Non-thermal leptogenesis with strongly hierarchical RH ν's

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$$m = m_D d_R^{-1} m_D^T \,, \quad d_R \equiv diag(M_1, M_2, M_3)$$

$$m = U_{\rm PMNS}^* d_\nu U_{\rm PMNS}^\dagger \,, d_\nu \equiv diag(m_1, m_2, m_3)$$

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \cdot K_0 \,,$$

$$c_{ij} \equiv \cos\theta_{ij},\, s_{ij} \equiv \sin\theta_{ij},\, K_0 = diag(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1)$$

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$$m_D = U_L^\dagger d_D U_R \,, \quad d_D \equiv diag(m_{D1}, m_{D2}, m_{D3})$$

$$m = U_L^\dagger d_D U_R d_R^{-1} U_R^T d_D U_L^*$$

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$$|||$$

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$$|||$$

$$\hat{m}$$

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$$W = \begin{pmatrix} \frac{\hat{m}_{ee}}{m_{D1}^2} & \frac{\hat{m}_{e\mu}}{m_{D1}m_{D2}} & \frac{\hat{m}_{e\tau}}{m_{D1}m_{D3}} \\ \cdots & \frac{\hat{m}_{\mu\mu}}{m_{D2}^2} & \frac{\hat{m}_{\mu\tau}}{m_{D2}m_{D3}} \\ \cdots & \cdots & \frac{\hat{m}_{\tau\tau}}{m_{D3}^2} \end{pmatrix}$$

$$m_{D1} : m_{D2} : m_{D3} \sim 1 : 10^{2.5} : 10^5 \,, U_L \approx U_{\text{CKM}} \approx \mathbb{1}$$

$$M_1 \approx \left| \frac{m_{D1}^2}{\hat{m}_{ee}} \right| \,,\; M_2 \approx \left| \frac{m_{D2}^2 \hat{m}_{ee}}{d_{12}} \right| \,,\; M_3 \approx \left| \frac{m_{D3}^2 d_{12}}{m_1 m_2 m_3} \right|$$

$$d_{12} \equiv \hat{m}_{ee}\hat{m}_{\mu\mu} - \hat{m}_{e\mu}^2$$

E. K. Akhmedov, M. Frigerio and A. Y. Smirnov, JHEP **0309**, 021 (2003), hep-ph/0305322

Non-thermal leptogenesis with strongly hierarchical RH ν's

$\phi \longrightarrow 2N_i$ with $Br \approx 1$

$$Y_N \equiv \frac{n_N}{s} = \frac{n_N}{n_\phi}\frac{n_\phi}{\rho_\phi}\frac{\rho_\phi}{s} = 2\frac{1}{m_\phi}\frac{3T_r}{4}$$

Non-thermal leptogenesis with strongly hierarchical RH ν's

$\phi \rightarrow 2N_i$ with $Br \approx 1$

$$Y_N \approx \frac{2T_r}{m_\phi}\,, \quad Y_\Delta \approx \frac{2T_r \epsilon_i \eta}{m_\phi}\,, \quad Y_B \approx \frac{2CT_r \epsilon_i \eta}{m_\phi}$$

$\epsilon_1 \leq \frac{3M_1 m_{\rm atm}}{8\pi v^2}\,, \quad Y_{B0} = 8.7 \times 10^{-11}$ requires

$$M_1 \gtrsim \left(\frac{1}{\eta}\right)\left(\frac{1/3}{C}\right)\left(\frac{0.05 \text{ eV}}{m_{\rm atm}}\right)\left(\frac{m_\phi}{T_r}\right) 7 \times 10^5 \text{ GeV}$$

