FLASY
11TH WORKSHOP
Flavor Symmetries and Consequences in Accelaratores and Cosmology
ROME 2025
June 30 - July 4
Aula Magna Architettura "Adalberto Libera", Università Roma Tre

CP violations of quarks and leptons in the setup with T^2/Z_3 orbifold compactification

— Texture zeros approach —

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July 1, 2025

FLASY2025 @ Rome

Collaborated with
T.T. Yanagida

Plan of my talk

1 Motivation

2 Model building of quarks/leptons with texture zeros

3 Two-zeros textures of quark mass matrices

3.1 Setup

3.2 Charged lepton mass matrices

3.3 Neutrino mass matrices

4 Summary

1 Motivation

QCD Lagrangian

$$\mathcal{L}_{QCD} = \bar{Q}(i\not{D} - M_Q)Q - \frac{1}{4}\mathrm{Tr}\,G^2 + \theta_{\mathrm{QCD}}\frac{g_3^2}{32\pi^2}\mathrm{Tr}\,G\tilde{G}$$

$$M_Q = \mathrm{Diag}\,(m_f\, e^{i\theta_f}) \qquad \arg\det M_Q = \sum \theta_f$$

Under the chiral transformation $q_f \to e^{i\gamma_5 \beta_f}\, q_f$

$$\mathcal{L}_{QCD} = \bar{Q}\,(i\not{D} - M_{\mathrm{real}})\,Q - \frac{1}{4}\,\mathrm{Tr}\,G^2 + \bar{\theta}\,\frac{g_3^2}{32\pi^2}\mathrm{Tr}\,G\bar{G}$$

$$\boxed{\bar{\theta} = \theta_{\mathrm{QCD}} + \sum \theta_f = \theta_{\mathrm{QCD}} + \arg\det\,[M_Q]}$$

CP is violated by O(1) CKM phase in quark sector.

The upper bound on the neutron EDM implies

the smallness of the QCD angle $\bar{\theta}$.

$$\boxed{|\bar{\theta}| \lesssim 10^{-10}}$$

This aspect of the SM is puzzling,
because CKM requires complex quark mass matrix M_Q .

Strong CP problem

This puzzle has been interpreted in two different ways:

Axion adjusting $\bar{\theta} = 0$ dynamically.

$U(1)_{PQ}$ Peccei and Quinn 1977

Special models in which

- $\theta_{QCD} = 0$ by imposing Parity (CP) symmetry.
- quark mass matrices M_Q have real determinant.
- The parity (or CP) is broken spontaneously.

Nelson-Barr models 1984

CP is violated only by the mixings of SM quarks with hypothetical extra heavy quarks

Babu and R. N. Mohapatra 1990 (left-right symmetric model)

Texture zeros with CP symmetry can produce Yukawa couplings such that the CKM phase is large and θ_{QCD} vanishes.

S.Antusch, M.Holthausen, M.A.Schmidt and M.Spinrath NPB, arXiv:1307.0710

$$M_d = \begin{pmatrix} 0 & b_d & 0 \\ b_d' & \mathrm{i}\, c_d & d_d \\ 0 & 0 & e_d \end{pmatrix} \quad \text{and} \quad M_u = \begin{pmatrix} a_u & b_u & 0 \\ 0 & c_u & d_u \\ 0 & d_u' & e_u \end{pmatrix}$$

Det (M_d M_u)=real

Framework : Non-Abelian discrete flavor symmetry

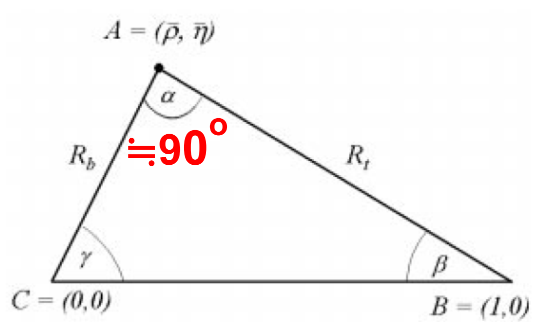
A_4 flavor symmetry

4 flavons

$$\langle \phi_1 \rangle \sim \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad \langle \phi_2 \rangle \sim \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \quad \langle \phi_3 \rangle \sim \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \quad \boxed{\langle \tilde{\phi}_2 \rangle \sim \mathrm{i} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}}$$

Spontaneous weak CP violation

One prediction



PDG 2024

$$\alpha = \left(84.1\,^{+4.5}_{-3.8}\right)^{\circ}$$

Texture zeros in modular flavor symmetry

F. Feruglio, A.Strumia and A.Titov, JHEP 07 (2023) [arXiv:2305.08908]

S.T. Petcov and M.Tanimoto, EPJC, arXiv 2404.00858

J.T. Penedo and S.T.Petcov, JHEP, arXiv 2404.08032

Det (M_d M_u)=real

$$M_Q = v_Q \begin{pmatrix} 0 & 0 & a_Q \\ 0 & b_Q & c_Q(2\mathrm{Im}\tau)^4 Y_1^{(8)} \\ d_Q & e_Q(2\mathrm{Im}\tau)^2 Y_1^{(4)} & f_Q(2\mathrm{Im}\tau)^6 (g_Q Y_{1\mathrm{A}}^{(12)} + Y_{1\mathrm{B}}^{(12)}) \end{pmatrix}_{RL}$$

Q=D, U

Modular forms $Y^{(k)}_i$ are written in terms of modulus τ

VEV of modulus τ leads to the spontaneous weak CP violation

Require assignments of relevant weight k for quarks

Texture zeros approach

Two generations of quarks

- In the basis in which the up-type quark mass matrix is diagonal,

$$m_{\text{down}} = \begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

$$\xrightarrow{M \gg m} \begin{pmatrix} m^2/M & 0 \\ 0 & M \end{pmatrix} = \begin{pmatrix} m_d & 0 \\ 0 & m_s \end{pmatrix}$$

The Cabibbo angle is successfully predicted to be

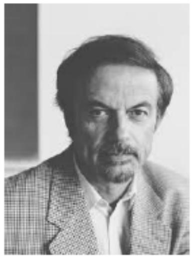
$$\sin\theta_c \sim \tan\theta_c = m/M = \sqrt{m_d/m_s}$$

S. Weinberg (1977)

H.Fritzsch and Z.z.Xing, Mass and flavor mixing schemes of quarks and leptons
Prog. Part. Nucl. Phys. 45 (2000)
Four zero texture of Hermitian quark mass matrices and current experimental tests
Phys. Lett. B 555(2003)

Three generations of quarks

- Fritzsch extended this approach to the three family case (1978)



$$m_{u,d}^{(\text{Fritzsch})} = \begin{pmatrix} 0 & a & 0 \\ a^* & 0 & b \\ 0 & b^* & c \end{pmatrix}$$

leading to various relations between masses and mixing angles

See for systematic approach with four or five zeros for symmetric or hermitian quark mass matrices by Ramond-Roberts-Ross (1993))

These textures are not viable today under the precise experimental data

"Occam's Razor" approach for mass matrices

K.Harigaya, M.Ibe and T.T.Yanagida, Phys. Rev. D 86 (2012) 013002, arXiv:1205.2198

For quark masses and CKM, Tanimoto and Yanagida arXiv:1601.04459

Three zeros of down-type quark mass matrix

Diagonal basis of up-type quarks Mu

10 parameters

$$M_d^{(1)} = \begin{pmatrix} 0 & a & 0 \\ a' & b\, e^{-i\phi} & c \\ 0 & c' & d \end{pmatrix}_{LR}, \quad M_d^{(2)} = \begin{pmatrix} a' & a & 0 \\ 0 & b\, e^{-i\phi} & c \\ 0 & c' & d \end{pmatrix}_{LR}, \quad M_d^{(3)} = \begin{pmatrix} 0 & a & 0 \\ 0 & b\, e^{-i\phi} & c \\ a' & c' & d \end{pmatrix}_{LR}$$

$$M_d^{(4)} = \begin{pmatrix} 0 & a & c' \\ a' & b\, e^{-i\phi} & c \\ 0 & 0 & d \end{pmatrix}_{LR}, \quad M_d^{(5)} = \begin{pmatrix} a' & a & c' \\ 0 & b\, e^{-i\phi} & c \\ 0 & 0 & d \end{pmatrix}_{LR}, \quad M_d^{(6)} = \begin{pmatrix} 0 & a & c' \\ 0 & b\, e^{-i\phi} & c \\ a' & 0 & d \end{pmatrix}_{LR}$$

