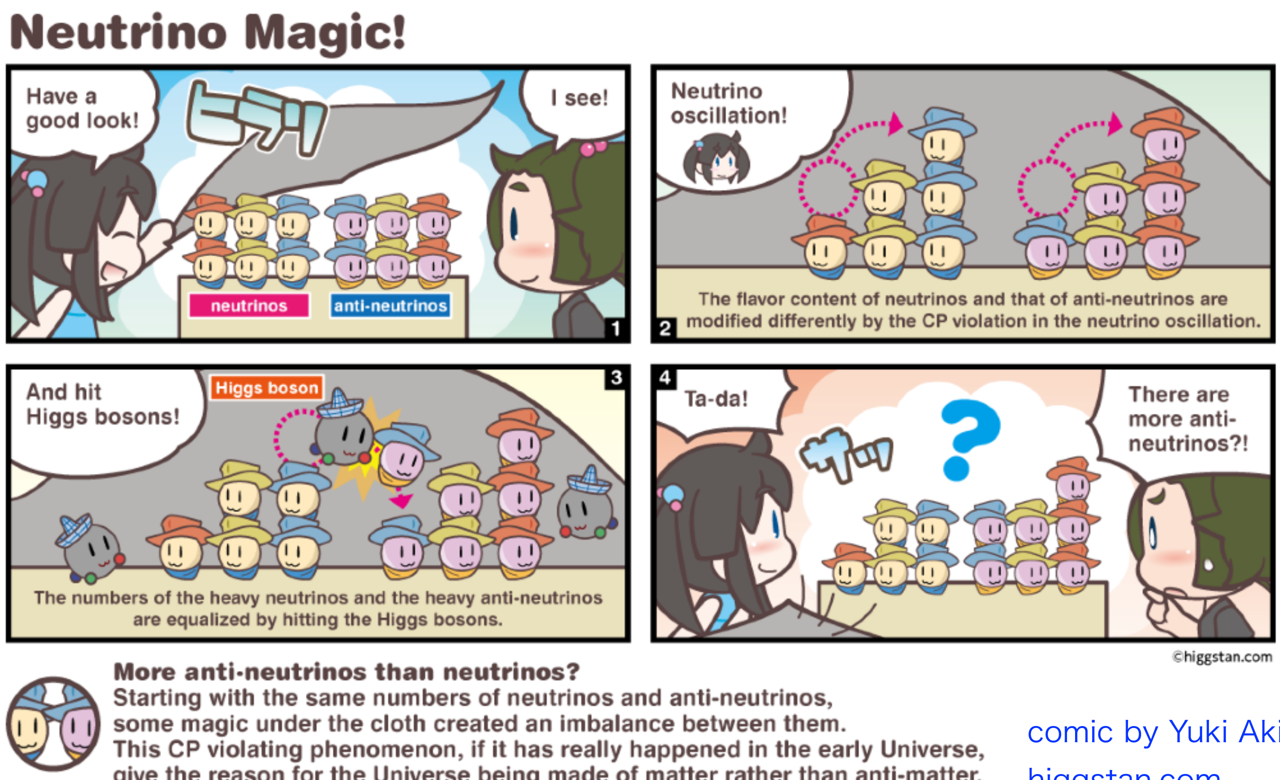
KAIST

1807.06582 with Ryuichiro Kitano, Yuta Hamada
1908.11864 with Shintaro Eijima, Ryuichiro Kitano

Leptogenesis via active neutrino oscillation

Wen Yin, KAIST in Korea



comic by Yuki Akimoto, higgstan.com

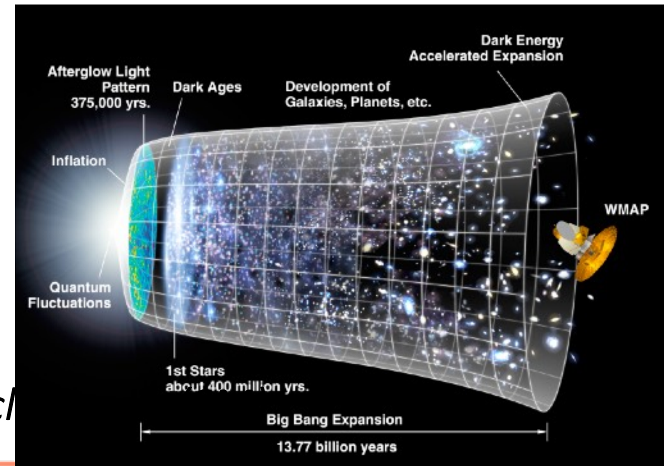
UC davis, 9th Sep 2019

Contents

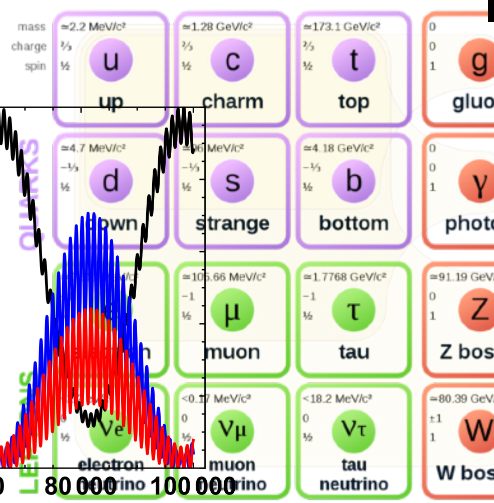
1. Introduction

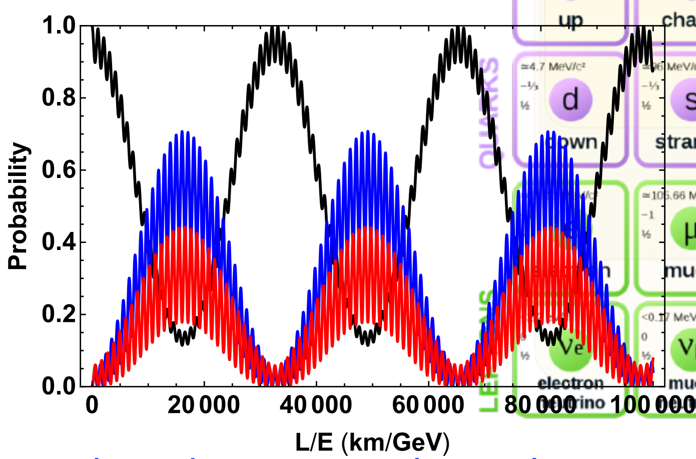
The mysteries of particle physics and particle cosmology.

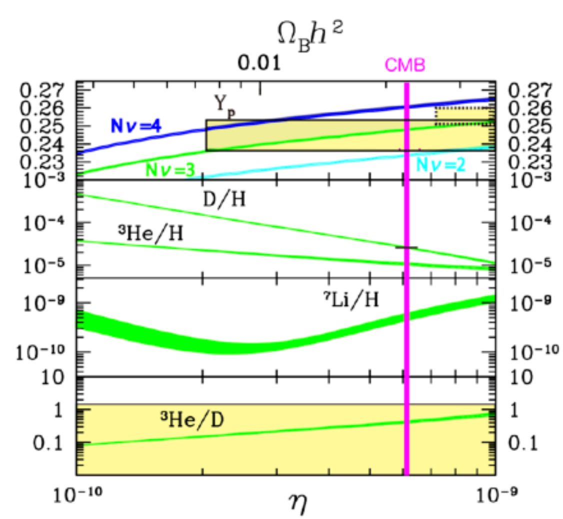
- Inflation
- Matter-antimatter asymmetry (Baryon asymmetry)
- Neutrino oscillation
- …



