Robustness of neutrino mass ordering determination

Julia Gehrlein

Brookhaven National Laboratory

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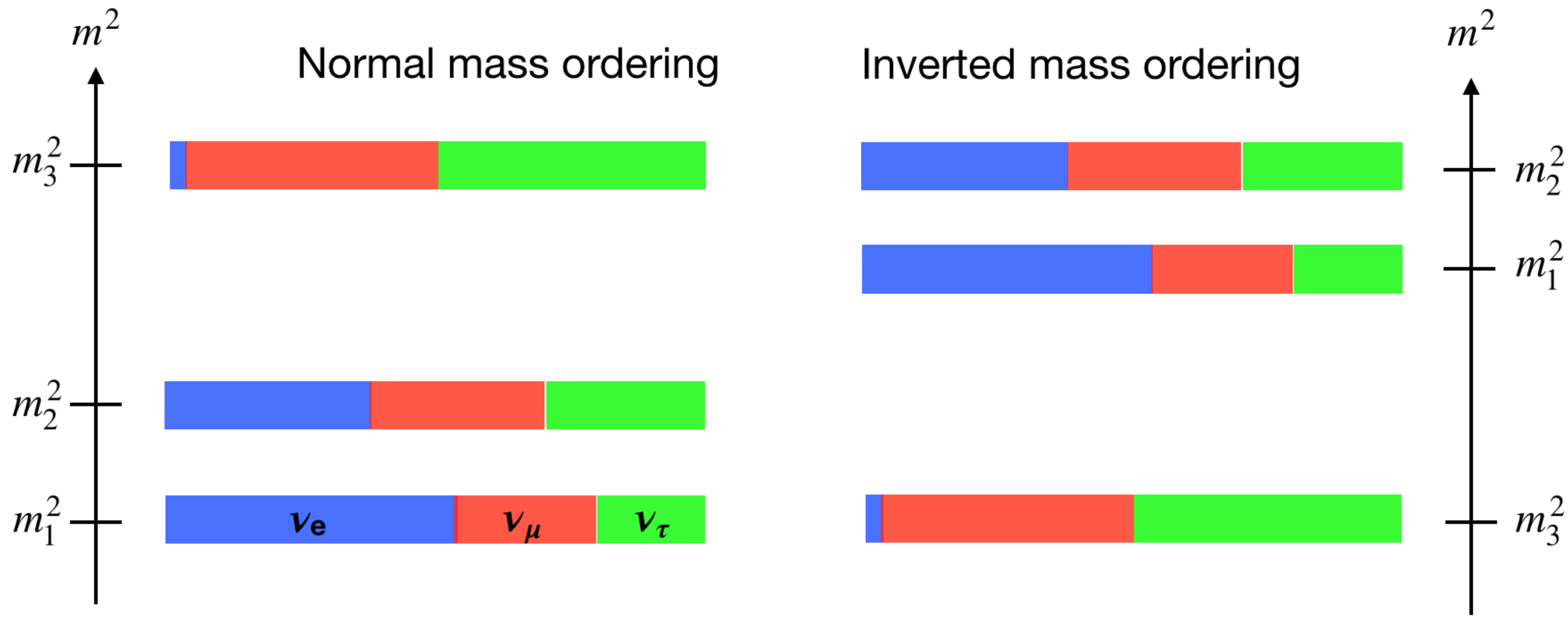
In collaboration with Peter B. Denton
arXiv: 2204.09060

Mitchell conference 2022

Neutrino mass ordering



known neutrino mass splittings:

one "large" mass splitting $|\Delta m_{32}^2| \approx 2.51 \times 10^{-3}$ eV^2

one "small" mass splitting $\Delta m_{21}^2 \approx 7.42 \times 10^{-5}$ eV^2

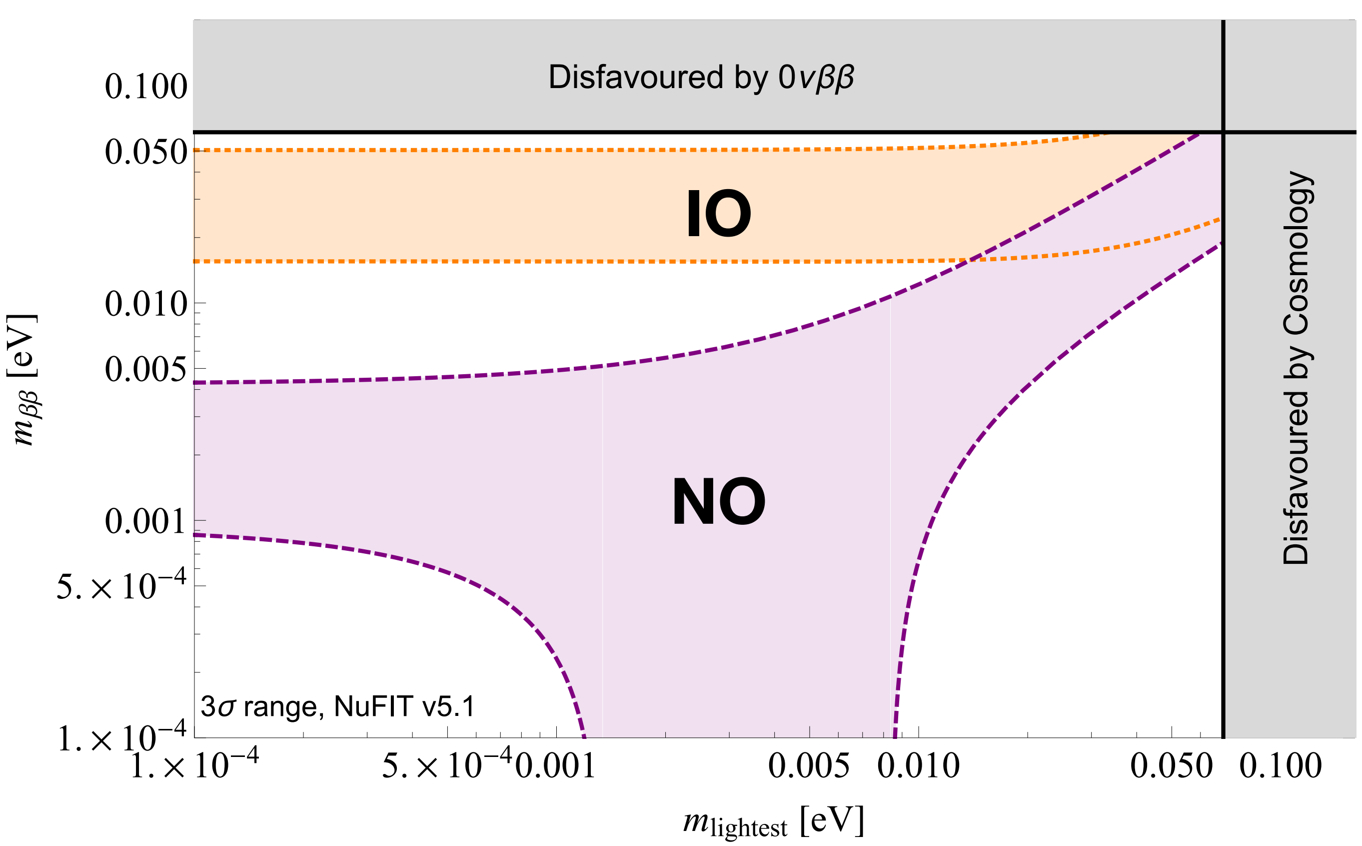
NO: $m_1 < m_2 < m_3$

IO: $m_3 < m_1 < m_2$

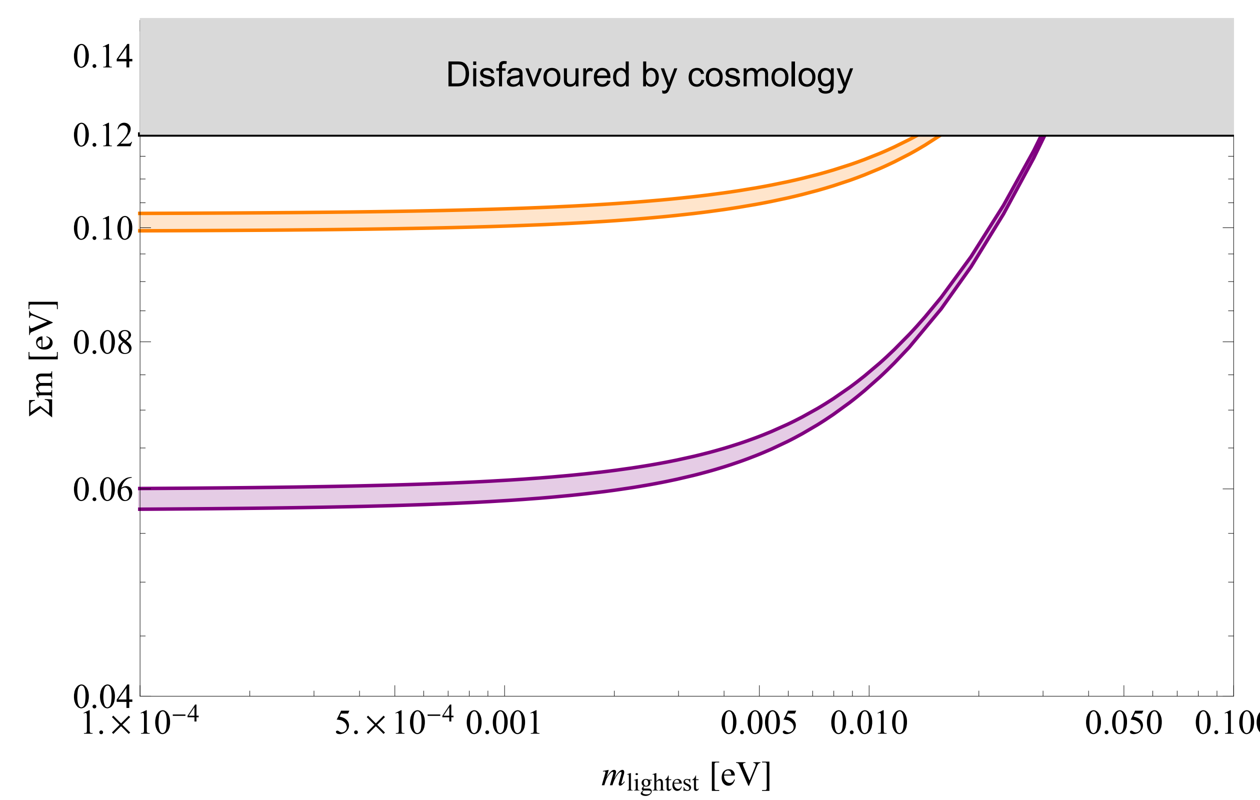
Impact of neutrino mass ordering

Neutrino mass ordering has important implications for observables

Neutrinoless double beta decay



Sum of neutrino masses, beta decay endpoint spectrum



Neutrino mass ordering determination

⇒ determination of MO possible in various experiments

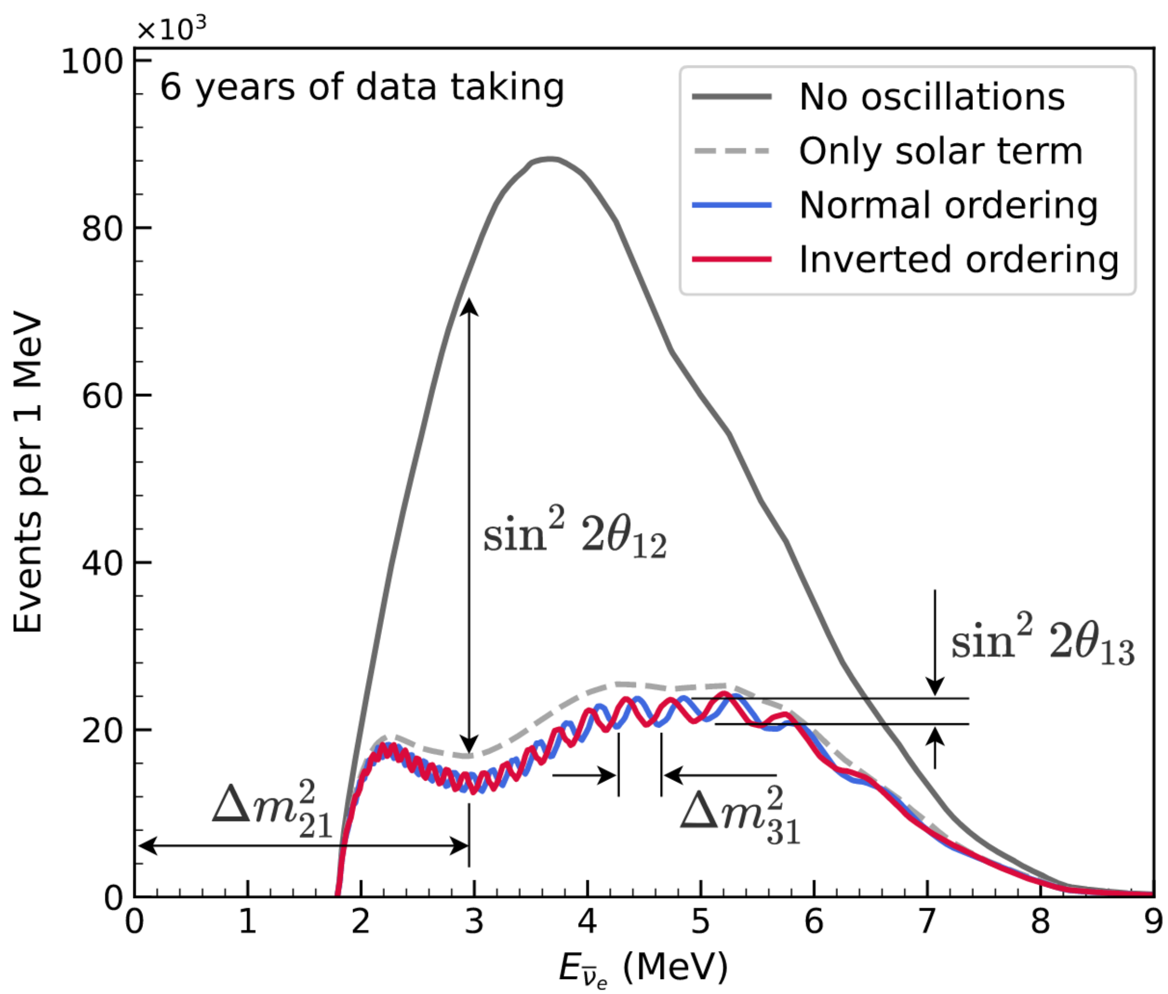
Focus on oscillation experiments here

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Neutrino mass ordering determination

In oscillation experiments

Make use of slight differences in oscillation frequency: amplitude of oscillations driven by Δm^2_{31} different than the ones driven by Δm^2_{32}



