

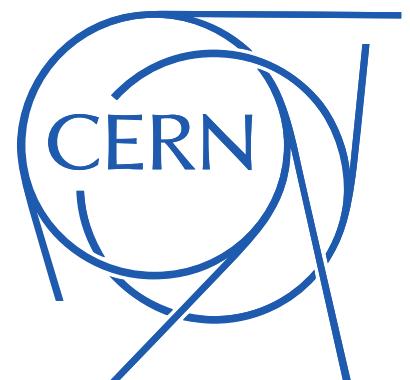
# Neutrino mass ordering & Reactor CEvNS

Julia Gehrlein

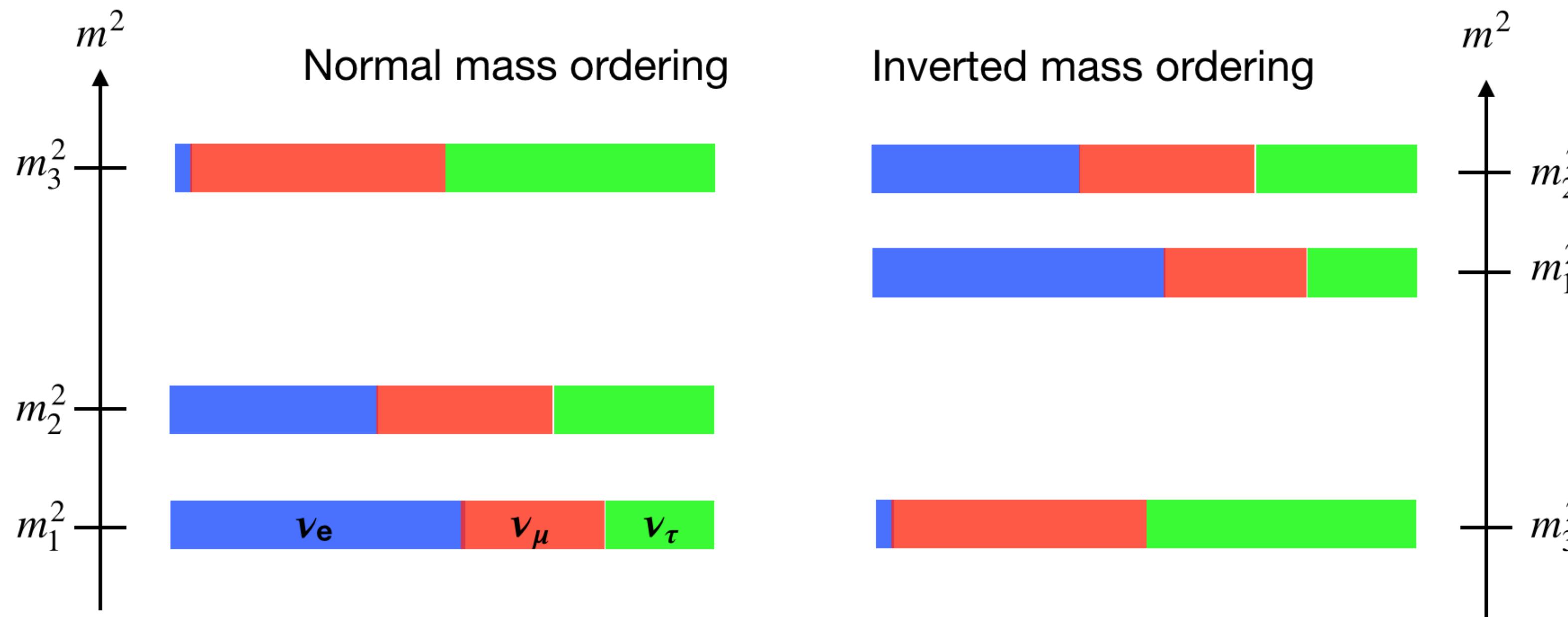
CERN TH Department

Magnificent CEvNS workshop 2023

23 March 2023



