Spontaneous leptogenesis via Majoron oscillation

Kunio Kaneta (CTPU, IBS)

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in collaboration with Masahiro Ibe (ICRR & IPMU)

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Outline

1. Introduction

2. Spontaneous leptogenesis via Majoron oscillation

3. Phenomenological implication

4. Viable models

5. Summary

1. Introduction

Baryon Asymmetry of the Universe (BAU)

➢ Two independent observations have achieved the consistent number:

$$\eta_{CMB} \simeq (6.0 - 6.1) \times 10^{-10}$$

$$\eta_{BBN} \simeq (5.7 - 6.7) \times 10^{-10}$$

[PDG '14]

$$\eta \equiv n_B / n_\gamma$$

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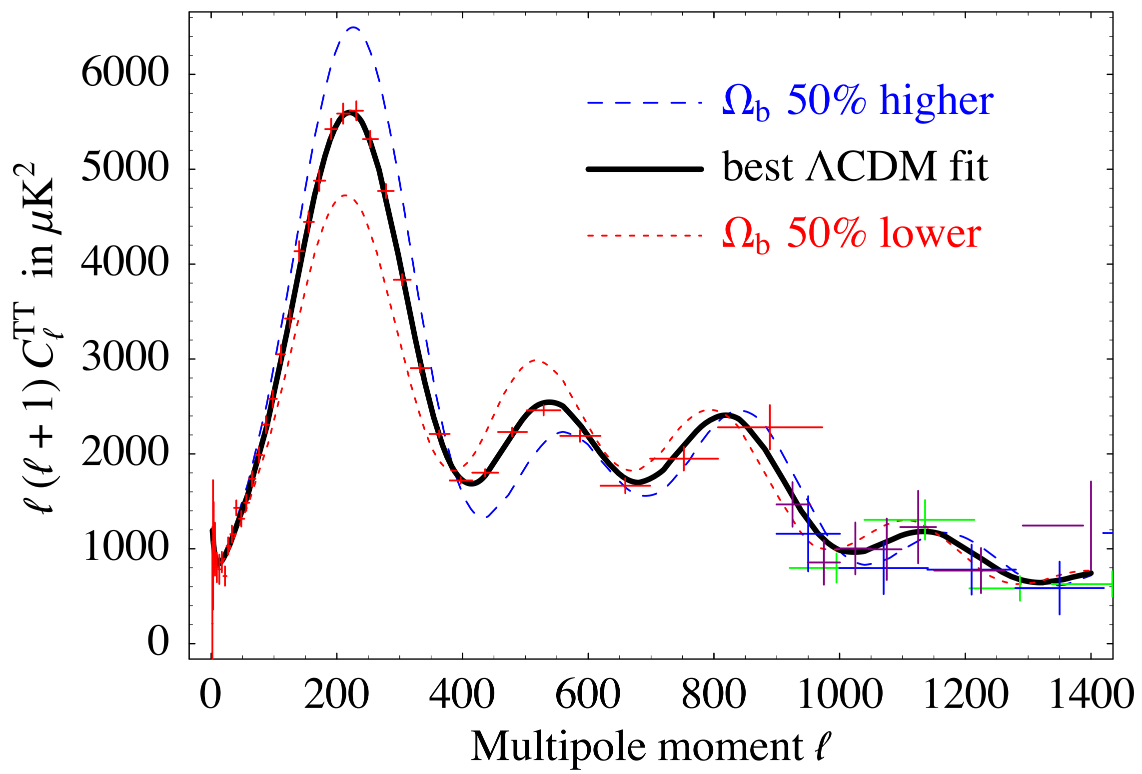

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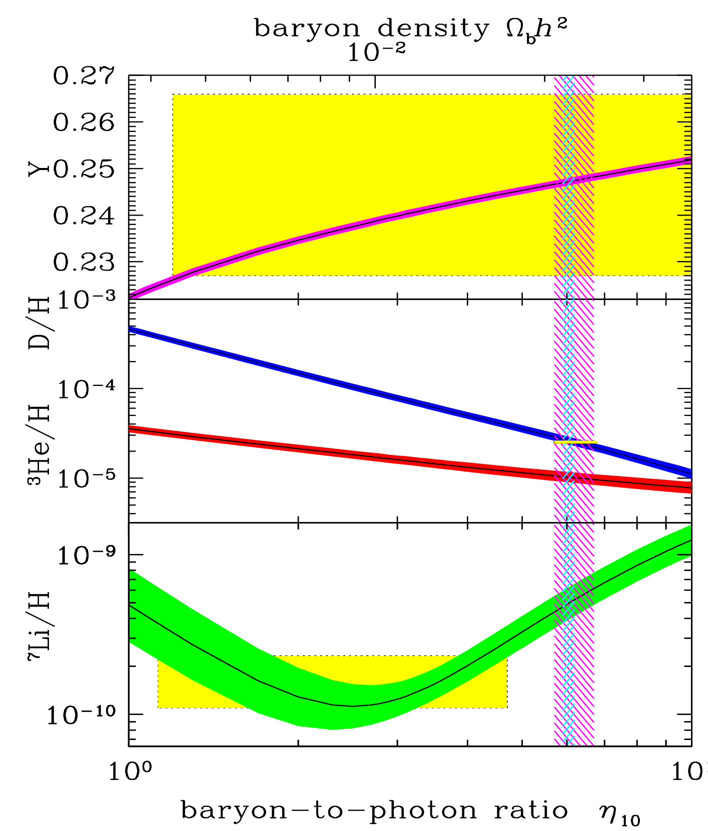

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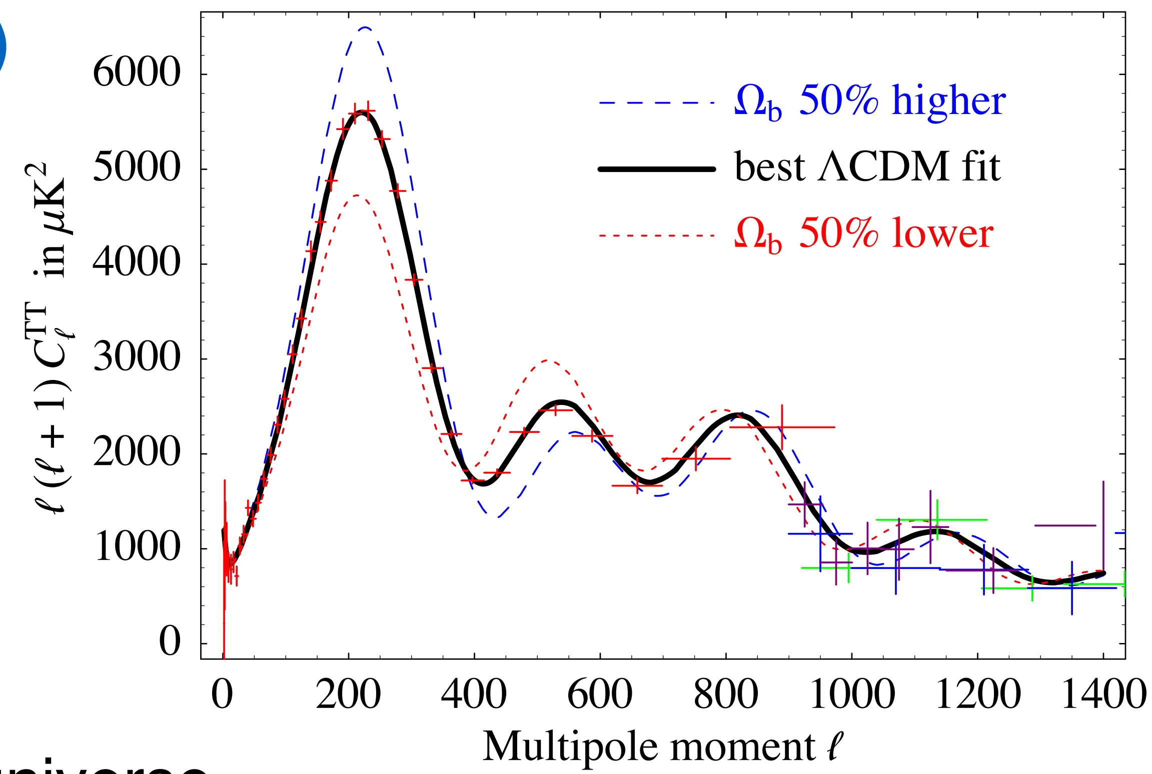

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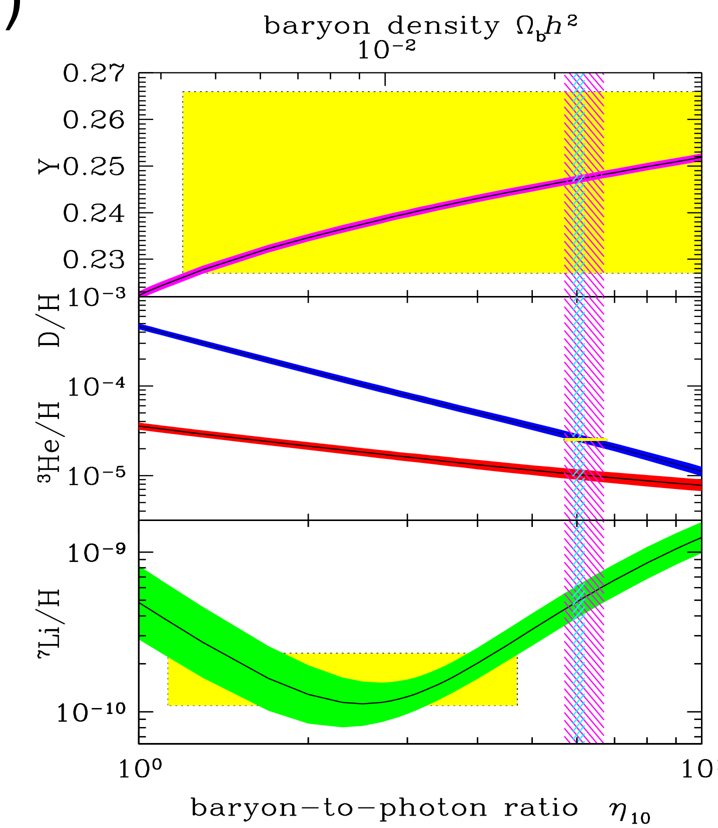

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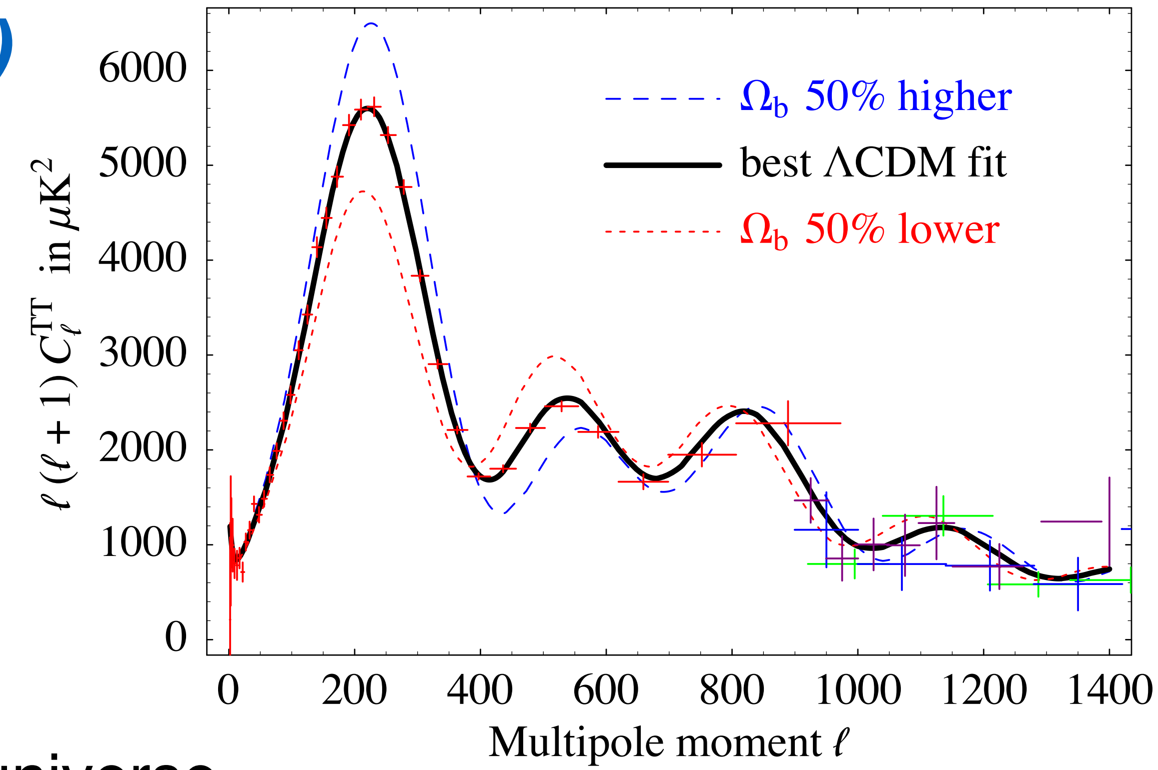

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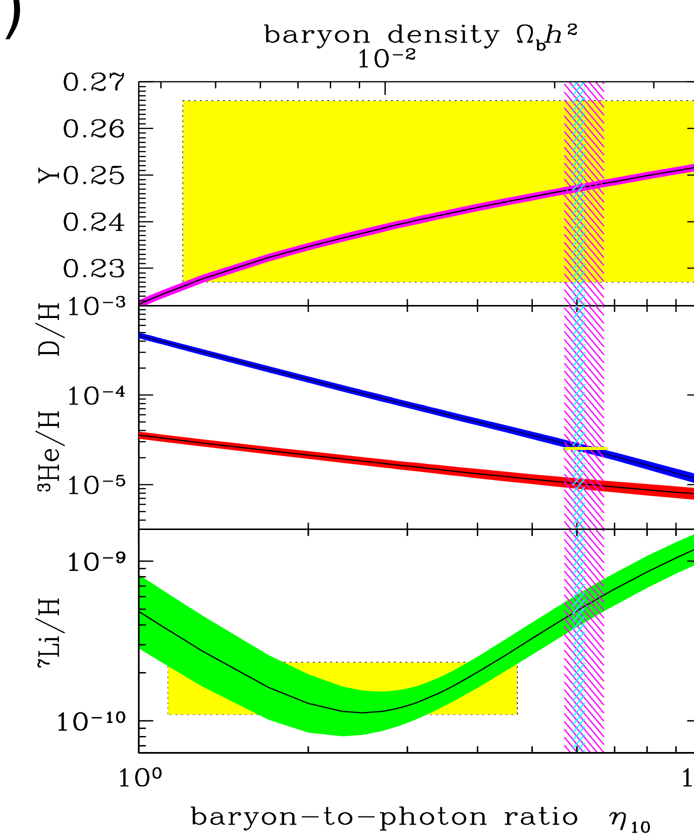

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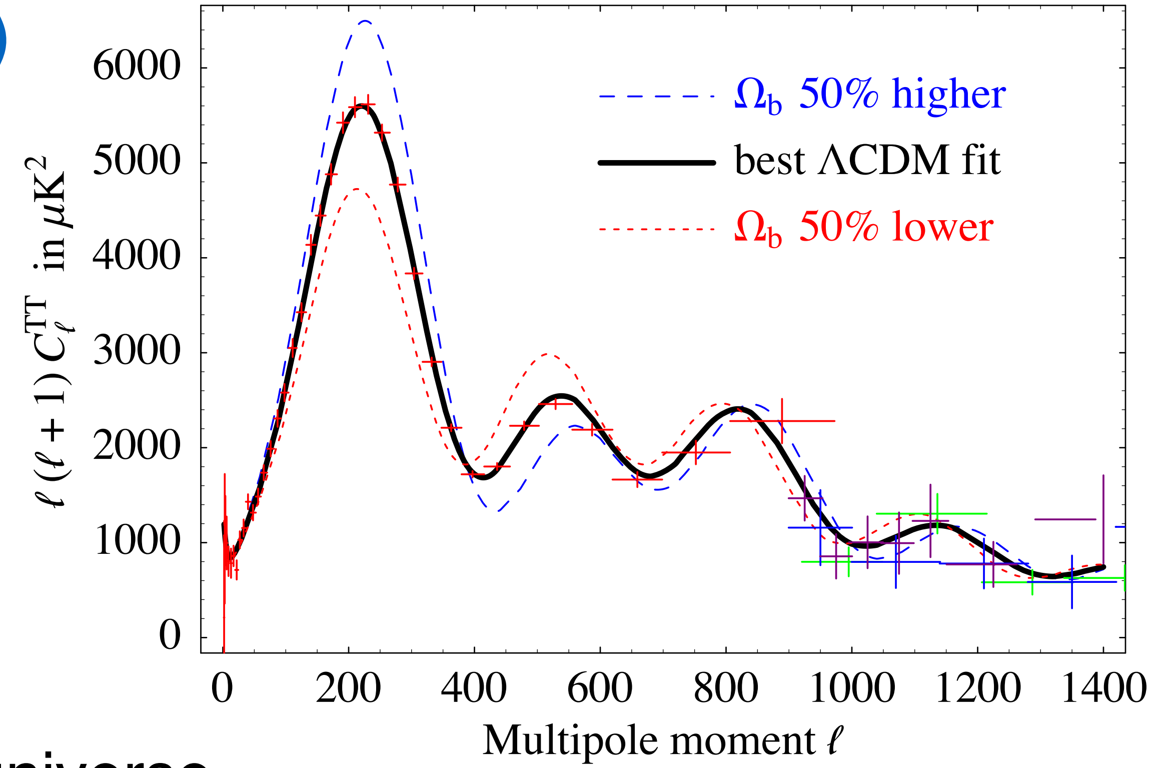

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sufficient condition for generating BAU dynamically

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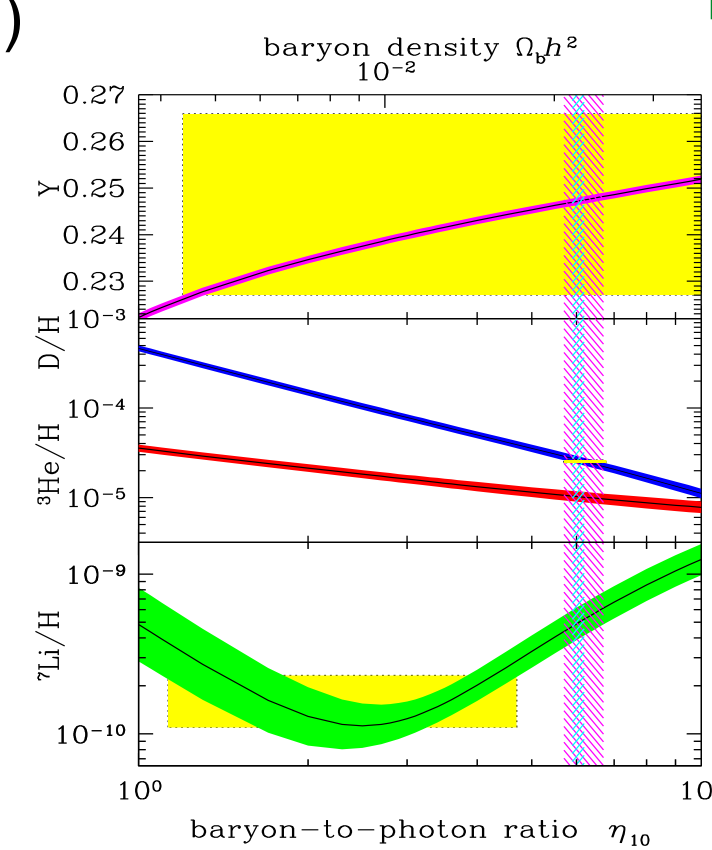
2. *C and CP violation*
3. *departure from thermal equilibrium*



