TÉCNICO LISBOA

DISCRETE

Bratislava, Slovakia, 13–17 November 2026

CFTP Centro de Física Teórica de Partículas

Spontaneous CP violation and leptogenesis in minimal flavour models

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In collaboration with: H. B. Câmara and F. R. Joaquim

arXiv: 2610.39858 [hep-ph]

fct Fundação para a Ciência e a Tecnologia

2025.00959.BD

PORTUGAL 2020

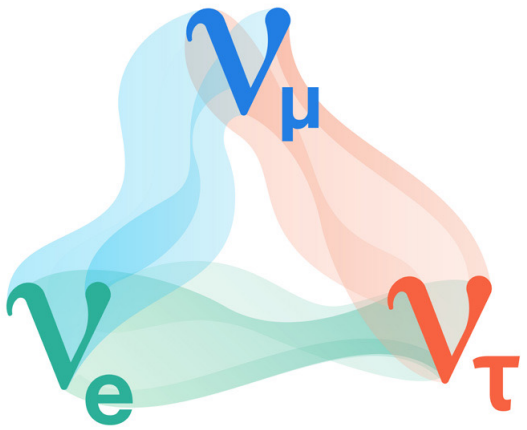
REPÚBLICA PORTUGUESA

COMPETE 2020

PROGRAMA OPERACIONAL CAPITAL HUMANO POCH

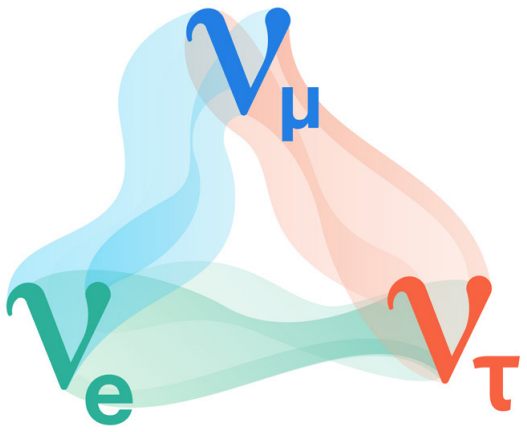
Introduction

Neutrino Oscillations

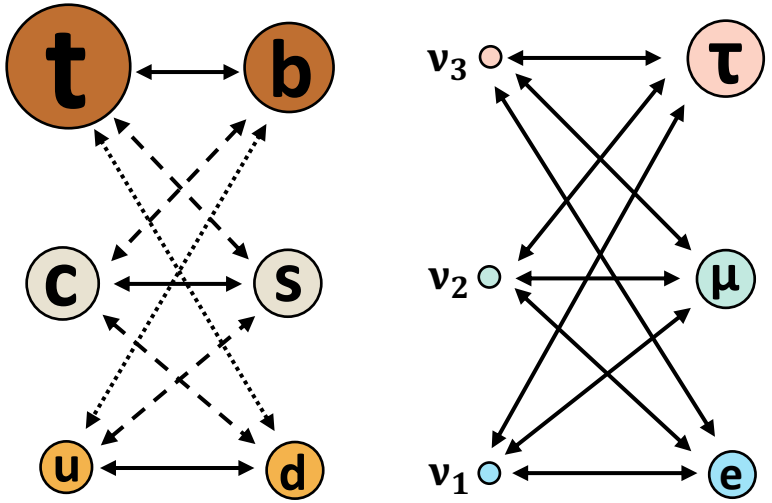


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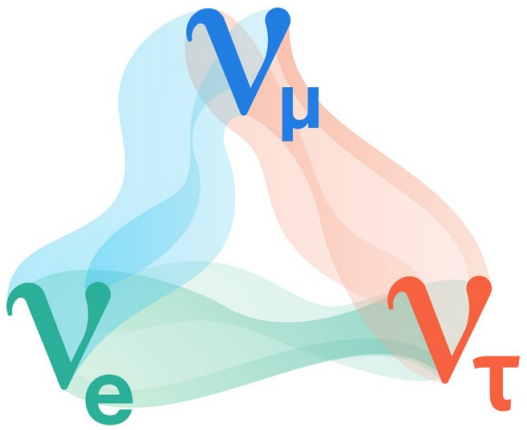


Flavour Puzzle

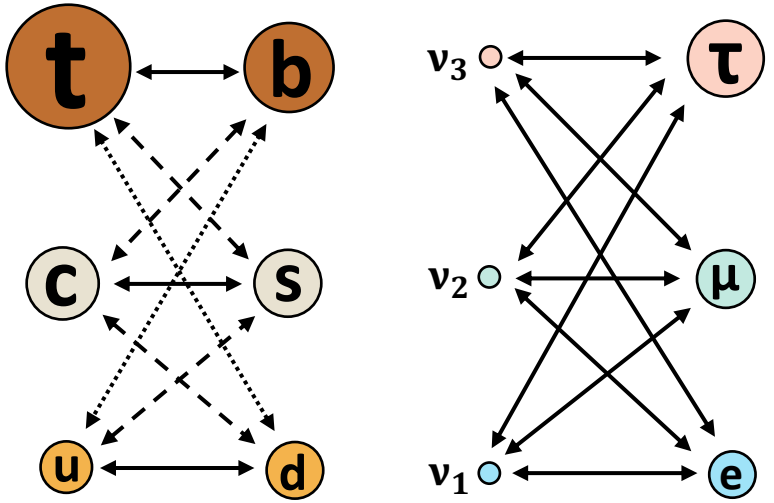


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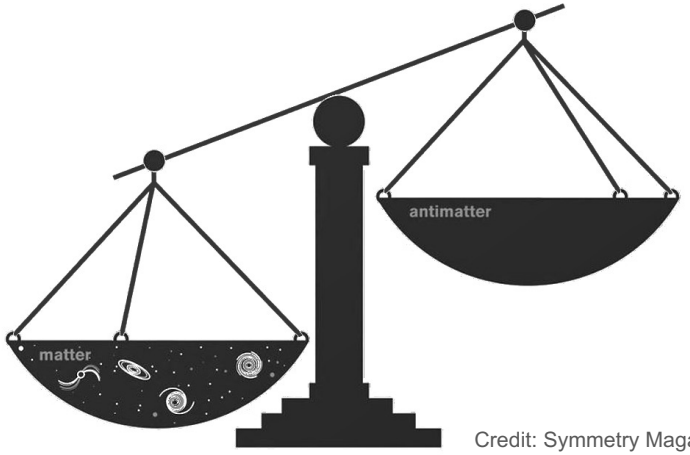
Neutrino Oscillations



Flavour Puzzle



Matter antimatter asymmetry



Credit: Symmetry Magazine

Type-I seesaw with spontaneous CP violation

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell \Phi e_R + \overline{\ell_L}\mathbf{Y}_D^* \tilde{\Phi}\nu_R + \frac{1}{2}\overline{\nu_R}\left(\mathbf{M}_R^0 + \mathbf{Y}_R\sigma + \mathbf{Y}'_R\sigma^*\right)\nu_R^c + \text{H.c.}$$

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Singlet SSB

$$\langle\sigma\rangle = \frac{v_\sigma e^{i\varphi}}{\sqrt{2}}$$

SCPV

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RH-neutrino Majorana masses

$$\mathbf{M}_R = \mathbf{M}_R^0 + \frac{v_\sigma}{\sqrt{2}}\left(\mathbf{Y}_R e^{i\varphi} + \mathbf{Y}'_R e^{-i\varphi}\right)$$

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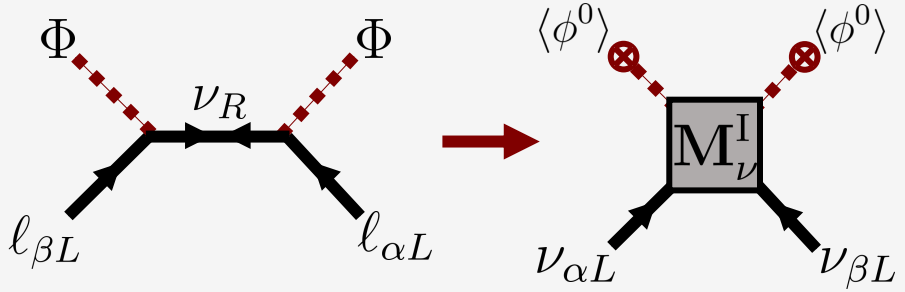
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Light neutrino masses



$$\mathbf{M}_\nu^{\rm I} = -v_\Phi^2 \mathbf{Y}_D \mathbf{M}_R^{-1} \mathbf{Y}_D^T/2$$

Spontaneous CP violation

Scalar Potential

$$V(\Phi,\sigma) = m_\Phi^2(\Phi^\dagger\Phi) + m_\sigma^2|\sigma|^2 + m_\sigma'^2(\sigma^2+\sigma^{*2}) + \frac{\lambda_\Phi}{2}(\Phi^\dagger\Phi)^2 + \lambda_{\Phi\sigma}(\Phi^\dagger\Phi)|\sigma|^2 + \frac{\lambda_\sigma}{2}|\sigma|^4 + \lambda_\sigma'(\sigma^4+\sigma^{*4})$$