# Neutrino mass ordering



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

mass ordering **unknown**

NO:  $m_1 < m_2 < m_3$

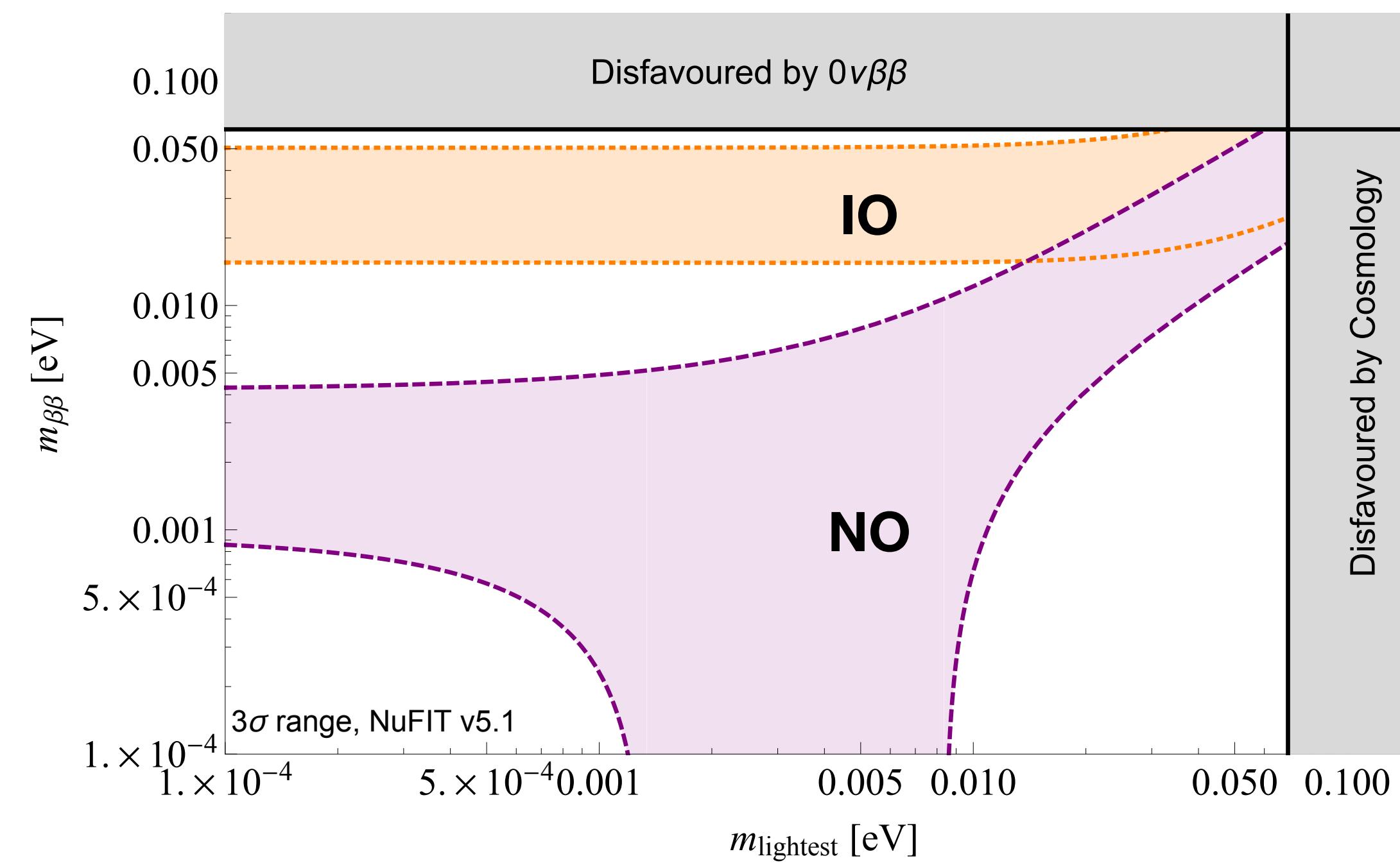
IO:  $m_3 < m_1 < m_2$