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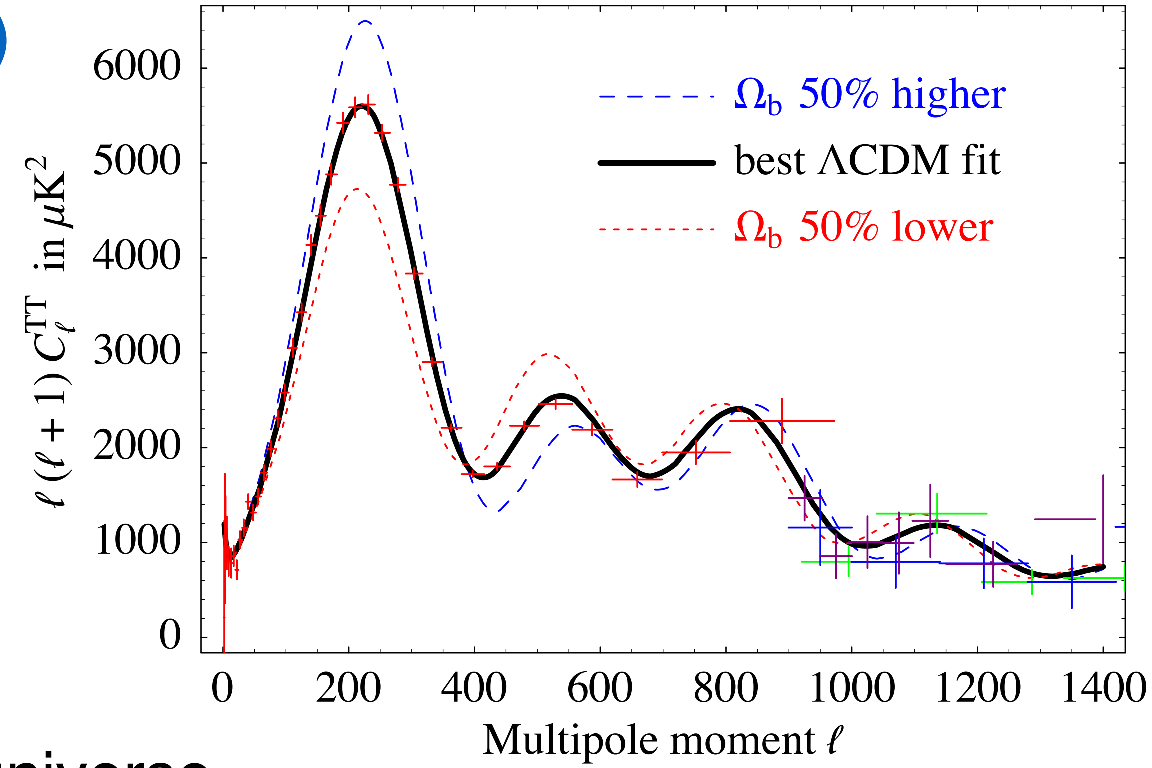

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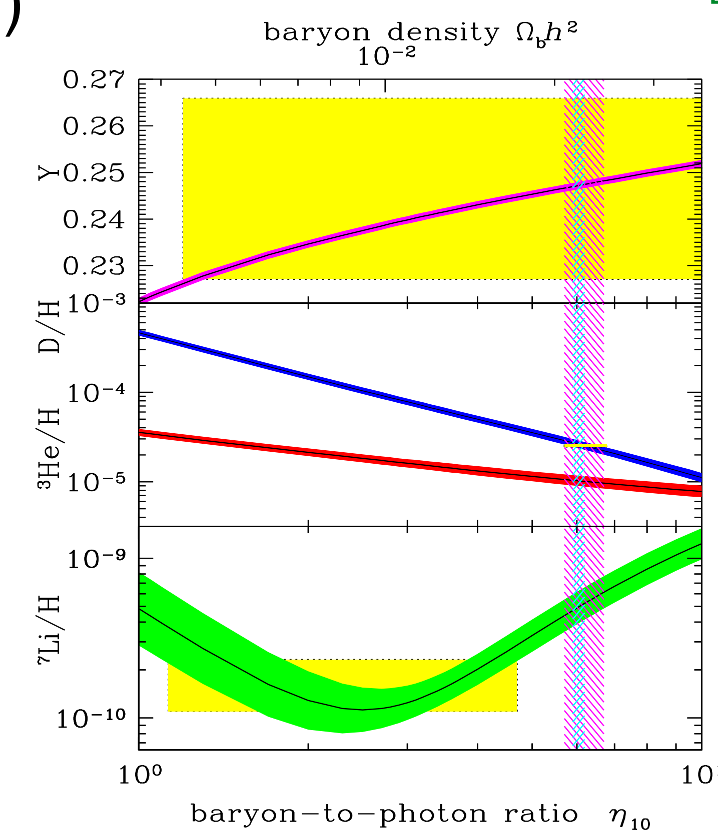
(small CP & observed Higgs mass)



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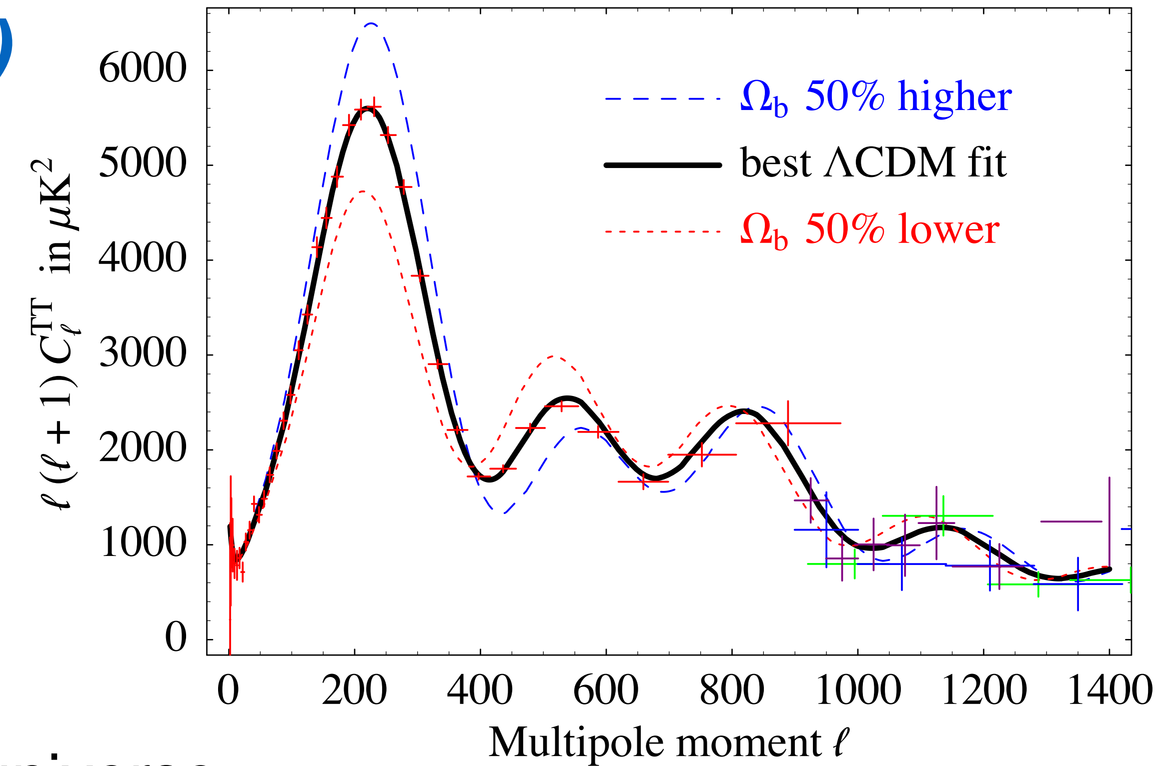

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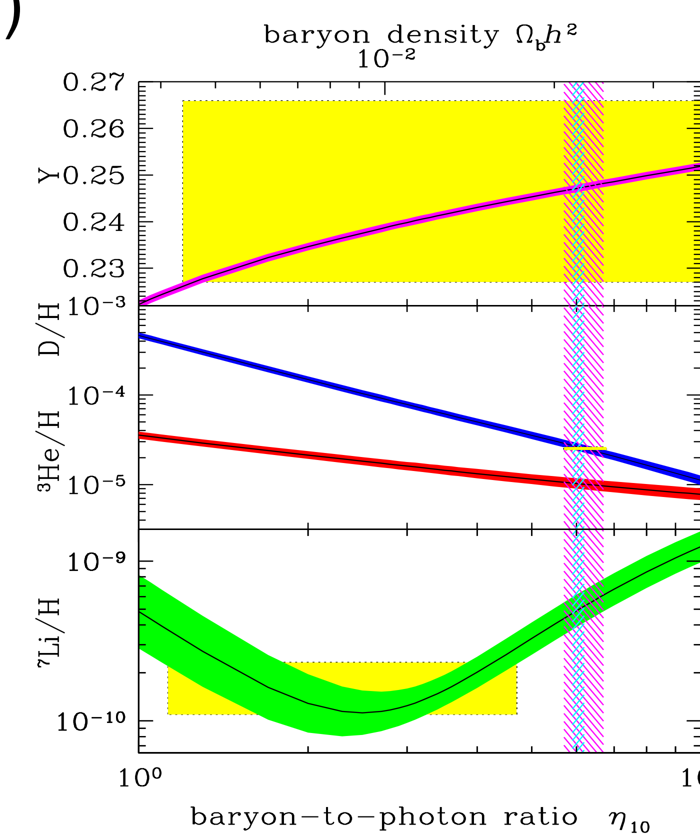

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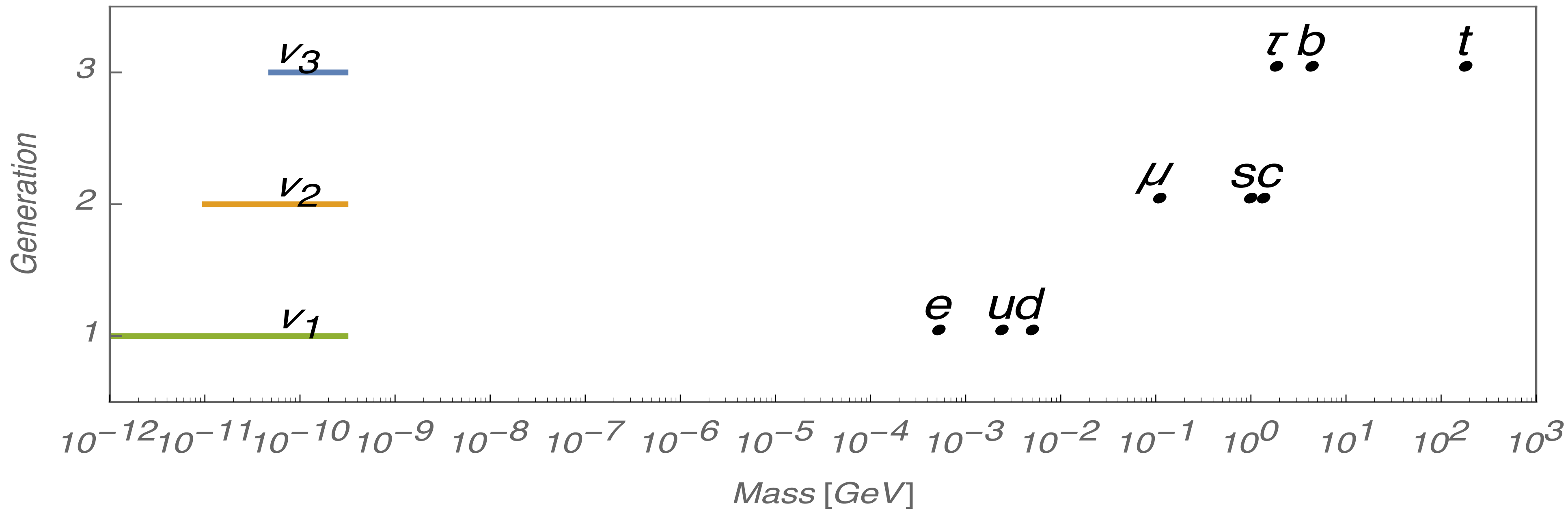
- ➢ These conditions are satisfied in the SM, but sufficient BAU can not be achieved… [Shaposhnikov '86]
  (small CP & observed Higgs mass)

Physics beyond the SM (BSM) is clearly needed

Neutrino masses

➢ Neutrinos are massless in the SM

➢ The tiny neutrino masses may also indicate BSM



➢ Seesaw mechanism is one of compelling descriptions:

[Minkowski ’77; Yanagida ’79; Gell-Mann, et al. ’79; etc.]

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{N}_R i\partial\!\!\!/ N_R - (y_\nu \bar{L} H N_R + h.c.) - \frac{1}{2}(M_R \bar{N}_R^C N_R + h.c.)$$

$$\Rightarrow \quad \mathcal{L}^{\nu}_{\rm mass} = -\frac{1}{2}\begin{bmatrix} \nu_L \\ N_R \end{bmatrix}^T \begin{bmatrix} 0 & m_D^T \\ m_D & M_R \end{bmatrix} \begin{bmatrix} \nu_L \\ N_R \end{bmatrix} + h.c.$$

neutrino mass:

$$m_\nu \simeq \frac{(y_\nu v_{ew})^2}{M_R}$$

ex) $\quad m_\nu \sim \dfrac{(100\ \mathrm{GeV})^2}{10^{14}\ \mathrm{GeV}} \sim 0.1\ \mathrm{eV}$

➢ Right-handed neutrino mass (M_R) violates $B-L$, which may lead to BAU, but *what is the origin?*

Spontaneous B−L breaking

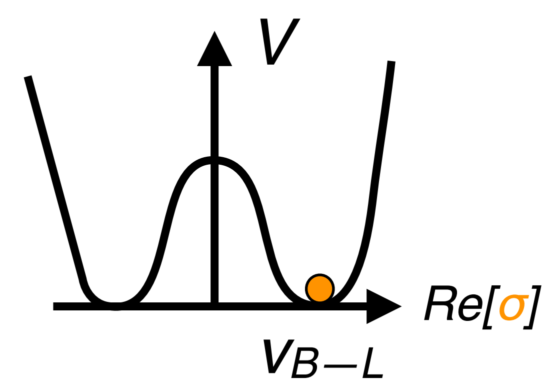
➢ Let us simply consider the model that a scalar condensate violates $B\!-\!L$ symmetry

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{N}_R i\partial\!\!\!/ N_R - (y_\nu \bar{L} H N_R + h.c.) - \frac{g_N}{2}(\sigma \bar{N}_R^C N_R + h.c.) - V(H,\sigma)$$

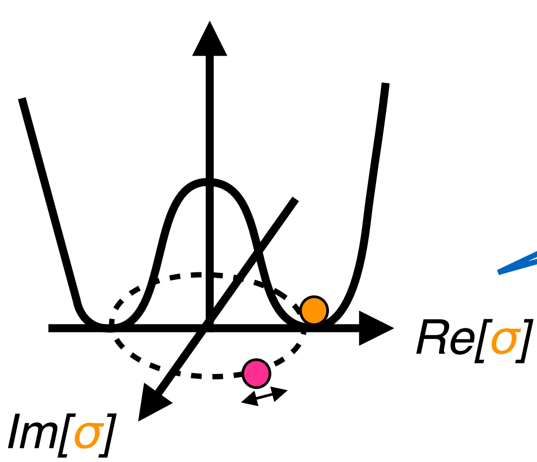
$$V(H,\sigma) = \lambda_H(|H|^2 - v_{ew}^2)^2 + \lambda_\sigma(|\sigma|^2 - v_{B-L}^2)^2 + \lambda_{\sigma H}(|\sigma|^2 - v_{B-L}^2)(|H|^2 - v_{ew}^2)$$

➢ Then, N_R acquires its mass through VEV of the singlet scalar σ :

$$M_R = g_N v_{B-L} \quad (\ v_{B-L} \equiv \langle \sigma \rangle \ )$$



➢ Spontaneous $U(1)_{B-L}$ breaking leads to a Nambu-Goldstone boson called "*Majoron*"



$$\sigma = (v_{B-L} + \rho/\sqrt{2})e^{i\chi/(\sqrt{2}v_{B-L})}$$

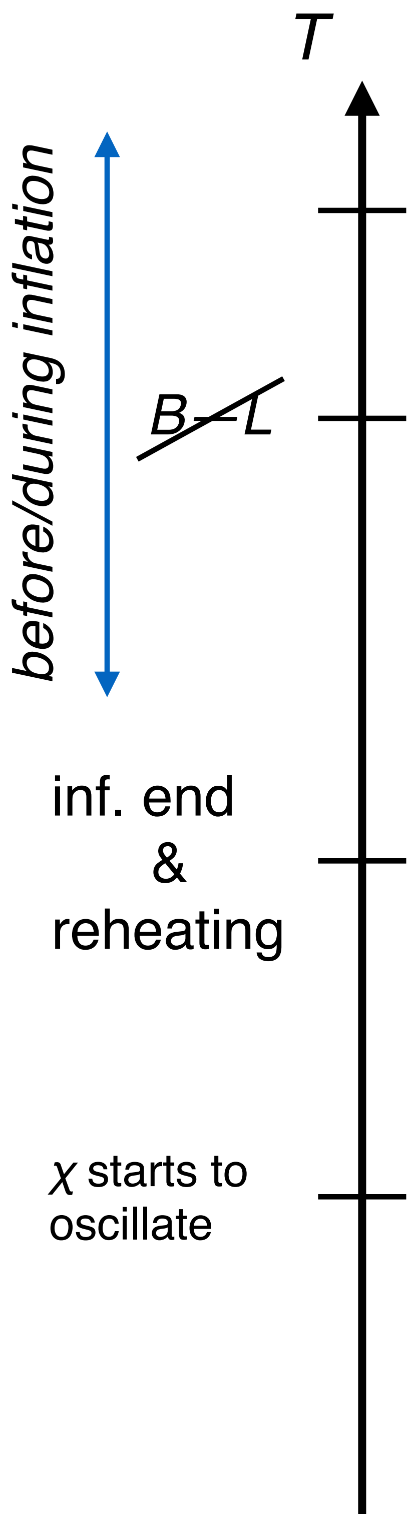
χ: *Majoron*

so-called "singlet Majoron model" [Chikashige, Mohapatra, Peccei, '80]

Majoron is responsible for BAU via leptogenesis!

