Quo vadis neutrinoless double beta decay?

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Unraveling the History of the Universe and Matter Evolution with Underground Physics

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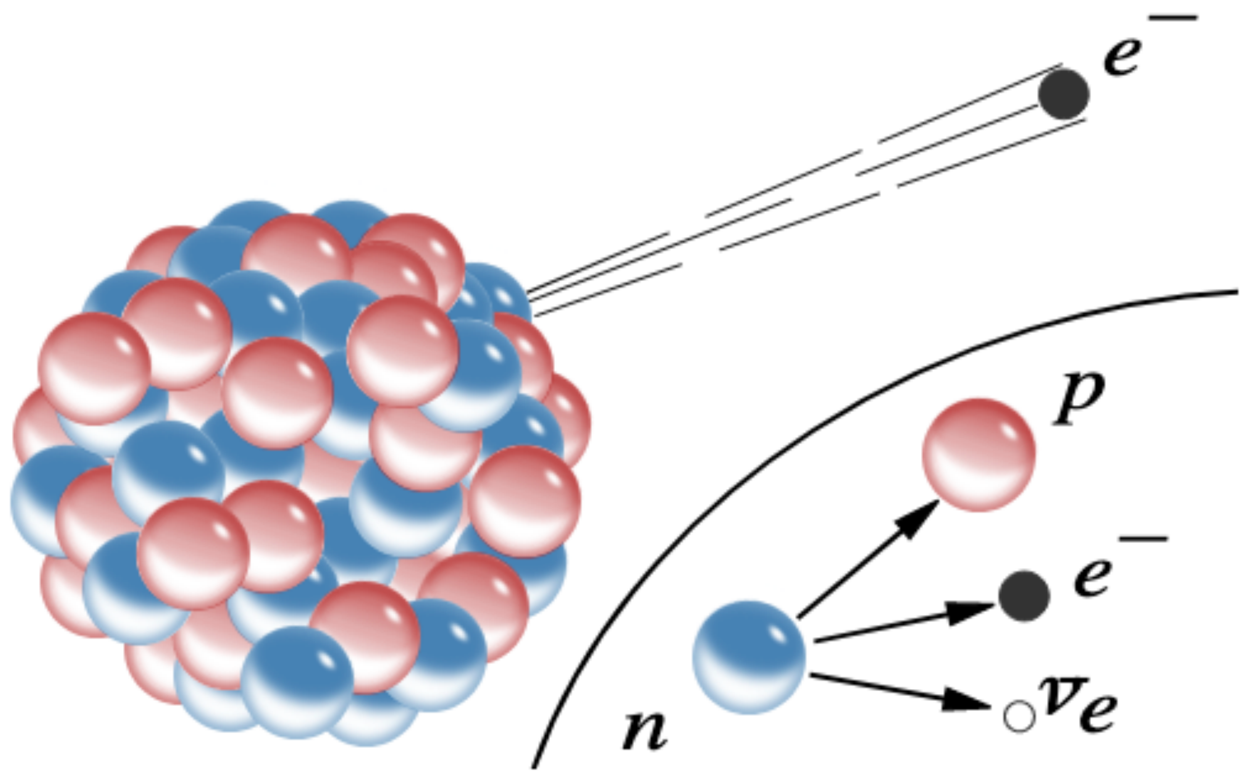
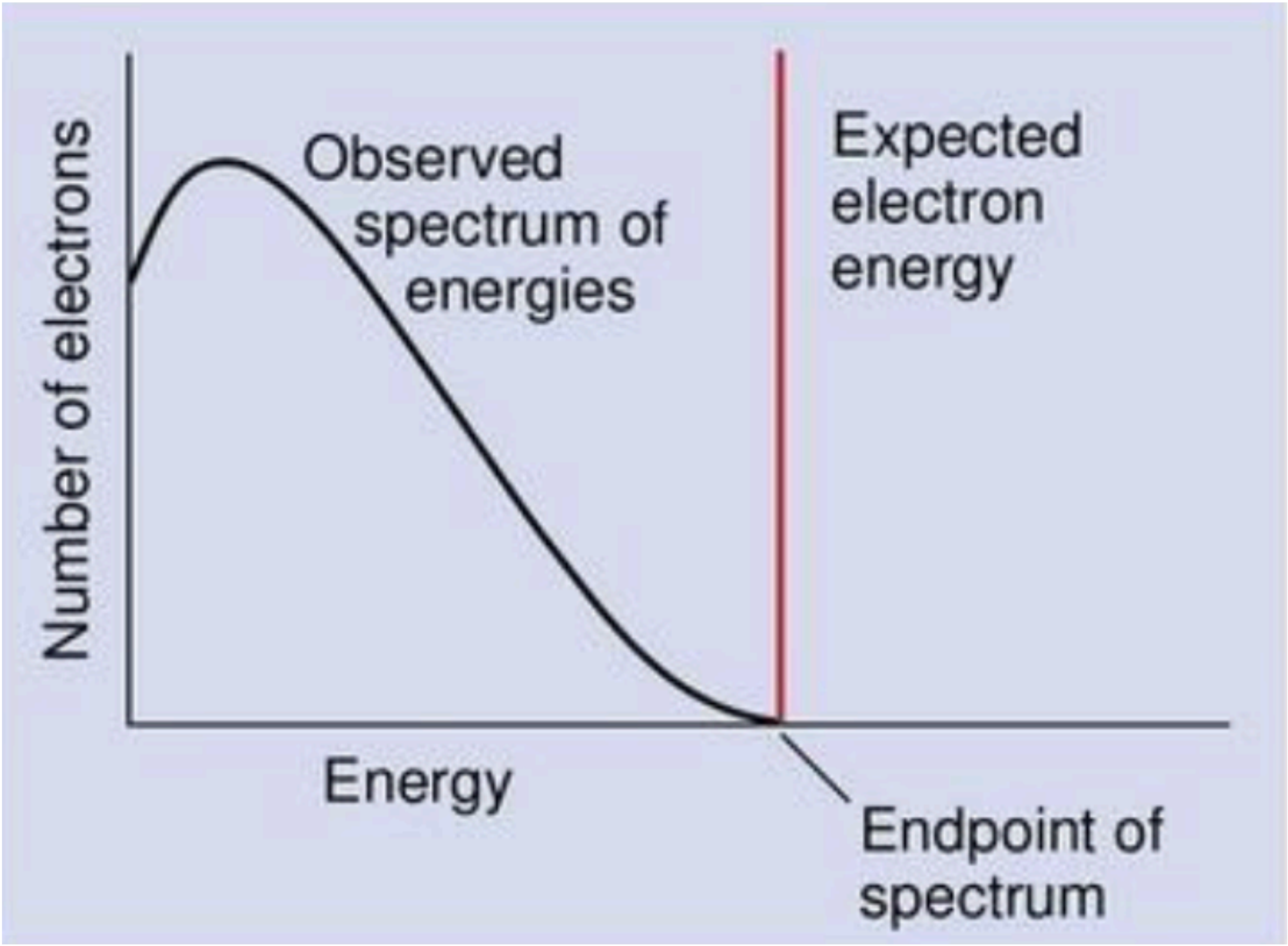
COLORADO STATE UNIVERSITY

Neutrinos and beta decay

Beta decay: $(Z, A) \rightarrow (Z+1, A) + e^- + \bar{\nu}_e$

→ need to introduce neutrino

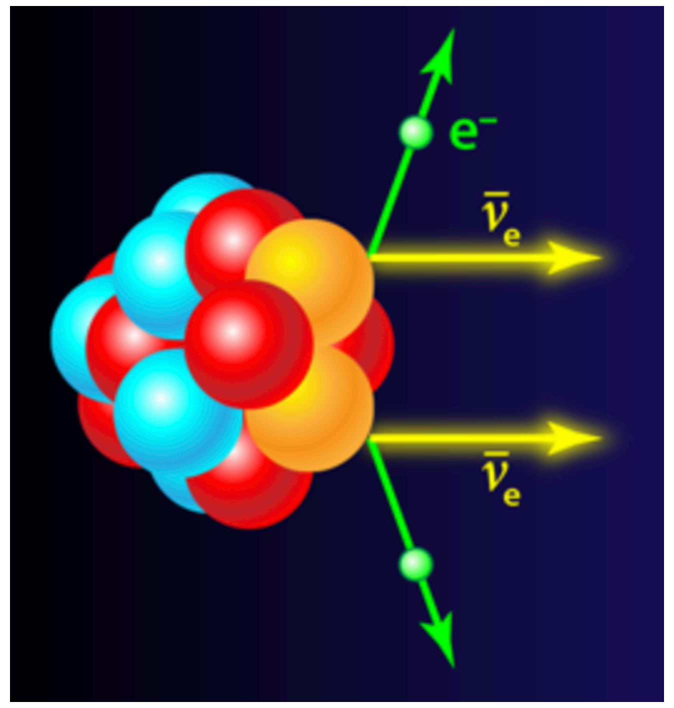




Neutrinos and beta decay

Beta decay: $(Z, A) \rightarrow (Z+1, A) + e^- + \bar{\nu}_e$
→ need to introduce neutrino

Double beta decay:
Maria Goeppert-Mayer (1935) (Nobel prize in 1963)
Simultaneous beta decay of
two neutrons inside of atomic nucleus: $(Z, A) \rightarrow (Z+2, A) + 2\, e^- + 2\, \bar{\nu}_e$
SM process!



Observed in several isotopes (Ge, Xe, Te, Se)
Double beta decay happens for elements where single beta decay is forbidden by energy conservation:
elements with an even atomic number and even neutron number

Neutrinos and beta decay

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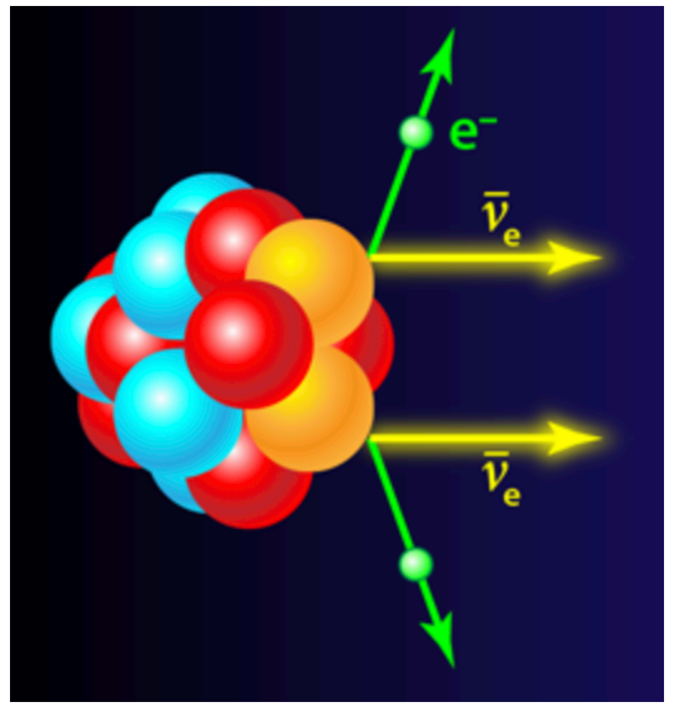


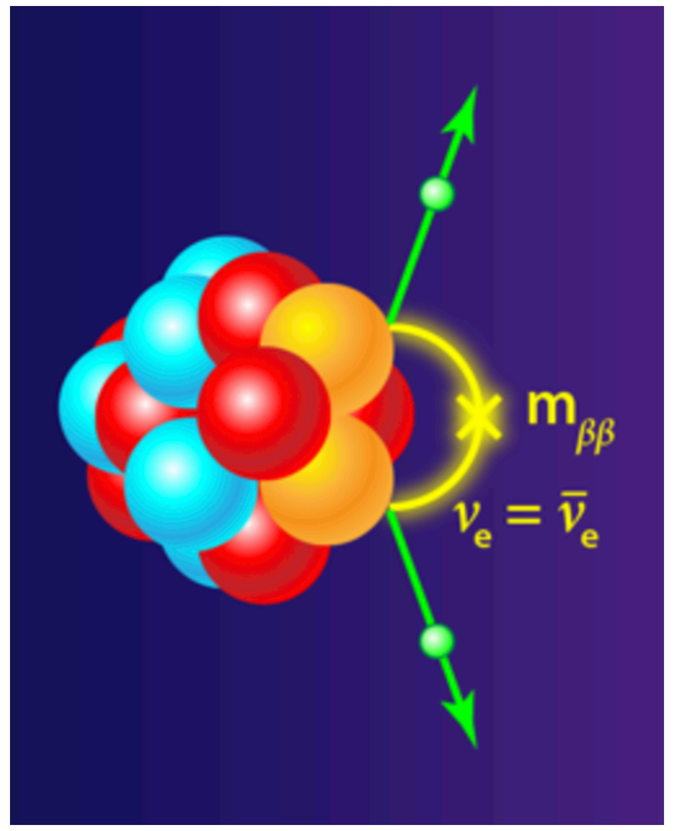
Neutrinoless double beta decay:

W. Furry (1939)

Neutrinos inside of nucleus emitted and absorbed if they are their own antiparticles: lepton number violation!

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

BSM process!



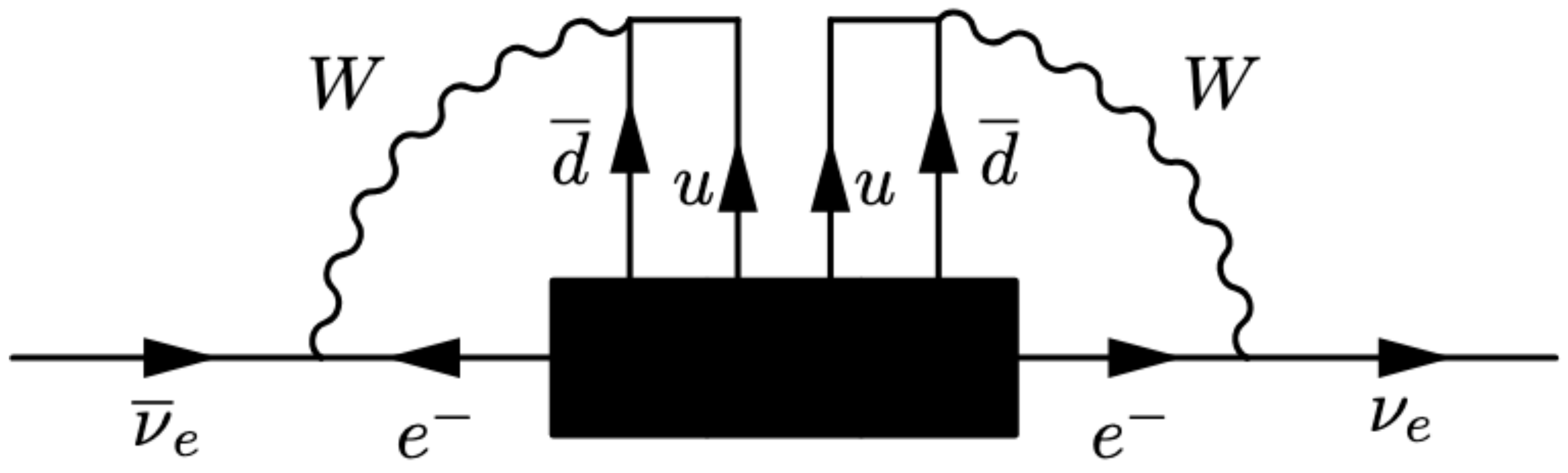
Neutrinoless double beta decay

Observation of neutrinoless double beta decay:
⇒ Lepton number violated!

Schechter-Valle theorem

Any $\Delta L = 2$ operator contributing to $0\nu\beta\beta$ will generate Majorana neutrino mass contribution

Schechter, Valle '82



Duerr, Lindner, Merle '11

Neutrino masses might still have (large) Dirac mass term
Majorana mass induced by this operator tiny: $\lesssim \mathcal{O}(10^{-28}\ \mathrm{eV})$
Lower limit on second-lightest neutrino mass $m_\nu \gtrsim 8 \times 10^{-3}$ eV

Neutrinoless double beta decay

Powerful way of testing lepton number violation!

Individual lepton number (L_e, L_μ, L_τ) violated in neutrino oscillations

total lepton number ($L_e + L_\mu + L_\tau$) (and baryon number) is accidental symmetry of the SM

Neutrinoless double beta decay

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Leptogenesis scenarios to generate matter-antimatter asymmetry of the universe rely on lepton number violation
$\rightarrow 0\nu\beta\beta$ probes history of the Universe and Matter Evolution

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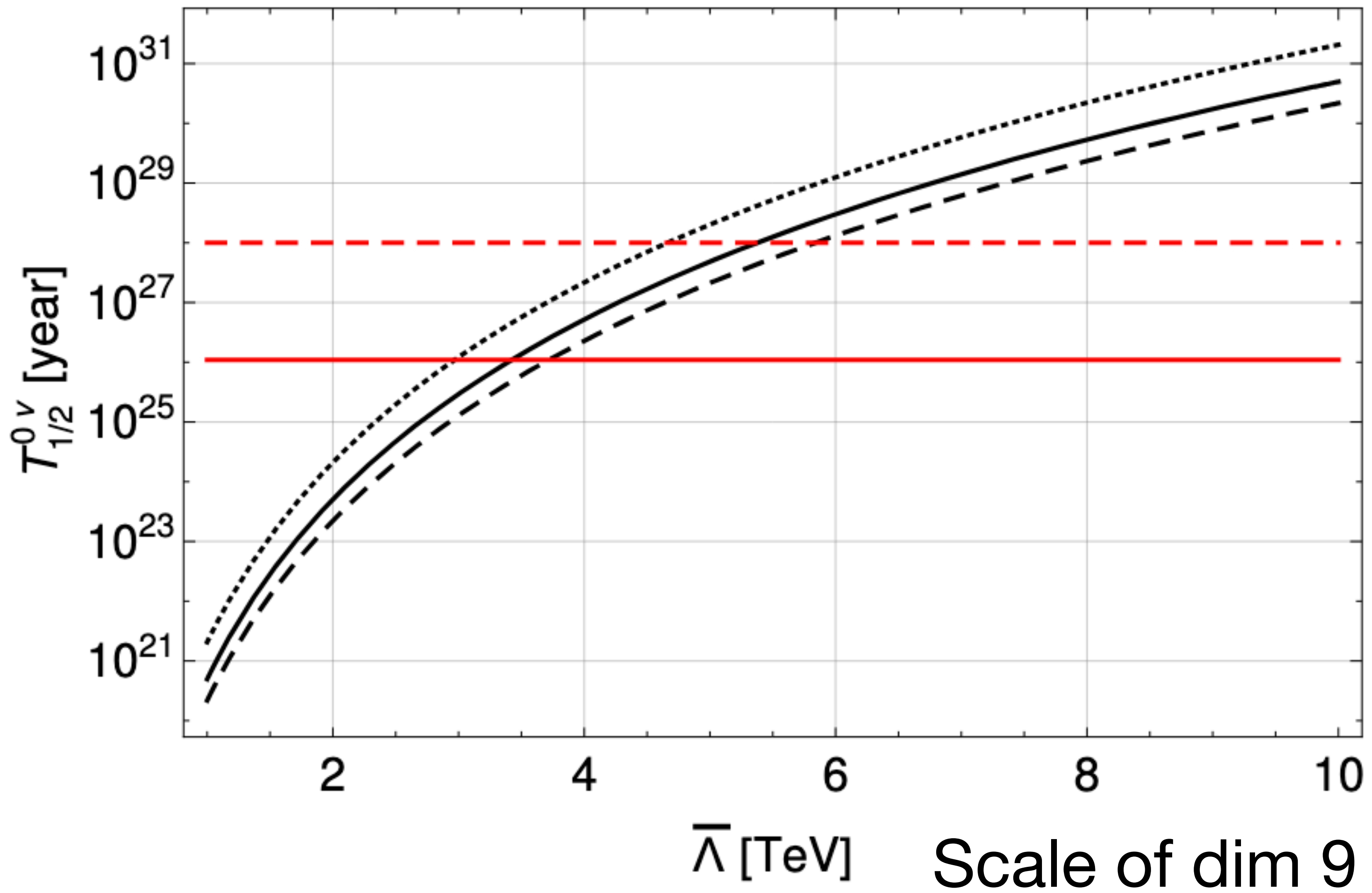


Scale of dim 9 operator

lepton number violation could come from an odd-dimensional (dim 5, 7, 9, …) EFT operator

