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

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@SUSY2024

SCHOOL OF SCIENCE
THE UNIVERSITY OF TOKYO

Based on JHEP 09 (2023) 079 [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)

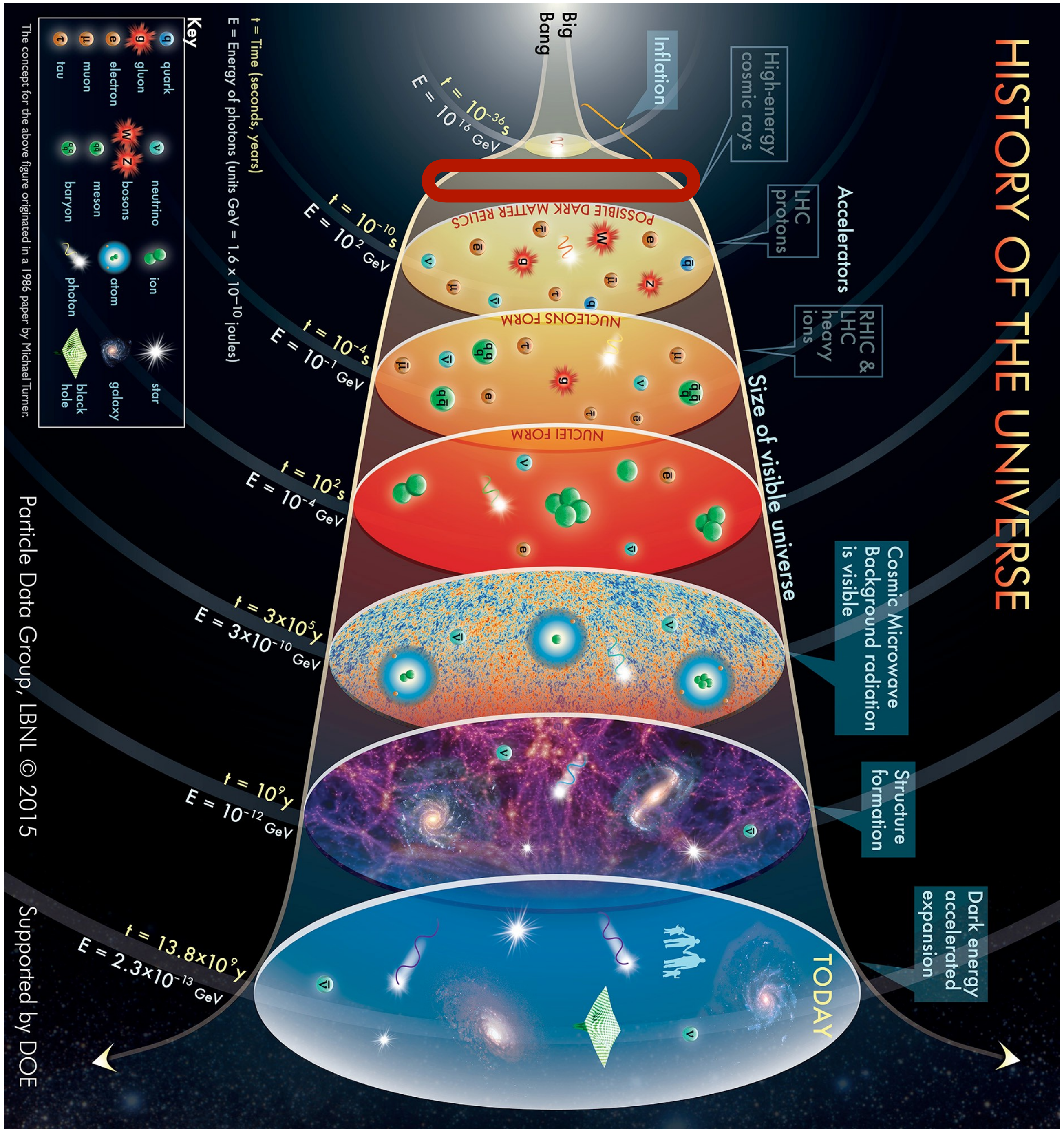
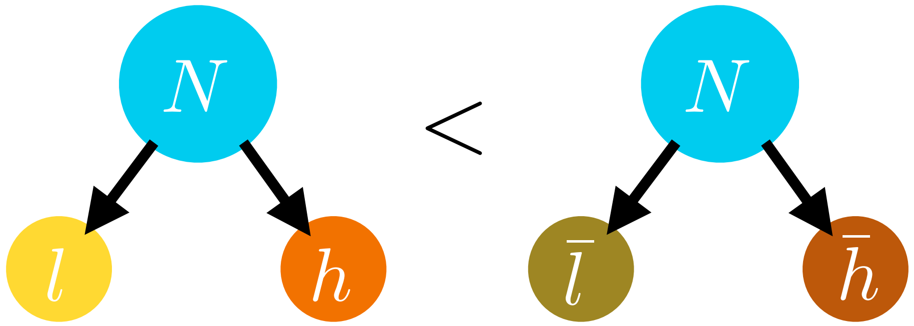


