

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

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@Hokkaido Workshop



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)

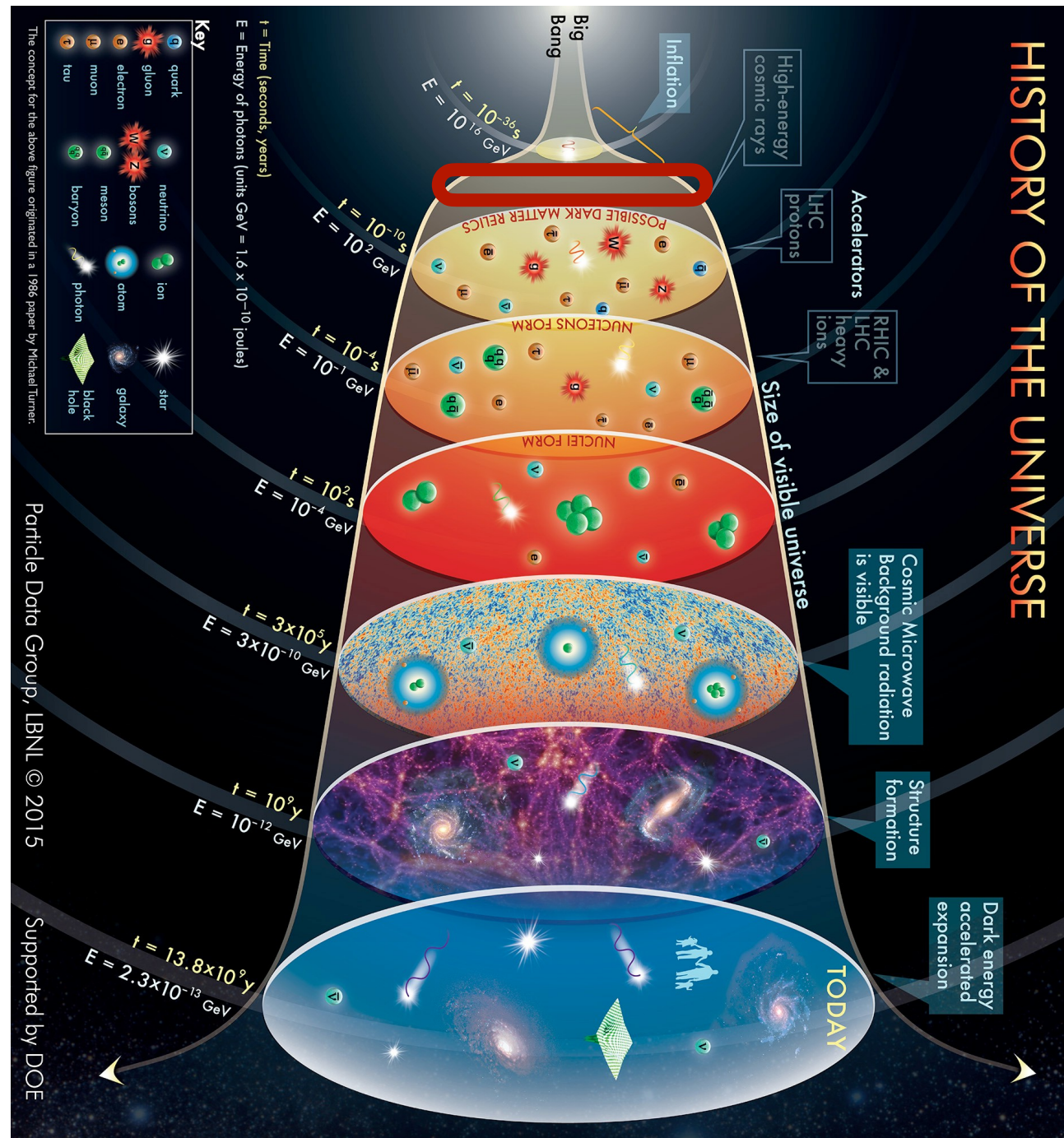
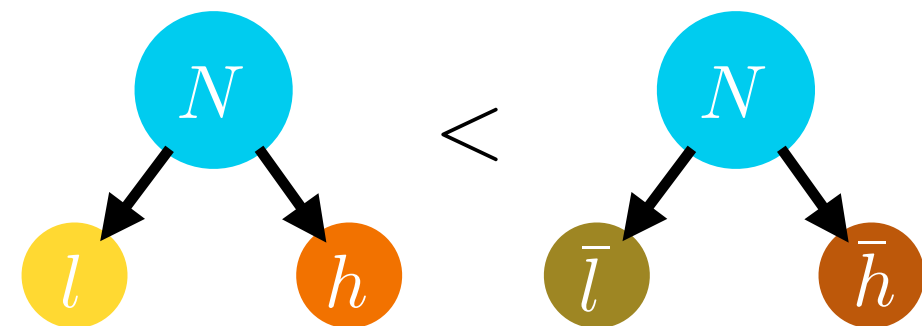


