

$\longrightarrow$ *Baryogenesis!*

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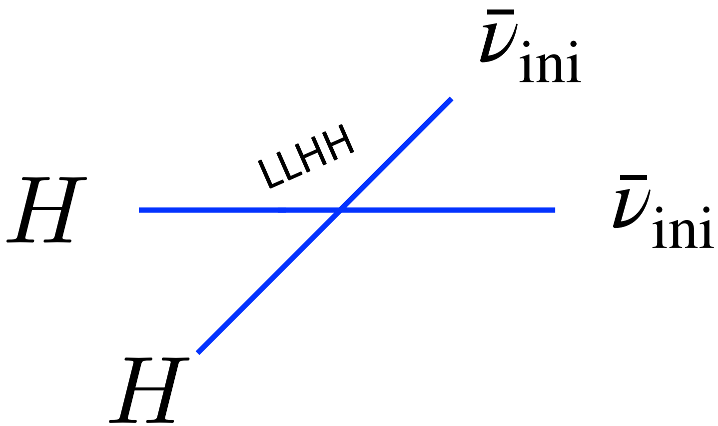
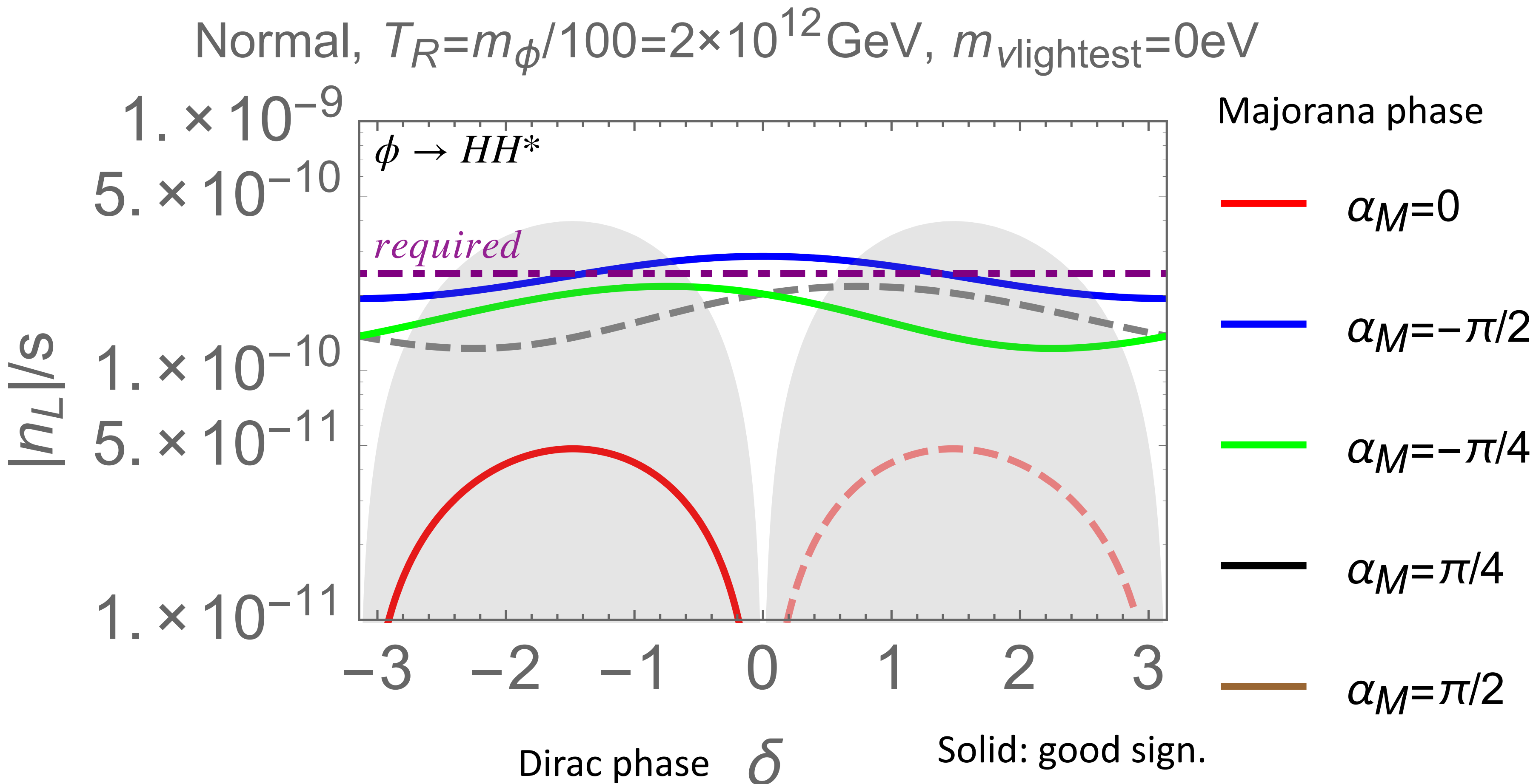


$\to$ *Neutrino flavor oscillation!*

$\to$ *Baryogenesis!*

CP violation can only appear via CP phases in LLHH interaction, i.e. the PMNS matrix. The baryon asymmetry is related with the PMNS matrix

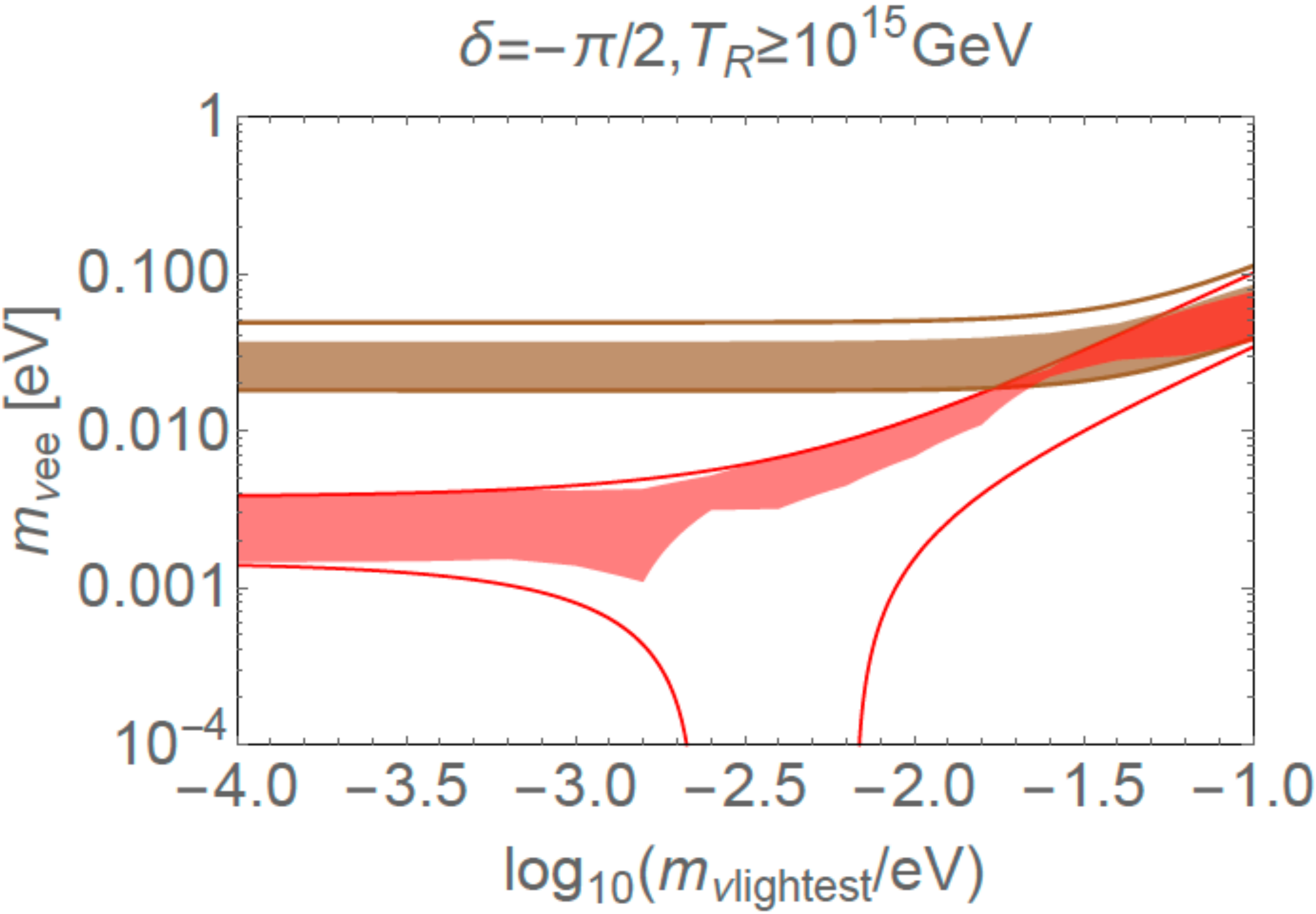
Numerical result: Dirac phase dependence



Solid: good sign.
Dashed: opposite sign

Neutrinoless double beta decay

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



Summary

Baryon asymmetry can be explained due to ***neutrino oscillation*** with

$$\mathcal{L} = \mathcal{L}_{SM}^{d\leq 4} - \frac{\kappa_{ij}}{2}\bar{L}^c{}_i \hat{P}_L L_j HH + h.c$$

at ***around reheating era.***

- $T_R \gtrsim 10^8 GeV$ for $\phi \to \nu + X, \bar{\nu} + \bar{X}$
- If $\phi \to HH^*$, the scenario, can be tested from ground-based experiments.

See also Eijima's talk for baryogenesis via active neutrino oscillation with sterile neutrinos.

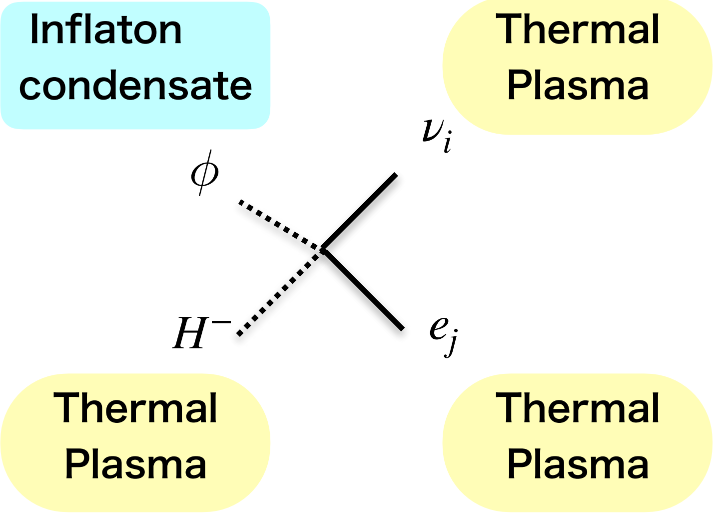
Backups

Enhancement by non-trivial reheating dynamics

Reheating can complete via the scattering process:

$$\phi + H^- \rightarrow \nu_i + e_j$$

Daido, Takahashi, WY, 1710.11107,1903.00462,



i.e. due to dissipation effect. Yokoyama 0510091 etc.

No thermal blocking process:

$$\frac{n_\phi}{s} \simeq \frac{3T_R}{4m_\phi} \gg 1$$

$T_R/m_\phi \sim 10^{2-3}$ in Refs. 1710.11107,1903.00462

Thus, the asymmetry is enhanced.

LLHH scenario:

$$T_R \gtrsim 10^6 GeV \times \left(\frac{10^3}{T_R/m_\phi} \right)^{1/2}$$

seesaw scenario:

$$T_R \gtrsim 10^2 GeV \left(\frac{10^2}{T_R/m_\phi} \right)$$

The upper bound of the QCD axion window can be relaxed in low-scale inflation with $H_{\rm inf} \lesssim \Lambda_{\rm QCD}$.

Peter W. Graham, Adam Scherlis, 1805.07362,
Fuminobu Takahashi, WY, Alan H. Guth, 1805.08763

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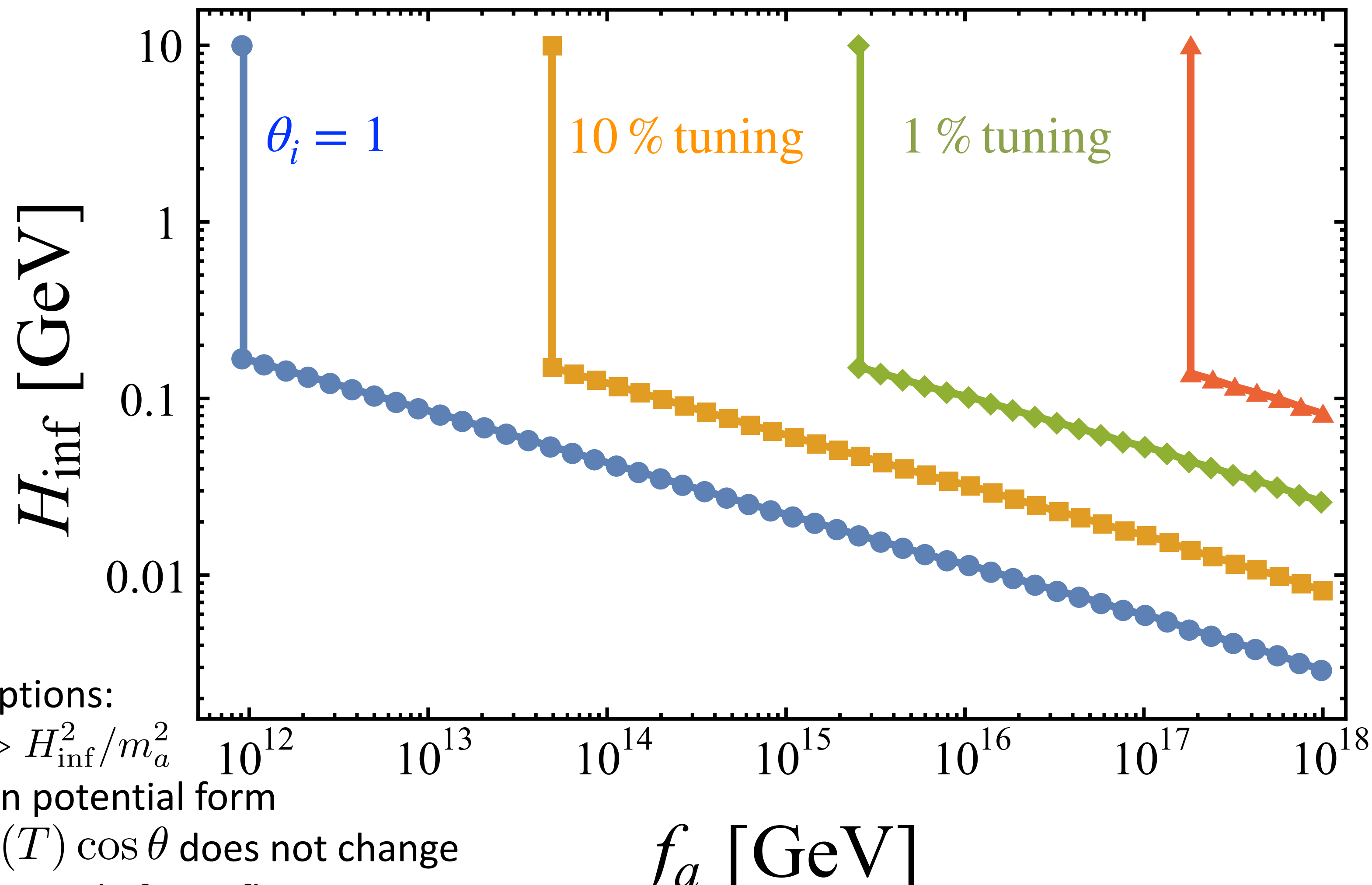

Assumptions:

1. $N \gg H_{\rm inf}^2/m_a^2$
2. Axion potential form $\simeq \chi(T)\cos\theta$ does not change during and after inflation.

