$\mu - \tau$ reflection symmetry with a high scale texture zero

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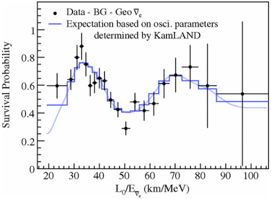
The flavor problem: leptonic mixing

Neutrinos oscillate  ’15 Kajita & Mcdonald

$\bar{\nu}_e \to \bar{\nu}_e$ KamLAND ’08



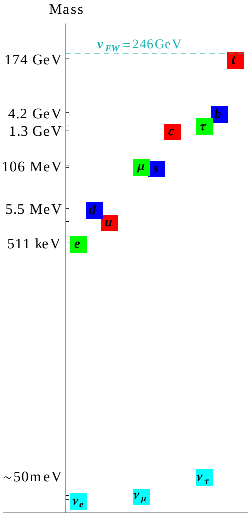
2012 $\theta_{13} \approx 8.5^\circ$ $\to$ ~~CP~~

Daya-Bay, RENO

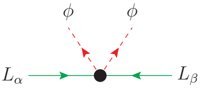
$$|V_{\text{PMNS}}| = \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.35 & 0.71 & 0.61 \\ 0.45 & 0.45 & 0.77 \end{pmatrix}$$

Strumia,Vissani,hep-ph/0606054

The flavor problem: neutrino masses



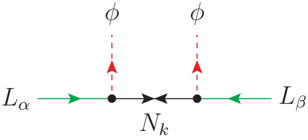
- If lepton number is broken at a scale $\Lambda \gg v$



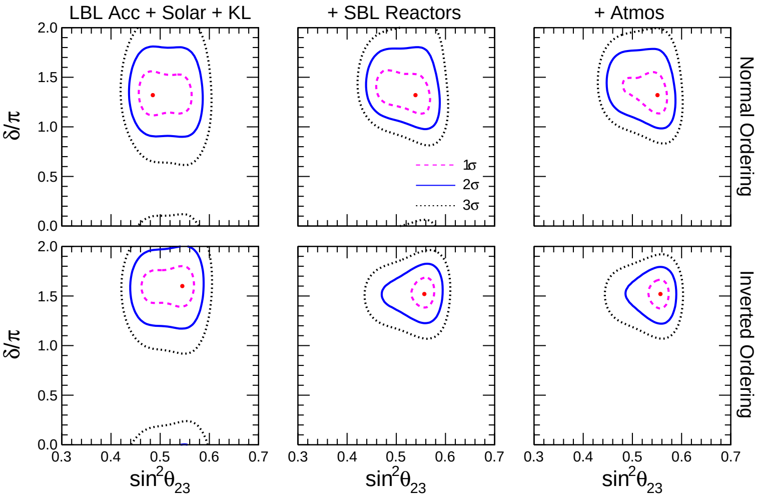
Weinberg,'79

$$\Longrightarrow \quad m_\nu \sim \frac{v^2}{\Lambda}$$

- $m_\nu \lesssim 0.1\,\text{eV}$ for $\Lambda \gtrsim 10^{12}\,\text{GeV}$
- The seesaw mechanism
- Type I: heavy singlets N_1, N_2, N_3



Maximal atmospheric angle and Dirac phase?



NO preferred over IO in 3σ

Capozzi, et al., 1804.09678

CP$^{\mu\tau}$ symmetry or $\mu\tau$ reflection

$$\nu_e \to {\nu_e}^{\rm CP}\,, \quad \nu_\mu \to {\nu_\tau}^{\rm CP}\,, \quad \nu_\tau \to {\nu_\mu}^{\rm CP}$$

$\theta_{23} = 45°$, $\delta_{CP} = \pm 90°$, trivial Majorana phases, θ_{13}, θ_{12} free

- CP$^{\mu\tau}$ $=$ CP with $\mu - \tau$ interchange
- Also known as $\mu - \tau$ reflection

Harrison,Scott, PLB'02
Grimus,Lavoura, PLB'04

- Badly broken in the charged lepton sector: $y_\mu \ll y_\tau$
- Hint from $|V_{\mu i}| \approx |V_{\tau i}|$
- Predict all CP phases still allowing ~~CP~~
- Accidental maximality