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CP violating solution

Branco *et al.* (1999, 2003)

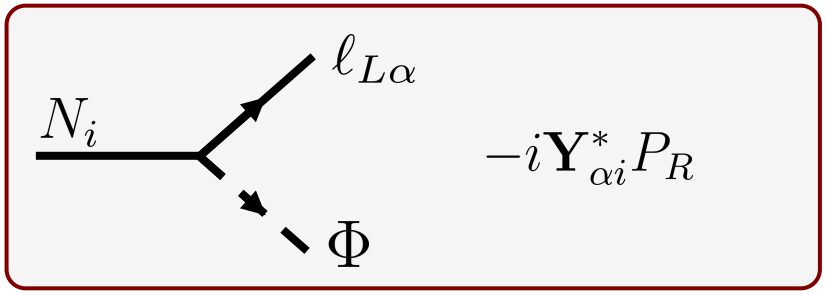
$$m_\Phi^2 = -\frac{\lambda_\Phi}{2}v_\Phi^2 - \frac{v_\sigma^2}{2}\lambda_{\Phi\sigma}\,, \quad m_\sigma^2 = \frac{v_\sigma^2(4\lambda_\sigma' - \lambda_\sigma) - v_\Phi^2\lambda_{\Phi\sigma}}{2}\,, \quad \cos(2\varphi) = -\frac{m_\sigma'^2}{2v_\sigma^2\lambda_\sigma'}$$

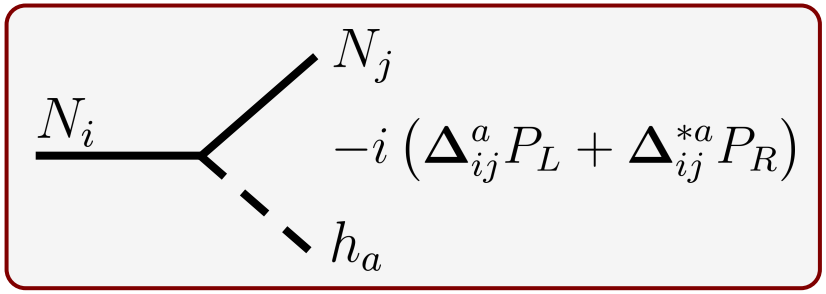
Existence of non-zero vacuum phase at the potential global minimum $\Rightarrow \varphi \neq k\,\pi/2$ is allowed!

New Interactions

Yukawa interactions

$$-\mathcal{L}_{\text{Yuk.}} \supset \overline{\ell_L}\mathbf{Y}^*\tilde{\Phi}N + \frac{1}{2}\sum_a h_a \overline{N}\boldsymbol{\Delta}_a P_L N + \text{H.c.}$$

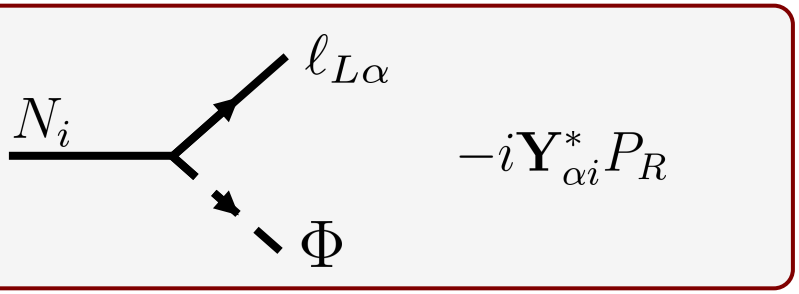


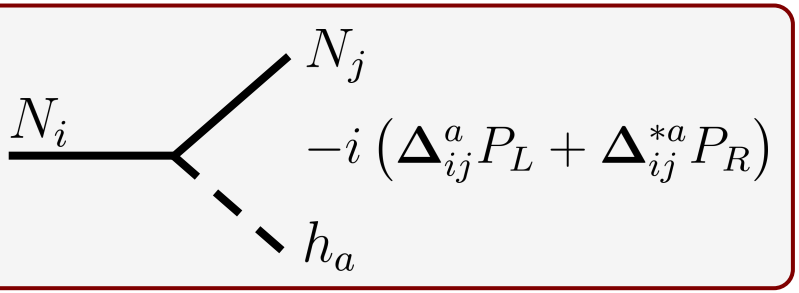


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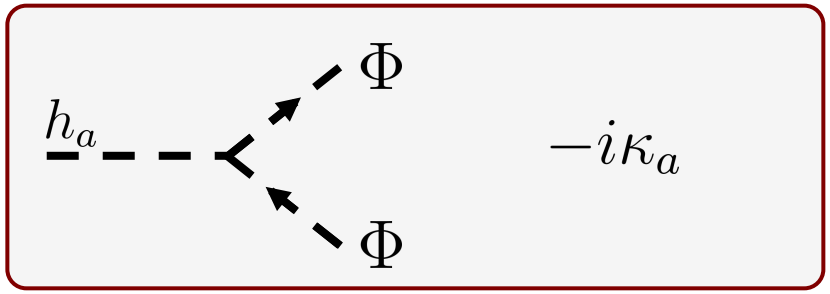
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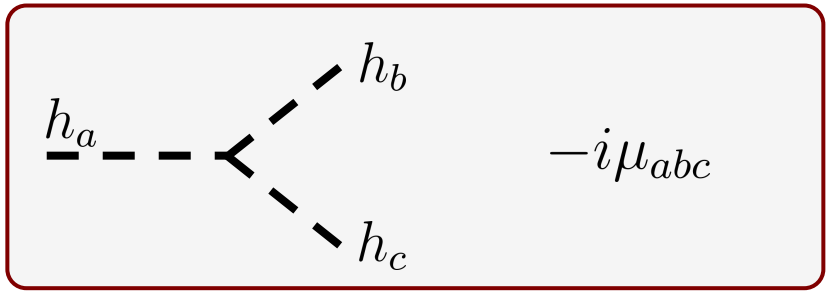




Scalar interactions

$$V(\Phi, h_1, h_2) \supset \sum_a \kappa_a(\Phi^\dagger\Phi)h_a + \sum_{a\le b\le c}\mu_{abc}h_a h_b h_c$$





Minimal Abelian Flavour Models

Imposing SCPV, and a Z_4 symmetry, we find two predictive flavour textures

	Fields	B_5 B_6
Leptons	e_L, e_R, ν_{R_1}	1
	μ_L, μ_R, ν_{R_2}	ω^2 ω^3
	$\tau_L, \tau_R, \nu_{R_3}$	ω^3 ω^2
Scalars	Φ	1
	σ	ω

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- Three RH neutrinos + one complex singlet
- $\mathbf{Y}_\ell$ and $\mathbf{Y}_D$ are **diagonal**
- All **couplings are real**, as the **VEV of the complex scalar is the sole source of CP**