Lowest dimensional SMEFT operator $\rightarrow$ Majorana neutrino mass term

Kochbach '16

Neutrinoless double beta decay

Observable: half-life of isotope

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

Phase space

Particle physics quantity

Nuclear matrix element

Neutrinoless double beta decay

See talks today and posters tomorrow

Observable: half-life of isotope

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

Phase space

Under control

See talk by N. Hinohara

Particle physics quantity

Under control

Nuclear matrix element

Source of uncertainty

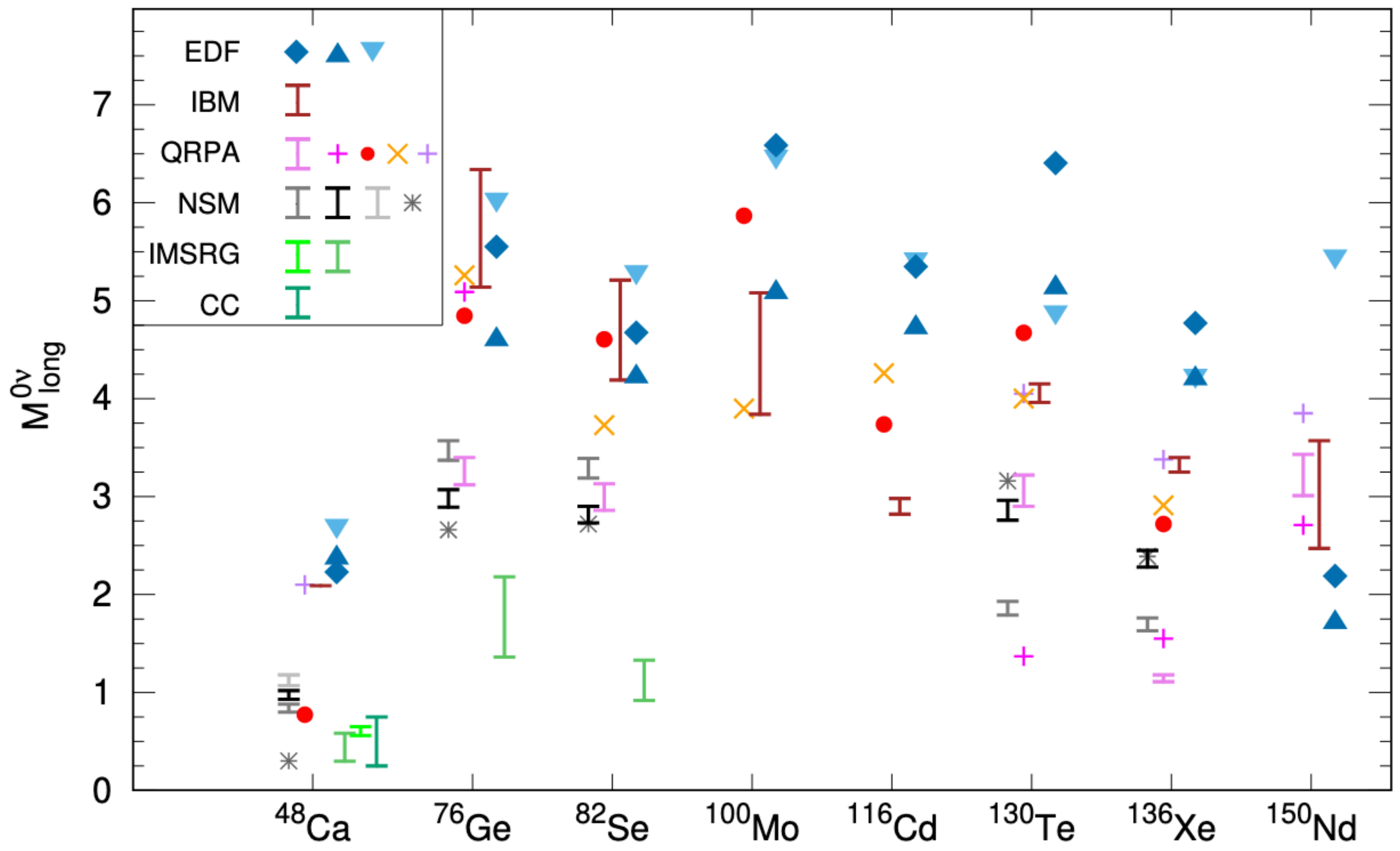
Neutrinoless double beta decay

Nuclear matrix element

Engel, Menendez '16

Disagreements between determinations using different nuclear models

Agostini, Benato, Detwiler, Menendez, Vissani '22



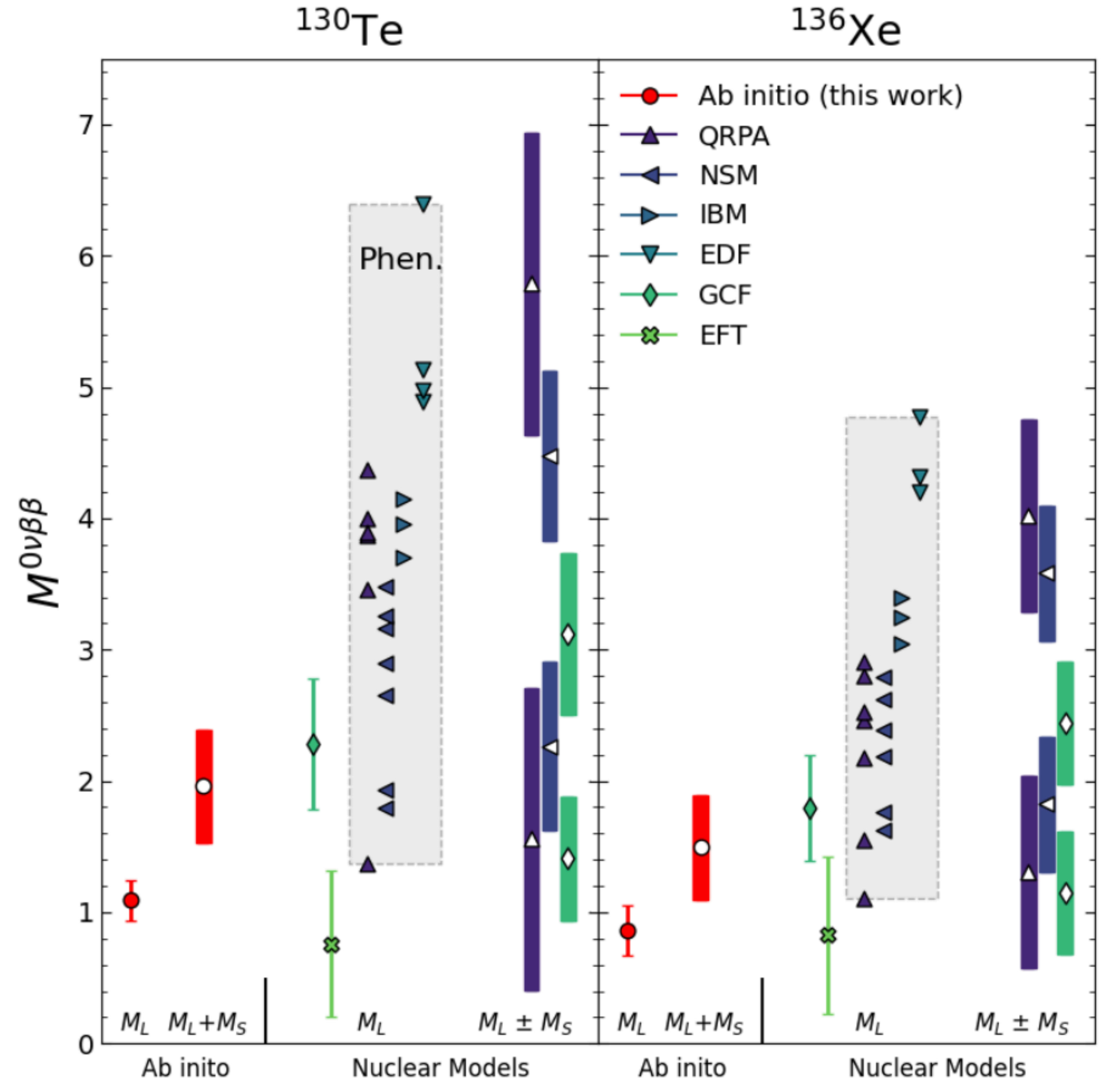
New idea:
Ab-initio many body methods
start with interactions and
operators determined from QCD
and/or fit to data in very light nuclei
produce solutions to the Schroedinger equation
in heavier nuclei, with systematically
improvable approximations

Goal: Reliable uncertainty quantification

Neutrinoless double beta decay

Nuclear matrix elei

Belley et al '23



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in heavier nuclei, with systematically
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Goal: Reliable uncertainty quantification

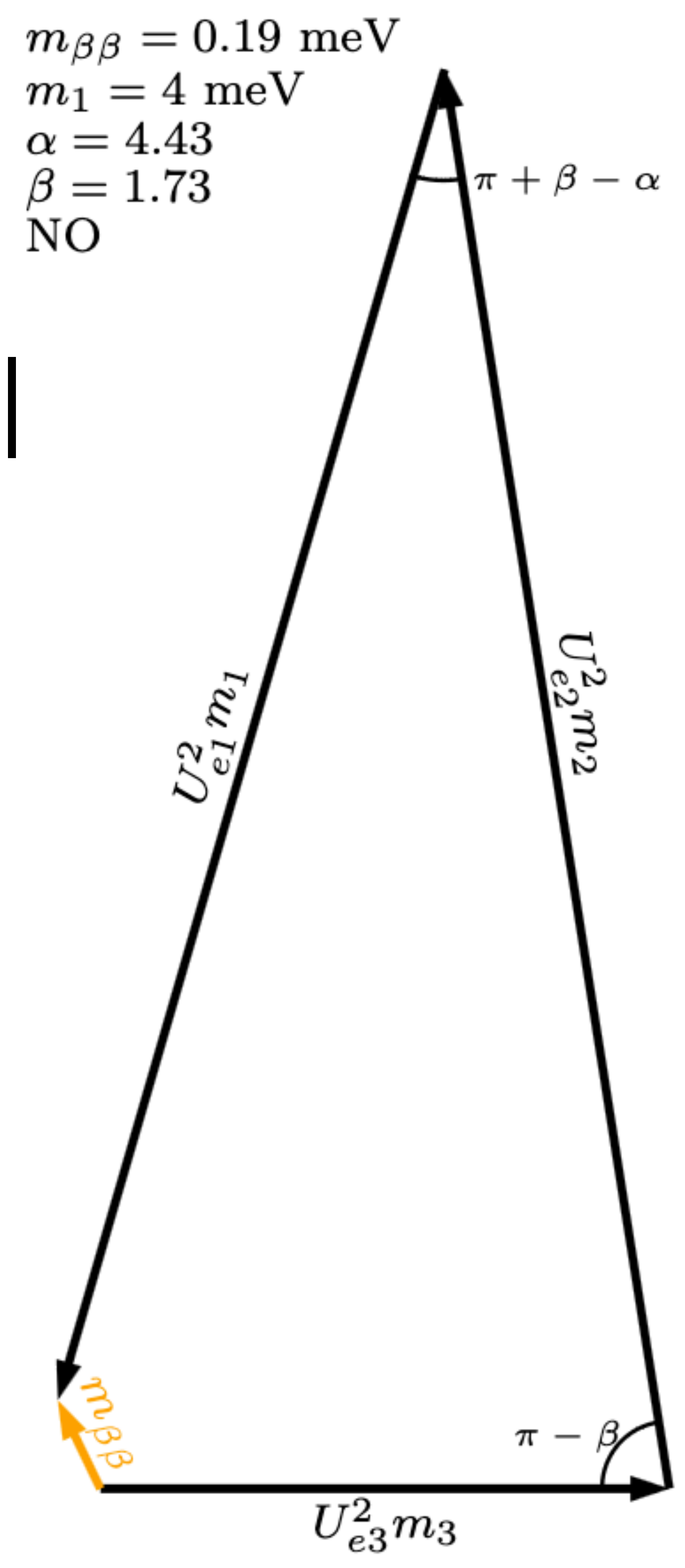
first comprehensive ab initio uncertainty quantification last year Belley et al '23

Neutrinoless double beta decay

Particle physics quantity

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

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



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!

Neutrinoless double beta decay

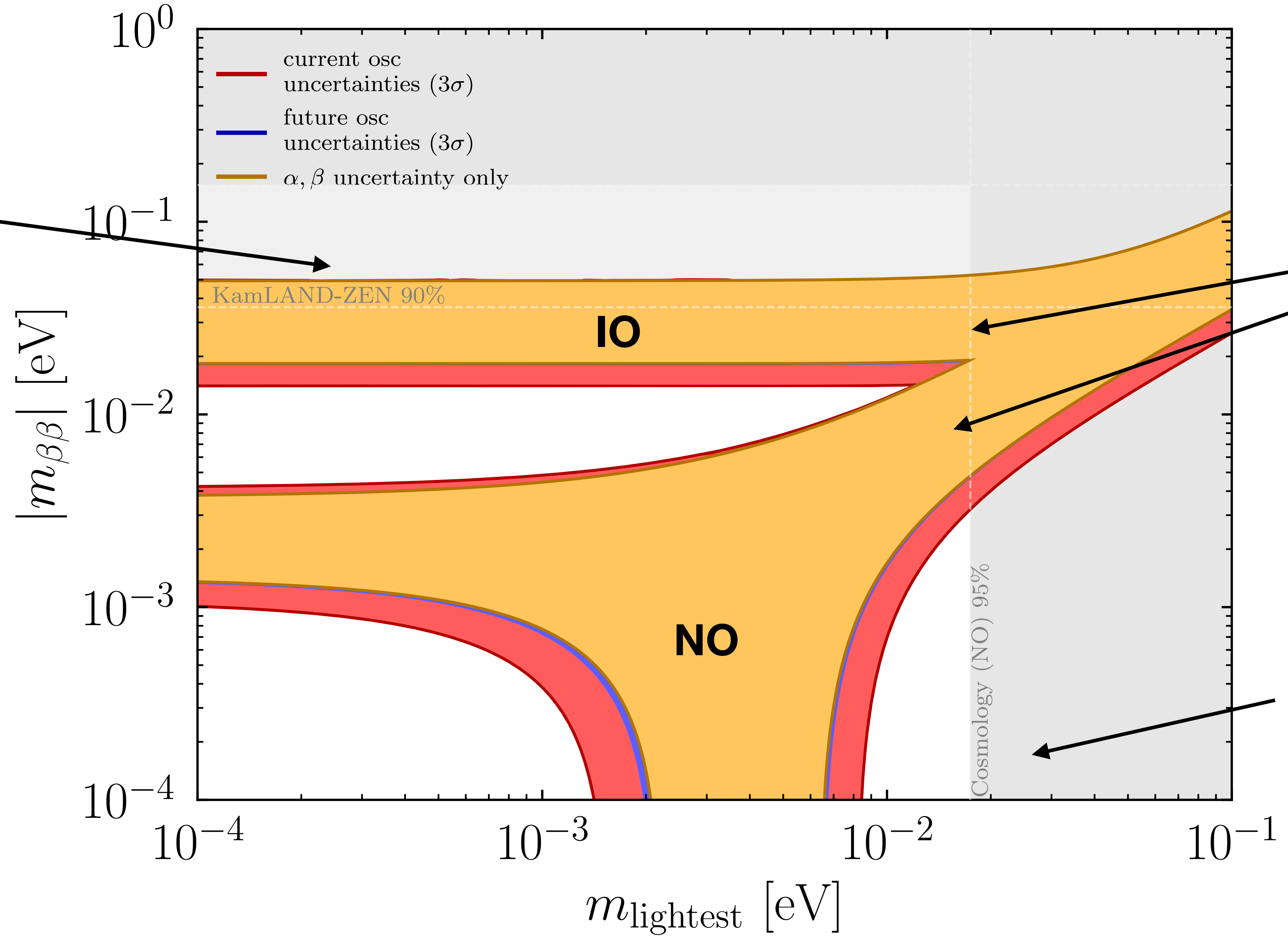
Particle physics quantity

Denton, JG '23

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

$$= |\cos^2\theta_{12}\cos^2\theta_{13} m_1 \mathrm{e}^{-i\alpha} + \sin^2\theta_{12}\cos^2\theta_{13}\mathrm{m}_2\mathrm{e}^{-i\beta} + \sin^2\theta_{13}\mathrm{m}_3|$$

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



Upcoming oscillation experiments will select MO and slightly decrease parameter space

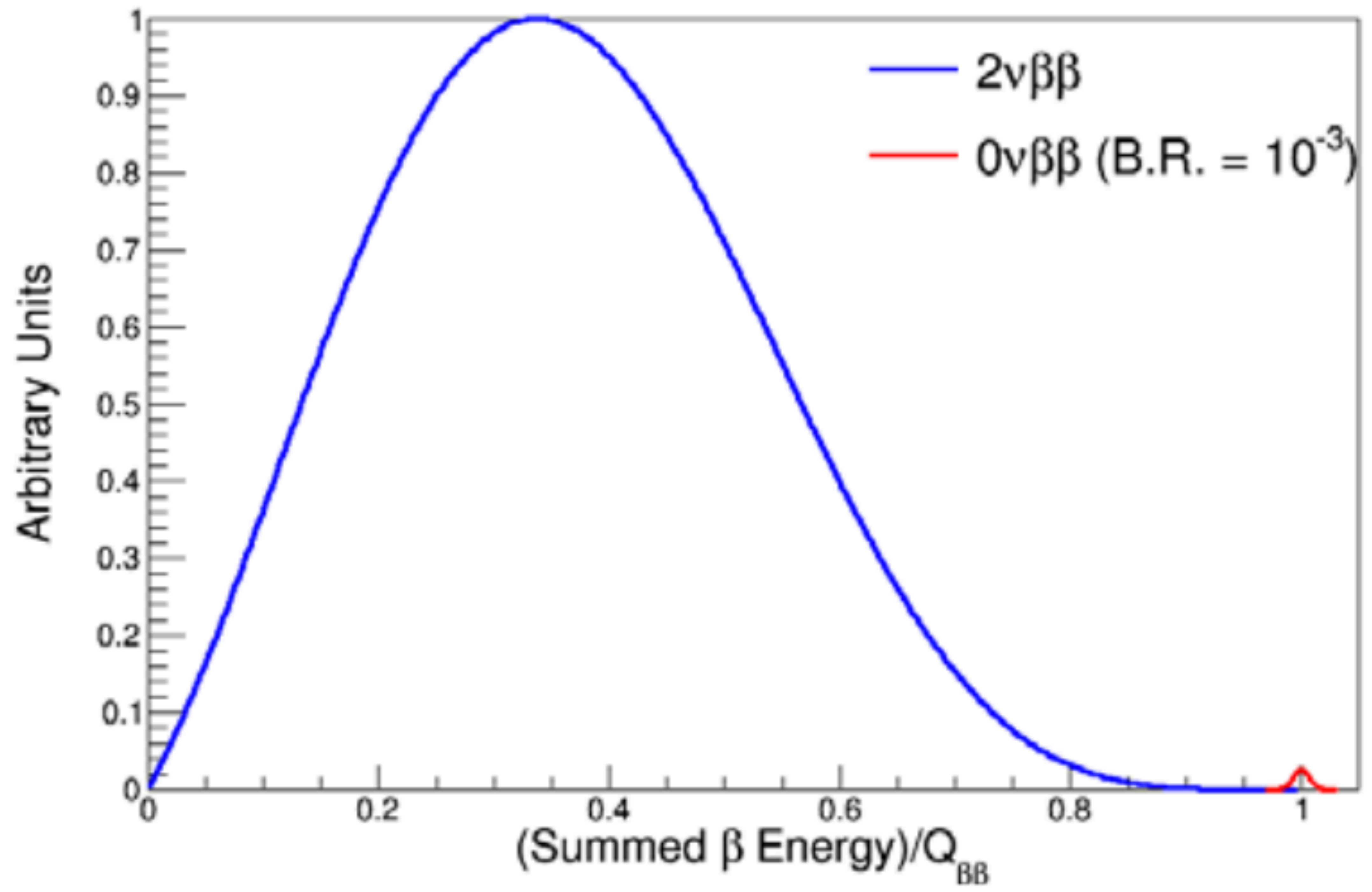
Interplay with cosmology: sum of neutrino masses

Neutrinoless double beta decay

Experiment

Observable: 2 emitted electrons (+daughter nucleus)

intrinsic, irreducible background: $2\nu\beta\beta$



Neutrinoless double beta decay

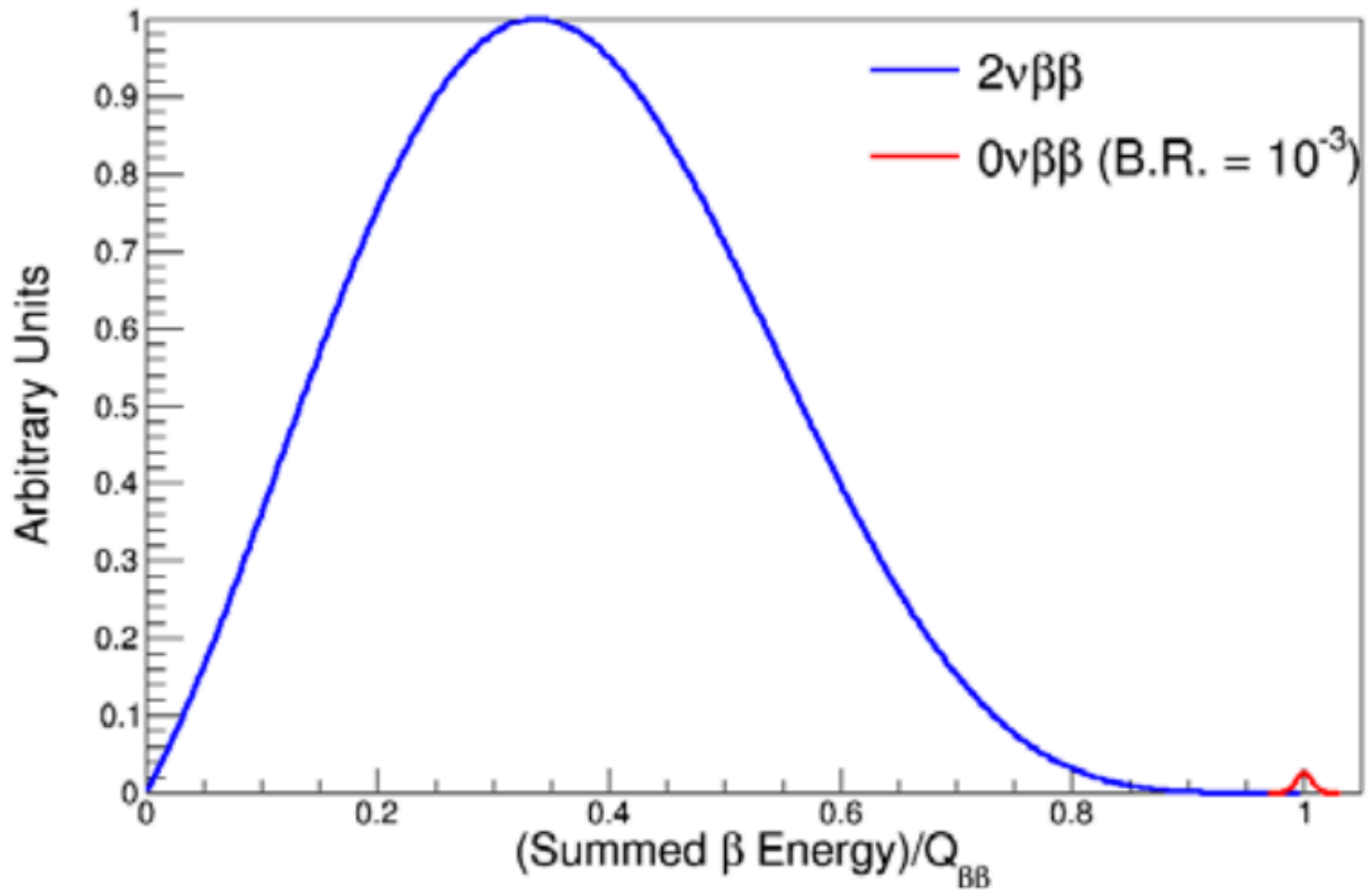
Experiment

Observable: 2 emitted electrons (+daughter nucleus)

intrinsic, irreducible background: $2\nu\beta\beta$

Experimental requirements:

- excellent energy resolution
- low backgrounds
- Large detectors (expect one decay per ton-year)
- Long exposure
- Topological information of signal and background



Neutrinoless double beta decay

Experiment

KamLAND-Zen '22

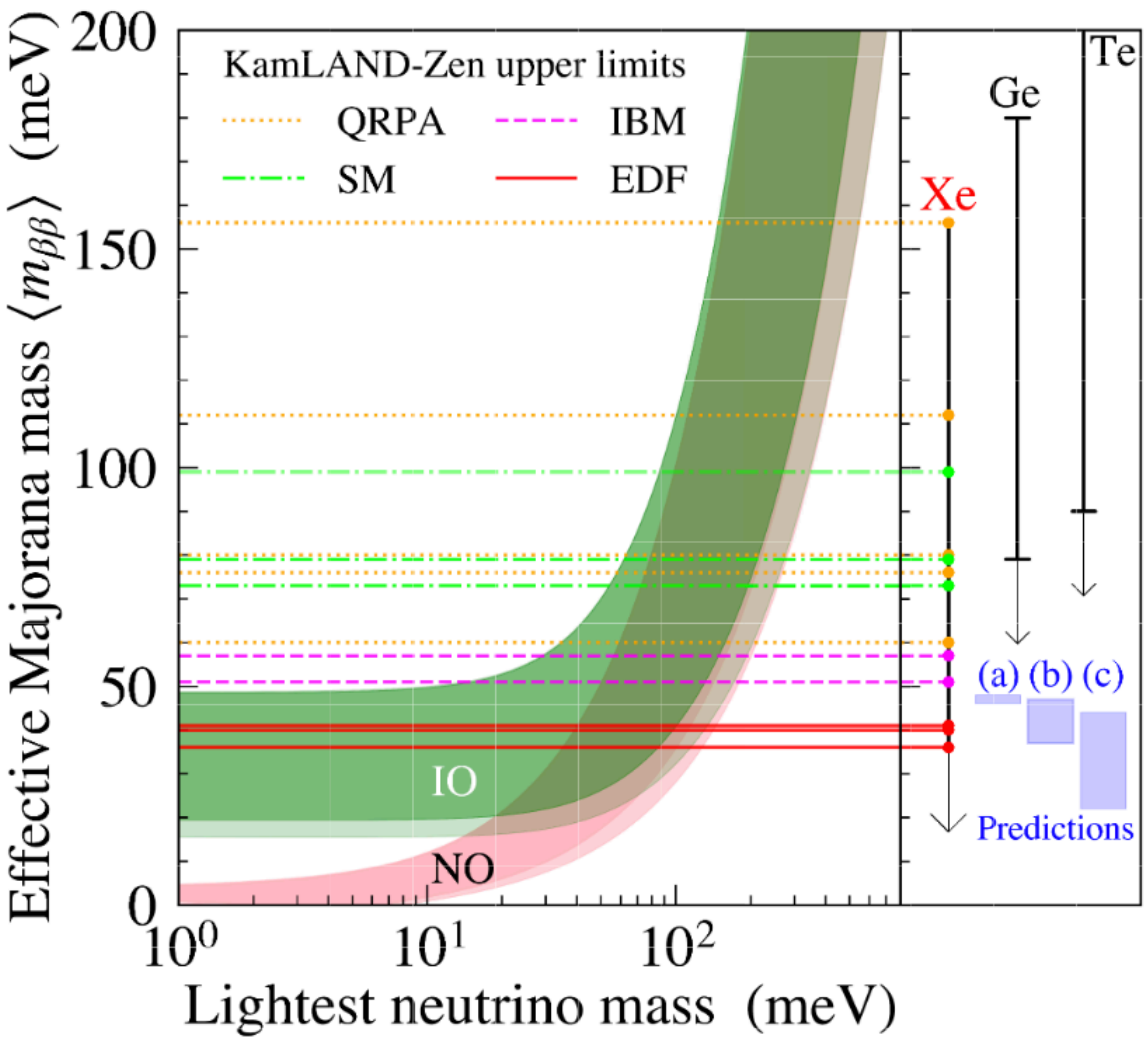
No observation

Best constraint from KamLAND-Zen:

$$T_{1/2}^{0\nu} > 2.3 \times 10^{26} \text{ yr}$$
$$\rightarrow m_{\beta\beta} < 36 - 156 \text{ meV}$$

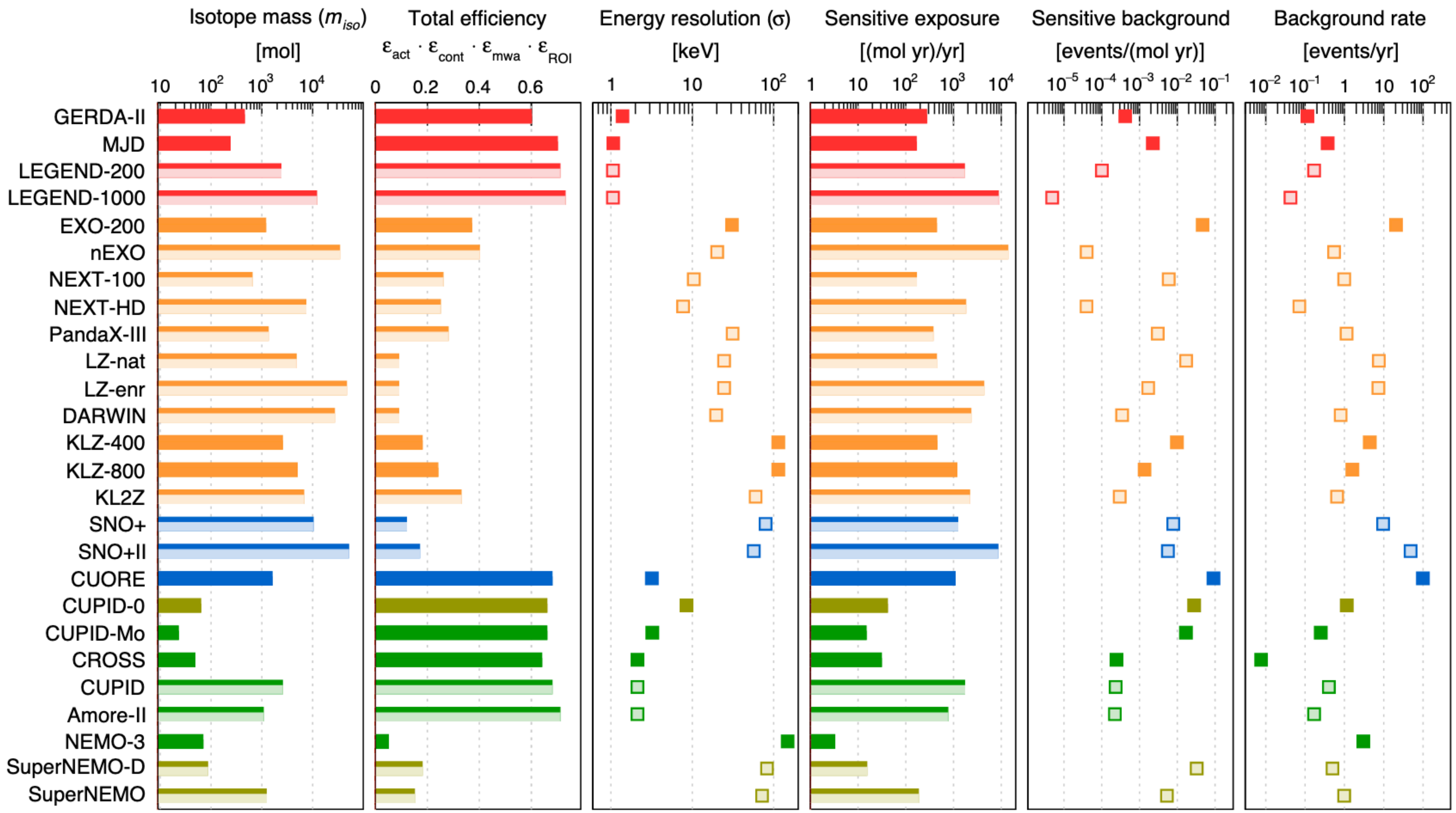
See previous talks

Several other experiments start to probe the IO



Neutrinoless double beta decay

Experiment



Experimental prospects are rich:
Different isotopes, different detection techniques,…

One of top priorities of US Nuclear Science Advisory Committee long-range plan: pursuit of ton-scale neutrinoless double beta decay experiments
KamLAND2-Zen: MEXT roadmap 2023

See talks today

Neutrinoless double beta decay

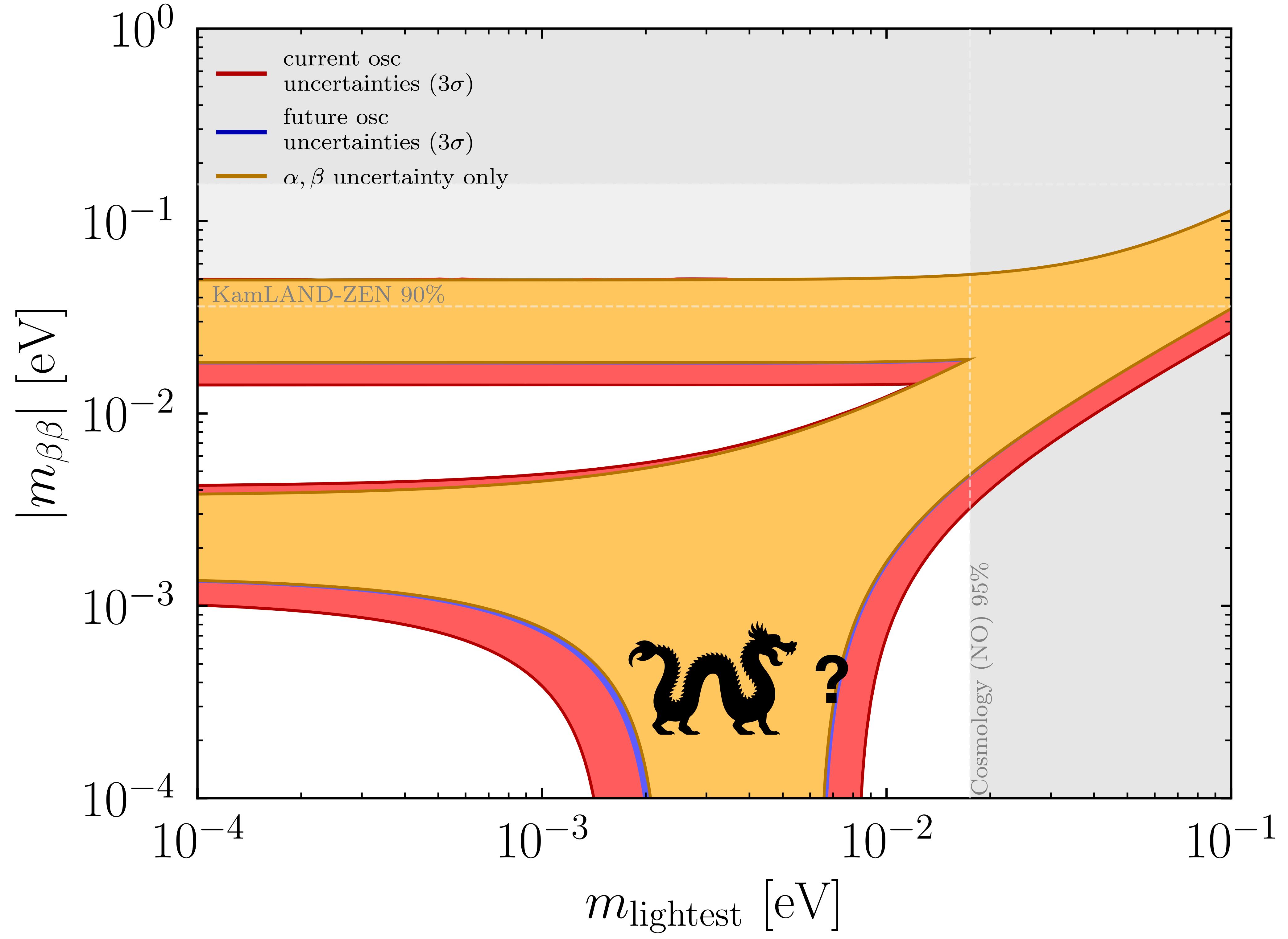
Future

Where are we going?

Experiments are moving forward

Where are the regions of interest?

Do we need/want to probe down to very small $m_{\beta\beta}$?



Neutrinoless double beta decay

Future

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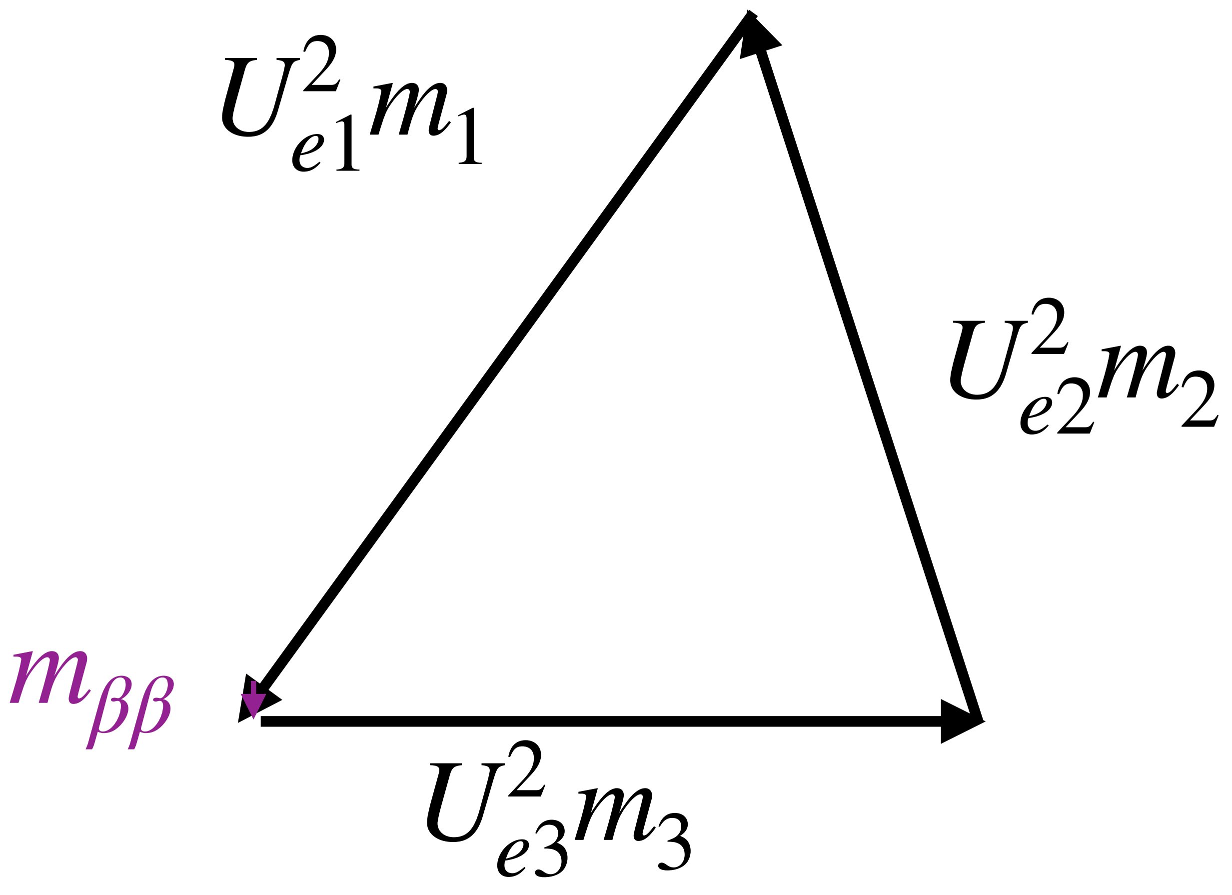
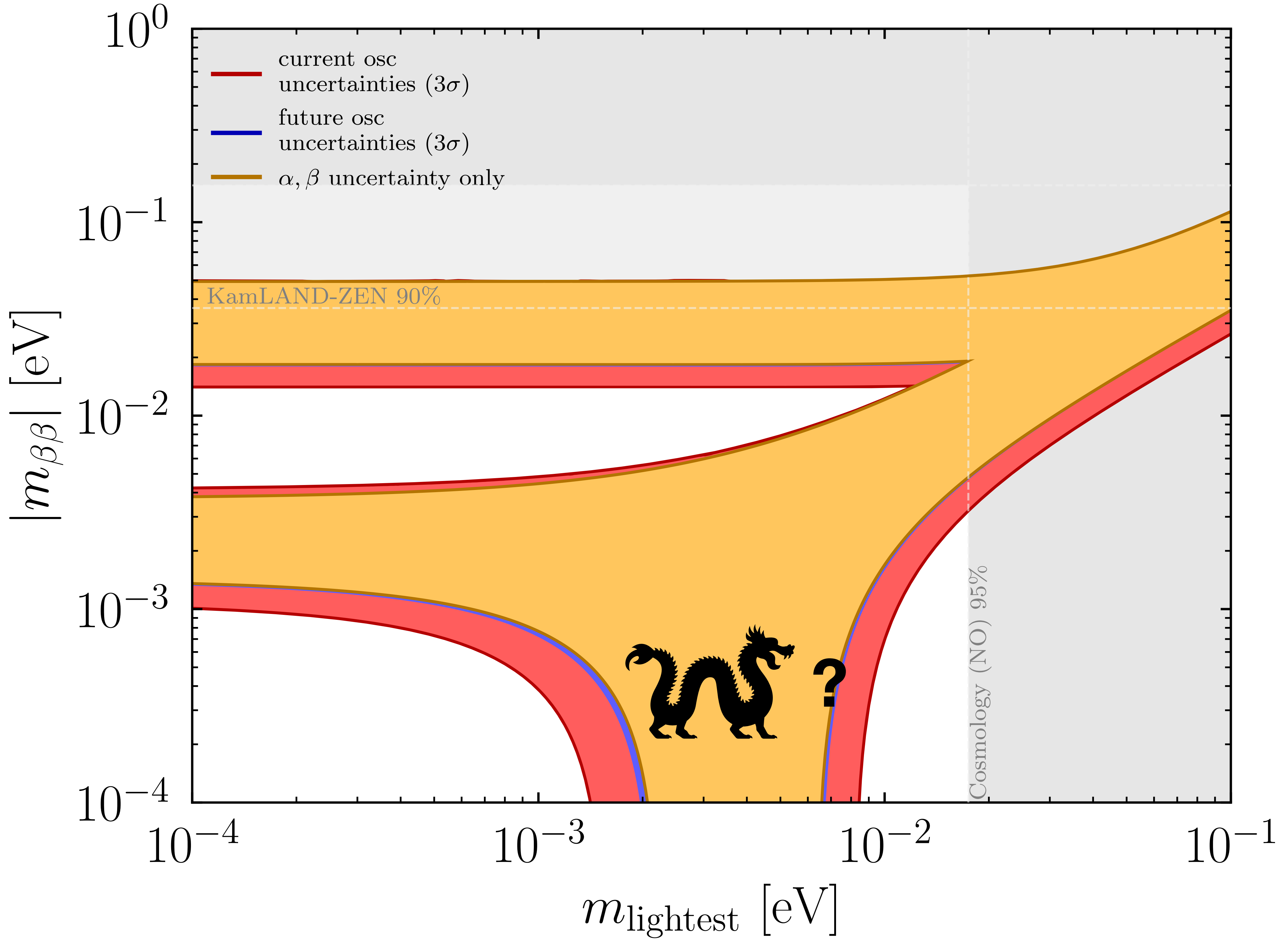
In funnel both Majorana phases
can be extracted

Ge, Lindner '16



Triangle closes
from the knowledge of
length of sides
we can determine the
Majorana phasese



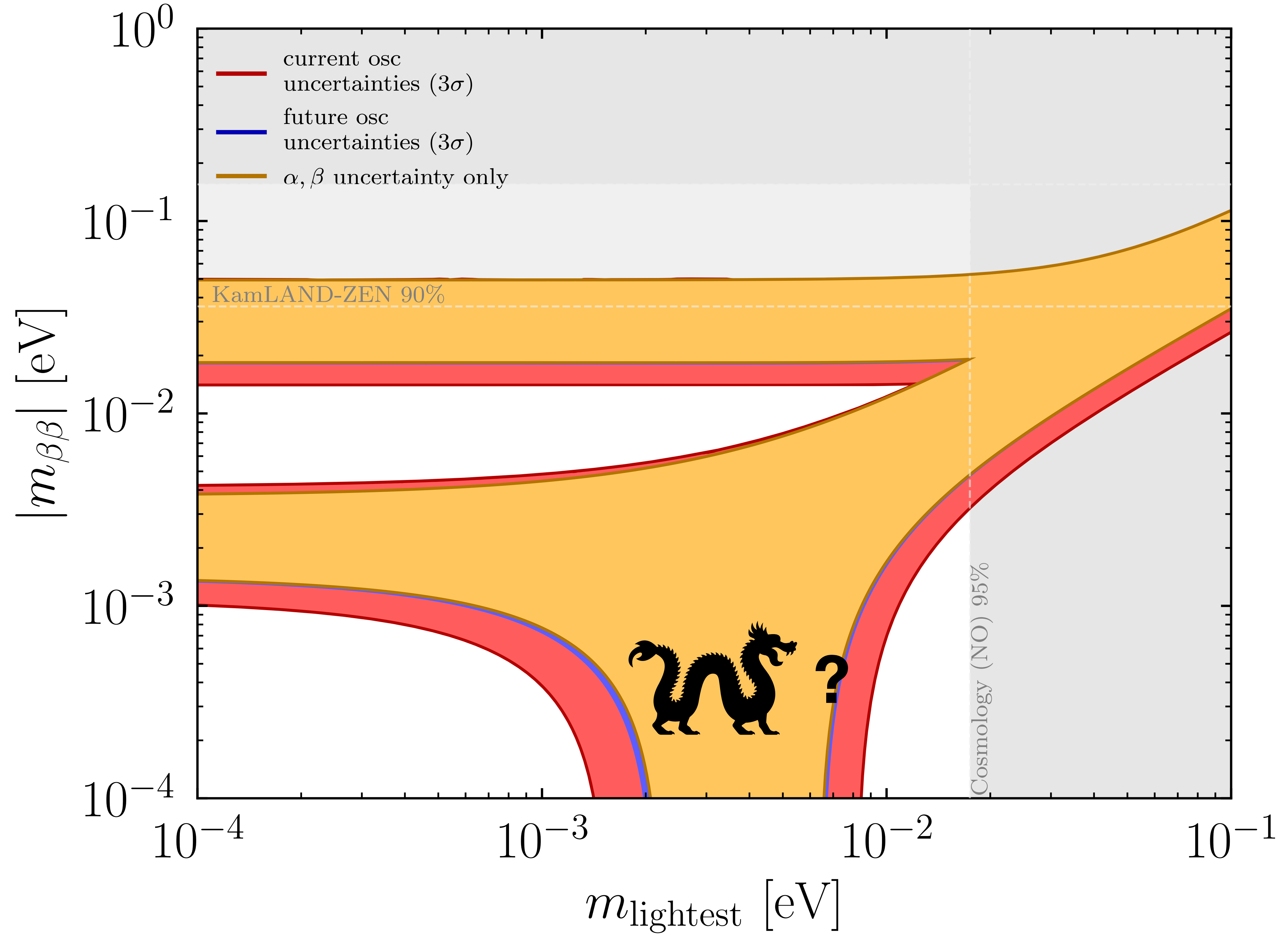
Neutrinoless double beta decay

Future

Where are we going?