He, Rodejohann, Xu, PLB'15
Joshipura&Patel, PLB'15

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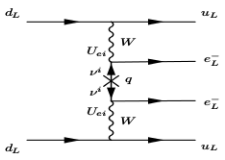
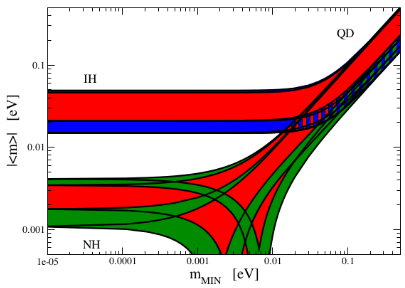
$CP^{\mu\tau}$ and neutrinoless double beta decay



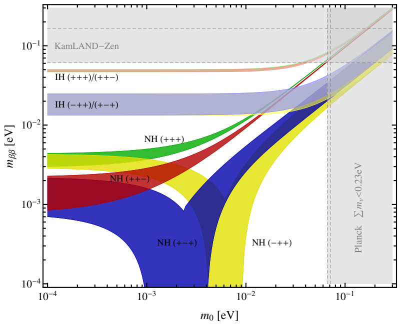
generic $m_{ee} = m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2$

$CP^{\mu\tau}$ $m_{ee} = \pm m_1 |U_{e1}|^2 \pm m_2 |U_{e2}|^2 \pm m_3 |U_{e3}|^2$

four CP parities



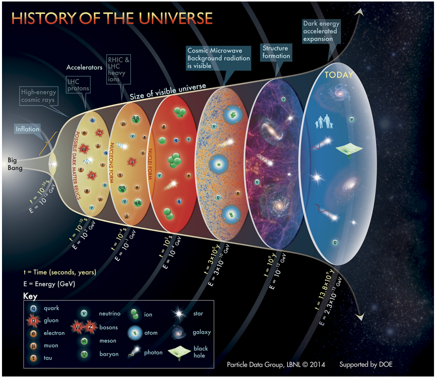
PDG



Mohapatra,Nishi,JHEP'15

Baryon asymmetry of the Universe

Baryogenesis mechanism
needed at $T \gtrsim 40\,\mathrm{MeV}$



- $\dfrac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$
- Sakharov conditions '67
  - violation of CP, C
  - violation of B
  - departure of themral equilibrium
- SM is not enough

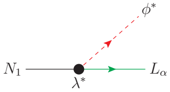
Leptogenesis

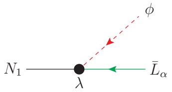
Matter-antimatter asymmetry

$$Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s} \sim \; -10^{-3} \times \epsilon \times \eta$$

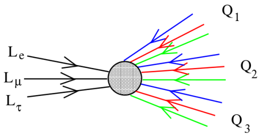
Fukugita, Yanagida, '86

- $Y_B\Big|_{\rm exp} = (8.65 \pm 0.09) \times 10^{-11}$
- N_1 decay generates L asymmetry

$\epsilon \propto$ 

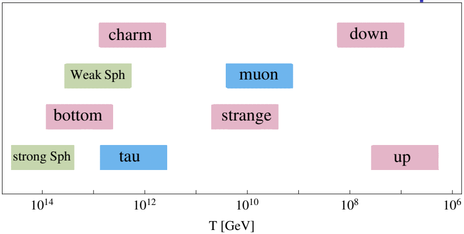
- 

- Spharelon processes $\Delta L \to \Delta B$
  $\Delta B = \Delta L = 3$
  Klinkhamer, Manton, '84



Cline, hep-ph/0609145

$CP^{\mu\tau}$ and leptogenesis



Garbrecht,Schwaller,JCAP'14

Washout in different flavors can be different

Abada et al., JCAP'06
Nardi et al. JHEP'06

- Unflavored leptogenesis does not work   Grimus& Lavoura, PLB'04
- For $T \sim M_1 > 10^{12}\mathrm{GeV}$: $Y_{\Delta B} \sim -10^{-3} \times \eta \times [\epsilon_\tau + \epsilon_\mu + \epsilon_e]$
- With $CP^{\mu\tau}$: $\epsilon_e = 0,\ \epsilon_\mu = -\epsilon_\tau \implies \epsilon_e + \epsilon_\mu + \epsilon_\tau = 0$

  Purely flavored scenario

- Flavored leptogenesis works for intermediate scales

  h_τ interactions fast   Mohapatra, Nishi, JHEP'15

$$10^9\,\mathrm{GeV} \lesssim T \sim M_1 \lesssim 10^{12}\,\mathrm{GeV}$$

Increasing predictivity with texture-zeros

- Flavor symmetries increase predictivity
  - Nonabelian: relate entries and/or fix mixing angles
  - Abelian: vanishing entries = texture-zeroes
- Texture zeroes in the lepton sector

