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

K. Asai, K. Hamaguchi, N. Nagata, S.-Y. Tseng, K. Tsumura, arXiv:1811.07571, PhysRevD.99.055029

K. Asai, K. Hamaguchi, N. Nagata, S.-Y. Tseng, in preparation

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Contents

Introduction

Introduction

- Extending the gauge sector of SM

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

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

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X.-G. He et al, Phys. Rev. D 43, R22

$$U(1)_{L_e - L_\mu} \qquad U(1)_{L_e - L_\tau} \qquad U(1)_{L_\mu - L_\tau}$$

- Transforming the lepton sector nontrivially
  compatible with the existing experimental data?

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

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

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

block-diagonal

this simple structure fails to explain the sizable neutrino mixing…

Introduction

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

  introduce only one additional scalar field

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

or

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

Two-zero structure leads into strong predictive power!

Minimal models

K. Asai, K. Hamaguchi, N. Nagata, S.-Y. Tseng, K. Tsumura, arXiv:1811.07571, PhysRevD.99.055029

A brief summary

The Standard Model $\otimes$ $\begin{cases} U(1)_{L_e-L_\mu} \\ U(1)_{L_e-L_\tau} \\ U(1)_{L_\mu-L_\tau} \end{cases}$

$\otimes$ 3 RH neutrinos

$$\otimes \begin{pmatrix} \text{an extra scalar singlet} \\ \text{an extra scalar doublet} \end{pmatrix}$$

$$\otimes \begin{pmatrix} \text{normal mass ordering} \\ \text{inverted mass ordering} \end{pmatrix}$$

A brief summary

Phys.Rev. D99 (2019) no.5, 055029

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$\otimes$ 3 RH neutrinos

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$\otimes \begin{pmatrix} \text{normal mass ordering} \\ \cancel{\text{inverted mass ordering}} \end{pmatrix}$

excluded by neutrino oscillation data, cosmological bound on $\sum_i m_i$, etc

- 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	$+\frac{1}{2}$
$\mathrm{U(1)}_{\mathrm{L}_\mu - \mathrm{L}_\tau}$	0,+1,-1	0,+1,-1	0,+1,-1	+1	0
SU(2)	**2**	**1**	**1**	**1**	**2**

- 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**

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

Neutrino physics

After the SSB of σ

- Lepton mass matrices

After the SSB of σ

- Lepton mass matrices

neutrino sector

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

After the SSB of σ

- Lepton mass matrices

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charged lepton sector

$$M_\ell = \frac{v}{\sqrt{2}} \begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix}$$

Analysis of M_ν

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

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

two-zero minor

$$U_{\mathrm{PMNS}} = U_L^\dagger U_\nu$$

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

$$M_\nu = U_\nu^* M_\nu^{\mathrm{d}} U_\nu^\dagger$$

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$$\left[U_L U_{\mathrm{PMNS}} (M_\nu^{\mathrm{d}})^{-1} U_{\mathrm{PMNS}}^T U_L^T\right]_{\mu\mu} = 0$$
$$\left[U_L U_{\mathrm{PMNS}} (M_\nu^{\mathrm{d}})^{-1} U_{\mathrm{PMNS}}^T U_L^T\right]_{\tau\tau} = 0$$

match

$$U_{\mathrm{PMNS}} = U_L^\dagger U_\nu$$

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

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

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solve

m_1 m_2 m_3 $\sum_i m_i$

$$f(\theta_{12}, \theta_{23}, \theta_{13}, \Delta m_{21}^2, \Delta m_{31}^2)$$

δ α_2 α_3 $\langle m_{\beta\beta}\rangle$

match

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

two-zero minor

$$U_{\mathrm{PMNS}} = U_L^\dagger U_\nu$$

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

$$M_\nu = U_\nu^* M_\nu^{\mathrm{d}} U_\nu^\dagger$$

Input parameters

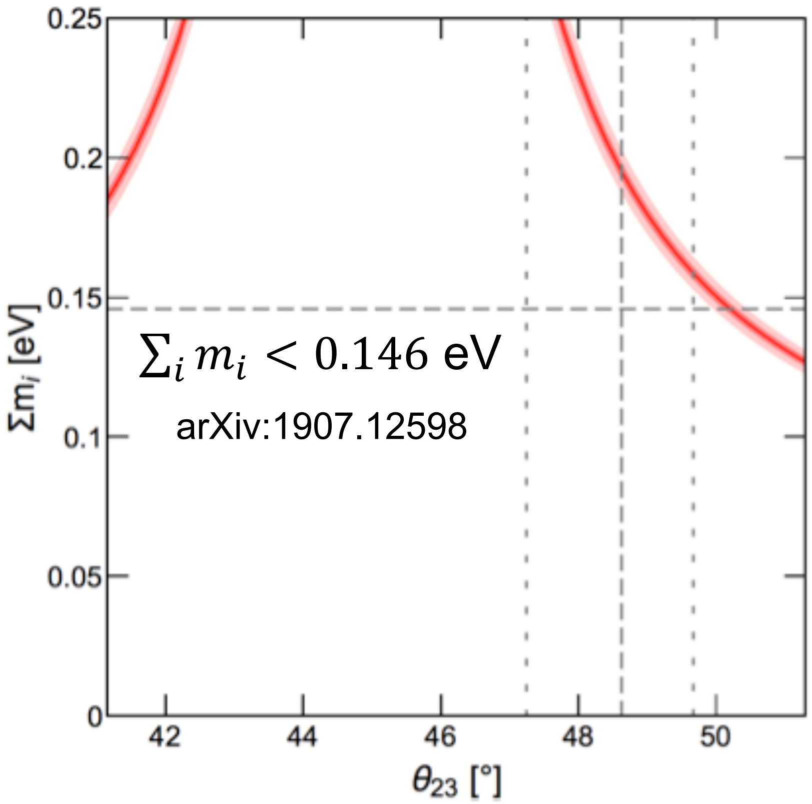
global-fitting group

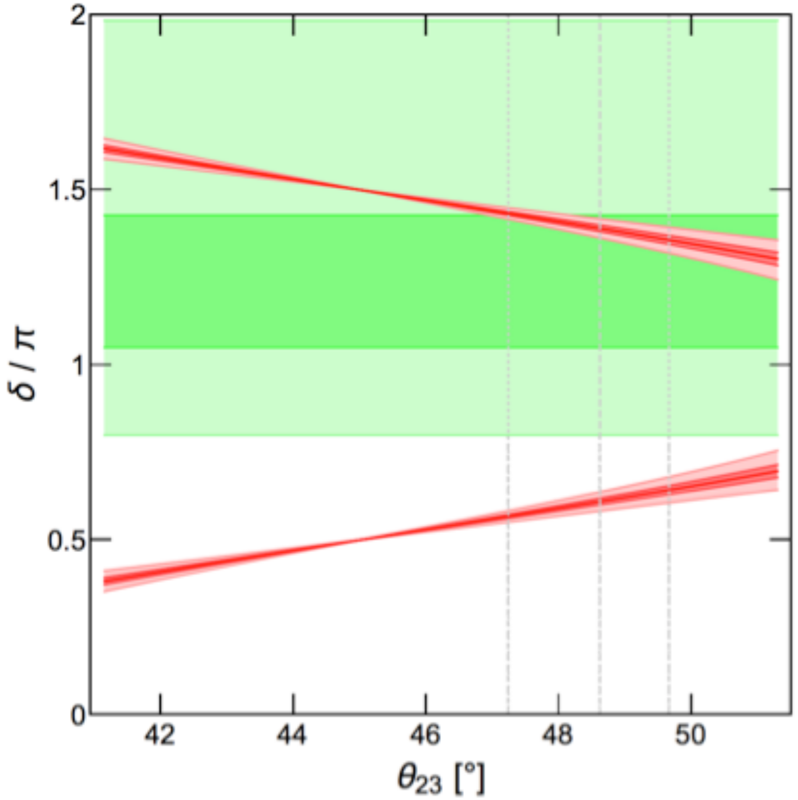
NuFIT 4.1 (2019)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 10.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.563^{+0.018}_{-0.024}$	$0.433 \to 0.609$	$0.565^{+0.017}_{-0.022}$	$0.436 \to 0.610$
	$\theta_{23}/^\circ$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$	$48.8^{+1.0}_{-1.2}$	$41.4 \to 51.3$
	$\sin^2\theta_{13}$	$0.02237^{+0.00066}_{-0.00065}$	$0.02044 \to 0.02435$	$0.02259^{+0.00065}_{-0.00065}$	$0.02064 \to 0.02457$
	$\theta_{13}/^\circ$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$	$8.64^{+0.12}_{-0.13}$	$8.26 \to 9.02$
	$\delta_{\rm CP}/^\circ$	221^{+39}_{-28}	$144 \to 357$	282^{+23}_{-25}	$205 \to 348$
	$\dfrac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.528^{+0.029}_{-0.031}$	$+2.436 \to +2.618$	$-2.510^{+0.030}_{-0.031}$	$-2.601 \to -2.419$

Results

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





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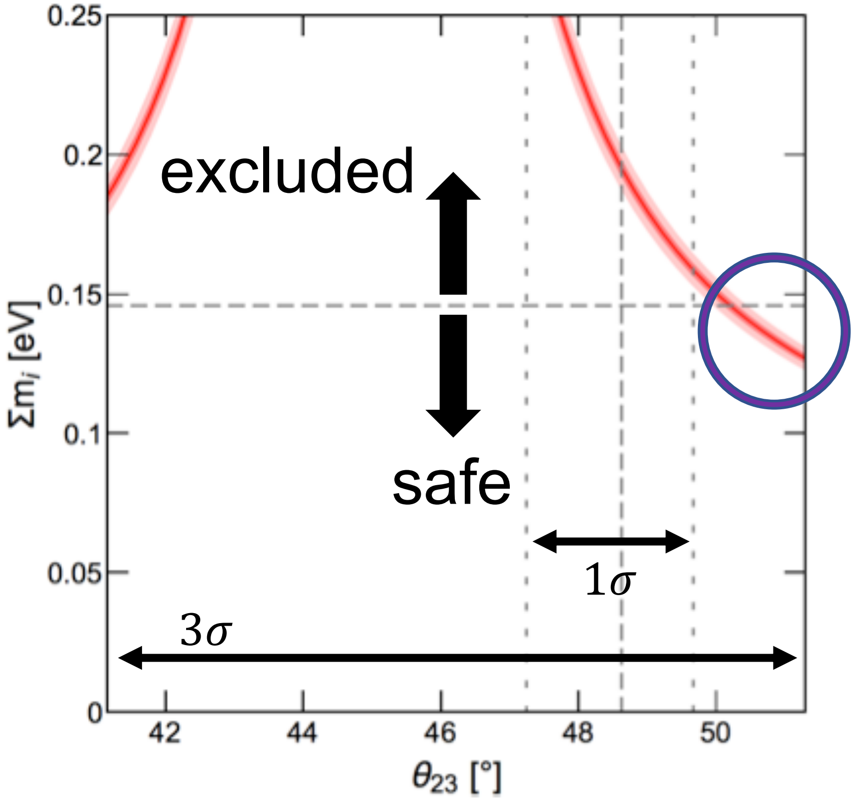
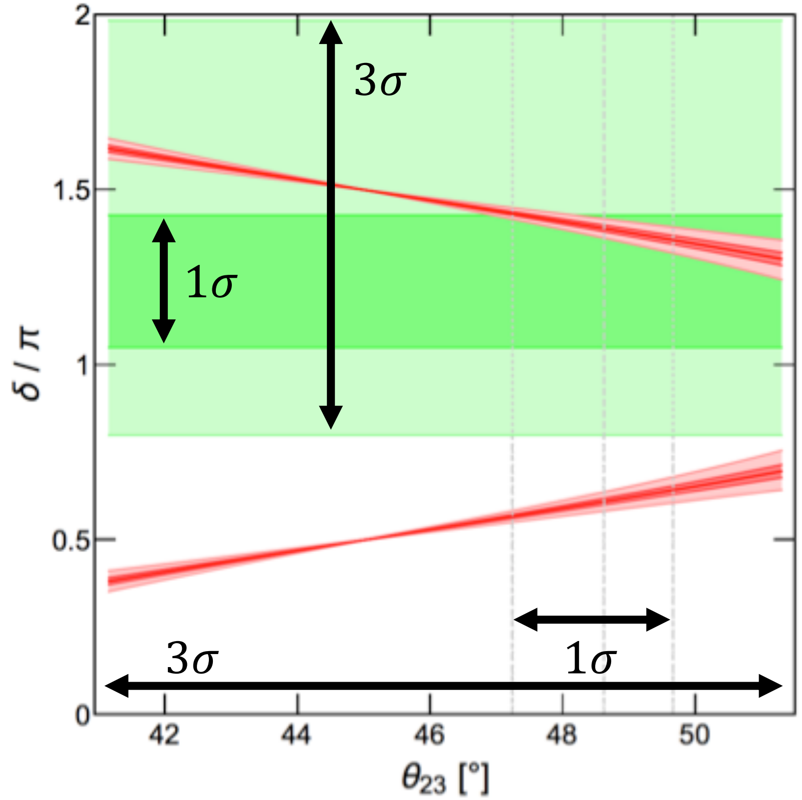