$$m_\phi > 2M_2\,, \quad \phi \rightarrow 2N_2$$

Non-thermal leptogenesis with strongly hierarchical RH ν's

$$m_D = U_L^\dagger d_D U_R \,, \quad d_D \equiv diag(m_{D1}, m_{D2}, m_{D3})$$

$$W \equiv U_R d_R^{-1} U_R^T = d_D^{-1} \hat{m} d_D^{-1}$$

$$U_R \approx \begin{pmatrix} 1 & -\left(\frac{\hat{m}_{e\mu}}{\hat{m}_{ee}}\right)^* \frac{m_{D1}}{m_{D2}} & \left(\frac{d_{23}}{d_{12}}\right)^* \frac{m_{D1}}{m_{D3}} \\ \left(\frac{\hat{m}_{e\mu}}{\hat{m}_{ee}}\right) \frac{m_{D1}}{m_{D2}} & 1 & -\left(\frac{d_{13}}{d_{12}}\right)^* \frac{m_{D2}}{m_{D3}} \\ \left(\frac{\hat{m}_{e\tau}}{\hat{m}_{ee}}\right) \frac{m_{D1}}{m_{D3}} & \left(\frac{d_{13}}{d_{12}}\right) \frac{m_{D2}}{m_{D3}} & 1 \end{pmatrix} \cdot K \,,$$

$$\begin{aligned} d_{23} &\equiv \hat{m}_{e\mu}\hat{m}_{\mu\tau} - \hat{m}_{\mu\mu}\hat{m}_{e\tau} \\ d_{13} &\equiv \hat{m}_{ee}\hat{m}_{\mu\tau} - \hat{m}_{e\mu}\hat{m}_{e\tau} \\ d_{12} &\equiv \hat{m}_{ee}\hat{m}_{\mu\mu} - \hat{m}_{e\mu}^2 \\ K &= diag(e^{-i\phi_1/2}, e^{-i\phi_2/2}, e^{-i\phi_3/2}) \,, \quad \phi_i \equiv \arg M_i \end{aligned}$$

Non-thermal leptogenesis with strongly hierarchical RH ν's

$$m_D = U_L^\dagger d_D U_R\,, \quad d_D \equiv diag(m_{D1}, m_{D2}, m_{D3})$$

$$(m_D^\dagger m_D)_{ij} \sim m_{Di} m_{Dj}$$

$$\epsilon_2 \equiv \sum_\alpha \epsilon_{2,\alpha} \approx \frac{3}{8\pi v^2} \frac{\sum_\alpha \mathrm{Im}\left[(m_D^\dagger)_{2\alpha}(m_D^\dagger m_D)_{23}(m_D^T)_{3\alpha}\right]}{\left(m_D^\dagger m_D\right)_{22}} \frac{M_2}{M_3}$$

$$m_D \sim \begin{pmatrix} m_{D1} & \theta_C m_{D2} & m_{D1}^2/m_{D3} \\ m_{D1} & m_{D2} & m_{D2}^2/m_{D3} \\ m_{D1} & m_{D2} & m_{D3} \end{pmatrix}$$

$$\epsilon_{2,\tau} \approx \frac{3\varphi}{8\pi v^2} \frac{\left|m_{D32}^* m_{D33}\right|^2}{\left(m_D^\dagger m_D\right)_{22}} \frac{M_2}{M_3} \approx \frac{3\varphi M_2}{8\pi v^2} \frac{|d_{13}|^2 m_1 m_2 m_3}{|d_{12}|(|d_{12}|^2+|d_{13}|^2)}$$

Results for NH spectrum

$$m_3 \approx m_{\text{atm}}\,, \quad m_2 \approx m_\odot\,, \quad m_1 \ll m_2$$

Set $U_L = \mathbb{1}$ and $s_{13} = 0$:

$$M_1 \approx \frac{m_{D1}^2}{s_{12}^2 m_2}\,, \quad M_2 \approx \frac{2m_{D2}^2}{m_3}\,, \quad M_3 \approx \frac{m_{D3}^2 s_{12}^2}{2m_1}$$

$$\epsilon_{2,\tau} \approx \frac{3\varphi M_2 m_1}{8\pi v^2 s_{12}^2}$$

$$\begin{aligned} Y_B &\approx \frac{2CT_r \epsilon\eta}{m_\phi} \approx \frac{3CT_r\varphi M_2 m_1 \eta_1\eta_2}{4\pi v^2 s_{12}^2 m_\phi} \\ &= \left(\frac{10T_r}{M_2}\right)\left(\frac{2M_2}{m_\phi}\right)\left(\frac{m_1}{m_2}\right)\frac{3C\varphi m_2 m_{D2}^2\eta_1\eta_2}{40\pi v^2 s_{12}^2 m_3} \\ &\approx \left(\frac{10T_r}{M_2}\right)\left(\frac{2M_2}{m_\phi}\right)\left(\frac{m_1}{m_2}\right) 2\times 10^{-8}\varphi\eta_1 \end{aligned}$$