Experiments are moving forward
Where are the regions of interest?
Do we need/want to probe down to very small $m_{\beta\beta}$?

Majorana phases, lightest mass, MO crucially determine allowed regions of $m_{\beta\beta}$
→ Predictions from flavor models



Neutrinoless double beta decay

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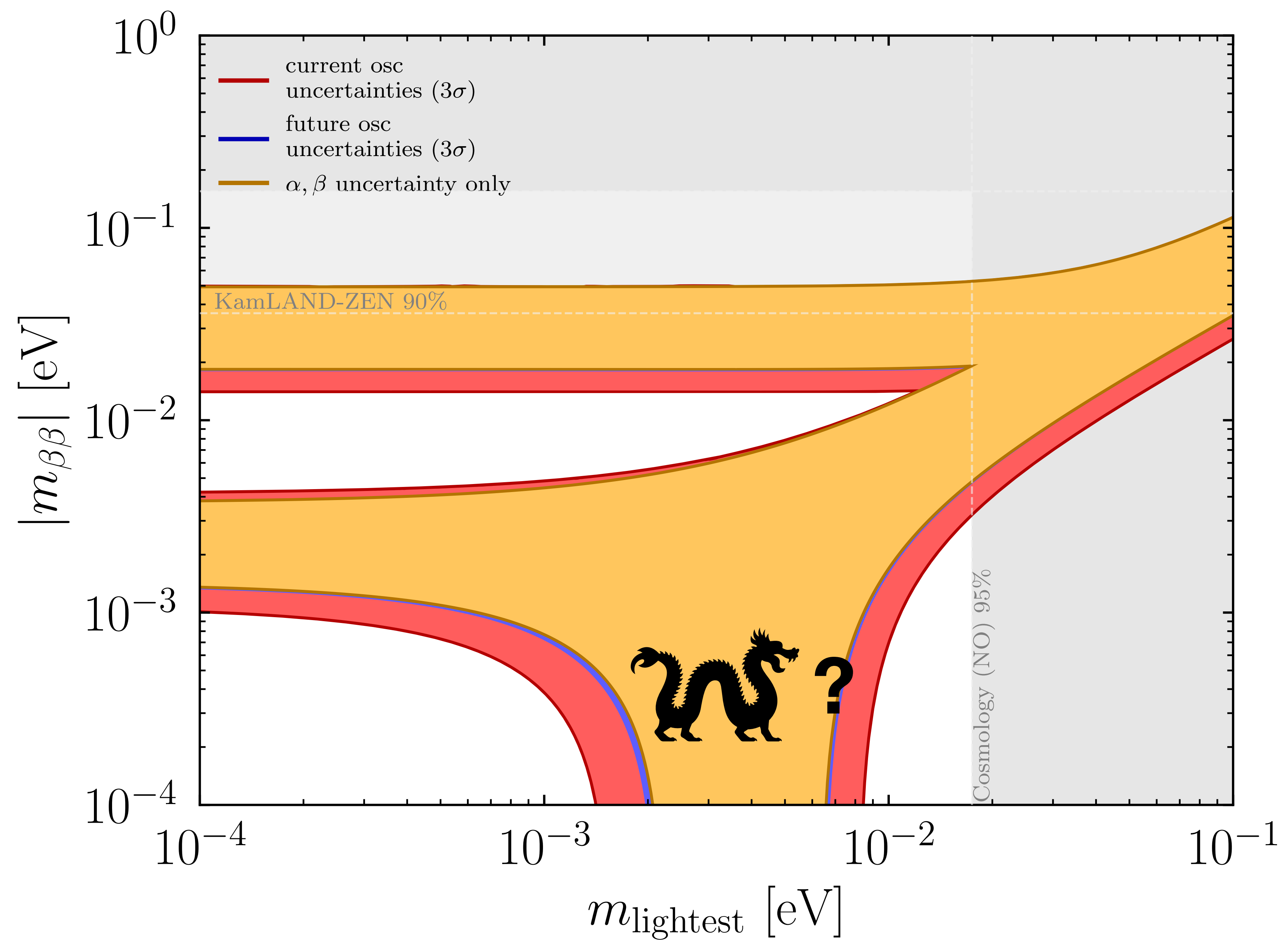


A Survey of Neutrino Flavor Models and the Neutrinoless Double Beta Decay Funnel

Denton, JG '23

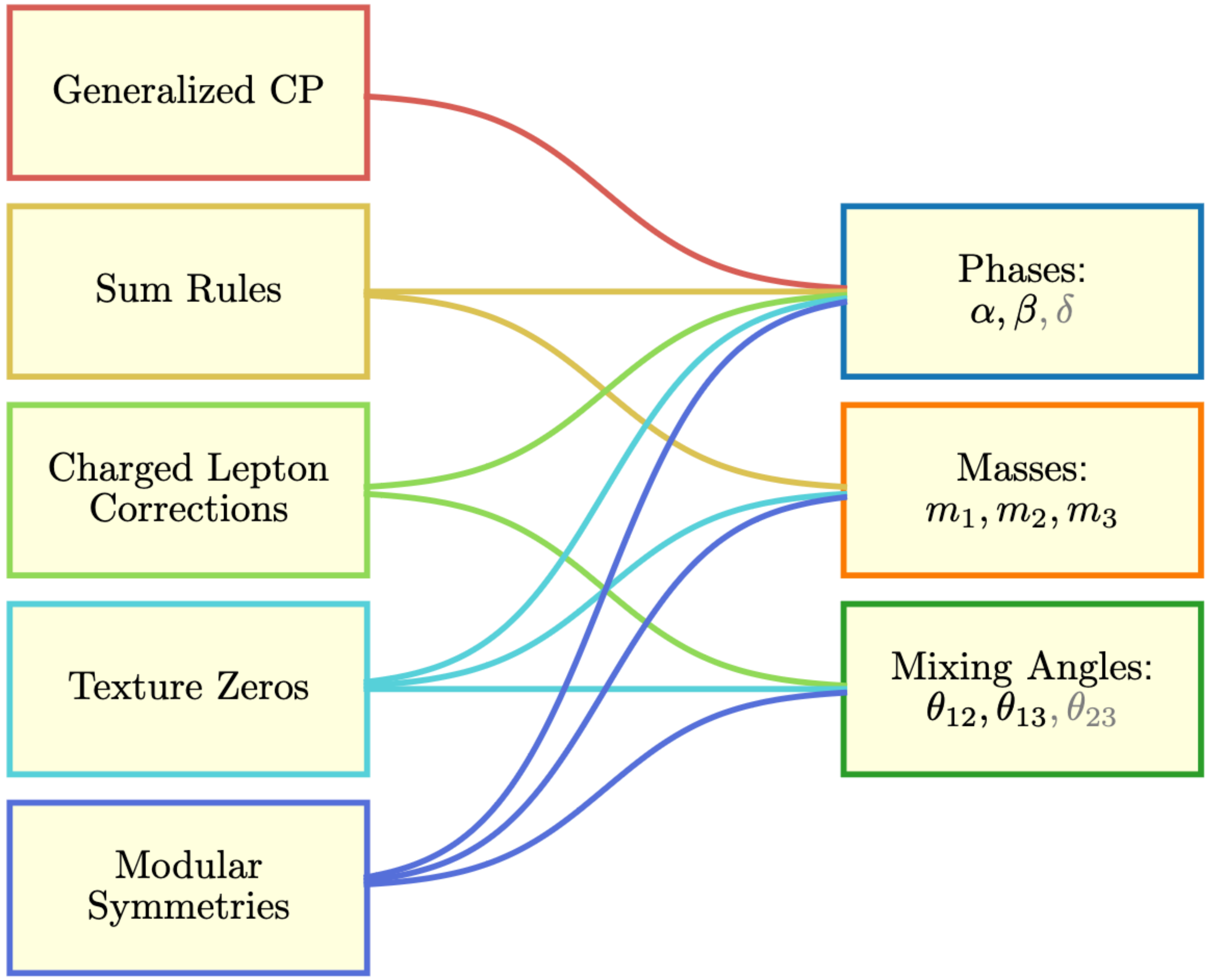
Peter B. Denton[a,1] **and Julia Gehrlein**[b,c,a,2]

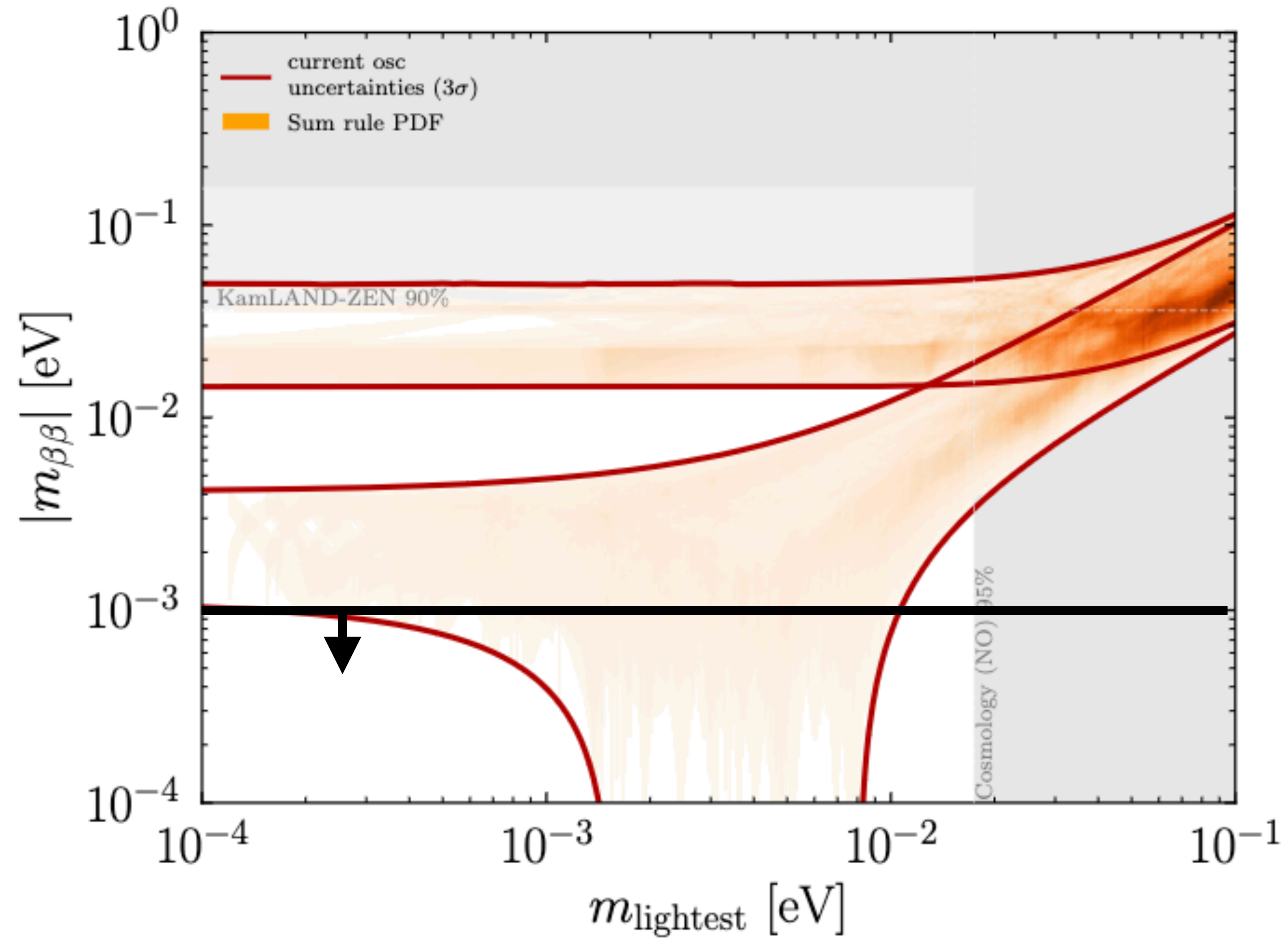
Neutrinoless double beta decay

Predictions from flavor models

Denton, JG '23

Extensive survey of five broad categories of flavor models (>3000 different models)





non-negligible fraction of flavor models (14-100%) are at least partially in the funnel region

→ interesting region to probe

Neutrinoless double beta decay

Sterile neutrinos

Vanilla scenario: $0\nu\beta\beta$ due to light Majorana neutrino exchange

Additional neutrino generations can affect $0\nu\beta\beta$ phenomenology

Phenomenology depends on ratio of sterile neutrino mass m_N to momentum transfer of process $\langle p^2 \rangle \sim (100\ \mathrm{MeV})^2$

Neutrinoless double beta decay

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Phenomenology depends on ratio of sterile neutrino mass m_N to momentum transfer of process $\langle p^2 \rangle \sim (100 \text{ MeV})^2$:

$$A \propto \sum_{i}^{\text{light}} m_i U_{ei}^2 M^{0\nu\beta\beta}(m_i) + \sum_{I}^{\text{light}} m_I U_{eI}^2 M^{0\nu\beta\beta}(m_I) + \sum_{I}^{\text{heavy}} m_I U_{eI}^2 M^{0\nu\beta\beta}(m_I)$$

Light active neutrinos — Light sterile neutrinos — Heavy sterile neutrinos

Blennow, Fernandez-Martinez, Lopez-Pavon, Menendez '10

Neutrinoless double beta decay

Sterile neutrinos

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$m_N < 100\ \mathrm{MeV}$: sterile neutrino acts like active neutrinos, A suppressed as

$$\sum_i^{\text{light}} m_i U_{ei}^2 + \sum_I^{\text{light}} m_I U_{eI}^2 = 0$$

Blennow, Fernandez-Martinez, Lopez-Pavon, Menendez '10

Neutrinoless double beta decay

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$m_N \gg 100\ \mathrm{MeV}$: sterile neutrinos heavy and integrated out, amplitude is 3-flavor amplitude

Blennow, Fernandez-Martinez, Lopez-Pavon, Menendez '10

Neutrinoless double beta decay

Sterile neutrinos

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$m_{N_1} > 100\ \mathrm{MeV},\ \mathrm{m}_{\mathrm{N}_2} < 100\ \mathrm{MeV}$: some sterile neutrinos are heavy, some are light

→ cancellation of light sterile amplitude with SM amplitude prevented

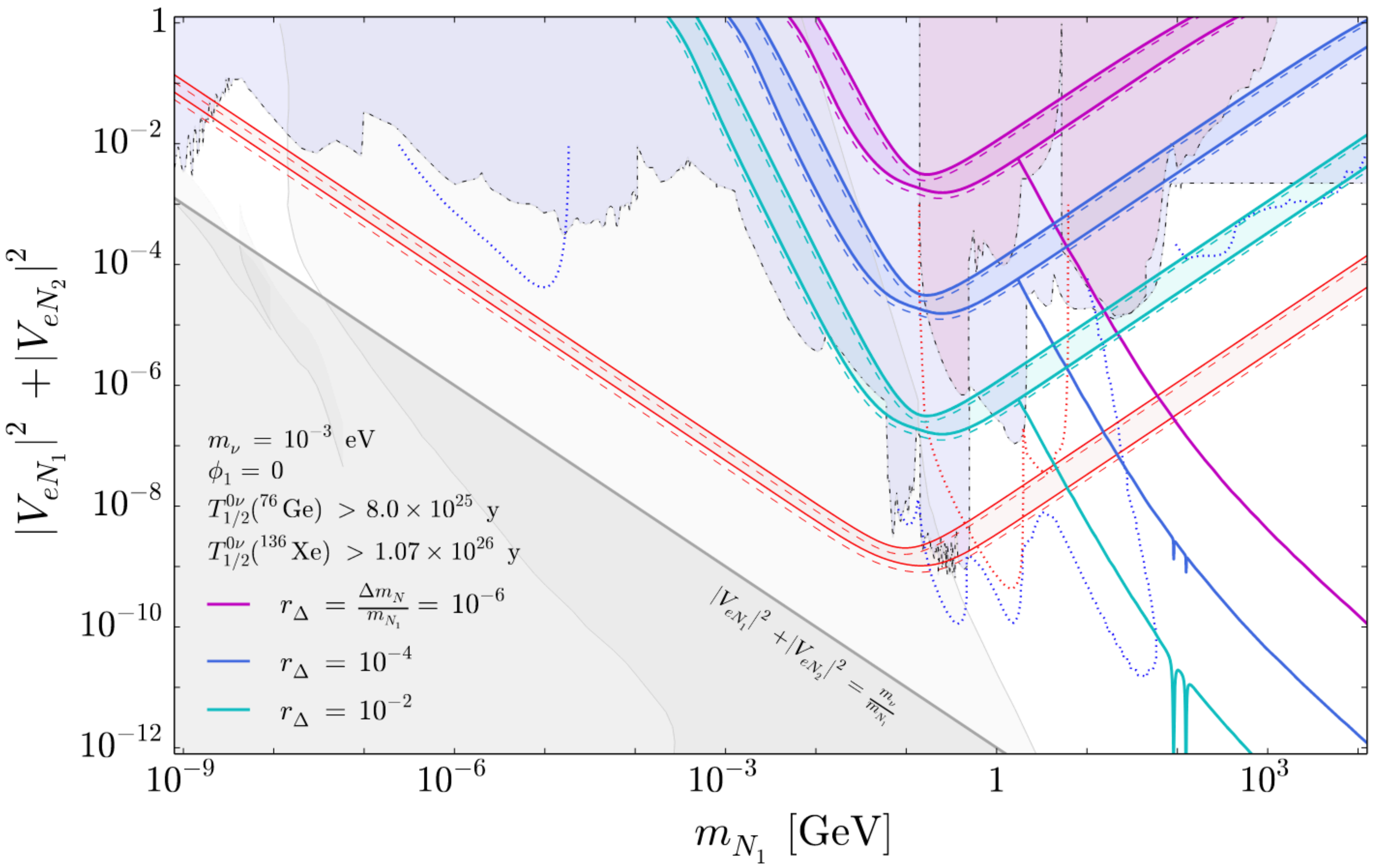
Blennow, Fernandez-Martinez, Lopez-Pavon, Menendez '10