  Frampton,Glashow,Marfatia,PLB'02
  Frampton,Glashow,Yanagida,PLB'02
- Can be always enforced by abelian symmetries

  Grimus,Joshipura,Lavoura,Tanimoto,EPJC'04
- $\mathrm{CP}^{\mu\tau}$ corresponds to the first case
- With only $\mathrm{CP}^{\mu\tau}$ there is no other sharp prediction
- Can we enforce an additional texture-zero on top of $\mathrm{CP}^{\mu\tau}$?

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Increasing predictivity with texture-zeros

- CP$^{\mu\tau}$ enforces (flavor basis)

$$M_\nu = \begin{pmatrix} a & d & d^* \\ d & c & b \\ d^* & b & c^* \end{pmatrix}, \quad \text{with real } a, b \text{ and } \mathrm{Im}(d^2 c^*) \neq 0\,.$$

- 5 parameters $a, b, \mathrm{Re}\, c, \mathrm{Im}\, c, |d|$
  to describe $m_1, m_2, m_3, \theta_{12}, \theta_{13}$ — $\theta_{23}, \delta, \alpha, \beta$ fixed by CP$^{\mu\tau}$
- Can we enforce an additional texture-zero on top of this structure?
- Only $a = 0$ or $b = 0$ are phenomenologically viable
- With one less parameters we can predict the lightest neutrino mass!

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$\mathrm{CP}^{\mu\tau}$ and $\mathbb{Z}_8$

Nishi,Sánchez-Vega, JHEP 1701 (2017) 068

- Symmetries in (e,μ,τ) and (ν_e,ν_μ,ν_τ)

$$\mathbb{Z}_8 : T = \begin{pmatrix} -1 & & \\ & \omega_8 & \\ & & \omega_8^3 \end{pmatrix}, \quad \omega_8 = e^{i2\pi/8}$$

$$\mathrm{CP}^{\mu\tau} : \quad \nu_{\alpha L} \to X_{\alpha\beta}\nu^{cp}_{\beta L}, \quad X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}.$$

- They are consistent $T \to XT^*X^{-1} = T^5$

- Extends the simplest case of $L_\mu - L_\tau$ with $\mathrm{CP}^{\mu\tau}$

Mohapatra,Nishi,JHEP15

- Smallest $\mathbb{Z}_n$ that can be combined nontrivially with $\mathrm{CP}^{\mu\tau}$

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One texture-zero in M_ν

- Different entries have different $\mathbb{Z}_8$ charges

$$\bar{\nu}^c_{\alpha L}\nu_{\beta L} \sim \begin{pmatrix} 1 & \omega_8^5 & \omega_8^{-1} \\ \star & \omega_8^2 & -1 \\ \star & \star & \omega_8^{-2} \end{pmatrix}, \quad \omega_8 = e^{i2\pi/8}$$

- Couple with scalars of different charges $\eta_k \sim \omega_8^k$
- Additional $\mathbb{Z}_4^{B-L}$ symmetry: $L_\alpha \sim -i$ and $\eta_k \sim -1$

$$\frac{1}{2}\frac{c_{ee}}{\Lambda^2}\eta_0 L_e H L_e H + \frac{1}{2}\frac{c_{\mu\mu}}{\Lambda^2}\eta_2^* L_\mu H L_\mu H + \frac{1}{2}\frac{c_{\tau\tau}}{\Lambda^2}\eta_2 L_\tau H L_\tau H$$
$$+ \frac{c_{\mu\tau}}{\Lambda^2}\eta_4 L_\mu H L_\tau H + \frac{c_{e\mu}}{\Lambda^2}\eta_3 L_e H L_\mu H + \frac{c_{e\tau}}{\Lambda^2}\eta_1 L_e H L_\tau H$$

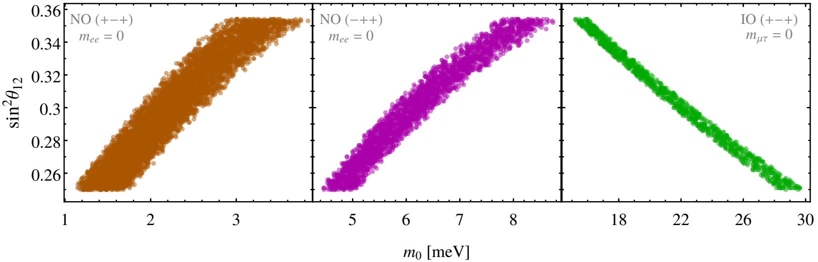
$c_{e\tau} = c^*_{e\mu}$, $c_{\tau\tau} = c^*_{\mu\mu}$ and real $c_{ee}, c_{\mu\tau}$

