Thermal Leptogenesis in the Minimal Gauged $U(1)_{L_\mu - L_\tau}$ Model

Juntaro Wada

@PPP2023

SCHOOL OF SCIENCE
THE UNIVERSITY OF TOKYO

Based on hep-ph 2305.18100

Alessandro Granelli, Koichi Hamaguchi, Natsumi Nagata, Maura E. Ramirez-Quezada, and JW

Leptogenesis

M. Fukugita, T. Yanagida Phys. Lett. B **174** 45-47 (1986)

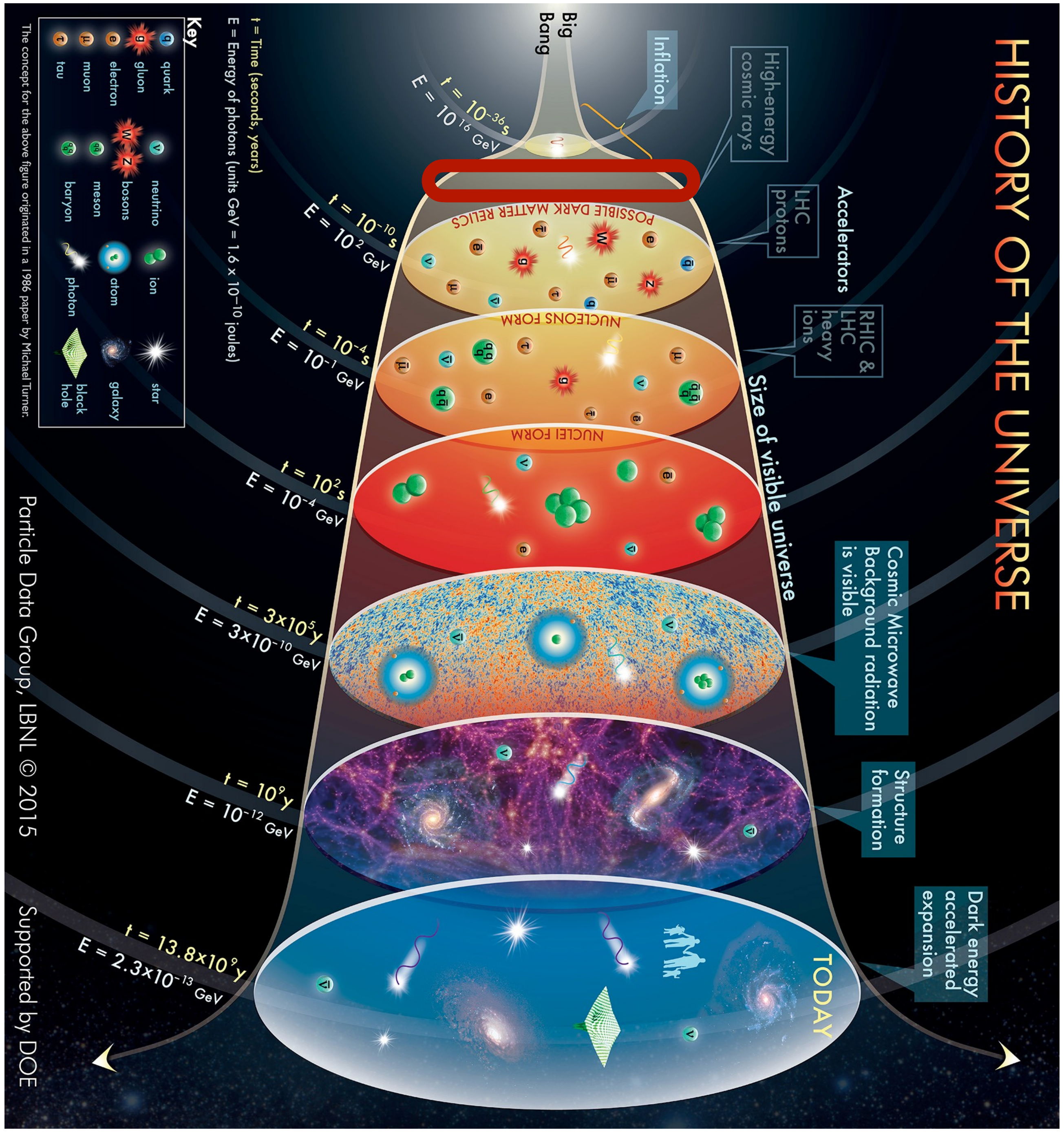
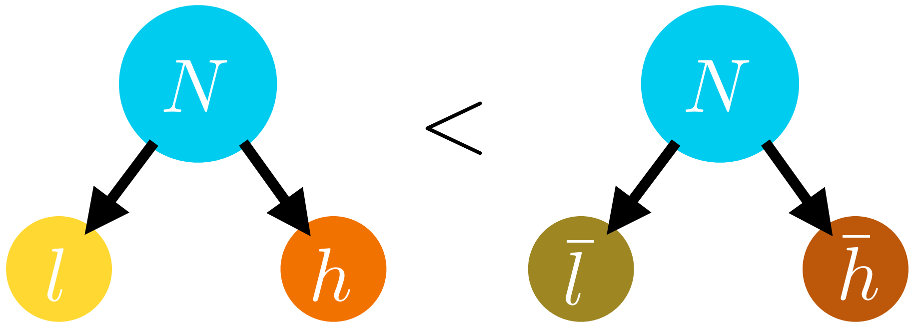


Fig from PDG

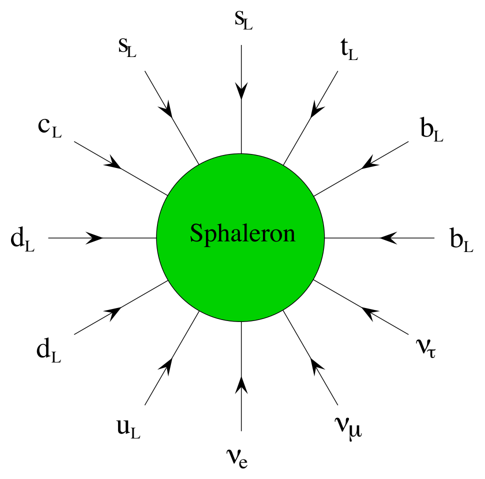
RH ν decay



$$> 10^{10}\ \mathrm{GeV}$$

Sphaleron process

V.A. Kuzmin et al., Phys. Rev. B **155** 36-42 (1985)

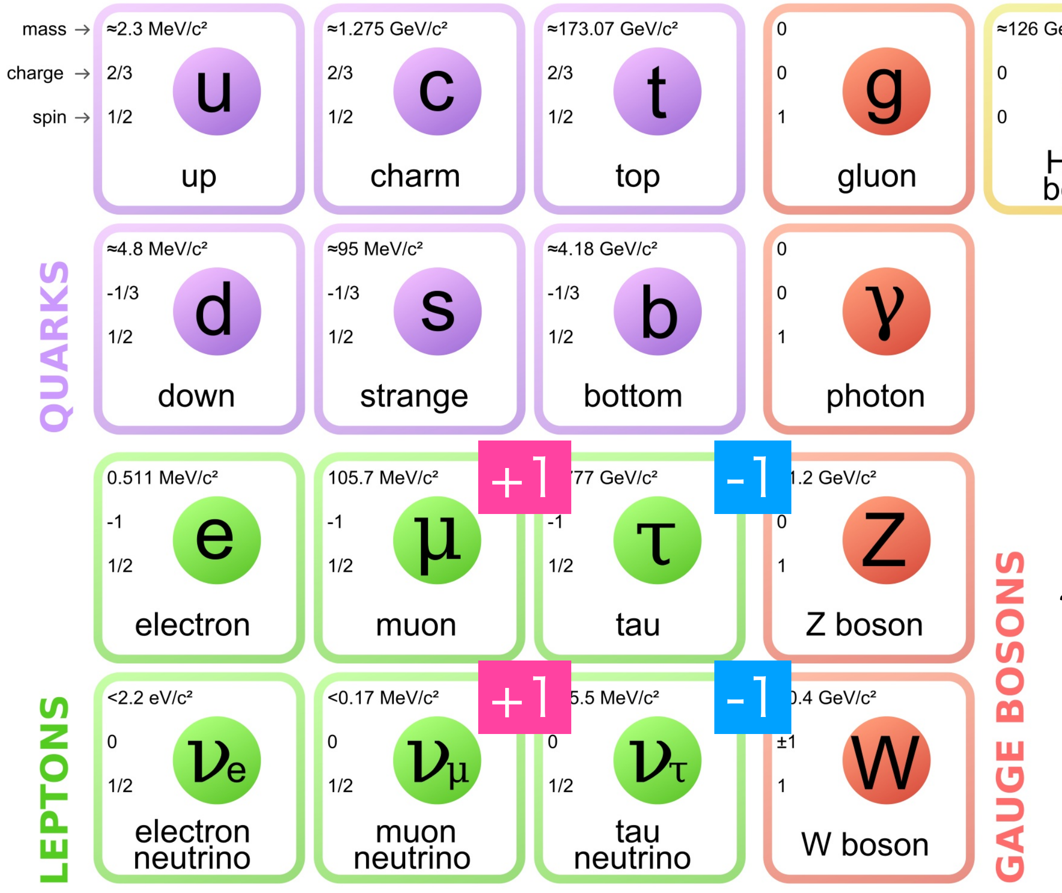


$$> 10^3 \mathrm{GeV}$$

Fig from W. Buchmüller,
Nucl. Phys. B Proc.Suppl. 235-236 329-335 (2013)

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

Minimal Setup



σ^{+1}

Z'

$N_e, N_\mu^{+1}, N_\tau^{-1}$

QUANTUM DIARIES
https://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory/