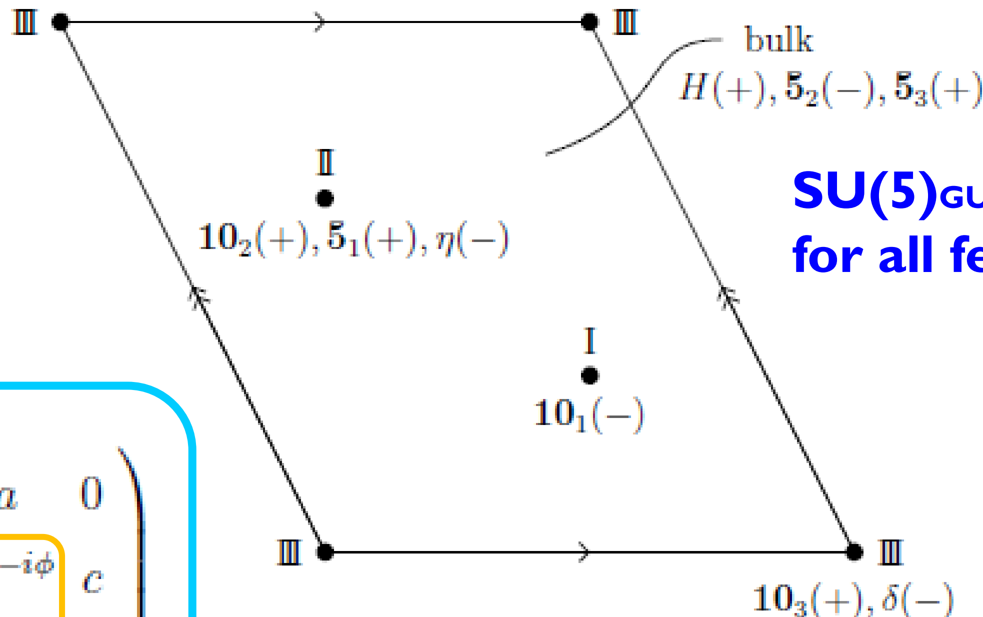
Det (M_d M_u)=real

There are other 7 textures

2 Model building of quarks/leptons with texture zeros

Q.Liang, R.Okabe and T.T.Yanagida, Phys. Lett. B859(2024)139123, arXiv:2408.12146

Orbifold compactification $\mathrm{T}^2/\mathbb{Z}_3$ three fixed points



SU(5)GUT representation for all fermions

$$M_d = \begin{pmatrix} 0 & a & 0 \\ a' & \boxed{be^{-i\phi}} & c \\ 0 & c' & d \end{pmatrix}$$

H is 5

	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_3$	$\bar{\mathbf{5}}_1$	$\bar{\mathbf{5}}_2$	$\bar{\mathbf{5}}_3$	H	η	δ
$\mathbb{Z}_2$	$-$	$+$	$+$	$+$	$-$	$+$	$+$	$-$	$-$

Anomaly free Z_2

Towards lepton sector

Tanimoto and Yanagida arXiv: 2410.01224

SU(5)

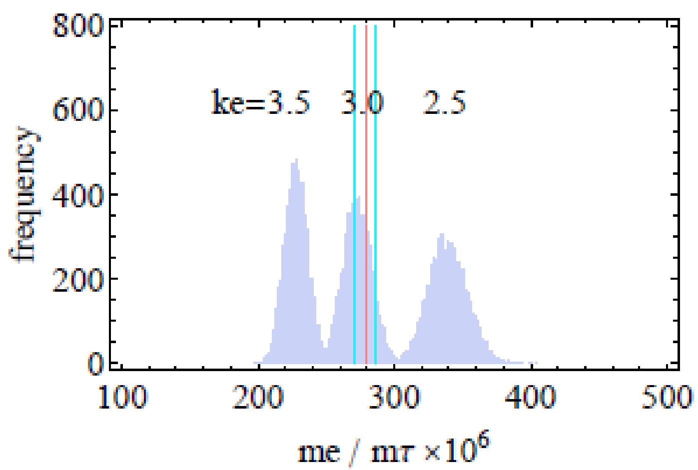
	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_3$	$\mathbf{5}^*_1$	$\mathbf{5}^*_2$	$\mathbf{5}^*_3$	N_1	N_2	N_3	H	H_{II}	η	δ
$\mathbb{Z}_2$	-	+	+	+	-	+	-	+	+	+	-	-	-
location	I	II	III	II	bulk	bulk	I	II	III	bulk	II	II	III

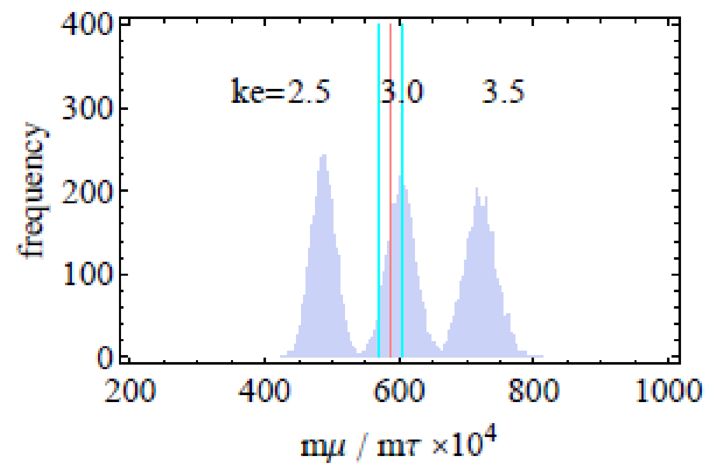
$$M_e = \begin{pmatrix} 0 & a' & 0 \\ a & k_e\, b\, e^{-i\phi} & c' \\ 0 & c & d \end{pmatrix}$$

Put k_e=3

Quark masses and CKM →

a [MeV]	a' [MeV]	b [MeV]	c [MeV]	c' [GeV]	d [GeV]	ϕ [$\circ$]
15 - 17.5	10 - 15	92 - 104	78 - 95	1.65 - 2.0	2.0 - 2.3	37 - 48





Neutrino sector

$$M_D = \begin{pmatrix} 0 & a'_\nu & 0 \\ a_\nu & b_\nu\, e^{i\phi} & c'_\nu \\ 0 & c_\nu & d_\nu \end{pmatrix} \Rightarrow \tilde{M}_D = \begin{pmatrix} 0 & A' & 0 \\ A & B\, e^{i\phi} & C' \\ 0 & C & D \end{pmatrix}$$

M_R is diagonal (M_1, M_2, M_3)

$$M_\nu = M_D\,(1/M_N)\,M_D^{\,t}$$

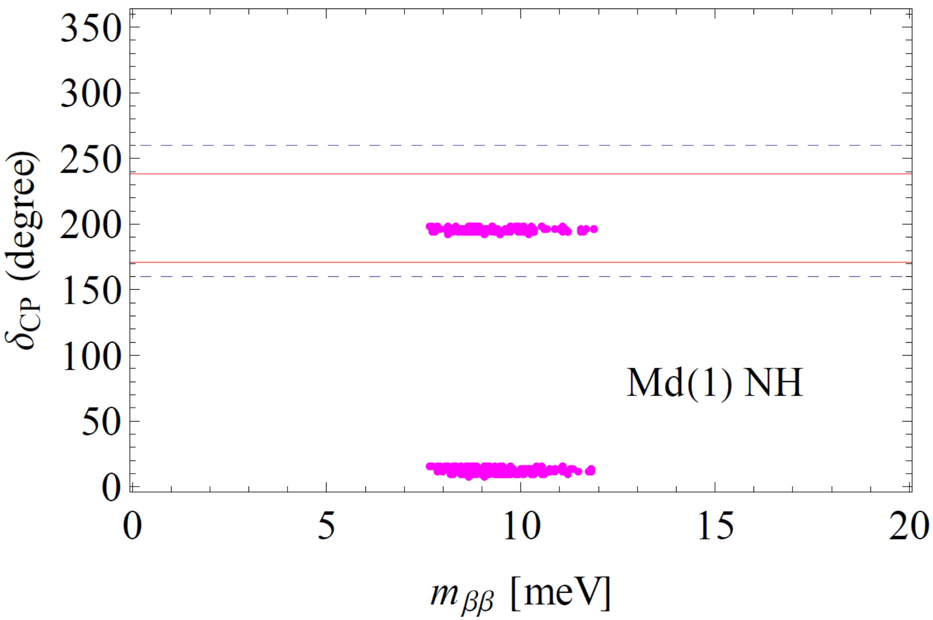
we absorb the $1/\sqrt{M_i}$ in the Dirac mass matrix M_D

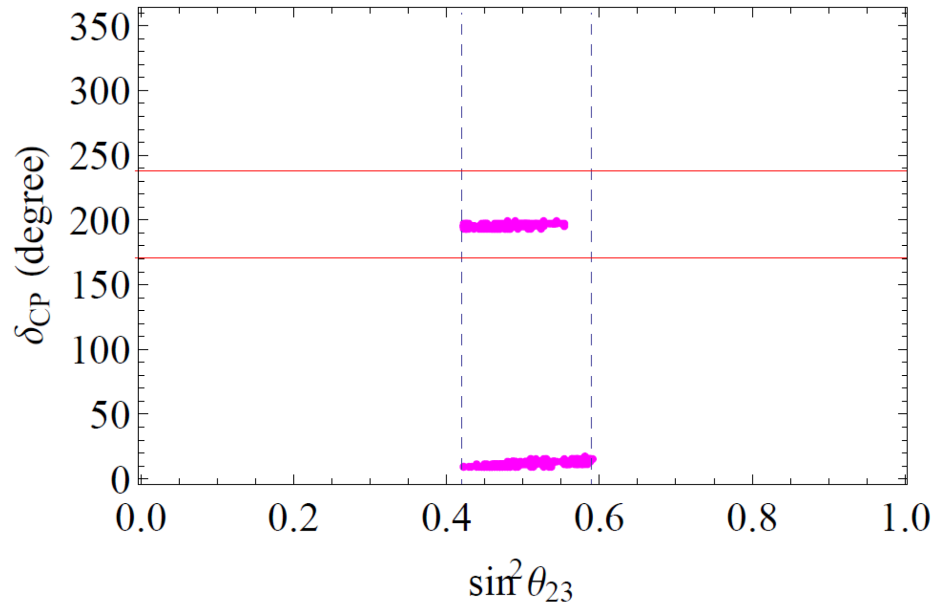
$$M_\nu = \begin{pmatrix} A'^2 & A'B\, e^{i\phi} & A'C \\ A'B\, e^{i\phi} & A^2 + C'^2 + B^2\, e^{2i\phi} & BC\, e^{i\phi} + C'D \\ A'C & BC\, e^{i\phi} + C'D & D^2 + C^2 \end{pmatrix}$$