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

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

JUNO '22

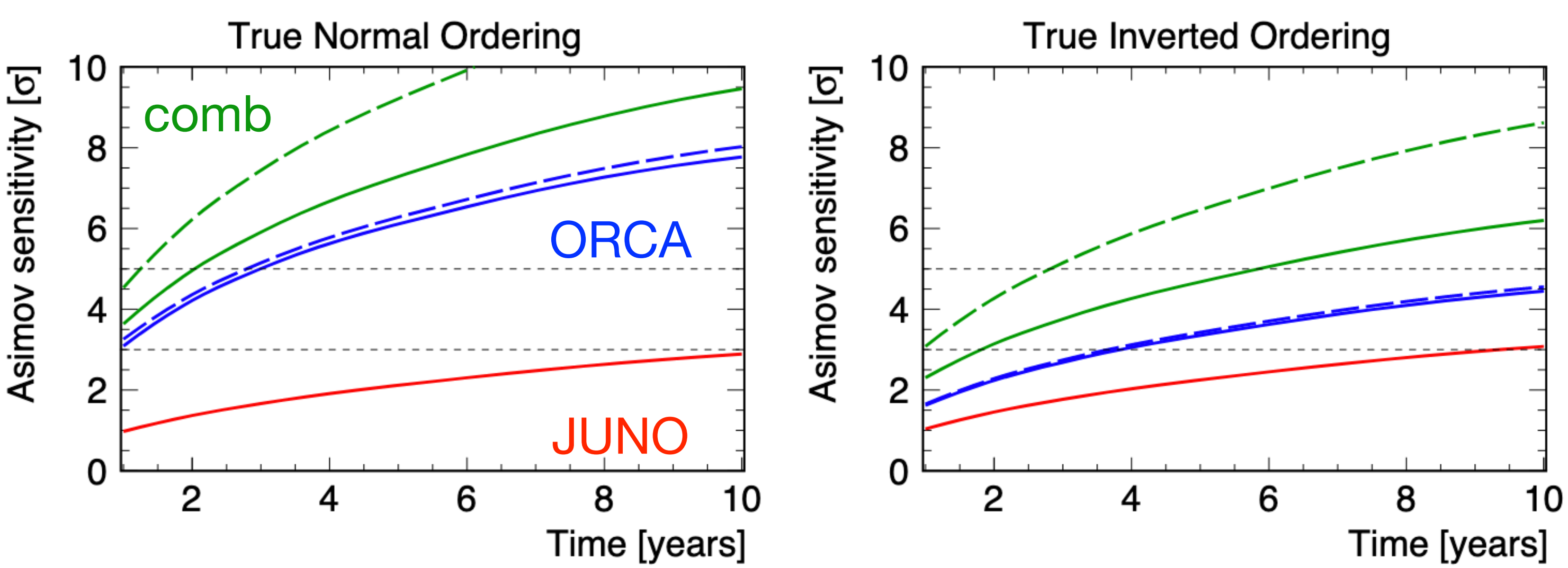
Neutrino mass ordering determination

In oscillation experiments

Use matter effects

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

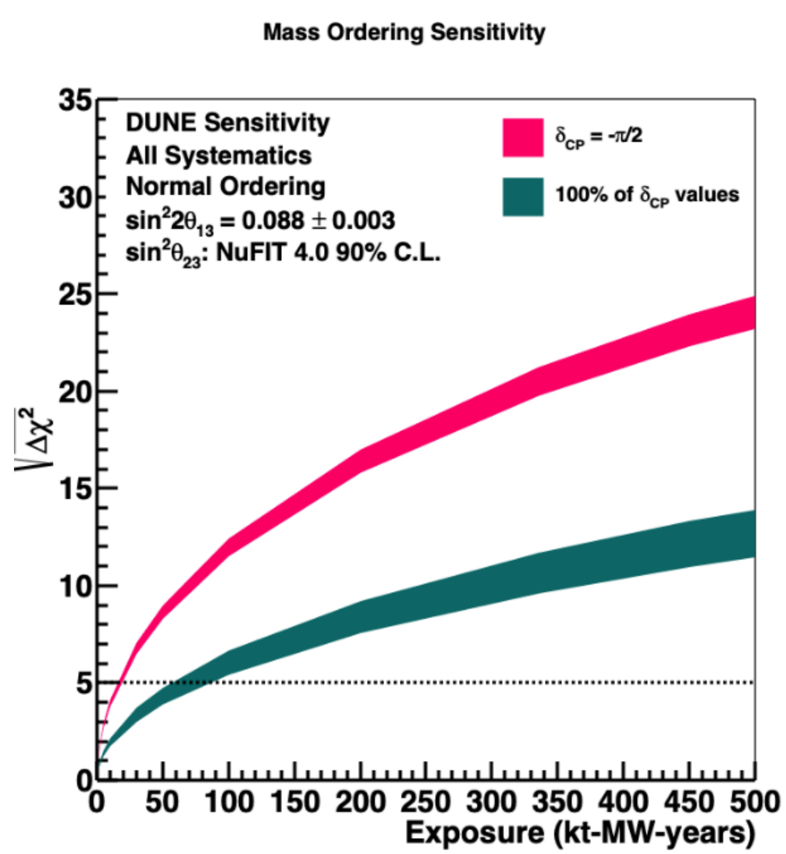


Neutrino mass ordering determination

In oscillation experiments

Use matter effects

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

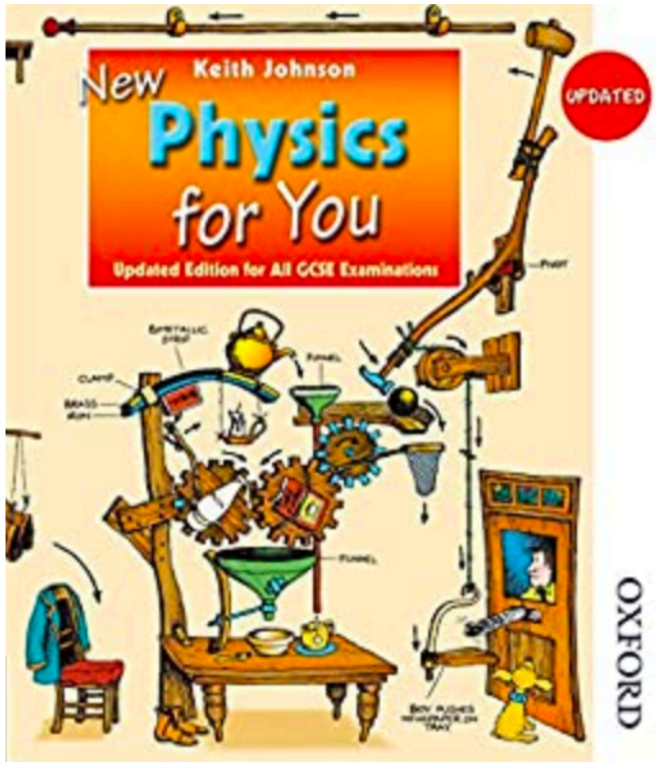


DUNE ‘20

Neutrino mass ordering determination

Ensure unambiguous interpretation of MO measurement:

What kind of new physics can impact the determination of the MO?



Neutrino mass ordering determination

Ensure unambiguous interpretation of MO measurement:

What kind of new physics can impact the determination of the MO?

Determination of MO relies on matter effects
$\Rightarrow$ What happens if neutrinos have new interactions with matter?

Neutrino non-standard interactions (NSI) make it impossible to determine MO at oscillation experiments alone!

Neutrino non-standard interactions

Hamiltonian in presence of NSI

Wolfenstein '78

$$H = \frac{1}{2E}\left[U^\dagger M^2 U + a\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau}\end{pmatrix}\right]$$

with $a = 2\sqrt{2}GFN_eE$

$$\epsilon_{\alpha\beta} = \sum_{f\in\{e,u,d\}} \frac{N_f}{N_e}\epsilon_{\alpha\beta}^{f,V}$$

$$\mathscr{L}_{\text{NSI}} = -2\sqrt{2}G_F\sum_{f,\alpha,\beta}\epsilon_{\alpha\beta}^{f,V}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu f)$$

→ new forward scattering interactions with matter

Focus on **diagonal NSI parameters**

Degeneracies

1. **Without new physics & in vacuum**: Miranda, Tortola, Valle '04

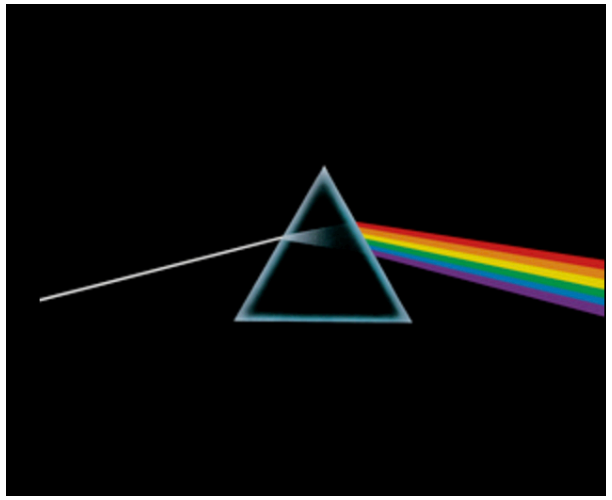
Hamiltonian invariant under

$\Delta m_{21}^2 \to -\Delta m_{21}^2, \Delta m_{31}^2 \to -\Delta m_{31}^2, \delta \to -\delta$