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Peter W. Graham, Adam Scherlis, 1805.07362,
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Conventional axion window, $f_a \lesssim 10^{12}\,{\rm GeV}$

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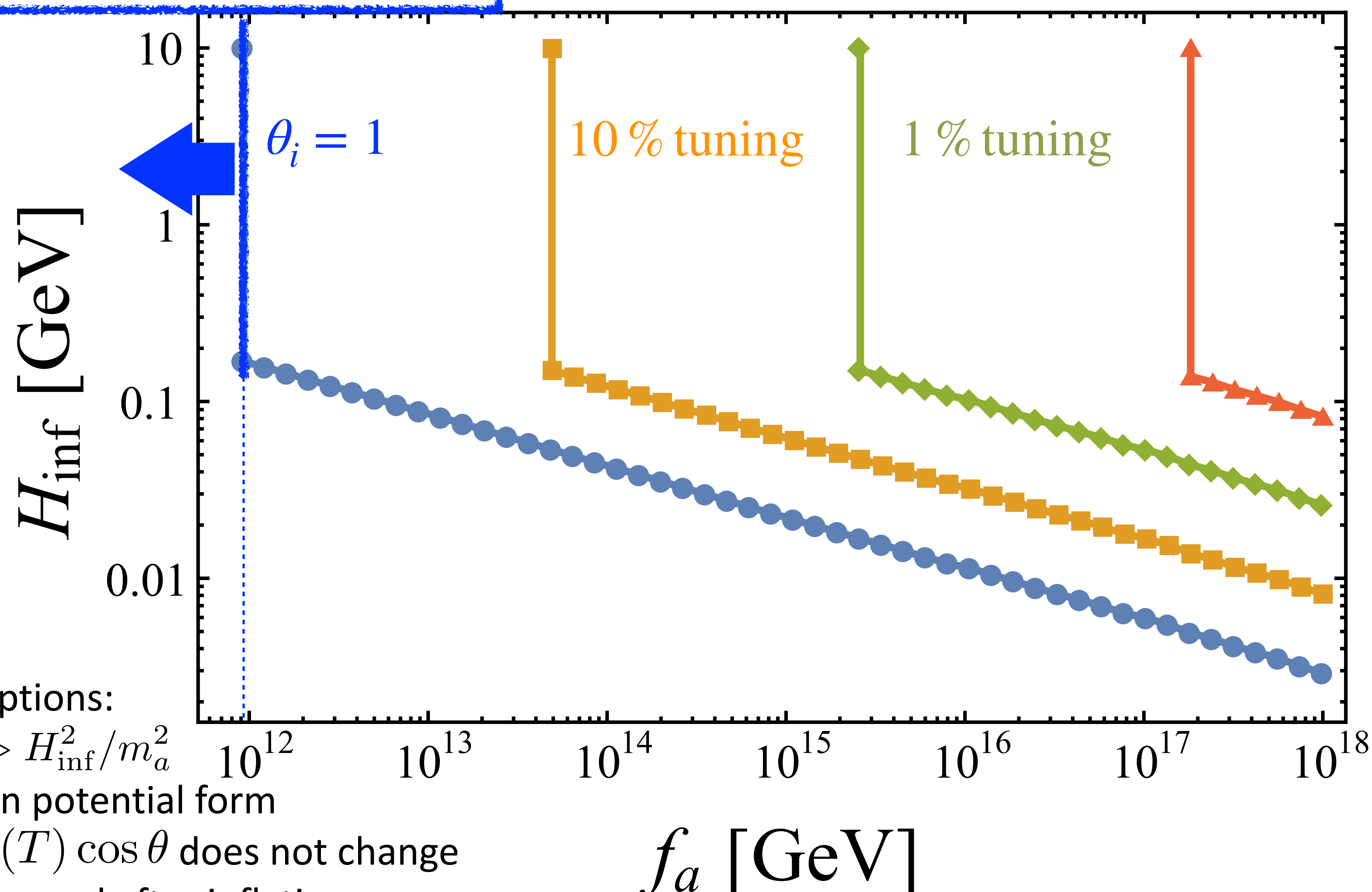

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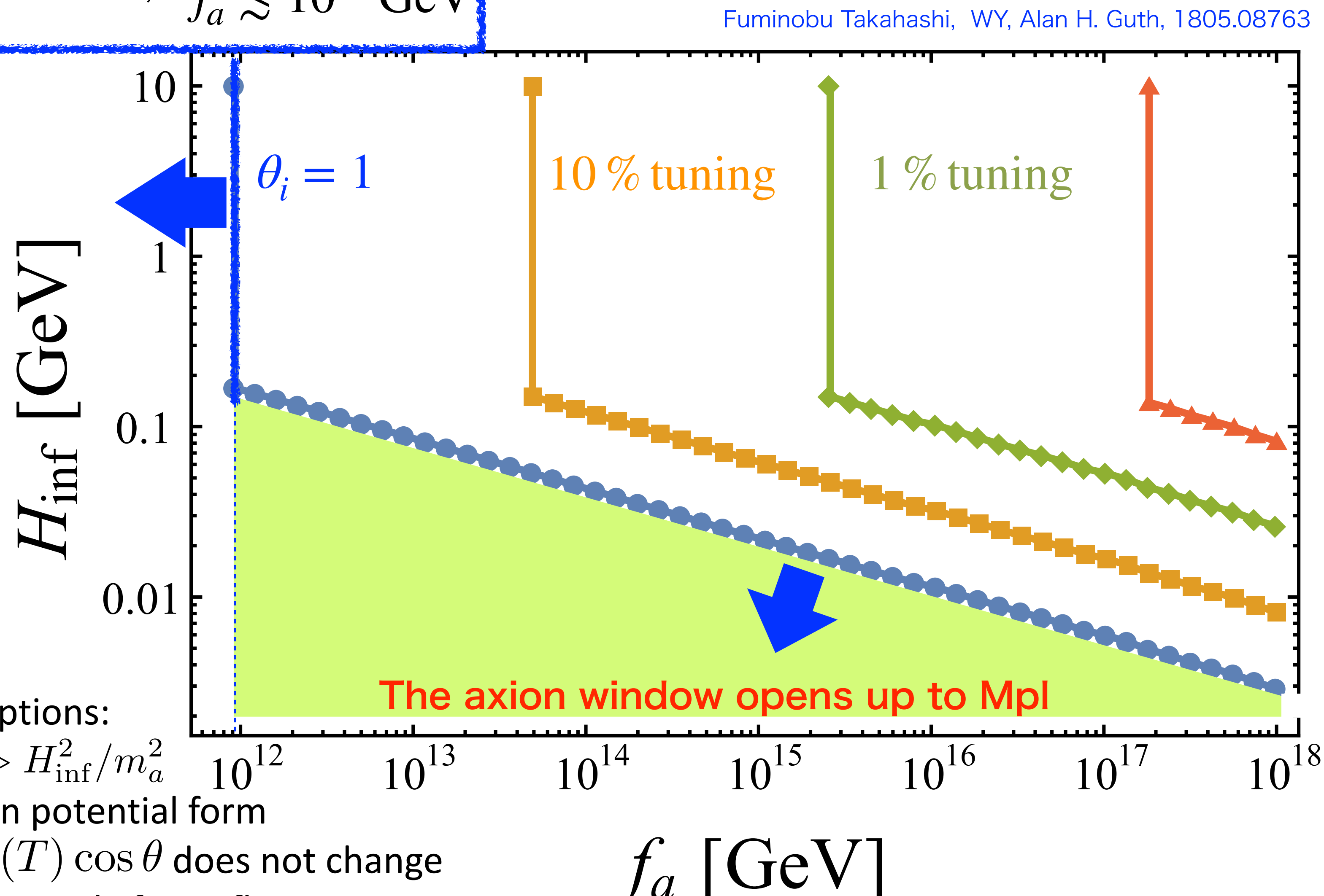

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Numerical estimation

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

Kinetic Equation (Extended Boltzmann Eqs)

Sigl, Raffelt, 1993

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

Oscillation term

Interaction terms (with CP phase)

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

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.

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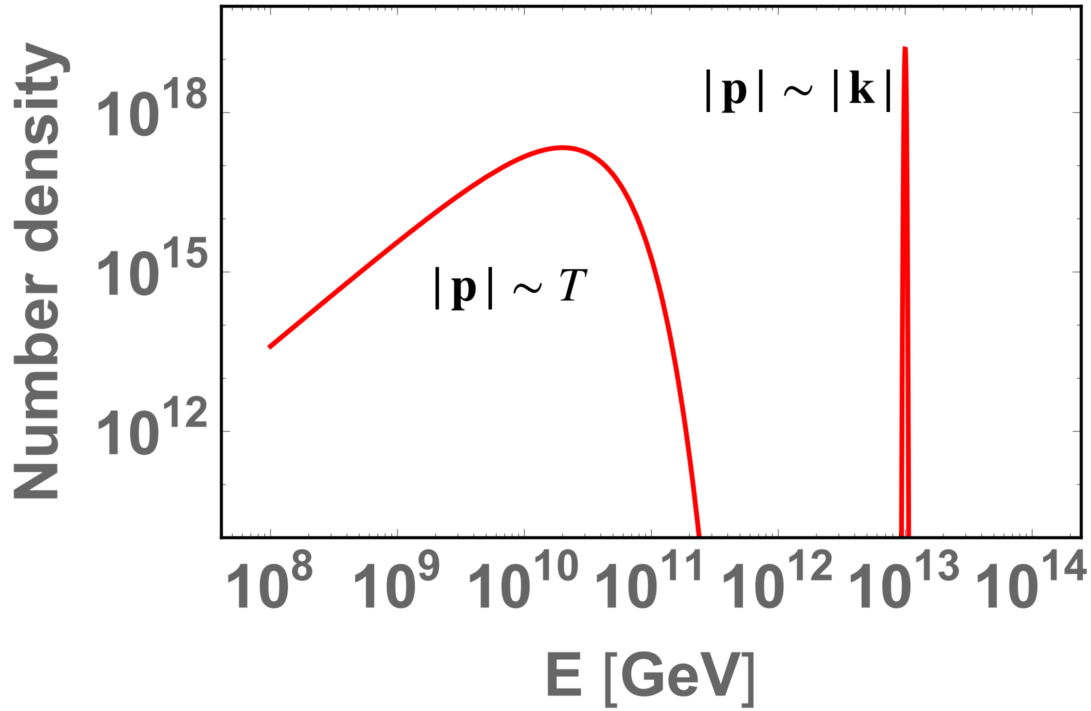
Oscillating phase *Thermalization, observation, L # violation*

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.

Two scale approximation



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

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

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 charged/anti leptons

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

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

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

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

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

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

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

Initial condition

$$\rho_{\mathbf{k}}|_{t=t_R} = \overline{\rho}_{\mathbf{k}}|_{t=t_R} = \mathcal{N} V_i V_j^*, \quad \delta\rho_T|_{t=t_R} = \delta\bar{\rho}_T|_{t=t_R} = 0.$$

$$\mathcal{N} = \frac{3}{4}\frac{T_R}{m_\phi}B,$$

Free parameters

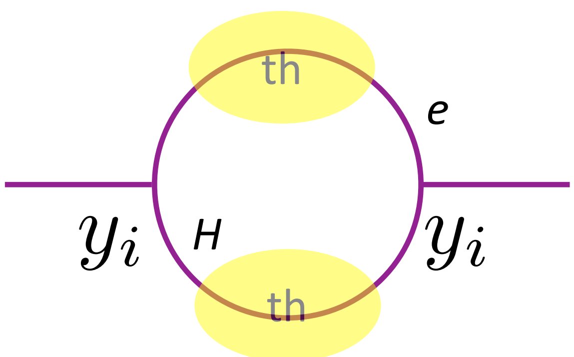
$$T_R, m_\phi, B, V_i$$

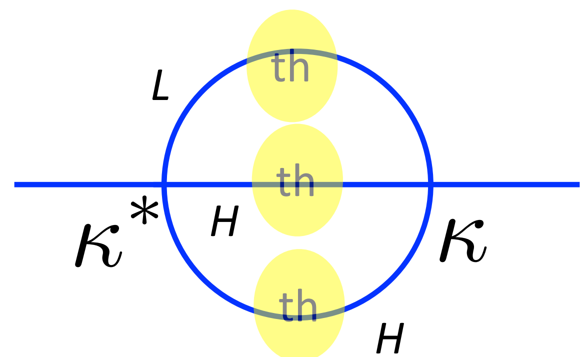
+Parameters in neutrino sector.

Thermal mass

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

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

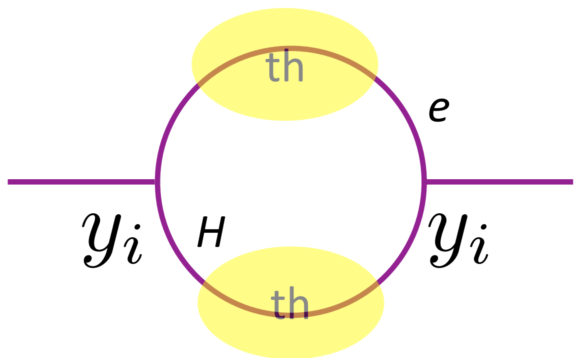


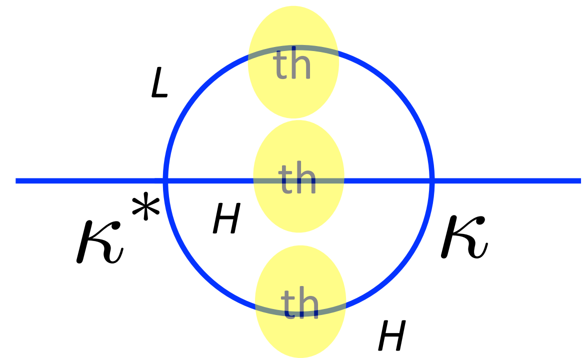


$|\nu_\alpha\rangle$ is the mass eigenstate.

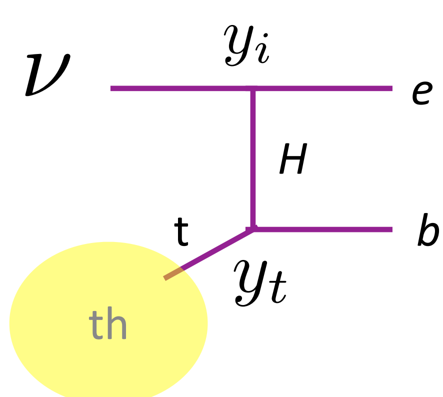
Mass basis $\neq$ interaction basis!