- Texture-zeros: $a = 0$ if η_0 absent $b = 0$ if η_4 absent

One texture-zero at low scale

Nishi,Sánchez-Vega, JHEP 1701 (2017) 068

Case	$(M_\nu)_{\alpha\beta}=0$	ordering	CP parities	m_0	$m_{\beta\beta}$	$\sum m_\nu$
I	(ee)	NO	$(-++)$	4.4 – 9.0	0	63 – 74
II	(ee)	NO	$(+-+)$	1.1 – 3.9	0	59 – 65
III	$(\mu\tau)$	NO	$(++-)$	151 – 185	142 – 178	460 – 561
IV	$(\mu\tau)$	IO	$(+-+)$	15 – 30	14.3 – 29.3	116 – 148



One texture-zero at high scale

- Type I seesaw: texture zero in M_R $\rightarrow$ texture zero in M_ν^{-1}

  diagonal M_D Lavoura,PLB'05

- M_R with $\mathrm{CP}^{\mu\tau}$ and one texture-zero in (ee) or $(\mu\tau)$

$$M_\nu^{-1} = \begin{pmatrix} a & d & d^* \\ d & c & b \\ d^* & b & c^* \end{pmatrix} \qquad M_D = m_D \begin{pmatrix} 1 & & \\ & \kappa & \\ & & \kappa \end{pmatrix}$$

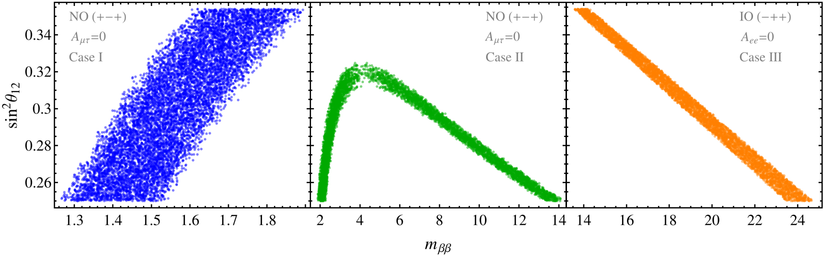
$$M_R = \begin{pmatrix} A & D & D^* \\ D & C & B \\ D^* & B & C^* \end{pmatrix} = -M_D M_\nu^{-1} M_D^{\mathrm{T}}$$

- Light neutrino sector completely fixed
- Heavy neutrino sector with only two free parameter: m_D, κ

One texture-zero at high scale: light neutrinos

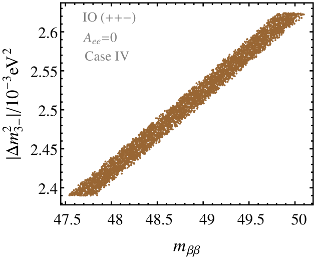
Nishi, Sánchez-Vega, Souza Silva, 1806.07412

Case	$(M_\nu^{-1})_{\alpha\beta}=0$	ordering	CP parities	m_0	$m_{\beta\beta}$	$\sum m_\nu$
I	$(\mu\tau)$	NO	$(-++)$	2.48 – 4.36	1.25 – 1.93	60.7 – 66.3
II	$(\mu\tau)$	NO	$(+-+)$	4.28 – 27.31	1.84 – 14.42	63.3 – 114.6
III	(ee)	IO	$(-++)$	1.86 – 4.27	13.48 – 24.77	99.7 – 107.1
IV	(ee)	IO	$(++-)$	0.943 – 1.27	47.49 – 50.14	98.7 – 103.7
V	$(\mu\tau)$	IO	$(++-)$	154 – 183	154 – 182	476 – 563



