A Survey of Neutrino Flavor Models and the Neutrinoless Double Beta Decay Funnel

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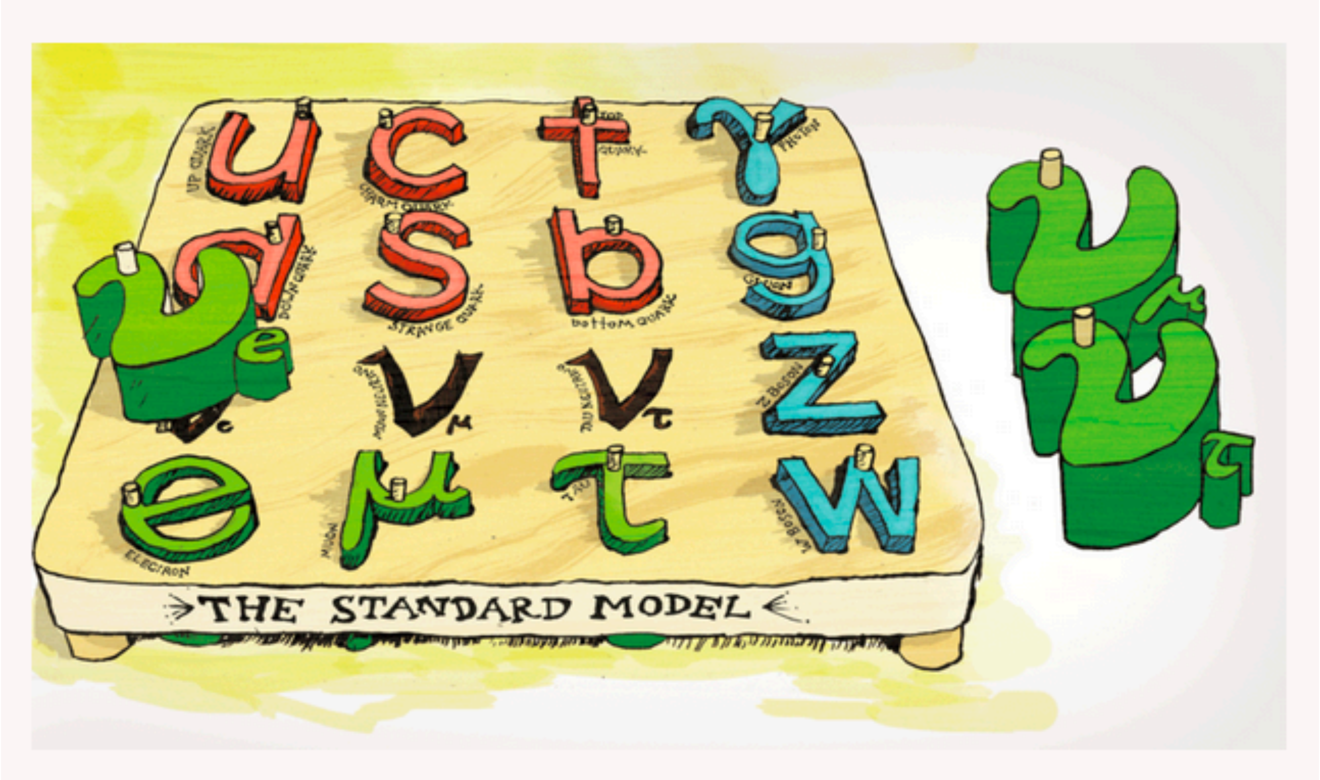
COLORADO STATE UNIVERSITY

Neutrino mass

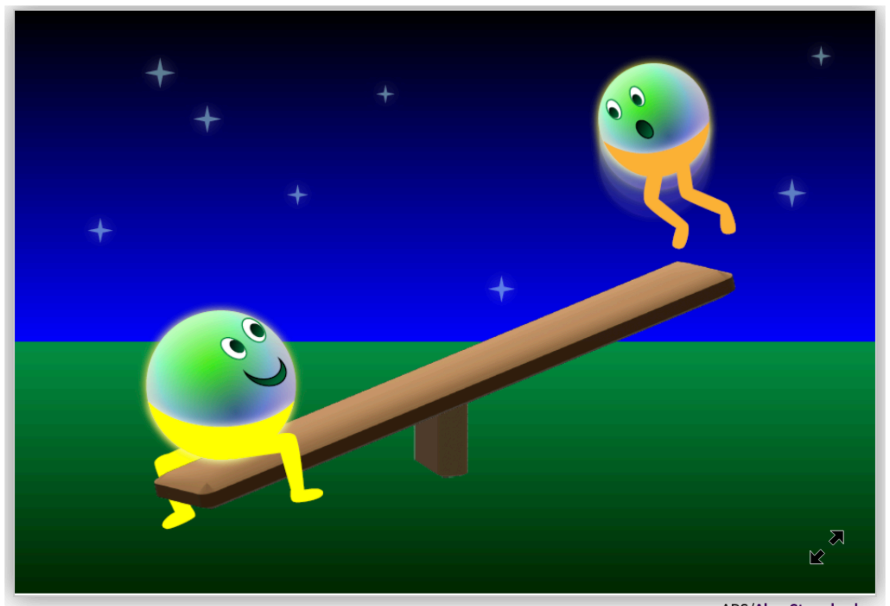
Observation of neutrino oscillations

$\Rightarrow$ neutrinos are massive



Where does their mass come from?

Dirac or Majorana mass term?



APS/Alan Stonebraker

Neutrino mass

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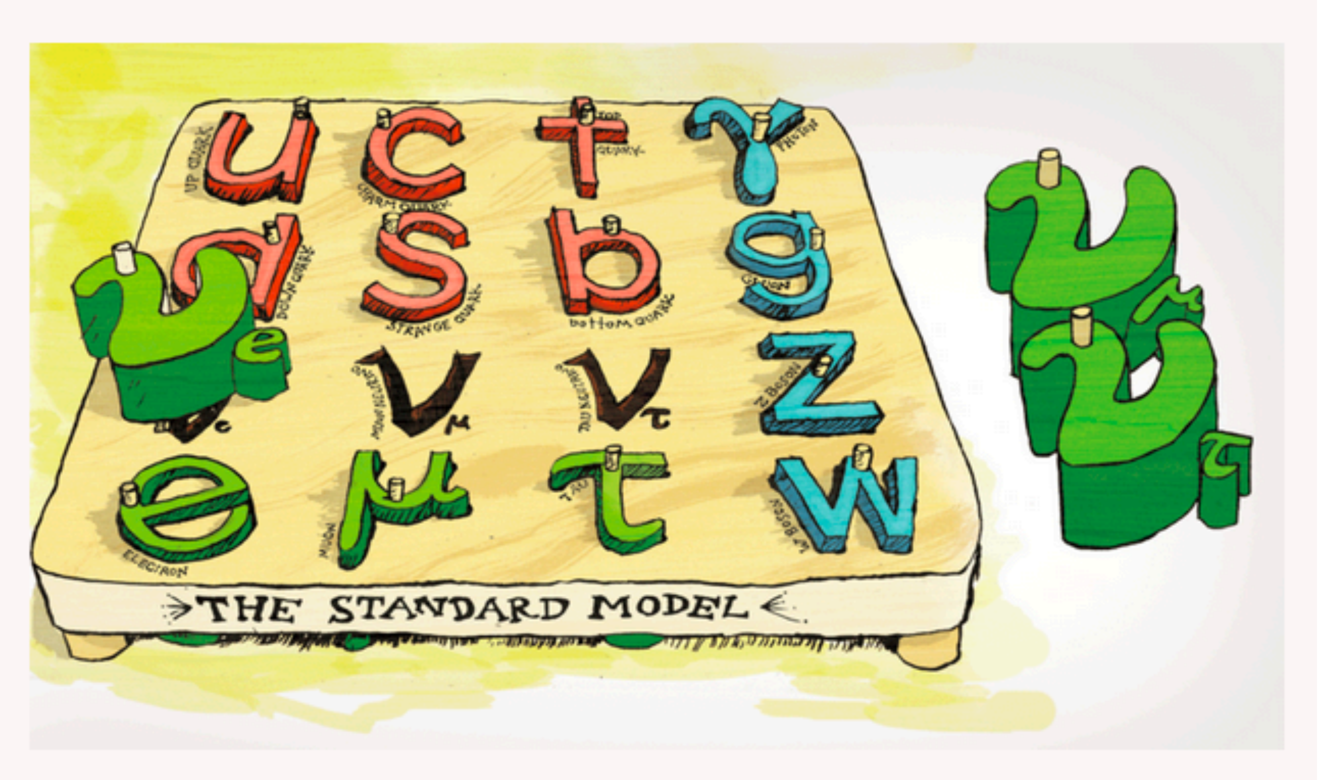
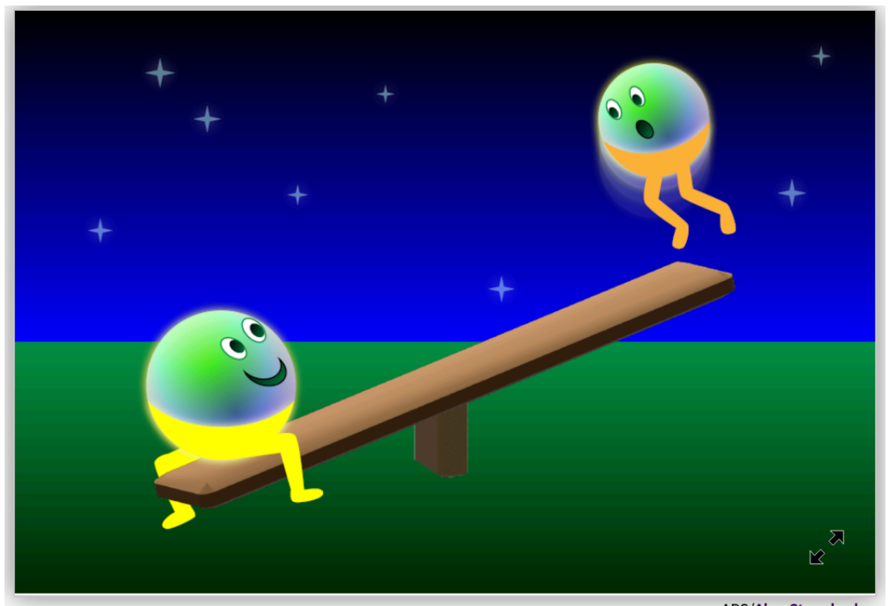


Where does their mass come from?

Dirac or Majorana mass term?

Is lepton number a conserved symmetry?



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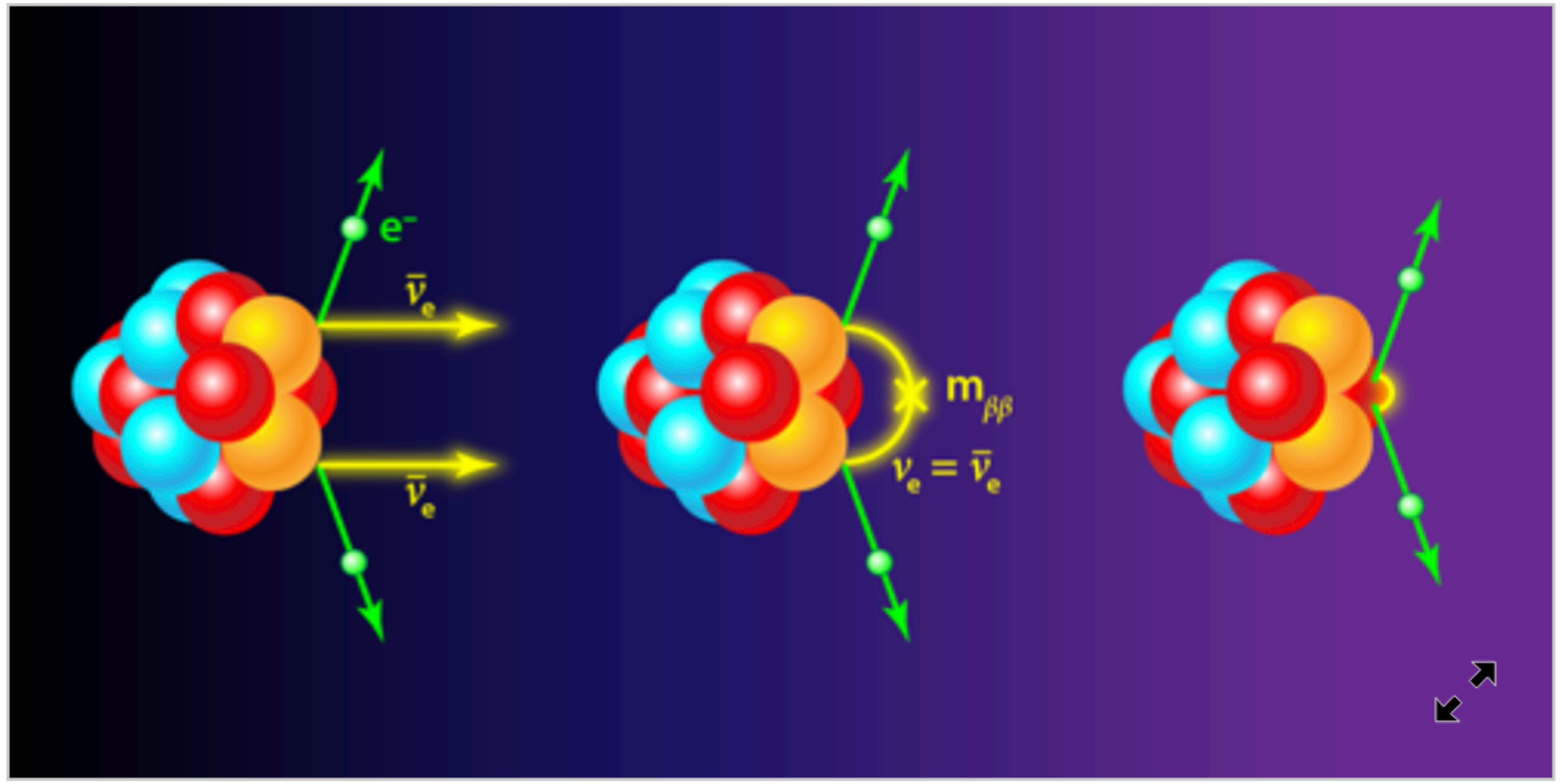
Neutrinoless double beta decay

Neutrinoless double beta decay: Neutrinos inside of nucleus absorbed if they are their own antiparticles: lepton number violation!

$$(Z, A) \to (Z+2, A) + 2\ e^-$$



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Neutrinoless double beta decay

Neutrinoless double beta decay:

$$(Z, A) \rightarrow (Z+2, A) + 2\ e^-$$

Nuclear matrix element

Observable: $T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2$

Half-life of decaying nucleus

Phase space factor of decay

Neutrinoless double beta decay

Neutrinoless double beta decay:

$$(Z, A) \rightarrow (Z+2, A) + 2\, e^-$$

Particle physics quantity

Nuclear matrix element

Source of large uncertainty

Observable: $T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2$

Half-life of decaying nucleus

Phase space factor of decay

Neutrinoless double beta decay

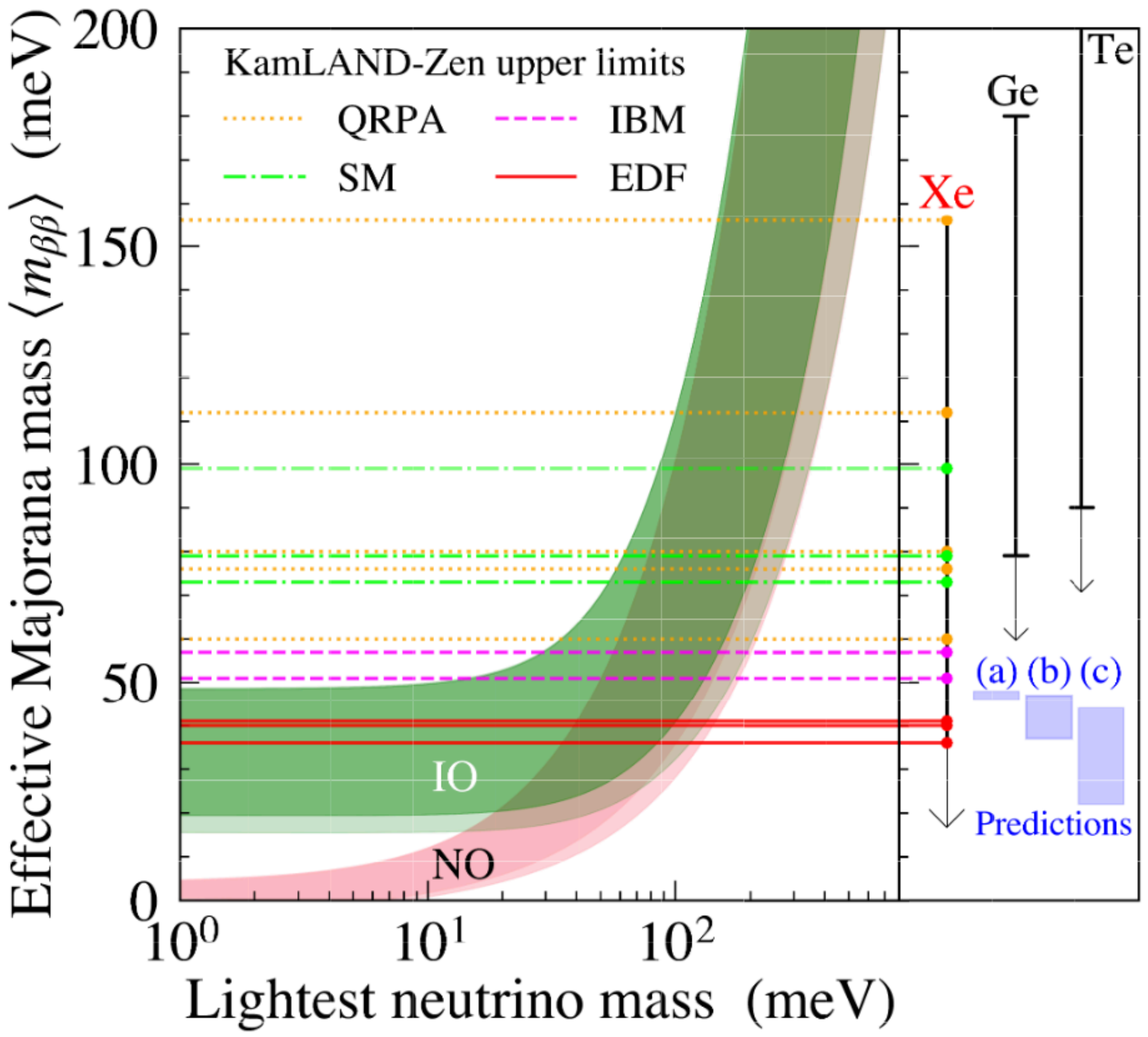
[KamLand-Zen 2203.02139]