$\lvert A/D\rvert$	$\lvert A'/D\rvert$	$\lvert B/D\rvert$	$\lvert C/D\rvert$	$\lvert C'/D\rvert$
$0.46-0.49$	$0.44-0.48$	$0.09-0.16$	$0.31-0.35$	$0-0.11$

6 parameters $\Leftrightarrow$ 5 observables

Predictions





$$\delta_{CP} = (\,212^{+26}_{-41}\,)^\circ \qquad \sum_{i=1}^{3} m_i < 120 \text{ meV}$$

Consider Sign of Baryon-number Asymmetry via Leptogenesis

$$\epsilon_i = \frac{\Gamma(N_i \to LH) - \Gamma(N_i \to \bar{L}\bar{H})}{\Gamma(N_i \to LH) + \Gamma(N_i \to \bar{L}\bar{H})} \simeq -\frac{1}{8\pi} \sum_{j \neq 1}^{3} \frac{\mathrm{Im}[(Y_D^\dagger Y_D)_{ij}^2]}{(Y_D^\dagger Y_D)_{11}} F^{V+S}\left(\frac{M_j^2}{M_i^2}\right)$$

$$F^{V+S}(x) = \sqrt{x}\left[(x+1)\ln\left(\frac{x+1}{x}\right) - 1 + \frac{1}{x-1}\right] \xrightarrow[x\to\infty]{} \frac{3}{2}\frac{1}{\sqrt{x}}$$

$$\boxed{Y_B \simeq -\frac{28}{79}\kappa\frac{\epsilon_i}{g^*}}$$

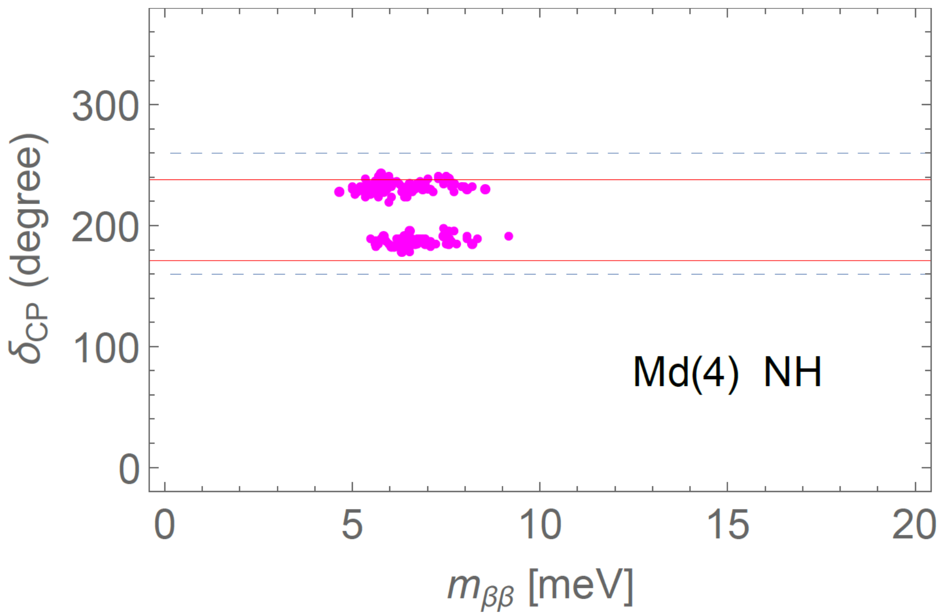
$$\mathrm{Im}[(Y_D^\dagger Y_D)_{12}^2] = \frac{1}{v^4} a_\nu^2 b_\nu^2 \sin 2\phi \; > 0 \qquad \boxed{\phi = 37^\circ - 48^\circ} \longleftarrow \text{CKM}$$

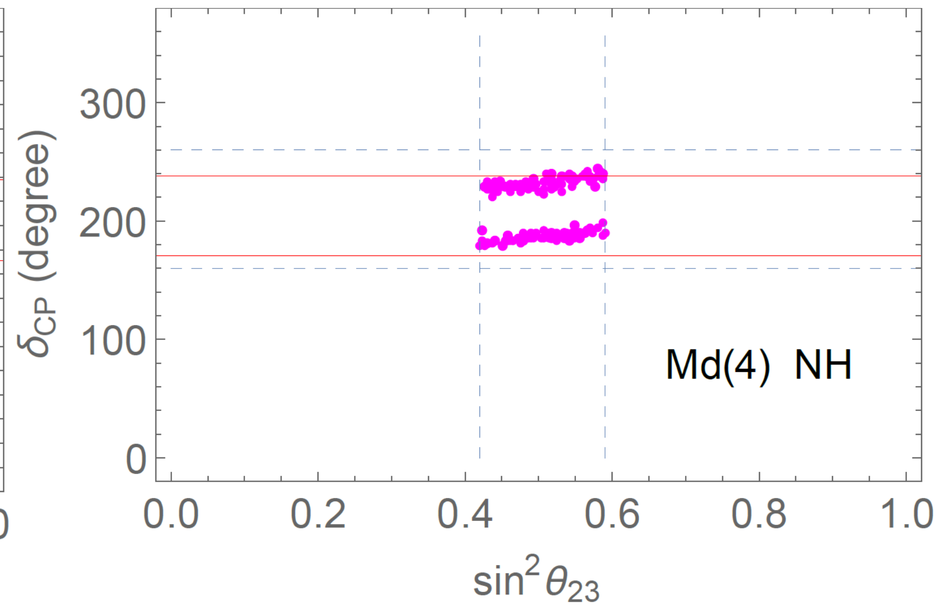
$Y_B > 0$ (if $M_1 < M_2$)

CKM phase is related successfully to the sign of BAU !

Another texture

$$M_d^{(4)} = \begin{pmatrix} 0 & a & c' \\ a' & b\,e^{-i\phi} & c \\ 0 & 0 & d \end{pmatrix} \quad M_e = \begin{pmatrix} 0 & a' & 0 \\ a & k_e\,b\,e^{-i\phi} & 0 \\ c' & c & d \end{pmatrix} \quad \tilde{M}_D = \begin{pmatrix} 0 & A' & 0 \\ A & B\,e^{i\phi} & 0 \\ C' & C & D \end{pmatrix}$$





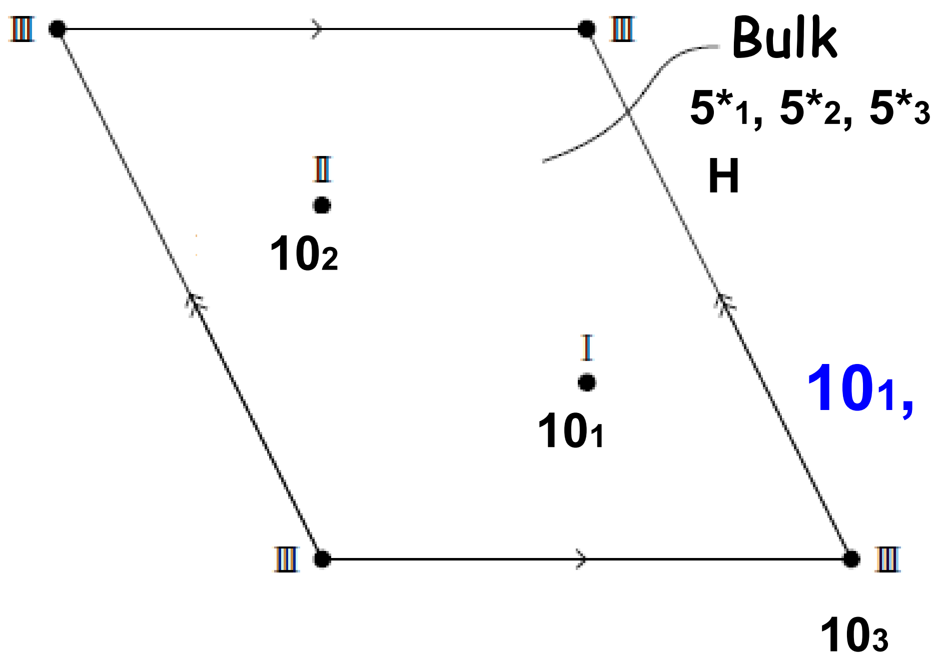
3 Two-zeros textures of quark mass matrices

Even two zeros textures can provide a solution to the strong CP problem.

