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

Juntaro Wada

@Nagoya Univ.

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)

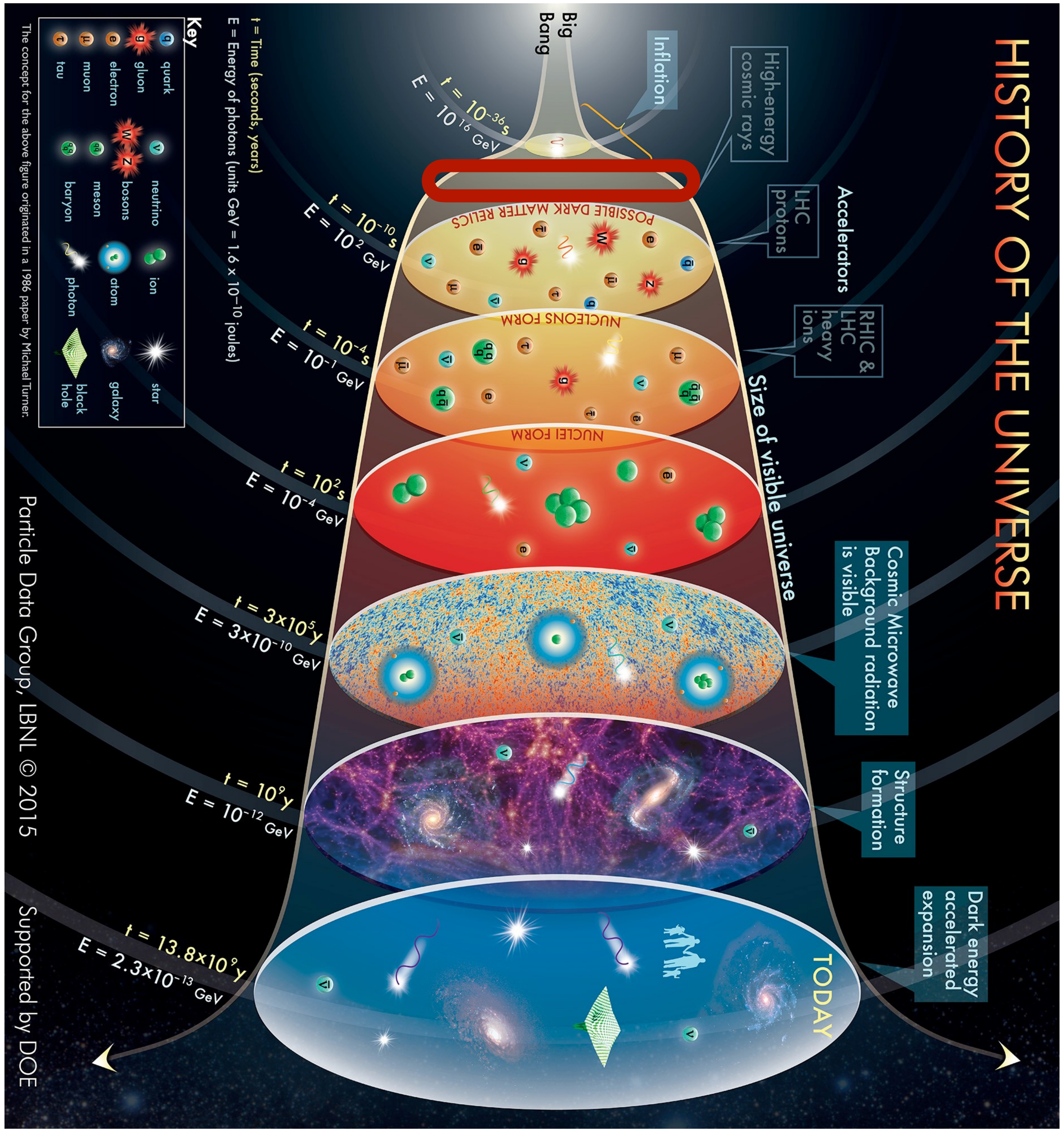
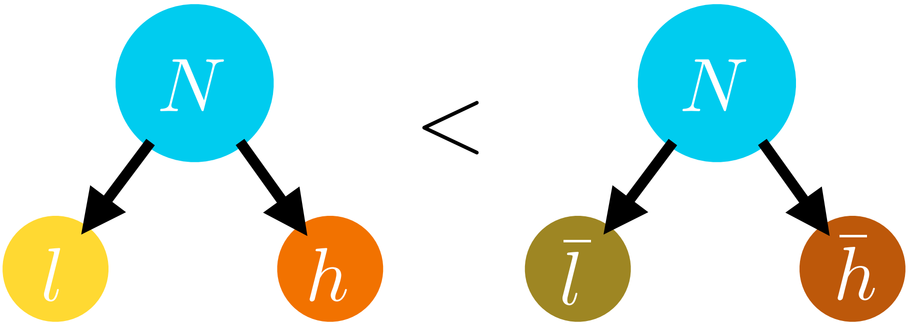


Fig from PDG

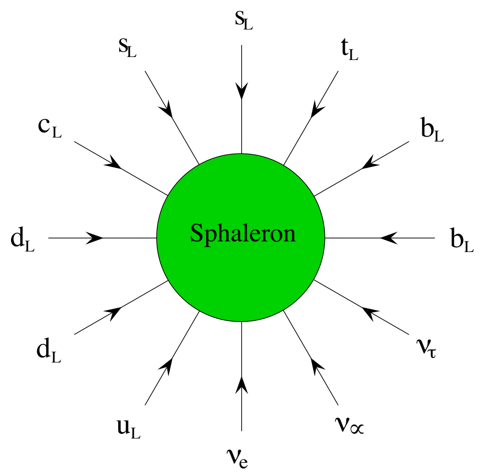
RH ν decay



$> 10^{10}$ GeV

Sphaleron process

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

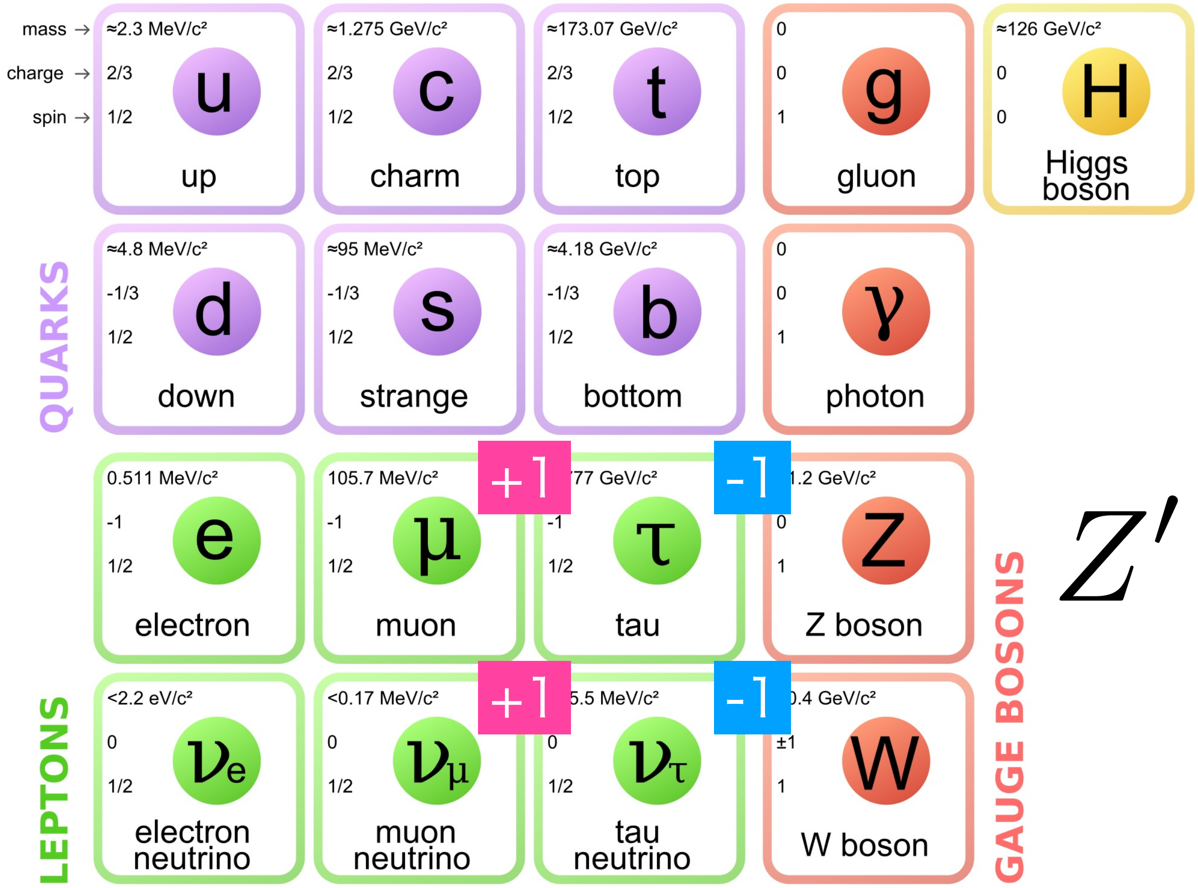


$> 10^3$GeV

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_μ, N_τ +1 -1

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

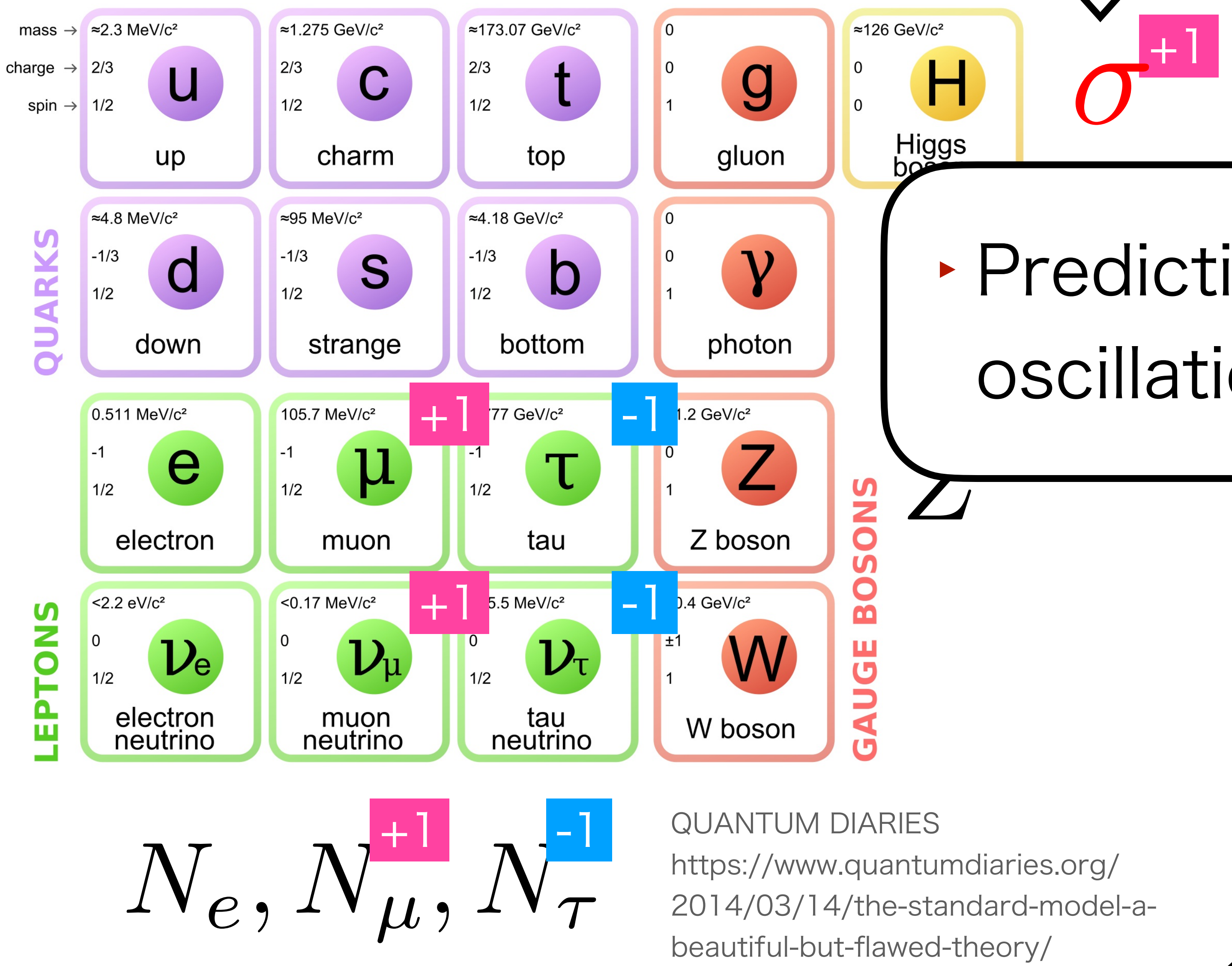
K. Asai, et.al., Eur. Phys. J.C 77 (2017) 11, 763