K. Asai, K. Hamaguchi, and N. Nagata, Eur. Phys. J.C 77 (2017) 11, 763

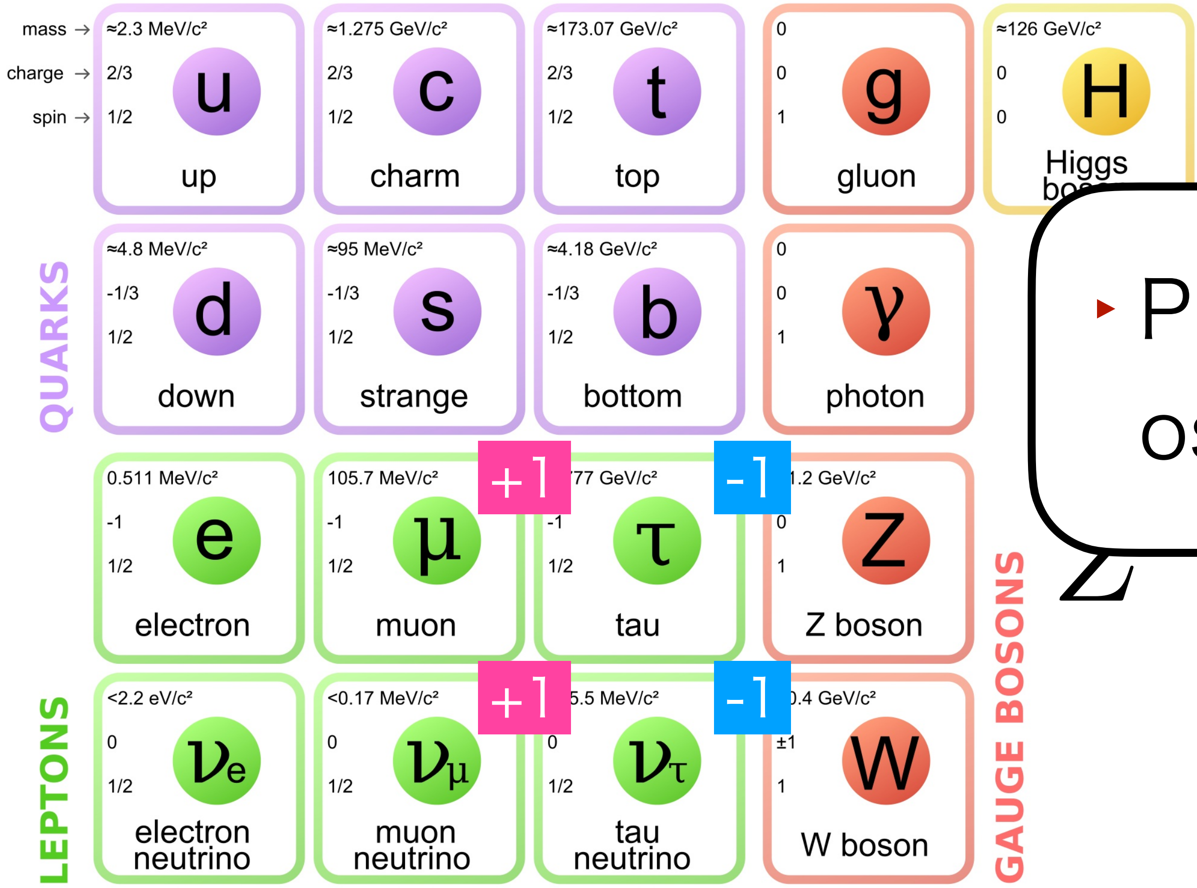
K. Asai, K. Hamaguchi, N. Nagata, S. Tseng, and K. Tsumura, Phys.Rev.D 99 (2019) 5, 055029

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

SM singlet

Breaking symmetry

Minimal Setup



σ +1

Z

- Predictive power for neutrino oscillation parameter

N_e, N_μ, N_τ +1 -1

QUANTUM DIARIES
https://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory/

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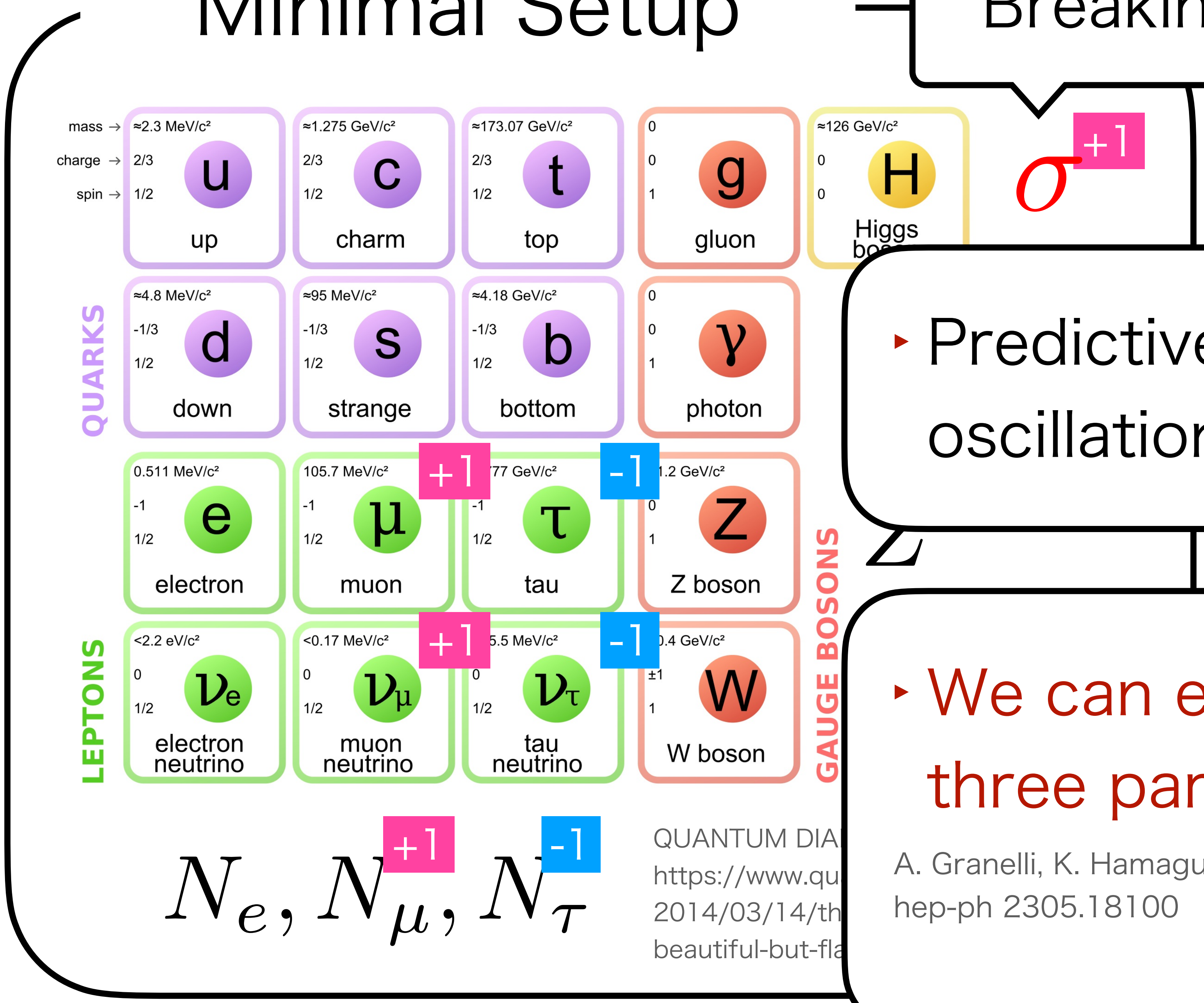


σ^{+1}

$N_e, \overset{+1}{N_\mu}, \overset{-1}{N_\tau}$

QUANTUM DIA
https://www.qu
2014/03/14/th
beautiful-but-fla

- Predictive power for neutrino oscillation parameter

- We can evaluate BAU with three parameters in thermal LG

A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, hep-ph 2305.18100

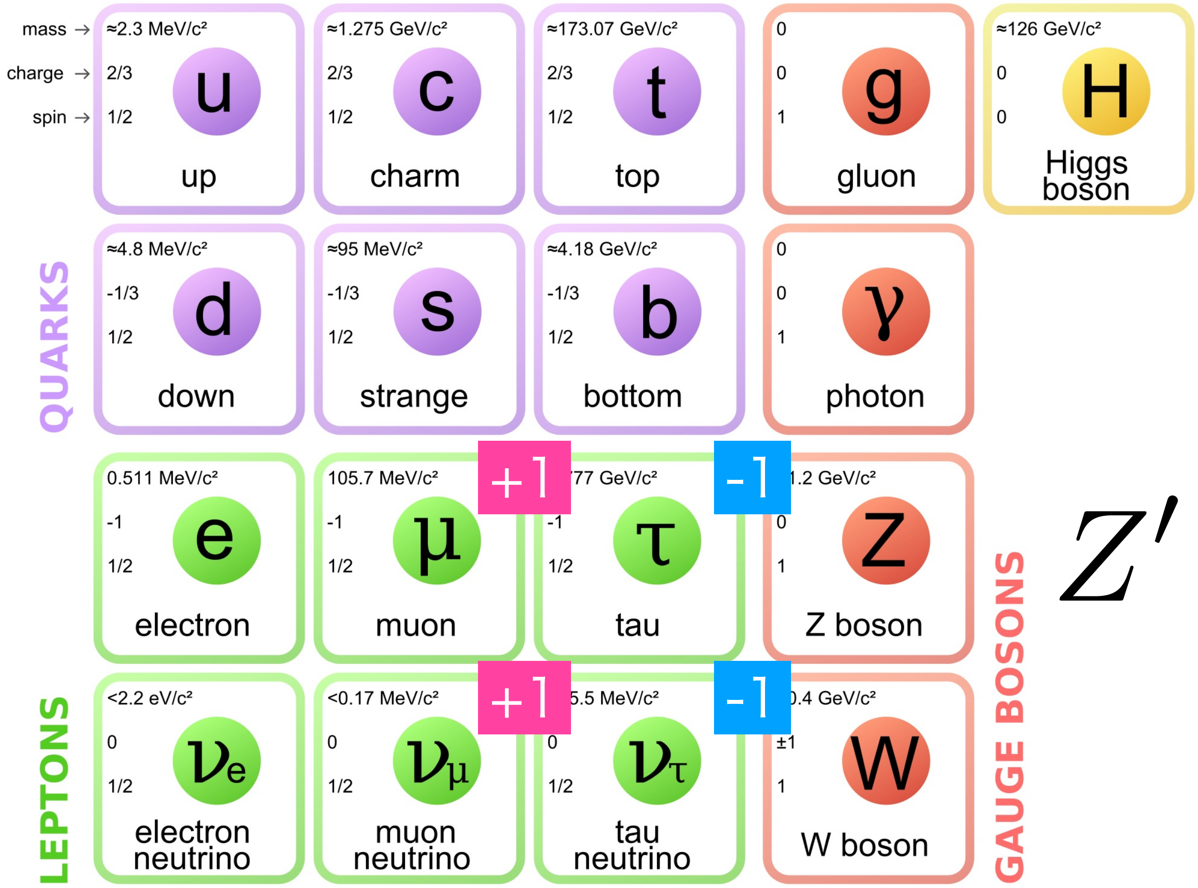
K. Asai, K. Hamaguchi, and N. Nagata, Eur. Phys. J.C 77 (2017) 11, 763
K. Asai, K. Hamaguchi, N. Nagata, S. Tseng, and K. Tsumura, Phys.Rev.D 99 (2019) 5, 055029

