Phenomenology of low-scale seesaw with flavour and CP symmetries

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Introduction

- Standard Model (SM) is very successful.
  Nevertheless, several phenomena are not explained within SM.
  - Replication of fermion generations
  - Fermion masses
  - Quark and lepton mixing
  - Baryon asymmetry of the Universe (BAU)

$$Y_B = \frac{n_B - n_{\overline{B}}}{s}\bigg|_0 = 8.75 \times 10^{-11}$$

Planck ('18)

Introduction

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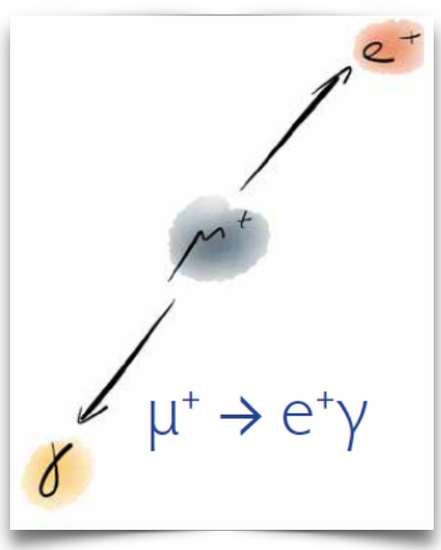
  - Baryon asymmetry of the Universe (BAU)
- Additionally, beyond SM (BSM) theories can have a rich phenomenology.
  - Processes forbidden/highly suppressed in SM can be in reach



Current experimental limit

$$\mathrm{BR}(\mu \to e\gamma) < 4.2 \cdot 10^{-13}$$

MEG at PSI ('16)

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  - Flavour and CP violation needs to be kept under control
  - Possible correlations among different signals

Introduction

Flavour and CP symmetry

Low-scale type I seesaw

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Flavour and CP symmetry

Flavour symmetries $\Delta(3\,n^2)$ and $\Delta(6\,n^2)$

- Have 3-dim irrep(s)
- Can also offer 1-dim irreps and 2-dim irreps
- Are subgroups of SU(3)
- Examples: permutation groups A_4 and S_4

Luhn/Nasri/Ramond ('07)
Escobar/Luhn ('08)

CP as further symmetry

Grimus/Rebelo ('95),
Ecker/Grimus/Neufeld (´84,'87,'88)

- Motivation:
  For more than one generation of certain particle species,
  define CP that also acts on generations of particles,
  e.g.

$$\Phi_i(x) \quad \rightarrow \quad X_{ij}\,\Phi_j^\dagger(x_P) \quad \text{with} \quad (x_P)_\mu = x^\mu$$

with

$$X\,X^\dagger = X\,X^\star = 1$$

Feruglio/CH/Ziegler ('12)
Harrison/Scott ('02), Grimus/Lavoura ('03)
Holthausen/Lindner/Schmidt ('12), Chen et al. ('14)

Flavour and CP symmetry

Breaking of symmetries

Feruglio / CH / Ziegler ('12)

G_f and CP

↙ ↘

charged leptons	neutrinos
G_e	$G_\nu = Z_2 \times$ CP
U_e	$U_\nu = \Omega_\nu R(\theta) K_\nu$

↘ ↙

$$U_{PMNS} = U_e^\dagger \Omega_\nu R(\theta) K_\nu$$

Minimal choice Z_3

3 different masses

Choice Z_2 and CP

Majorana masses

Free parameter

Size of masses not explained

CH / Meroni / Molinaro ('14)

Result: four different types of mixing patterns with different properties

Case 1) **Case 2)** **Case 3 a)** **Case 3 b.1)**

Lepton mixing

Case 1)

- Leads to lepton mixing angles

$$\sin^2\theta_{13} = \frac{2}{3}\sin^2\theta \quad , \quad \sin^2\theta_{12} = \frac{1}{2+\cos 2\theta} \quad , \quad \sin^2\theta_{23} = \frac{1}{2}\left(1 + \frac{\sqrt{3}\sin 2\theta}{2+\cos 2\theta}\right)$$

- Result of fit

$$\sin^2\theta_{13} \approx 0.0220\ (0.0222) \quad , \quad \sin^2\theta_{12} \approx 0.341 \quad , \quad \sin^2\theta_{23} \approx 0.605\ (0.606)$$

for

$$\theta_L \approx 0.183\ (0.184)$$

assuming light neutrino masses with NO (IO).

- Predictions for CP phases

s fixed by CP symmetry

$$|\sin\alpha| = \left|\sin\left(\frac{6\pi s}{n}\right)\right| \ , \ \sin\beta = 0 \ , \ \sin\delta = 0$$

NuFIT 5.2 ('22)

	NO, 1 σ	NO, 3 σ	IO, 1 σ	IO, 3 σ
$\delta_{\rm CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$

Low-scale seesaw

- Consider a scenario of **type I seesaw with 3 RH neutrinos**, i.e. 3 generations of LH doublets and 3 generations of gauge singlets $\nu_{R\,i}$

$$\mathcal{L} \supset \mathrm{i}\,\overline{\nu_R}\,\partial\!\!\!/\,\nu_R - \frac{1}{2}\overline{\nu_R^c}\,M_R\,\nu_R - \overline{l_L}\,Y_D\,\varepsilon H^*\,\nu_R + \text{h.c.}$$

- Light neutrino masses

$$m_\nu = -\,m_D\,M_R^{-1}\,m_D^T$$

with

$$m_D = Y_D\,\langle H\rangle$$

Minkowski ('77), Glashow ('80), Gell-Mann/Ramond/Slansky ('79), Mohapatra/Senjanovic ('80), Yanagida ('80), Schechter/Valle ('80)

Low-scale seesaw

- We take

$$\alpha_R \sim 1 \qquad\qquad l_{L\,\alpha} \sim 3\ , \nu_{R\,i} \sim 3'$$

see also Dev/CH/Molinaro ('18); Chauhan/Dev ('22)

Low-scale seesaw

- We take

$$\alpha_R \sim 1$$

$$l_{L\,\alpha} \sim 3 \quad \nu_{R\,i} \sim 3'$$

irreducible, faithful, complex

Reason:
Fully explore the predictive power of flavour and CP symmetry

CH/Meroni/Molinaro ('14)

see also Dev/CH/Molinaro ('18); Chauhan/Dev ('22)

Low-scale seesaw

- We take

$$\alpha_R \sim 1 \qquad\qquad l_{L\,\alpha} \sim 3\ , \nu_{R\,i} \sim 3'$$

- We get

Charged lepton mass matrix

$$\begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

residual symmetry G_e

Low-scale seesaw

- We take

$$\alpha_R \sim 1 \qquad\qquad l_{L\,\alpha} \sim 3\ , \nu_{R\,i} \sim 3'$$

irreducible, in general unfaithful, real

Reason:
(flavour-universal) mass term for $\nu_{R\,i}$ w/o breaking flavour and CP symmetry, breaking encoded in Y_D

see also Dev/CH/Molinaro ('18); Chauhan/Dev ('22)

Low-scale seesaw

- We take

$$\alpha_R \sim 1 \qquad\qquad l_{L\,\alpha} \sim 3\ , \nu_{R\,i} \sim 3'$$

- We get

Neutral lepton sector

residual symmetry G_ν

$$\mathcal{L} \supset \mathrm{i}\,\overline{\nu_R}\,\partial\!\!\!/\,\nu_R - \frac{1}{2}\overline{\nu_R^c}\,M_R\,\nu_R + \overline{l_L}\,Y_D\,\varepsilon H^*\,\nu_R + \text{h.c.}$$

No symmetry breaking

$$M_R = M_R^0 = M \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

RH neutrino masses are degenerate

Symmetry breaking

$$Y_D = \Omega(\mathbf{3})\,R_{ij}(\theta_L)\,\mathrm{diag}(y_1, y_2, y_3)\,P^{ij}_{kl}\,R_{kl}(-\theta_R)\,\Omega(\mathbf{3}')^\dagger$$

Low-scale seesaw

Neutral lepton sector

$$Y_D = \Omega(\mathbf{3})\, R_{ij}(\theta_L)\, \mathrm{diag}(y_1, y_2, y_3)\, P^{ij}_{kl}\, R_{kl}(-\theta_R)\, \Omega(\mathbf{3}')^\dagger$$

In total five free real parameters corresponding to three light neutrino masses, one free parameter for lepton mixing and one free parameter related to RH neutrinos

Possible small symmetry breaking for RH neutrino masses

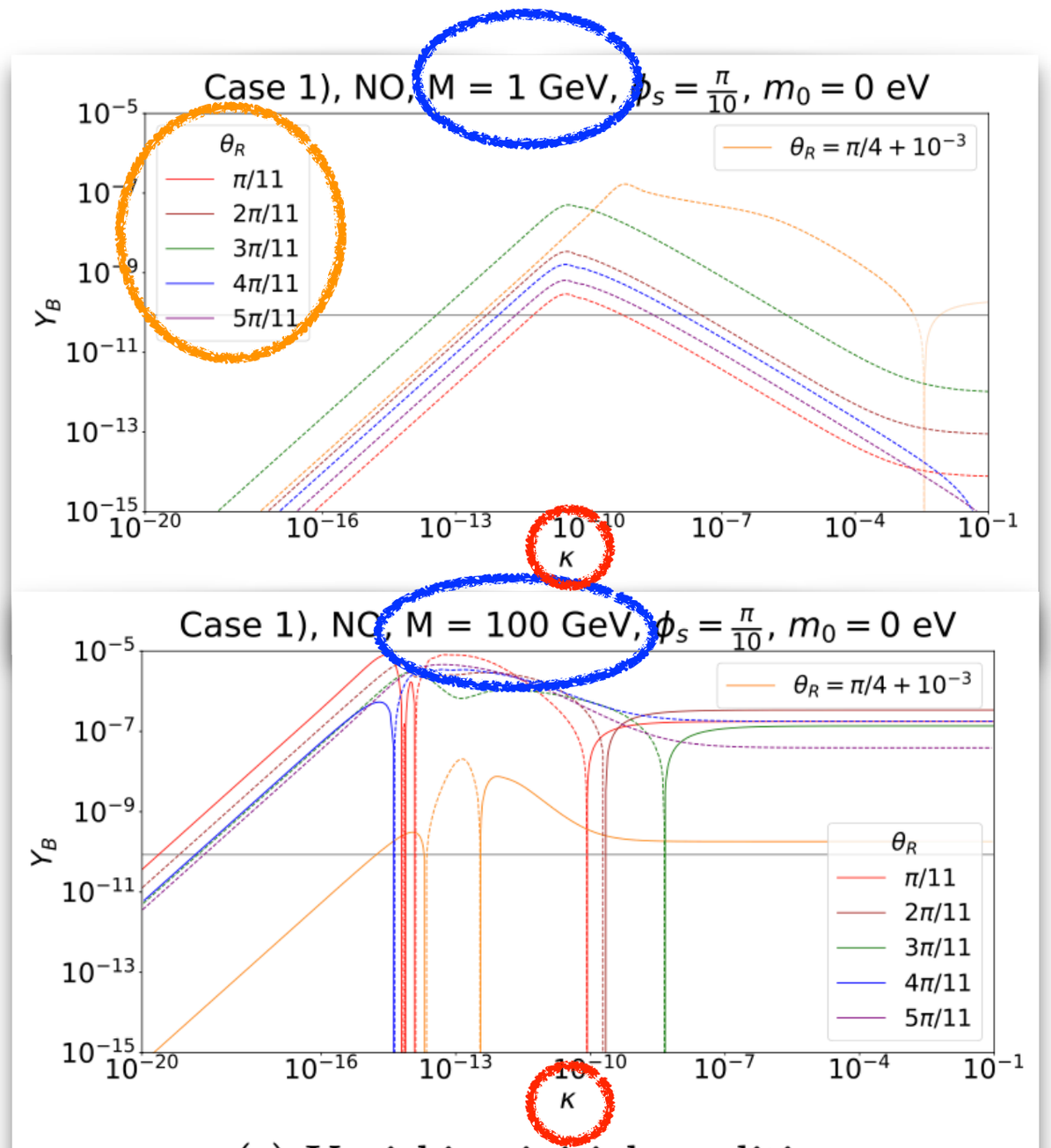
$$\delta M_R = \kappa\, M \begin{pmatrix} 2 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{pmatrix}$$

