Phenomenology of scenarios with flavor and CP symmetries

C. Hagedorn

EC 'Universe', TUM, Munich, Germany

H/Meroni/Molinaro, 1408.7118 [hep-ph] and H/Molinaro, work in progress

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Outline

- lepton mixing: parametrization and data
- combination of flavor and CP symmetries: general idea
- highlights of survey of $G_f = \Delta(3\,n^2)$ and $G_f = \Delta(6\,n^2)$ and CP
- examples for predictions of $0\nu\beta\beta$ decay and leptogenesis
- conclusions

Lepton mixing: parametrization

Parametrization ***(PDG)***

$$U_{PMNS} = \tilde{U}\ \mathrm{diag}(1, e^{i\alpha/2}, e^{i(\beta/2+\delta)})$$

with

$$\tilde{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

and $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$

Lepton mixing: data

Global fits *(Gonzalez-Garcia et al. ('14) [after Neutrino'14])*

best fit and $1\,\sigma$ error	$3\,\sigma$ range
$\sin^2\theta_{13} = 0.0219^{+0.0010}_{-0.0011}$	$0.0188 \leq \sin^2\theta_{13} \leq 0.0251$
$\sin^2\theta_{12} = 0.304^{+0.012}_{-0.012}$	$0.270 \leq \sin^2\theta_{12} \leq 0.344$
$\sin^2\theta_{23} = \begin{cases} [0.451^{+0.06}_{-0.03}] \\ 0.577^{+0.027}_{-0.035} \end{cases}$	$0.385 \leq \sin^2\theta_{23} \leq 0.644$
$\delta = \left(1.39^{+0.37}_{-0.33}\right)\,\pi$	$0 \leq \delta \leq 2\,\pi$
$\alpha\ ,\ \ \beta$	unconstrained

Lepton mixing: data

Global fits NH [IH] ***(Gonzalez-Garcia et al. ('14) [after Neutrino'14])***

$$||U_{PMNS}|| \approx \begin{pmatrix} 0.83 & 0.55 & 0.15 \\ 0.39[4] & 0.64[57] & 0.66[75] \\ 0.41[5] & 0.54[62] & 0.73[64] \end{pmatrix}$$

and no information on Majorana phases

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$$\Downarrow$$

Mismatch in lepton flavor space is large!

Lepton mixing: data

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CP phases have not been measured up to now!

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and no information on Majorana phases

$$\Downarrow$$

Use flavor and CP symmetry to explain/predict these features

General idea

- interpret this mismatch in lepton flavor space as mismatch of residual symmetries G_ν and G_e
- if we want to predict lepton mixing, we have to derive this mismatch
- let us assume that there is a symmetry, broken to G_ν and G_e
- this symmetry is in the following a combination of a

finite, discrete, non-abelian symmetry G_f and CP

(Grimus/Rebelo ('95), Feruglio et al. ('12,'13), Holthausen et al. ('12), Chen et al. ('14))

[Masses do not play a role in this approach.]

General idea

- three generations of LH leptons are in $\mathbf{3}$ of group G_f

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- effect of residual symmetry G_e in charged lepton sector: constraints on mass matrix combination $m_l^\dagger m_l$ for $e^c m_l l$

$$Q^\dagger m_l^\dagger m_l Q = m_l^\dagger m_l$$

for Q generating G_e

- matrix U_e diagonalizing $m_l^\dagger m_l$ is determined by choice of Q

General idea

- three generations of LH leptons are in $\mathbf{3}$ of group G_f
- effect of residual symmetry $G_\nu = Z_2 \times$ CP in neutrino sector: constraints on Majorana mass matrix m_ν

$$Z^T m_\nu Z = m_\nu \quad \text{and} \quad X m_\nu X = m_\nu^\star$$

  for Z generating Z_2 and CP transformation X
- matrix U_ν diagonalizing m_ν is constrained by choice of Z and X

General idea

- three generations of LH leptons are in $\mathbf{3}$ of group G_f
- residual symmetries G_e and $G_\nu = Z_2 \times$ CP
- matrix U_e diagonalizing $m_l^\dagger m_l$ is determined by choice of Q
- matrix U_ν diagonalizing m_ν is constrained by choice of Z and X
- PMNS mixing matrix

$$U_{PMNS} = U_e^\dagger U_\nu$$

is constrained by choice of G_e and G_ν, i.e. (Q, Z, X)

[Masses are free parameters in this approach.]

General idea

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

- U_{PMNS} contains one parameter θ
- permutations of rows and columns of U_{PMNS} possible
- 3 unphysical phases are removed by $U_e \to U_e K_e$

$$\Downarrow$$

Predictions:

Mixing angles and CP phases are predicted
in terms of one parameter θ only,
up to permutations of rows/columns

General idea

To remember

- CP transformation X also acts on flavor space: $\phi_i \xrightarrow{\text{CP}} X_{ij}\phi_j^\star$ (X unitary)
- only "useful" choice in this context: X symmetric
- combination of flavor and CP symmetry requires

$$(X^\star A X)^\star = A' \quad \text{with in general} \quad A \neq A' \quad \text{and} \quad A,\, A' \in G_f$$

- in particular $G_\nu = Z_2 \times$ CP: $\qquad XZ^\star - ZX = 0$
- LH leptons in irred rep $\mathbf{3}$ to be mapped into c.c. under CP

(Chen et al. ('14))

Group theory of $\mathbf{\Delta(3\,n^2)}$ and $\mathbf{\Delta(6\,n^2)}$

- $\Delta(3\,n^2)$ can be characterized with three generators a, c and d ***(Luhn et al. ('07))***

$$a^3 = 1 \;\;, \quad c^n = 1 \;\;, \quad d^n = 1 \;\;,$$
$$cd = dc \;\;, \quad aca^{-1} = c^{-1}d^{-1} \;\;, \quad ada^{-1} = c$$

- all elements of the group can be written as

$$g = a^\alpha c^\gamma d^\delta \quad \text{with} \quad \alpha = 0, 1, 2 \;\;, \quad 0 \leq \gamma, \delta \leq n-1$$

- for $n \geq 2$: group is non-abelian and has irred three-dimensional reps $\mathbf{3}$

Group theory of $\boldsymbol{\Delta(3\,n^2)}$ and $\boldsymbol{\Delta(6\,n^2)}$

- $\Delta(6\,n^2)$ can be characterized with the generators a, c, d and b ***(Escobar/Luhn ('08))***

$$b^2 = 1 \;\; , \;\; (ab)^2 = 1 \;\; ,$$
$$bcb^{-1} = d^{-1} \;\; , \;\; bdb^{-1} = c^{-1}$$

- all elements of the group can be written as

$$g = a^\alpha b^\beta c^\gamma d^\delta \quad \text{with} \quad \alpha = 0,1,2 \;\; , \;\; \beta = 0,1 \;\; , \;\; 0 \leq \gamma, \delta \leq n-1$$

- for $n \geq 2$: group is non-abelian and has irred three-dimensional reps $\mathbf{3}$

Group theory of $\boldsymbol{\Delta(3\,n^2)}$ and $\boldsymbol{\Delta(6\,n^2)}$

- we can choose as representation matrices for $\mathbf{3}$

$$a = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^2 \end{pmatrix} \quad \text{with} \quad \omega = e^{2\pi i/3}$$

and

$$c = \frac{1}{3} \begin{pmatrix} 1 + 2\cos\phi_n & 1 - \cos\phi_n - \sqrt{3}\sin\phi_n & 1 - \cos\phi_n + \sqrt{3}\sin\phi_n \\ 1 - \cos\phi_n + \sqrt{3}\sin\phi_n & 1 + 2\cos\phi_n & 1 - \cos\phi_n - \sqrt{3}\sin\phi_n \\ 1 - \cos\phi_n - \sqrt{3}\sin\phi_n & 1 - \cos\phi_n + \sqrt{3}\sin\phi_n & 1 + 2\cos\phi_n \end{pmatrix}$$

with $\phi_n = \dfrac{2\,\pi}{n}$

Group theory of $\boldsymbol{\Delta(3\,n^2)}$ and $\boldsymbol{\Delta(6\,n^2)}$

- for $\mathbf{3}$ of $\Delta(6\,n^2)$ we also choose

$$b = \pm \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & \omega^2 \\ 0 & \omega & 0 \end{pmatrix}$$

- Nota bene: we always take $3 \nmid n$ and, if necessary, n even

Choice of CP transformation

- we consider in the following X in $\mathbf{3}$ to be of the form

$$X = g\, P_{23} \quad \text{with} \quad P_{23} = \left(\begin{array}{ccc} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{array} \right)$$

  with g representing an element of the flavor group
- fulfills relevant conditions

Choice of $(\boldsymbol{Q}, \boldsymbol{Z}, \boldsymbol{X})$

$G_e = Z_3$ $\qquad$ Z $\qquad$ X

Choice of $(\boldsymbol{Q}, \boldsymbol{Z}, \boldsymbol{X})$

$G_e = Z_3$	Z	X
$\vdots$	$\vdots$	$\vdots$

can be reduced to

$$Q = a \qquad Z = c^{n/2} \qquad X = a\,b\,c^s\,d^{2s}\,P_{23} \quad \text{(Case 1)}$$

$$X = c^s\,d^t\,P_{23} \quad \text{(Case 2)}$$

$$Z = b\,c^m\,d^m \qquad X = b\,c^s\,d^{n-s}\,P_{23} \quad \text{(Case 3a, Case 3b.1)}$$

Choice of $(\boldsymbol{Q}, \boldsymbol{Z}, \boldsymbol{X})$

$G_e = Z_3$ $\qquad$ Z $\qquad$ X

$\vdots$ $\qquad$ $\vdots$ $\qquad$ $\vdots$

special cases have been discussed

(Feruglio et al. ('12,'13), Ding/Zhou ('13,'14), Ding/King ('14), King/Neder ('14))

recently, also $G_e \neq Z_3$ has been studied

(Ding et al. ('14))

Choice of $(\boldsymbol{Q}, \boldsymbol{Z}, \boldsymbol{X})$

- $Q = a$ with a being diagonal in our basis tells us

$$U_e = \mathbb{1}$$

- the form of $Z = c^{n/2}$ does not depend on n

$$Z = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{pmatrix}$$

Choice of $(\boldsymbol{Q}, \boldsymbol{Z}, \boldsymbol{X})$

- $Q = a$ with a being diagonal in our basis tells us

$$U_e = \mathbb{1}$$

- non-degenerate eigenvalue of $Z = c^{n/2}$ has trimaximal eigenvector
  thus one column of PMNS mixing matrix is trimaximal
  consequently, we find in Case 1 and Case 2

$$\sin^2\theta_{12} = \frac{1}{3\,\cos^2\theta_{13}} \gtrsim \frac{1}{3}$$

Case 2: $(\boldsymbol{Q}, \boldsymbol{Z}, \boldsymbol{X}) = (\boldsymbol{a}, \boldsymbol{c}^{\boldsymbol{n/2}}, \boldsymbol{c}^{\boldsymbol{s}}\, \boldsymbol{d}^{\boldsymbol{t}}\, \boldsymbol{P}_{\boldsymbol{23}})$