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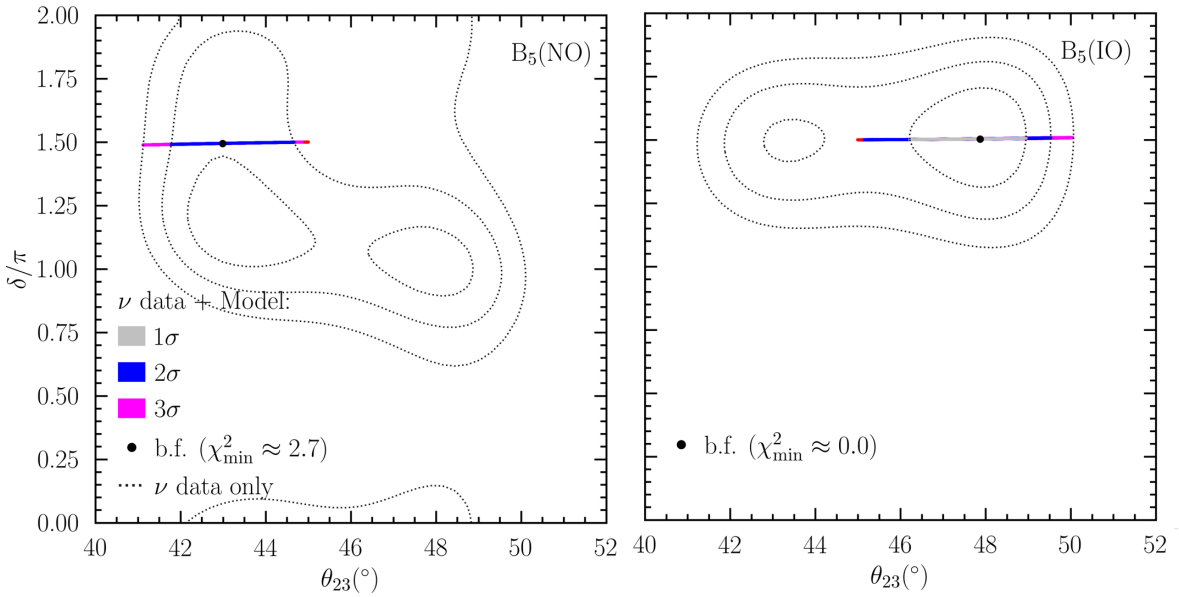
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	$\mathbf{M}_\nu^{-1}$	$\mathbf{Y}_D$	$\mathbf{M}_R^0$	$\mathbf{Y}_R$	$\mathbf{Y}'_R$
B_5	$-\frac{2}{v_\Phi^2}\begin{pmatrix} \frac{\mu_1}{y_1^2} & 0 & \frac{v_\sigma\, y'_R}{\sqrt{2}\, y_1 y_3} e^{-i\varphi} \\ \cdot & \frac{\mu_2}{y_2^2} & \frac{v_\sigma\, y_R}{\sqrt{2}\, y_2 y_3} e^{i\varphi} \\ \cdot & \cdot & 0 \end{pmatrix}$	$\begin{pmatrix} y_1 & 0 & 0 \\ 0 & y_2 & 0 \\ 0 & 0 & y_3 \end{pmatrix}$	$\begin{pmatrix} \mu_1 & 0 & 0 \\ \cdot & \mu_2 & 0 \\ \cdot & \cdot & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ \cdot & 0 & y_R \\ \cdot & \cdot & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & y'_R \\ \cdot & 0 & 0 \\ \cdot & \cdot & 0 \end{pmatrix}$
B_6	$-\frac{2}{v_\Phi^2}\begin{pmatrix} \frac{\mu_1}{y_1^2} & \frac{v_\sigma\, y'_R}{\sqrt{2}\, y_1 y_2} e^{-i\varphi} & 0 \\ \cdot & 0 & \frac{v_\sigma\, y_R}{\sqrt{2}\, y_2 y_3} e^{i\varphi} \\ \cdot & \cdot & \frac{\mu_2}{y_3^2} \end{pmatrix}$	$\begin{pmatrix} y_1 & 0 & 0 \\ 0 & y_2 & 0 \\ 0 & 0 & y_3 \end{pmatrix}$	$\begin{pmatrix} \mu_1 & 0 & 0 \\ \cdot & 0 & 0 \\ \cdot & \cdot & \mu_2 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ \cdot & 0 & y_R \\ \cdot & \cdot & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & y'_R & 0 \\ \cdot & 0 & 0 \\ \cdot & \cdot & 0 \end{pmatrix}$

Neutrino Predictions for B_5



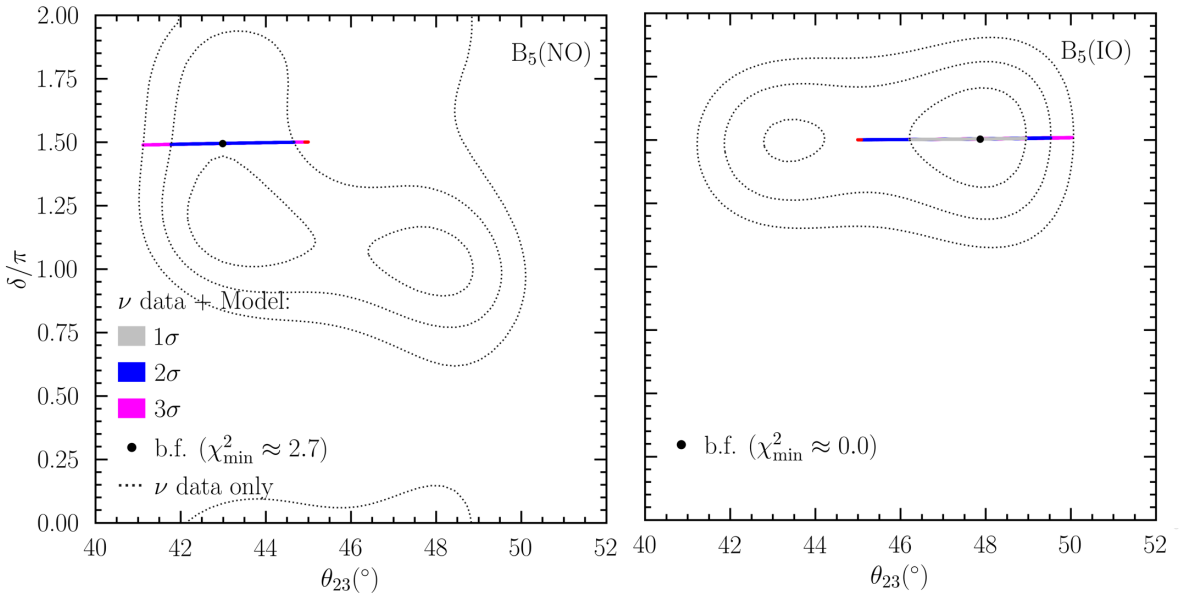
CP phase

$$\delta \simeq \frac{3\pi}{2}$$

Octant

NO	IO
$\theta_{23} < 45°$	$\theta_{23} > 45°$

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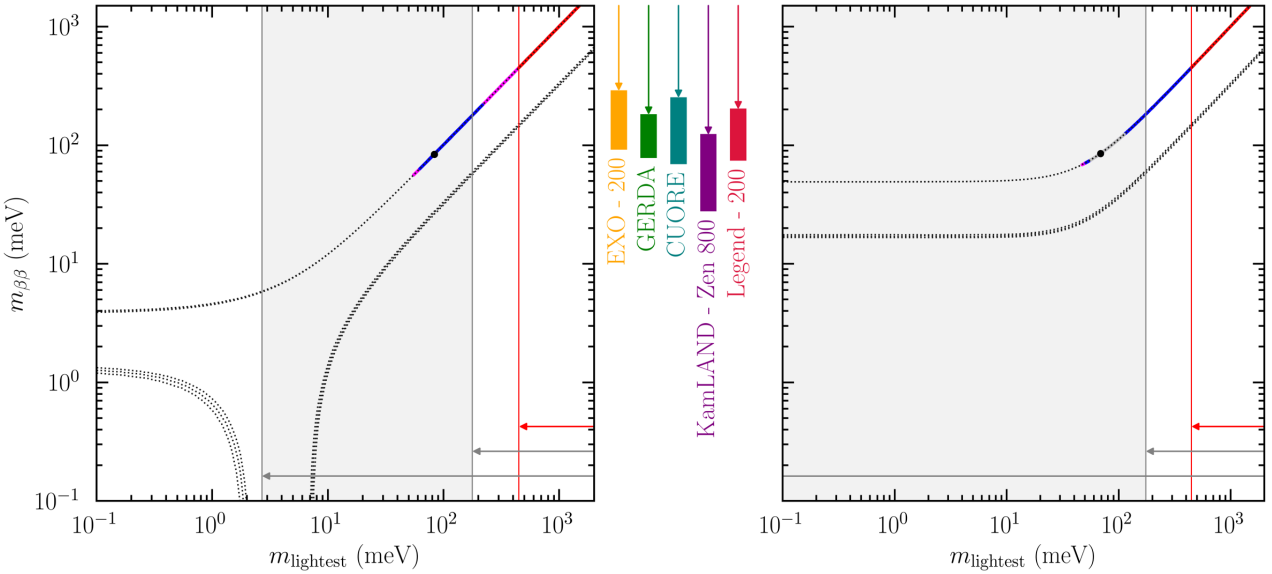
Mass bounds