$$M_1 = M\,(1 + 2\,\kappa) \;\text{ and }\; M_2 = M_3 = M\,(1 - \kappa)$$

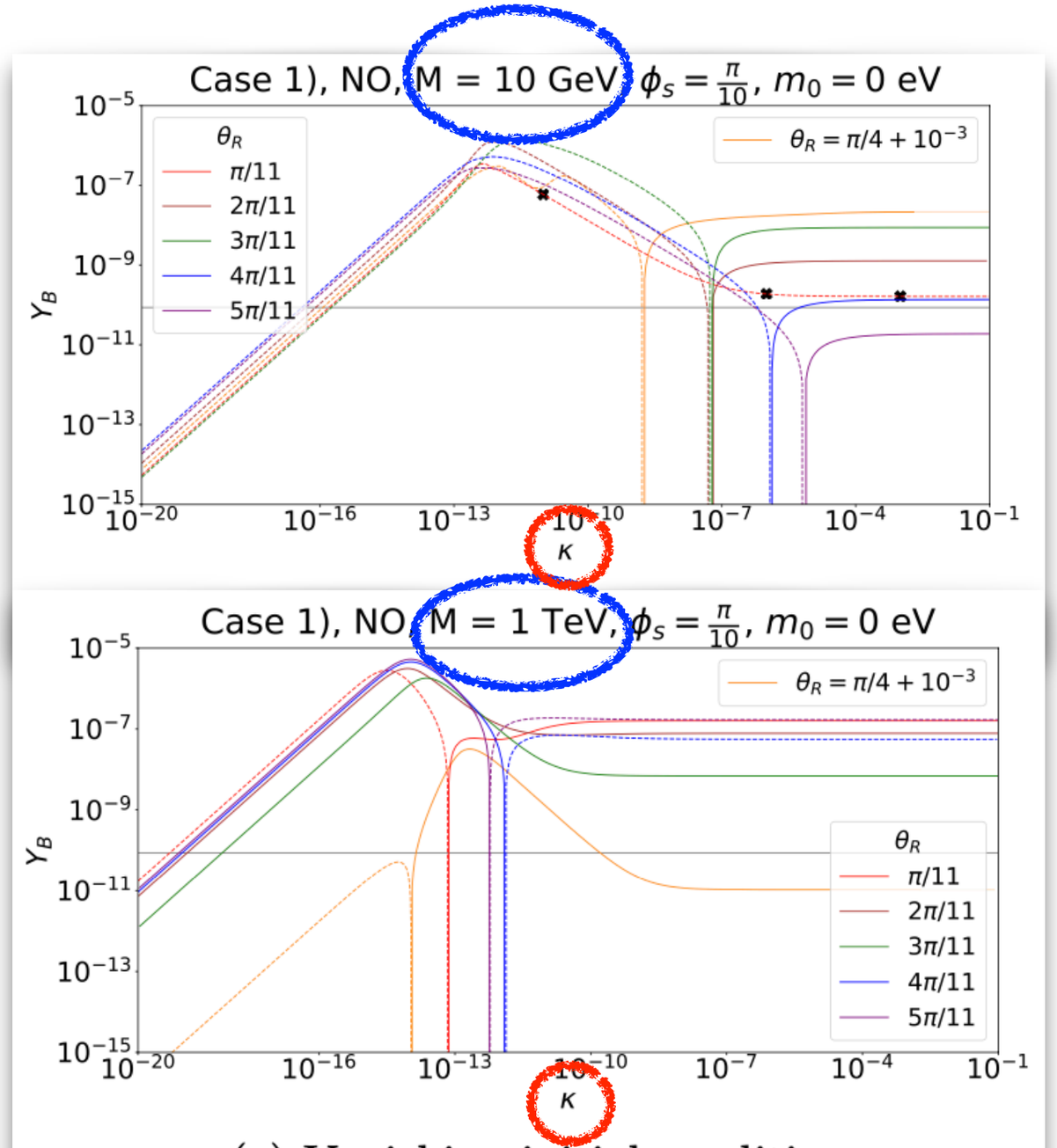
Often needed for generating correct amount of BAU.

Leptogenesis

Case 1)



(e) Vanishing initial conditions.



(g) Vanishing initial conditions.

Leptogenesis

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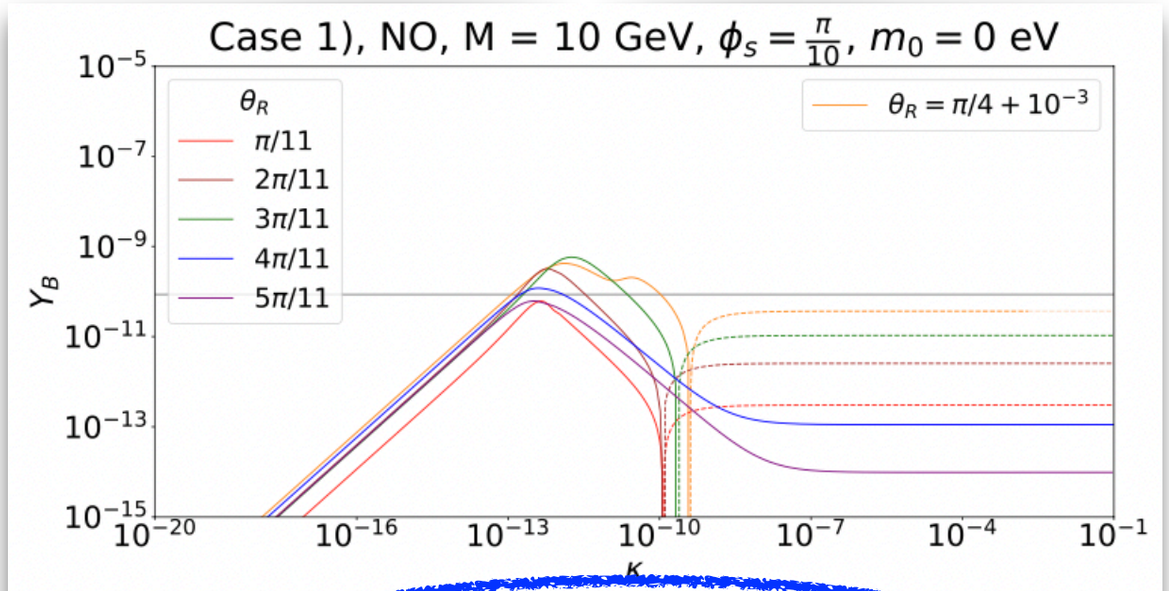
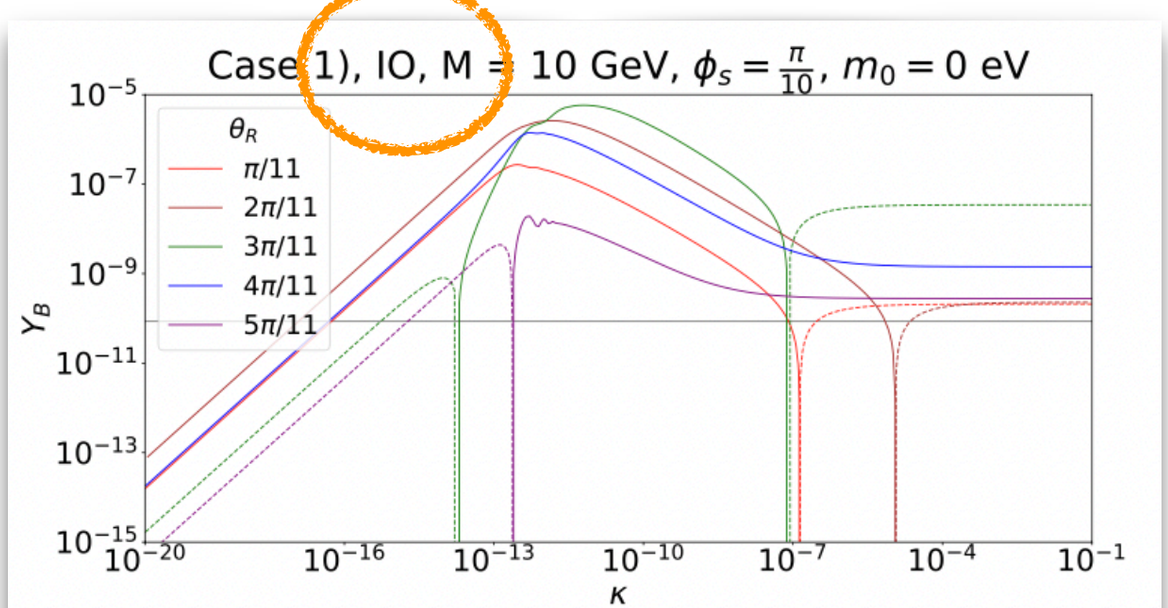
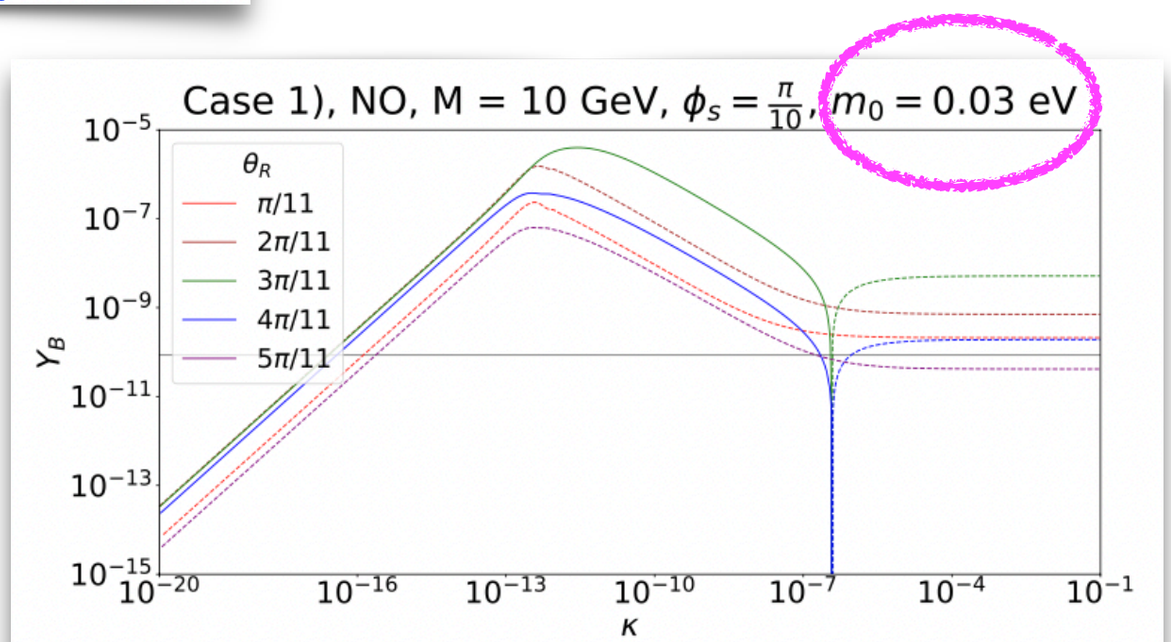


(d) Thermal initial conditions.



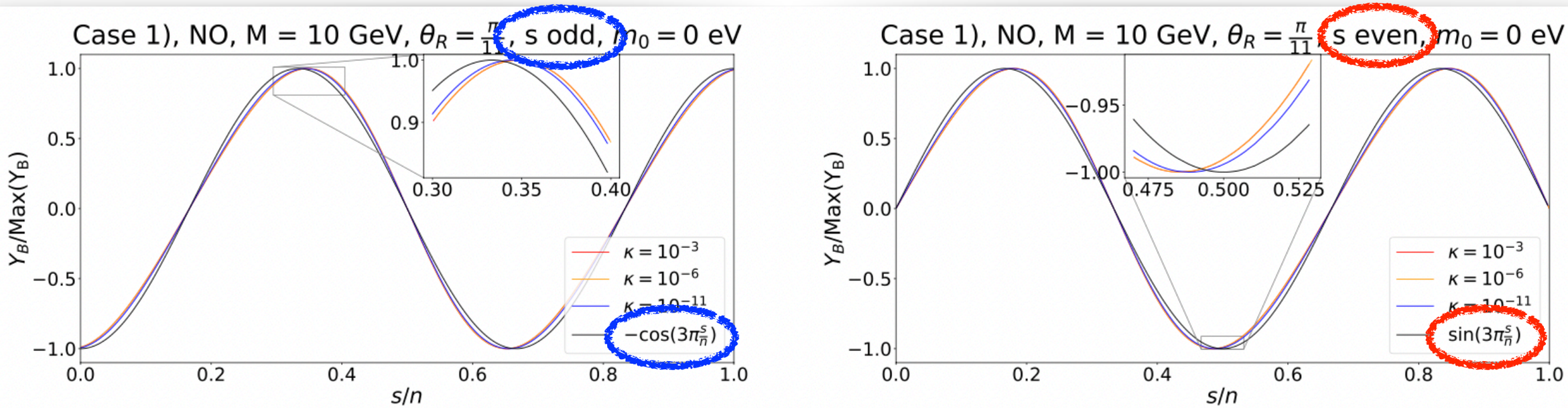
(a) Vanishing initial conditions.



(b) Vanishing initial conditions.

Leptogenesis

Case 1)



(a) Vanishing initial conditions. (b) Vanishing initial conditions.