# Neutrino mass ordering

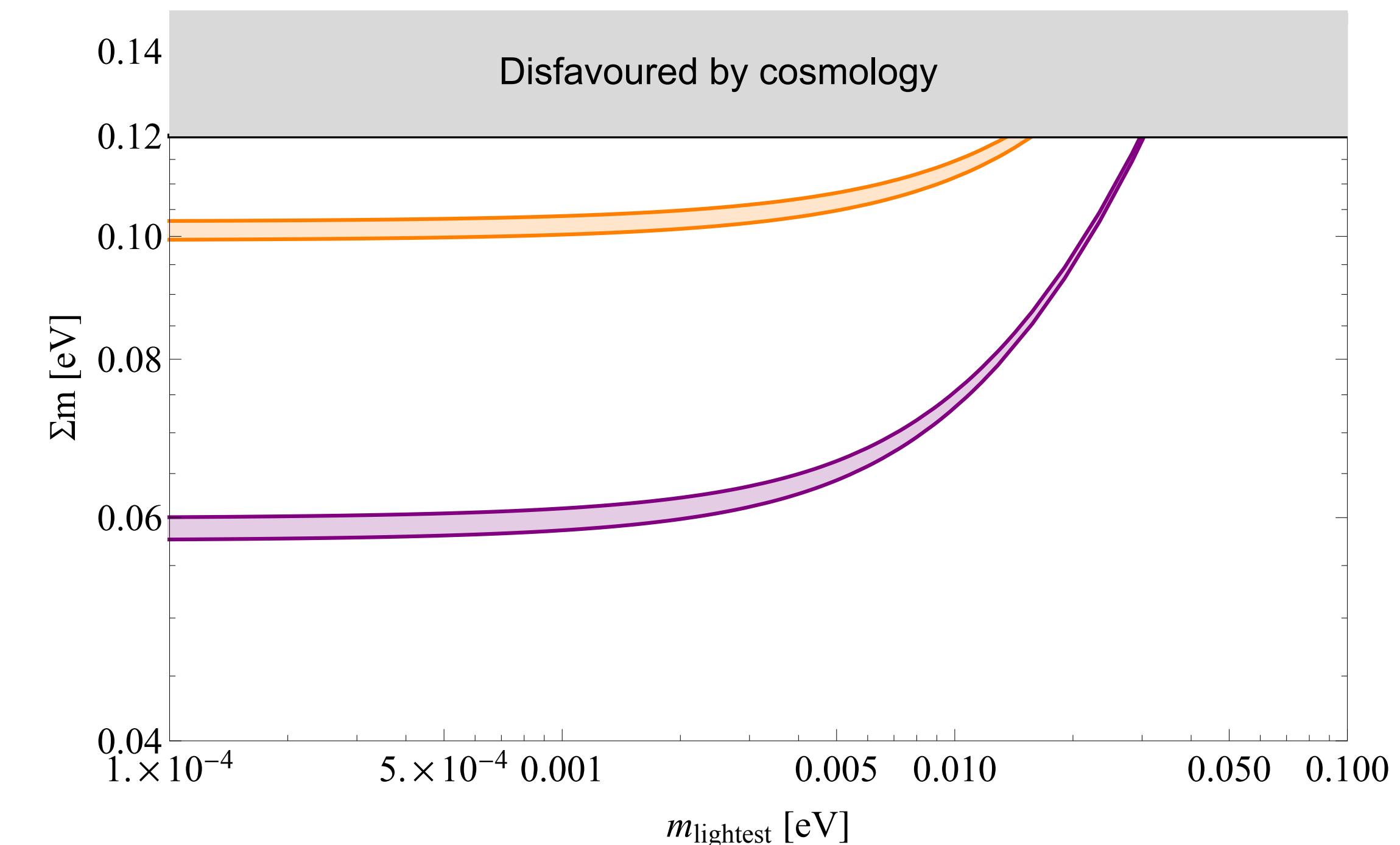
Neutrino mass ordering has **important implications** for observables

Are neutrinos normal?  
Which neutrino mass model is correct?