NO

$$m_{lightest} \geq 60 \text{ meV}$$
$$m_{\beta\beta} \geq 60 \text{ meV}$$

IO

$$m_{lightest} \geq 50 \text{ meV}$$
$$m_{\beta\beta} \geq 70 \text{ meV}$$



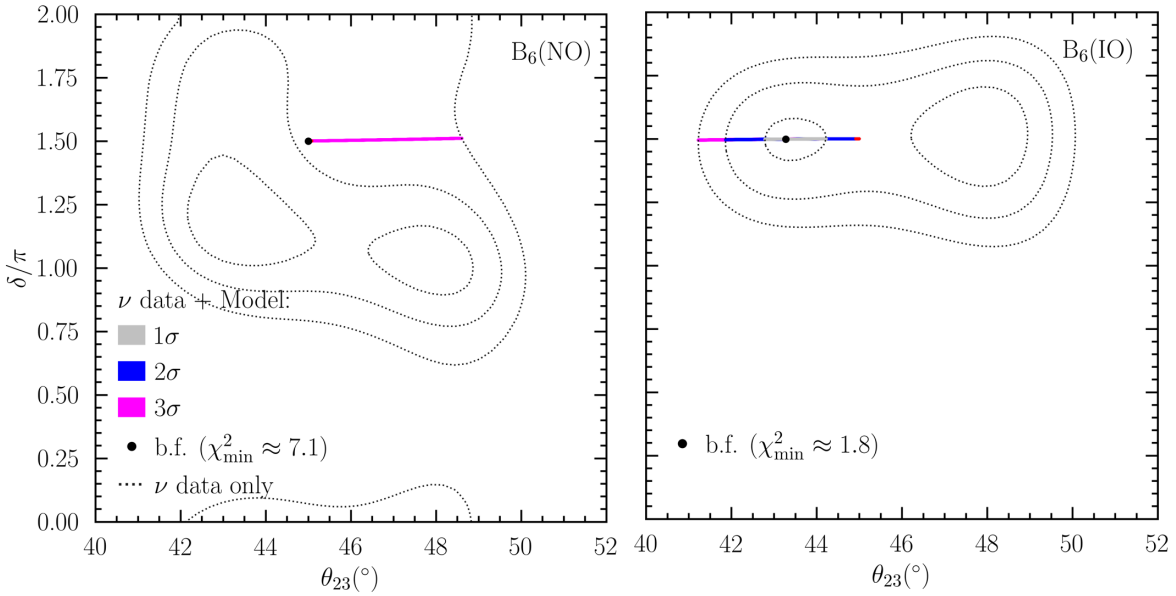
Neutrino Predictions for B_6

CP phase

$$\delta \simeq \frac{3\pi}{2}$$

Octant

NO	IO
$\theta_{23} > 45°$	$\theta_{23} < 45°$



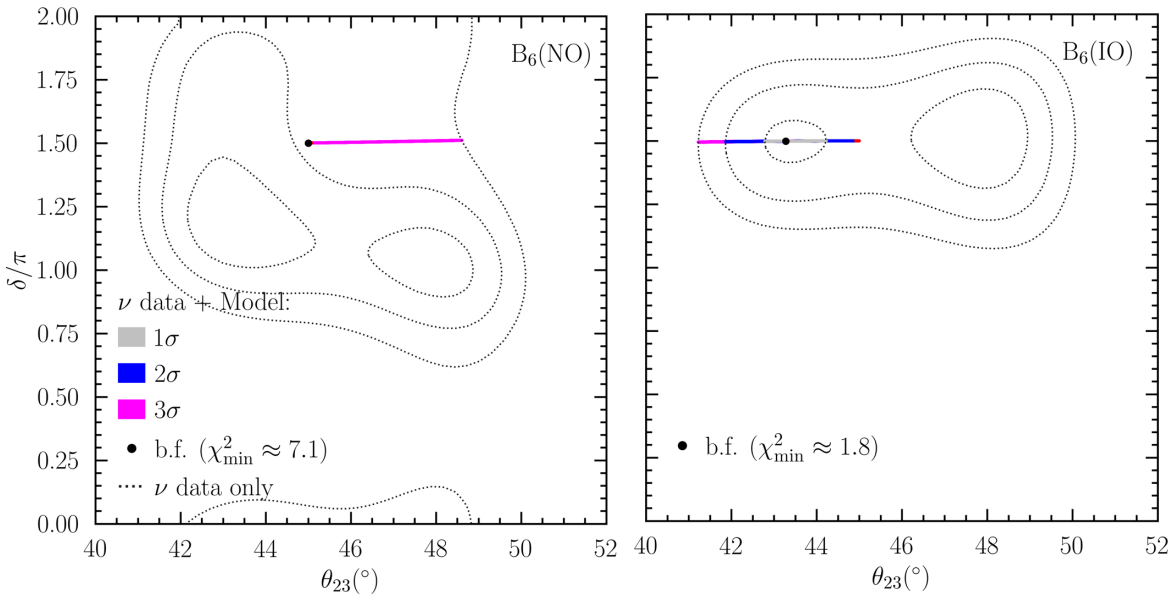
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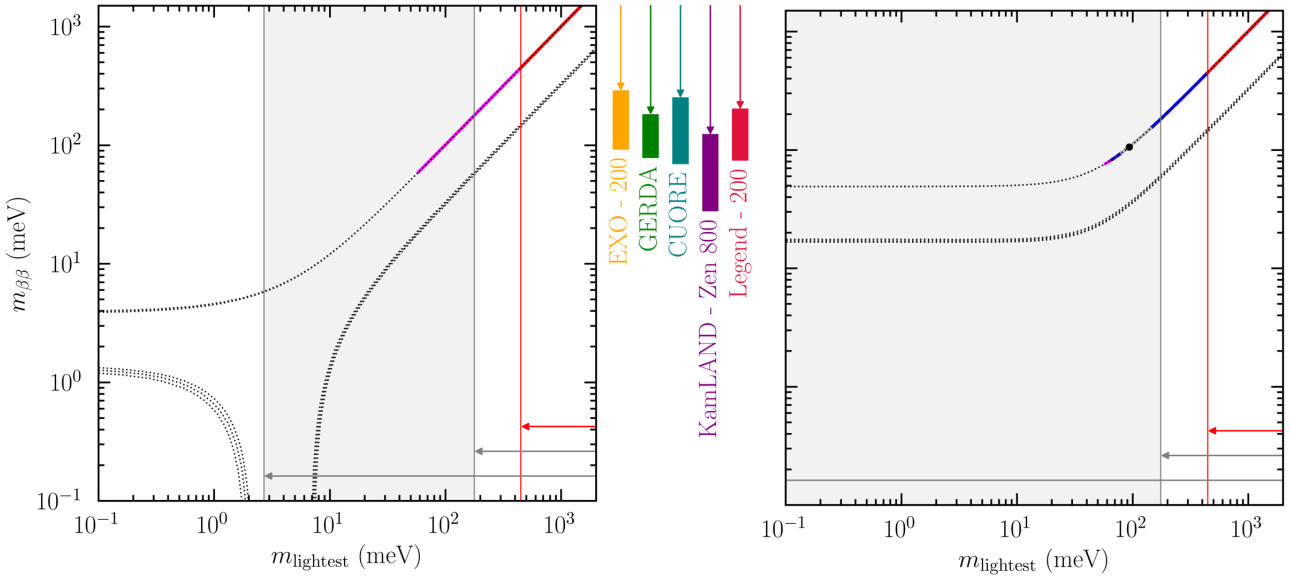
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Neutrino analytical results

Neutrino-sector expansion in the parameter

$$\varepsilon \equiv \frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \simeq 0.03$$

Inverse-mass texture

$$(\widehat{\mathrm{M}}_\nu^{-1})_{13} \simeq 0 \quad (B_5) \qquad (\widehat{\mathrm{M}}_\nu^{-1})_{12} \simeq 0 \quad (B_6)$$

Both textures suppress ν_{R_1} mixing, i.e. $\nu_{R_1} \simeq N_3$.

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Predicted singlet vacuum phase

$$\varphi/\pi \simeq 0.27 \quad (B_5, \mathrm{NO}) \qquad \varphi/\pi \simeq 0.49 \quad (B_5, \mathrm{IO})$$

$$\varphi/\pi \simeq 0.23 \quad (B_6, \mathrm{NO}) \qquad \varphi/\pi \simeq 0.01 \quad (B_6, \mathrm{IO})$$

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Scalar mixing and mass ratio

A real θ_σ requires ($r_h = m_{h_1}/m_{h_2}$)

$$r_h \leq 0.87 \quad (B_5, \mathrm{NO}) \qquad r_h \leq 0.03 \quad (B_5, \mathrm{IO})$$
$$r_h \leq 0.90 \quad (B_6, \mathrm{NO}) \qquad r_h \leq 0.03 \quad (B_6, \mathrm{IO})$$

Leptogenesis assisted by complex scalar singlet

Key ingredients for Leptogenesis

Sakharov (1967)

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Sphalerons

$$a_{\rm sph} \equiv \frac{B}{B-L} = \frac{24+4n_H}{66+13n_H}$$

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$$\hat{\mathcal{L}} f_\varphi = \hat{\mathcal{C}} f_\varphi$$

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Lepton asymmetry is dynamically generated via **out-of-equilibrium decays** of the heavy neutrinos added to the SM, and later transformed into baryon asymmetry via **sphaleron processes**

Yanagida, Fukugita (1986)

CP asymmetries

Flavoured CP asymmetry

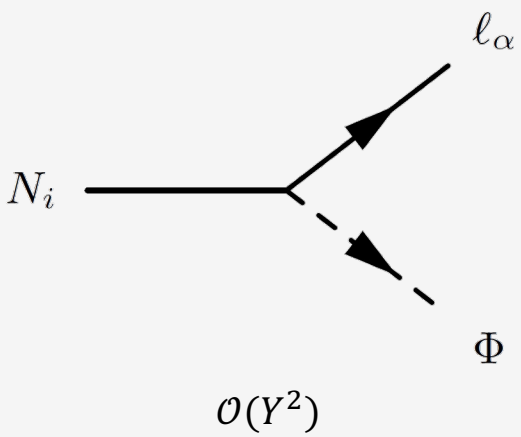
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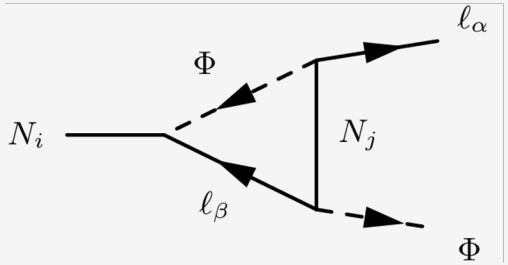
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Tree level

