Neutrino theory overview

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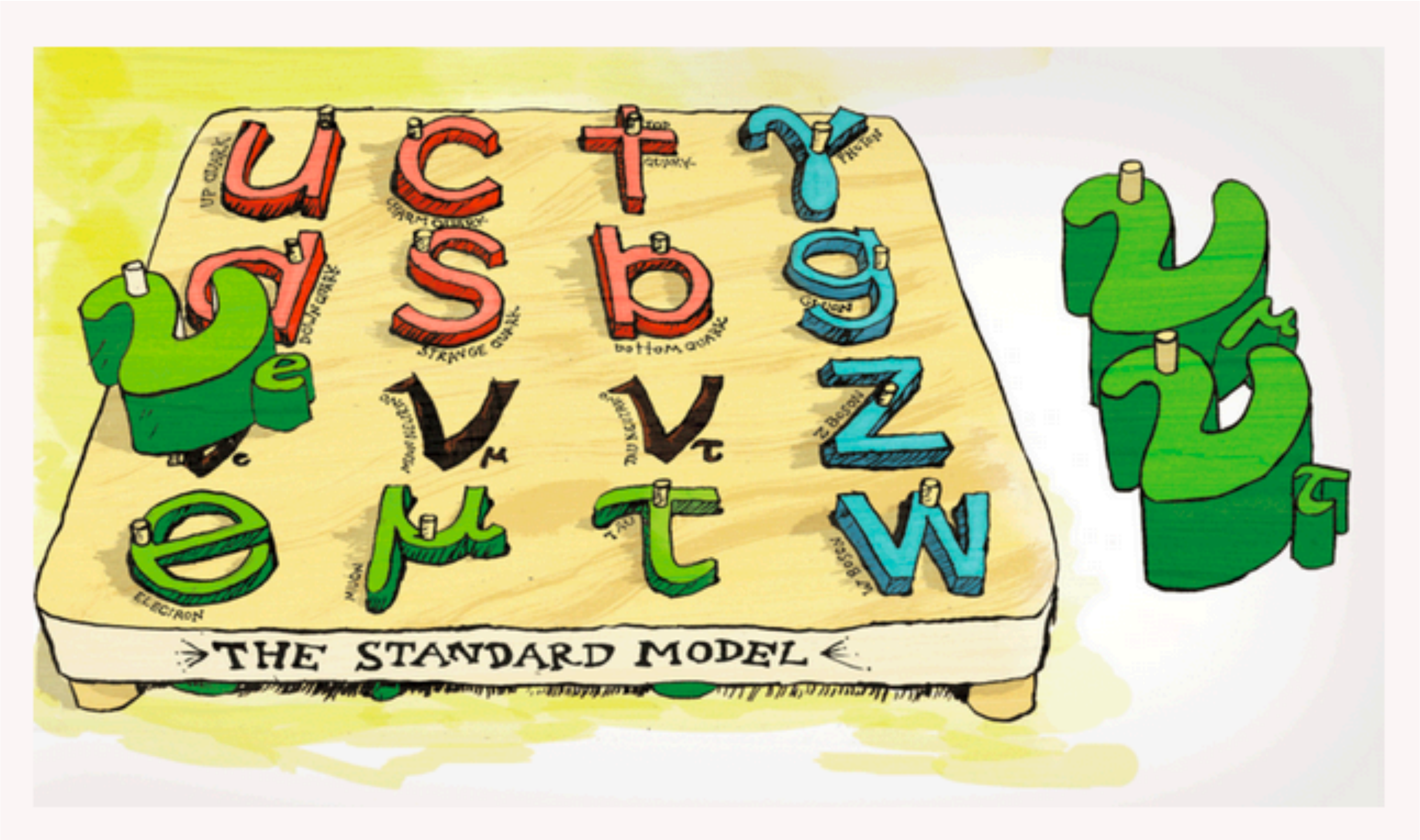
Neutrino oscillations

Observation of neutrino oscillations:

→ Strong evidence of physics beyond the SM

→ introduce more parameters to the model
(3 angles, at least one phase, 3 masses)

→ need to introduce neutrino mass mechanism



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)

$$U_{\text{PMNS}} = U_{23}(\theta_{23})U_{13}(\theta_{13}, \delta)U_{12}(\theta_{12})\mathrm{diag}(\mathrm{e}^{\mathrm{i}\alpha_1/2}, \mathrm{e}^{\mathrm{i}\alpha_2/2}, 1)$$

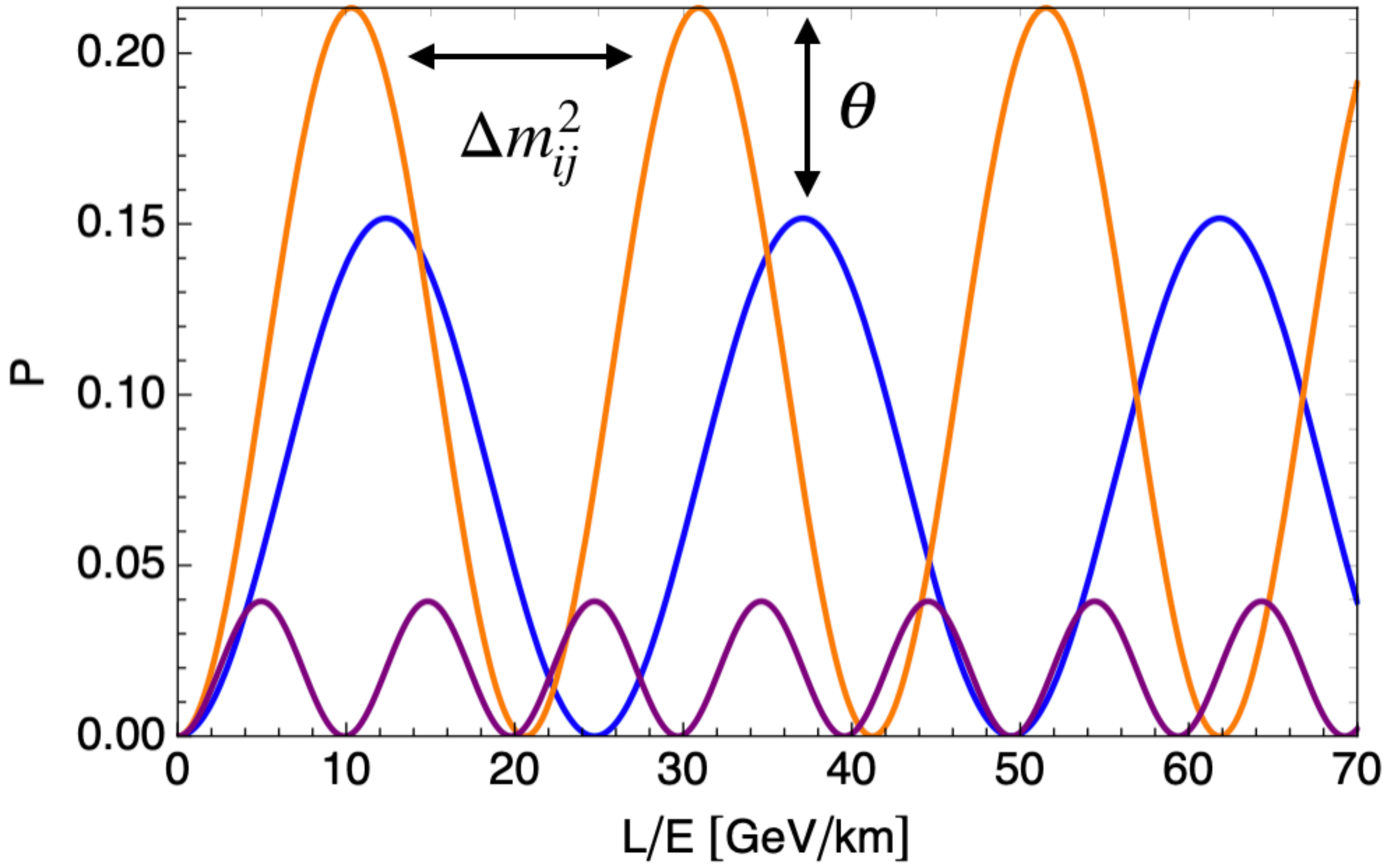
Majorana phases: only physical for Majorana neutrinos,
oscillation experiments not sensitive to them but
experiments sensitive to lepton number violation are

Neutrino oscillation parameters

produce neutrino of flavor α with energy *E*, probability to detect neutrino with flavor β at distance *L* is

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2(\Delta m_{ij}^2 L/4E), \ \Delta m_{ij}^2 = m_i^2 - m_j^2$$

In a 2-flavor approximation



Neutrino oscillation parameters

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$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2(\Delta m_{ij}^2 L/4E), \ \Delta m_{ij}^2 = m_i^2 - m_j^2$$

In a 2-flavor approximation

Compare number of events at near detector to number of events at far detector to extract probability

$$N^{\text{ND}}(E_{\text{obs}}) = \int dE_\nu \cdot \phi_{\text{ND}}(E_\nu) \cdot \sigma(E_\nu) \cdot D_{\text{ND}}$$

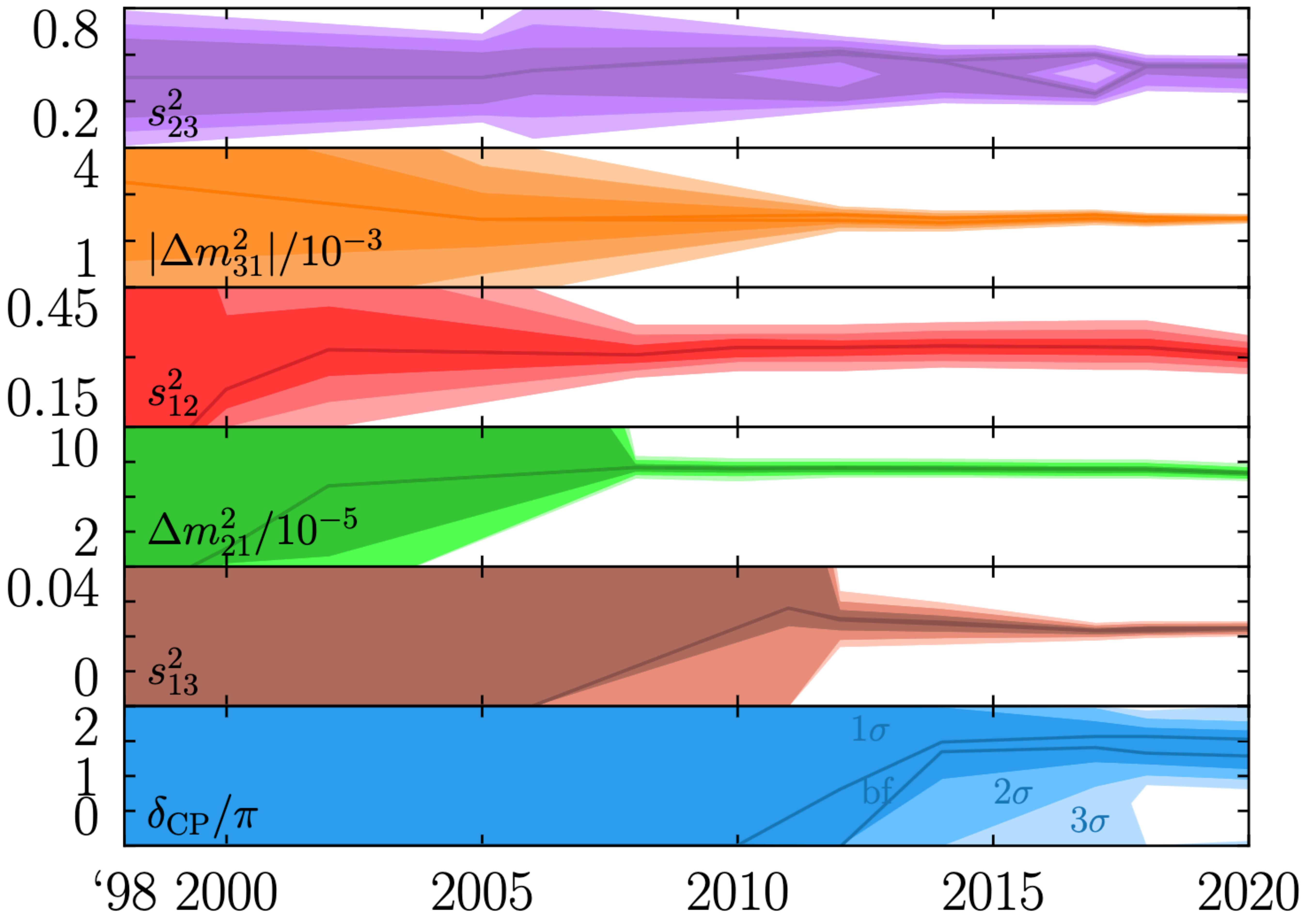
$$N^{\text{FD}}(E_{\text{obs}}) = \int dE_\nu \cdot \phi_{\text{FD}}(E_\nu) \cdot \boxed{P(E_\nu)} \cdot \sigma(E_\nu) \cdot D_{\text{FD}}$$

→ Good knowledge of fluxes, cross sections, detector effects required to extract probability

Neutrino oscillation parameters

Global fits to oscillation data:

Information on mixing angles, mass splittings



[Denton et al, 22]

Neutrino oscillation parameters

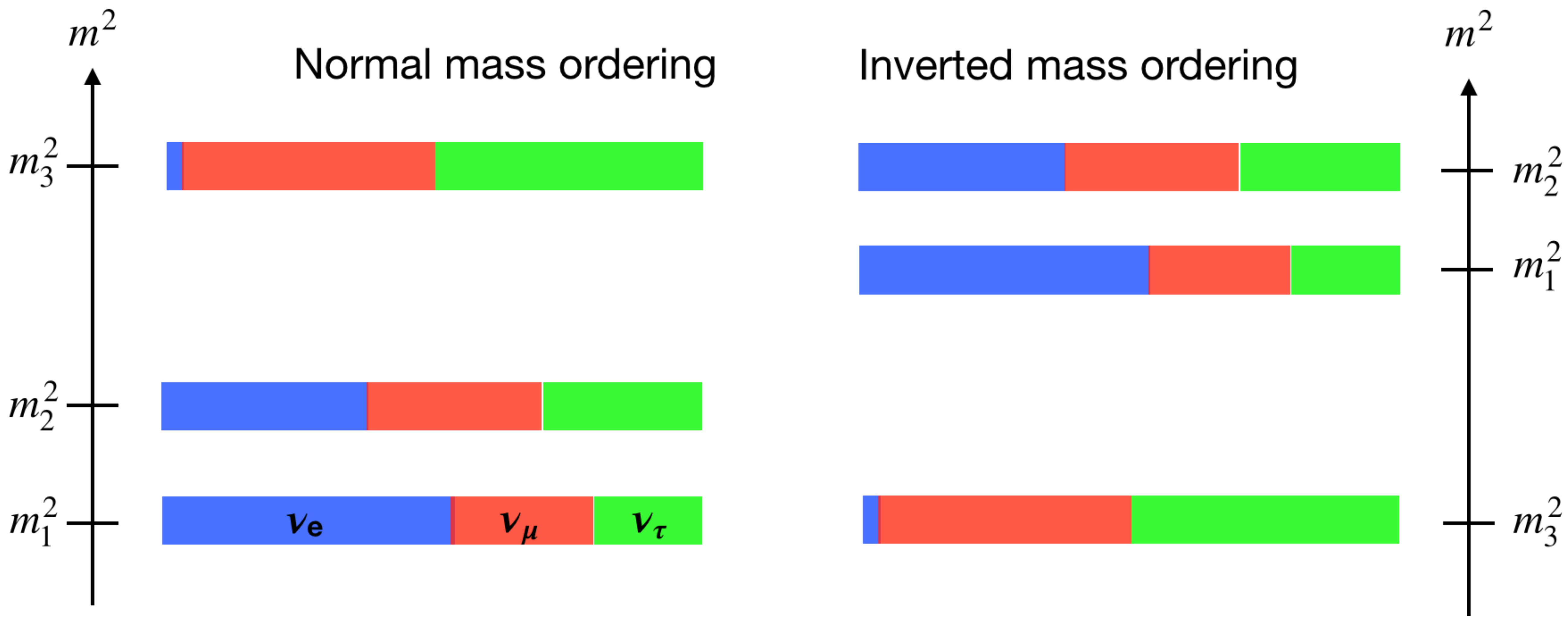
Global fits to oscillation data:

Information on mixing angles, mass splittings

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



$m_1 < m_2 < m_3$ $m_3 < m_1 < m_2$

Neutrino oscillation parameters

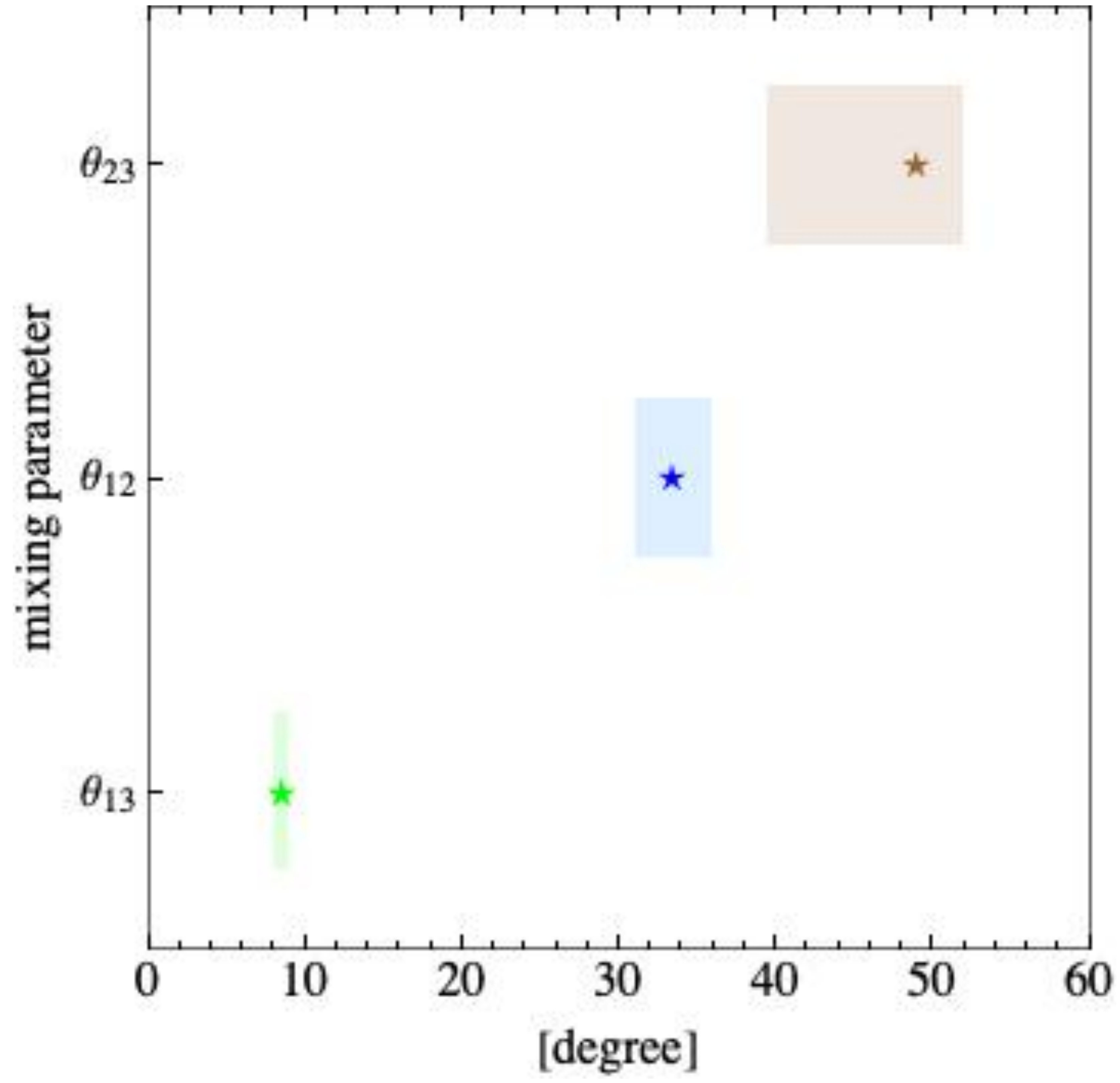
Global fits to oscillation data:

Information on mixing angles, mass splittings

[nufit v5.1]

all three angles non-zero
mixing angles are large!

$$\theta_{12} \approx 33.6^\circ,\ \theta_{23} \approx 49^\circ, \theta_{13} \approx 8.5^\circ$$



Neutrino oscillation parameters

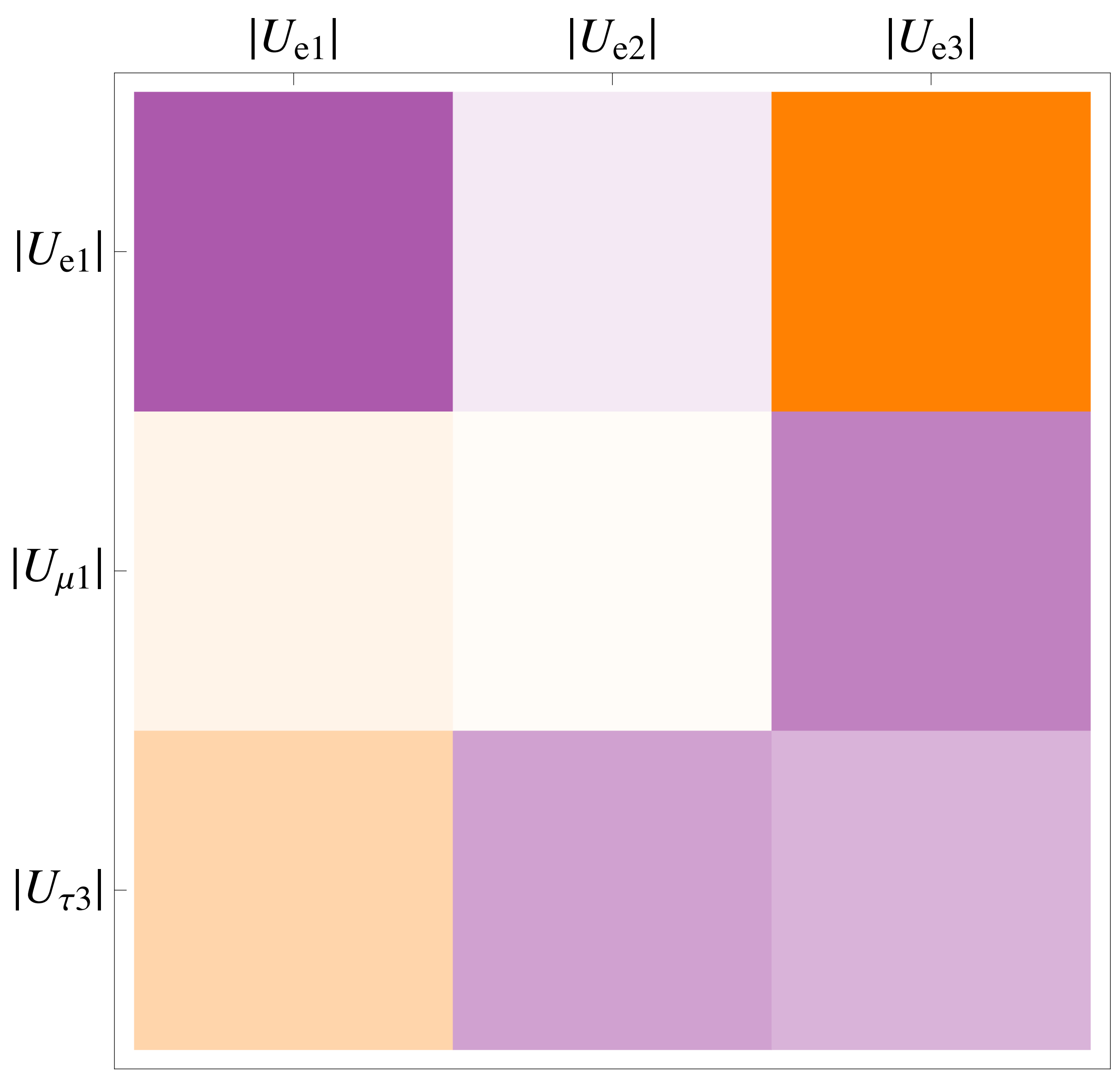
Global fits to oscillation data:

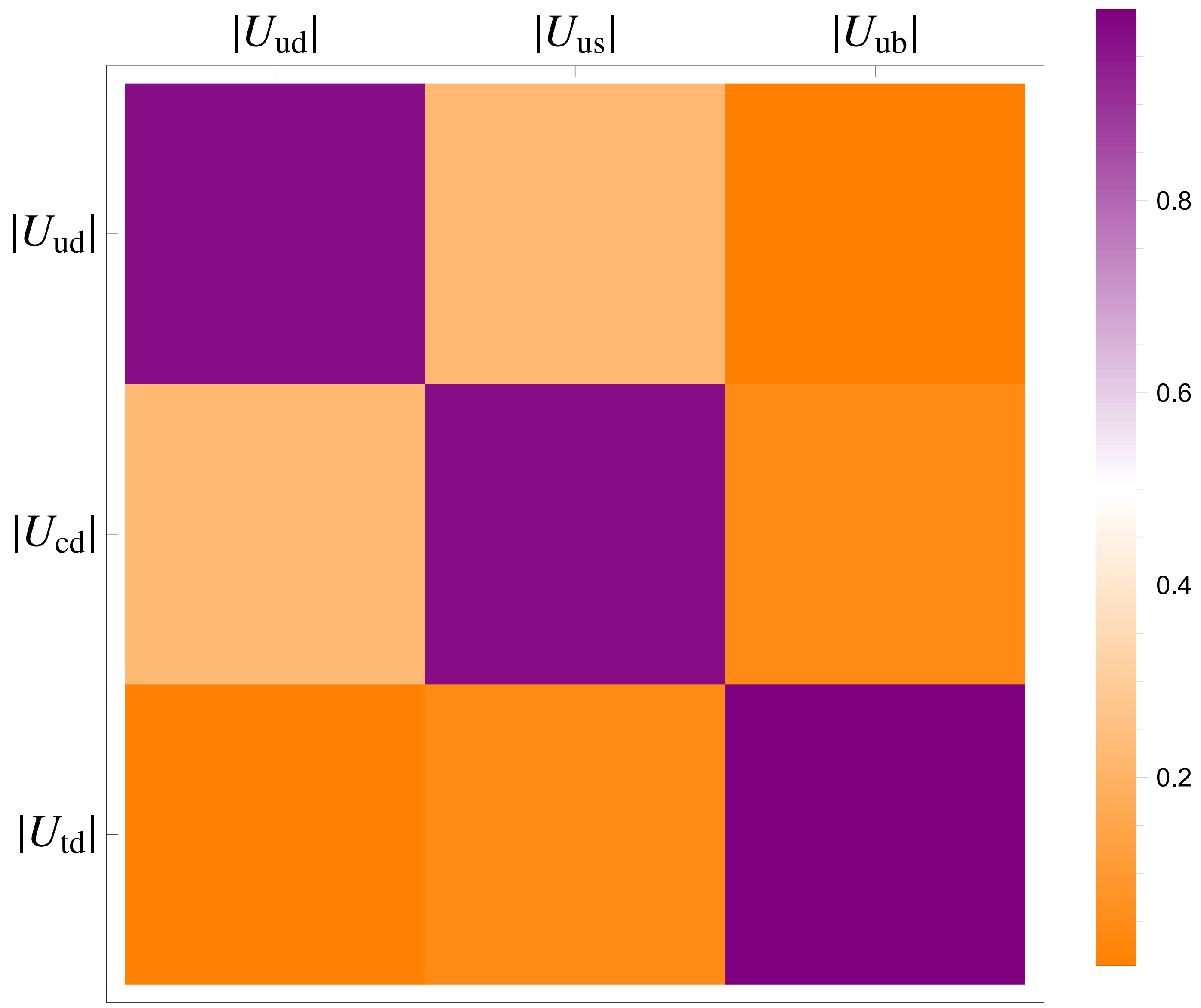
Information on mixing angles, mass splittings

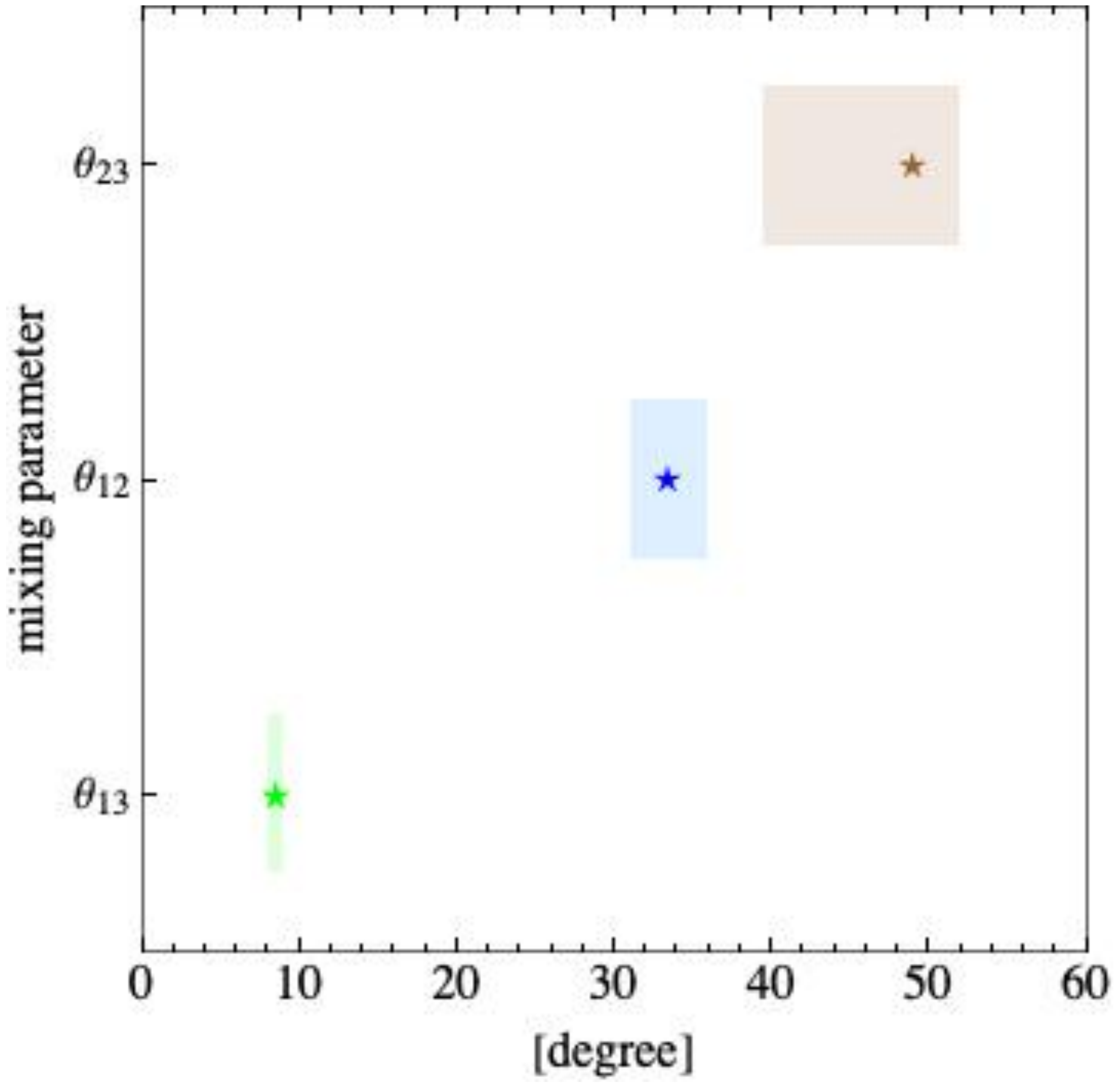
[nufit v5.1]

all three angles non-zero
mixing angles are large!

surprising if compared to small quark mixing

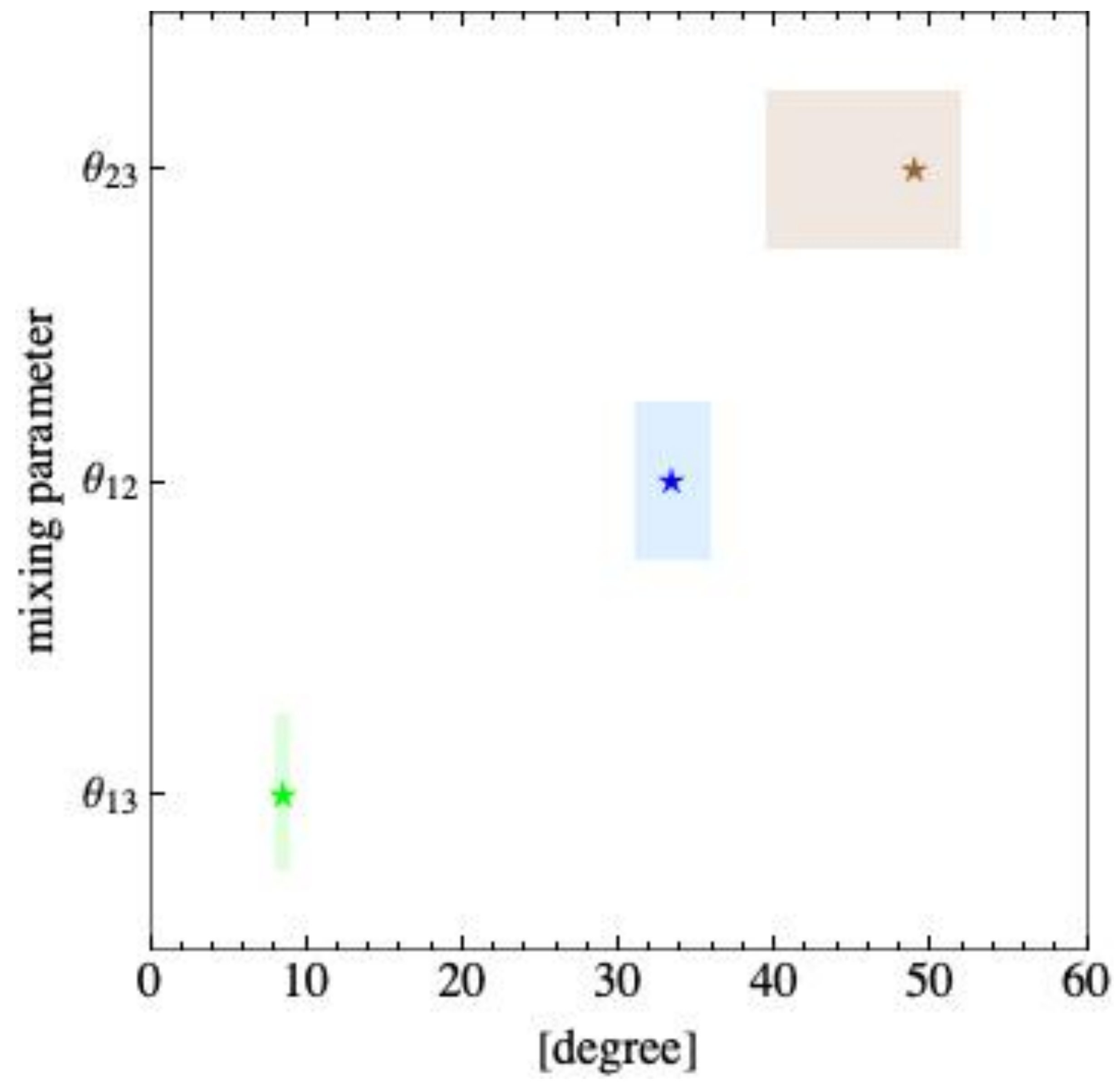






Neutrino oscillation parameters

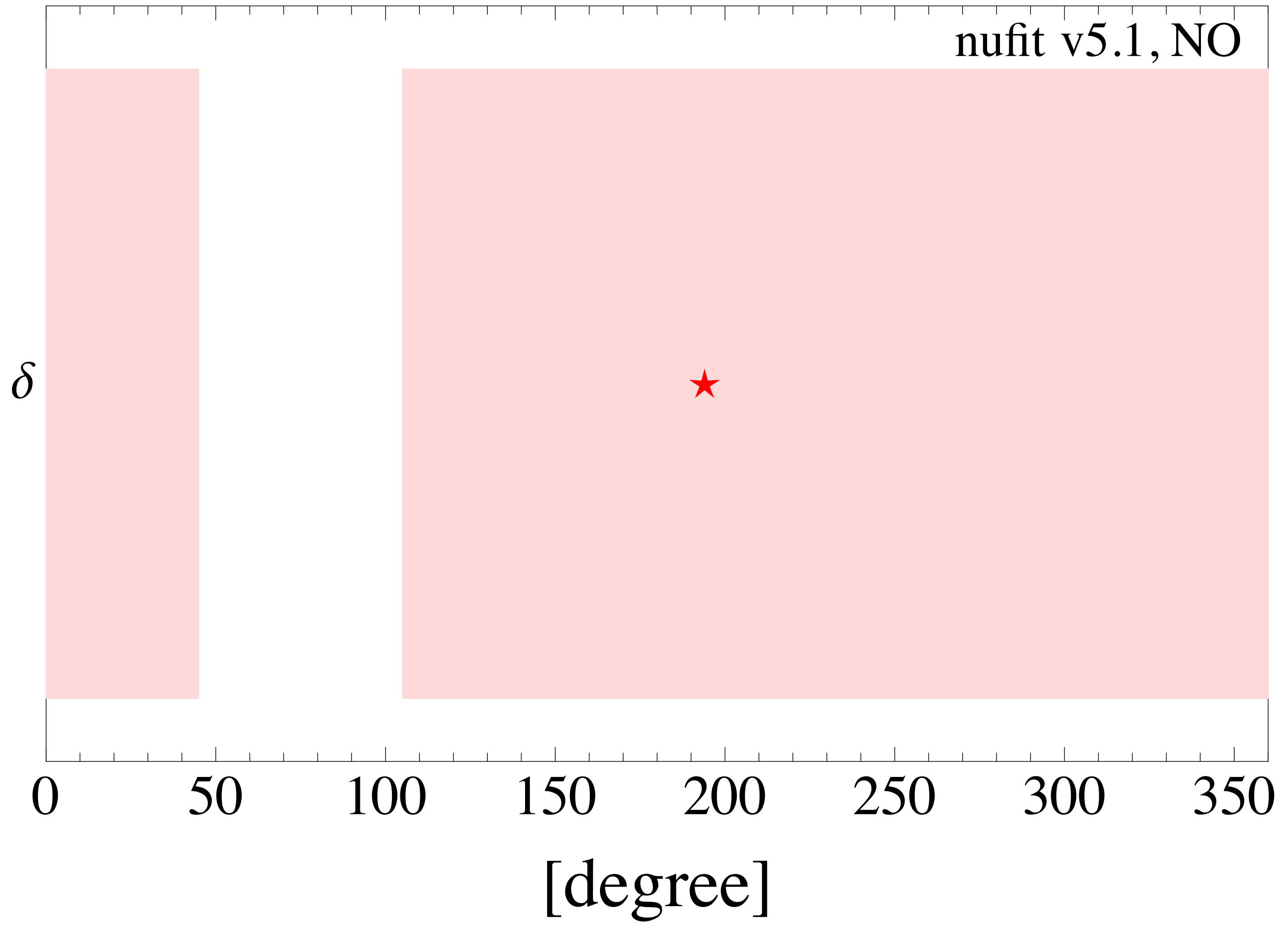
Global fits to oscillation data:
Information on mixing angles, mass splittings



all three mixing angles are non-zero
→ possibility for CPV in lepton sector

currently least known parameter is δ which governs CPV in lepton sector

⇒ Want to measure δ!