Neutrinoless double beta decay



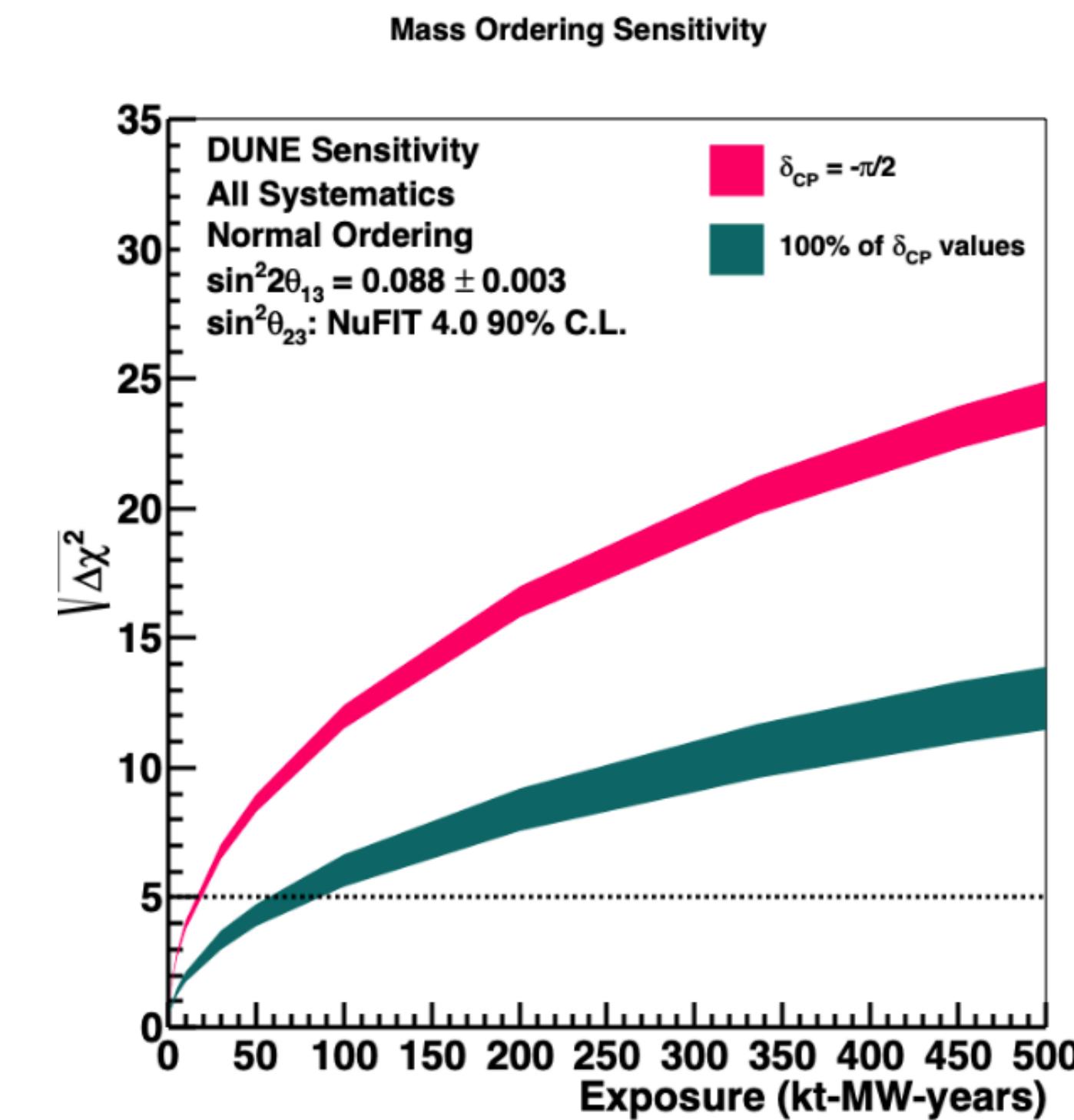
Sum of neutrino masses,  
beta decay endpoint spectrum



# How to determine MO?

Major goal of upcoming LBL experiments like DUNE, JUNO,  
HK

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



DUNE '20

# How to determine MO?

Major goal of upcoming LBL experiments like DUNE, JUNO,  
HK

Want **unambiguous** measurement of MO

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

# How to determine MO?

Major goal of upcoming LBL experiments like DUNE, JUNO,  
HK

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

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

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

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

# Neutrino non-standard interactions

NSI: New forward scattering with matter  
→ independent of mass of new mediator!  
Affect neutrino oscillations as a **new matter effect**