Outline

- ✓ Introduction
- ▸ Minimal Gauged $U(1)_{L_\mu - L_\tau}$ Model
- ▸ Thermal LG in $U(1)_{L_\mu - L_\tau}$ model
- ▸ Result
- ▸ Summary

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

Minimal Setup



σ +1

Z'

N_e, N_μ, N_τ +1 -1

QUANTUM DIARIES
https://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory/

$\langle \sigma \rangle \gg 10^{10}$ GeV

Interacting with Sterile neutrino

K. Asai, K. Hamaguchi, and N. Nagata, Eur. Phys. J.C 77 (2017) 11, 763

K. Asai, K. Hamaguchi, N. Nagata, S. Tseng, and K. Tsumura, Phys.Rev.D 99 (2019) 5, 055029

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

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

After H and σ getting VEVs…

$$\mathcal{L}_{mass} = -(\nu_e, \nu_\nu, \nu_\tau,) \mathcal{M}_D \begin{pmatrix} N_e^c \\ N_\mu^c \\ N_\tau^c \end{pmatrix} - \frac{1}{2} (N_e^c, N_\mu^c, N_\tau^c,) \mathcal{M}_R \begin{pmatrix} N_e^c \\ N_\mu^c \\ N_\tau^c \end{pmatrix} + h.c.$$

Where $\mathcal{M}_D = \frac{v}{\sqrt{2}} \begin{pmatrix} \lambda_e & 0 & 0 \\ 0 & \lambda_\mu & 0 \\ 0 & 0 & \lambda_\tau \end{pmatrix}$ $\mathcal{M}_R = \begin{pmatrix} M_{ee} & \lambda_{e\mu} \langle \sigma \rangle & \lambda_{e\tau} \langle \sigma \rangle \\ \lambda_{e\mu} \langle \sigma \rangle & 0 & M_{\mu\tau} \\ \lambda_{e\tau} \langle \sigma \rangle & M_{\mu\tau} & 0 \end{pmatrix}$

K. Asai, K. Hamaguchi, and N. Nagata, Eur. Phys. J.C 77 (2017) 11, 763

K. Asai, K. Hamaguchi, N. Nagata, S. Tseng, and K. Tsumura, Phys.Rev.D 99 (2019) 5, 055029

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

Because of this symmetry, structure of both Dirac and Majorana mass terms are tightly restricted.

→Strong predictive power for the neutrino sector

$$\mathcal{M}_{\nu_L} \simeq -\mathcal{M}_D \mathcal{M}_R^{-1} \mathcal{M}_D^T$$

$$U_{PMNS}^T \mathcal{M}_{\nu_L} U_{PMNS} = \mathrm{diag}(m_1, m_2, m_3)$$

Input

$\Delta m^2, \delta m^2,$

$\theta_{12}, \theta_{23}, \theta_{31}$

➡

Output

$\delta, \alpha_1, \alpha_2,$

m_1, m_2, m_3

Where $\mathcal{M}_D = \frac{v}{\sqrt{2}} \begin{pmatrix} \lambda_e & 0 & 0 \\ 0 & \lambda_\mu & 0 \\ 0 & 0 & \lambda_\tau \end{pmatrix}$ $\mathcal{M}_R = \begin{pmatrix} M_{ee} & \lambda_{e\mu} \langle \sigma \rangle & \lambda_{e\tau} \langle \sigma \rangle \\ \lambda_{e\mu} \langle \sigma \rangle & 0 & M_{\mu\tau} \\ \lambda_{e\tau} \langle \sigma \rangle & M_{\mu\tau} & 0 \end{pmatrix}$

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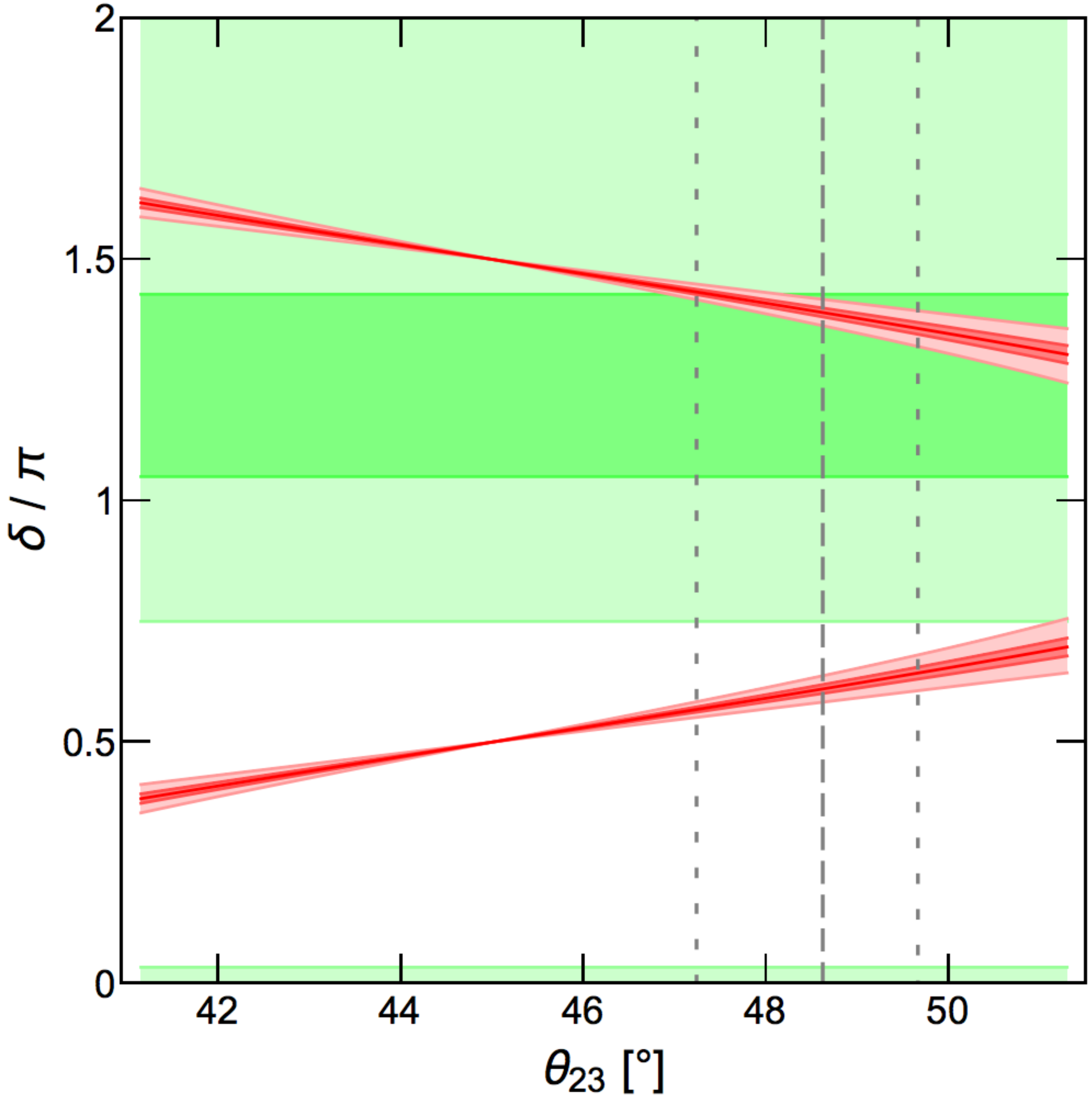

Fig from K. Asai et.al., JCAP 11 (2020) 013

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ghtly restricted.