Fig from PDG

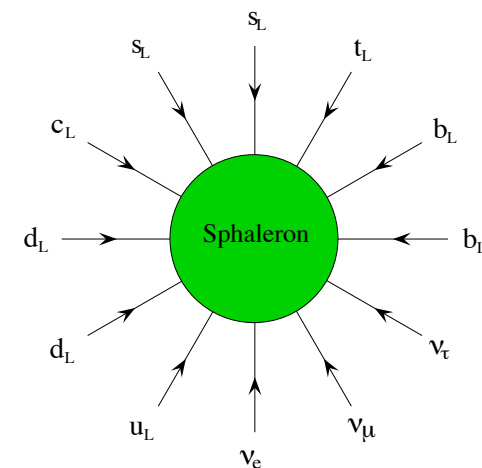
RH ν decay



$> 10^{10}$ 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

mass →	≈2.3 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²	
charge →	2/3	2/3	2/3	0	0	
spin →	1/2	1/2	1/2	1	0	
	u up	c charm	t top	g gluon	H Higgs boson	σ +1
QUARKS	d down	s strange	b bottom	γ photon		
	0.511 MeV/c ²	105.7 MeV/c ² +1	1.777 GeV/c ² -1	91.2 GeV/c ²		
	-1	-1	-1	0		
	1/2	1/2	1/2	1		
	e electron	μ muon	τ tau	Z Z boson		
LEPTONS	<2.2 eV/c ²	<0.17 MeV/c ² +1	1.5 MeV/c ² -1	80.4 GeV/c ²		
	0	0	0	±1		
	1/2	1/2	1/2	1		
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson		
					GAUGE BOSONS	

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

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

Minimal Setup

SM singlet

Breaking symmetry

mass →	≈2.3 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS	≈4.8 MeV/c ²	≈95 MeV/c ²	≈4.18 GeV/c ²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	γ photon	
LEPTONS	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	0	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	Z Z boson	
	<2.2 eV/c ²	<0.17 MeV/c ²	5.5 MeV/c ²	±1	
	0	0	0	1	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

► Predictive power for neutrino oscillation parameter

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

QUANTUM DIARIES

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

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

Minimal Setup

SM singlet

Breaking symmetry

mass →	≈2.3 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²
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QUARKS					
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LEPTONS					
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	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

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

QUANTUM DIA
<https://www.quantumdiaries.org/2014/03/14/the-beautiful-but-flawed-standard-model/>

► 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]

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

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

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

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

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

→ Strong predictive power for the neutrino sector

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

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

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

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

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

To evaluate baryon asymmetry,

Input	Output
$\Delta m^2, \delta m^2,$ $\theta_{12}, \theta_{23}, \theta_{31}$	$\delta, \alpha_1, \alpha_2,$ m_1, m_2, m_3

$\Rightarrow \mathcal{M}_{\nu_L} = U_{PMNS}^* \text{diag}(m_1, m_2, m_3) U_{PMNS}^{-1}$

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

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

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
	$\Rightarrow$	$\mathcal{M}_{\nu_L} = U_{PMNS}^* \text{diag}(m_1, m_2, m_3) U_{PMNS}^{-1}$

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

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

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

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

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

$$\mathcal{M}_D, \mathcal{M}_R \rightarrow \eta b \quad \text{baryon asymmetry}$$