[nufit v5.1]

Neutrino oscillation parameters

CPV in mass matrices quantified via basis invariant

$$J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta$$ [Jarlskog '85]

All mixing angles play a role!

$$J_{CP}^{max} = 1/(6\sqrt{3}) \approx 0.096$$

quark mixing matrix: non-zero $\delta_{\rm CKM}$ but CPV is small $|J_{\rm CKM}|/J_{CP}^{\rm max} = 3 \cdot 10^{-4}$ [PDG]

Is CP violated in the lepton sector? $|J_{\rm PMNS}|/J_{CP}^{\rm max} < 0.34$

Future experiments will find the answer

Future of oscillation physics

Goals: Measurement of CP phase, octant of θ_{23}, mass ordering

Long baseline (300 km, 1300 km) accelerator neutrino experiments:
Hyper-Kamiokande, DUNE
$\rightarrow$ CP phase, octant of θ_{23}, mass ordering

See talks by K. Wood, S. Gollapinni
+talks in parallel sessions

Medium baseline (~50 km) reactor neutrino experiment:
JUNO
$\rightarrow \theta_{12}, \Delta m^2_{21},$ mass ordering

See talk by R.Mandujano

Atmospheric neutrino experiments:
IceCube, KM3NeT
$\rightarrow \theta_{23}$, mass ordering

Future of oscillation physics

What will we learn?

- Neutrino mass ordering has important implications for observables

- Distinguish different flavor models with precision oscillation measurements

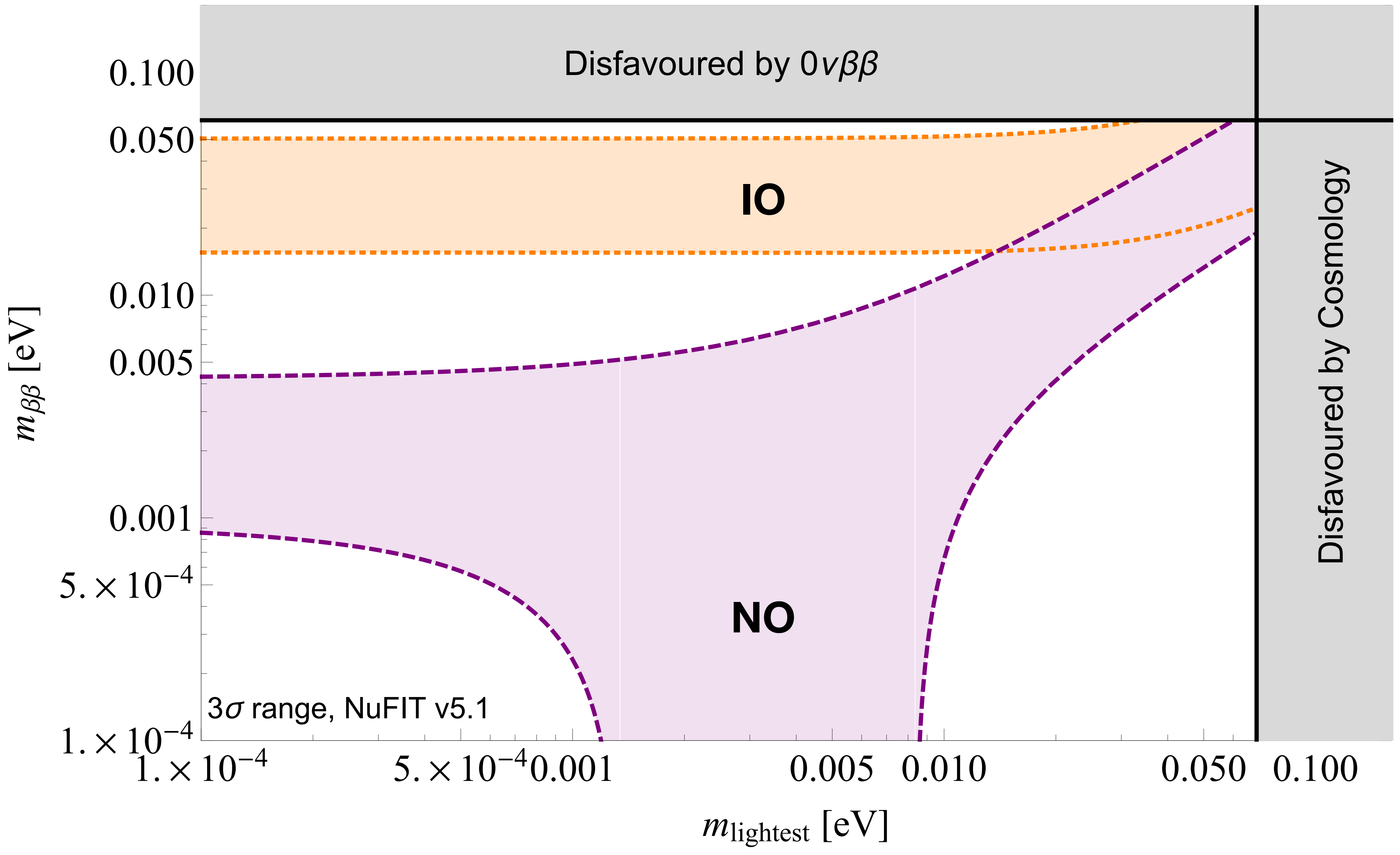
- New physics in oscillations

Future of oscillation physics

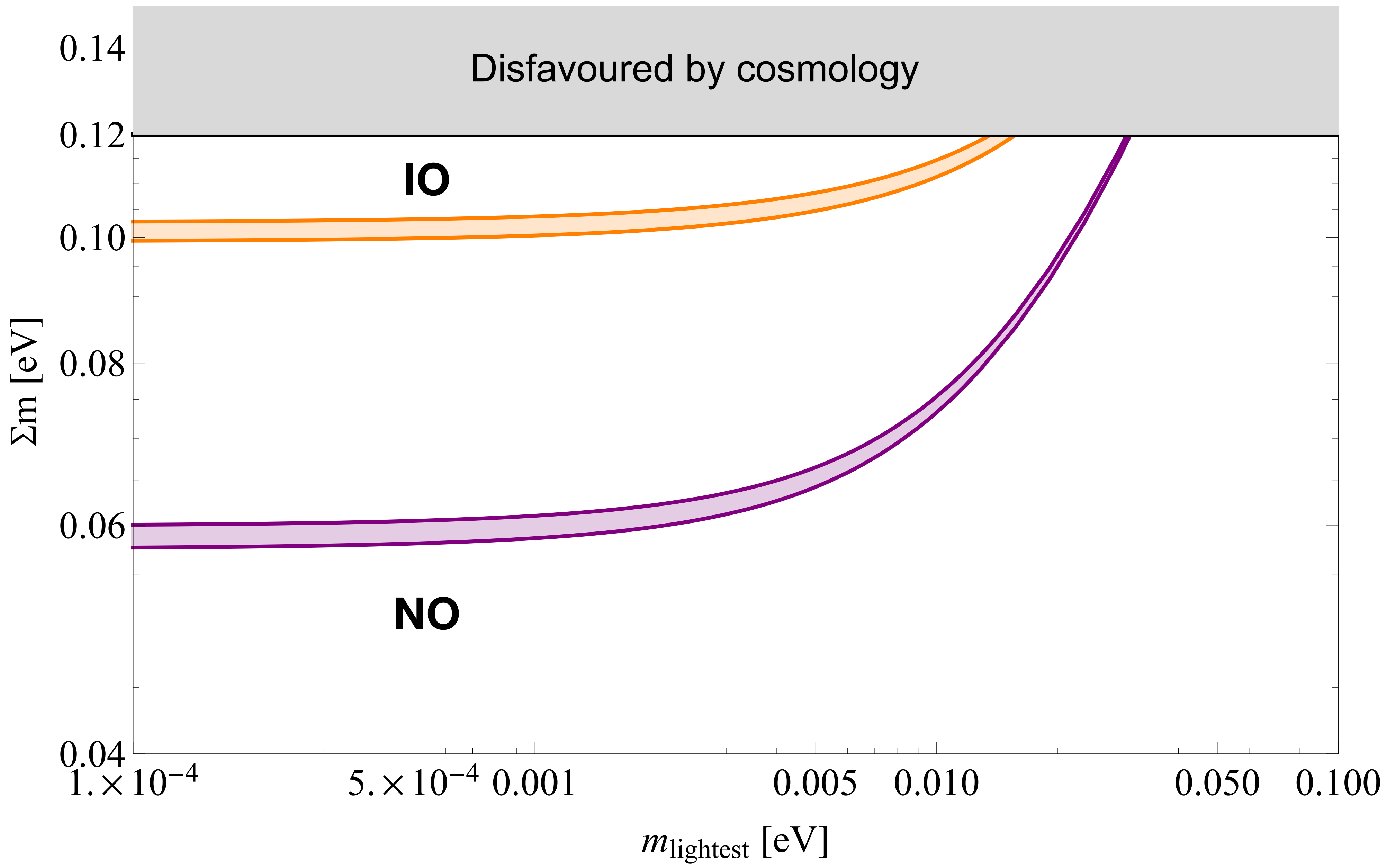
What will we learn?

- Neutrino mass ordering has important implications for observables

Neutrinoless double beta decay



Sum of neutrino masses, beta decay endpoint spectrum



See talks by K. Mistry, A. Piepke + talks in parallel sessions

See talk by A. Gavin

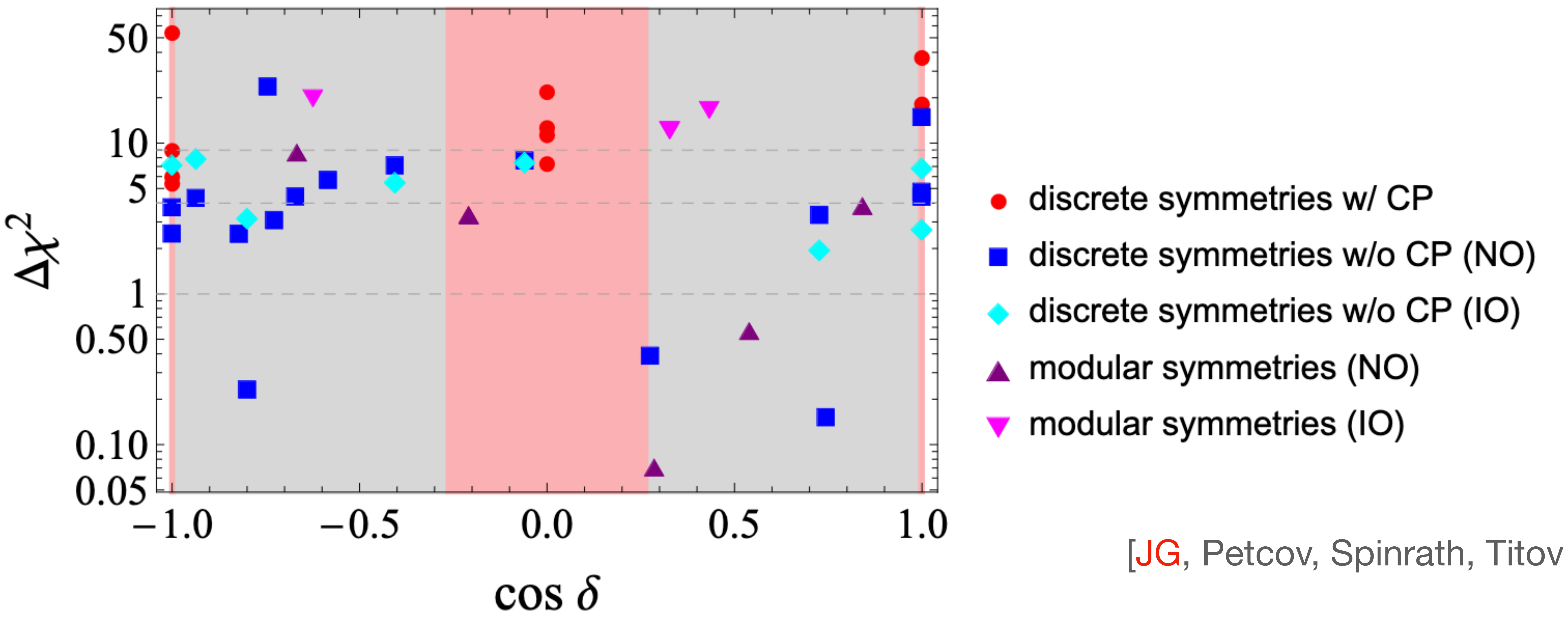
Future of oscillation physics

- Distinguish different flavor models with precision oscillation measurements

Most predictive flavor models predict relations between mixing parameter like

$$\theta_{12}^{\text{PMNS}} - \theta_{12}^{\nu} \approx \theta_{13}^{\text{PMNS}} \cos \delta$$

Can be used to distinguish different mixing pattern



[JG, Petcov, Spinrath, Titov 2203.06219]

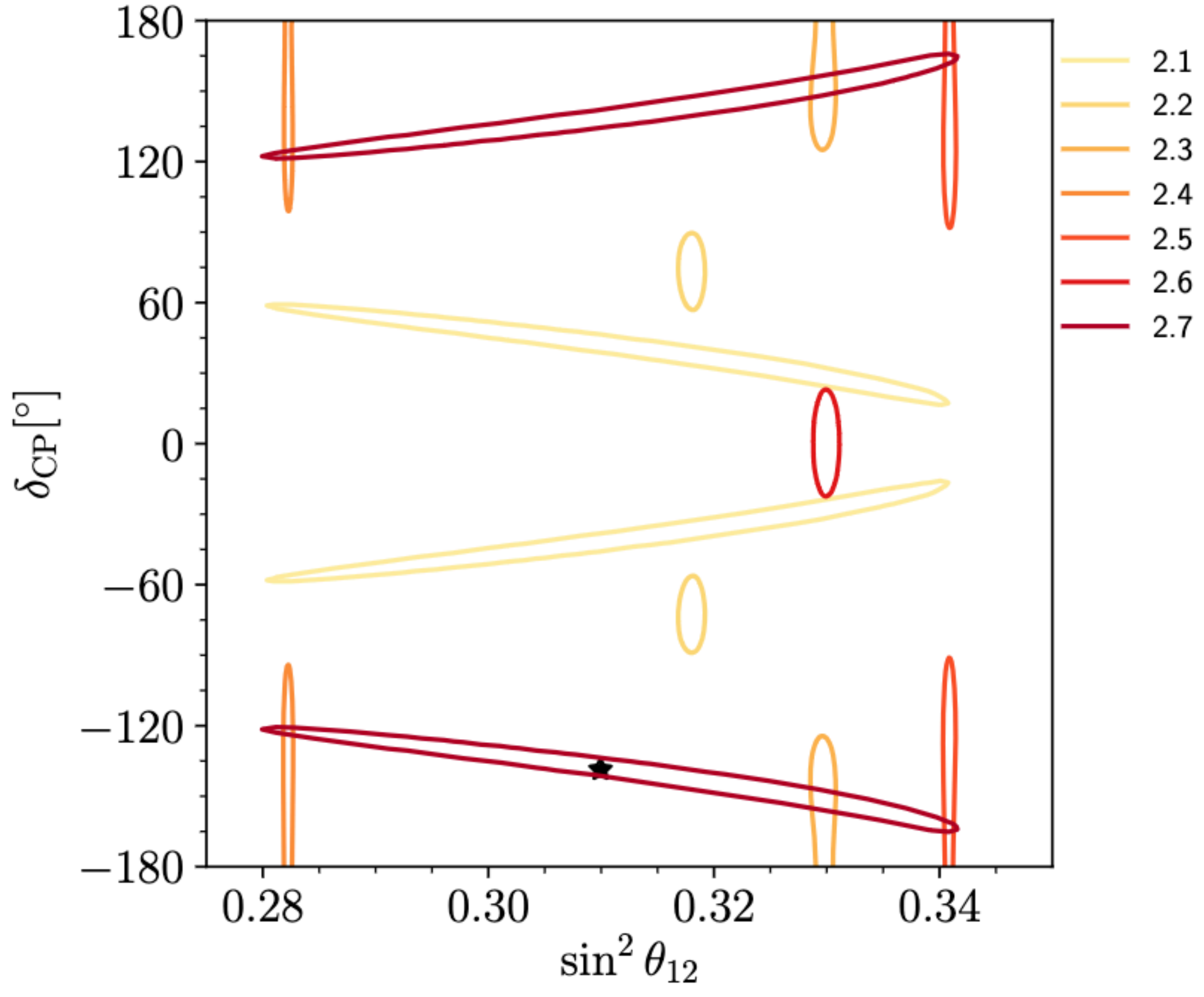
Future of oscillation physics

- Distinguish different flavor models with precision oscillation measurements

Sum rules can be used to distinguish different mixing pattern

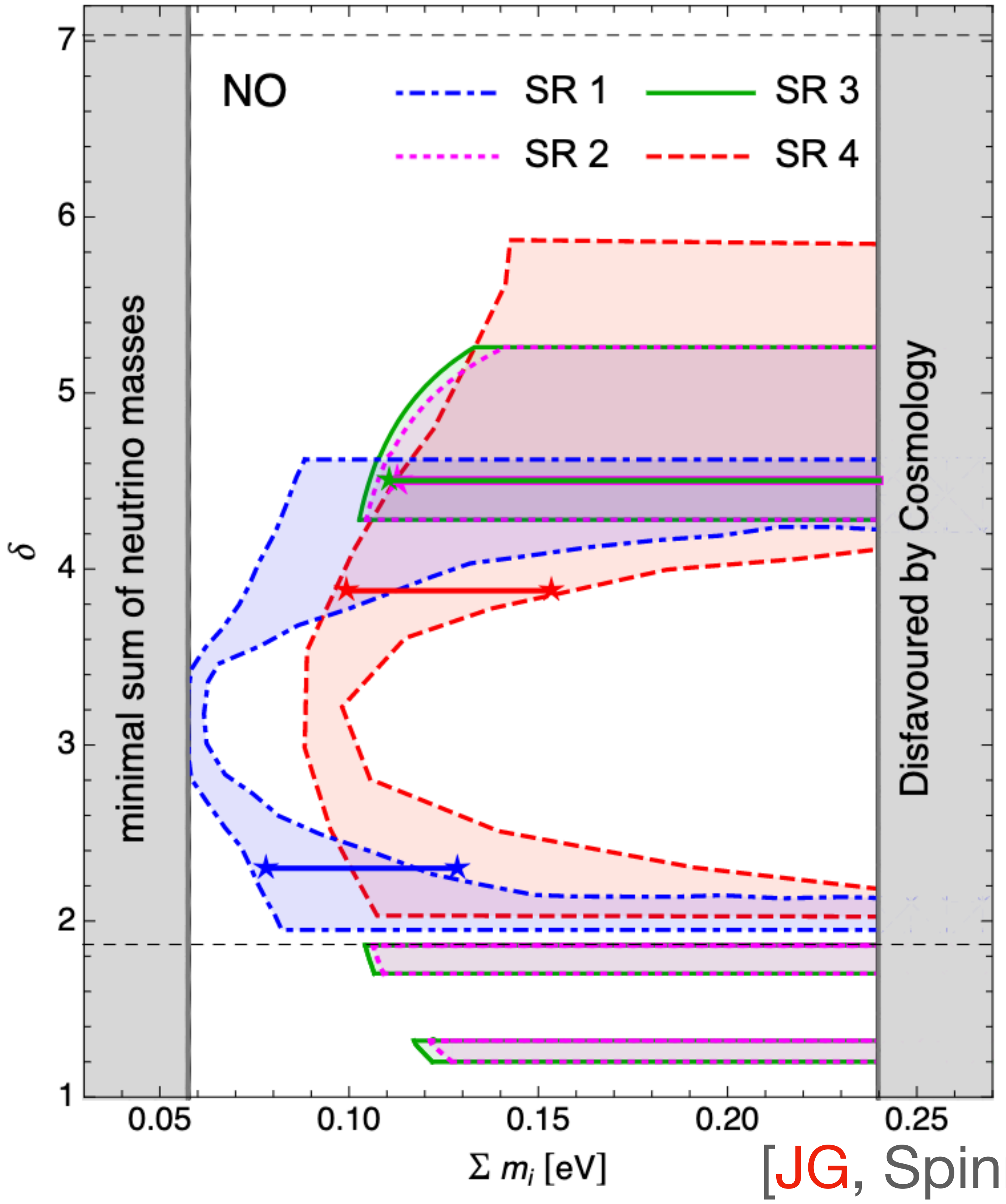
Future experiments can disentangle different models

at >5σ!