Fig from PDG

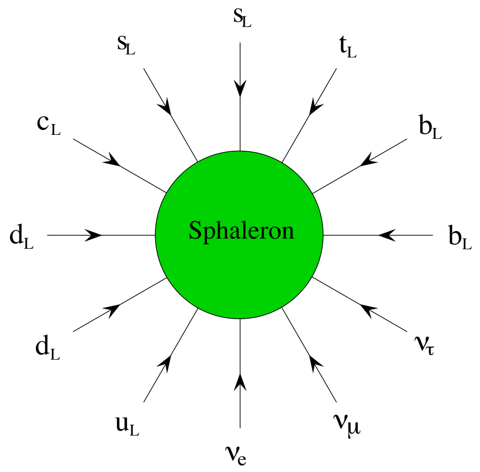
RH ν decay



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

Sphaleron process

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

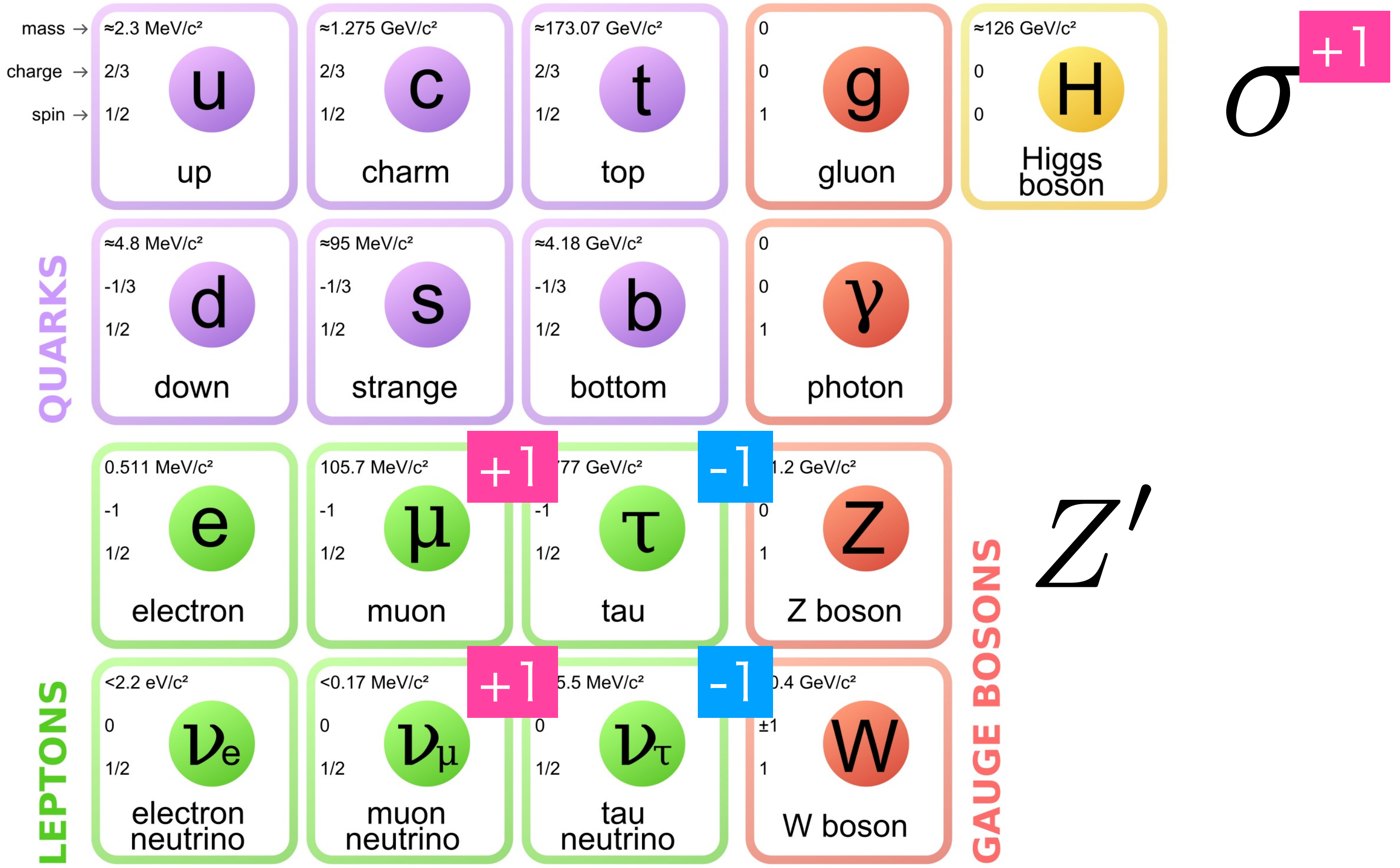


$$> 10^3\mathrm{GeV}$$

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

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

Minimal Setup



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

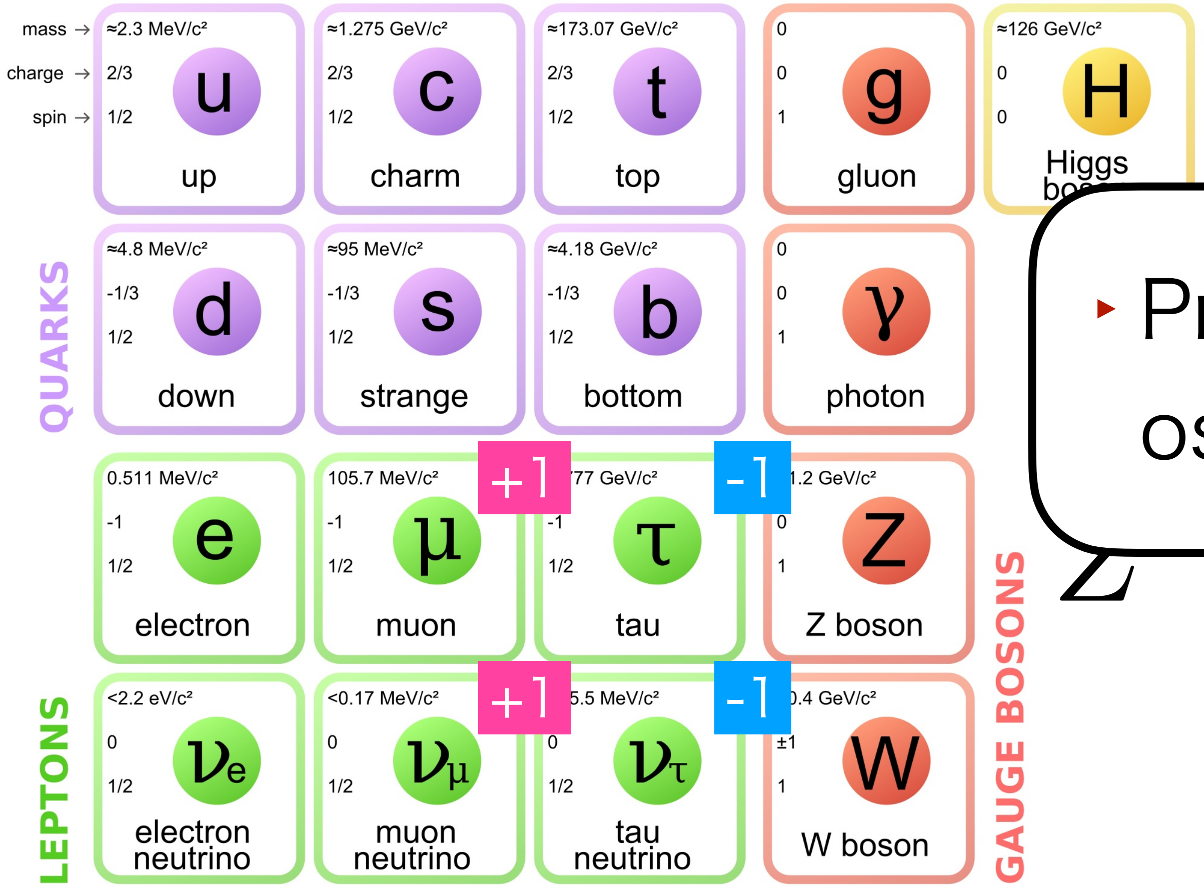
QUANTUM DIARIES
https://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory/

K. Asai, et.al., Eur. Phys. J.C 77 (2017) 11, 763

K. Asai, et.al., Phys.Rev.D 99 (2019) 5, 055029

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

Minimal Setup



σ +1

Z

- Predictive power for neutrino oscillation parameter

N_e, N_μ, N_τ +1 -1

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

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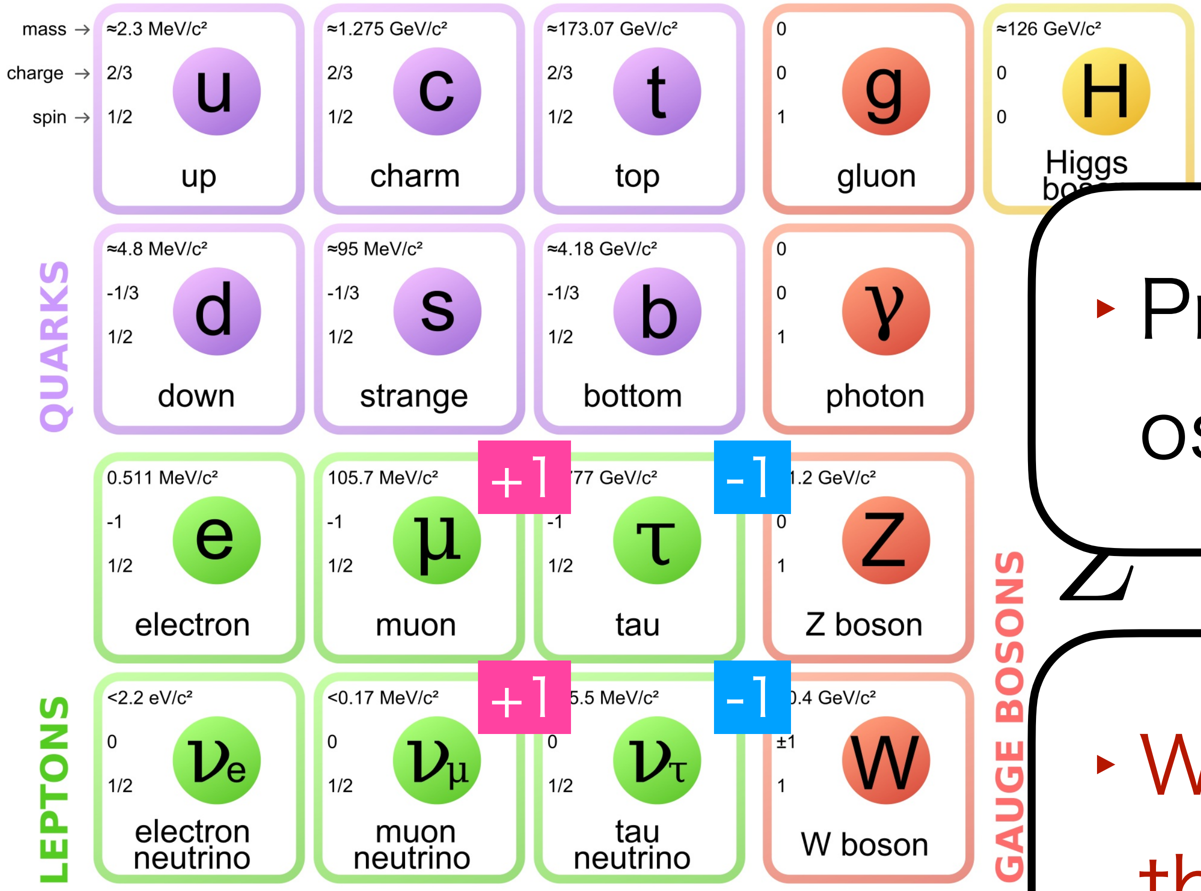

σ^{+1}

Z

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

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, JHEP 09 (2023) 079 [hep-ph 2305.18100]

K. Asai, et.al., Eur. Phys. J.C 77 (2017) 11, 763

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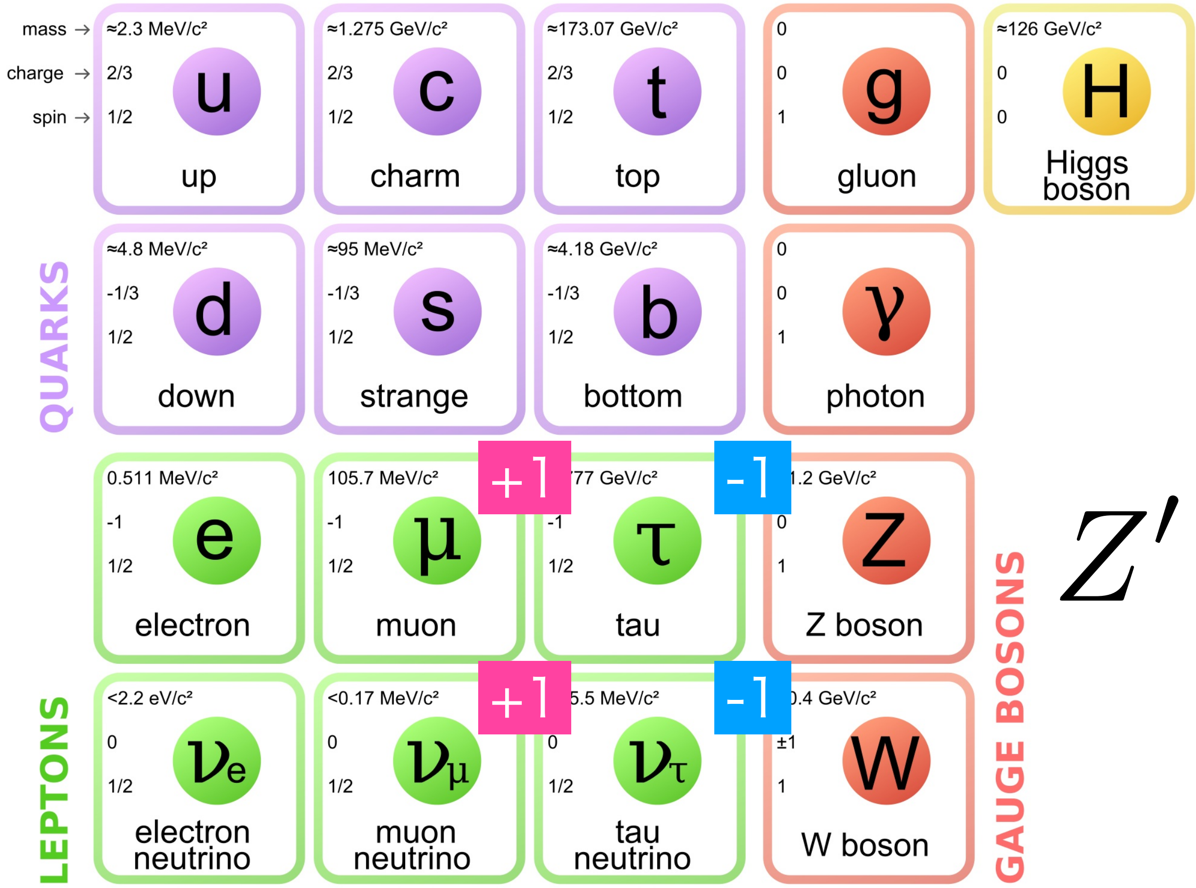
Outline