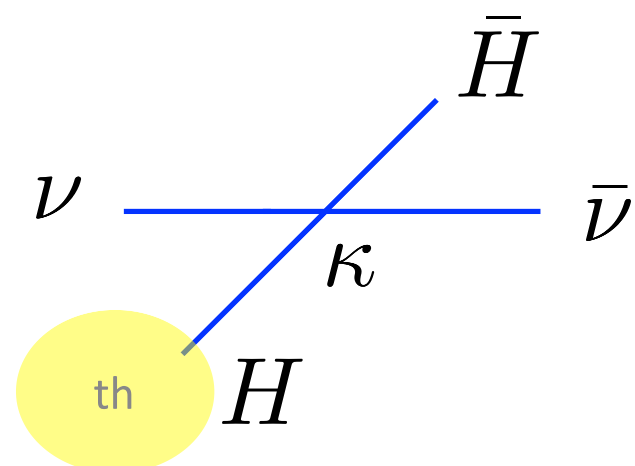
Mass:





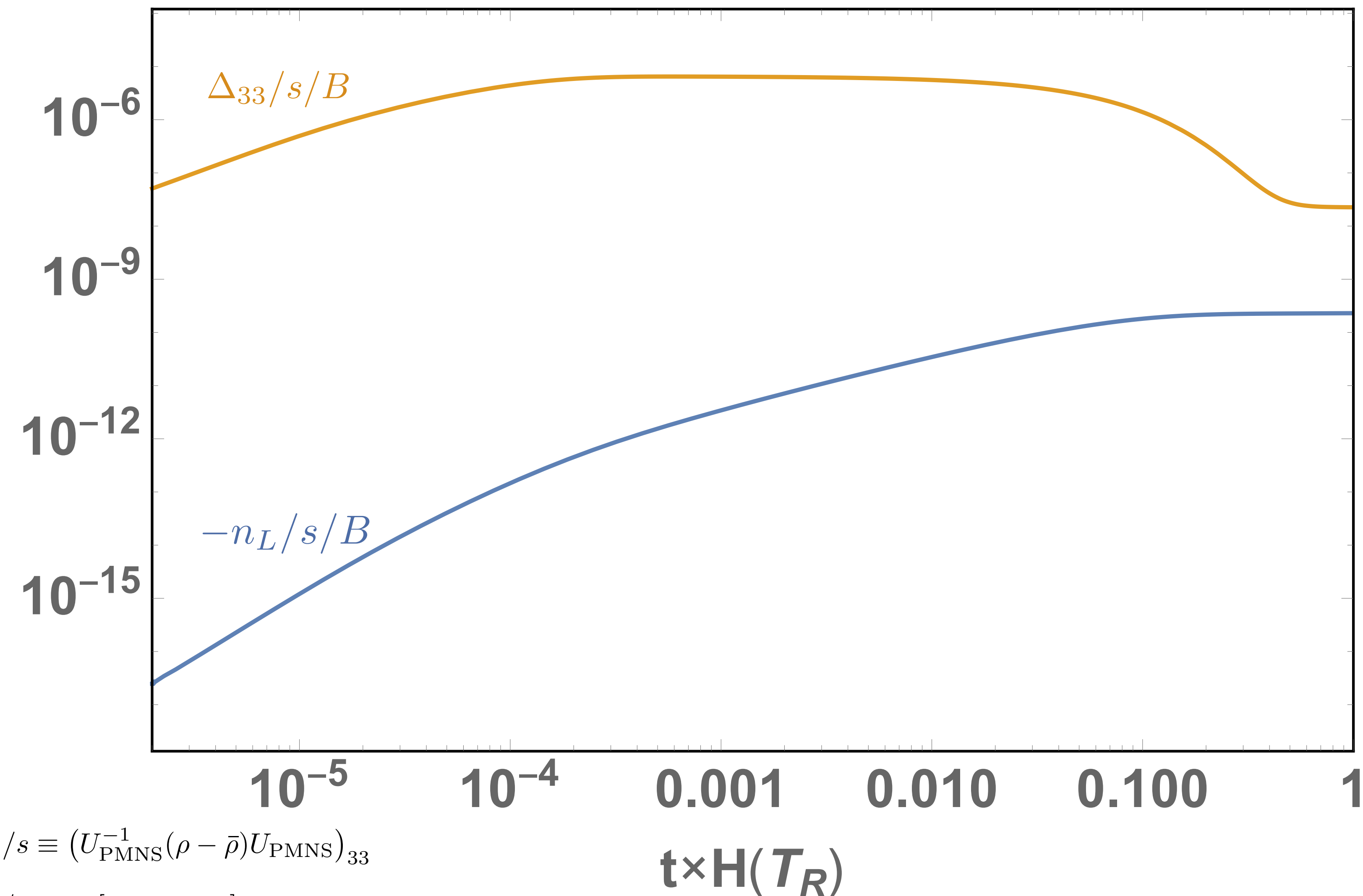
Interaction:





CP violation can take place!

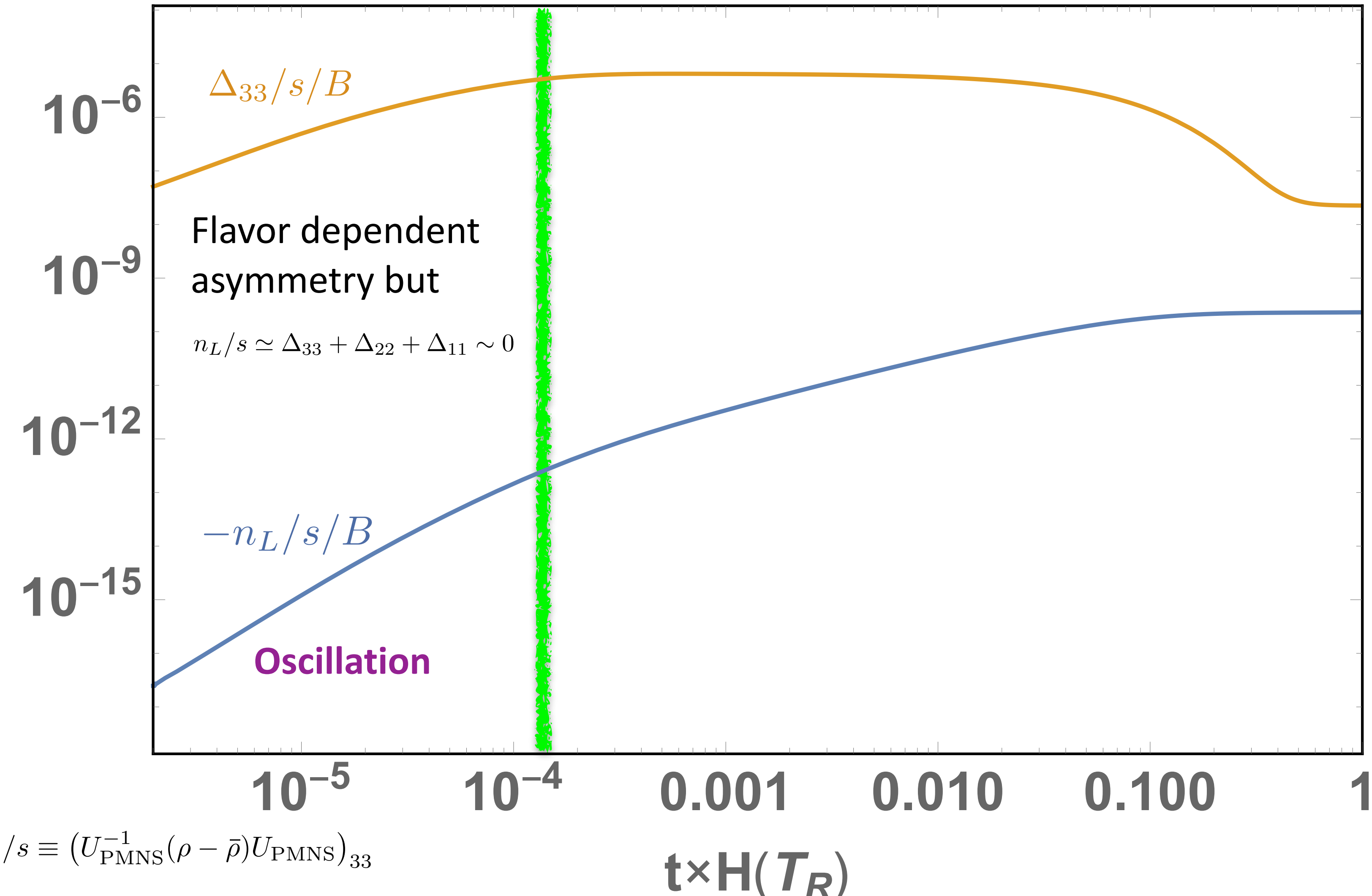
★



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

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

★



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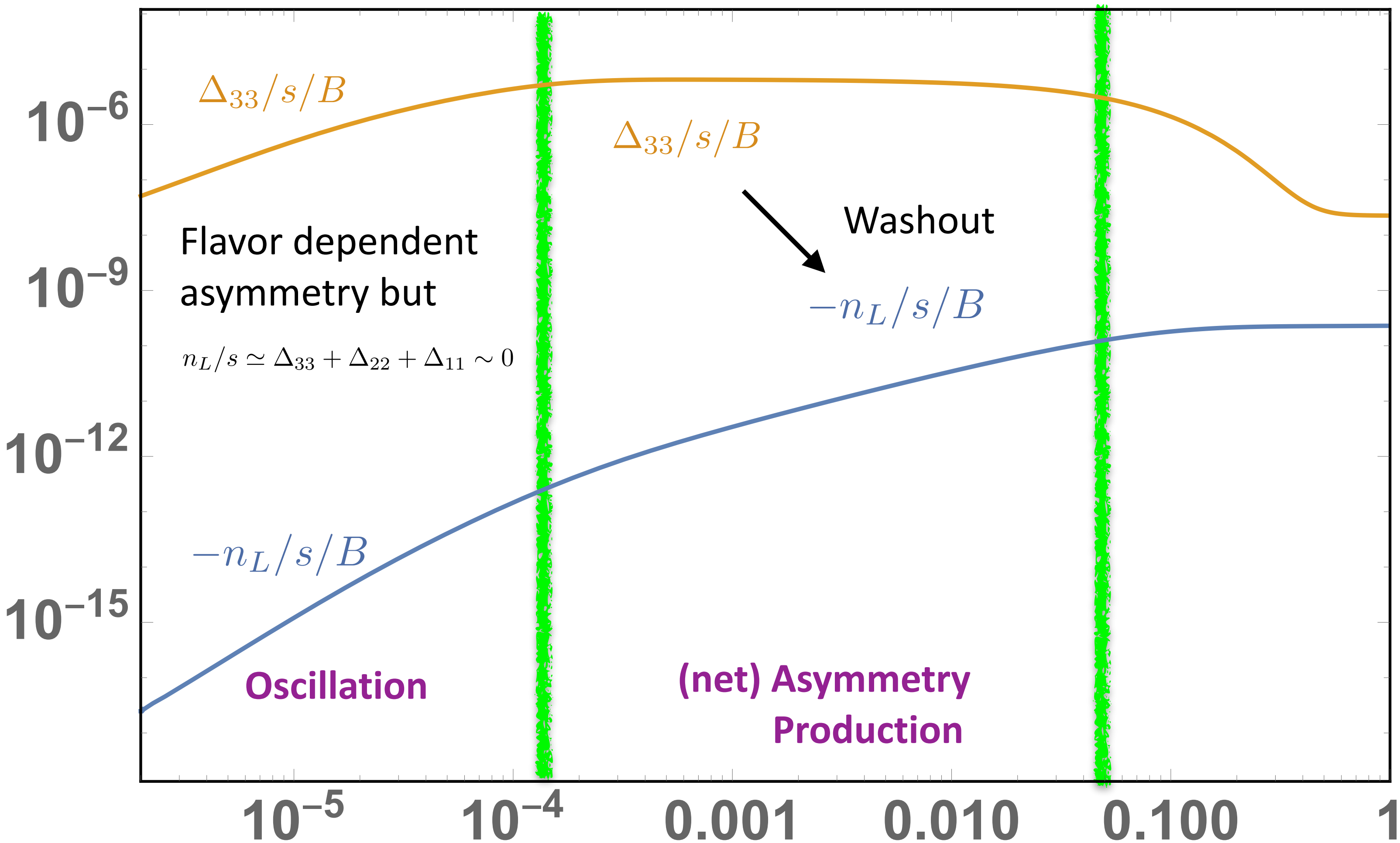
★ $(\Gamma_{wo})_\alpha \propto m_{\nu_\alpha}^2$

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



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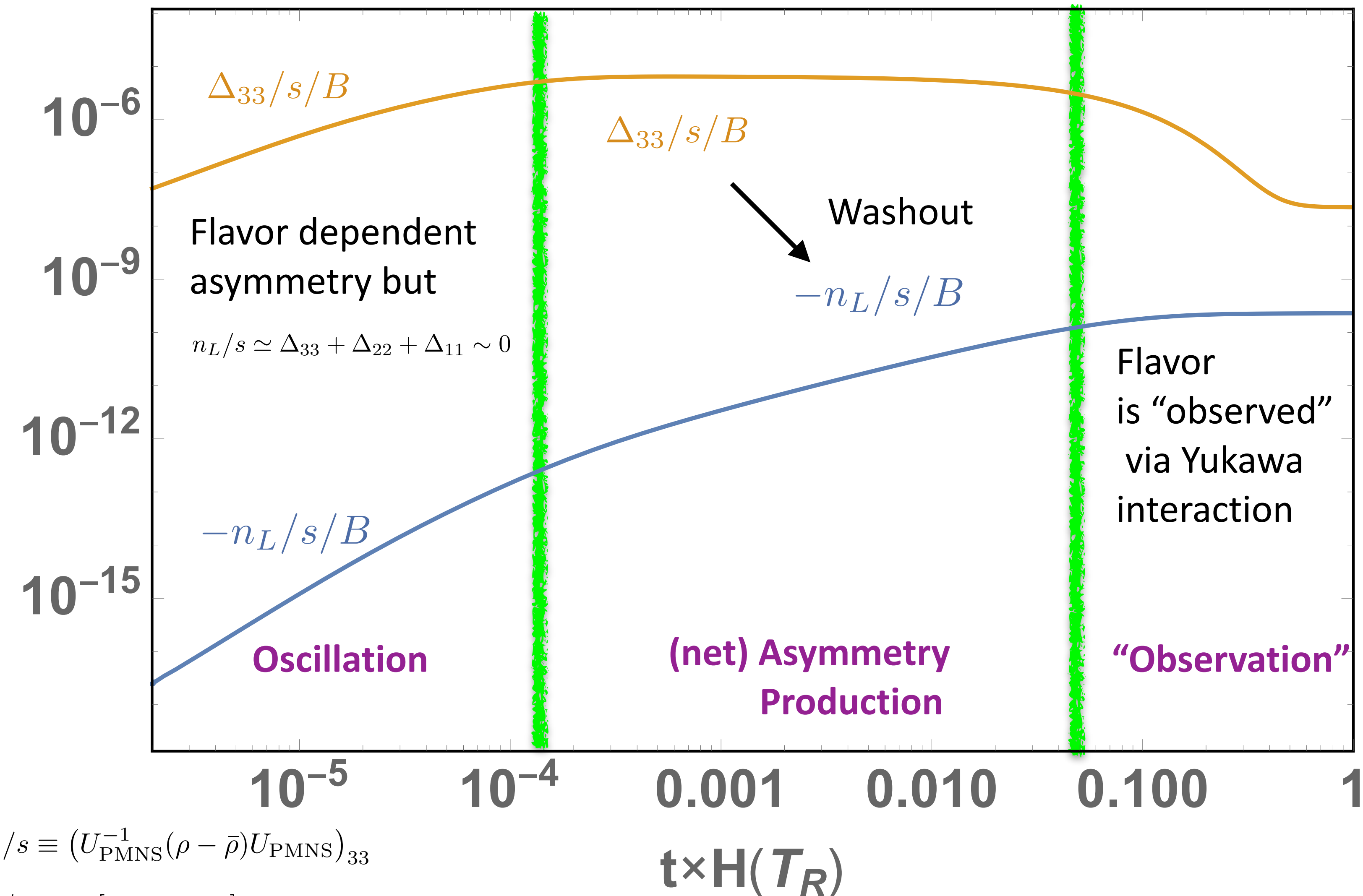