[Blennow, Ghosh, Ohlsson, Titov 2004.00017]

Correlations can be probed!



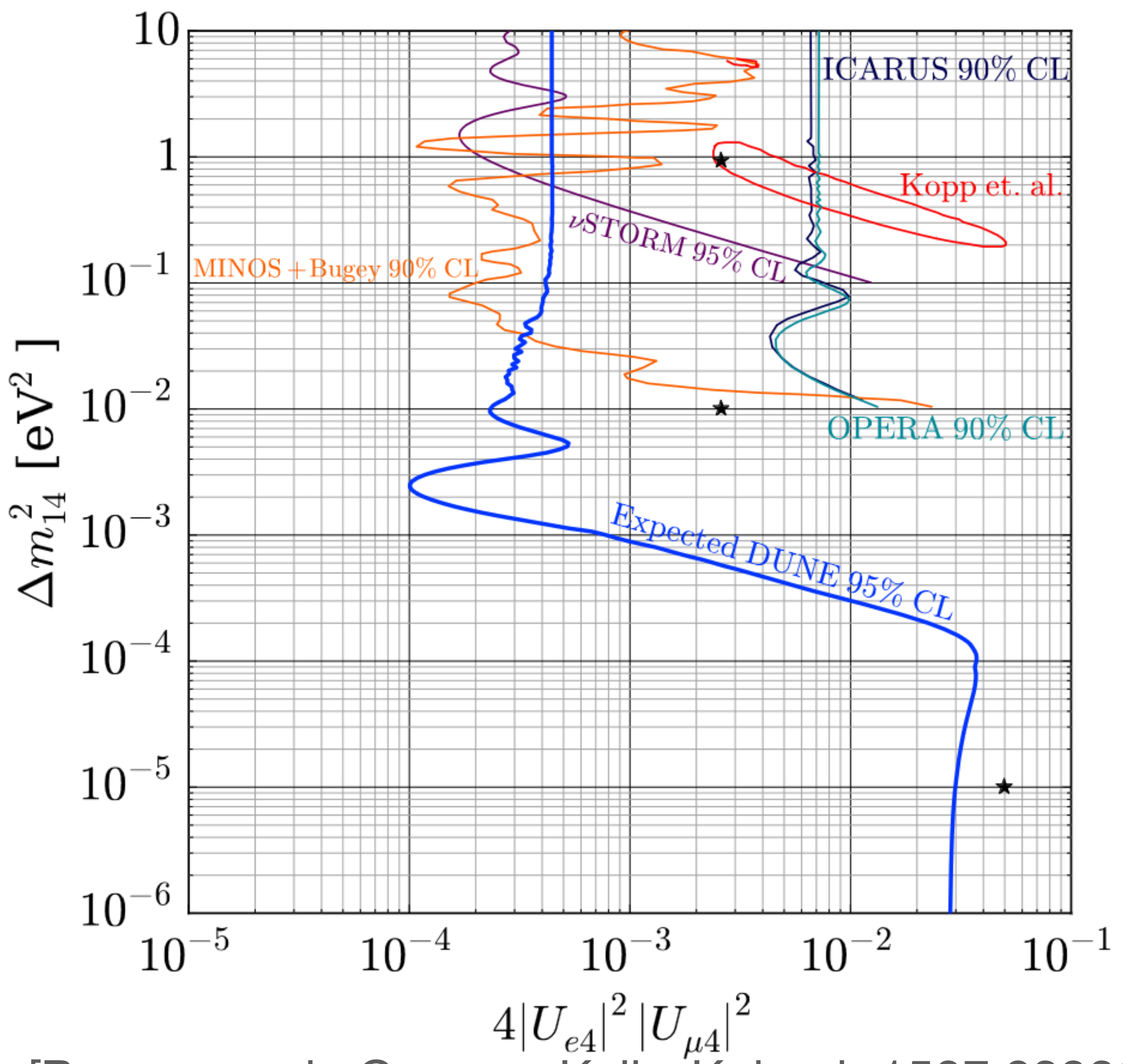
[JG, Spinrath 2012.04131]

Future of oscillation physics

Sterile neutrinos

- **Light** sterile neutrino(~eV mass): direct imprint in oscillations
- **Medium** heavy (~MeV-GeV mass): impact of meson decay spectrum, observable at ND
- **Heavy** (>GeV mass): non-unitarity of PMNS matrix

DUNE



[Berryman, de Gouvea, Kelly, Kobach 1507.03986]

Future of oscillation physics

Neutrino non-standard interactions (NSI)

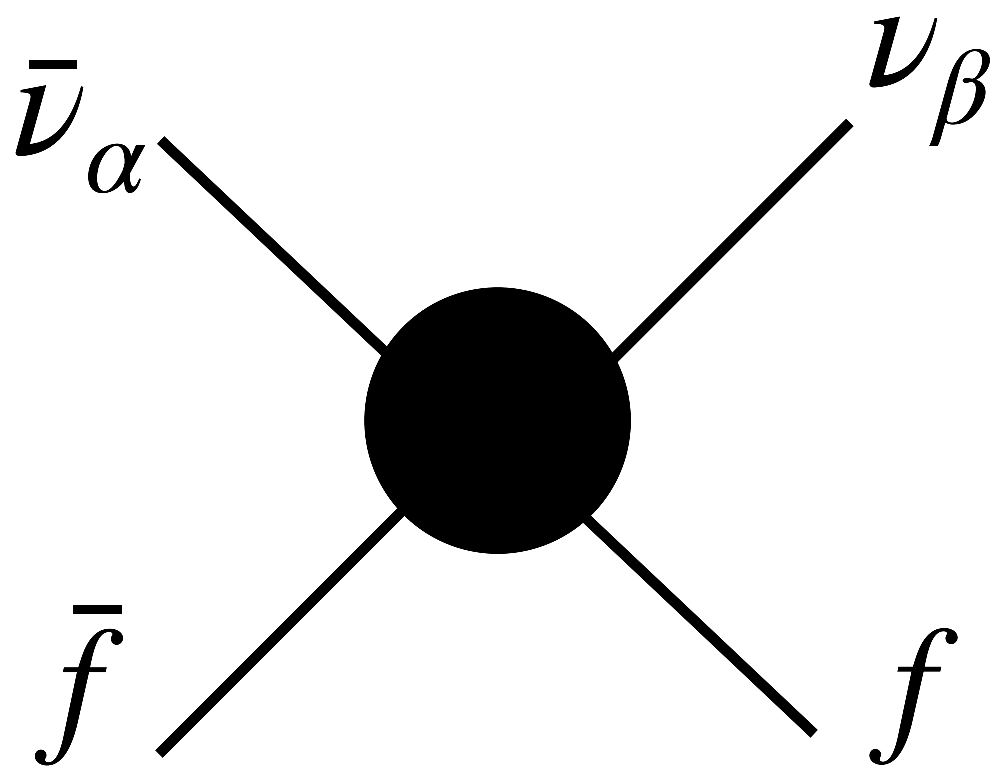
EFT framework:

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \frac{1}{\Lambda}\delta\mathscr{L}^{d=5} + \frac{1}{\Lambda^2}\delta\mathscr{L}^{d=6} + \dots$$

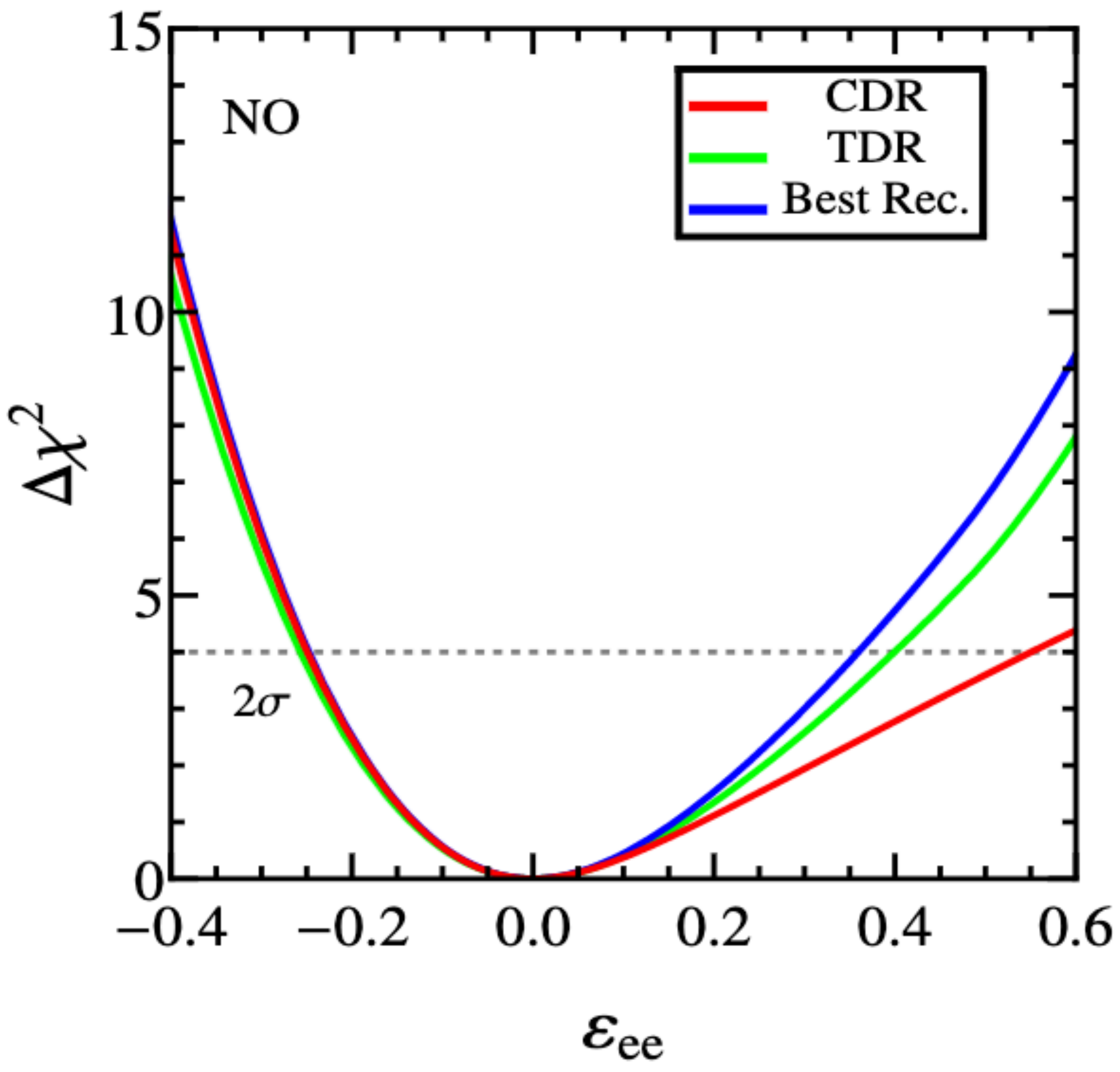
NC NSI: $$\mathscr{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon^f_{\alpha\beta}(\bar{\nu}_\alpha P \nu_\beta)(\bar{f} P f)$$

Affect neutrino oscillations as a new matter effect

$$\epsilon \sim \mathcal{O}(G_X/G_F)$$



DUNE



[Chatterjee, Dev, Machado 2106.04597]

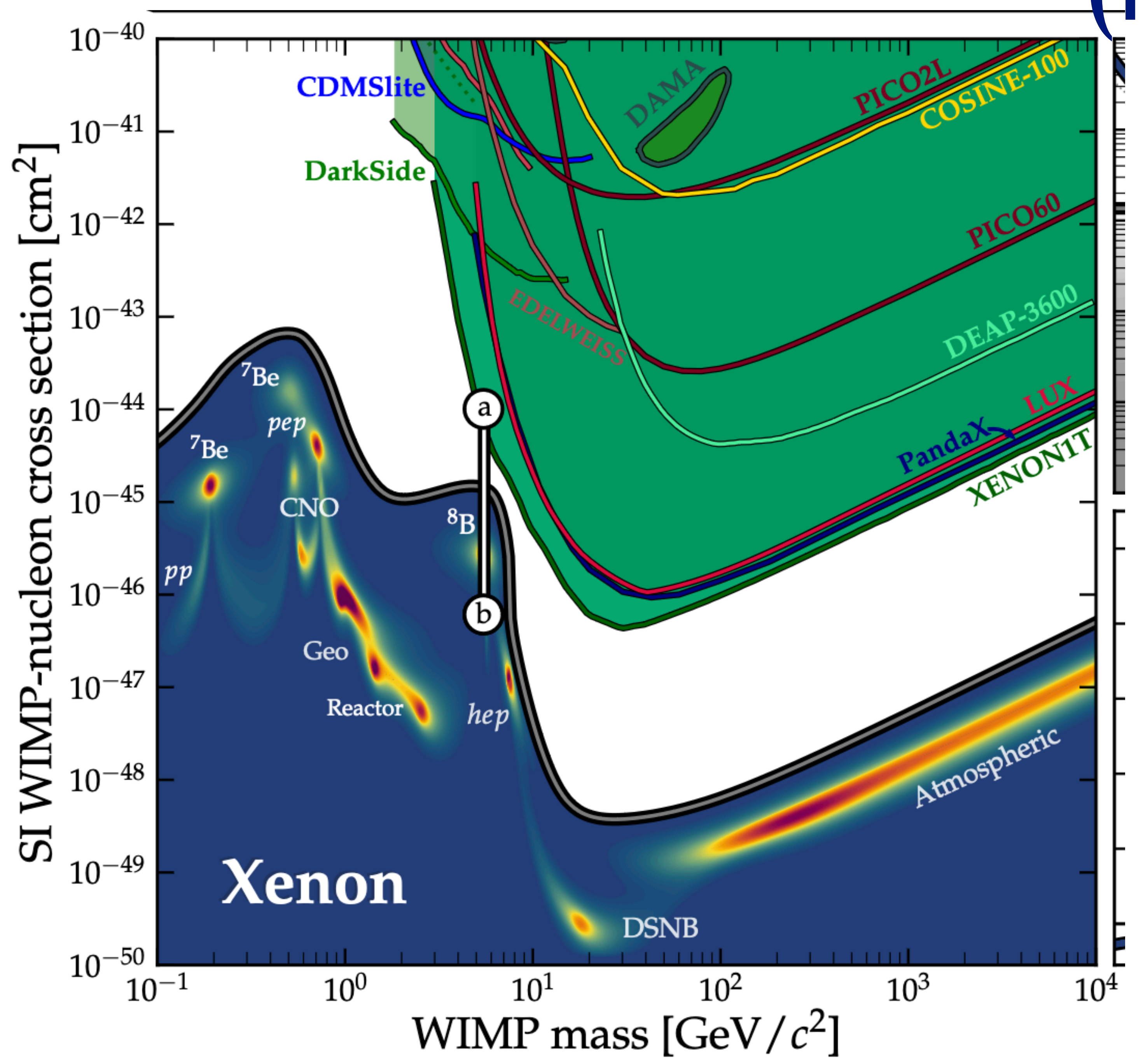
New physics in scattering

Neutrino non-standard interactions (NSI)

NSI also affect neutrino scattering experiments

→ resolves degeneracy present in oscillation experiments

DM direct detection experiments will be sensitive to neutrino fog (neutrino-nucleus scattering events) soon

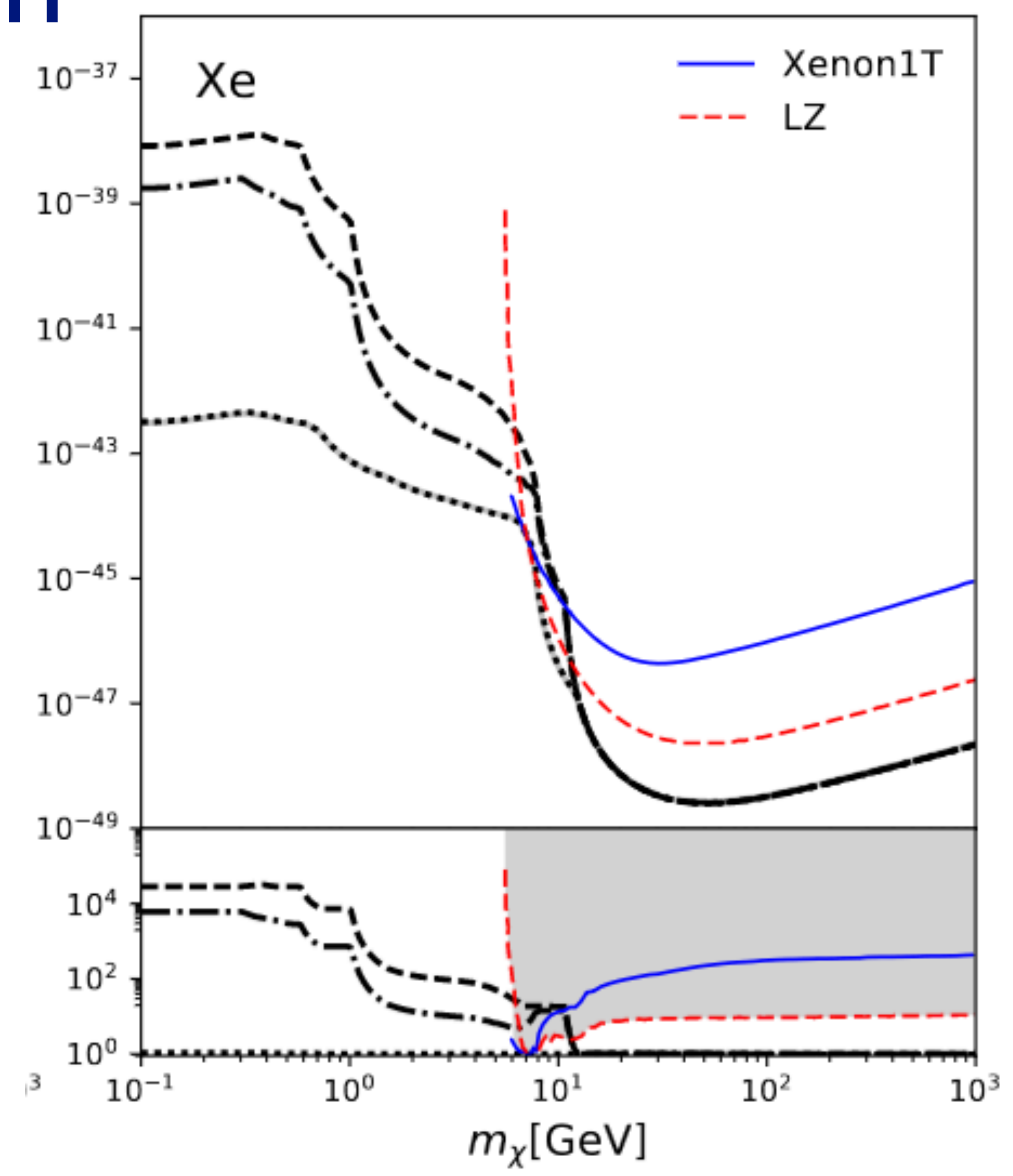


See DM talks tomorrow!