$H_{\text{vac}} \to -H_{\text{vac}}^*$ leaves all observables invariant

Dark side of oscillations

LMA-Dark



Degeneracies

1. Without new physics & in vacuum:

Hamiltonian invariant under

$$\Delta m^2_{21} \to -\Delta m^2_{21}, \Delta m^2_{31} \to -\Delta m^2_{31}, \delta \to -\delta$$

$H_{\mathrm{vac}} \to -H^*_{\mathrm{vac}}$ leaves all observables invariant

2. **Degeneracy broken** when considering oscillations **in matter**

Matter term does not change sign together with other parameters

$$H = \frac{1}{2E}\left[U^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U + a \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}\right]$$

Degeneracies

1. Without new physics & in vacuum:

Hamiltonian invariant under

$\Delta m^2_{21} \to -\Delta m^2_{21}, \Delta m^2_{31} \to -\Delta m^2_{31}, \delta \to -\delta$

$H_{\rm vac} \to -H^*_{\rm vac}$ leaves all observables invariant

2. Degeneracy broken when considering oscillations in matter

⇒ possibility to determine MO in vacuum

3. **Degeneracy restored** if $\epsilon_{ee} = -2$, all other NSI parameters zero

⇔ this case is equivalent to necessary sign change

$$P_{\alpha\beta}(\mathrm{NO}, L, E, \rho, \epsilon = 0) = P_{\alpha\beta}(\mathrm{IO}, L, E, \rho, \epsilon = -2)$$

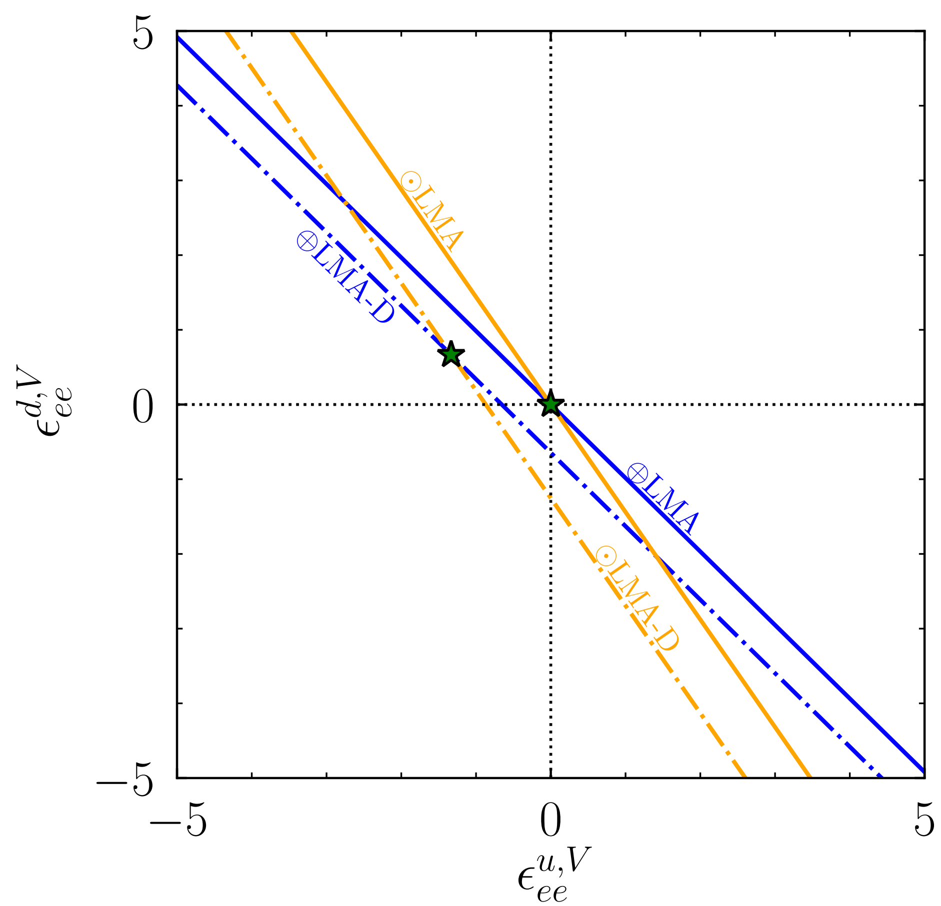
$$P_{\alpha\beta}(\mathrm{IO}, L, E, \rho, \epsilon = 0) = P_{\alpha\beta}(\mathrm{NO}, L, E, \rho, \epsilon = -2)$$

In all oscillation channels!

Degeneracies

3. Degeneracy restored if $\epsilon_{ee} = -2$, all other NSI parameters zero
⇔ this case is equivalent to necessary sign change

4. **Precise measurement** of ϵ_{ee} in **different materials** can lift degeneracy unless new mediator is coupled to electrons only or specific combination to up and down quarks



→ in this case no combination of oscillation experiments can break degeneracy

Degeneracies

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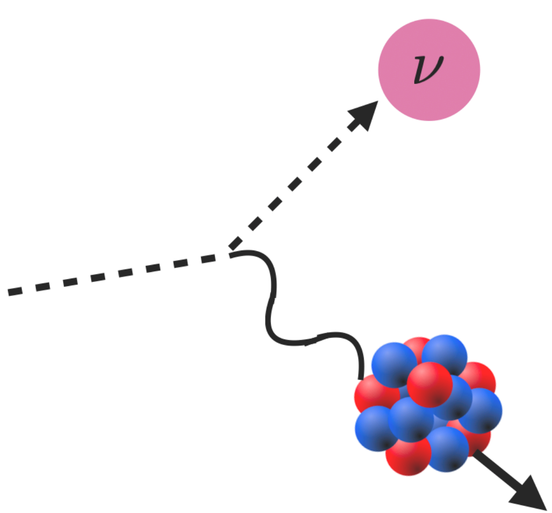
4. Precise measurement of ϵ_{ee} in different materials can lift degeneracy unless new mediator is coupled to electrons only or specific combination to up and down quarks

5. **Scattering experiments** don't suffer from LMA-D degeneracy
⇒ provide probes of LMA-D parameter space



Degeneracies

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5. Scattering experiments don't suffer from LMA-D degeneracy
⇒ provide probes of LMA-D parameter space