Leptogenesis in the minimal gauged $\mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau}$ model

K. Asai, K. Hamaguchi, N. Nagata, S.-Y. Tseng, in preparation

Leptogenesis

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

- Baryon asymmetry in the universe

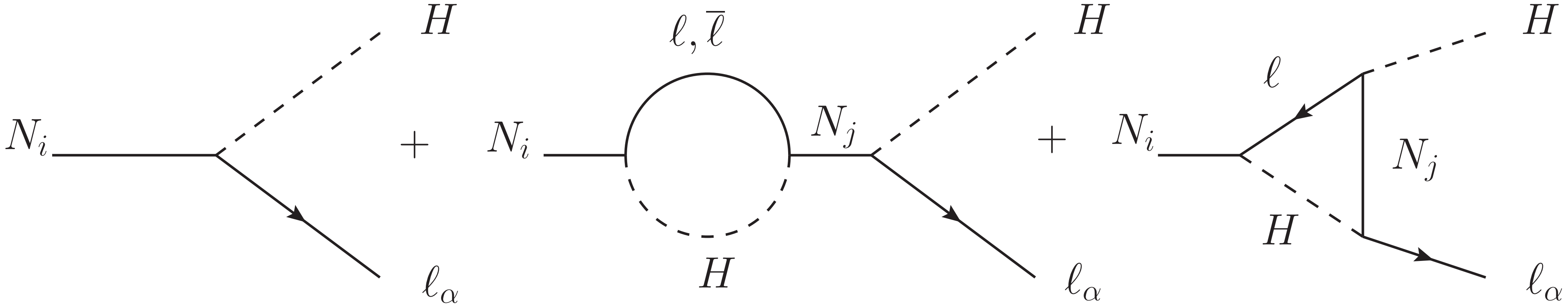
$$Y_{\Delta B} \equiv \frac{n_B}{s} \simeq 8.7 \times 10^{-11}$$

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

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



Leptogenesis

- Baryon asymmetry in the universe $Y_{\Delta B} \equiv \frac{n_B}{s} \simeq 8.7 \times 10^{-11}$

- Decays of RH neutrinos generate lepton asymmetry

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

λ: Yukawa coupling

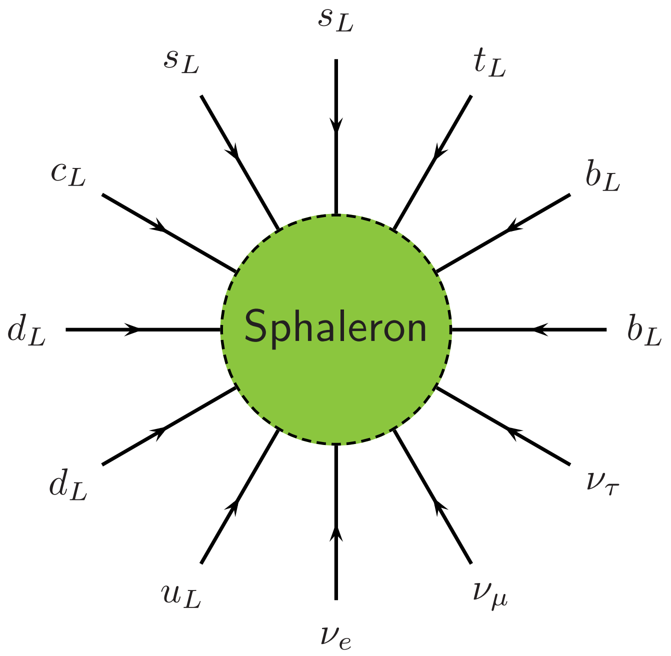
$$g(x) = \sqrt{x}\left[\frac{1}{1-x} + 1 - (1+x)\ln\left(\frac{1+x}{x}\right)\right] \qquad x_j = \frac{M_j^2}{M_1^2}$$

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

$$n_B = \frac{28}{79} \times (n_B - n_L)$$



Right-handed neutrino sector

- RH neutrino mass matrix $M_R = -M_D^T M_\nu^{-1} M_D$

Right-handed neutrino sector

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

Right-handed neutrino sector

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

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

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

Non-thermal leptogenesis

- RH neutrino non-thermal decay : $T_R = \left(\frac{90}{\pi^2 g_*}\right)^{\frac{1}{4}} \sqrt{\Gamma_\sigma M_P} < M_1$

Non-thermal leptogenesis

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- Pairs of RH neutrinos generated from inflaton decays

- Taking σ as inflaton

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

Non-thermal leptogenesis

- RH neutrino non-thermal decay : $T_R = \left(\frac{90}{\pi^2 g_*}\right)^{\frac{1}{4}} \sqrt{\Gamma_\sigma M_P} < M_1$

- Pairs of RH neutrinos generated from inflaton decays

- 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

- RH neutrino non-thermal decay : $T_R = \left(\frac{90}{\pi^2 g_*}\right)^{\frac{1}{4}} \sqrt{\Gamma_\sigma M_P} < M_1$

- Pairs of RH neutrinos generated from inflaton decays

- 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

- RH neutrino non-thermal decay : $T_R = \left(\frac{90}{\pi^2 g_*}\right)^{\frac{1}{4}} \sqrt{\Gamma_\sigma M_P} < M_1$

- Pairs of RH neutrinos generated from inflaton decays

- Taking σ as inflaton

$$m_\sigma \simeq 3.4 \times 10^{13} \times \left(\langle\sigma\rangle / \Lambda\right) \ \mathrm{GeV}$$

from CMB normalization

Non-thermal leptogenesis

- Inflaton σ

$$m_\sigma \simeq 3.4 \times 10^{13} \times (\langle \sigma \rangle / \Lambda) \text{ GeV}$$

- Pairs of RH neutrinos generated from inflaton decays
- RH neutrino non-thermal decay : $T_R = \left(\frac{90}{\pi^2 g_*} \right)^{\frac{1}{4}} \sqrt{\Gamma_\sigma M_P} < M_1$
- Baryon asymmetry

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

Non-thermal leptogenesis

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

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

Non-thermal leptogenesis

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

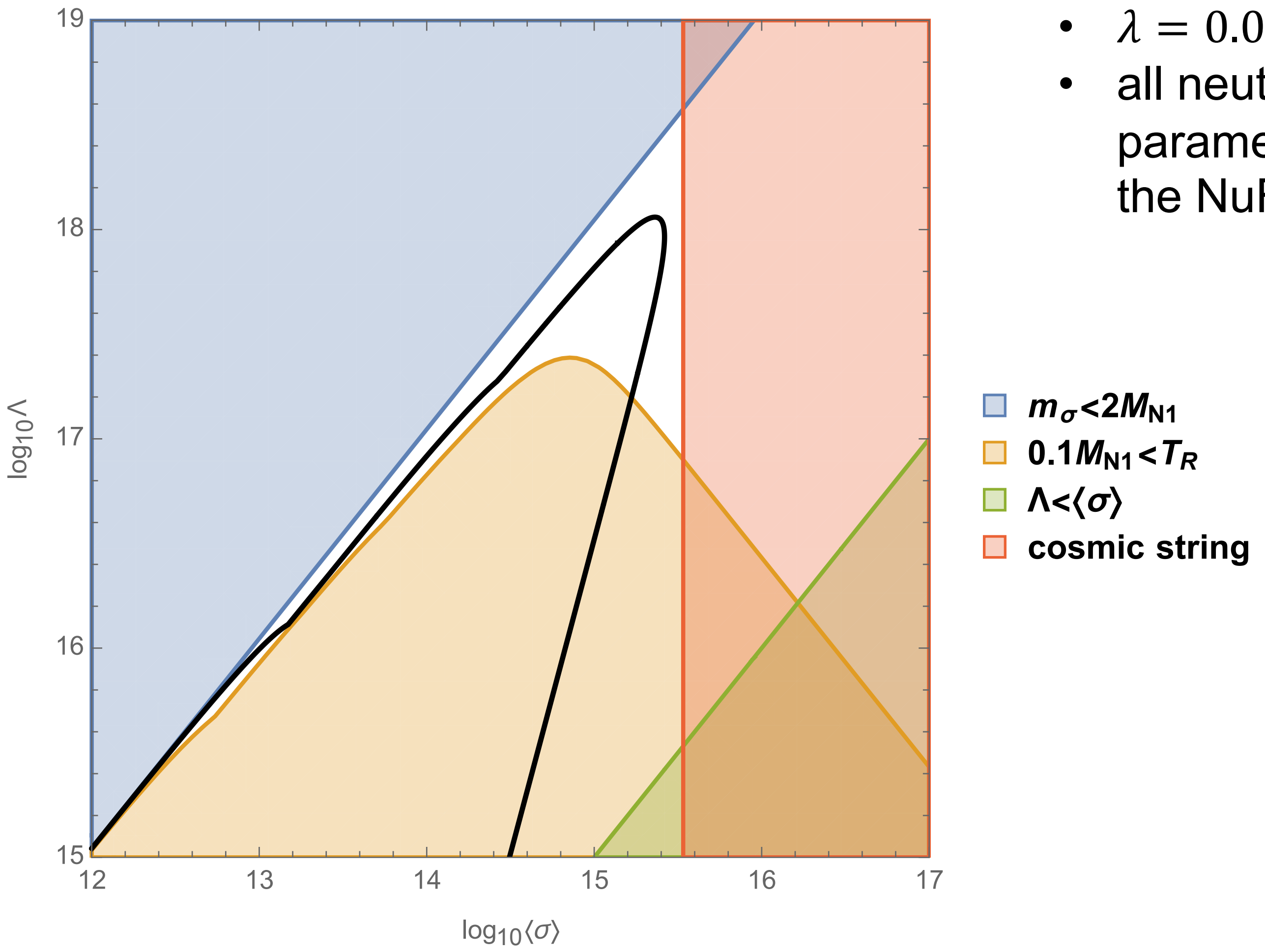
$$2\sum_{i=1}^{3} \epsilon_i Br(\phi \to N_i N_i) + \sum_{m \neq n} (\epsilon_m + \epsilon_n)\, Br(\phi \to N_m N_n)$$