Results for NH spectrum

$$Y_B \approx \left(\frac{10T_r}{M_2}\right)\left(\frac{2M_2}{m_\phi}\right)\left(\frac{m_1}{m_2}\right) 2\times 10^{-8}\varphi\eta_1$$

$$\eta_1 \approx \exp\left[-\frac{3\pi}{8}\frac{\tilde{m}_{1,\tau}}{m_*}A_{\tau\tau}\right]$$

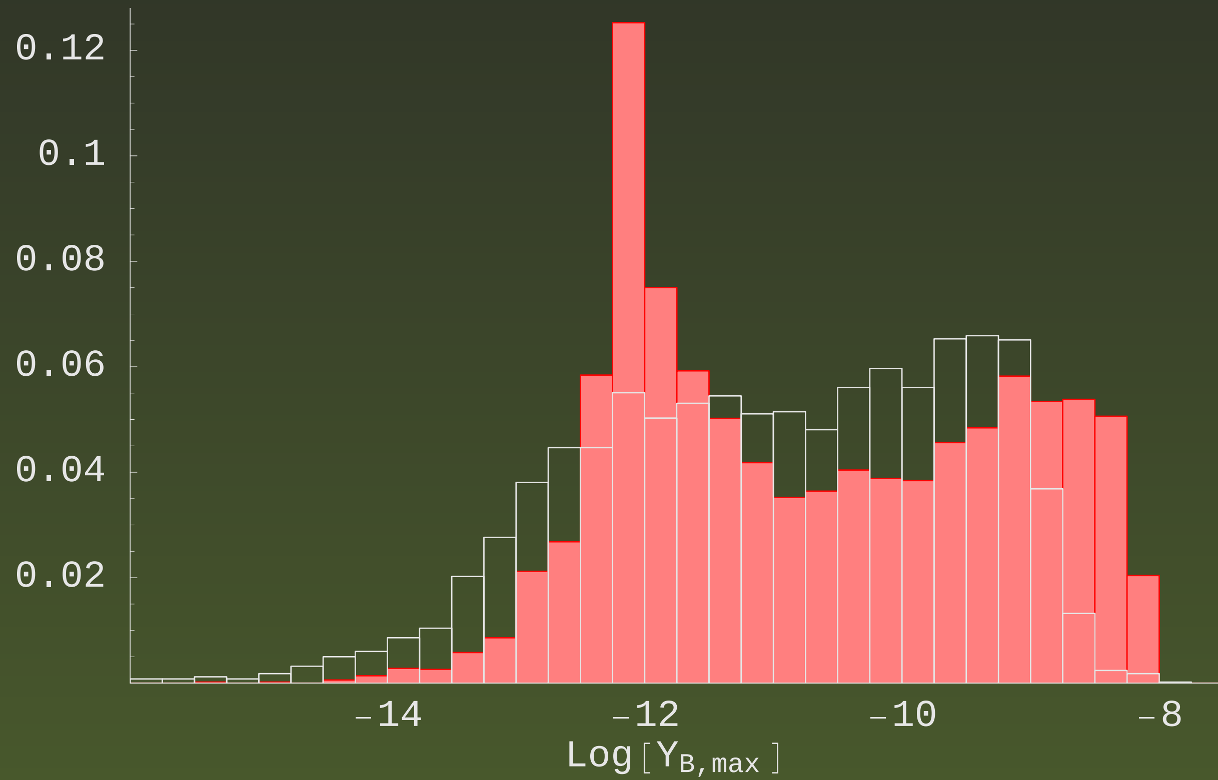
$$m_* \approx (\sin^2\beta) 1.58\times 10^{-3}\ \mathrm{eV}$$

$$Y_{\ell_\tau} = -A_{\tau\tau}Y_{\Delta_\tau} \quad (Y_{\Delta_\tau} \equiv Y_B/3 - Y_{L_\tau}\,, \quad Y_{L_\tau} = Y_{\ell_\tau} + Y_{\tau_R})$$

$$\tilde{m}_{1,\tau} \equiv \frac{|m_{D31}|^2}{M_1} \approx |\hat{m}_{e\tau}|^2/|\hat{m}_{ee}|$$

$$\approx \frac{\left|-c_{12}s_{12}e^{i\alpha_2}m_2 + \left(s_{13}e^{-i\delta} + \frac{\theta_C}{\sqrt{2}}\right)m_3\right|^2}{2\left|s_{12}^2 e^{i\alpha_2}m_2 + \left(s_{13}e^{-i\delta} + \frac{\theta_C}{\sqrt{2}}\right)^2 m_3\right|}$$