2. Spontaneous leptogenesis via Majoron oscillation

Majoron dynamics



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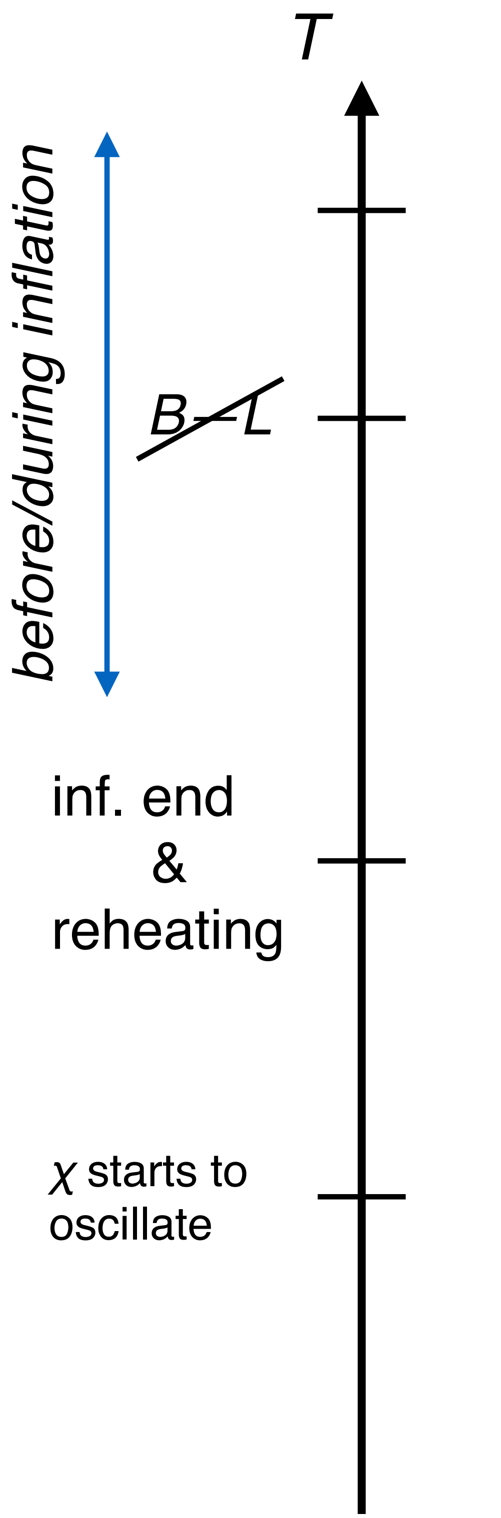

➢ $B-L$ would be a good symmetry in the very early universe

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{N}_R i \partial\!\!\!/ N_R - (y_\nu \bar{L} H N_R + h.c.) - \frac{g_N}{2}(\sigma \bar{N}_R^C N_R + h.c.) - V(H, \sigma)$$

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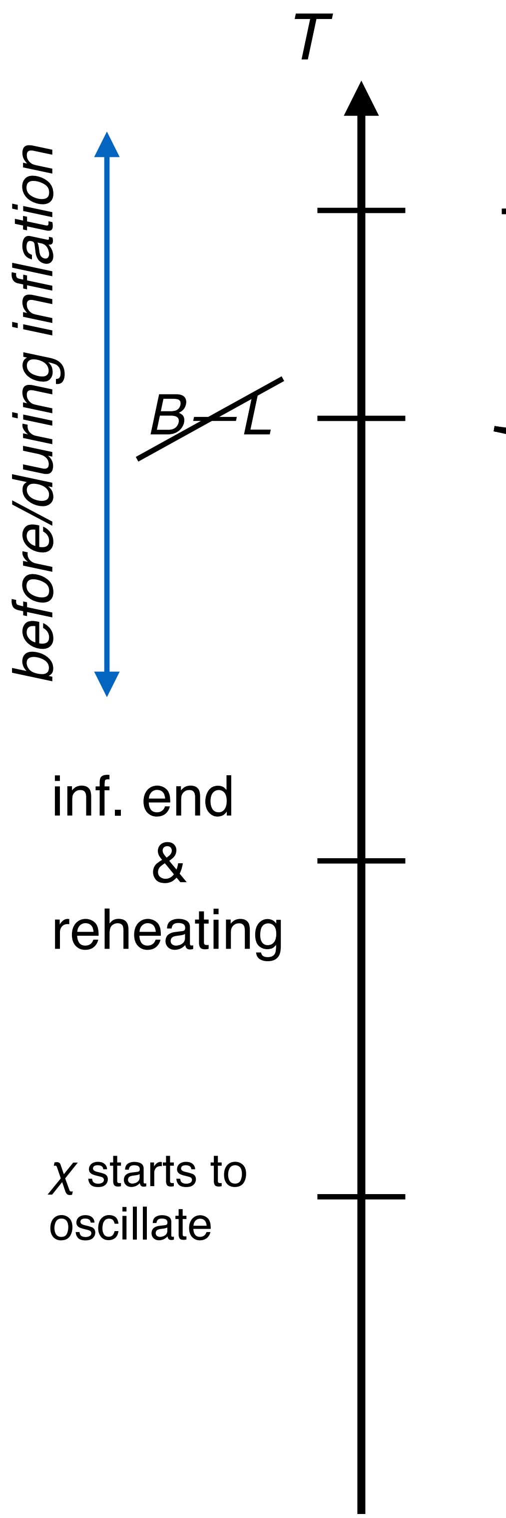

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- $B-L$ is broken before/during inflation so that N_R acquires its mass, while Majoron χ arises

Majoron dynamics

T

before/during inflation

$\cancel{B-L}$

inf. end & reheating

χ starts to oscillate

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$(v_{B-L} \sim M_R)$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{2}\chi\partial^2\chi - \frac{\partial_\mu \chi}{M_R}\bar{L}\gamma^\mu L + \frac{m_\nu}{v_{ew}^2}(LH)(LH) + \cdots$$

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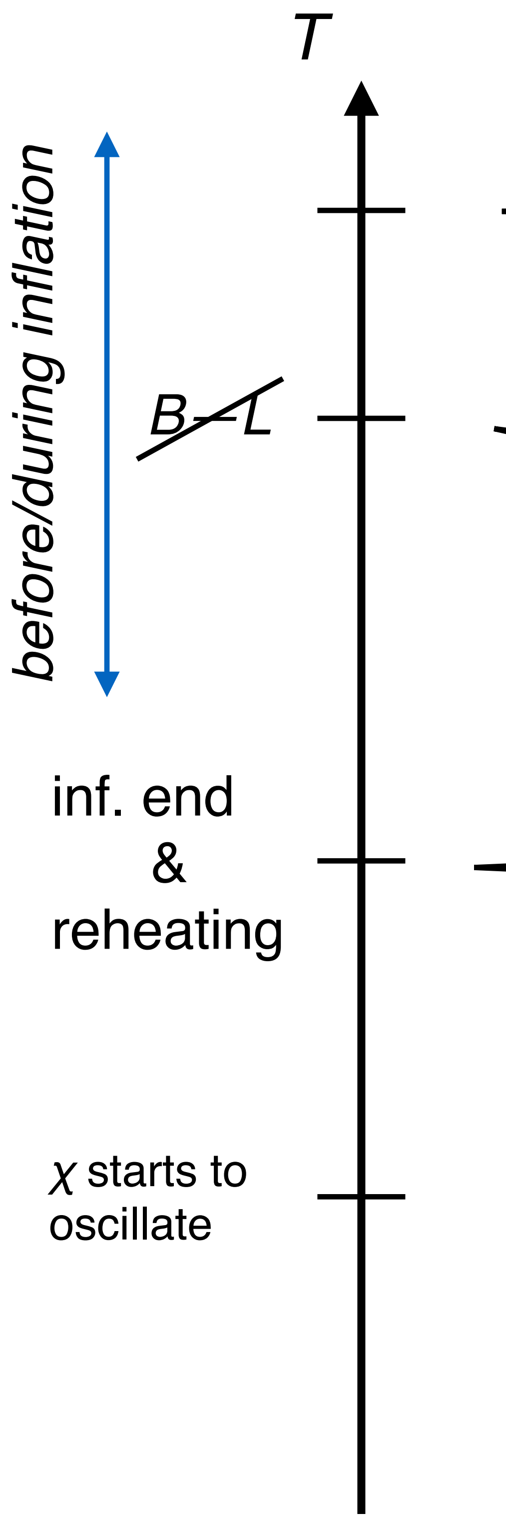

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➢ Global $B-L$ symmetry might be explicitly broken by gravitational effect: [Giddings, Strominger, ’88; Akhmedov et al., ‘92]

$$V_{PL}(\sigma) = \frac{\sigma^5}{M_{PL}} + \frac{\sigma^6}{M_{PL}^2} + \frac{\sigma^7}{M_{PL}^3} + \cdots \longrightarrow$$

Majoron acquires a mass

$$m_\chi^{(n)} \sim M_{PL} \times [M_R/M_{PL}]^{(n-2)/2}$$

$(n = 5, 6, 7, \ldots)$

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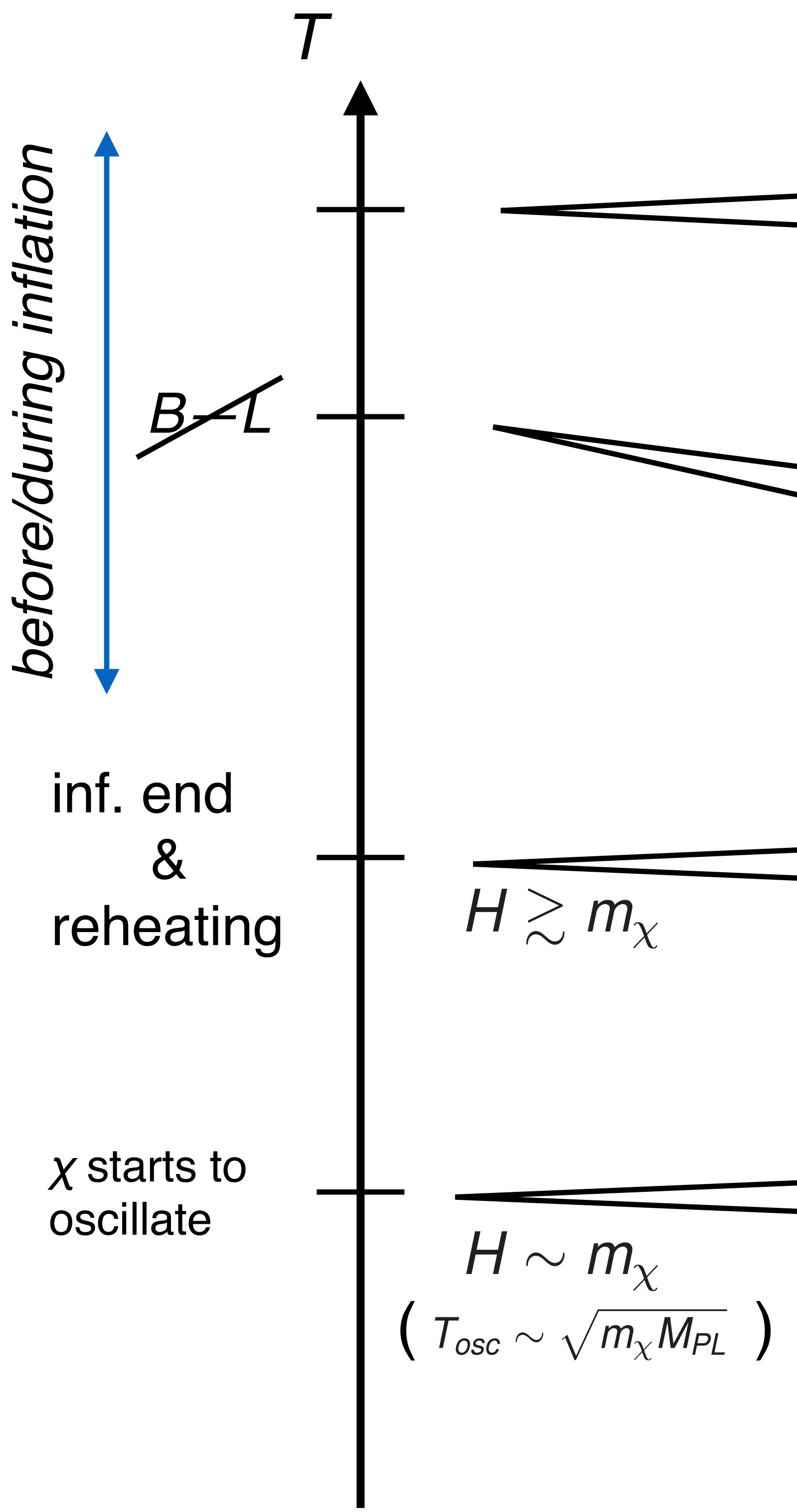

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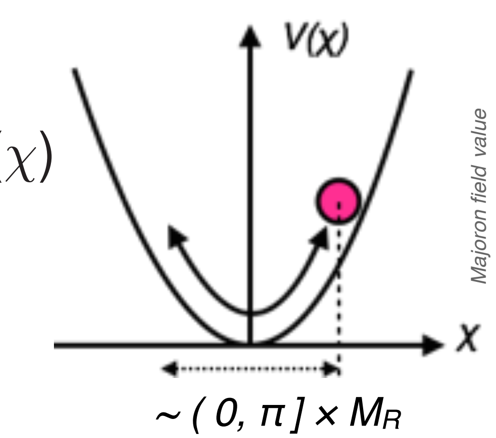
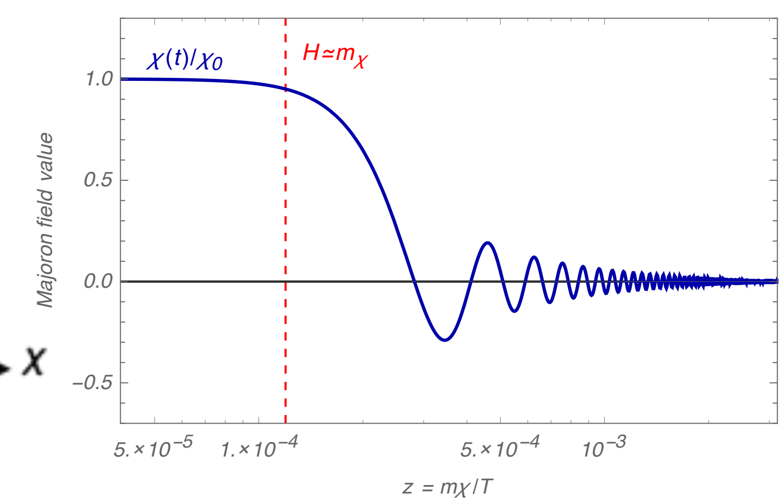
- Majoron starts to oscillate at $H \sim m_\chi$: ($T_{osc} \sim \sqrt{m_\chi M_{PL}}$)

EOM:

$$\partial_t^2 \chi + 3H\partial_t \chi = -\partial_\chi V(\chi)$$

$$V(\chi) \simeq (1/2) m_\chi^2 \chi^2$$





Dynamical level splitting by background Majoron

- Leptons in the thermal bath feel the background Majoron oscillation

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{2}\chi\partial^2\chi - \frac{\partial_\mu \chi}{M_R}\bar{L}\gamma^\mu L + \frac{m_\nu}{v_{ew}^2}(LH)(LH) + \cdots$$

- This derivative coupling affects the kinetic term

$$\mathcal{L}_{kin} \supset \bar{L}(i\partial\!\!\!/ - m - (\partial_\mu\chi/M_R)\gamma^\mu)L$$

- Suppose the coherent Majoron oscillation is homogeneous, lepton kinetic term is modified as

$$\mathcal{L}_{kin} \supset \bar{L}(i\partial\!\!\!/ - m - \mu_\chi\gamma^0)L$$

$$\boxed{\partial_\mu\chi/M_R = (\dot{\chi}, \vec{\partial}\chi)_\mu/M_R \equiv (\mu_\chi, \vec{0})_\mu}$$

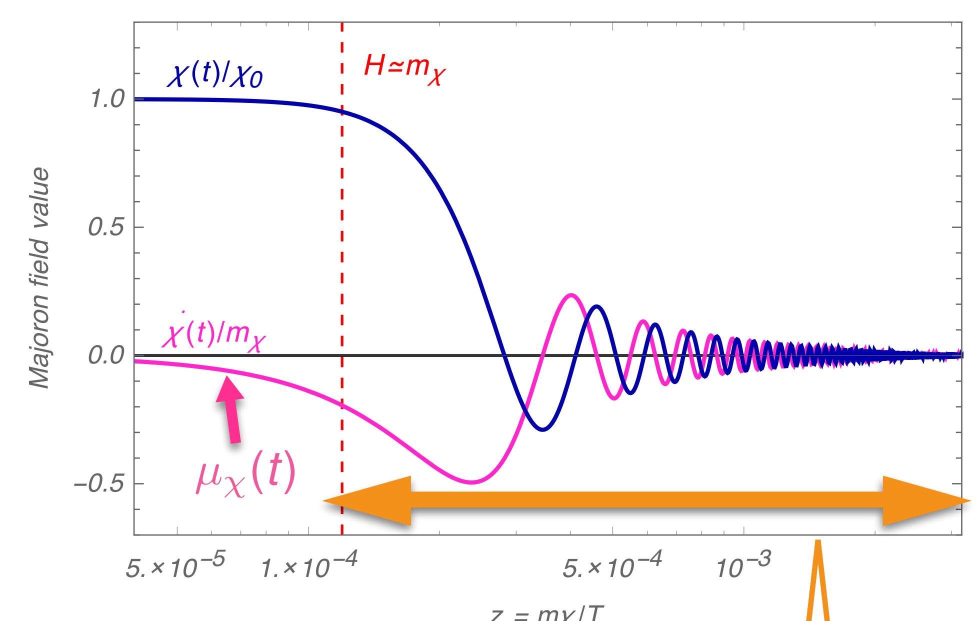
- Then, we have the modified dispersion relation:

$$E = \pm\sqrt{|\vec{p}|^2 + m^2} + \mu_\chi$$

level splitting
(effective chemical potential)

$n_L \equiv n_l - n_{\bar{l}} \propto \mu_\chi$ *does not vanish even when the particles are in thermal equilibrium.*

(c.f. spontaneous Baryogenesis [Cohen and Kaplan, '87])



generating non-zero lepton asymmetry

Boltzmann equation *(by taking the background Majoron into account)*

$$\partial_t n_i + 3Hn_i = C[n_i]$$

- Without μ_χ-term, collision terms are given by

$$C[n_1] = \int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 \delta^4(p_1 + p_2 - p_3 - p_4)$$
$$\times [-|\mathcal{M}_{12\to34}|^2 f_1 f_2 (1 \pm f_3)(1 \pm f_4) + |\mathcal{M}_{34\to12}|^2 f_3 f_4 (1 \pm f_1)(1 \pm f_2)]$$

- By remembering the non-zero μ_χ-term raises the energy shifts, the collision terms are modified, for example,

$$C[n_1] = \int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 \delta(E_1 + E_2 - E_3 - E_4 + 2\mu_\chi)\delta(\vec{p}_1 + \vec{p}_2 - \vec{p}_3 - \vec{p}_4)$$
$$\times [-|\mathcal{M}_{12\to34}|^2 f_1 f_2 (1 \pm f_3)(1 \pm f_4) + |\mathcal{M}_{34\to12}|^2 f_3 f_4 (1 \pm f_1)(1 \pm f_2)]$$

- In our case, since the SM particles are in the thermal bath (chemical equilibrium), we can use the distribution functions for thermal equilibrium

$$f_i \to f_i^{eq}$$

- Hereafter we use the approximation that all of the particles have Maxwell-Boltzmann distribution

$$f_i^{eq} = e^{-(E_i \pm \mu_i)/T}$$

Boltzmann equation *(by taking the background Majoron into account)*

$$\partial_t n_i + 3Hn_i = C[n_i]$$

➢ Then, we have a set of Boltzmann eqs. for the following chemical potentials:

gauge bosons	:	$\mu_\gamma, \quad \mu_{W^\pm}, \quad \mu_Z, \quad \mu_g,$	5
matter fermions	:	$\mu_{e_{Li}}, \quad \mu_{\bar{e}_{Li}}, \quad \mu_{\nu_{Li}}, \quad \mu_{\bar{\nu}_{Li}},$	
		$\mu_{e_{Ri}}, \quad \mu_{\bar{e}_{Ri}},$	
		$\mu_{u_{Li}}, \quad \mu_{\bar{u}_{Li}}, \quad \mu_{d_{Li}}, \quad \mu_{\bar{d}_{Li}},$	+ 14×3
		$\mu_{u_{Ri}}, \quad \mu_{\bar{u}_{Ri}}, \quad \mu_{d_{Ri}}, \quad \mu_{\bar{d}_{Ri}},$	
Higgs boson	:	$\mu_{h^0}, \quad \mu_{h^\pm},$	+ 3 ($\mu_{\gamma,g}=0$)
			= 50 → 25 (parameters)

➢ To simplify the equations, we put the assumptions that

- neglect flavor mixings [$\mu_{\psi i} = \mu_\psi$, ($\psi = e_L, \nu_L, e_R, u_L, d_L, u_R, d_R$)] 7×2
- EW symmetric phase [$\mu_{W\pm} = \mu_Z = 0$, $\mu_{uL}=\mu_{dL}\equiv\mu_Q$, $\mu_{\nu L}=\mu_{eL}\equiv\mu_L$, $\mu_{h+}=\mu_{h0}\equiv\mu_H$] + 5
- Yukawa interactions are in the thermal bath [$\mu_H=\mu_L-\mu_{eR}=\mu_{uR}-\mu_Q=\mu_Q-\mu_{dR}$] + 3
- sphaleron process is in the thermal bath [$3\mu_Q+\mu_L=0$] + 1
- neutrality condition of the universe [$2N_g(\mu_Q-\mu_L)+(4N_g+N_h)\mu_H=0$] + 1 = 24

➢ All of the chemical potentials can be written in terms of only one chem. pot.