Non-thermal leptogenesis

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

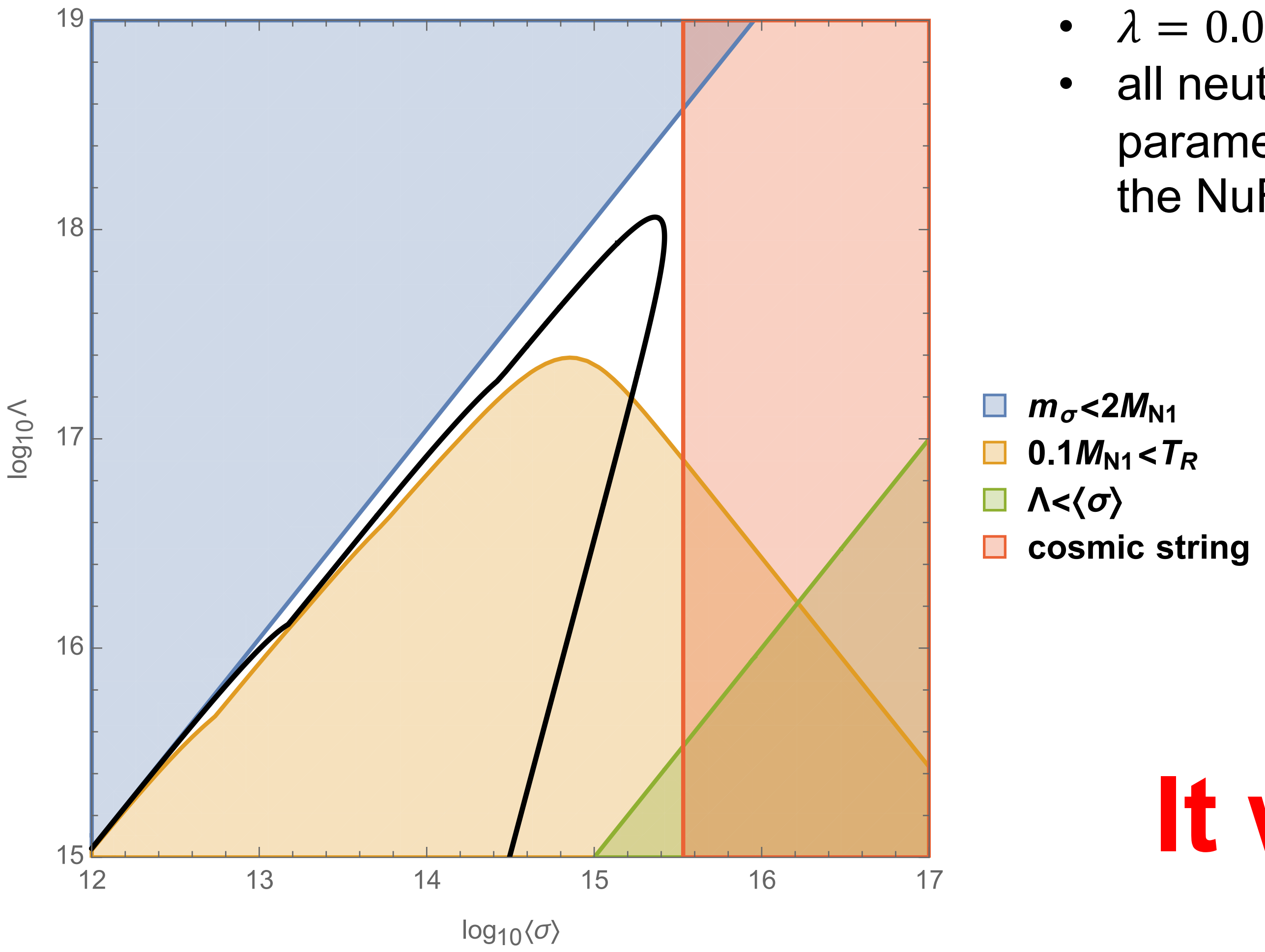
$$Y_B = \frac{n_B}{s} = \frac{n_\phi}{s} \times \frac{n_N}{n_\phi} \times \frac{n_L}{n_N} \times \boxed{\frac{n_B}{n_L}}$$

Result



- $\lambda = 0.01, \theta = 60°, \phi = 30°$
- all neutrino oscillation parameters determined by the NuFIT inputs

Result



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- all neutrino oscillation parameters determined by the NuFIT inputs

It works!

Summary

Summary

- Among minimal $\mathrm{U(1)}_{\mathrm{L}_\alpha-\mathrm{L}_\beta}$ models, only one survives constraints

  $\mathrm{U(1)}_{\mathrm{L}_\mu-\mathrm{L}_\tau}$ extension with an extra $SU(2)_\mathrm{L}$ scalar singlet

- Minimal gauged $\mathrm{U(1)}_{\mathrm{L}_\alpha-\mathrm{L}_\beta}$ models are driven into a corner

- Potential of successful leptogenesis

Backup

Inflaton mass

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

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

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

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

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

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

$$m_\sigma \simeq 3.4\times10^{13}\times\left(\langle\sigma\rangle/\Lambda\right)\ {\rm GeV}$$

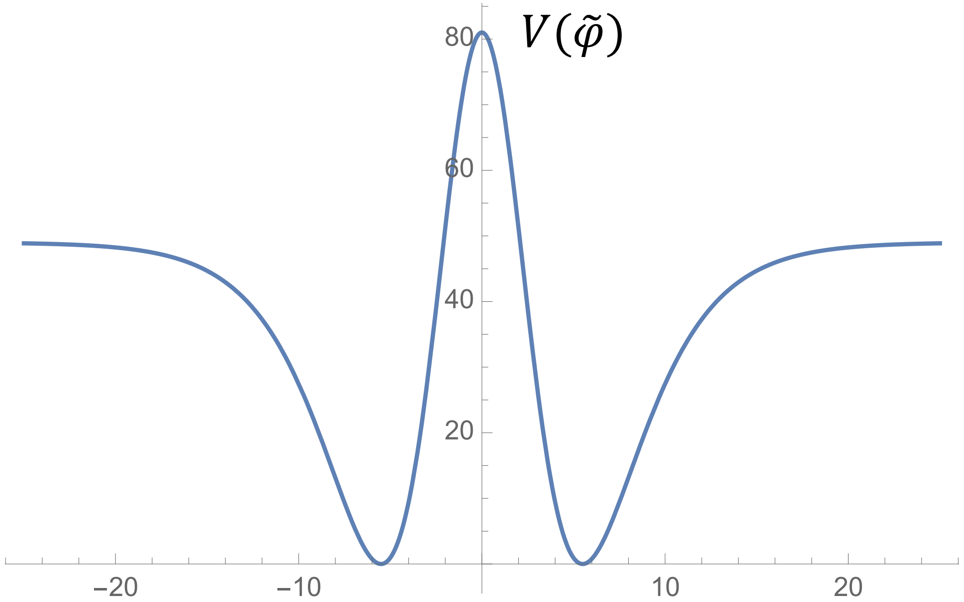
$$\kappa \simeq 2.9\times10^{-2}\times\left(\frac{50}{N_e}\right)^2\times\left(\frac{10^{14}\ {\rm GeV}}{\Lambda}\right)^2\times\left(1-\frac{\langle\sigma\rangle^2}{\Lambda^2}\right)^{-2}$$

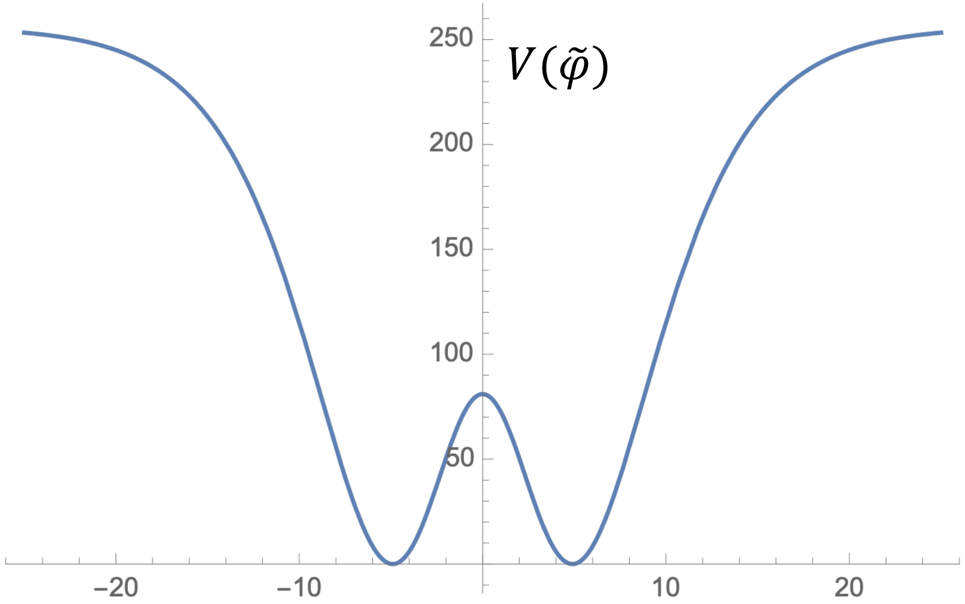
Non-thermal leptogenesis

- Taking σ as inflaton

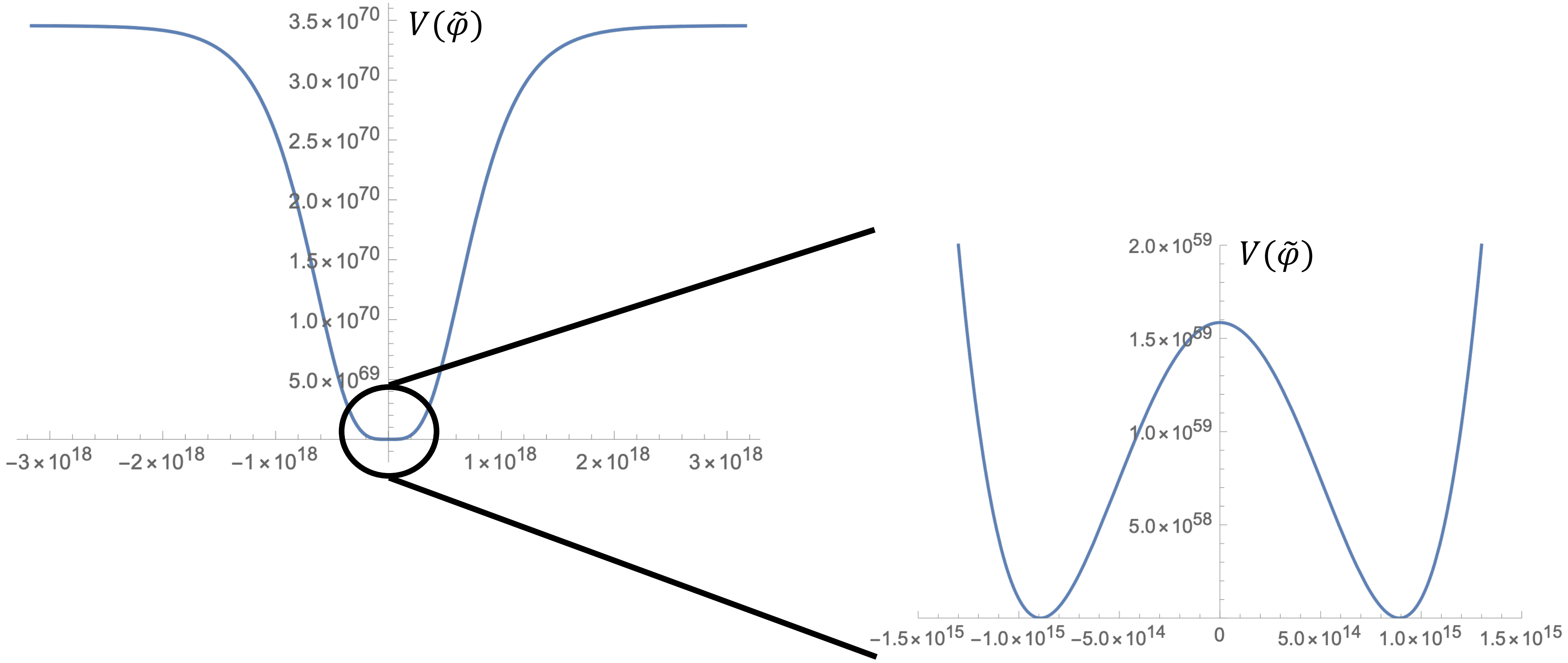
$$\mathcal{L}_\sigma = \frac{1}{2}(\partial\widetilde{\varphi})^2 - \kappa\Lambda^4\left[\tanh^2\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right) - \left(\frac{\langle\sigma\rangle}{\Lambda}\right)^2\right]^2$$

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





Inflaton potential



Cosmic string

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

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

$$\Longrightarrow \qquad \mu \simeq \pi \sigma^2$$

Cosmic string

$$\mu \simeq \pi\sigma^2$$

$$G\mu < 2.4\times10^{-7}$$

$$\Rightarrow \quad \sigma < 3.4\times10^{15}\ \text{GeV}$$

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	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$

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- Three RH neutrinos

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
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$\mathrm{U(1)_Y}$	$-\frac{1}{2}$	-1	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$

- Three RH neutrinos
- One extra scalar field

- Case (i)

  one $SU(2)_L$ scalar singlet σ with Y = 0 and $Q(U(1)_{L_\alpha - L_\beta})$ = +1

- Case (ii)

  one $SU(2)_L$ scalar doublet Φ_1 with Y = +1/2 and $Q(U(1)_{L_\alpha - L_\beta})$ = +1

- Case (iii)

  one $SU(2)_L$ scalar doublet Φ_1 with Y = +1/2 and $Q(U(1)_{L_\alpha - L_\beta})$ = -1

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

- Case (i)