Standard model of particl







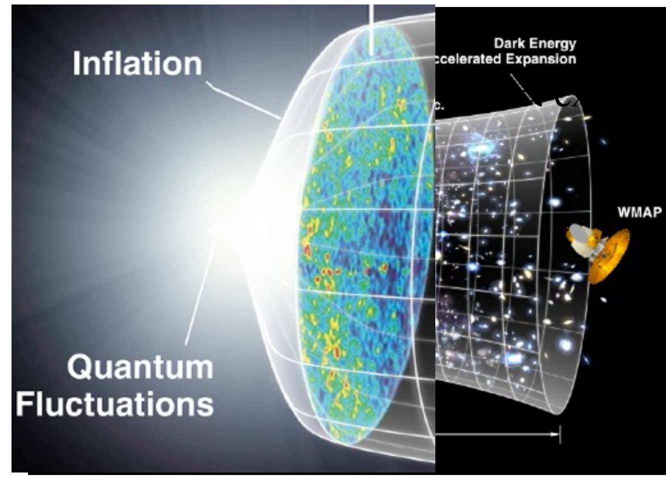
wikipedia, Kawasaki et al, 1709.01211

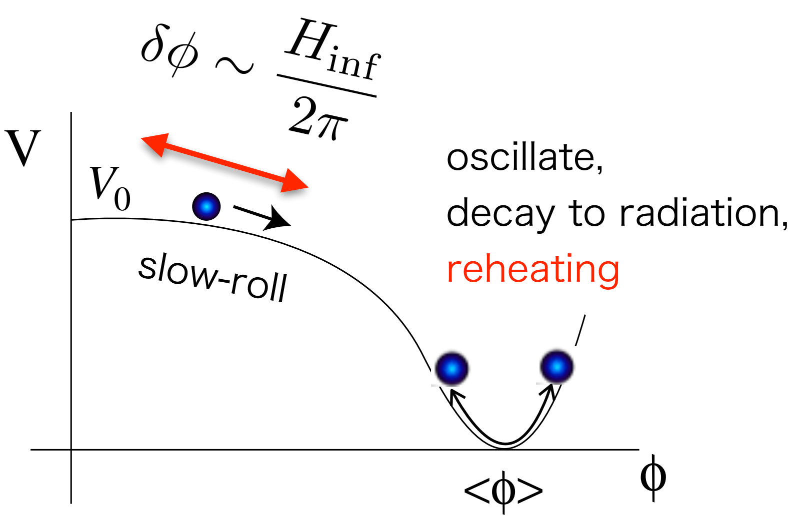
New physics: inflation

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.

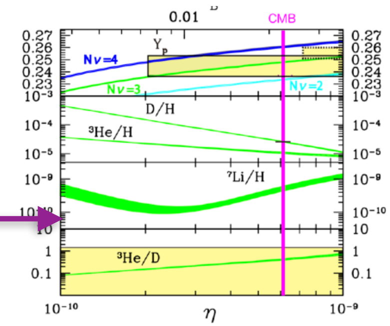




Inflaton ϕ:

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

New physics: baryogenesis



Baryogenesis happens

$\Delta n_B \simeq 0$

Inflation ends — *reheating* — BBN, CMB (recombination) → t

To generate the baryon asymmetry of our universe (BAU) *Sakharov's conditions* should be satisfied:

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

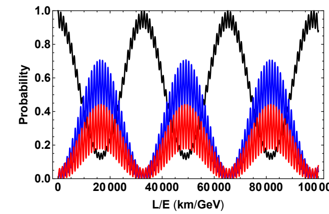
**C and CP violation*

**Out of thermal equilibrium*

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

New physics: neutrino oscillation

A simple explanation:



the SM is non-renormalizable effective theory

i.e. Majorana neutrino

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

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

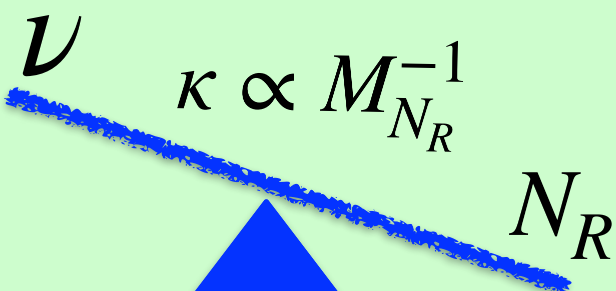
Lepton # violating

Possible origins of higher dimensional terms

Generated by heavy particles

e.g. *seesaw mechanism*

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



Just exist as it is valid up to very high energy scale.

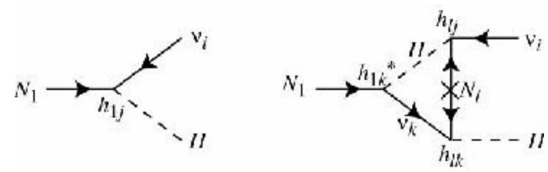
(cf. Perturbative calculation is justified up to $10^{17} GeV$.)

Baryogenesis with Majorana neutrino

By assuming seesaw mechanism, Sakharov's conditions are satisfied in N_R sector

- **Thermal leptogenesis**

  M. Fukugita, T. Yanagida 1986



- **Resonant leptogenesis**

  Pilaftsis 1997; Buchmuller Plumacher, 1998

CP-violating decay

- **Baryogenesis via right-handed neutrino oscillation** Akhmedov et al,1998; Asaka, Shaposhnikov, 2005;

Sakharov's conditions are satisfied at around reheating era, *without* N_R.

- **Leptogenesis via active neutrino oscillation** Hamada, Kitano, 2016; Hamada, Kitano, WY, 2018;

Today's topic

I will be talking about

BAU can be explained due to neutrino oscillation with $\mathscr{L} = \mathscr{L}_{SM}^{d\leq 4} - \frac{\kappa_{ij}}{2}\bar{L^c}_i \hat{P}_L L_j HH + h.c$ at around reheating era.

- BAU explained with $T_R \gtrsim 10^8 GeV$ for ϕ decays to leptons.
- If ϕ dominantly decays to Higgs bosons, the scenario can be tested from ground-based experiments.
- Application of the mechanism with lower reheat temperature is discussed.

2. Leptogenesis via active neutrino oscillation

Kitano, Hamada, WY 1807.06582

Setup:

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

<u>*Sakharov's conditions*</u>

**Baryon/Lepton number violation* ✓

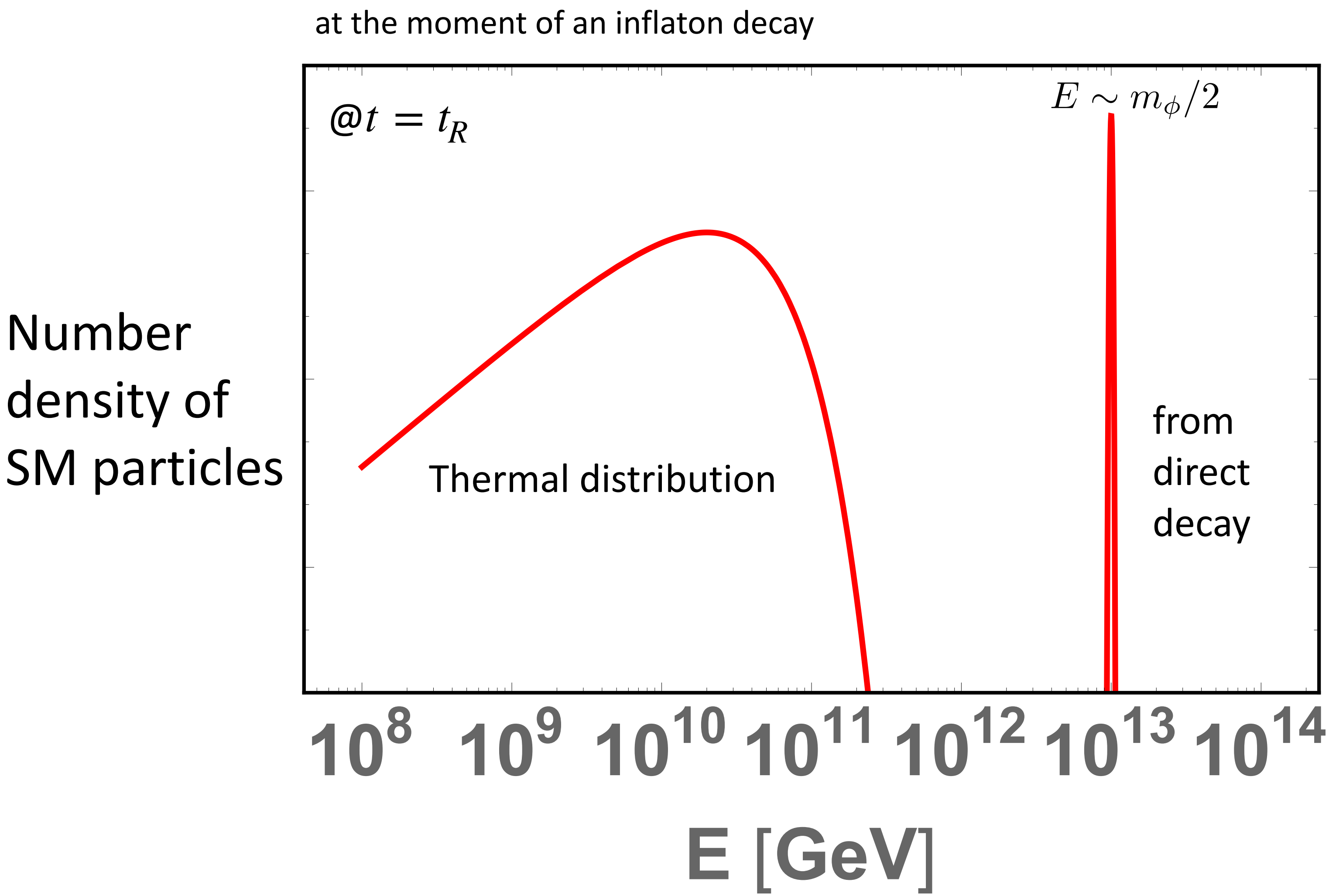
**C and CP violation* ✓ *neutrino oscillation. CP-violation is favored at 2σ* *T2K,1701.00432*

**Out of thermal equilibrium* ✓ *thermalization around reheating*

See also leptogenesis via active neutrino oscillation with dimension 5 and 8 terms. Kitano, Hamada 1609.05028.

Thermalization during reheating

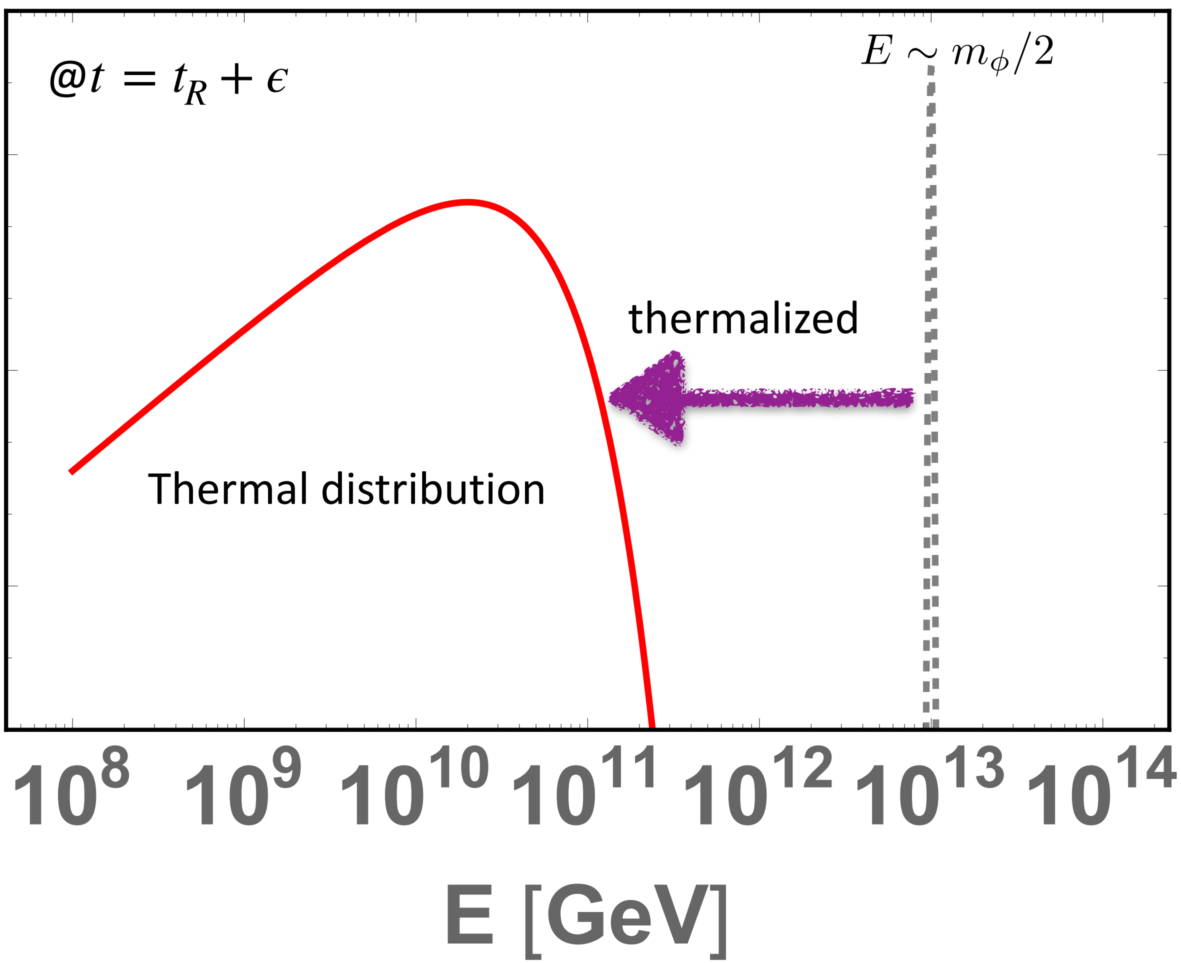
Inflaton decay: $\phi \to \text{SM particles}$ (2 body)