→ We take "μ_L" so that $n_B = -\dfrac{4(4N_g+N_h)}{28N_g+9Nh} n_L = -\dfrac{52}{93} n_L \qquad n_L \equiv n_l - n_{\bar{l}} \propto \mu_L / T$

Boltzmann equation *(by taking the background Majoron into account)*

$$\partial_t n_i + 3Hn_i = C[n_i]$$

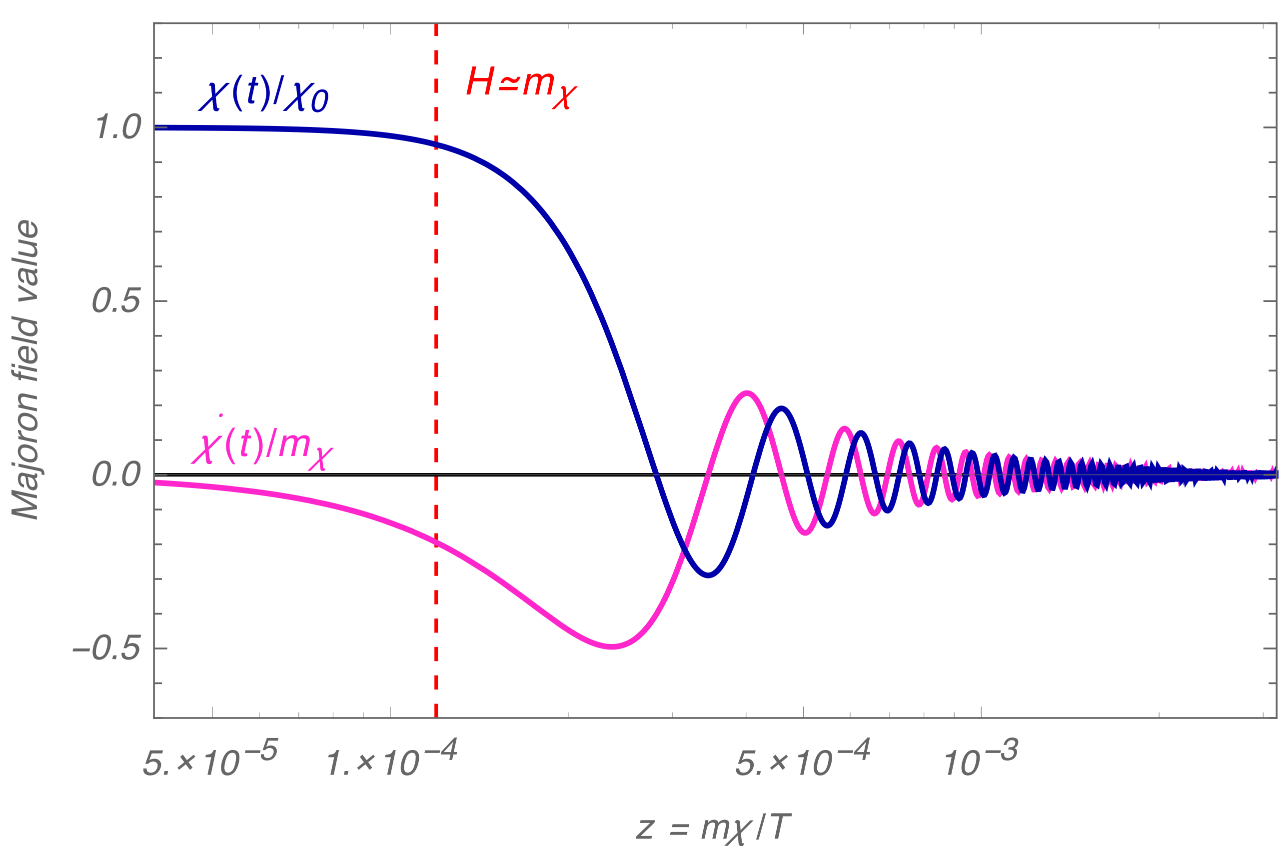
➢ It is reasonable to solve the Boltzmann equation for $n_L \equiv n_l - n_{\bar{l}} \propto \mu_L/T$

$$\partial_t n_L + 3Hn_L = C[n_L] \longrightarrow \frac{d}{dT}\frac{\mu_L}{T} = w\left(\frac{\mu_L}{T} - \alpha\frac{\mu_\chi}{T}\right)$$

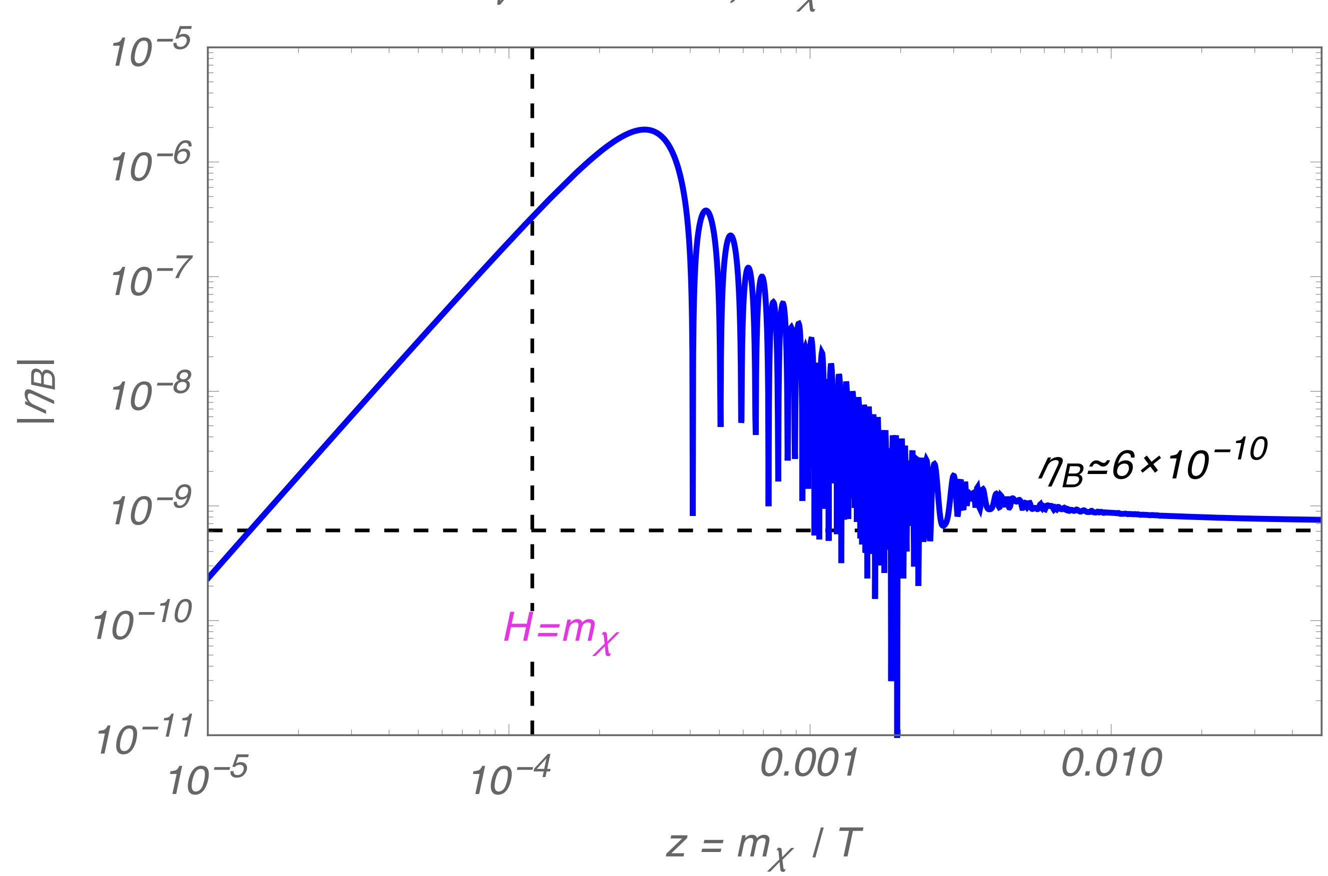
$\alpha \sim 0.5$: numerical factor

$w \propto \langle\sigma_0 v\rangle$: wash-out factor

$\langle\sigma_0 v\rangle \sim \frac{\sum_i m_{\nu_i}^2}{32\pi^2 v_{ew}^4}$ determined by $\frac{m_\nu}{v_{ew}^2}(LH)(LH)$ $(LH \leftrightarrow \bar{L}H^\dagger, LL \leftrightarrow H^\dagger H^\dagger)$



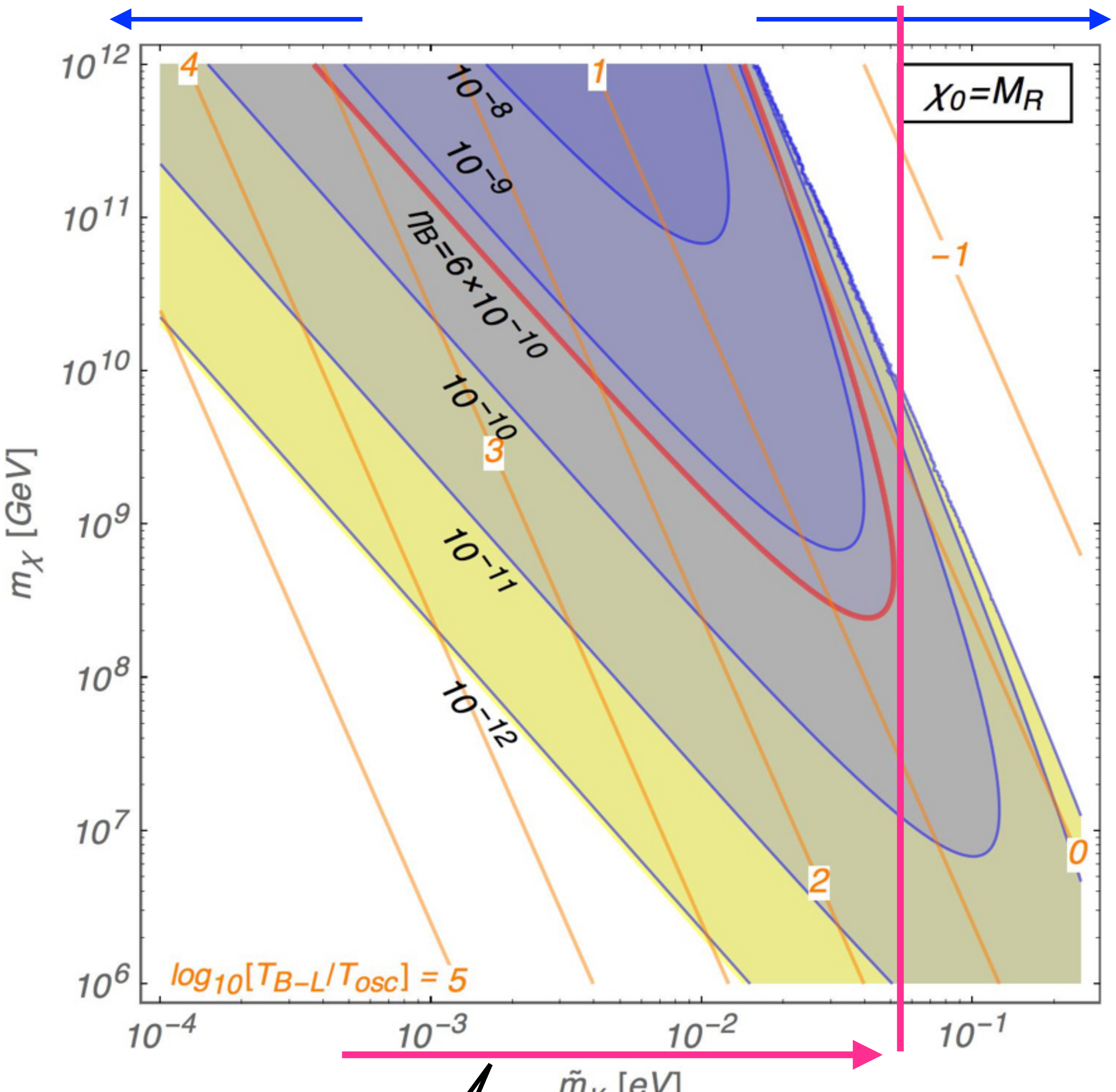
$m_\nu \simeq 0.05$ eV , $m_\chi = 10^{10}$ GeV



Parameter scan

diluted by expansion

strong wash-out



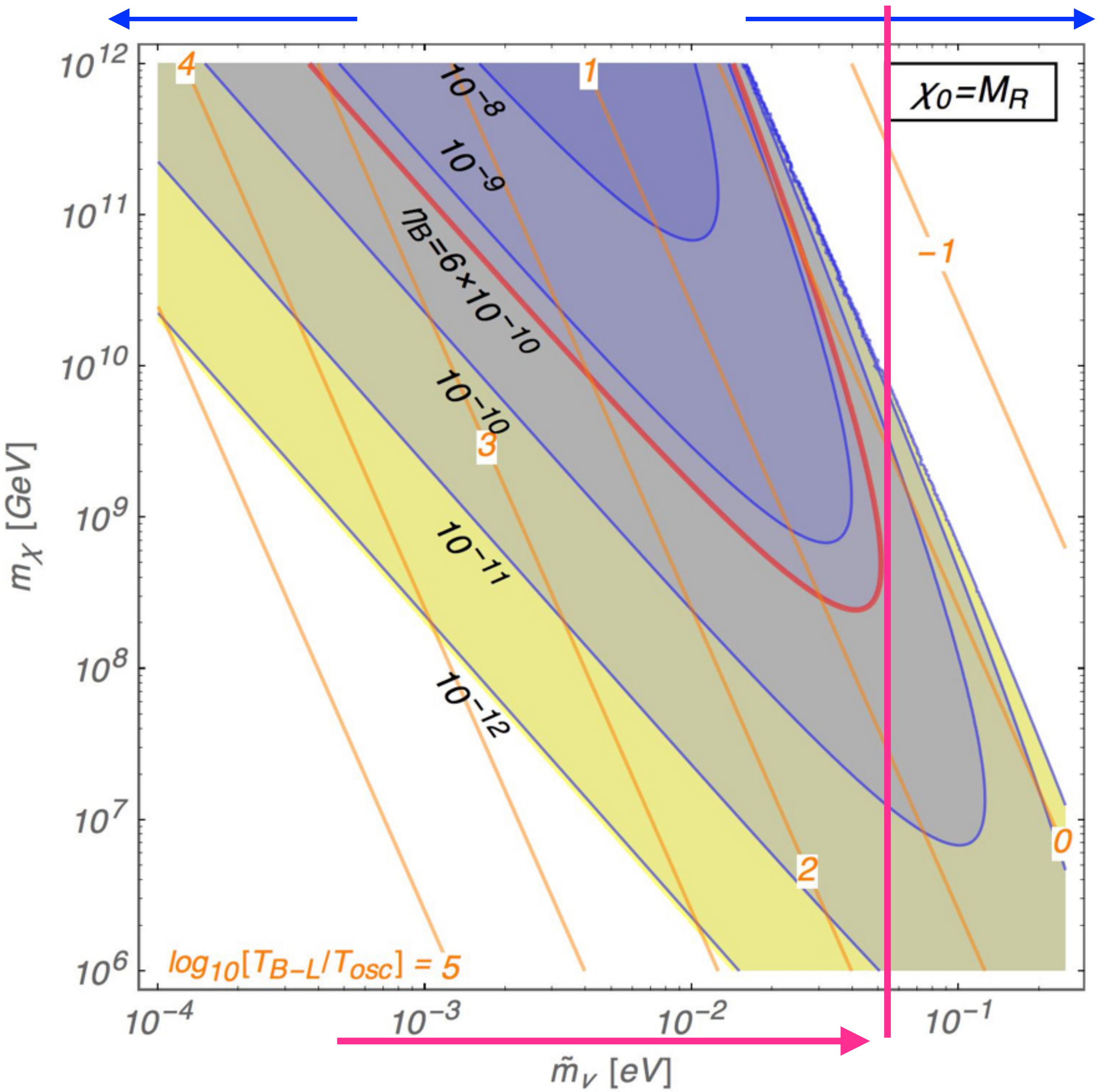
$\eta_B \sim 10^{-10}$

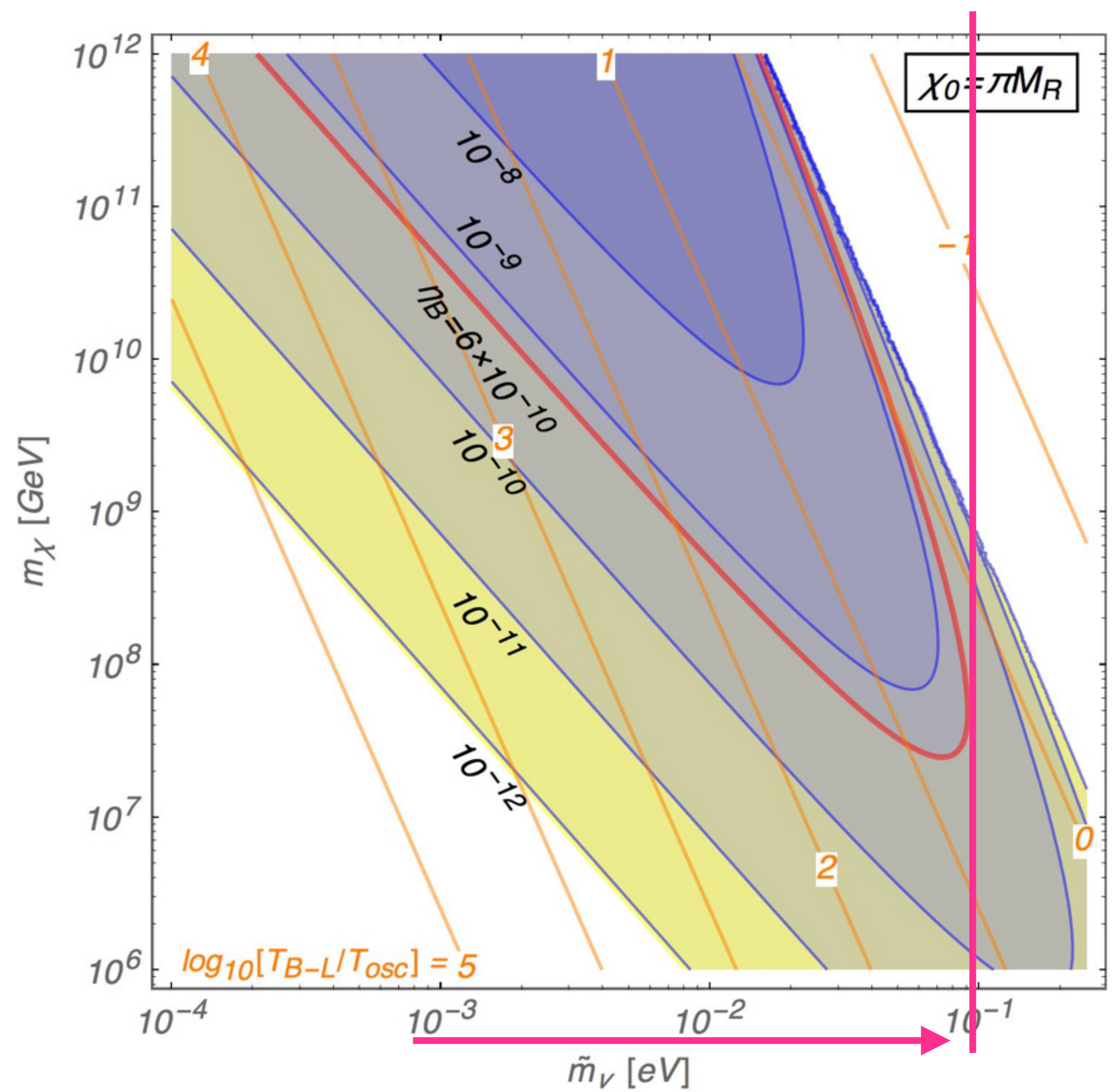
$(\tilde{m}_\nu \equiv \sqrt{m_{\nu_1}^2 + m_{\nu_2}^2 + m_{\nu_3}^2})$

Parameter scan

diluted by expansion

strong wash-out





➢ *constraint on neutrino masses for successful leptogenesis*

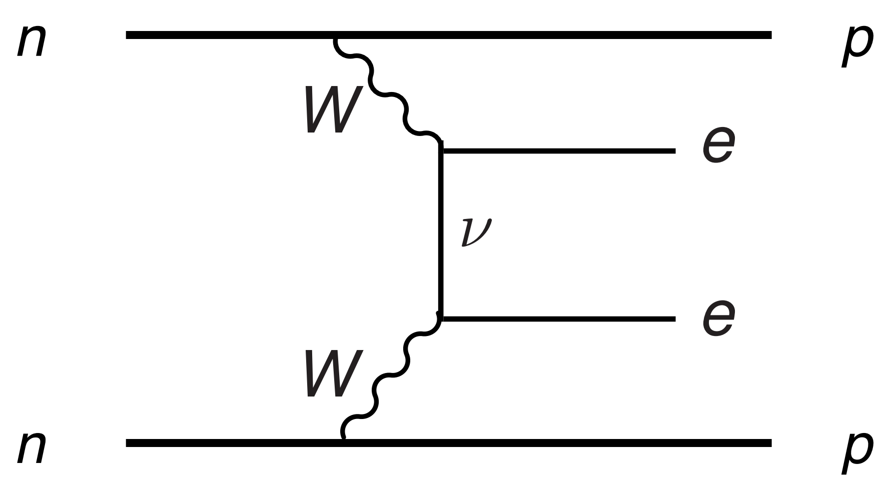
$\tilde{m}_\nu \lesssim 5.5 \times 10^{-2}$ eV $\quad (\chi_0 = M_R)$