for the neutrino sector

Input

$\Delta m^2, \delta m^2,$

$\theta_{12}, \theta_{23}, \theta_{31}$

➡

Output

$\delta, \alpha_1, \alpha_2,$

m_1, m_2, m_3

$$\cos\delta \simeq \frac{\cot\theta_{12}\cot\theta_{23}}{\sin\theta_{13}}$$

Two solutions $\delta,\ 2\pi - \delta$

K. Asai, K. Hamaguchi, and N. Nagata, Eur. Phys. J.C 77 (2017) 11, 763

K. Asai, K. Hamaguchi, N. Nagata, S. Tseng, and K. Tsumura, Phys.Rev.D 99 (2019) 5, 055029

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

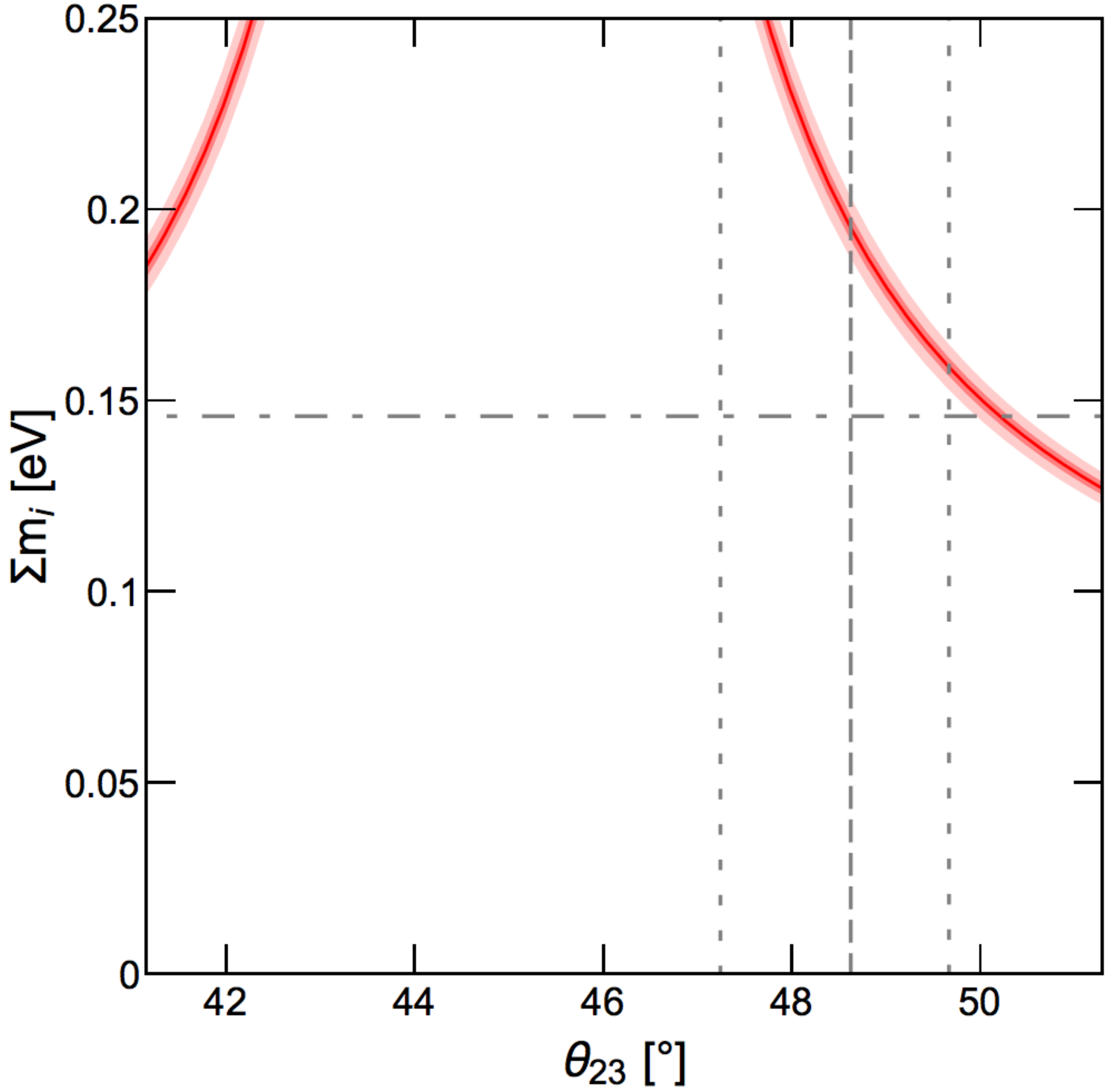

Fig from K. Asai et.al., JCAP 11 (2020) 013

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K. Asai, K. Hamaguchi, and N. Nagata, Eur. Phys. J.C 77 (2017) 11, 763

K. Asai, K. Hamaguchi, N. Nagata, S. Tseng, and K. Tsumura, Phys.Rev.D 99 (2019) 5, 055029

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Thermal LG in $U(1)_{L_\mu - L_\tau}$ model

To evaluate baryon asymmetry,

Input Output

$$\begin{array}{l}\Delta m^2, \delta m^2, \\ \theta_{12}, \theta_{23}, \theta_{31}\end{array} \Rightarrow \begin{array}{l}\delta, \alpha_1, \alpha_2, \\ m_1, m_2, m_3\end{array} \Rightarrow \mathcal{M}_{\nu_L} = U^*_{PMNS}\mathrm{diag}(m_1, m_2, m_3)U^{-1}_{PMNS}$$

$$\mathcal{M}_D = \frac{v}{\sqrt{2}}\begin{pmatrix}\lambda_e & 0 & 0 \\ 0 & \lambda_\mu & 0 \\ 0 & 0 & \lambda_\tau\end{pmatrix} \Rightarrow \mathcal{M}_R \simeq -\mathcal{M}_D^T \mathcal{M}_{\nu_L}^{-1} \mathcal{M}_D$$

$\mathcal{M}_D, \mathcal{M}_R \Rightarrow \eta_b$ baryon asymmetry

A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, hep-ph 2305.18100

Thermal LG in $U(1)_{L_\mu - L_\tau}$ model

To evaluate baryon as

Input

$\Delta m^2, \delta m^2,$

$\theta_{12}, \theta_{23}, \theta_{31}$

➡

Output

$\delta, \alpha_1, \alpha_2,$

m_1, m_2, m

Cf) Neutrino parameters in

CI parameterization

J. A. Casas and A. Ibarra. Nucl.Phys.B 618 (2001) 171-204

$$m_1, \Delta m^2, \delta m^2, \theta_{12}, \theta_{23}, \theta_{31},$$

$$\delta, \alpha_1, \alpha_2, M_1, M_2, M_3,$$

$$x_1, x_2, x_3, y_1, y_2, y_3$$

$$\mathcal{M}_D = \frac{v}{\sqrt{2}} \begin{pmatrix} \lambda_e & 0 & 0 \\ 0 & \lambda_\mu & 0 \\ 0 & 0 & \lambda_\tau \end{pmatrix} \Rightarrow \mathcal{M}_R \simeq -\mathcal{M}_D^T \mathcal{M}_{\nu_L}^{-1} \mathcal{M}_D$$

$\mathcal{M}_D, \mathcal{M}_R$ ➡ η_b baryon asymmetry

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Thermal LG in $U(1)_{L_\mu - L_\tau}$ model

$$M_i \simeq 6 \times 10^{14}\ \mathrm{GeV} \left(\frac{0.05\ \mathrm{eV}}{m_1}\right) \lambda^2 \beta_i(\theta, \phi)$$

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

$n_3)U^{-1}_{PMNS}$

$\theta_{12}, \theta_{23}, \theta_{31}$ m_1, m_2, m_3

$$\mathcal{M}_D = \frac{v}{\sqrt{2}} \begin{pmatrix} \lambda_e & 0 & 0 \\ 0 & \lambda_\mu & 0 \\ 0 & 0 & \lambda_\tau \end{pmatrix}$$ ➡ $$\mathcal{M}_R \simeq -\mathcal{M}_D^T \mathcal{M}_{\nu_L}^{-1} \mathcal{M}_D$$

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Thermal LG works when

$$10^{11-12}\ \mathrm{GeV} \lesssim M_1$$

$n_3)U_{PMNS}^{-1}$

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Thermal LG works when

$$10^{11-12}\ \text{GeV} \lesssim M_1$$

y_τ in thermal equilibrium at

$$T \sim 10^{12}\text{GeV}$$

Flavor effect affects thermal LG

R. Barbieri, et.al., Nucl.Phys.B 575 (2000) 61-77

E. Nardi, et.al., JHEP 01 (2006) 164

A. Abada, et.al., JCAP 04 (2006) 004

$$\mathcal{M}_D = \frac{v}{\sqrt{2}} \begin{pmatrix} \lambda_e & 0 & 0 \\ 0 & \lambda_\mu & 0 \\ 0 & 0 & \lambda_\tau \end{pmatrix}$$

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Thermal LG works when

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$^{-1}_{PMNS}$

Numerical calculation with DME by ULYSSES

A. Granelli, et.al., Comput.Phys.Commun. 262 (2021) 107813

A. Granelli, et.al., Comput.Phys.Commun. 291 (2023) 108834

$$\mathcal{M}_D = \frac{v}{\sqrt{2}} \begin{pmatrix} \lambda_e & 0 & 0 \\ 0 & \lambda_\mu & 0 \\ 0 & 0 & \lambda_\tau \end{pmatrix}$$

$\mathcal{M}_D, \mathcal{M}_R$ → η_b baryon asymmetry

A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, hep-ph 2305.18100

Assumption

- $U(1)_{L_\mu - L_\tau}$ gauge symmetry is never restored after the reheating
- singlet scalar field associated σ and Z' are sufficiently heavy so that these fields are always absent from the thermal bath

▶ $\langle \sigma \rangle >> T_R$

- The masses of all three right-handed neutrinos are smaller than the reheating temperature.

