Leptogenesis in the minimal gauged $U(1)_{L_\mu - L_\tau}$ model and the sign of the cosmological baryon asymmetry

K. Asai, K. Hamaguchi, N. Nagata, S.-Y. Tseng, arXiv:2005.01039

東京大学
THE UNIVERSITY OF TOKYO

Shih-Yen Tseng

High Energy Physics Theory Group

Department of Physics, The Univ. of Tokyo

Introduction

- Baryon asymmetry of the Universe $Y_B \equiv \frac{n_B}{s} \sim 8.7\times10^{-11}$

- Baryogenesis
  - heavy particle decays in GUT scenarios (Sakharov 1967)
  - electroweak baryogenesis (Kuzmin et al. 1985)
  - leptogenesis (Fukugita and Yanagida 1986)
  - supersymmetric condensate baryogenesis (Affleck and Dine 1985)
  - and many others…

- In this work, we discuss the generation of Y_B through leptogenesis
  - in the framework of minimal gauged $\mathrm{U(1)}_{\mathrm{L}_\mu-\mathrm{L}_\tau}$ model

Minimal gauged $\mathrm{U(1)}_{\mathrm{L}_\mu - \mathrm{L}_\tau}$ model model

K. Asai, K. Hamaguchi, N. Nagata, arXiv:1705.00419, Eur. Phys. J. C77 (2017) 763

- Extending the gauge sector of SM

$$\underbrace{\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}}_{\mathrm{G_{SM}}} \times \mathrm{U(1)}_{\mathrm{L}_\alpha - \mathrm{L}_\beta}$$

R. Foot, Mod.Phys.Lett. A6 (1991) 527-530
X.-G. He et al, Phys. Rev. D 43, R22

$\mathrm{U(1)}_{\mathrm{L}_e - \mathrm{L}_\mu}$ $\mathrm{U(1)}_{\mathrm{L}_e - \mathrm{L}_\tau}$ $\mathrm{U(1)}_{\mathrm{L}_\mu - \mathrm{L}_\tau}$

- Less constrained by the experiments

- Charge assignment

$L_\mu - L_\tau$	$L_{e,\mu,\tau}$	e_R, μ_R, τ_R	$N_{e,\mu,\tau}$	σ	H
$\mathrm{U(1)_Y}$	$-\frac{1}{2}$	-1	0	0	$+\frac{1}{2}$
$\mathrm{U(1)_{L_\mu - L_\tau}}$	0,+1,-1	0,+1,-1	0,+1,-1	+1	0
SU(2)	**2**	**1**	**1**	**1**	**2**

$$\mathcal{L}_N = -\lambda_e N_e^c (L_e \cdot H) - \lambda_\mu N_\mu^c (L_\mu \cdot H) - \lambda_\tau N_\tau^c (L_\tau \cdot H) \\ -\frac{1}{2} M_{ee} N_e^c N_e^c - M_{\mu\tau} N_\mu^c N_\tau^c - \frac{1}{2} \sum_{\alpha,\beta=e,\mu} h_{\alpha\beta} \sigma N_\alpha^c N_\beta^c - \frac{1}{2} \sum_{\alpha,\beta=e,\tau} h_{\alpha\beta} \sigma^* N_\alpha^c N_\beta^c + \mathrm{h.c.}$$

Nertrino physics : after the SSB of σ

- Neutrino mass matrices

$$M_D = \frac{v}{\sqrt{2}} \begin{pmatrix} \lambda_e & 0 & 0 \\ 0 & \lambda_\mu & 0 \\ 0 & 0 & \lambda_\tau \end{pmatrix} \qquad M_R = \begin{pmatrix} M_{ee} & \lambda_{e\mu}\langle\sigma\rangle & \lambda_{e\tau}\langle\sigma\rangle \\ \lambda_{e\mu}\langle\sigma\rangle & \boxed{0} & M_{\mu\tau} \\ \lambda_{e\tau}\langle\sigma\rangle & M_{\mu\tau} & \boxed{0} \end{pmatrix}$$

$$M_\nu^{-1} = -(M_D^{-1})^T M_R M_D^{-1} \simeq \begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix}$$

two-zero minor structure

Nertrino physics : analysis of M_ν

$$\underbrace{M_\nu^{-1} = -(M_D^{-1})^T M_R M_D^{-1}}_{\text{two-zero minor structure}} = U_\nu (M_\nu^{\mathrm{d}})^{-1} U_\nu^T$$

U_ν: PMNS matrix

M_ν^{d}: $\mathrm{diag}(m_1, m_2, m_3)$

PMNS matrix

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\frac{\alpha_2}{2}} & \\ & & e^{i\frac{\alpha_3}{2}} \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, θ_{ij}: mixing angles, δ: Dirac CP phase, α_2, α_3: Majorana phases

Solve the equations corresponding to the zero entries in M_ν^{-1}

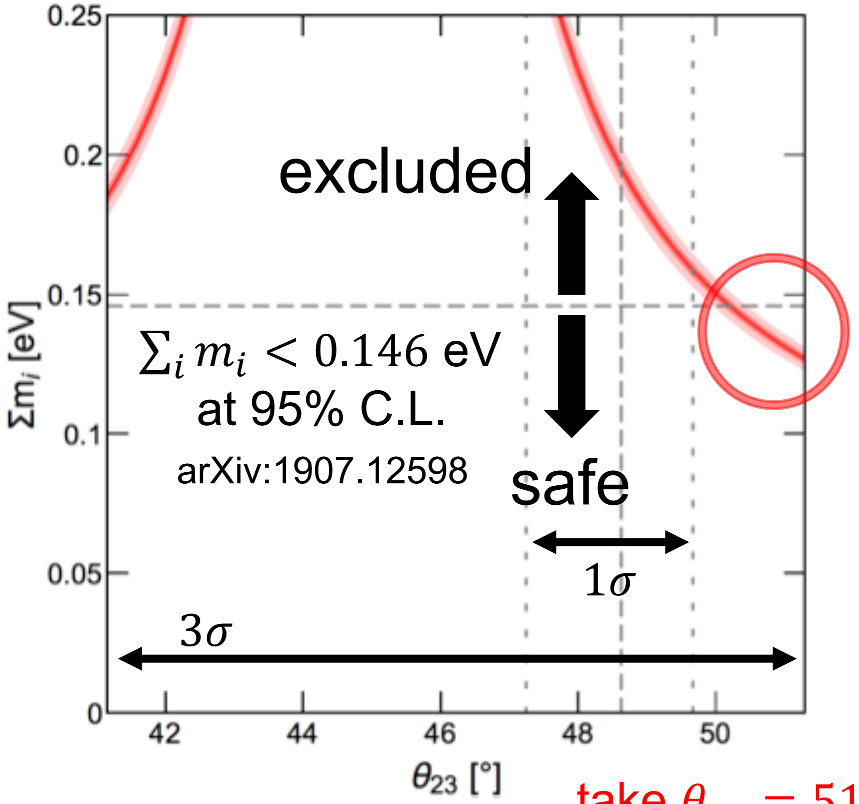
$\rightarrow$ $m_0 = m_0(\theta_{ij}, \Delta m_{ij}^2)$, $\delta = \delta(\theta_{ij}, \Delta m_{ij}^2)$, $\alpha_{2,3} = \alpha_{2,3}(\theta_{ij}, \Delta m_{ij}^2)$