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

- Case (ii)

$$\begin{aligned}\Delta\mathcal{L} =& - y_e e_R^c L_e \Phi_2^\dagger - y_\mu \mu_R^c L_\mu \Phi_2^\dagger - y_\tau \tau_R^c L_\tau \Phi_2^\dagger - y_{\mu e} e_R^c L_\mu \Phi_1^\dagger - y_{e\tau} \tau_R^c L_e \Phi_1^\dagger \\ & - \lambda_e N_e^c (L_e \cdot \Phi_2) - \lambda_\mu N_\mu^c (L_\mu \cdot \Phi_2) - \lambda_\tau N_\tau^c (L_\tau \cdot \Phi_2) \\ & - \lambda_{\tau e} N_e^c (L_\tau \cdot \Phi_1) - \lambda_{e\mu} N_\mu^c (L_e \cdot \Phi_1) - \frac{1}{2} M_{ee} N_e^c N_e^c - M_{\mu\tau} N_\mu^c N_\tau^c + \text{h.c.}\end{aligned}$$

- Case (iii)

$$\begin{aligned}\Delta\mathcal{L} =& - y_e e_R^c L_e \Phi_2^\dagger - y_\mu \mu_R^c L_\mu \Phi_2^\dagger - y_\tau \tau_R^c L_\tau \Phi_2^\dagger - y_{\tau e} e_R^c L_\tau \Phi_1^\dagger - y_{e\mu} \mu_R^c L_e \Phi_1^\dagger \\ & - \lambda_e N_e^c (L_e \cdot \Phi_2) - \lambda_\mu N_\mu^c (L_\mu \cdot \Phi_2) - \lambda_\tau N_\tau^c (L_\tau \cdot \Phi_2) \\ & - \lambda_{\mu e} N_e^c (L_\mu \cdot \Phi_1) - \lambda_{e\tau} N_\tau^c (L_e \cdot \Phi_1) - \frac{1}{2} M_{ee} N_e^c N_e^c - M_{\mu\tau} N_\mu^c N_\tau^c + \text{h.c.}\end{aligned}$$

After the SSB…

- Case (i)

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

- Case (ii)

$$M_D = \frac{1}{\sqrt{2}}\begin{pmatrix} \lambda_e v_2 & \lambda_{e\mu} v_1 & 0 \\ 0 & \lambda_\mu v_2 & 0 \\ \lambda_{\tau e} v_1 & 0 & \lambda_\tau v_2 \end{pmatrix} \quad M_R = \begin{pmatrix} M_{ee} & 0 & 0 \\ 0 & 0 & M_{\mu\tau} \\ 0 & M_{\mu\tau} & 0 \end{pmatrix} \quad M_\ell = \frac{1}{\sqrt{2}}\begin{pmatrix} y_e v_2 & 0 & \boxed{y_{e\tau} v_1} \\ \boxed{y_{\mu e} v_1} & y_\mu v_2 & 0 \\ 0 & 0 & y_\tau v_2 \end{pmatrix}$$

- Case (iii)

$$M_D = \frac{1}{\sqrt{2}}\begin{pmatrix} \lambda_e v_2 & 0 & \lambda_{e\tau} v_1 \\ \lambda_{\mu e} v_1 & \lambda_\mu v_2 & 0 \\ 0 & 0 & \lambda_\tau v_2 \end{pmatrix} \quad M_R = \begin{pmatrix} M_{ee} & 0 & 0 \\ 0 & 0 & M_{\mu\tau} \\ 0 & M_{\mu\tau} & 0 \end{pmatrix} \quad M_\ell = \frac{1}{\sqrt{2}}\begin{pmatrix} y_e v_2 & \boxed{y_{e\mu} v_1} & 0 \\ 0 & y_\mu v_2 & 0 \\ \boxed{y_{\tau e} v_1} & 0 & y_\tau v_2 \end{pmatrix}$$

After the SSB…

! cases (ii), (iii),

$$v=\sqrt{v_1^2+v_2^2}\simeq 246\ \text{GeV}$$

- Case (i)

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

- Case (ii)

$$M_D=\frac{1}{\sqrt{2}}\begin{pmatrix}\lambda_e v_2 & \lambda_{e\mu}v_1 & 0\\ 0 & \lambda_\mu v_2 & 0\\ \lambda_{\tau e}v_1 & 0 & \lambda_\tau v_2\end{pmatrix}\quad M_R=\begin{pmatrix}M_{ee} & 0 & 0\\ 0 & 0 & M_{\mu\tau}\\ 0 & M_{\mu\tau} & 0\end{pmatrix}\quad M_\ell=\frac{1}{\sqrt{2}}\begin{pmatrix}y_e v_2 & 0 & y_{e\tau}v_1\\ y_{\mu e}v_1 & y_\mu v_2 & 0\\ 0 & 0 & y_\tau v_2\end{pmatrix}$$

- Case (iii)

$$M_D=\frac{1}{\sqrt{2}}\begin{pmatrix}\lambda_e v_2 & 0 & \lambda_{e\tau}v_1\\ \lambda_{\mu e}v_1 & \lambda_\mu v_2 & 0\\ 0 & 0 & \lambda_\tau v_2\end{pmatrix}\quad M_R=\begin{pmatrix}M_{ee} & 0 & 0\\ 0 & 0 & M_{\mu\tau}\\ 0 & M_{\mu\tau} & 0\end{pmatrix}\quad M_\ell=\frac{1}{\sqrt{2}}\begin{pmatrix}y_e v_2 & y_{e\mu}v_1 & 0\\ 0 & y_\mu v_2 & 0\\ y_{\tau e}v_1 & 0 & y_\tau v_2\end{pmatrix}$$

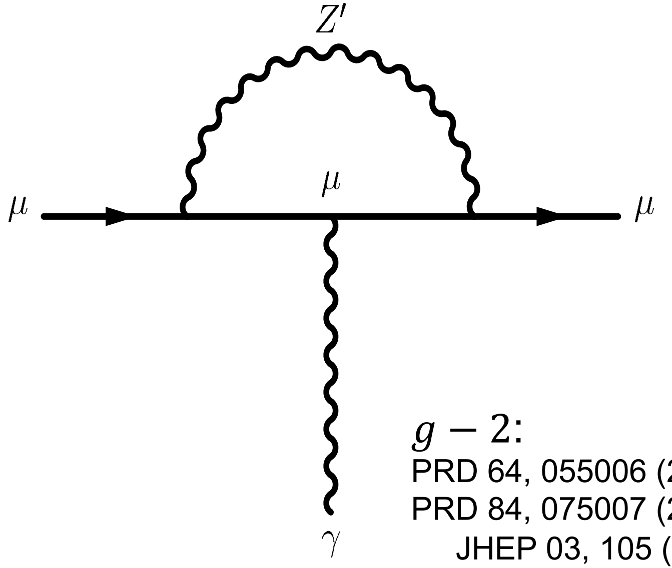
Introduction

- Possible extension of SM

$$\underbrace{SU(3)_C \times SU(2)_L \times U(1)_Y}_{G_{SM}} \times U(1)_{L_\alpha - L_\beta} \quad \alpha, \beta \in e, \mu, \tau$$

Mod.Phys.Lett. A6 (1991) 527-530
Phys. Rev. D 43, R22

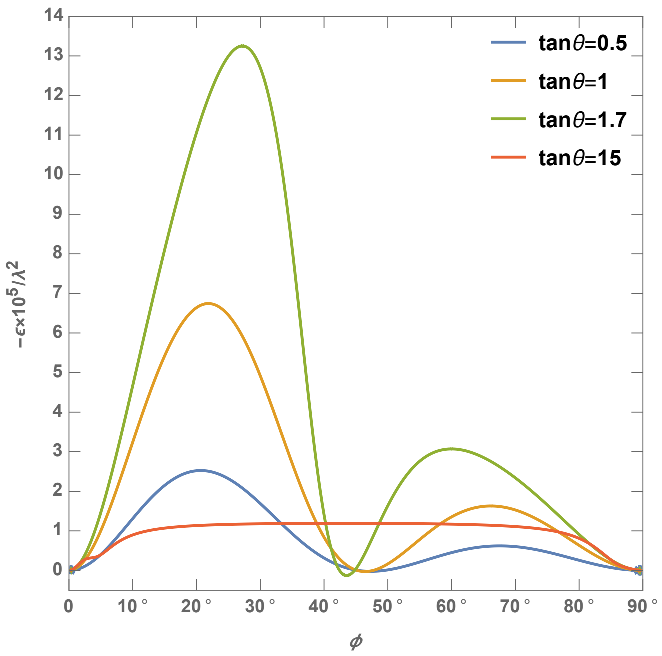
- $U(1)_{L_\mu - L_\tau}$ models

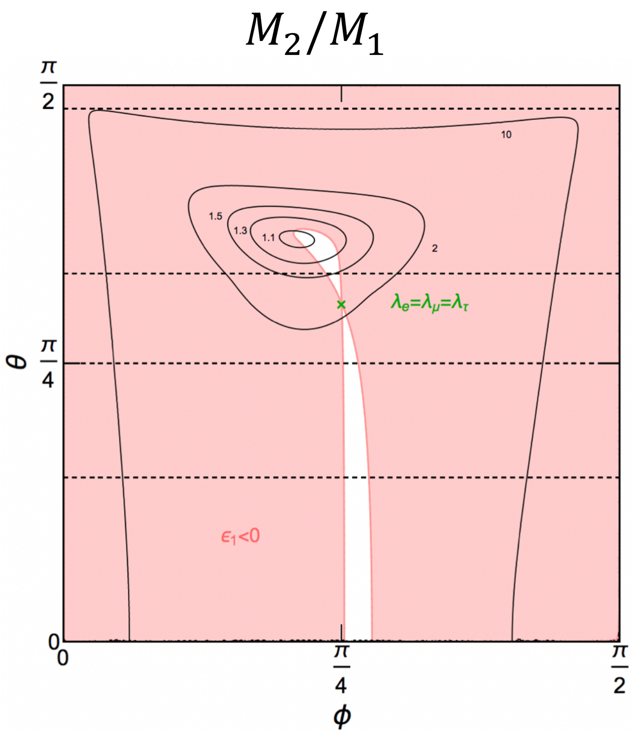


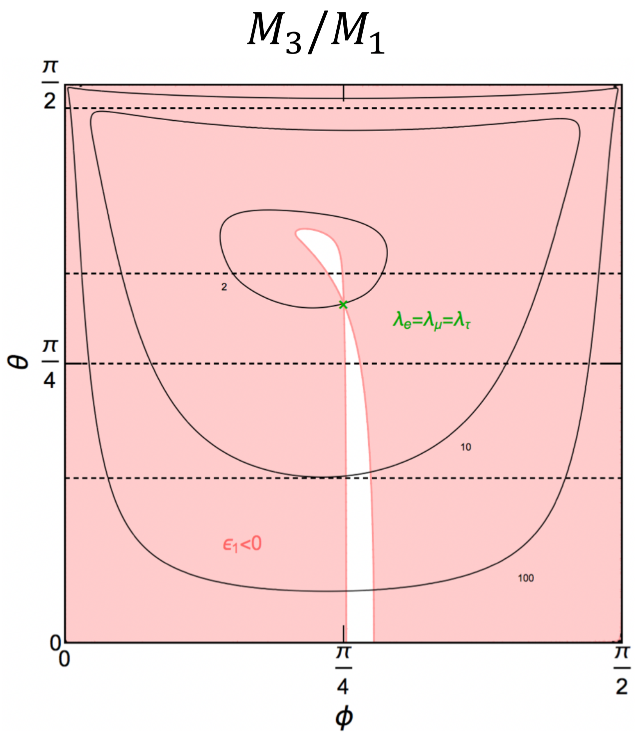
$g-2$:
PRD 64, 055006 (2001),
PRD 84, 075007 (2011),
JHEP 03, 105 (2014)