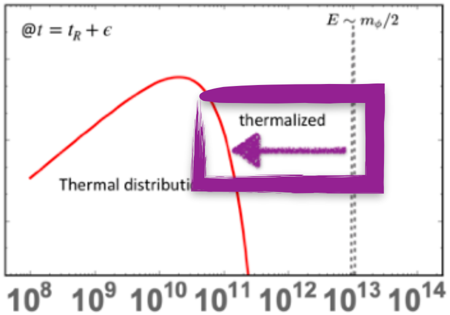
Thermalization during reheating

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

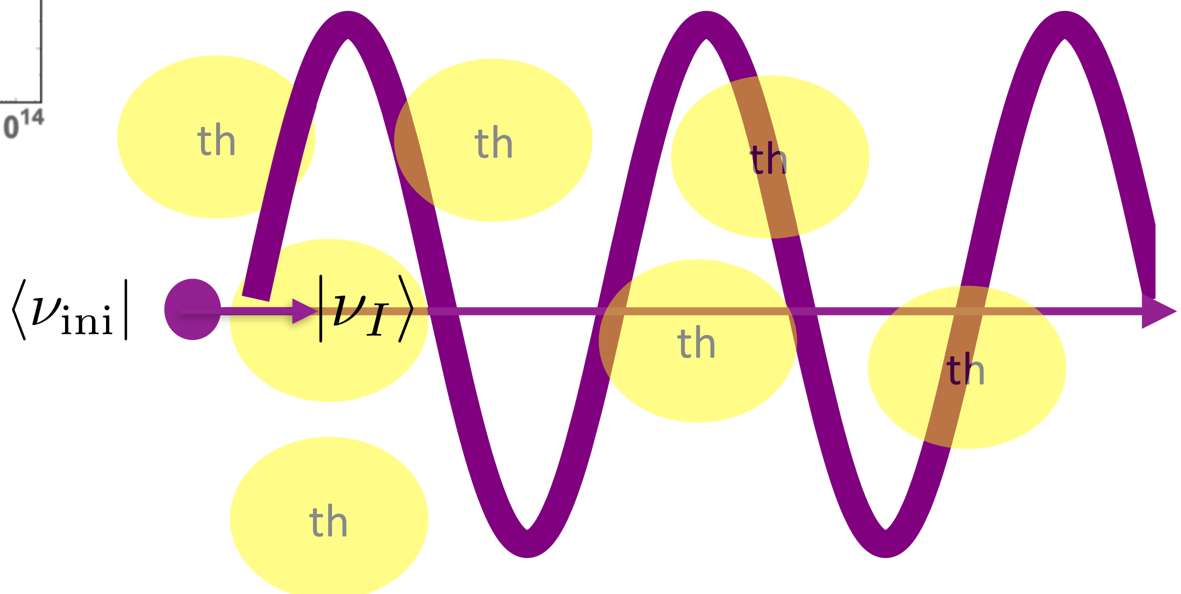
Number density of SM particles



Neutrino oscillation during thermalization



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



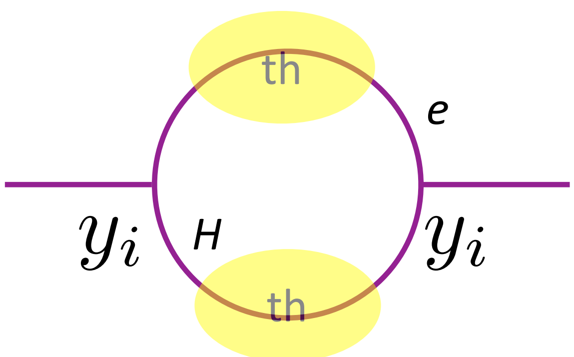
$$P_{{\rm ini}\to I} \simeq |\sum_\alpha \langle \nu_{\rm ini}|\nu_\alpha\rangle e^{it_{\rm MFP}(m^{\rm th}_{\nu_\alpha})^2/k}\langle\nu_\alpha|\nu_I\rangle|^2$$

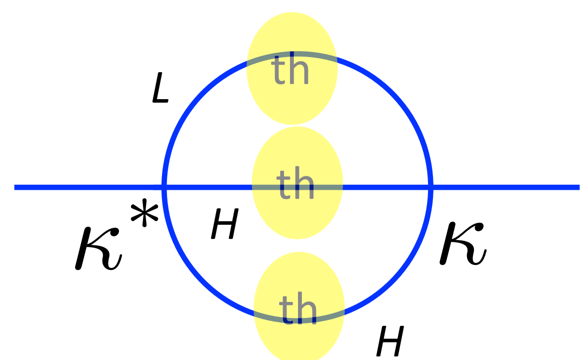
c.f. $P_{e\to\mu} \simeq |\sum_\alpha \langle \nu_e|\nu_\alpha\rangle e^{itm^2_{\nu_\alpha}/k}\langle\nu_\alpha|\nu_\mu\rangle|^2$ @ vacuum

Thermal mass

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

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





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

Neutrino oscillation provides CP violation

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

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

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

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

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

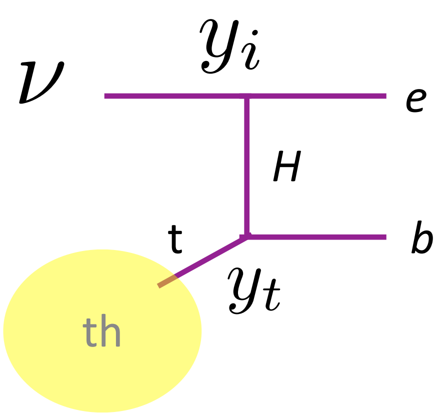
Oscillation phase is not too small at the reheating era.

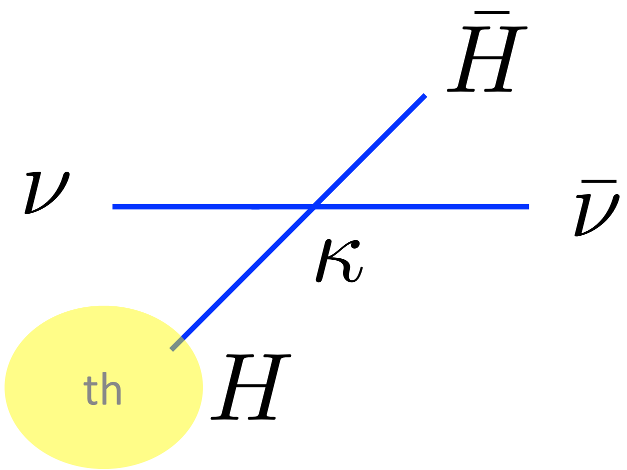
How to observe "flavor"?

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

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".

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

Only flavor dependent process can identify the flavor.

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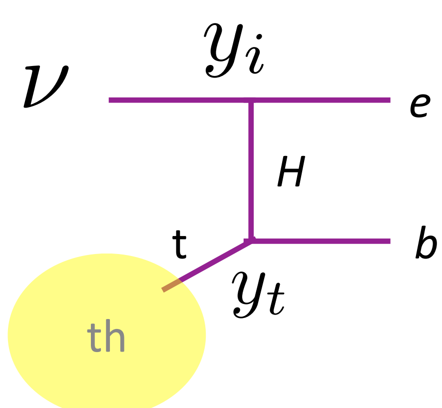
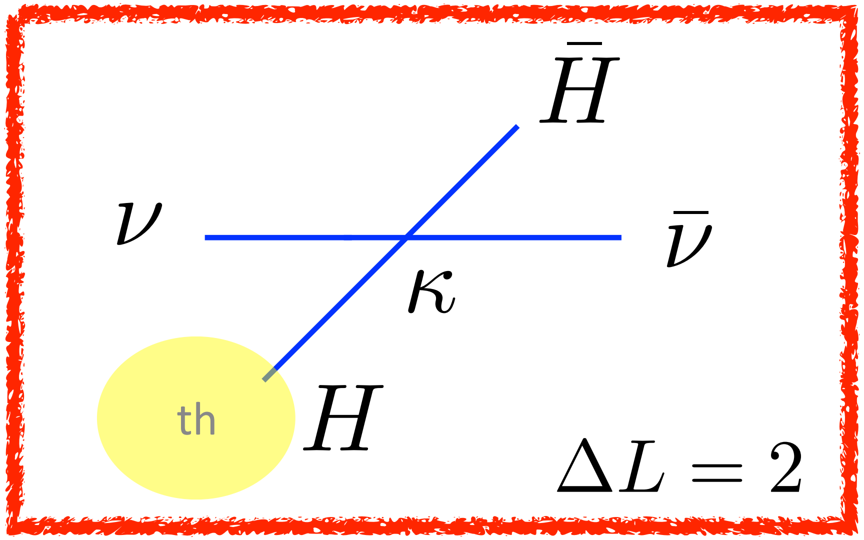




Lepton asymmetry can be made!

The (naive) estimation of lepton asymmetry

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

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

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

lepton # violation (red underline: $\frac{\sigma_{LLHH}^{\rm th}}{\sigma_{\rm yukawa}^{\rm th}}$)

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

(red) How frequently the flavor is observed by the llHH interaction.

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

The (naive) estimation of lepton asymmetry

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

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

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

Enough asymmetry can be generated with sufficiently high reheating temperature.