$\tilde{m}_\nu \lesssim 9.1 \times 10^{-2}$ eV $\quad (\chi_0 = \pi M_R)$

3. Phenomenological implication

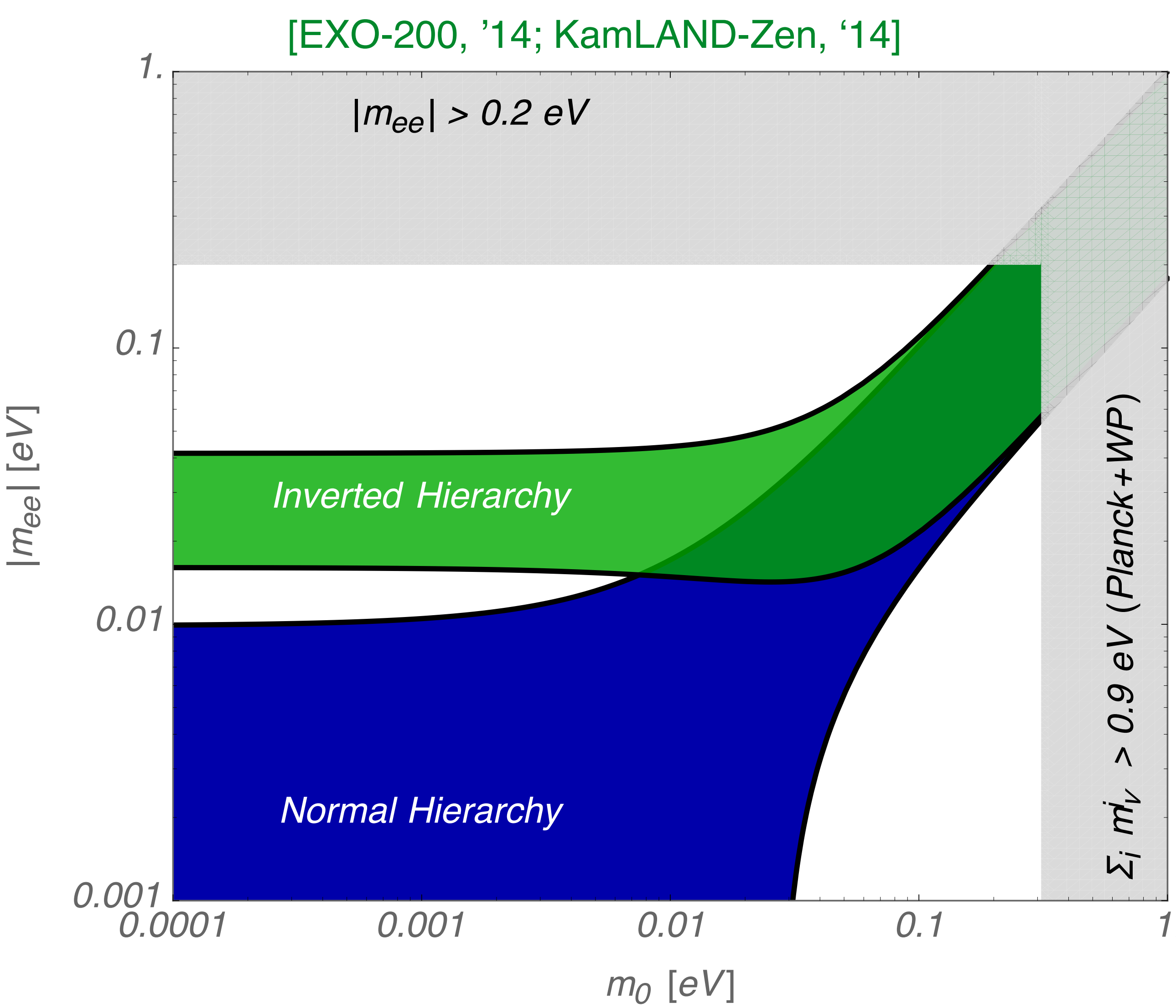
- neutrinoless double beta decay -

0νββ decay

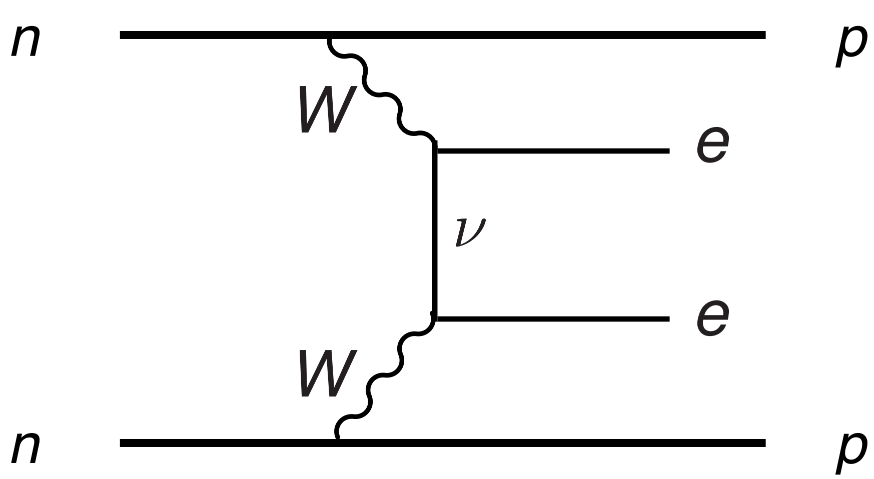


$$1/\tau_{1/2} \propto |m_{ee}|^2$$

$$|m_{ee}| \equiv \sum_i (U_{PMNS})^2_{ei} m_i$$



0νββ decay



$$1/\tau_{1/2} \propto |m_{ee}|^2$$

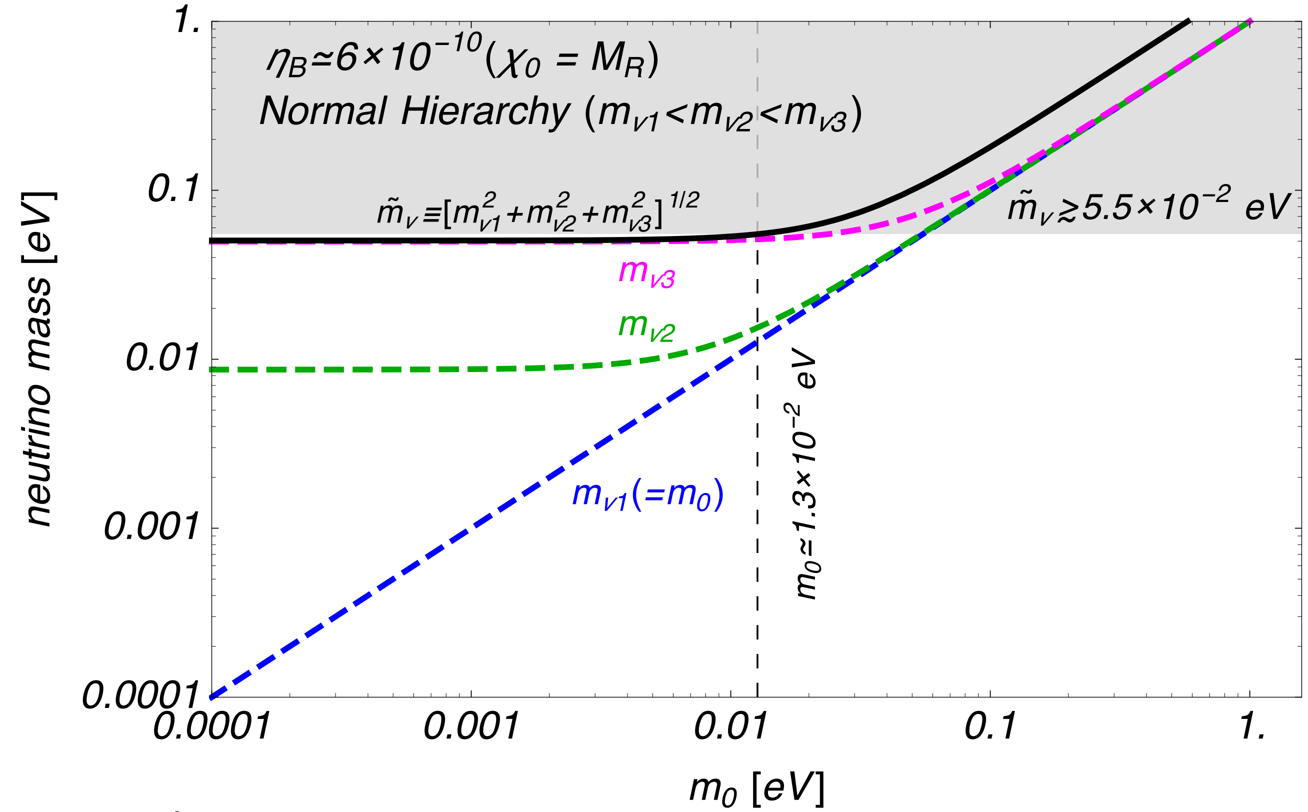
$$|m_{ee}| \equiv \sum_i (U_{PMNS})^2_{ei} m_i$$

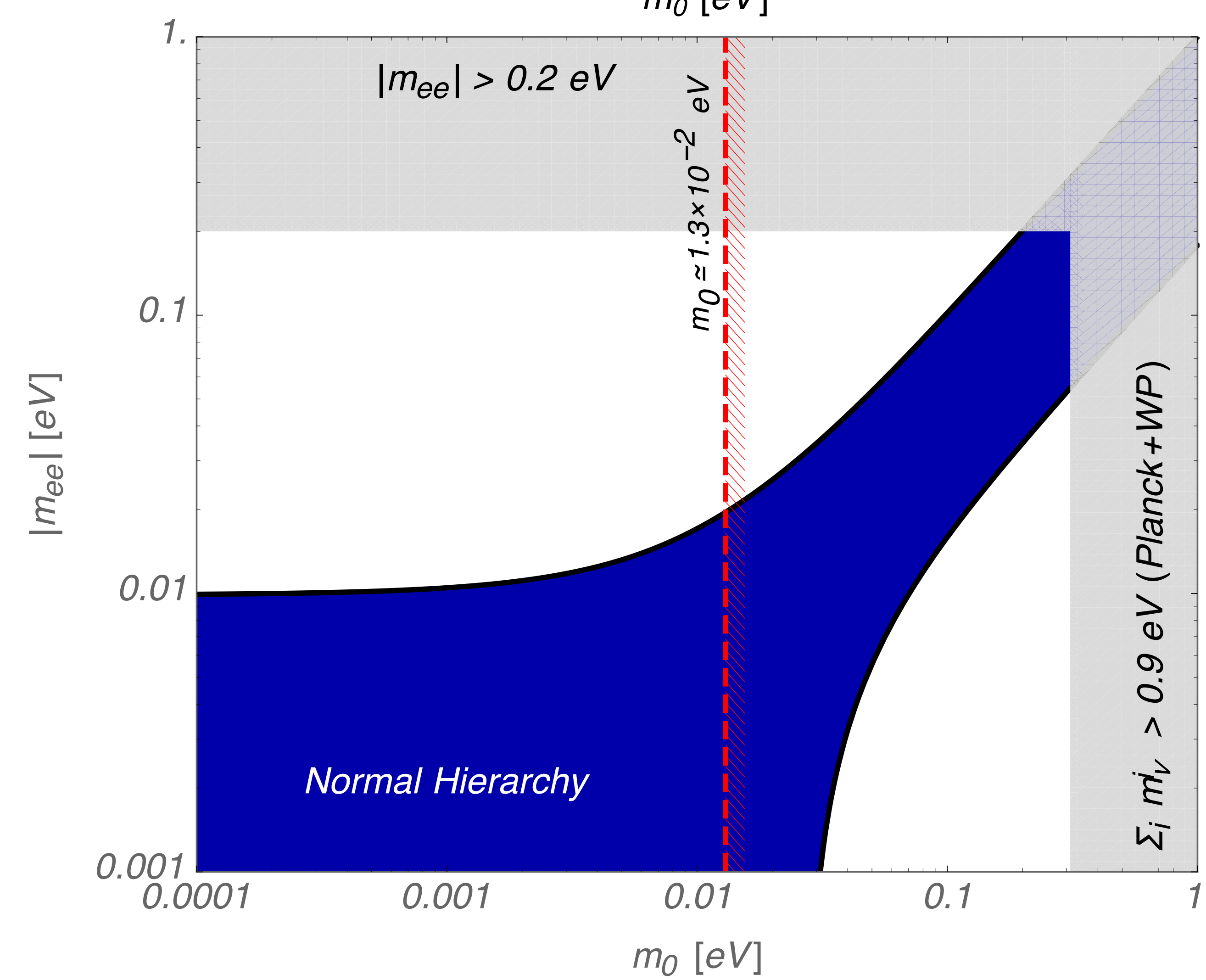
1. $\chi_0 = M_R$

successful leptogenesis:

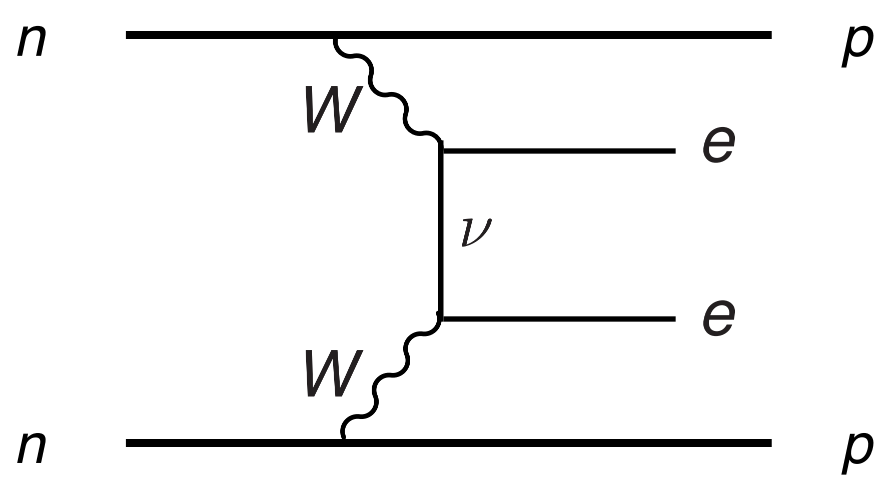
$\tilde{m}_\nu \lesssim 5.5 \times 10^{-2}$ eV

$\longleftrightarrow$ $m_0 \lesssim 1.3 \times 10^{-2}$ eV





$0\nu\beta\beta$ decay



$$1/\tau_{1/2} \propto |m_{ee}|^2$$

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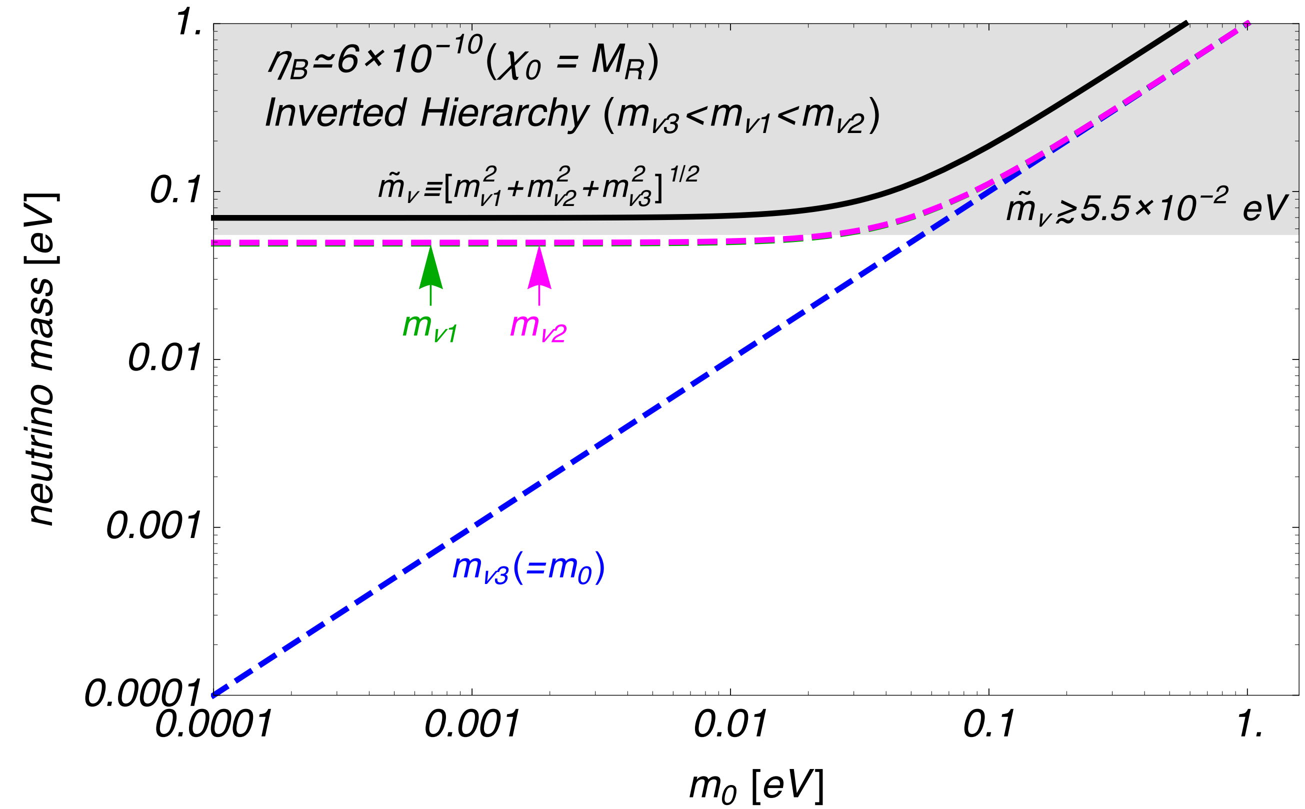
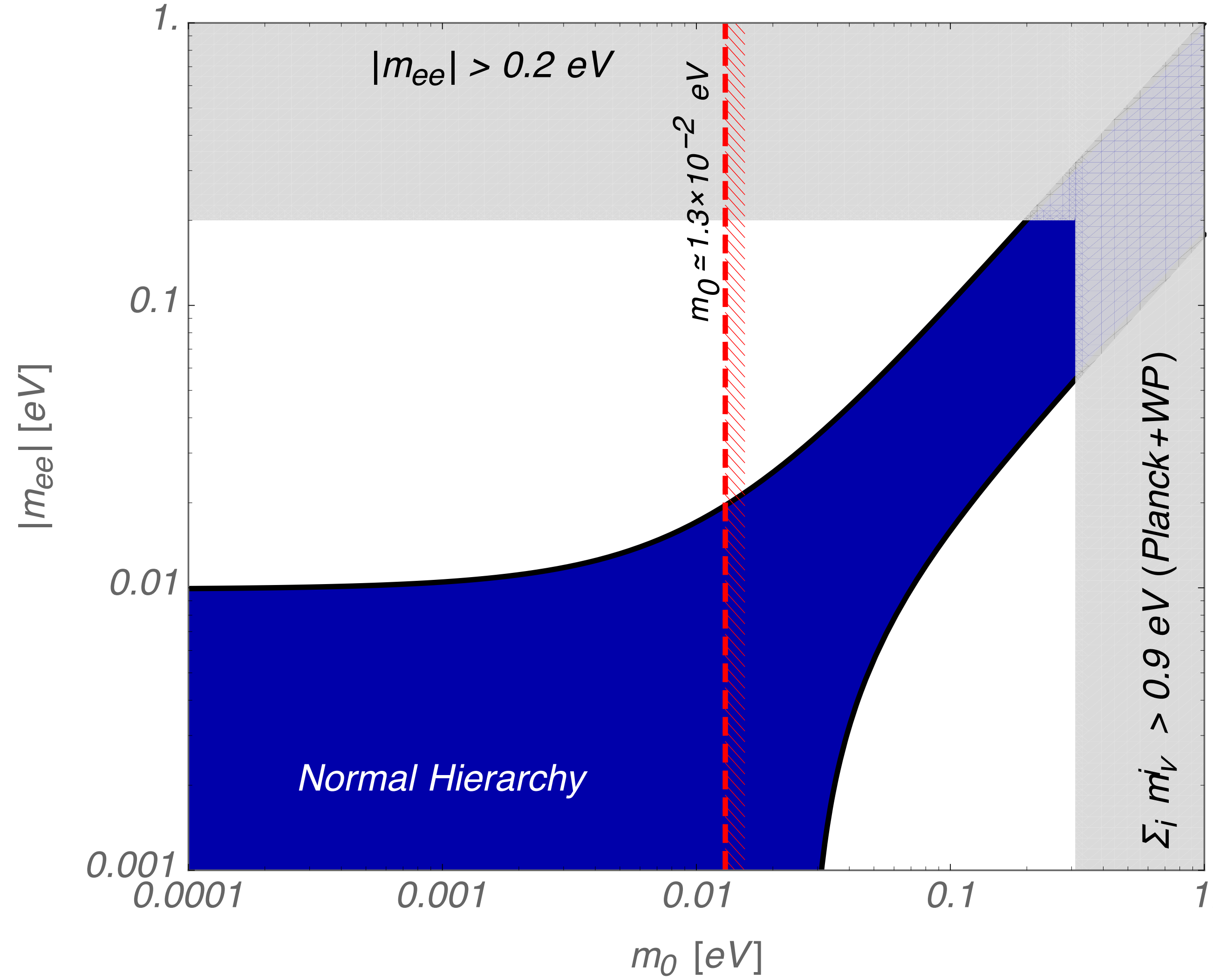
1. $\chi_0 = M_R$

successful leptogenesis:

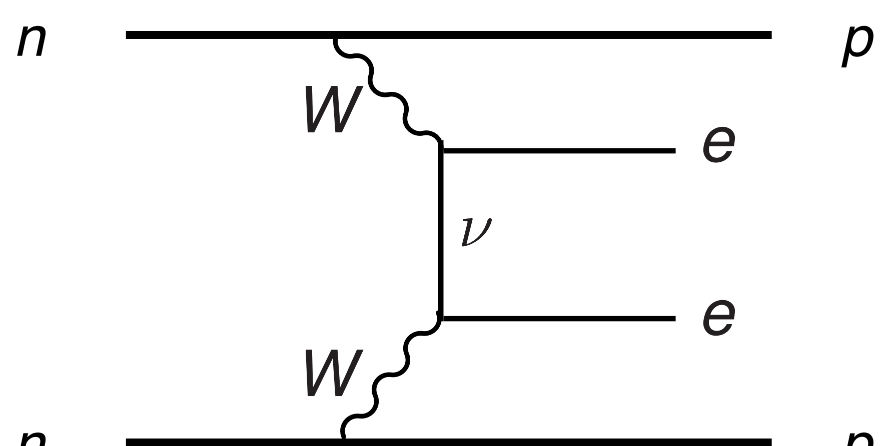
$\tilde{m}_\nu \lesssim 5.5 \times 10^{-2}$ eV

$\longleftrightarrow$ $m_0 \lesssim 1.3 \times 10^{-2}$ eV (only NH)





0νββ decay



$$1/\tau_{1/2} \propto |m_{ee}|^2$$

$$|m_{ee}| \equiv \sum_i (U_{PMNS})^2_{ei} m_i$$

1. $\chi_0 = M_R$

successful leptogenesis:

$\tilde{m}_\nu \lesssim 5.5 \times 10^{-2}$ eV

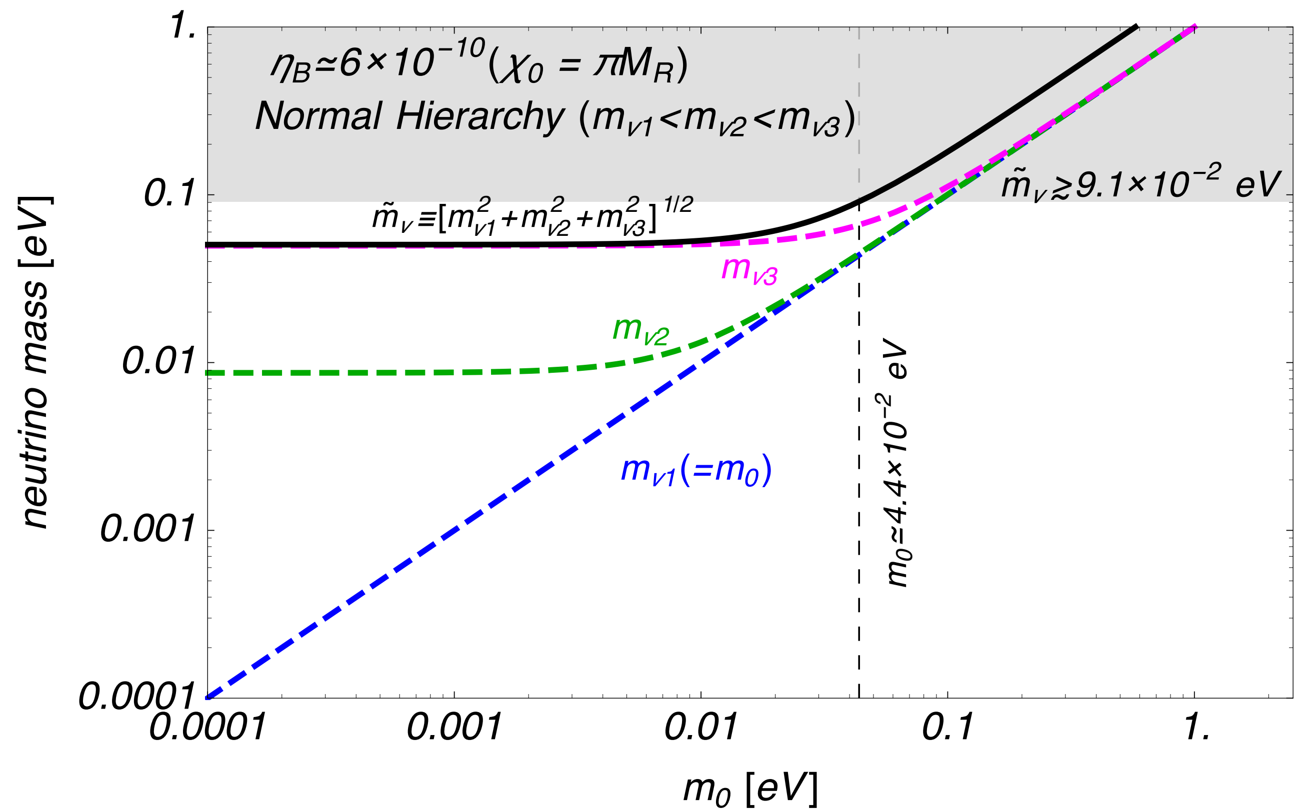
$\longleftrightarrow$ $m_0 \lesssim 1.3 \times 10^{-2}$ *eV* (only NH)

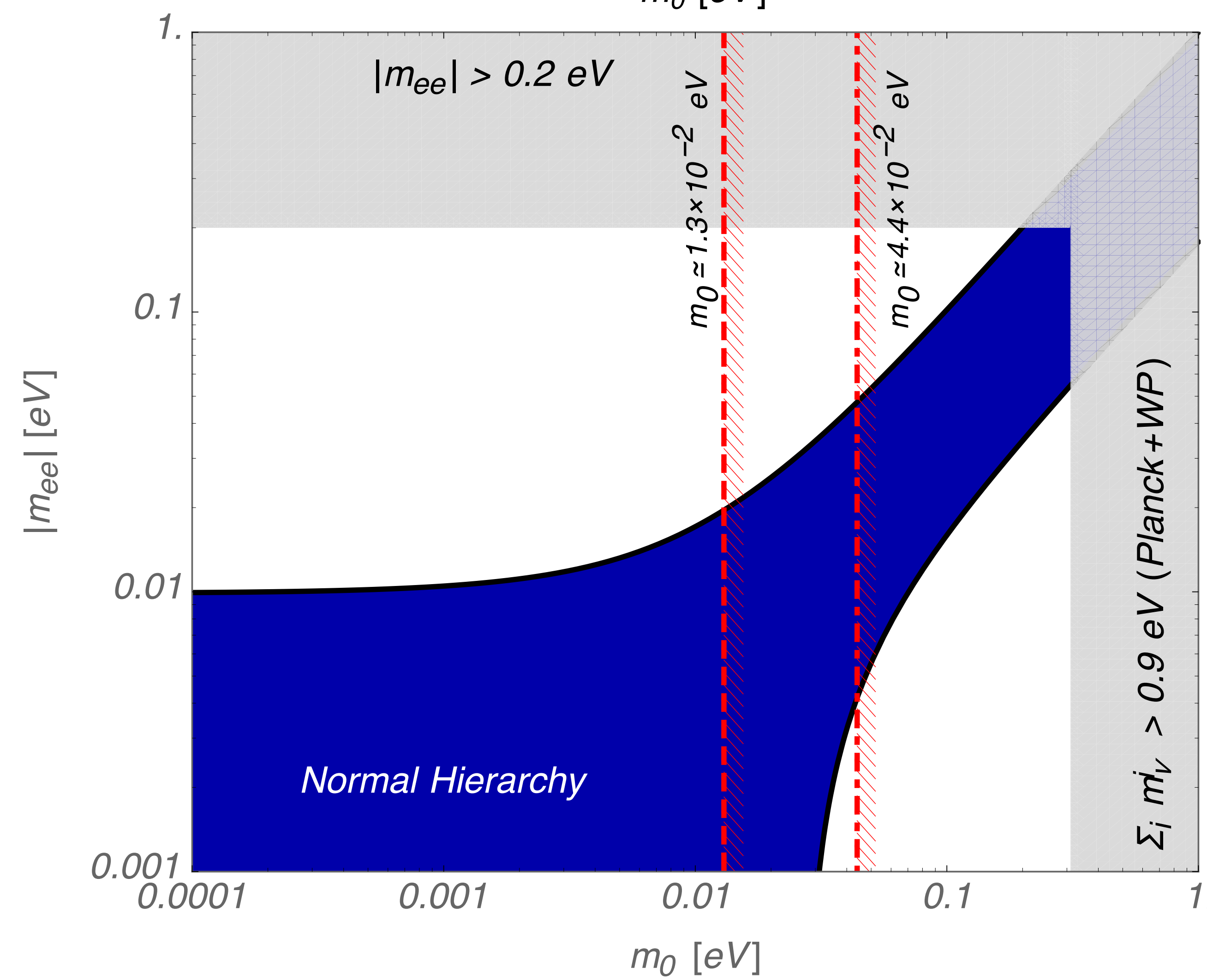
2. $\chi_0 < \pi M_R$

successful leptogenesis:

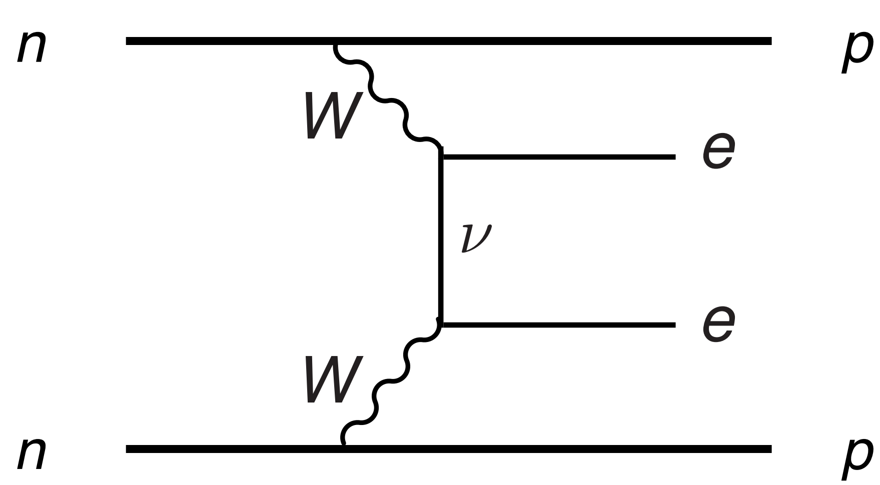
$\tilde{m}_\nu \lesssim 9.1 \times 10^{-2}$ eV

$\longleftrightarrow$ $m_0 \lesssim 4.4 \times 10^{-2}$ eV (NH)





0νββ decay



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$\longleftrightarrow$ $m_0 \lesssim 1.3 \times 10^{-2}$ eV (only NH)

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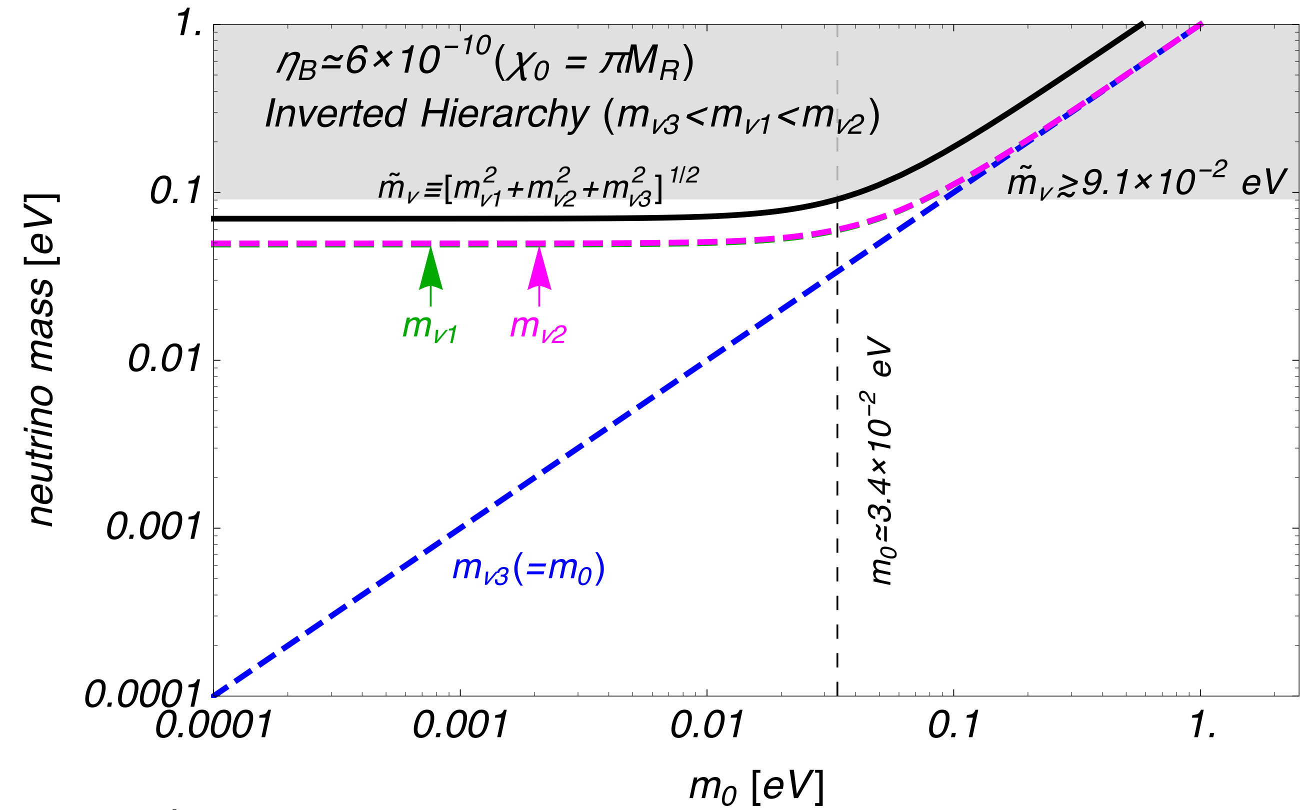
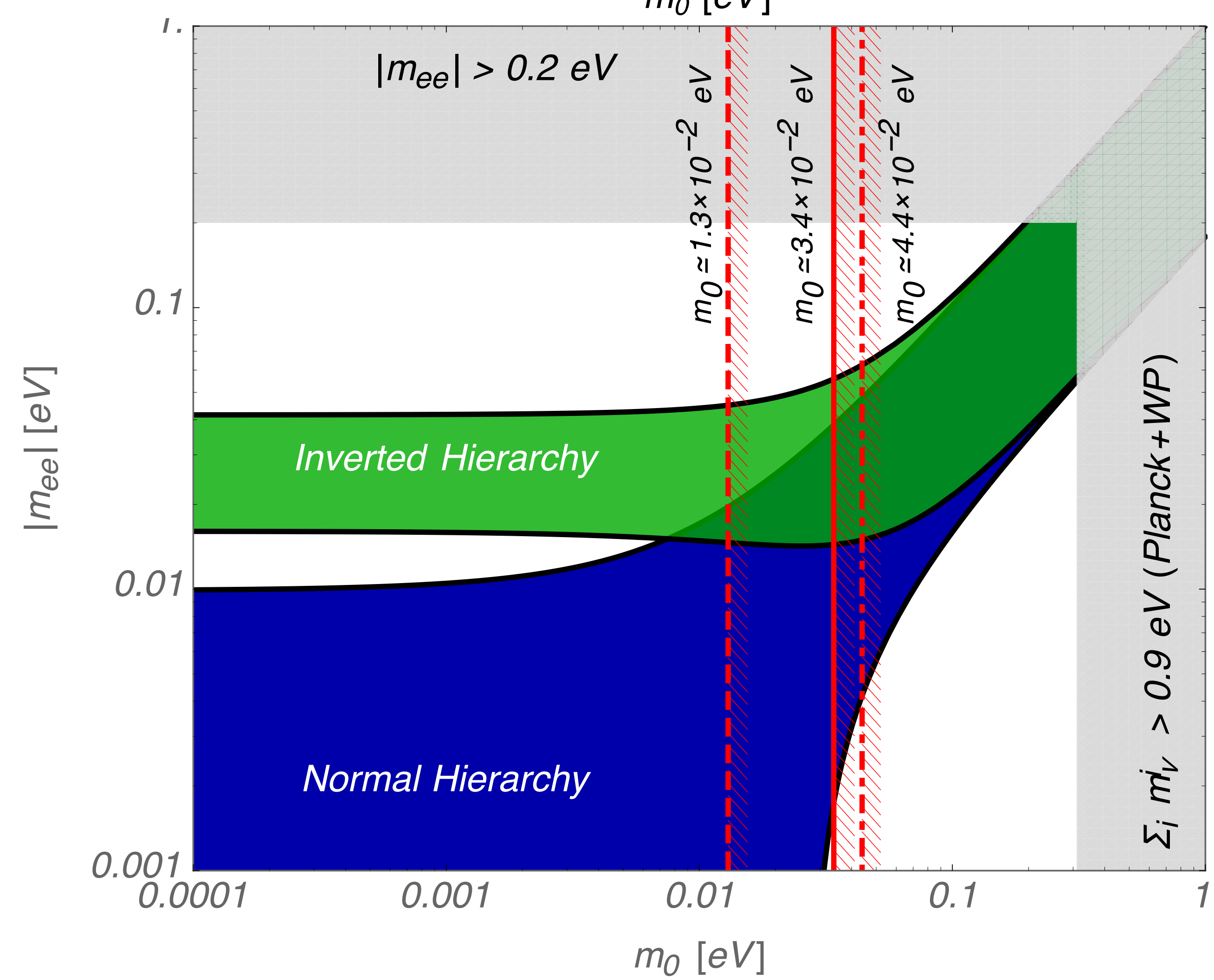
successful leptogenesis:

$\tilde{m}_\nu \lesssim 9.1 \times 10^{-2}$ eV

$\longleftrightarrow$ $m_0 \lesssim 4.4 \times 10^{-2}$ eV (NH)