Neutrinoless double beta decay

Sterile neutrinos

Additional neutrino generation can affect $0\nu\beta\beta$ phenomenology

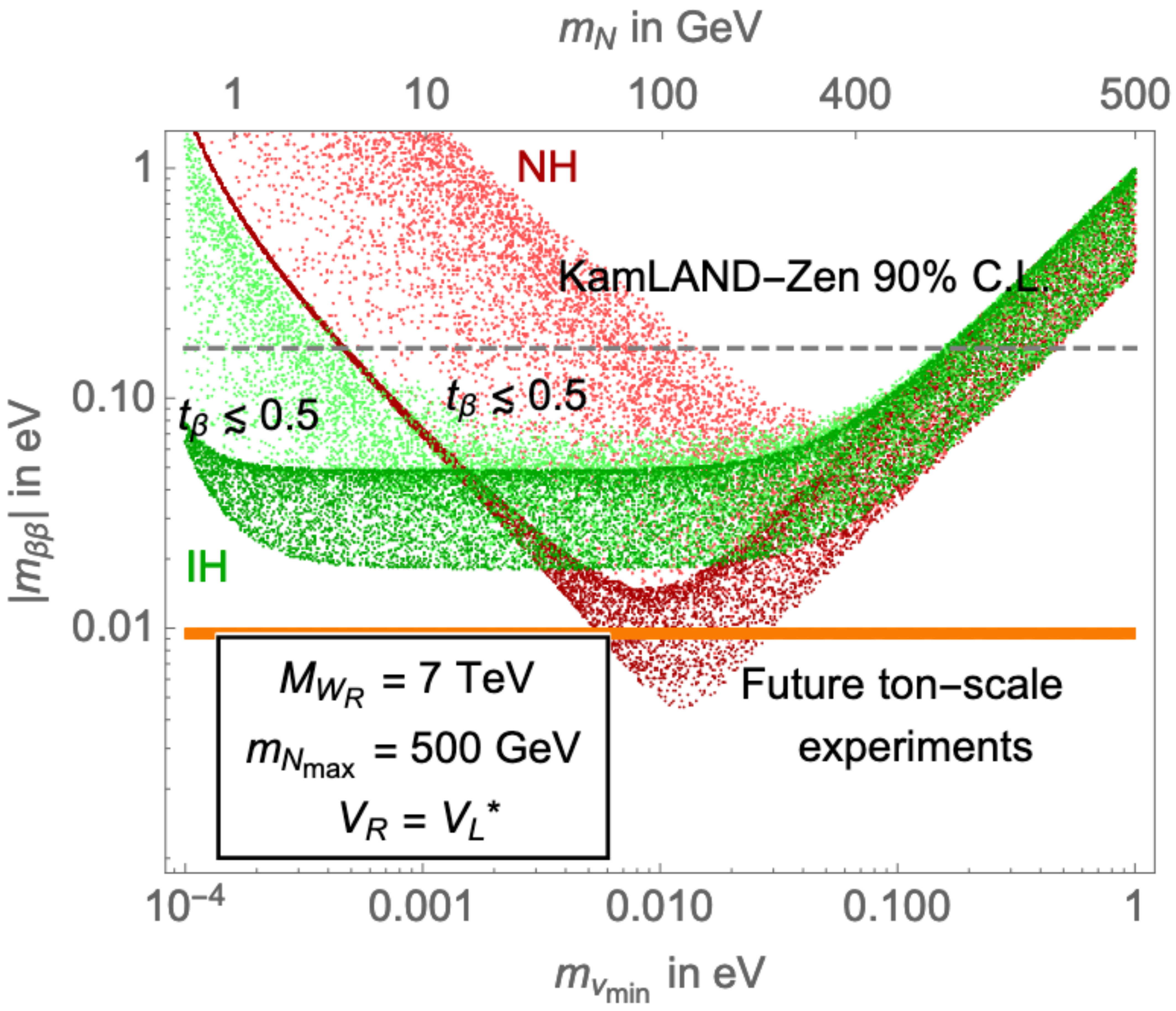
$\rightarrow$ Constraints on sterile neutrinos



Bolton, Dev, Deppisch '19

Neutrinoless double beta decay

Minimal left-right symmetric model

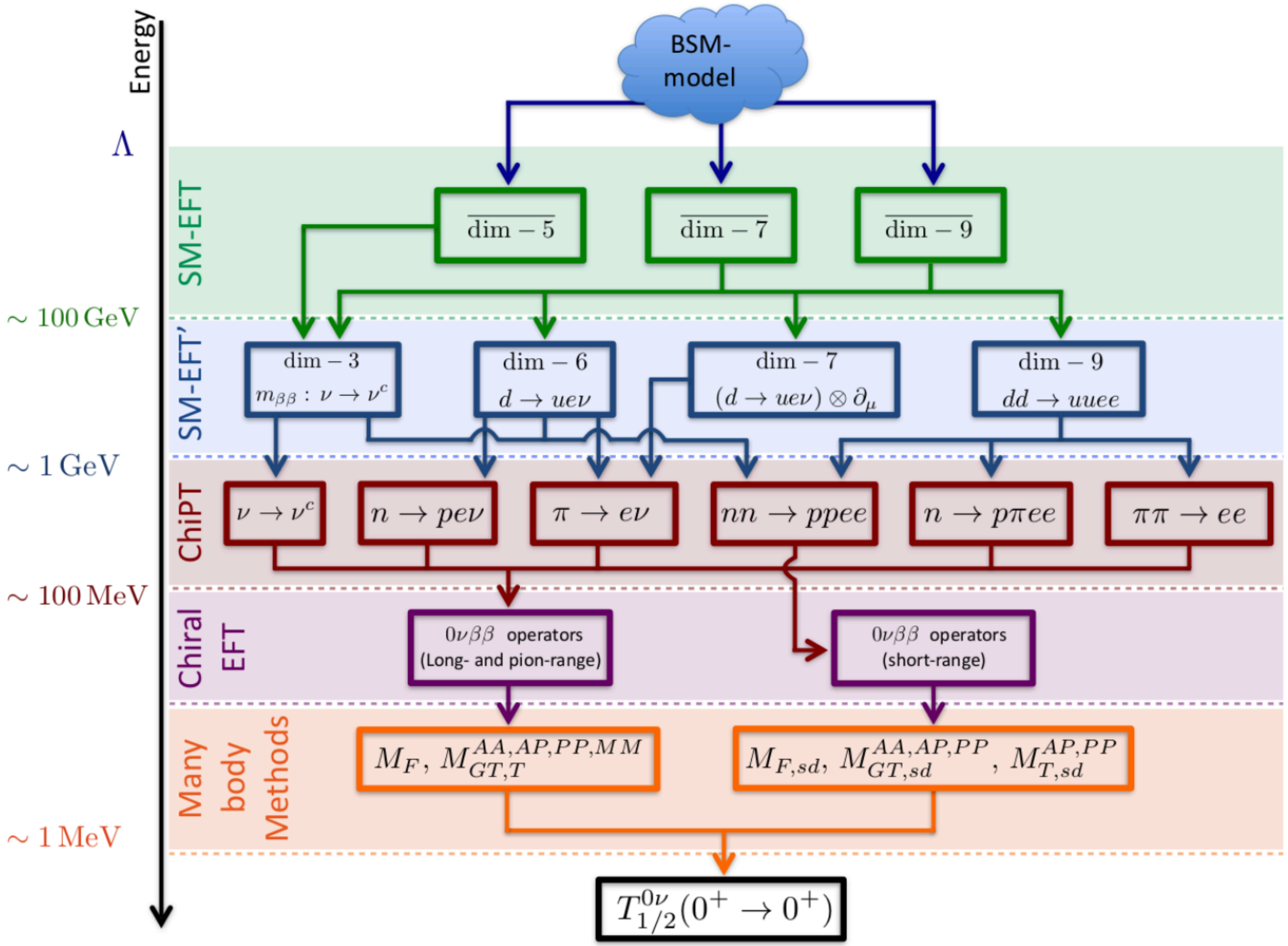


New mediators!

Particle physics quantity is not $|m_{\beta\beta}| = |\sum U_{ei}^2 m_i|$ anymore

Li, Ramsey-Musolf, Vasquez '20

Neutrinoless double beta decay



Cirigliano, JG et at '22

Nuclear matrix elements affected by new physics

Physics spans a large range of energies

→ need a tower of EFTs to go from high-energy model to the nuclear matrix element

Neutrinoless double beta decay

Summary and conclusions

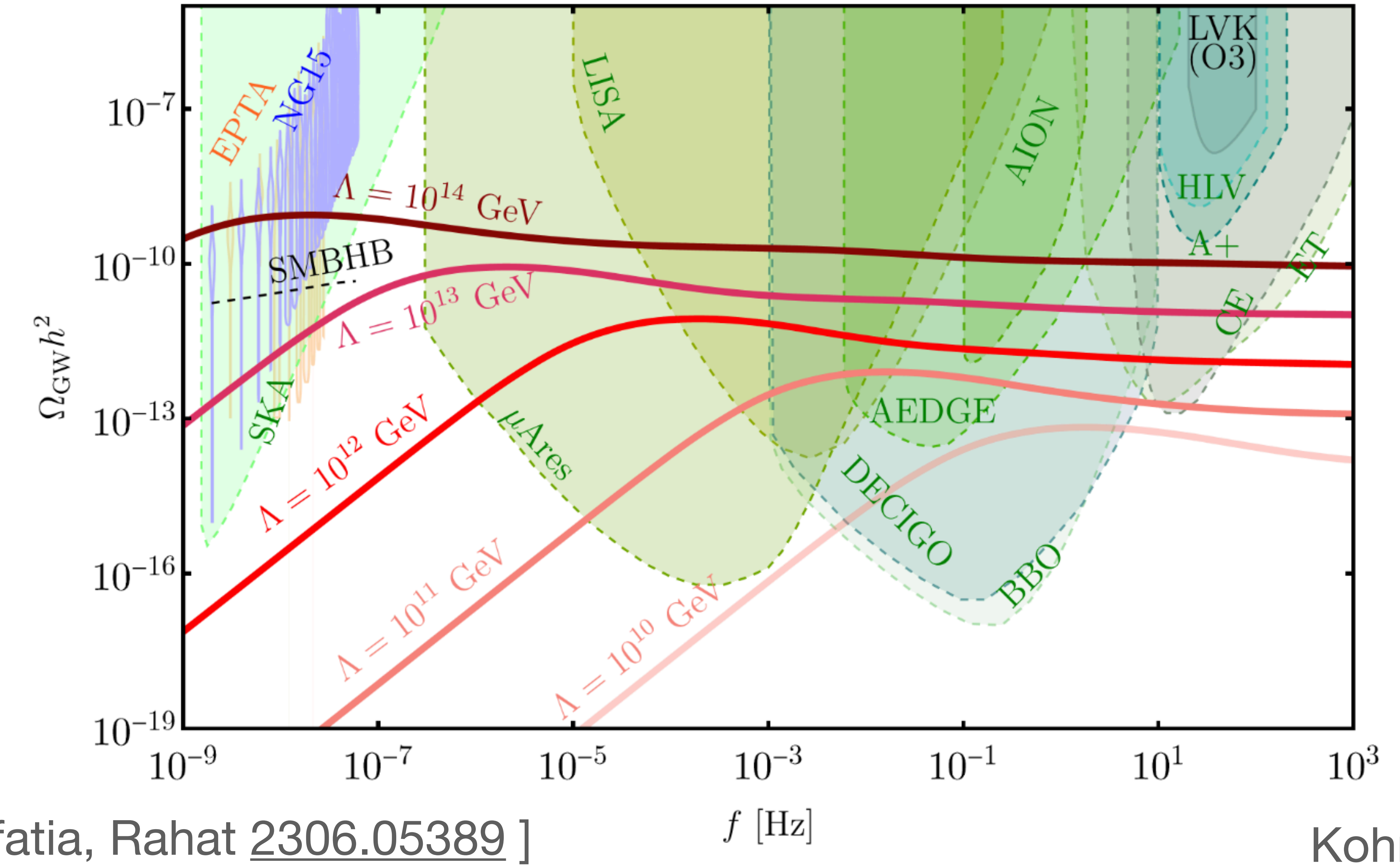
Neutrinoless double beta decay allows to probe lepton number violation and can provide insights into matter-antimatter asymmetry generation, and test symmetries of SM

- Current $0\nu\beta\beta$ experiments are ongoing
- New experimental collaborations are forming and will continue in future
- Need to define theoretical goals/targets for these experiments to provide benchmarks
- Sensitivity studies needed for new physics scenarios affecting $0\nu\beta\beta$
- For correct interpretation of results: theory work on nuclear matrix elements required with robust uncertainty quantification

Thanks for your attention!

Appendix: Lepton number violation

Signs of lepton number breaking in the early Universe
Gravitational waves from decay of cosmic strings from breaking of lepton number symmetry



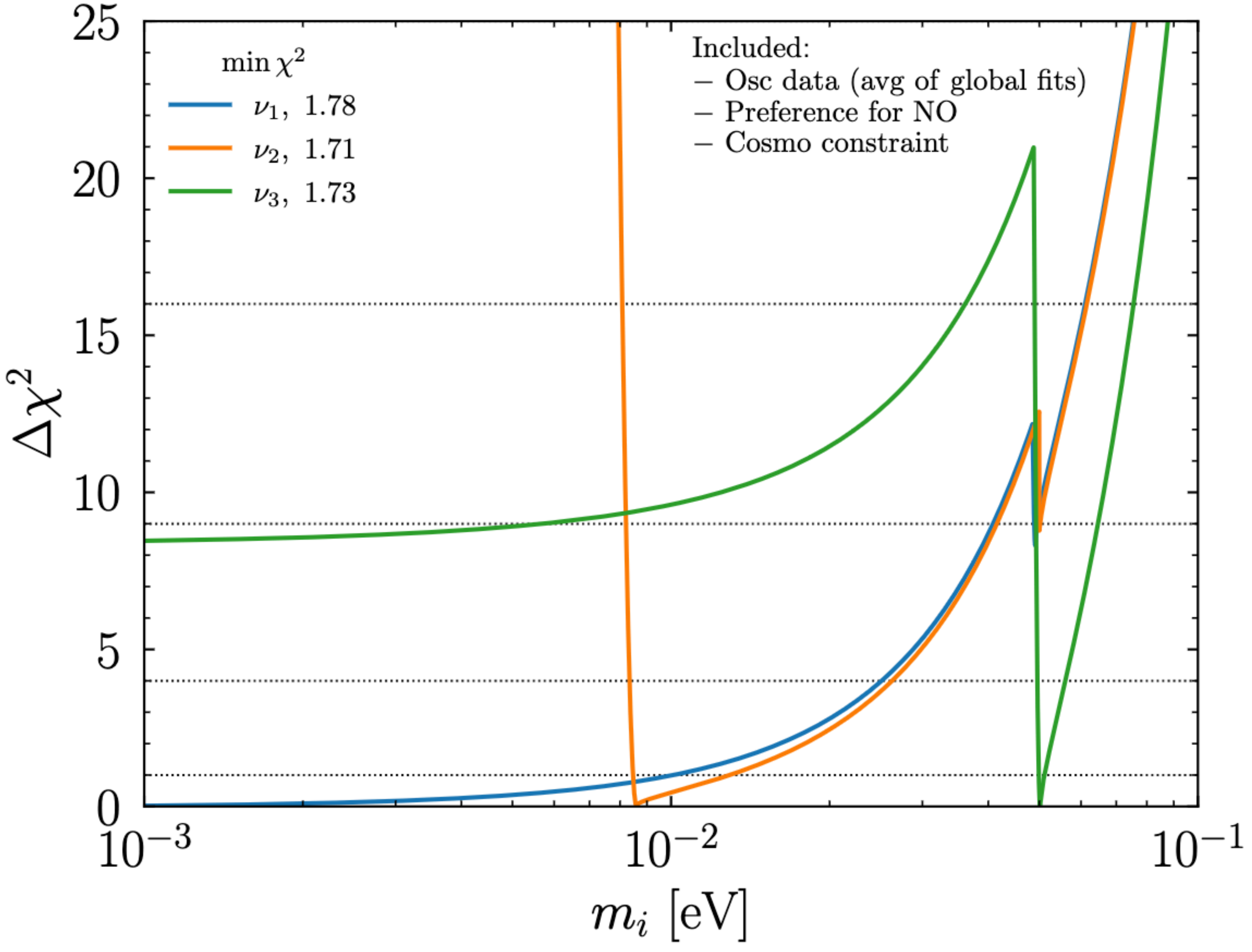
[King, Marfatia, Rahat 2306.05389]

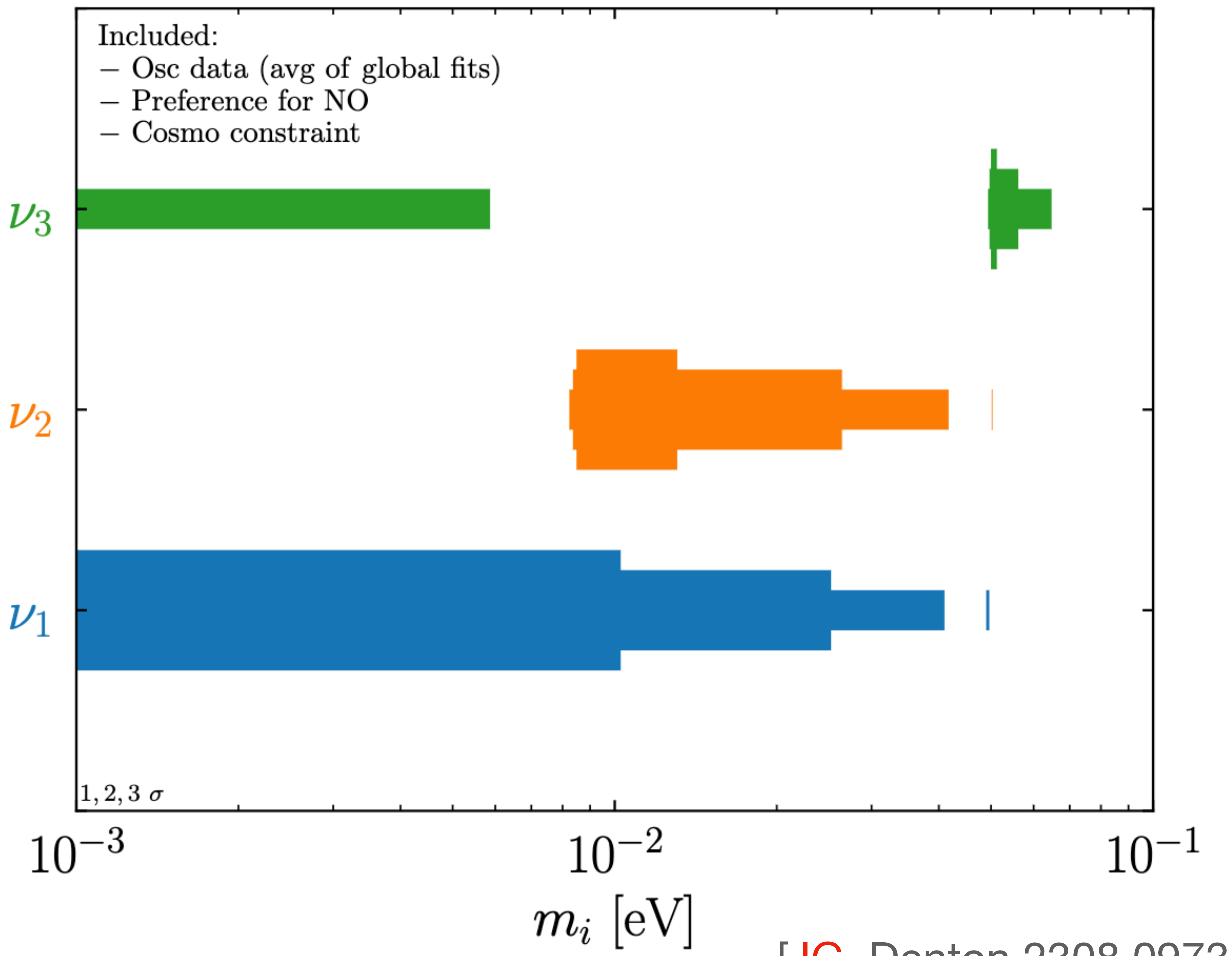
Signature depends on

Lepton number breaking scale

[see also Dror, Hiramatsu, Kohri, Murayama, White 2306.05389]

Appendix: Neutrino mass

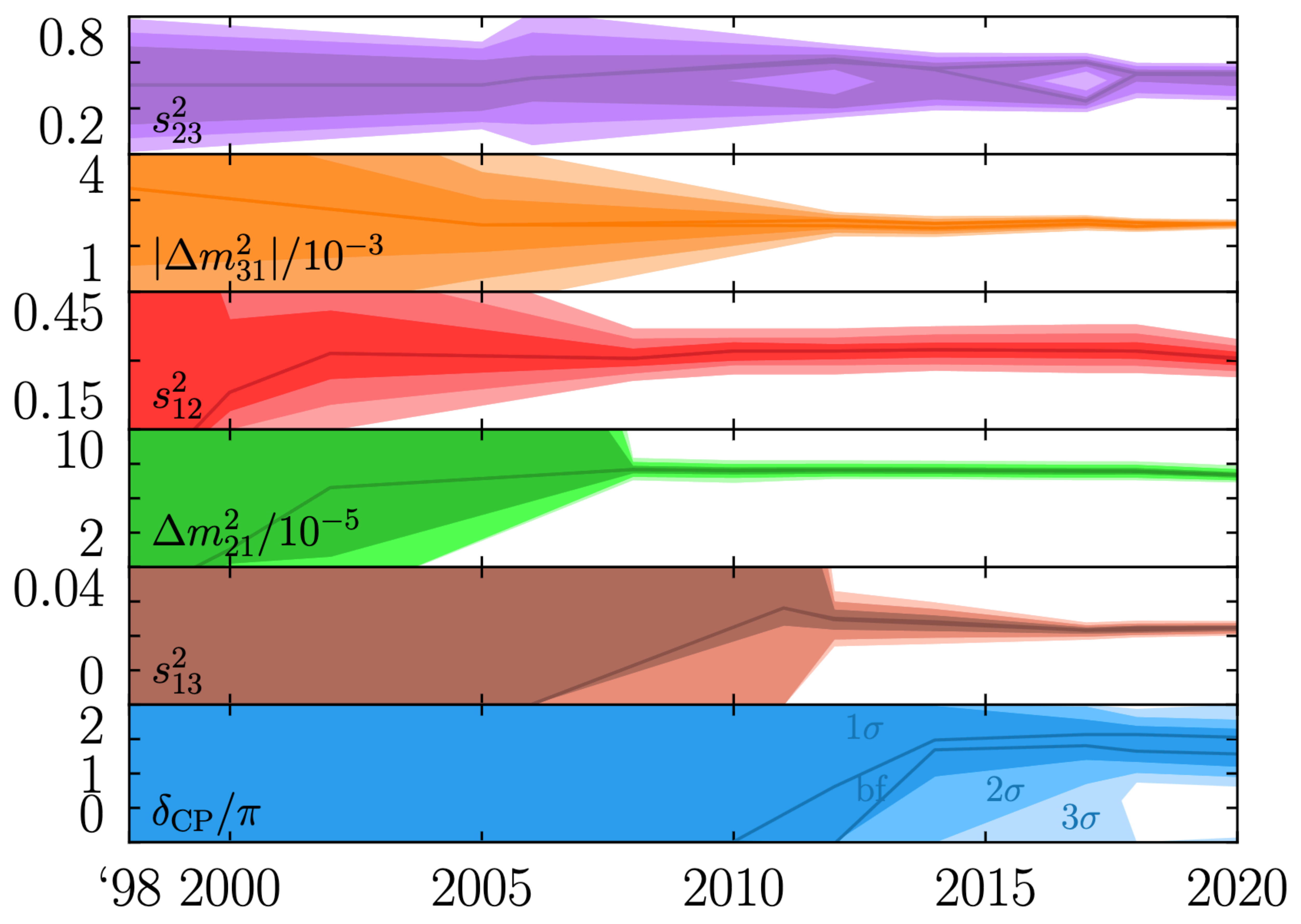




[JG, Denton 2308.09737]