6. NSI in oscillations not sensitive to mediator masses
⇔ NSI in scattering depends on **mediator mass**

→ lower bound on mediator mass which can be probed

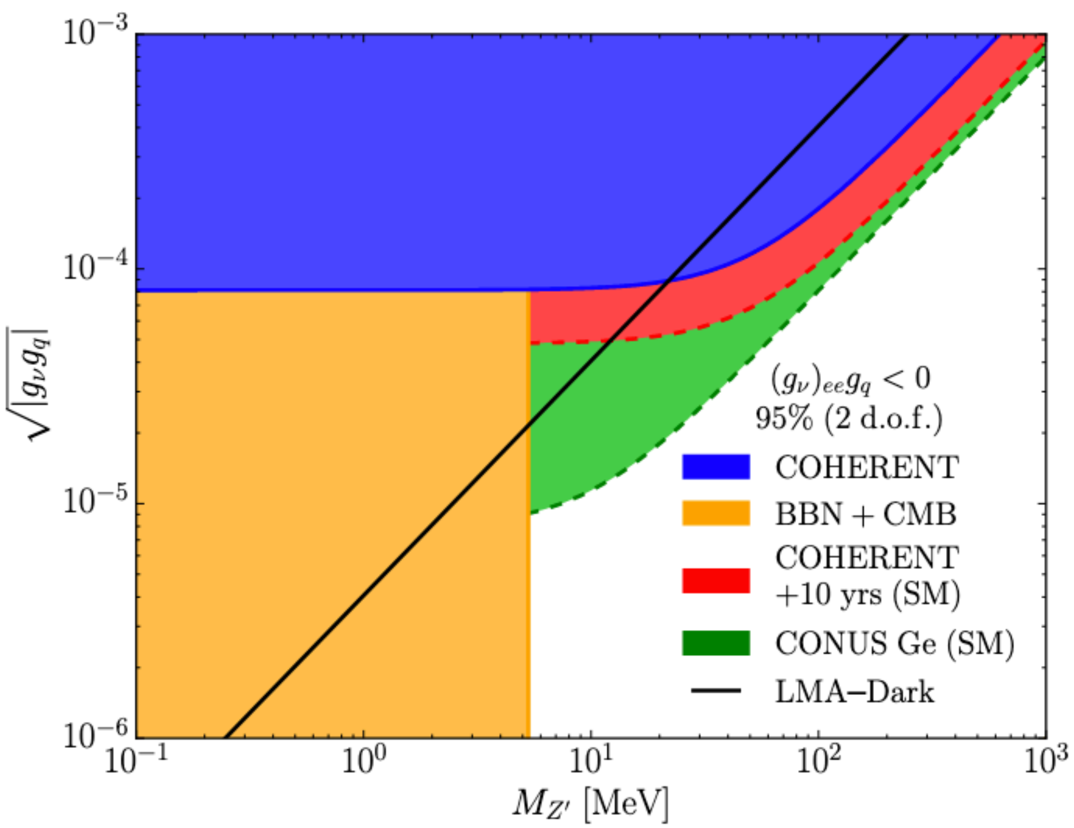
Neutrino scattering experiment with lowest momentum transfer: CEvNS

Degeneracies

5. Scattering experiments don't suffer from LMA-D degeneracy
⇒ provide probes of LMA-D parameter space

6. NSI in oscillations not sensitive to mediator masses
⇔ NSI constraints from scattering experiments depend on mediator mass

From COHERENT: LMA-D ruled out for mediator mass >50 MeV
To access lighter mediators need process with lower thresholds/neutrino energies: CEvNS with reactor neutrinos!



Denton, Farzan, Shoemaker '18

Degeneracies

6. NSI in oscillations not sensitive to mediator masses
⇔ NSI in scattering depends on mediator mass

From COHERENT: LMA-D ruled out for mediator mass >50 MeV
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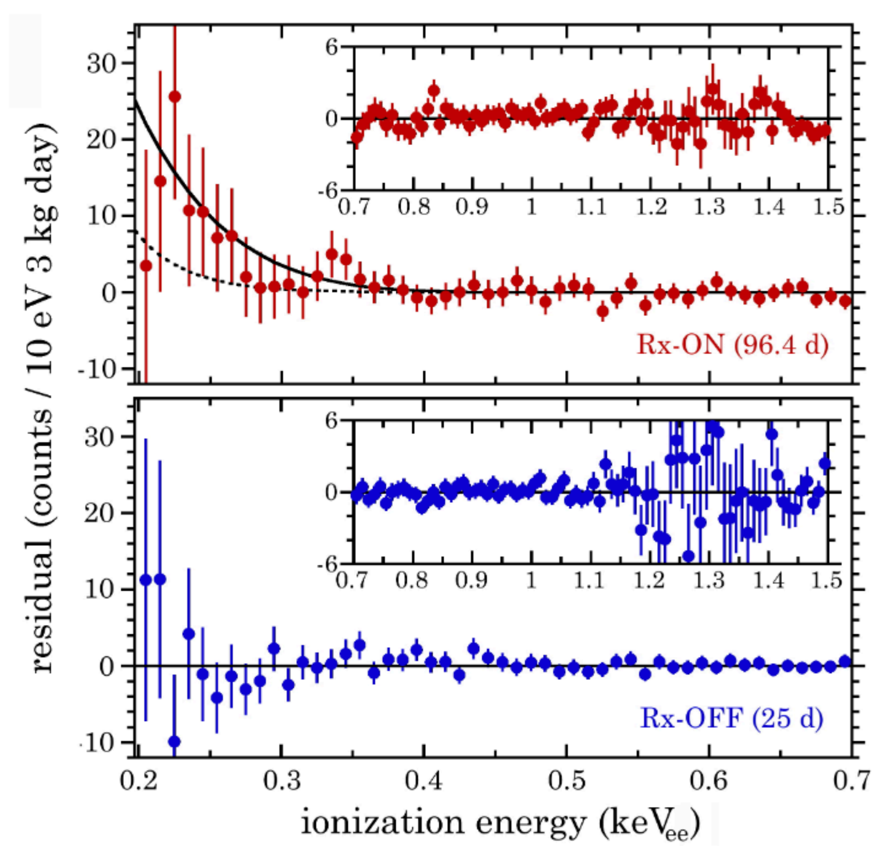
First evidence for CEvNS at reactor from Dresden-II experiment