One texture-zero at high scale: light neutrinos

Nishi,Sánchez-Vega, Souza Silva, 1806.07412

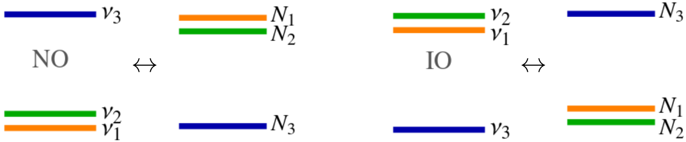


- $m_{\beta\beta}$ can be measured in KamLAND-Zen 800 phase

One texture-zero at high scale: heavy neutrinos

For $\kappa = 1$, $M_D \sim \mathbb{1}_3$

- The spectrum obeys $M_i = \dfrac{m_D^2}{m_i}$

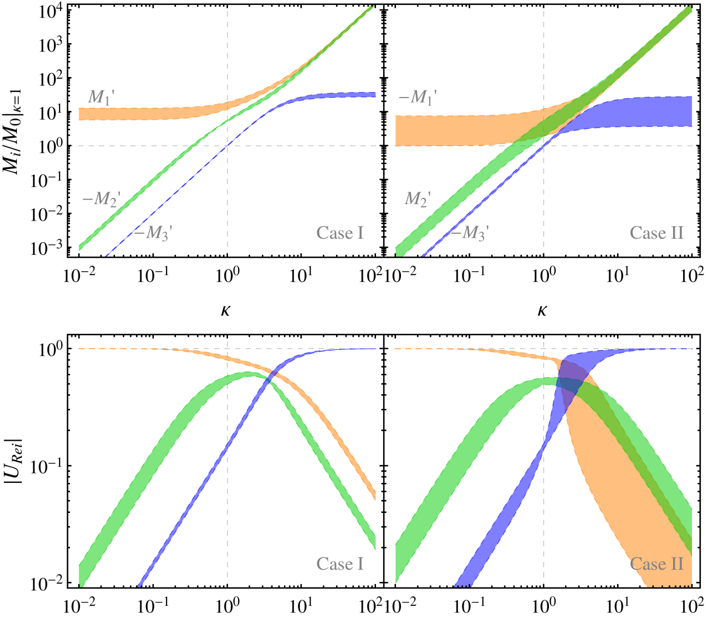


- $K_R = iK_\nu$ with $U_\nu^{(0)} = U_R^{(0)} = \begin{pmatrix} u_1 & u_2 & u_3 \\ w_1 & w_2 & w_3 \\ w_1^* & w_2^* & w_3^* \end{pmatrix}$

- $|U_{Re1}| \sim 0.83, \quad |U_{Re2}| \sim 0.54, \quad |U_{Re3}| \sim 0.15$

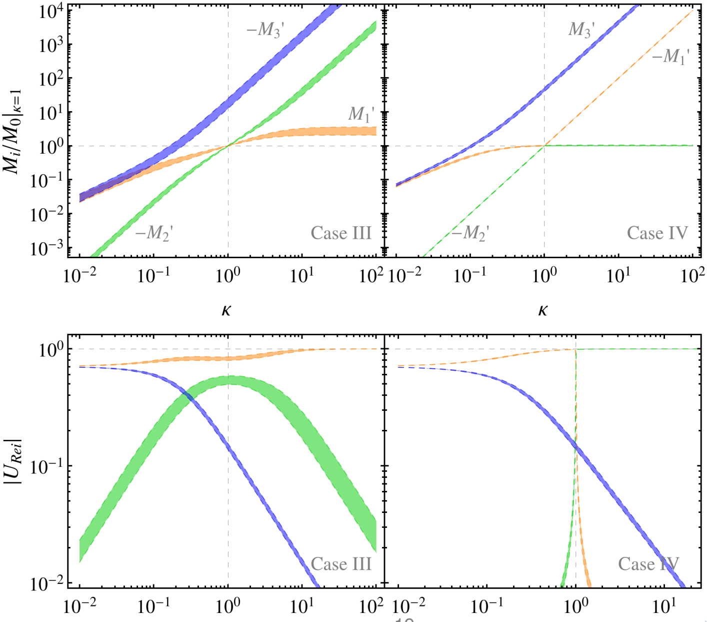
For $\kappa \neq 1$, the mass ratios and heavy mixing angles deviate