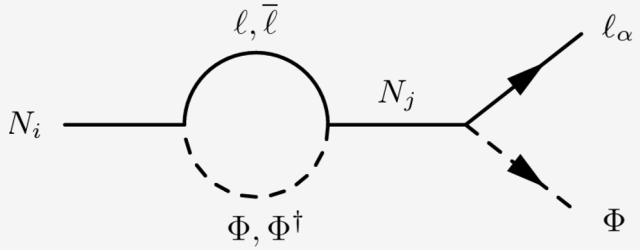


$\mathcal{O}(Y^2)$

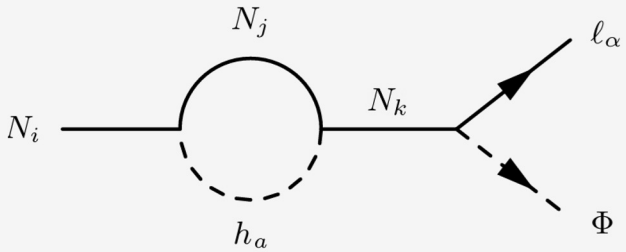
One-loop level



$\mathcal{O}(Y^4)$



$\mathcal{O}(Y^4)$



$\mathcal{O}(Y^2\Delta^2)$

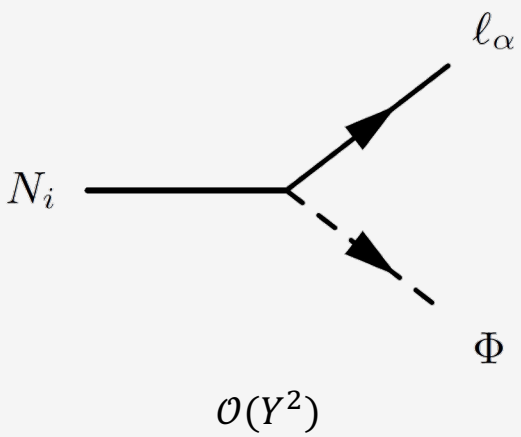
Le Dall, Ritz (2014)
Barreiros, Câmara, Felipe, Joaquim (2023)

CP asymmetries

Flavoured CP asymmetry

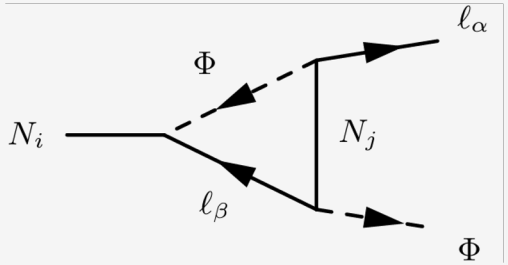
$$\varepsilon_{i\alpha} = \frac{\Gamma(N_i \to \Phi \ell_\alpha) - \Gamma(N_i \to \Phi^\dagger \overline{\ell_\alpha})}{\sum_{\beta=e,\mu,\tau} \left[\Gamma(N_i \to \Phi \ell_\beta) + \Gamma(N_i \to \Phi^\dagger \overline{\ell_\beta})\right]}$$

Tree level

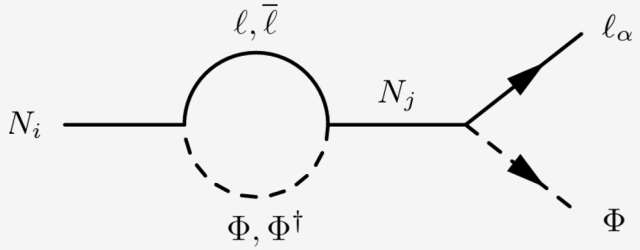


$\mathcal{O}(Y^2)$

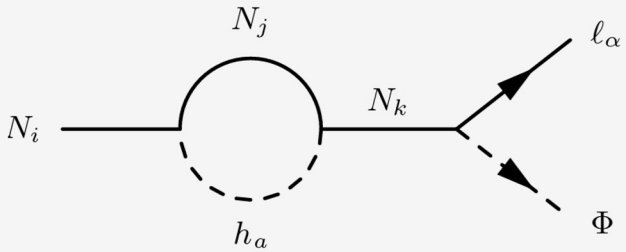
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Le Dall, Ritz (2014)
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$$\varepsilon_i = \sum_\alpha \varepsilon_{i\alpha} = \varepsilon_i(\text{type-I}) + \varepsilon_i(\text{wave})$$

Analytical results for CP asymmetries

N_3 decouples

$$M_3 \simeq |(\mathbf{M}_R^0)_{11}|$$

Its contribution to ε is negligible

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Scalar-assisted wave

$$\varepsilon \simeq \varepsilon_2(\text{wave}) \simeq -\frac{M_1^2 M_2 y_R^2 (y_{2,3}^2 - y_{3,2}^2)(\sqrt{\rho_{211}} - \sqrt{\rho_{212}})}{16\pi (M_1 + M_2)^2 (M_2 y_{2,3}^2 + M_1 y_{3,2}^2)} \frac{\sin 4\varphi}{1 - r_h^2}$$

$$\times \left[1 + r_h^2 \pm \text{sgn}(\sin 2\varphi) \sqrt{(1 + r_h^2)^2 - \frac{4 r_h^2}{\sin^2 2\varphi}} \right]$$