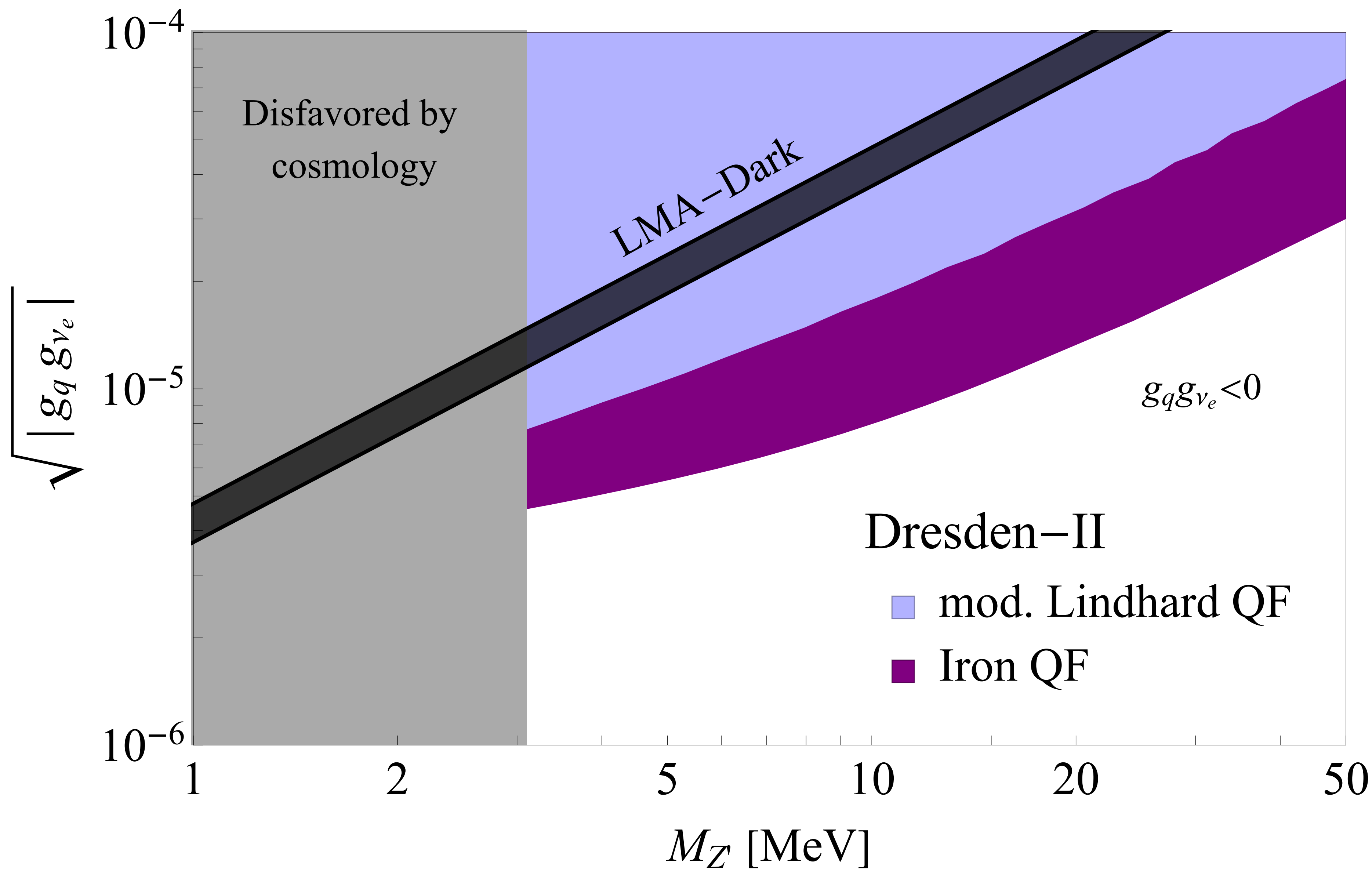


Colaresi et al '22

Constraints on LMA-Dark

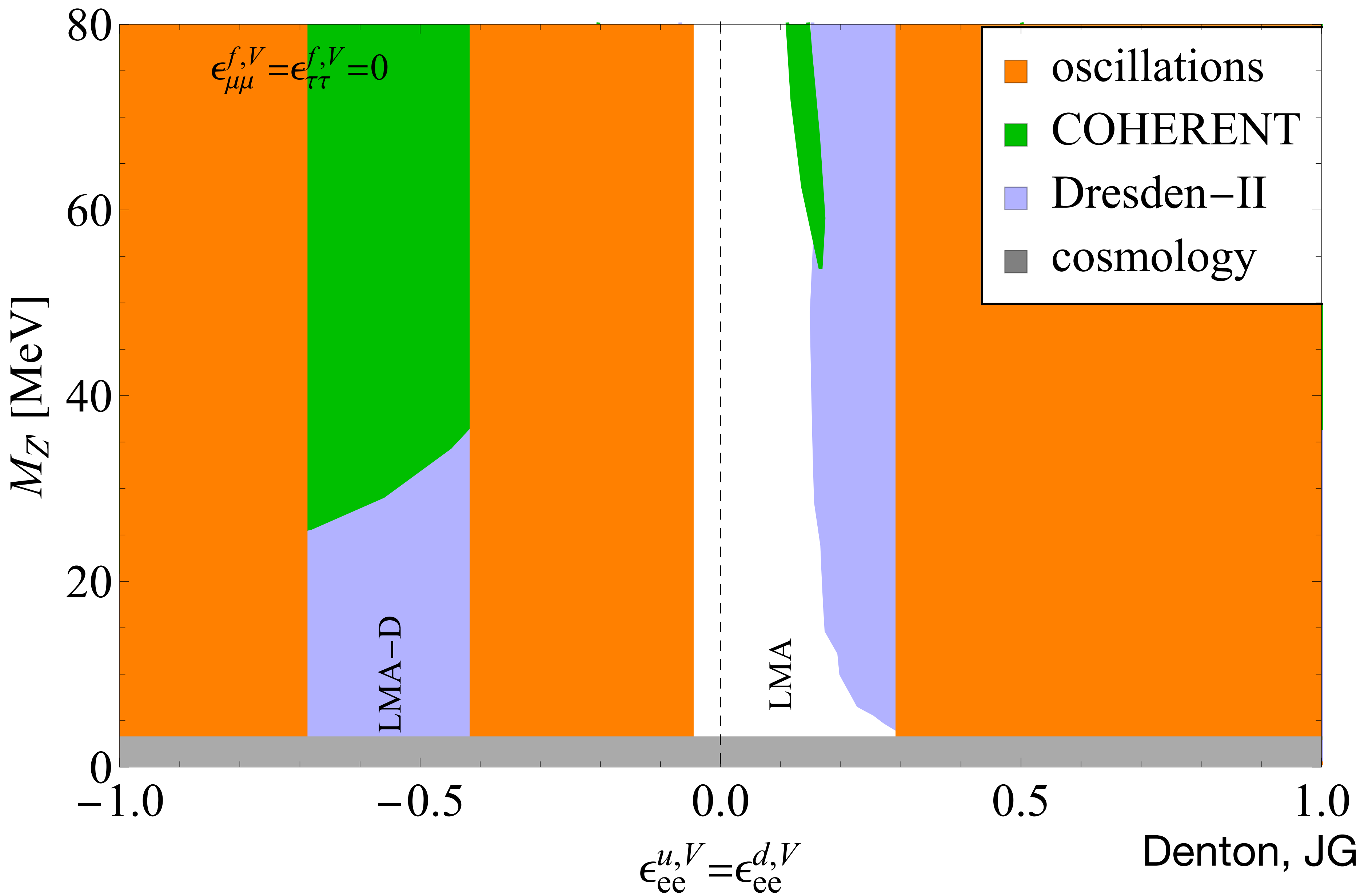
In collaboration with Peter B. Denton
arXiv: 2204.09060

Reinterpret results from Aristibal Sierra, De Romeri, Papoulias '22 to obtain constraints on LMA-D



Constraints on LMA-Dark

Constraints on NSI parameters in electron sector

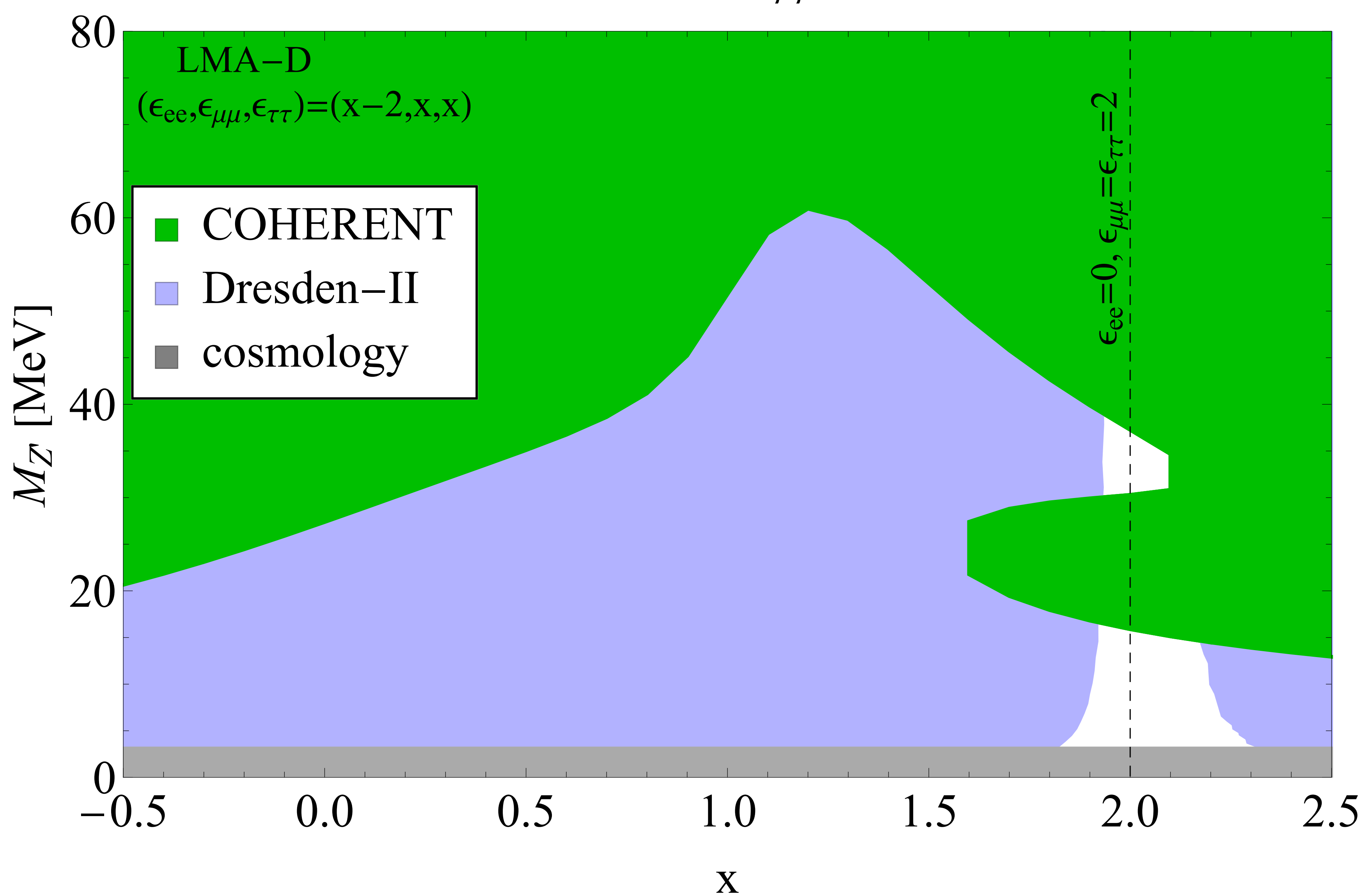


Denton, JG, 2204.09060

Constraints on LMA-Dark

Diagonal degeneracy of Hamiltonian:

$$(\epsilon_{ee},\ \epsilon_{\mu\mu},\ \epsilon_{\tau\tau}) = (x-2,\ x,\ x)$$

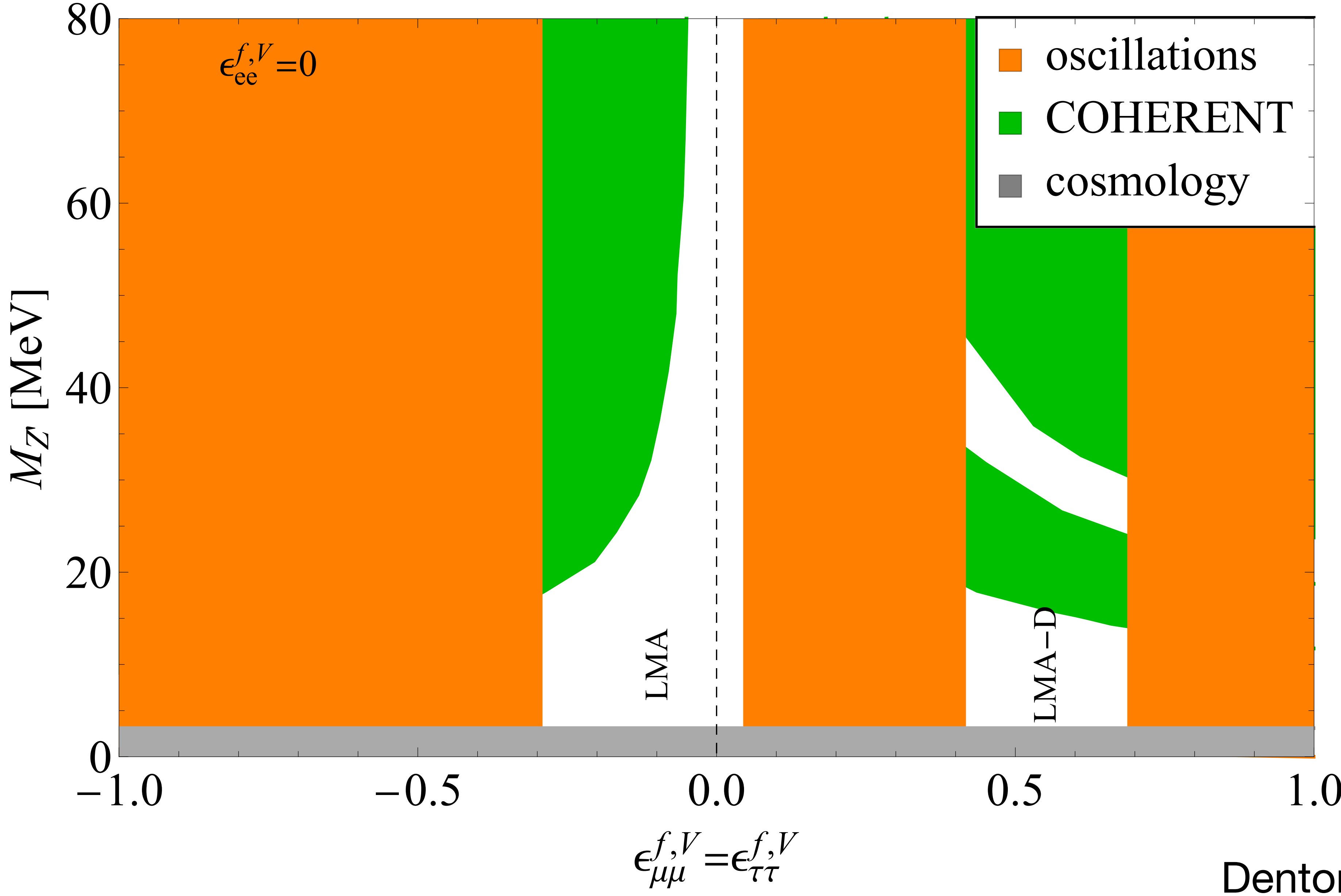


x=0: LMA-D only in electron sector
x=2: LMA-D only in muon and tau sector

Denton, JG, 2204.09060

Constraints on LMA-Dark

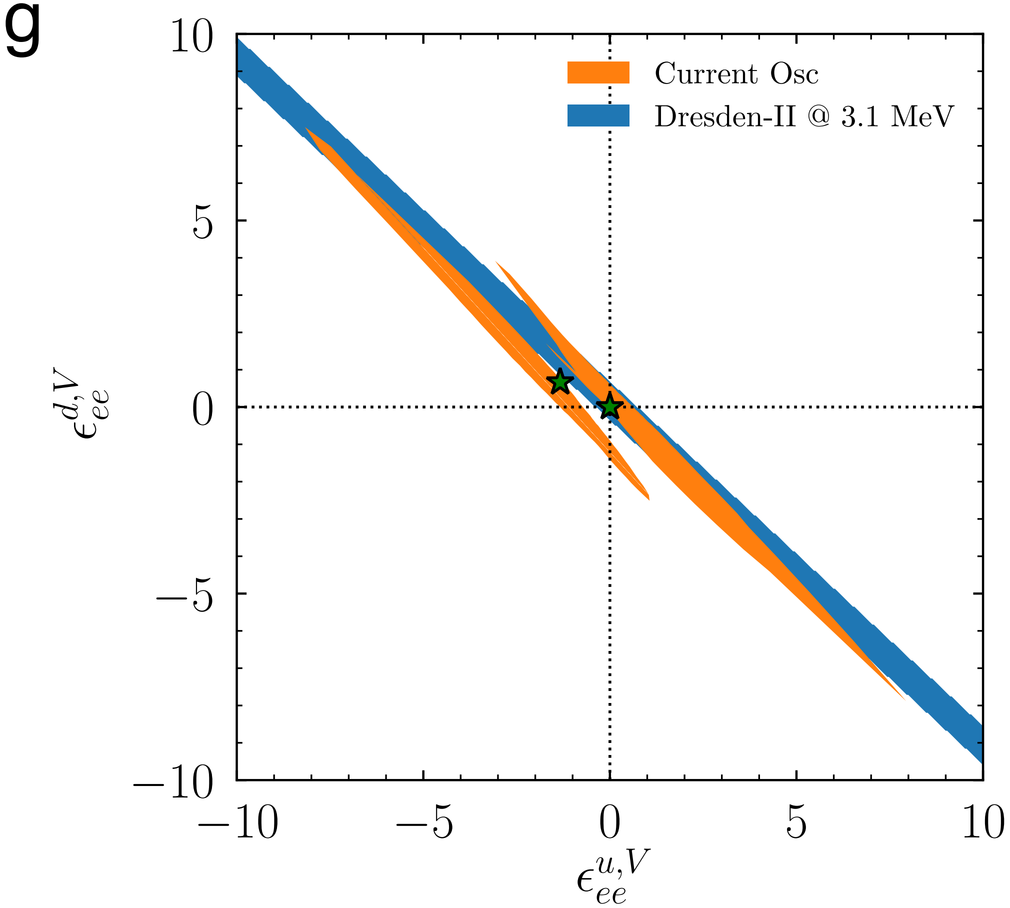
Constraints on NSI parameters in muon and tau sector