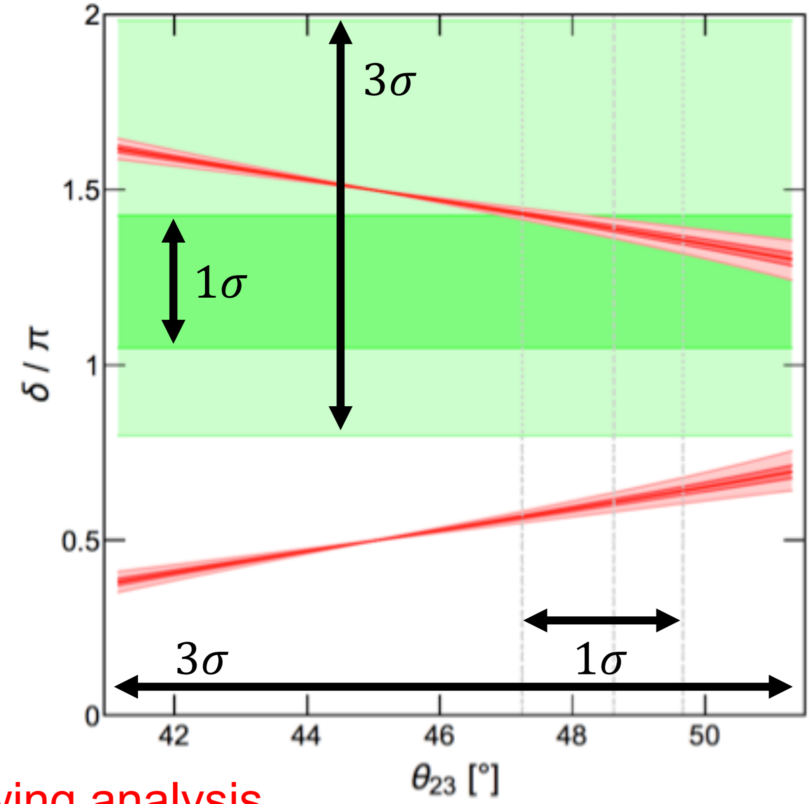
Nertrino physics : results

global-fitting group

$\theta_{ij}, \Delta m^2_{ij}$ from NuFIT 4.1 (2019)

Minimal gauged $\mathrm{U(1)}_{\mathrm{L}_\mu - \mathrm{L}_\tau}$ model, normal mass ordering





take $\theta_{23} = 51^\circ$ in the following analysis

Leptogenesis

M. Fukugita, T. Yanagida, Phys. Lett. B174, 45 (1986)

- $Y_B \equiv n_B/s \sim 8.7\times10^{-11}$
- Sakharov conditions A.D. Sakharov, JETP Lett. 5 (1967) 24-27
  - nonconserved baryon number
  - C and CP violations
  - departure from thermal equilibrium

we consider $T_R < M_1$

V. A. Kuzmin et al., Phys. Lett. 155B (1985) 36

sphaleron

$$Y_B \leftarrow \epsilon_i = \frac{\Gamma(\hat{N}_i \to LH) - \Gamma(\hat{N}_i \to \bar{L}H^*)}{\Gamma(\hat{N}_i \to LH) + \Gamma(\hat{N}_i \to \bar{L}H^*)} = \frac{1}{8\pi}\frac{1}{(\hat{\lambda}\hat{\lambda}^\dagger)_{ii}}\sum_{j\neq i}\mathrm{Im}\{(\hat{\lambda}\hat{\lambda}^\dagger)^2_{ij}\}f\left(\frac{M_j^2}{M_i^2}\right)$$

$$f(x) = \sqrt{x}\left[1-(1+x)\ln\left(\frac{1+x}{x}\right)+\frac{1}{1-x}\right]$$

- Nonthermal leptogenesis T. Asaka et al., Phys. Lett. B 464 (1999) 12
  - N_is are produced nonthermally in inflaton decays

inflaton → $\mathrm{U}(1)_{L_\mu - L_\tau}$ breaking field σ

Nonthermal leptogenesis

- Take σ as inflaton

$$\mathcal{L}_N = -\lambda_e N_e^c (L_e \cdot H) - \lambda_\mu N_\mu^c (L_\mu \cdot H) - \lambda_\tau N_\tau^c (L_\tau \cdot H) - \frac{1}{2} M_{ee} N_e^c N_e^c - M_{\mu\tau} N_\mu^c N_\tau^c - \frac{1}{2} \sum_{\alpha,\beta=e,\mu} h_{\alpha\beta} \sigma N_\alpha^c N_\beta^c - \frac{1}{2} \sum_{\alpha,\beta=e,\tau} h_{\alpha\beta} \sigma^* N_\alpha^c N_\beta^c + \text{h.c.}$$

$$\mathcal{L}_\sigma = \frac{|\partial_\mu \sigma|^2}{(1-|\sigma|^2/\Lambda^2)^2} - \kappa(|\sigma|^2 - \langle\sigma\rangle^2)^2 \longrightarrow \mathcal{L}_\sigma = \frac{1}{2}(\partial\tilde{\varphi})^2 - \kappa\Lambda^4 \left[\tanh^2\left(\frac{\tilde{\varphi}}{\sqrt{2}\Lambda}\right) - \left(\frac{\langle\sigma\rangle}{\Lambda}\right)^2\right]^2$$

$(1-|\sigma|^2/\Lambda^2)^2$ → ensure the flatness of inflaton potential at large σ

$$\varphi \equiv \sqrt{2}\text{Re}(\sigma)$$

$$\frac{\varphi}{\sqrt{2}\Lambda} \equiv \tanh\left(\frac{\tilde{\varphi}}{\sqrt{2}\Lambda}\right)$$

- Inflaton mass

$$m_\varphi \simeq 2\sqrt{\kappa}\langle\sigma\rangle \simeq 3\times 10^{10}\ \text{GeV} \times \left(\frac{\langle\sigma\rangle}{10^{13}\ \text{GeV}}\right)\left(\frac{\Lambda}{10^{16}\ \text{GeV}}\right)^{-1}\left(\frac{N_e}{50}\right)^{-1}$$