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

Matter potential  $a \propto G_F \rho E$

# Neutrino non-standard interactions

Affect neutrino oscillations as a new matter effect

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

- Parameters related to parameters in Lagrangian as  $\epsilon_{\alpha\beta} = \sum_f \epsilon_{\alpha\beta}^{f,V} \langle N_f(x)/N_e(x) \rangle$
- Focus on **diagonal NSI parameters** → affect **mass splittings**

# LMA-D degeneracy

- LMA-D degeneracy: Neutrino oscillations exhibit an exact degeneracy in the presence of NSI which makes it impossible to determine the neutrino mass ordering

If  $\epsilon_{ee} = -2$ , all other NSI parameters zero

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

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

In all oscillation channels

⇒ use neutrino scattering data to probe parameter space

# LMA-D degeneracy

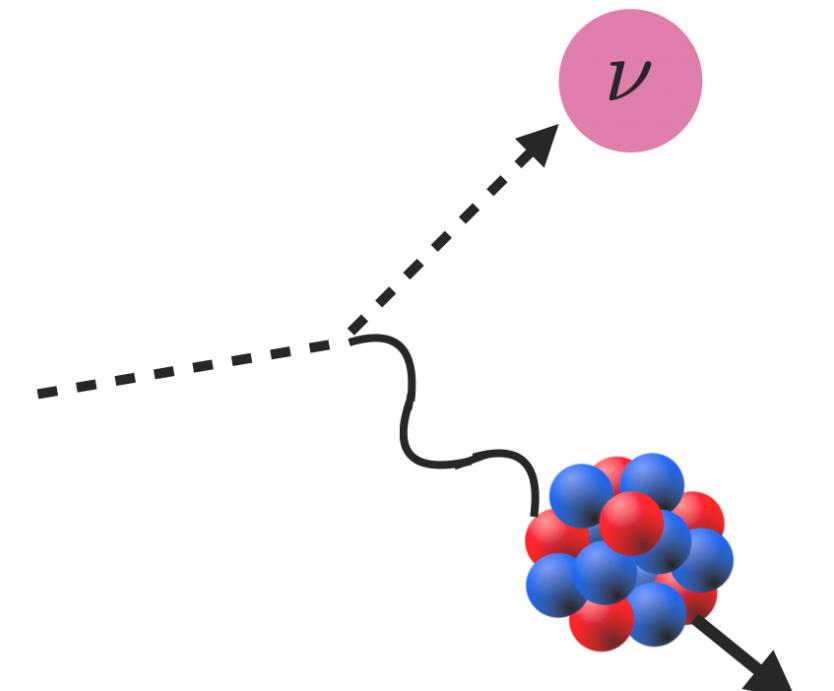
neutrino scattering data to probe LMA-D parameter space

NSI in oscillations not sensitive to mediator masses  $\Leftrightarrow$  NSI in scattering

depends on mediator mass

- heavy mediator regime ( $M_{Z'}^2 > q^2$ ) :  $\epsilon \propto g_x^2/M_{Z'}^2$
- light mediator regime  $\epsilon \propto g_X^2/(q^2 + M_{Z'}^2)$