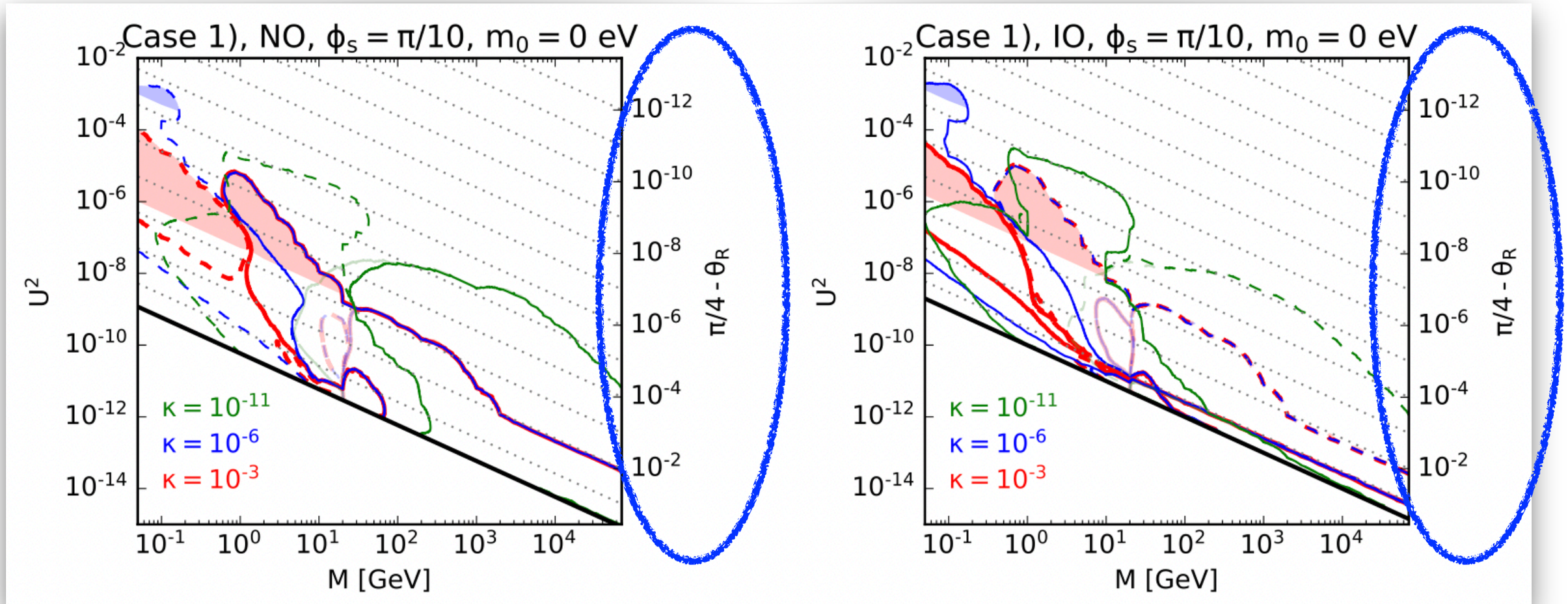
Majorana phase α fulfils $$|\sin\alpha| = \left|\sin\left(\frac{6\pi s}{n}\right)\right|$$

$$\left[\text{Remember} \quad \sin\left(\frac{6\pi s}{n}\right) = 2\cos\left(\frac{3\pi s}{n}\right)\sin\left(\frac{3\pi s}{n}\right)\right]$$

Leptogenesis Light neutrino masses for strong NO

Case 1)

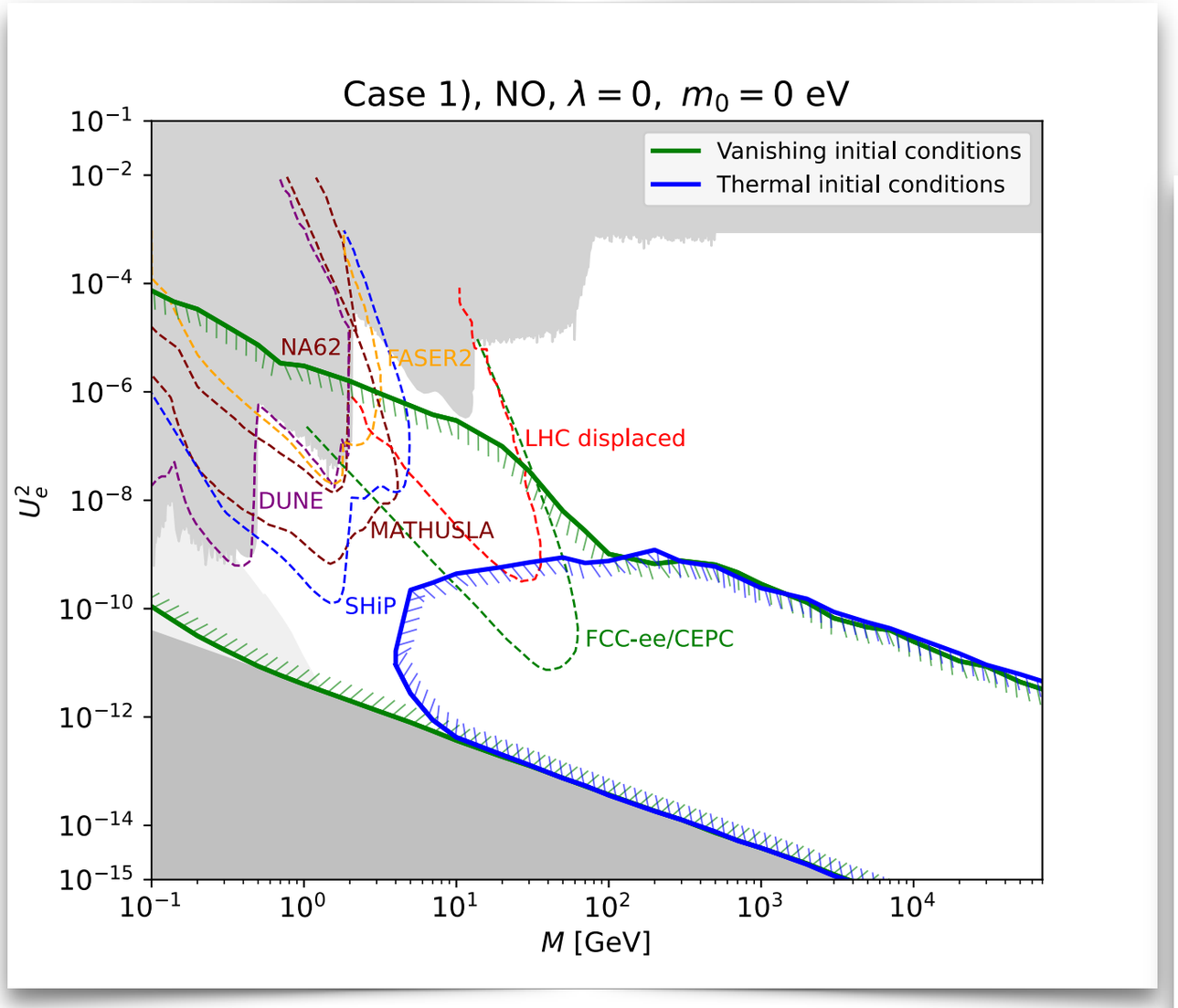
$$m_2 = \frac{y_2^2 \langle H \rangle^2}{M} \quad m_1 = 0 \text{ and } m_3 = \frac{y_3^2 \langle H \rangle^2}{M} |\cos 2\theta_R|$$

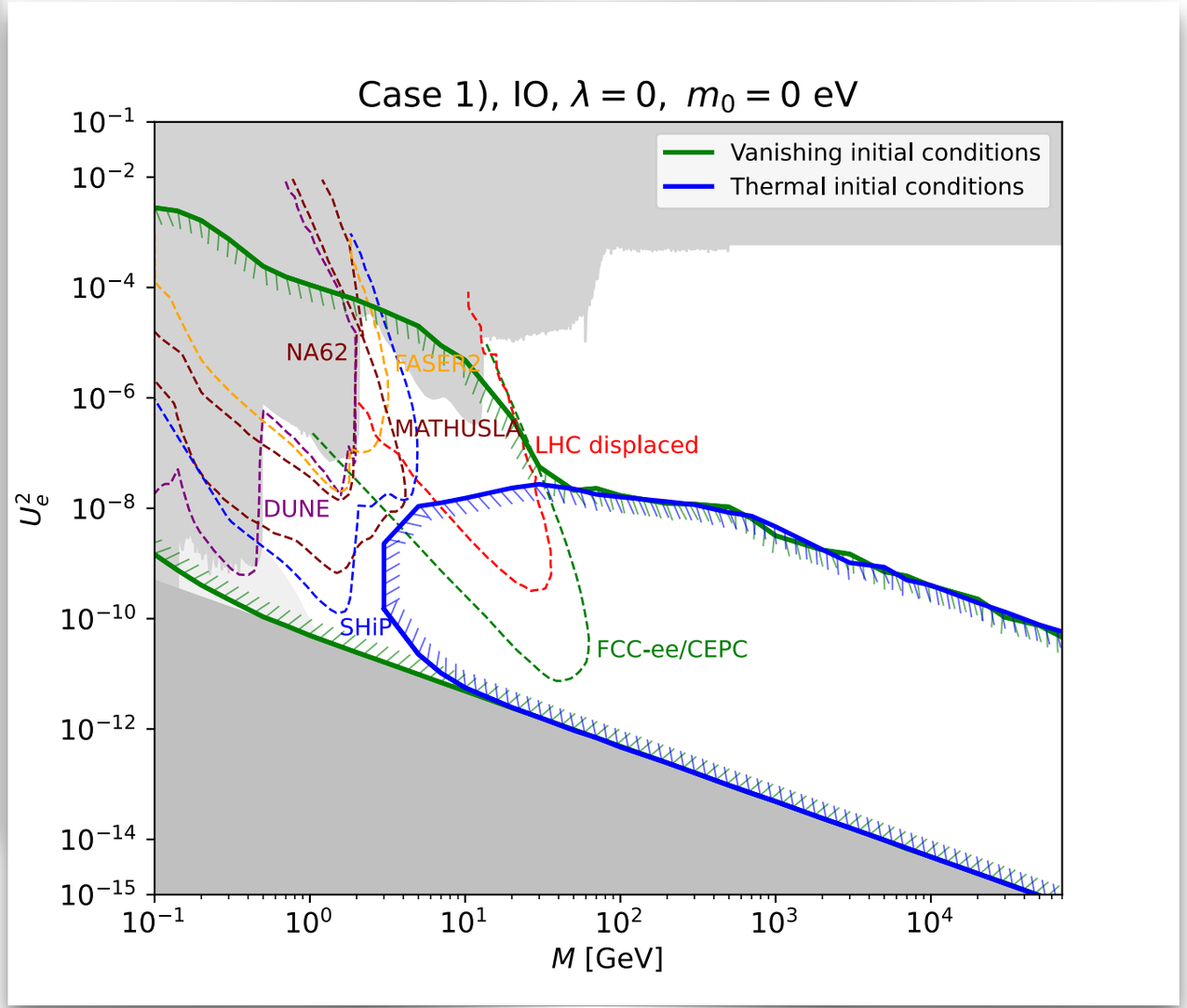


Values of θ_R so close to $\frac{\pi}{4}$ are not (always) a tuning, but related to enhanced residual symmetry, i.e. check $Y_D^\dagger Y_D$

Heavy neutrino searches and testability

Case 1)





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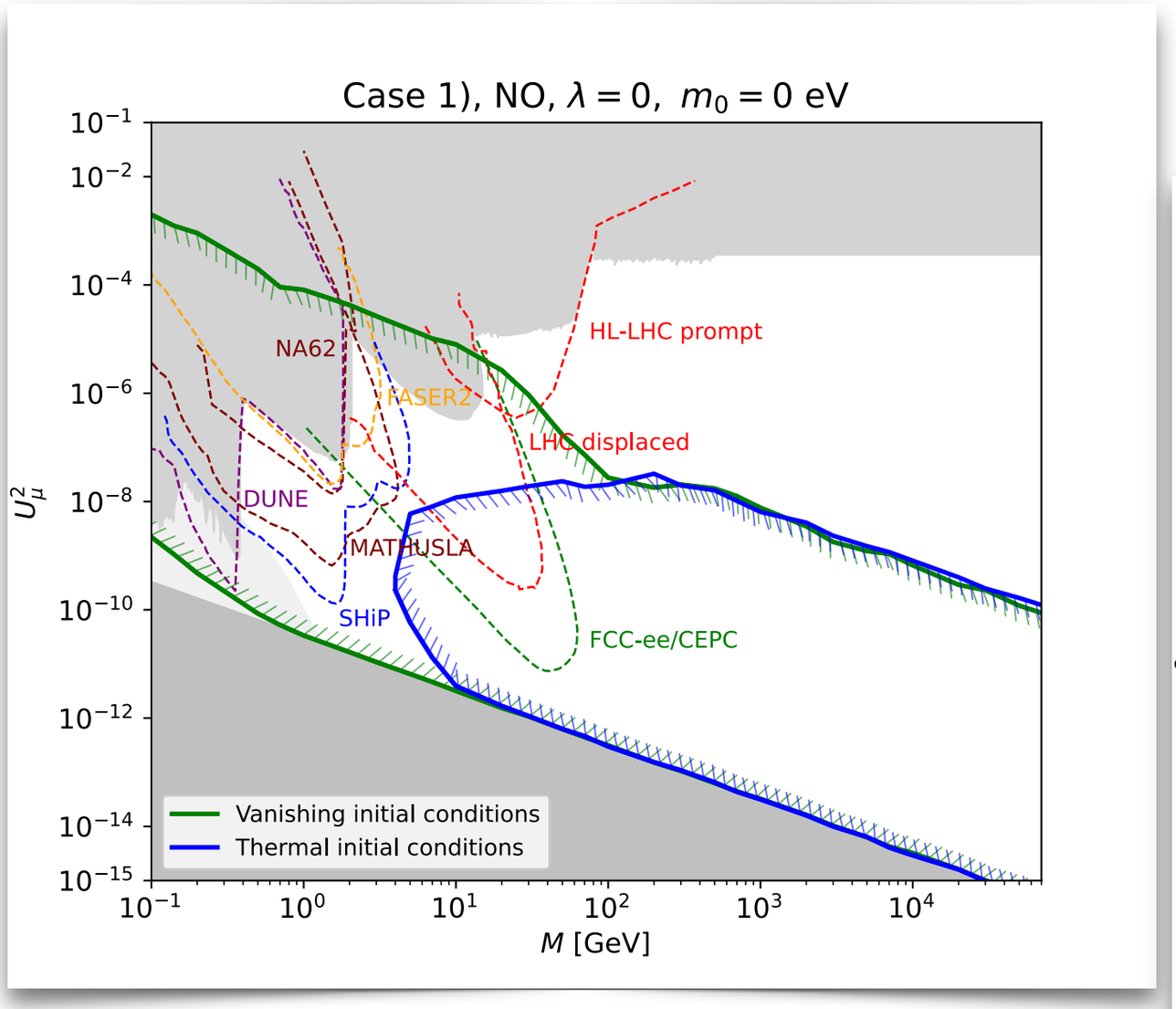