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

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

Minimal Setup

SM singlet
Breaking symmetry



$$N_e, N_\mu, N_\tau$$

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

- Predictive power for neutrino oscillation parameter

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

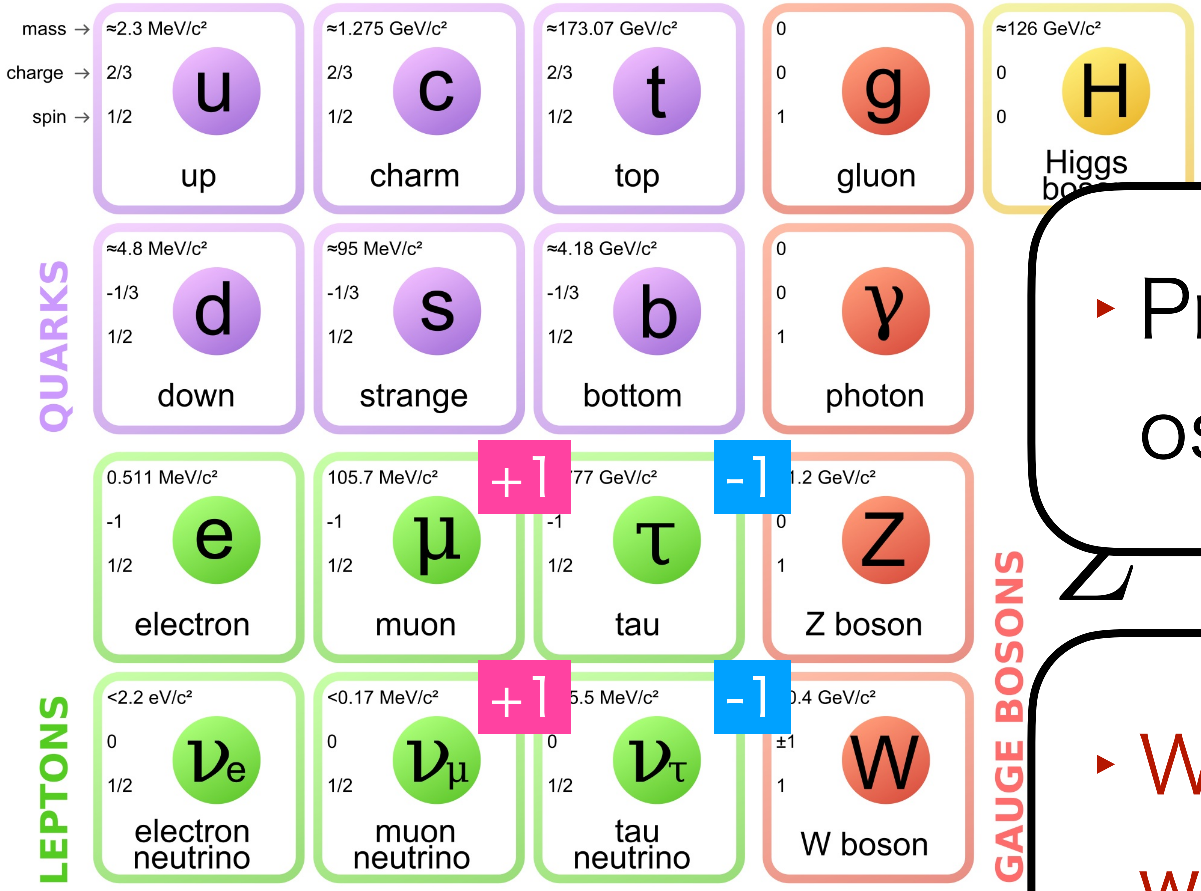
K. Asai, et.al., Phys.Rev.D 99 (2019) 5, 055029

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

Minimal Setup

SM singlet

Breaking symmetry



σ^{+1}

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

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

- Predictive power for neutrino oscillation parameter

- We evaluate BAU in this model with density matrix equation

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

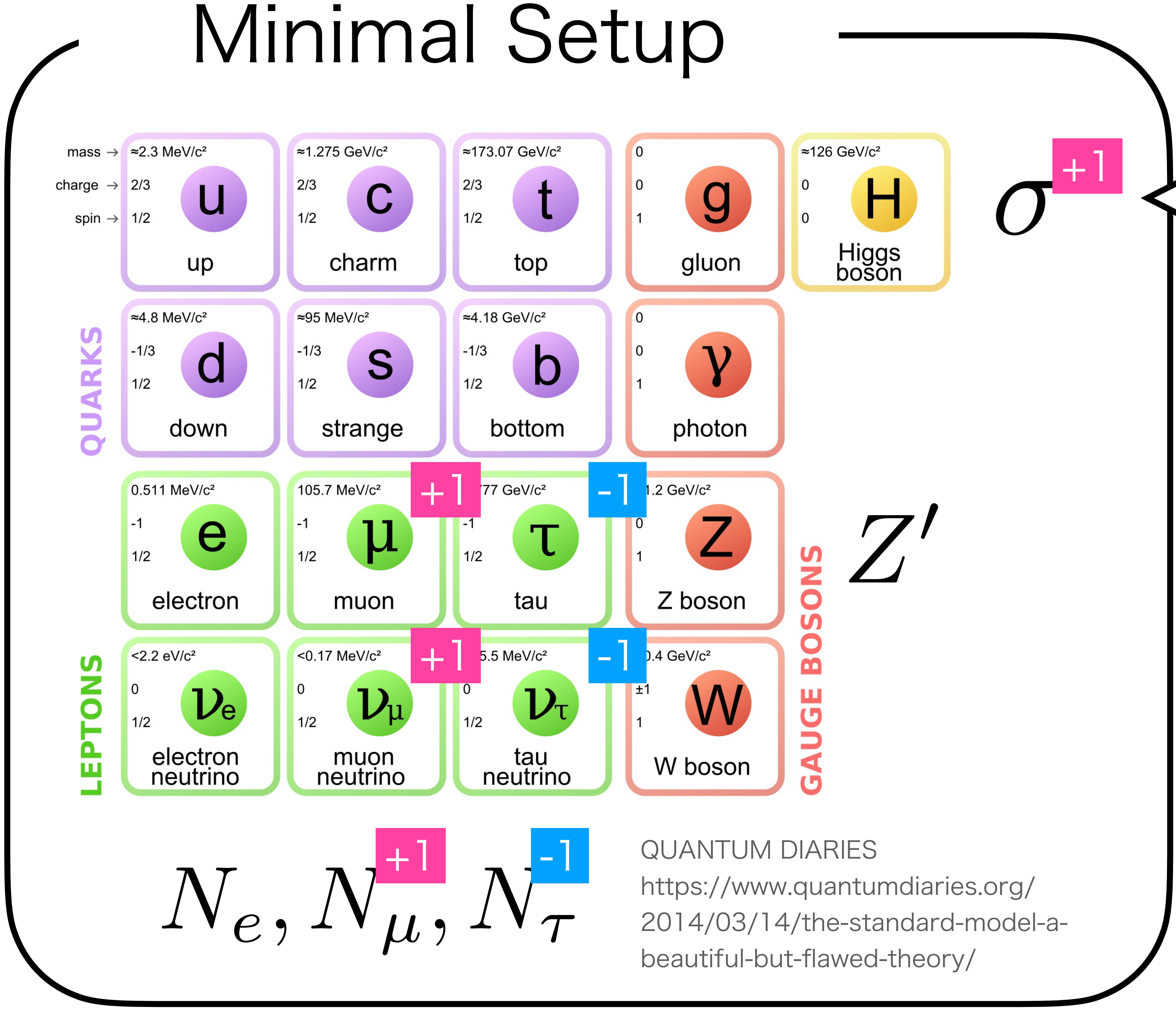
K. Asai, et.al., Phys.Rev.D 99 (2019) 5, 055029

Outline

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

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

Minimal Setup



σ

Z'