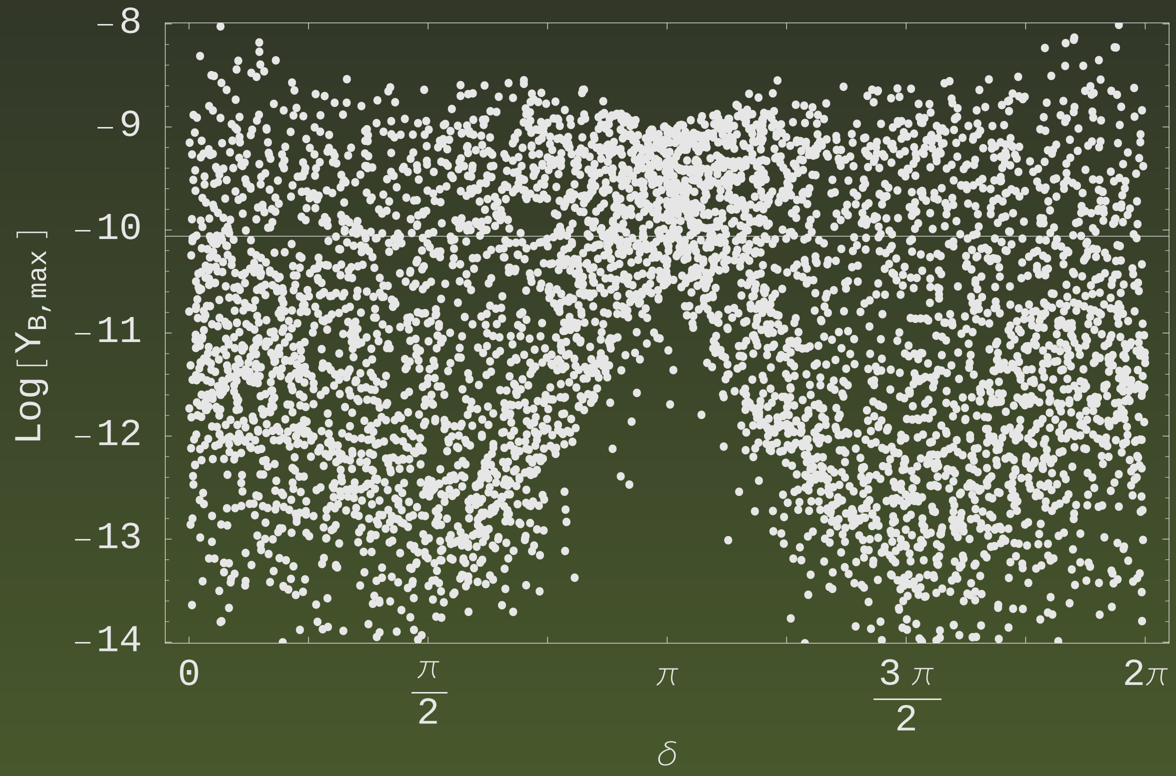
Results for NH spectrum



Histograms for $Y_{B,\mathrm{max}}$ with $d_D = d_u$, $m_1 = 0.2m_2$ and $U_L = U_{\mathrm{CKM}}$.

Filled: $s_{13} = 0$, unfilled: $s_{13} = 0.2$.

Results for NH spectrum



$Y_{B,\max}$ versus the Dirac phase δ, with $d_D = d_u$, $m_1 = 0.2 m_2$, $U_L = U_{\rm CKM}$ and $s_{13} = 0.2$.