Depending on type of interaction:

→ large NSI effects

O' Hare 2109.03116]



Neutrino mass

What is neutrino mass generation mechanism?

Dirac neutrinos

$$m_D = y_\nu \bar{\nu}_L \tilde{H} N_R$$

like other SM fermions

Neutrino mass

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Dirac neutrinos

$$m_D = y_\nu \bar{\nu}_L \tilde{H} N_R$$

like other SM fermions

Majorana neutrinos

$$m_M = M_N \bar{\nu}_L \nu_L^c$$

Neutrinos are the only SM particles that could have such a mass term

Term not gauge invariant!

Neutrino mass

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Dirac neutrinos

$$m_D = y_\nu \bar{\nu}_L \tilde{H} N_R$$

like other SM fermions

Majorana neutrinos

$$m_M = M_N \bar{\nu}_L \nu_L^c$$

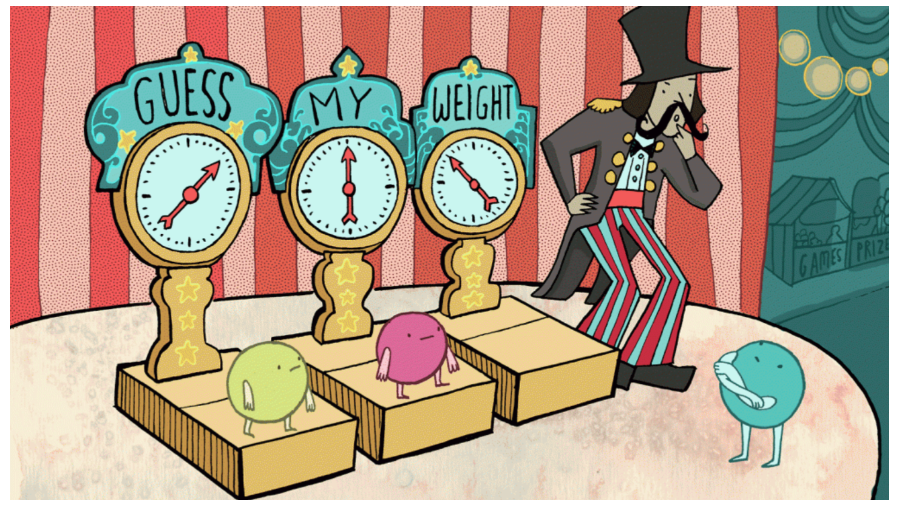
Neutrinos are the only SM particles that could have such a mass term

Term not gauge invariant!

In any case need new particles!

$\rightarrow$ observation of neutrino oscillations predicts new particles!

Neutrino mass



What is the neutrino mass scale?

Only upper limit on neutrino mass scale so far!

Cosmological sum of neutrino masses:

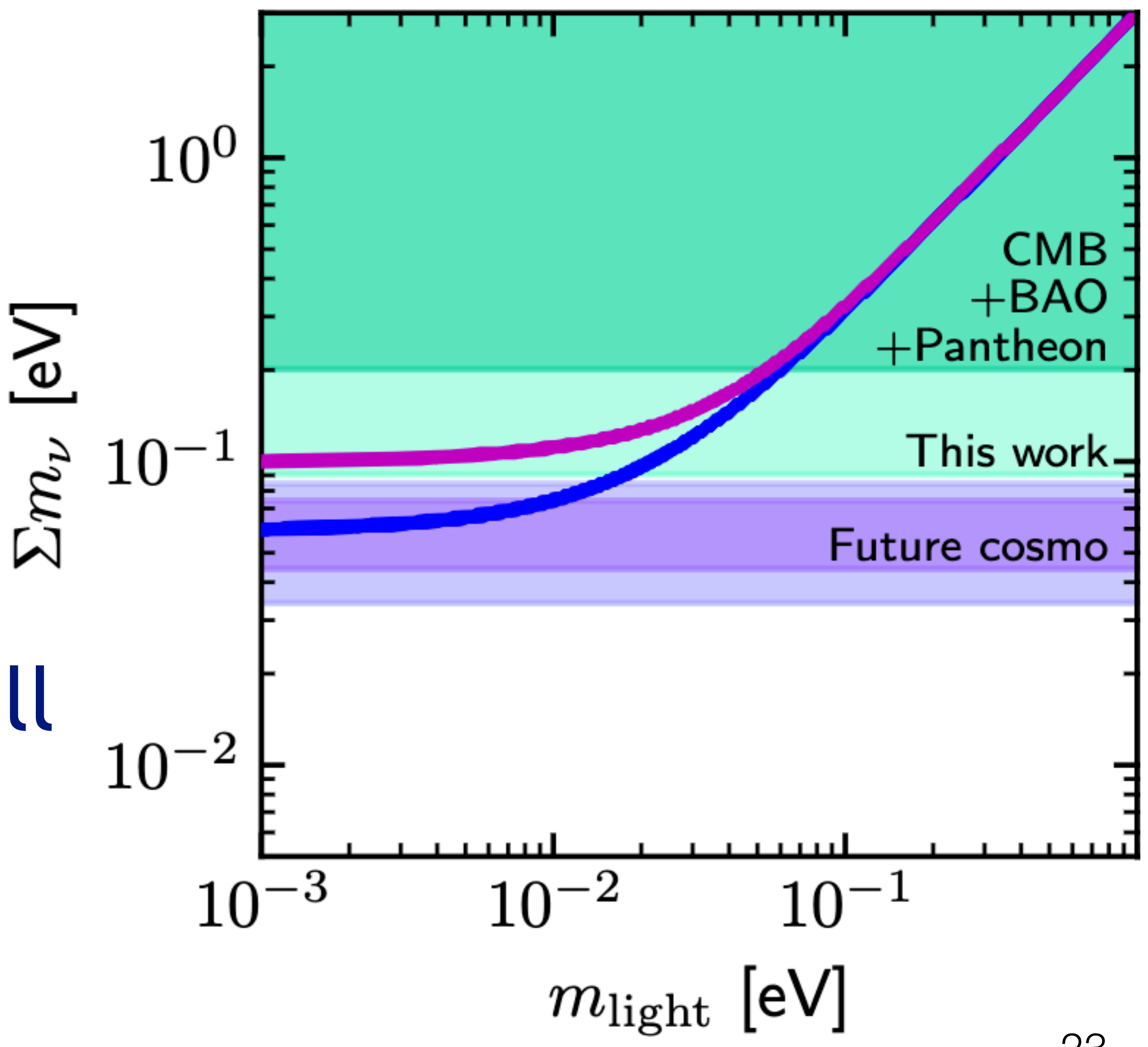
$$\sum m_\nu \lesssim 0.1 \text{ eV}$$

[Di Valentino, Gariazzo, Mena, 2207.05167]

Depending on data sets combined

Future cosmological observatories will measure sum of neutrino masses

[Di Valentino, Gariazzo, Mena, 2106.15267]



Neutrino mass

What is neutrino mass scale?

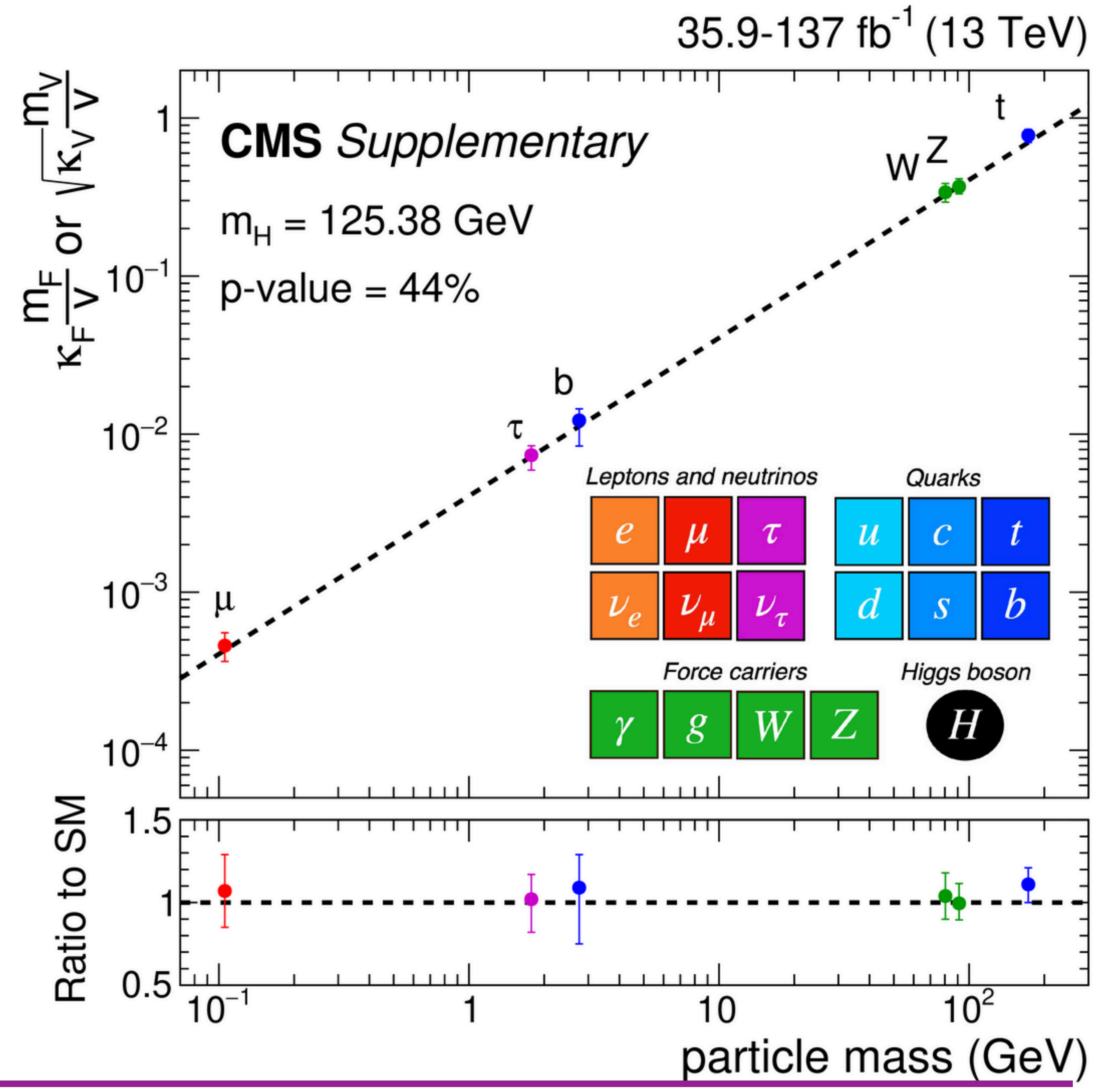
Neutrinos much lighter than other fermions

Dirac neutrinos: Yukawa coupling $y_\nu \lesssim 10^{-13}$

Dirac neutrinos would have a much smaller Yukawa coupling than other fermions

Direct probe of $H \to \bar{\nu}\nu$ colliders not possible

Reason for smallness of neutrino mass?



[CMS 2009.04363]

Neutrino mass

Majorana mass term arises from higher dimension operators!

→ explains smallness of neutrino mass due to suppression by high scale

Majorana neutrino mass operators occur at odd dimension

[Kobach 1604.05726]

$$\mathcal{O} \propto (LLHH)(H^\dagger H)^n$$

$$\rightarrow m_\nu \propto c\frac{v^2}{\Lambda}\left(\frac{v}{\Lambda}\right)^{d-5}$$

Neutrino mass

Majorana mass term arises from higher dimension operators!

→ explains smallness of neutrino mass due to suppression by high scale

Dimension 5 operator

$$\mathscr{L}_5 = c_5 \frac{(\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L_L)}{\Lambda}$$

Only dim-5 operator that can be build with SM fields alone

Expect first signs of new physics from lowest SMEFT operator

→ neutrino mass

Dimension 7

$$\mathscr{L}_7 \propto c_7 \frac{(LLHH)(H^\dagger H)}{\Lambda^3}$$

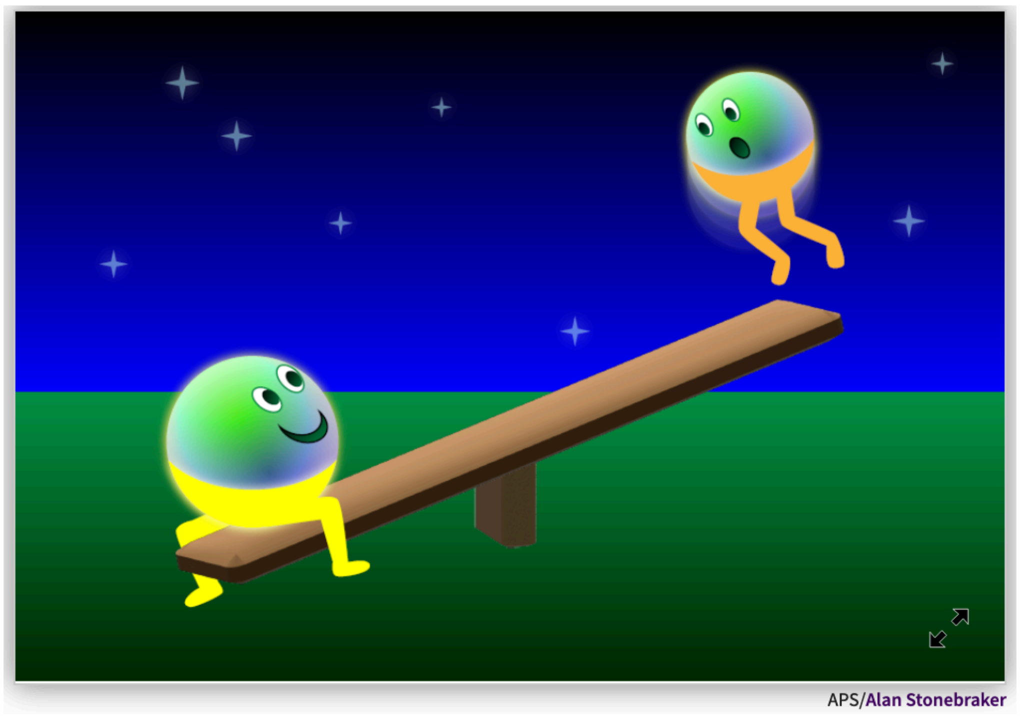
Dimension 9

$$\mathscr{L}_9 \propto c_9 \frac{(LLHH)(H^\dagger H)(H^\dagger H)}{\Lambda^5}$$

...

Maze of possibilities

- Neutrino mass mechanism
  - Dirac
  - Majorana
    - Dimension 5 operator
    - Dimension 7 operator
    - Dimension 9 operator
    - ...



Testing neutrino mass mechanisms

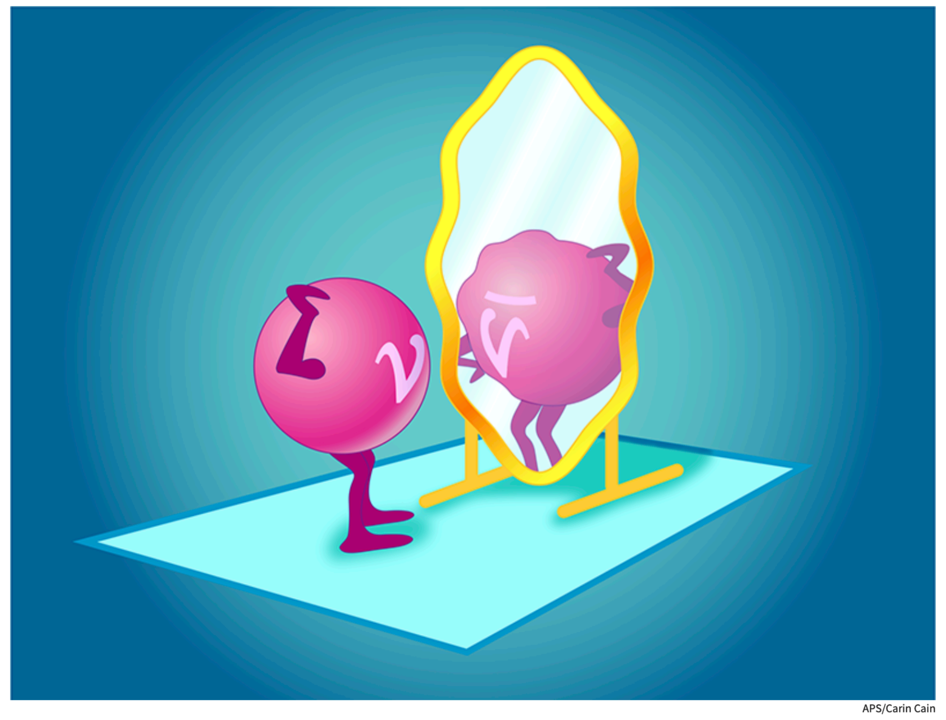
Dirac vs Majorana neutrinos

Dirac

Majorana

Majorana mass term violates lepton number
Dirac mass term conserves lepton number
$\Rightarrow$ search for lepton number violating processes

Effect $\propto$ neutrino mass!