N_e, N_μ, N_τ

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

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

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

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

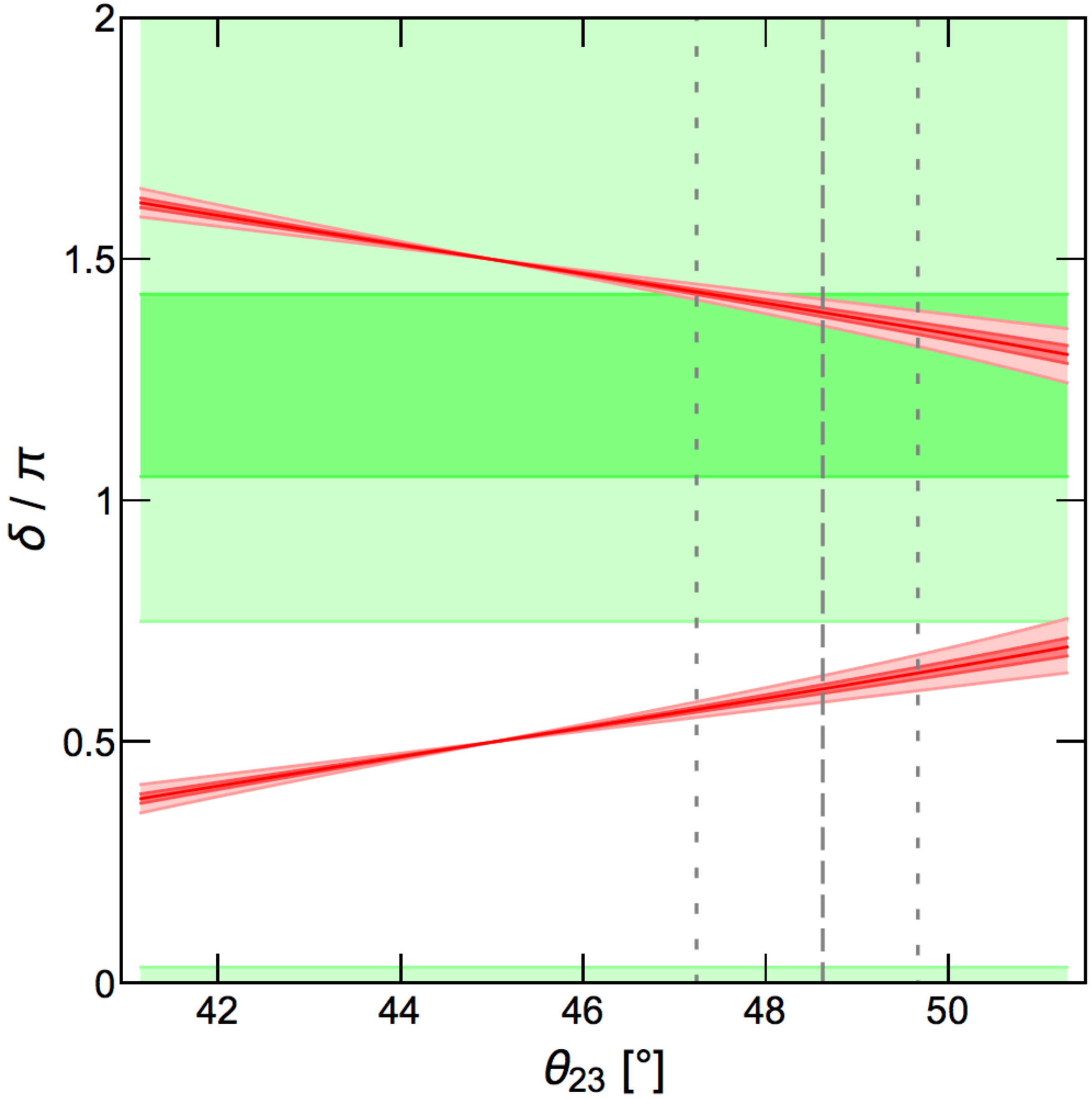


Fig taken from K. Asai et.al., JCAP 11 (2020) 013

tructure of both Dirac and

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

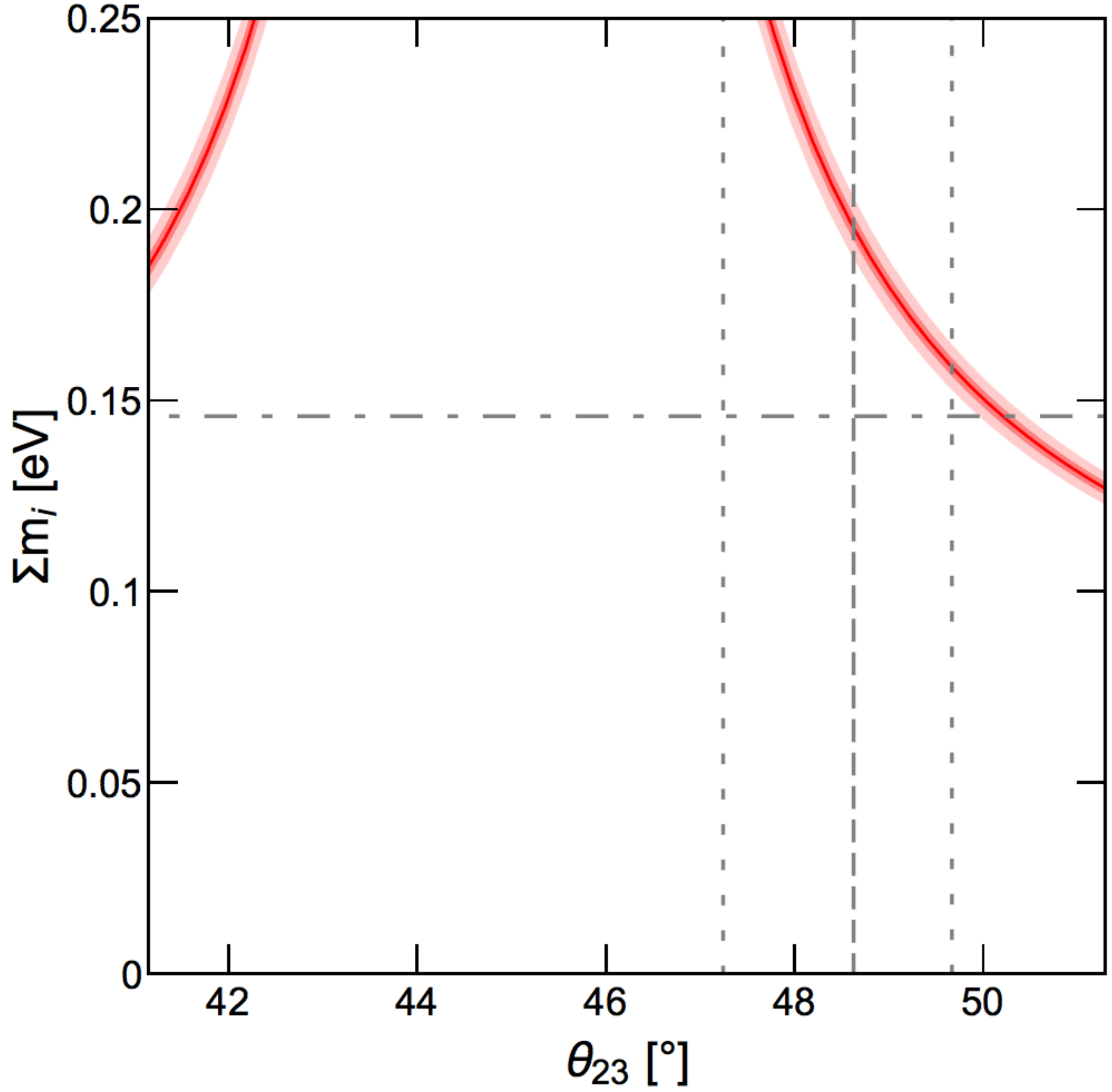
$$\cos\delta \simeq \frac{\cot\theta_{12}\cot\theta_{23}}{\sin\theta_{13}}$$

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

K. Asai, 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



structure of both Dirac and

ghtly restricted.

for the neutrino sector

Input

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

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

$\rightarrow$

Output

$$\delta, \alpha_1, \alpha_2,$$

$$m_1, m_2, m_3$$

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

Outline

✓ Introduction

✓ Minimal Gauged $U(1)_{L_\mu - L_\tau}$ Model

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

‣ Flavor effect & DME

‣ Result

‣ Summary

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

To evaluate baryon asymmetry,

Input → Output

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

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

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

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

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

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

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

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

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

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

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

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

Thermal LG works when

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

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

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

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

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

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

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

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

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

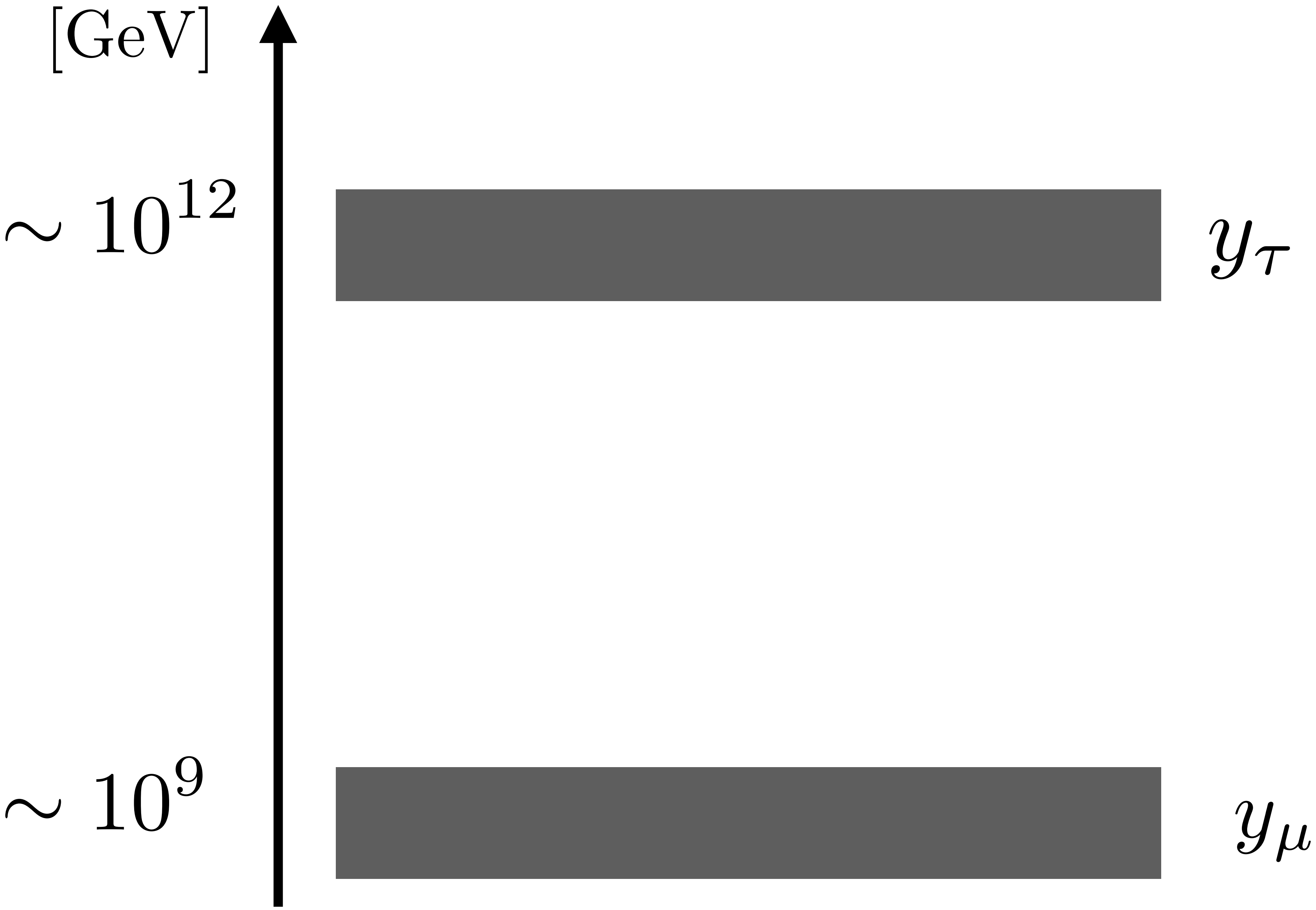
$\mathcal{M}_D, \mathcal{M}_R$ ➡ η_b baryon asymmetry