Neutrinoless double beta decay:

$$(Z, A) \rightarrow (Z+2, A) + 2\, e^-$$

Observable: $T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2$

constraint: $m_{\beta\beta} < (36 - 156)$ eV, depending on nuclear matrix element $|M^{0\nu}|^2$



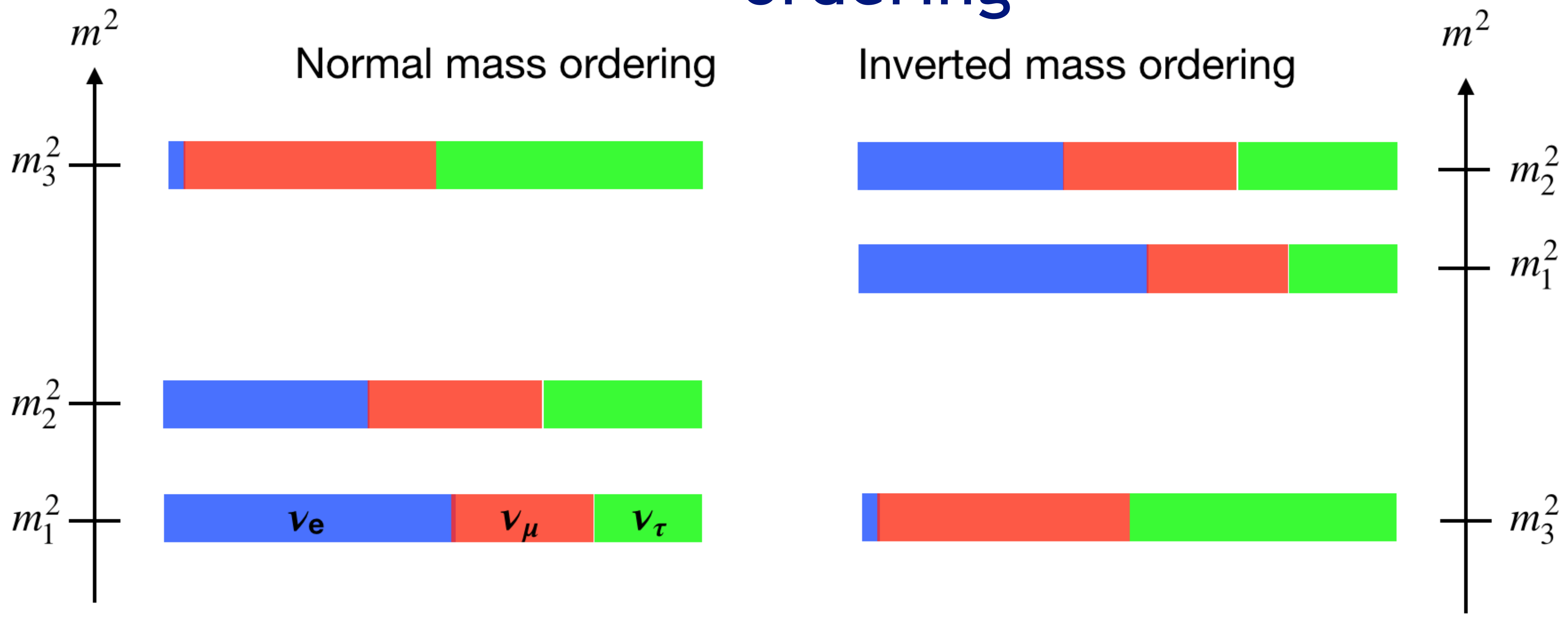
Neutrinoless double beta decay

$$|m_{\beta\beta}| = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$

$$= |\cos^2\theta_{12}\cos^2\theta_{13} m_1 e^{-i\alpha} + \sin^2\theta_{12}\cos^2\theta_{13} m_2 e^{-i\beta} + \sin^2\theta_{13} m_3|$$

With measured values of mixing angles and mass splittings:

Unknown parameters in $|m_{\beta\beta}|$: absolute mass scale, unknown Majorana phases, mass ordering



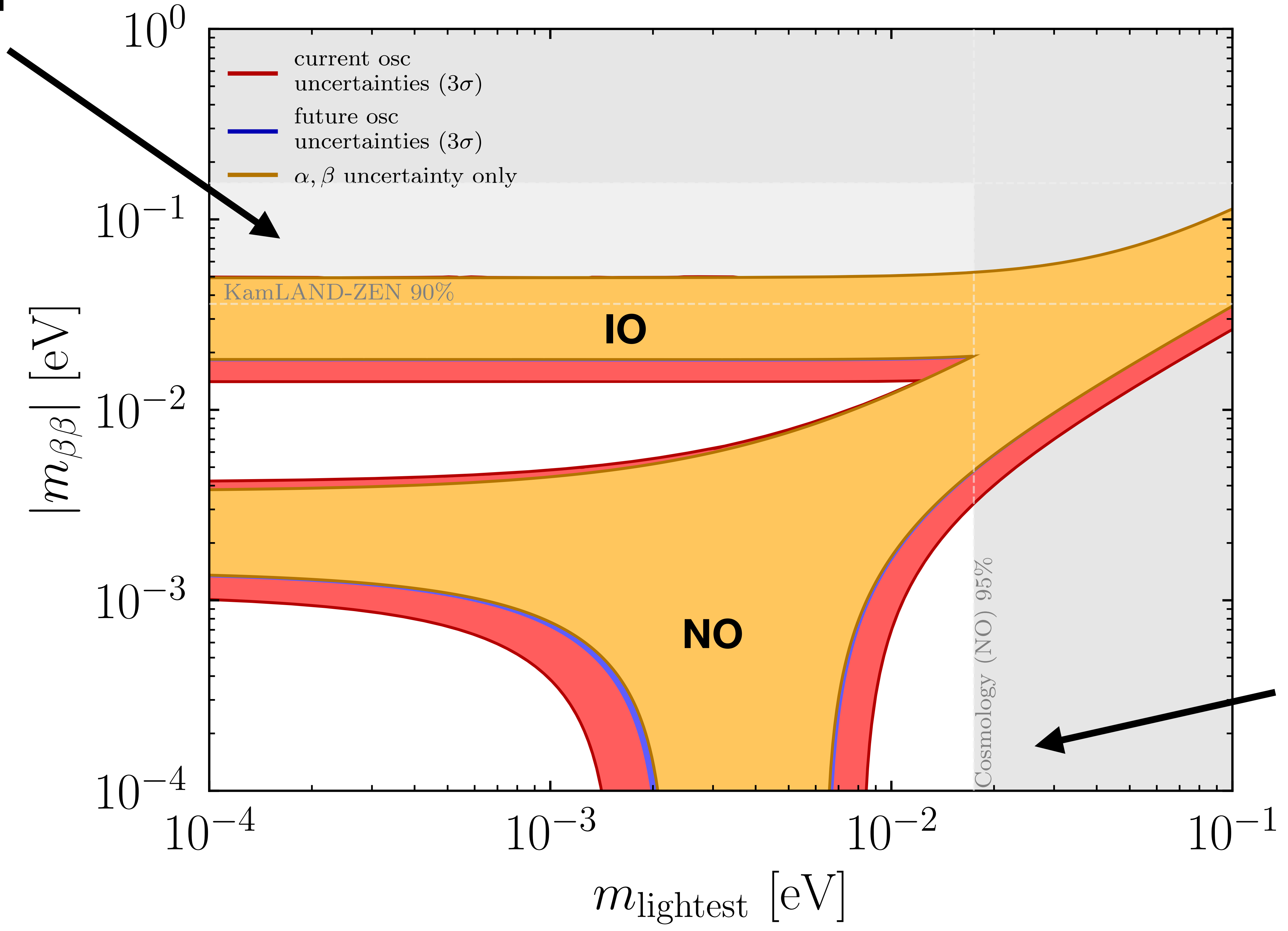
Slight preference (2.7σ) for NO from oscillation experiments

Neutrinoless double beta decay

$$|m_{\beta\beta}| = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$

$$= |\cos^2\theta_{12}\cos^2\theta_{13} m_1 e^{-i\alpha} + \sin^2\theta_{12}\cos^2\theta_{13} m_2 e^{-i\beta} + \sin^2\theta_{13} m_3|$$

Current bound on $|m_{\beta\beta}|$



Width of bands: unknown Majorana phases

Upcoming oscillation experiments will select MO and slightly decrease parameter space

Interplay with cosmology: sum of neutrino masses

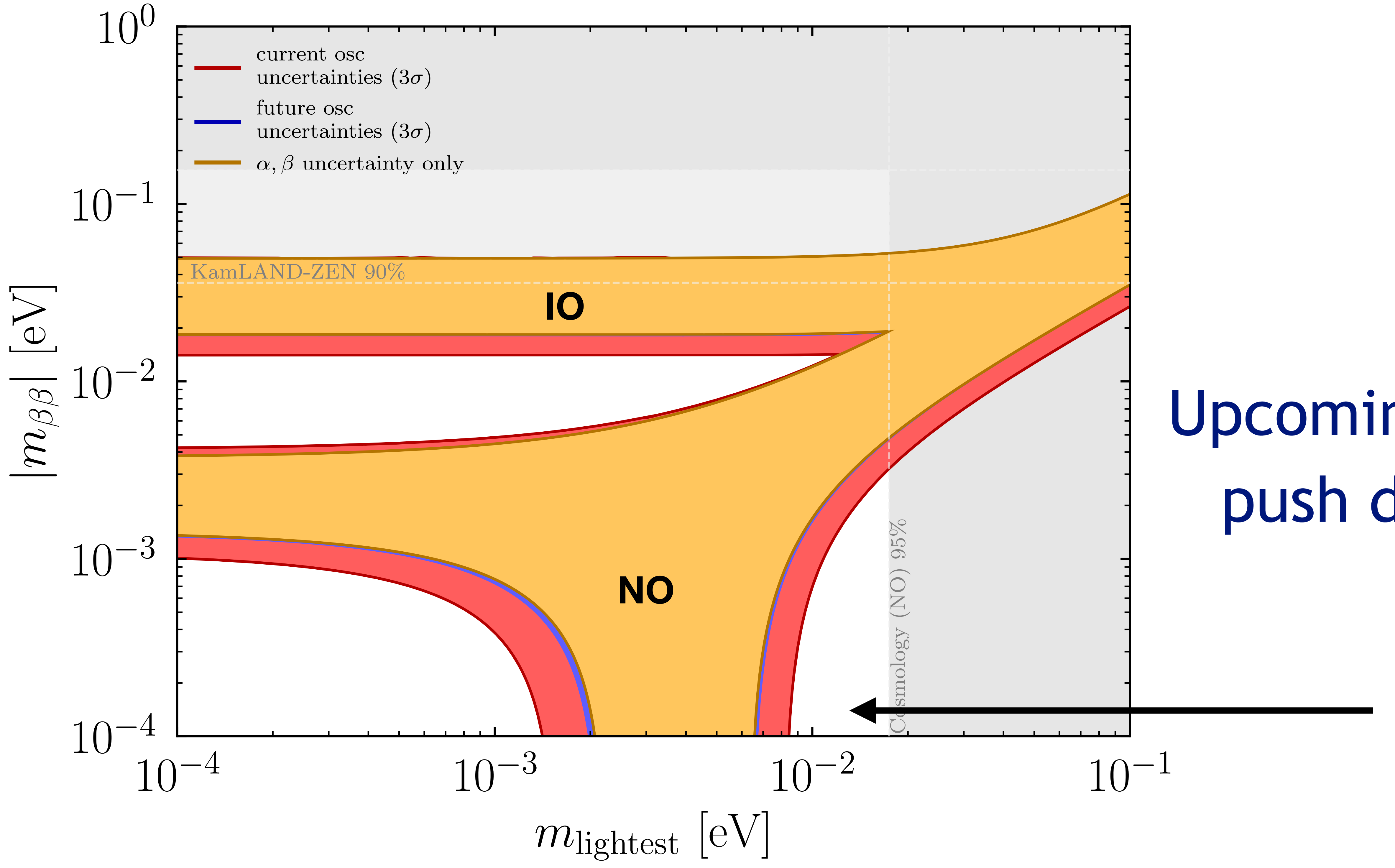
[JG, Denton 2308.09737]

Neutrinoless double beta decay

$$|m_{\beta\beta}| = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$

$$= |\cos^2\theta_{12}\cos^2\theta_{13}m_1 e^{-i\alpha} + \sin^2\theta_{12}\cos^2\theta_{13}m_2 e^{-i\beta} + \sin^2\theta_{13}m_3|$$

$0\nu\beta\beta$ experiments push sensitivities down to probe IO



Upcoming experiments will continue to push down constraints on m_{lightest}

[JG, Denton 2308.09737]

Neutrinoless double beta decay

$$|m_{\beta\beta}| = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$

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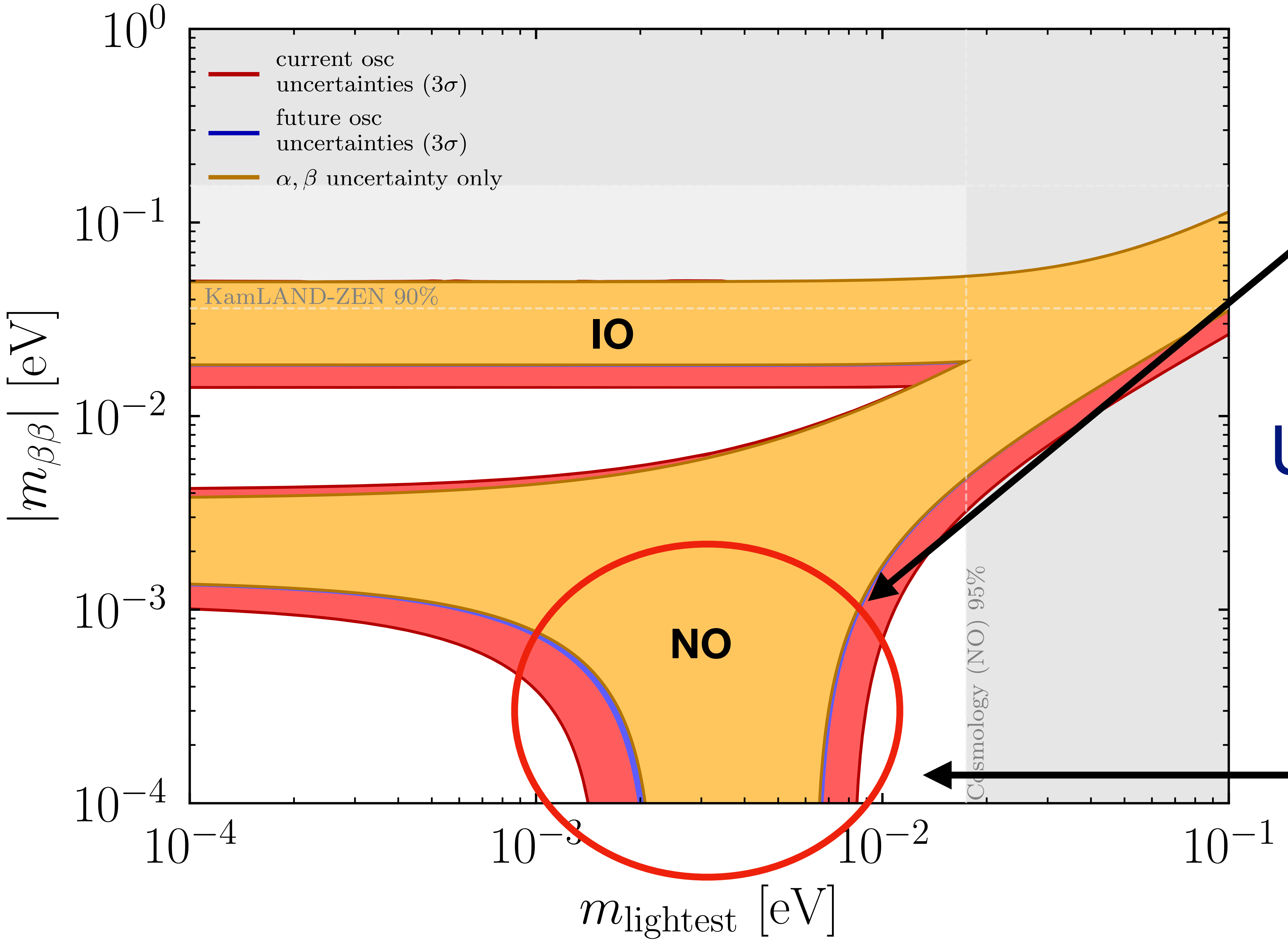
$0\nu\beta\beta$ experiments push sensitivities down to probe IO



Funnel region in NO experimentally challenging $|m_{\beta\beta}|$ very small due to accidental cancellation

Upcoming experiments will continue to push down constraints on m_{lightest}

[JG, Denton 2308.09737]

Neutrinoless double beta decay

Is the funnel region in NO with $|m_{\beta\beta}| < 1$ meV

theoretically preferred?