CMB normalization

Baryon asymmetry

Nonthermal leptogenesis

$$\frac{3}{4}\cdot\frac{T_R}{m_\varphi}$$

$$\frac{-28}{79}$$

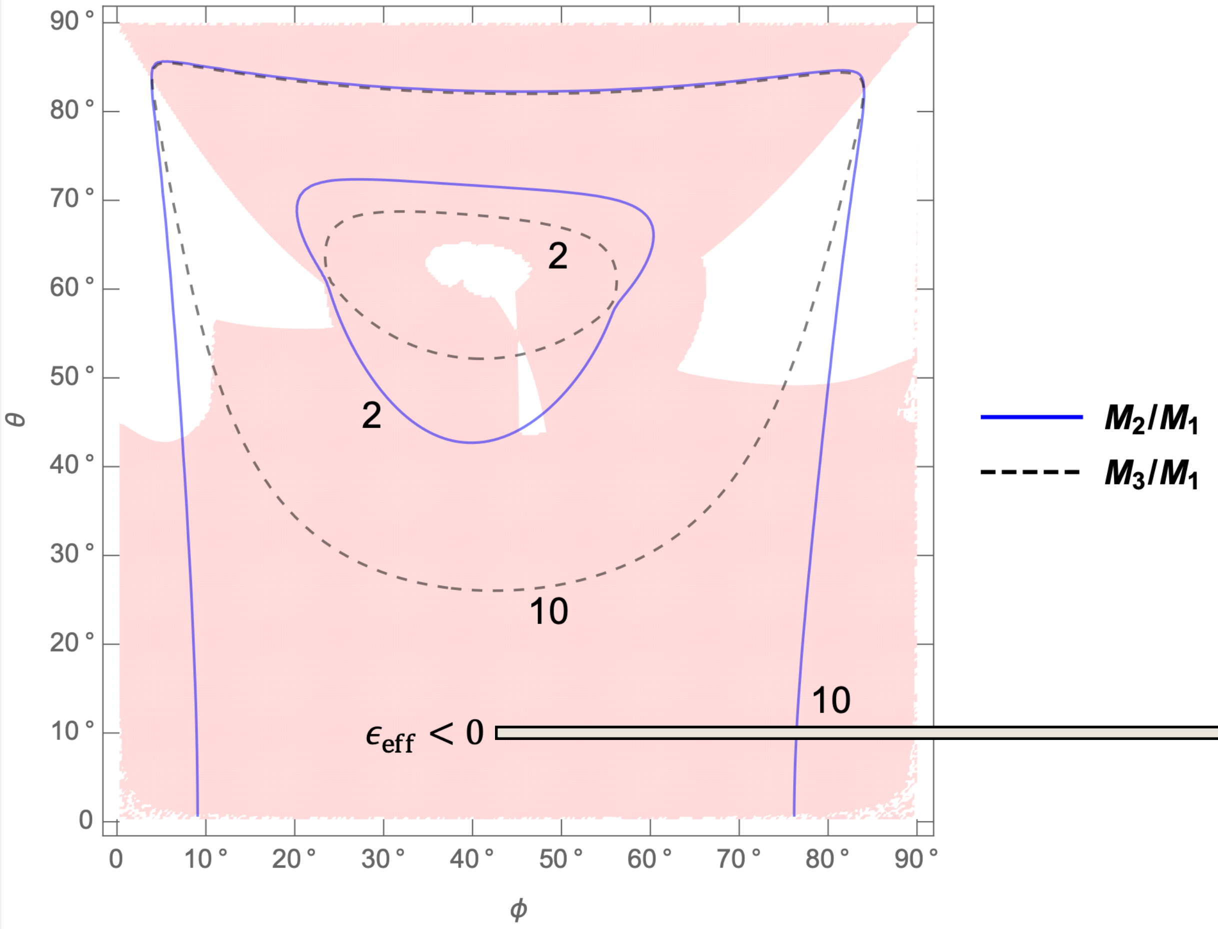
$$Y_B = \frac{n_B}{s} = \frac{n_\varphi}{s} \times \frac{n_N}{n_\varphi} \times \frac{n_L}{n_N} \times \frac{n_B}{n_L}$$

$$2\sum_i \epsilon_i Br(\varphi \to N_i N_i) + \sum_{m<n} (\epsilon_m + \epsilon_n)\, Br(\varphi \to N_m N_n) \equiv 2\times\epsilon_{\mathrm{eff}}$$

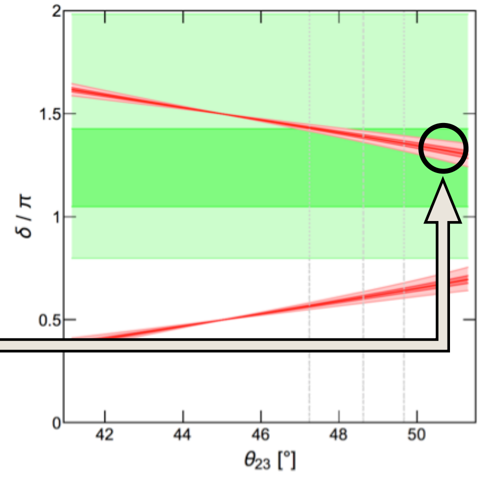
$\epsilon_{\text{eff}} < 0$

$$\epsilon_{\text{eff}} = \sum_i \epsilon_i Br(\phi \to N_i N_i) + (1/2) \sum_{m<n} (\epsilon_m + \epsilon_n)\, Br(\phi \to N_m N_n)$$

- $\lambda = 0.01$
- $\langle \sigma \rangle = 10^{13}$ GeV
- $\Lambda = 10^{16}$ GeV
- NuFIT inputs