- ✓ 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, et.al., Eur. Phys. J.C 77 (2017) 11, 763
K. Asai, et.al., 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, et.al., Eur. Phys. J.C 77 (2017) 11, 763

K. Asai, et.al., 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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$U(1)_{L_\mu - L_\tau}$ gauge symmetry

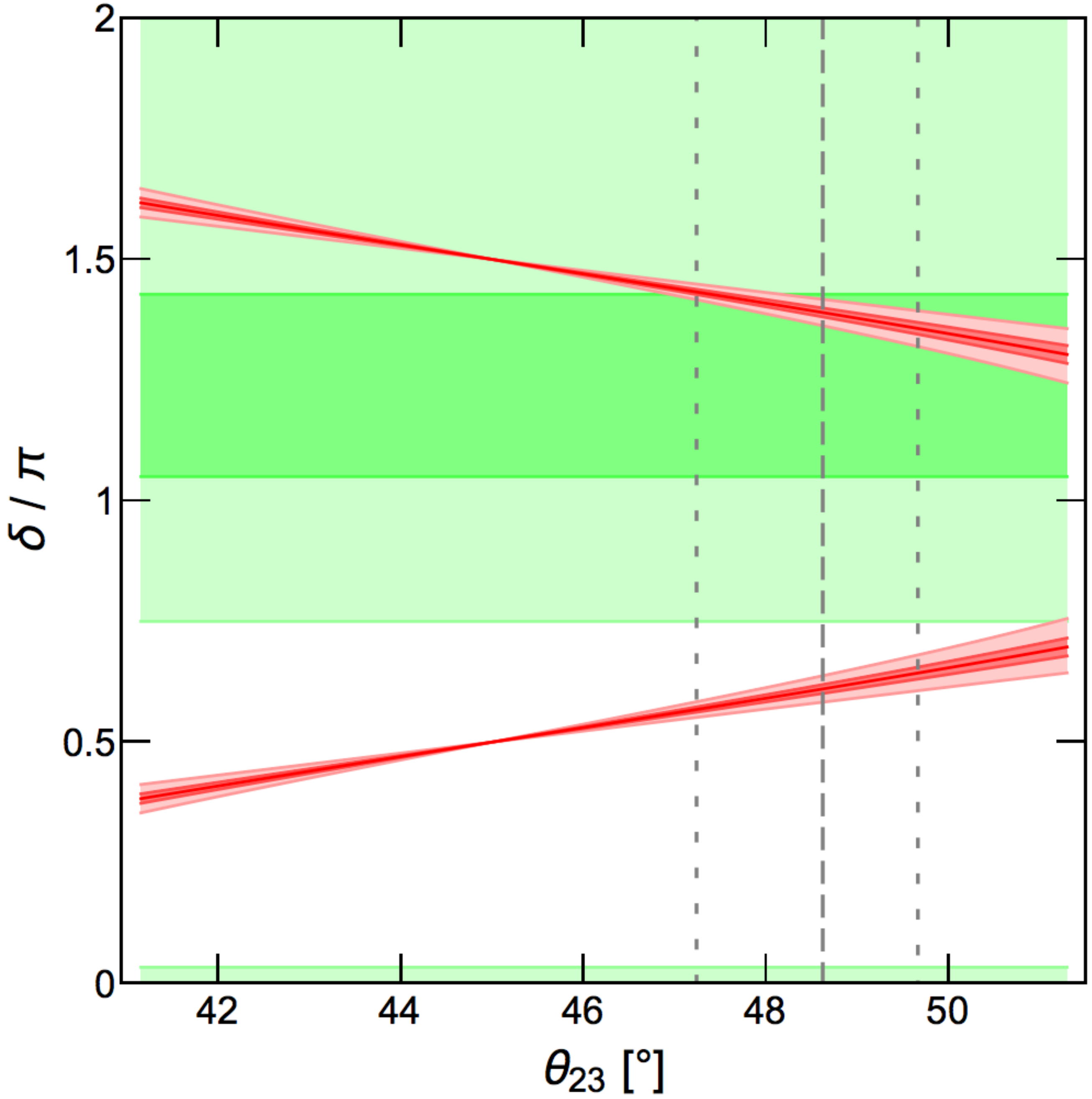

Fig taken from K. Asai et.al., JCAP 11 (2020) 013

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ghtly restricted.

for the neutrino sector

Input

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

➡

Output

$\delta, \alpha_1, \alpha_2,$

m_1, m_2, m_3

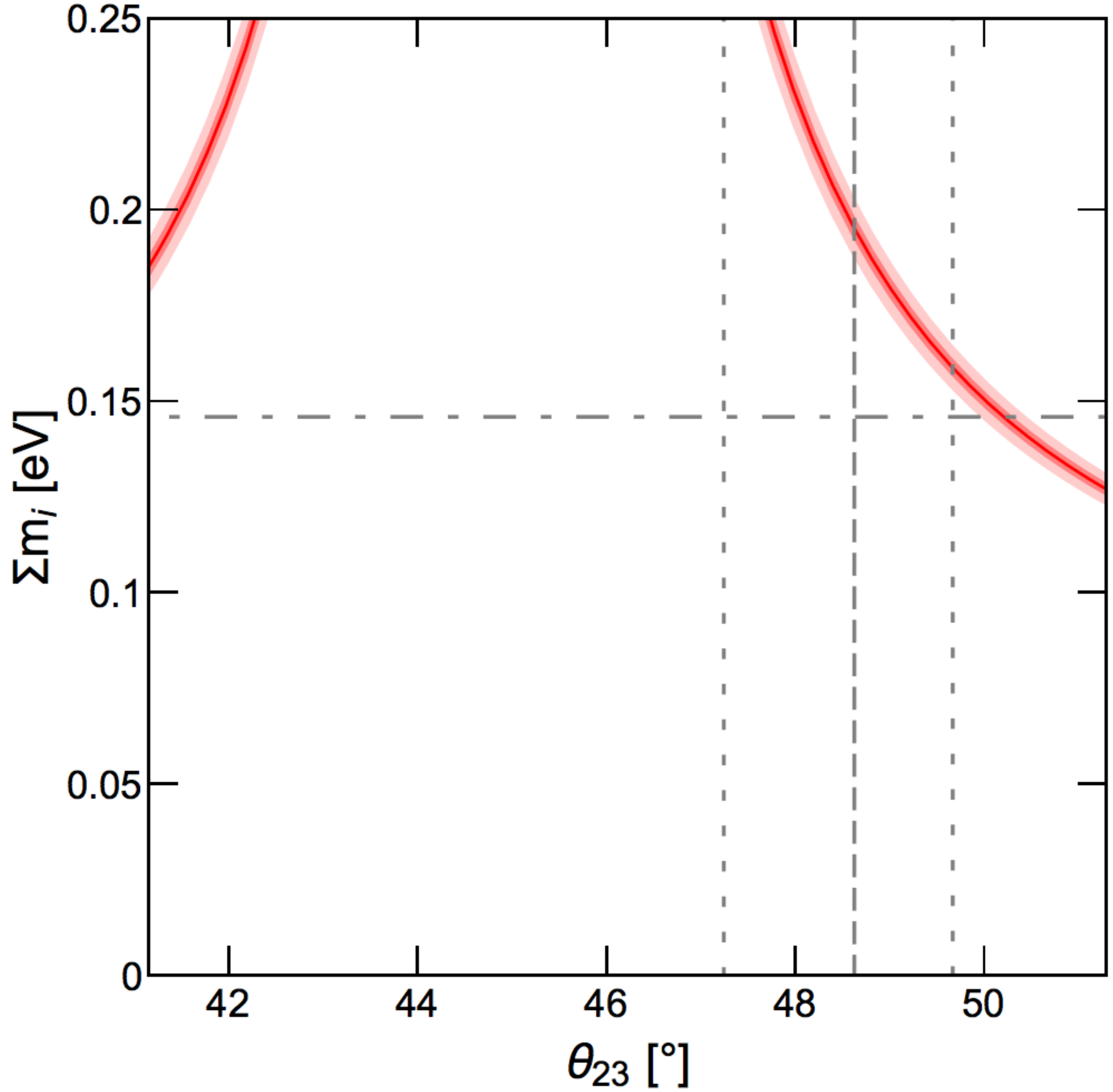
$$\cos\delta \simeq \frac{\cot\theta_{12}\cot\theta_{23}}{\sin\theta_{13}}$$