One texture-zero at high scale: heavy neutrinos



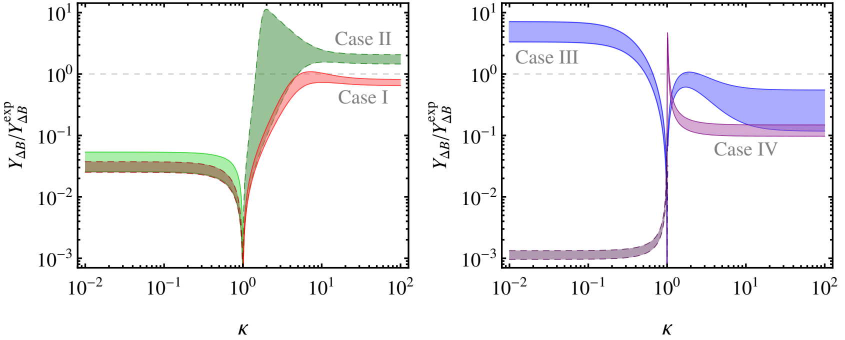
NO

One texture-zero at high scale: heavy neutrinos



IO

Leptogenesis



- $M_0 = 10^{12}\,\mathrm{GeV}$ and $\delta = -90^\circ$ (lighter-solid)
- Case III: degenerate $\mathcal{N}_1$-$\mathcal{N}_2$ for $\kappa \approx 1$

  but no resonant enhancement

$$\epsilon_\tau \sim \frac{1}{1 - x_2}$$

- Cancellation of states with opposite CP parity
- Caveat: hierarchical approximation (but $\epsilon_\tau^{(2)} \lesssim \epsilon_\tau^{(1)}$)

Leptogenesis

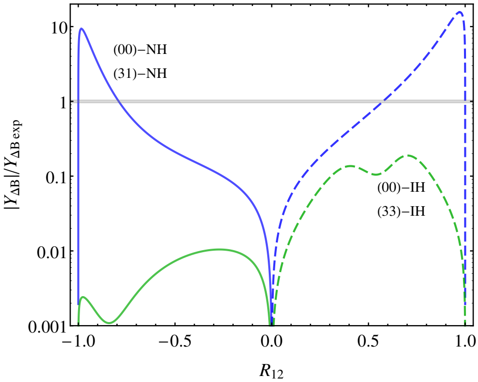
	$\delta = -90^\circ$		$\delta = +90^\circ$	
Case	κ	$M_0/10^{12}\,\mathrm{GeV}$	κ	$M_0/10^{12}\,\mathrm{GeV}$
I	5.2 – 12	0.92 – 1	$\times$	$\times$
II	$\times$	$\times$	1.5 – 100	0.09 – 1
III	0.01 – 0.66	0.14 – 1	$\times$	$\times$
	1.55 – 2.57	0.93 – 1	$\times$	$\times$
IV	1.004 – 1.06	0.21 – 1	$\times$	$\times$

- Narrow range: $10^{11}\,\mathrm{GeV} \lesssim T \sim M_0 \lesssim 10^{12}\,\mathrm{GeV}$
- Only cases I, III, IV for $\delta = -90^\circ$
- If η_f 10% lower, only IO cases III, IV

Conclusions

- $\mathrm{CP}^{\mu\tau}$ is a viable symmetry that predicts all CP phases and it is compatible with flavored leptogenesis.
- Maximal θ_{23} and δ_{CP} will be tested in the future
- We have shown by explicit construction highly predictive scenarios where the neutrino mass matrix (or its inverse) is symmetric by $\mathrm{CP}^{\mu\tau}$ and *additionally* contains one texture-zero in the (ee) or $(\mu\tau)$ entry.
- The possibility of $\mathrm{CP}^{\mu\tau}$ symmetric M_ν (M_ν^{-1}) *simultaneously* with a texture-zero is only allowed by combining in a non-trivial way a discrete abelian symmetry at least as large as $\mathbb{Z}_8$ and $\mathrm{CP}^{\mu\tau}$.
- Predicted for ν_i: lightest neutrino mass, $m_{\beta\beta}$, observable correlations.
- Predicted for $\mathcal{N}_i$: two free parameters, small regions for successful leptogenesis.

Leptogenesis and $\mu\tau$ reflection



Mohapatra,Nishi,JHEP15

$M_3 \to \infty$
$M_1 = 10^{12}\,\mathrm{GeV}$

- Leptogenesis is only possible for $10^9\,\mathrm{GeV} \lesssim M_1 \lesssim 10^{12}\,\mathrm{GeV}$
- For $M_1 \gtrsim 10^{12}\mathrm{GeV}$, we cannot distinguish any flavor and $Y_B \approx 0$
- For $M_1 \lesssim 10^9\mathrm{GeV}$, we can distinguish e, μ, τ and $Y_B \approx 0$