Leptogenesis

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







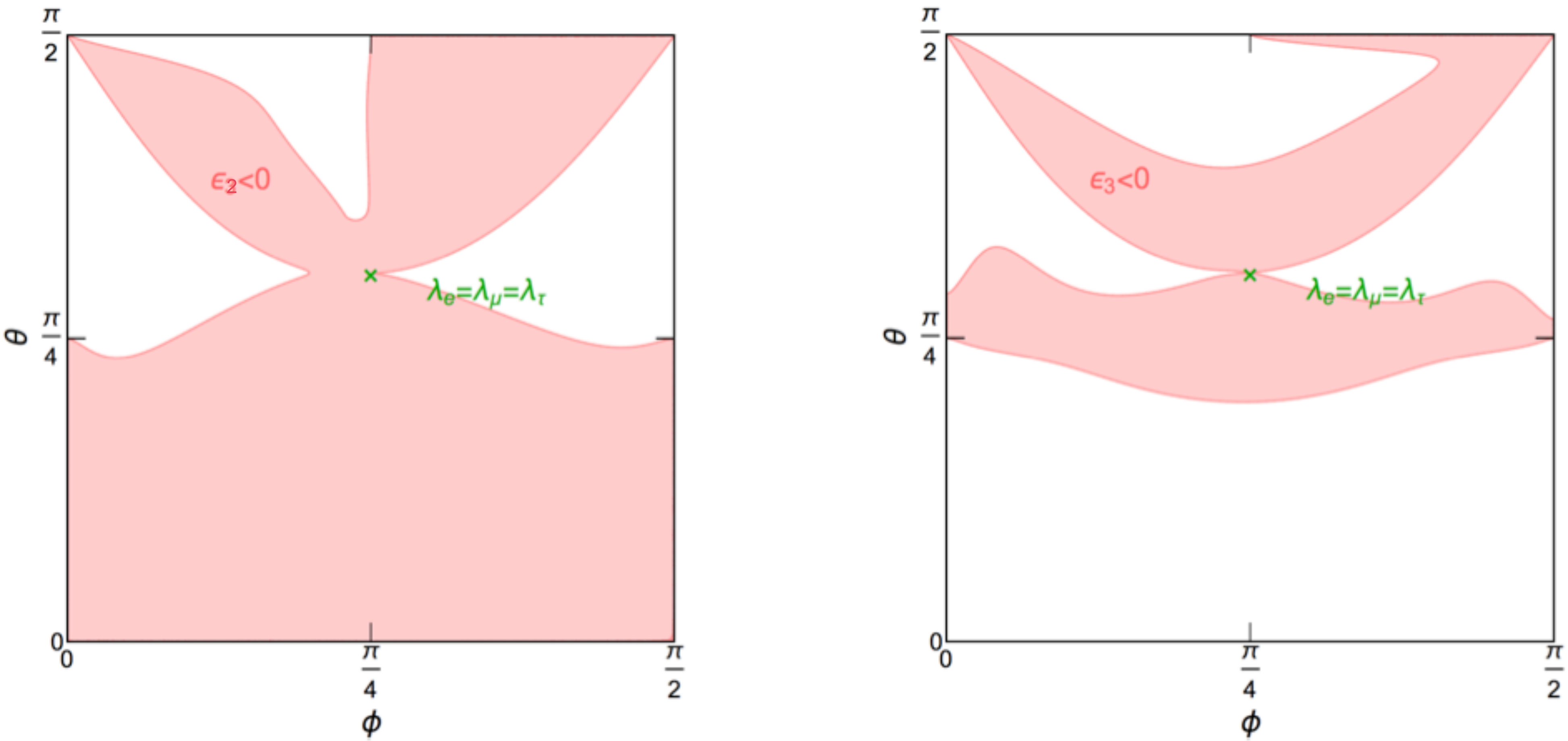
$$Y_{\Delta B} \equiv \frac{n_B}{s} \simeq 8.7 \times 10^{-11} > 0$$

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

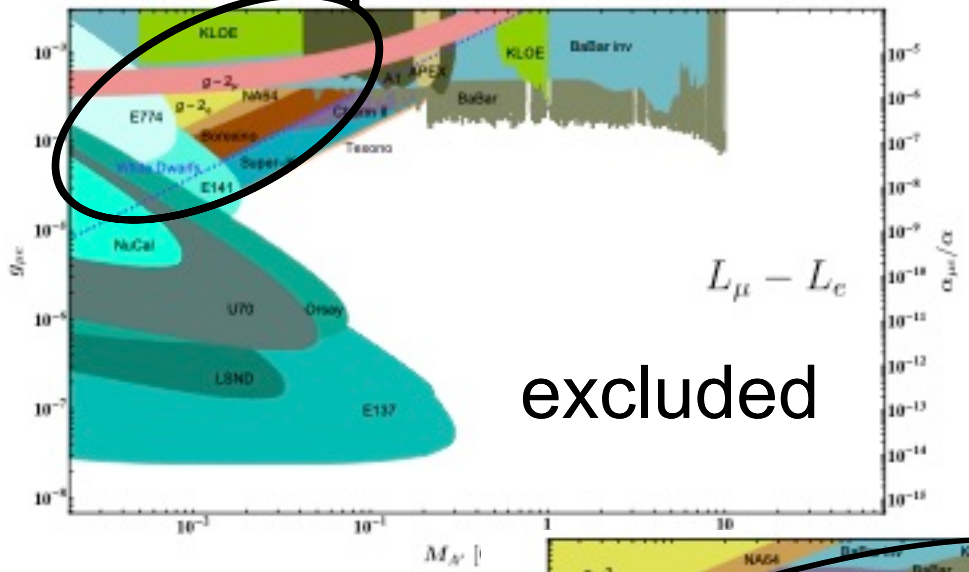
$\Rightarrow$

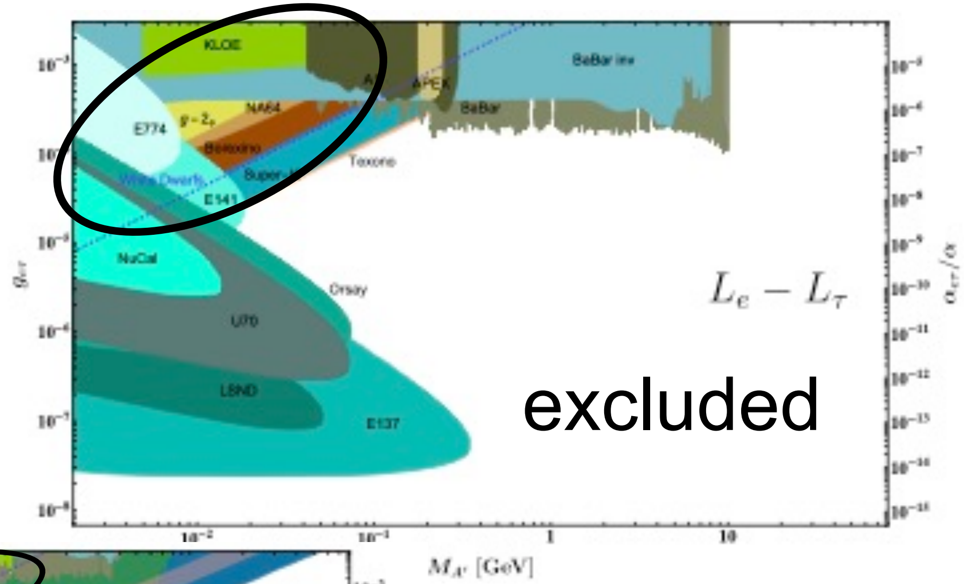
$$\epsilon_1 < 0$$

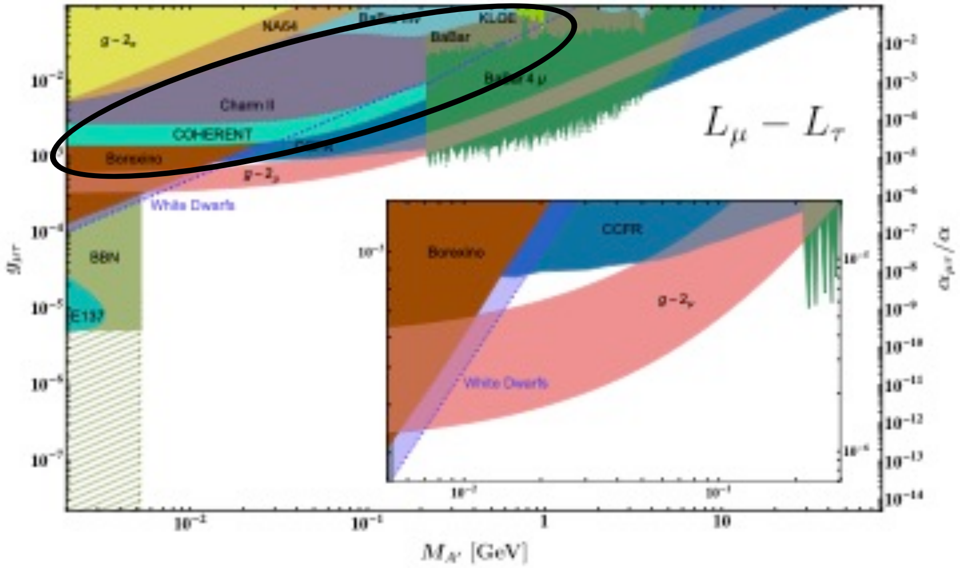
Leptogenesis



$\mathrm{U(1)}_{\mathrm{L}_\alpha - \mathrm{L}_\beta}$ bosons in cases (ii) and (iii)





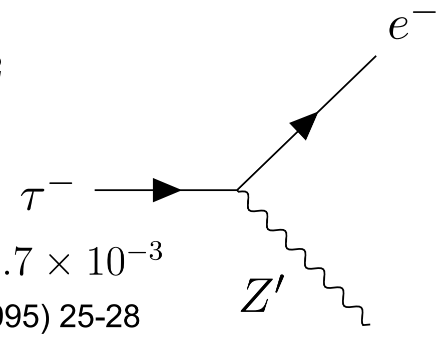


$M_{Z'} \lesssim 100 \times g_{Z'}$ GeV

JHEP (2018) 2018: 94

LFV process in cases (ii) and (iii)

$$\Gamma(\tau \to eZ') = \frac{g_{Z'}^2 m_\tau}{128\pi} \sin^2 2\theta_L \left(2 + \frac{m_\tau^2}{m_{Z'}^2}\right)\left(1 - \frac{m_{Z'}^2}{m_\tau^2}\right)^2$$



$$|\sin 2\theta_L| < \begin{cases} 7 \times 10^{-5} & \text{for } m_{Z'} = 100\text{ MeV and } g_{Z'} = 10^{-3} \\ 1 \times 10^{-5} & \text{for } m_{Z'} = 10\text{ MeV and } g_{Z'} = 5 \times 10^{-4} \end{cases}$$

$$\mathrm{BR}(\tau \to eX) \lesssim 2.7 \times 10^{-3}$$

Z.Phys. C68 (1995) 25-28

$$\theta_{L,R} \simeq 0 \text{ or } \pi/2 \quad U_{L,R} \simeq \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix} \Rightarrow Q_{\mu-\tau} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \to \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} = Q_{\mu-e}$$

$$M_l = U_L \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} U_R^T$$

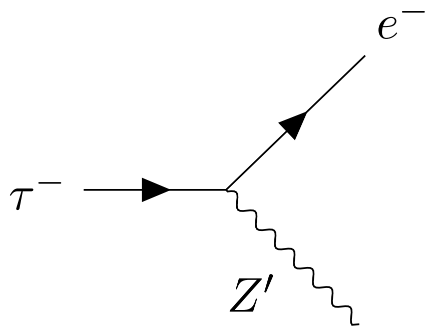
⇒ Symmetry group S_3 : $D_3(g) \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} D_3^T(g)$

$$g = \underbrace{g_{e\mu\tau}, g_{e\tau\mu}}_{\mathrm{U}(1)_{L_\mu - L_\tau}}, \underbrace{\cancel{g_{\mu e\tau}}, \cancel{g_{\mu\tau e}}}_{\cancel{\mathrm{U}(1)_{L_e - L_\tau}}}, \underbrace{\cancel{g_{\tau e\mu}}, \cancel{g_{\tau\mu e}}}_{\cancel{\mathrm{U}(1)_{L_e - L_\mu}}}$$