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

K. Asai, et.al., Eur. Phys. J.C 77 (2017) 11, 763

K. Asai, et.al., Phys.Rev.D 99 (2019) 5, 055029

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



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m_1, m_2, m_3

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

K. Asai, et.al., Eur. Phys. J.C 77 (2017) 11, 763

K. Asai, et.al., 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

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

Output

$\delta, \alpha_1, \alpha_2,$
m_1, m_2, m_3

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

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

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

A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, JHEP 09 (2023) 079 [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

$$\delta, \alpha_1, \alpha_2,$$
$$m_1, m_2, m_$$

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

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

Cf) Neutrino parameters in CI parameterization

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

$$m_1, \Delta m^2, \delta m^2, \theta_{12}, \theta_{23}, \theta_{31},$$
$$\delta, \alpha_1, \alpha_2, M_1, M_2, M_3,$$
$$x_1, x_2, x_3, y_1, y_2, y_3$$

A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, JHEP 09 (2023) 079 [hep-ph 2305.18100]

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

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

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

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

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

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

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

A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, JHEP 09 (2023) 079 [hep-ph 2305.18100]

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Thermal LG works when

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

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

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

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

A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, JHEP 09 (2023) 079 [hep-ph 2305.18100]

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Thermal LG works when

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

y_τ in thermal equilibrium at

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

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

Density Matrix Equation is required

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

$\mathcal{M}_D, \mathcal{M}_R$ ➡ η_b bary

A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, JHEP 09 (2023) 079 [hep-ph 2305.18100]

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

To e

Input data take from Nufit 5.2

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

Input

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

Output

$$\delta, \alpha_1, \alpha_2, m_1, m_2, m_3$$

$$\rightarrow \mathcal{M}_{\nu_L} = U^*_{PMNS} \mathrm{diag}(m_1, m_2, m_3) U^{-1}_{PMNS}$$

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

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

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

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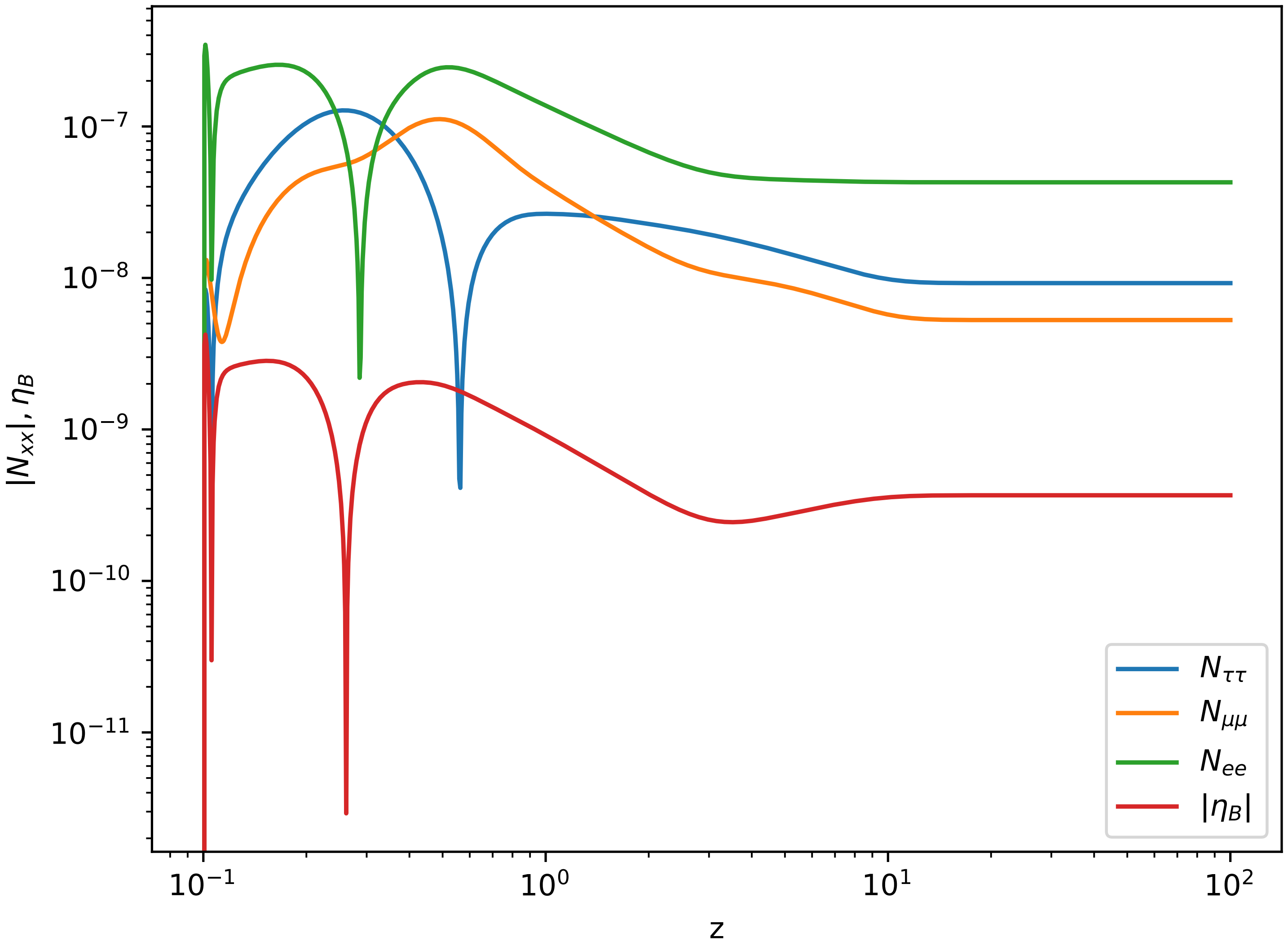
Thermal LG in $U(1)_{L_\mu - L_\tau}$ model



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$= U^*_{PMNS}\mathrm{diag}(m_1, m_2, m_3)U^{-1}_{PMNS}$

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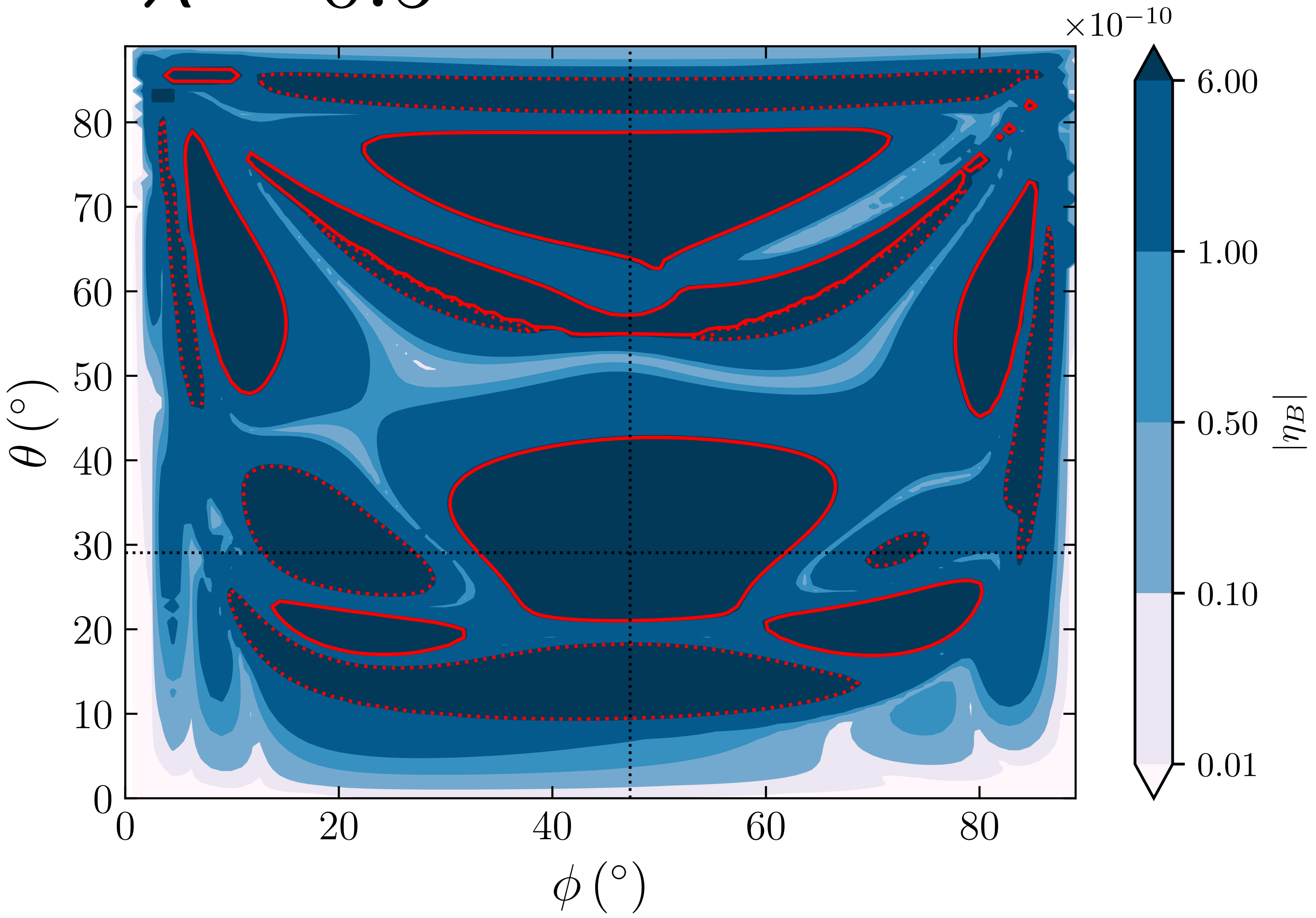
Result

$\lambda = 0.5$



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.