Numerical estimation

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

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

Different

Interaction terms (with CP phase)

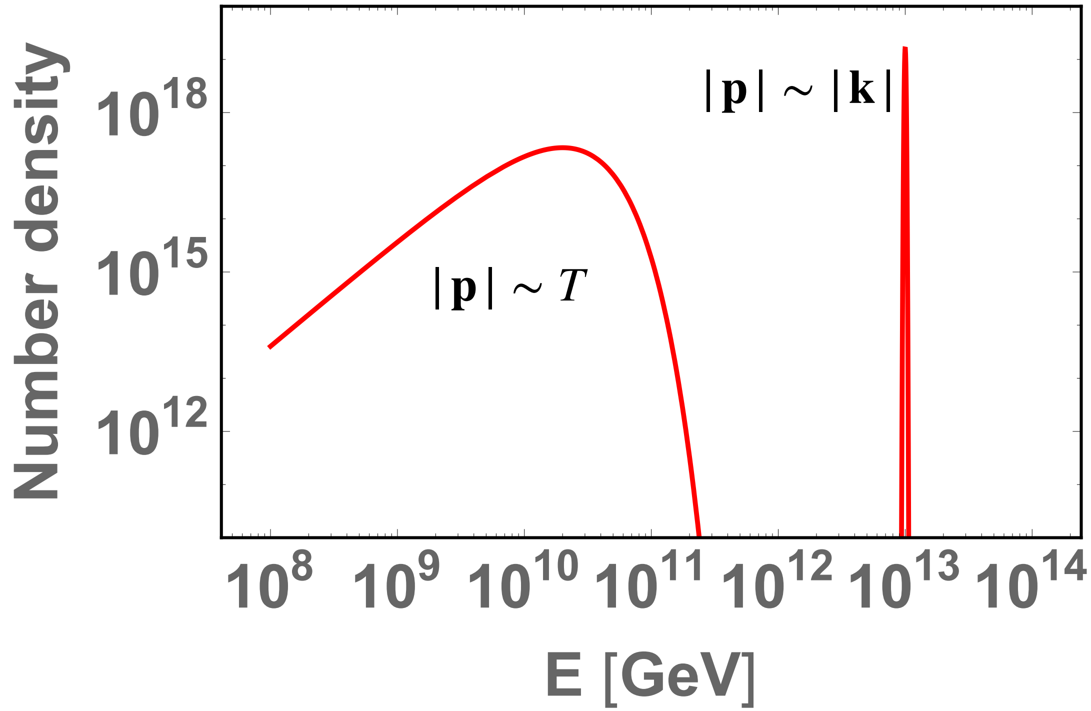
$$i\frac{d\bar{\rho}(\mathbf{p})}{dt} = -[\Omega(\mathbf{p}), \bar{\rho}(\mathbf{p})] - \frac{i}{2}\{\Gamma^d_{\mathbf{p}}, \bar{\rho}(\mathbf{p})\} + \frac{i}{2}\{\Gamma^p_{\mathbf{p}}, 1 - \bar{\rho}(\mathbf{p})\},$$

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



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

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

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

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

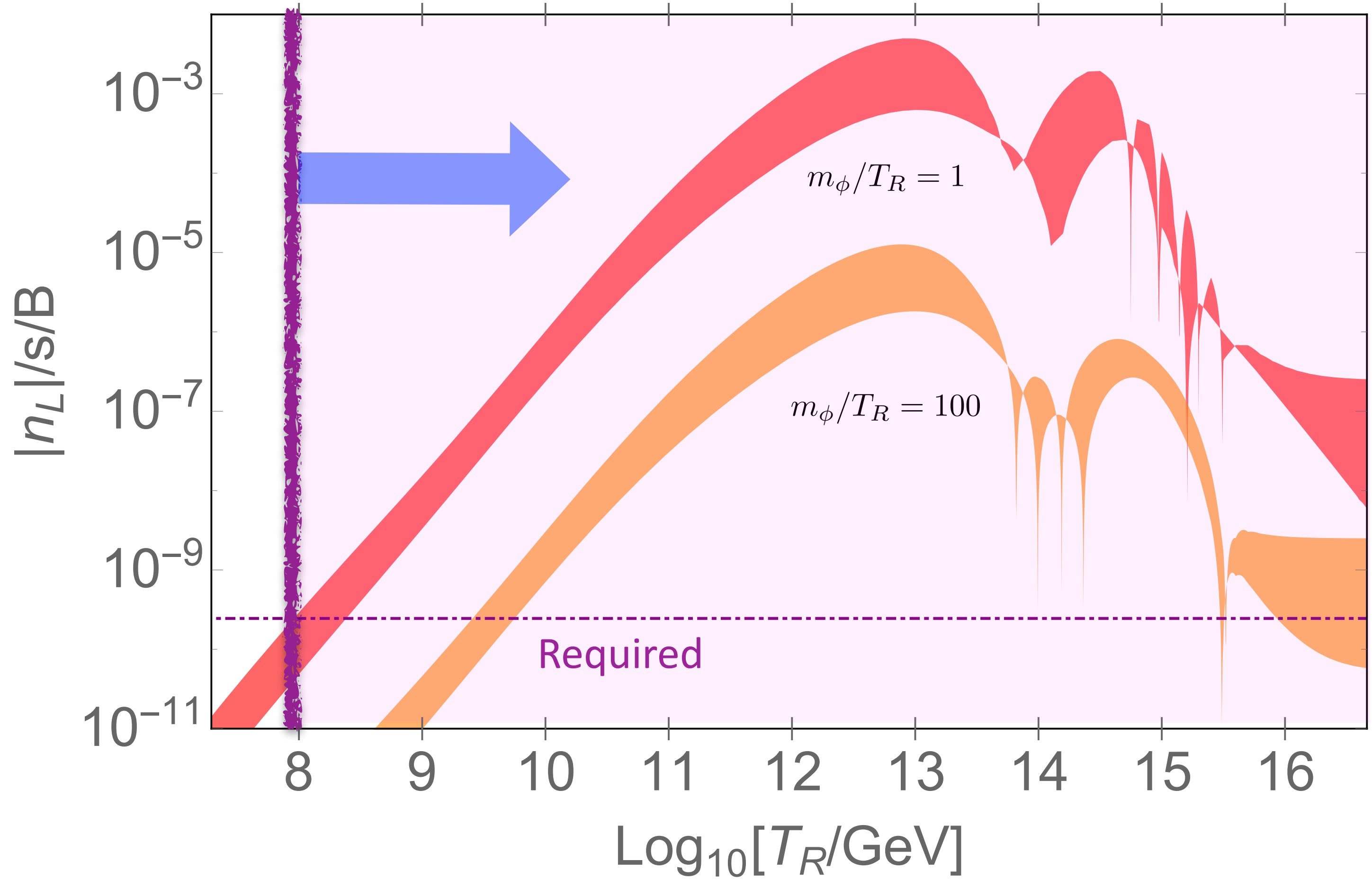
$$\mathcal{N} = \frac{3}{4}\frac{T_R}{m_\phi}B,$$

Free parameters

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

+Parameters in neutrino sector.

Numerical result (Normal Hierarchy)