Testing neutrino mass mechanisms

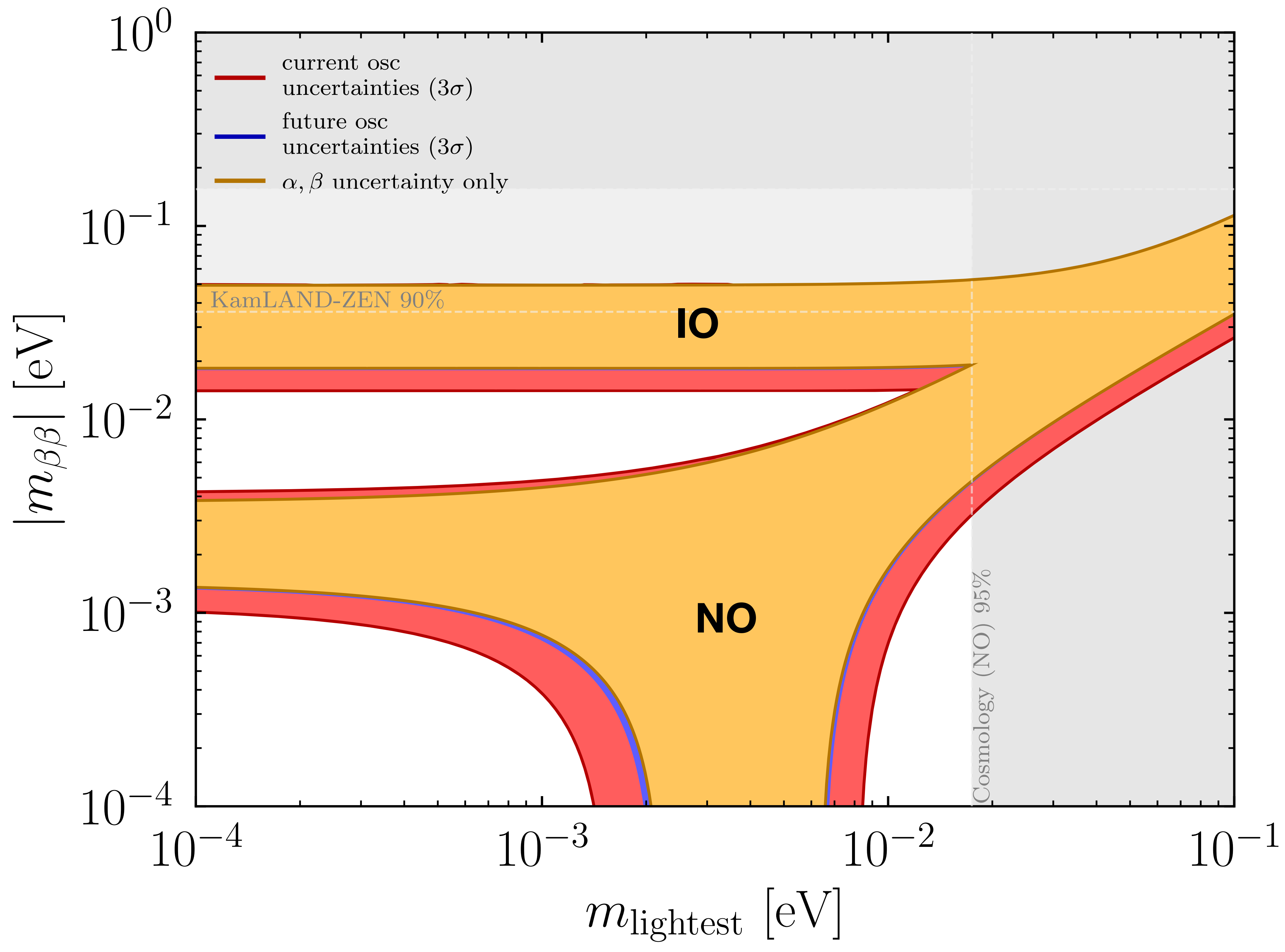
Dirac vs Majorana neutrinos

Neutrinoless double beta decay experiments aim to provide an answer

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

Nuclear matrix element: large uncertainty

See talks by K. Mistry, A. Piepke + talks in parallel sessions



Currently just upper limit, no observation

Large parameter space, depending on absolute mass scale and mass ordering

Width of allowed bands depends on Majorana phases

Testing neutrino mass mechanisms

New particles associated to mass generation

New particles are introduced in neutrino mass generation mechanisms
$\rightarrow$ search for them!

Identify UV complete models for higher dimensional operators

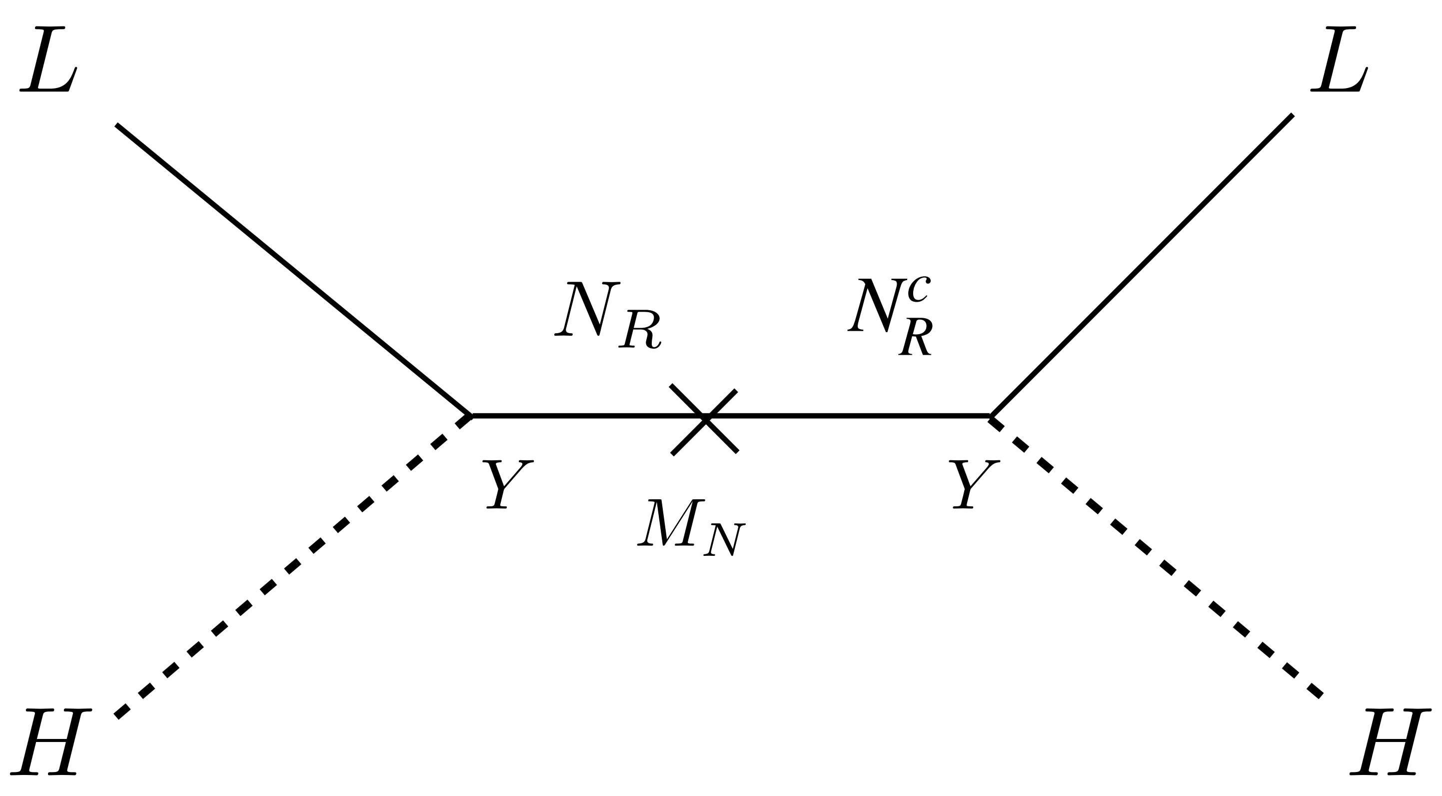
Testing neutrino mass mechanisms

New particles associated to mass generation

Identify UV complete models for higher dimensional operators

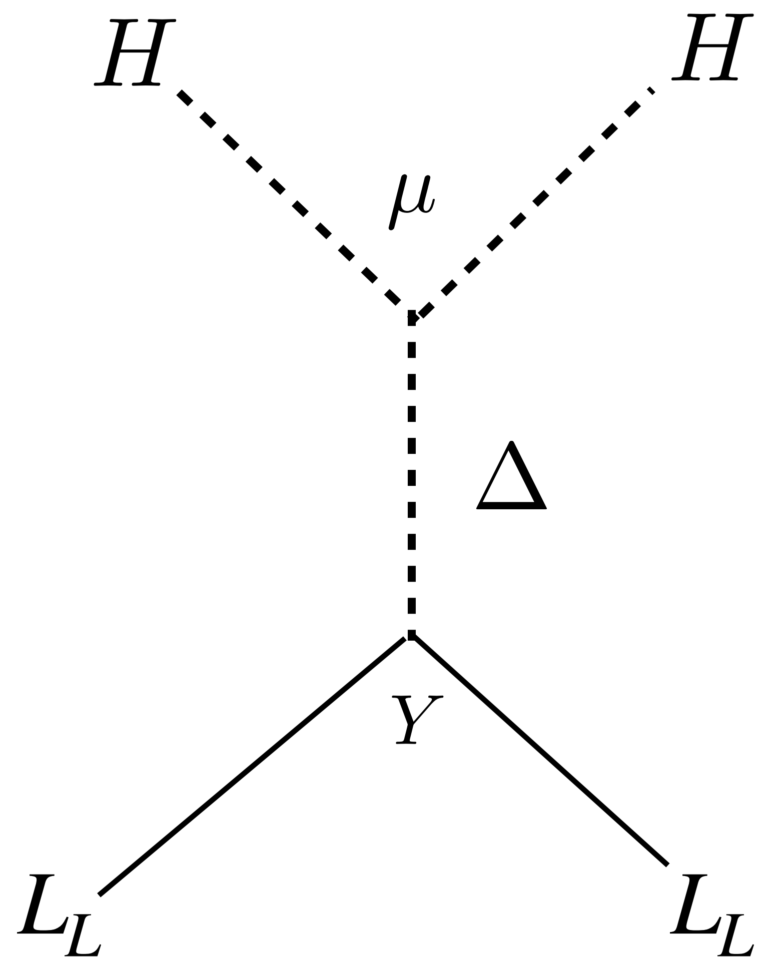
Example: realizations of dim-5 operator

Type I seesaw



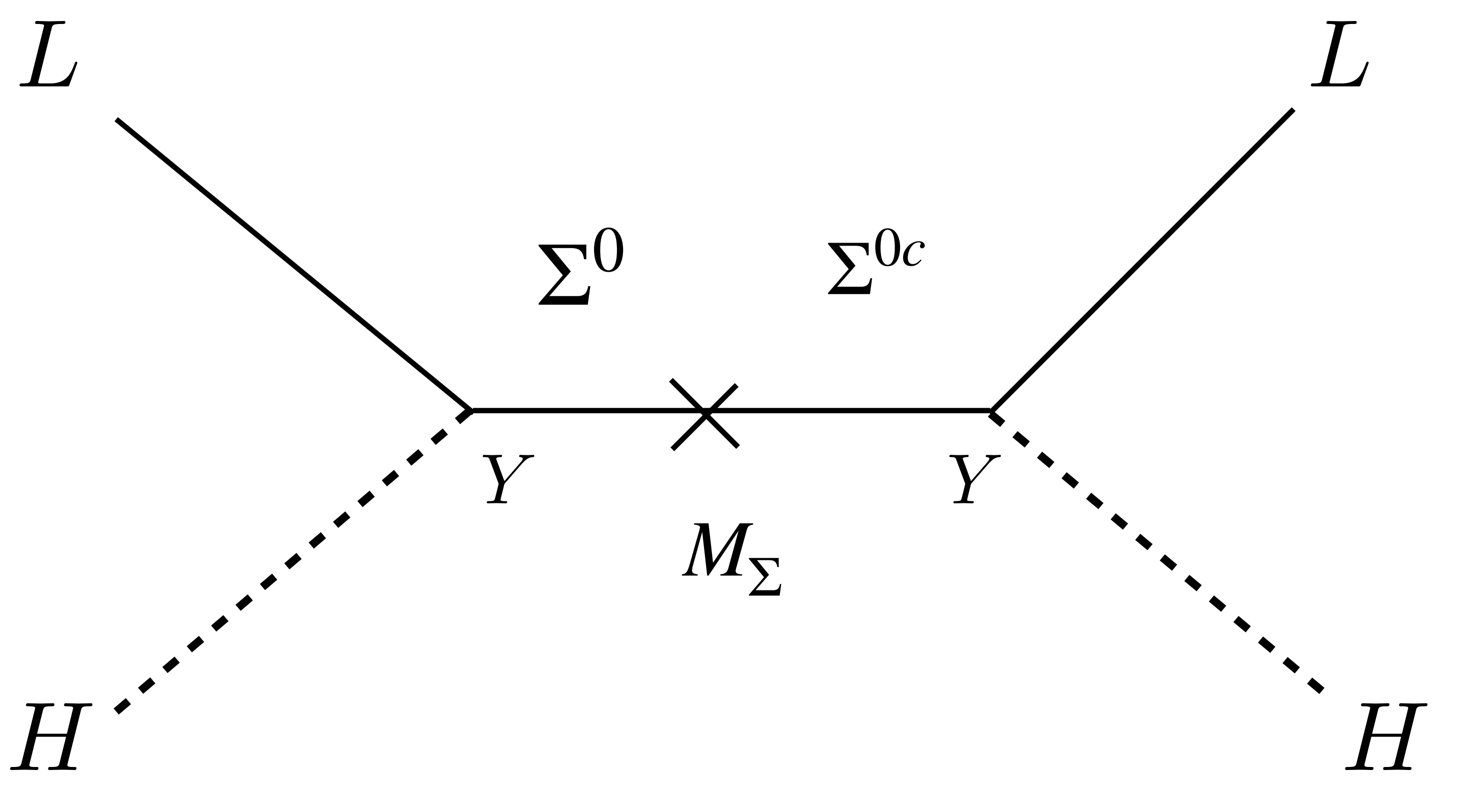
N_R : SM singlet
"Right-handed neutrino"

Type II seesaw



Δ: $SU(2)_L$ scalar triplet

Type III seesaw



Σ: $SU(2)_L$ fermion triplet

Summary & Conclusion

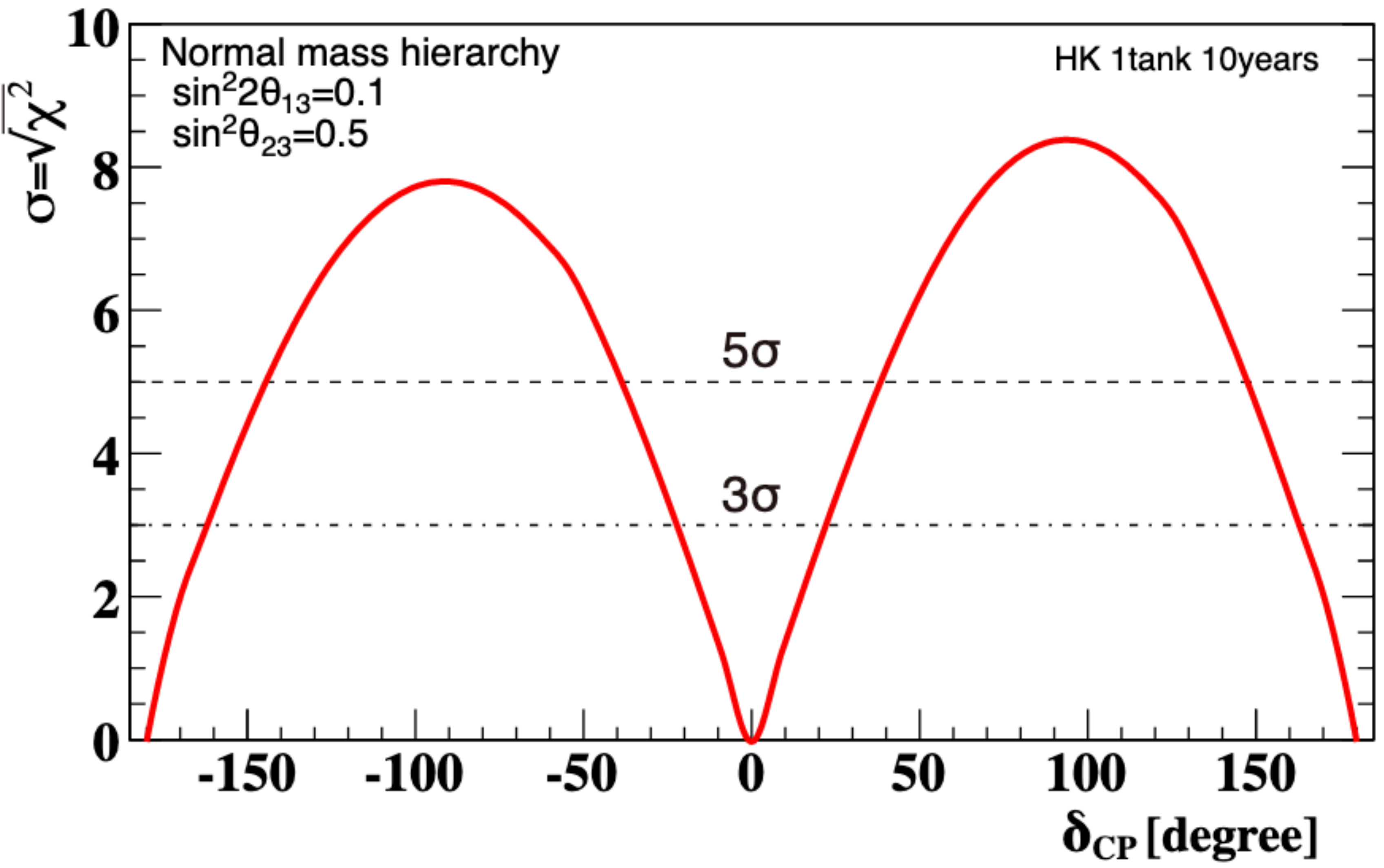
- Neutrino oscillations → Very strong evidence for physics beyond the SM
- Next generation experiments will lead to precision measurement of oscillation parameters
- We will learn more about neutrino sector and neutrino theory in the near future
- Many different possibilities for neutrino mass generation mechanism: need to test their predictions and build more testable models

Thanks for your attention!