- consider all permutations of rows and columns:
  either pattern is excluded
  or results of mixing angles and CP phases can be formally written in unique way
- opportune choice of parameters

$$u = 2\,s - t \;\;,\;\; v = 3\,t$$

Case 2

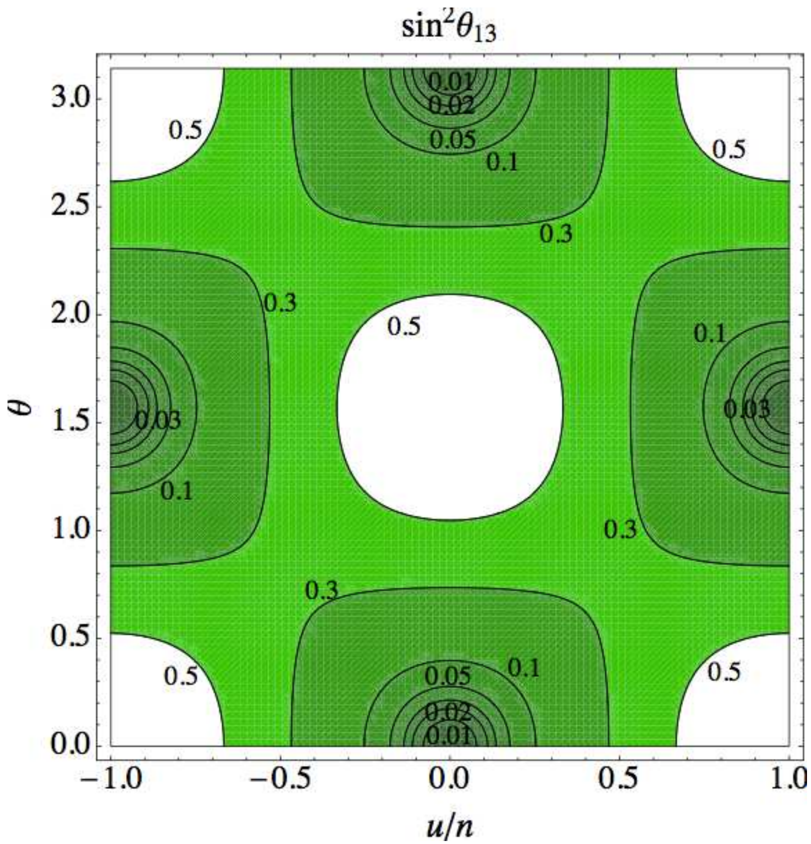
- results for mixing angles

$$\sin^2\theta_{13} = \frac{1}{3}\left(1 - \cos\left(\frac{\pi\, u}{n}\right)\cos 2\theta\right) \quad , \quad \sin^2\theta_{12} = \frac{1}{2+\cos\left(\frac{\pi\, u}{n}\right)\cos 2\theta} \quad ,$$

$$\sin^2\theta_{23} = \frac{1}{2}\left(1 + \frac{\sqrt{3}\sin\left(\frac{\pi\, u}{n}\right)\cos 2\theta}{2+\cos\left(\frac{\pi\, u}{n}\right)\cos 2\theta}\right)$$

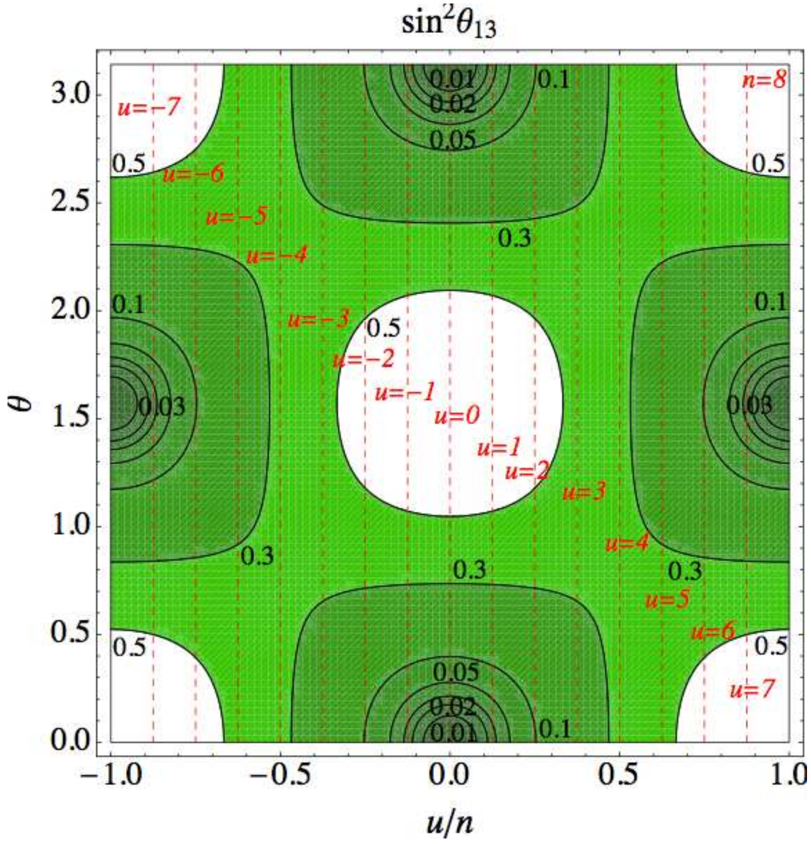
Case 2

First consider only the reactor mixing angle



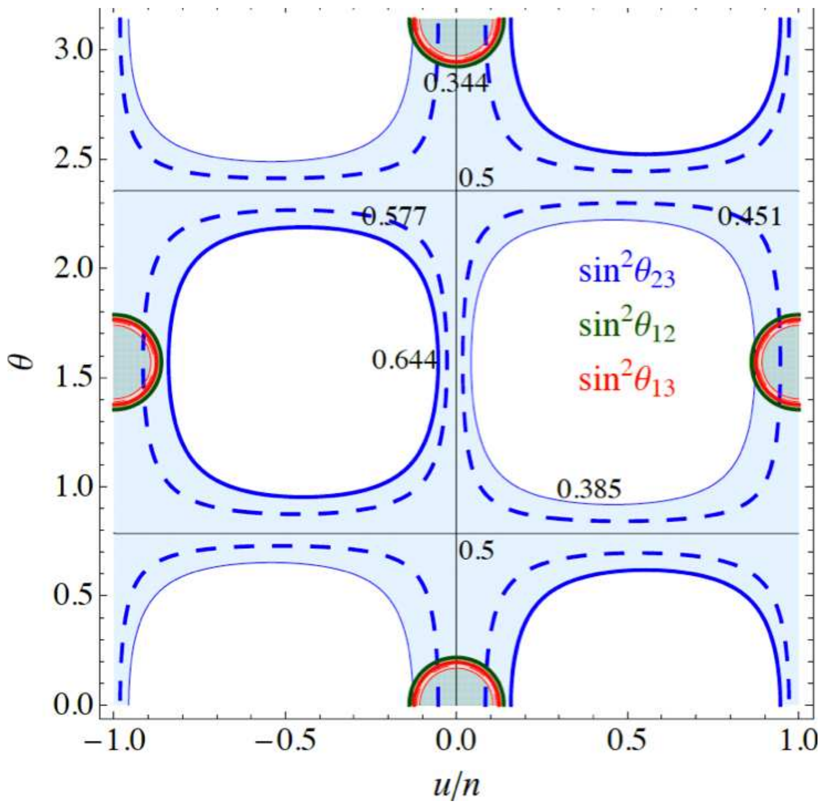
Case 2

For the particular choice $n = 8$ you find



Case 2

Results for mixing angles put together



Case 2

Numerical example: $n = 8$

u	$\sin^2\theta_{13}$	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$
$u = 0$	0.0218	0.341	0.5
$u = -1$	0.0254	0.342	0.387
$u = 1$	0.0254	0.342	0.613

Case 2

- results for CP phases
  - in general all are non-trivial
  - however, for particular values, e.g. $\theta = 0$, some can vanish
  - most importantly:
    $\sin\delta$ and $\sin\beta$ depend only on θ and u/n,
    whereas $\sin\alpha$ is the **only** quantity also depending on v

Here and in the following we set $K_\nu = \mathbb{1}$.

Case 2

Numerical example: $n = 8$

u	$\sin^2\theta_{13}$	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin\delta$	$\sin\beta$
$u = 0$	0.0218	0.341	0.5	1	0
$u = -1$	0.0254	0.342	0.387	0	0
$u = 1$	0.0254	0.342	0.613	0	0

values of $\sin\alpha$ for $u = 0$

$\sin\alpha = 0$, $\sin\alpha = 1$ and $\sin\alpha = -1/\sqrt{2}$

values of $\sin\alpha$ for $u = \pm 1$

$\sin\alpha \approx -0.924$ and $\sin\alpha \approx 0.383$

Choice of $(\boldsymbol{Q}, \boldsymbol{Z}, \boldsymbol{X})$

- $Q = a$ with a being diagonal in our basis tells us

$$U_e = \mathbb{1}$$

- non-degenerate eigenvalue of $Z = b\, c^m\, d^m$ has eigenvector of form

$$\frac{1}{\sqrt{6}} \begin{pmatrix} -1 + e^{2\pi i m/n} \\ -\omega^2 + e^{2\pi i m/n} \\ -\omega + e^{2\pi i m/n} \end{pmatrix}$$

Choice of $(\boldsymbol{Q}, \boldsymbol{Z}, \boldsymbol{X})$

- $Q = a$ with a being diagonal in our basis tells us

$$U_e = \mathbb{1}$$

- this eigenvector can be identified with the third column of the PMNS mixing matrix,
  then we find $\sin^2\theta_{13}$ and $\sin^2\theta_{23}$ as functions of m/n
  (Case 3a)

Choice of $(\boldsymbol{Q}, \boldsymbol{Z}, \boldsymbol{X})$

- $Q = a$ with a being diagonal in our basis tells us

$$U_e = \mathbb{1}$$

- this eigenvector can be identified with the first column of the PMNS mixing matrix,
  for $m = n/2$ the vector reads

$$\frac{1}{\sqrt{6}} \begin{pmatrix} -2 \\ \omega \\ \omega^2 \end{pmatrix}$$

Choice of $(\boldsymbol{Q}, \boldsymbol{Z}, \boldsymbol{X})$

- $Q = a$ with a being diagonal in our basis tells us

$$U_e = \mathbb{1}$$

- this eigenvector can be identified with the first column of the PMNS mixing matrix,
  for $m = n/2$ we then know that

$$\sin^2 \theta_{12} \lesssim \frac{1}{3}$$

  (special choice for Case 3b.1)

Case 3a:

$$(Q, Z, X) = (a, b\, c^m\, d^m, b\, c^s\, d^{n-s}\, P_{23})$$

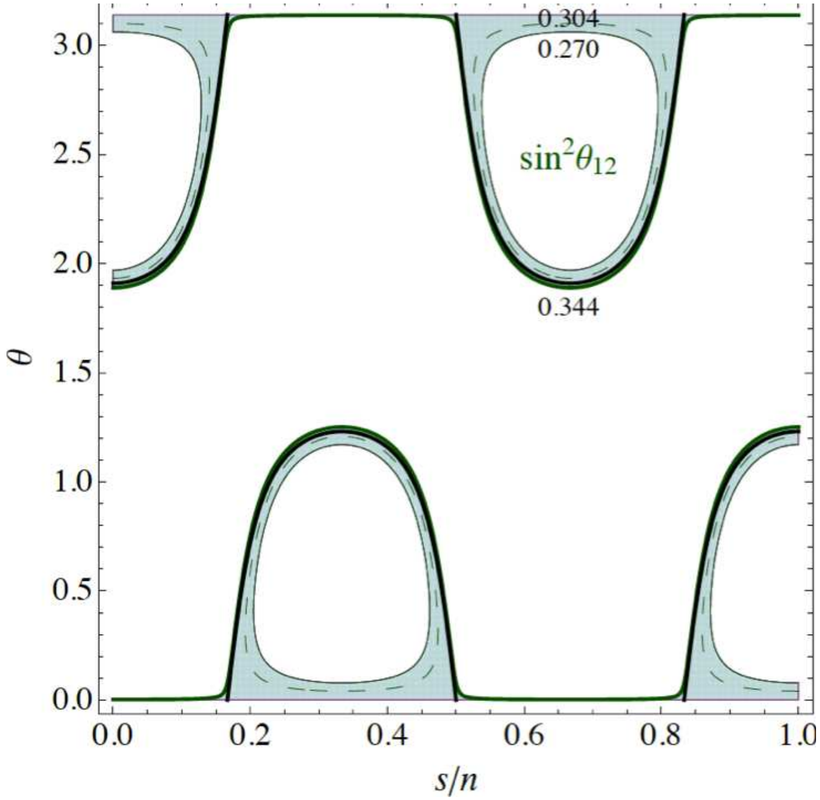
- $\sin^2\theta_{13}$ and $\sin^2\theta_{23}$ only depend on m/n
- $m/n = 1/16$ ($m/n = 15/16$) leads to good fit of data:

$$\sin^2\theta_{13} \approx 0.0254 \quad \text{and} \quad \sin^2\theta_{23} \approx \begin{cases} 0.613 \\ 0.387 \end{cases}$$