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.***

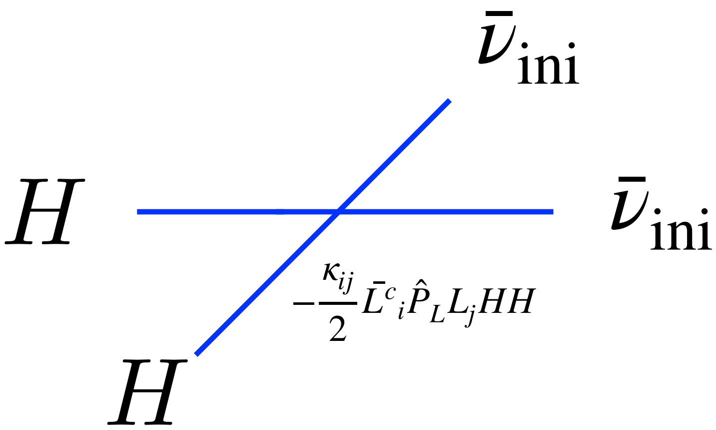
3. Baryogenesis from PMNS matrix

Let us consider the renormalizable inflaton coupling to the SM

$$\mathscr{L} \supset -A\phi|H|^2 - \lambda_\phi \phi^2 |H|^2$$

A, λ_ϕ: real parameters

$$\phi \to HH^*$$

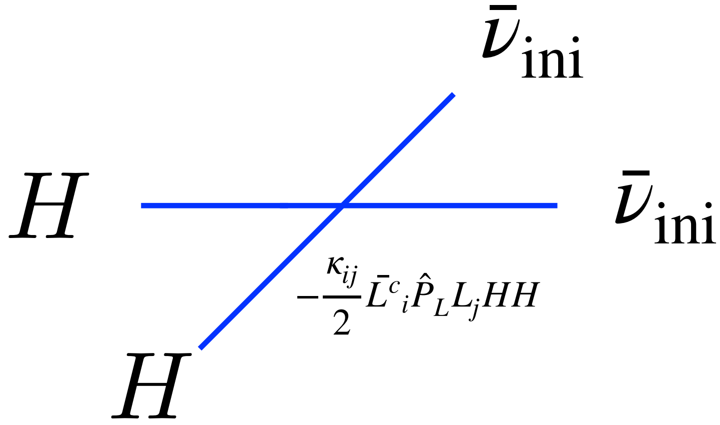


$\to$ *neutrino flavor oscillation!*

$\to$ *Baryogeneis!*

CP phase can appear only through κ_{ij}, i.e. the PMNS matrix.

The BAU is related with the PMNS matrix



Initial conditions

$$(\rho_{\mathbf{k}})_{ij} = (\bar{\rho}_{\mathbf{k}})_{ij} = \mathcal{N} t^{H}_{MFP} \Gamma^{LLHH}_{ij}$$

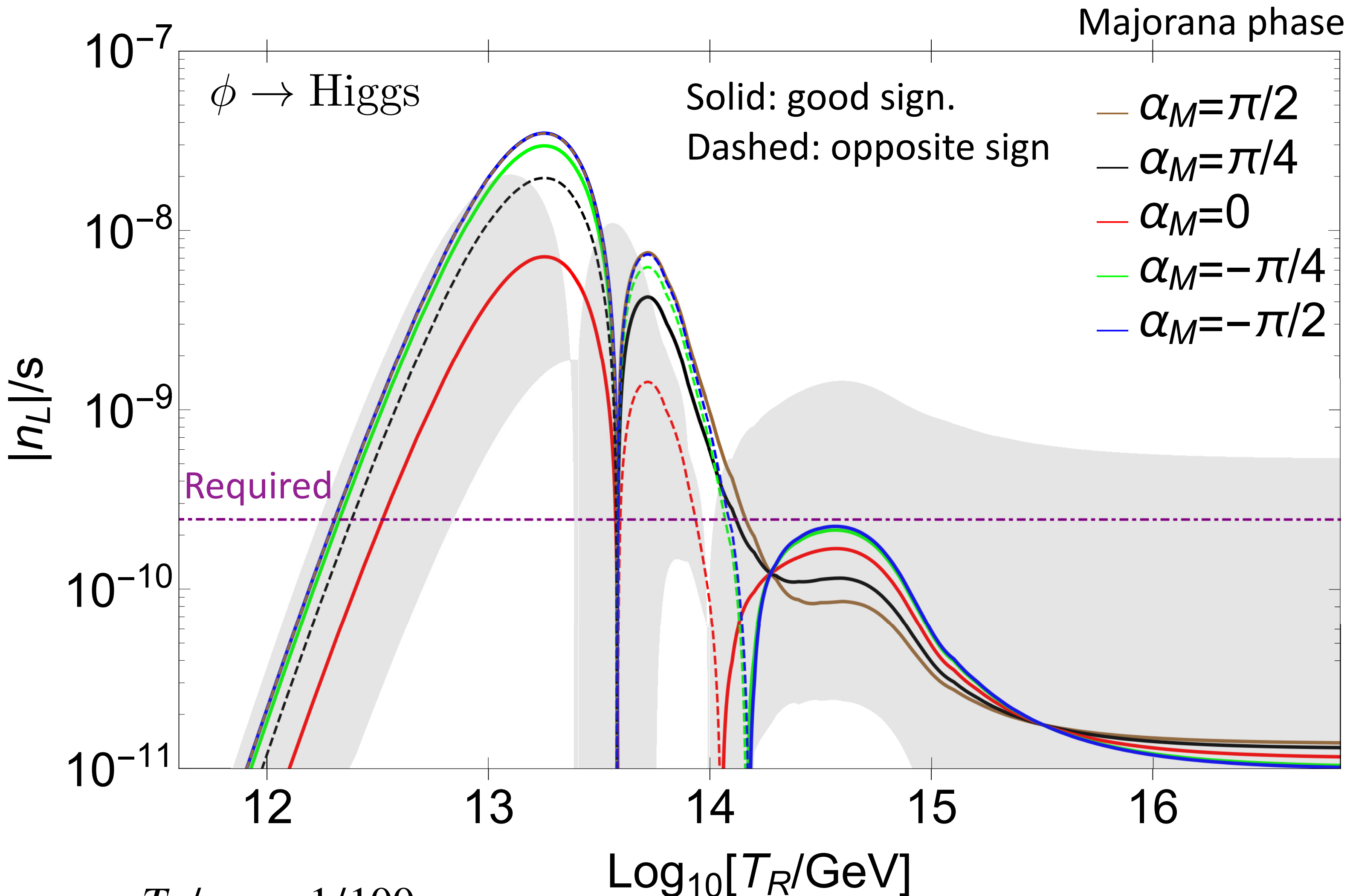
$$\rho_T\big|_{t=t_R} = \bar{\rho}_T\big|_{t=t_R} = 0$$ (Leptons are not thermalized initially)

Free parameters

$$T_R, m_\phi$$

and those for neutrino sector.

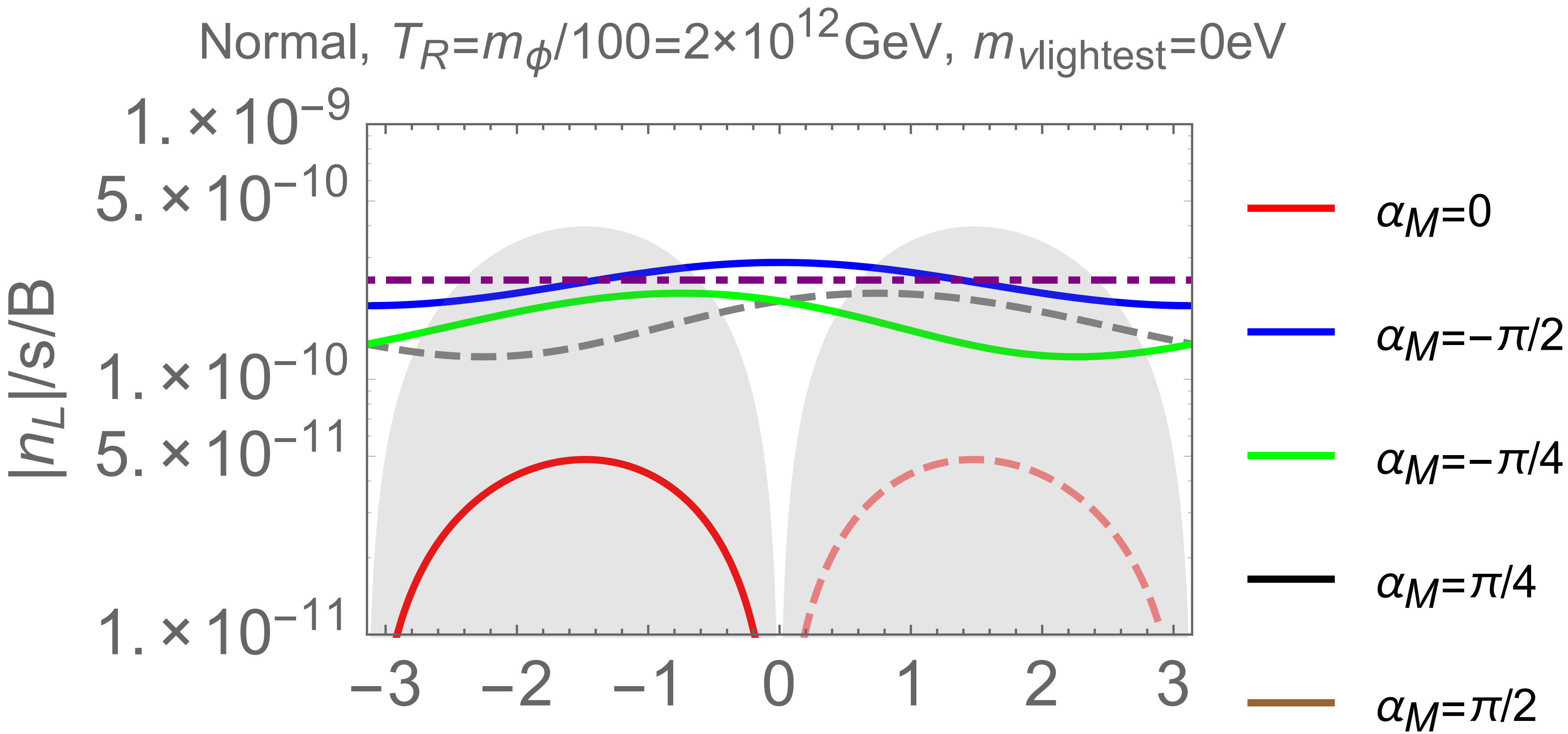
Numerical result (Normal Hierarchy)