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

Outline

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

Flavor effect on LG

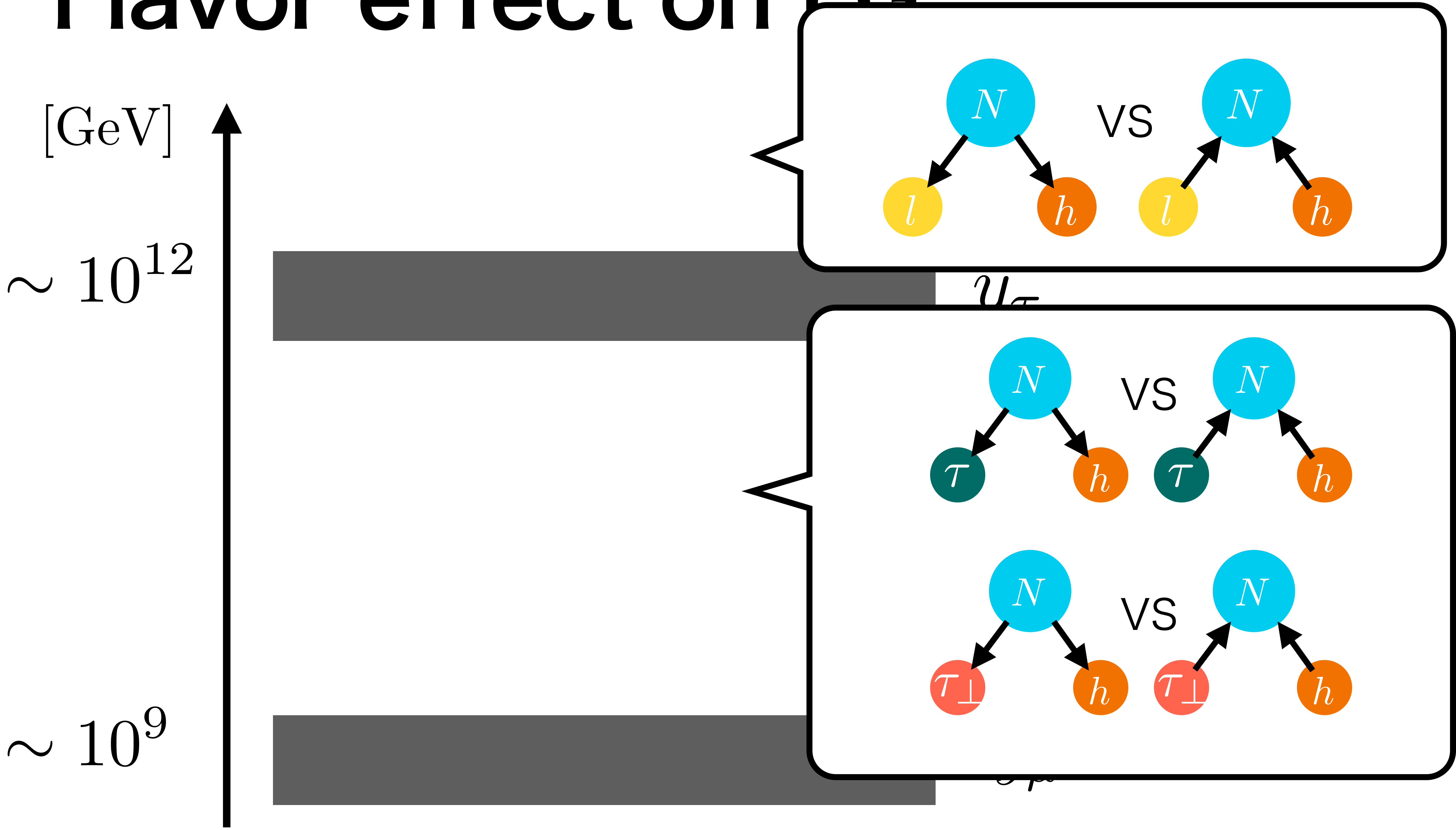


R. Barbieri, et.al., Nucl.Phys.B 575 (2000) 61-77

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

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

Flavor effect on LG



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

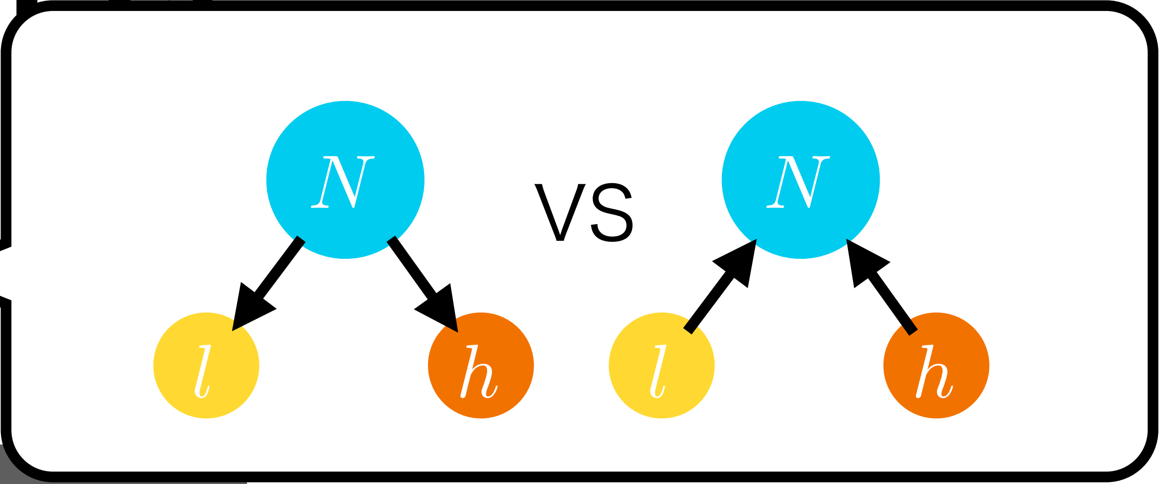
E. Nardi, et.al., JHEP 01 (2006) 164

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

Flavor effect on LG

$$\epsilon_1 \simeq -\frac{3M_1}{8\pi v^2}\frac{\sum_i m_i^2 \mathrm{Im}\left[(R_{1i})^2\right]}{\sum_i m_i |R_{1i}|^2}$$

S. Davidson and A. Ibarra, Phys.Lett.B 535 (2002) 25-32



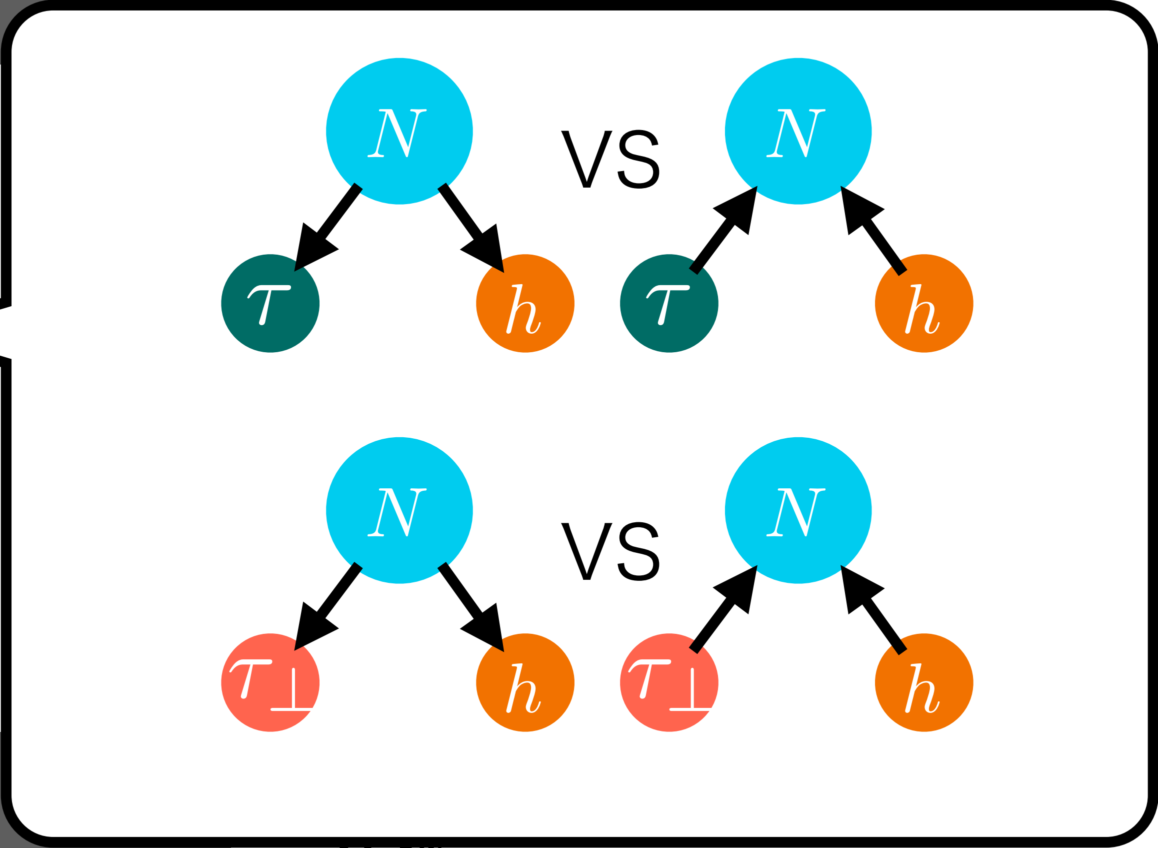
$\sim 10^{12}$

y_τ

$$\epsilon_{1,\alpha} \propto \frac{\mathrm{Im}\left[\sum_{jk} m_j^{1/2} m_k^{1/2} U_{\alpha j}^* U_{\alpha k} R_{1j} R_{1k}\right]}{\sum_i m_i |R_{1i}|^2}$$

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

E. Molinaro and S. T. Petcov, Eur. Phys. J. C 61 (2009) 93–109



$\sim 10^9$

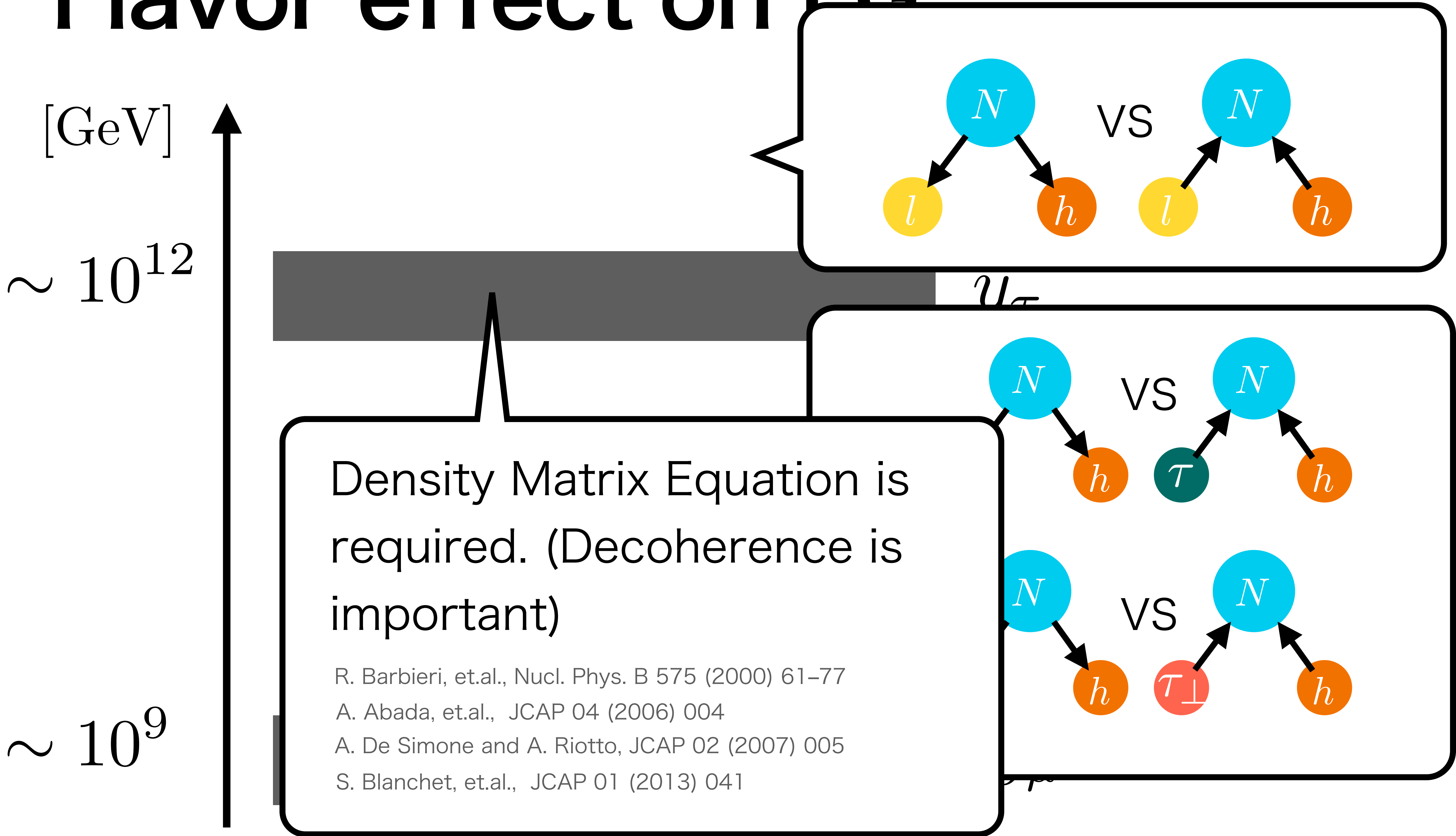
Dependence PMNS phase is important.

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

Flavor effect on LG

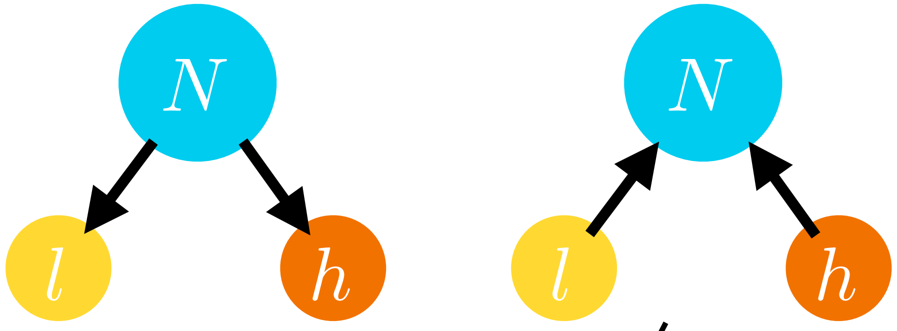


Density Matrix Equation is required. (Decoherence is important)

R. Barbieri, et.al., Nucl. Phys. B 575 (2000) 61–77
A. Abada, et.al., JCAP 04 (2006) 004
A. De Simone and A. Riotto, JCAP 02 (2007) 005
S. Blanchet, et.al., JCAP 01 (2013) 041