▶ $|M_{ee,\mu\tau}|, |\lambda_{e\mu,e\tau} \langle \sigma \rangle| < T_R$

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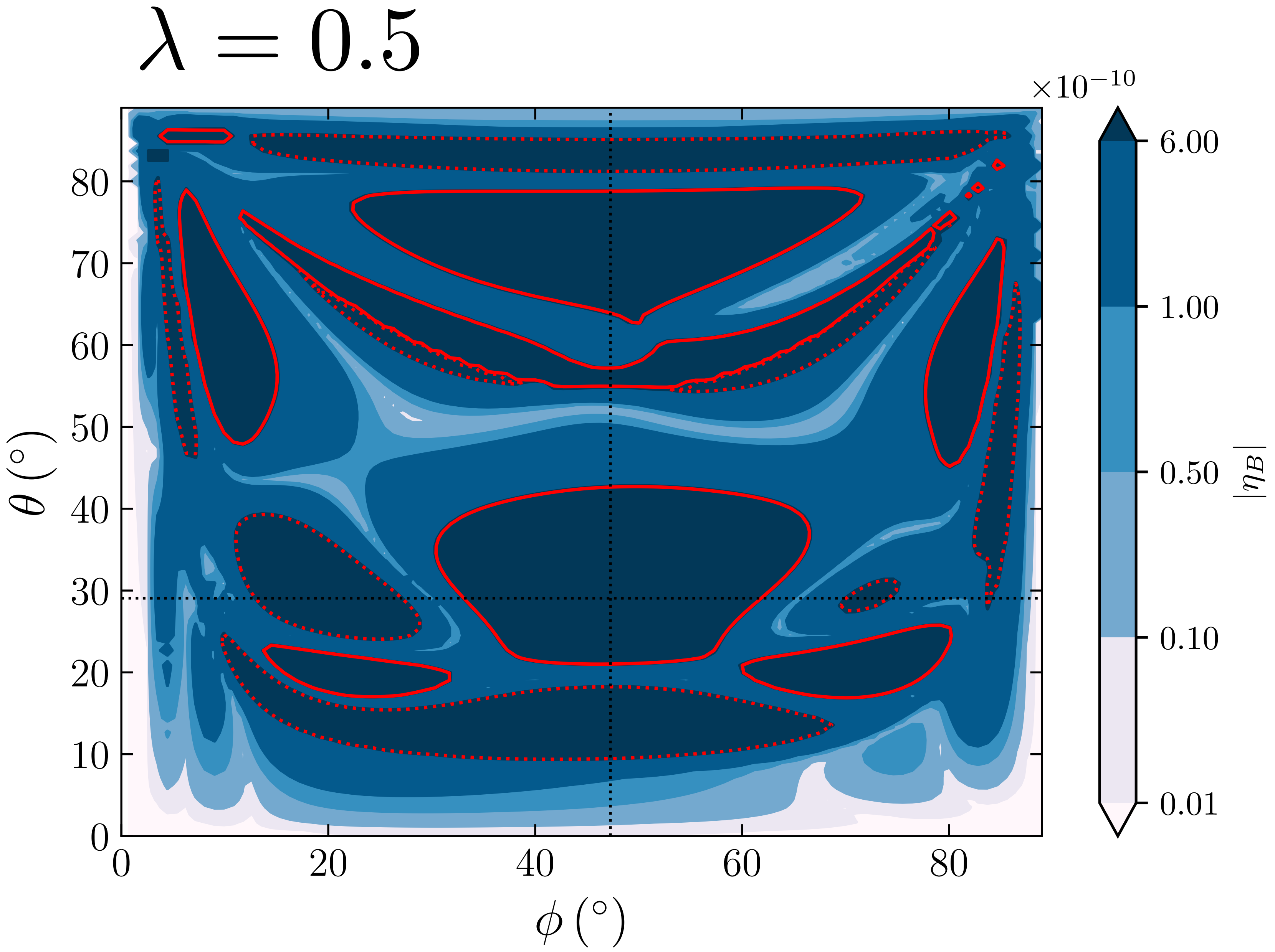
Result



Set I

$\theta_{12} = 33.41^\circ$

$\theta_{13} = 8.58^\circ$

$\theta_{23} = 39.7^\circ$

$\Delta m^2_{21} = 7.41 \times 10^{-5}\,\mathrm{eV}^2$

$\Delta m^2_{31} = 2.507 \times 10^{-3}\,\mathrm{eV}^2$

Input parameters are taken from NuFit ver 5.2

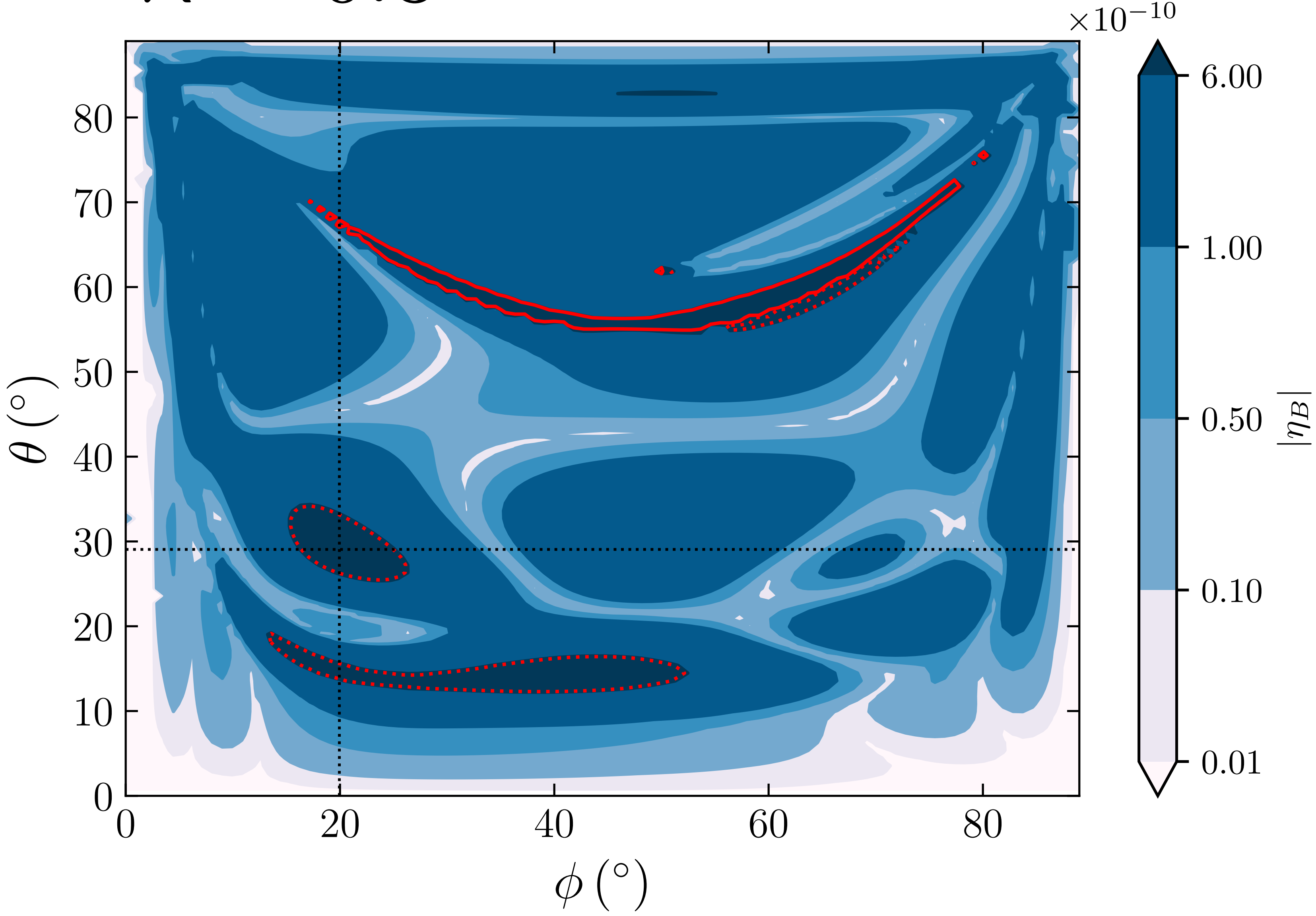
NuFIT Collaboration, NuFIT v5.2, http://www.nu-fit.org.

I. Esteban, et.al., JHEP 09 (2020) 178

A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, hep-ph 2305.18100

Result

$\lambda = 0.3$



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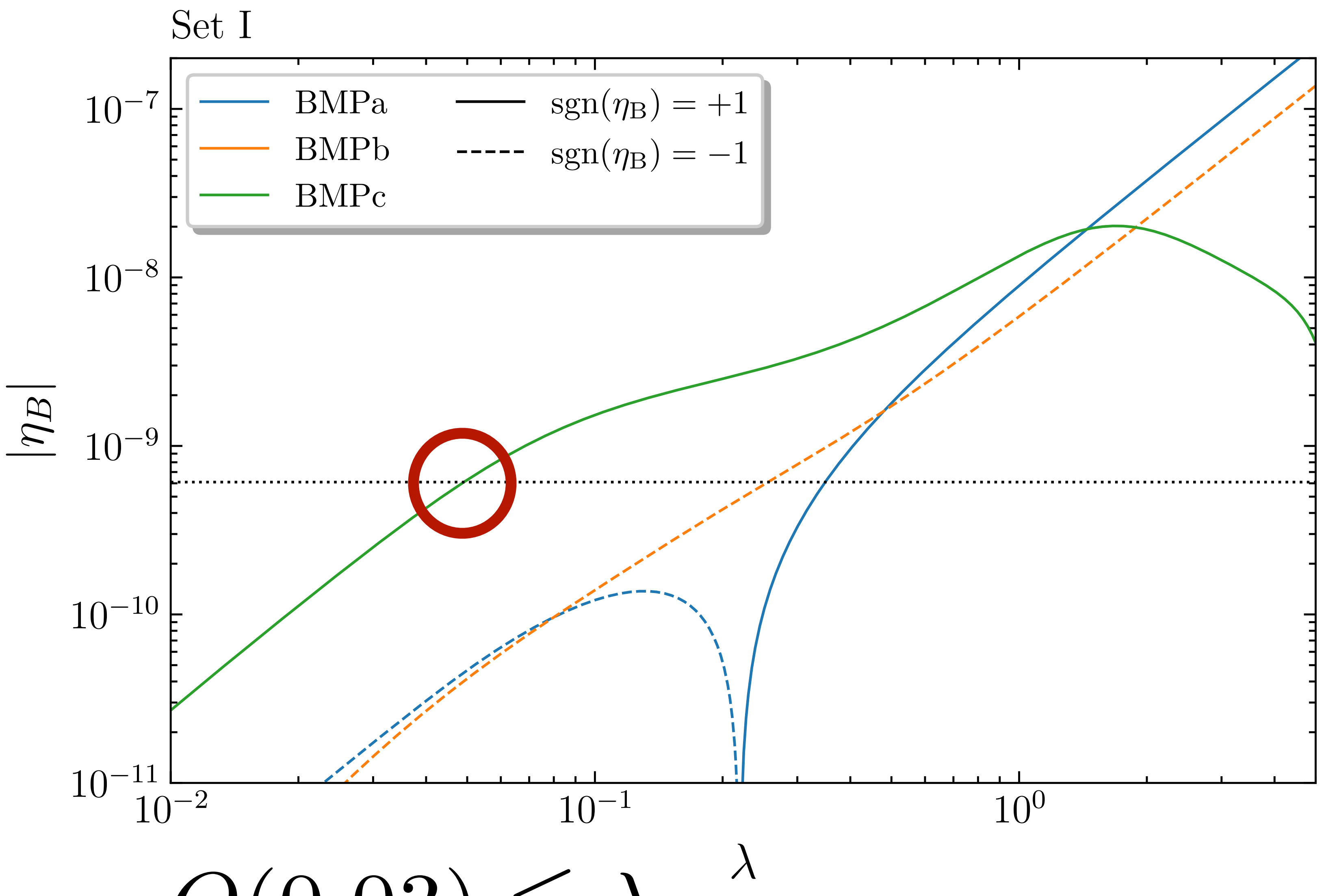
Result



$$O(0.03) \lesssim \lambda$$

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This is larger than those obtained in the context of non-thermal LG K. Asai, K. Hamaguchi, N. Nagata, and S. Tseng, JCAP 11 (2020) 013