Appendix: Neutrino oscillation parameters

Neutrino oscillation parameters measured over years



[Denton et al 2212.00809]

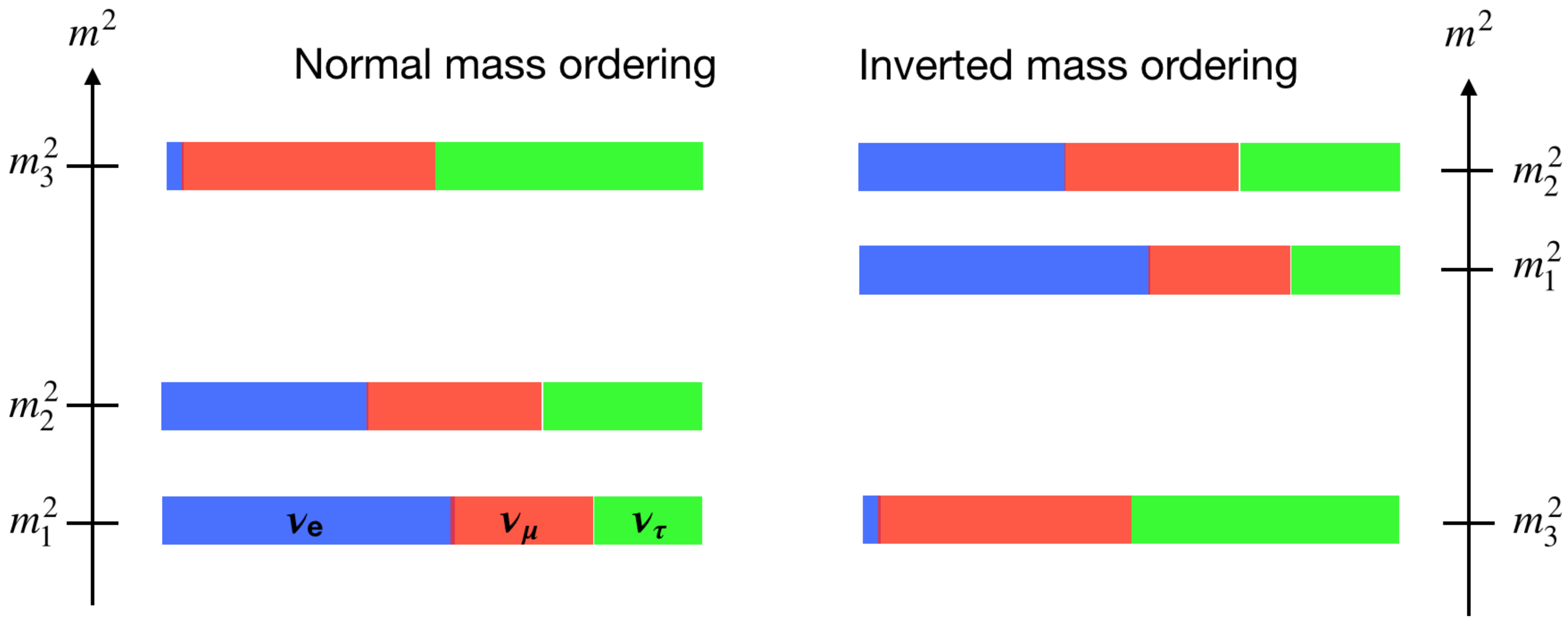
Appendix: Neutrino oscillation parameters

Global fits to oscillation data:

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



$m_1 < m_2 < m_3$ $\quad$ $m_3 < m_1 < m_2$

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: Texture zeros

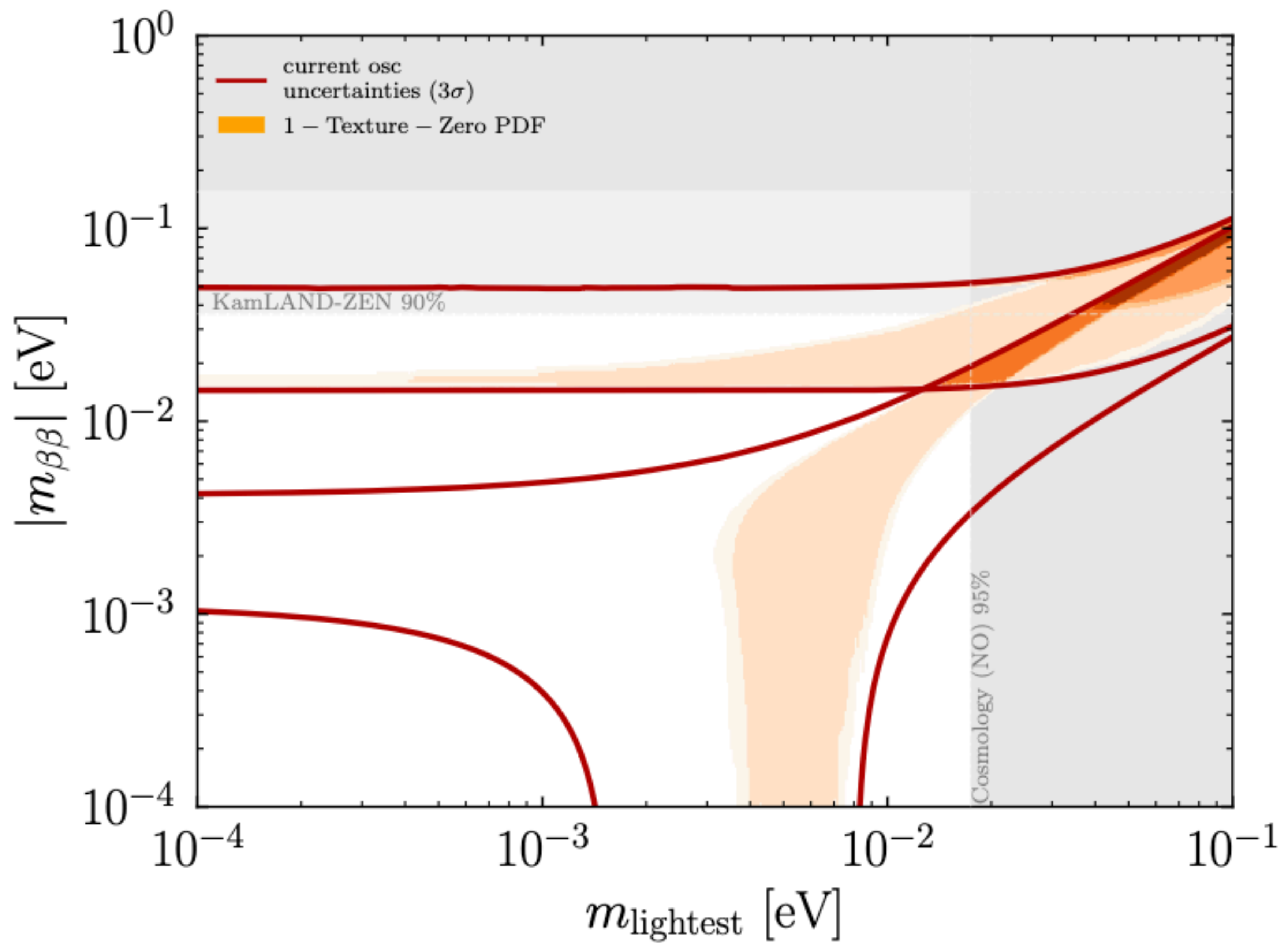
Assume symmetric Majorana mass matrix has vanishing entries

[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



Appendix: Texture zeros

Assume symmetric Majorana mass matrix has vanishing entries

[JG, Denton 2308.09737]

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

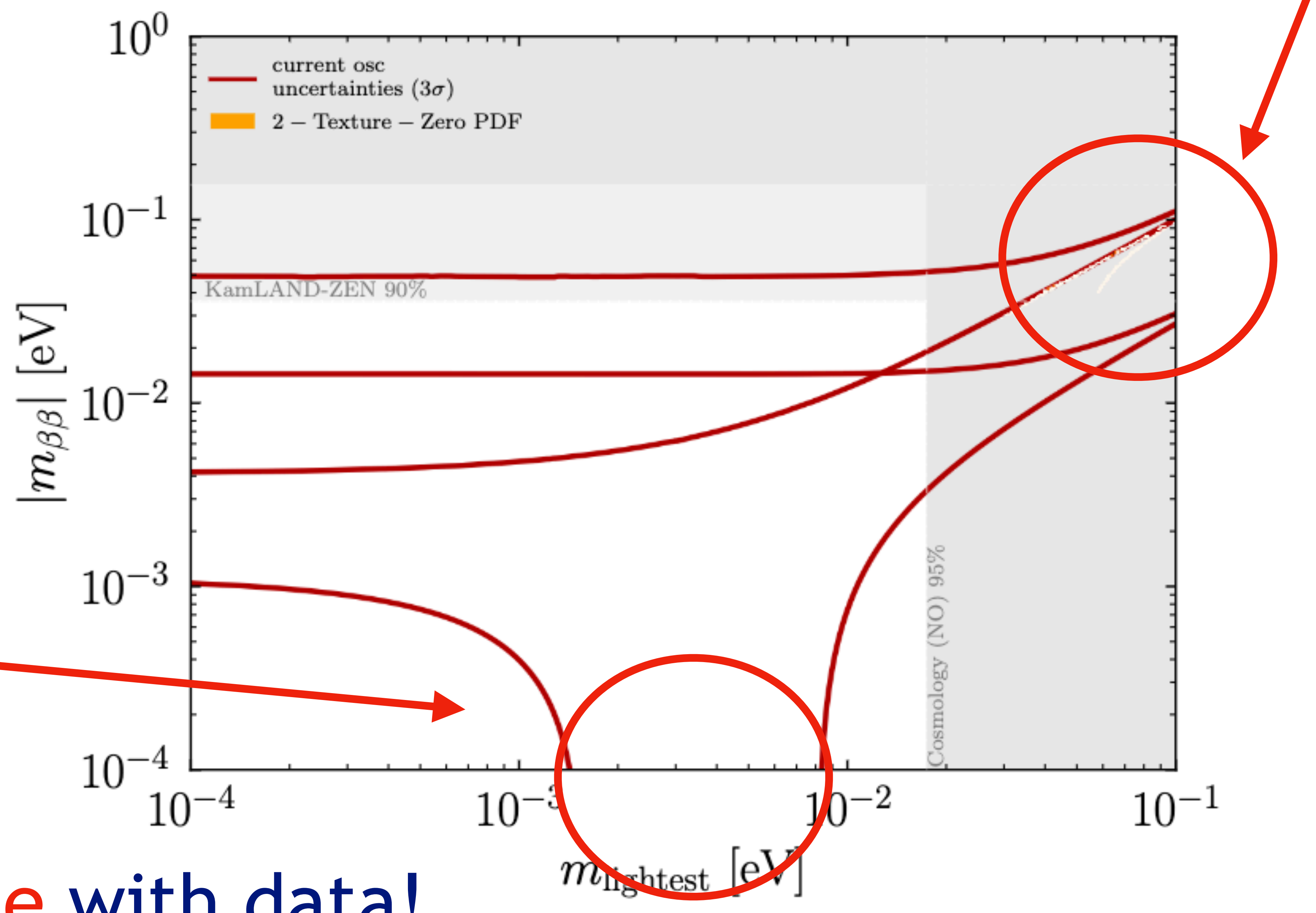
7 of 15 possible two-texture zero mass matrices in agreement with data

New result!

	$M_{e\mu}$	$M_{e\tau}$	$M_{\mu\mu}$	$M_{\mu\tau}$	$M_{\tau\tau}$
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

Constrained by cosmology

Models fully in funnel



Models with 3+ texture zeros not compatible with data!

Appendix: Mass sum rules

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

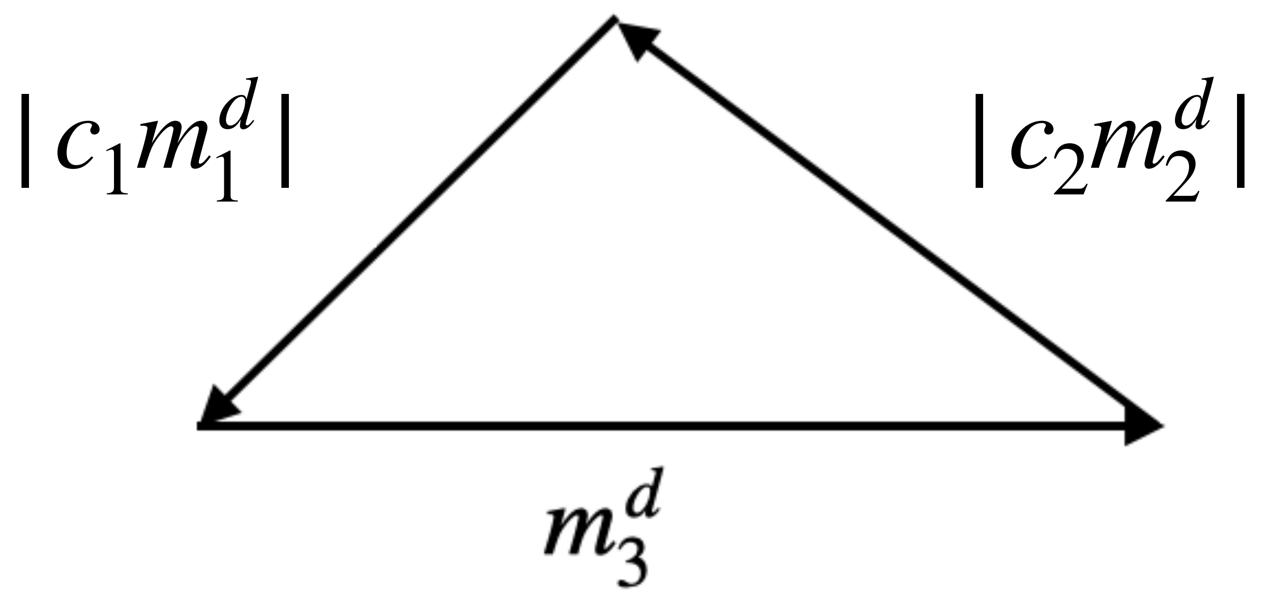
[S. King, A. Merle, A. Stuart '13
J. Barry, W. Rodejohann '10]

12 different SR in over 60 models realized in literature

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

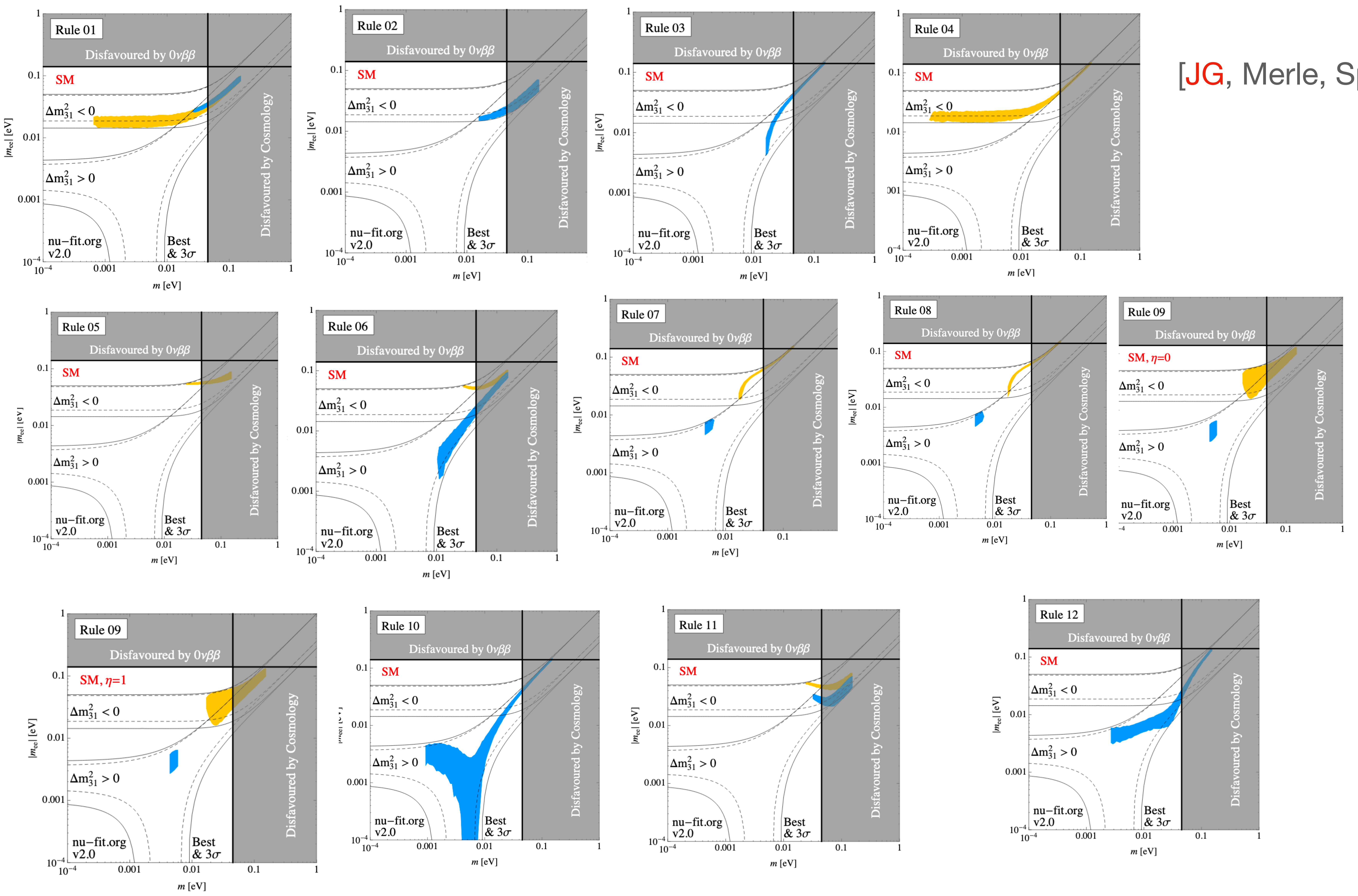
constant and fixed by model

parametrized as triangle in complex plane



Appendix: Mass sum rules

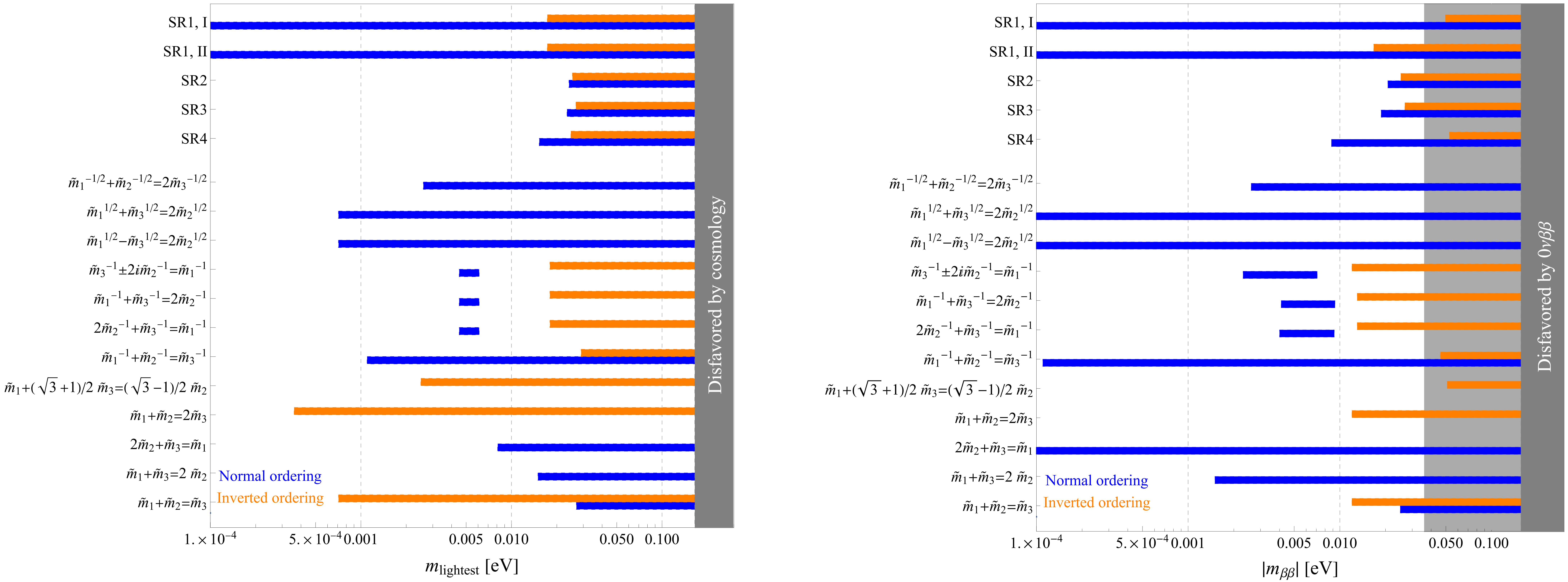
[JG, Merle, Spinrath 1506.06139]