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

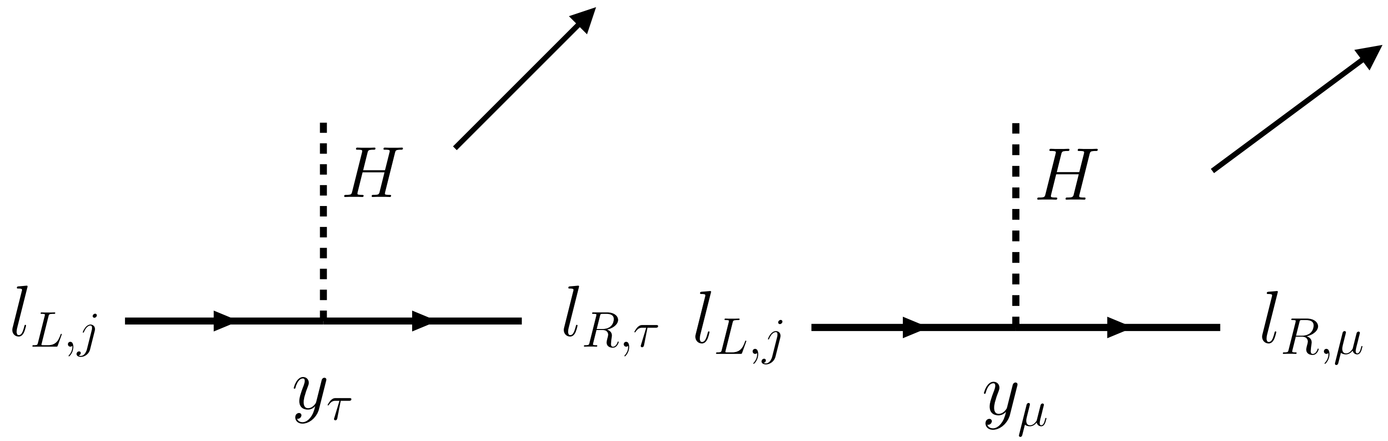
Density Matrix Equation



$$\frac{dN_{N_j}}{dz} = -D_j(N_{N_j} - N_{N_j}^{\rm eq})$$

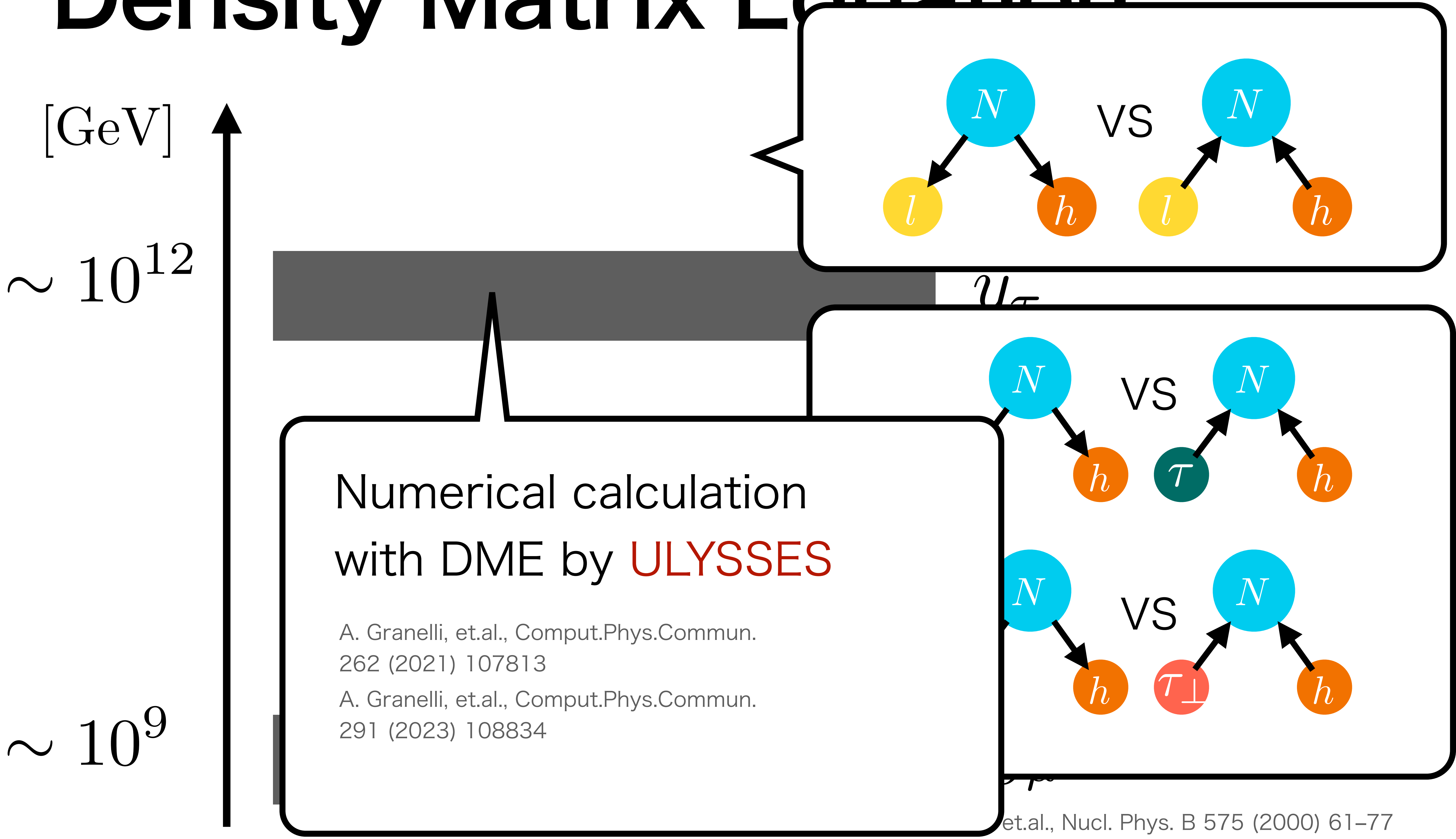
$$\frac{dN_{\alpha\beta}}{dz} = \sum_{j=1}^{3}\left[\underline{\epsilon_{\alpha\beta}^{(j)} D_j (N_{N_j} - N_{N_j}^{\rm eq})} - \underline{\frac{1}{2} W_j \left\{P^{0(j)}, N\right\}_{\alpha\beta}}\right]$$

$$\underline{-\frac{\Gamma_\tau}{Hz}[I_\tau,[I_\tau,N]]_{\alpha\beta}} - \underline{\frac{\Gamma_\mu}{Hz}[I_\mu,[I_\mu,N]]_{\alpha\beta}} \ ,$$



R. Barbieri, et.al., Nucl. Phys. B 575 (2000) 61–77
A. Abada, et.al., JCAP 04 (2006) 004
A. De Simone and A. Riotto, JCAP 02 (2007) 005
S. Blanchet, et.al., JCAP 01 (2013) 041

Density Matrix Equation



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

et.al., Nucl. Phys. B 575 (2000) 61–77

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

A. De Simone and A. Riotto, JCAP 02 (2007) 005

S. Blanchet, et.al., JCAP 01 (2013) 041

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.

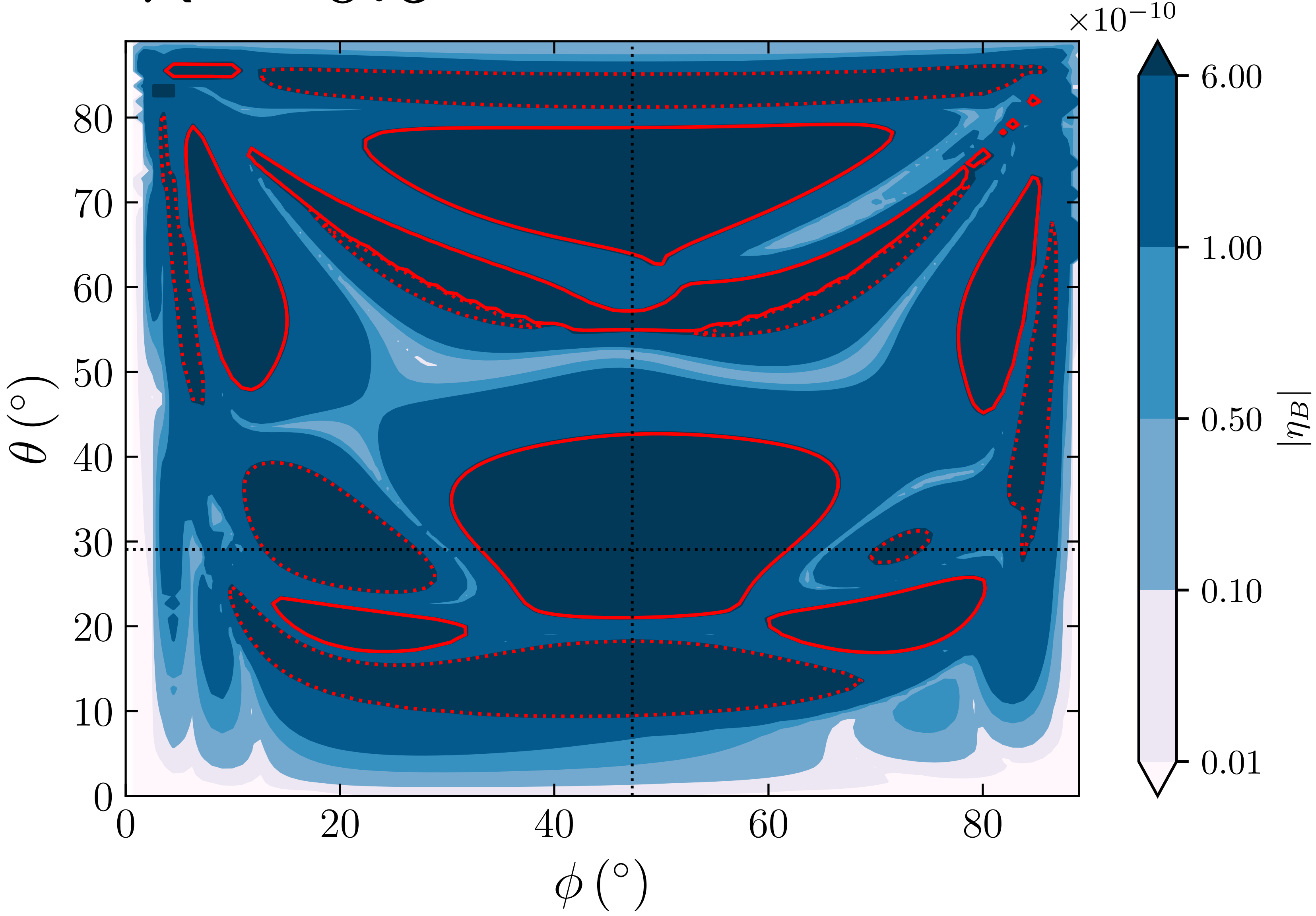
▶ $|M_{ee,\mu\tau}|, |\lambda_{e\mu,e\tau} \langle \sigma \rangle| < T_R$

Outline

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

Result

$\lambda = 0.5$



Set I

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

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

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

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

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

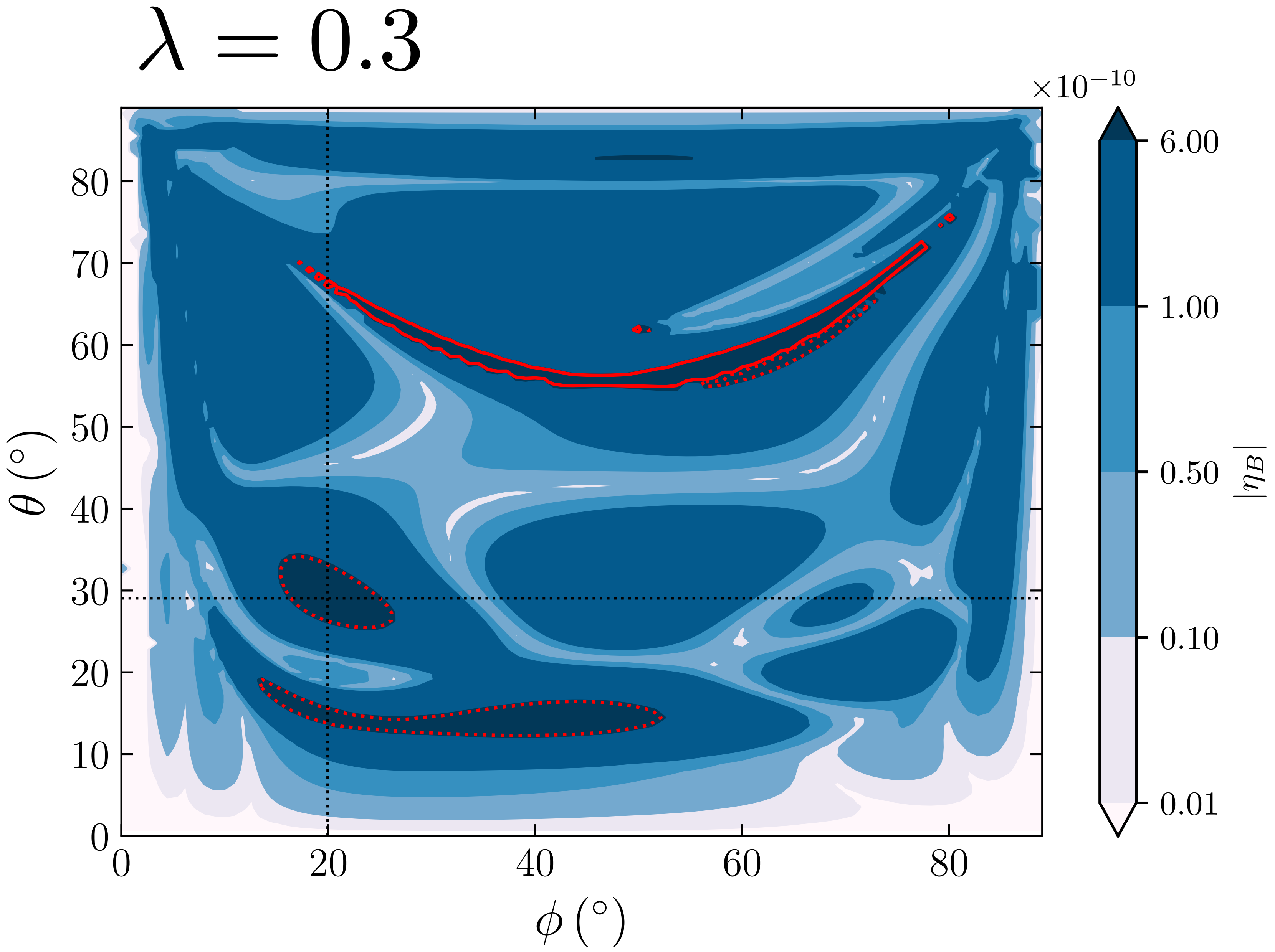
Input parameters are taken from NuFit ver 5.2