- solar mixing angle depends on additional parameters s and θ

Case 3a

Results for solar mixing angle for $m/n = 1/16$

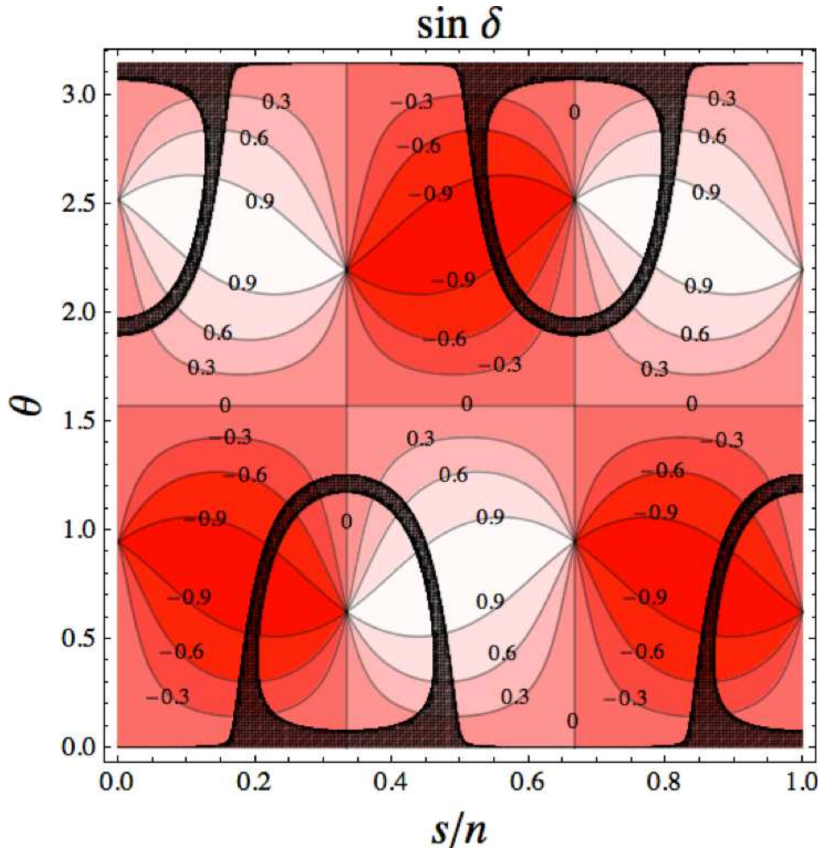


Case 3a

- CP phases depend on all parameters: m, n, s and θ
- CP phases are non-trivial in general
- particular choices of parameters lead to no CP violation

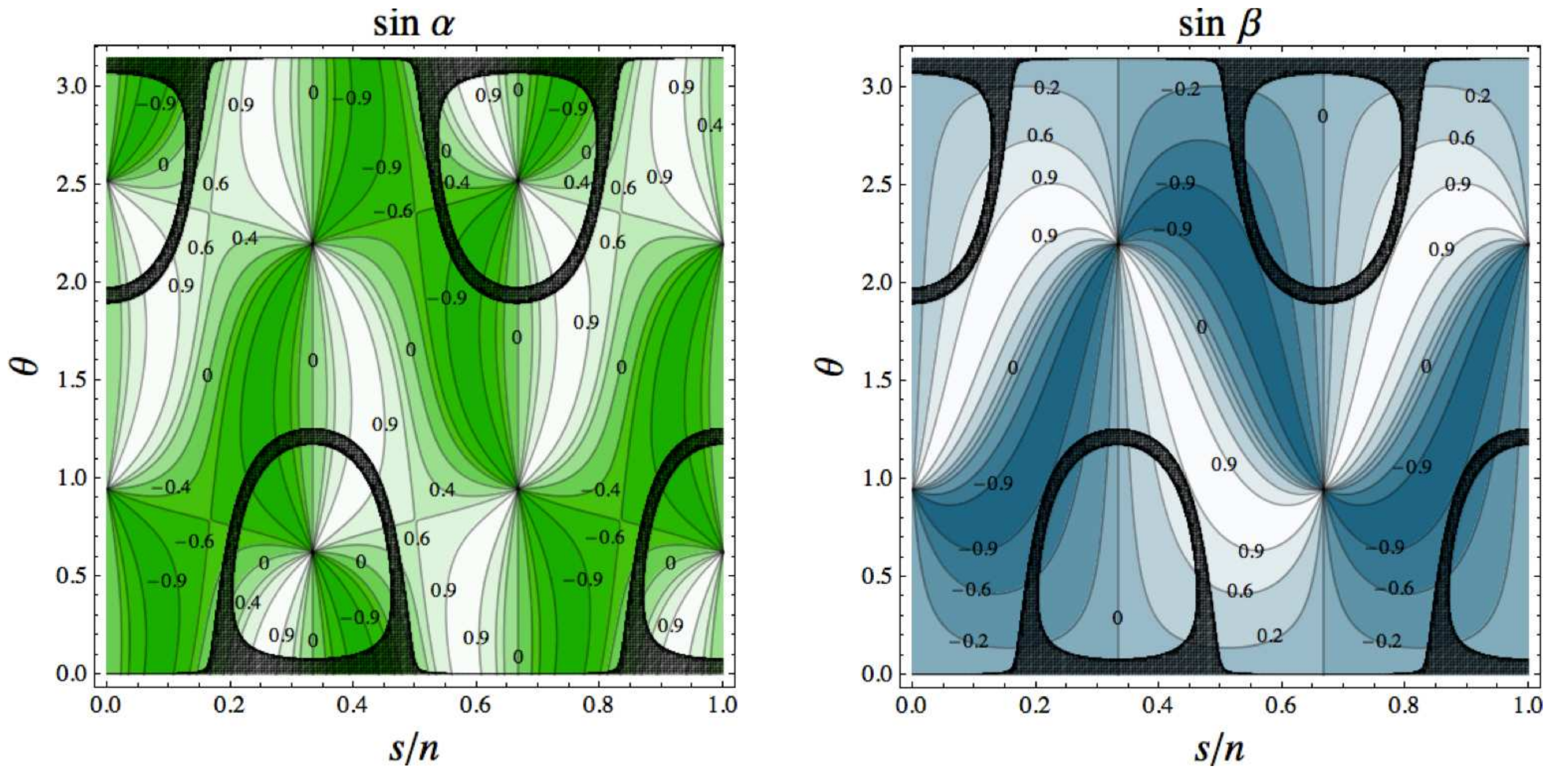
Case 3a

Results for Dirac phase δ for $m/n = 1/16$



Case 3a

Results for Majorana phases α and β for $m/n = 1/16$



Case 3a

Numerical example: $n = 16$, $m = 1$

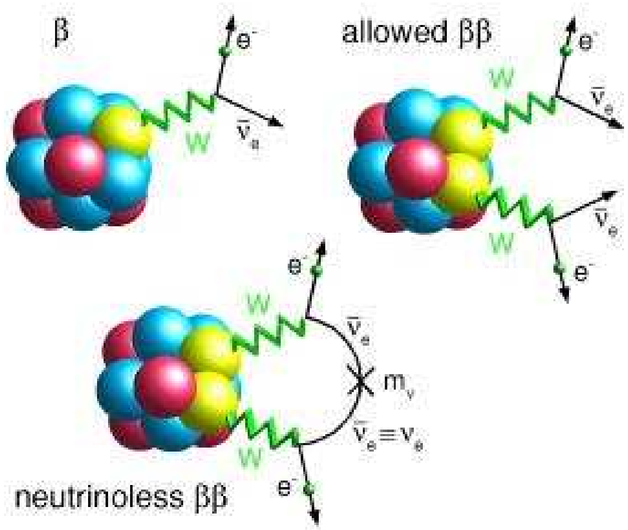
$\sin^2\theta_{13} \approx 0.0254$ and $\sin^2\theta_{23} \approx 0.613$

some viable choices of s

s	$\sin^2\theta_{12}$	$\sin\delta$	$\sin\alpha$	$\sin\beta$
$s = 0$	0.304	0	0	0
$s = 1$	0.304	0.458	0.939	0.662
	0.304	0.0594	-0.939	0.0383
$s = 3$	0.317	-0.533	0	-0.357

Neutrinoless double beta decay

- neutrinos can be their own antiparticles
- if true, a process called $0\nu\beta\beta$ decay is allowed



Neutrinoless double beta decay

- neutrinos can be their own antiparticles
- if true, a process called $0\nu\beta\beta$ decay is allowed

$$m_{ee} = \left|\cos^2\theta_{12}\ \cos^2\theta_{13}\, m_1 + \sin^2\theta_{12}\ \cos^2\theta_{13}\, e^{i\alpha}\, m_2 + \sin^2\theta_{13}\, e^{i\beta}\, m_3\right|$$

using the experimentally preferred 3 σ ranges of $\sin^2\theta_{13}$, $\sin^2\theta_{12}$ and of the mass splittings and varying the unknown Majorana phases α and β and the lightest neutrino mass we get ...

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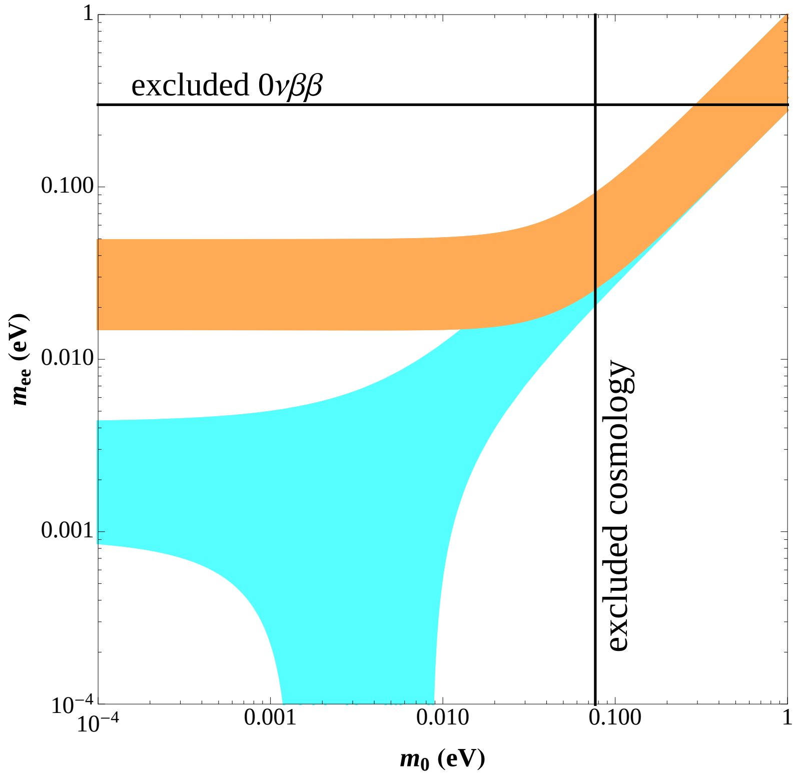
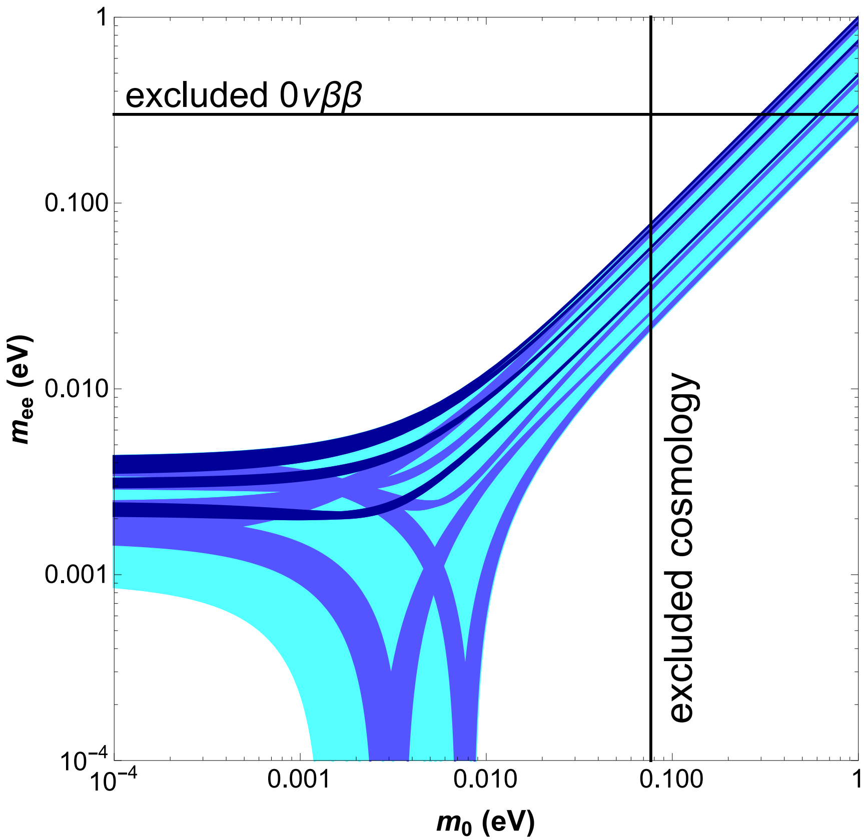