Appendix: Mass sum rules

Predictions for upcoming experiments

Can be used to plan stages of experiments like in [Merle, Agostini, Zuber 1506.06133]

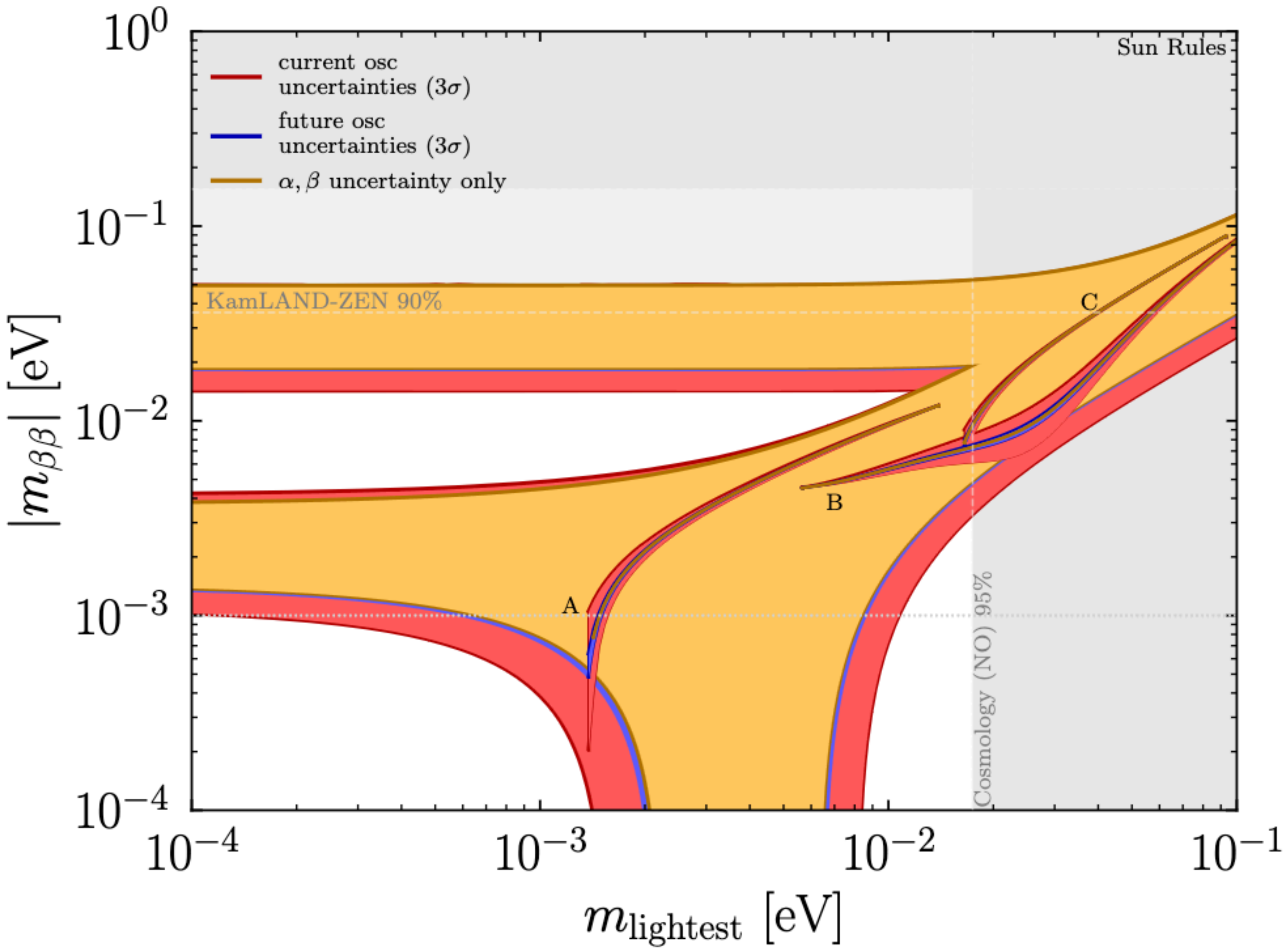


[JG, et al 2203.12169]

Appendix: 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]



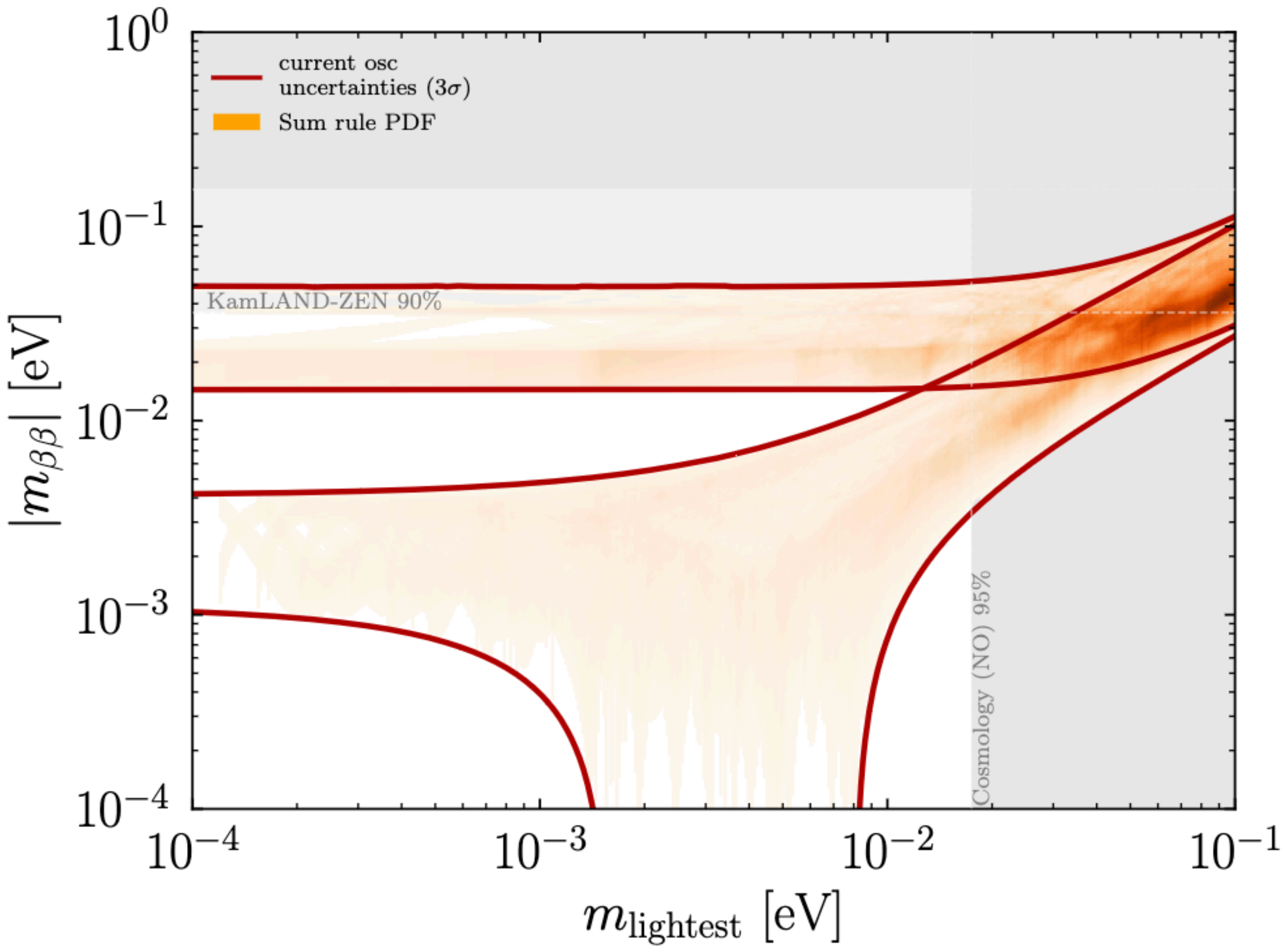
$$(c_1, c_2, d, \chi_1, \chi_2) : A : (1,2,1/2,\pi,\pi/2), B : (1/2,1/2,-1/2,\pi,\pi), C : (1,2,1,\pi,0)$$

Appendix: Mass sum rules

3137 models tested, found 1968 viable models

[JG, Denton 2308.09737]

Probability density plot



Predict large neutrino masses

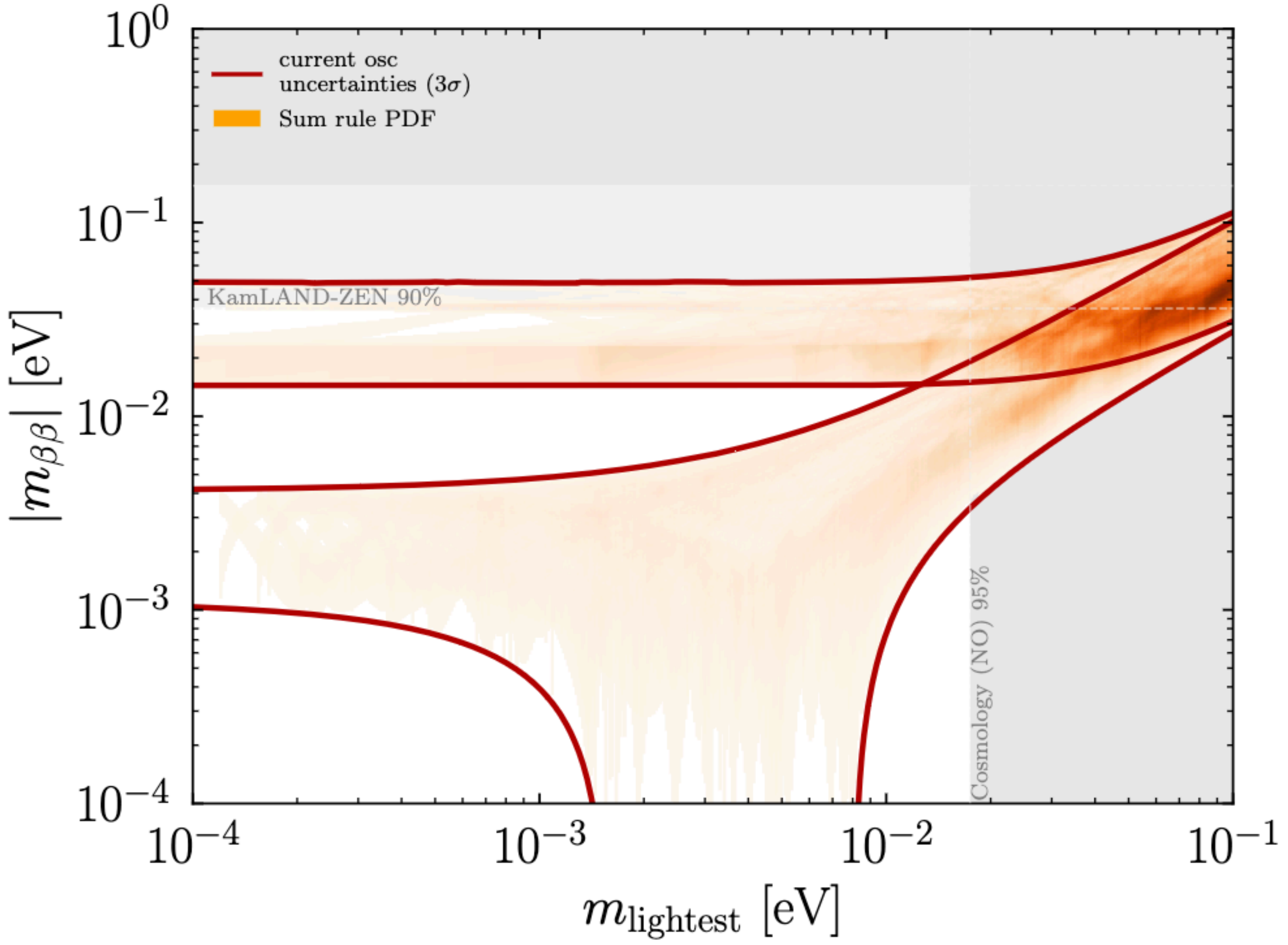
→ tested with cosmology

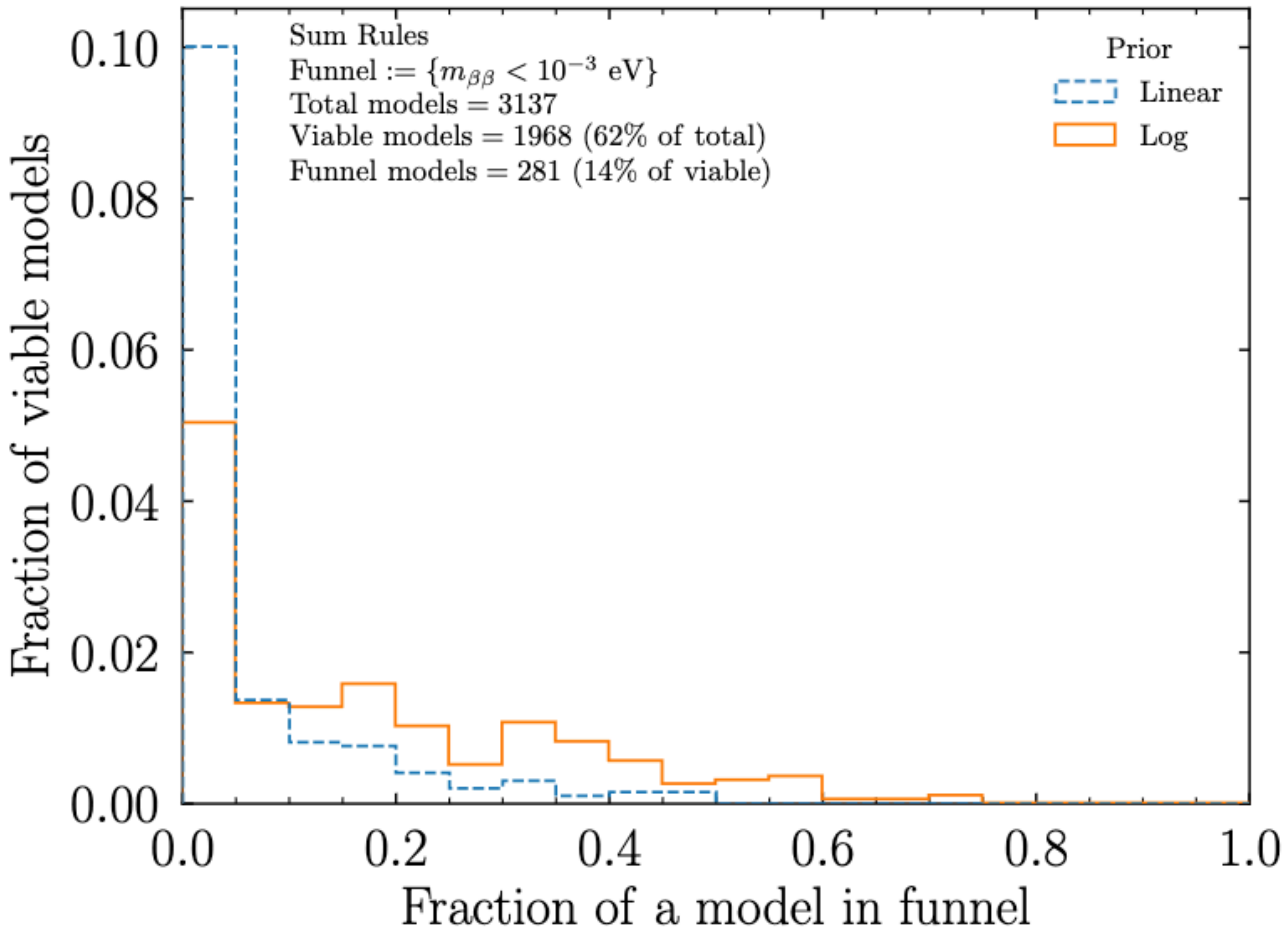
Appendix: Mass sum rules

3137 models tested, found 1968 viable models

[JG, Denton 2308.09737]