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]

Result



Set I

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

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

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

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

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

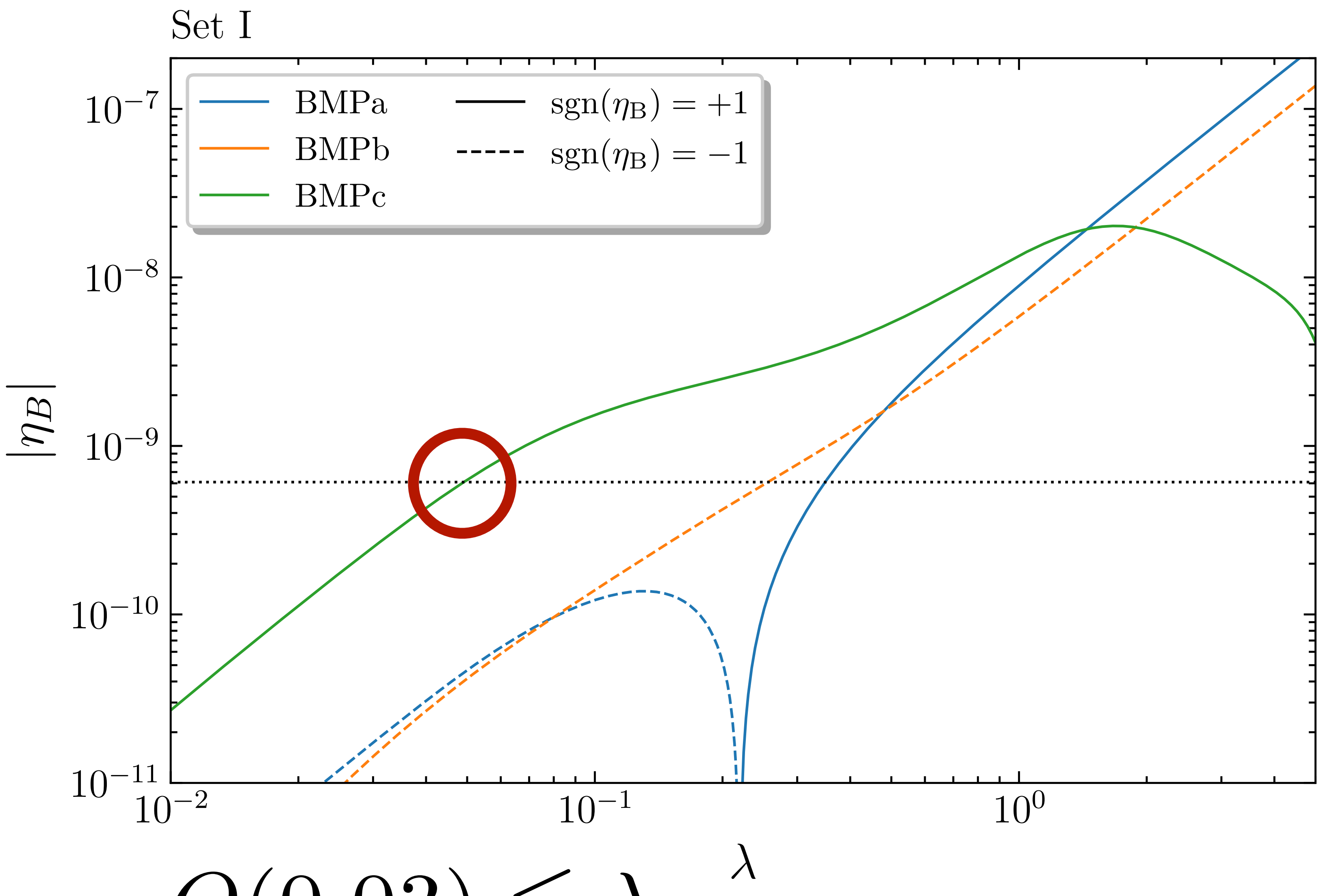
Input parameters are taken from NuFit ver 5.2

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]

Result



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

Set I

$\theta_{12} = 33.41°$

$\theta_{13} = 8.58°$

$\theta_{23} = 39.7°$

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

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

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

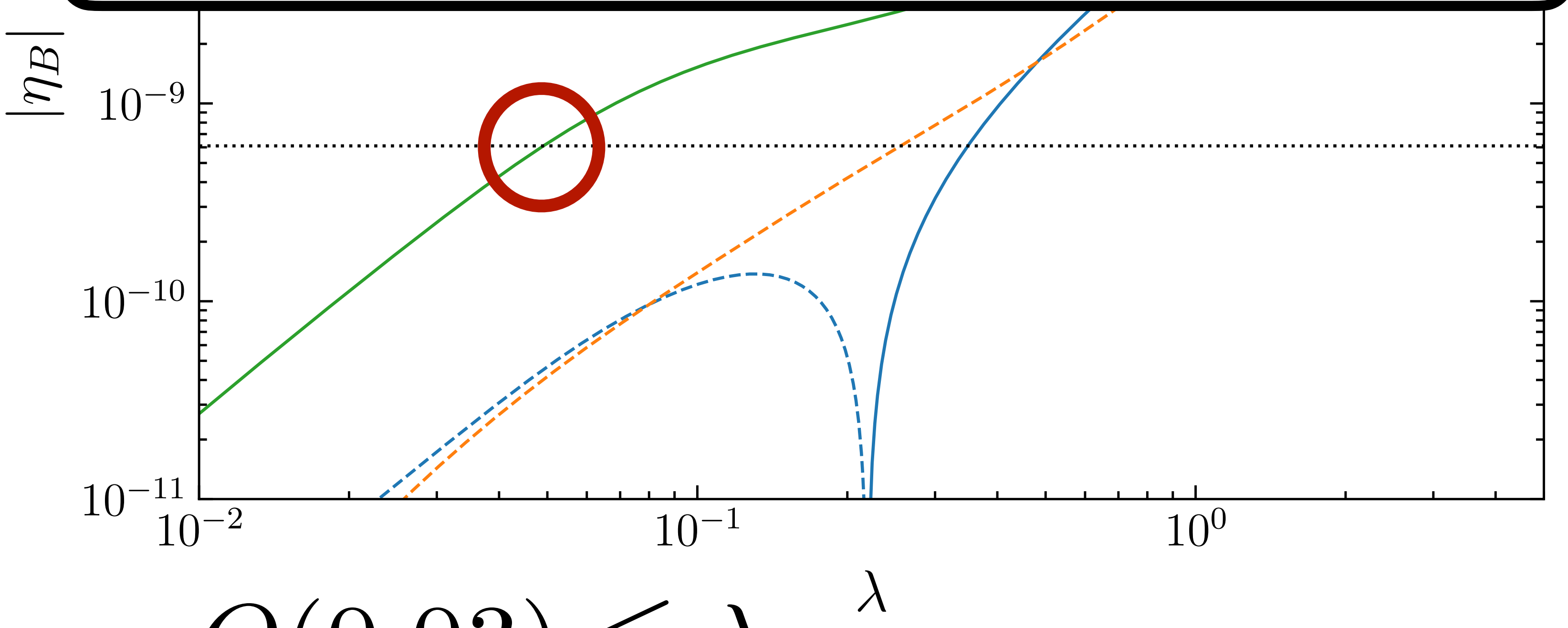
A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, JHEP 09 (2023) 079 [hep-ph 2305.18100]

This is larger than the conventional bound due to the restriction from gauge symmetry. S. Davidson, A. Ibarra, Phys. Lett. B 535 (2002) 25-32

Result

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

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



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

Set I

$\theta_{12} = 33.41°$

$\theta_{13} = 8.58°$

$\theta_{23} = 39.7°$

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

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

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]

This is larger than the conventional bound due to the restriction from gauge symmetry. S. Davidson, A. Ibarra, Phys. Lett. B 535 (2002) 25-32

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, $M_1 \gtrsim 10^{11-12}$ GeV setting LG scale in the considered model which is higher than Davidson-Ibarra bound.

Backup

Benchmark Point

Set I

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

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

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

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

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

Set II

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

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

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

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

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

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

Cf) NuFit data

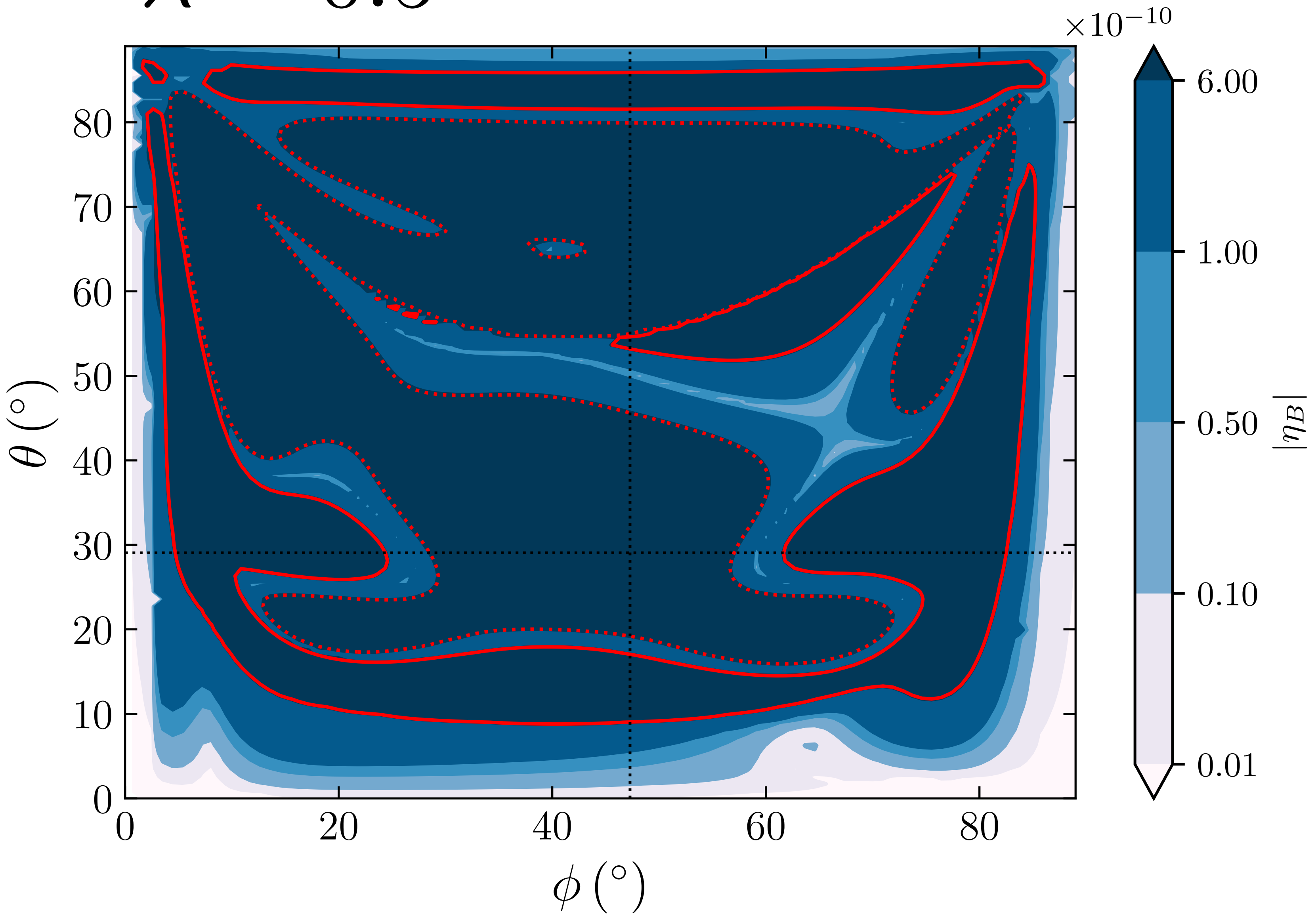
NuFIT Collaboration, NuFIT v5.2, http://www.nu-fit.org.
I. Esteban, et.al., JHEP 09 (2020) 178