$T_R/m_\phi = 1/100$

Two massive neutrinos.   Dirac Phase=-Pi/2

Dirac phase dependence (Normal hierarchy)

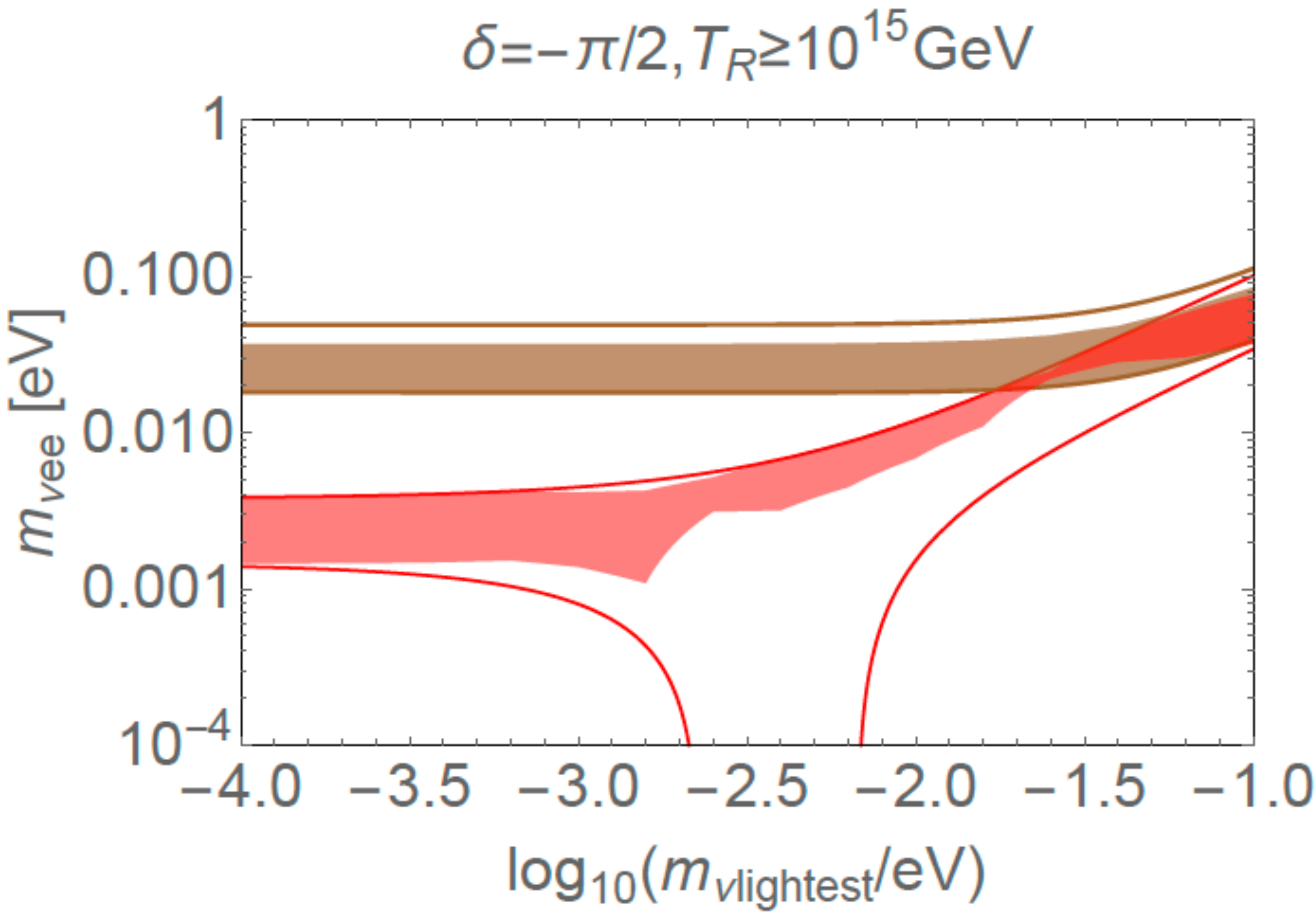


Dirac phase δ

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.



4. Leptogenesis with low reheat temp

1908.11864 with Shintaro Eijima, Ryuichiro Kitano

What if RHNs are very light? $T_R > M$

$$\mathscr{L} = \mathscr{L}_{SM}^{d\leq 4} + \mathscr{L}_N$$

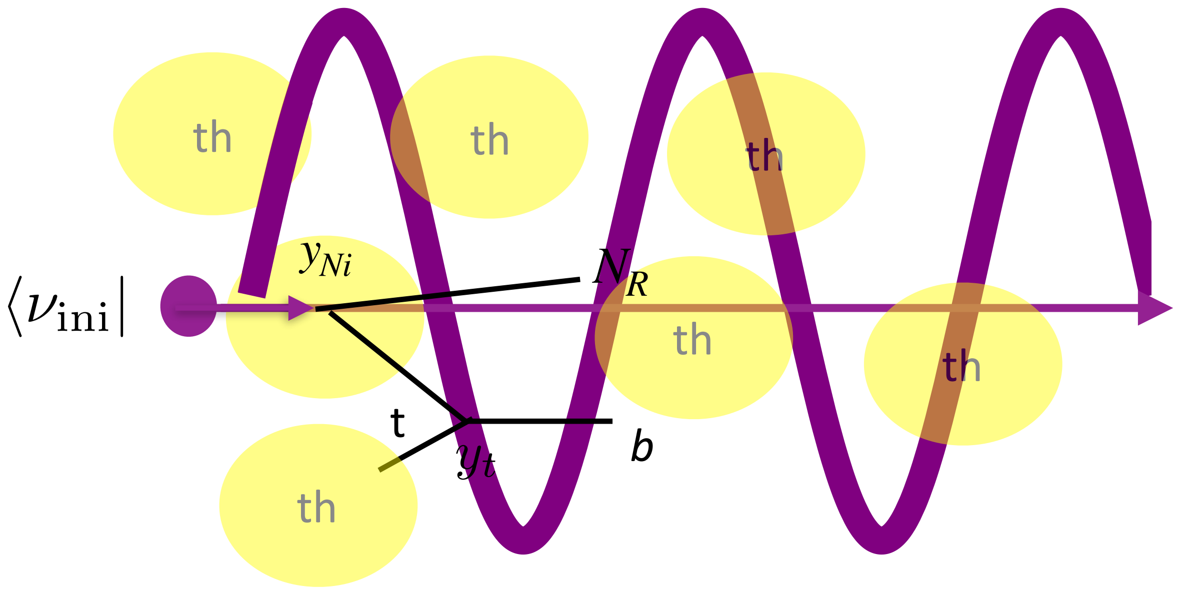
$$\mathscr{L}_N = -y_{Ni}\tilde{H}^* \bar{N}_R \hat{P}_L L_i + \frac{M}{2}\bar{N}_R \hat{P}_L N_R$$

Lepton # violation is suppressed at the reheating era.