Denton, JG, 2204.09060

Surviving parameter space of LMA-Dark

- new physics is in the ν_e sector via ϵ_{ee} with very specific couplings to up and down quarks: mediator must be lighter than ~ 50 MeV, COHERENT has already ruled out heavier mediator masses for all combinations of up and down quark coupling



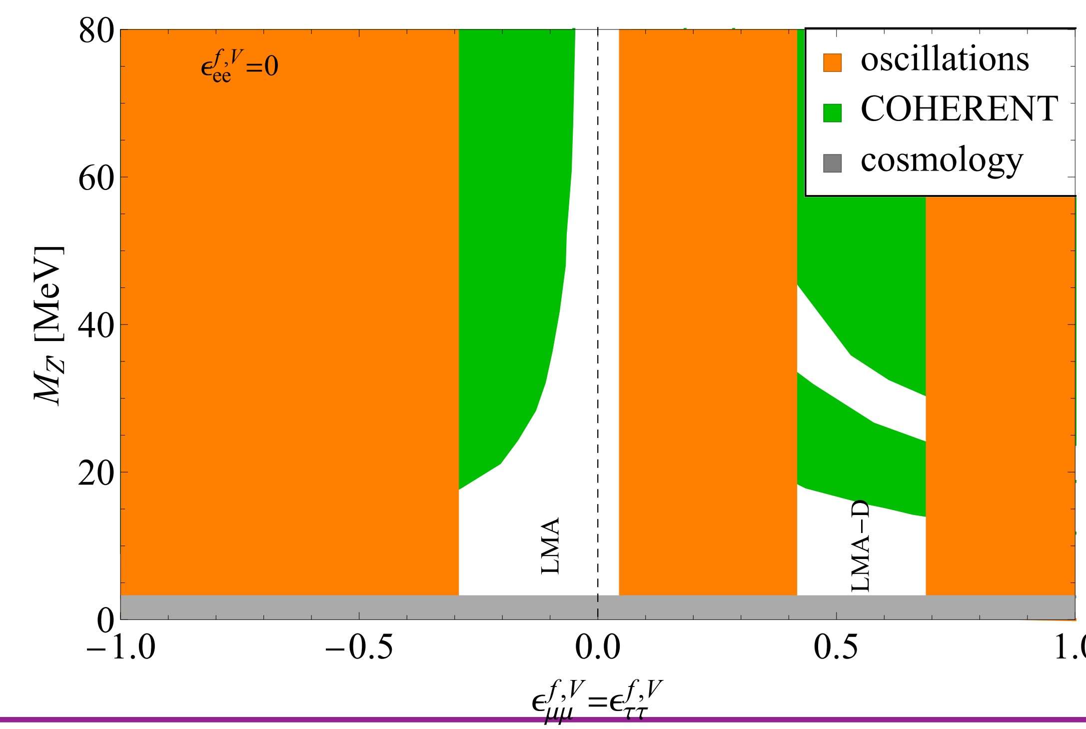
$\epsilon_{ee}^{u,V} = -4/3,\ \epsilon_{ee}^{d,V} = 2/3$

Denton, JG, 2204.09060

Surviving parameter space of LMA-Dark

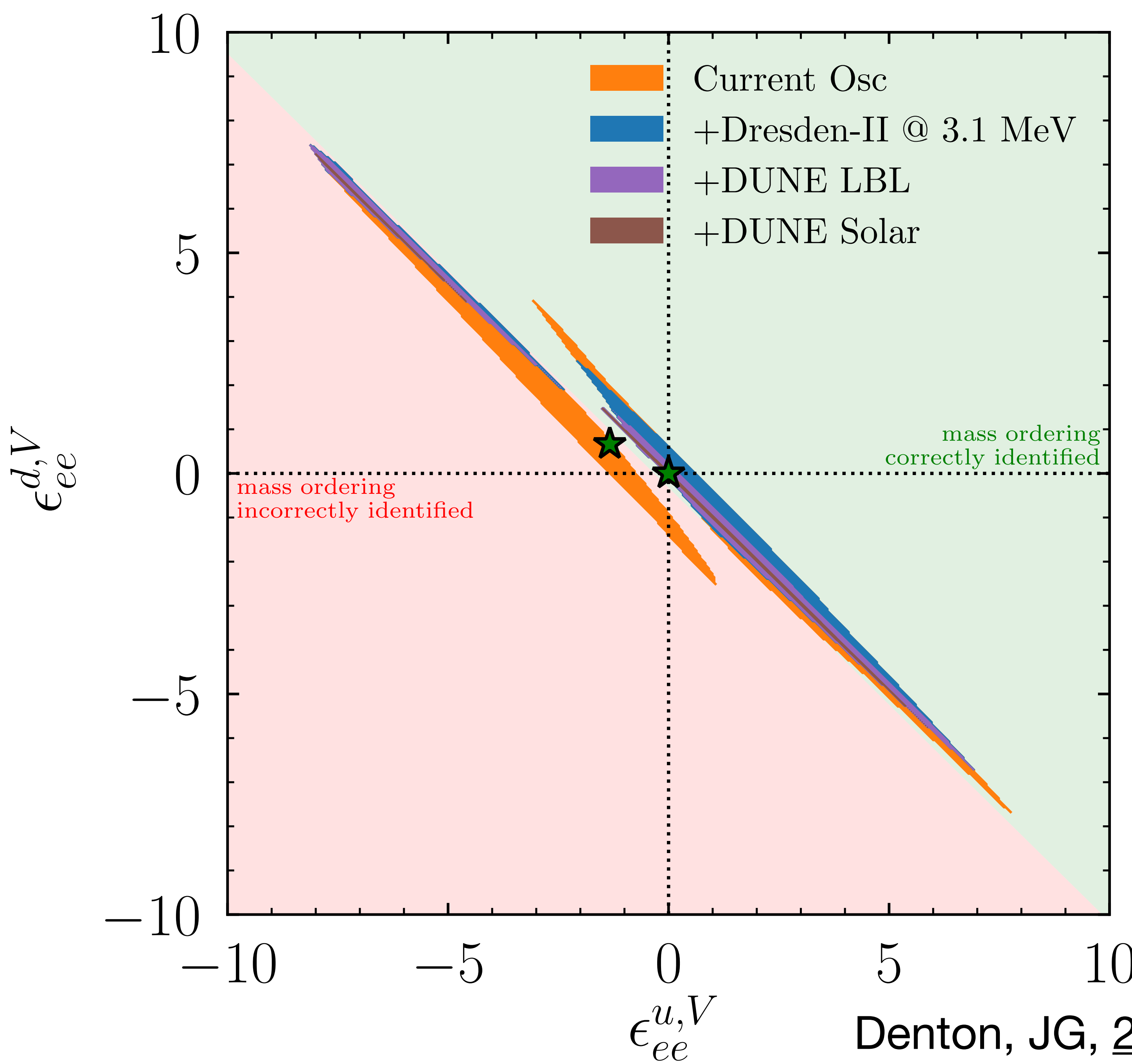
- new physics is in the ν_e sector via ϵ_{ee} with very specific couplings to up and down quarks: mediator must be lighter than ~ 50 MeV, COHERENT has already ruled out heavier mediator masses for all combinations of up and down quark couplings

- new physics is in the ν_μ, ν_τ sectors with similar or equal couplings: mediator needs to be lighter than ~ 40 MeV (constraints on some combinations of up and down quark combinations from NuTeV data for mediator masses above 10 GeV)



Denton, JG, 2204.09060

Future of LMA-Dark



Denton, JG, 2204.09060

- Improved constraint on ϵ_{ee} from DUNE
- CEvNS experiments with different materials, slope depends on $(2N+Z)/(2Z+N)$
- CEvNS experiment with low threshold to rule out LMA-D in $\epsilon_{\mu\mu}$

⇒ robust determination of MO possible in future!

Thank you for your attention!