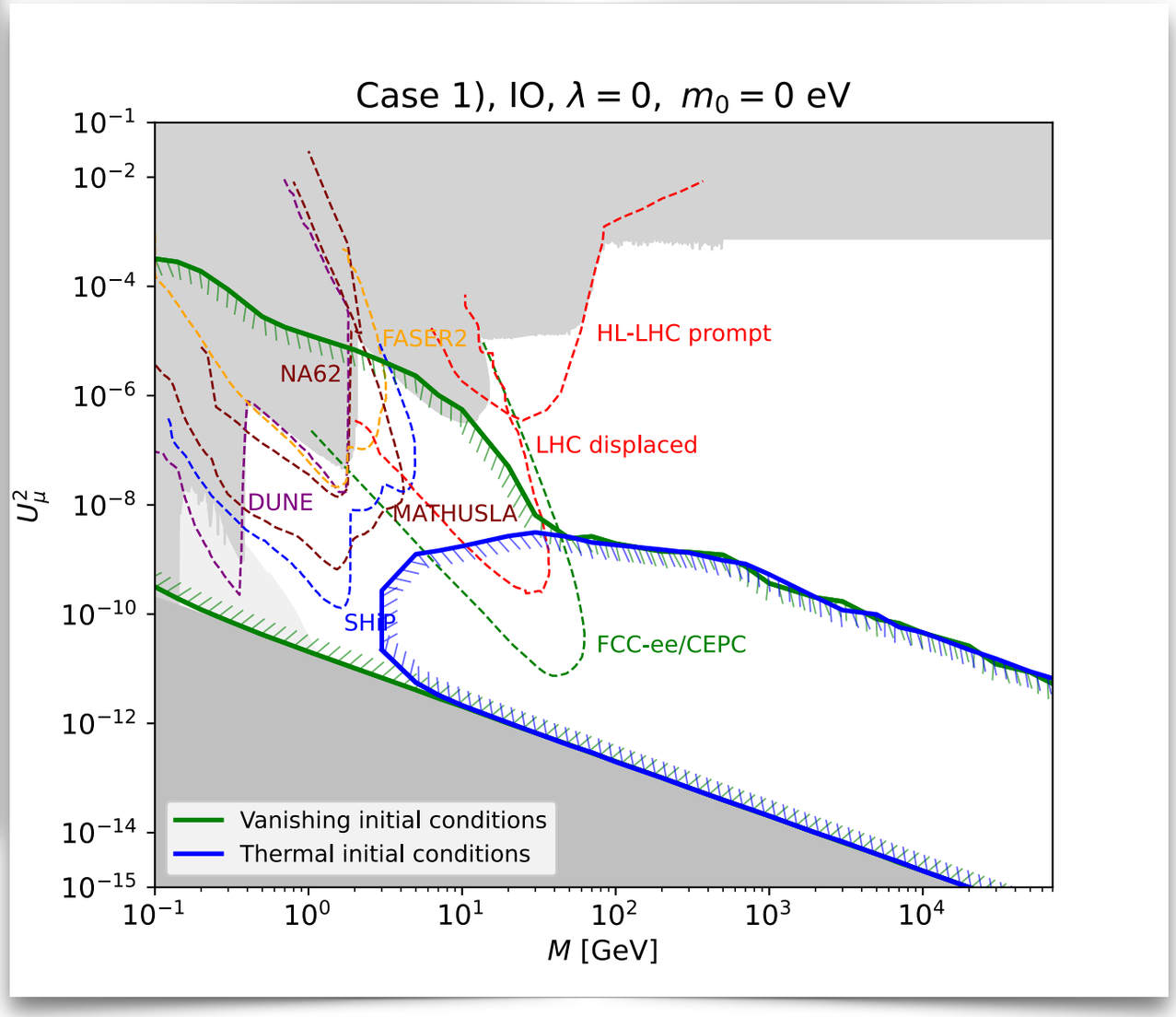

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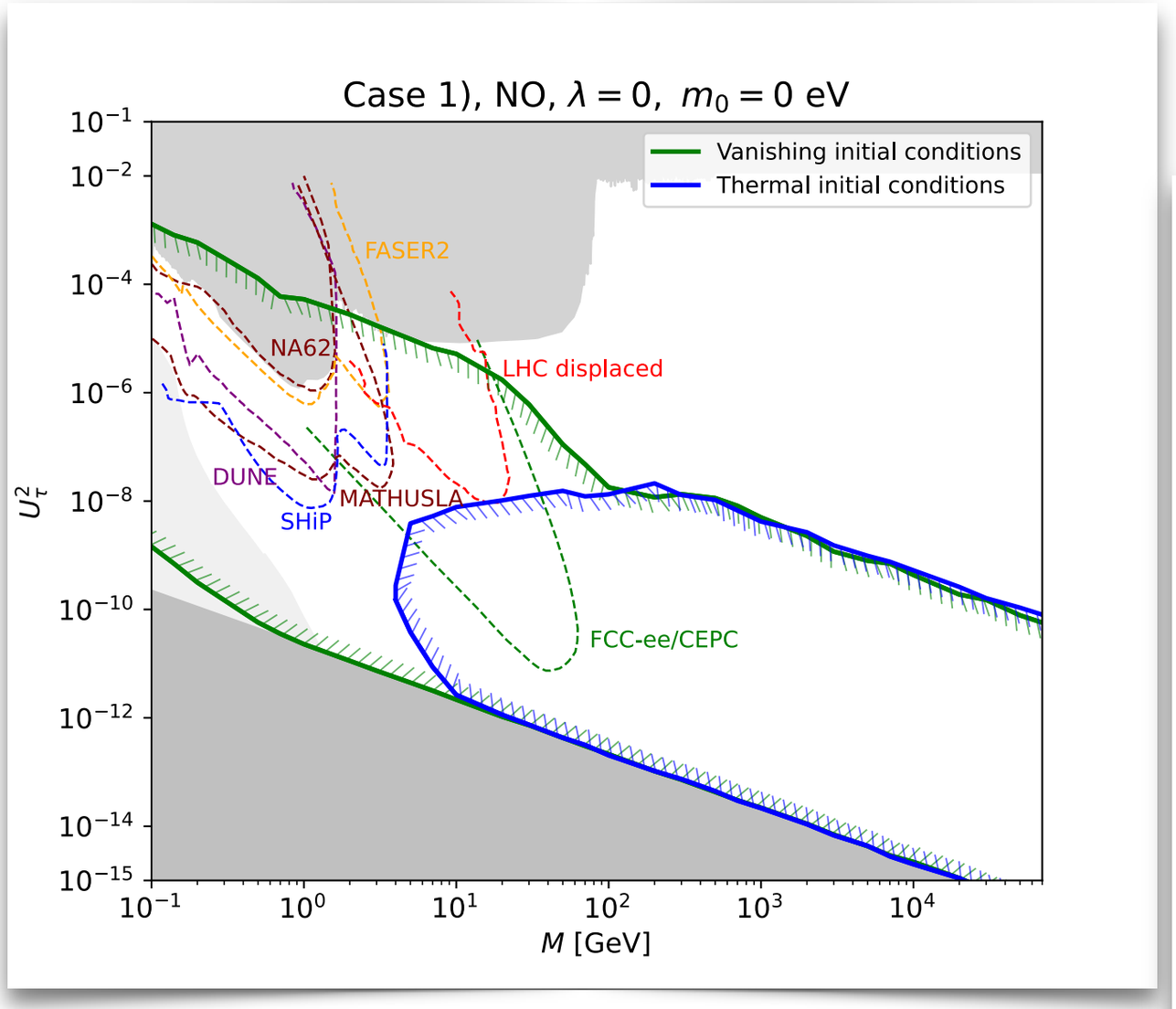