$m_{Z'}$ below EW scale ruled out by experiments

JHEP (2018) 2018: 53
JHEP (2018) 2018: 94
PRL **113**, 091801

LFV process



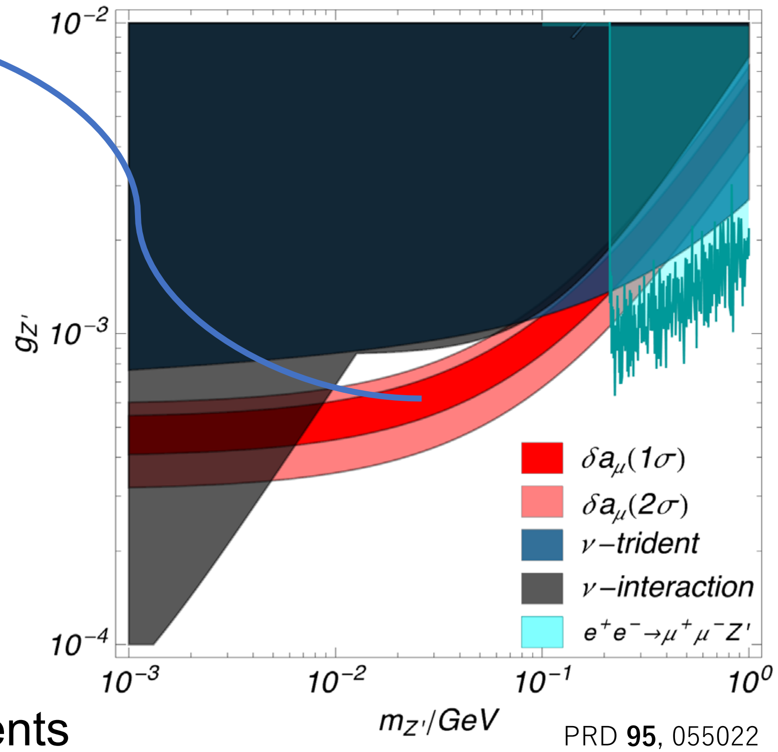
$10\ \mathrm{MeV} \lesssim m_{Z'} \lesssim 100\ \mathrm{MeV}$
$5\times10^{-4} \lesssim g_{Z'} \lesssim 10^{-3}$

$$\mathcal{L}_{Z'} = g_{Z'}\overline{\ell'}\gamma^\mu\left[U_L^\dagger Q_{\mu-\tau}U_L P_L + U_R^\dagger Q_{\mu-\tau}U_R P_R\right]\ell' Z'_\mu$$

$$\Gamma(\tau\to eZ') = \frac{g_{Z'}^2 m_\tau}{128\pi}\sin^2 2\theta_L\left(2+\frac{m_\tau^2}{m_{Z'}^2}\right)\left(1-\frac{m_{Z'}^2}{m_\tau^2}\right)^2$$

$$\mathrm{BR}(\tau\to eX) \lesssim 2.7\times10^{-3}$$

ARGUS, Z. Phys. C (1995) 68: 25



PRD **95**, 055022

charged lepton-mixing are constrained severely by experiments

LFV decay

$$M_\ell = U_L^* \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} U_R^T \qquad U_{L,R} = \begin{pmatrix} \cos\theta_{L,R} & 0 & e^{-i\phi}\sin\theta_{L,R} \\ 0 & 1 & 0 \\ -e^{i\phi}\sin\theta_{L,R} & 0 & \cos\theta_{L,R} \end{pmatrix}$$

$$\mathcal{L}_{Z'} = g_{Z'}\overline{\ell'}\gamma^\mu \left[U_L^\dagger Q_{\mu-\tau} U_L P_L + U_R^\dagger Q_{\mu-\tau} U_R P_R\right] \ell' Z'_\mu \qquad \frac{\tan\theta_R}{\tan\theta_L} = \frac{m_e}{m_\tau}$$

$$Q_{\mu-\tau} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \qquad |y_{e\tau} v_1| = \frac{(m_\tau^2 - m_e^2)\sin 2\theta_L}{\sqrt{(m_\tau^2 + m_e^2) + (m_\tau^2 - m_e^2)\cos 2\theta_L}}$$

$$\Gamma(\tau \to eZ') = \frac{g_{Z'}^2 m_\tau}{32\pi}\left[\left|\left(U_L^\dagger Q_{\mu-\tau} U_L\right)_{13}\right|^2 + \left|\left(U_R^\dagger Q_{\mu-\tau} U_R\right)_{13}\right|^2\right]\left(2 + \frac{m_\tau^2}{m_{Z'}^2}\right)\left(1 - \frac{m_{Z'}^2}{m_\tau^2}\right)^2$$

$\mathrm{BR}(\tau \to eX) \lesssim 2.7 \times 10^{-3}$ — Z.Phys. C68 (1995) 25-28

$\mathrm{BR}(\tau^- \to e^-\mu^+\mu^-) < 2.7 \times 10^{-8}$ — PLB 687:139-143,2010

$\mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$ — PRL 104:021802,2010

$\mu - e$ mixing

Massless $m_{Z'}$

$\mathrm{BR}(\mu \to eX) \lesssim 10^{-6}$

Phys. Rev. D **34**, 1967

$13\ \mathrm{MeV} \lesssim m_{Z'} \lesssim 80\ \mathrm{MeV}$

$\mathrm{BR}(\mu \to eX) \lesssim 10^{-5}$

Phys. Rev. D **91**, 052020

$m_{Z'} \lesssim 100\ \mathrm{MeV}$

$\mathrm{BR}(\mu \to eX) \lesssim 10^{-4}$

Phys. Rev. Lett. **57**, 2787

Z' contributes to $\mu \to e\gamma$ loop corrections

$\mathrm{BR}(\mu \to e\gamma) \lesssim 10^{-13}$

Eur. Phys. J. C (2016) 76: 434

Analysis of M_ν : Model 1

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

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

$$M_\nu = U_\nu^* M_\nu^{\mathrm{d}} U_\nu^\dagger$$

$$U_{\mathrm{PMNS}} \equiv U_L^\dagger U_\nu$$

$$U_{\mathrm{PMNS}} = \overbrace{\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}}^{V\equiv} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_3}{2}} \end{pmatrix} \equiv U_L^\dagger U_\nu = D_3^T(g) U_\nu$$

Two-zero minor

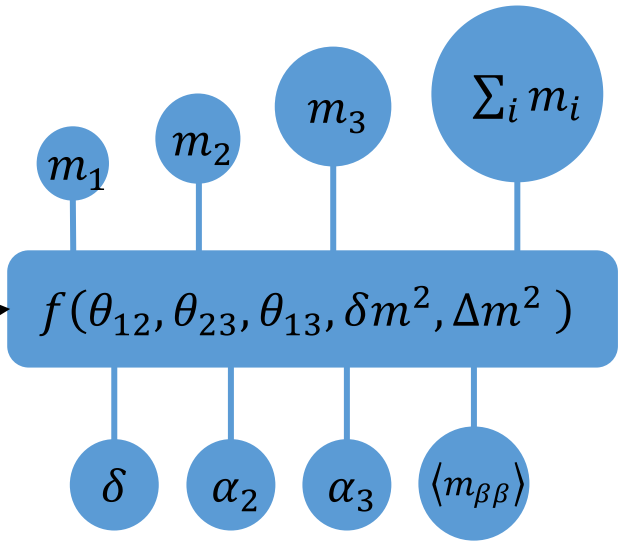
$$\nu_{L\alpha} = \sum_{j=1}^{3} (U_{PMNS})_{\alpha j} \nu_{Lj} \ (\alpha = e, \mu, \tau)$$

$$M_\nu^{-1} = -(M_D^{-1})^T M_R M_D^{-1} = \begin{pmatrix} * & * & * \\ * & \boxed{0} & * \\ * & * & \boxed{0} \end{pmatrix} = U_\nu (M_\nu^{\mathrm{d}})^{-1} U_\nu^T = D_3(g) U_{\mathrm{PMNS}} (M_\nu^{\mathrm{d}})^{-1} U_{\mathrm{PMNS}}^T D_3^T(g)$$

Analysis of M_ν : Model 1

$$\left[D_3(g)U_{\rm PMNS}{\rm diag}(m_1^{-1},m_2^{-1},m_3^{-1})U_{\rm PMNS}^T D_3^T(g)\right]_{\mu\mu}=0$$
$$\left[D_3(g)U_{\rm PMNS}{\rm diag}(m_1^{-1},m_2^{-1},m_3^{-1})U_{\rm PMNS}^T D_3^T(g)\right]_{\tau\tau}=0$$

$$\frac{1}{m_1}V_{\mu 1}^2+\frac{1}{m_2}V_{\mu 2}^2\,{\rm e}^{i\alpha_2}+\frac{1}{m_3}V_{\mu 3}^2\,{\rm e}^{i\alpha_3}=0$$
$$\frac{1}{m_1}V_{\tau 1}^2+\frac{1}{m_2}V_{\tau 2}^2\,{\rm e}^{i\alpha_2}+\frac{1}{m_3}V_{\tau 3}^2\,{\rm e}^{i\alpha_3}=0$$

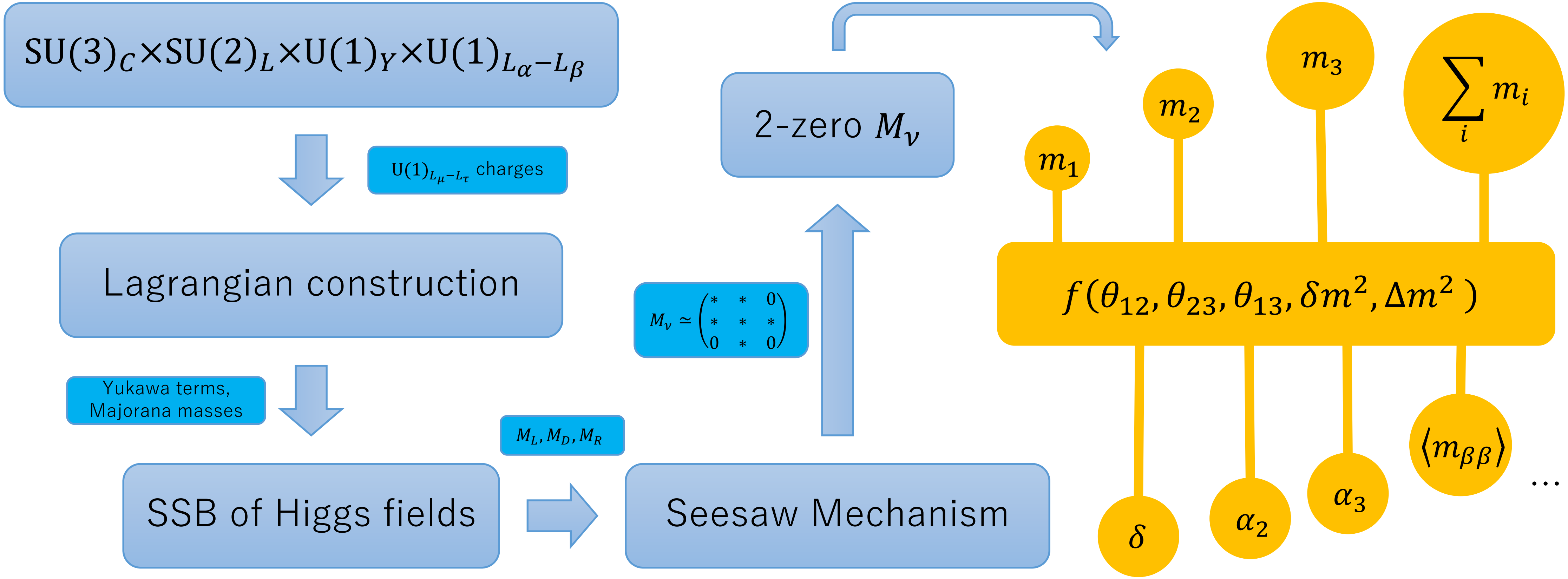


$$\delta m^2=\Delta m^2_{\rm sol},$$
$$\Delta m^2=\Delta m^2_{\rm atm}-\frac{1}{2}\Delta m^2_{\rm sol}$$

Analysis of M_ν : Model 2

	$\mathrm{Q}_{\mathrm{L}_\mu-\mathrm{L}_\tau}(\Phi_1)=+1$	$\mathrm{Q}_{\mathrm{L}_\mu-\mathrm{L}_\tau}(\Phi_1)=-1$
M_ν	$-\frac{1}{2}\begin{pmatrix} \frac{v_2^2 y'^2_{11}}{M_{11}} & 0 & v_1 v_2\left(\frac{y'_{11}g'_{31}}{M_{11}}+\frac{y'_{33}g'_{12}}{M_{23}}\right) \\ 0 & 0 & \frac{v_2^2 y'_{22}y'_{33}}{M_{23}} \\ v_1 v_2\left(\frac{y'_{11}g'_{31}}{M_{11}}+\frac{y'_{33}g'_{12}}{M_{23}}\right) & \frac{v_2^2 y'_{22}y'_{33}}{M_{23}} & \frac{v_2^1 g'^2_{31}}{M_{11}} \end{pmatrix}$	$-\frac{1}{2}\begin{pmatrix} \frac{v_2^2 y'^2_{11}}{M_{11}} & v_1 v_2\left(\frac{y'_{11}g'_{21}}{M_{11}}+\frac{y'_{22}g'_{13}}{M_{23}}\right) & 0 \\ v_1 v_2\left(\frac{y'_{11}g'_{21}}{M_{11}}+\frac{y'_{22}g'_{13}}{M_{23}}\right) & \frac{v_1^2 g'^2_{21}}{M_{11}} & \frac{v_2^2 y'_{22}y'_{33}}{M_{23}} \\ 0 & \frac{v_2^2 y'_{22}y'_{33}}{M23} & 0 \end{pmatrix}$