Numerical calculation
with DME by **ULYSSES**

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

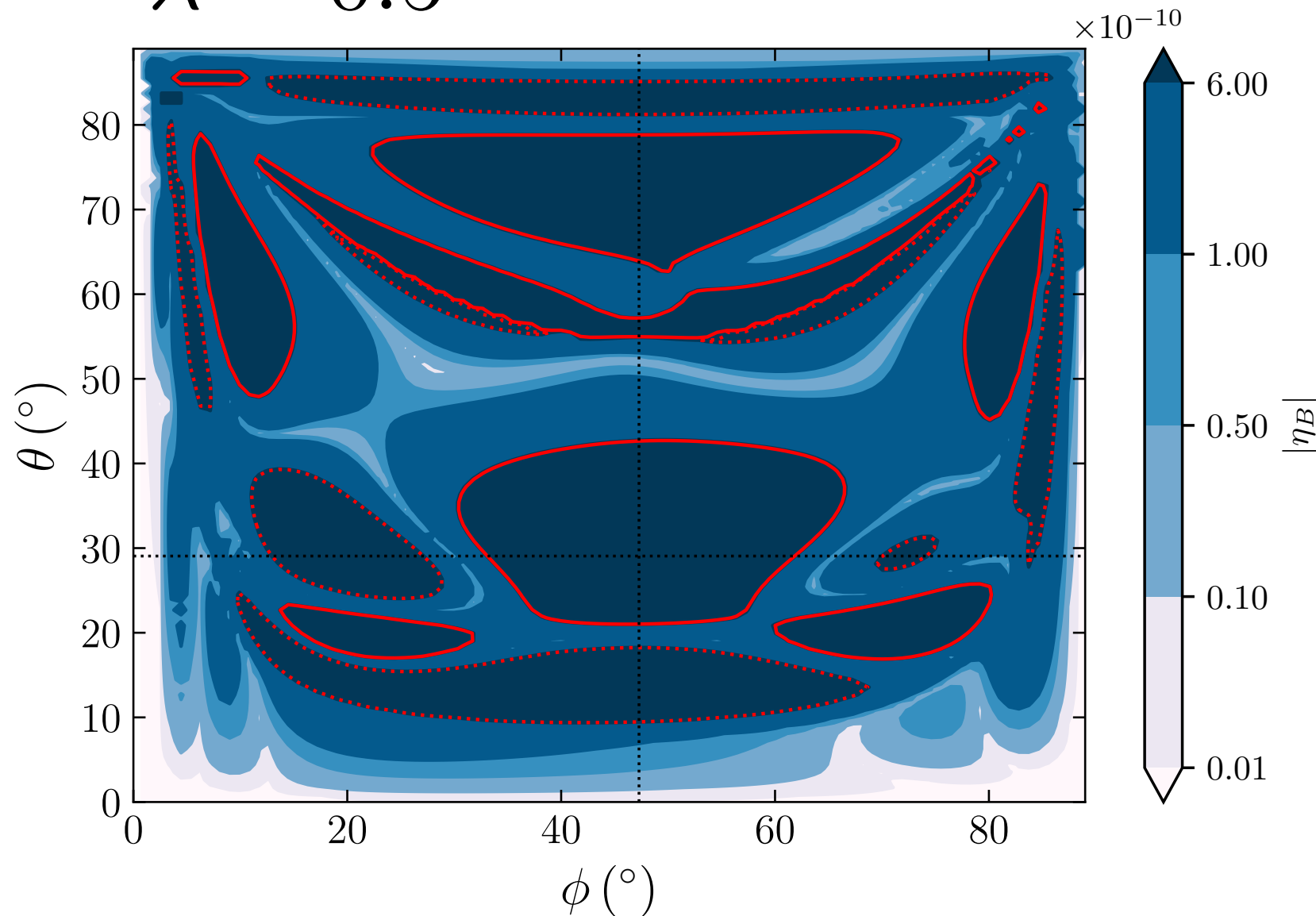
A. Granelli, et.al., Comput.Phys.Commun.
291 (2023) 108834