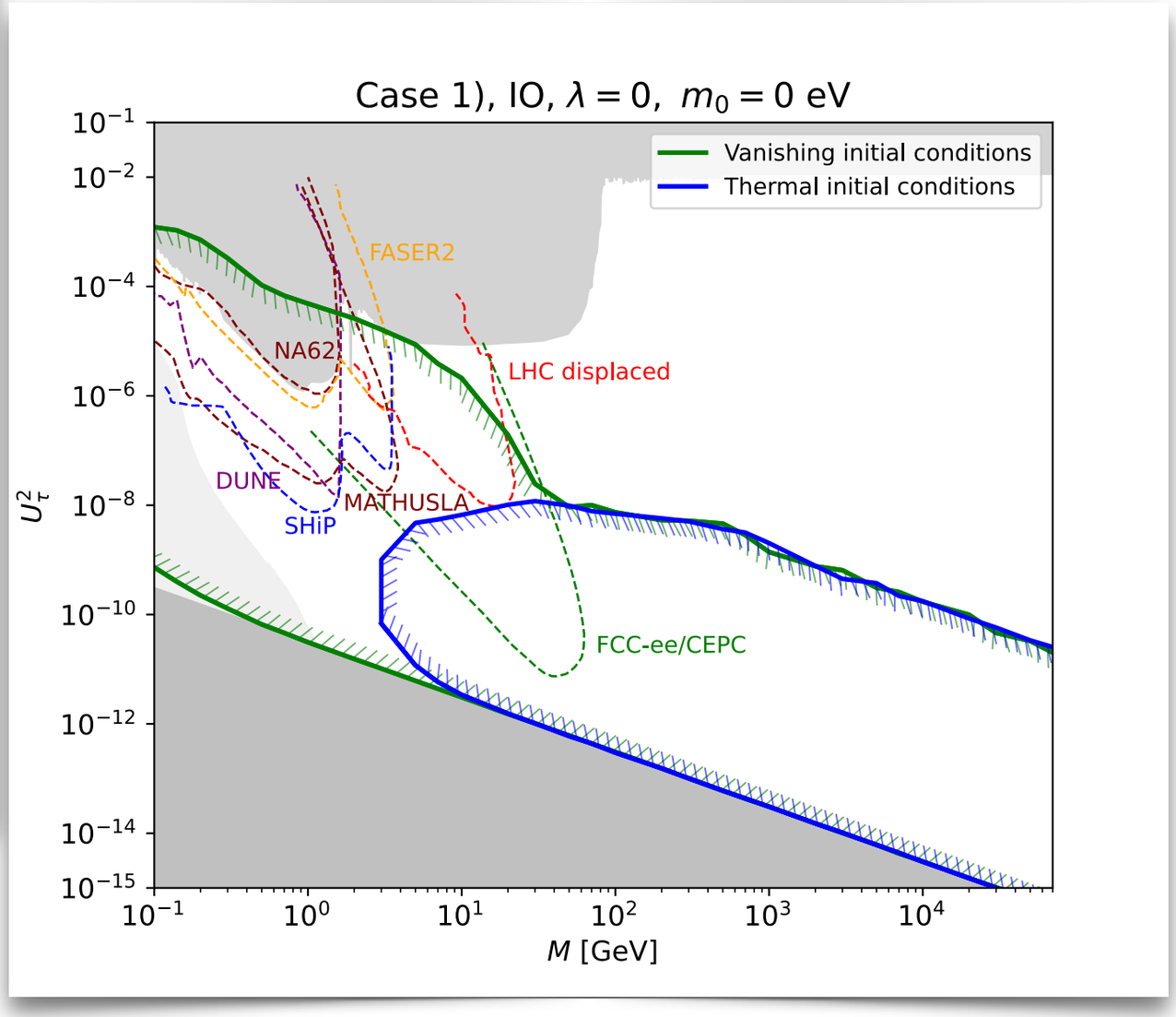

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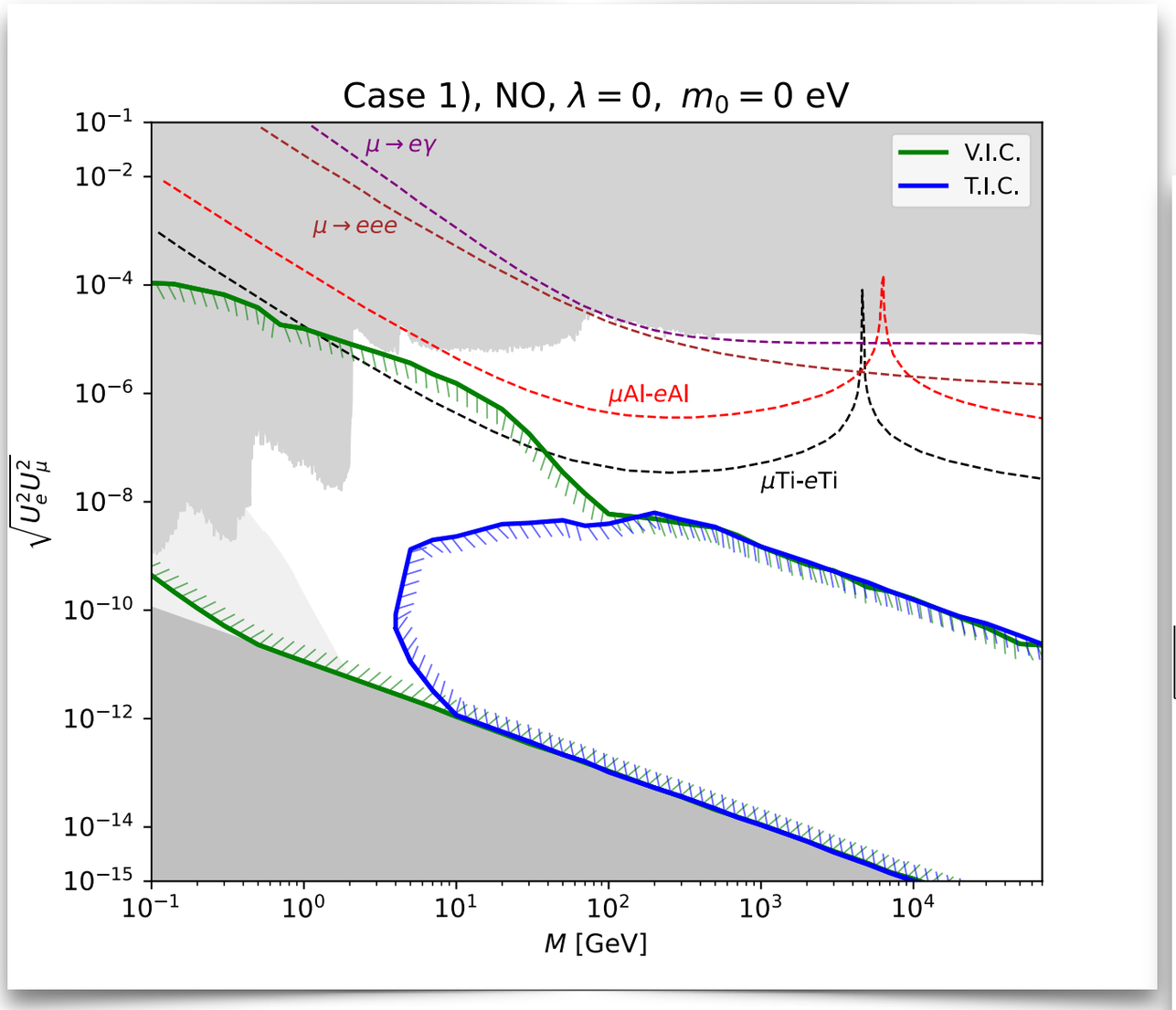
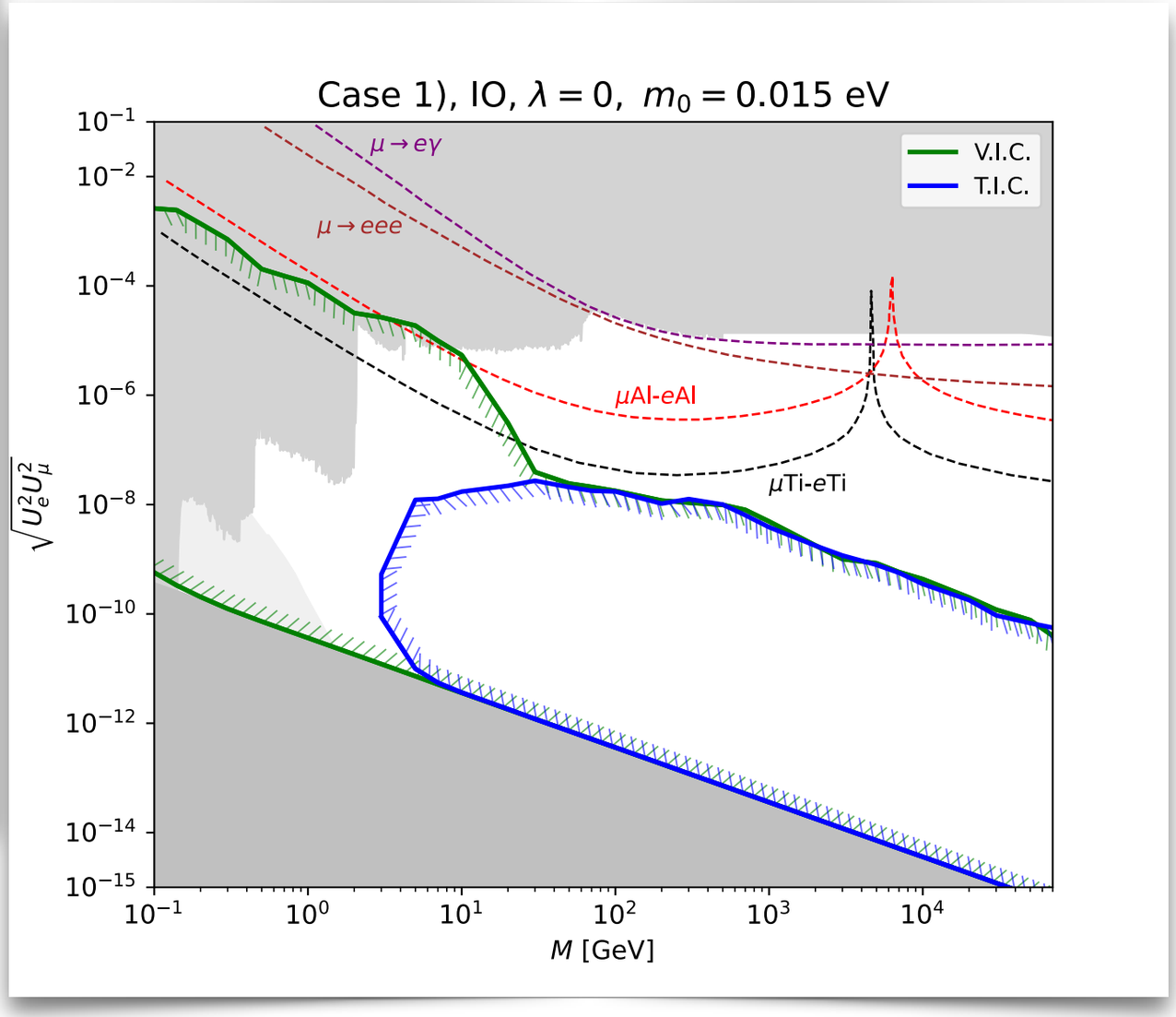




Summary and Outlook

- Low-scale seesaw mechanism with flavour and CP symmetry has a rich phenomenology
  - lepton mixing
  - leptogenesis
  - heavy neutrino searches and testability

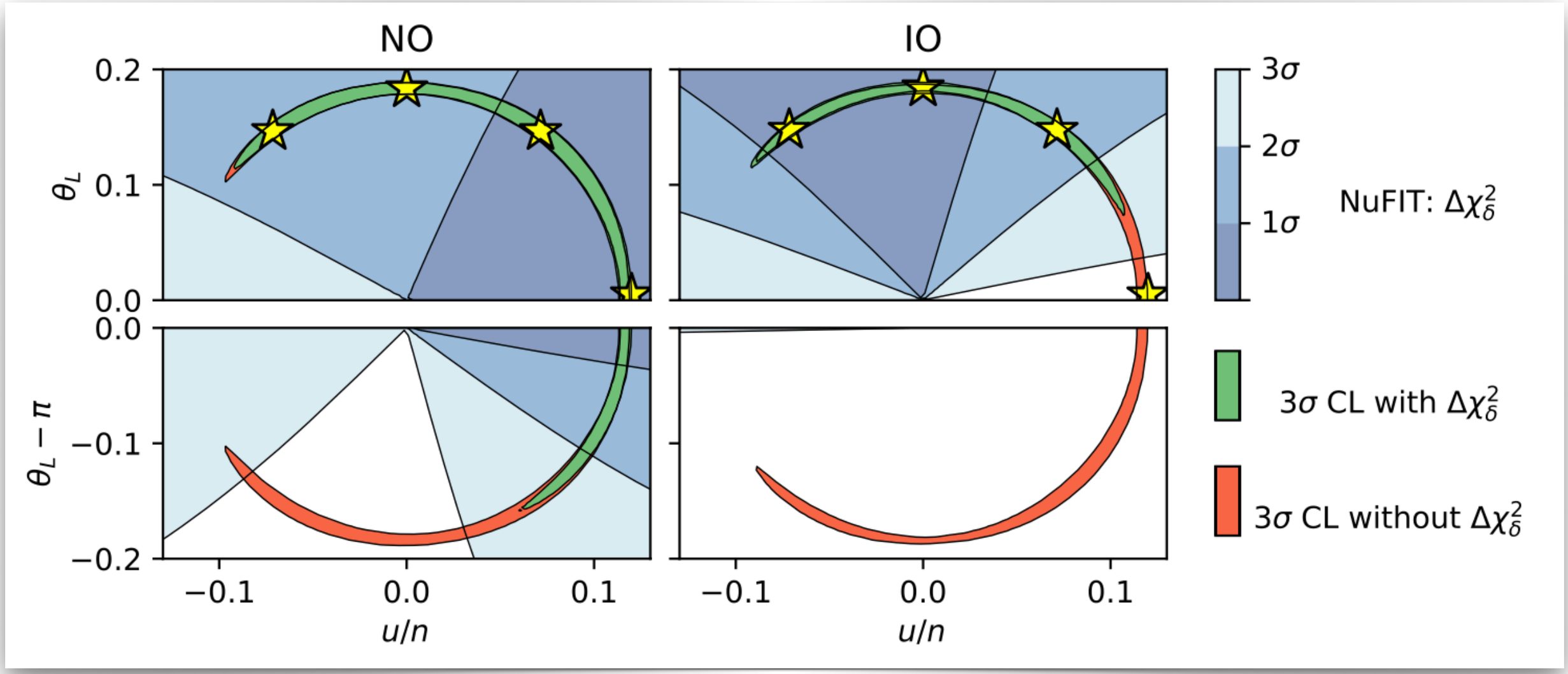
- More signals can be explored
- More options/variants of low-scale seesaw can be considered
- Embedding in larger framework can be interesting
- …

Many thanks for your attention!

Back-up slides

Lepton mixing

Case 2)



$$u = 2\,s - t$$

$$v = 3\,t$$

fixed by CP symmetry

Lepton mixing

Case 2)

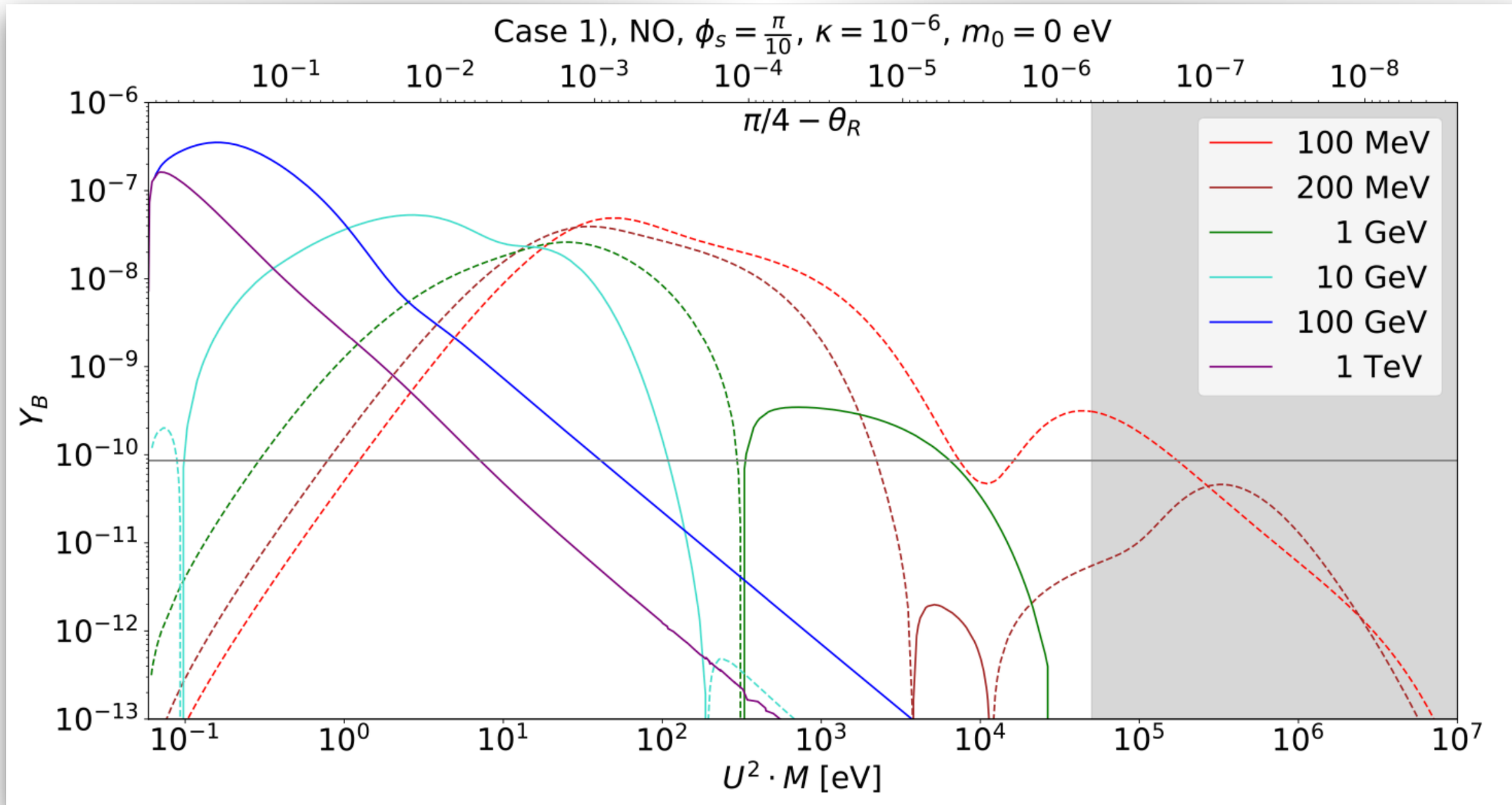
$n = 14$

u	$u = -1$	$u = 0$	$u = +1$
θ_L	0.146 (0.148)	0.184	0.146 (0.148)
$\sin^2\theta_{12}$	0.341	0.341	0.341
$\sin^2\theta_{13}$	0.0222 (0.0224)	0.0222 (0.0224)	0.0222 (0.0224)
$\sin^2\theta_{23}$	0.437	0.5	0.563
$\Delta\chi^2$	9.25 (11.2)	10.8 (12.5)	8.27 (8.62)

several choices for v admitted

Leptogenesis

Case 1)