M.Tanimoto and T.T.Yanagida, arXiv:2504.06599

3.1 Setup

$T^2/\mathbb{Z}_3$ three fixed points



5^*_1, 5^*_2, 5^*_3 in bulk

H in bulk

10_1, 10_2, 10_3 on each fixed point

Systematic construction of texture zeros

Anomaly free Z_2

$$10_{1,2,3} = (-,+,+);(+,-,+);(+,+,-)$$

$$5^*_{1,2,3} = (-,+,+);(+,-,+);(+,+,-)$$

9 possiblity

Phenomenologically, only $10_{1,2,3} = (-,+,+)$ is available.

Finally, we have three possiblity

$$A_1; 10_{1,2,3} = (-,+,+), \quad 5^*_{1,2,3} = (+,-,+);$$
$$A_2; 10_{1,2,3} = (-,+,+), \quad 5^*_{1,2,3} = (+,+,-);$$
$$A_3; 10_{1,2,3} = (-,+,+), \quad 5^*_{1,2,3} = (-,+,+).$$

Let us consider Case A_1

$$M_d^{0\,(A_1)} = \begin{pmatrix} 0 & a & 0 \\ a' & 0 & c \\ a'' & 0 & d \end{pmatrix}$$

Introduce singlet scalars η and η' to get viable textures

Z_2 charges are odd (-) for both.

$\langle\eta\rangle$ and $\langle\eta'\rangle$ have complex VEV, and then
break both CP and Z_2 flavor symmetry.

η and η' localize on fixed point II and III, respectively, to get a viable texture.

$$M_d^{(A_1)} = \begin{pmatrix} 0 & a & 0 \\ a' & \kappa < \eta > & c \\ a'' & \kappa' < \eta' > & d \end{pmatrix}$$

η and η' terms are induced by heavy Higgs H_I and H_{II}

$$\kappa = (f/M_I^2) < H^\dagger > \text{ and } \kappa' = (f'/M_{II}^2) < H^\dagger >$$

Finally, we parametrize as

$$M_d^{(A_1)} = \begin{pmatrix} 0 & a & 0 \\ a' & be^{i\phi} & c \\ a'' & c'e^{i\phi'} & d \end{pmatrix}$$

Case A_1	10_1	10_2	10_3	5_1^*	5_2^*	5_3^*	N_1	N_2	N_3	H	η	η'
Z_2	-	+	+	+	-	+	-	+	+	+	-	-
location	I	II	III	bulk	bulk	bulk	I	II	III	bulk	II	III

$$M_d^{(A_1)} = \begin{pmatrix} 0 & a & 0 \\ a' & be^{i\phi} & c \\ a'' & c'e^{i\phi'} & d \end{pmatrix}_{LR}$$

$$M_d^{(A_2)} = \begin{pmatrix} 0 & 0 & a \\ a' & c & be^{i\phi} \\ a'' & d & c'e^{i\phi'} \end{pmatrix}_{LR}$$

$$M_d^{(A_3)} = \begin{pmatrix} a & 0 & 0 \\ be^{i\phi} & a' & c \\ c'e^{i\phi'} & a'' & d \end{pmatrix}_{LR}$$

give same CKM

LOY

$$M_d = \begin{pmatrix} 0 & a & 0 \\ a' & be^{-i\phi} & c \\ 0 & c' & d \end{pmatrix}$$

$$J_{CP} = a^2\, b\, c'\, (\, c\, d + a'\, a''\,)\, \sin(\phi' - \phi) \times \frac{1}{(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)}$$

$a/d \times 10^2$	$a'/d \times 10^2$	$\lvert a''/d \rvert \times 10^2$	$b/d \times 10^2$	$c/d \times 10^2$	c'/d	$\phi' - \phi$ [°]
$0.70 \to 0.79$	$0.40 \to 0.99$	$0 \to 10$	$4.3 \to 4.9$	$3.6 \to 3.9$	$0.79 \to 1.0$	$37 \to 48$

3.2 Charged lepton mass matrices

Charged lepton mass matrix is given by transposed matrix of M_d.

However, it cannot reproduce the observed charged lepton masses.

Suppose: Heavy Higgs H_I and H_{II} are mixture of 5* and 45 of SU(5).

Case A1

$$M_e^{(A_1)} = \begin{pmatrix} 0 & a' & a'' \\ a & k_e b e^{i\phi} & k'_e c' e^{i\phi'} \\ 0 & c & d \end{pmatrix}$$

Case A2

$$M_e^{(A_2)} = \begin{pmatrix} 0 & a' & a'' \\ 0 & c & d \\ a & k_e b e^{i\phi} & k'_e c' e^{i\phi'} \end{pmatrix}$$

Case A3

$$M_e^{(A_3)} = \begin{pmatrix} a & k_e b e^{i\phi} & k'_e c' e^{i\phi'} \\ 0 & a' & a'' \\ 0 & c & d \end{pmatrix}$$

Simple choice to get observed masses : k_e=3, k_e'=1

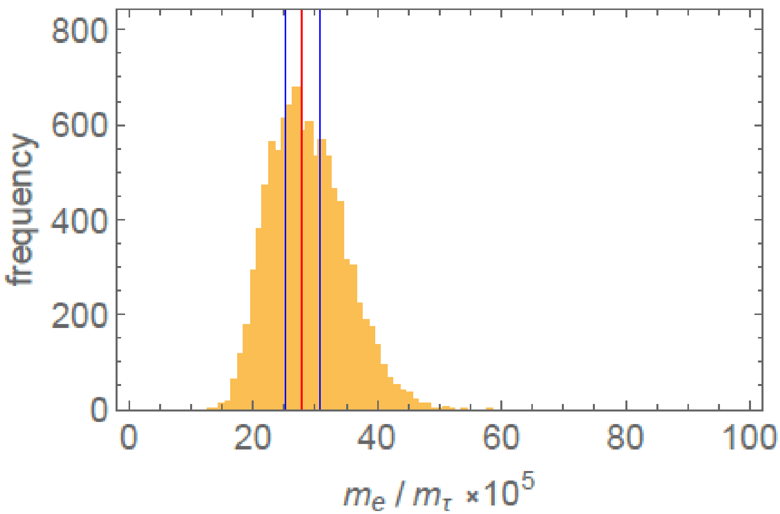


Figure 1: The predicted distribution of m_e/m_τ by taking $k_e = 3$ and $k'_e = 1$ in the case of $\boldsymbol{A_1}$. The vertical red line denotes the central value of the observed one, and blue ones denote ±10% error-bars for eye guide.

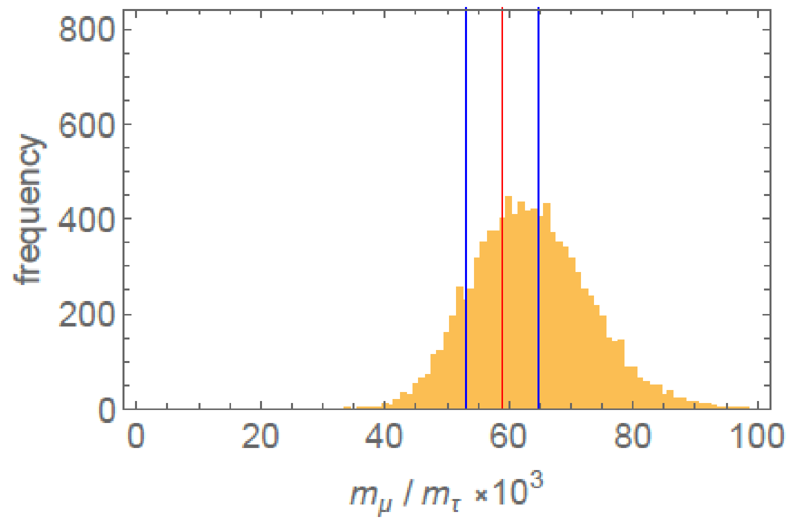


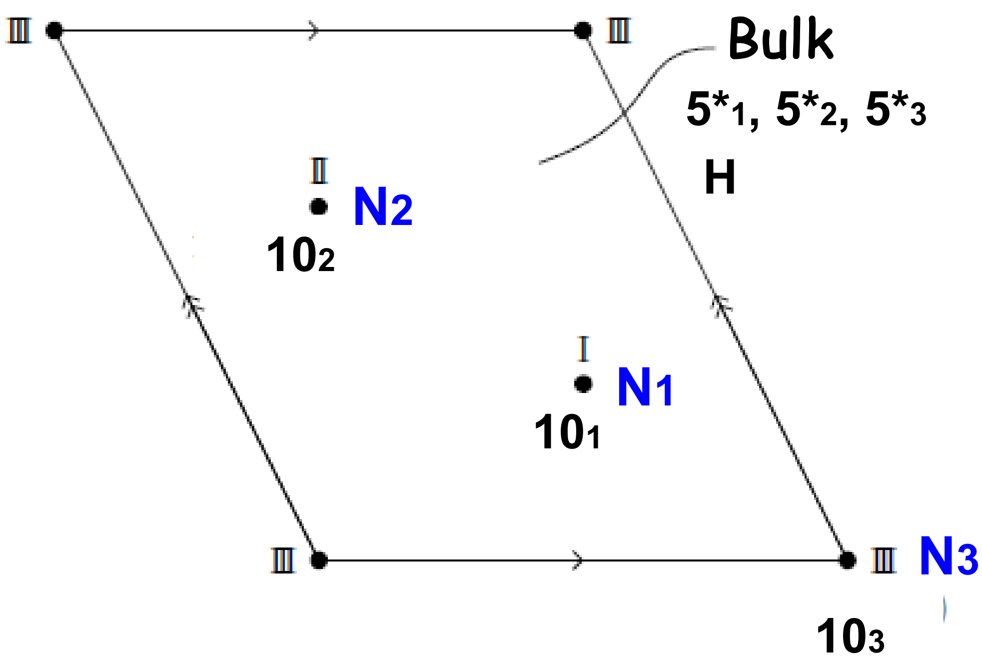
Figure 2: The predicted distribution of m_μ/m_τ by taking $k_e = 3$ and $k'_e = 1$ in the case of $\boldsymbol{A_1}$. The vertical red line denotes the central value of the observed one, and blue ones denote ±10% error-bars for eye guide.