-1
 $PMNS$

Result

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

$$\lambda = 0.5$$



Set I

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

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

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

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

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

Input parameters are
taken from NuFit ver
5.2

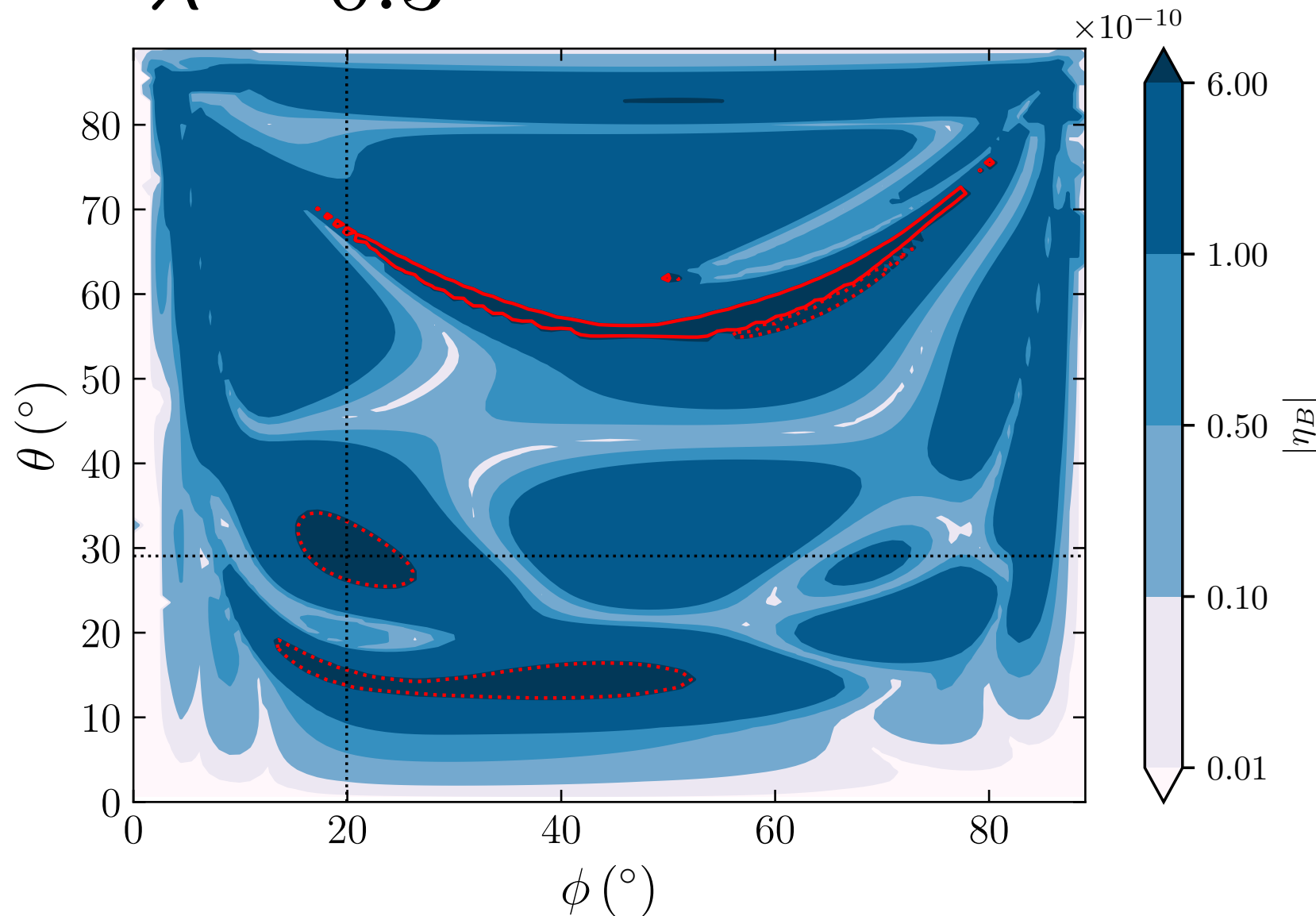
NuFIT Collaboration, NuFIT v5.2, <http://www.nu-fit.org>.