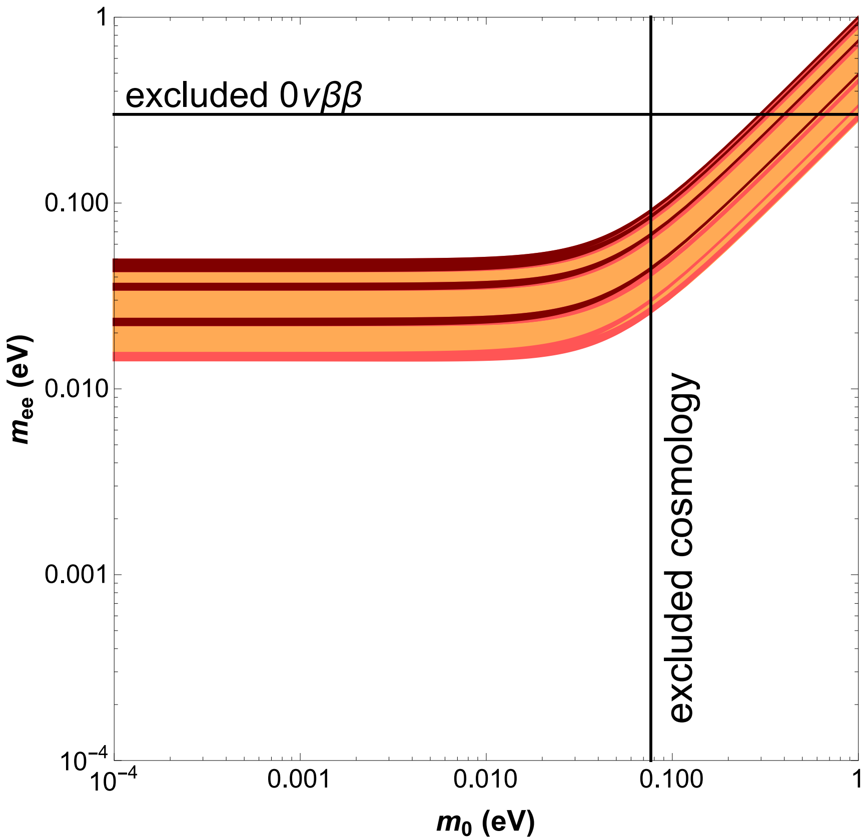
Neutrinoless double beta decay

Case 2 with $n = 8$, $u = 0$ and normal ordering



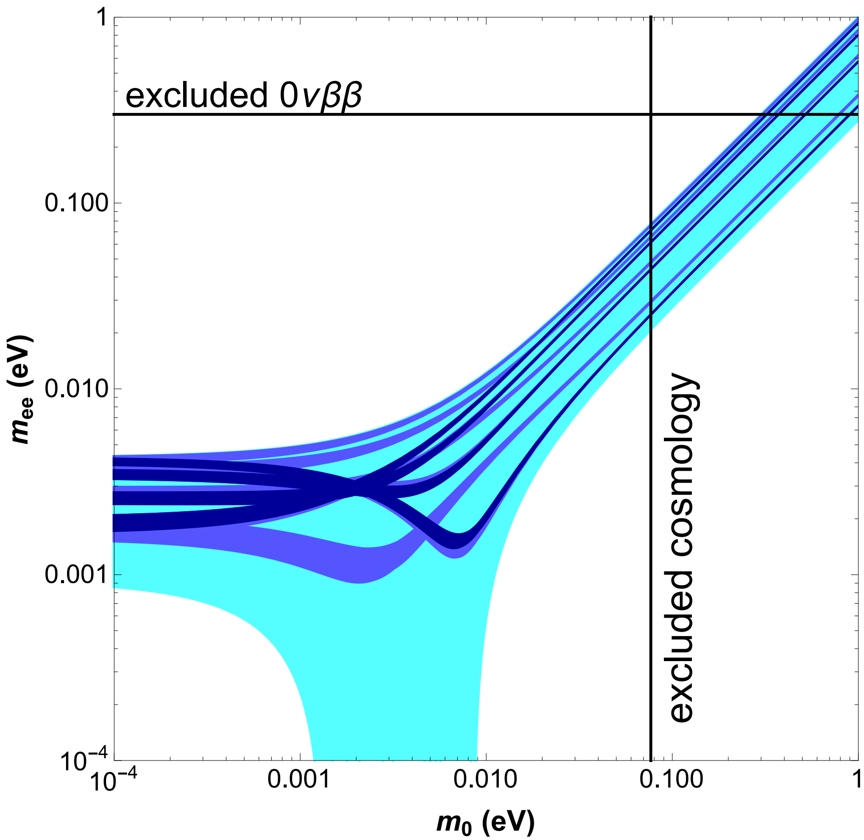
Neutrinoless double beta decay

Case 2 with $n = 8$, $u = 0$ and inverted ordering



Neutrinoless double beta decay

Case 2 with $n = 8$, $u = 1$ and normal ordering



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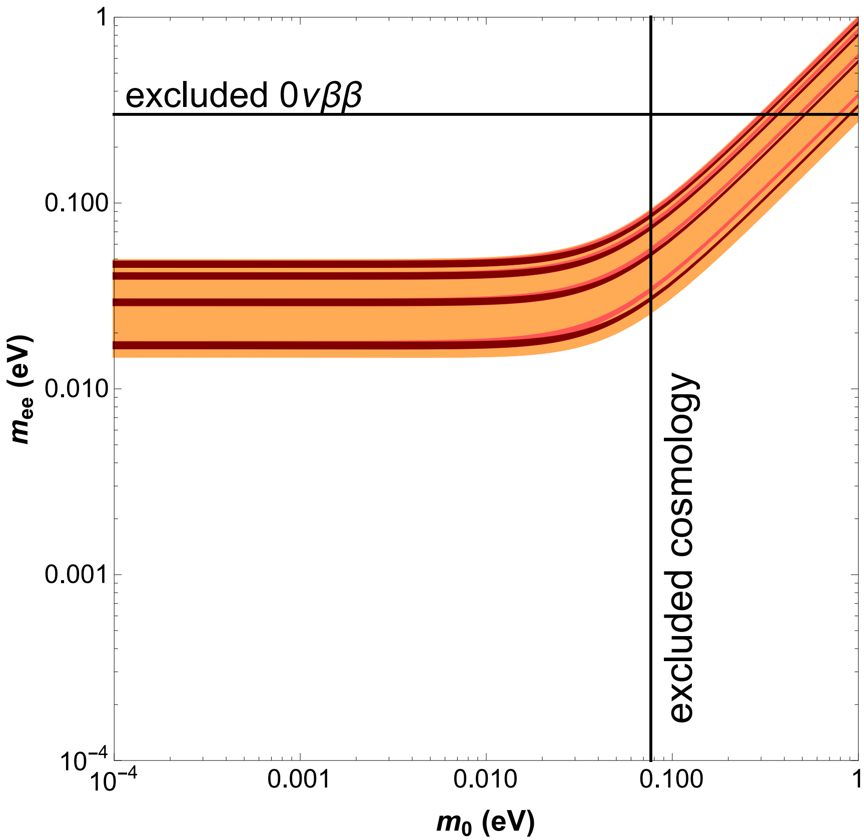
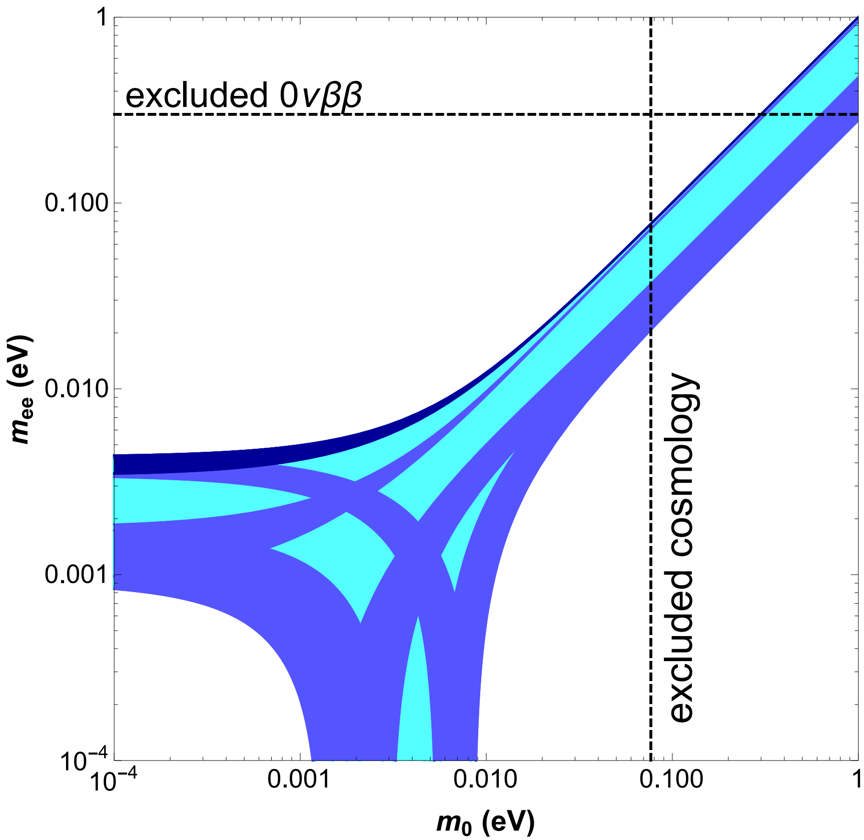