A Survey of Neutrino Flavor Models and the Neutrinoless Double Beta Decay Funnel

Peter B. Denton[a,1] **and Julia Gehrlein**[b,c,a,2]

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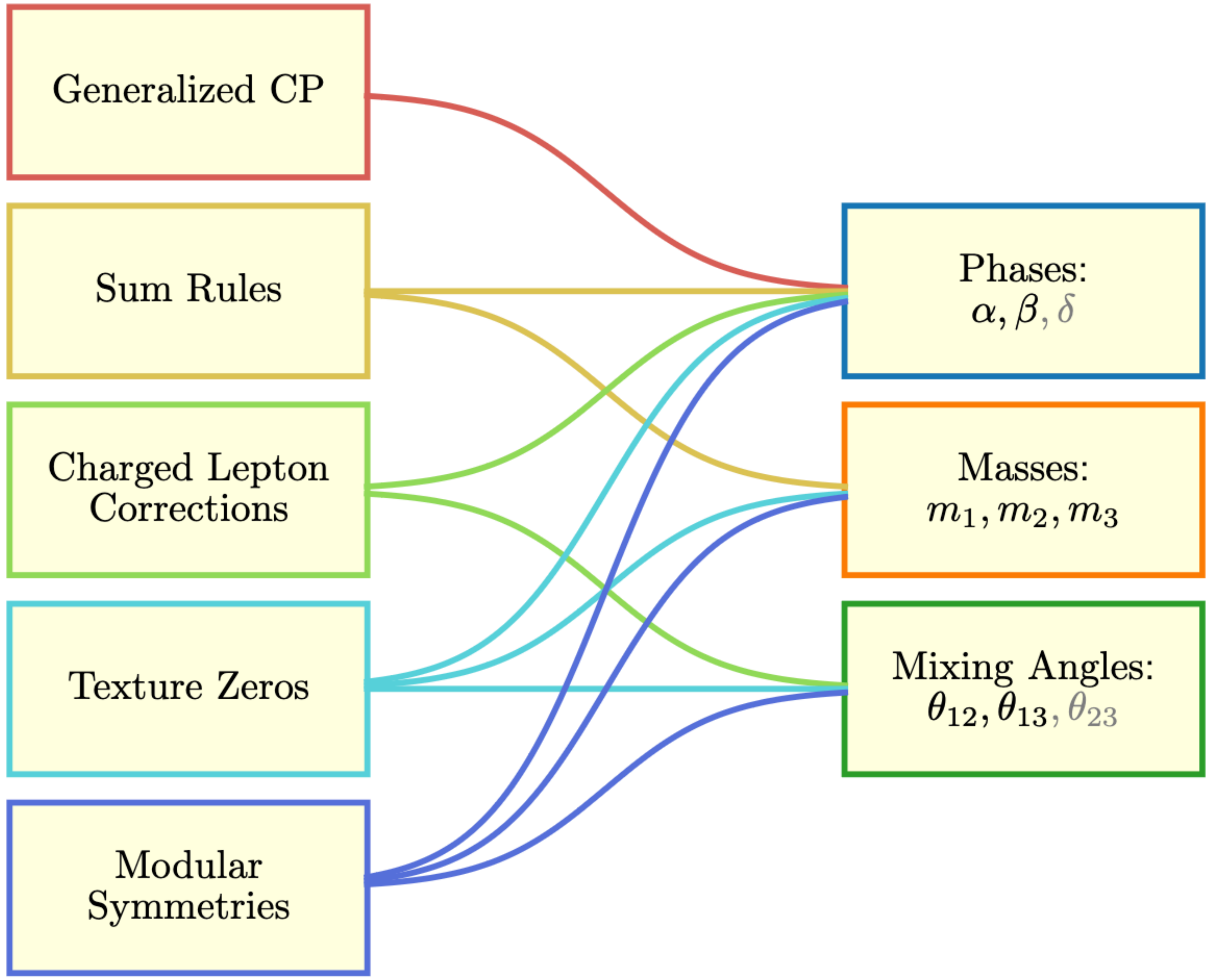
[b] *Physics Department, Colorado State University, Fort Collins, CO 80523, USA*

[c] *Theoretical Physics Department, CERN, 1 Esplanade des Particules, 1211 Geneva 23, Switzerland*

[JG, Denton 2308.09737]

Flavor models

Surveyed five broad categories of flavor models with various different predictions for parameters relevant for neutrinoless double beta decay



Determine fraction of parameter space in funnel

[JG, Denton 2308.09737]

Texture zeros

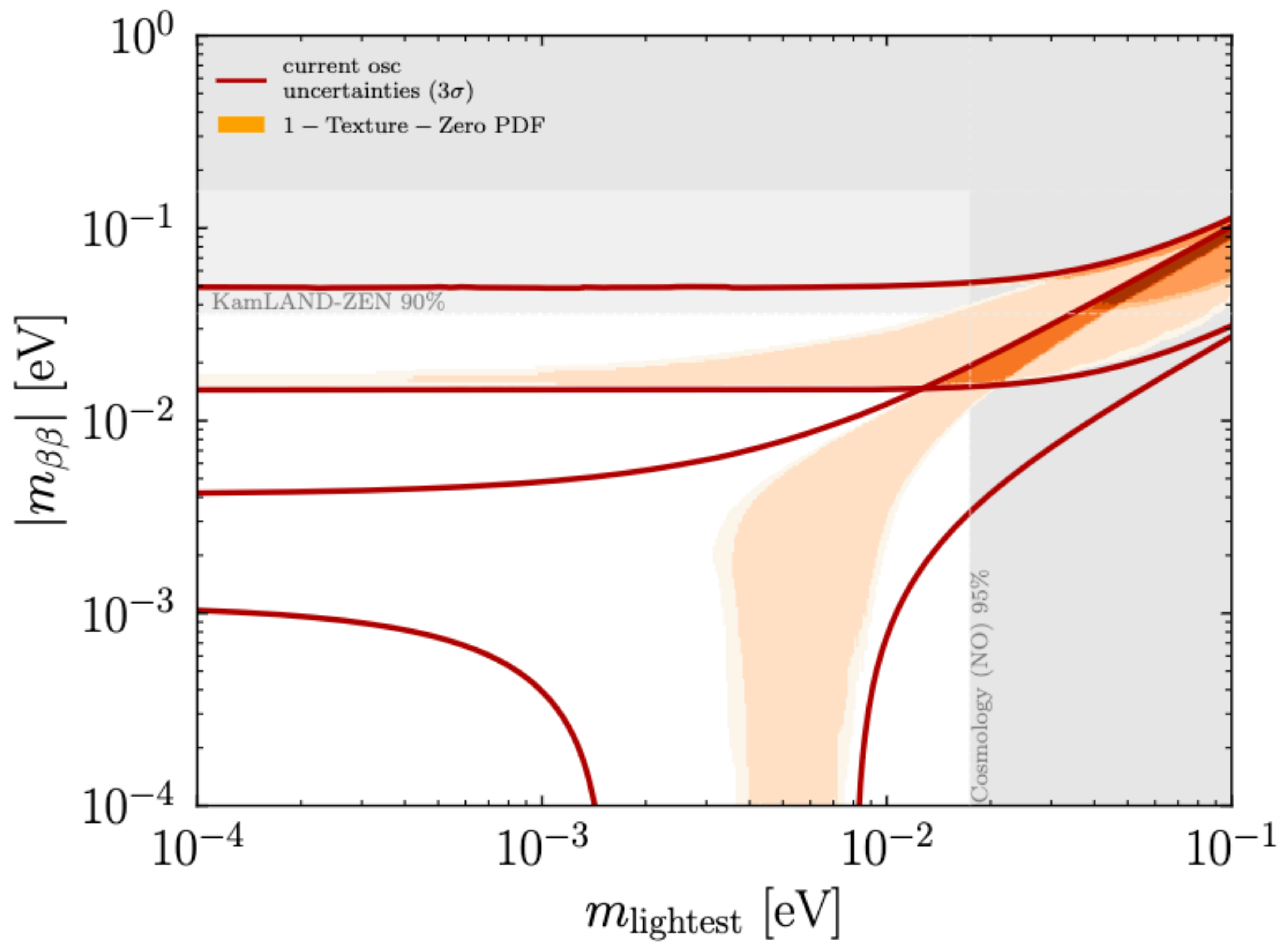
Assume symmetric Majorana mass matrix has vanishing entries

[JG, Denton 2308.09737]

1-1 elements is $|m_{\beta\beta}|$

All 6 possible one-texture zero mass matrices in agreement with data

	Fraction in funnel
M_{ee}	1
$M_{e\mu}$	0.31
$M_{e\tau}$	0.30
$M_{\mu\mu}$	0
$M_{\mu\tau}$	0
$M_{\tau\tau}$	0



Texture zeros

Assume symmetric Majorana mass matrix has vanishing entries

[JG, Denton 2308.09737]

1-1 elements is $|m_{\beta\beta}|$

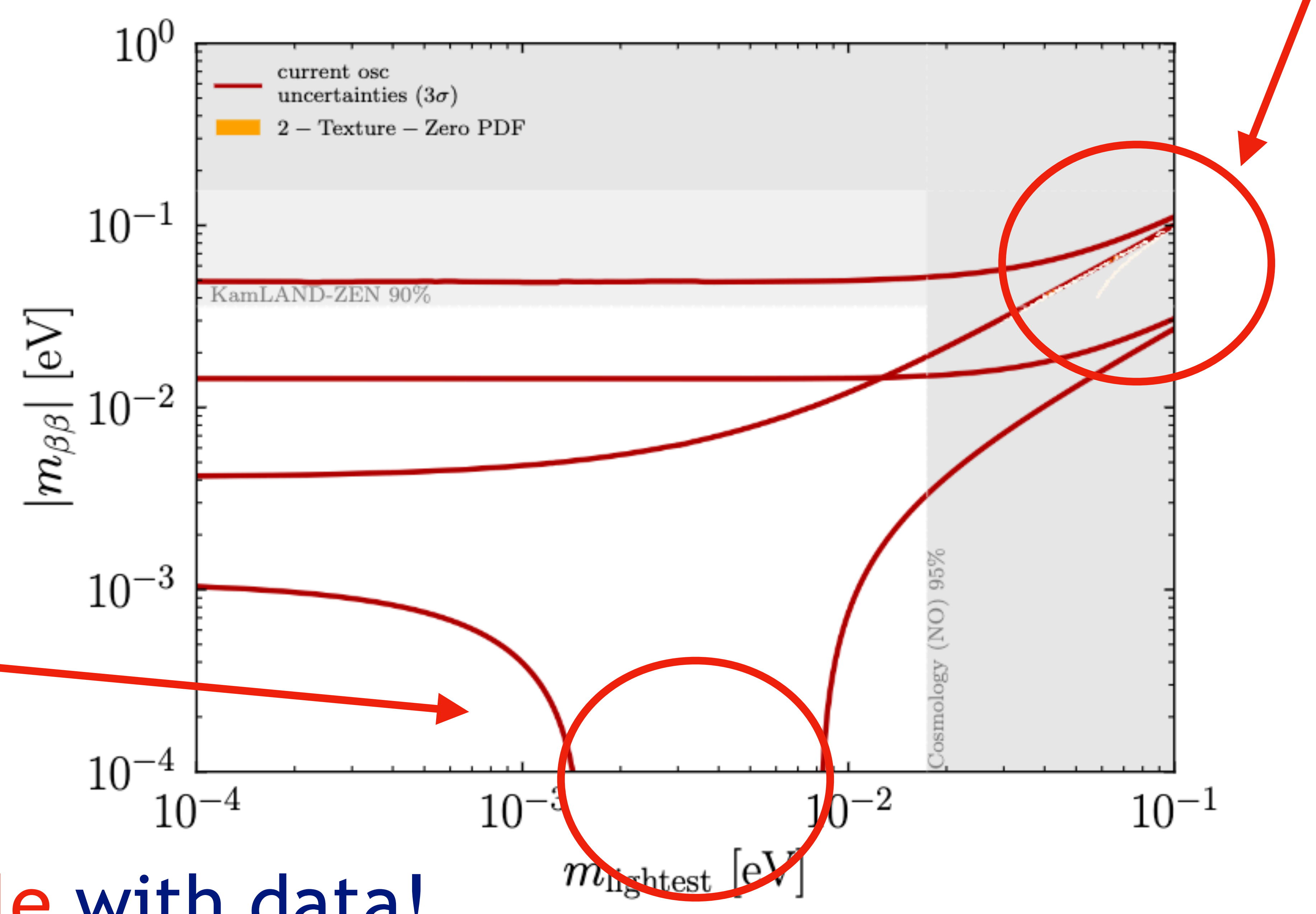
7 of 15 possible two-texture zero mass matrices in agreement with data

	$M_{e\mu}$	$M_{e\tau}$	$M_{\mu\mu}$	$M_{\mu\tau}$	$M_{\tau\tau}$
M_{ee}	1	1	X	X	X
$M_{e\mu}$		X	0	X	0
$M_{e\tau}$			0	X	0
$M_{\mu\mu}$				X	0
$M_{\mu\tau}$					X

New result!

Constrained by cosmology

Models fully in funnel



Models with 3+ texture zeros not compatible with data!

Mass sum rules

$$c_1 e^{i\chi_1}(m_1 e^{i\alpha})^d + c_2 e^{i\chi_2}(m_2 e^{i\beta})^d + m_3^d = 0$$

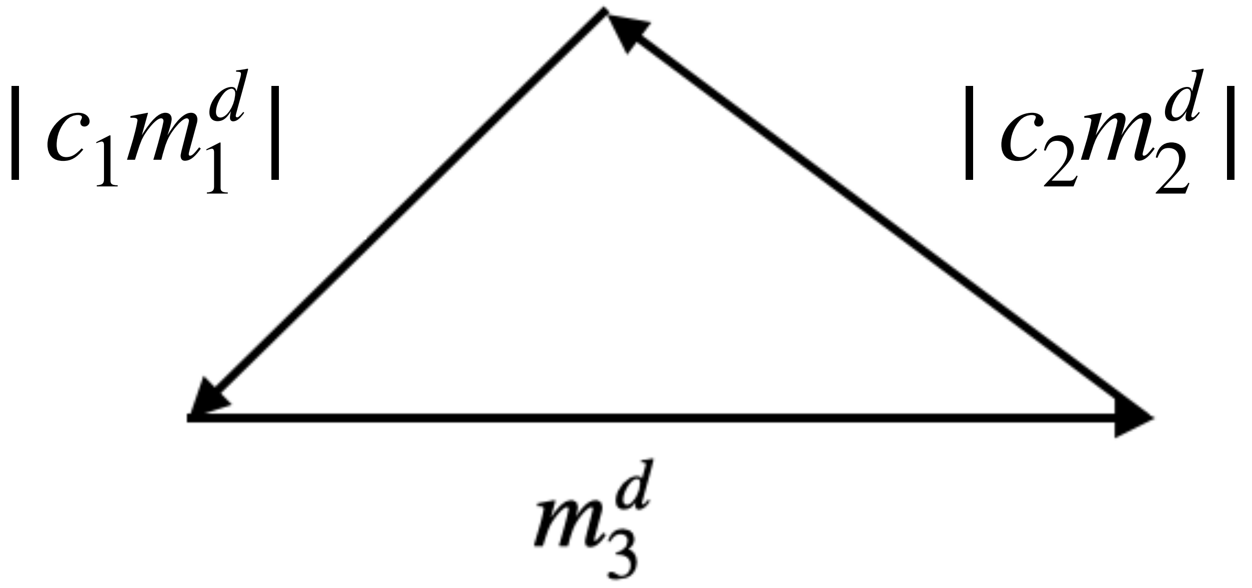
[S. King, A. Merle, A. Stuart '13
J. Barry, W. Rodejohann '10]

12 different SR in over 60 models realized in literature

$$c_i \sim \mathcal{O}(1),\ \chi_i = (0,\ \pi,\ \pm\pi/2),\ d = (1,\ -1,\ \pm 1/2),$$

constant and fixed by model

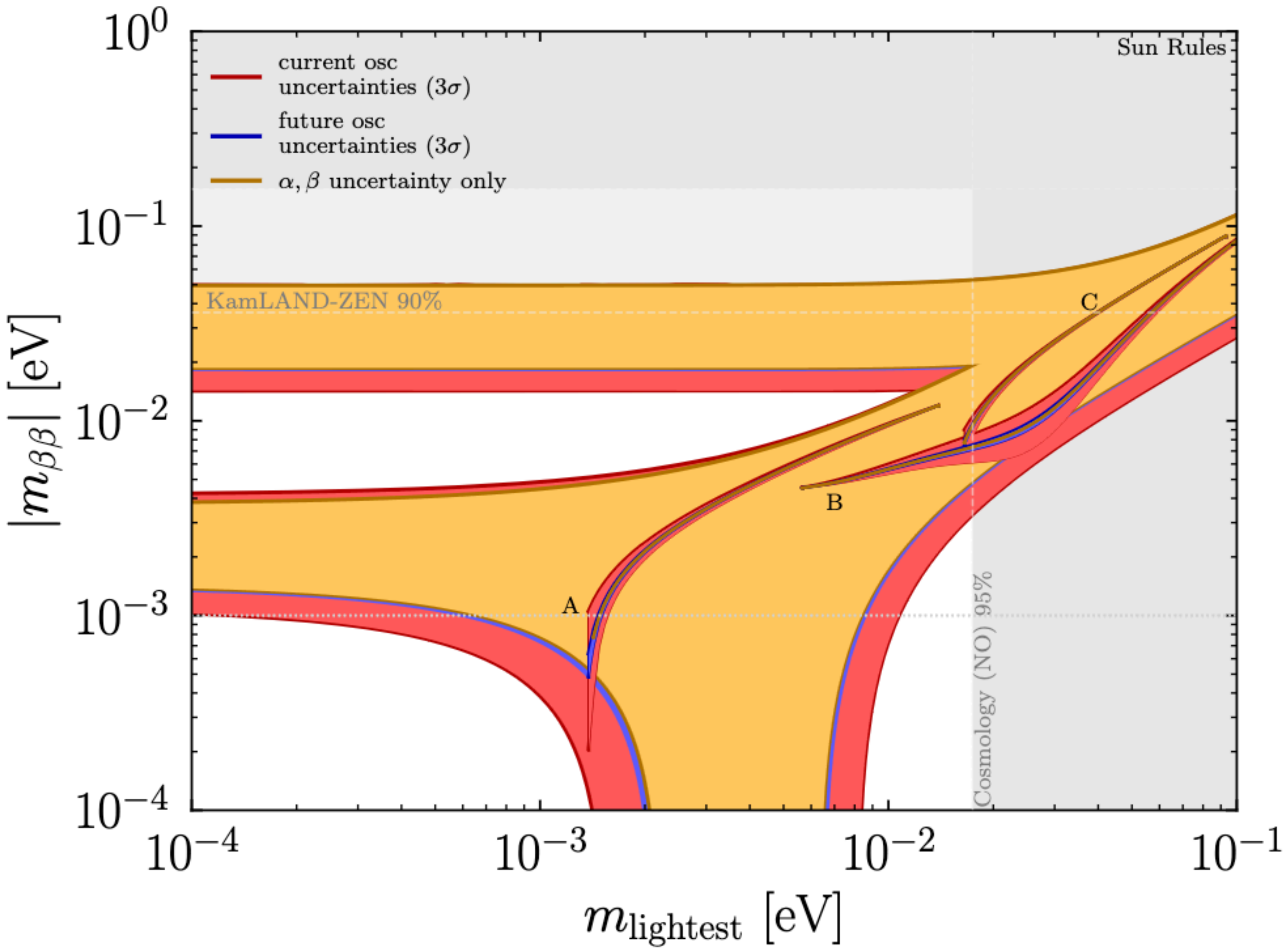
parametrized as triangle in complex plane