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

Result

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

$$\lambda = 0.3$$



Set I

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

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

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

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

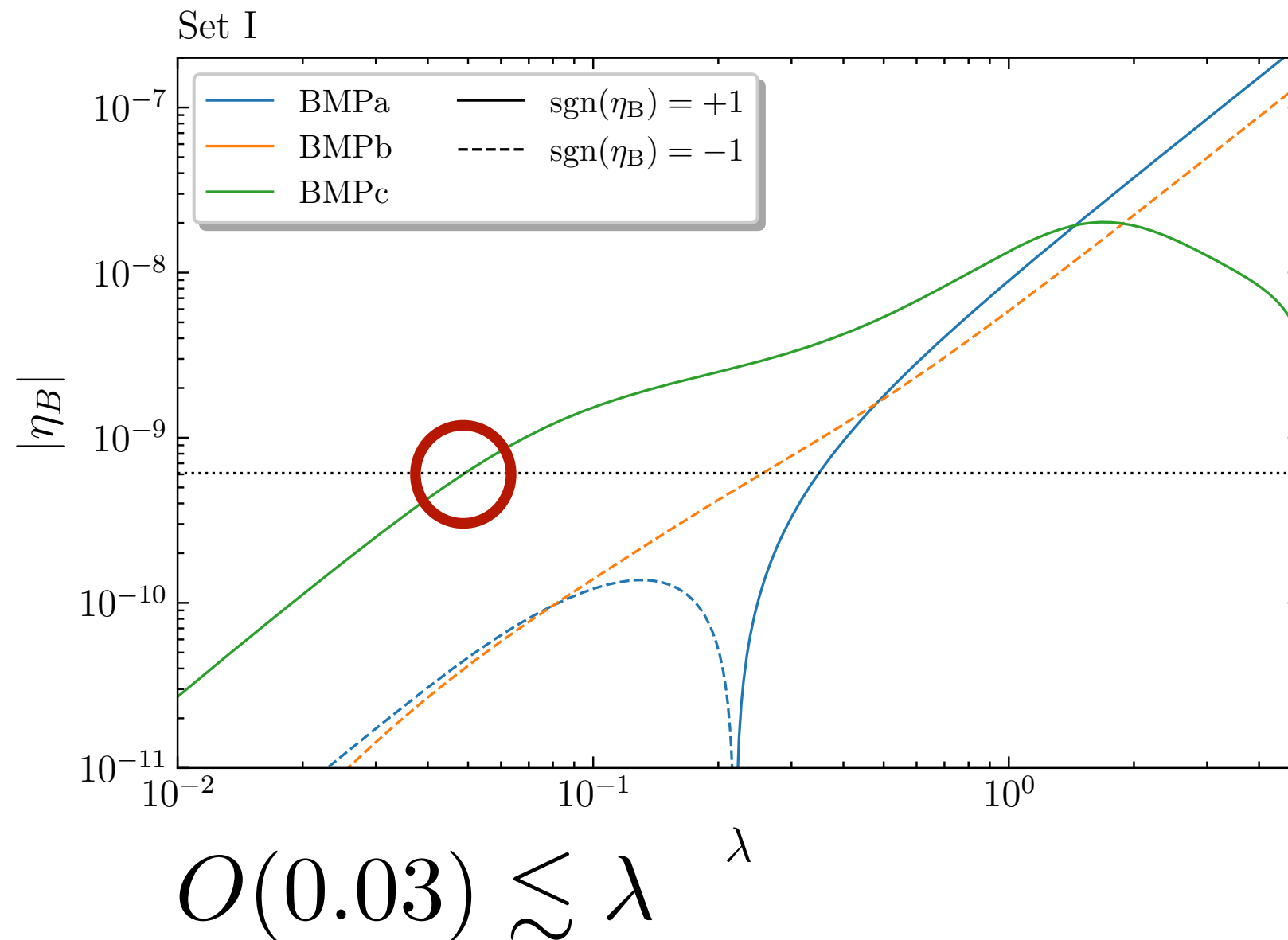
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NuFIT Collaboration, NuFIT v5.2, <http://www.nu-fit.org>.

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

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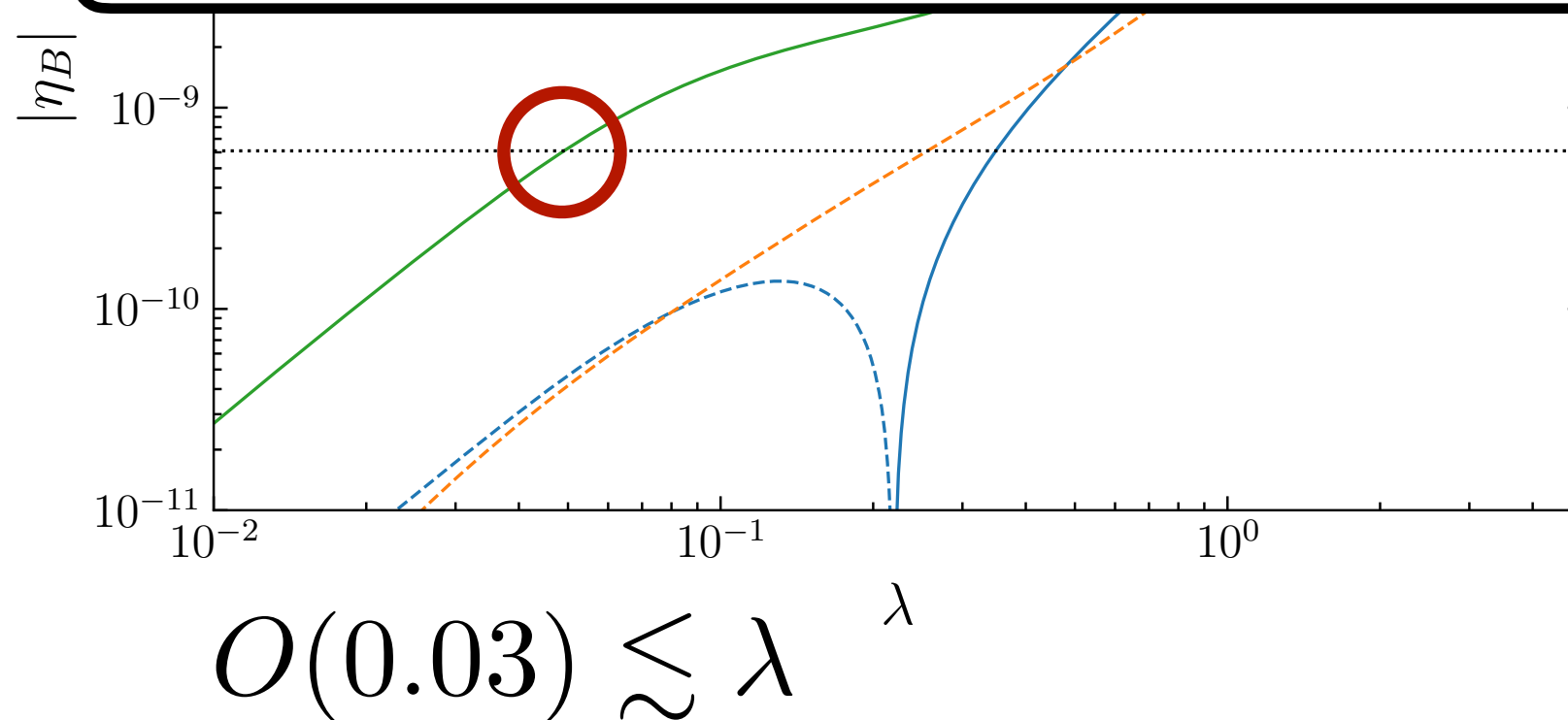
NuFIT Collaboration, NuFIT v5.2, <http://www.nu-fit.org>.