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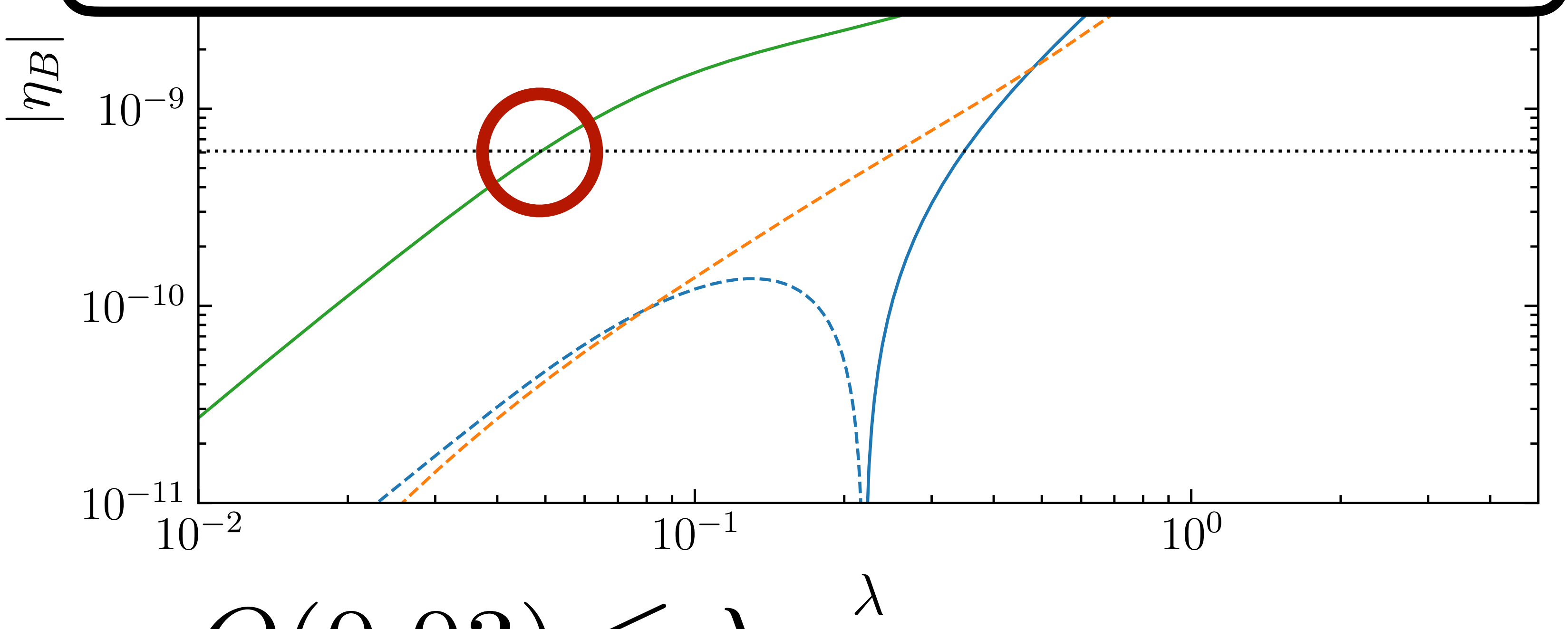
▶ $10^{11-12}\ \mathrm{GeV} \lesssim M_1$



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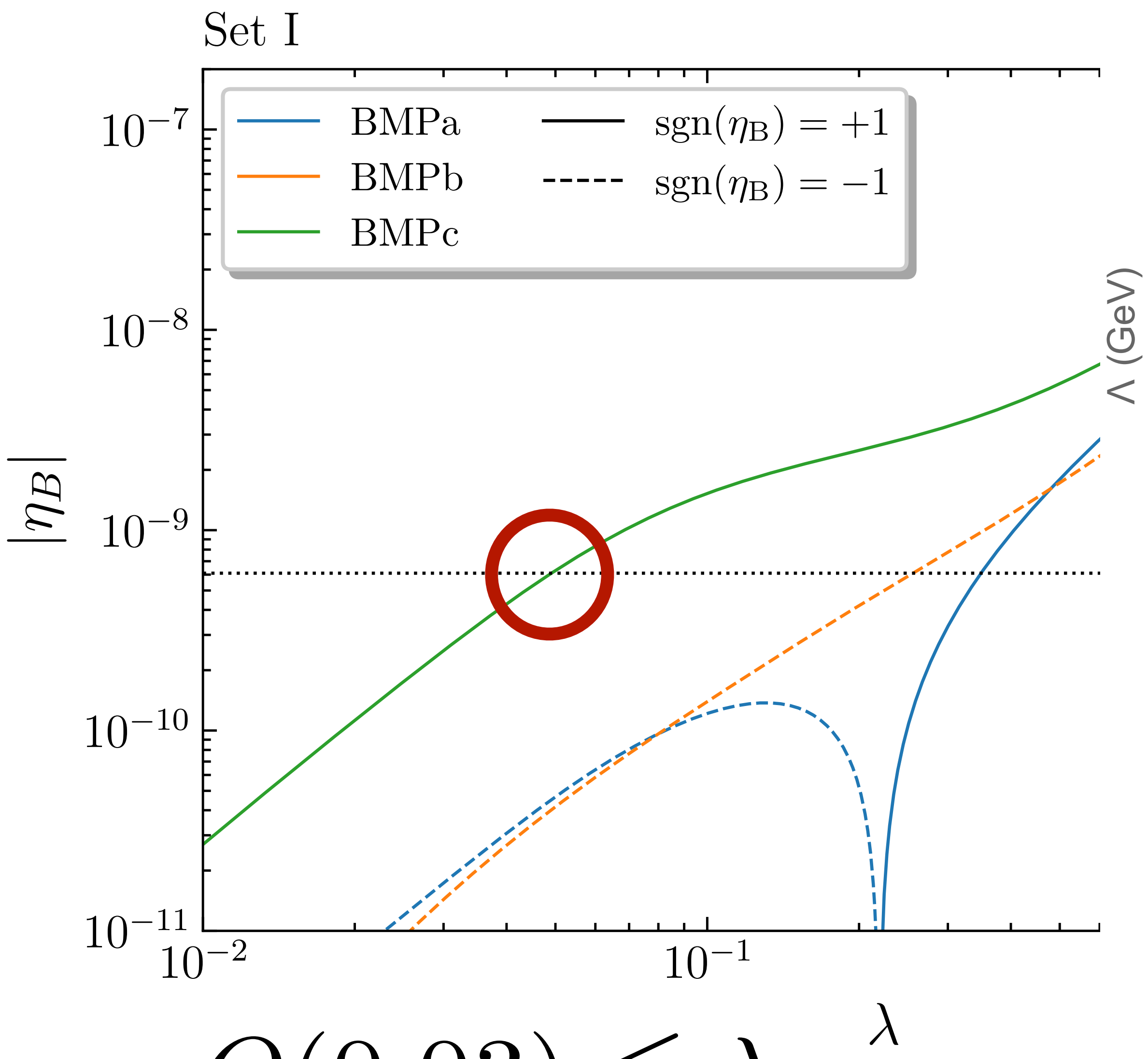