Results for IH and QD spectrum

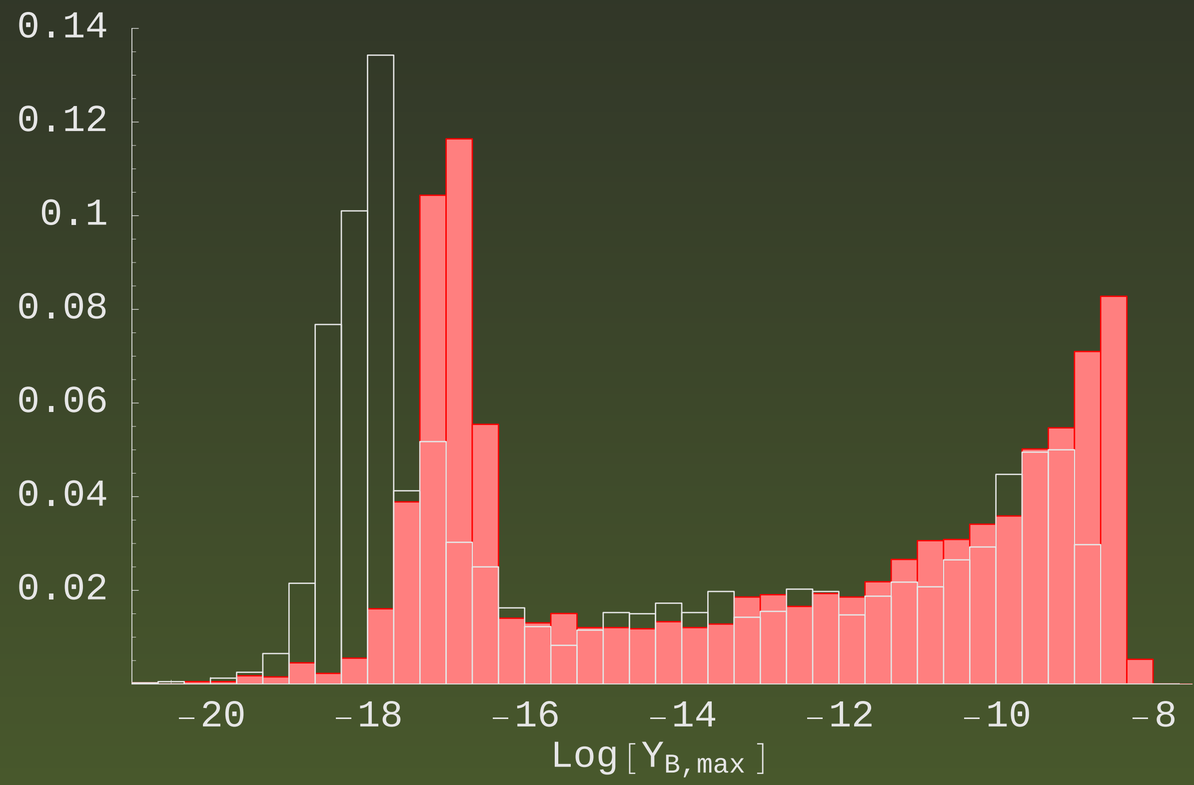
IH spectrum: $m_3 \ll m_1 < m_2 \approx m_{\rm atm}$

$$\tilde{m}_{1,\tau} \approx \frac{c_{12}^2 s_{12}^2 \left| e^{i\alpha_1} m_1 - e^{i\alpha_2} m_2 \right|^2}{2 |c_{12}^2 e^{i\alpha_1} m_1 + s_{12}^2 e^{i\alpha_2} m_2|}$$

$$M_1 \approx \frac{m_{D1}^2}{m_{\rm atm}}\,, \qquad M_2 \approx \frac{2 m_{D2}^2}{m_{\rm atm}}\,, \qquad M_3 \approx \frac{m_{D3}^2}{2 m_3}$$