Appendix: CP violation searches

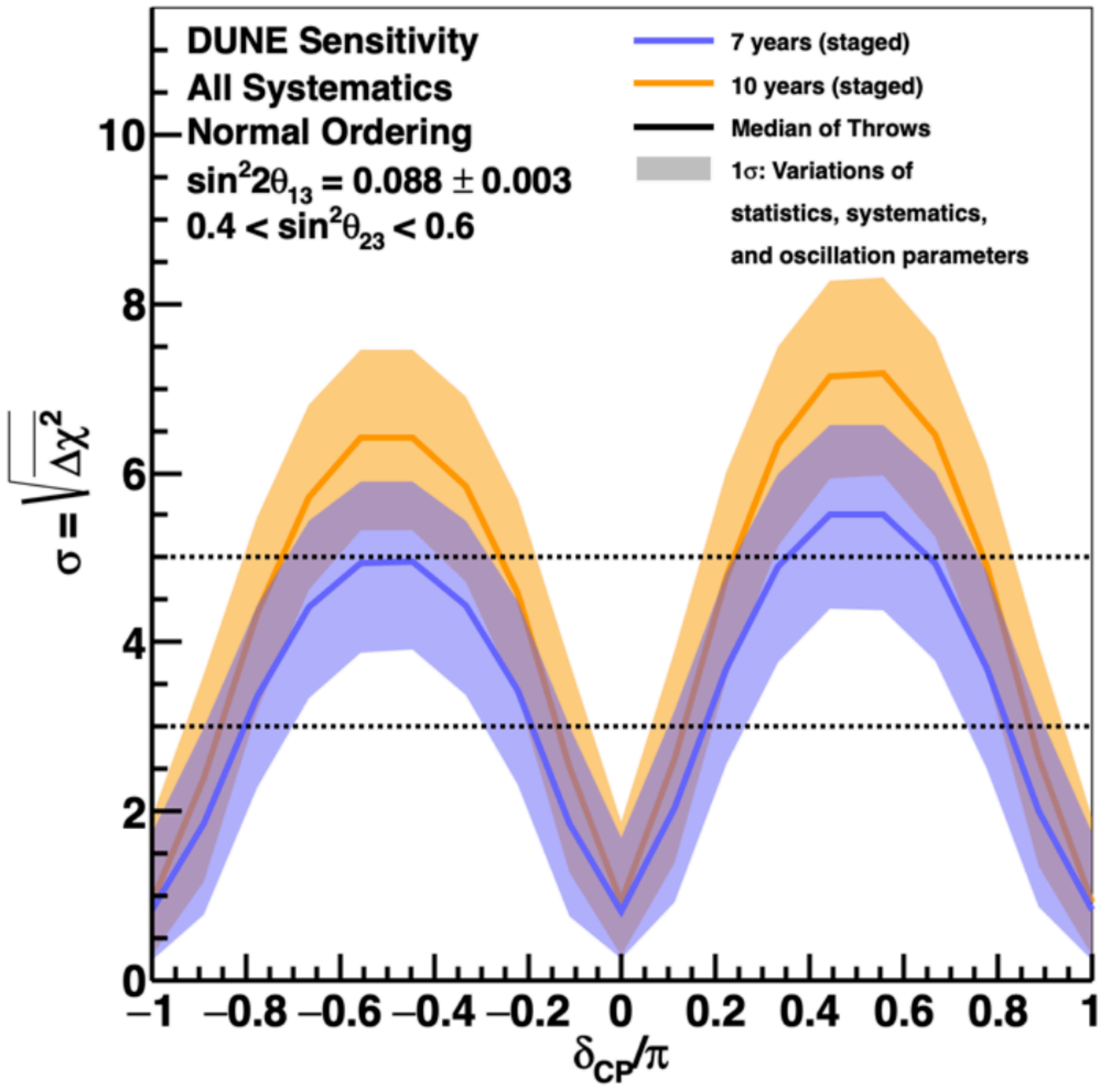
Hyper-Kamiokande sensitivity

[HK DR ’18]



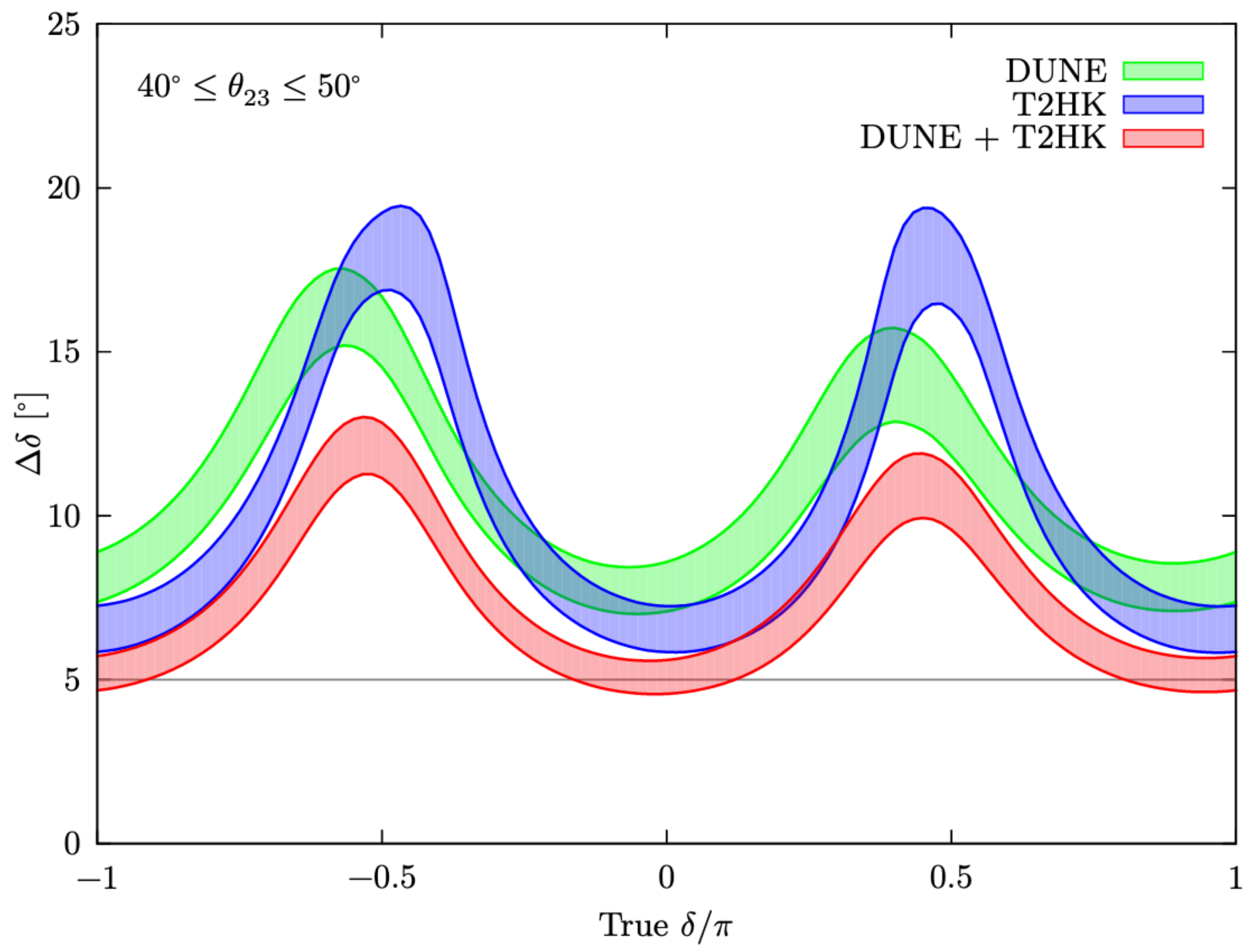
DUNE sensitivity

[DUNE TDR ’20]



DUNE & HK combination

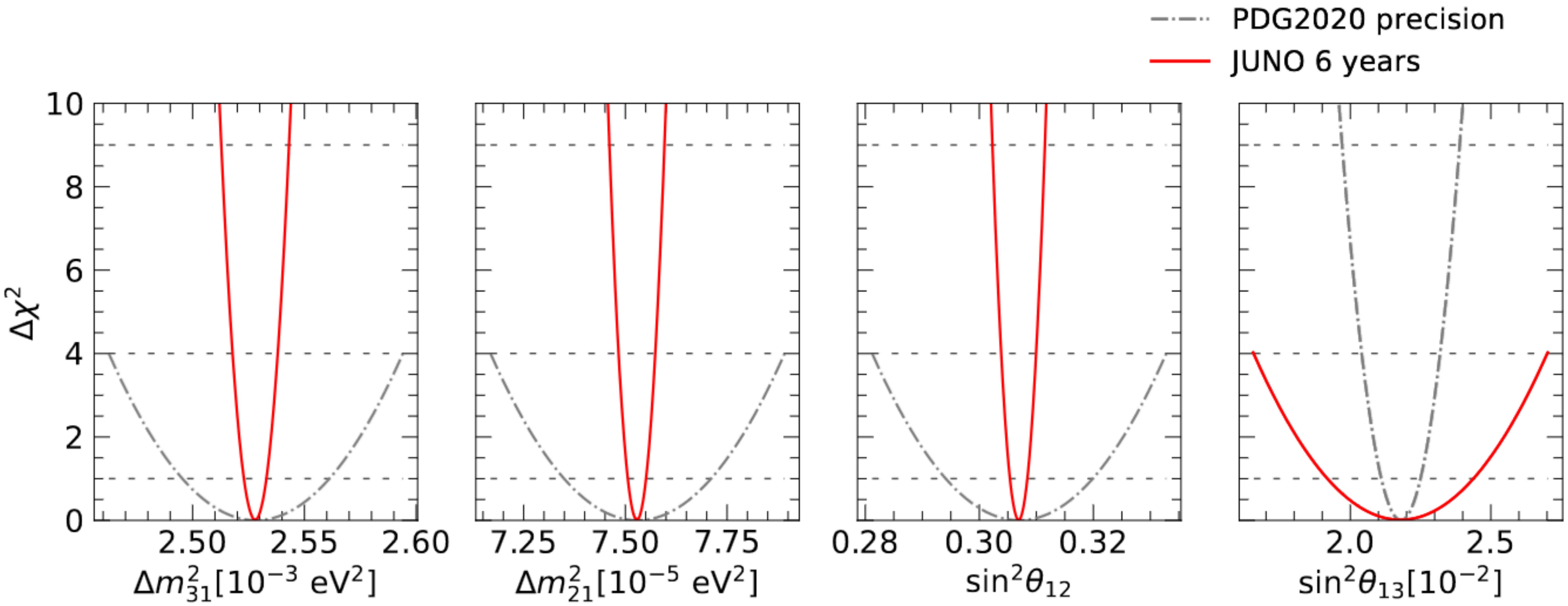
[Ballett et al, 1612.07275]



Assuming no new physics and known other oscillation parameters

Appendix: Future of oscillation physics

[JUNO '23]



Appendix: Future of oscillation physics

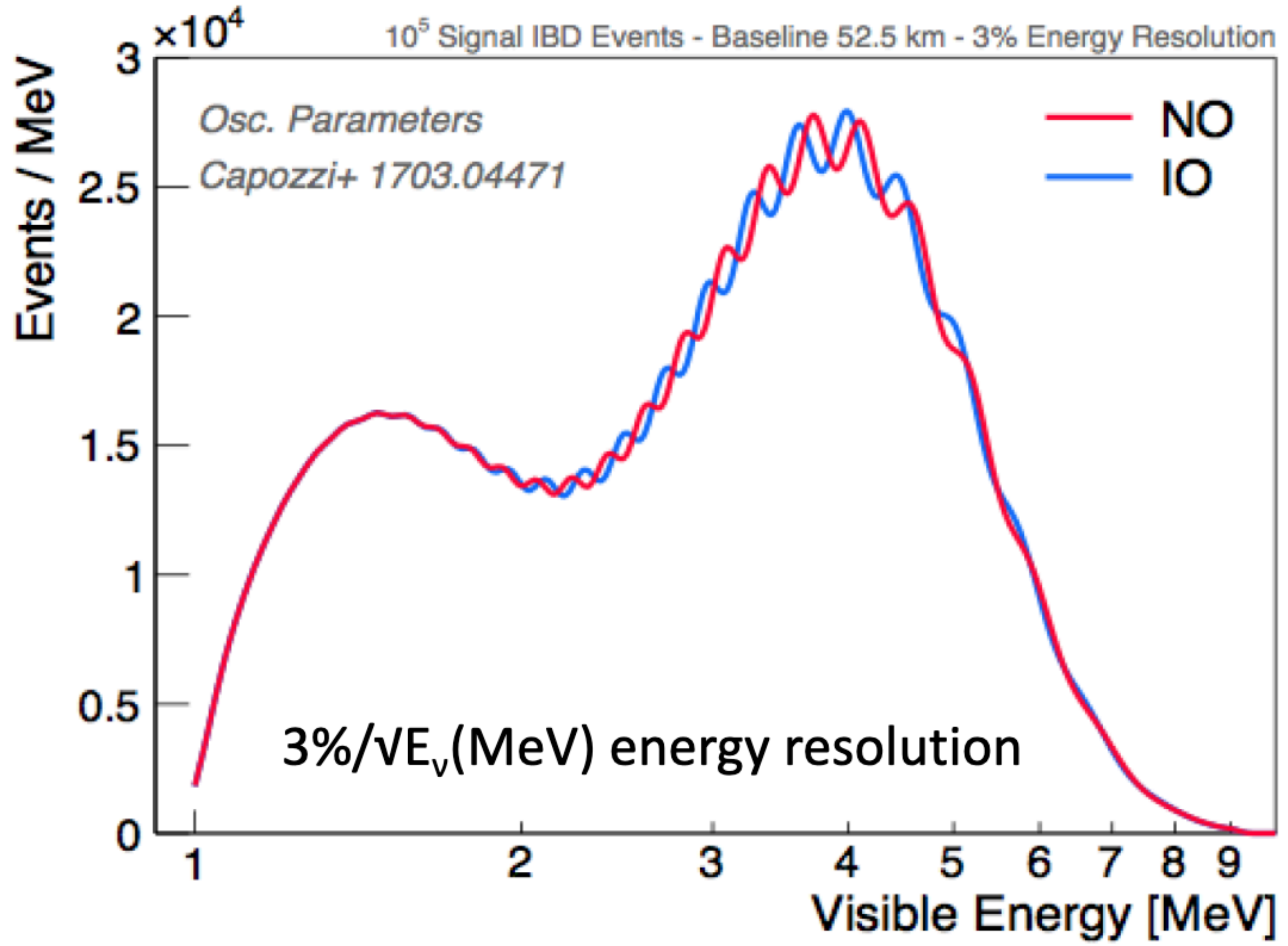
JUNO

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{ee}$$

$$\Delta m^2_{ee} = \cos^2 \theta_{12} |\Delta m^2_{31}| + \sin^2 \theta_{12} |\Delta m^2_{32}|$$

in NO $|\Delta m^2_{31}| > |\Delta m^2_{32}|$

in IO $|\Delta m^2_{31}| < |\Delta m^2_{32}|$



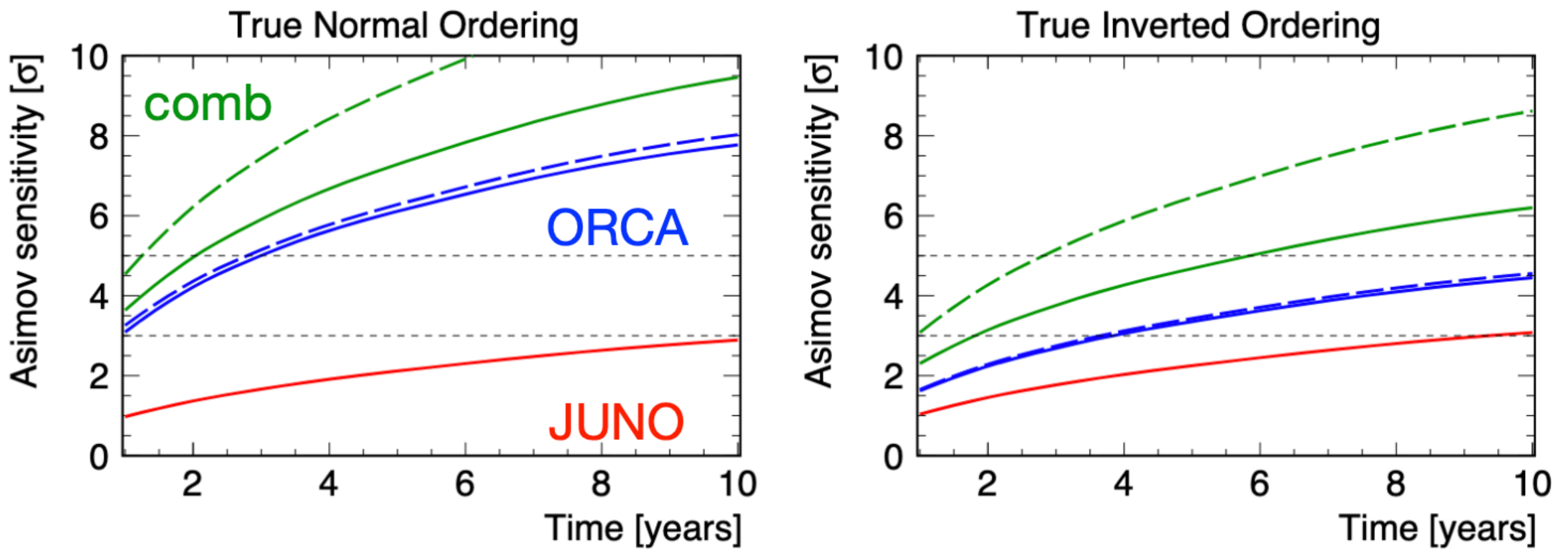
Appendix: Future of oscillation physics

Atmospheric neutrinos encounter resonance when traveling through Earth

NO ($\Delta m^2_{31} > 0$) resonance for neutrinos

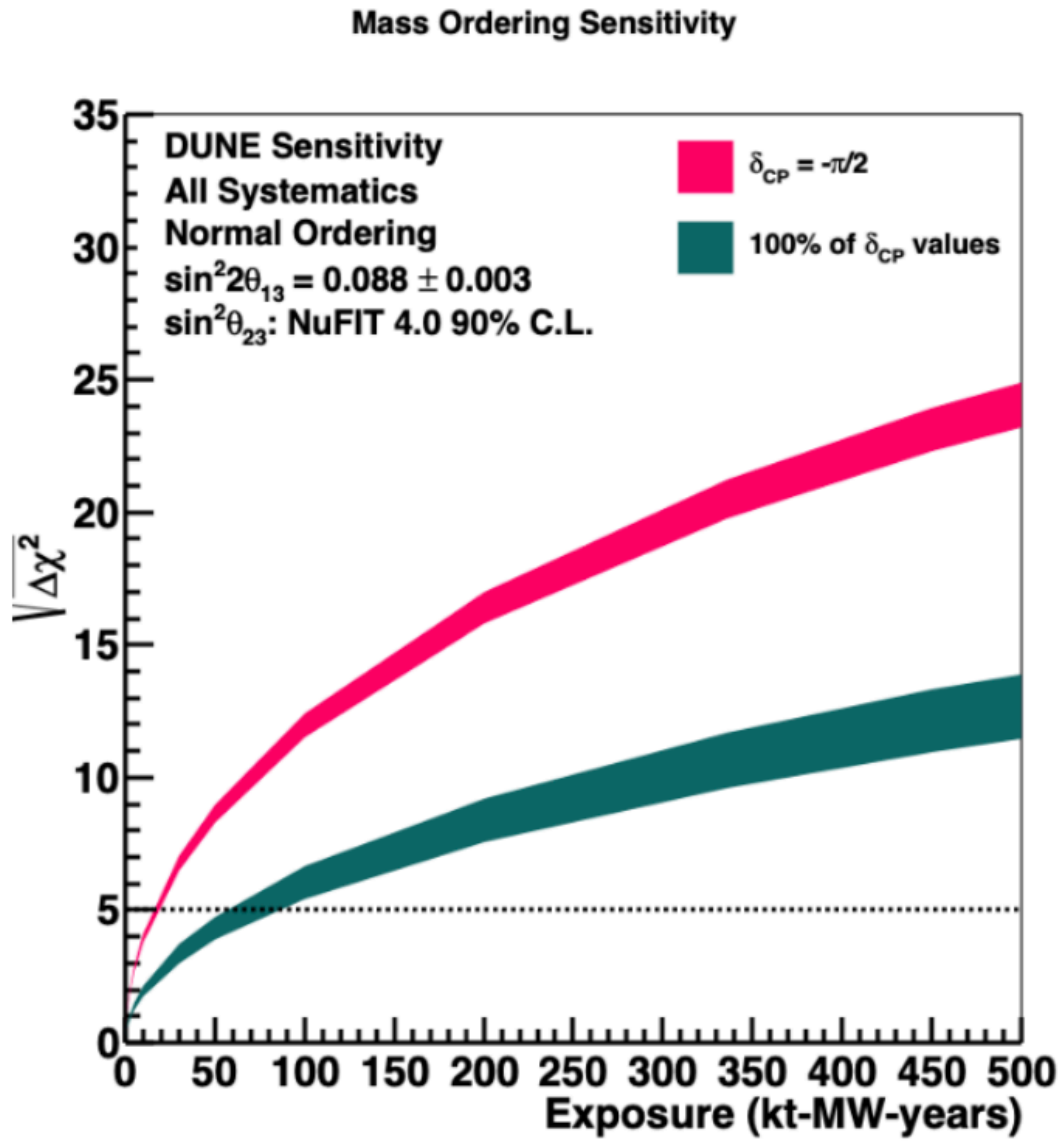
IO ($\Delta m^2_{31} < 0$) resonance for antineutrinos