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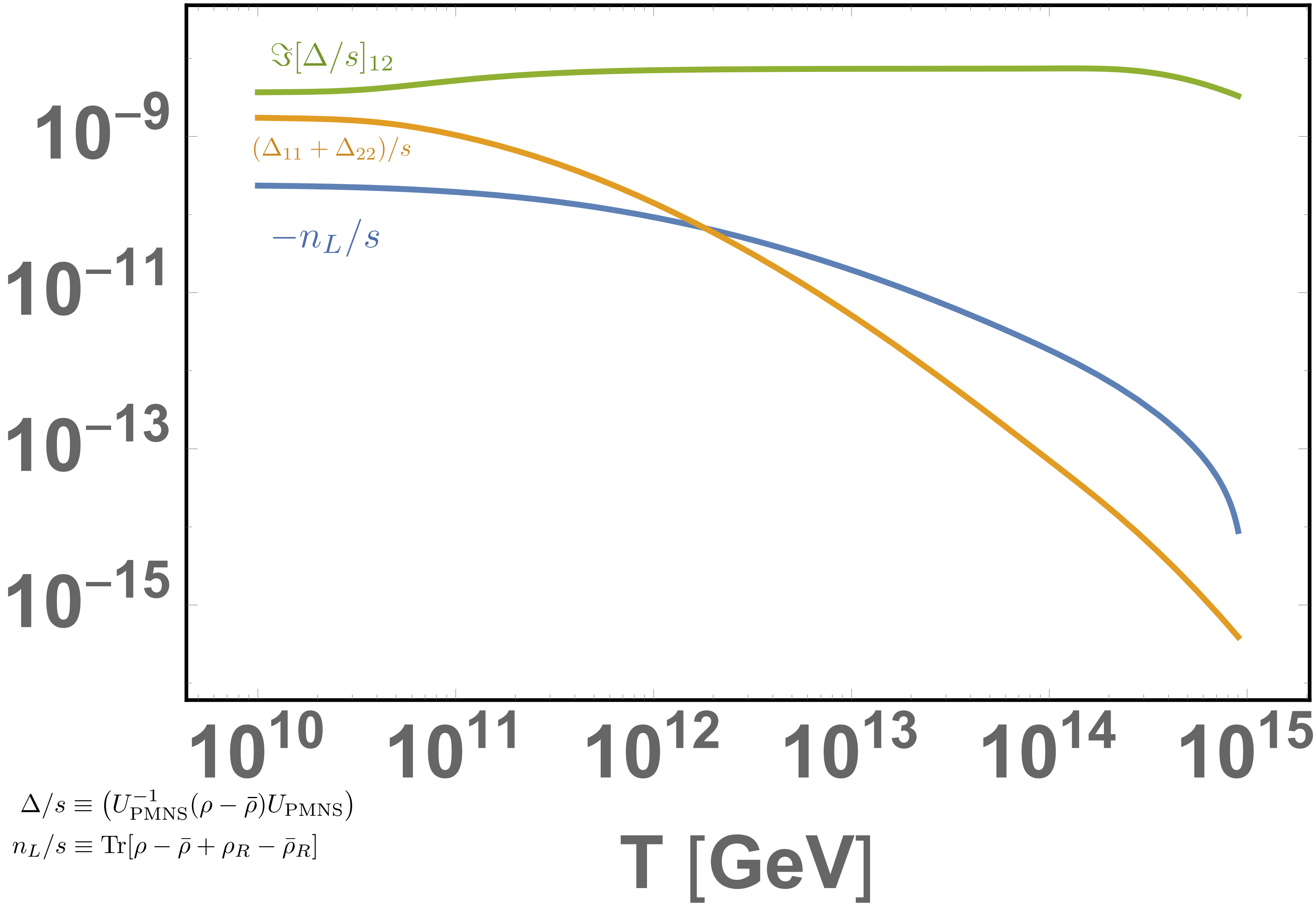
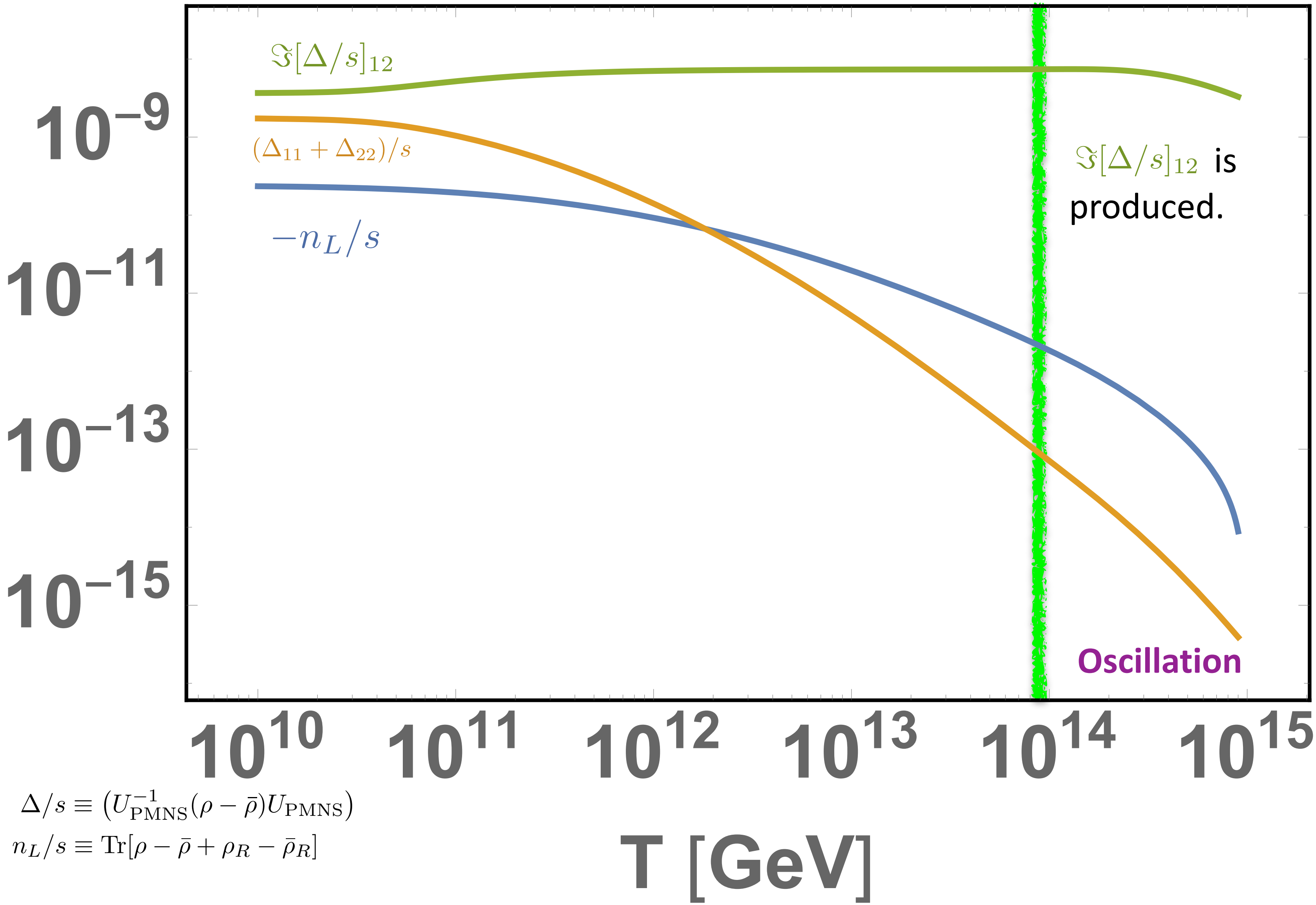


$\Delta/s \equiv \left(U_{\mathrm{PMNS}}^{-1}(\rho-\bar\rho)U_{\mathrm{PMNS}}\right)$

$n_L/s \equiv \mathrm{Tr}[\rho-\bar\rho+\rho_R-\bar\rho_R]$

★



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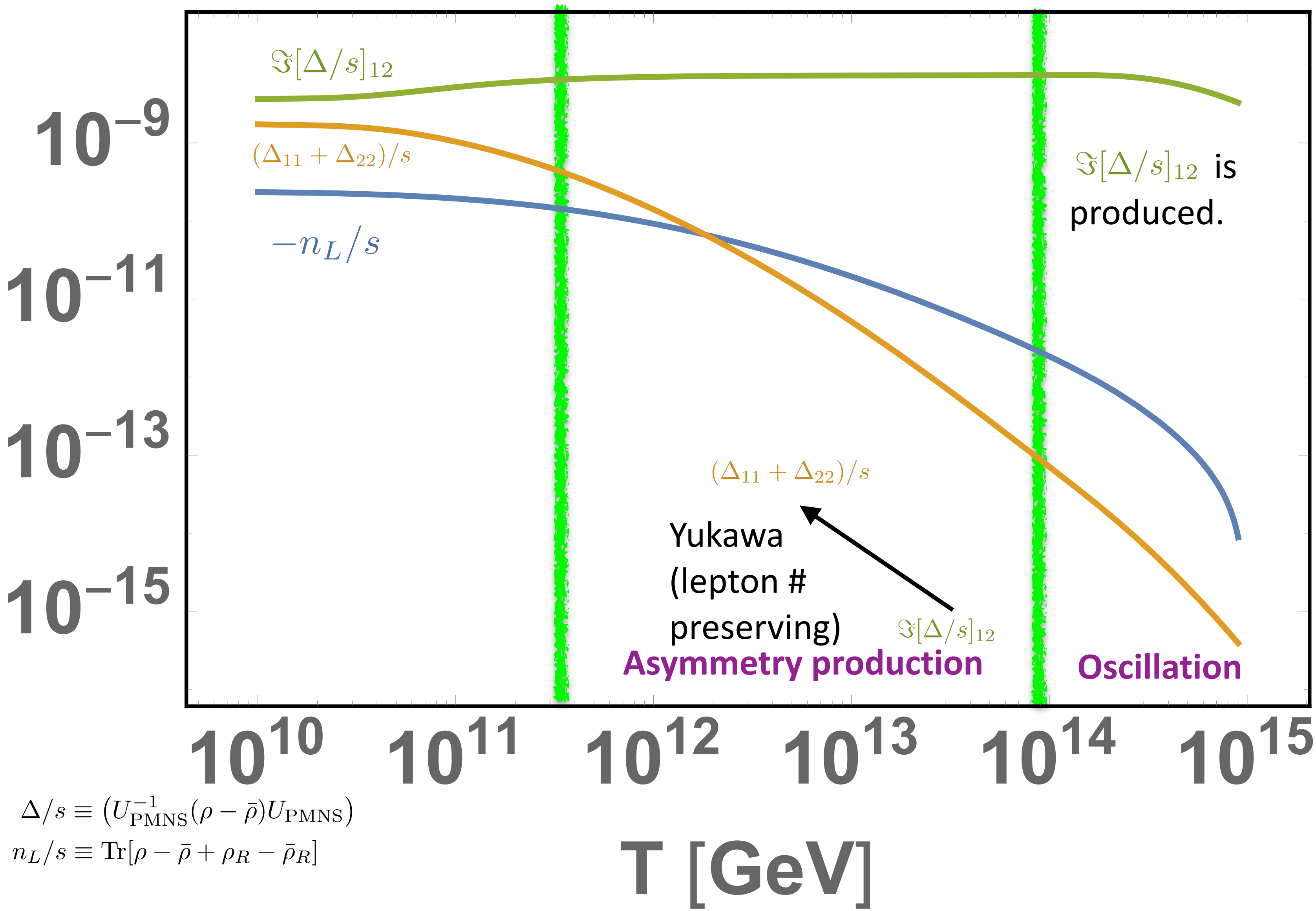
★ Inverted Hierarchy: $(\Gamma_{wo})_1 \sim (\Gamma_{wo})_2 \gg (\Gamma_{wo})_3$



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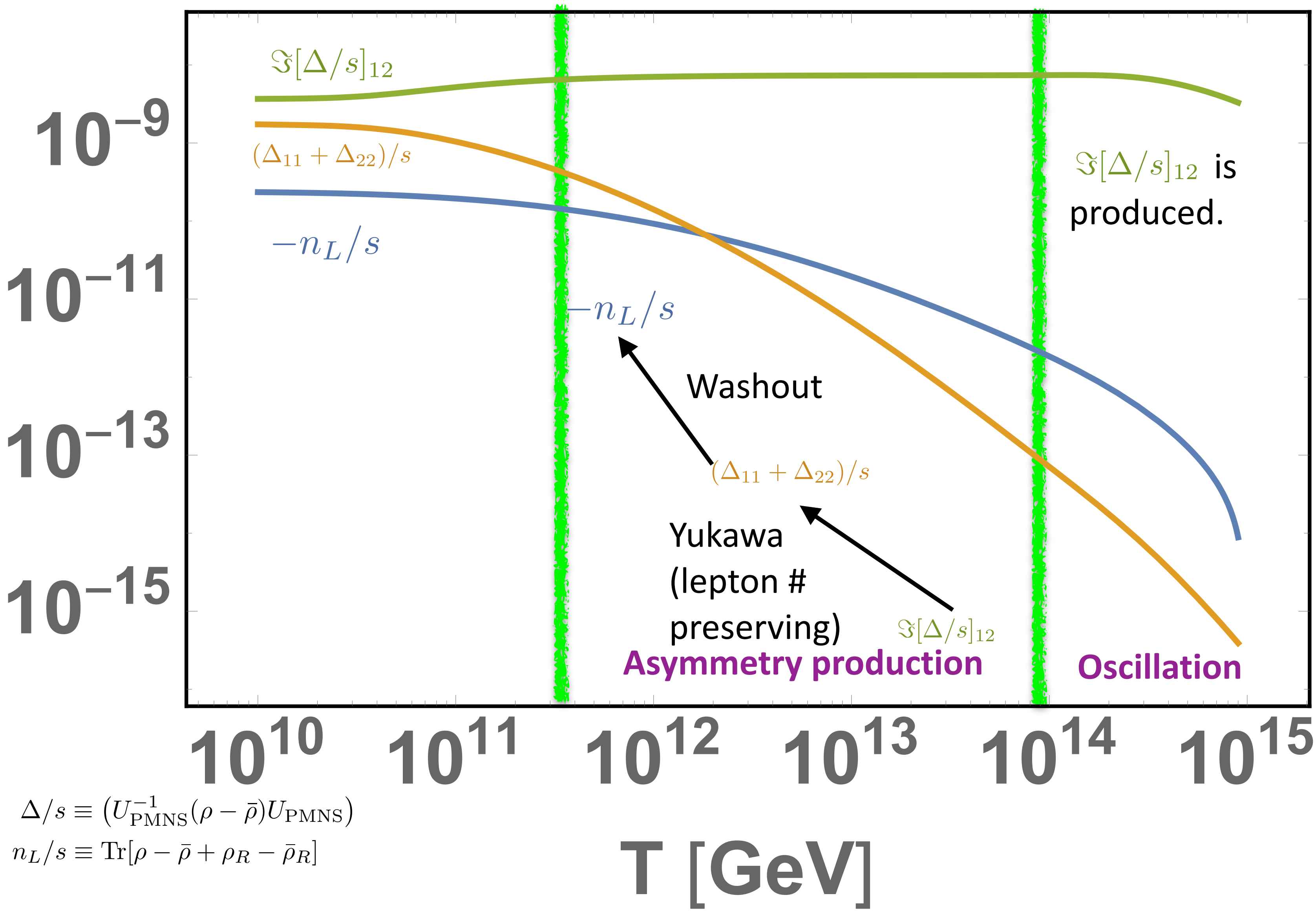

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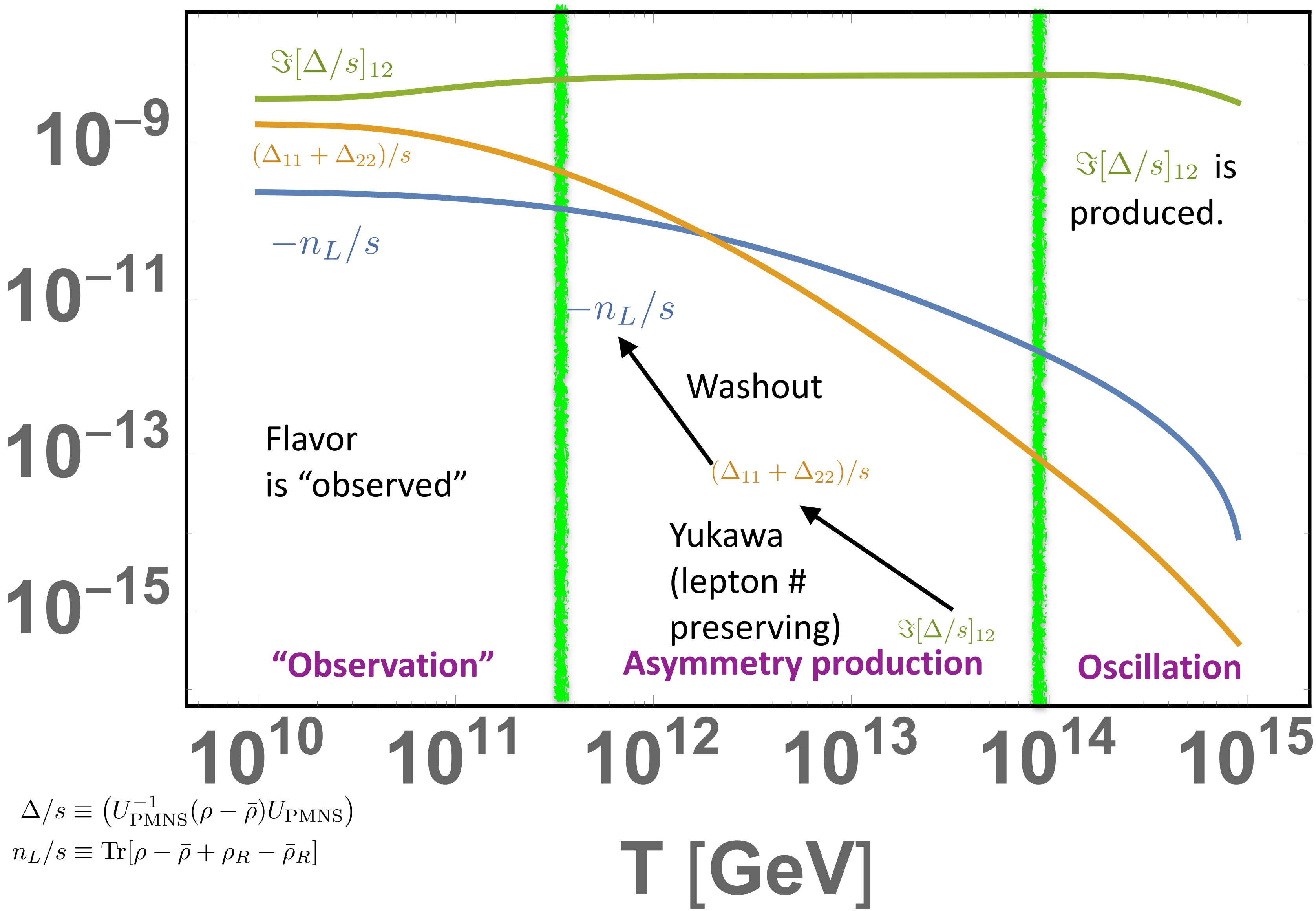