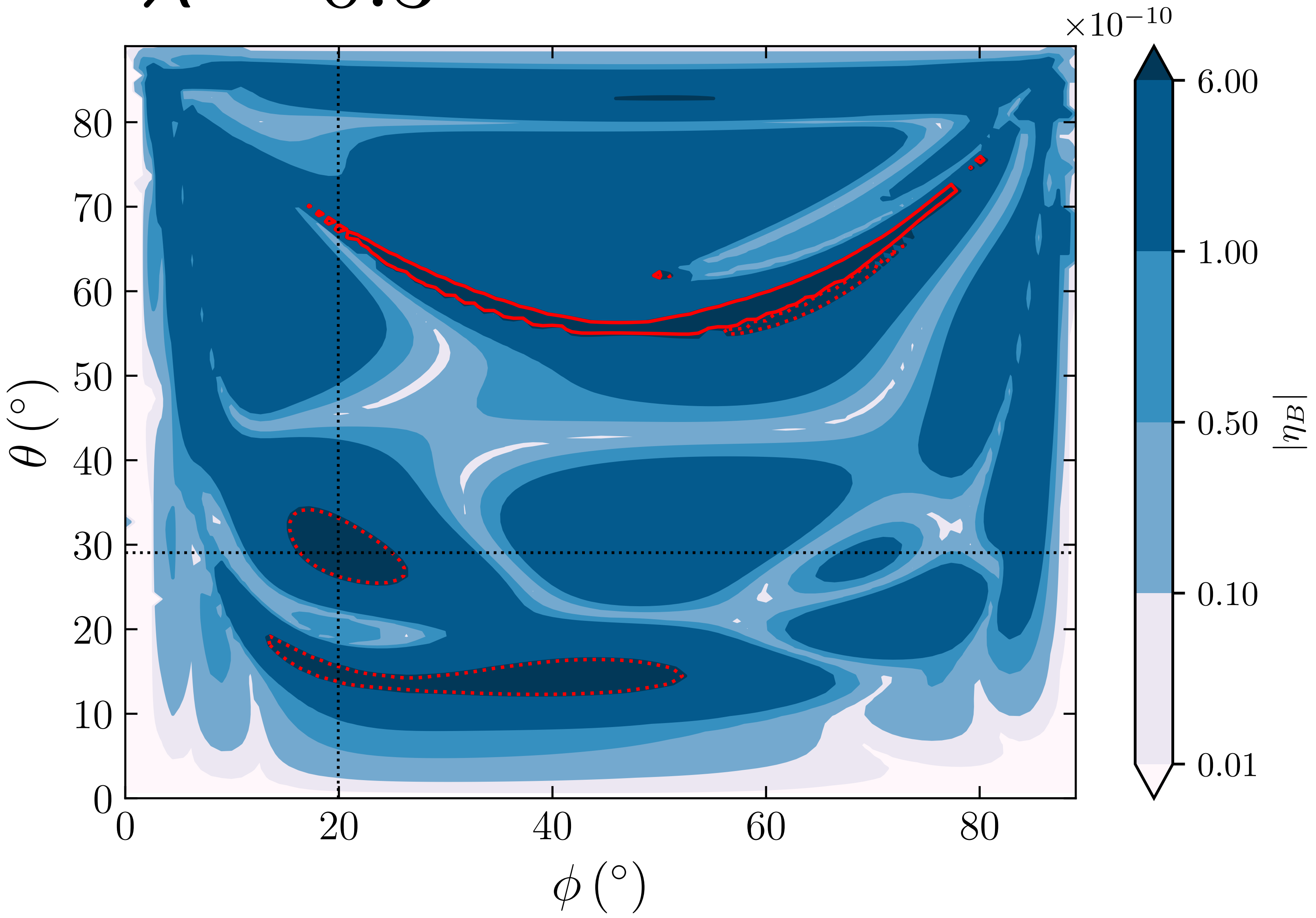
I. Esteban, et.al., JHEP 09 (2020) 178

A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, JHEP 09 (2023) 079 [hep-ph 2305.18100]

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

Result

$\lambda = 0.3$



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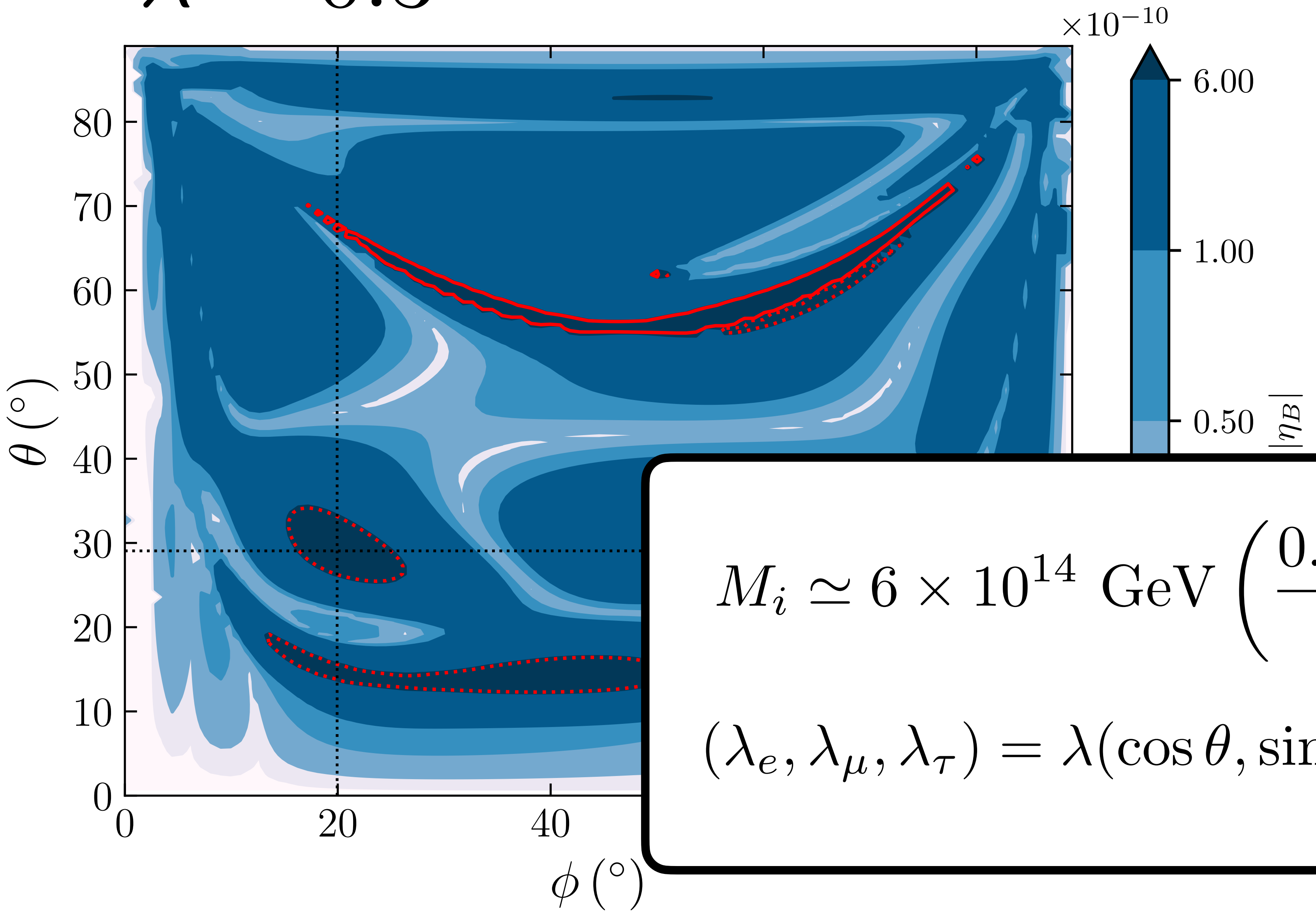
Result