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

Result

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

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



Set I

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

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

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

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

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

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

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 that of the non-thermal scenario.

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

▶ $\langle \sigma \rangle \gg T_R$

- ▶ 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

Set I

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

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

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

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

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

Set II

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

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

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

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

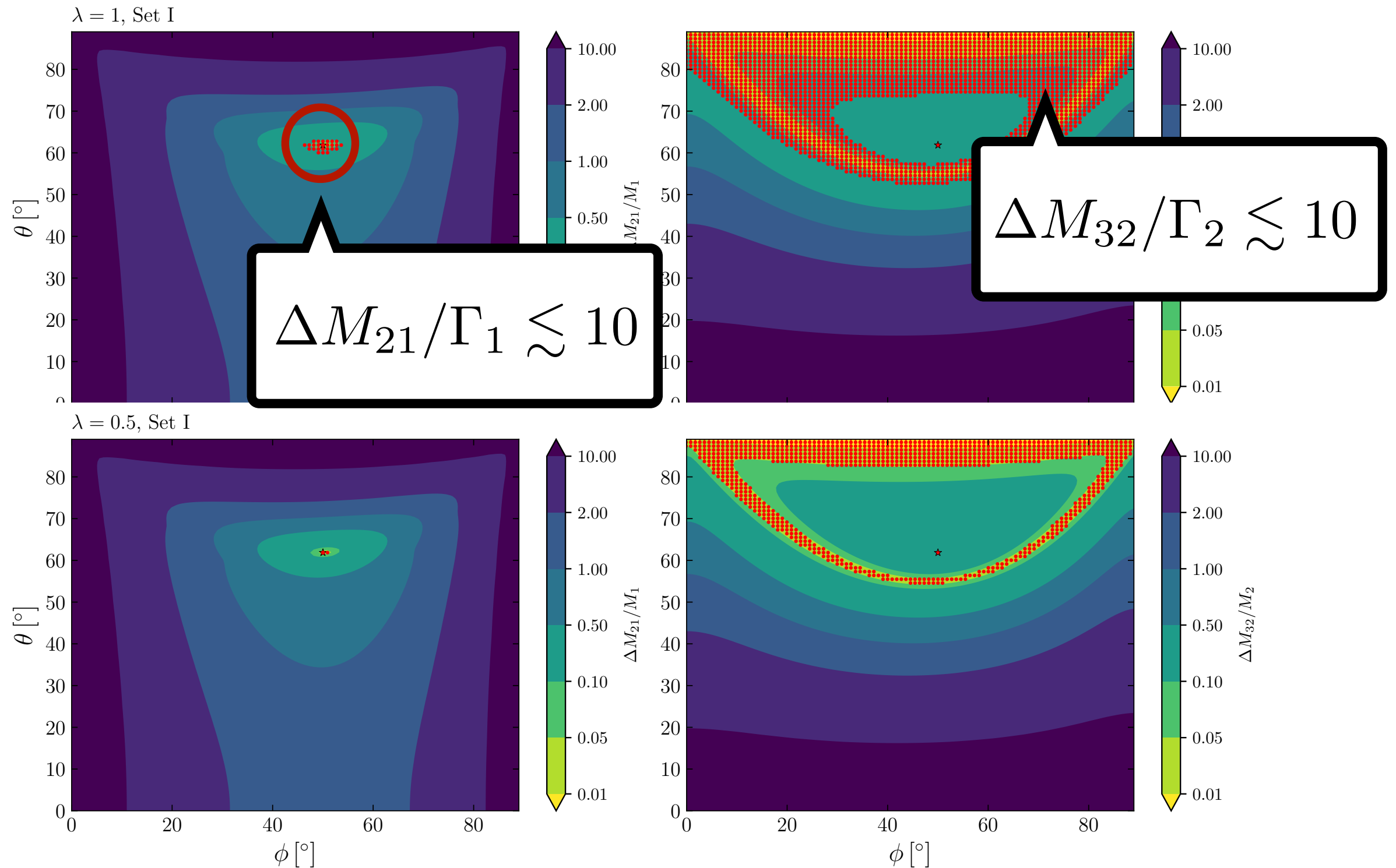
$$\Delta m_{31}^2 = 2.511 \times 10^{-3} \text{ eV}^2$$