→ lower bound on mediator mass which can be probed



# LMA-D degeneracy

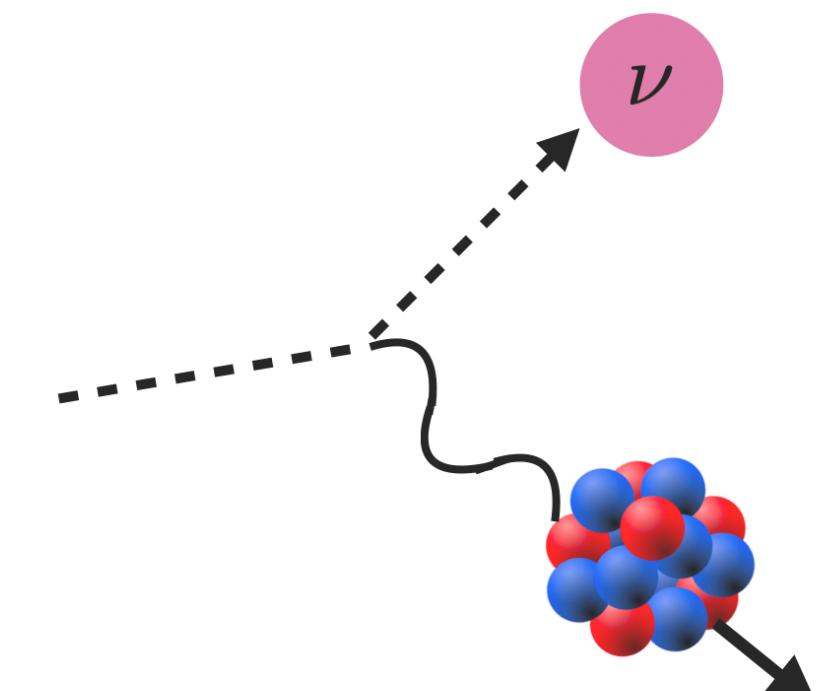
neutrino scattering data to probe LMA-D parameter space  
NSI in scattering depends on mediator mass  
→ lower bound on mediator mass which can be probed

NuTeV and CHARM rule out LMA-D for  $M_{Z'} \gtrsim 10$  GeV

[Coloma et al [1701.04828](#)]

Need process with lower momentum transfer  
to probe lighter mediators!