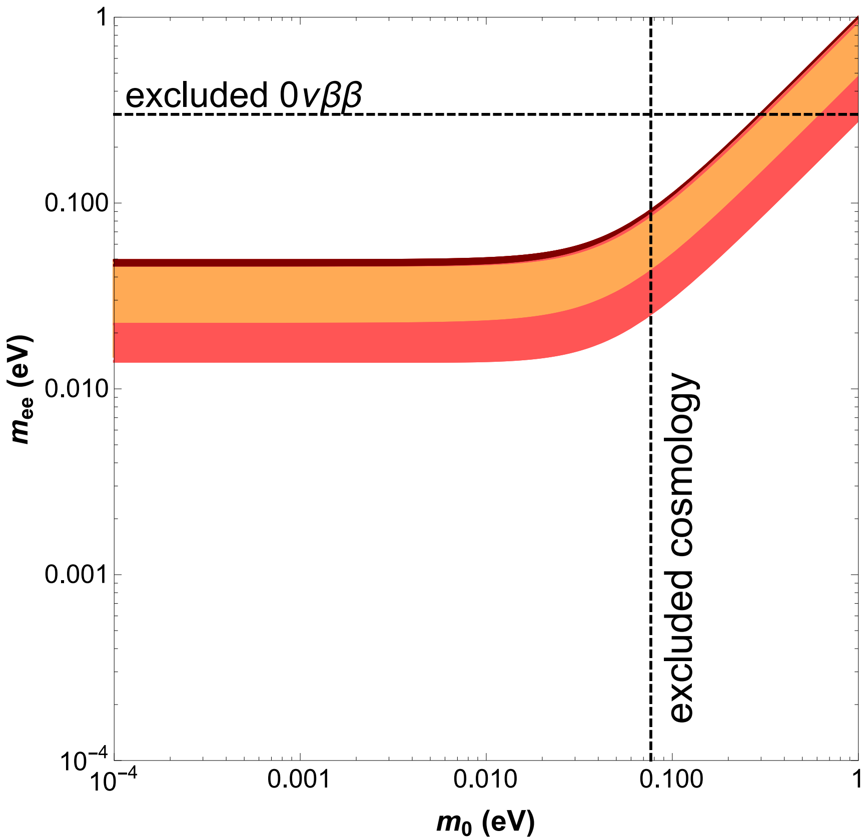
Neutrinoless double beta decay

Case 3a with $n = 16$, $m = 1$, $s = 0$ and normal ordering



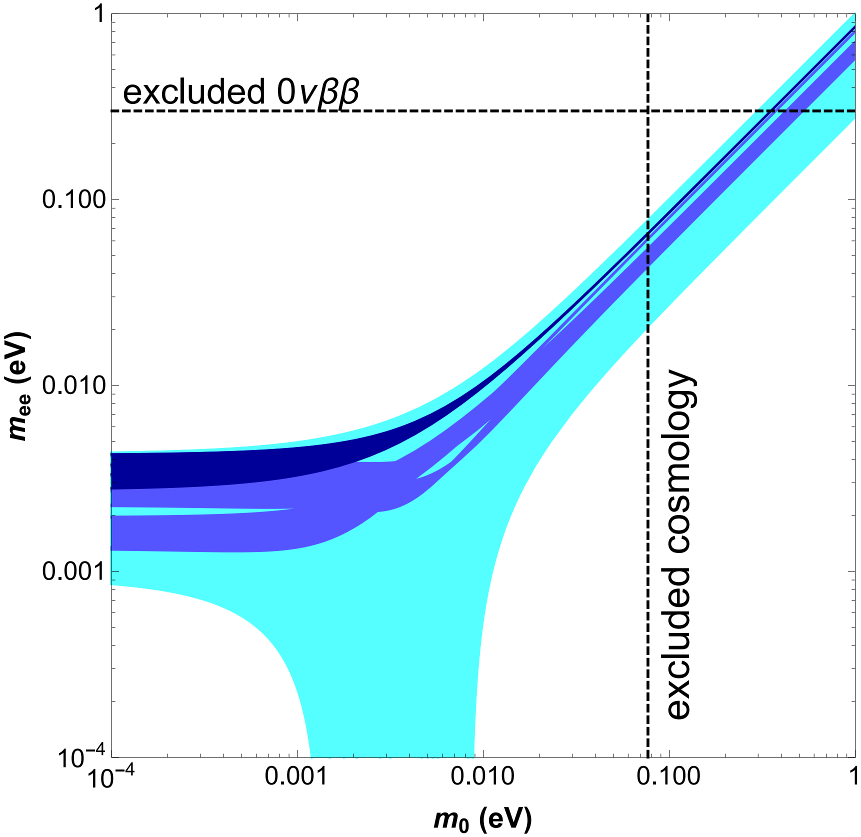
Neutrinoless double beta decay

Case 3a with $n = 16$, $m = 1$, $s = 0$ and inverted ordering



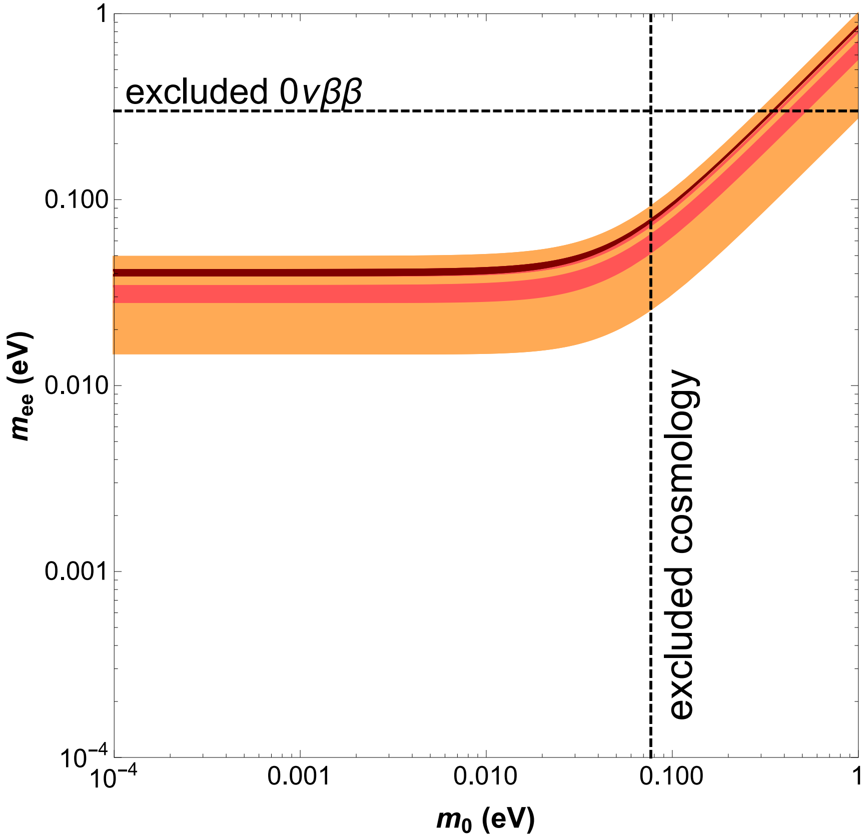
Neutrinoless double beta decay

Case 3a with $n = 16$, $m = 1$, $s = 1$ and normal ordering



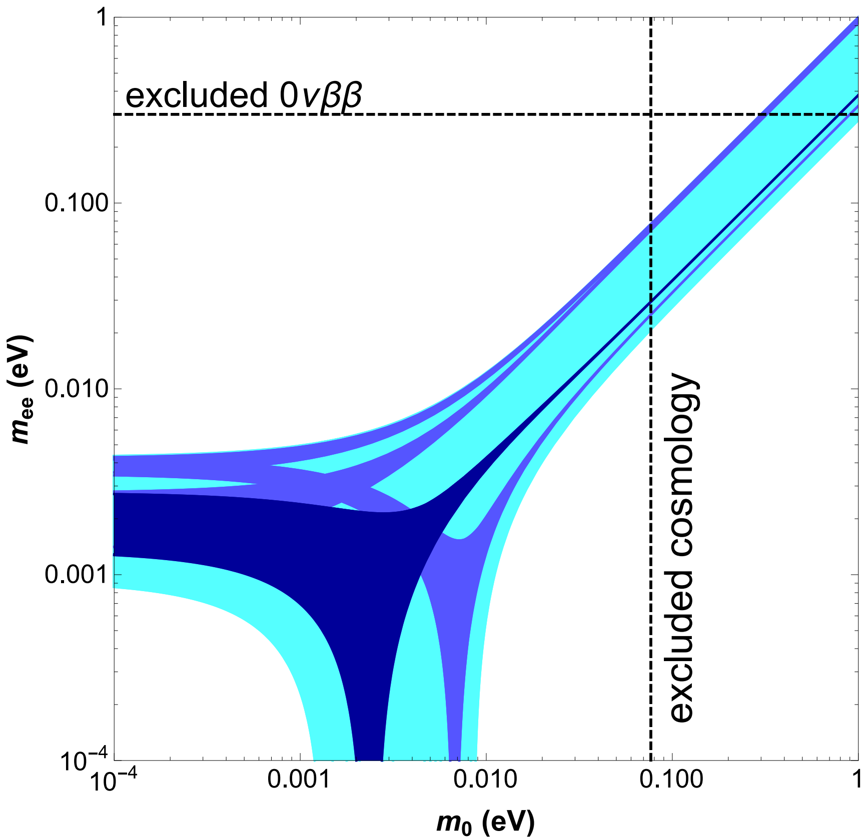
Neutrinoless double beta decay

Case 3a with $n = 16$, $m = 1$, $s = 1$ and inverted ordering



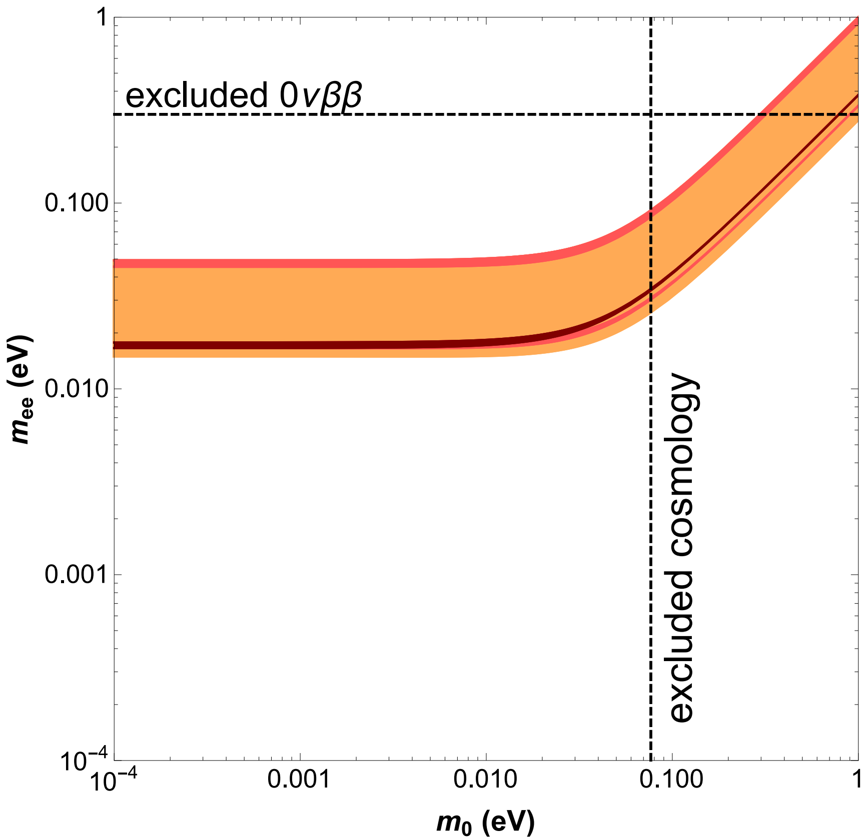
Neutrinoless double beta decay

Case 3a with $n = 16$, $m = 1$, $s = 3$ and normal ordering



Neutrinoless double beta decay

Case 3a with $n = 16$, $m = 1$, $s = 3$ and inverted ordering



Leptogenesis

- baryon asymmetry of the Universe is measured well

$$Y_B = \left. \frac{n_B - n_{\bar{B}}}{s} \right|_0 = (8.77 \pm 0.24) \times 10^{-11}$$ ***(WMAP ('08), Planck ('13))***

- this asymmetry can be explained by decay of heavy right-handed neutrinos ***(Fukugita/Yanagida ('86))***
- the three Sakharov conditions are fulfilled ***(Sakharov ('67))***