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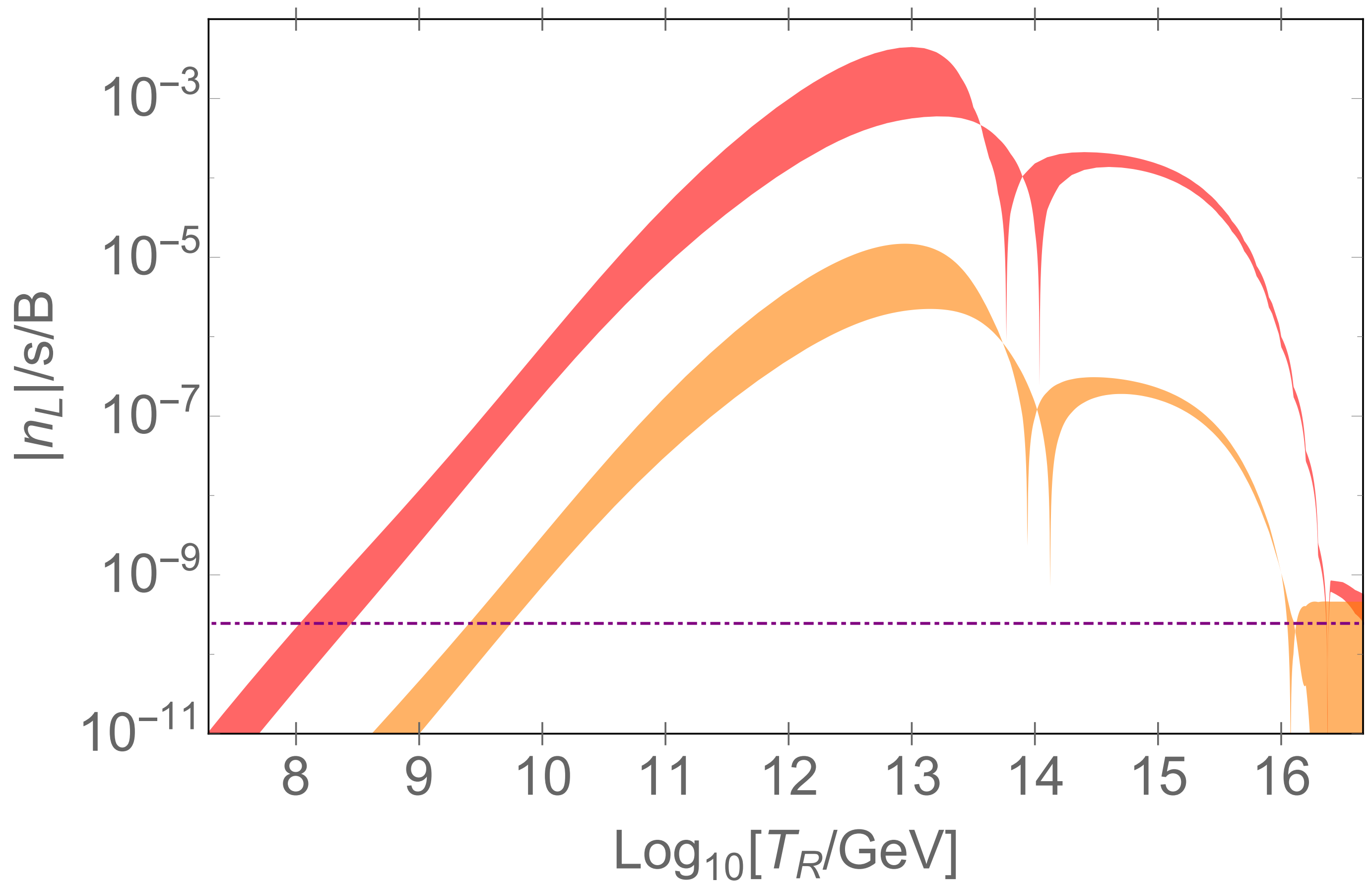
FIGURES FOR INFLATON->LEPTON

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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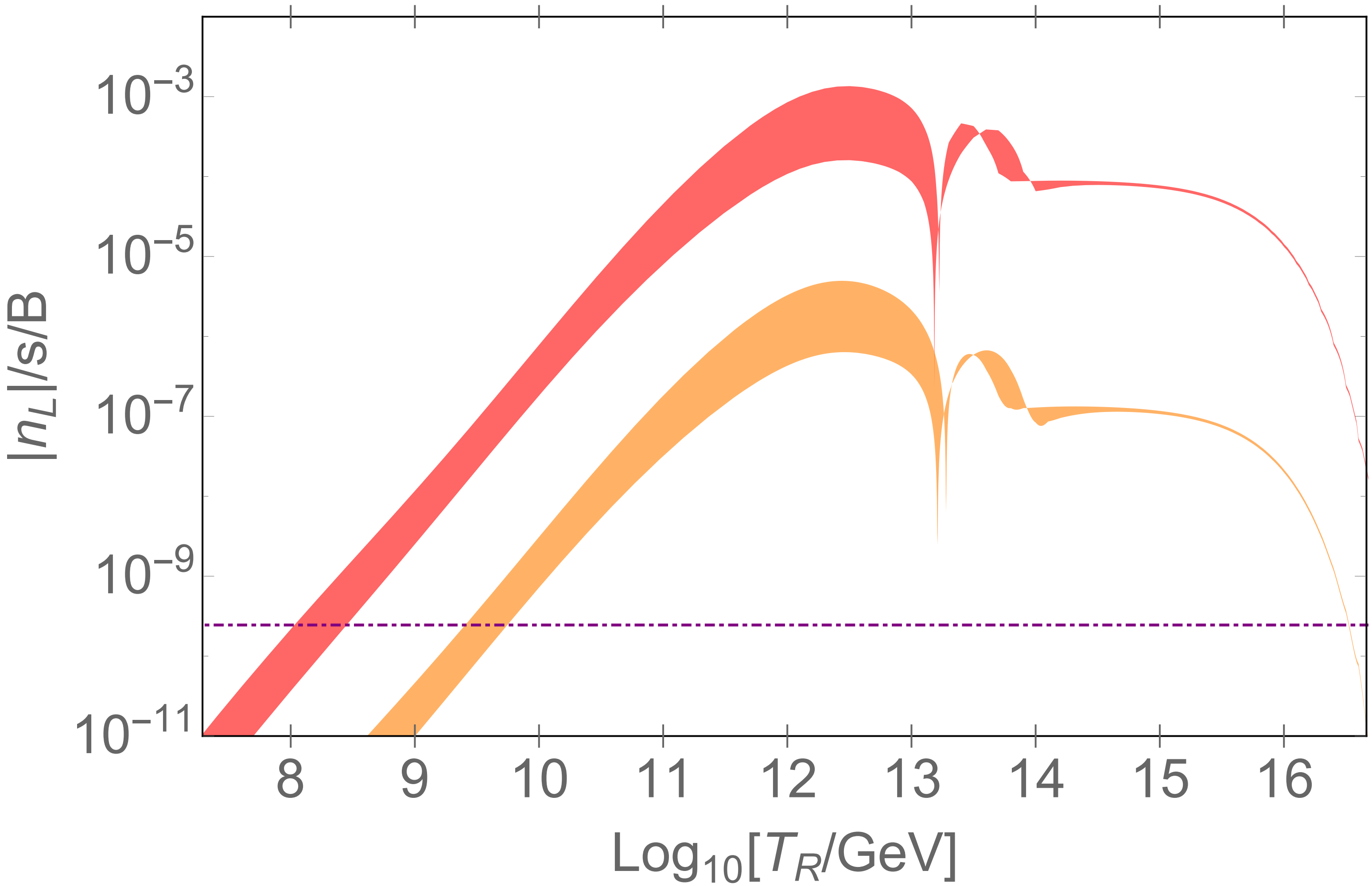

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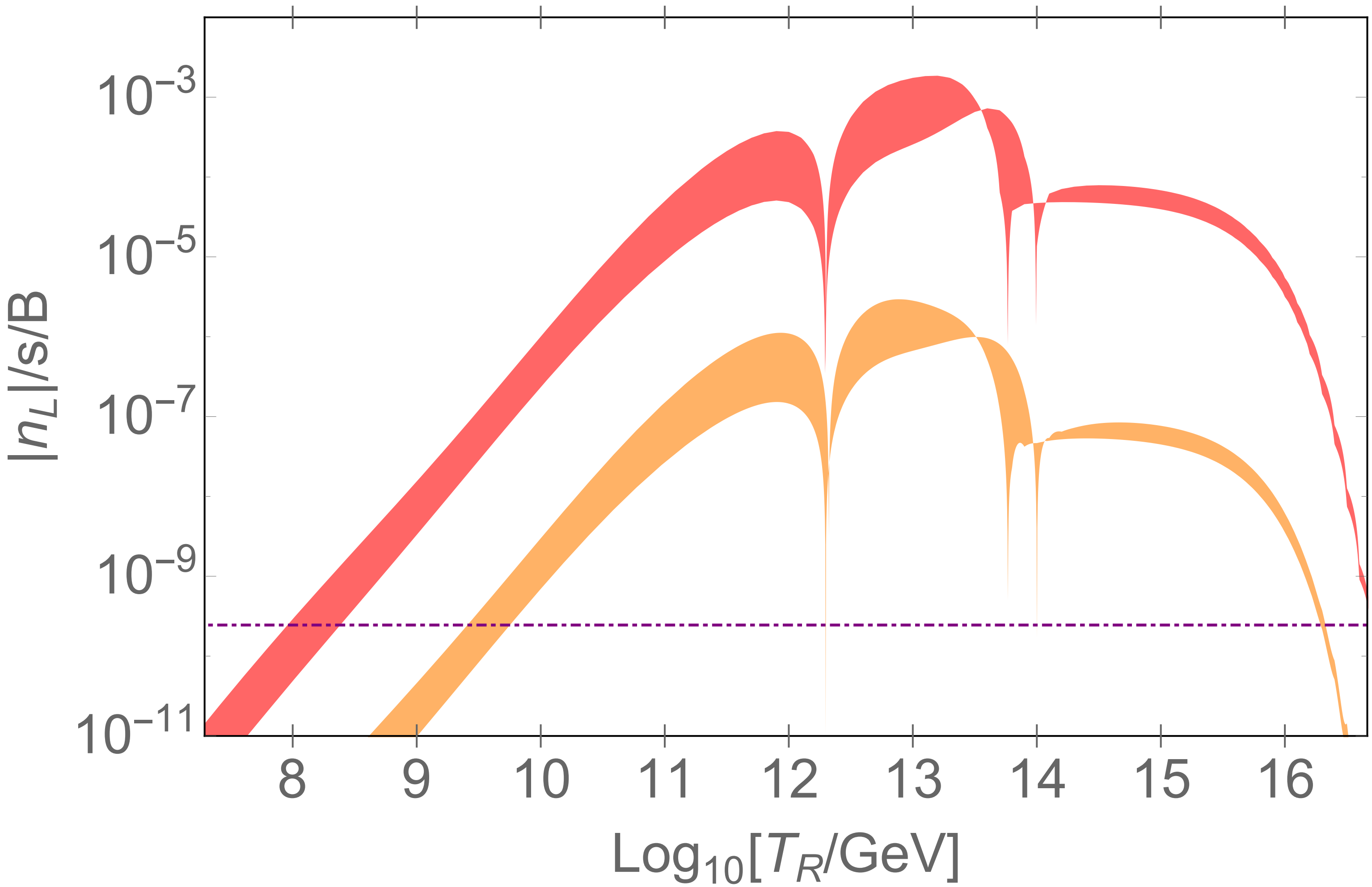
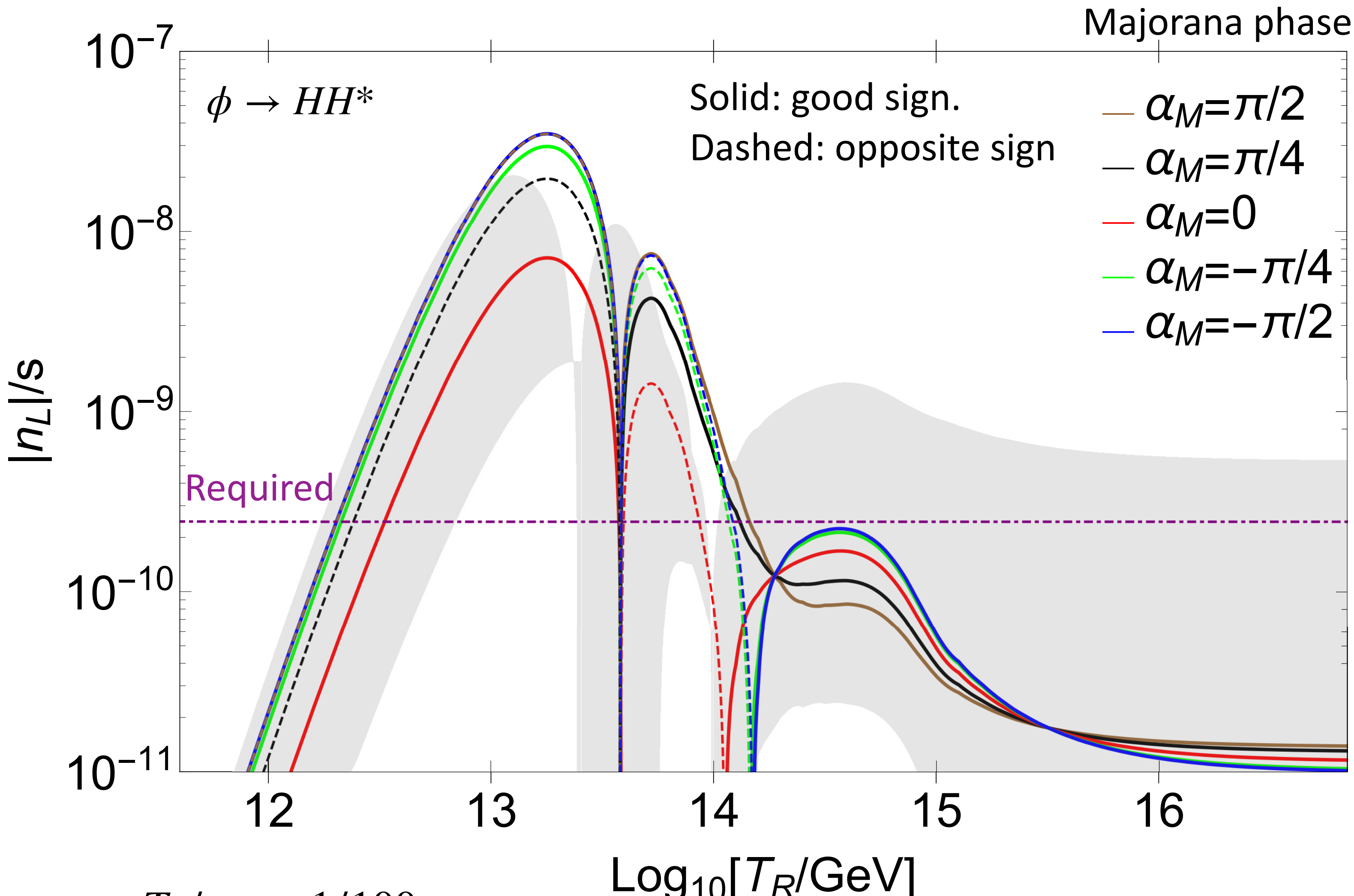