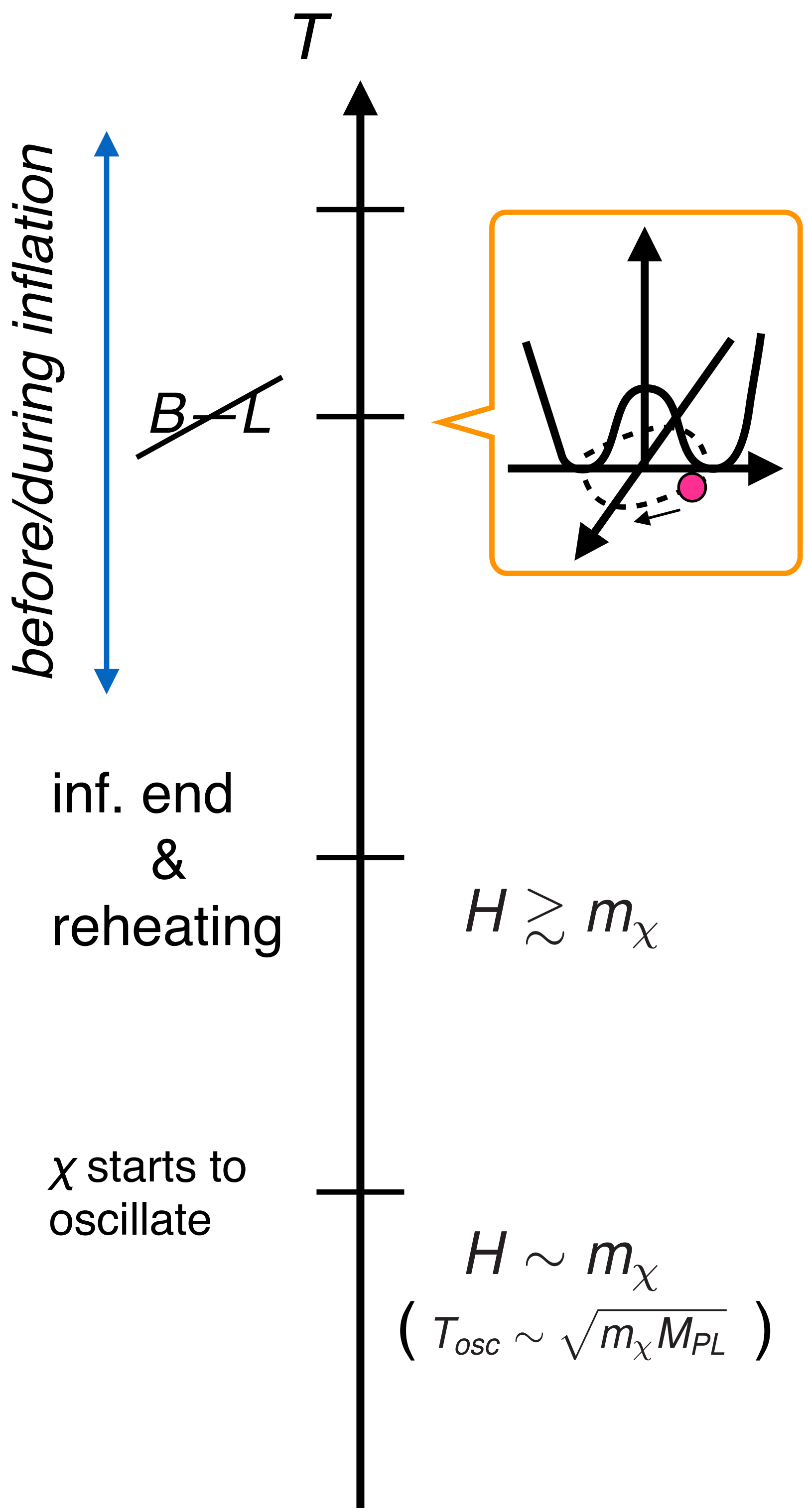
$\longleftrightarrow$ $m_0 \lesssim 3.4 \times 10^{-2}$ eV (IH)





4. Viable models

Viable models consistent with cosmological observations



- Majoron decay

Since the Majoron is very heavy, Planck scale suppressed operators are important.

ex)
$$\mathcal{O}_D^{(n)} = \frac{\sigma^{n-2}|H|^2}{M_{\rm Pl}^{n-4}} \qquad (n = 5, 6, 7, \ldots)$$

c.f.) mass operators
$$\mathcal{O}_M^{(n)} = \frac{\sigma^n}{M_{\rm Pl}^{n-4}}$$

- Suppose that $U(1)_{B-L}$ is a gauge symmetry
- Let us consider the case that $U(1)_{B-L}$ is broken by a scalar field condensate $\langle \Phi \rangle = v_\Phi$

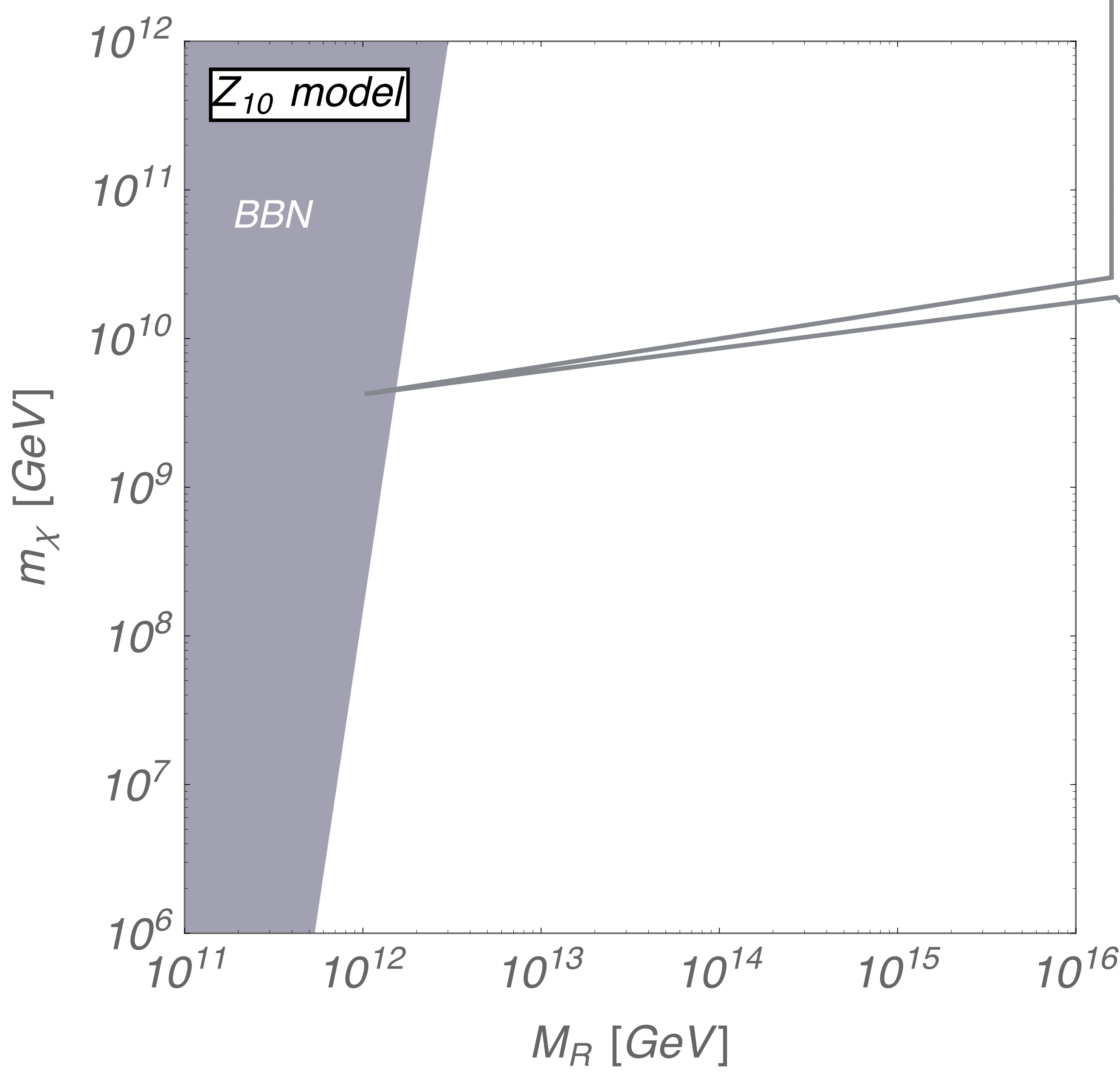
$$\tilde{\mathcal{O}}_M = \frac{\Phi}{M_*}\frac{\sigma^{q_\Phi/2}}{M_{\rm Pl}^{q_\Phi/2-4}} \rightarrow \mathcal{O}_M^{(q_\Phi/2)} = \frac{v_\Phi}{M_*}\frac{\sigma^{q_\Phi/2}}{M_{\rm Pl}^{q_\Phi/2-4}}$$

$$\tilde{\mathcal{O}}_D = \frac{\Phi}{M_*}\frac{\sigma^{q_\Phi/2}|H|^2}{M_{\rm Pl}^{q_\Phi/2-2}} \rightarrow \mathcal{O}_D^{(q_\Phi/2+2)} = \frac{v_\Phi}{M_*}\frac{\sigma^{q_\Phi/2}|H|^2}{M_{\rm Pl}^{q_\Phi/2-2}}$$

q_Φ: $U(1)_{B-L}$ charge of Φ $\quad (q_\Phi \geqq 10)$

- We will demonstrate the case of $q_\Phi = 10$
- *After Φ acquires VEV, Z_{10} discrete symmetry remains*

Z_{10} model



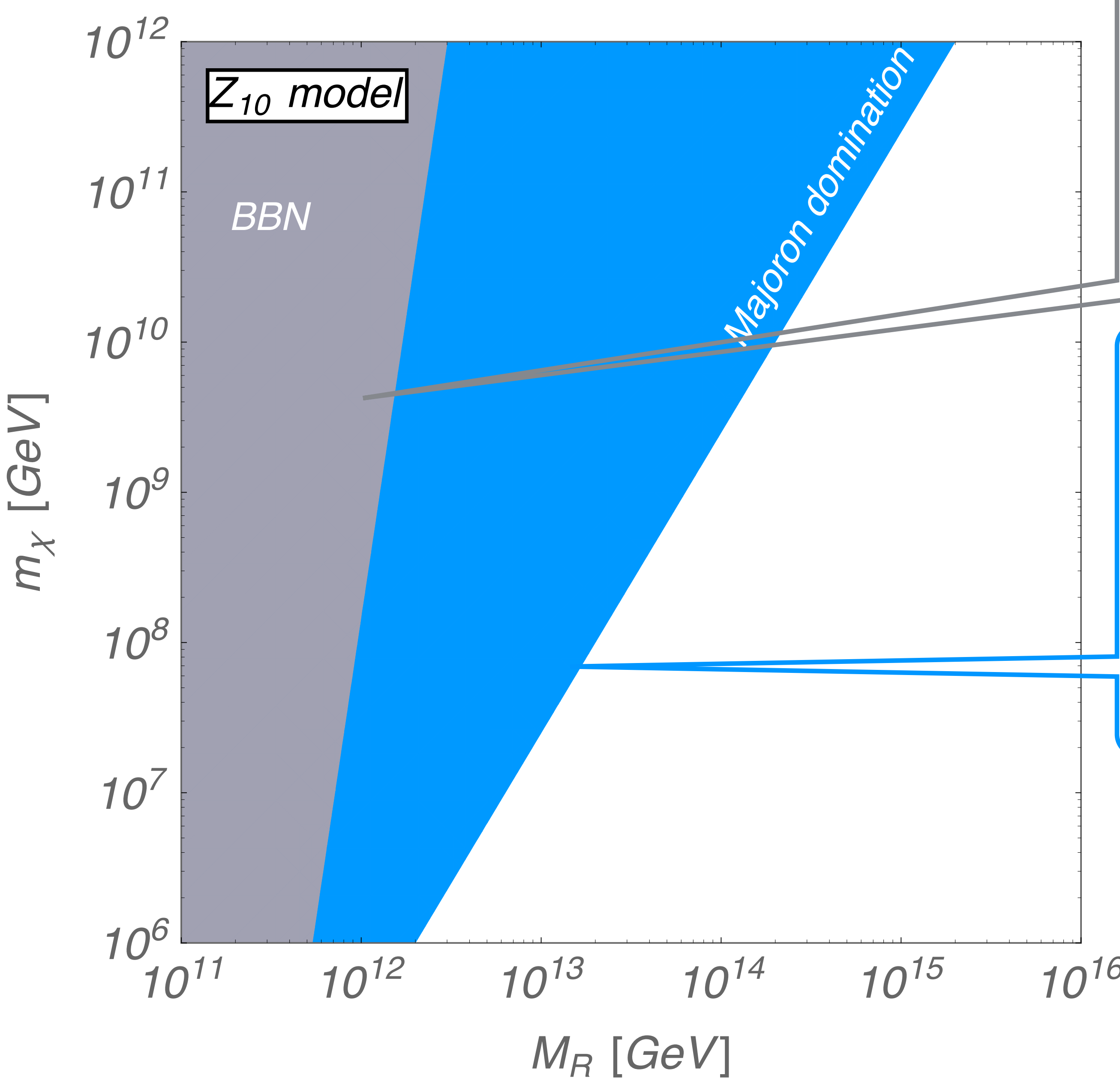
- ➢ Decay operator: $\mathcal{O}_D^{(7)} \sim (M_R^4/M_{\rm Pl}^3)\sigma|H|^2$
- ➢ Decay temperature:

$$T_{\rm decay} \sim \sqrt{M_{\rm Pl}\Gamma_D}$$

$$\sim 1.2 \times 10^4 \left(\frac{M_R}{10^{14}\text{GeV}}\right)^4 \left(\frac{m_\chi}{10^{10}\text{GeV}}\right)^{-1/2} \text{ GeV}$$

- ➢ When $T_{decay} < O(1)\ MeV$, the Majoron decay spoils BBN.

Z_{10} model



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- When $T_{decay} < O(1)\ MeV$, the Majoron decay spoils BBN.

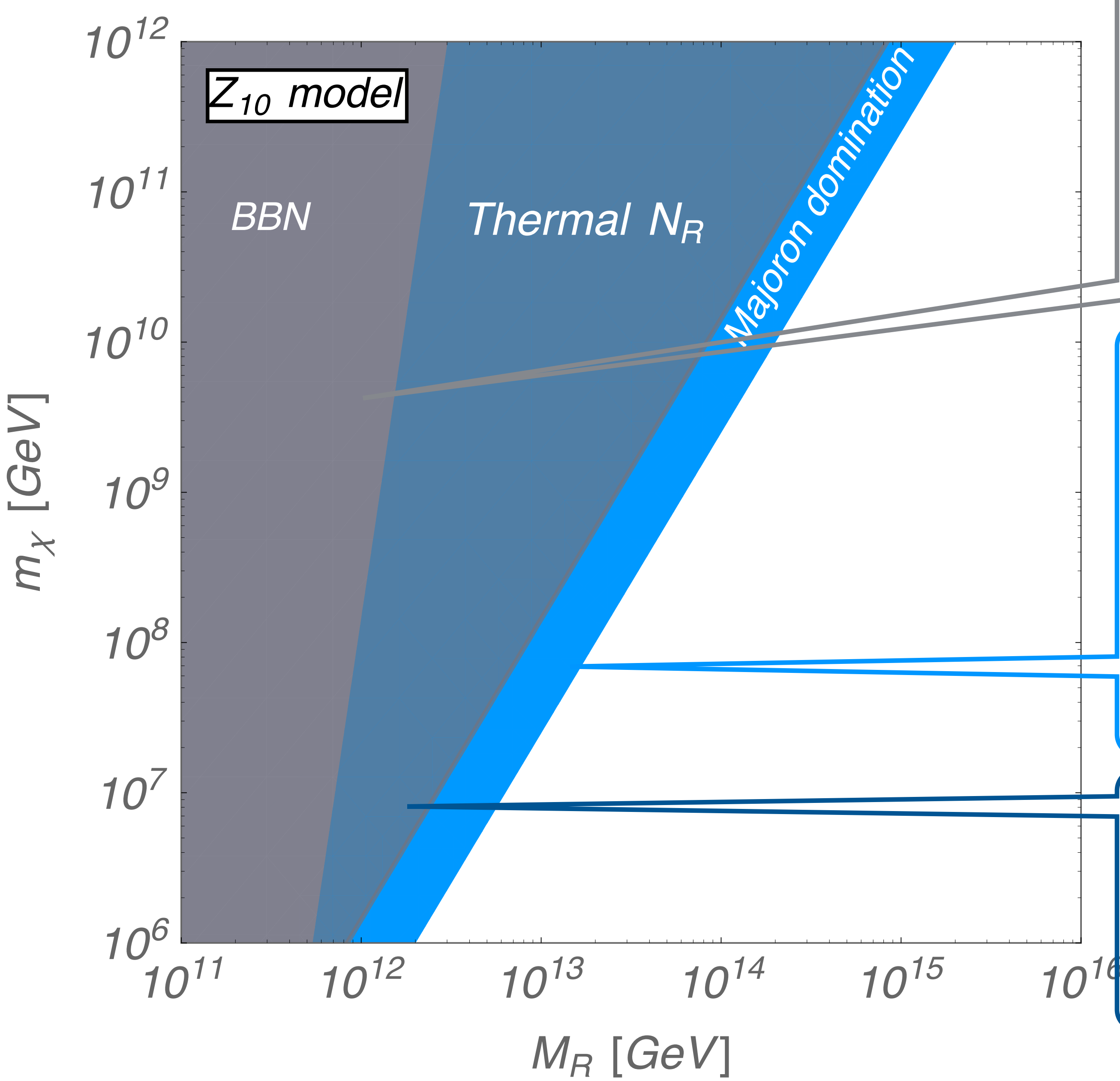
- Majoron domination temperature:

$$T_{\rm dom} \sim (M_R^2/M_{\rm Pl}^2)\,T_{\rm osc}(\sim (M_R^2/M_{\rm Pl}^2)\sqrt{M_{\rm Pl}m_\chi})$$

$(\leftarrow \rho_\chi(T_{dom})/\rho_\gamma(T_{dom})=1)$

- When $T_{decay} < T_{dom}$, Majoron dominates the universe, and dilutes baryon asymmetry.

Z_{10} model



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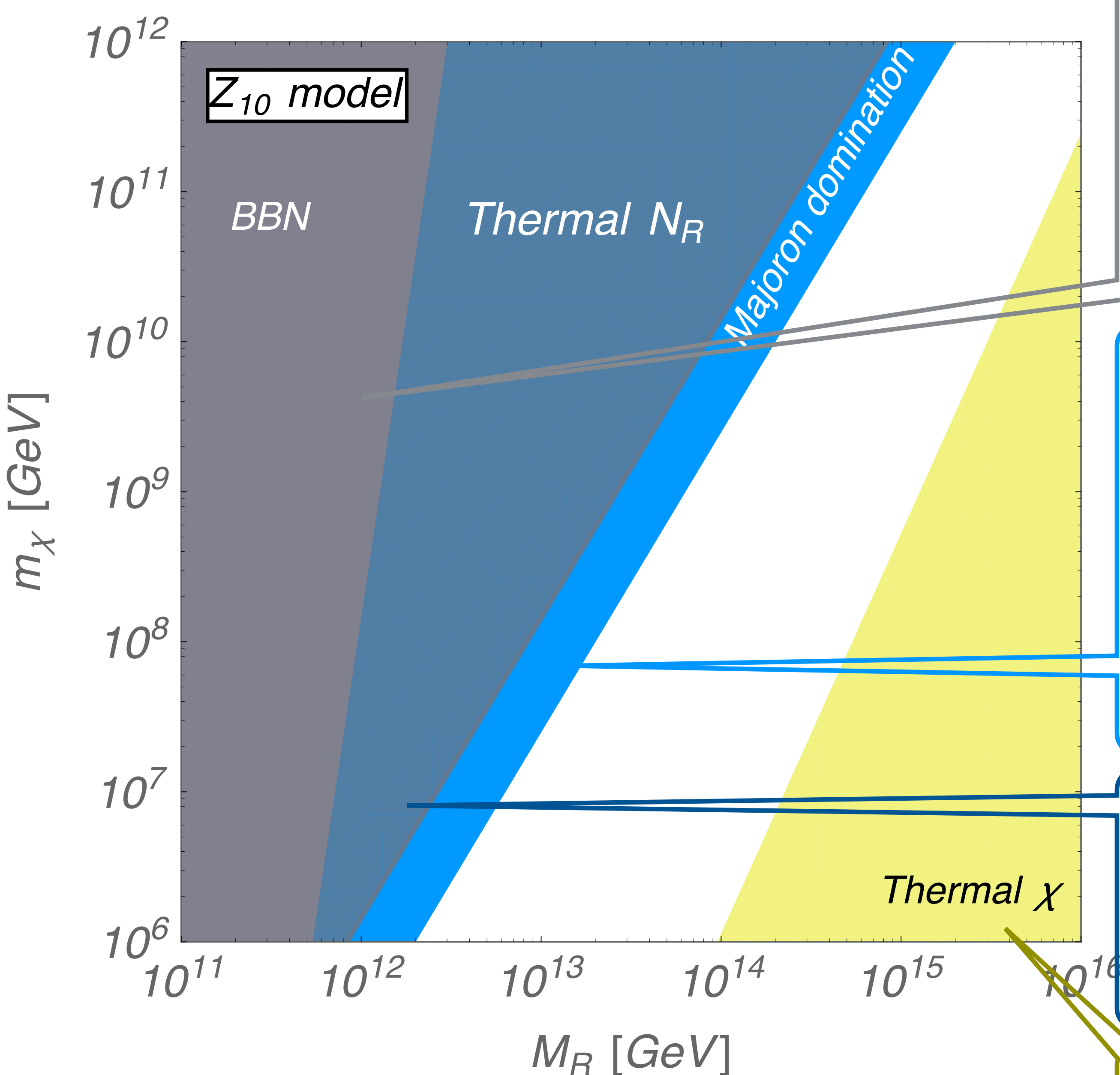
($\leftarrow \rho_\chi(T_{dom})/\rho_\gamma(T_{dom})=1$)

- When $T_{decay} < T_{dom}$, Majoron dominates the universe, and dilutes baryon asymmetry.