Dominant CP asymmetry when $N_2 \to N_1 h_a$ is kinematically open

Unflavoured Boltzmann equations

$$\frac{dN_{N_i}}{dz} = -(D_i + S_i)(N_{N_i} - N_{N_i}^{\rm eq}) - \sum_j S_{ij}(N_{N_i}N_{N_j} - N_{N_i}^{\rm eq}N_{N_j}^{\rm eq})$$
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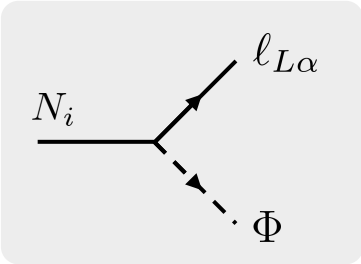
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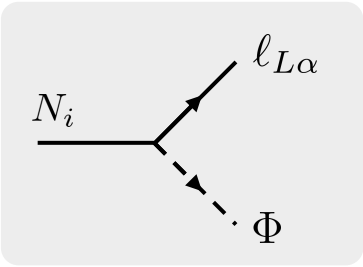
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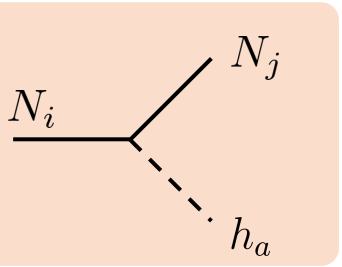
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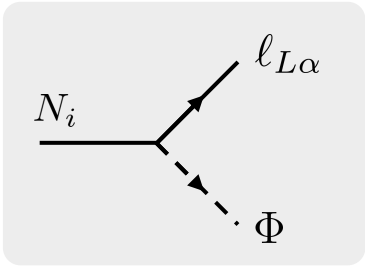
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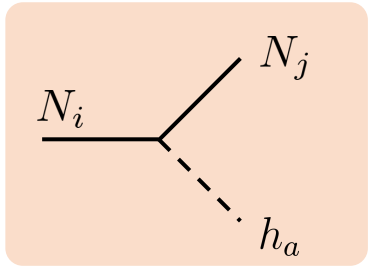
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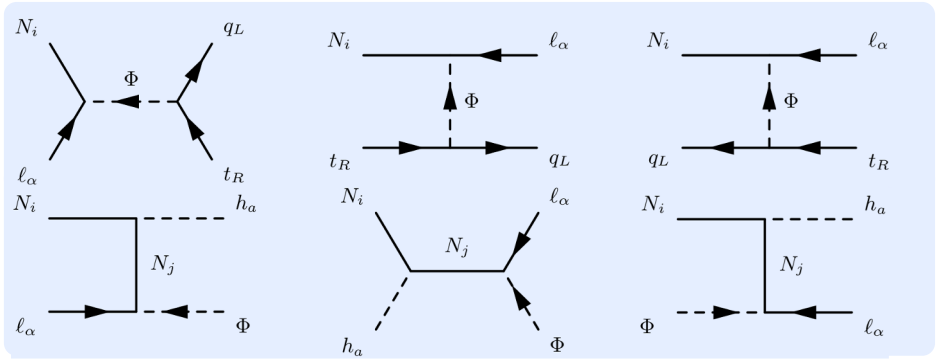
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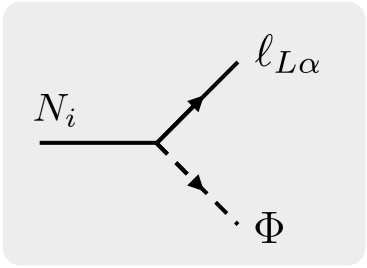
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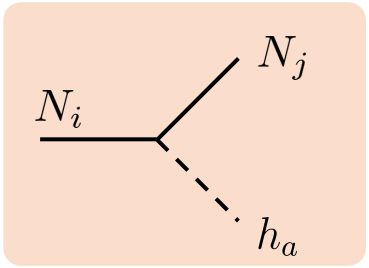
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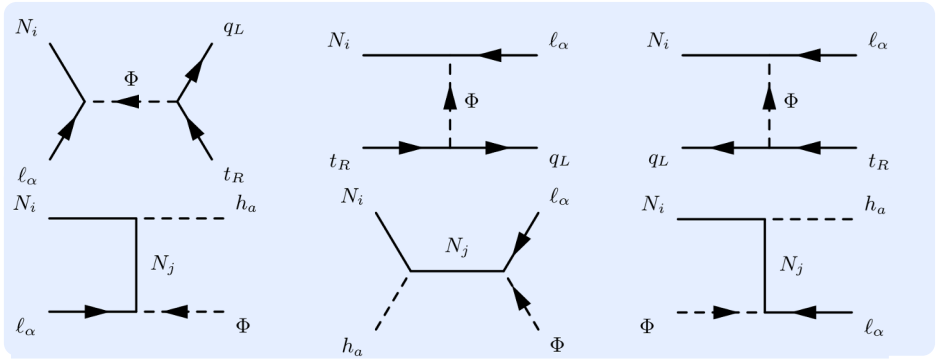
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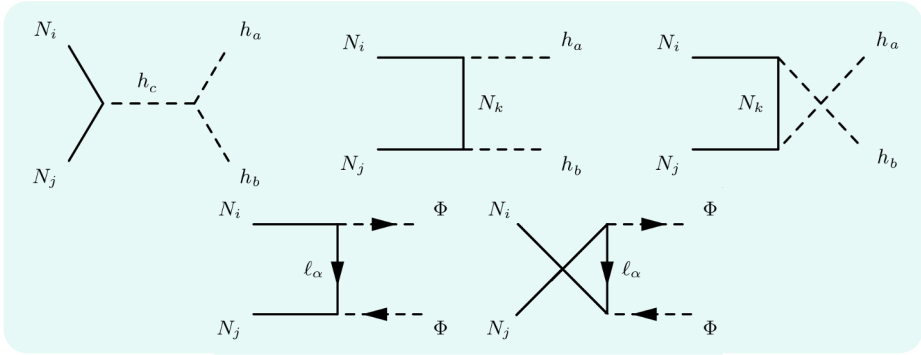
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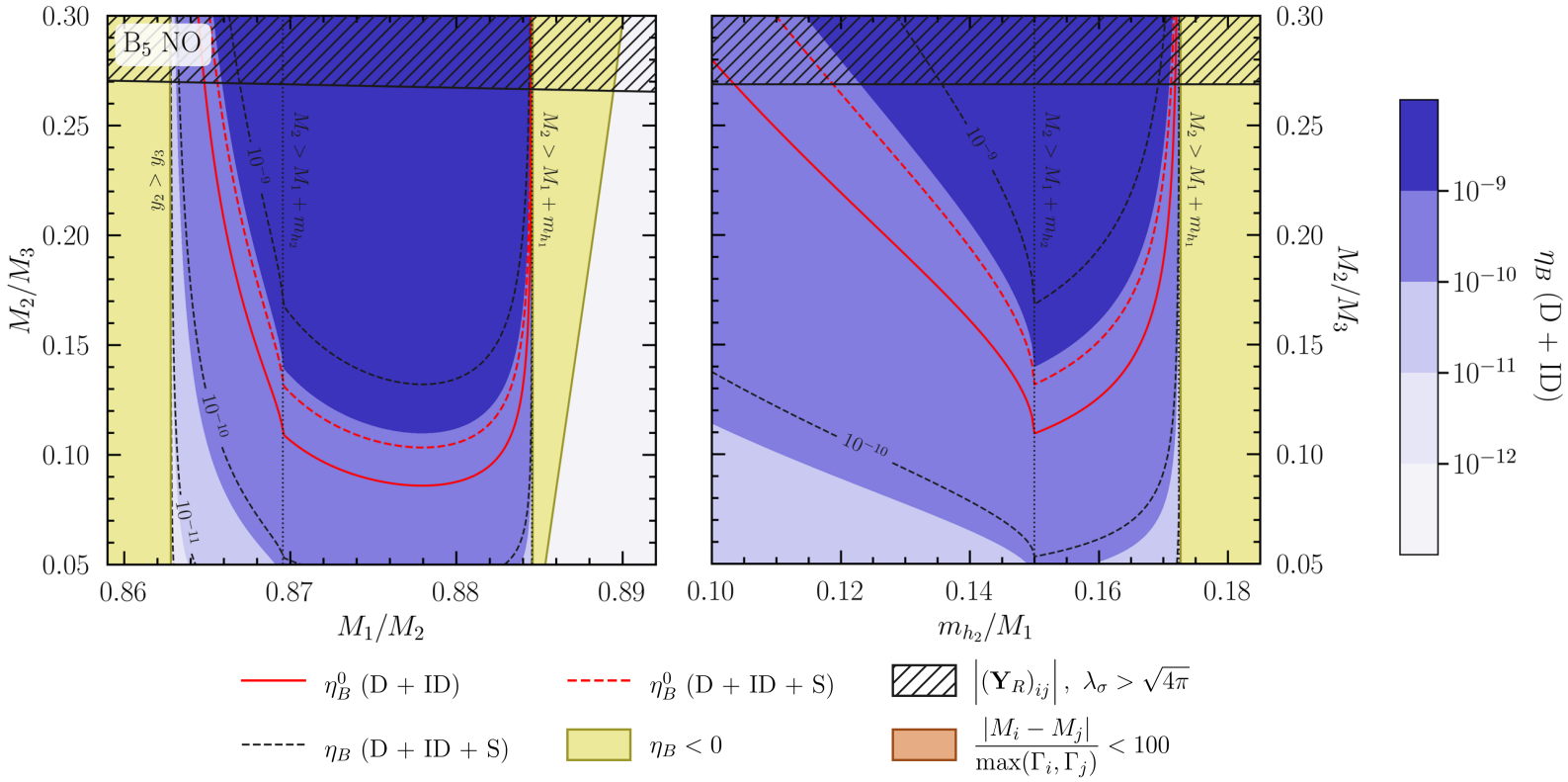


$\Delta N = 2$ scatterings (S_{ij})



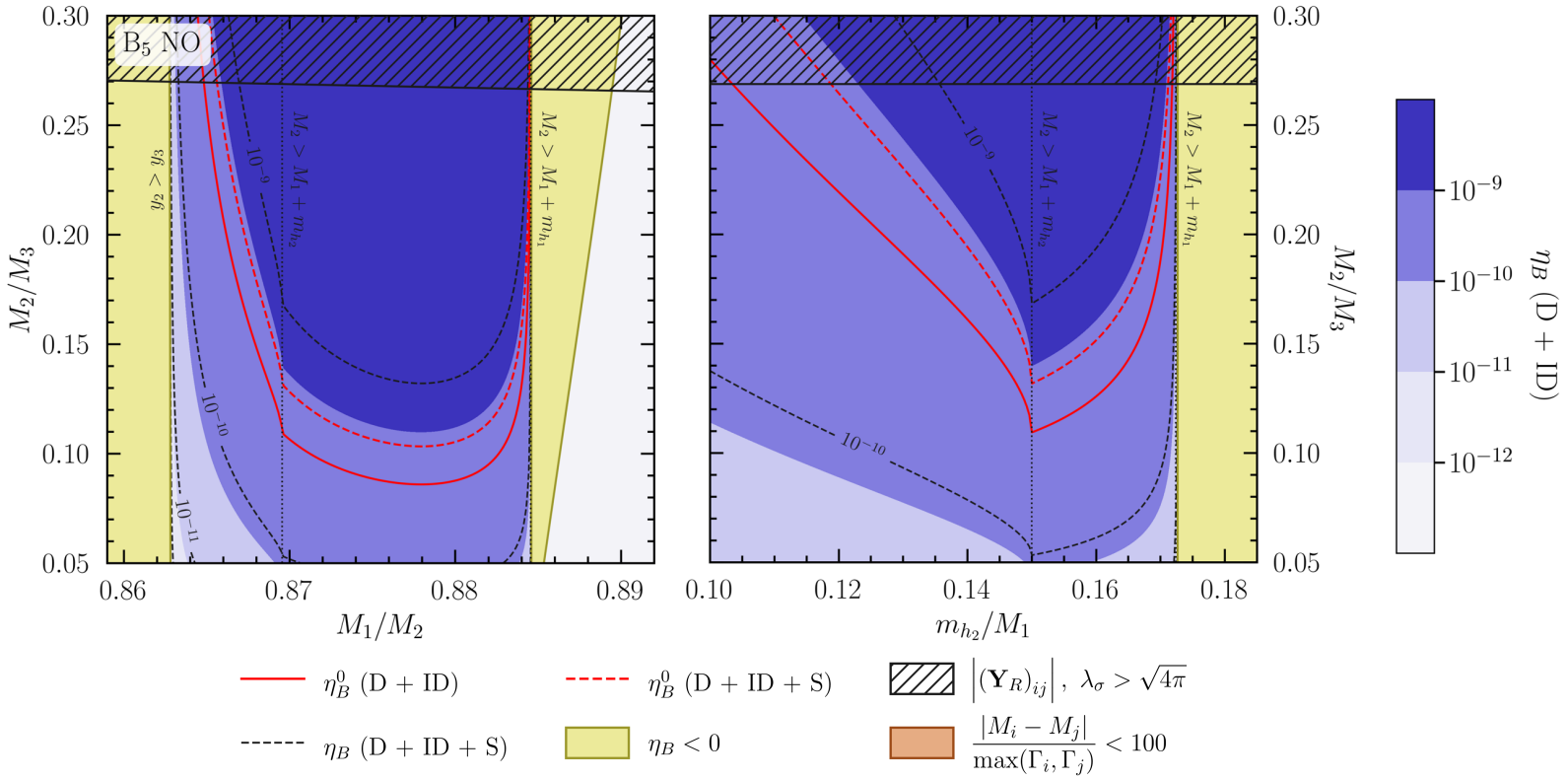
B_5 (NO): baryon asymmetry of the Universe