FIGURES FOR INFLATON->HIGGS

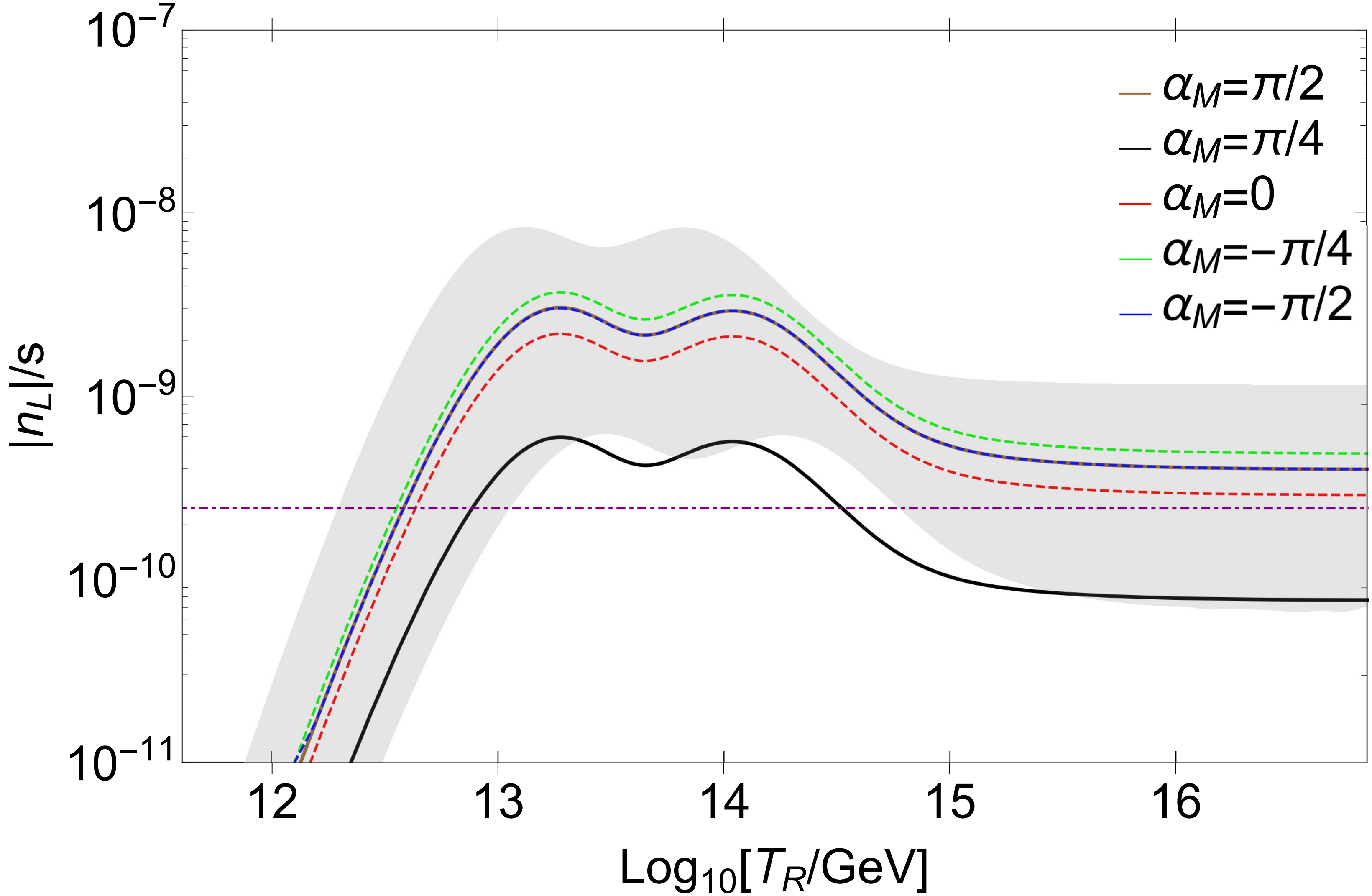
Numerical result (Normal Hierarchy)



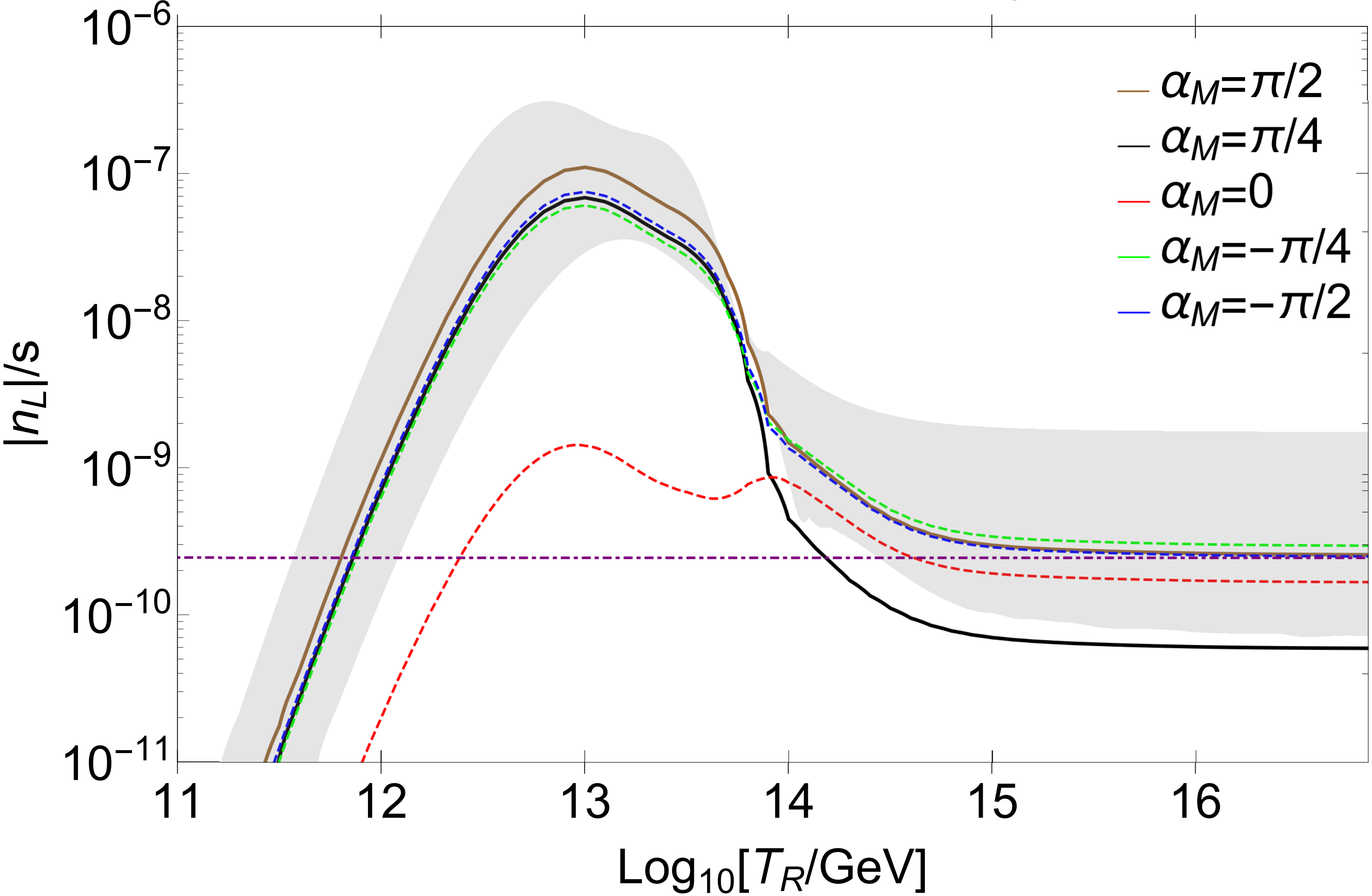
$T_R/m_\phi = 1/100$

Two massive neutrinos. Dirac Phase=-Pi/2

Inverted hierarchy



Inverted degenerate case.
mnulightest=0.07eV



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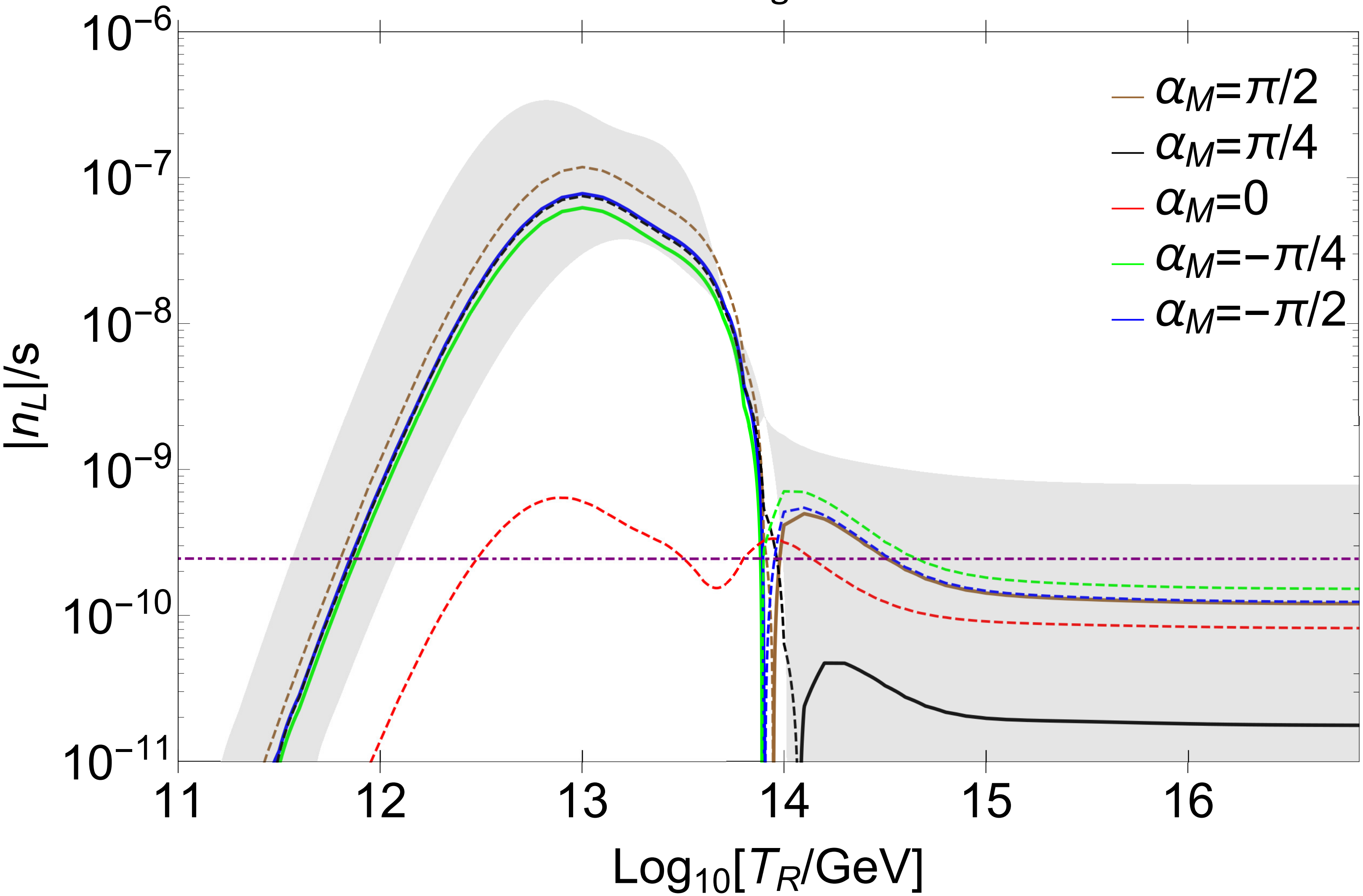
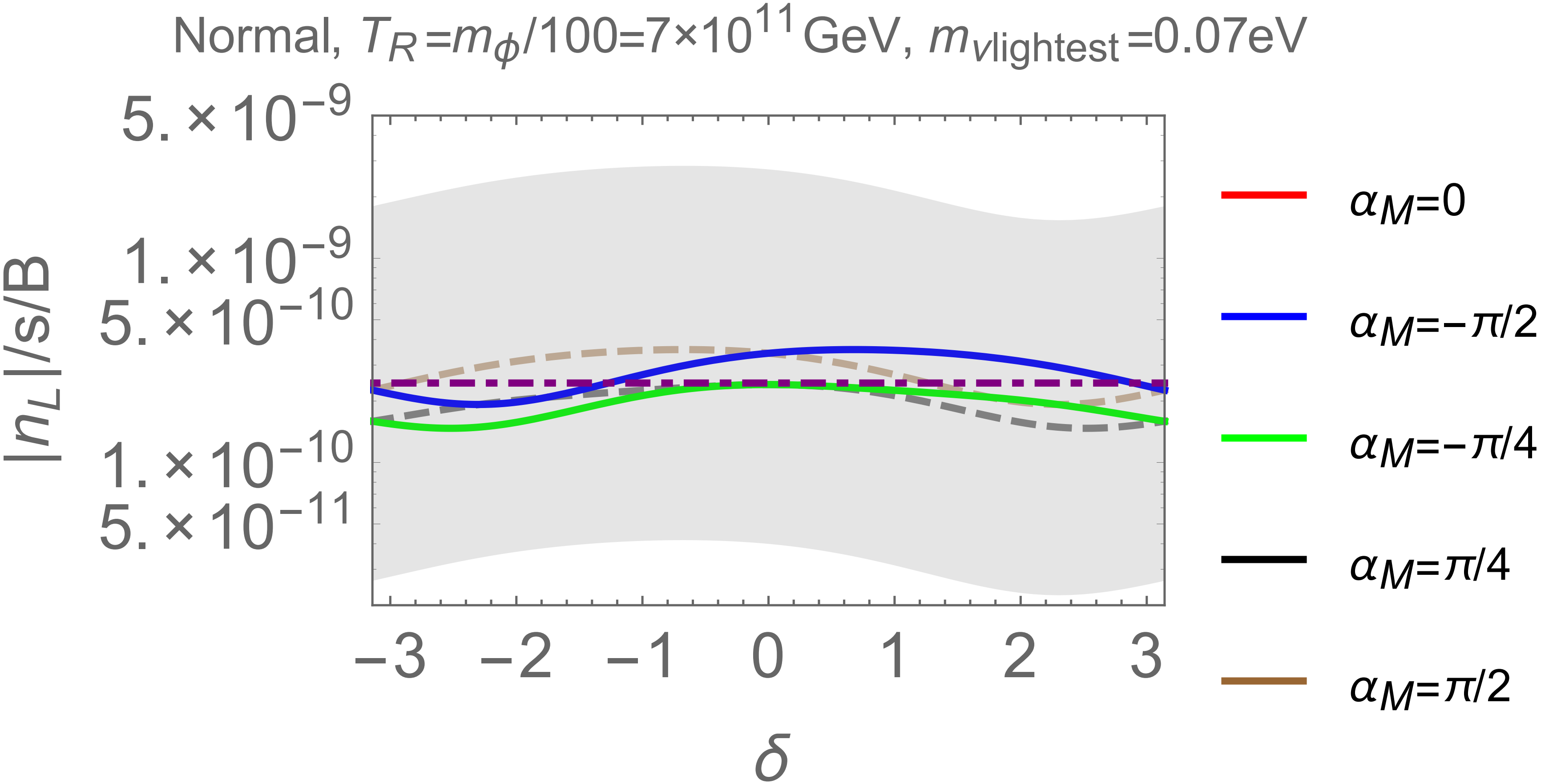
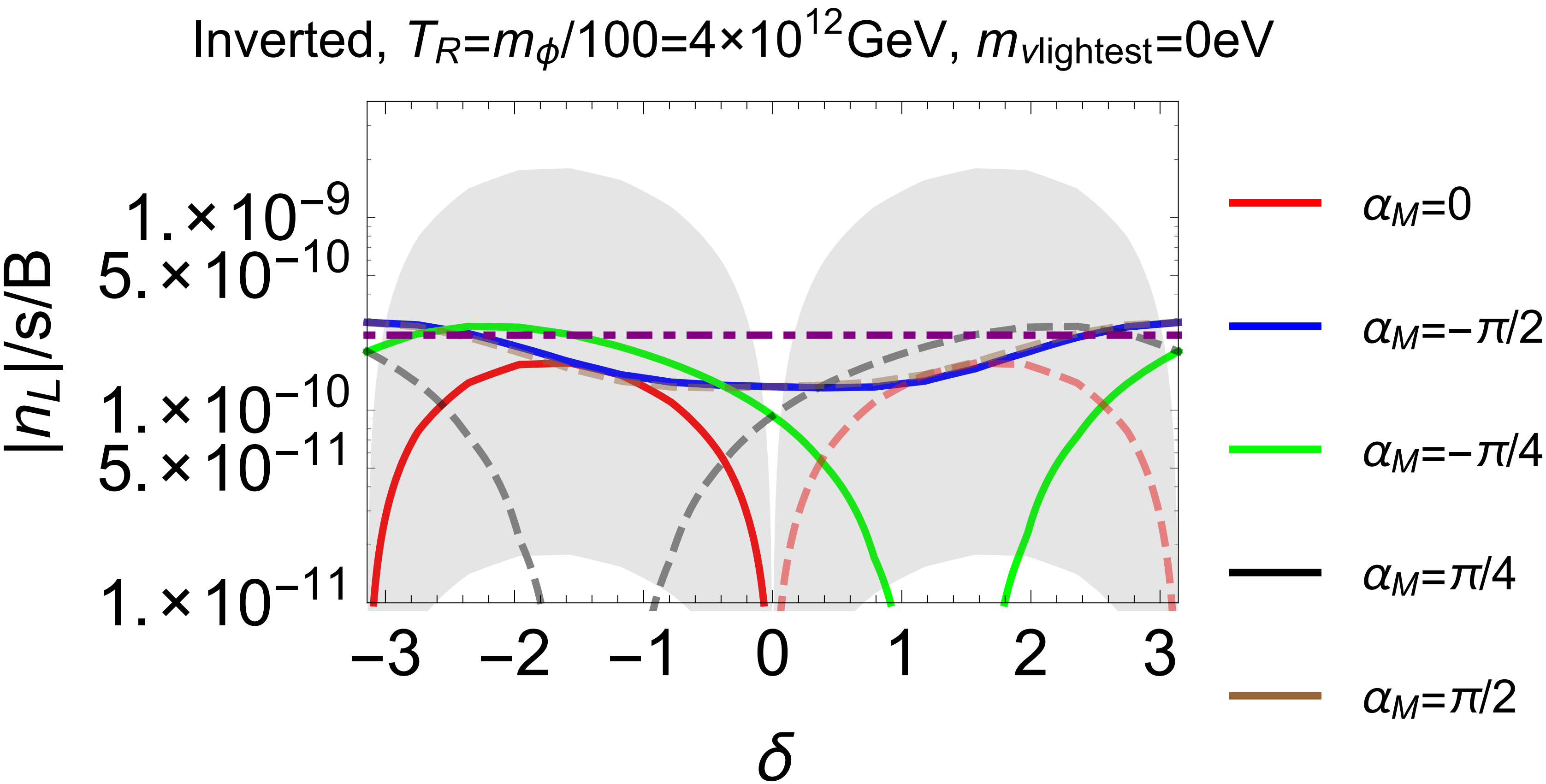
mnulightest=0.07eV