Neutrino Masses and Mixing Parameters

Parameters (units)	θ_{12} $(^\circ)$	θ_{13} $(^\circ)$	θ_{23} $(^\circ)$	Δm^2_{21} $(10^{-5}\ \mathrm{eV}^2)$	Δm^2_{31} $(10^{-3}\ \mathrm{eV}^2)$
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	$[31.31, 35.74]$	$[8.19, 8.89]$	$[39.6, 51.9]$	$[6.82, 8.03]$	$[2.427, 2.590]$

Result

$\lambda = 0.5$



Set II

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

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

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

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

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

Input parameters are taken from NuFit ver 5.2

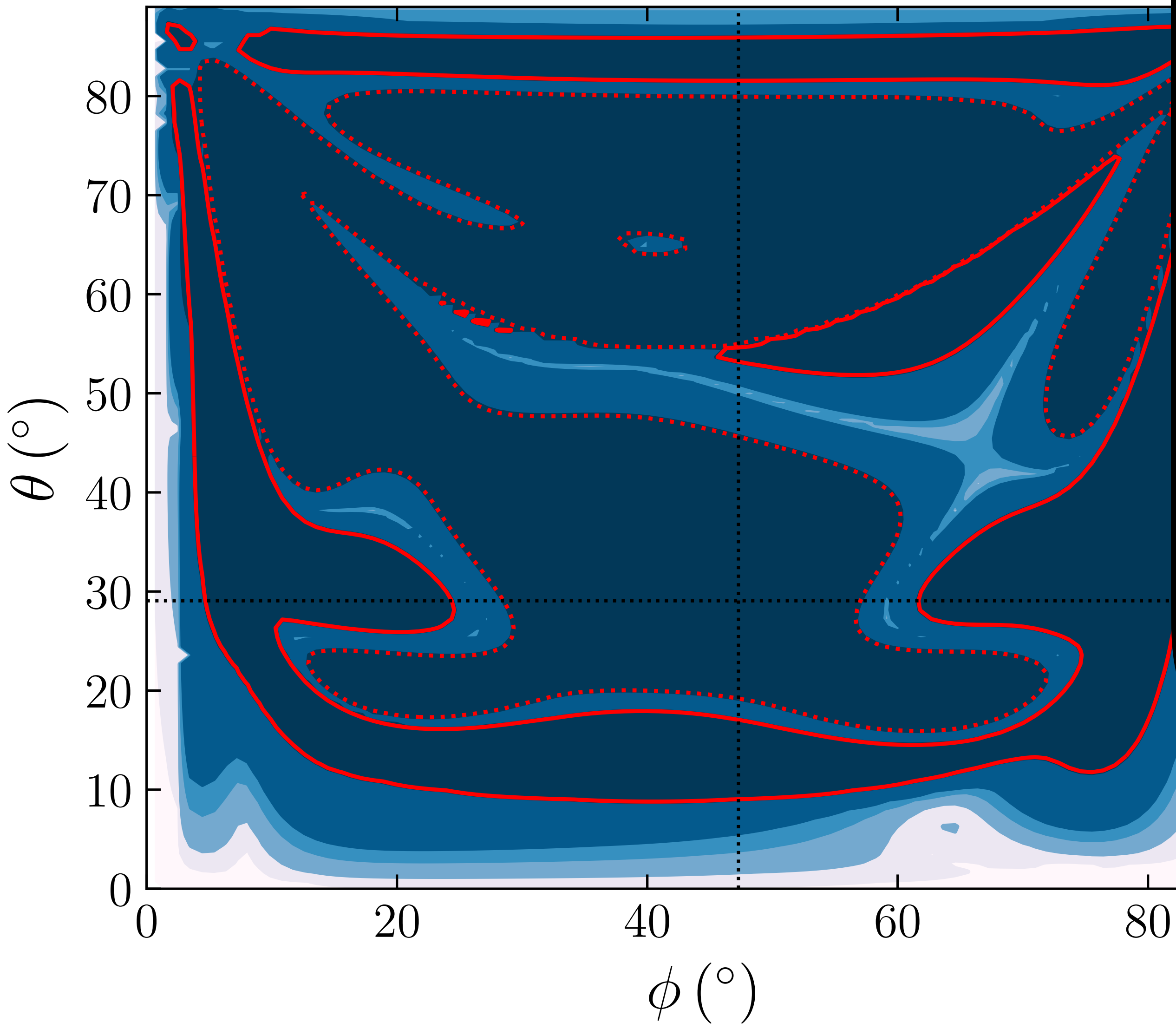
NuFIT Collaboration, NuFIT v5.2, http://www.nu-fit.org.

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

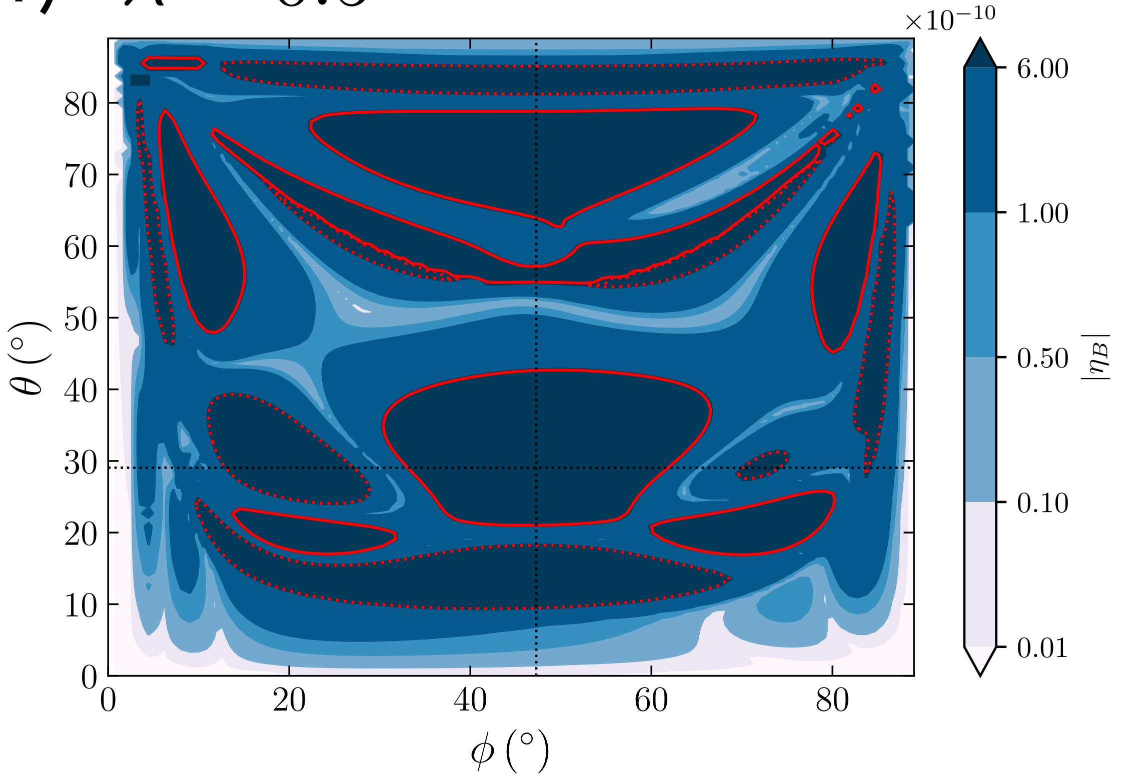
A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, JHEP 09 (2023) 079 [hep-ph 2305.18100]

Result

$\lambda = 0.5$



Cf) $\lambda = 0.5$

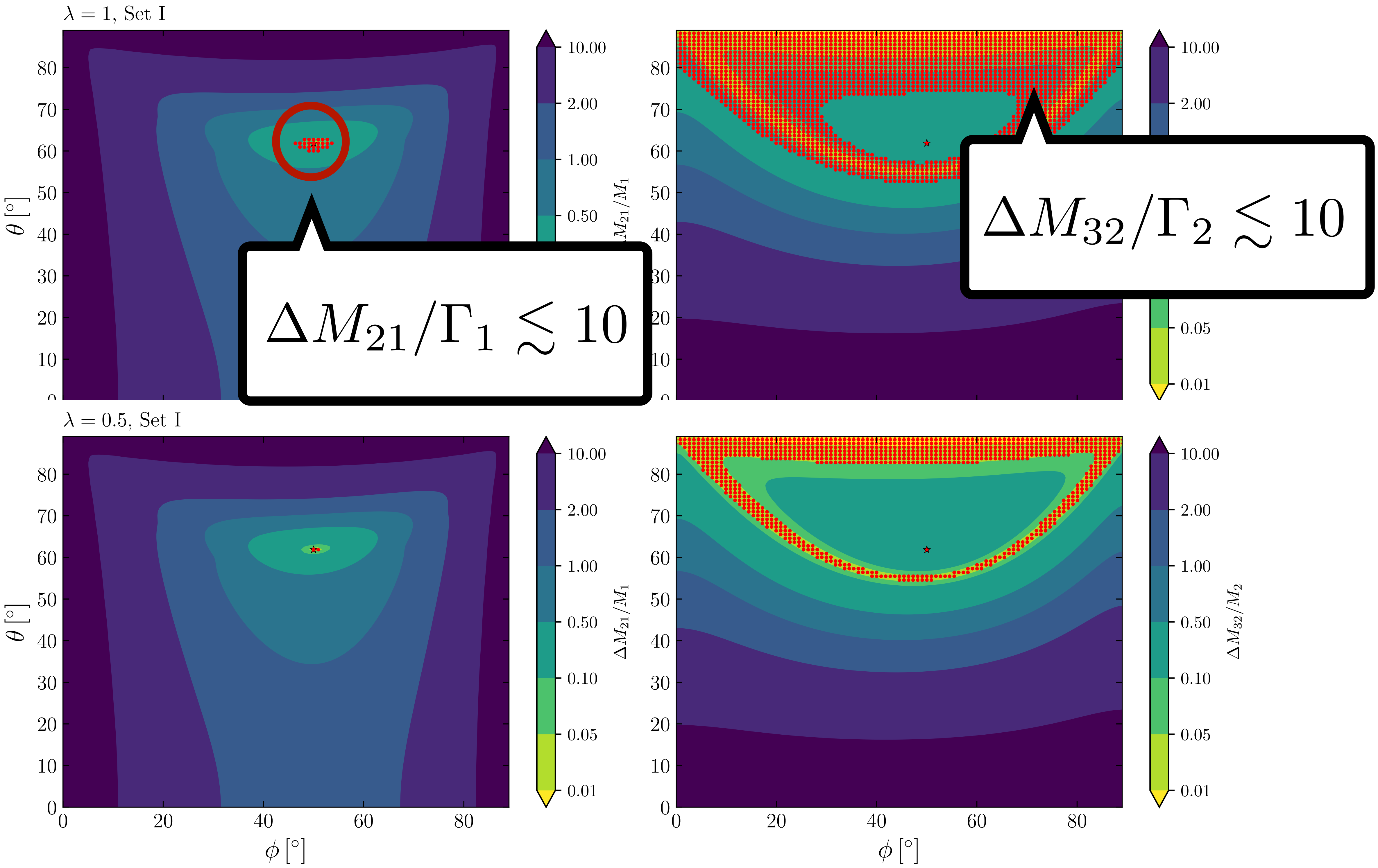


NuFIT Collaboration, NuFIT v5.2, http://www.nu-fit.org.