Mass sum rules

$$c_1 e^{i\chi_1}(m_1 e^{i\alpha})^d + c_2 e^{i\chi_2}(m_2 e^{i\beta})^d + m_3^d = 0$$

[JG, Denton 2308.09737]



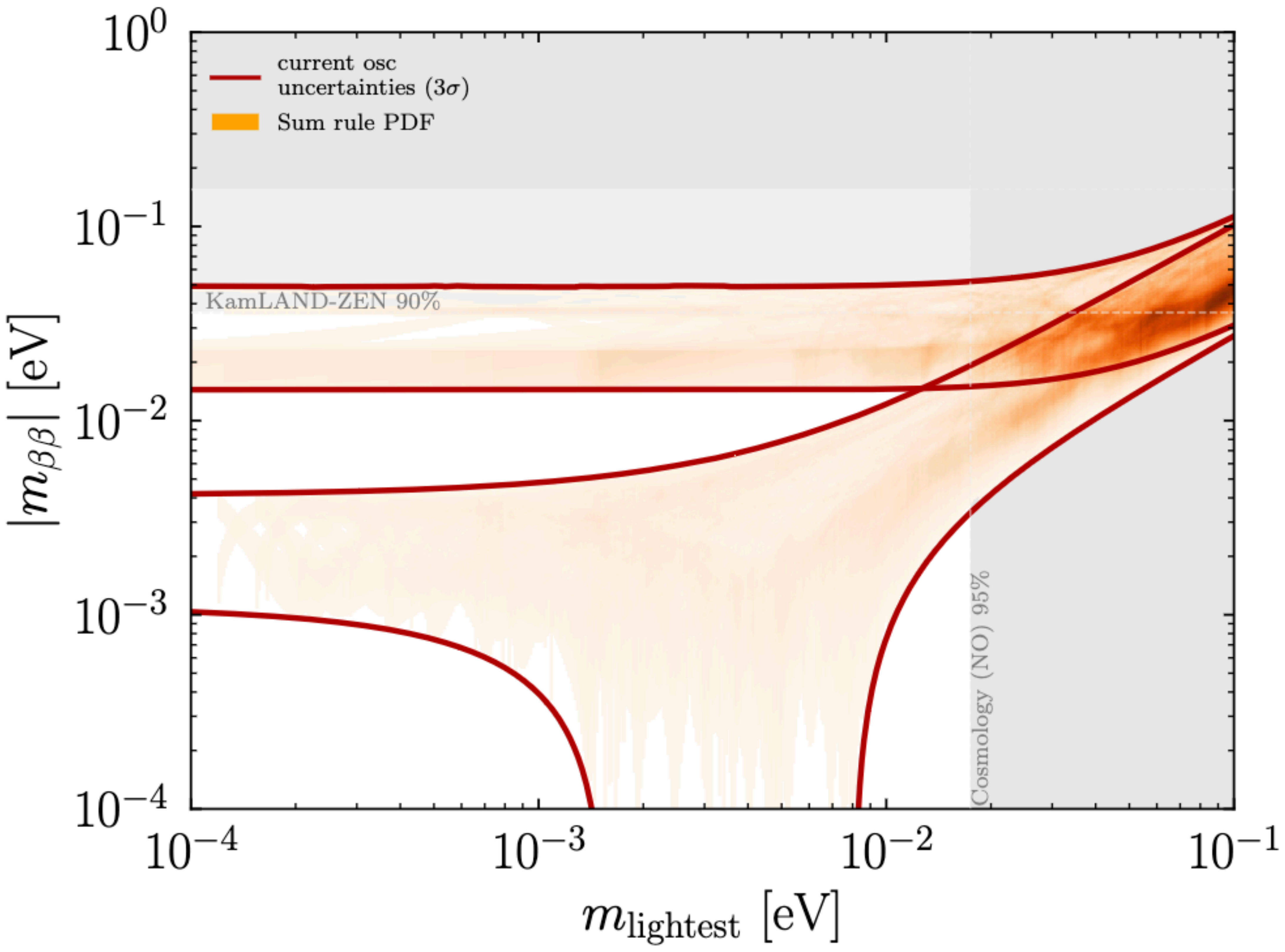
$$(c_1, c_2, d, \chi_1, \chi_2) : A : (1,2,1/2,\pi, \pi/2), B : (1/2,1/2, -1/2,\pi, \pi), C : (1,2,1,\pi,0)$$

Mass sum rules

3137 models tested, found 1968 viable models

[JG, Denton 2308.09737]

Probability density plot



Predict large neutrino masses

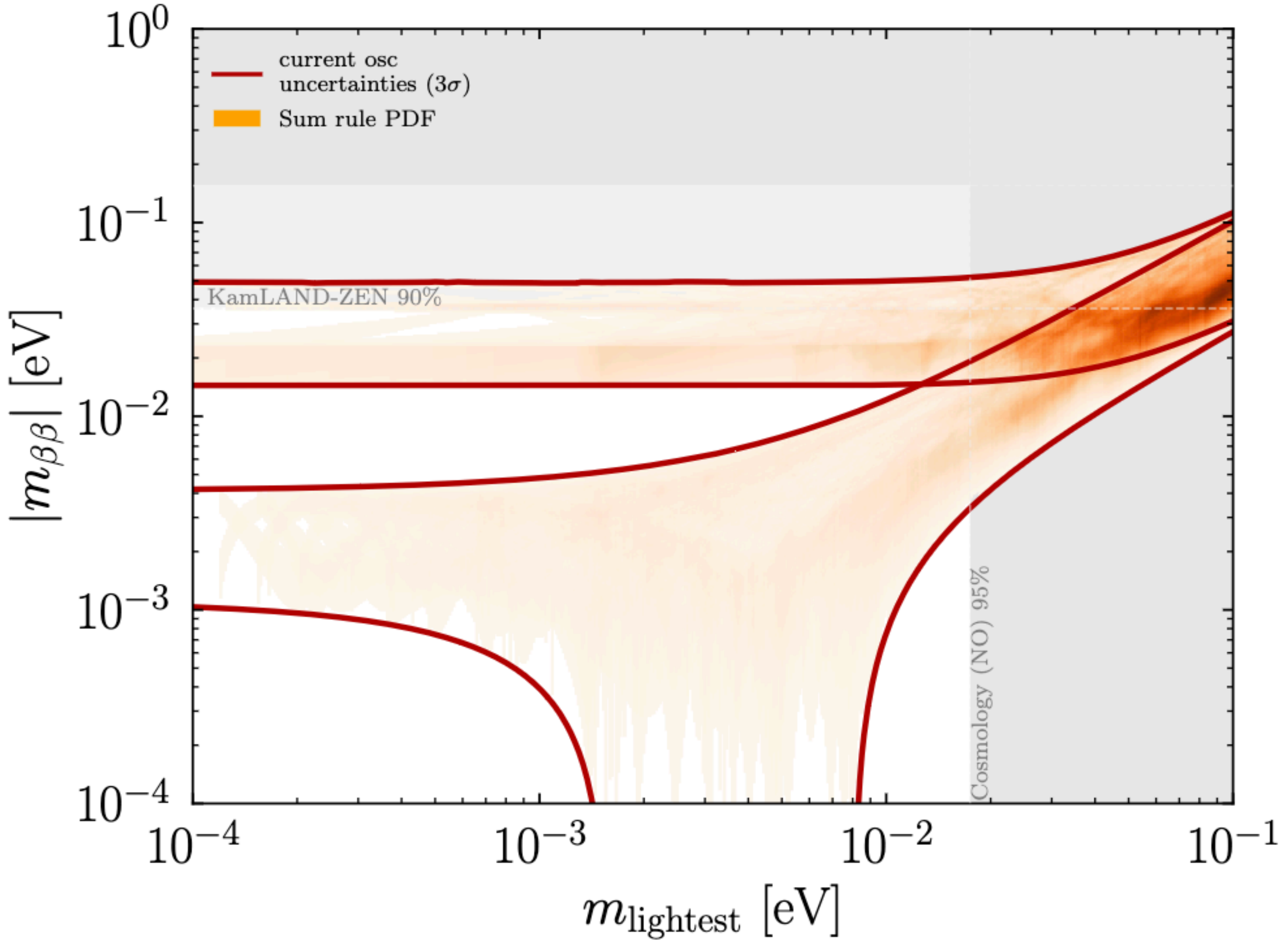
→ tested with cosmology

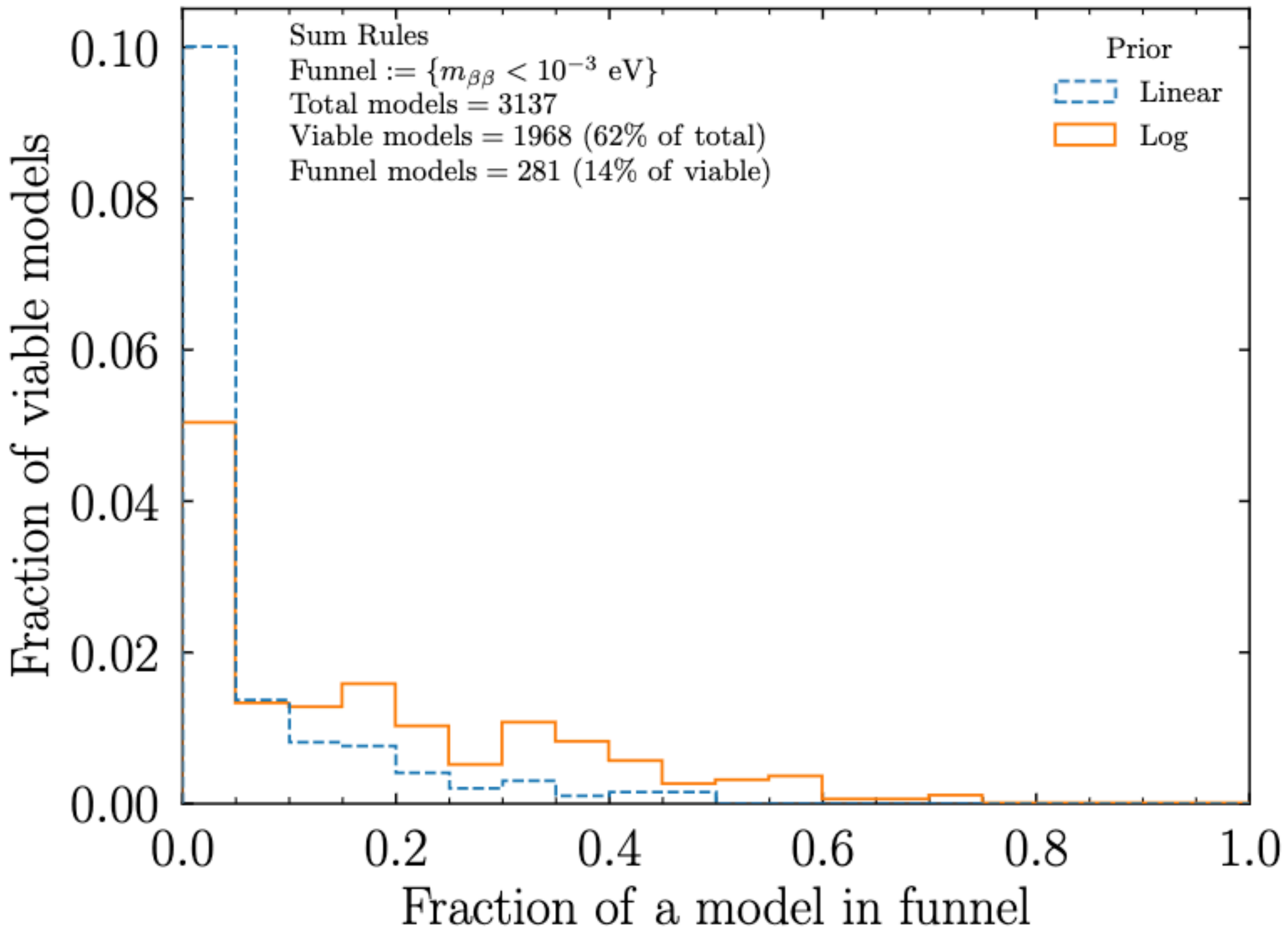
Mass sum rules

3137 models tested, found 1968 viable models

[JG, Denton 2308.09737]

Probability density plot





Summary & Conclusions

- Advancing searches for new physics by identifying motivated and theoretically preferred regions of parameter space
- Studied predictions of flavor models for neutrinoless double beta decay: fractions of viable models that are in the funnel region range from 5–100%
- Combination of oscillation experiments, experiments measuring the neutrino mass scale, and $0\nu\beta\beta$ experiments will tell us more about neutrino sector and models in future

Thanks for your attention!

Appendix: numerical approach

[JG, Denton 2308.09737]

1. We first calculate the number of models which are viable. These are the models that are in agreement with the oscillation data.
2. Then we determine which of those have any fraction within the funnel which we define to be $m_{\beta\beta} < 10^{-3}$ eV.
3. Then we determine the fraction of each model that is within the funnel as outlined below.

$$f = \frac{\int_{\text{funnel}} d\log m_{\text{lightest}} d\log m_{\beta\beta}}{\int d\log m_{\text{lightest}} d\log m_{\beta\beta}}$$