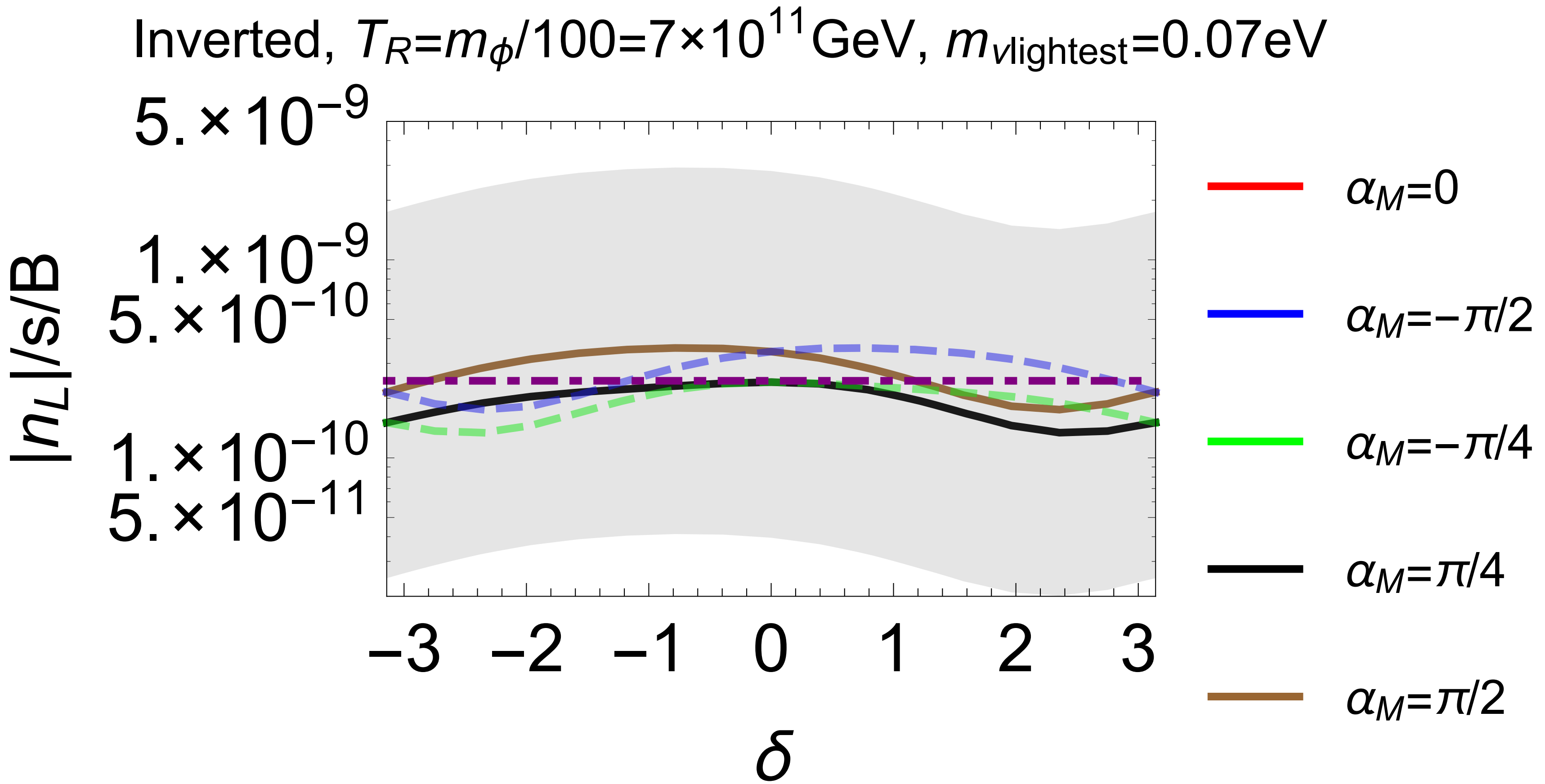




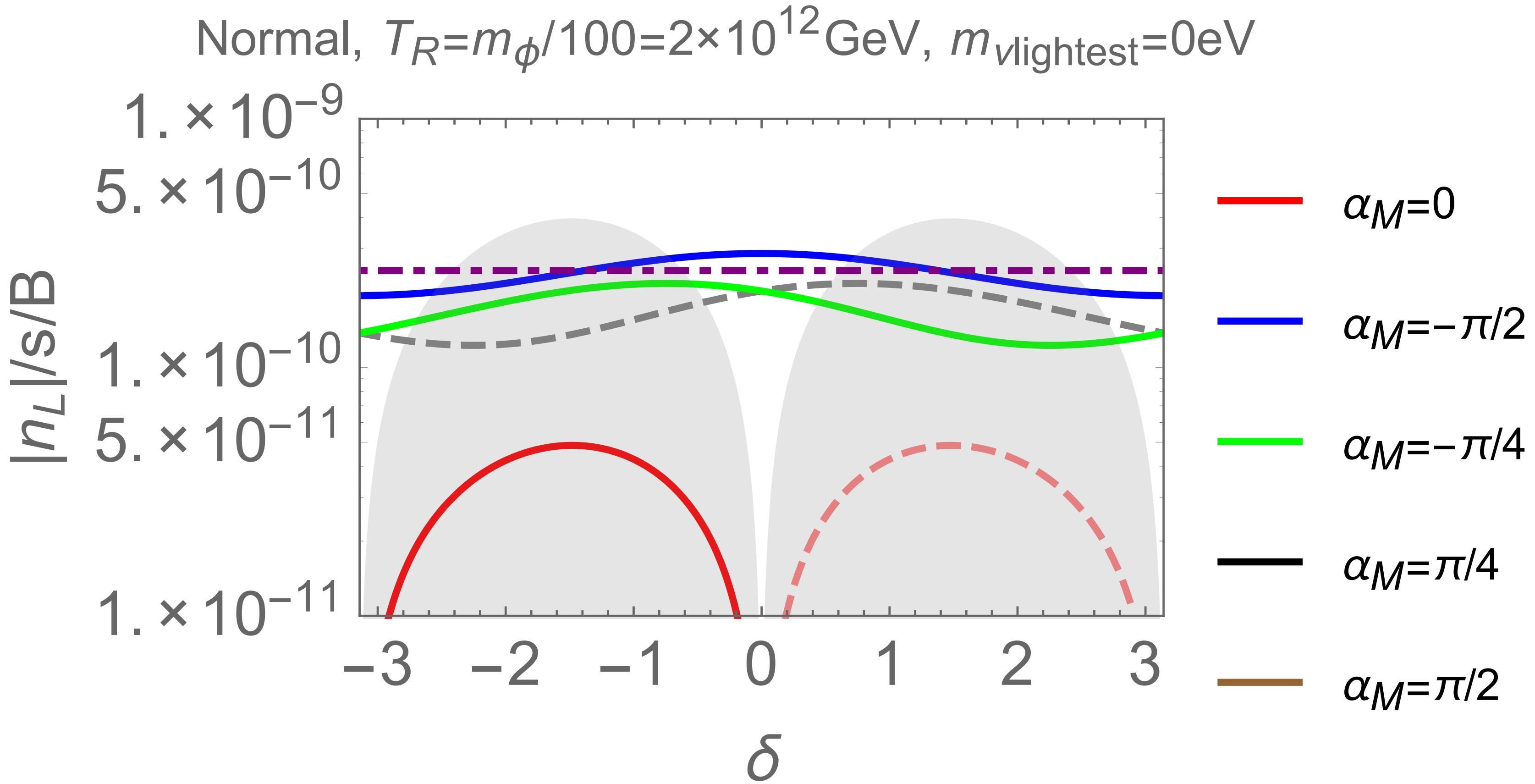
Normal, $T_R = m_\phi/100 = 7\times10^{11}$ GeV, $m_{\nu\text{lightest}} = 0.07$eV
5. × 10^−9
1. × 10^−9
5. × 10^−10
1. × 10^−10
5. × 10^−11
|n_L|/s/B
−3
−2
−1
0
1
2
3
δ
α_M=0
α_M=−π/2
α_M=−π/4
α_M=π/4
α_M=π/2



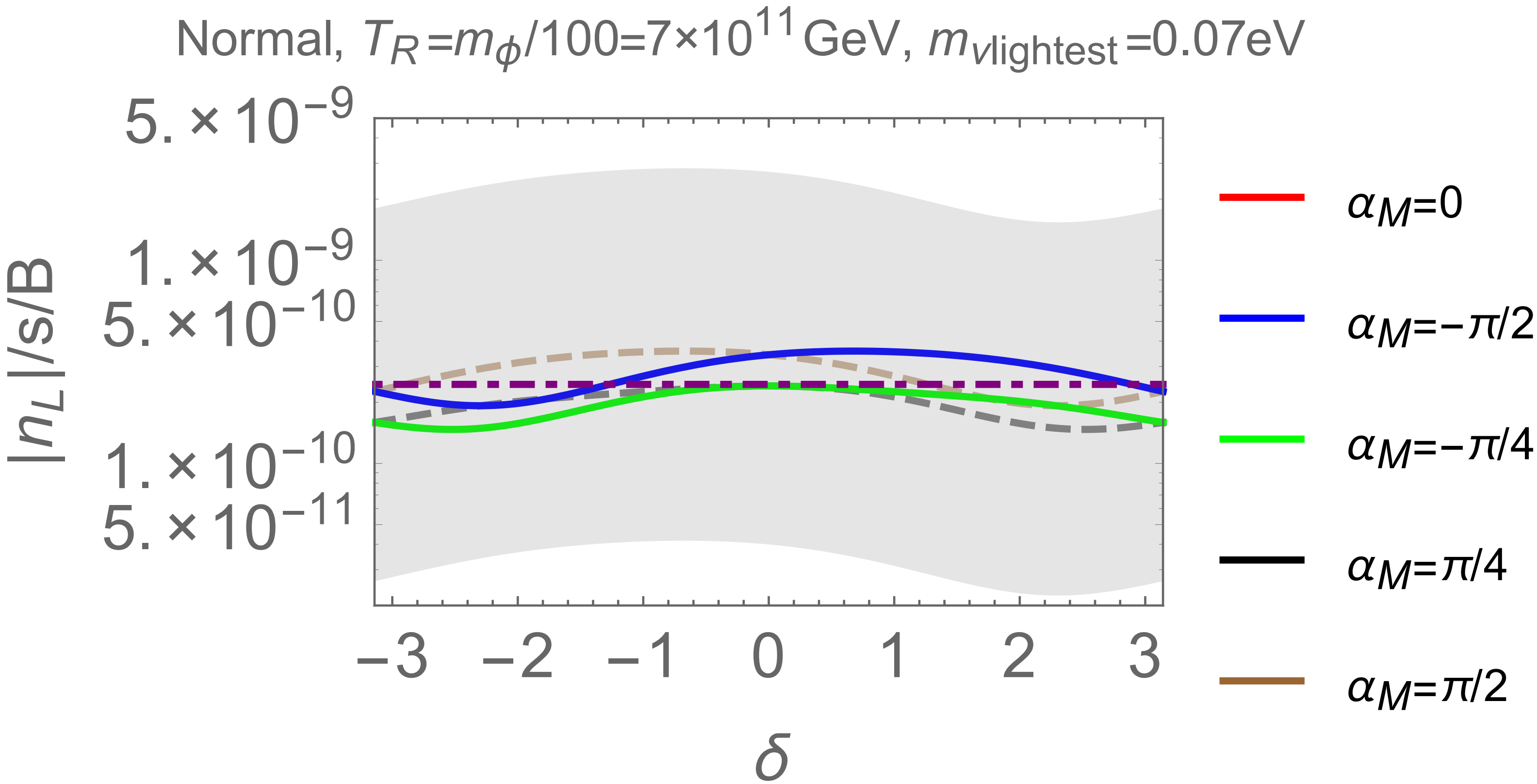
Inverted, T_R=m_ϕ/100=4×10^{12}GeV, $m_{\nu\mathrm{lightest}}$=0eV
|n_L|/s/B
1.×10^{-9}
5.×10^{-10}
1.×10^{-10}
5.×10^{-11}
1.×10^{-11}
−3
−2
−1
0
1
2
3
δ
α_M=0
α_M=−π/2
α_M=−π/4
α_M=π/4
α_M=π/2