Basic Idea of the analysis



Analysis of M_ν

Scalar-doublet case

$$\begin{cases} e^{-i\alpha_2} = \dfrac{m_1}{m_2} R_2 \\ e^{-i\alpha_3} = \dfrac{m_1}{m_3} R_3 \end{cases}$$

$$\begin{cases} \dfrac{m_2}{m_1} = |R_2| \\ \dfrac{m_3}{m_1} = |R_3| \end{cases}$$

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

$$m_1 = \sqrt{\frac{\delta m^2}{|R_2|^2 - 1}} = \sqrt{\frac{\Delta m^2 + \underbrace{\frac{\delta m^2}{2}}_{\delta}}{|R_3|^2 - 1}}$$

$$\begin{cases} \delta m^2 = m_2^2 - m_1^2 \\ \Delta m^2 = m_3^2 - \dfrac{m_1^2 + m_2^2}{2} \end{cases}$$

$NO: m_1 < m_2 < m_3$

$IO: m_3 < m_1 < m_2$

$$\begin{cases} m_2 = \sqrt{\dfrac{|R_2|^2 \delta m^2}{|R_2|^2 - 1}} \\ m_3 = \sqrt{\dfrac{|R_3|^2 \delta m^2}{|R_2|^2 - 1}} \end{cases}$$

Analysis of M_ν : case(iii)

$$M_\nu = -\begin{pmatrix} \frac{\lambda_e^2 v_2^2}{2M_{ee}} & \frac{\lambda_{e\tau}\lambda_\mu v_1 v_2}{2M_{\mu\tau}} + \frac{\lambda_e \lambda_{\mu e} v_1 v_2}{2M_{ee}} & 0 \\ \frac{\lambda_{e\tau}\lambda_\mu v_1 v_2}{2M_{\mu\tau}} + \frac{\lambda_e \lambda_{\mu e} v_1 v_2}{2M_{ee}} & \frac{\lambda_{\mu e}^2 v_1^2}{2M_{ee}} & \frac{\lambda_\mu \lambda_\tau v_2^2}{2M_{\mu\tau}} \\ 0 & \frac{\lambda_\mu \lambda_\tau v_2^2}{2M_{\mu\tau}} & 0 \end{pmatrix}$$

$$\left[D_3(g)U^*_{\mathrm{PMNS}}\mathrm{diag}(m_1, m_2, m_3)U^\dagger_{\mathrm{PMNS}}D_3^T(g)\right]_{e\tau} = 0$$

$$\left[D_3(g)U^*_{\mathrm{PMNS}}\mathrm{diag}(m_1, m_2, m_3)U^\dagger_{\mathrm{PMNS}}D_3^T(g)\right]_{\tau\tau} = 0$$

Analysis of M_ν : case (ii)

$$M_D = \frac{1}{\sqrt{2}}\begin{pmatrix} \lambda_e v_2 & \lambda_{e\mu} v_1 & 0 \\ 0 & \lambda_\mu v_2 & 0 \\ \lambda_{\tau e} v_1 & 0 & \lambda_\tau v_2 \end{pmatrix} \qquad M_R = \begin{pmatrix} M_{ee} & 0 & 0 \\ 0 & 0 & M_{\mu\tau} \\ 0 & M_{\mu\tau} & 0 \end{pmatrix}$$

$$M_\nu = -\begin{pmatrix} \frac{\lambda_e^2 v_2^2}{2M_{ee}} & \boxed{0} & \frac{\lambda_{e\mu}\lambda_\tau v_1 v_2}{2M_{\mu\tau}} + \frac{\lambda_e \lambda_{\tau e} v_1 v_2}{2M_{ee}} \\ 0 & \boxed{0} & \frac{\lambda_\mu \lambda_\tau v_2^2}{2M_{\mu\tau}} \\ \frac{\lambda_{e\mu}\lambda_\tau v_1 v_2}{2M_{\mu\tau}} + \frac{\lambda_e \lambda_{\tau e} v_1 v_2}{2M_{ee}} & \frac{\lambda_\mu \lambda_\tau v_2^2}{2M_{\mu\tau}} & \frac{\lambda_{\tau e}^2 v_1^2}{2M_{ee}} \end{pmatrix}$$

Two-zero texture

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

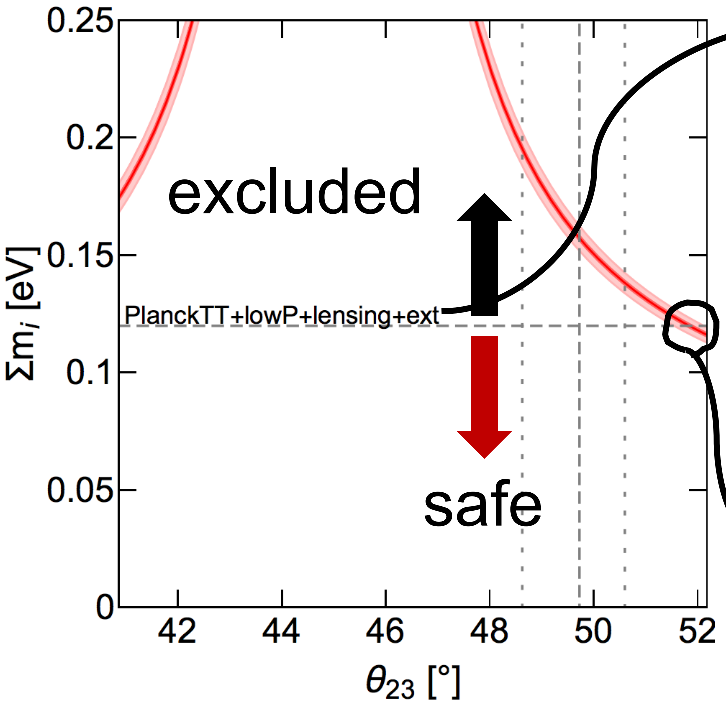
$$\left[D_3(g) U^*_{PMNS} M_\nu^{\mathrm{d}} U^\dagger_{\mathrm{PMNS}} D_3^T(g)\right]_{e\mu} = 0$$
$$\left[D_3(g) U^*_{PMNS} M_\nu^{\mathrm{d}} U^\dagger_{\mathrm{PMNS}} D_3^T(g)\right]_{\mu\mu} = 0$$

Predictions of $\sum_i m_i$, δ , α_2 , α_3…

$f(\theta_{12}, \theta_{23}, \theta_{13}, \Delta m^2_{21}, \Delta m^2_{31})$

Neutrino phenomenology : case (i)

$\mathrm{U(1)}_{\mathrm{L}_\mu-\mathrm{L}_\tau}$ normal ordering :

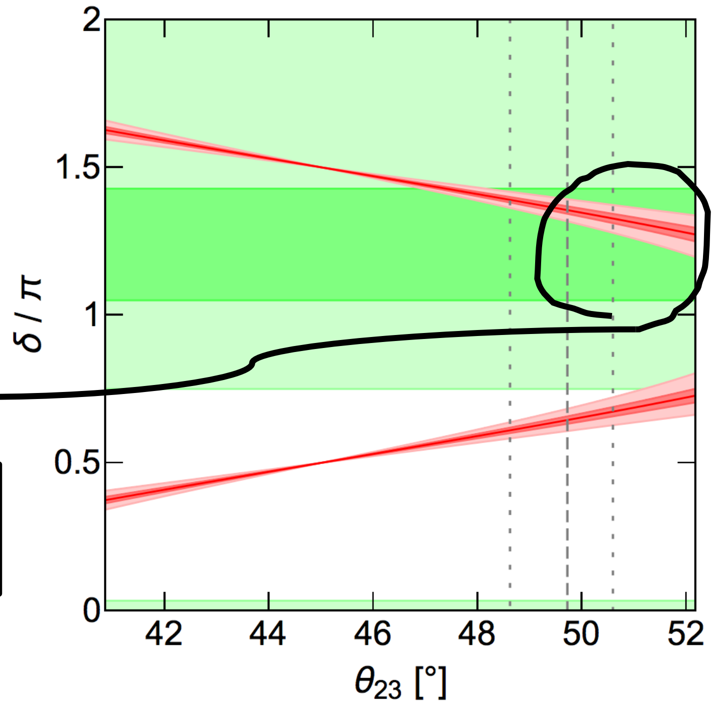


The tight bound set by Planck exp.

$\sum_i m_i < 0.12$ eV

Planck, arXiv:1807.06209

around experimental 3σ bound



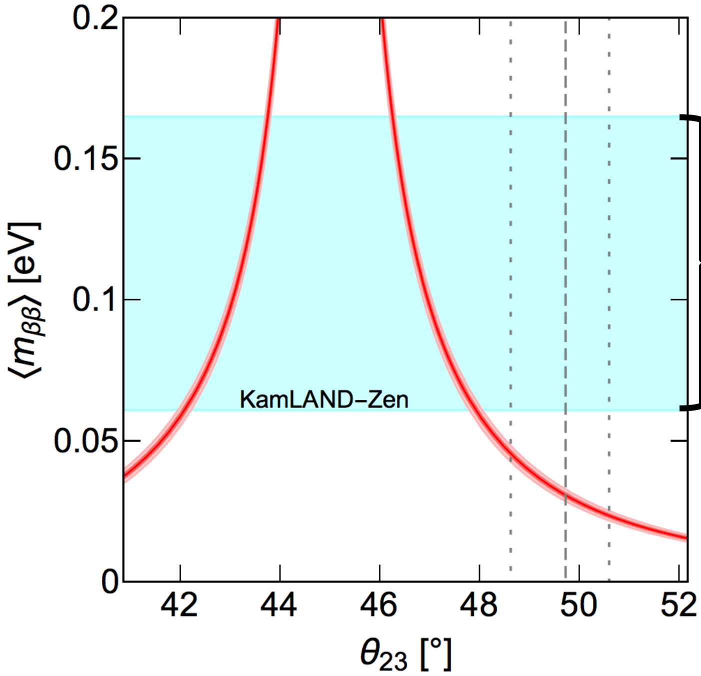
$\mathrm{U(1)}_{\mathrm{L}_\mu-\mathrm{L}_\tau}$ inverted ordering

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

incorrect mass orderings, no real δ_{CP} solutions

Neutrino phenomenology : case (i)

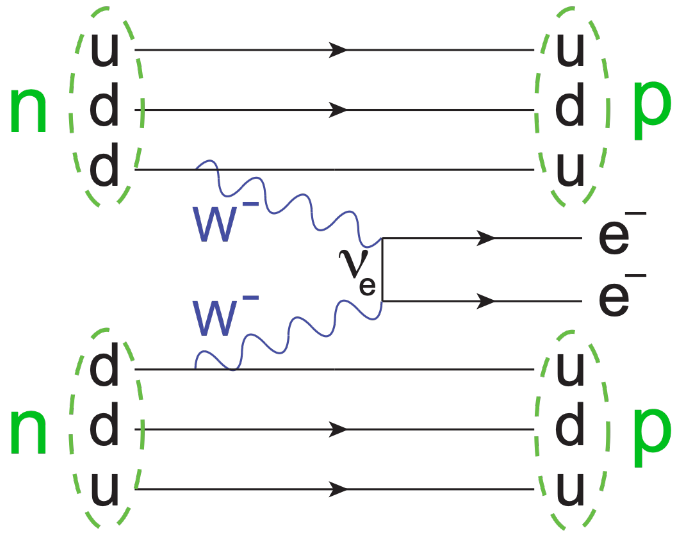
$\mathrm{U(1)}_{\mathrm{L}_\mu - \mathrm{L}_\tau}$ normal ordering :



The strongest bound set by KamLAND-Zen exp.