- When $M_R < T_{osc}$, N_R is in the thermal bath, and conventional leptogenesis would take place if possible.

Z_{10} model



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- When $T_{decay} < T_{dom}$, Majoron dominates the universe, and dilutes baryon asymmetry.

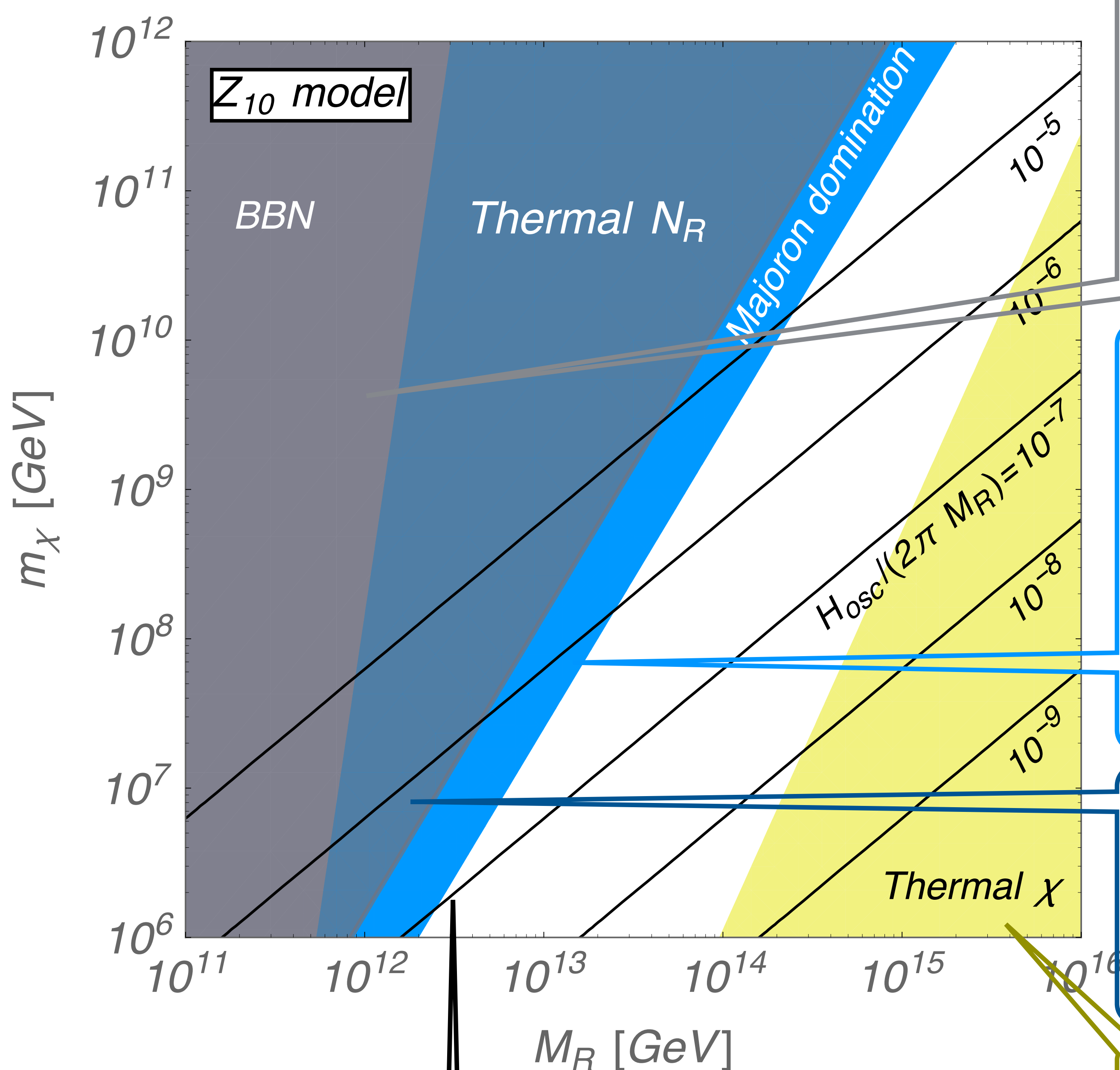
- When $M_R < T_{osc}$, N_R is in the thermal bath, and conventional leptogenesis would take place if possible.

- Majoron is thermalized by χ-H-H interaction.
- Thermalization temperature:

$$T_{\rm th} \sim 1.1\times 10^6 \left(M_R/10^{14}\mathrm{GeV}\right)^{8/3}\ \mathrm{GeV}$$

- When $m_\chi < T_{th}$, Majoron is thermalized.

Z_{10} model



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- When $T_{decay} < O(1)$ *MeV*, the Majoron decay spoils BBN.

- Majoron domination temperature:

$$T_{\rm dom} \sim (M_R^2/M_{\rm Pl}^2)\,T_{\rm osc}(\sim (M_R^2/M_{\rm Pl}^2)\sqrt{M_{\rm Pl}m_\chi})$$

($\leftarrow \rho_\chi(T_{dom})/\rho_\gamma(T_{dom})=1$)

- When $T_{decay} < T_{dom}$, Majoron dominates the universe, and dilutes baryon asymmetry.

- When $M_R < T_{osc}$, N_R is in the thermal bath, and conventional leptogenesis would take place if possible.

- Isocurvature perturbation: $H_{inf}/(2\pi M_R) < 10^{-5}$
- Since $H_{osc} < H_{inf}$, at least $H_{osc}/(2\pi M_R) < 10^{-5}$ should be satisfied.

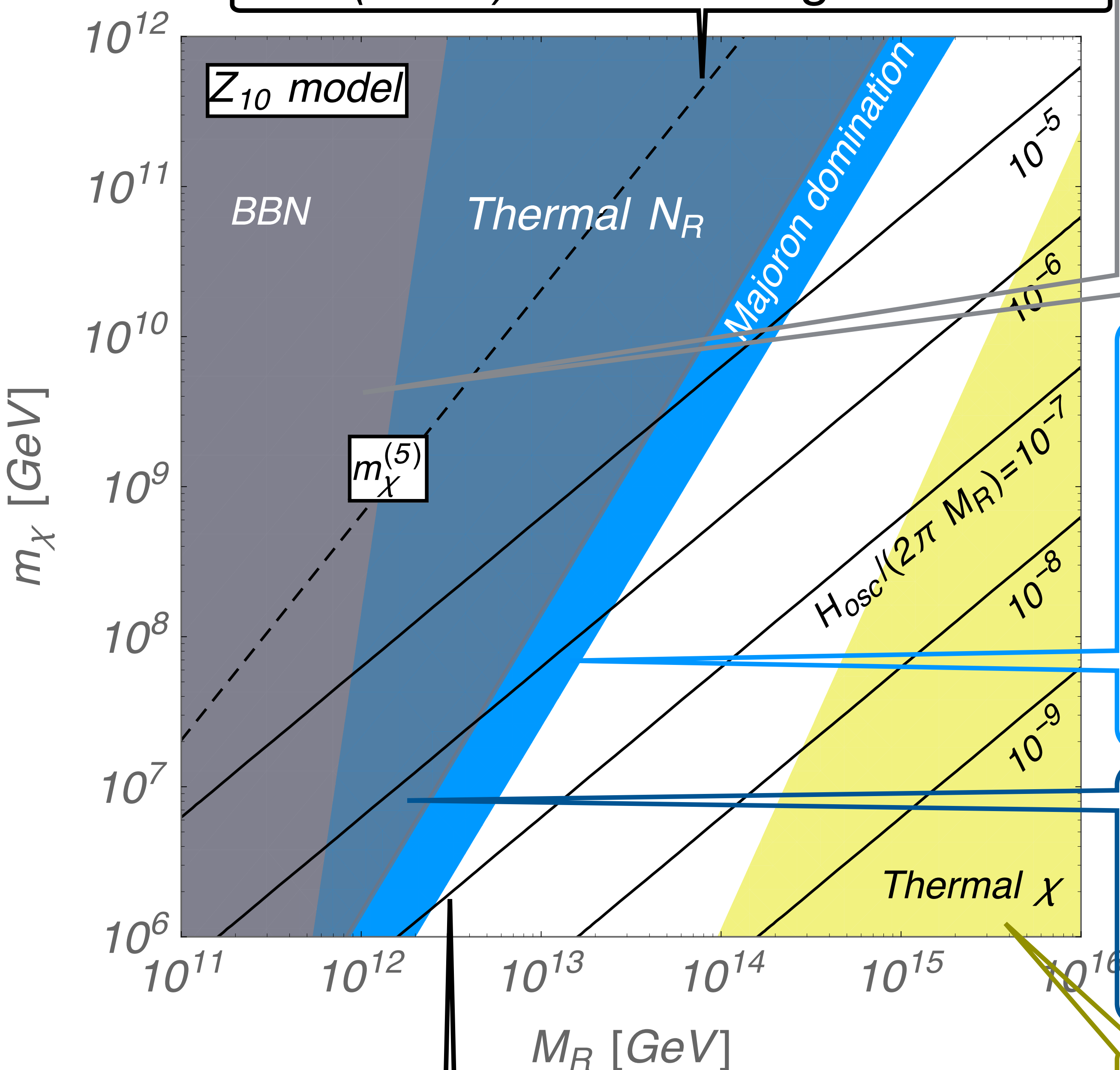
- Majoron is thermalized by χ-H-H interaction.
- Thermalization temperature:

$$T_{\rm th} \sim 1.1\times 10^6\,(M_R/10^{14}{\rm GeV})^{8/3}\ \ {\rm GeV}$$

- When $m_\chi < T_{th}$, Majoron is thermalized.

Z_{10} model

- Majoron mass: $m_\chi^{(5)} \sim [M_R^3/M_{\rm Pl}]^{1/2}$
- *O(1-0.1)%* fine-tuning is needed.



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- When $T_{decay} < O(1)$ *MeV*, the Majoron decay spoils BBN.

- Majoron domination temperature:

$$T_{\rm dom} \sim (M_R^2/M_{\rm Pl}^2)\,T_{\rm osc}(\sim (M_R^2/M_{\rm Pl}^2)\sqrt{M_{\rm Pl} m_\chi})$$

($\leftarrow \rho_\chi(T_{dom})/\rho_\gamma(T_{dom})=1$)

- When $T_{decay} < T_{dom}$, Majoron dominates the universe, and dilutes baryon asymmetry.

- When $M_R < T_{osc}$, N_R is in the thermal bath, and conventional leptogenesis would take place if possible.

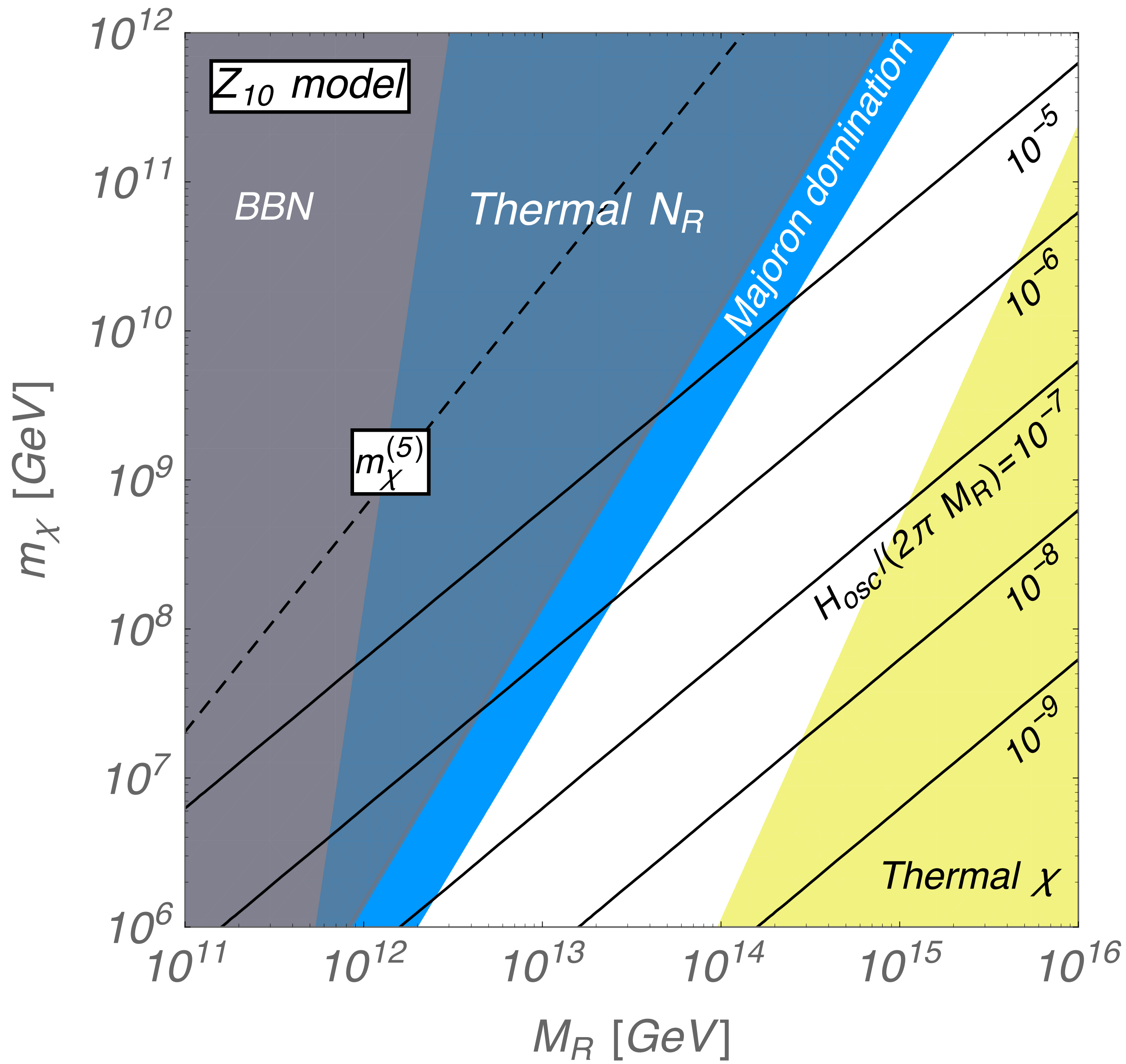
- Majoron is thermalized by *χ-H-H* interaction.
- Thermalization temperature:

$$T_{\rm th} \sim 1.1\times 10^6\,(M_R/10^{14}{\rm GeV})^{8/3} \ {\rm GeV}$$

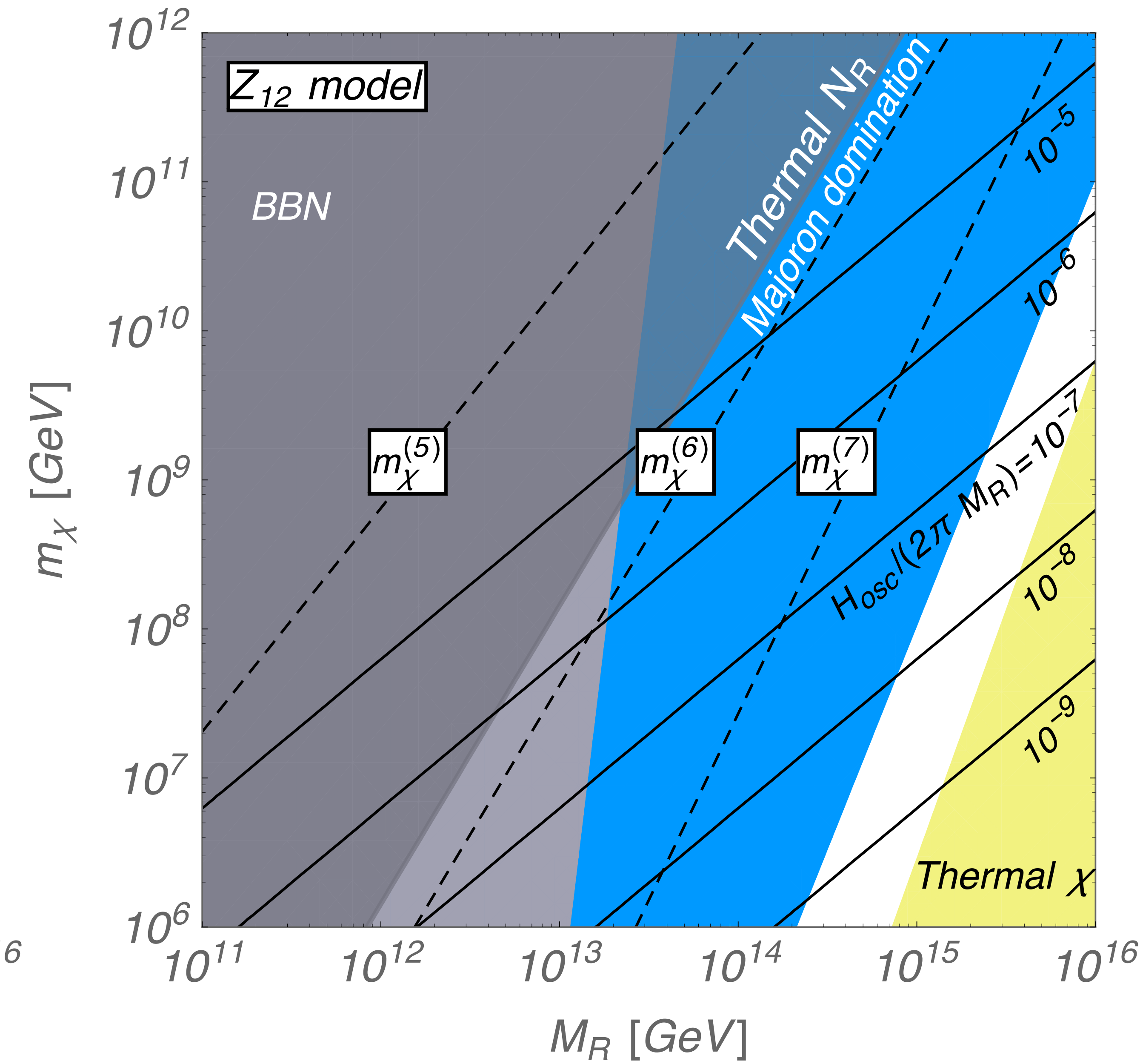
- When $m_\chi < T_{th}$, Majoron is thermalized.

- Isocurvature perturbation: $H_{inf}/(2\pi M_R) < 10^{-5}$
- Since $H_{osc} < H_{inf}$, at least $H_{osc}/(2\pi M_R) < 10^{-5}$ should be satisfied.

Z_{10} model



Z_{12} model



- Majoron becomes rather stable in Z_{12} model, and thus, viable regions become narrow
- *O(1-0.1)%* fine-tuning is also needed in Z_{12} model

Summary

- We have studied a novel leptogenesis scenario; ***spontaneous leptogenesis.***

- All of the necessary ingredients are automatically equipped in the Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{N}_R i\partial\!\!\!/ N_R - (y_\nu \bar{L} H N_R + h.c.) - \frac{g_N}{2}(\sigma \bar{N}_R^C N_R + h.c.) - V(H, \sigma)$$

- The neutrinoless double beta decay is a good probe of our scenario.

- We have shown that some viable models can be constructed.