However, I will show enough baryon asymmetry can be generated due to an asymmetry separation process.

Distributing neutrinos during thermalization

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



CP-violation!

$$\frac{\Delta n_{N_R}}{s} = -\frac{\Delta n_L}{s} \neq 0$$

The (naive) estimation of lepton asymmetry

$m_\phi \sim T$ with O(1) CP phase, general flavor structure

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

CP violation

lepton # separation

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 $\mathscr{L}_{\mathscr{N}}$ interaction.

$$\frac{\sigma_{y_N}^{th}}{\sigma_{\rm yukawa}^{th}} \sim \frac{y_N^2}{y_\tau^2}$$

The (naive) estimation of lepton asymmetry

$m_\phi \sim T$ with O(1) CP phase, general flavor structure

$$\frac{\Delta n_L}{s} \propto Br_{\phi\to\nu_{\rm ini}+X/\bar{\nu}_{\rm ini}+\bar{X}} \times 10^{-10}\left(\frac{|y_N|}{10^{-6}}\right)^2$$

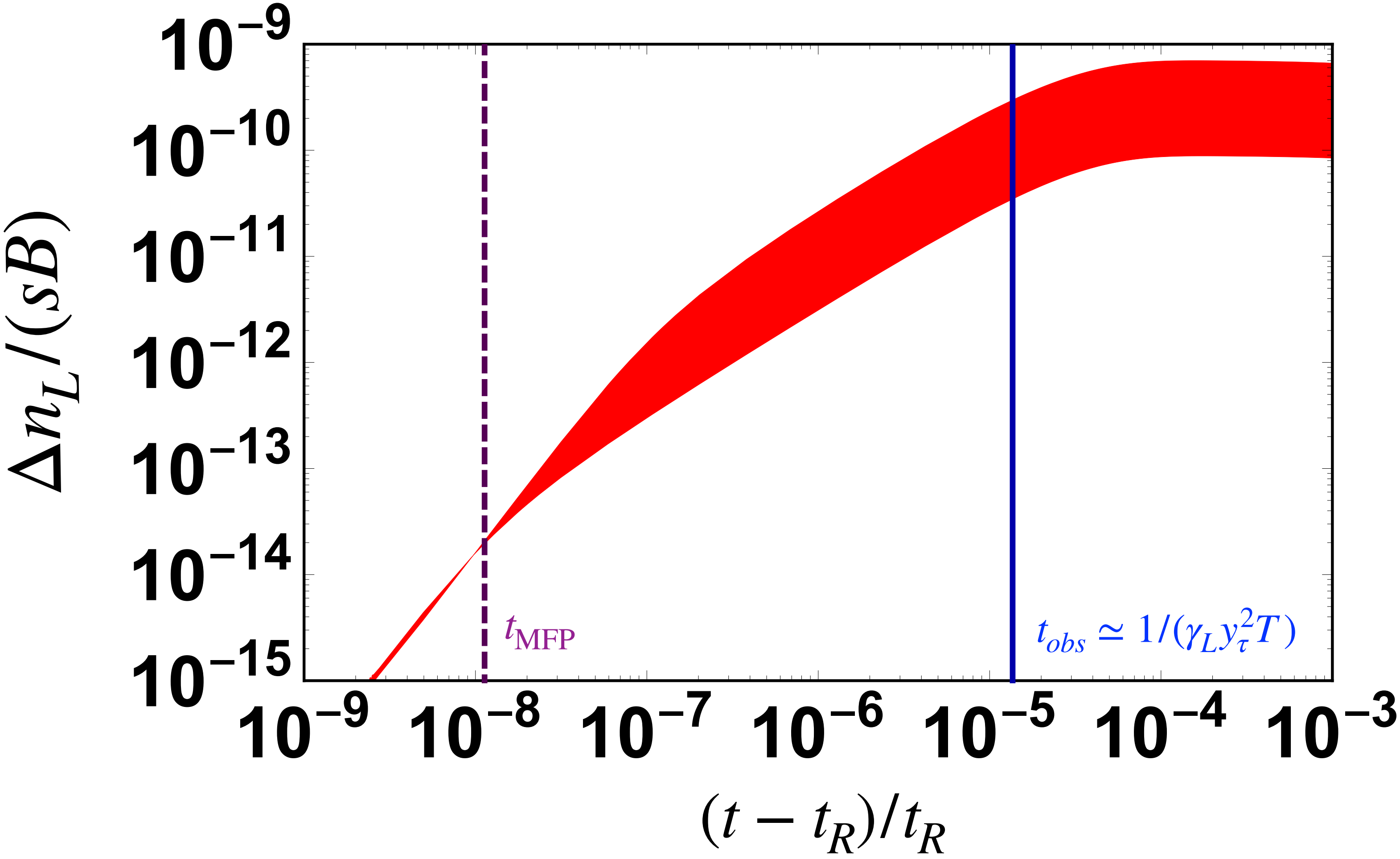
(temperature independent)

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

Enough asymmetry can be obtained for not too large y_N.

Numerical result of asymmetry production

$y_{Ni} \sim 10^{-6}$



Lower bound of reheat temperature

N_R should not be thermalized:

$$T_R \gtrsim M \gtrsim T_{\rm th}^N \simeq 7\,{\rm TeV}\left(\frac{|y_N|}{10^{-6}}\right)^2 .$$

Leptogenesis can be successful with

$T_R \gtrsim O(10)TeV$ (without tuning among RHN masses.)

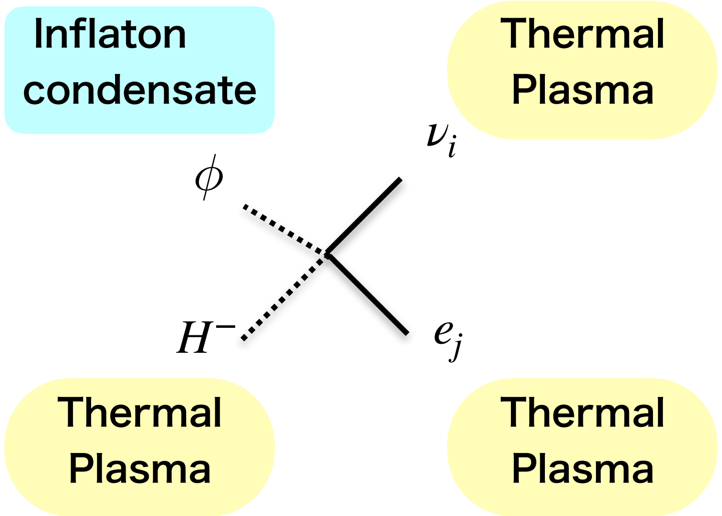
The scenario also predicts the neutrinos are in normal or inverted hierarchies (but not degenerated). Some hierarchies of right-handed neutrino masses are also predicted.

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:

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

Summary

BAU can be explained due to neutrino oscillation with

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

- BAU explained with $T_R \gtrsim 10^8 GeV$ for $\phi \to \nu + X, \bar{\nu} + \bar{X}$
- If ϕ dominantly decays to Higgs bosons, the scenario can be tested from ground based experiments.

If there is a light right-handed neutrino,

$T_R \gtrsim O(10) TeV$ for $\phi \to \nu + X, \bar{\nu} + \bar{X}$

- $T_R \sim$ 100GeV is possible to explain the BAU if reheating completes via dissipation.