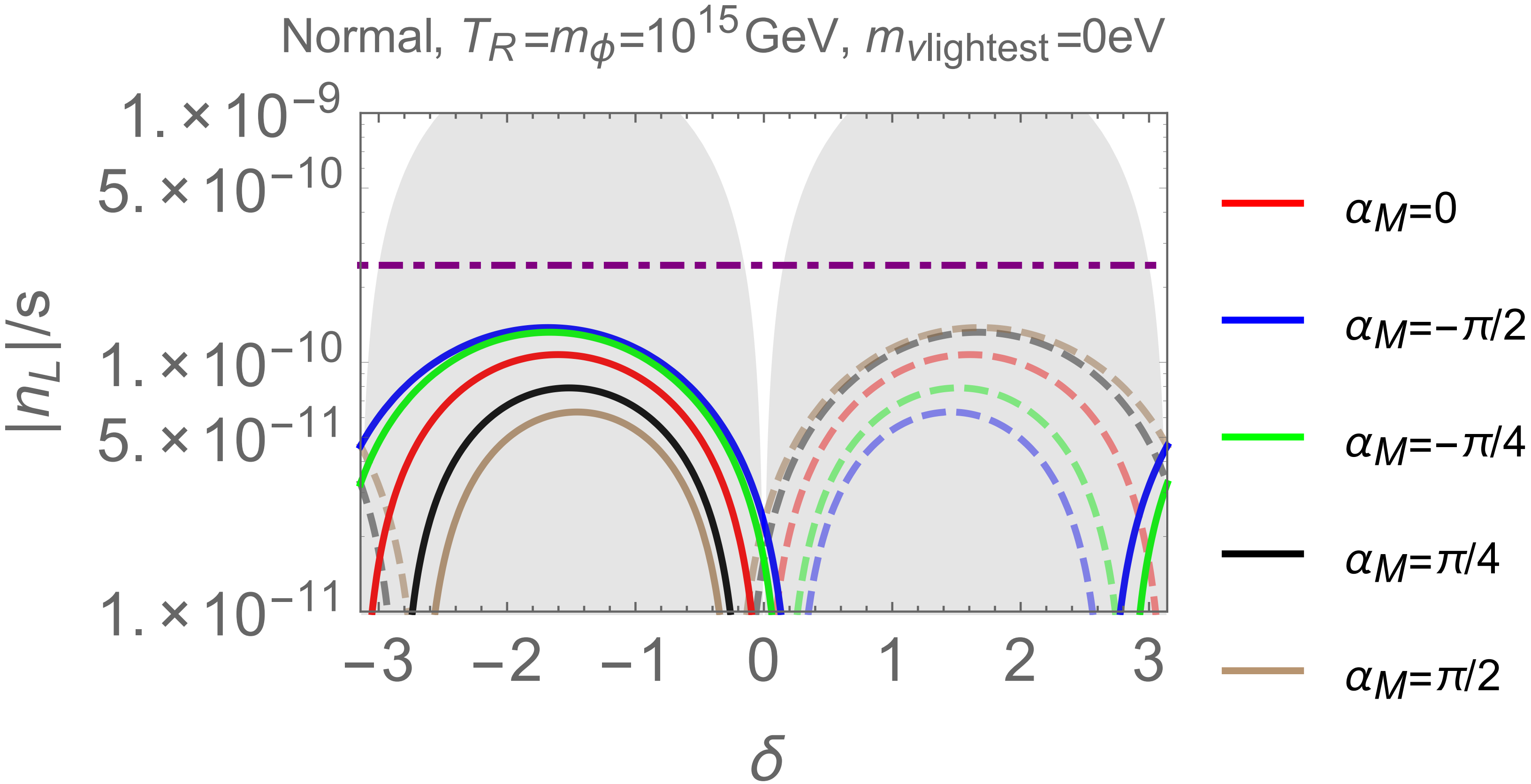


Inverted, $T_R=m_\phi/100=7\times10^{11}$GeV, $m_{\nu\text{lightest}}=0.07$eV
$5.\times10^{-9}$
$1.\times10^{-9}$
$5.\times10^{-10}$
$1.\times10^{-10}$
$5.\times10^{-11}$
$|n_L|/s/B$
−3 −2 −1 0 1 2 3
δ
$\alpha_M=0$
$\alpha_M=-\pi/2$
$\alpha_M=-\pi/4$
$\alpha_M=\pi/4$
$\alpha_M=\pi/2$

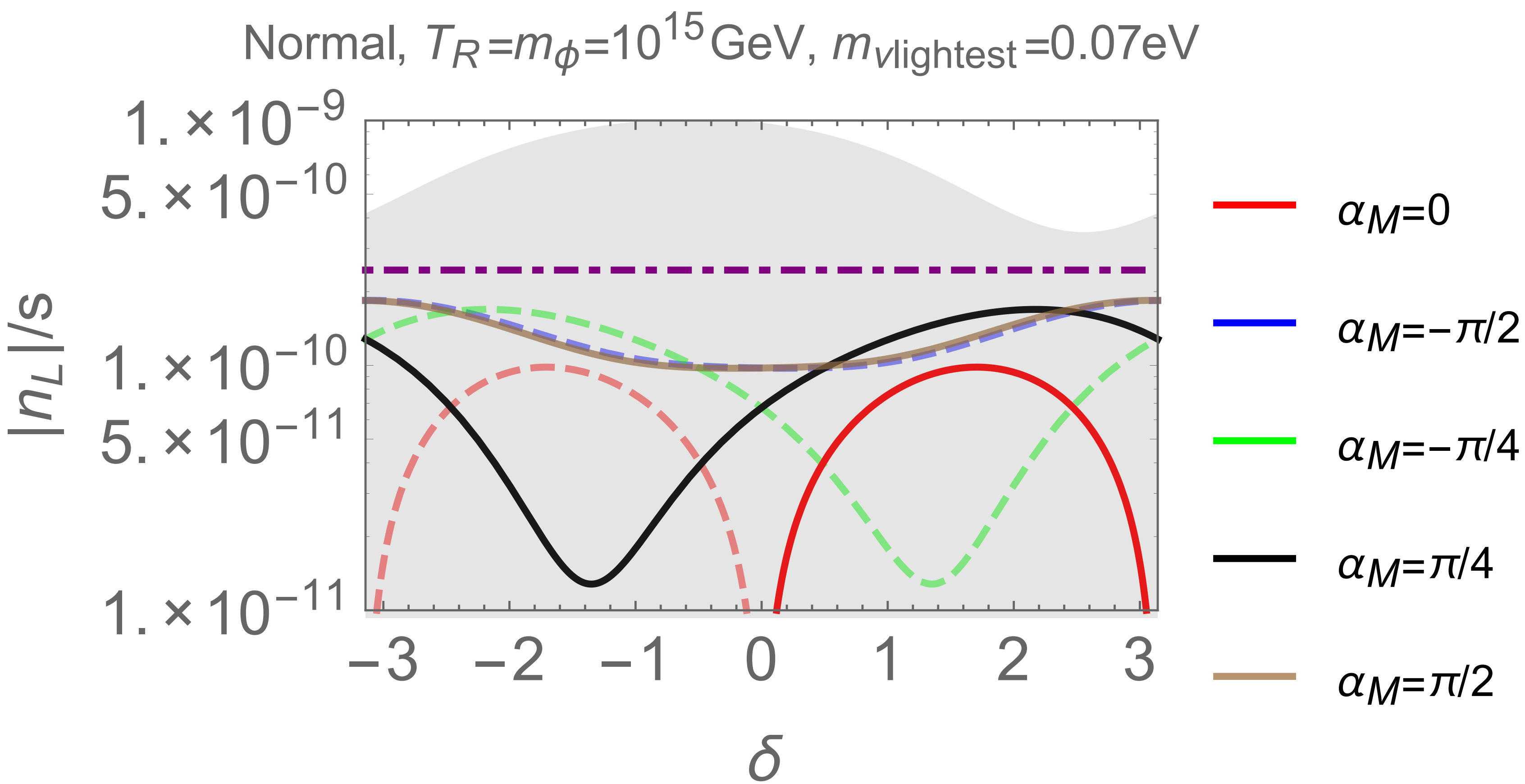


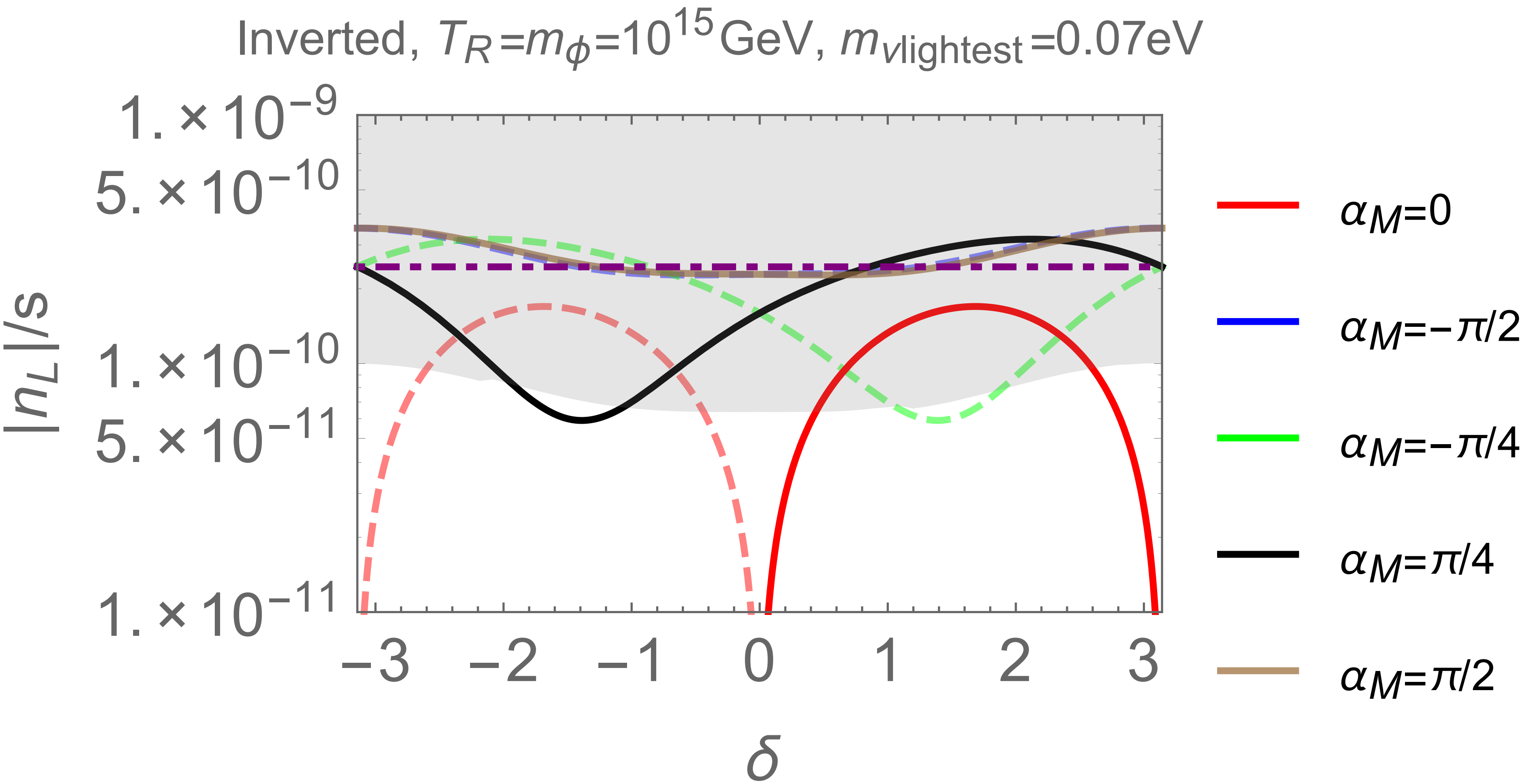
Normal, $T_R=m_\phi/100=2\times10^{12}$GeV, $m_{\nu\text{lightest}}$=0eV
$1.\times10^{-9}$
$5.\times10^{-10}$
$1.\times10^{-10}$
$5.\times10^{-11}$
$1.\times10^{-11}$
$|n_L|/s/B$
−3
−2
−1
0
1
2
3
δ
$\alpha_M=0$
$\alpha_M=-\pi/2$
$\alpha_M=-\pi/4$
$\alpha_M=\pi/4$
$\alpha_M=\pi/2$


Normal, $T_R = m_\phi/100 = 7\times10^{11}$ GeV, $m_{\nu\text{lightest}} = 0.07$eV
$5.\times10^{-9}$
$1.\times10^{-9}$
$5.\times10^{-10}$
$1.\times10^{-10}$
$5.\times10^{-11}$
$|n_L|/s/B$
−3
−2
−1
0
1
2
3
δ
$\alpha_M=0$
$\alpha_M=-\pi/2$
$\alpha_M=-\pi/4$
$\alpha_M=\pi/4$
$\alpha_M=\pi/2$

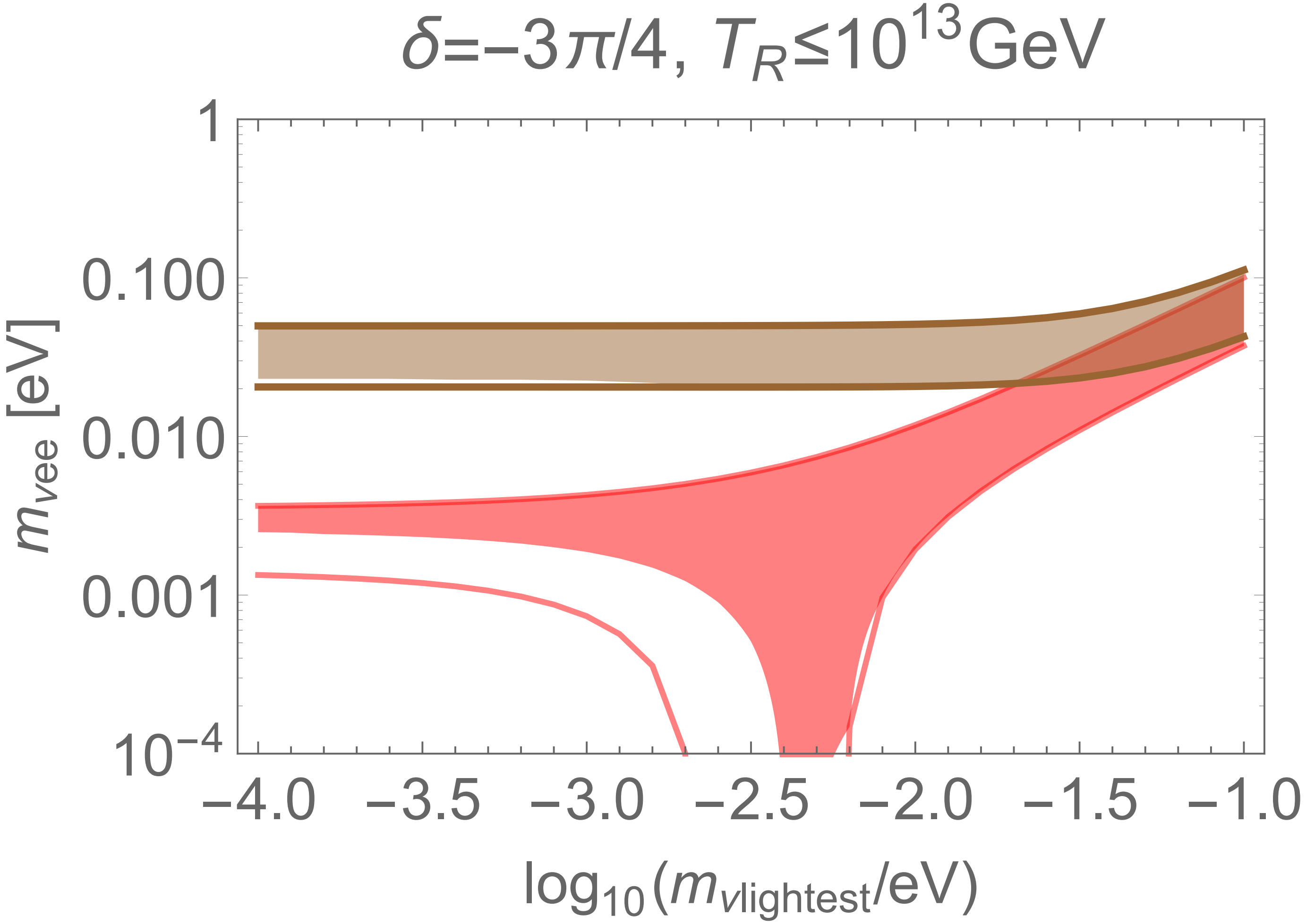


Normal, $T_R = m_\phi = 10^{15}$ GeV, $m_{\nu\text{lightest}} = 0$eV
$|n_L|/s$
1. × 10^−9
5. × 10^−10
1. × 10^−10
5. × 10^−11
1. × 10^−11
−3
−2
−1
0
1
2
3
δ
α_M=0
α_M=−π/2
α_M=−π/4
α_M=π/4
α_M=π/2


Normal, $T_R = m_\phi = 10^{15}$ GeV, $m_{\nu\text{lightest}} = 0.07$eV
$1. \times 10^{-9}$
$5. \times 10^{-10}$
$1. \times 10^{-10}$
$5. \times 10^{-11}$
$1. \times 10^{-11}$
$|n_L|/s$
−3
−2
−1
0
1
2
3
δ
α_M=0
α_M=−π/2
α_M=−π/4
α_M=π/4
α_M=π/2



Inverted, $T_R=m_\phi=10^{15}$GeV, $m_{\nu\text{lightest}}=0.07$eV
$1.\times10^{-9}$
$5.\times10^{-10}$
$1.\times10^{-10}$
$5.\times10^{-11}$
$1.\times10^{-11}$
$|n_L|/s$
−3
−2
−1
0
1
2
3
δ
α_M=0
α_M=−π/2
α_M=−π/4
α_M=π/4
α_M=π/2


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