$\lambda = 0.3$



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

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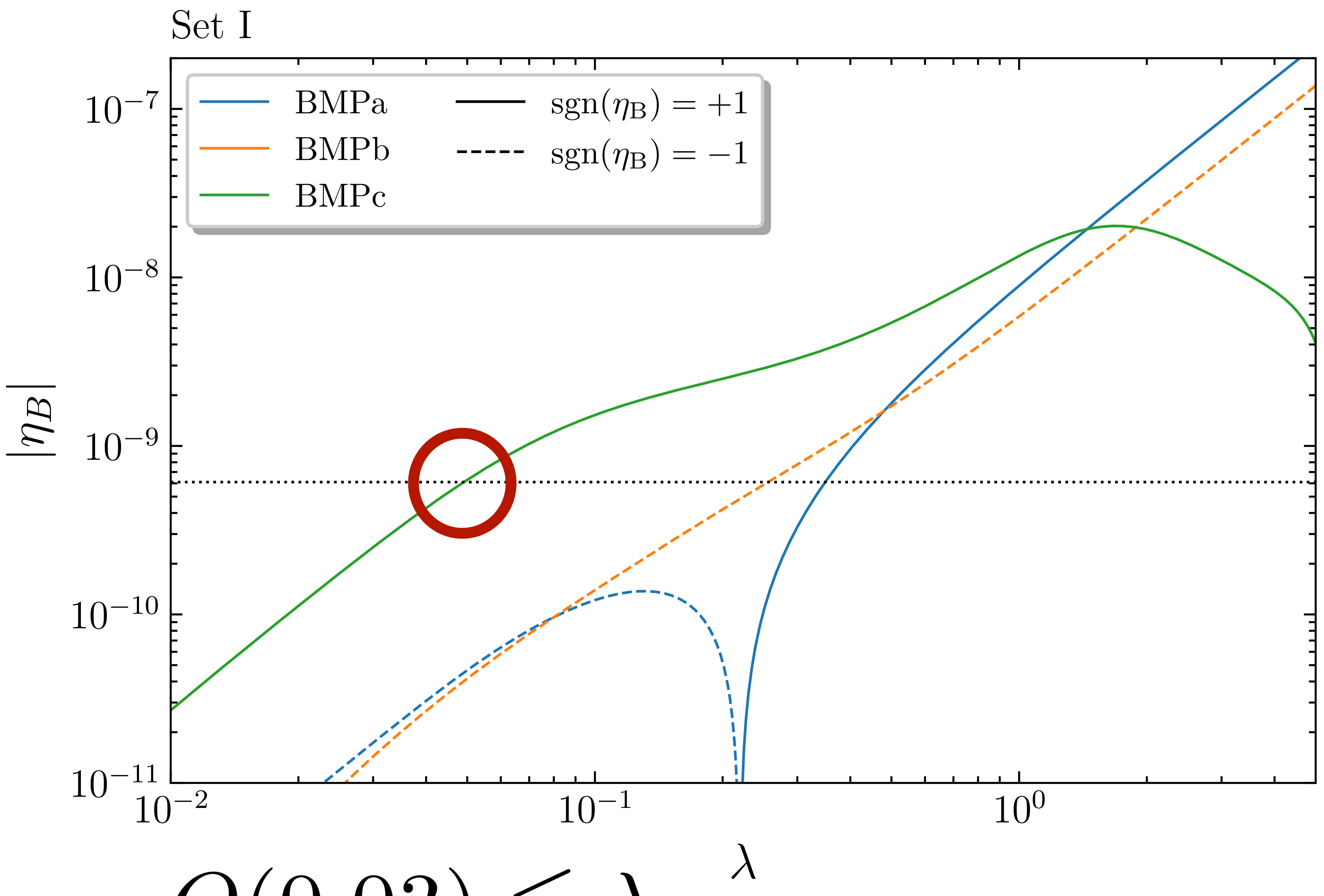

$$O(0.03) \lesssim \lambda$$

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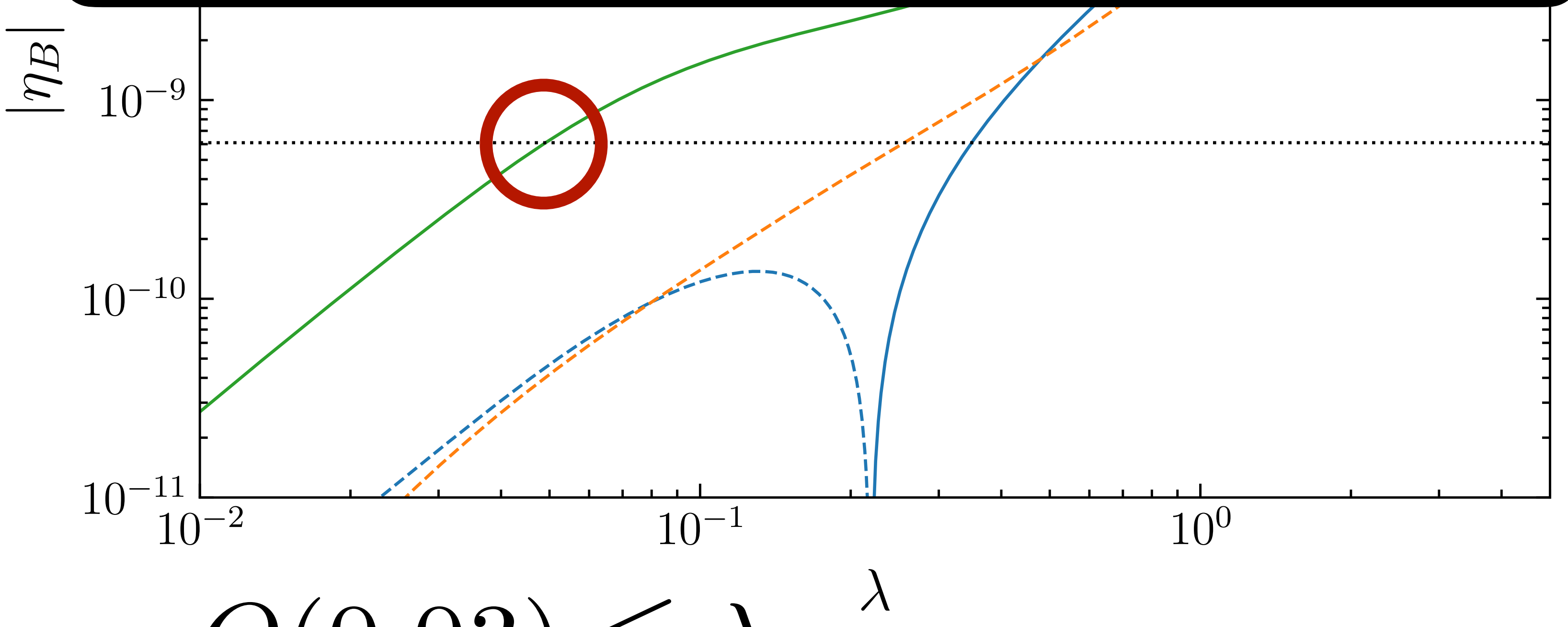
A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, JHEP 09 (2023) 079 [hep-ph 2305.18100]

Result

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

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



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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
- We found that thermal leptogenesis is viable for $M_1 \gtrsim 10^{11-12}\ \mathrm{GeV}$ across the entire parameter space

Backup

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.

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

Benchmark Point

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

Set II

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

$\theta_{13} = 8.54^\circ$

$\theta_{23} = 51.9^\circ$

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

$\Delta m^2_{31} = 2.511 \times 10^{-3}\,\mathrm{eV}^2$

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

Cf) NuFit data

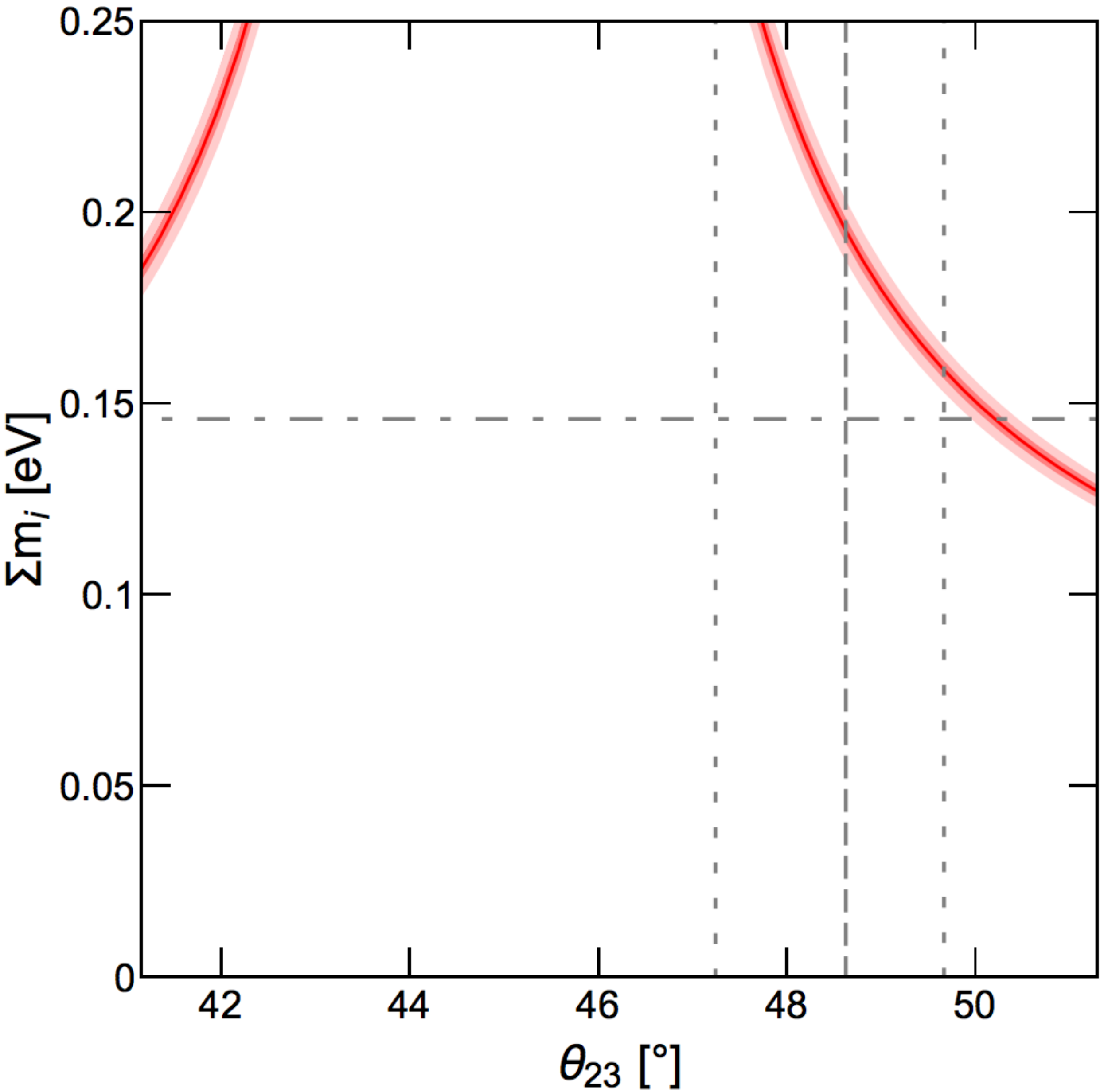
NuFIT Collaboration, NuFIT v5.2, http://www.nu-fit.org.
I. Esteban, et.al., JHEP 09 (2020) 178