Leptogenesis

Way towards capturing main dependencies analytically

- CP-violating combinations
- washout parameter

CP-violating combinations: see for related work Hernandez et al. ('15)

Perturbatively solve quantum kinetic equations in H_N and Γ

Leading term for lepton asymmetries

$$\mathrm{Tr}\left[\tilde{\Gamma}_\alpha(\bar{\rho}_N - \rho_N)\right] \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\,[H_N, \Gamma]\right) \quad \text{with} \quad \alpha = e, \mu, \tau.$$

Three types of CP-violating combinations are found

$$\begin{aligned}
C_{\mathrm{LFV},\alpha} &= i\,\mathrm{Tr}\Big(\left[\hat{M}_R^2, \hat{Y}_D^\dagger \hat{Y}_D\right] \hat{Y}_D^\dagger P_\alpha \hat{Y}_D\Big)\,, \\
C_{\mathrm{LNV},\alpha} &= i\,\mathrm{Tr}\Big(\left[\hat{M}_R^2, \hat{Y}_D^\dagger \hat{Y}_D\right] \hat{Y}_D^T P_\alpha \hat{Y}_D^*\Big)\,, \\
C_{\mathrm{DEG},\alpha} &= i\,\mathrm{Tr}\Big(\left[\hat{Y}_D^T \hat{Y}_D^*, \hat{Y}_D^\dagger \hat{Y}_D\right] \hat{Y}_D^T P_\alpha \hat{Y}_D^*\Big)
\end{aligned}$$

Leptogenesis

$$
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\end{aligned}
$$

with

$$
P_e = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}\,,\quad P_\mu = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}\,,\quad P_\tau = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}
$$

and in mass basis of heavy states, i.e.

$$
\hat{Y}_D = Y_D\, U_R
$$

$$
U_R = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} & 0 & 0 \\ 0 & 1 & i \\ 0 & 1 & -i \end{pmatrix}
$$

Leptogenesis

$$C_{\mathrm{LFV},\alpha} = i\,\mathrm{Tr}\left(\left[\hat{M}_R^2, \hat{Y}_D^\dagger \hat{Y}_D\right] \hat{Y}_D^\dagger P_\alpha \hat{Y}_D\right)$$

Note the following

- Dominant combination when N_i are in relativistic regime
- Only leads to lepton flavour asymmetry, since

$$\sum_\alpha C_{\mathrm{LFV},\alpha} = 0.$$

- Crucially depends on a flavoured washout

Leptogenesis

$$C_{\mathrm{LFV},\alpha} = i\,\mathrm{Tr}\left(\left[\hat{M}_R^2, \hat{Y}_D^\dagger \hat{Y}_D\right] \hat{Y}_D^\dagger P_\alpha \hat{Y}_D\right)$$

Note the following

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$$C_{\mathrm{LNV},\alpha} = i\,\mathrm{Tr}\left(\left[\hat{M}_R^2, \hat{Y}_D^\dagger \hat{Y}_D\right] \hat{Y}_D^T P_\alpha \hat{Y}_D^*\right)$$

Note the following

- Sizeable for intermediate/larger masses of N_i
- Directly violates lepton number with

$$C_{\mathrm{LNV}} = \sum_\alpha C_{\mathrm{LNV},\alpha} \neq 0$$

compare to flavoured decay asymmetries $\epsilon_{i\alpha}$ see Dev et al. ('17)

Leptogenesis

$$C_{\mathrm{DEG},\alpha} \;=\; i\,\mathrm{Tr}\Big(\Big[\hat{Y}_D^T\,\hat{Y}_D^*, \hat{Y}_D^\dagger\,\hat{Y}_D\Big]\;\hat{Y}_D^T\,P_\alpha\,\hat{Y}_D^*\Big)$$

Note the following

- Only this CP-violating combination could be non-zero for zero κ and λ
- Only possible at intermediate temperatures $M/T \sim 1$
- Only leads to lepton flavour asymmetry, since $\sum_\alpha C_{\mathrm{DEG},\alpha} = 0.$

Furthermore, for the limit $\lambda \ll \kappa \lesssim 1$ consider subset of two mass-degenerate states. Define $(\hat{Y}_{(23)})_{\alpha i} = (\hat{Y}_D)_{\alpha i} \quad \text{for} \quad i \in \{2,3\}$

For $\lambda = 0$ we only need

$$C^{(23)}_{\mathrm{DEG},\alpha} = i\,\mathrm{Tr}\Big(\Big[\hat{Y}^T_{(23)}\,\hat{Y}^*_{(23)}, \hat{Y}^\dagger_{(23)}\,\hat{Y}_{(23)}\Big]\;\hat{Y}^T_{(23)}\,P_\alpha\,\hat{Y}^*_{(23)}\Big)$$

Clearly, $\sum_\alpha C^{(23)}_{\mathrm{DEG},\alpha} = 0.$

Leptogenesis

Way towards capturing main dependencies analytically

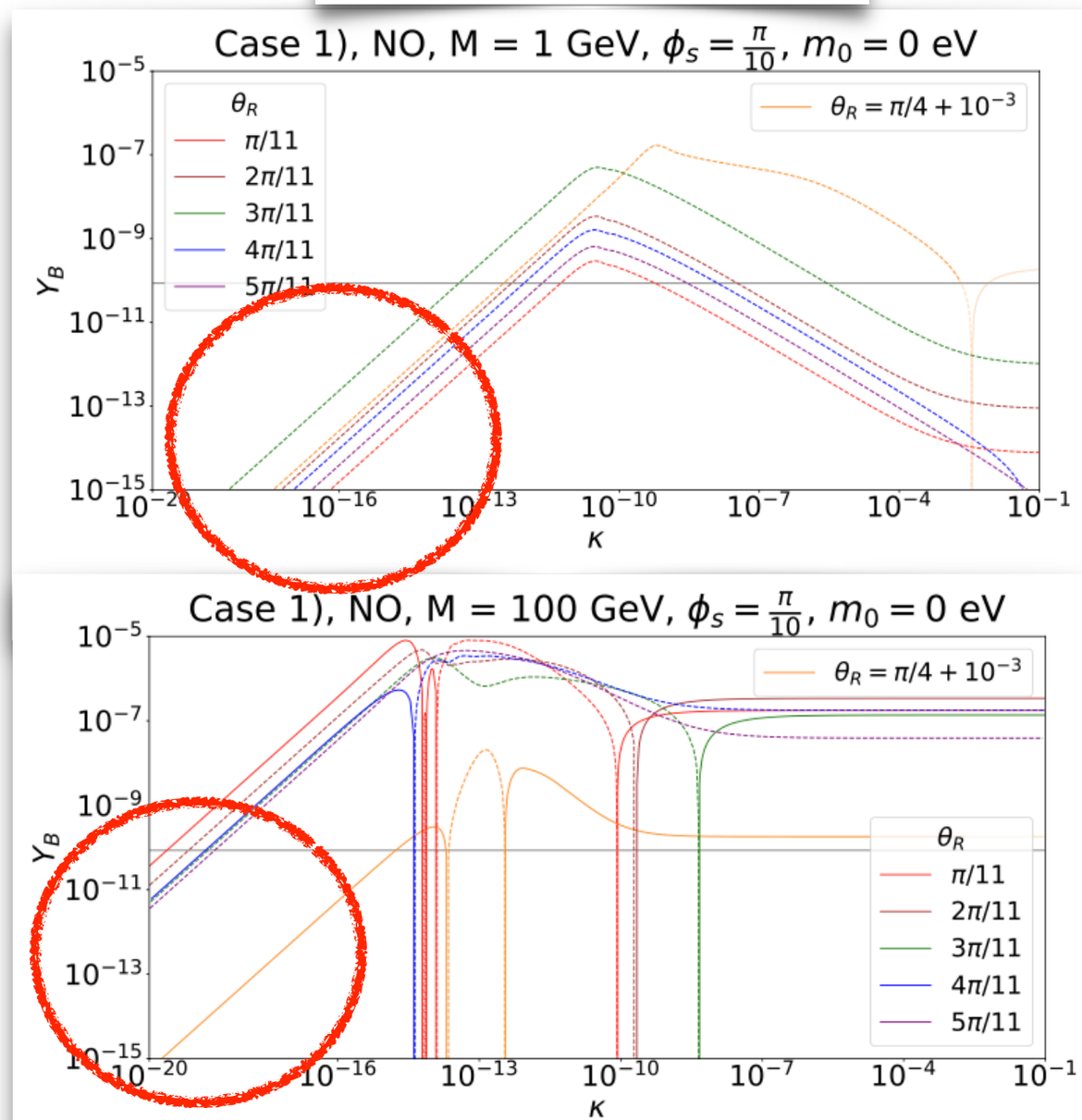
- CP-violating combinations
- washout parameter

Flavoured washout parameter:

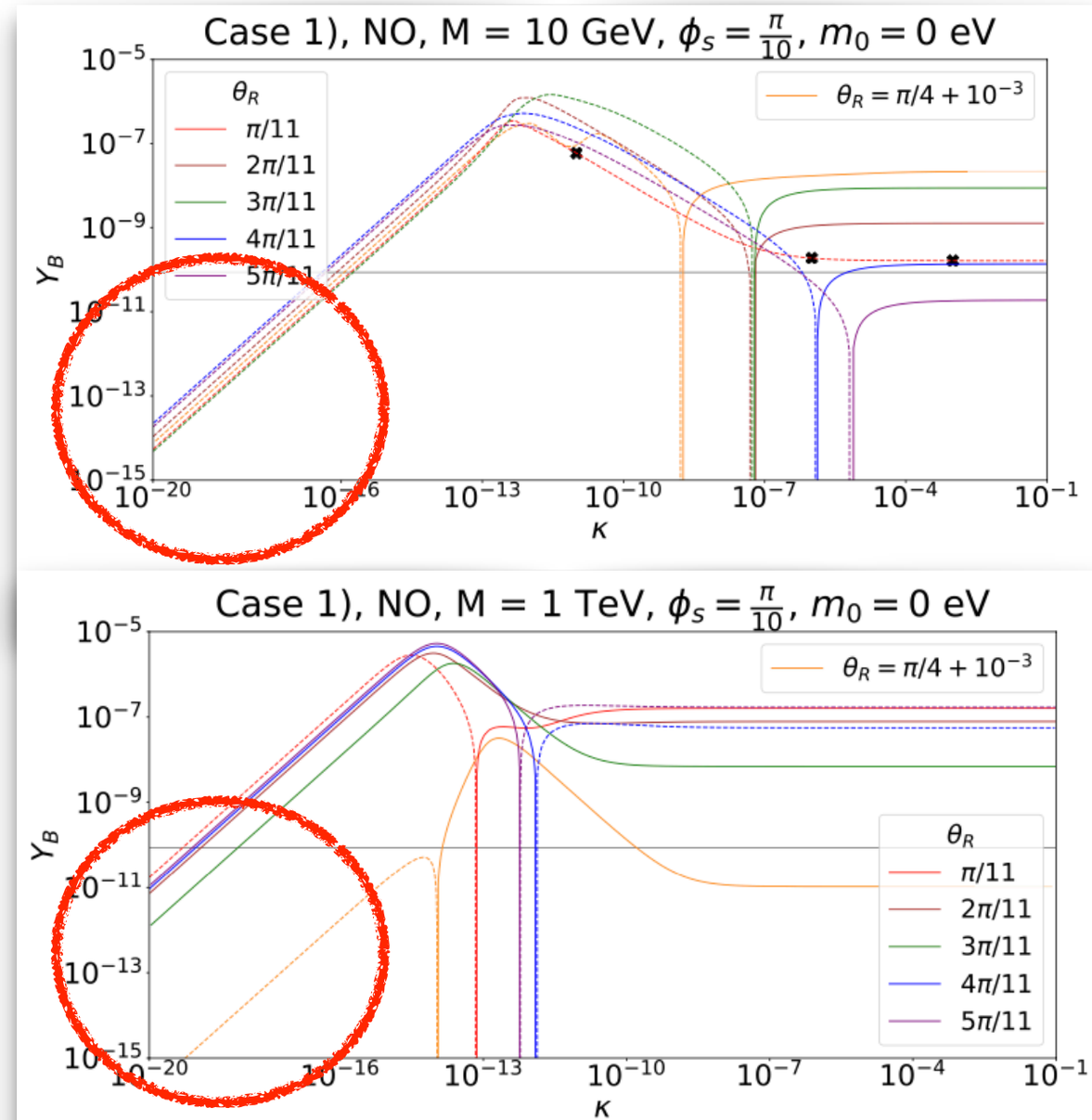
$$f_\alpha = \frac{(\hat{Y}_D \hat{Y}_D^\dagger)_{\alpha\alpha}}{\mathrm{Tr}\left(\hat{Y}_D \hat{Y}_D^\dagger\right)}$$

Leptogenesis

Case 1) $C_{\mathrm{DEG},\alpha}$ is zero.