3.3 Neutrino mass matrices

Let us introduce right-handed neutrinos:

N_1 (-), N_2 (+), N_3 (-) on each fixed point I, II, III

Same as 10_i



M_N is diagonal

Dirac neutrino mass matrix M_D

we absorb the $1/\sqrt{M_i}$ in the Dirac mass matrix M_D

$$M\nu = M_D(1/M_N)M_D{}^t$$

Case A_1

$$M_D'^{(A_1)} = \begin{pmatrix} 0 & A' & A'' \\ A & B\,e^{-i\phi} & C'\,e^{-i\phi'} \\ 0 & C & D \end{pmatrix}$$

Case A_2

$$M_D'^{(A_2)} = \begin{pmatrix} 0 & A' & A'' \\ 0 & C & D \\ A & B\,e^{-i\phi} & C'\,e^{-i\phi'} \end{pmatrix}$$

Case A_3

$$M_D'^{(A_3)} = \begin{pmatrix} A & B\,e^{-i\phi} & C'\,e^{-i\phi'} \\ 0 & A' & A'' \\ 0 & C & D \end{pmatrix}$$

Let us consider Minimal model of neutrinos

Two right-handed neutrinos

Two heavy Majorana neutrinos are enough to explain
the observed baryon asymmetry in the present universe

NH $M_1 \to \infty$ IH $M_3 \to \infty$

$$M_D'^{(A_1)} = \begin{pmatrix} 0 & A' & A'' \\ A & B\,e^{-i\phi} & C'\,e^{-i\phi'} \\ 0 & C & D \end{pmatrix} \qquad M_D'^{(A_1)} = \begin{pmatrix} 0 & A' & A'' \\ A & B\,e^{-i\phi} & C'\,e^{-i\phi} \\ 0 & C & D \end{pmatrix}$$

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Sign of Baryon-number Asymmetry via Leptogenesis

$$\epsilon_i = \frac{\Gamma(N_i \to LH) - \Gamma(N_i \to \bar{L}\bar{H})}{\Gamma(N_i \to LH) + \Gamma(N_i \to \bar{L}\bar{H})} \simeq -\frac{1}{8\pi} \sum_{j\neq 1}^{3} \frac{\mathrm{Im}[(Y_D^\dagger Y_D)_{ij}^2]}{(Y_D^\dagger Y_D)_{11}} F^{V+S}\left(\frac{M_j^2}{M_i^2}\right)$$

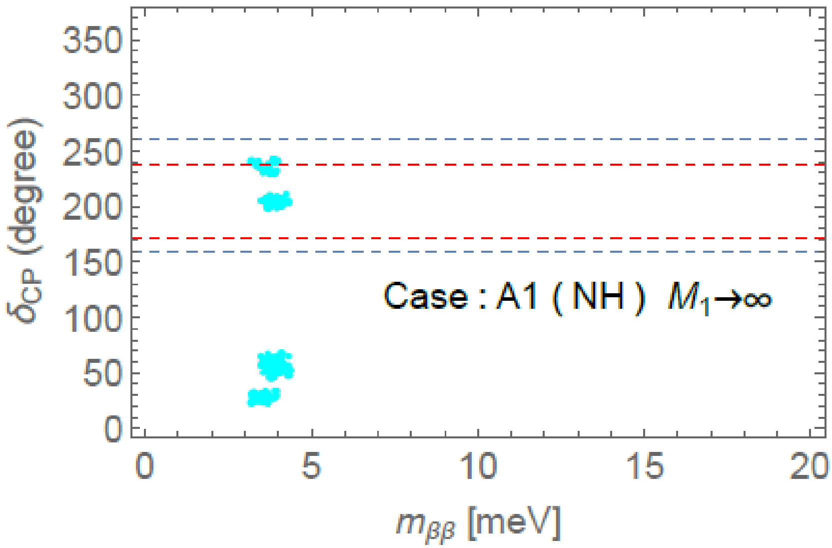
$$F^{V+S}(x) = \sqrt{x}\left[(x+1)\ln\left(\frac{x+1}{x}\right) - 1 + \frac{1}{x-1}\right] \xrightarrow[x\to\infty]{} \frac{3}{2}\frac{1}{\sqrt{x}}$$

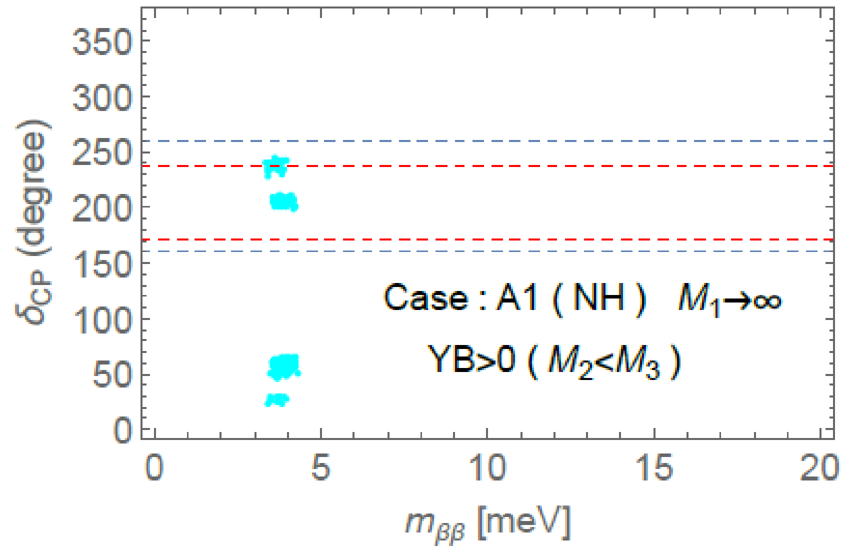
$$\boxed{Y_B \simeq -\frac{28}{79}\,\kappa\,\frac{\epsilon_i}{g^*}}$$