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**	$[31.31, 35.74]$	$[8.19, 8.89]$	$[39.6, 51.9]$	$[6.82, 8.03]$	$[2.427, 2.590]$

Benchmark Point

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



Set I

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

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

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

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

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

Set II

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

$\theta_{13} = 8.54^\circ$

$\theta_{23} = 51.9^\circ$

$\Delta m^2_{21} = 7.41 \times$

$\Delta m^2_{31} = 2.511$

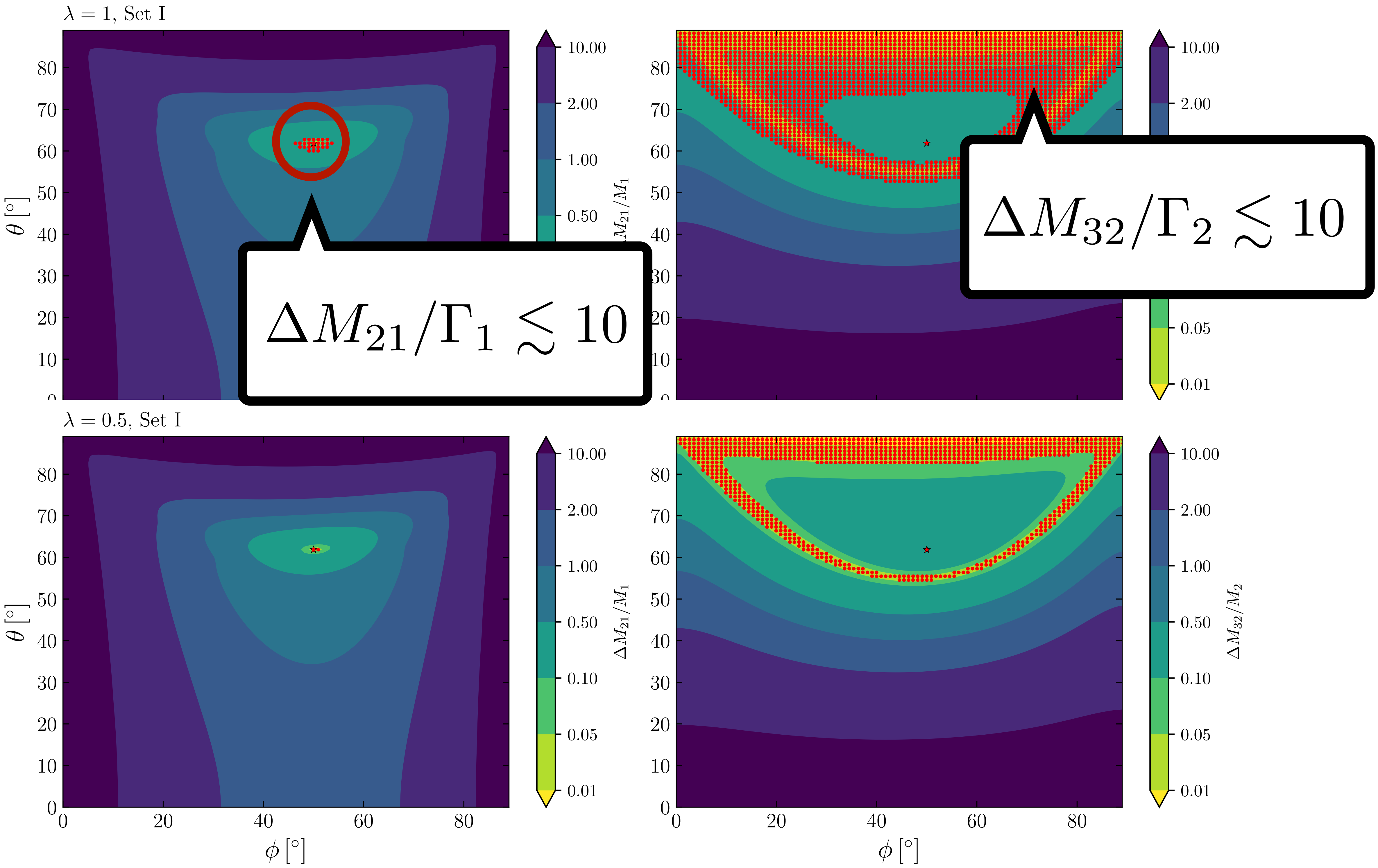
Cf) NuFit data

NuFIT Collaboration, NuFIT v5.2,
I. Esteban, et.al., JHEP 09 (2020)

Neutrino Masses and Mixing

Parameters (units)	θ_{12} (°)	θ_{13} (°)	θ_{23} (°)		
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