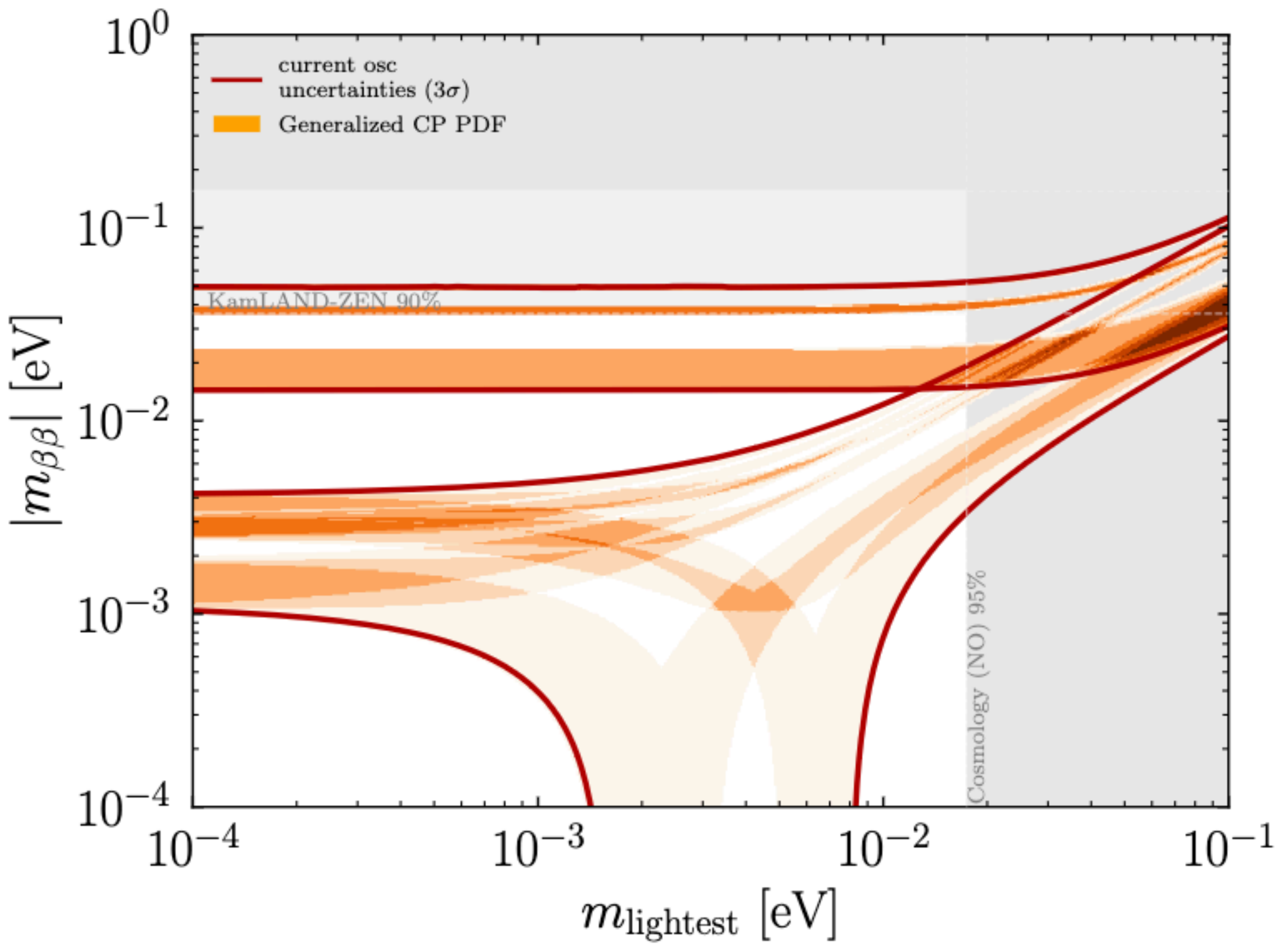
Appendix: Results for generalized CP

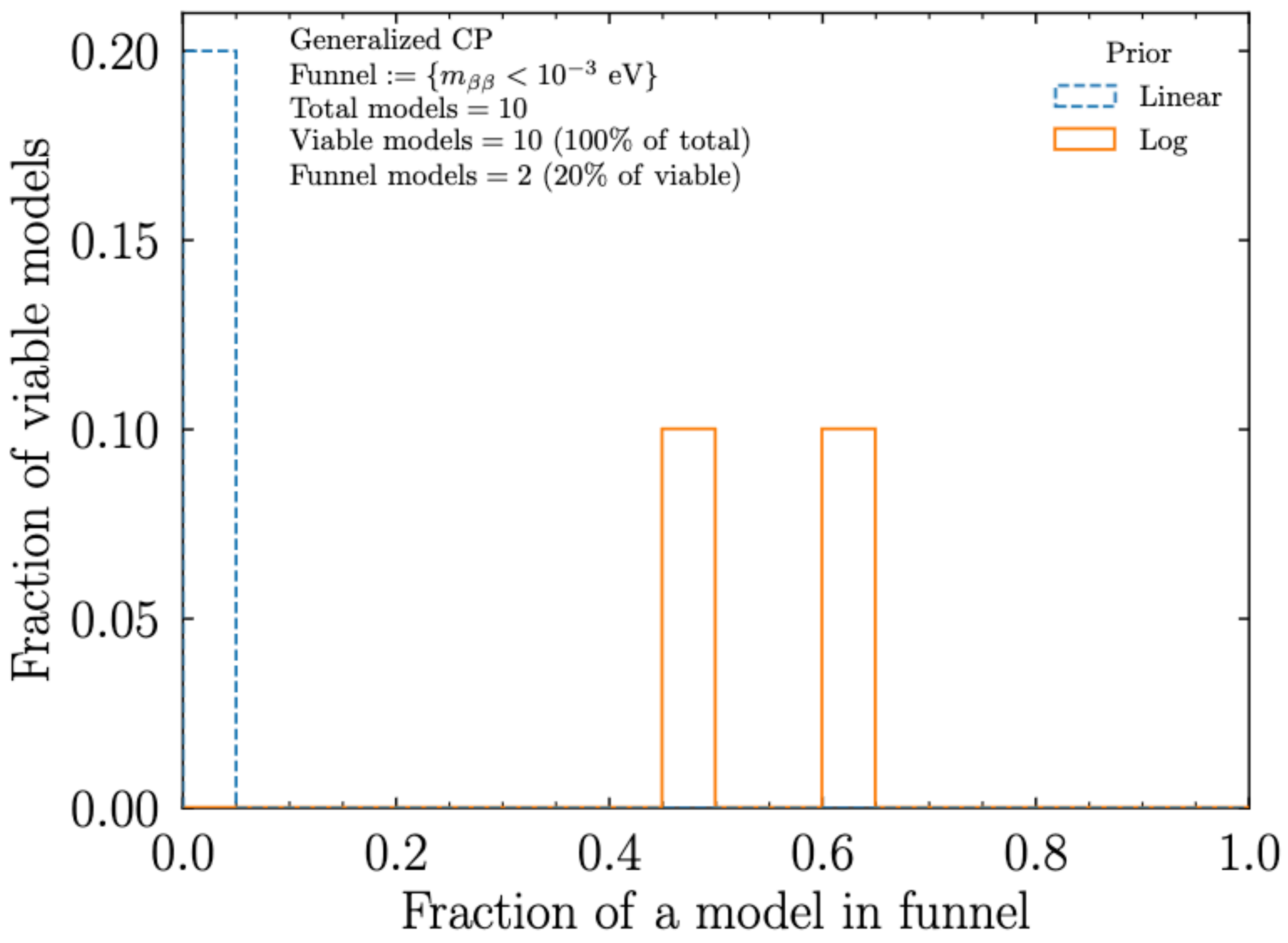
Phases have specific values

$(\alpha,\ \beta)$
$(\boldsymbol{0}, \boldsymbol{\pi})$
$(\boldsymbol{\pi}, \boldsymbol{0})$
$(0, 0)$
(π, π)

$(\alpha,\ \beta)$
$(0, \pi/2)$ or $(0, 3\pi/2)$
$(\pi/2, 3\pi/2)$ or $(3\pi/2, \pi/2)$
$(\pi, \pi/2)$ or $(\pi, 3\pi/2)$
$(\pi/2, 0)$ or $(3\pi/2, 0)$
$(\pi/2, \pi/2)$ or $(3\pi/2, 3\pi/2)$
$(\pi/2, \pi)$ or $(3\pi/2, \pi)$

[JG, Denton 2308.09737]





Appendix: Results for charged lepton corrections

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

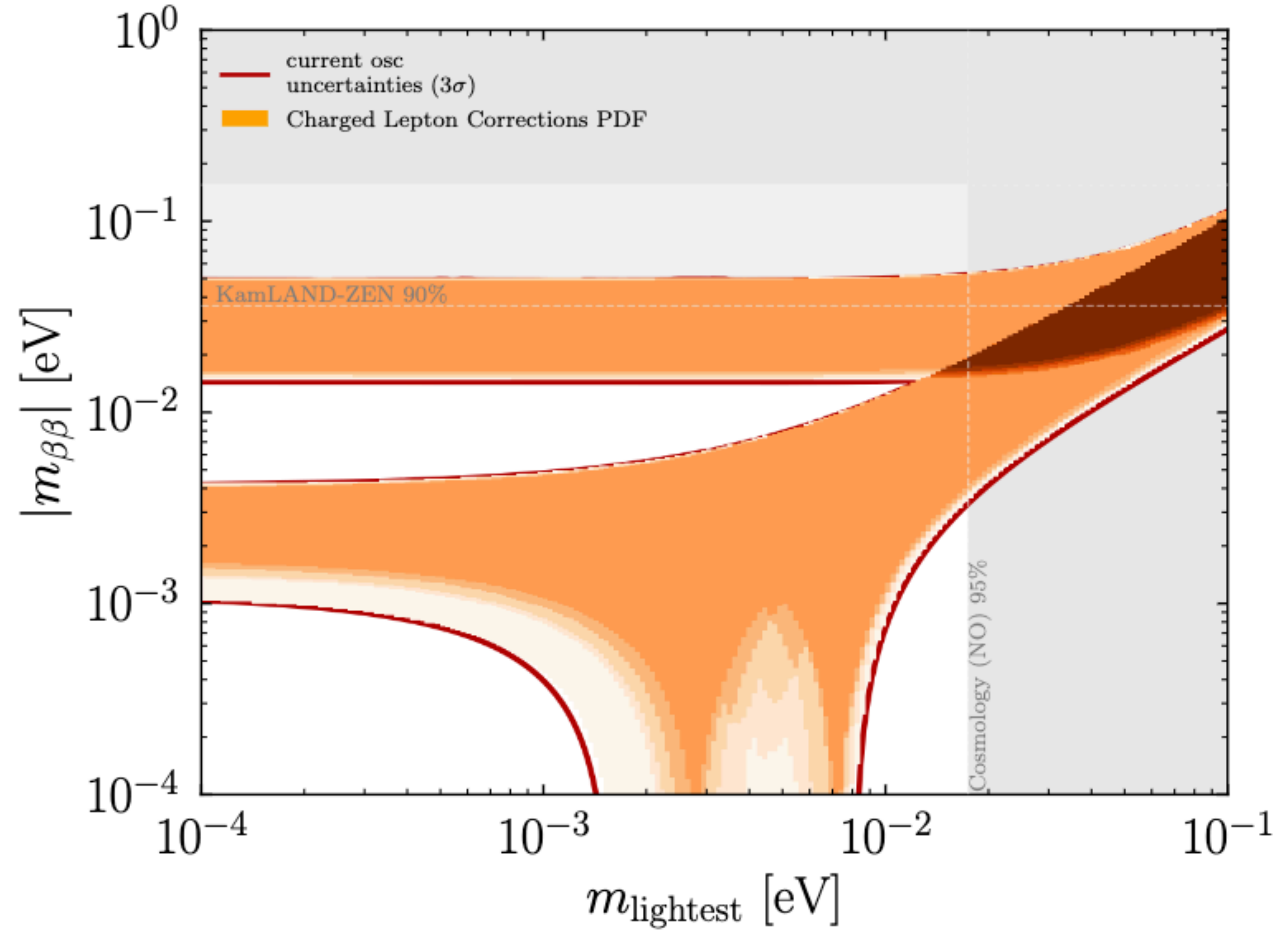
[JG, Denton 2308.09737]

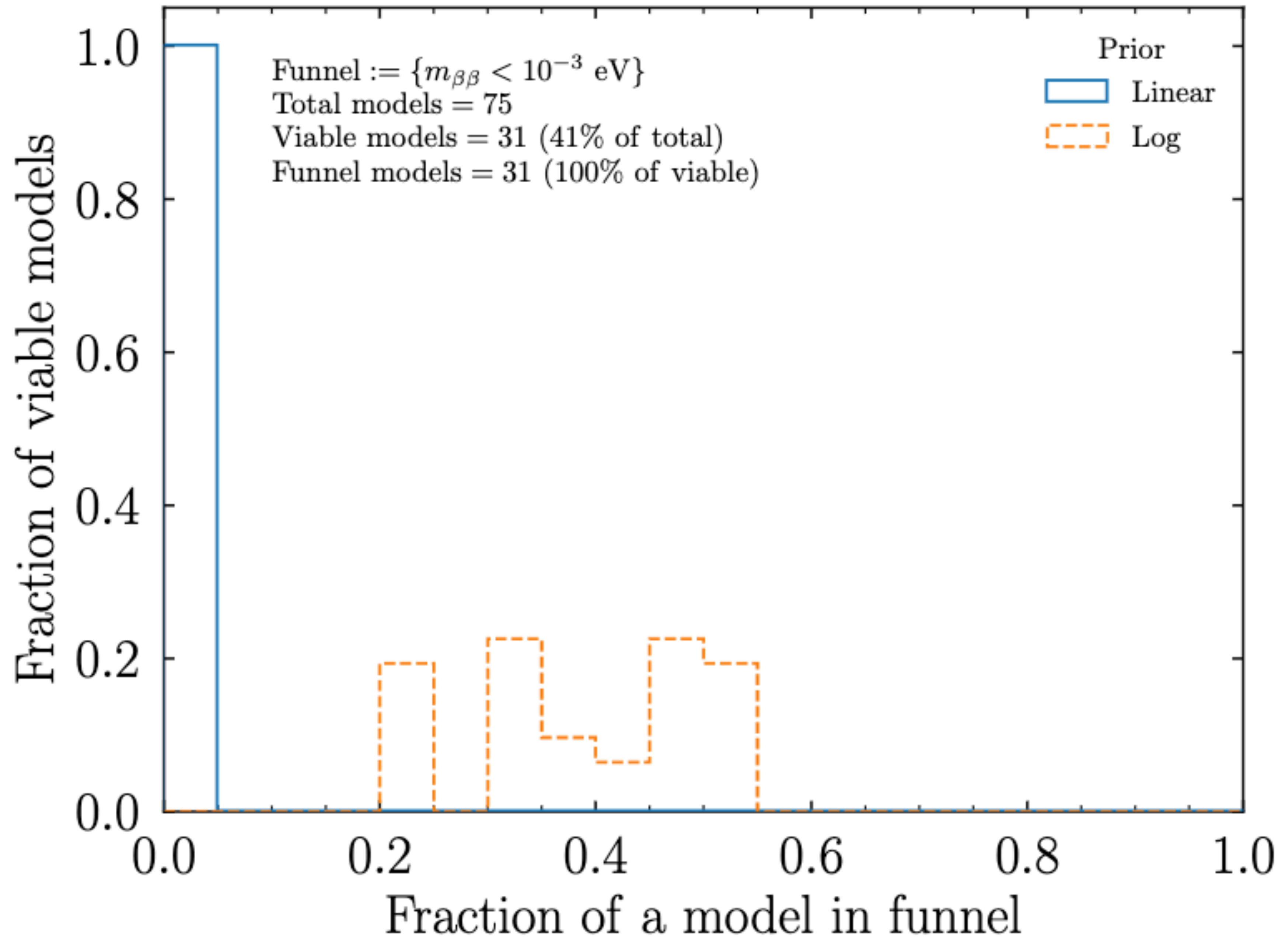
Angles in neutrino sector determined by underlying symmetry

Studied two rotations in the neutrino sector, one charged lepton rotation

two rotations in the neutrino sector, two charged lepton rotation

three rotations in the neutrino sector, one charged lepton rotation





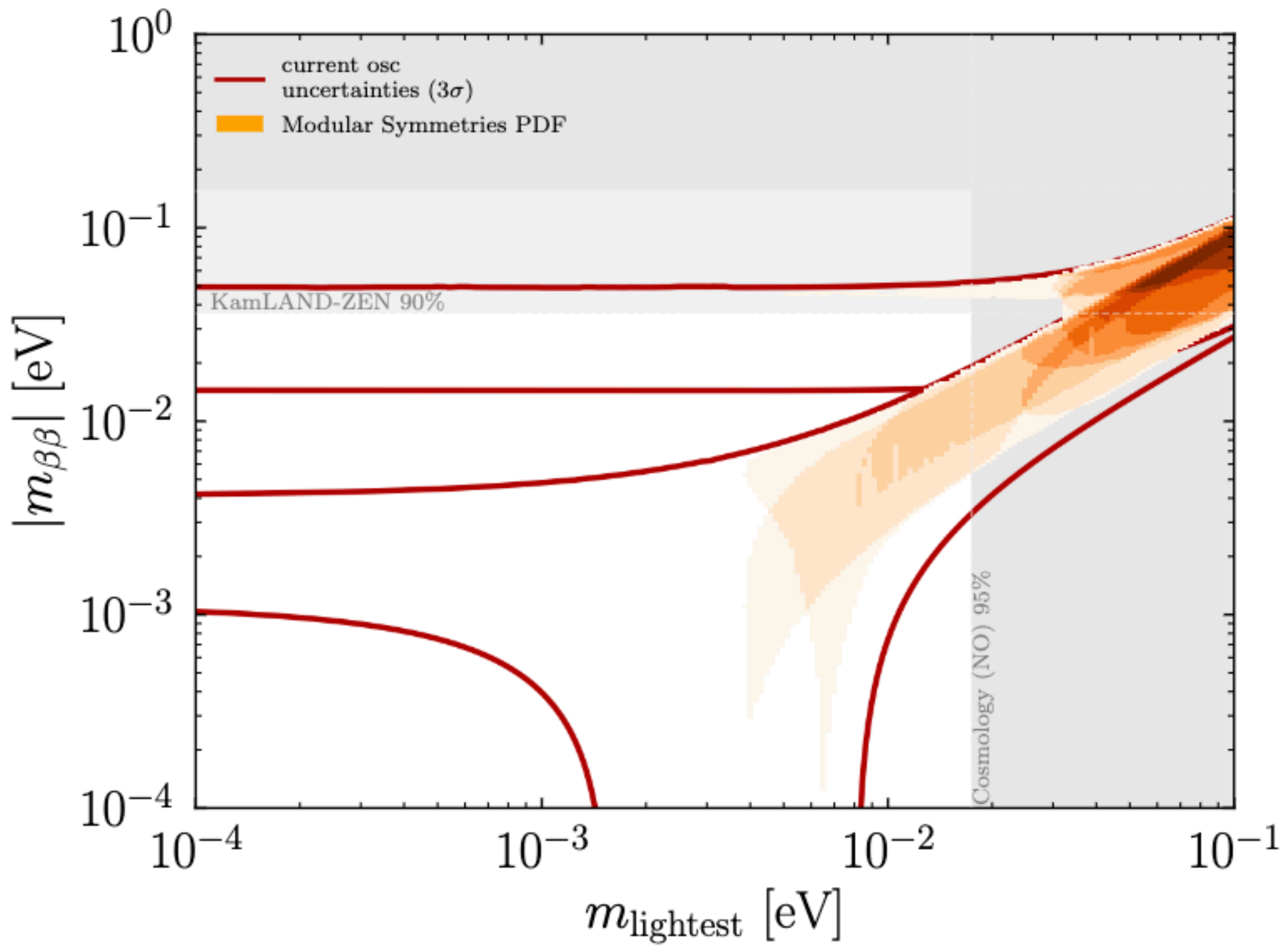
Appendix: Results for modular symmetries

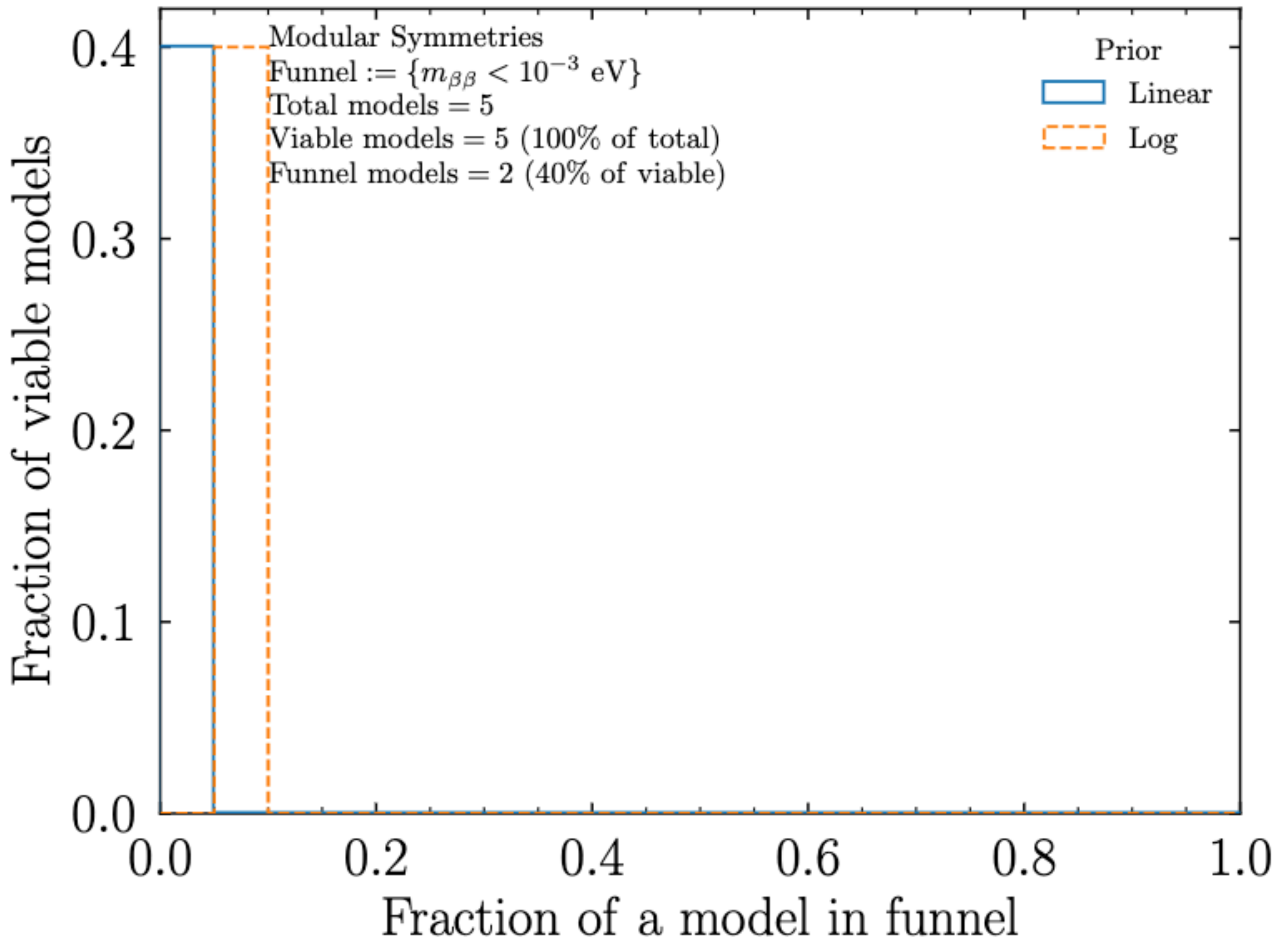
[JG, Denton 2308.09737]