Probability density plot





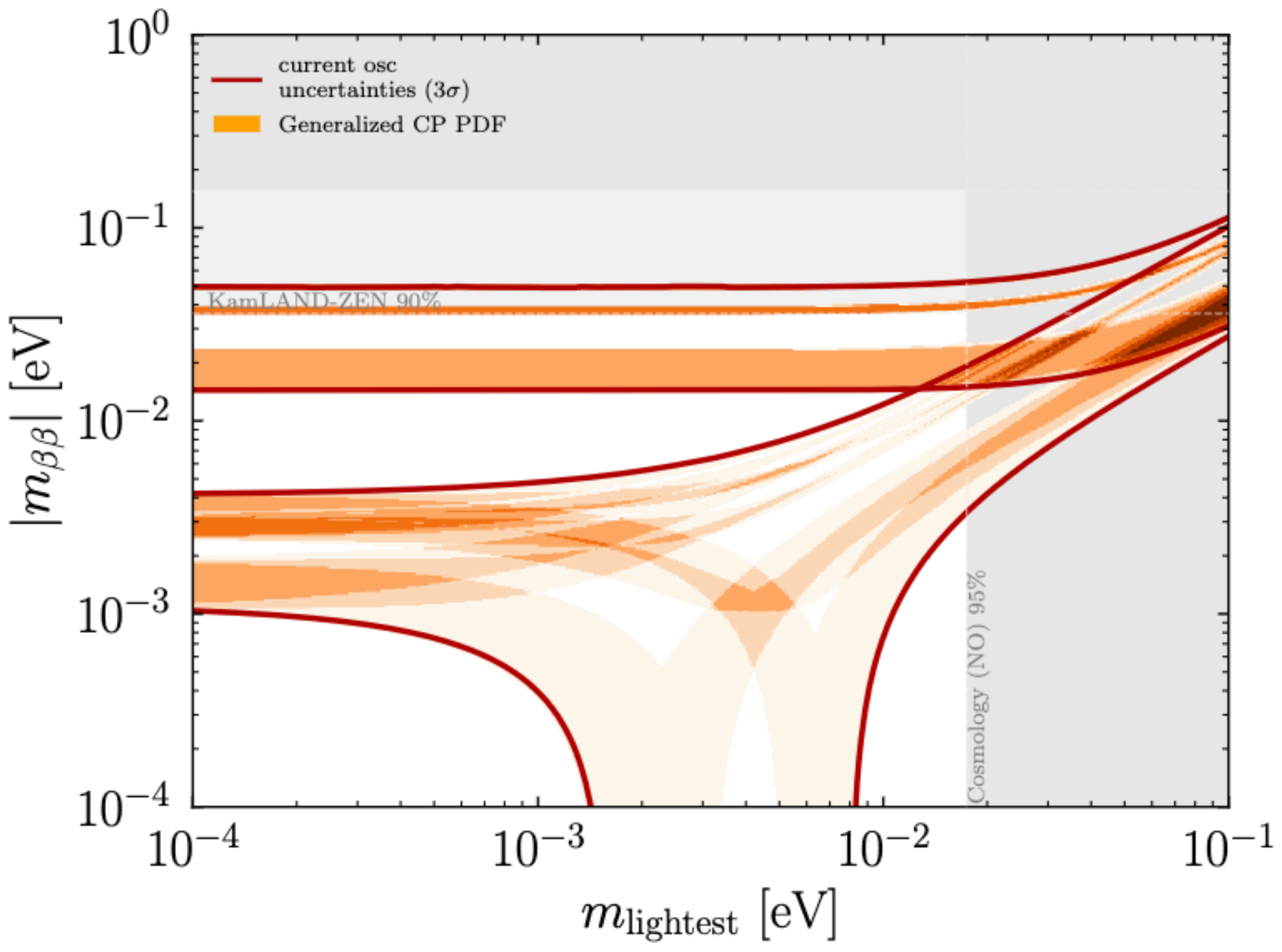
Appendix: Results for generalized CP

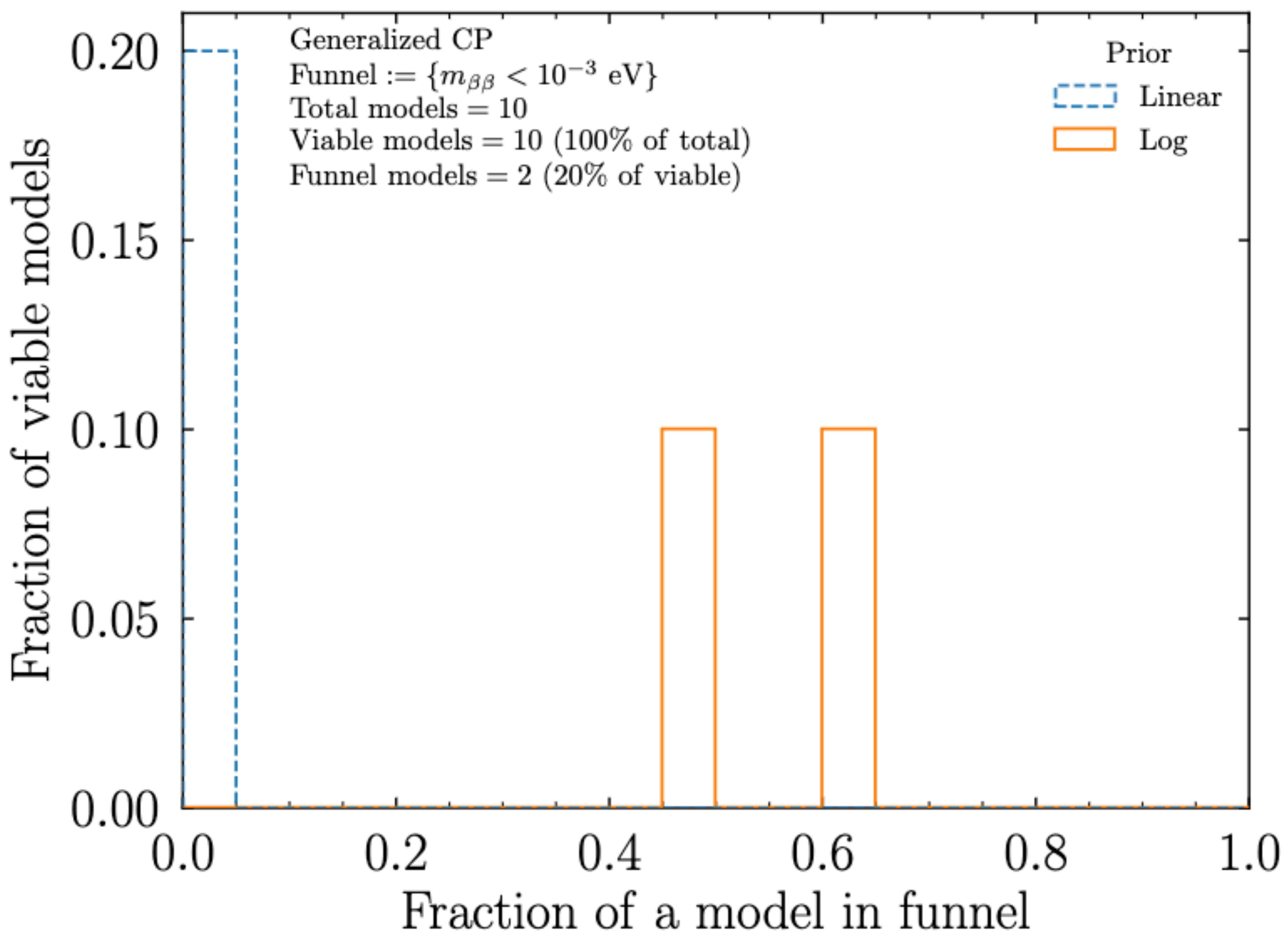
Phases have specific values

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

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

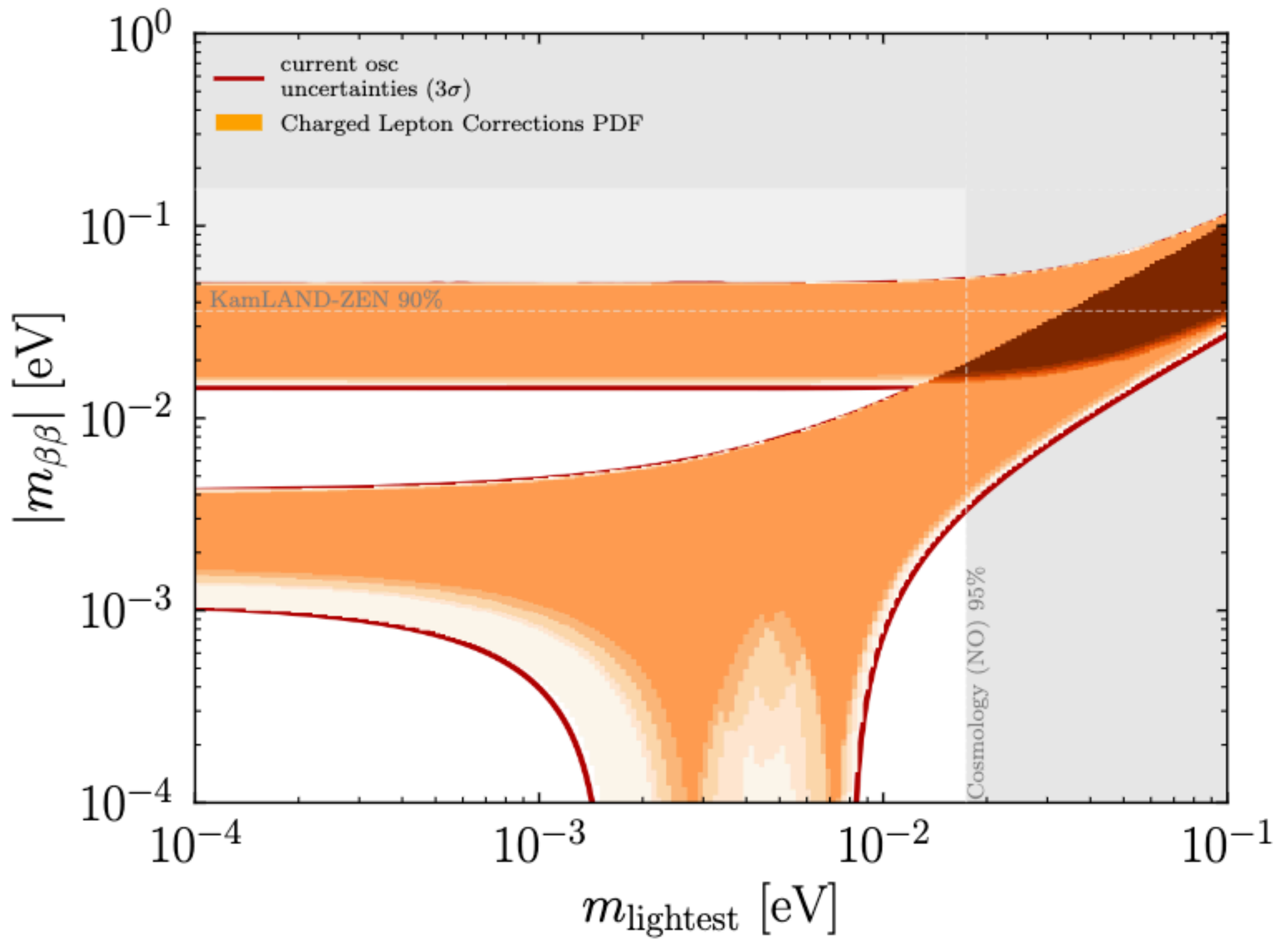
[JG, Denton 2308.09737]

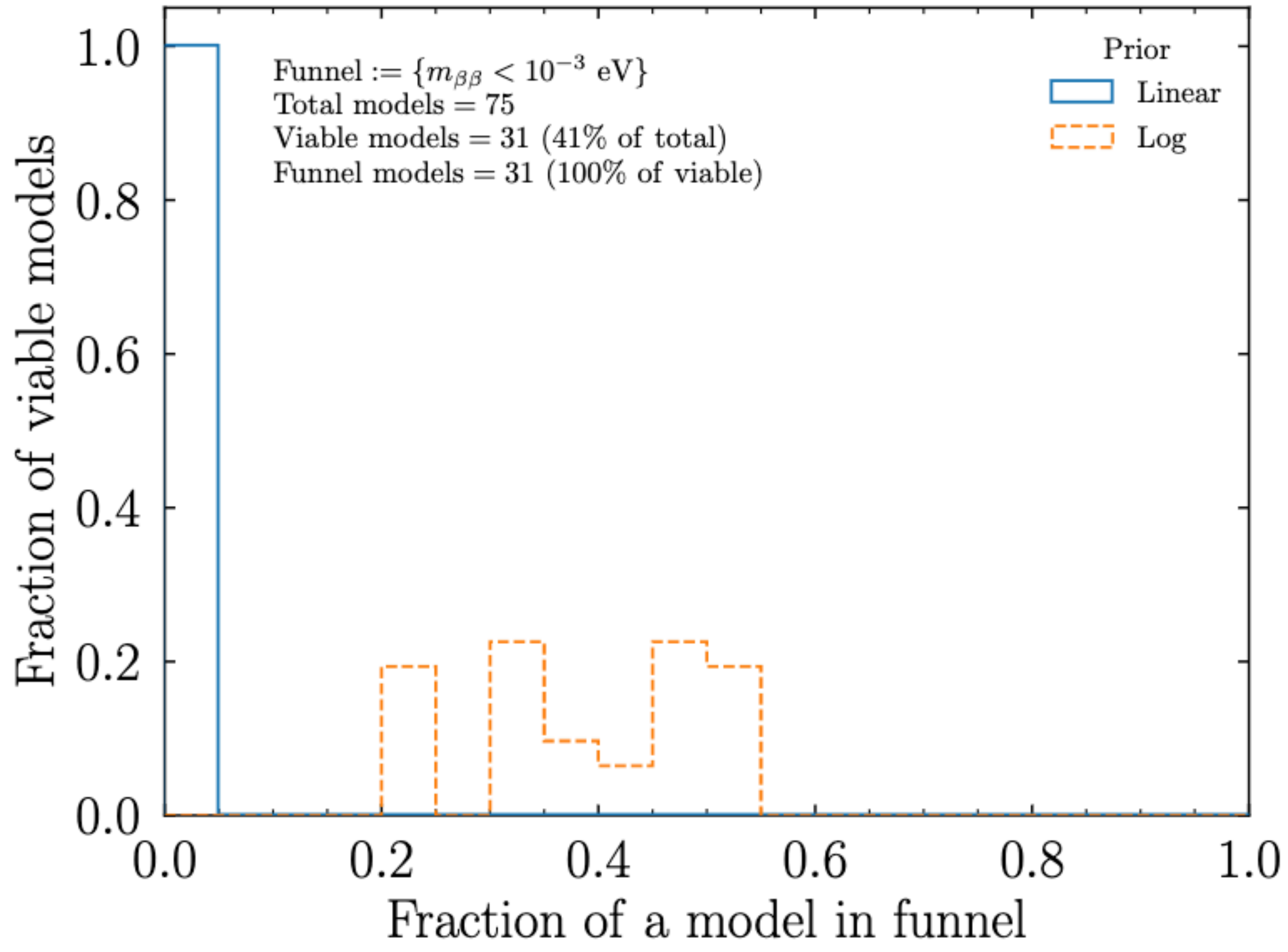
Angles in neutrino sector determined by underlying symmetry

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





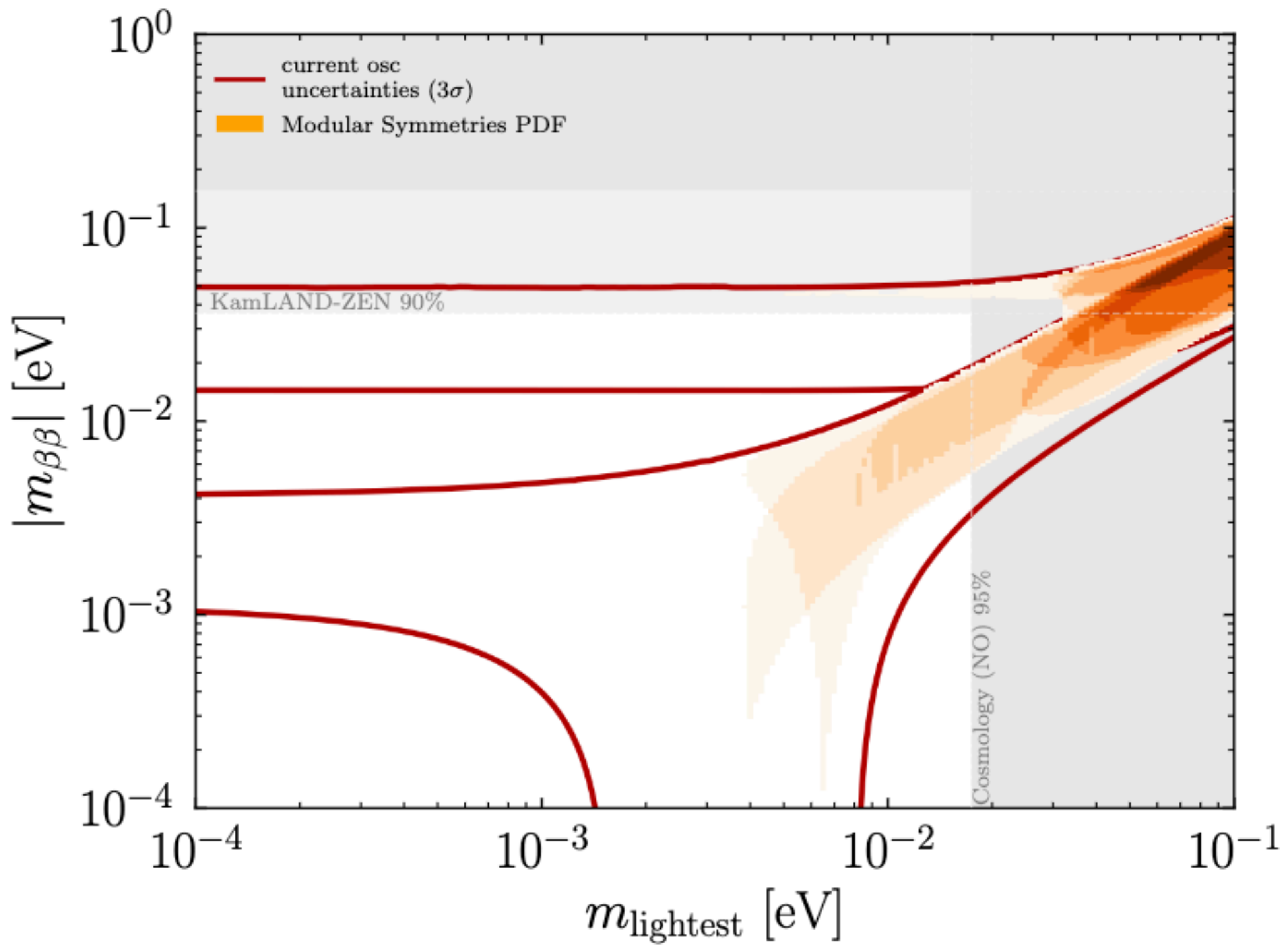
Appendix: Results for modular symmetries

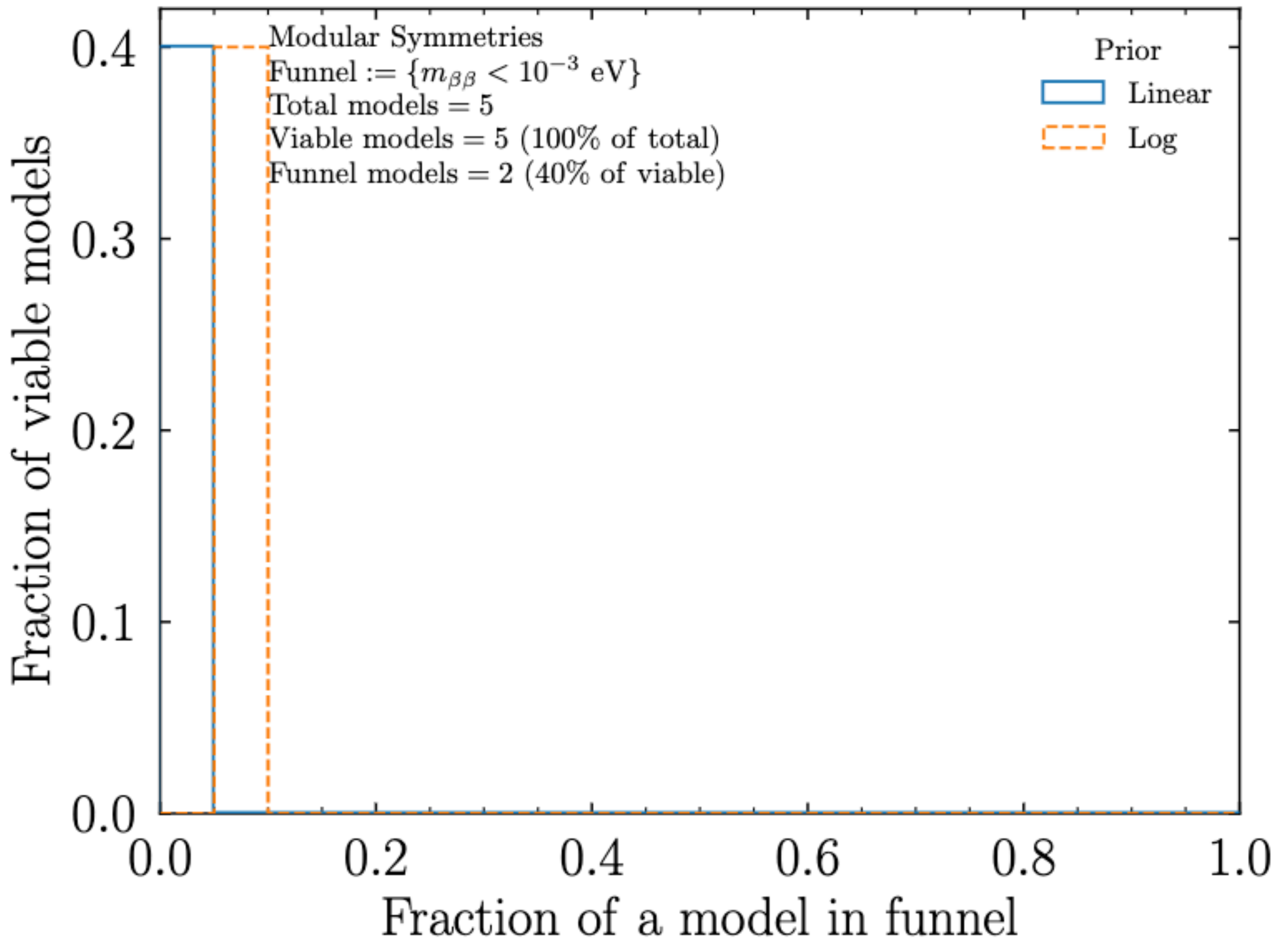
[JG, Denton 2308.09737]

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

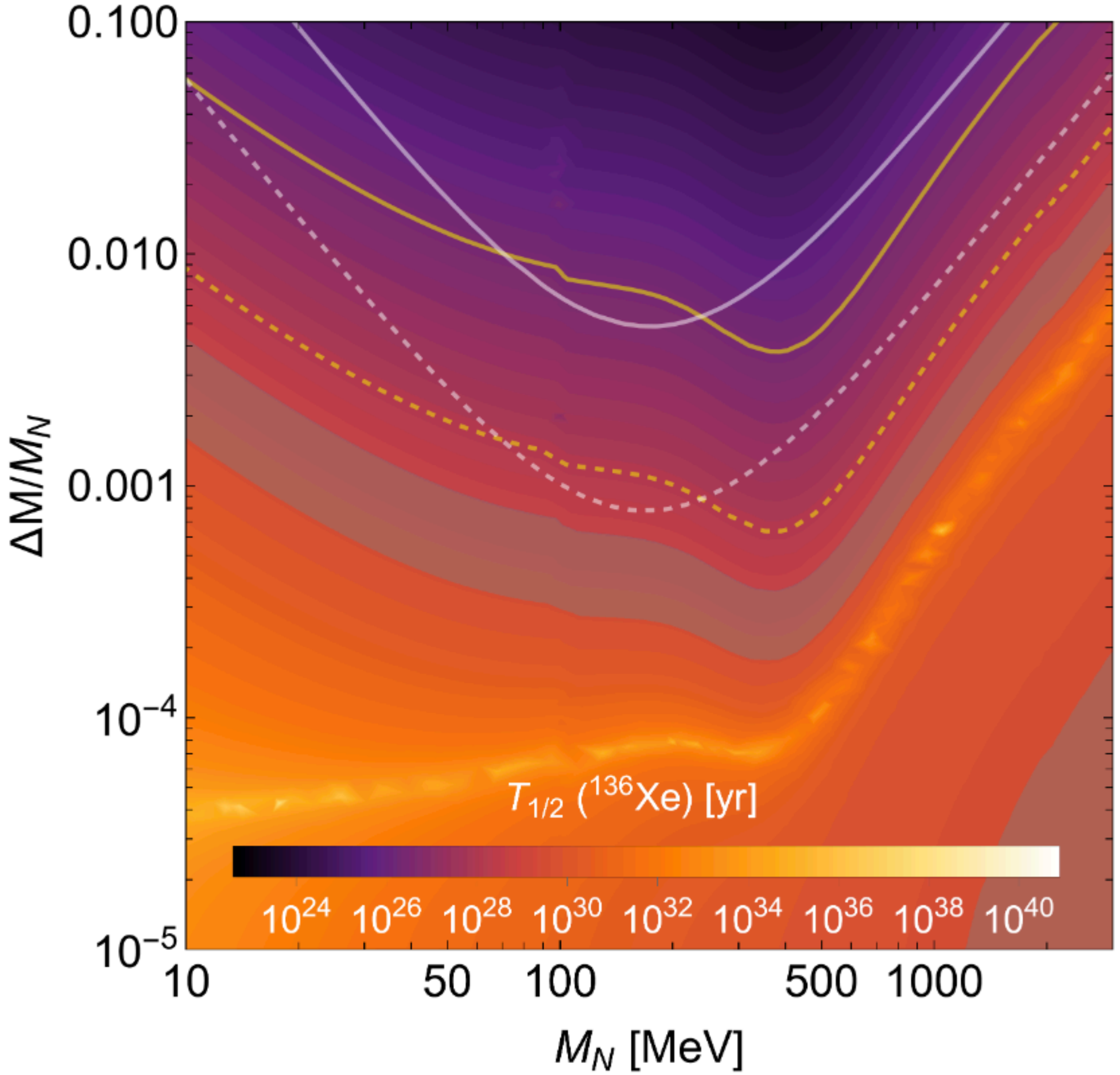
5 models with maximal number of predictions realized in literature

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





Appendix: Sterile neutrinos in $0\nu\beta\beta$



[Dekens et al '24]

3+2 scenario