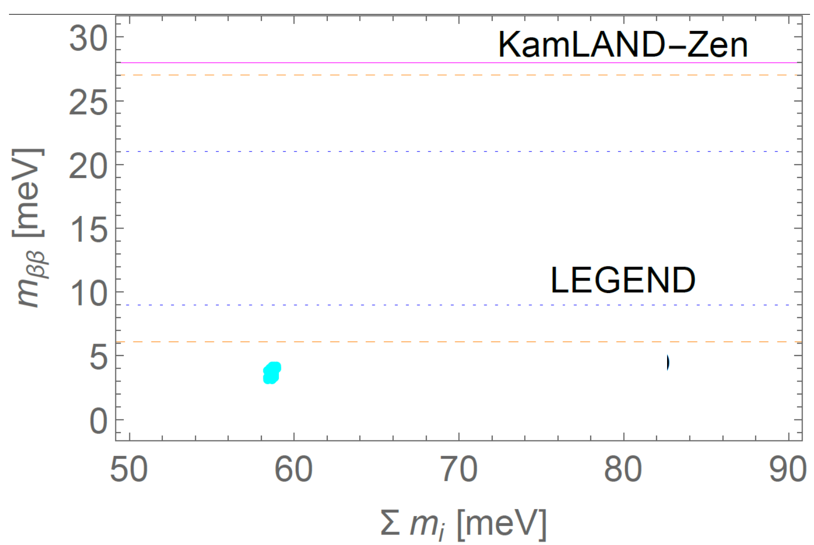
$Y_B > 0$

$\Phi' - \Phi = 37^\circ - 48^\circ$ ← CKM

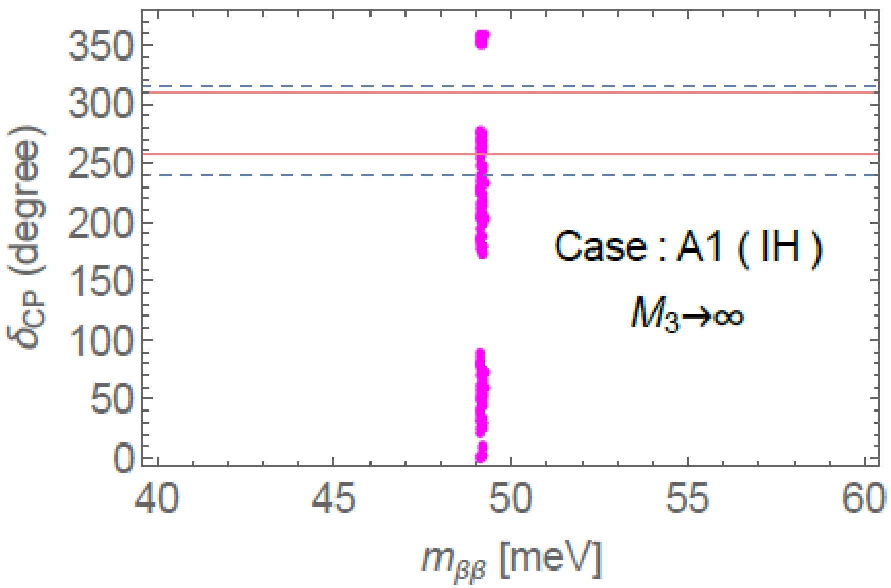
Case of NH $M_1 \to \infty$

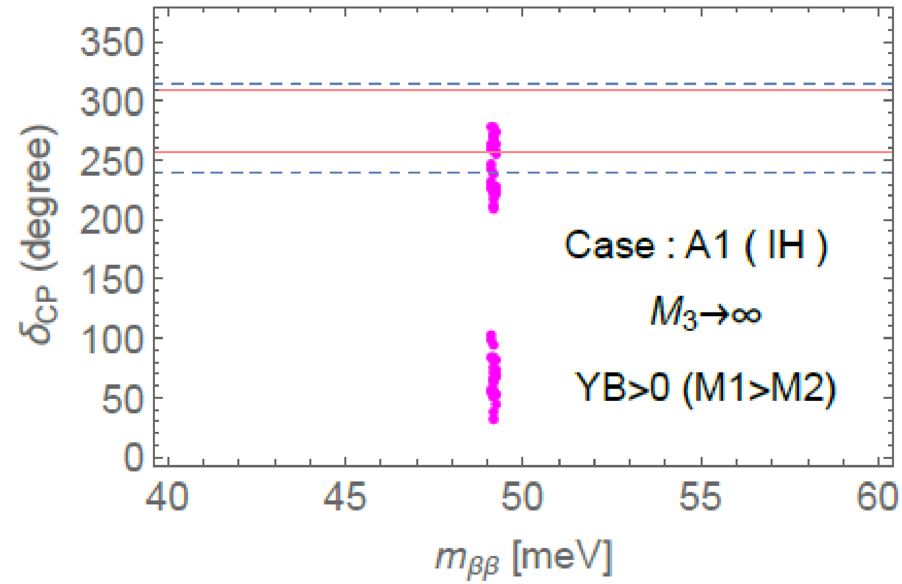


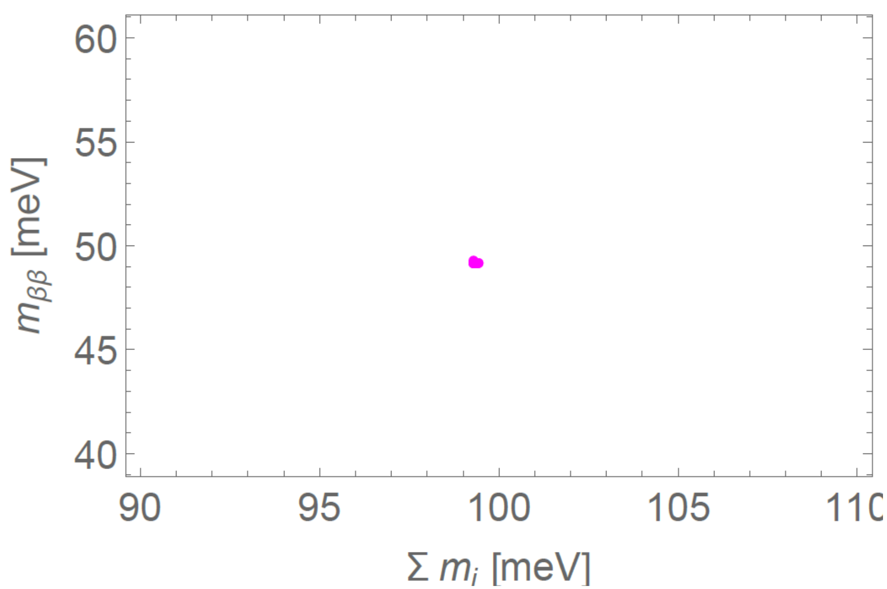




Case of IH $M_3 \to \infty$







4 Summary

Texture zeros can apply to the axion-less solution to the strong CP problem.

Vanishing arg [det M_d det M_u]

Such texture zeros are systematically obtained in

orbifold compactification $T^2/\mathbb{Z}_3$(three fixed points)

We discuss texture zeros of quarks and extend them to the lepton sector.
Common origin for CP violations of quark / lepton and BAU.

- Cases of three zeros give clear predictions for CP violation of leptons.
- Cases of two zeros also give clear predictions in 2 right-handed neutrinos

$m_{\beta\beta} \simeq 4\mathrm{meV} \quad \delta_{CP} \simeq 200^\circ \text{ or } \ 250^\circ$ (NH)

Another approach to texture zeros " non-invertible symmetry "

Japanese group

Back up slide

NuFIT 6.0

observable	best fit $\pm 1\,\sigma$ for NH	$2\ \sigma$ range for NH
$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.28 \to 0.33$
$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.42 \to 0.59$
$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.021 \to 0.023$
Δm^2_{21}	$7.49^{+0.19}_{-0.19} \times 10^{-5}\mathrm{eV}^2$	$(7.11 \to 7.87) \times 10^{-5}\,\mathrm{eV}^2$
Δm^2_{31}	$2.513^{+0.021}_{-0.019} \times 10^{-3}\mathrm{eV}^2$	$(2.47 \to 2.56) \times 10^{-3}\,\mathrm{eV}^2$

observable	best fit $\pm 1\,\sigma$ for IH	$2\ \sigma$ range for IH
$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.28 \to 0.33$
$\sin^2\theta_{23}$	$0.562^{+0.012}_{-0.015}$	$0.45 \to 0.59$
$\sin^2\theta_{13}$	$0.02224^{+0.00056}_{-0.00057}$	$0.021 \to 0.023$
Δm^2_{21}	$7.49^{+0.19}_{-0.19} \times 10^{-5}\mathrm{eV}^2$	$(7.11 \to 7.87) \times 10^{-5}\,\mathrm{eV}^2$
Δm^2_{31}	$-2.510^{+0.024}_{-0.025} \times 10^{-3}\mathrm{eV}^2$	$-(2.46 \to 2.56) \times 10^{-3}\,\mathrm{eV}^2$

$$\delta_{CP} = (\,212^{+26}_{-41}\,)^\circ \quad \text{for} \quad \text{NH} \quad \text{and} \quad (\,285^{+25}_{-28}\,)^\circ \quad \text{for} \quad \text{IH}$$

$$\boxed{\sum_{i=1}^{3} m_i < 120\ \text{meV}}$$

Cosmological bound

A simple example with vanishing strong CP

$$\boxed{\sum_{i=1}^{3}(2k_{Q_i}+k_{u_{Ri}}+k_{d_{Ri}})=0}$$

F. Feruglio, A.Strumia and A.Titov, JHEP 07 (2023) [arXiv:2305.08908].

N=1

Trivial singlet

	$(d,u)_L,(s,c)_L,(b,t)_L$	$(d^c,s^c,b^c),\ (u^c,c^c,t^c)$	H_U	H_D
$SU(2)$	2	1	2	2
N=1	$(1,\,1\,,1)$	$(1,\,1\,,1),\ (1,\,1\,,1)$	1	1
k	$(-6,-2,6)$	$(-6,2,6)$	0	0

$$w_D=\left[a_D d^c b+b_D s^c s+c_D s^c b Y_1^{(8)}+d_D b^c d+e_D b^c s Y_1^{(4)}+f_D b^c b\,\boxed{\left(g_D Y_{1A}^{(12)}+Y_{1B}^{(12)}\right)}\right]H_D\,,$$

$$w_U=\left[a_U u^c t+b_U c^c c+c_U c^c t Y_1^{(8)}+d_U t^c u+e_U t^c c Y_1^{(4)}+f_U t^c t\,\boxed{\left(g_U Y_{1A}^{(12)}+Y_{1B}^{(12)}\right)}\right]H_U\,,$$

$$M_D=v_D\begin{pmatrix}0&0&a_D\\0&b_D&c_D Y_1^{(8)}\\d_D&e_D Y_1^{(4)}&f_D(g_D Y_{1A}^{(12)}+Y_{1B}^{(12)})\end{pmatrix}_{RL}\qquad M_U=v_U\begin{pmatrix}0&0&a_U\\0&b_U&c_U Y_1^{(8)}\\d_U&e_U Y_1^{(4)}&f_U(g_U Y_{1A}^{(12)}+Y_{1B}^{(12)})\end{pmatrix}_{RL}$$

$$\det\left[M_D\right]=-a_D b_D d_D\,,\qquad\qquad \det\left[M_U\right]=-a_U b_U d_U\,.$$

Texture zeros approach

Three generations of quarks

The Fritzsch texture belongs to the more generic
Nearest-neighbor-interaction (NNI) form of quark mass matrices :

G.C.Branco, L.Lavoura, F.Mota (89),

$$m_{u,d}^{(\mathrm{NNI})} = \begin{pmatrix} 0 & a & 0 \\ b & 0 & c \\ 0 & d & e \end{pmatrix}$$

consistent with observed CKM matrices and quark masses

(also for leptons)

(obtained by choosing a weak-basis transformation
from general 3×3 matrices of Yukawa matrices)

Q : Origin of these textures ?