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- this asymmetry can be explained by decay of heavy right-handed neutrinos ***(Fukugita/Yanagida ('86))***
- the three Sakharov conditions are fulfilled ***(Sakharov ('67))***
- simplest scenario:

$Y_B \sim 10^{-3}\,\epsilon\,\eta$ with ϵ CP asymmetry , η washout factor

Leptogenesis

- CP asymmetry ϵ_i for right-handed neutrino N_i

$$\epsilon_i = -\frac{\Gamma(N_i \to Hl) - \Gamma(N_i \to H^\star \bar{l})}{\Gamma(N_i \to Hl) + \Gamma(N_i \to H^\star \bar{l})}$$

- computation of ϵ_i in case of unflavored leptogenesis

$$\epsilon_i = -\frac{1}{8\pi} \sum_{j \neq i} \frac{\mathrm{Im}\left((\hat{Y}_D^\dagger \hat{Y}_D)^2_{ij} \right)}{(\hat{Y}_D^\dagger \hat{Y}_D)_{ii}} \, f(x_{ji})$$

with $\hat{Y}_D = Y_D U_R$ and $U_R^T M_R U_R = \mathrm{diag}(M_1, M_2, M_3)$

[Y_D: Dirac neutrino coupling,

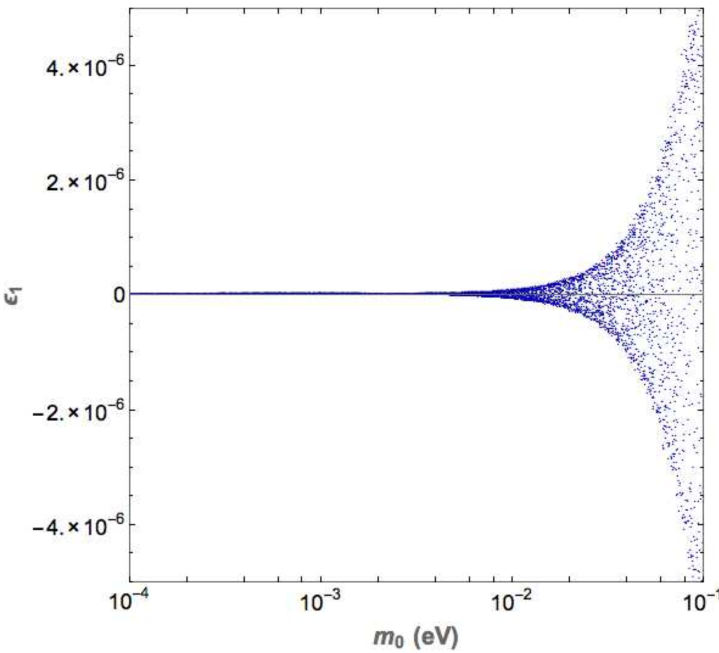
M_R: Majorana mass matrix of right-handed neutrinos]

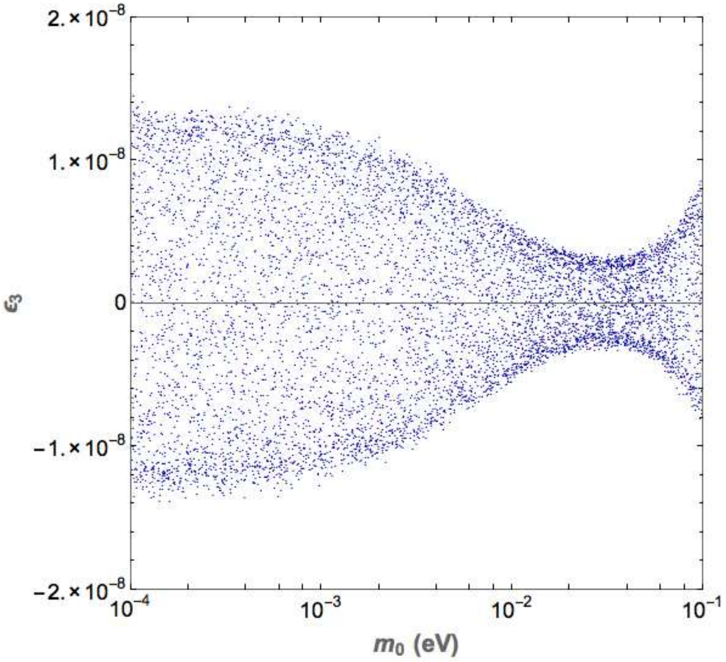
Leptogenesis in models with flavor and CP

Case 2 with $n = 8$, $u = 0$, $v = 0$:

Prediction for ϵ_1 and ϵ_3 vs lightest neutrino mass

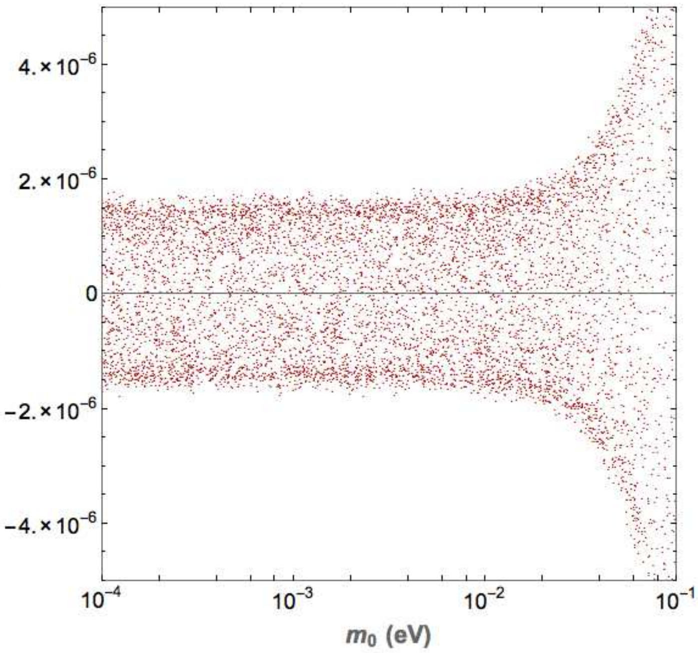
for normal ordering, $\kappa = 1.6 \times 10^{-3}$

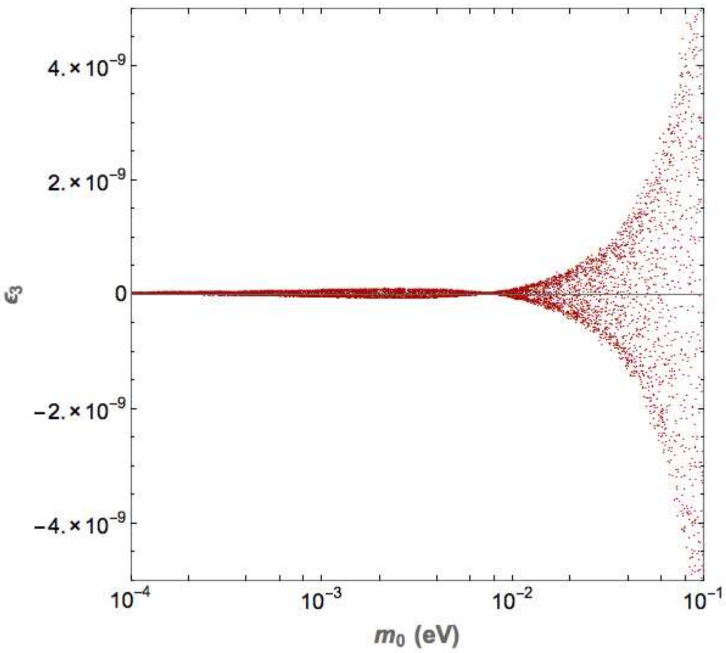




Leptogenesis in models with flavor and CP

Case 2 with $n = 8$, $u = 0$, $v = 0$:
Prediction for ϵ_1 and ϵ_3 vs lightest neutrino mass
for inverted ordering, $\kappa = 1.6 \times 10^{-3}$



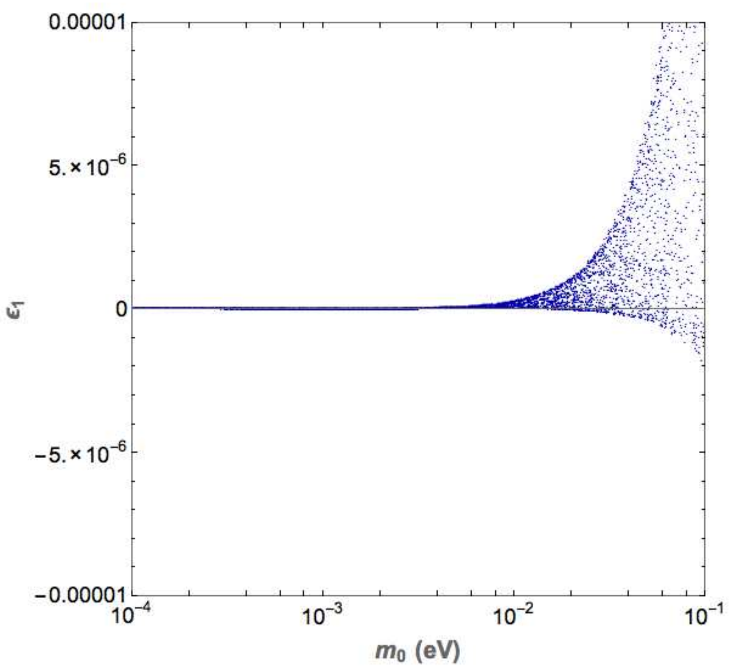


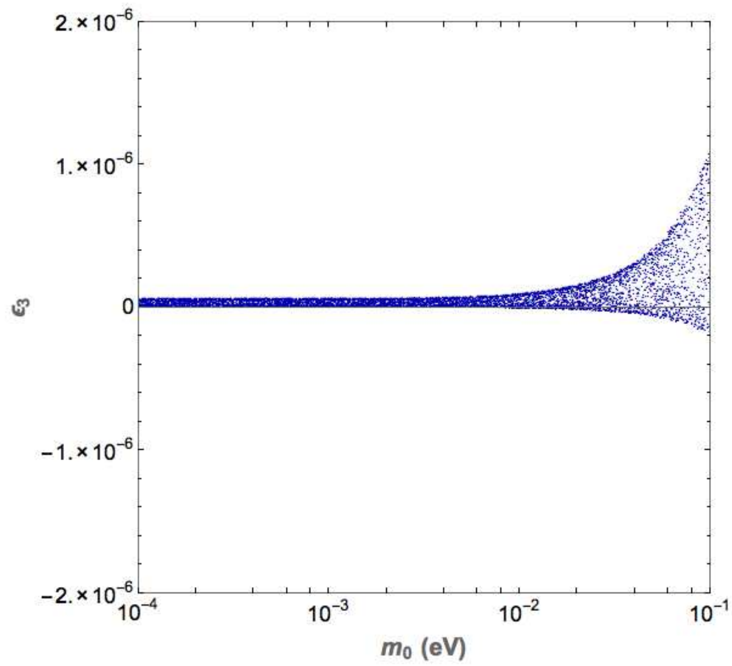
Leptogenesis in models with flavor and CP

Case 2 with $n = 8$, $u = 0$, $v = 6$:

Prediction for ϵ_1 and ϵ_3 vs lightest neutrino mass

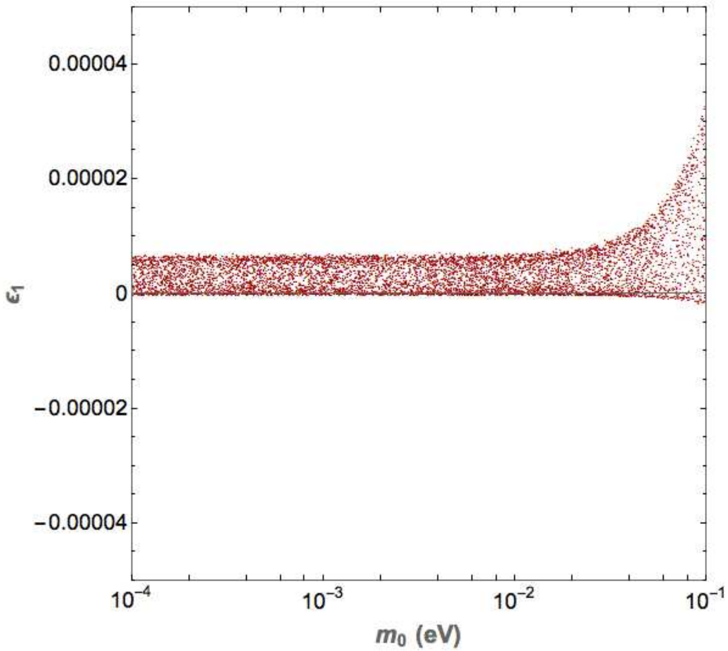
for normal ordering, $\kappa = 1.6 \times 10^{-3}$

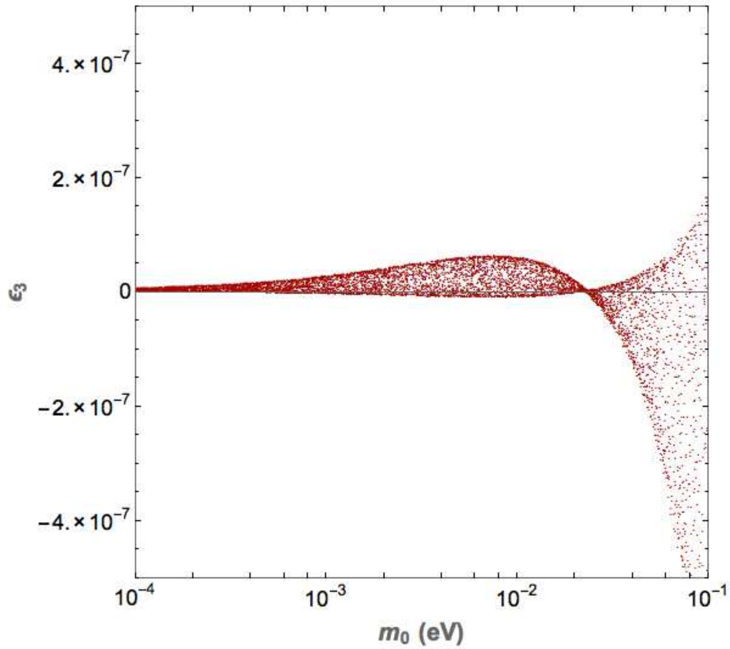




Leptogenesis in models with flavor and CP

Case 2 with $n = 8$, $u = 0$, $v = 6$:
Prediction for ϵ_1 and ϵ_3 vs lightest neutrino mass
for inverted ordering, $\kappa = 1.6 \times 10^{-3}$



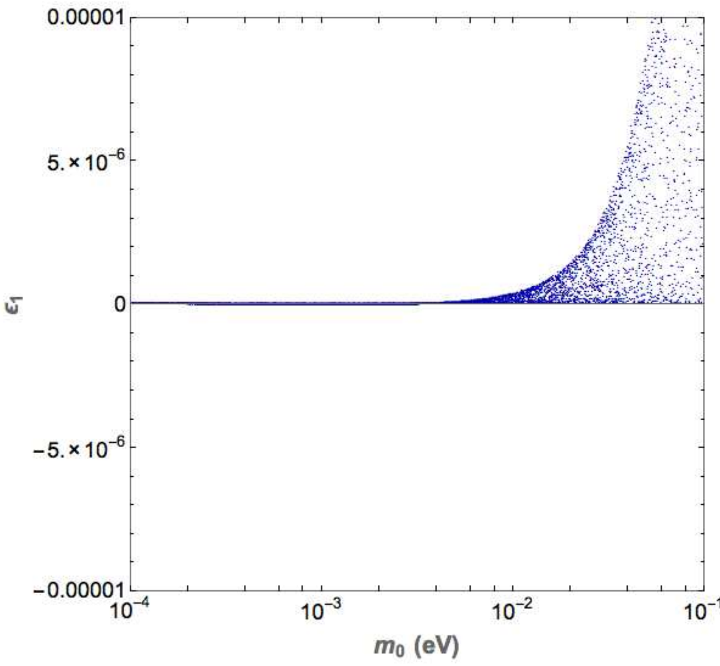


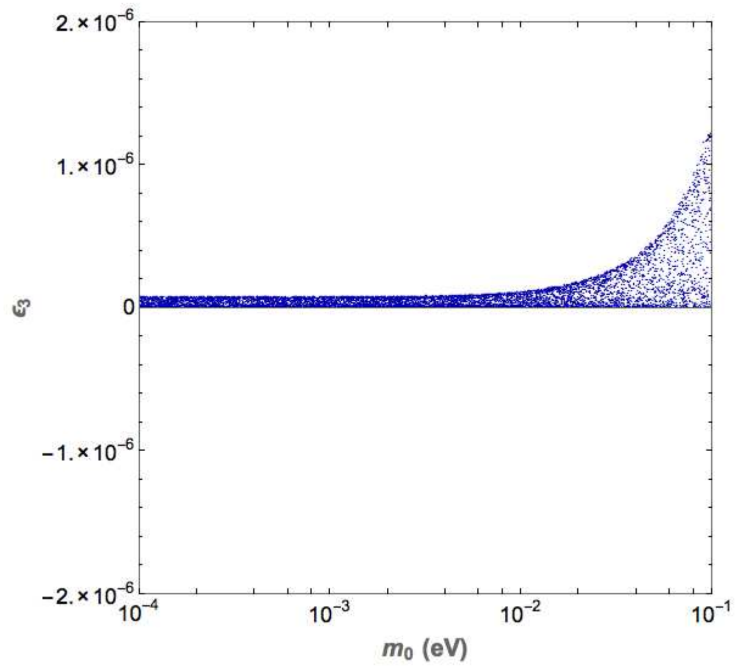
Leptogenesis in models with flavor and CP

Case 2 with $n = 8$, $u = 1$, $v = 3$:

Prediction for ϵ_1 and ϵ_3 vs lightest neutrino mass

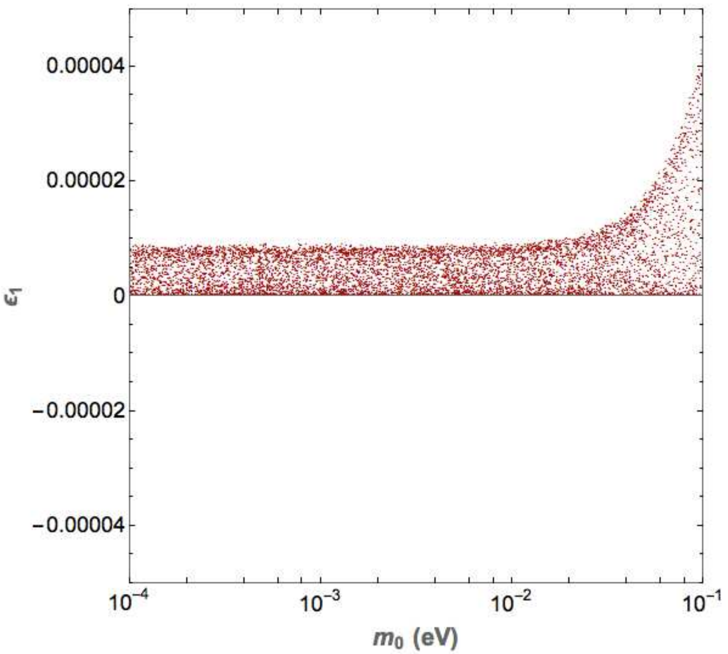
for normal ordering, $\kappa = 1.6 \times 10^{-3}$

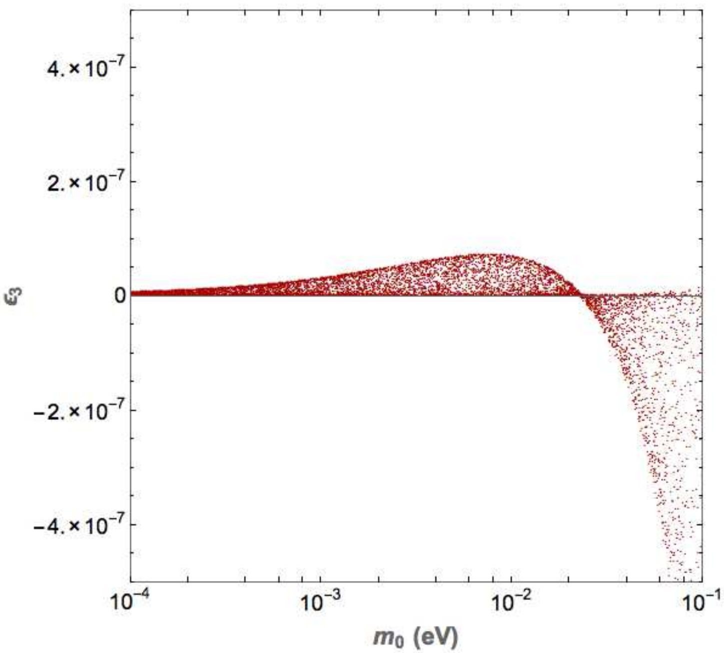




Leptogenesis in models with flavor and CP

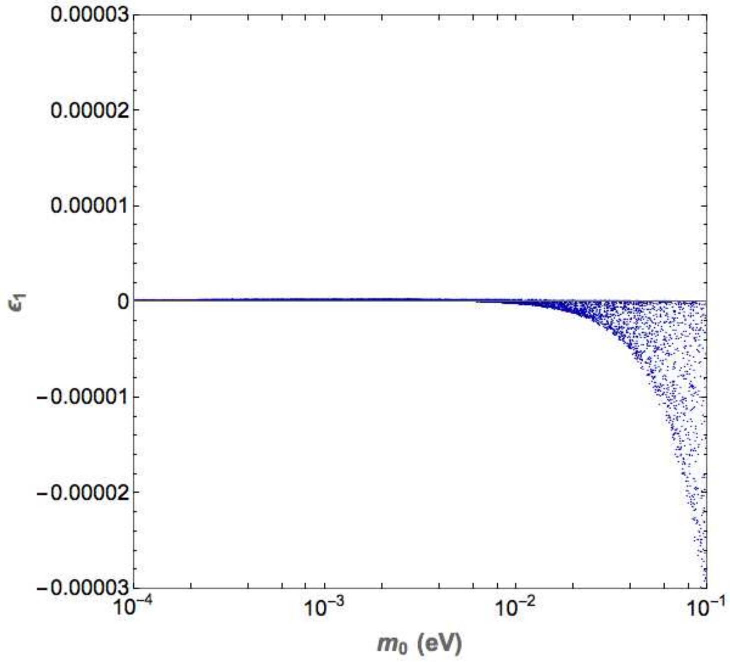
Case 2 with $n = 8$, $u = 1$, $v = 3$:
Prediction for ϵ_1 and ϵ_3 vs lightest neutrino mass
for inverted ordering, $\kappa = 1.6 \times 10^{-3}$