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]

Impact of Resonance Effects



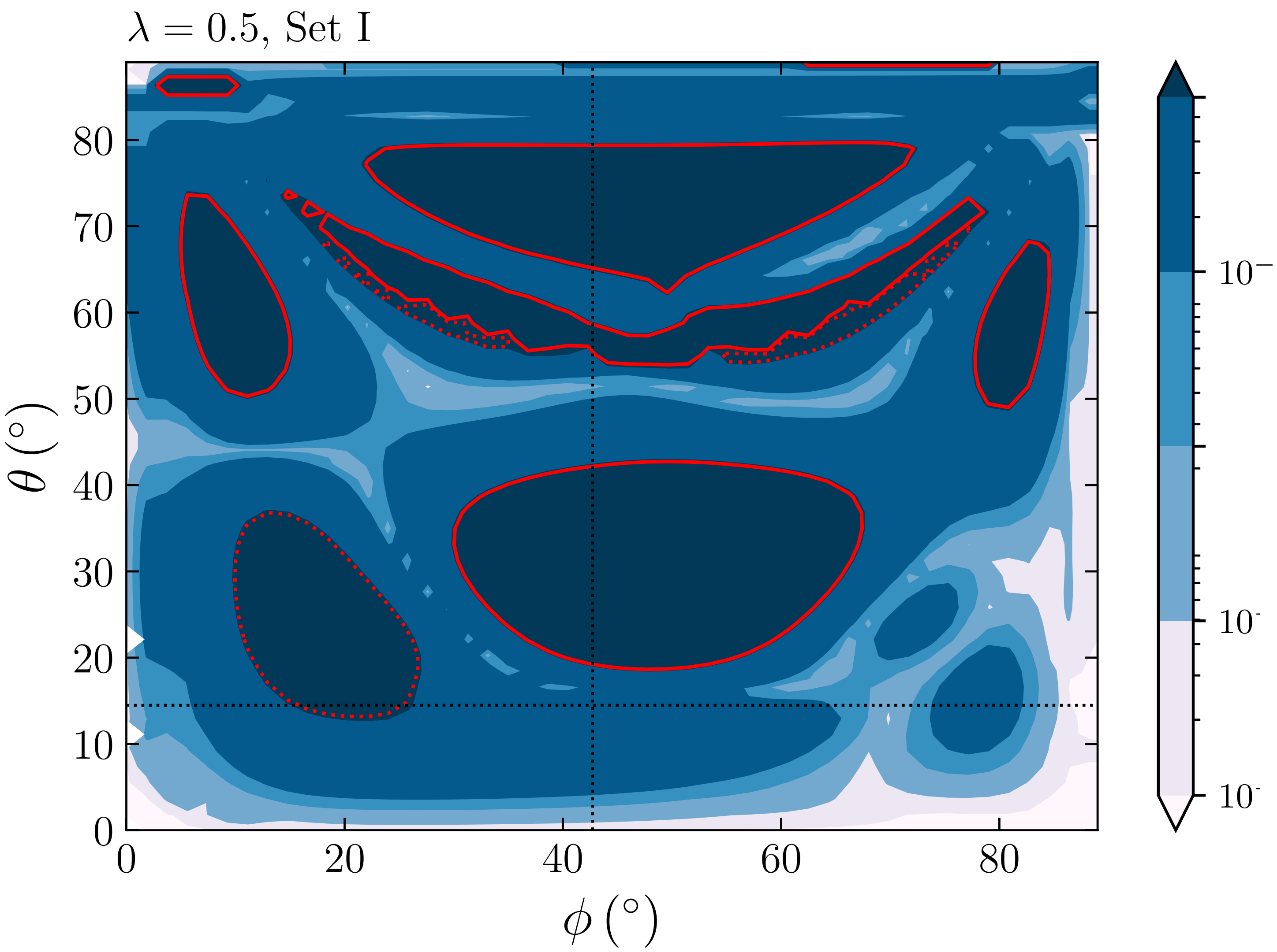
$\Delta M_{21}/\Gamma_1 \lesssim 10$

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

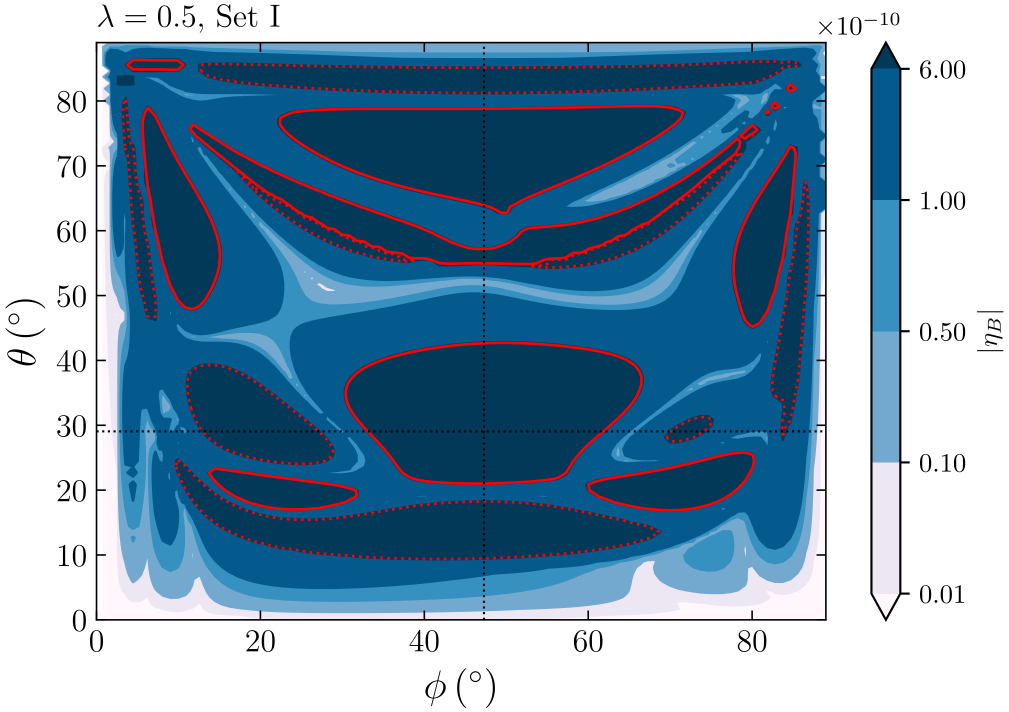
A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, hep-ph 2305.18100

Dependence of initial condition

When we take thermal initial abundance (TIA),



Cf) VIA

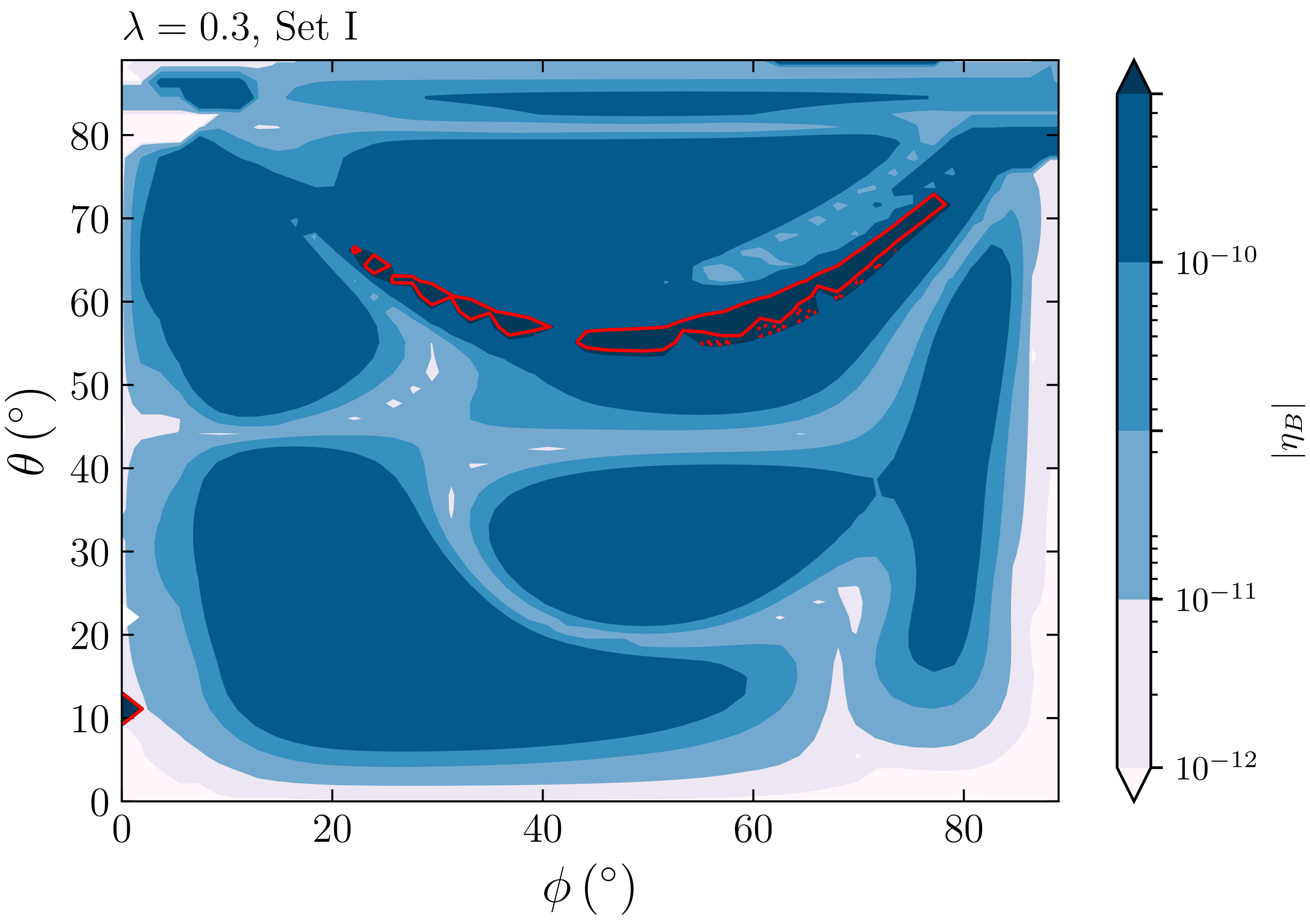


$$(\lambda_e, \lambda_\mu, \lambda_\tau) = \lambda(\cos\theta, \sin\theta\cos\phi, \sin\theta\sin\phi)$$

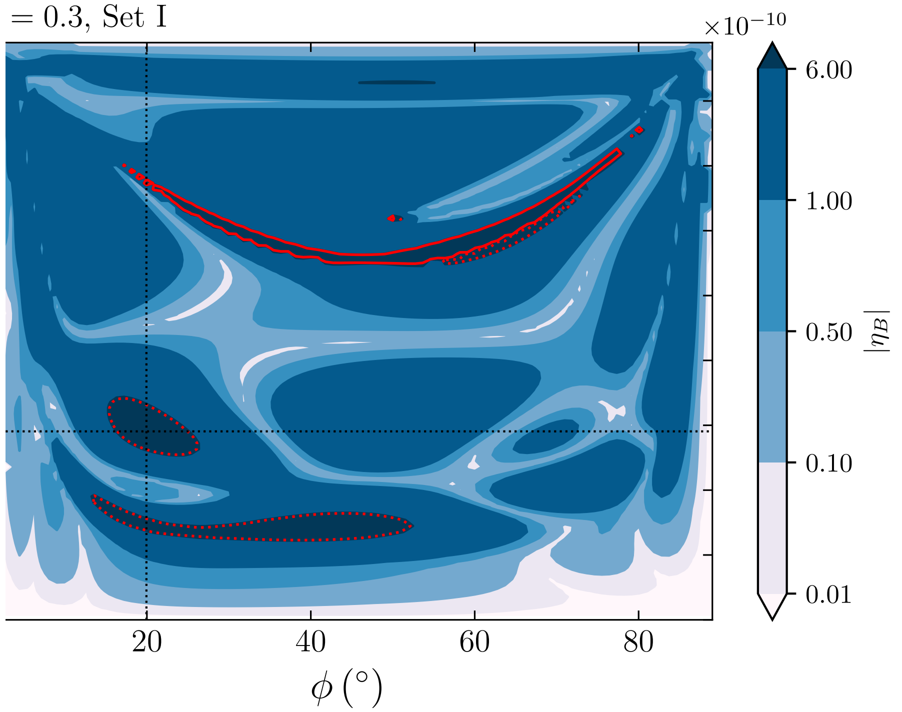
A. Granelli, K. Hamaguchi, N. Nagata, M E. Ramirez-Quezada, and JW, JHEP 09 (2023) 079 [hep-ph 2305.18100]

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]