A : They cannot be derived by the conventional symmetry

Parameters of IH predictions

$\lvert A/A'\rvert$	$\lvert B/A'\rvert$	$\lvert C/A'\rvert$	$\phi' - \phi$	ϕ'
$1.006 - 1.010$	$0.0071 - 0.0087$	$0.096 - 0.109$	$(37 - 48)^\circ$	$(90 - 180)^\circ \oplus (270 - 360)^\circ$

Table 1: The allowed regions of parameters in M_ν (IH) in the case of $M_3 \to \infty$.

$Y_B>0$

$\lvert A/A'\rvert$	$\lvert B/A'\rvert$	$\lvert C/A'\rvert$	$\phi' - \phi$	ϕ'
$1.006 - 1.010$	$0.0071 - 0.0087$	$0.096 - 0.109$	$(37 - 48)^\circ$	$(90 - 135)^\circ \oplus (270 - 315)^\circ$

Table 2: The allowed regions of parameters in M_ν (IH) in the case of $M_3 \to \infty$ with $Y_B > 0$ for $M_1 > M_2$.

Case of finite M_3

As far as $|A''/A'|<0.02$, $|C'/A'|<0.02$, $|D/A'|<0.02$, IH result is reproduced.

Our predictions

3 Right-handed neutrinos

NH : $m_{\beta\beta} \simeq 4\text{meV and } (8 \to 10)\text{meV}$

δ_{CP} : very broad region

2 Right-handed neutrinos (minimal model)

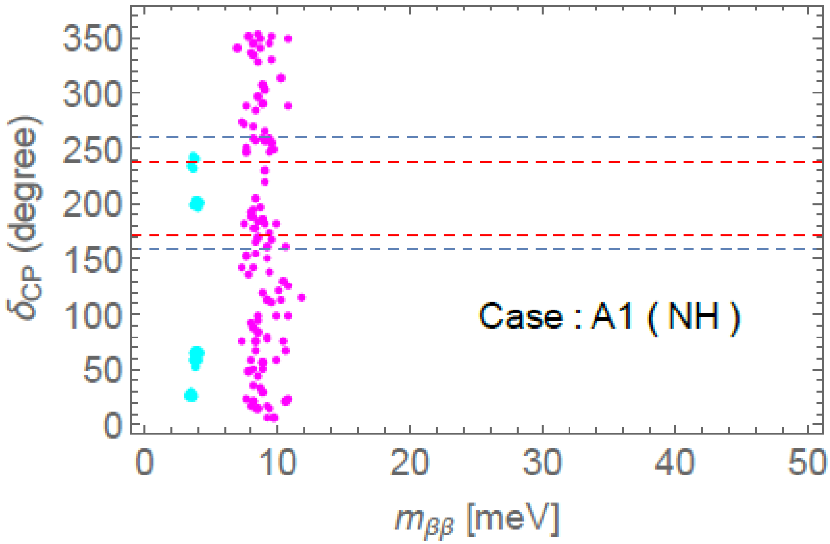
NH : $m_{\beta\beta} \simeq 4\text{meV}$

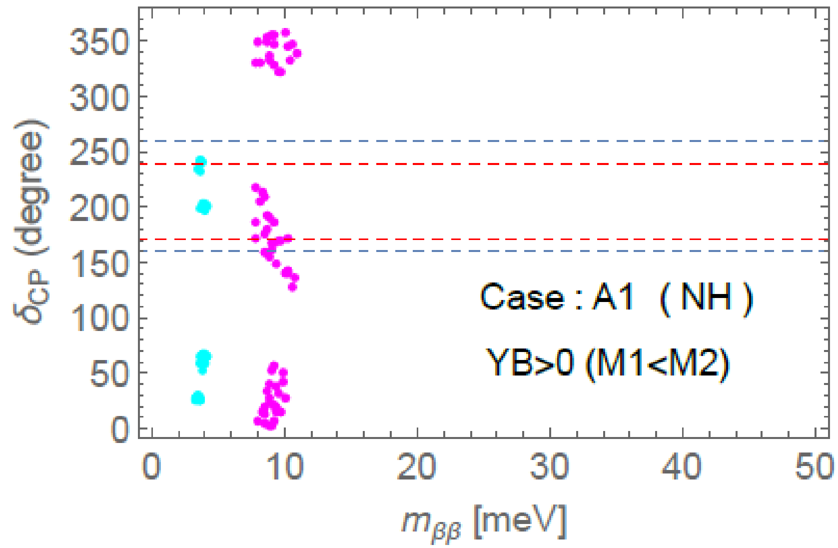
$\delta_{CP} \simeq 200^\circ \text{ or } 250^\circ$

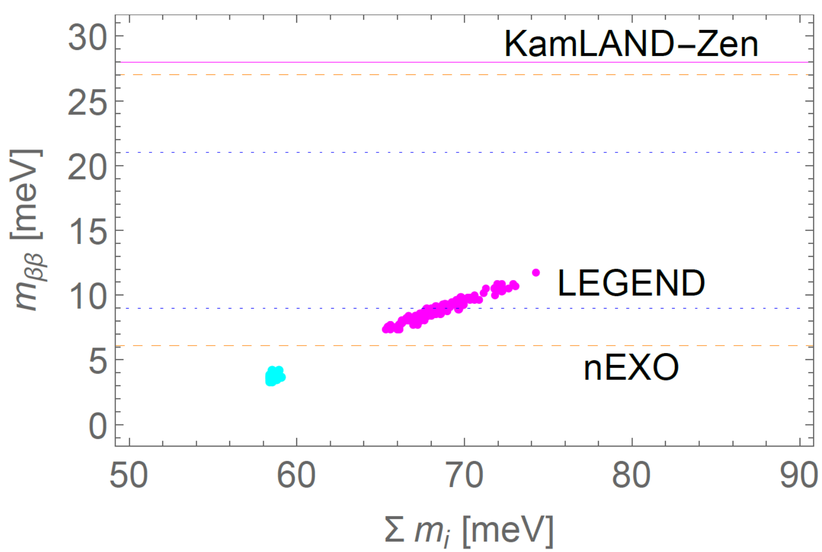
IH : $m_{\beta\beta} \simeq 49\text{meV}$