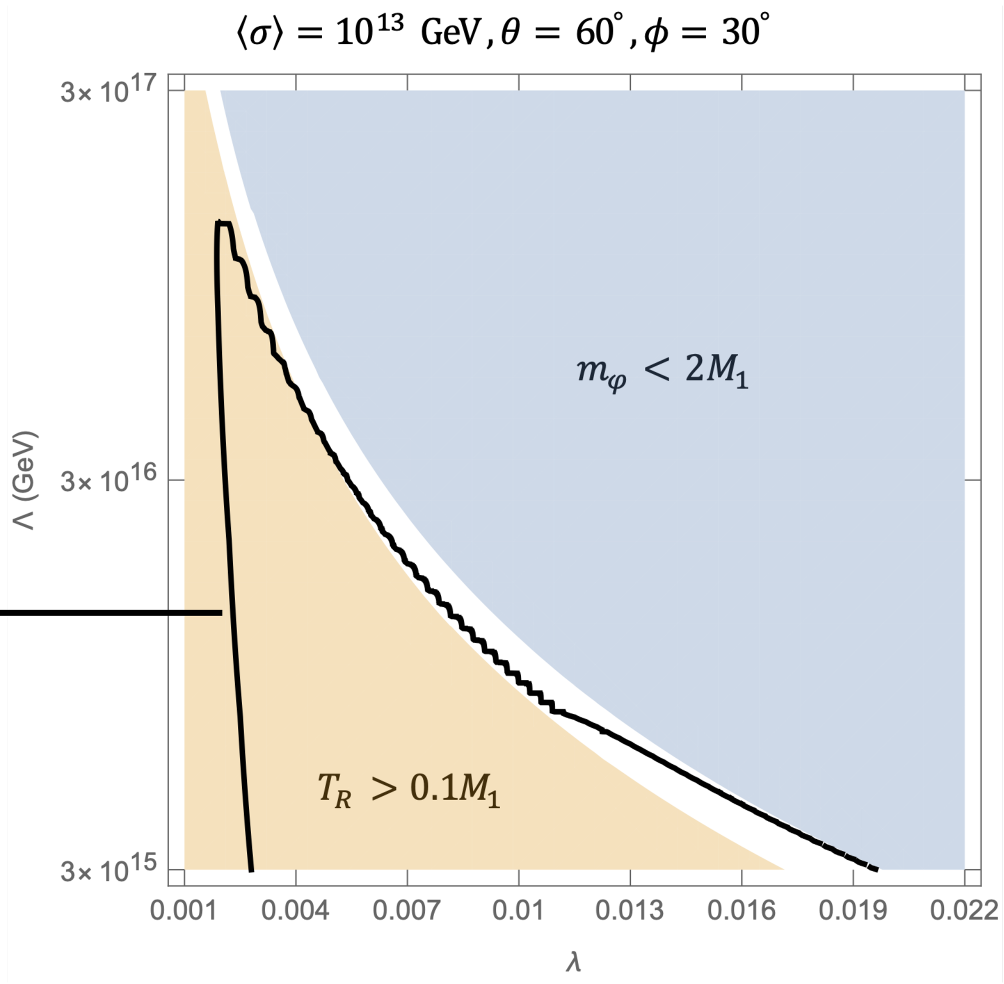


depend on δ



Baryon asymmetry : result

$Y_B \simeq 8.7\times10^{-11}$



cosmic string

$\langle\sigma\rangle \lesssim 2\times10^{13}$ GeV

It works!

Summary

- We have investigated the baryon asymmetry in the Universe
  - nonthermal leptogenesis with minimal gauged $\mathrm{U}(1)_{L_\mu - L_\tau}$ model

- It is shown that Y_B can be reproduced in this framework

- Future prospect
  - thermal leptogenesis, etc

Backup

Introduction

- Light neutrino mass → adding RH neutrinos

$$M_\nu = -M_D M_R^{-1} M_D^T$$

Seesaw mechanism
P. Minkowski, Phys. Lett. B67 (1977) 421–428
T. Yanagida, Conf. Proc. C7902131 (1979) 95–99

! mass terms tightly restricted by the $\mathrm{U}(1)_{\mathrm{L}_\alpha - \mathrm{L}_\beta}$ symmetry

$$\begin{pmatrix} * & 0 & 0 \\ 0 & 0 & * \\ 0 & * & 0 \end{pmatrix} \simeq \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & 0 & * \end{pmatrix} \begin{pmatrix} * & 0 & 0 \\ 0 & 0 & * \\ 0 & * & 0 \end{pmatrix} \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & 0 & * \end{pmatrix}$$

block-diagonal

this simple structure fails to explain the sizable neutrino mixing…

Introduction

- Spontaneous breaking of $U(1)_{L_\alpha - L_\beta}$ symmetry

  introduce only one additional scalar field

$$M_\nu^{-1} \simeq \begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix}$$

or

$$M_\nu \simeq \begin{pmatrix} * & 0 & * \\ 0 & 0 & * \\ * & * & * \end{pmatrix}$$

Two-zero structure leads into strong predictive power!

What are the contents?

- The SM

	$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	e_R	$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	u_R	d_R	H
$\mathrm{SU(3)_C}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$
$\mathrm{SU(2)_L}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$
$\mathrm{U(1)_Y}$	$-\frac{1}{2}$	-1	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$

- Three RH neutrinos

- One extra scalar field

Input parameters

global-fitting group

NuFIT 4.1 (2019)

		Normal Ordering (best fit)	
		bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.563^{+0.018}_{-0.024}$	$0.433 \to 0.609$
	$\theta_{23}/^\circ$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$
	$\sin^2\theta_{13}$	$0.02237^{+0.00066}_{-0.00065}$	$0.02044 \to 0.02435$
	$\theta_{13}/^\circ$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$
	$\delta_{\rm CP}/^\circ$	221^{+39}_{-28}	$144 \to 357$
	$\dfrac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.528^{+0.029}_{-0.031}$	$+2.436 \to +2.618$

Inflaton physics

$$\langle\zeta(\vec{k})\,\zeta(\vec{k}')\rangle = (2\pi)^3\delta(\vec{k}+\vec{k}')\frac{2\pi^2}{k^3}\mathcal{P}_\zeta(k)$$

$$\zeta = -\frac{H_{\rm inf}}{\dot{\phi}}\delta\phi$$

$$\mathcal{P}_\zeta(k) = \frac{H_{\rm inf}^4}{4\pi^2(\dot{\phi})^2} = \frac{V^3}{12\pi^2(V')^2M_G^6}$$

$$P_\zeta = \frac{V^3}{12\pi^2 M_P^6 V'^2}$$
$$= \frac{\kappa\Lambda^6}{96\pi^2M_P^6}\left\{1-\left[\frac{\kappa}{\Lambda}\coth\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right)\right]^2\right\}^4\sinh^4\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right)\tanh^2\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right)$$
$$\simeq \frac{\kappa}{6\pi^2}\left[\frac{N_e\big(\Lambda^2-\langle\sigma\rangle^2\big)}{M_P\Lambda}\right]^2.$$

$$m_\sigma^2 = \left.\frac{d^2V}{d\widetilde{\varphi}^2}\right|_{\widetilde{\varphi}=\widetilde{\varphi}_{\rm min}} = 4\kappa\langle\sigma\rangle^2\left(1-\frac{\langle\sigma\rangle^2}{\Lambda^2}\right)^2$$

$$P_\zeta \simeq 2.1\times10^{-9}$$

$$\kappa \simeq 3\times10^{-6}\times\left(\frac{N_e}{50}\right)^{-2}\left(\frac{\Lambda}{10^{16}\ \text{GeV}}\right)^{-2}$$