(e) Vanishing initial conditions.

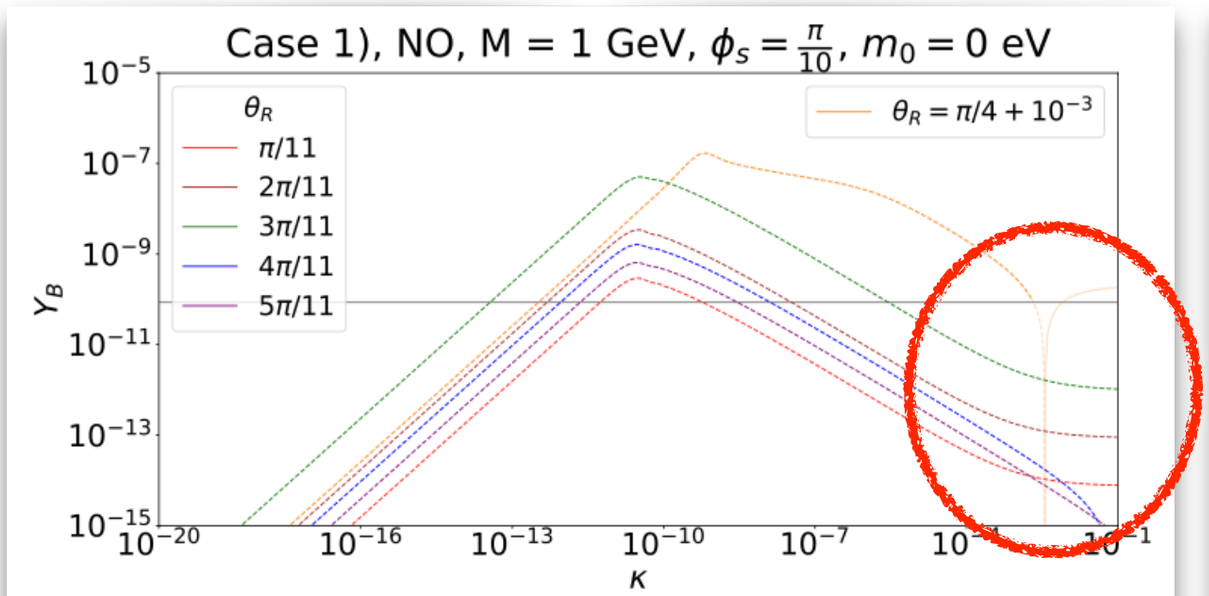


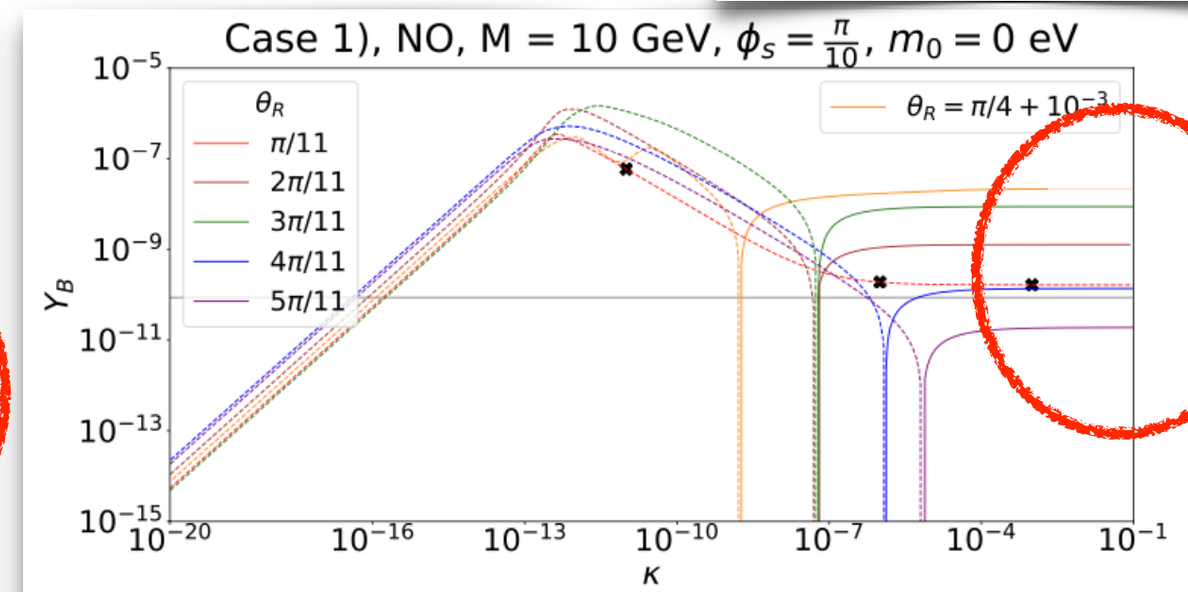
(g) Vanishing initial conditions.

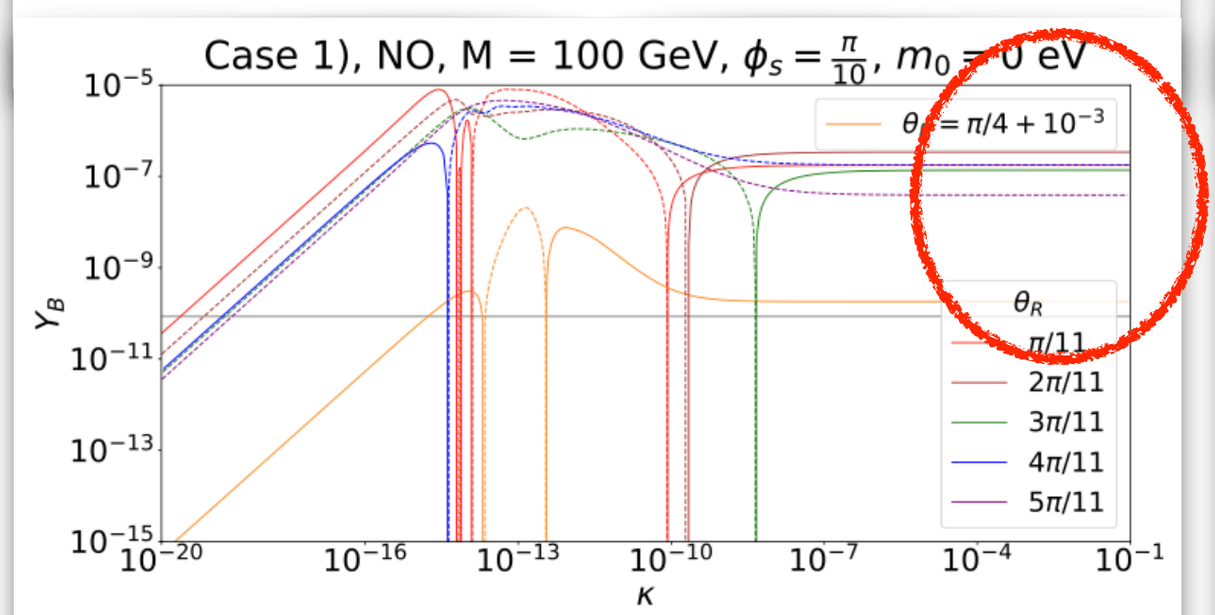
Leptogenesis

Case 1)

$C^{(23)}_{\mathrm{DEG},\alpha}$ is non-zero







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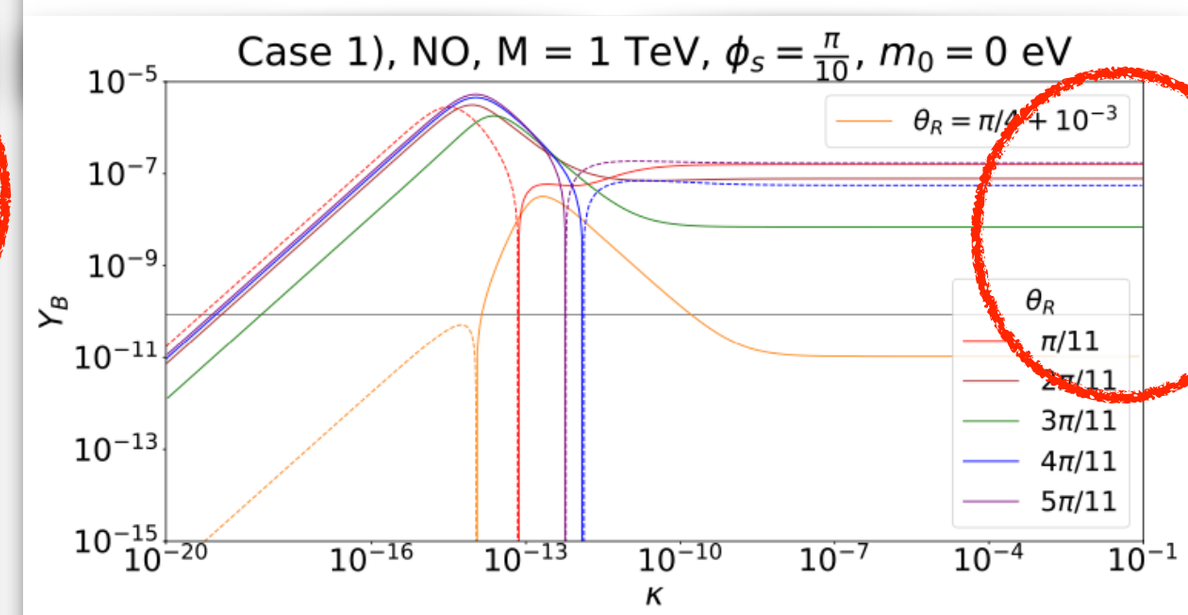


(g) Vanishing initial conditions.