$$O(0.03) \lesssim \lambda$$

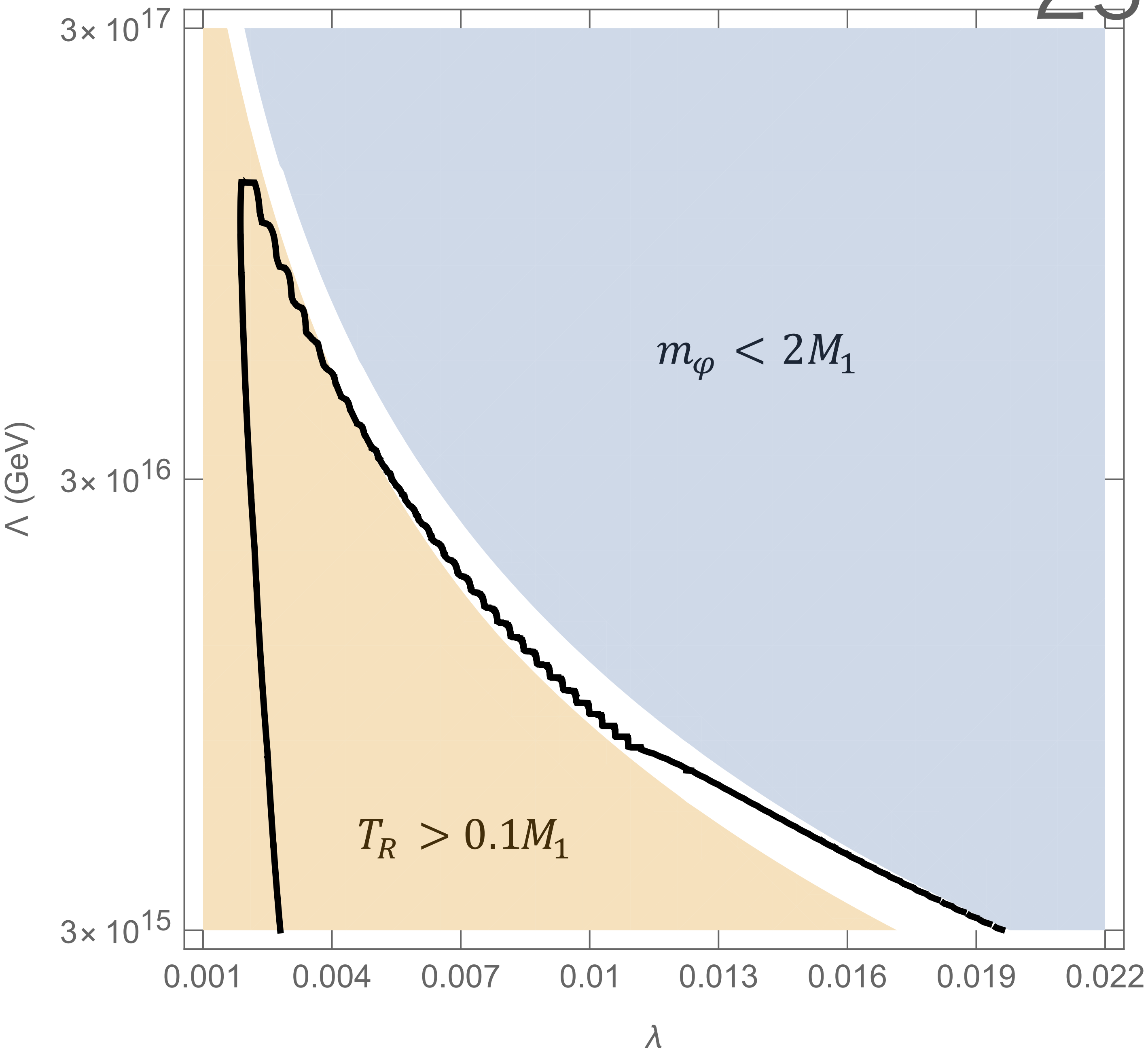

Fig from
K. Asai, K. Hamaguchi, N. Nagata, and S. Tseng, JCAP 11 (2020) 013

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Summary

- In Minimal gauged $U(1)_{L_\mu - L_\tau}$ model, the phases and the sum of the light neutrino masses are predictable because of a restricted neutrino mass matrix structure.
- Additionally, in the context of thermal leptogenesis, the BAU can be computed in terms of the three remaining free variables
- Mass of the lightest RH ν, $M_1 \gtrsim 10^{11-12}~\mathrm{GeV}$ setting LG scale in the considered model which is higher than that of the non-thermal scenario.

Backup

Benchmark Point

Set I	**Set II**
$\theta_{12} = 33.41^\circ$	$\theta_{12} = 33.41^\circ$
$\theta_{13} = 8.58^\circ$	$\theta_{13} = 8.54^\circ$
$\theta_{23} = 39.7^\circ$	$\theta_{23} = 51.9^\circ$
$\Delta m^2_{21} = 7.41 \times 10^{-5}\,\mathrm{eV}^2$	$\Delta m^2_{21} = 7.41 \times 10^{-5}$
$\Delta m^2_{31} = 2.507 \times 10^{-3}\,\mathrm{eV}^2$	$\Delta m^2_{31} = 2.511 \times 10^{-3}\,\mathrm{eV}^2$

We have taken $3\,\sigma$ ranges of the neutrino mixing angle θ_{23} to avoid constraint on sum of neutrino mass.

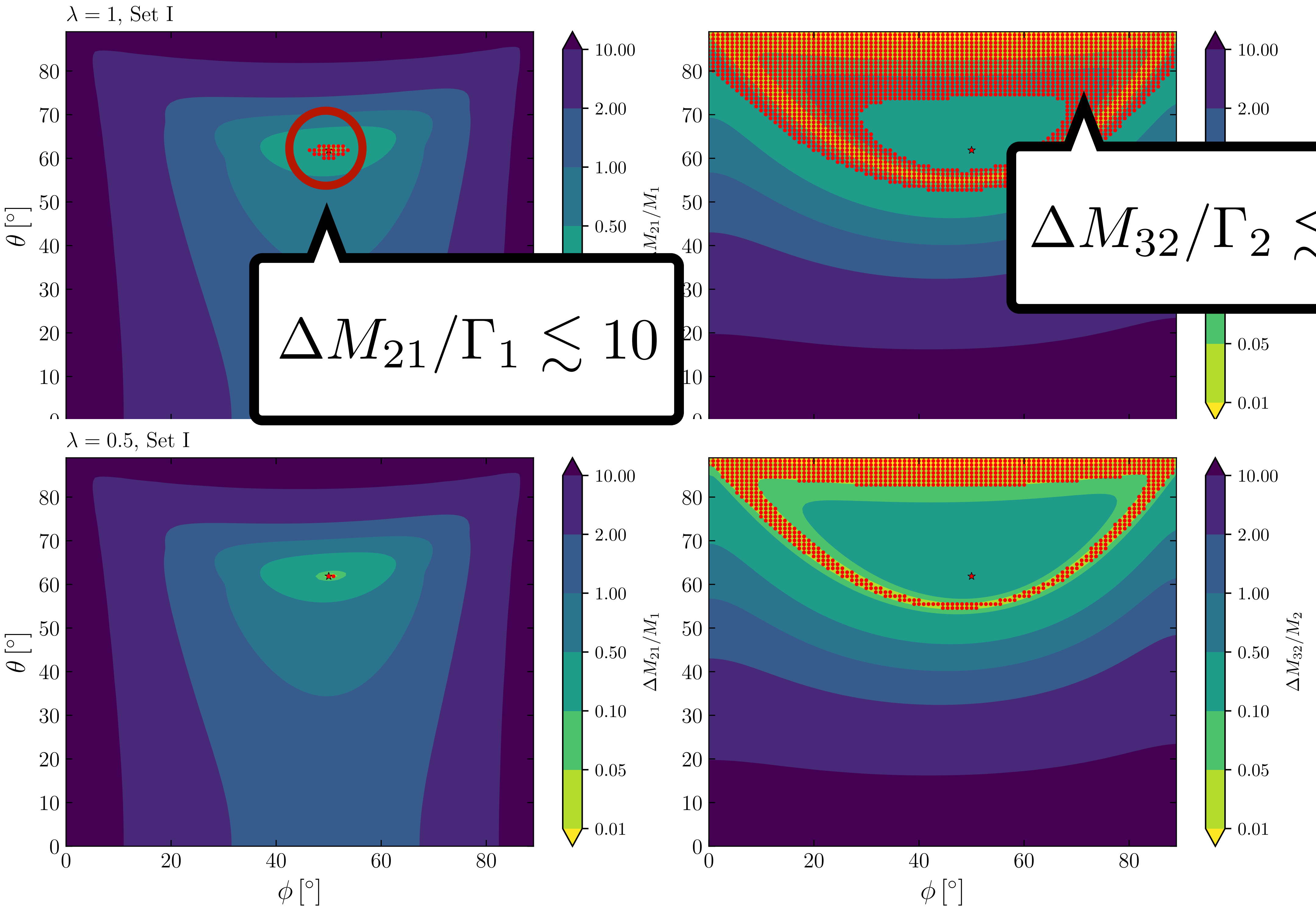
Cf) NuFit data

NuFIT Collaboration, NuFIT v5.2, http://www.nu-fit.org.
I. Esteban, et.al., JHEP 09 (2020) 178

Neutrino Masses and Mixing Parameters

Parameters (units)	θ_{12} ($^\circ$)	θ_{13} ($^\circ$)	θ_{23} ($^\circ$)	Δm^2_{21} (10^{-5} eV^2)	Δm^2_{31} (10^{-3} eV^2)
With SK	$33.41^{+0.75}_{-0.72}$	$8.58^{+0.11}_{-0.11}$	$42.2^{+1.1}_{-0.9}$	$7.41^{+0.21}_{-0.20}$	$2.507^{+0.026}_{-0.027}$
3σ **range**	$[31.31, 35.74]$	$[8.23, 8.91]$	$[39.7, 51.0]$	$[6.82, 8.03]$	$[2.427, 2.590]$
Without SK	$33.41^{+0.75}_{-0.72}$	$8.54^{+0.11}_{-0.12}$	$49.1^{+1.0}_{-1.3}$	$7.41^{+0.21}_{-0.20}$	$2.511^{+0.028}_{-0.027}$
3σ **range**	$[31.31, 35.74]$	$[8.19, 8.89]$	$[39.6, 51.9]$	$[6.82, 8.03]$	$[2.427, 2.590]$