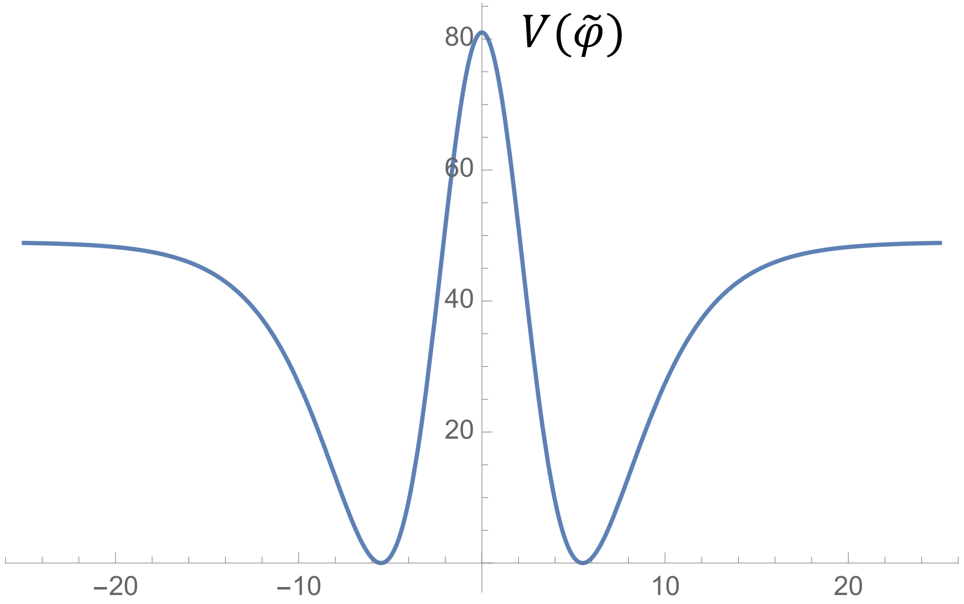
$$H_{\rm inf} \simeq \frac{\Lambda^2}{M_P}\sqrt{\frac{\kappa}{3}} \simeq 4\times10^{10}\ \text{GeV}\times\left(\frac{\Lambda}{10^{16}\ \text{GeV}}\right)\left(\frac{N_e}{50}\right)^{-1}$$

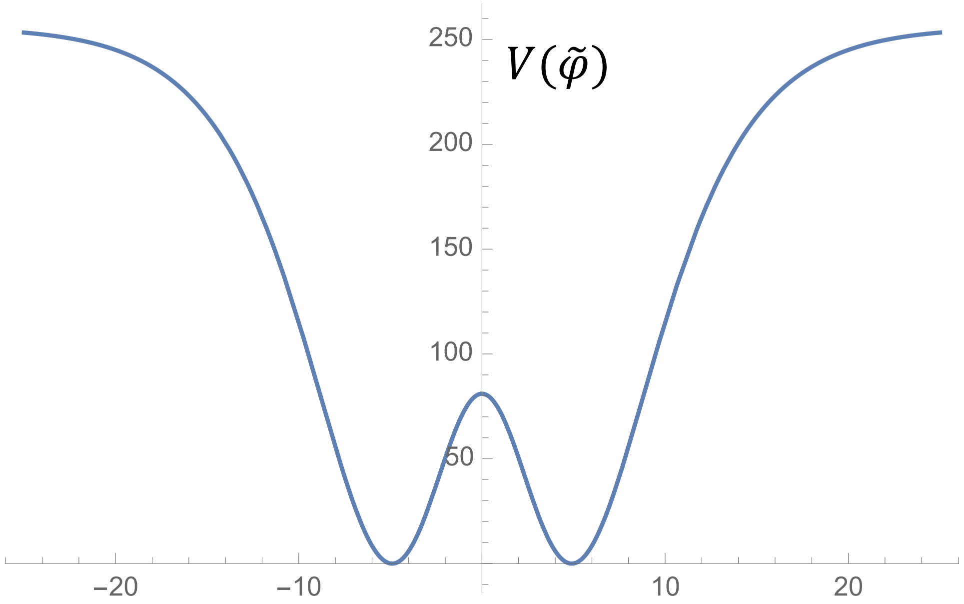
Non-thermal leptogenesis

- Taking σ as inflaton

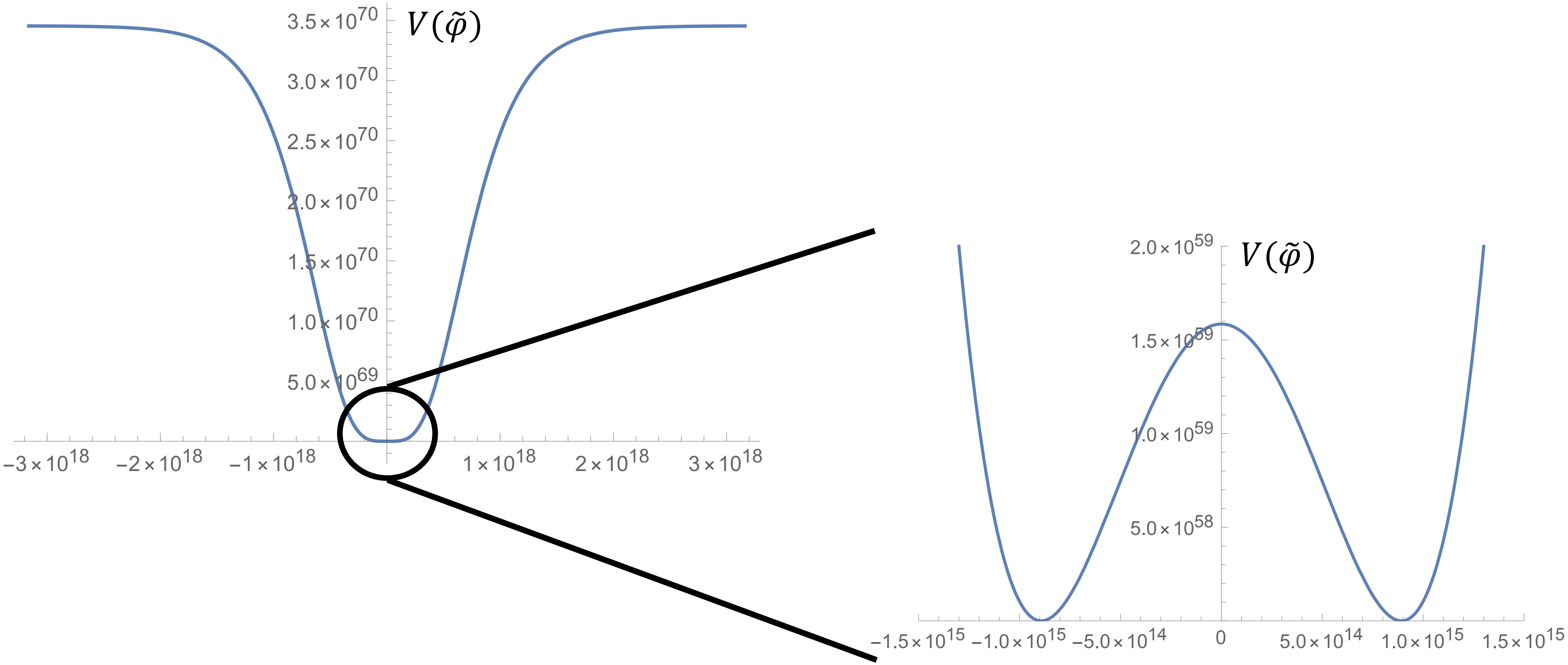
$$\mathcal{L}_\sigma = \frac{1}{2}(\partial\widetilde{\varphi})^2 - \kappa\Lambda^4\left[\tanh^2\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right) - \left(\frac{\langle\sigma\rangle}{\Lambda}\right)^2\right]^2$$

$$\frac{\varphi}{\sqrt{2}\Lambda} \equiv \tanh\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right)$$