Combination of experiments using different methods (JUNO & KM3NeT/ORCA) → increase in sensitivity



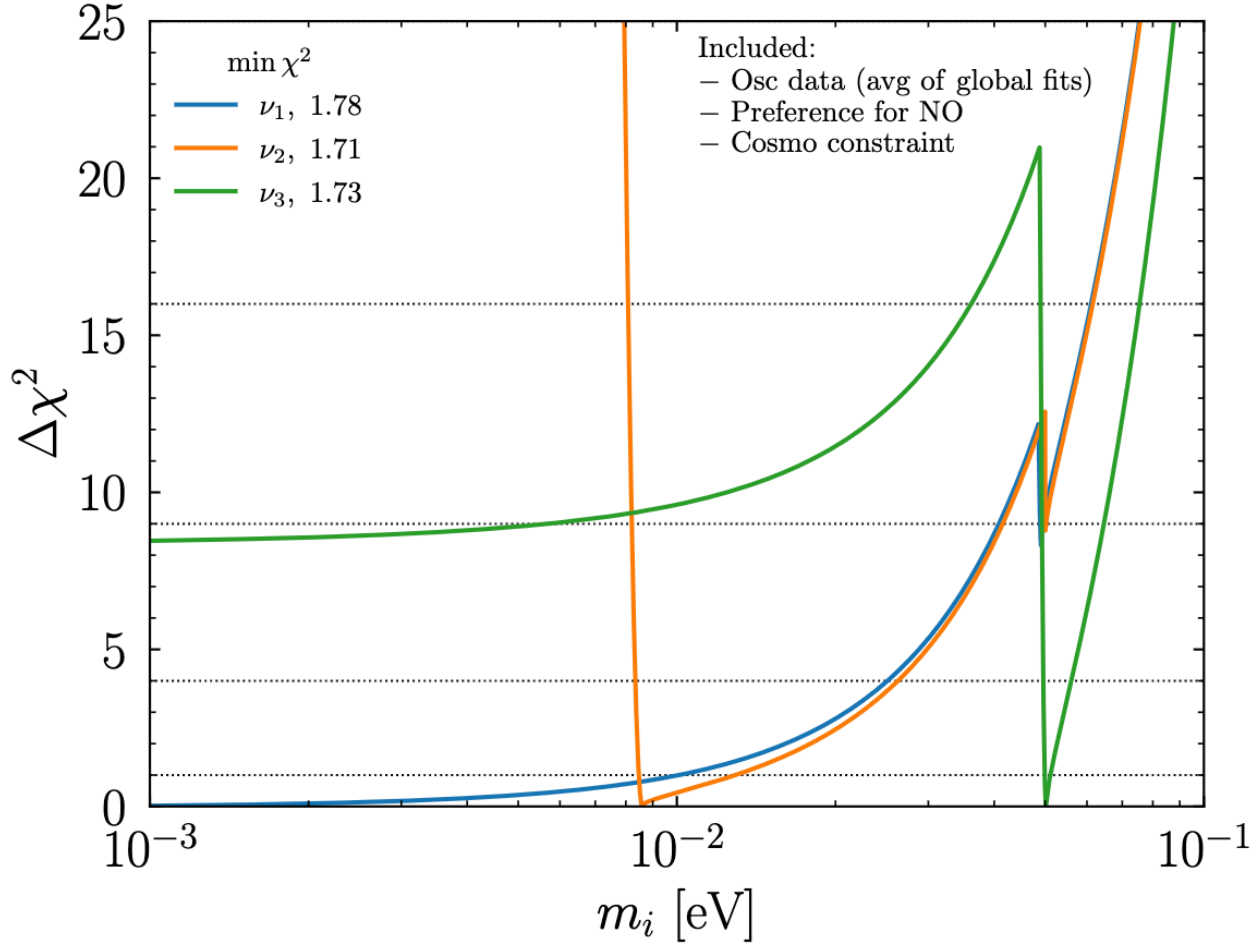
Appendix: Future of oscillation physics

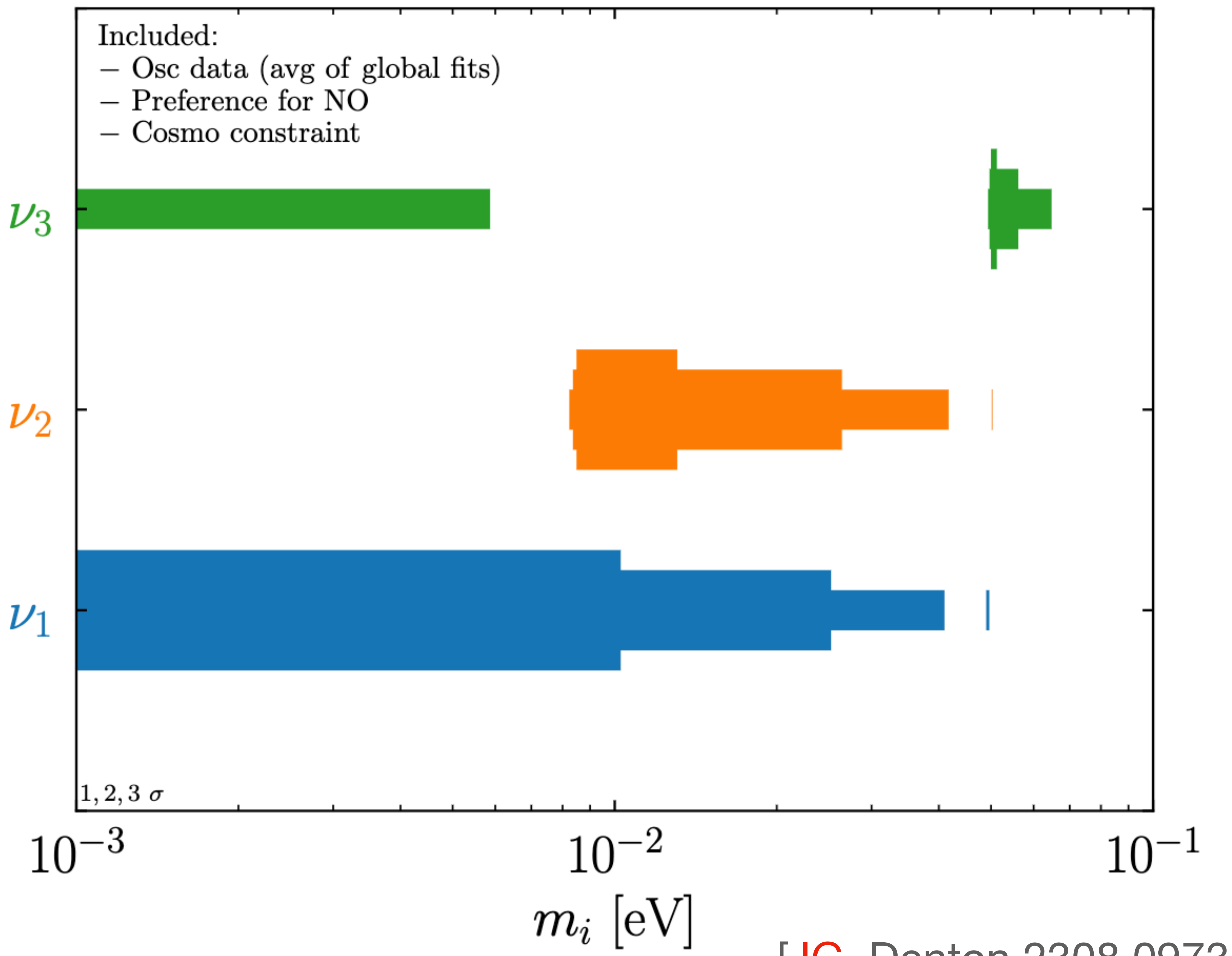
positive $\Delta m^2_{31} \Rightarrow$ larger $\nu_\mu \to \nu_e$ appearance probability & smaller $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance probability at the first oscillation maximum in matter



DUNE '20

Appendix: Neutrino mass



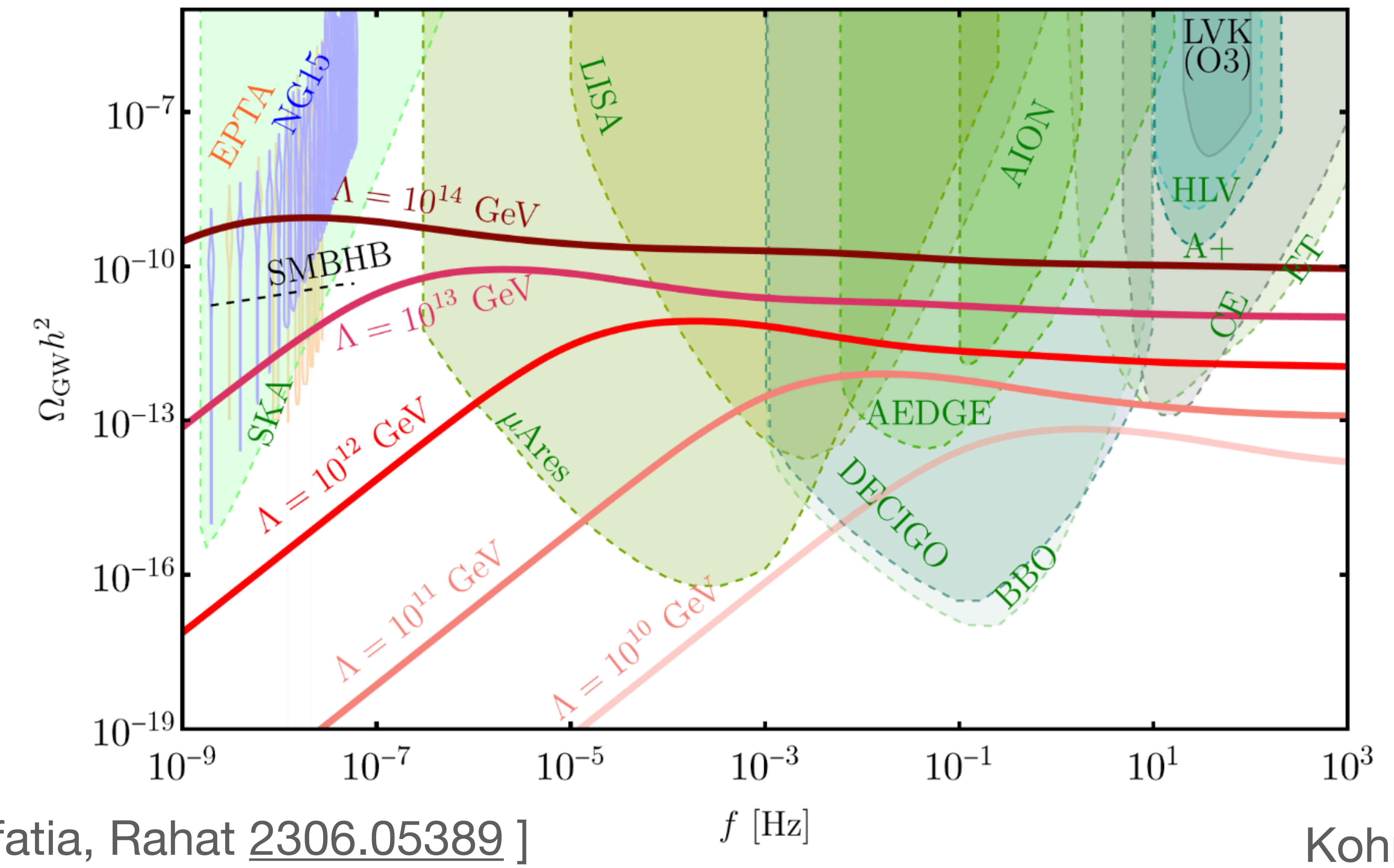


[JG, Denton 2308.09737]

Appendix: Neutrino mass mechanism

Dirac vs Majorana neutrinos

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

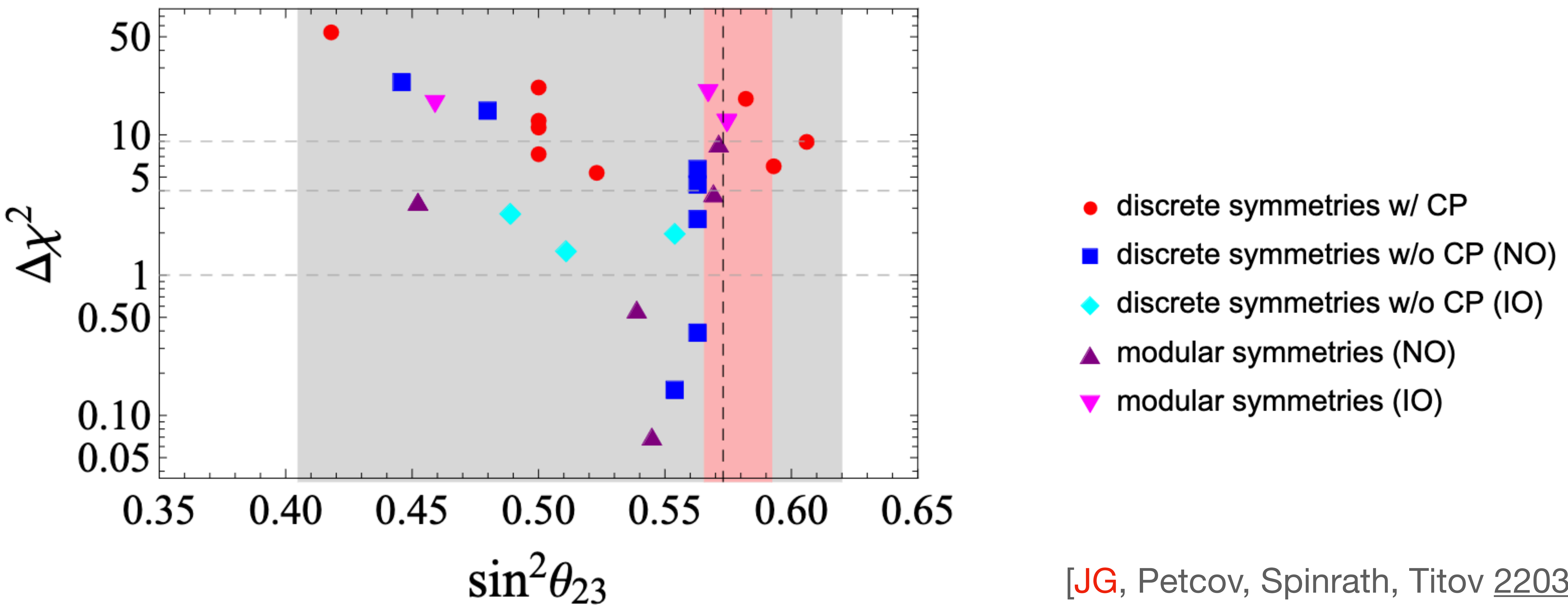
Lepton number breaking scale

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

Appendix: Mixing sum rules

Sum rules can be used to distinguish different mixing pattern

Future experiments can disentangle different models

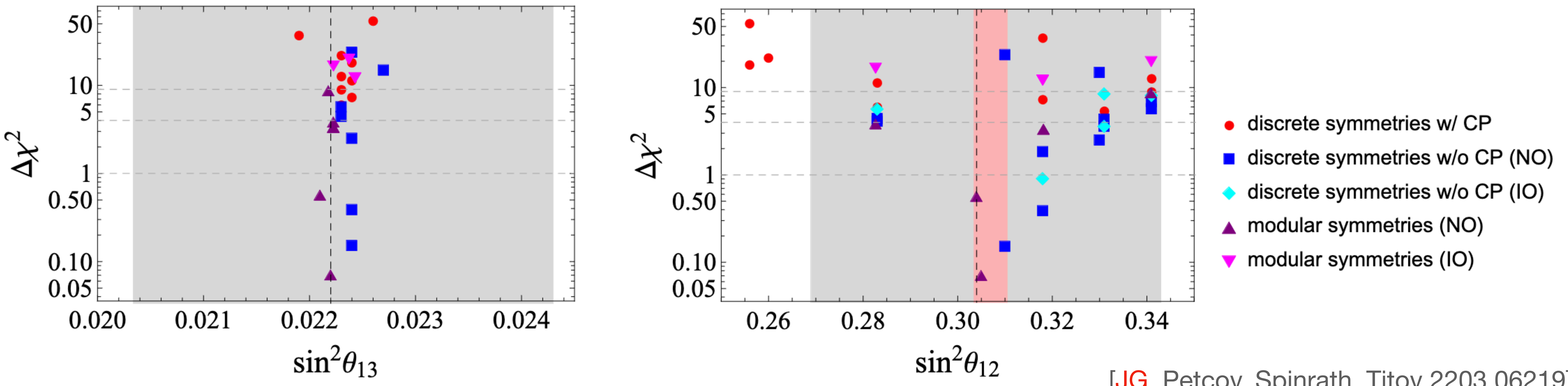


[JG, Petcov, Spinrath, Titov 2203.06219]

Appendix: Mixing sum rules

Sum rules can be used to distinguish different mixing pattern

Future experiments can disentangle different models



[JG, Petcov, Spinrath, Titov 2203.06219]

Appendix: New physics

[de Gouvea, Kelly 1511.05562]

[Chatterjee, Dev, Machado 2106.04597]