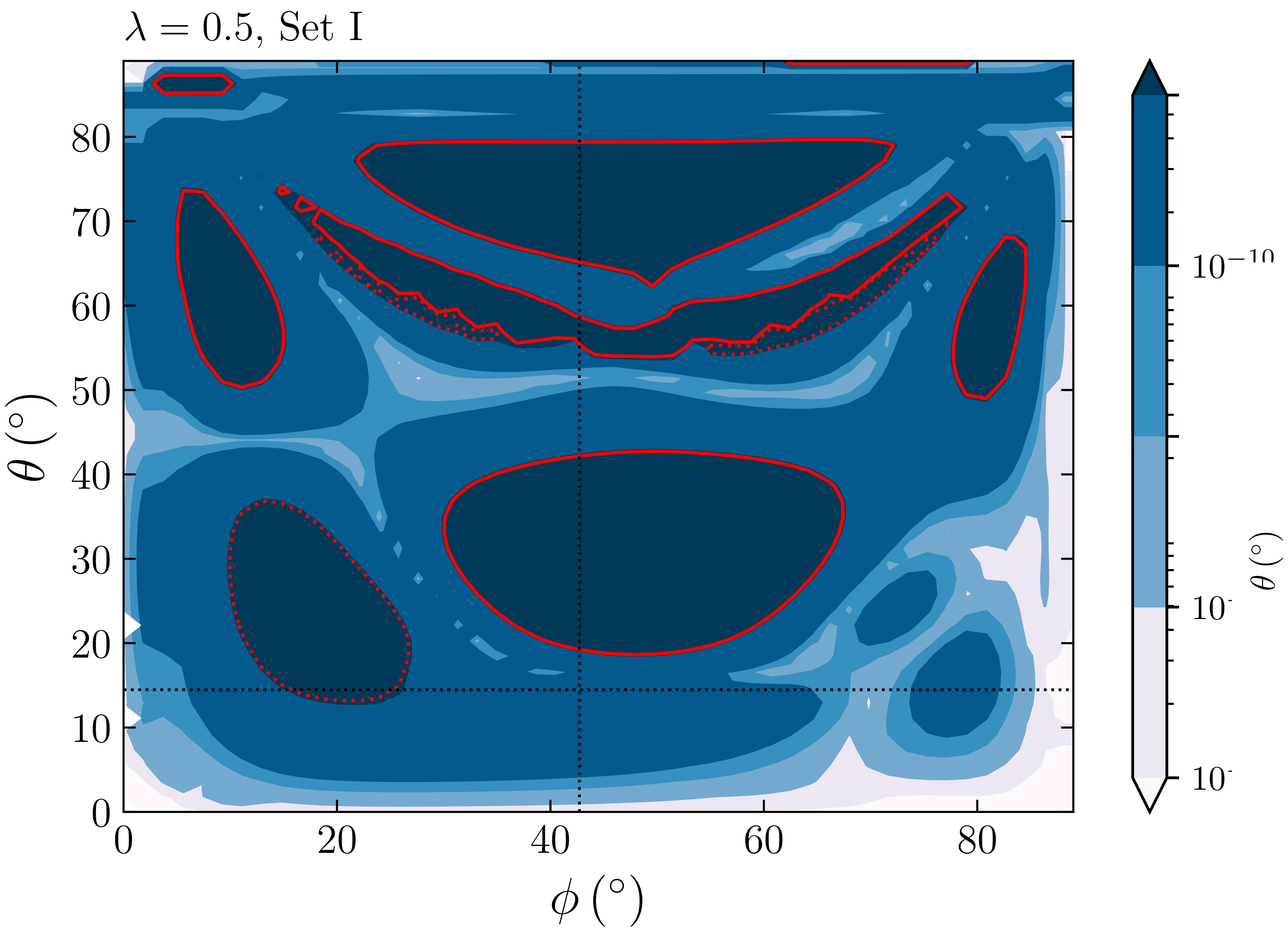
$\Delta M_{21}/\Gamma_1 \lesssim 10$

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

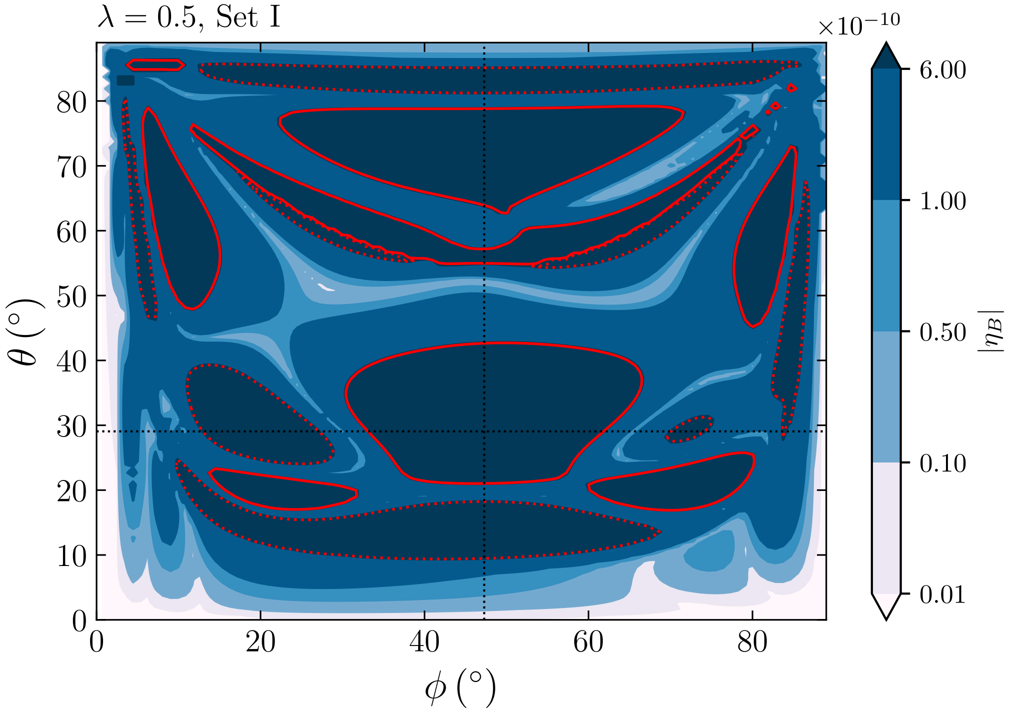
A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, hep-ph 2305.18100

Dependence of initial condition

When we take thermal initial abundance (TIA),



Cf) VIA

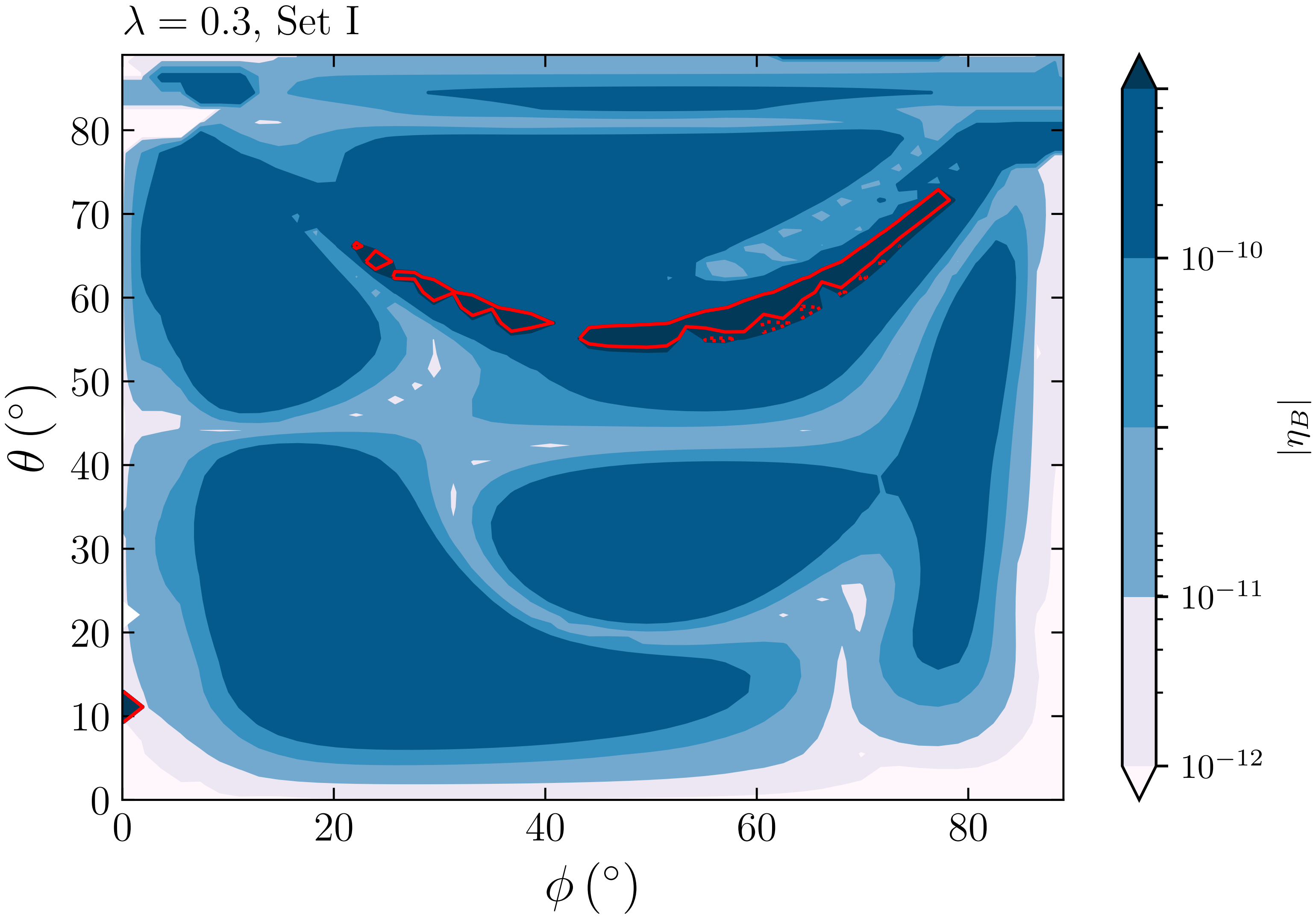


$$(\lambda_e, \lambda_\mu, \lambda_\tau) = \lambda(\cos\theta, \sin\theta\cos\phi, \sin\theta\sin\phi)$$

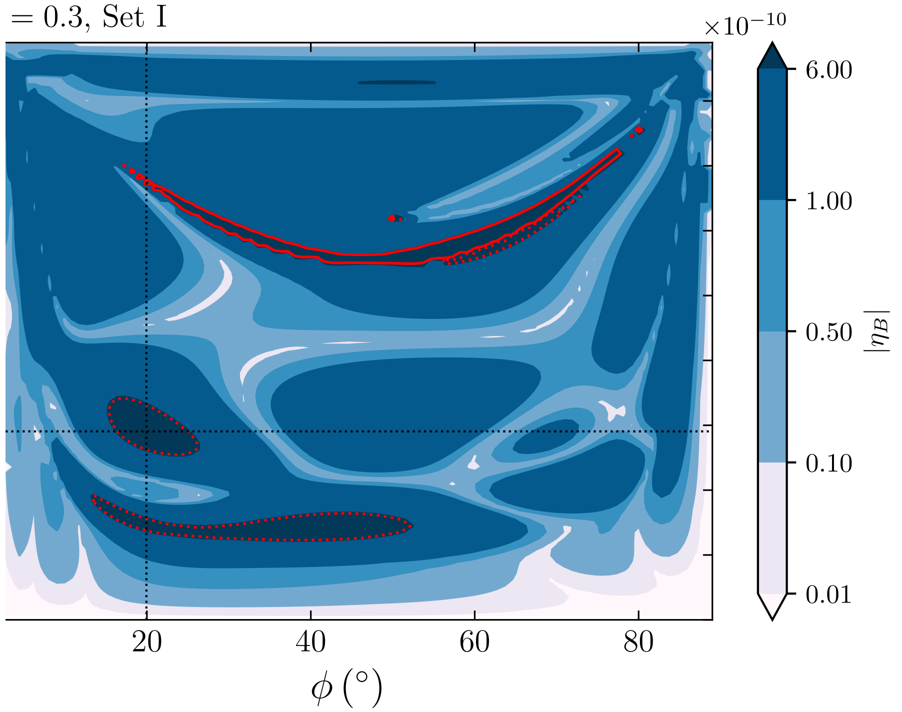
A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, JHEP 09 (2023) 079 [hep-ph 2305.18100]

Dependence of initial condition

When we take thermal initial abundance (TIA),



Cf) VIA



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

A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, JHEP 09 (2023) 079 [hep-ph 2305.18100]