We have taken 3σ 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

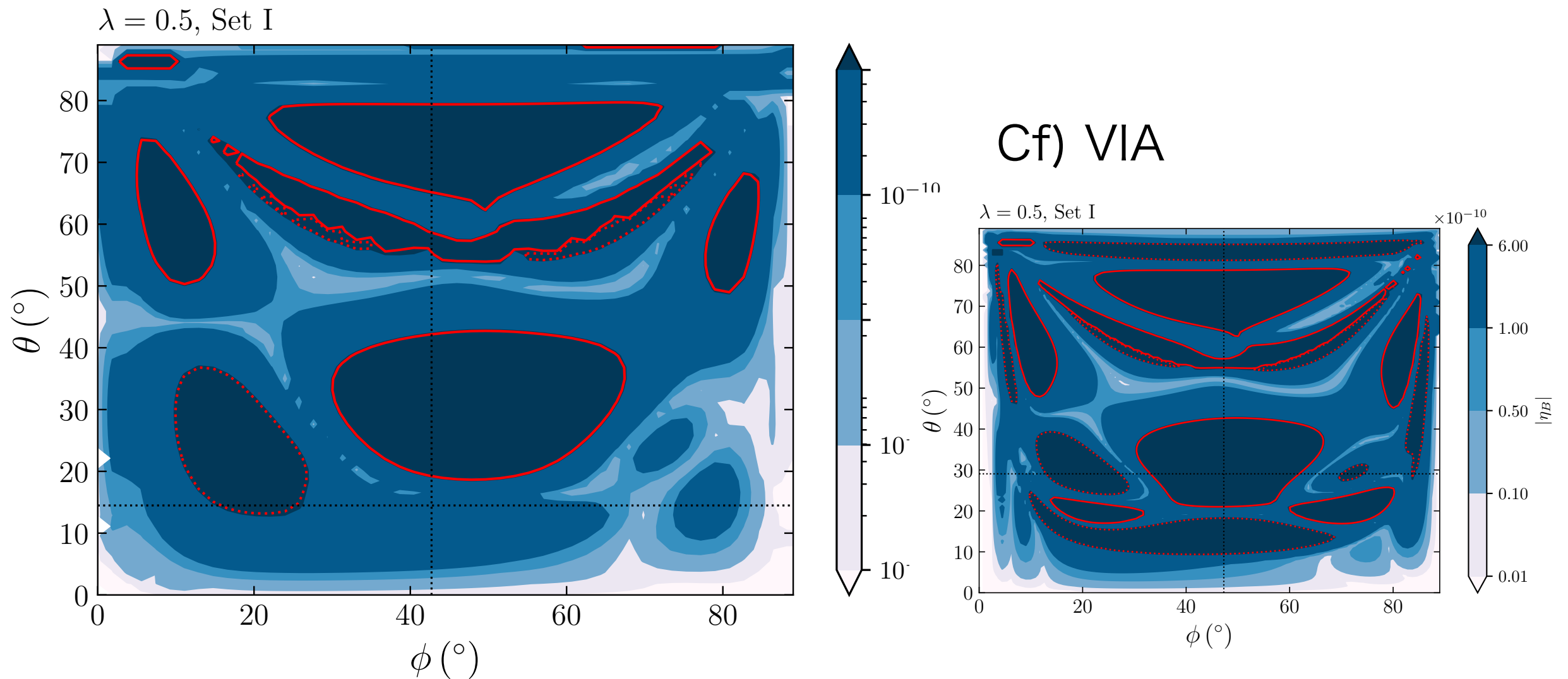
Neutrino Masses and Mixing Parameters					
Parameters (units)	θ_{12} ($^\circ$)	θ_{13} ($^\circ$)	θ_{23} ($^\circ$)	Δm_{21}^2 (10^{-5} eV^2)	Δm_{31}^2 (10^{-3} eV^2)
With SK	$33.41^{+0.75}_{-0.72}$	$8.58^{+0.11}_{-0.11}$	$42.2^{+1.1}_{-0.9}$	$7.41^{+0.21}_{-0.20}$	$2.507^{+0.026}_{-0.027}$
3σ range	[31.31, 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