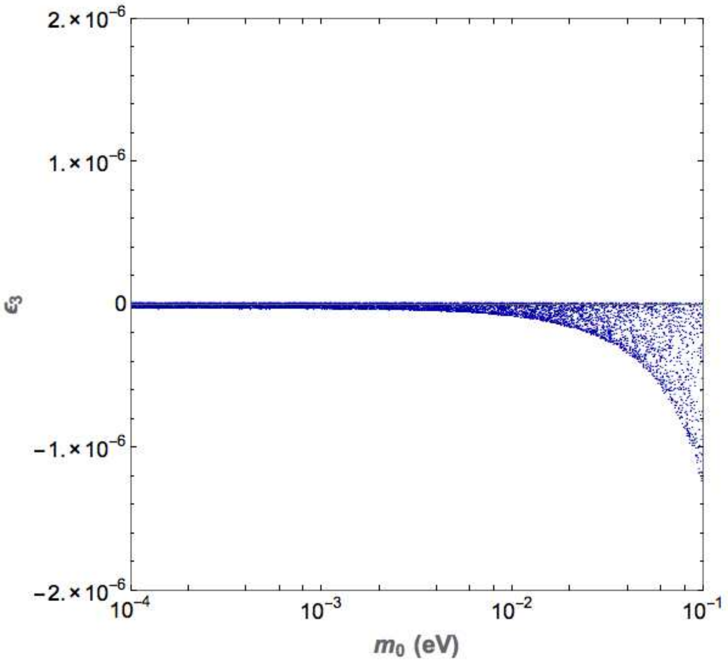




Leptogenesis in models with flavor and CP

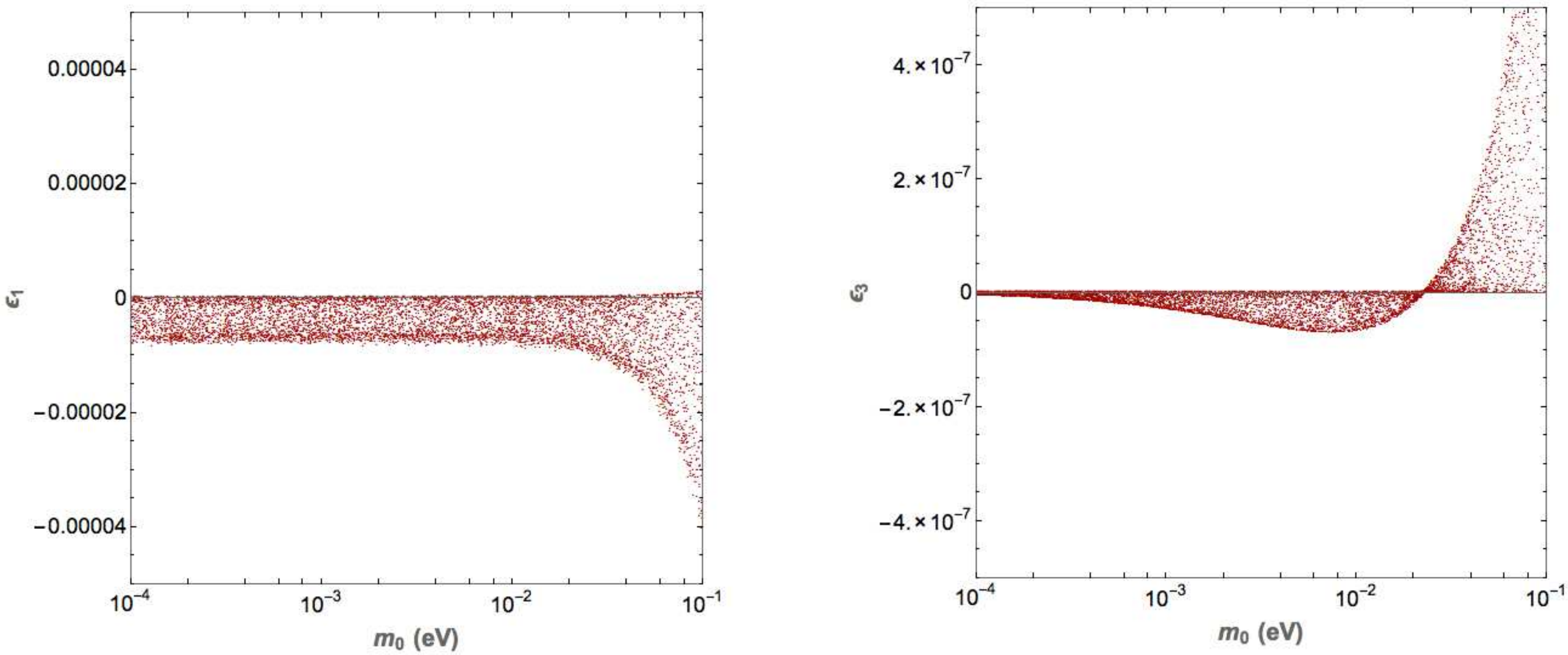
Case 3a with $n = 16$, $m = 1$, $s = 1$:
Prediction for ϵ_1 and ϵ_3 vs lightest neutrino mass
for normal ordering, $\kappa = 1.6 \times 10^{-3}$





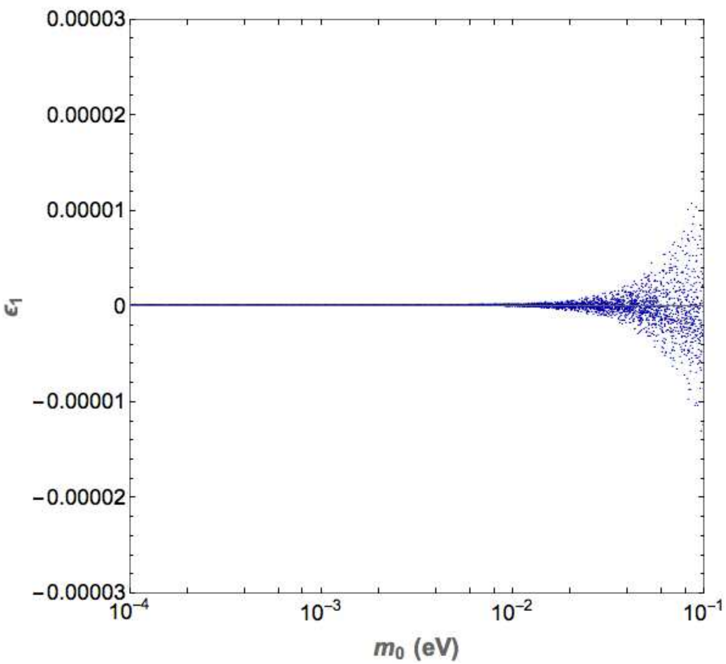
Leptogenesis in models with flavor and CP

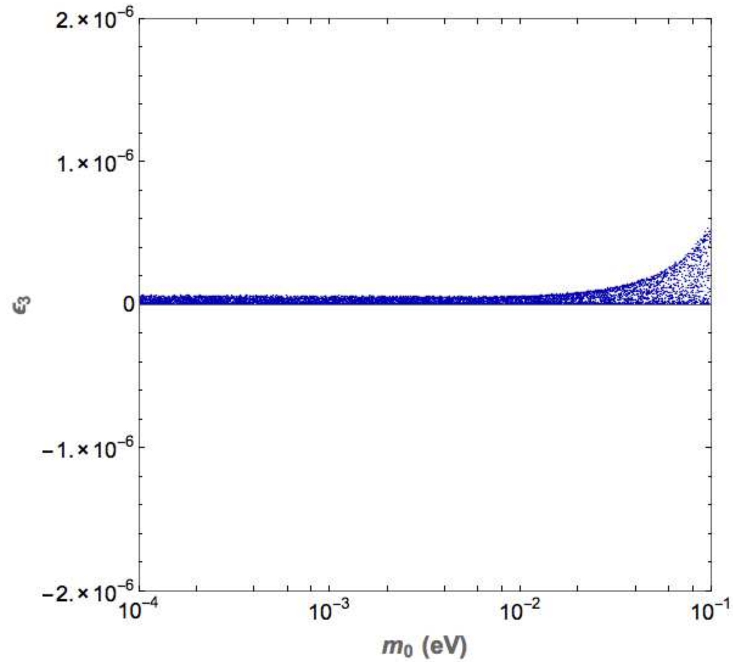
Case 3a with $n = 16$, $m = 1$, $s = 1$:
Prediction for ϵ_1 and ϵ_3 vs lightest neutrino mass
for inverted ordering, $\kappa = 1.6 \times 10^{-3}$



Leptogenesis in models with flavor and CP

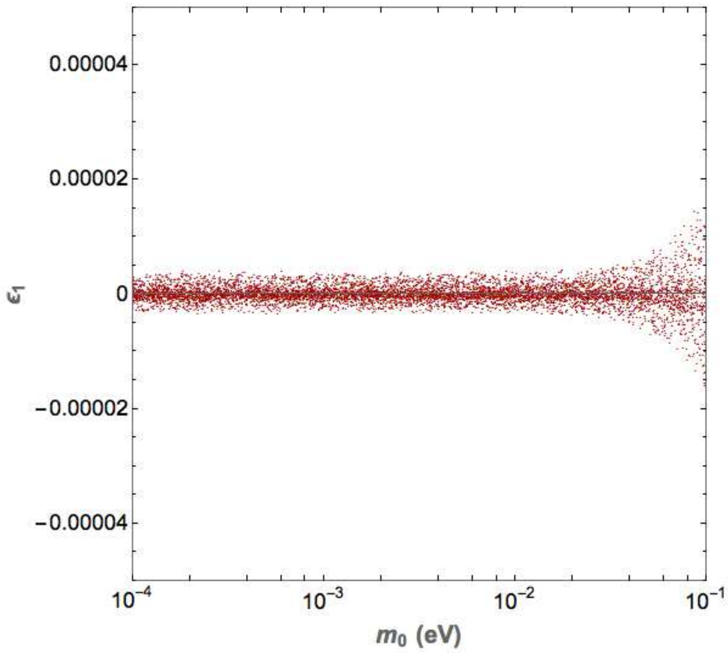
Case 3a with $n = 16$, $m = 1$, $s = 3$:
Prediction for ϵ_1 and ϵ_3 vs lightest neutrino mass
for normal ordering, $\kappa = 1.6 \times 10^{-3}$

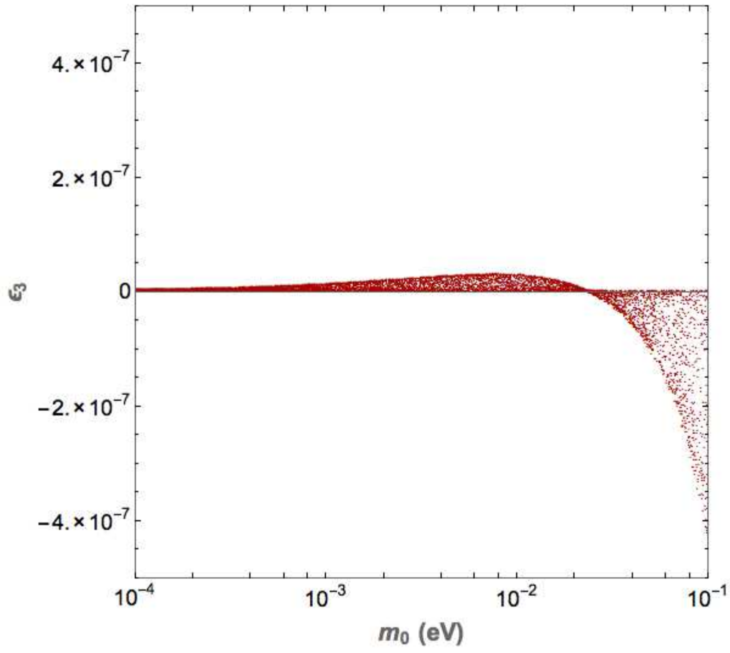




Leptogenesis in models with flavor and CP

Case 3a with $n = 16$, $m = 1$, $s = 3$:
Prediction for ϵ_1 and ϵ_3 vs lightest neutrino mass
for inverted ordering, $\kappa = 1.6 \times 10^{-3}$





Conclusions

- approach with flavor and CP symmetry very interesting: allows to predict CP phases and free parameter θ helps to accommodate mixing angles
- very rich structure of results for $G_f = \Delta(3\,n^2)$ and $\Delta(6\,n^2)$
- comprehensive study and analytical understanding of results
- study of $0\nu\beta\beta$ decay and leptogenesis in progress: constraints and correlations possible

Thank you for your attention.