Reduced numbers of fields which break flavor symmetry [F. Feruglio '17]

5 models with maximal number of predictions realized in literature

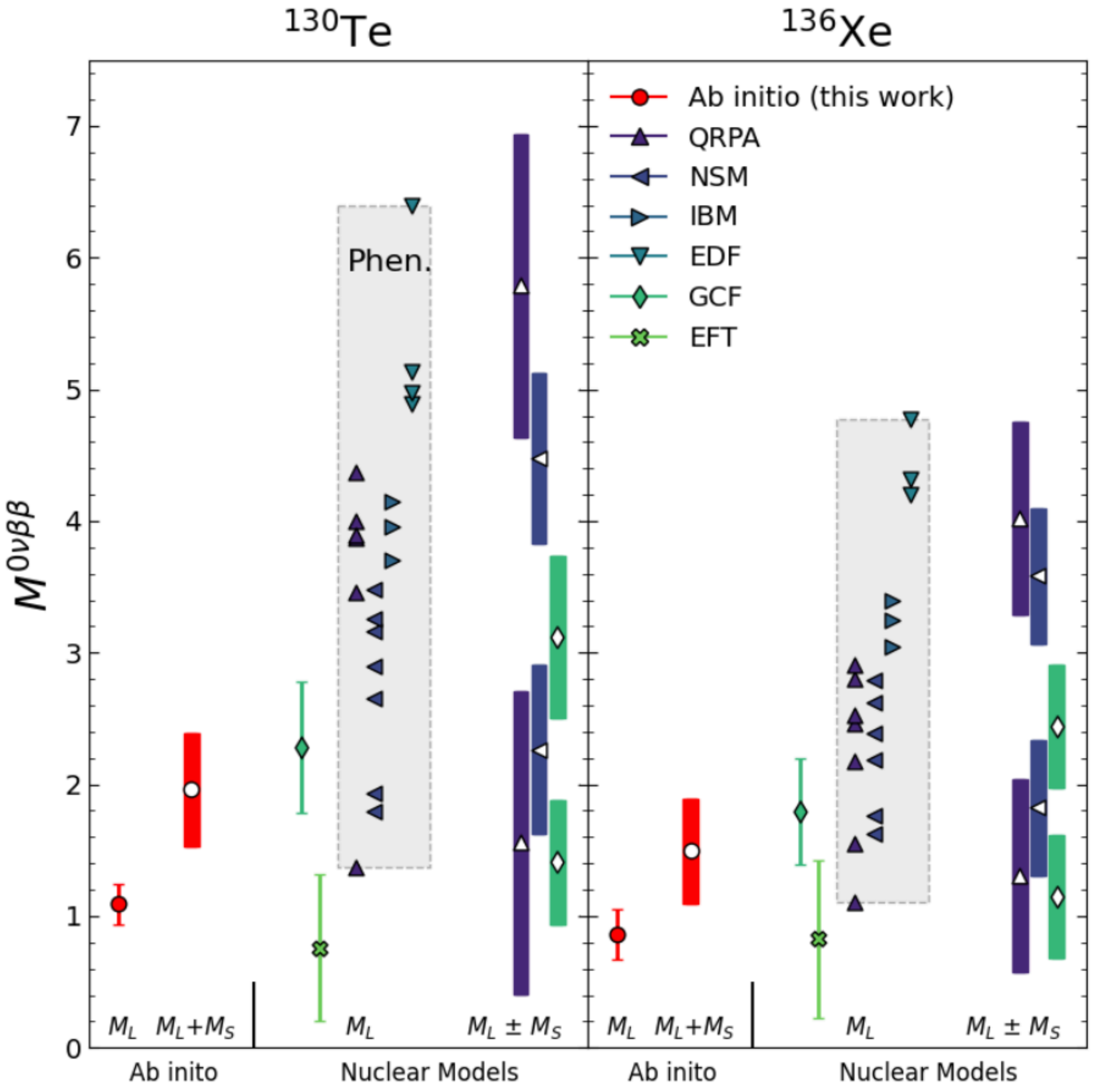
Coefficients of sum rules depend on mixing parameters [JG, Spinrath 2012.04131]





Appendix: Nuclear matrix elements

[Belley, Miyagi, Stroberg, Holt 2307.15156]



Appendix: Neutrino oscillations

flavor eigenstates (of weak interaction) and mass eigenstates (of free particle Hamiltonian)
not aligned for neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U_{PMNS}: relates flavor and mass states

Parametrized by four parameters (3 angles and at least one phase)

$$U_{\mathrm{PMNS}} = U_{23}(\theta_{23})U_{13}(\theta_{13}, \delta)U_{12}(\theta_{12})\mathrm{diag}(\mathrm{e}^{\mathrm{i}\alpha/2}, \mathrm{e}^{\mathrm{i}\beta/2}, 1)$$

Majorana phases: only physical for Majorana neutrinos

For other parametrization see P. Denton, R. Pestes '20

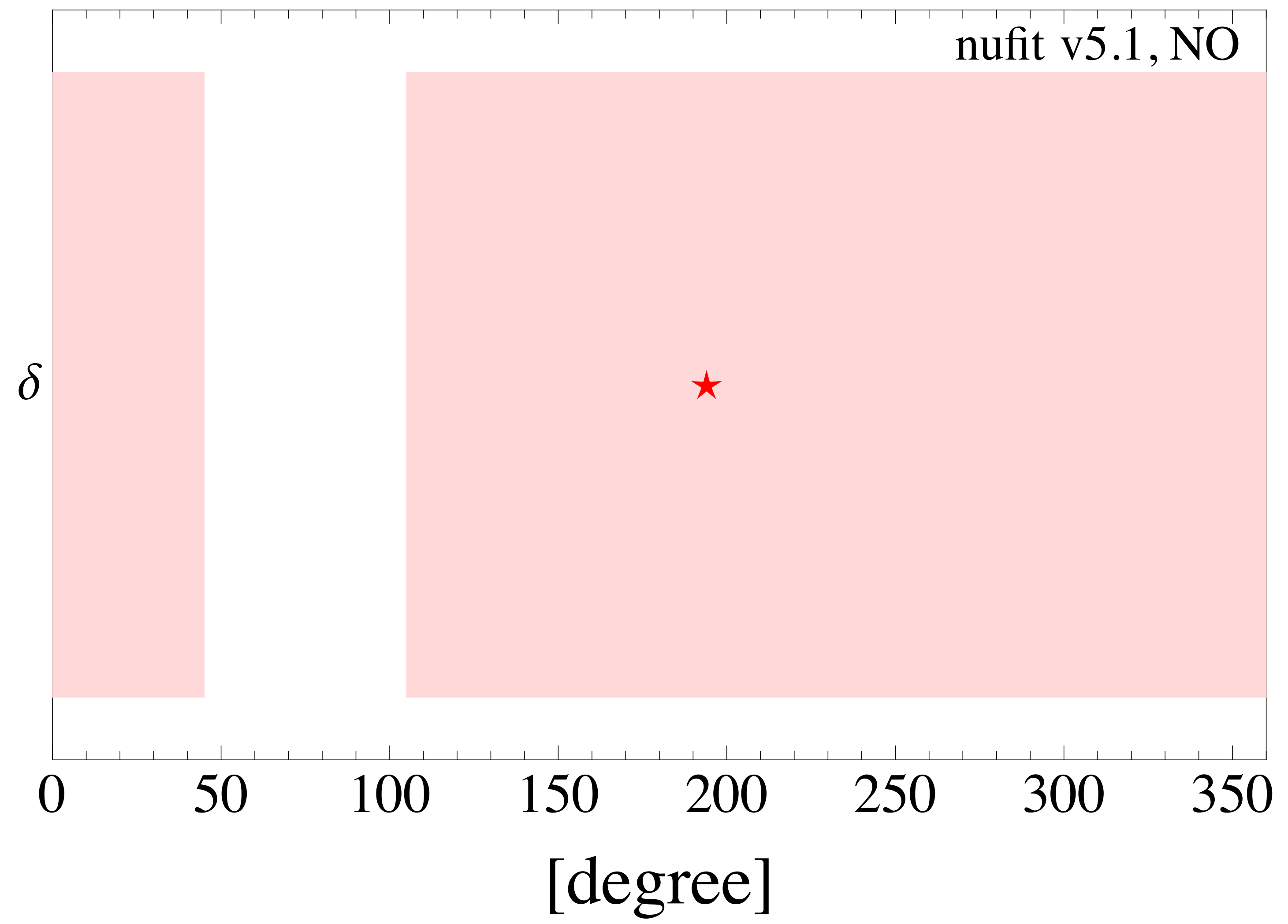
Appendix: Neutrino oscillation parameters

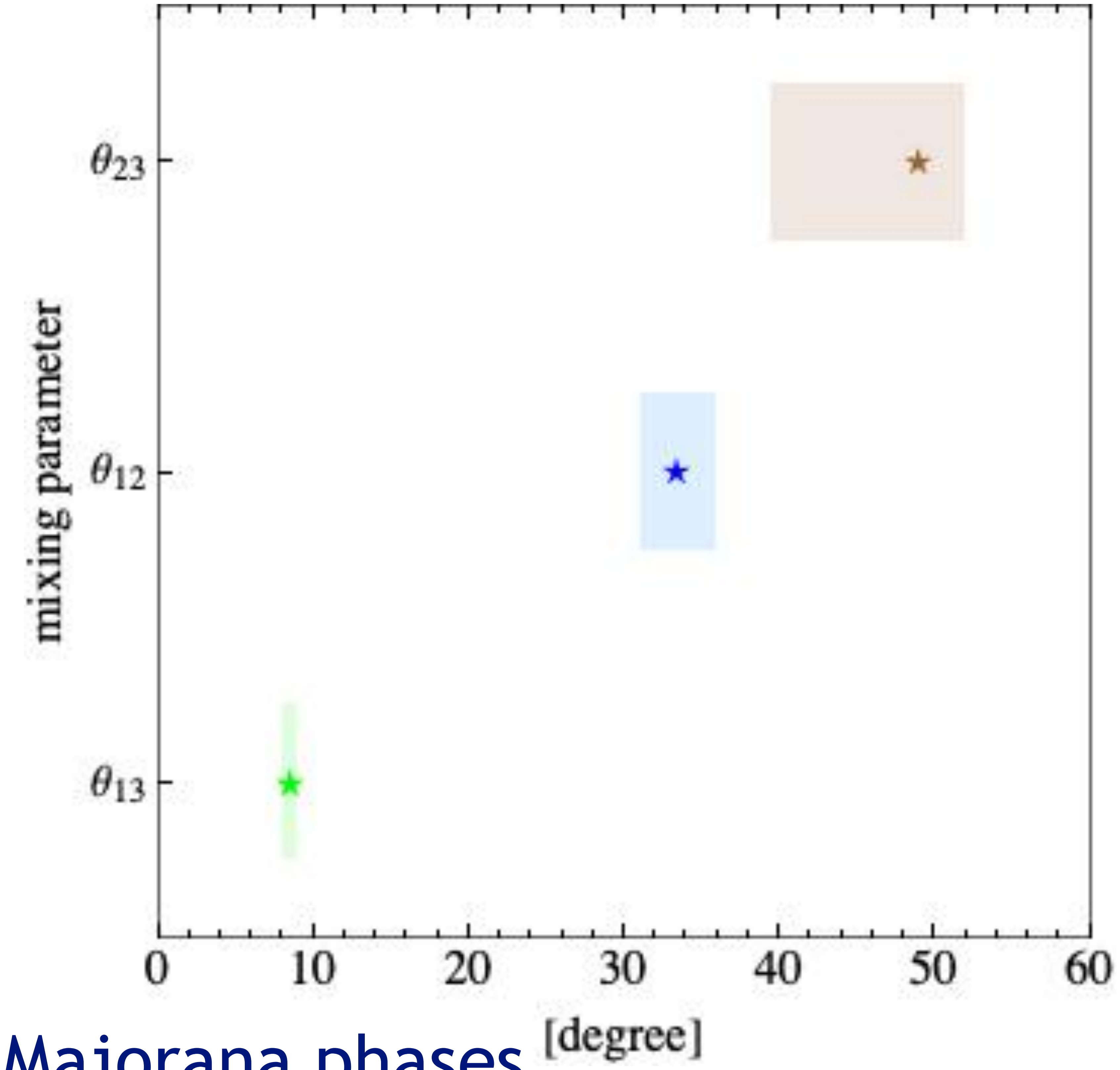
Global fits to oscillation data:

Information on mixing angles, mass splittings

[nufit v5.1]

all three angles non-zero
mixing angles are large!