$$\epsilon_{2,\tau} \approx \frac{3 \varphi M_2 m_3}{8 \pi v^2}$$

Results for IH and QD spectrum

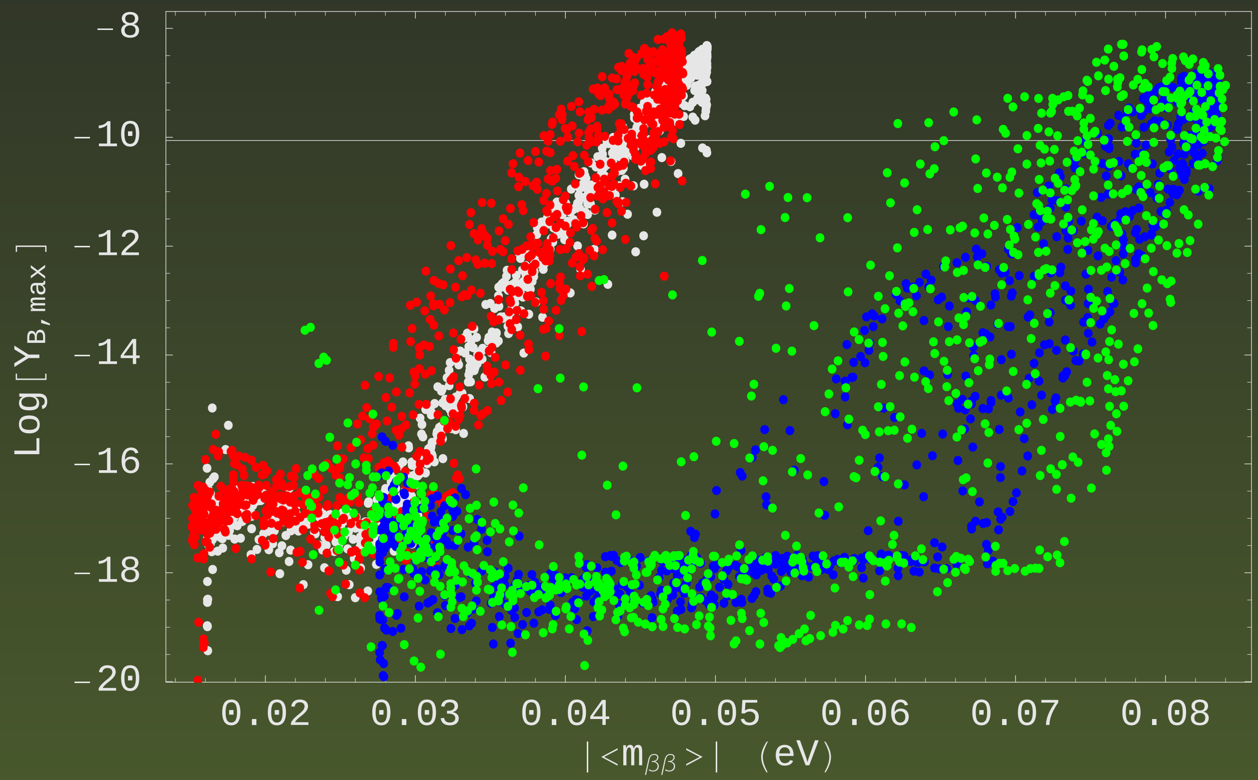


Histograms for $Y_{B,\max}$ with $d_D = d_u$, $m_3 = 0.2 m_2$, $U_L = U_{\rm CKM}$ and $s_{13} = 0$. Filled: IH spectrum, unfilled: QD spectrum.

Results for IH and QD spectrum

$$|\langle m_{\beta\beta}\rangle| \approx \left|c_{12}^2 e^{i\alpha_1} m_1 + s_{12}^2 e^{i\alpha_2} m_2\right|$$

Results for IH and QD spectrum



$Y_{B,\max}$ versus the effective Majorana mass $|\langle m_{\beta\beta}\rangle|$, with $d_D = d_u$ and $U_L = U_{\rm CKM}$. Light grey (red): IH spectrum with $s_{13} = 0$ ($s_{13} = 0.2$). Blue (green): QD spectrum with $s_{13} = 0$ ($s_{13} = 0.2$).

Conclusion

$$\left(\frac{10T_r}{M_2}\right)\left(\frac{2M_2}{m_\phi}\right)\left(\frac{\min(m_i)}{m_2}\right) \gtrsim \left(\frac{m_c}{m_{D2}}\right)^2 10^{-2}$$

$$M_2 \sim 6 \times 10^9 \text{ GeV}\,, \quad m_\phi \sim 10^{10.5} \text{ GeV}\,, \quad T_r \sim 10^8 \text{ GeV}$$

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- $Y_B = Y_{B0}$ requires $|\langle m_{\beta\beta}\rangle| \lesssim 0.2$ eV