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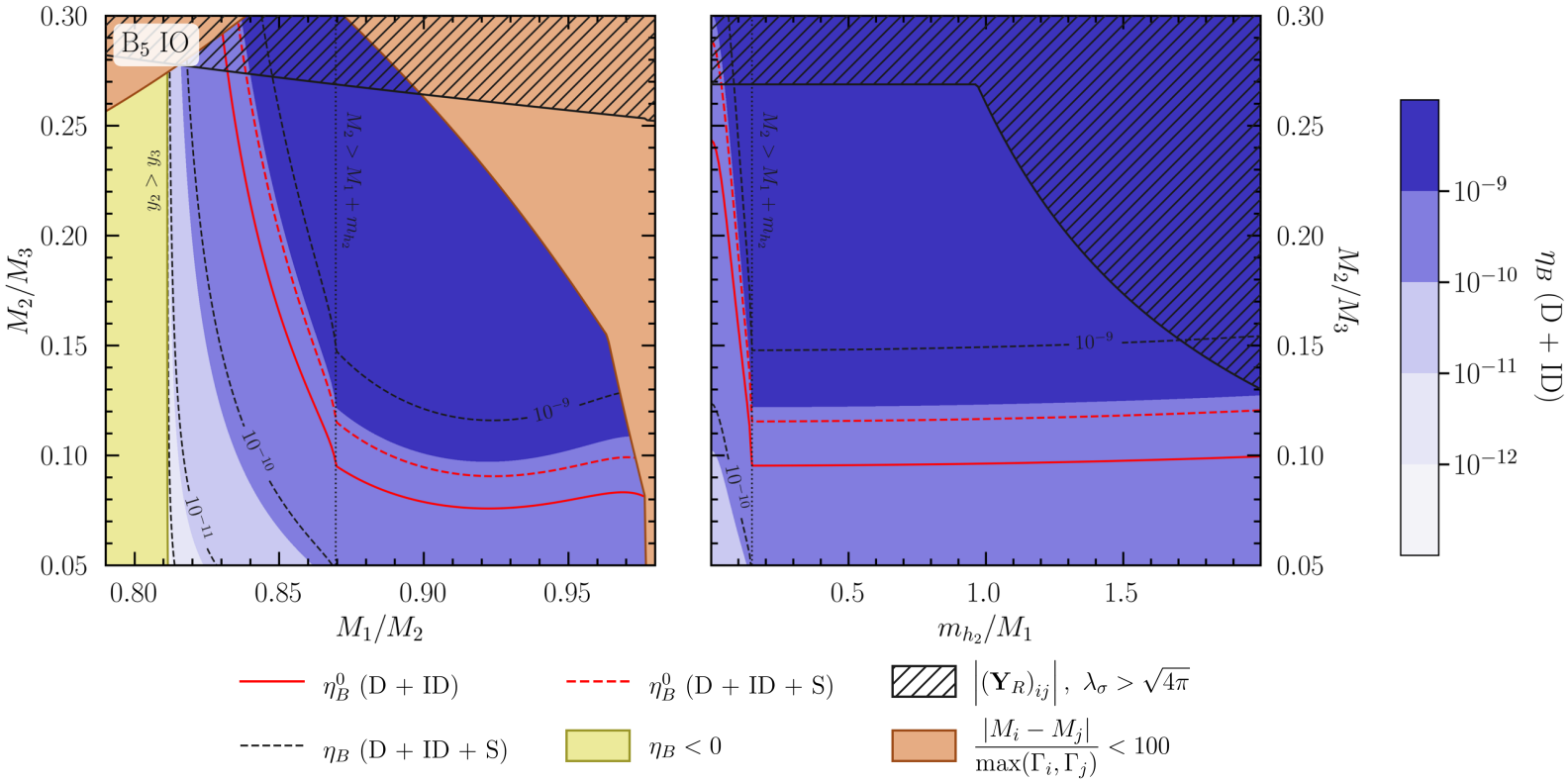


Planck (2018)

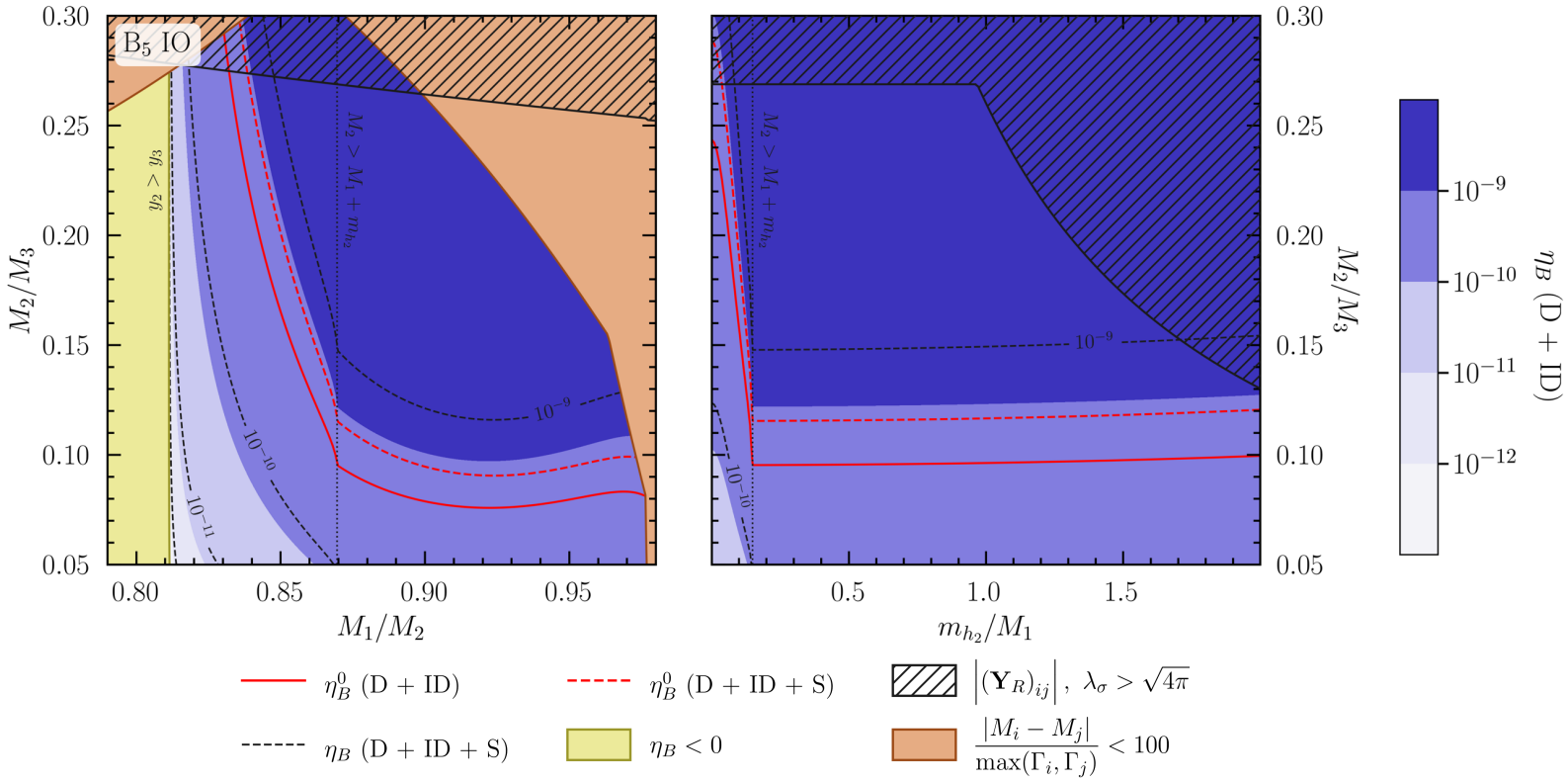
Region reproducing observed $\eta_B^0 = (6.12 \pm 0.04) \times 10^{-10}$

- **Left plot:** with fixed $m_{h_2}/M_1 = 0.15$; $0.867 \lesssim M_1/M_2 \lesssim 0.885$; $M_2/M_3 \gtrsim 0.11$
- **Right plot:** with fixed $M_1/M_2 = 1/1.15$; $0.12 \lesssim m_{h_2}/M_1 \lesssim 0.17$; $M_2/M_3 \gtrsim 0.13$