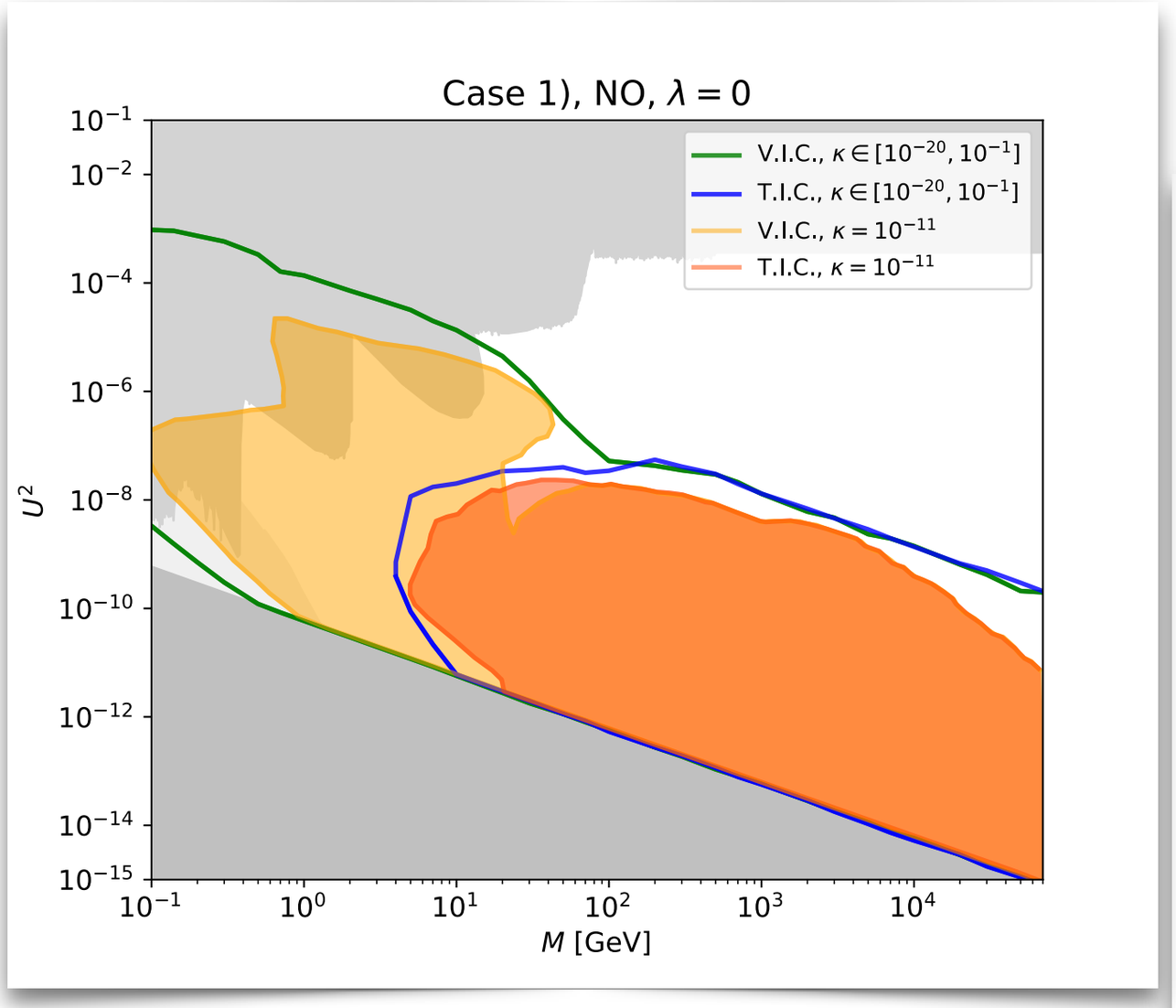
Leptogenesis

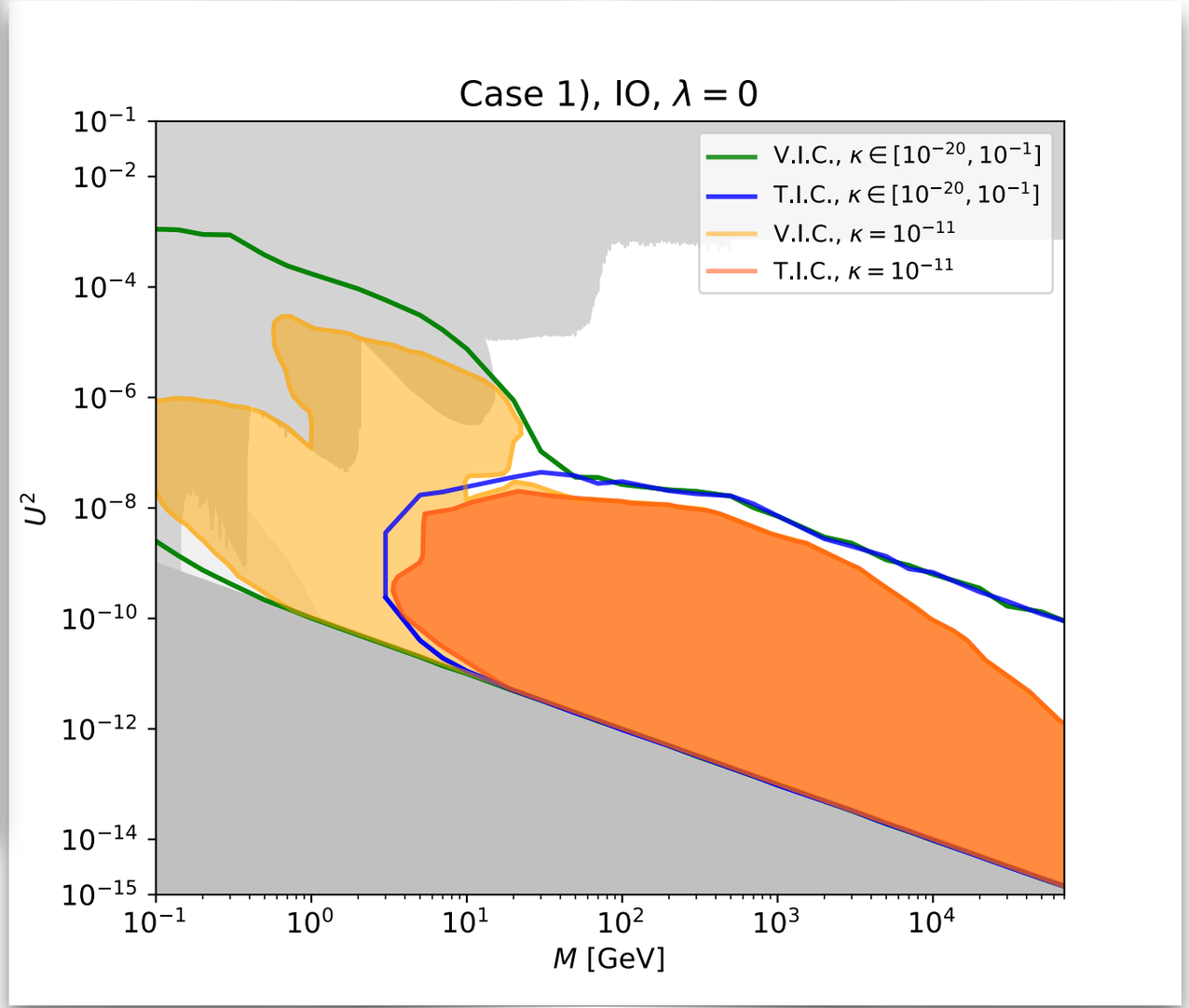
Overview over results

Type of mixing pattern	BAU non-zero for $\kappa = 0$?	BAU non-zero for large κ?	Large total mixing angle U^2 possible?
Case 1)	No, see Fig. 4	Yes, see Fig. 4	Yes, for $\cos 2\,\theta_R \approx 0$ see Fig. 9
Case 2), t even	No, see Fig. 12	No, see Fig. 12	No
Case 2), t odd	Yes, for $m_0 \neq 0$ see Fig. 17, plot (a)	Yes, see Fig. 16	Yes, for $\sin 2\,\theta_R \approx 0$ see Fig. 19
Case 3 b.1), m and s even	No, see Fig. 20	No, see Fig. 20	No
Case 3 b.1), m even, s odd	Yes, see Fig. 22 except for strong IO	No, see Fig. 22	Yes, for $\cos 2\,\theta_R \approx 0$ see Fig. 25
Case 3 b.1), m odd, s even	Yes, see Fig. 26 except for strong IO	Yes, see Fig. 26	Yes, for $\cos 2\,\theta_R \approx 0$
Case 3 b.1), m and s odd	No	No	No

Heavy neutrino searches and testability

Case 1)





Heavy neutrino searches and testability

Case 1)

For θ_R close to $\frac{\pi}{4}$ active-sterile mixing U_α^2 can be large and approximately one finds

$$\frac{U_\alpha^2}{U^2} \approx \begin{cases} \frac{2}{3}\sin^2\theta_{L,\alpha} & \text{for NO,} \\ \frac{2}{3}\cos^2\theta_{L,\alpha} & \text{for IO.} \end{cases}$$

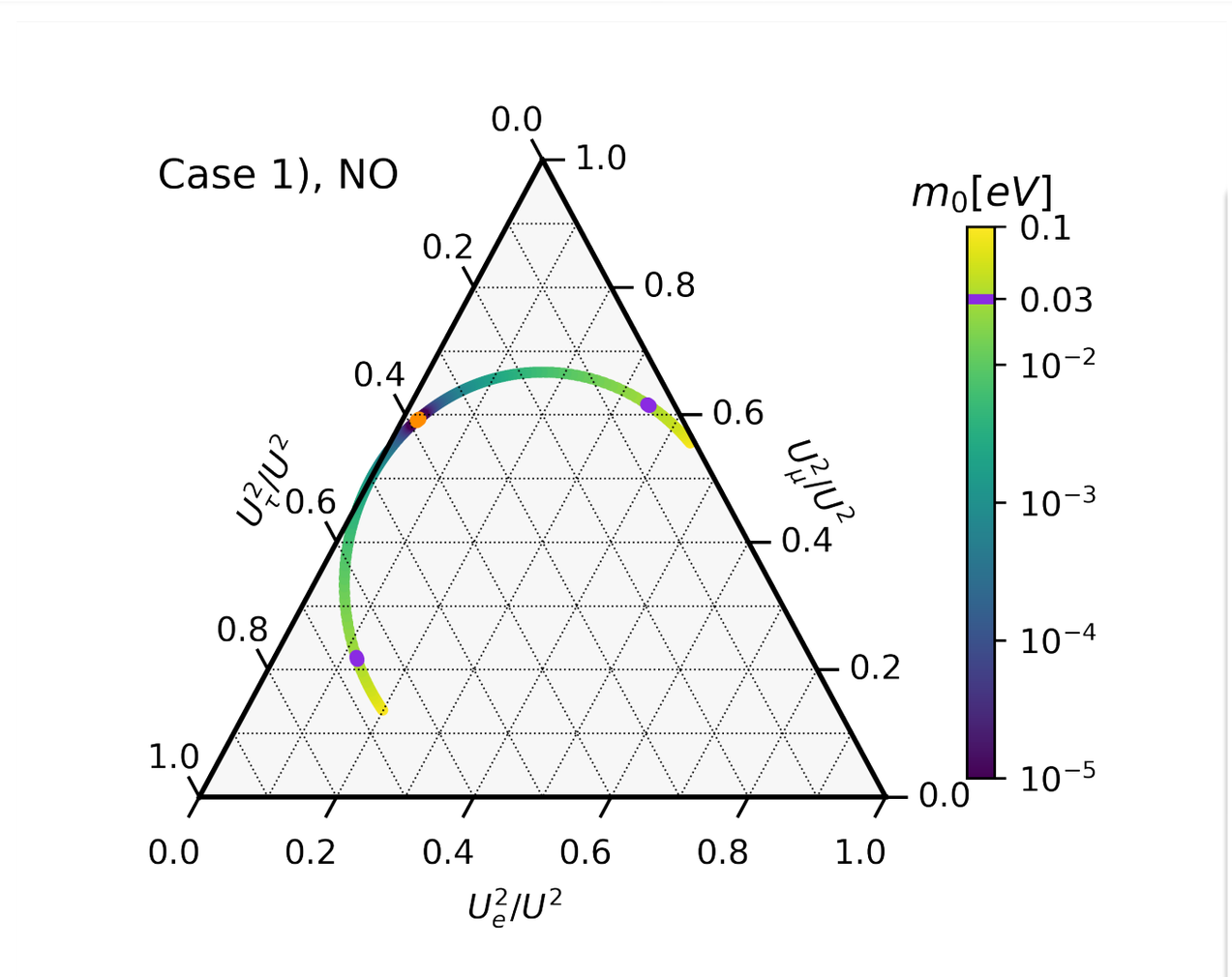
with

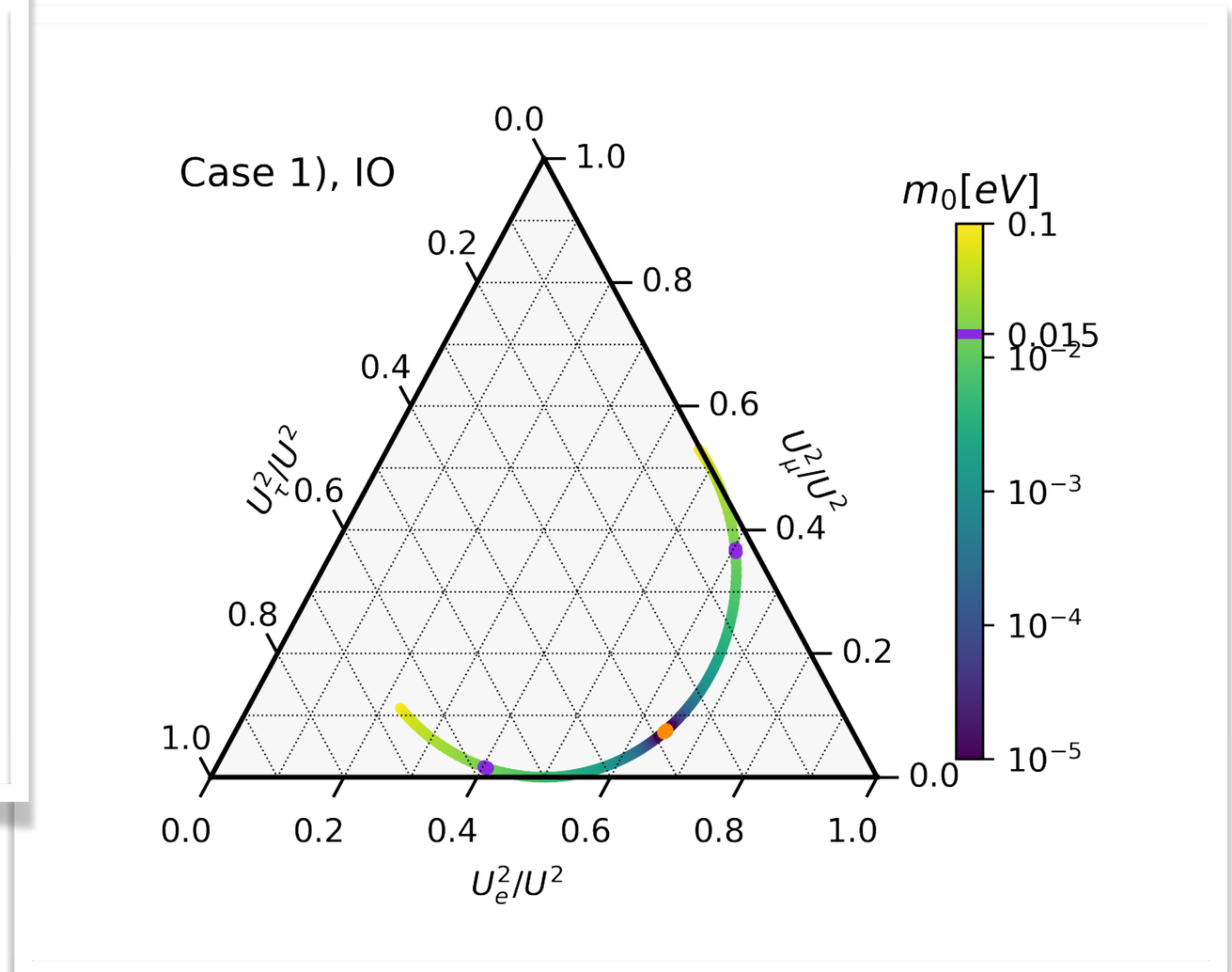
$$\theta_{L,\alpha} = \theta_L + \rho_\alpha \frac{4\pi}{3} \qquad \rho_e = 0,\ \rho_\mu = +1 \text{ and } \rho_\tau = -1.$$

Note this result does not depend on the parameter s.
However, it depends on the lightest neutrino mass m_0, since for $m_0 \neq 0$ the angle θ_L has to be read as $\widetilde{\theta}_L$ with dependence on the light neutrino mass spectrum and the angle θ_R.

Heavy neutrino searches and testability

Case 1)





orange $m_0 = 0$

Heavy neutrino searches and testability

Case 1)