Inflaton potential



Cosmic string

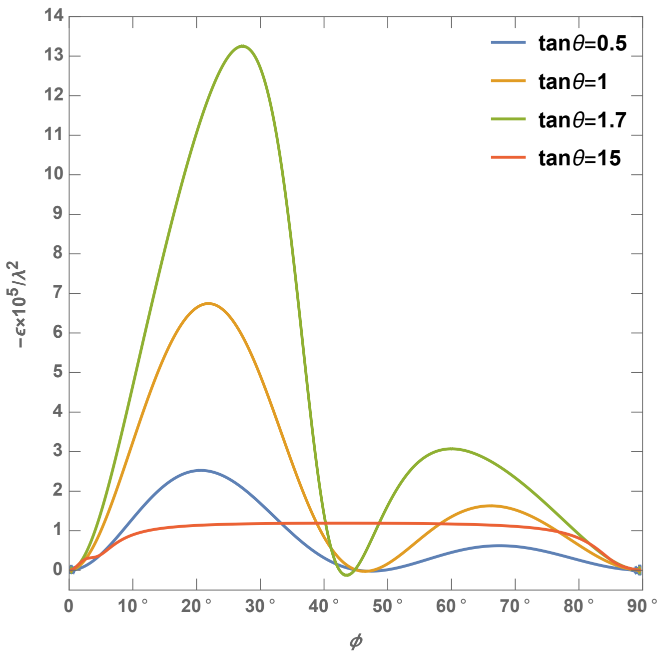
$$\mathcal{L} = D_\mu \Phi D^\mu \Phi^\dagger - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \lambda(\Phi^\dagger \Phi - \sigma^2/2)^2$$

$$\begin{aligned} \mu &\equiv \frac{dH}{dz} = \int r\,dr\,d\theta\, \mathcal{H} = -\int r\,dr\,d\theta\, \mathcal{L} \\ &= \int_0^\infty \int_0^{2\pi} r\,dr\,d\theta \left[\left| \frac{\partial \Phi}{\partial r} \right|^2 + \left| \frac{1}{r} \frac{\partial \Phi}{\partial \theta} - ieA_\theta \Phi \right|^2 + V(\Phi) + \frac{B^2}{2} \right] \end{aligned}$$

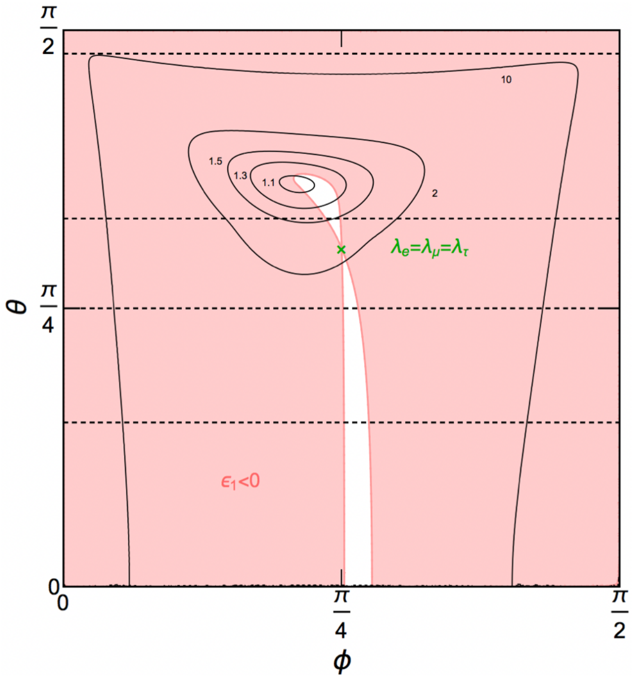
→ $\mu \simeq \pi \sigma^2$

Leptogenesis

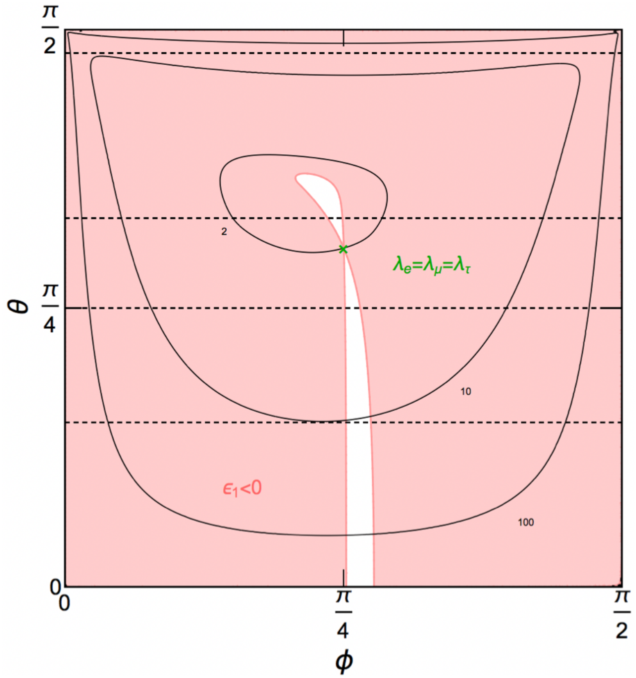
$$(\lambda_e, \lambda_\mu, \lambda_\tau) \equiv \lambda(\cos\theta, \sin\theta\cos\phi, \sin\theta\sin\phi)$$