Dependence of initial condition

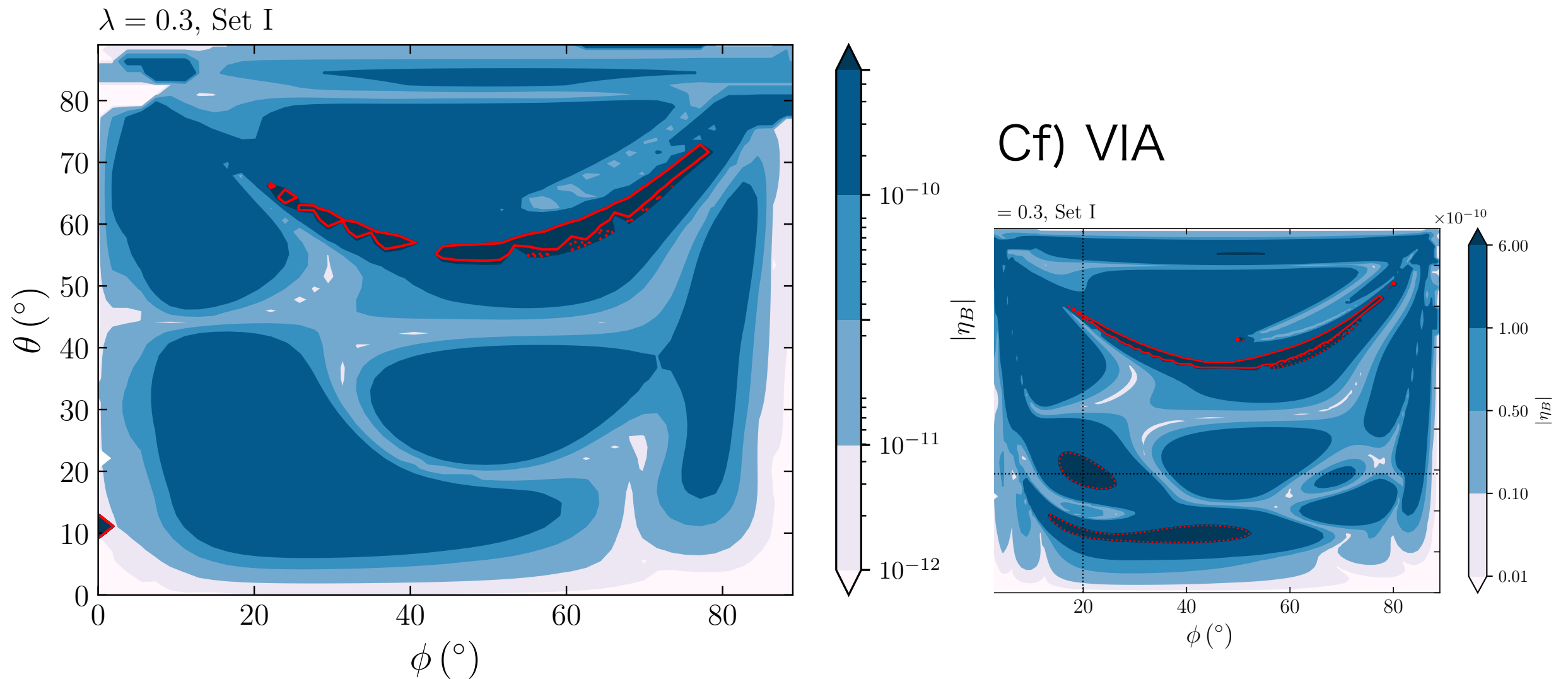
When we take thermal initial abundance (TIA),



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

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