$\langle m_{\beta\beta}\rangle < 61\sim165$ meV

PRL 117, 082503 (2016)

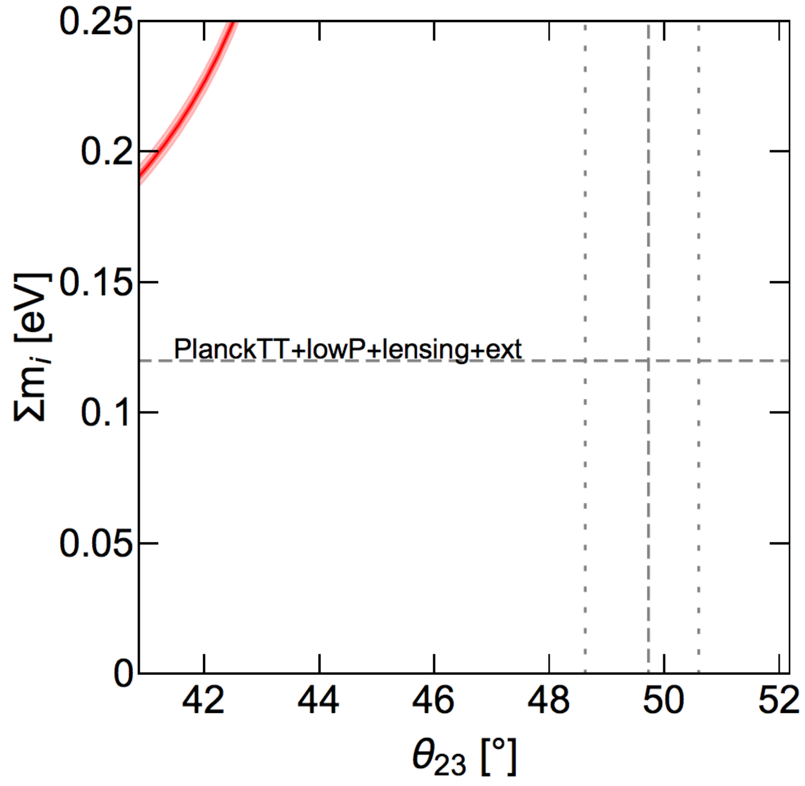


$$\Gamma \propto \mathrm{G_F^4} \times \langle \mathrm{m}_{\beta\beta} \rangle^2 \times |\mathrm{M_{nucl}}|^2$$

$$\langle m_{\beta\beta}\rangle \equiv \left|\sum_i (U_{\mathrm{PMNS}})_{ei}^2\, m_i\right| = \left|c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_2} m_2 + s_{13}^2 e^{i(\alpha_3 - 2\delta)} m_3\right|$$

Neutrino phenomenology : cases (ii), (iii)

$\mathrm{U(1)_{L_\mu - L_\tau}}$ normal ordering with $\mathrm{U(1)_{L_\mu - L_\tau}}(\Phi_1) = +1$:



The tight bound set by Planck exp.

$$\sum_i m_i < 0.12 \text{ eV}$$

Planck, arXiv:1807.06209

$\mathrm{U(1)}_{L_\alpha - L_\beta}$ models with an extra scalar doublet are excluded

Update of the results for case (i)

- The latest result of NuFIT

  NuFIT 4.1 released in 2019

- Adopting different constraint on $\sum_i m_i$

  degenerate m_is are assumed in the Planck results

- From a new analysis,

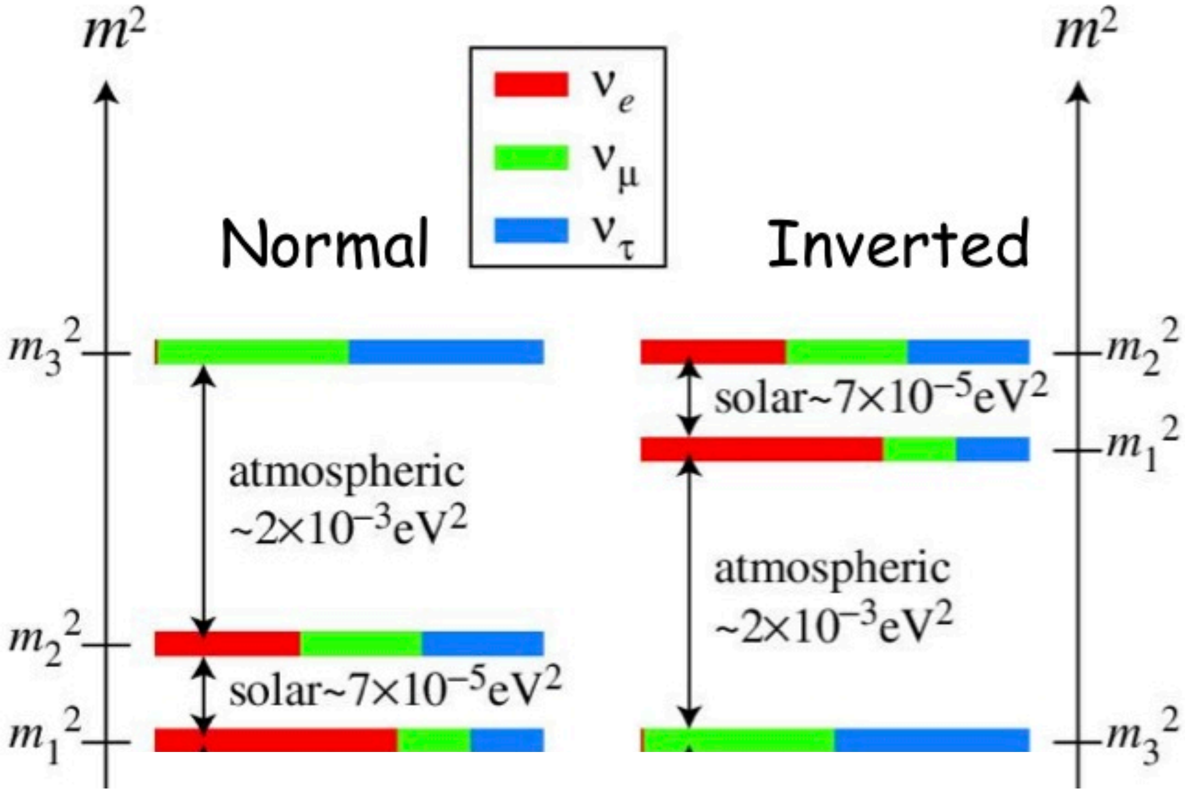
  $\sum_i m_i < 0.121$ eV (degenerate)

  $\boxed{\sum_i m_i < 0.146 \text{ eV (normal)}}$ We need this one.

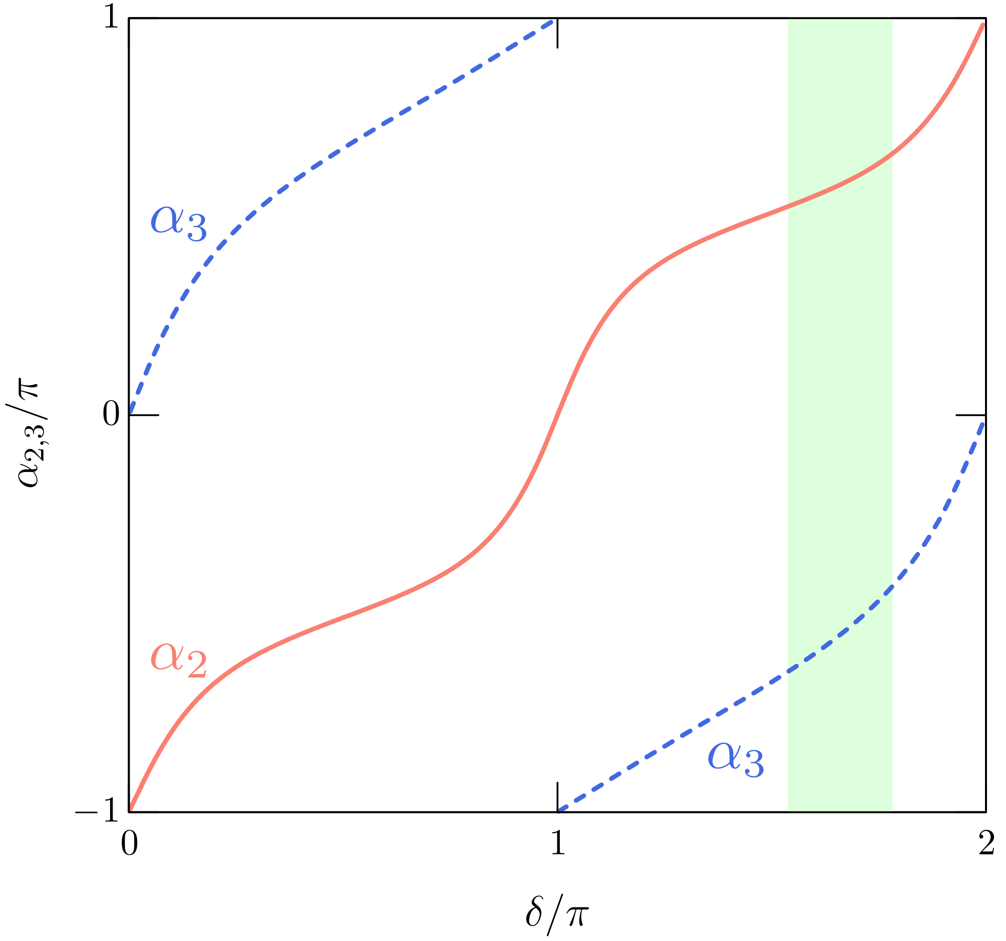
  $\sum_i m_i < 0.172$ eV (inverted)

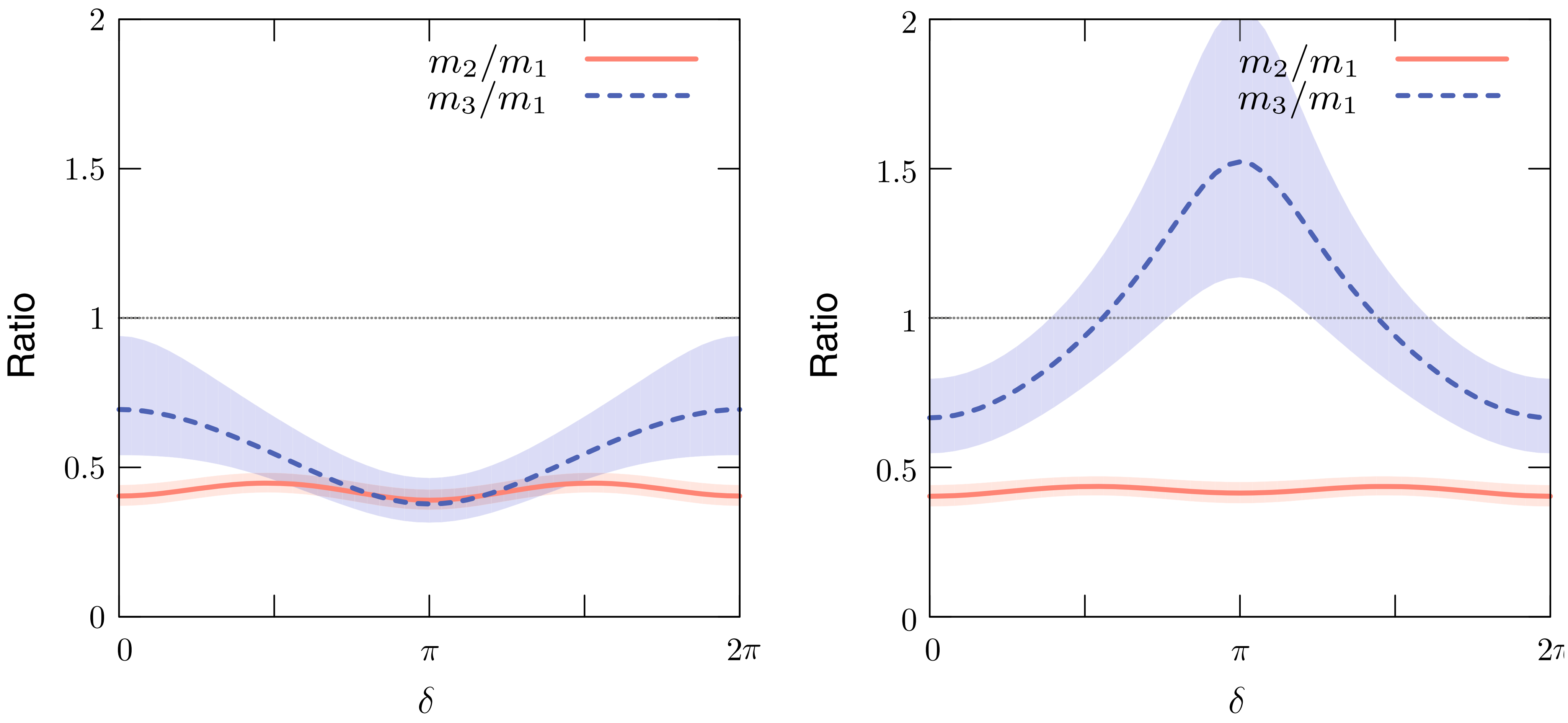
  arXiv:1907.12598 [astro-ph.CO]

Mass ordering



Majorana phase





(a) $\mathrm{U}(1)_{L_e-L_\mu}$ **(b)** $\mathrm{U}(1)_{L_e-L_\tau}$