M_2/M_1



M_3/M_1

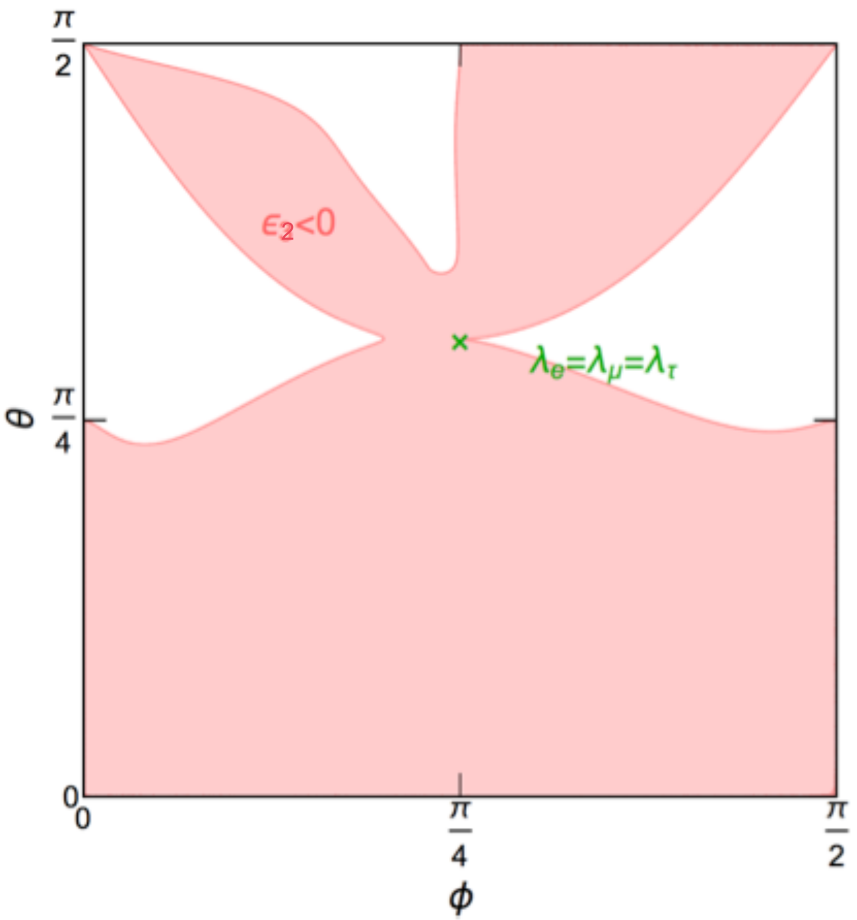


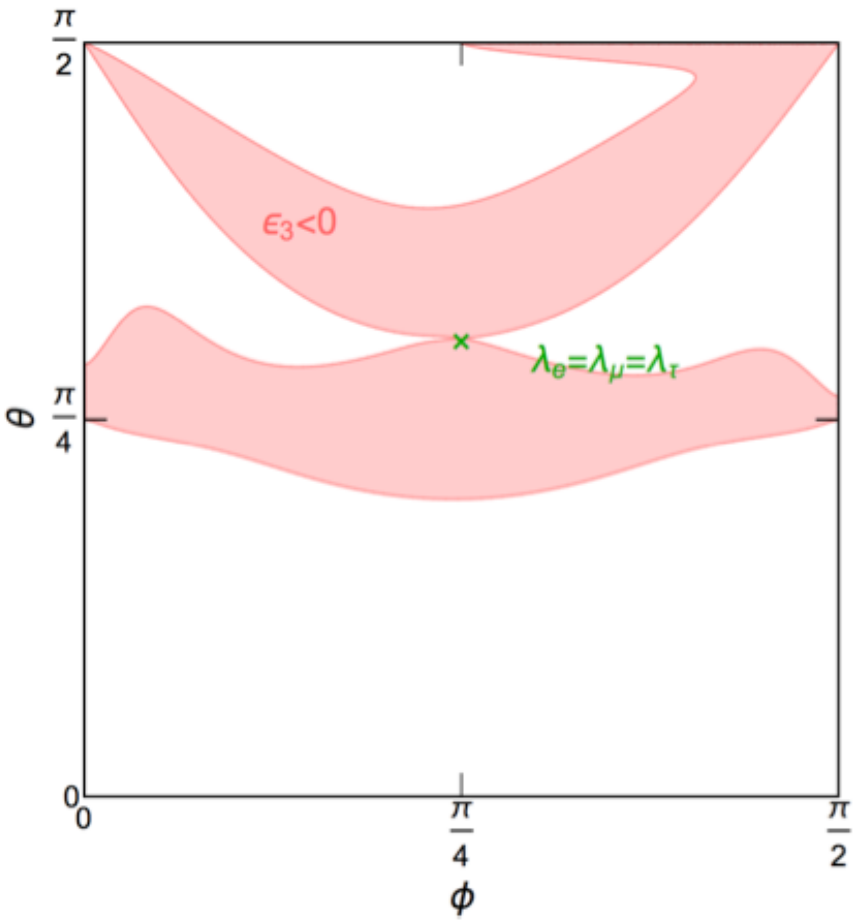
$$Y_{\Delta B} \equiv \frac{n_B}{s} \simeq 8.7 \times 10^{-11} > 0$$

$$\frac{n_B}{n_L} = -\frac{28}{79}$$

$$\Rightarrow \quad \epsilon_1 < 0$$

Leptogenesis



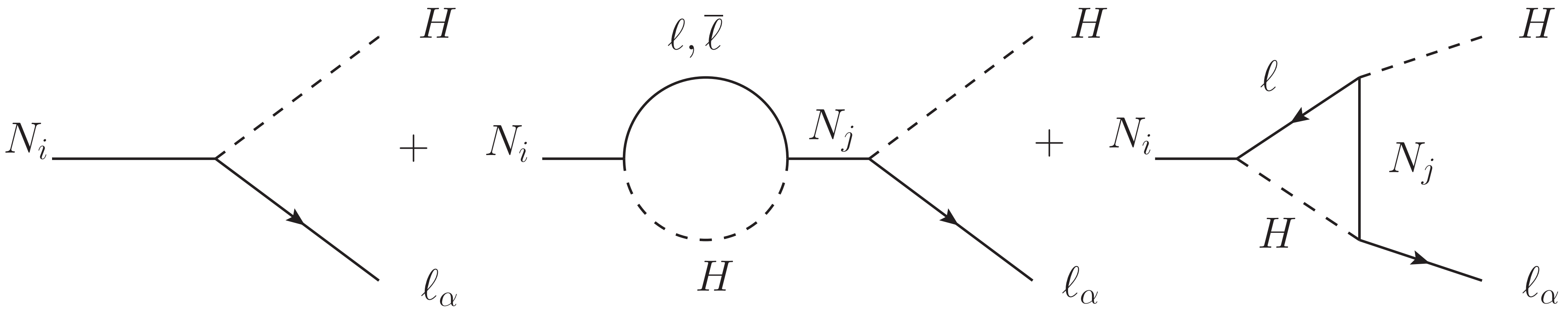


Leptogenesis

M. Fukugita, T. Yanagida, Phys. Lett. B174, 45 (1986)

- $Y_B \equiv n_B/s \sim 8.7\times10^{-11}$
- Decays of RH neutrinos generate lepton asymmetry

$$\epsilon = \frac{\Gamma(N \to lH) - \Gamma(N \to \bar{l}H^\dagger)}{\Gamma(N \to lH) + \Gamma(N \to \bar{l}H^\dagger)}$$



Leptogenesis

- Baryon asymmetry in the universe
- Decays of RH neutrinos generate lepton asymmetry

$$\frac{1}{(8\pi)}\frac{1}{[\lambda^\dagger\lambda]_{11}}\sum_j \mathrm{Im}\left\{[(\lambda^\dagger\lambda)_{1j}]^2\right\} g\left(x_j\right)$$