δ_{CP} : rather broad region

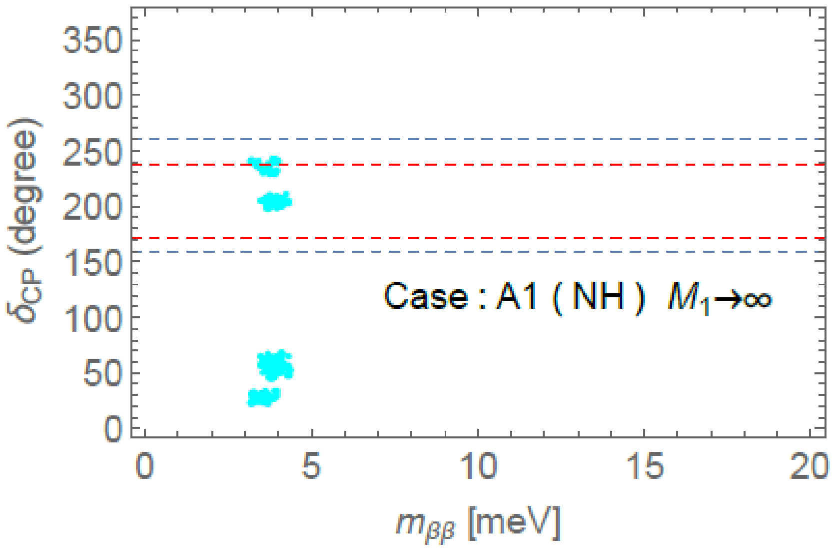
Predictions of CP phase and <m$_{ee}$>

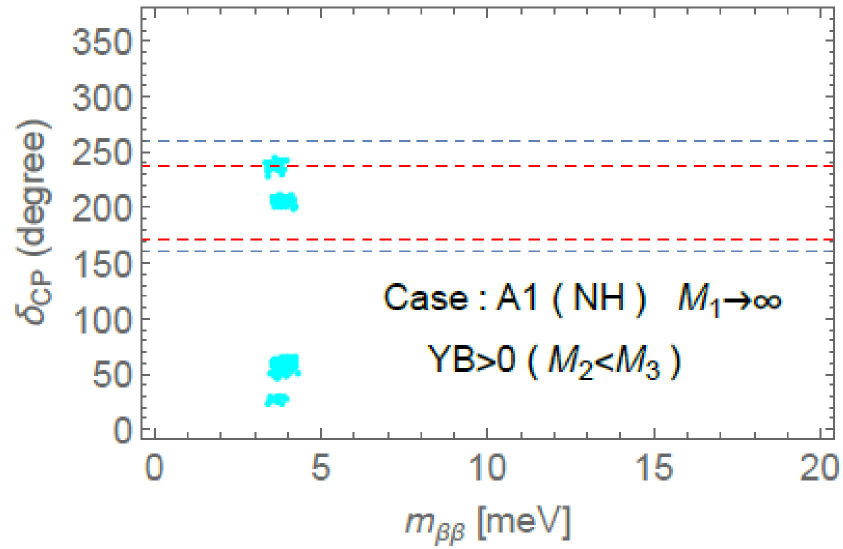




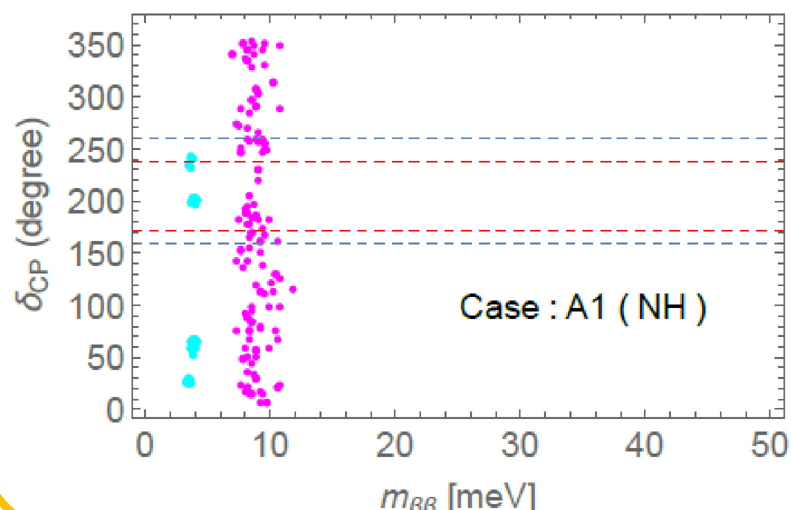


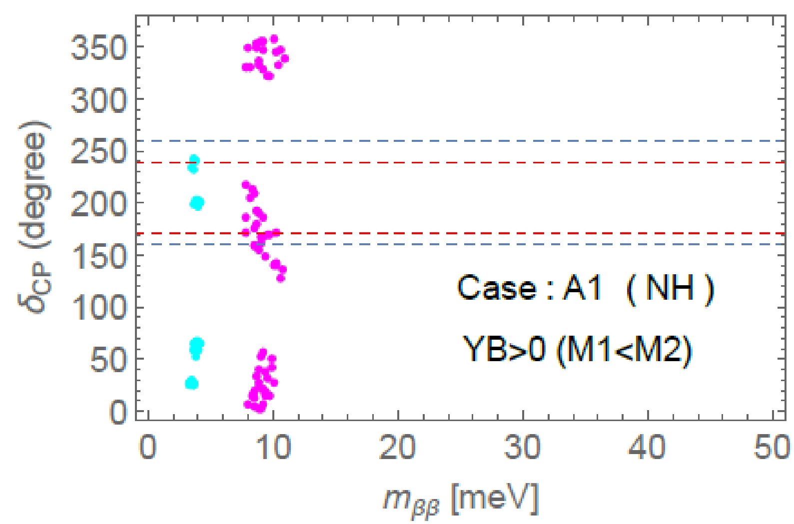
Case of NH $M_1 \to \infty$

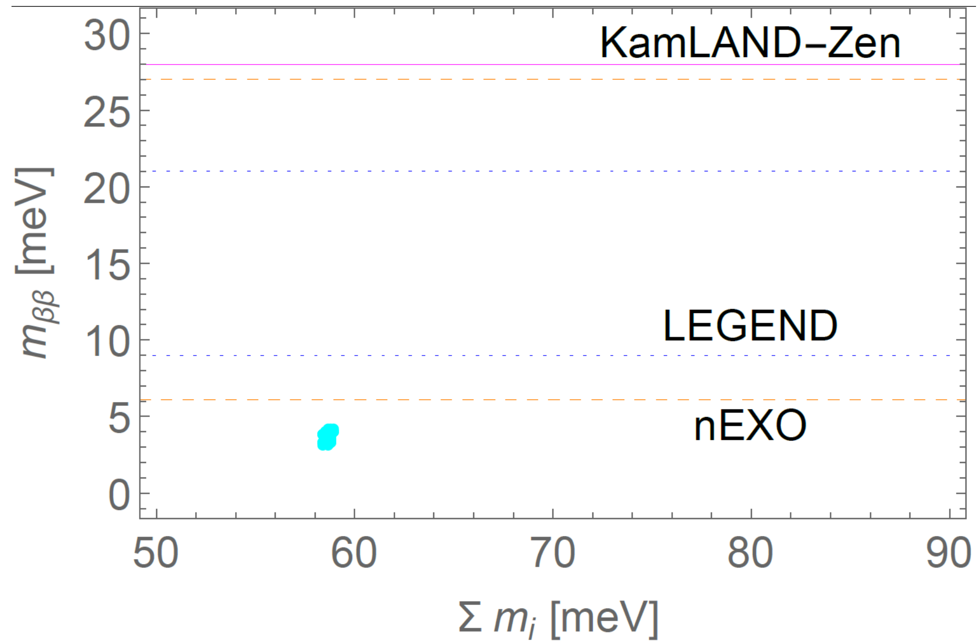


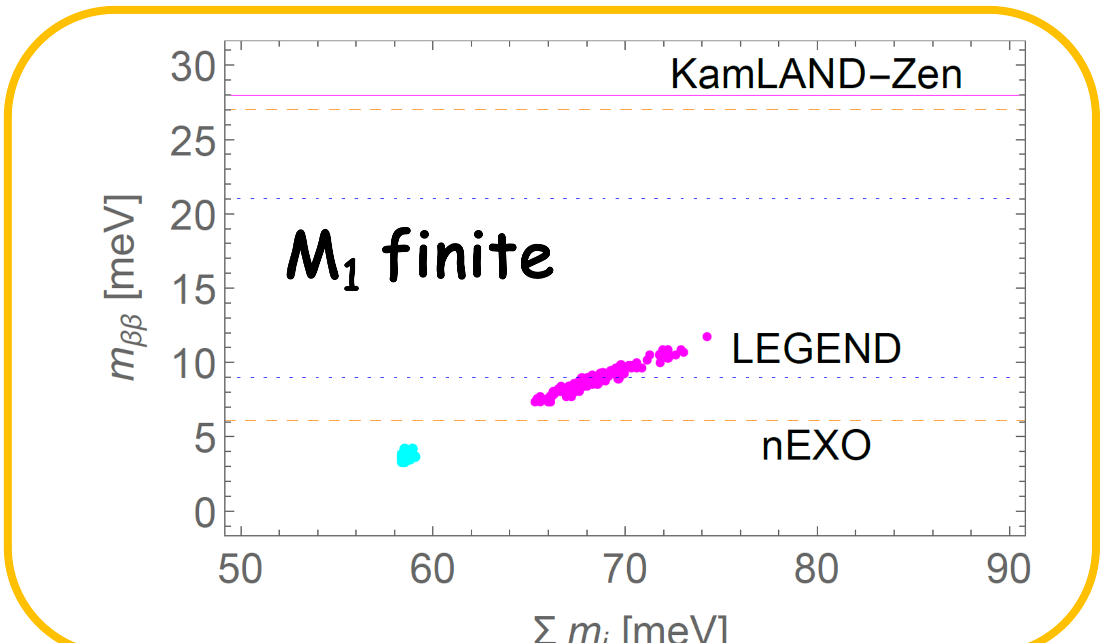


M_1 finite






KamLAND−Zen
LEGEND
nEXO
$m_{\beta\beta}$ [meV]
$\Sigma\, m_i$ [meV]


KamLAND−Zen
M_1 finite
LEGEND
nEXO
$m_{\beta\beta}$ [meV]
$\Sigma\, m_i$ [meV]

4 Summary

Texture zeros give the axion-less solution to the strong CP problem.

Vanishing arg [det M_d det M_u]

Such texture zeros are systematically obtained in

Orbifold compactification $\mathrm{T}^2/\mathbb{Z}_3$ (three fixed points)

We discuss two zeros texture of quarks and extend them to the lepton sector.

- **Common origin for CP violations of quark / lepton and BAU.**

2 Right-handed neutrinos (minimal model)

NH : $m_{\beta\beta} \simeq 4\mathrm{meV}$ $\delta_{CP} \simeq 200^\circ$ or 250°

IH : $m_{\beta\beta} \simeq 49\mathrm{meV}$ δ_{CP} : rather broad region