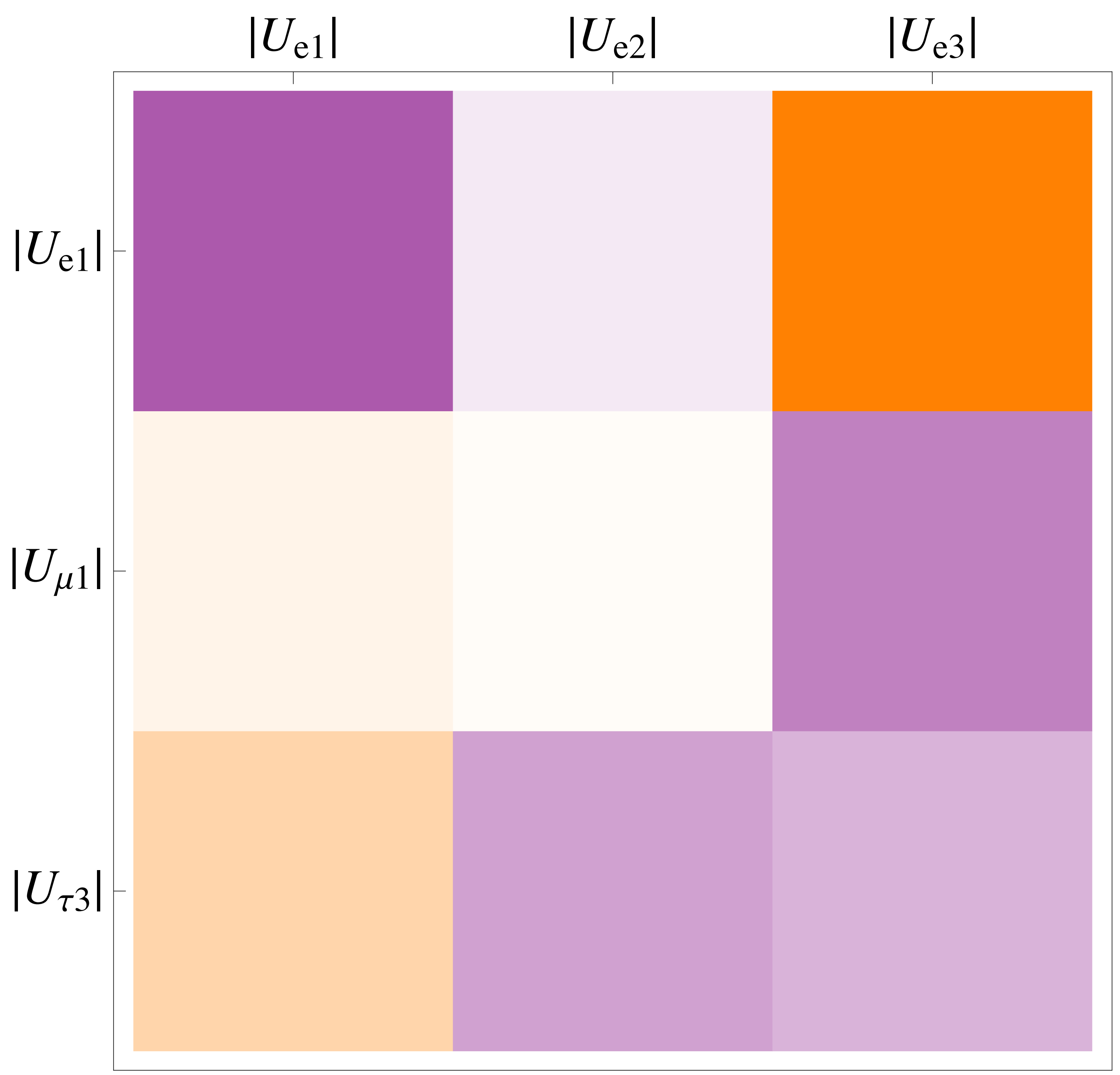


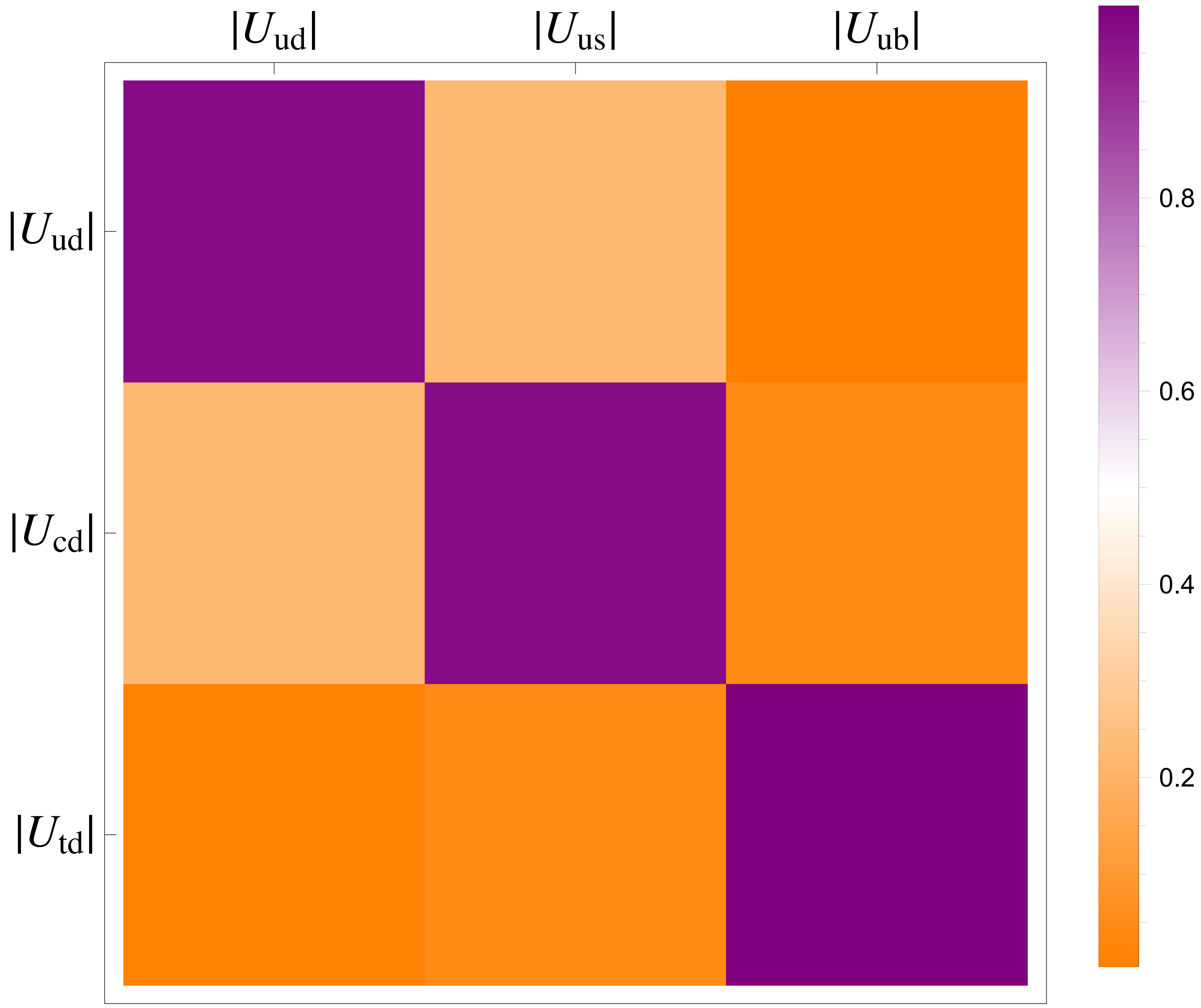
No information on Majorana phases

Appendix: Neutrino oscillation parameters

Leptonic mixing pattern very different from the one for quarks

[nufit v5.1]





[PDG '20]

Very off-diagonal
→ large mixings

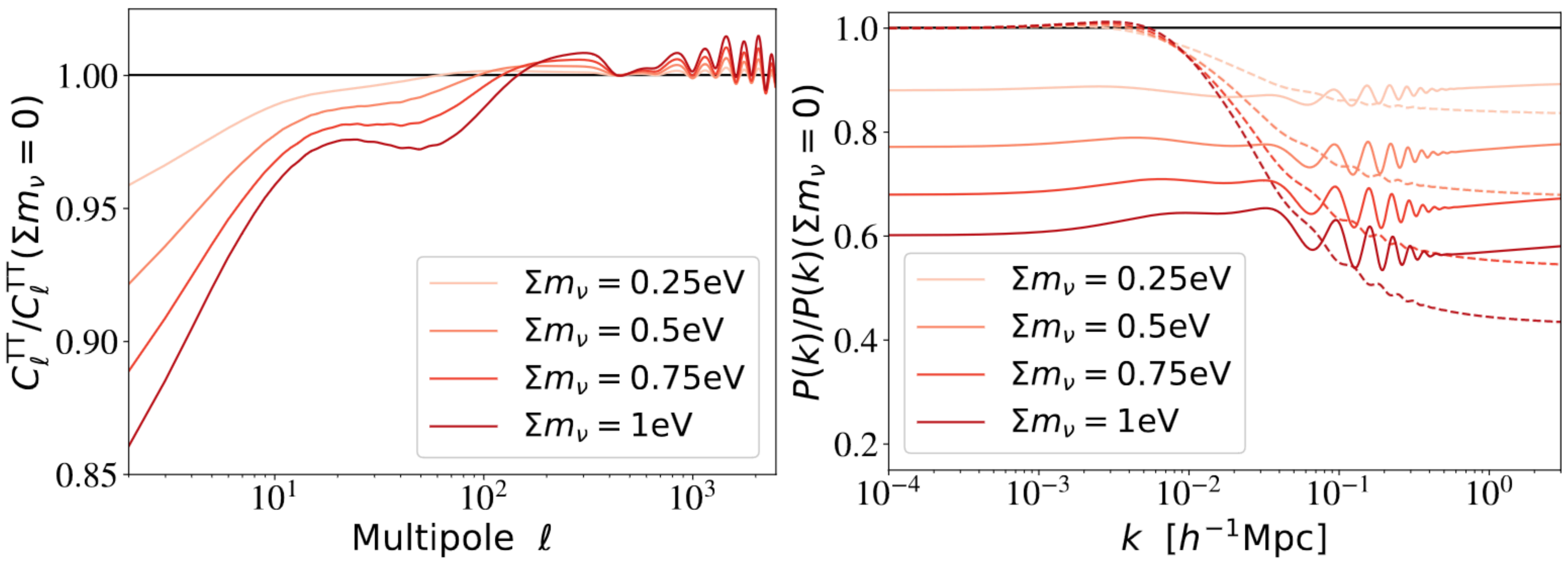
Close to diagonal
→ little flavor mixings

Appendix: Neutrino masses

Cosmological sum of neutrino masses:

$$\sum m_\nu \lesssim 90 \text{ meV}$$

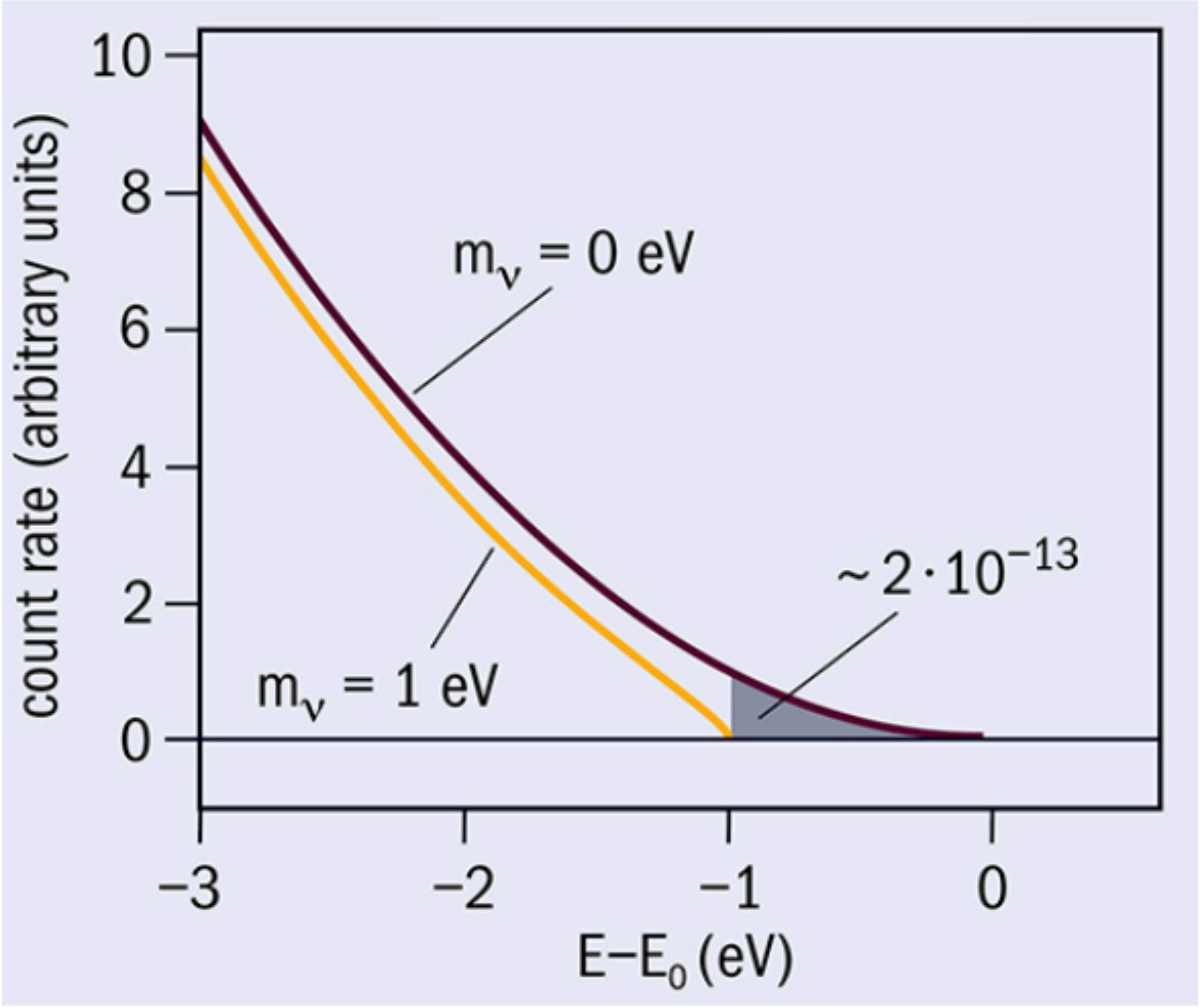
[Planck '18]



Beta decay endpoint:

$$m_\beta < 0.8 \text{ eV}$$

[KATRIN '21]



Neutrino mass splittings: oscillation physics

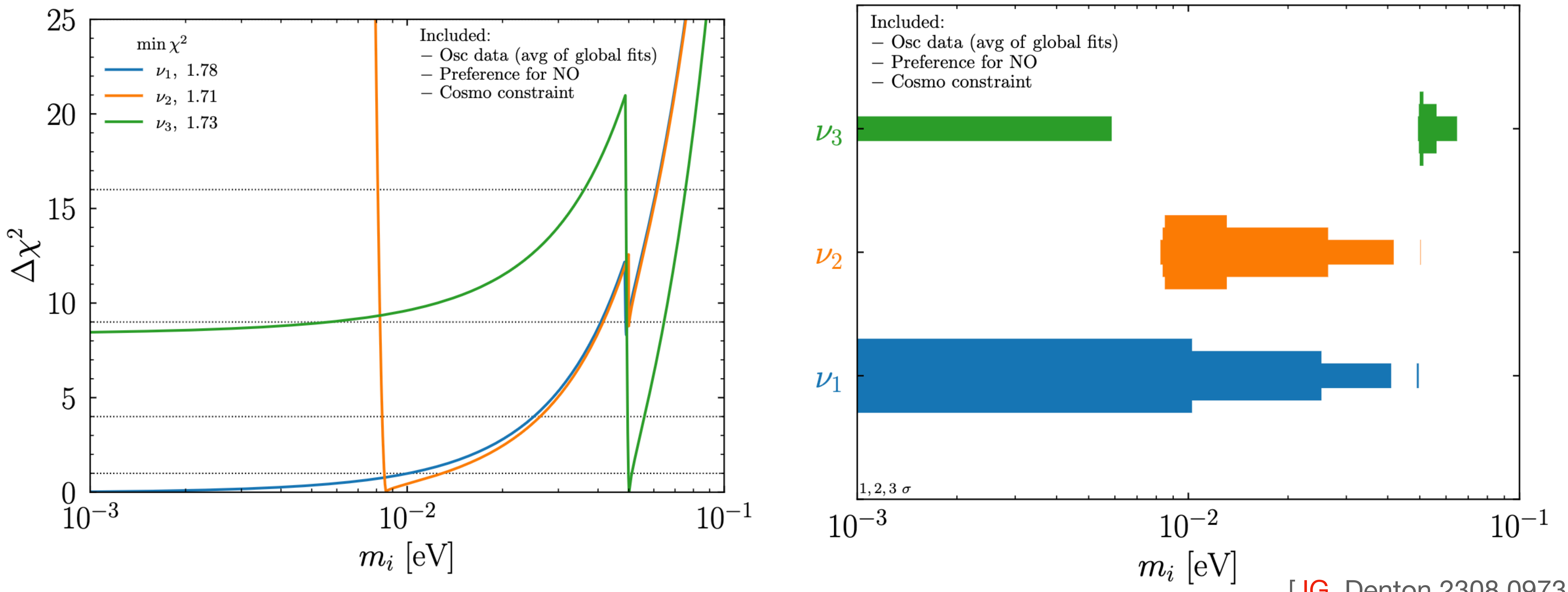
$$|\Delta m_{32}^2| = 2.5 \cdot 10^{-3} \text{ eV}^2, \ \Delta \text{m}_{21}^2 = 7.4 \cdot 10^{-5} \text{ eV}^2$$

Neutrino mass ordering: oscillation physics prefer NO at 2.7σ

$$m_1 < m_2 < m_3$$

[nufit v5.1]

Appendix: Neutrino masses



[JG, Denton 2308.09737]

Appendix: Neutrinoless double beta decay

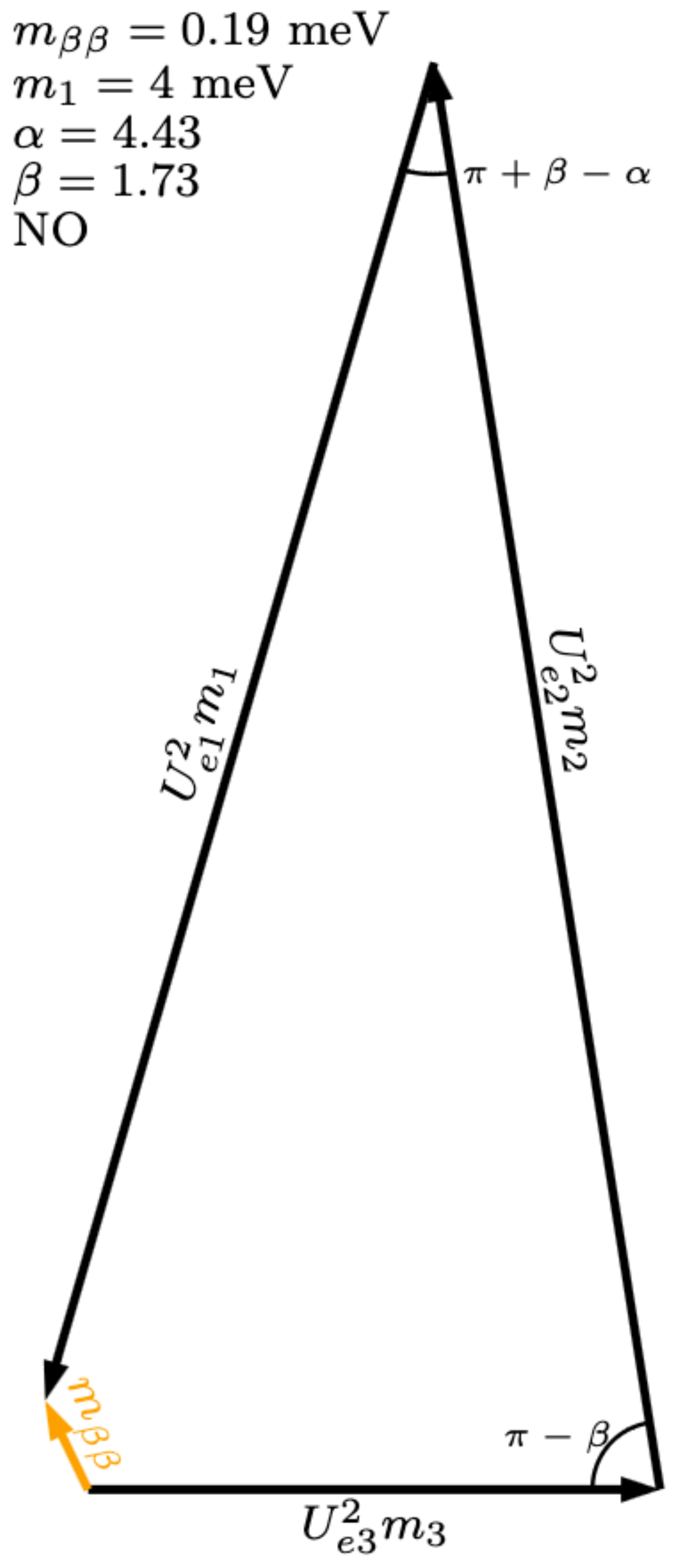
$$|m_{\beta\beta}| = |\sum U_{ei}^2 m_i|$$

$$= |\cos^2\theta_{12}\cos^2\theta_{13}m_1 e^{-i\alpha} + \sin^2\theta_{12}\cos^2\theta_{13}m_2 e^{-i\beta} + \sin^2\theta_{13}m_3|$$