B_5 (IO): baryon asymmetry of the Universe



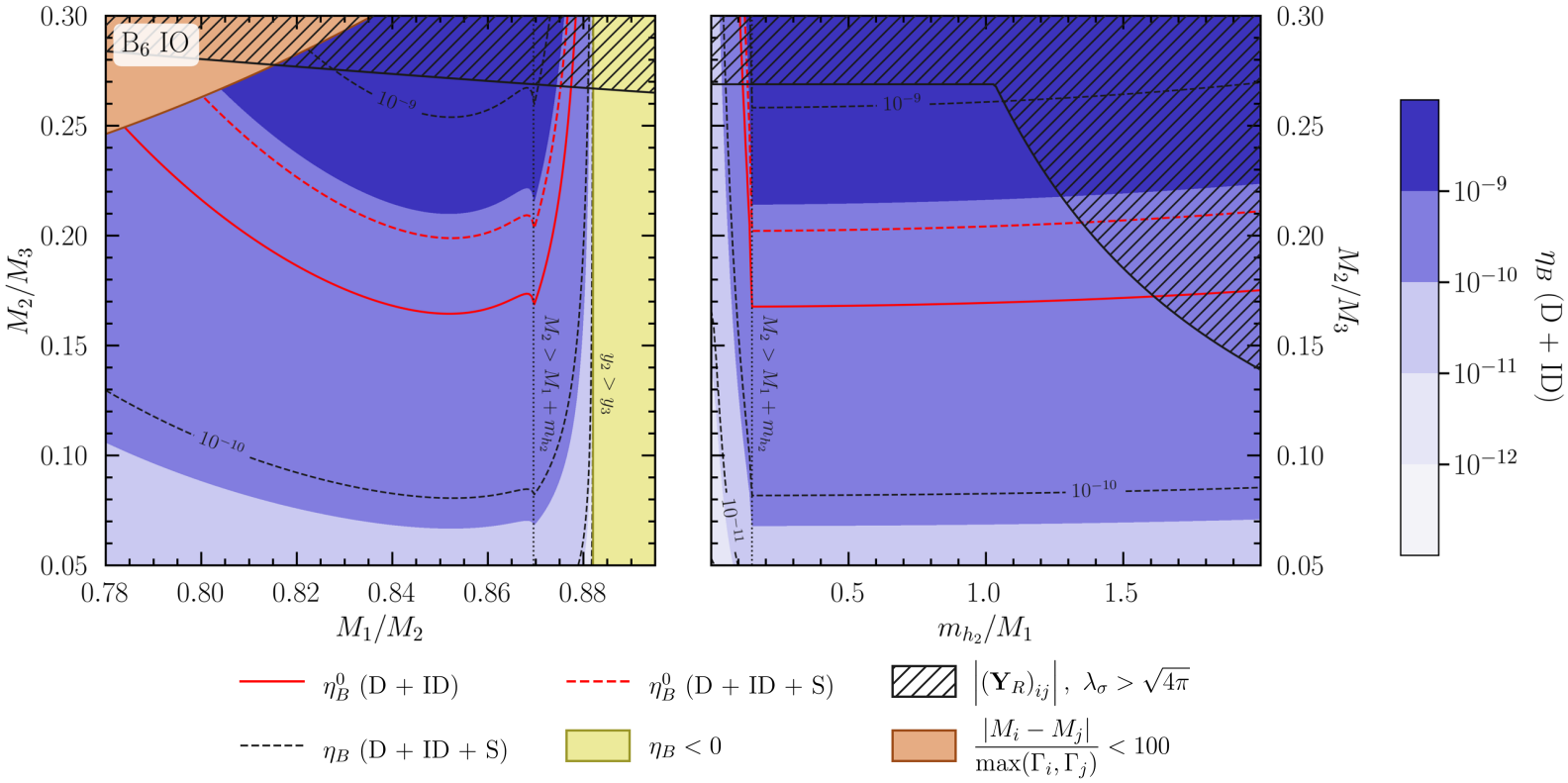
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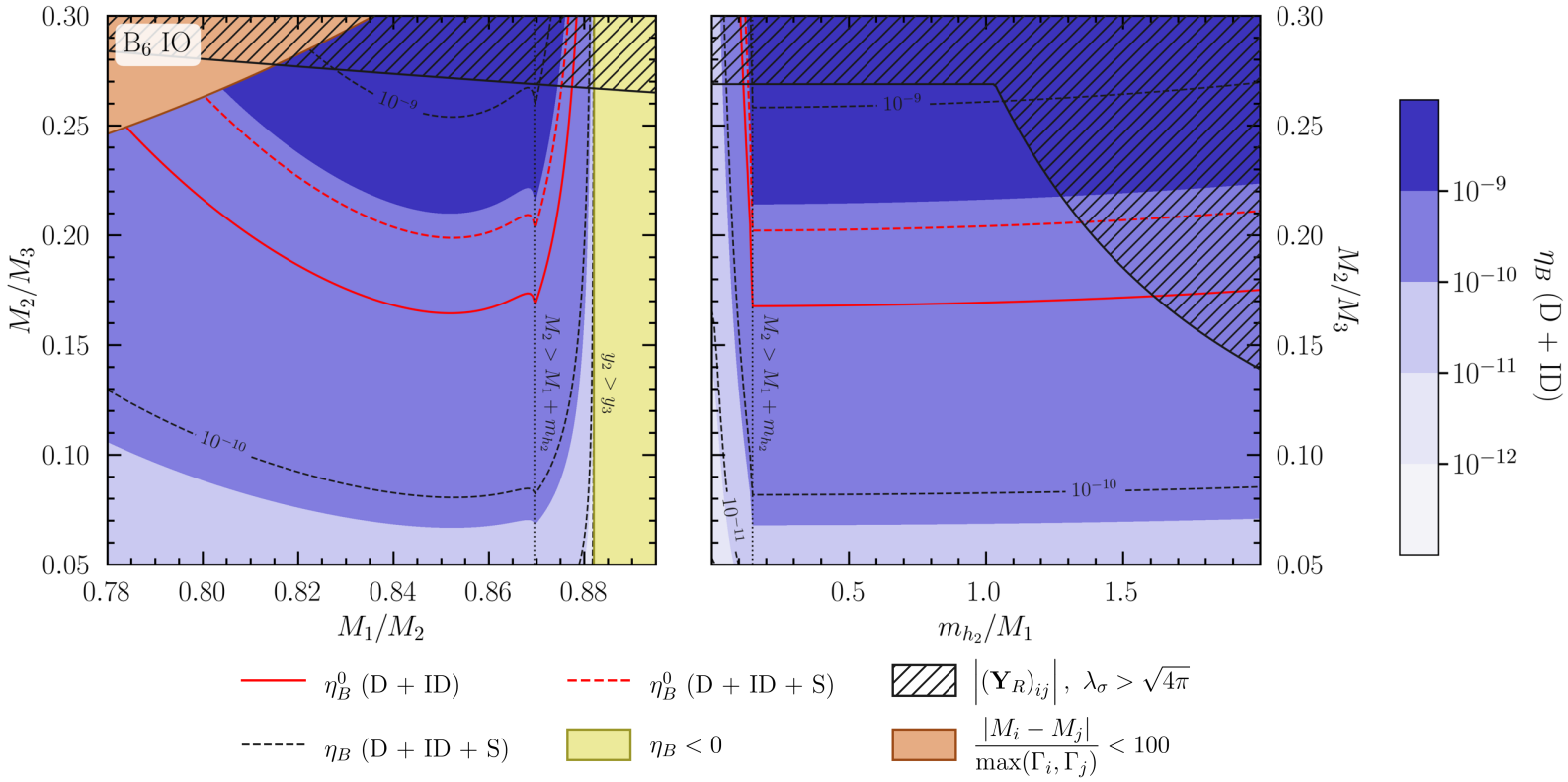
Region reproducing observed η_B^0

- **Left plot:** with fixed $m_{h_2}/M_1 = 0.15;\ 0.85 \lesssim M_1/M_2 \lesssim 0.97;\ M_2/M_3 \gtrsim 0.10$
- **Right plot:** with fixed $M_1/M_2 = 1/1.15;\ 0.15 \lesssim m_{h_2}/M_1 \lesssim 2;\ M_2/M_3 \gtrsim 0.12$

B_6 (IO): baryon asymmetry of the Universe



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Region reproducing observed η_B^0

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- **Right plot:** with fixed $M_1/M_2 = 1/1.15;\ 0.15 \lesssim m_{h_2}/M_1 \lesssim 1.3;\ M_2/M_3 \gtrsim 0.21$

Conclusions and outlook

Work done:

- ✓ **Minimal Z_4 models**: three RH neutrinos and one scalar singlet;
- ✓ **$\mathbf{B}_5$ and $\mathbf{B}_6$** predict **$\delta \simeq 3\pi/2$** and **definite θ_{23} octants**, with lower bounds on the **lightest neutrino mass** of $\approx 60\,(50)\,\mathrm{meV}$ for normal (inverted) ordering;
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Thank you !