Impact of Resonance Effects



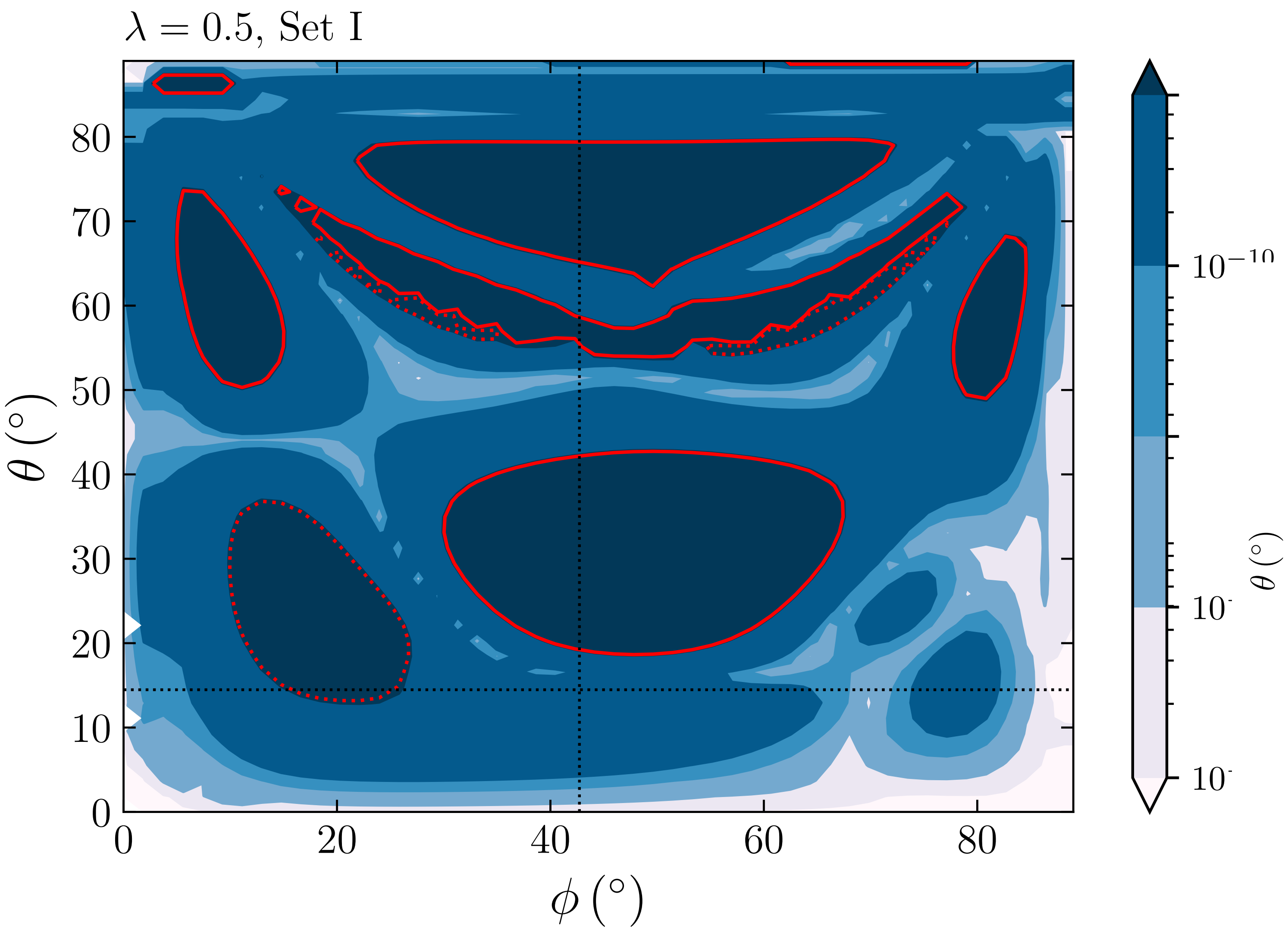
$\Delta M_{21}/\Gamma_1 \lesssim 10$

$\Delta M_{32}/\Gamma_2 \lesssim 10$

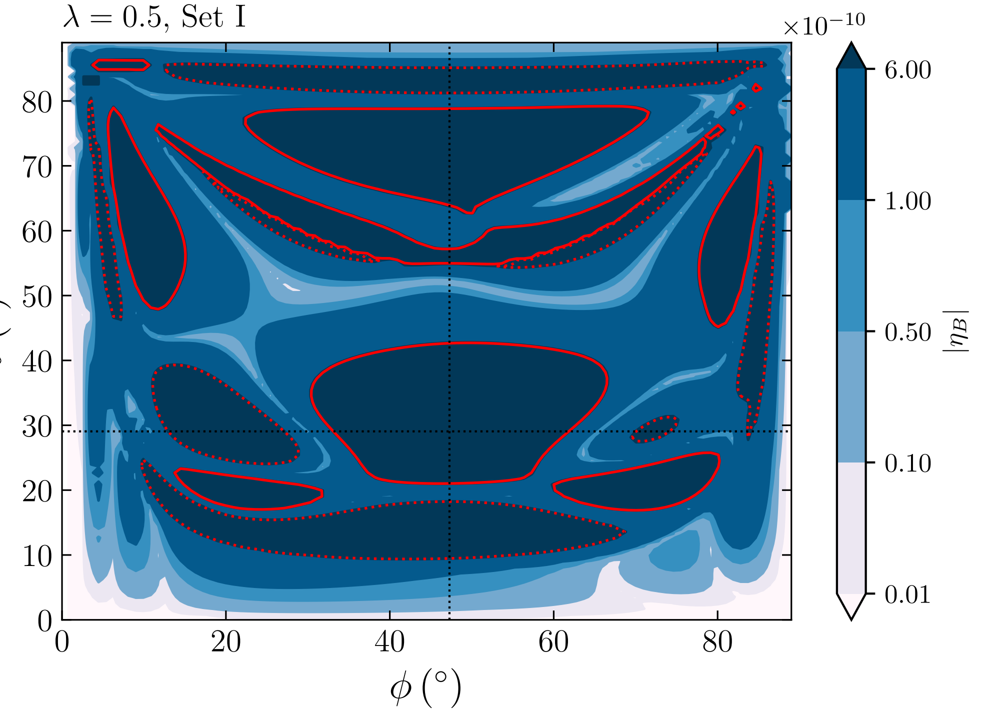
A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, hep-ph 2305.18100

Dependence of initial condition

When we take thermal initial abundance (TIA),



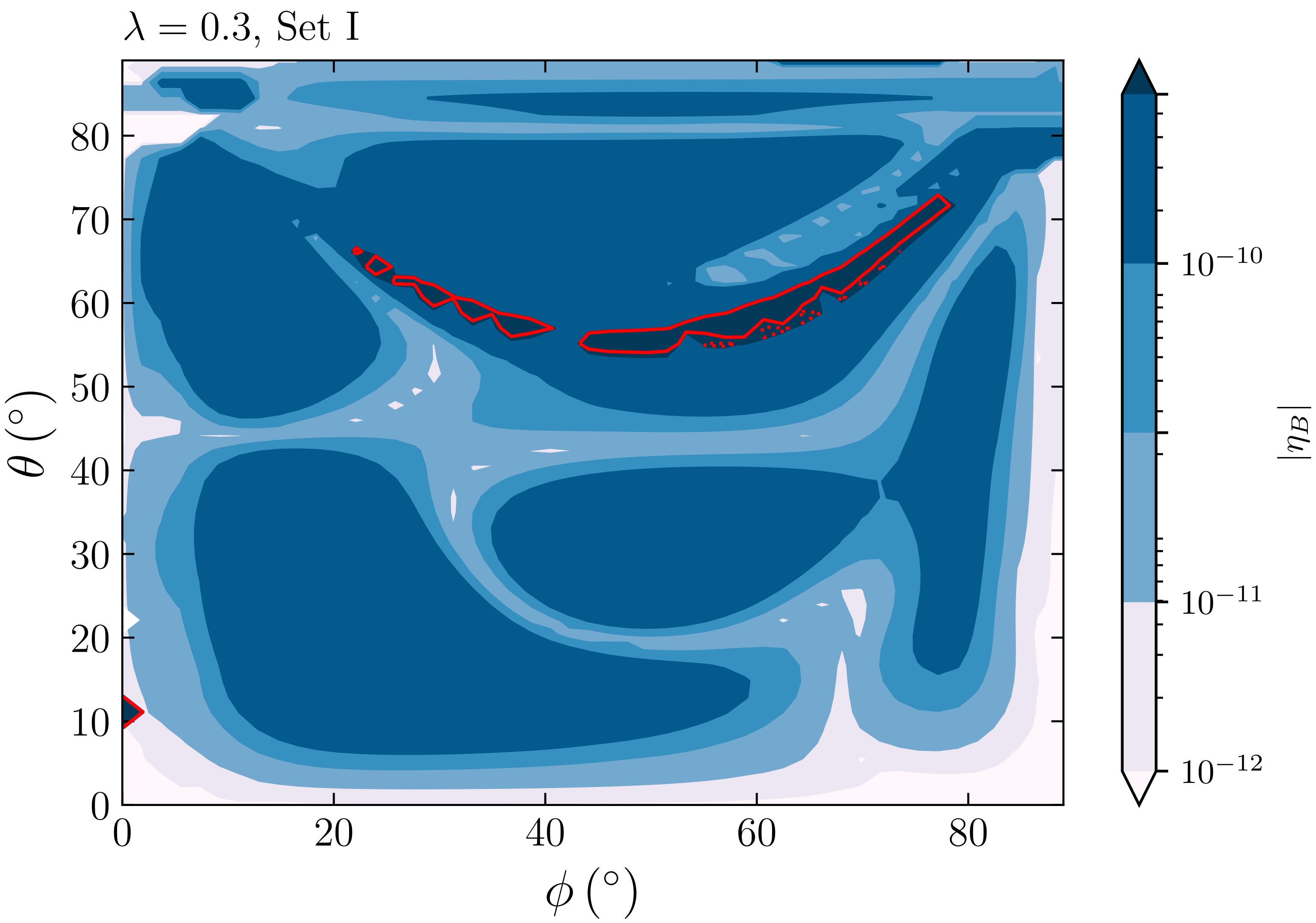
Cf) VIA



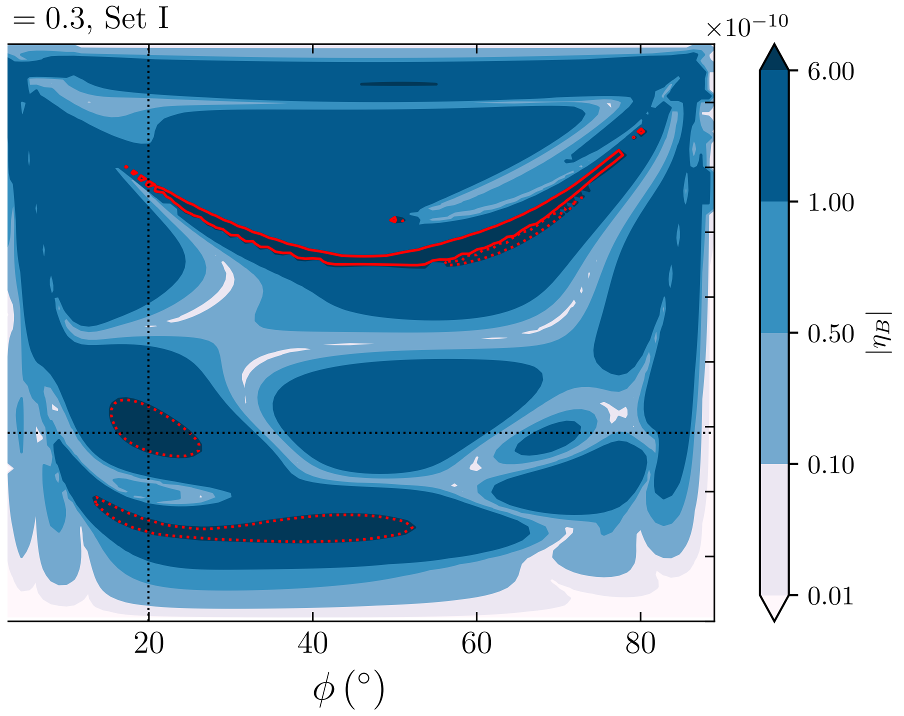
$$(\lambda_e, \lambda_\mu, \lambda_\tau) = \lambda(\cos\theta, \sin\theta\cos\phi, \sin\theta\sin\phi)$$

Dependence of initial condition

When we take thermal initial abundance (TIA),


$\lambda = 0.3$, Set I

Cf) VIA


= 0.3, Set I

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