λ: Yukawa coupling

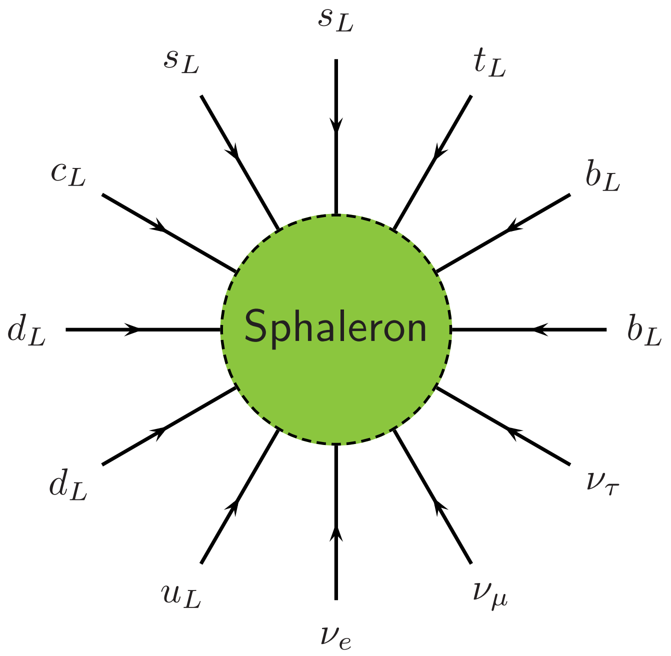
$$g(x) = \sqrt{x}\left[\frac{1}{1-x} + 1 - (1+x)\ln\left(\frac{1+x}{x}\right)\right] \qquad x_j = \frac{M_j^2}{M_1^2}$$

Leptogenesis

- Baryon asymmetry in the universe $Y_{\Delta B} \equiv \frac{n_B}{s} \simeq 8.7 \times 10^{-11}$
- Decays of RH neutrinos generate lepton asymmetry
- Sphaleron processes

V. A. Kuzmin et al., Phys. Lett. 155B (1985) 36

$$B = \frac{28}{79} \times (B - L)$$



Right-handed neutrino sector

- RH neutrino mass matrix $M_R = -M_D^T M_\nu^{-1} M_D$
- Parameters $(\lambda_e, \lambda_\mu, \lambda_\tau) \equiv \lambda(\cos\theta, \sin\theta\cos\phi, \sin\theta\sin\phi)$

$$\Delta\mathcal{L} = -\sum_{\alpha=e,\mu,\tau}\sum_{i=1}^{3}\hat{\lambda}_{\alpha i}\big(L_\alpha \cdot H\big)\hat{N}_i^c - \frac{1}{2}\sum_{i=1}^{3} M_{Ri}^{\rm diag}\hat{N}_i^c\hat{N}_i^c + \text{h.c.}$$

$$M_R = \Omega^* M_R^{\rm diag}\Omega^\dagger\ ,\ \hat{N}_i^c = \sum_\alpha \Omega_{i\alpha}^\dagger N_\alpha^c\ ,\ \hat{\lambda}_{\alpha i} = \sum_\beta \lambda_{\alpha\beta}\Omega_{\beta i}$$

Non-thermal leptogenesis

- As a concrete example, we first consider this simple scenario
- Pairs of RH neutrinos generated from inflaton decays
- N_R out-of-equilibrium decay : $T_R \simeq \left(\frac{90}{\pi^2 g_*}\right)^{\frac{1}{4}} \sqrt{\Gamma_\varphi M_P} < M_1$
- Taking σ as inflaton

$$\begin{aligned}\Delta\mathcal{L} = & - y_e e_R^c L_e H^\dagger - y_\mu \mu_R^c L_\mu H^\dagger - y_\tau \tau_R^c L_\tau H^\dagger \\ & - \lambda_e N_e^c (L_e \cdot H) - \lambda_\mu N_\mu^c (L_\mu \cdot H) - \lambda_\tau N_\tau^c (L_\tau \cdot H) \\ & - \frac{1}{2} M_{ee} N_e^c N_e^c - M_{\mu\tau} N_\mu^c N_\tau^c - \lambda_{e\mu} \sigma N_e^c N_\mu^c - \lambda_{e\tau} \sigma^* N_e^c N_\tau^c + \text{h.c.}\end{aligned}$$

Non-thermal leptogenesis

- Pairs of RH neutrinos generated from inflaton decays

- N_R out-of-equilibrium decay : $T_R \simeq \left(\frac{90}{\pi^2 g_*}\right)^{\frac{1}{4}} \sqrt{\Gamma_\varphi M_P} < M_1$

- Taking σ as inflaton

$$\mathcal{L}_\sigma = \frac{|\partial_\mu \sigma|^2}{(1 - |\sigma|^2/\Lambda^2)^2} - \kappa(|\sigma|^2 - \langle\sigma\rangle^2)^2$$

Non-thermal leptogenesis

- Pairs of RH neutrinos generated from inflaton decays

- N_R out-of-equilibrium decay : $T_R \simeq \left(\frac{90}{\pi^2 g_*}\right)^{\frac{1}{4}} \sqrt{\Gamma_\varphi M_P} < M_1$

- Taking σ as inflaton

$$\varphi \equiv \sqrt{2}\mathrm{Re}(\sigma)$$

$$\mathcal{L}_\sigma = \frac{1}{2}(\partial\widetilde{\varphi})^2 - \kappa\Lambda^4 \left[\tanh^2\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right) - \left(\frac{\langle\sigma\rangle}{\Lambda}\right)^2\right]^2 \qquad \frac{\varphi}{\sqrt{2}\Lambda} \equiv \tanh\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right)$$

Non-thermal leptogenesis

- Pairs of RH neutrinos generated from inflaton decays

- N_R out-of-equilibrium decay : $T_R \simeq \left(\frac{90}{\pi^2 g_*}\right)^{\frac{1}{4}} \sqrt{\Gamma_\varphi M_P} < M_1$

- Taking σ as inflaton

$$m_\varphi \simeq 2\sqrt{\kappa}\,\langle\sigma\rangle \simeq 3\times 10^{10}\ \mathrm{GeV}\times\left(\frac{\langle\sigma\rangle}{10^{13}\ \mathrm{GeV}}\right)\left(\frac{\Lambda}{10^{16}\ \mathrm{GeV}}\right)^{-1}\left(\frac{N_e}{50}\right)^{-1}$$

from CMB normalization

Non-thermal leptogenesis

- Inflaton decay

$$\Gamma_\varphi = \sum_{i,j} \frac{m_\varphi}{32\pi} \left[1 - \frac{2(M_i^2 + M_j^2)}{m_\varphi^2} + \frac{(M_i^2 - M_j^2)^2}{m_\varphi^4}\right]^{\frac{1}{2}}$$
$$\times \left[\mathrm{Re}\left(\hat{h}_{ij}\right)^2 \left\{1 - \frac{(M_i + M_j)^2}{m_\varphi^2}\right\} + \mathrm{Im}\left(\hat{h}_{ij}\right)^2 \left\{1 - \frac{(M_i - M_j)^2}{m_\varphi^2}\right\}\right]$$