With measurement of mixing angles and mass splittings

→ 3 unknowns: Majorana phases α, β, mass of lightest neutrino

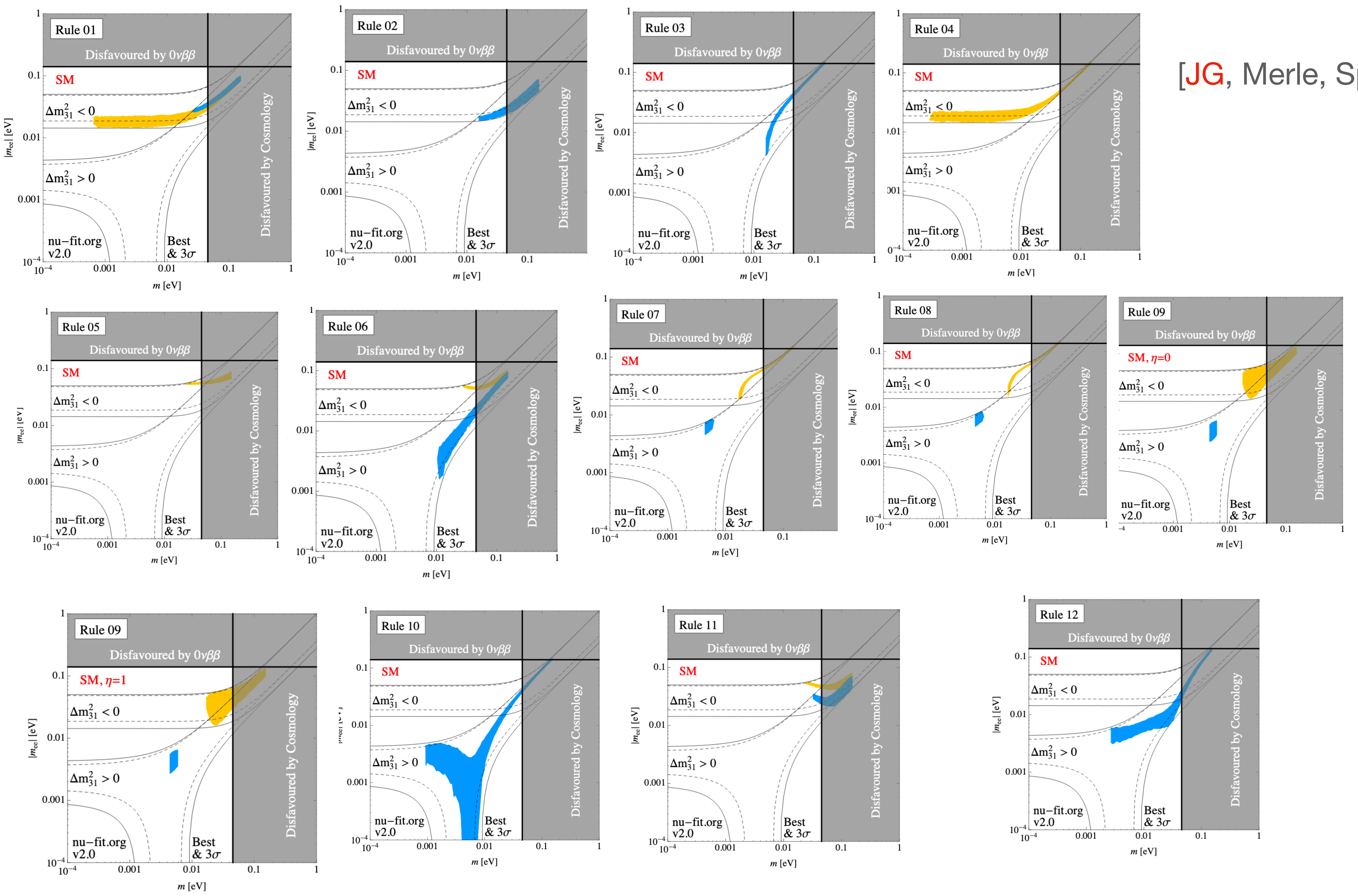
Only sensitive to a combination of Majorana phases!



[JG, Denton 2308.09737]

Appendix: Mass sum rules

[JG, Merle, Spinrath 1506.06139]



Appendix: Neutrino oscillation parameters

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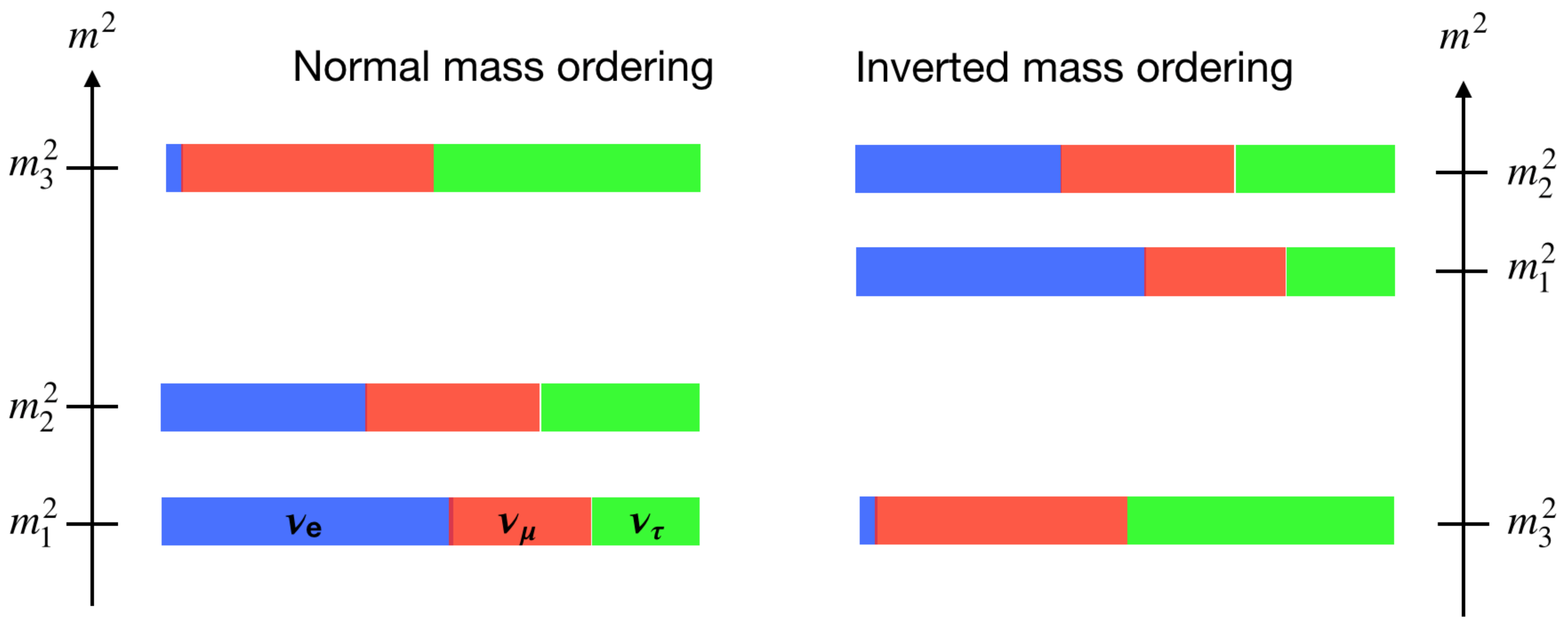
mass splittings: $|\Delta m_{32}^2| = 2.5 \cdot 10^{-3}\ \mathrm{eV}^2,\ \Delta \mathrm{m}_{21}^2 = 7.4 \cdot 10^{-5}\ \mathrm{eV}^2$

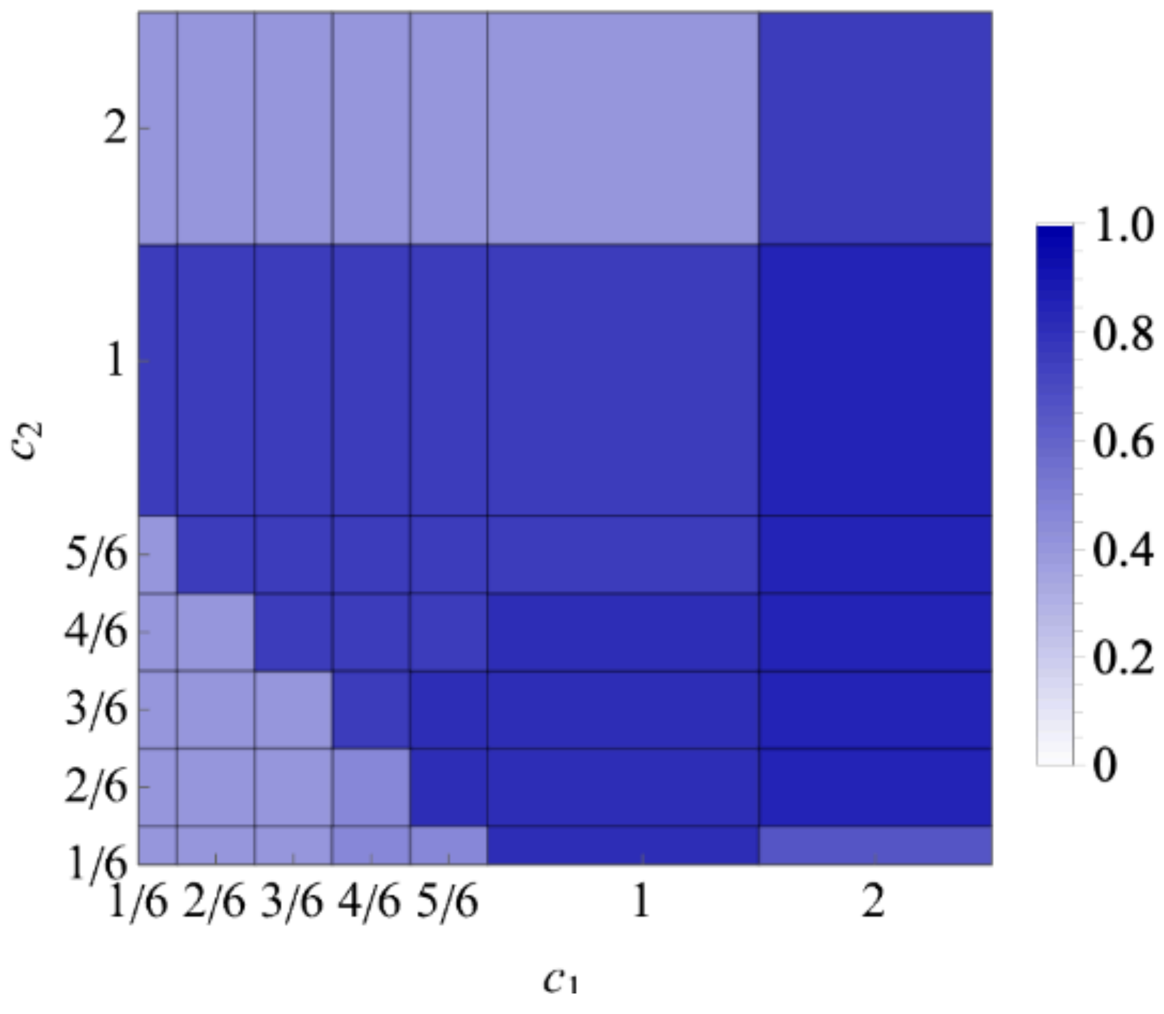
[nufit v5.1]

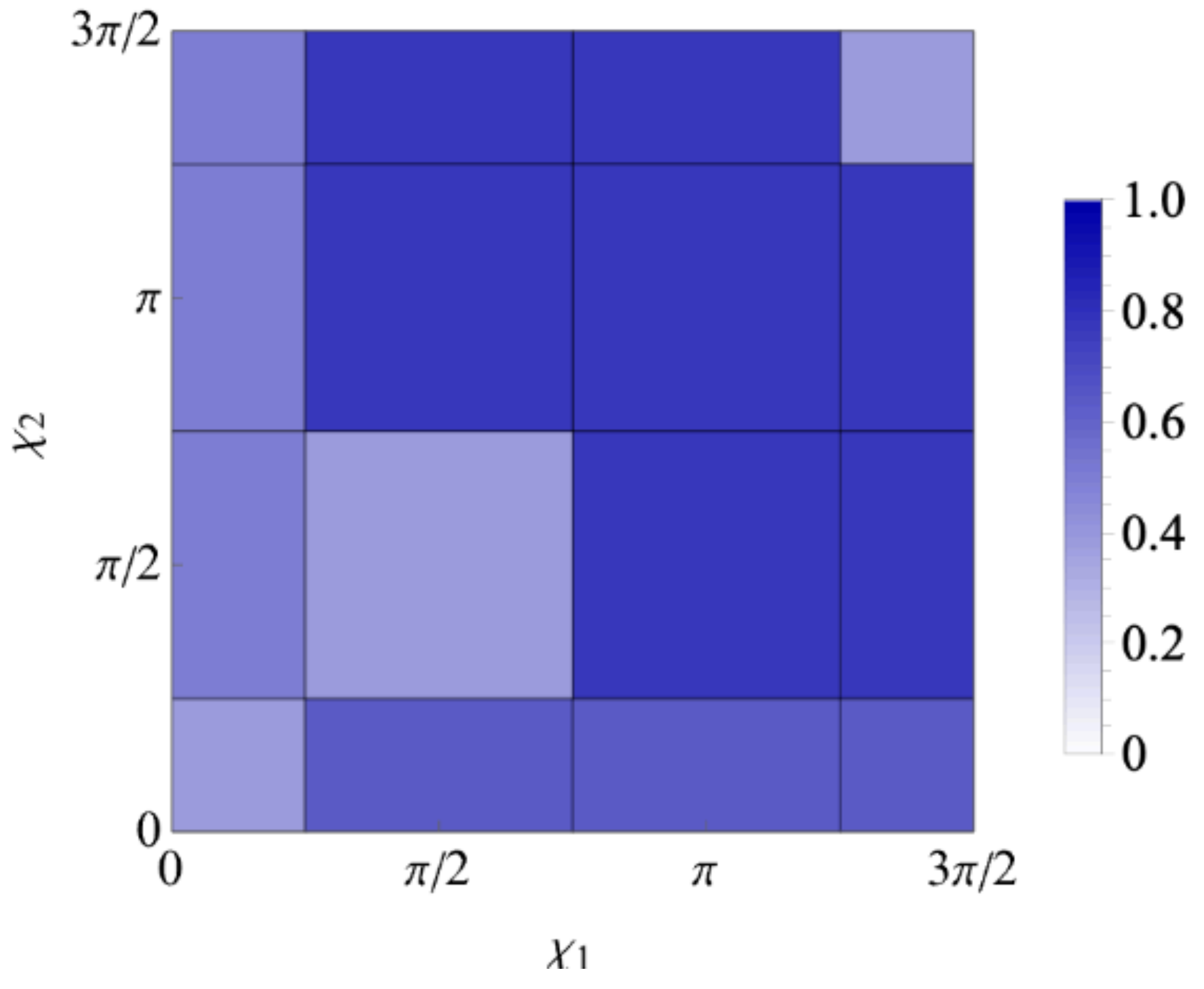
mass ordering unknown

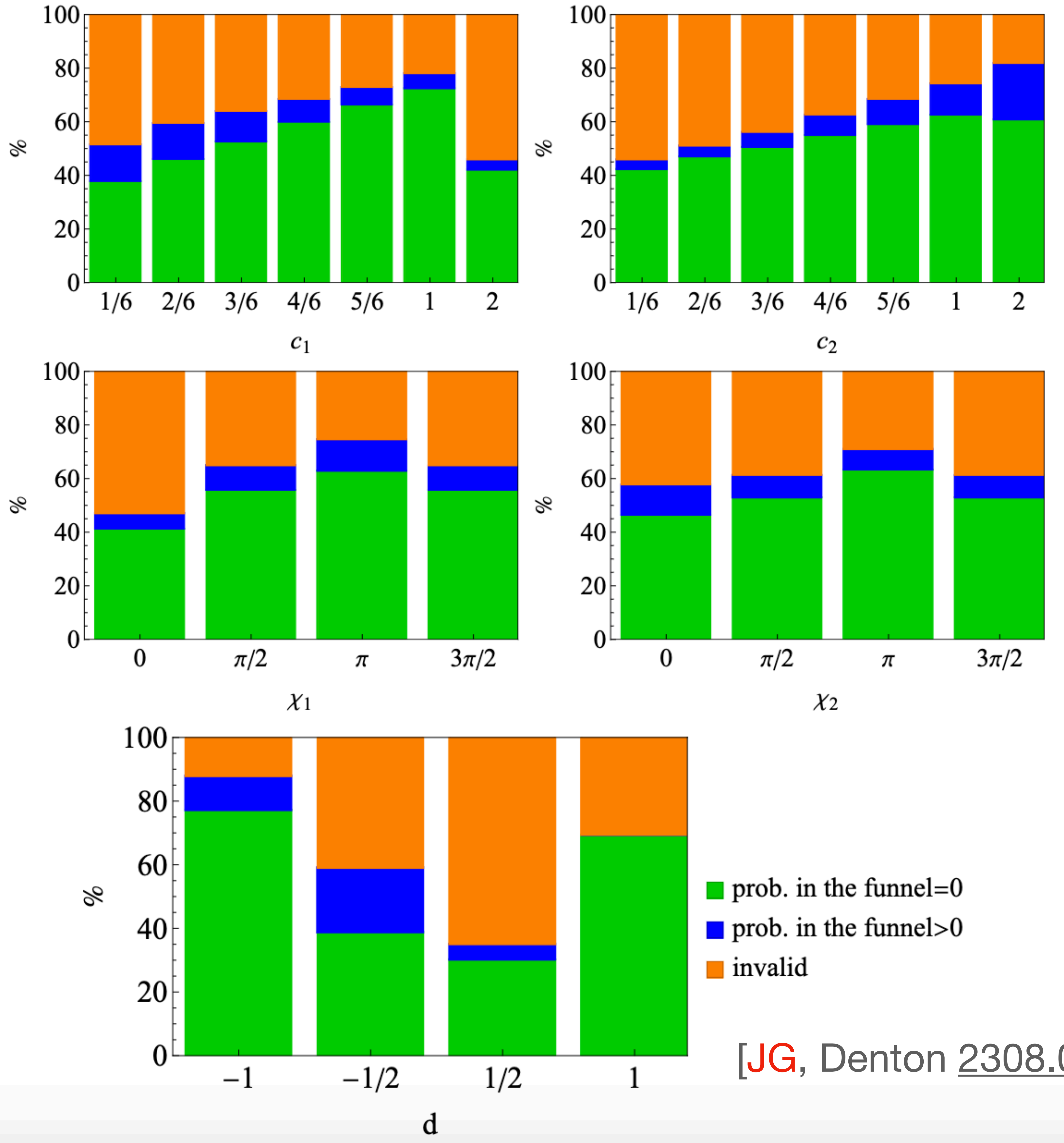


Appendix: Mass sum rules

Validity of sum rules







[JG, Denton 2308.09737]