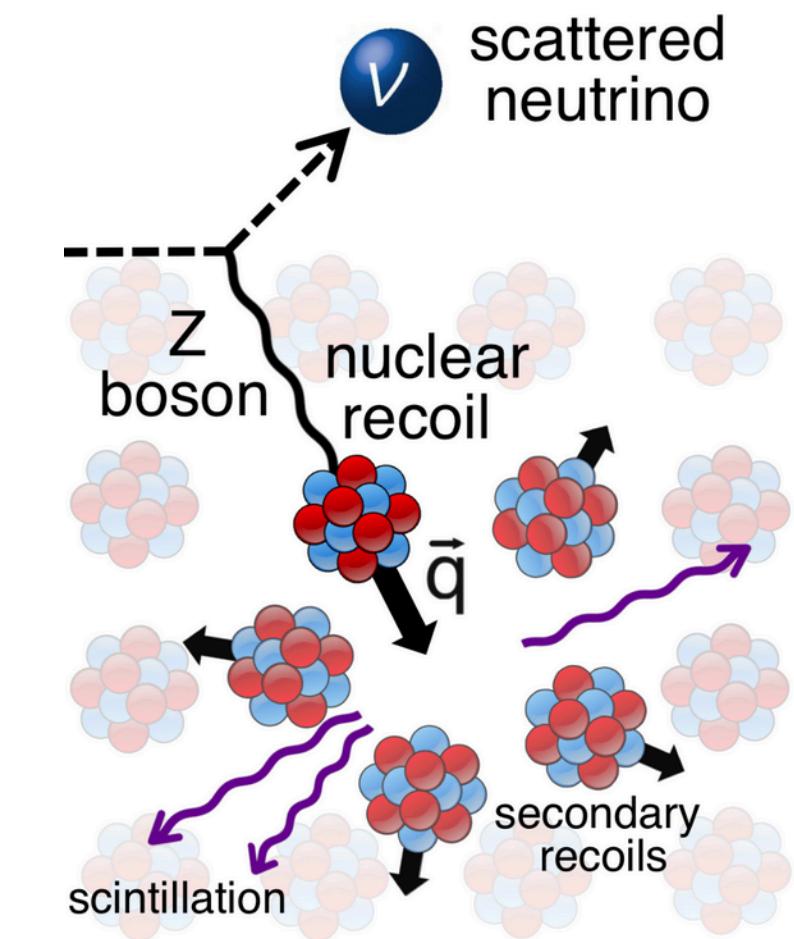
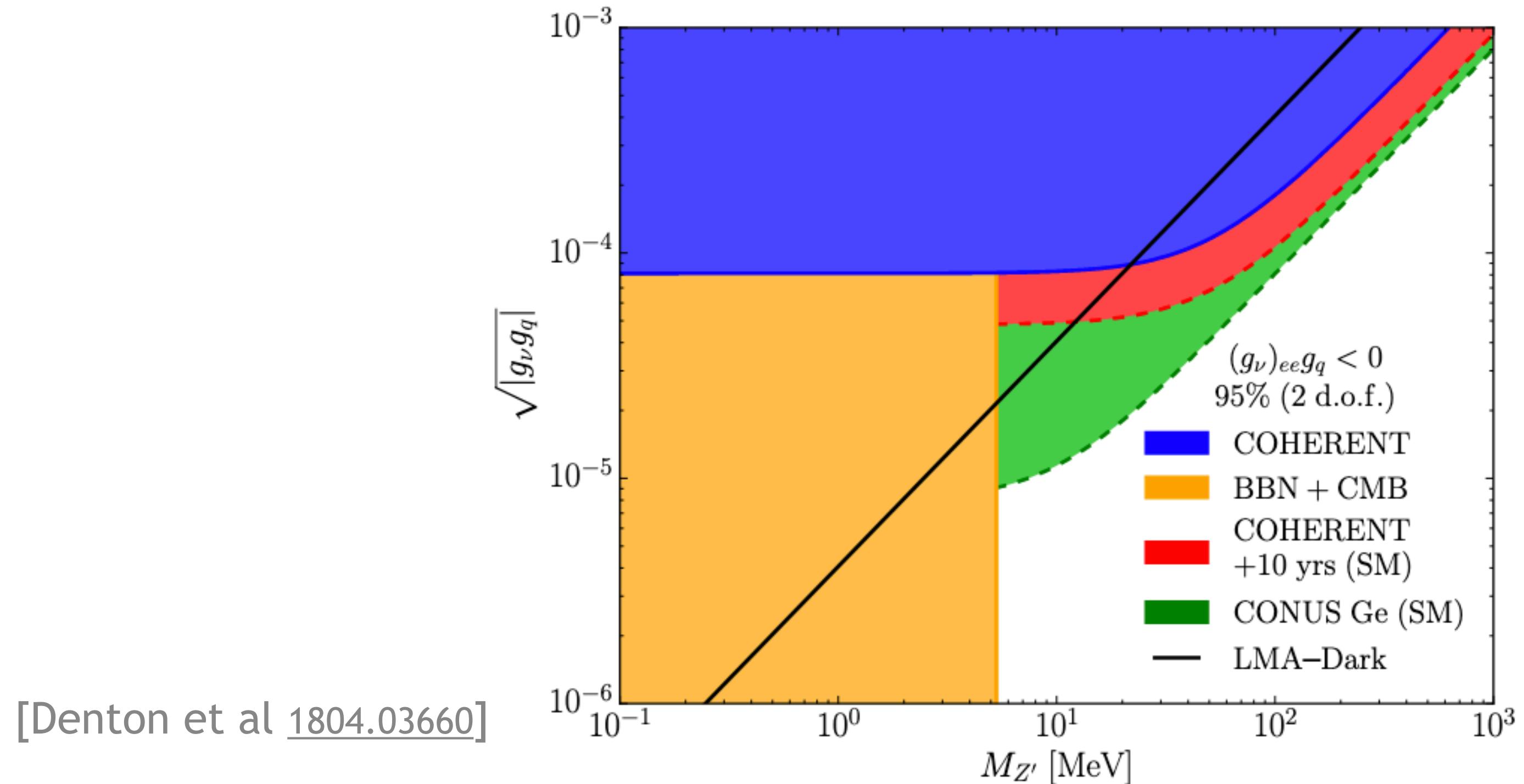
Unique ability of CEvNS experiments to probe light mediators



# LMA-D degeneracy

Scattering with low momentum transfer:  
CEvNS

COHERENT data  
rules out LMA-D for  $M_{Z'} > 50$  MeV



Need experiment with  
lower neutrino energy  
and low threshold to probe  
lighter mediators!

# LMA-D degeneracy

Use reactor neutrinos for CEvNS!

→ Use data from Dresden-II experiment  
to constrain LMA-D

[Collar et al [2202.09672](#)]

New reactor data improves robustness of neutrino mass ordering determination

Peter B. Denton\* and Julia Gehrlein†  
*High Energy Theory Group, Physics Department,  
Brookhaven National Laboratory, Upton, NY 11973, USA*  
(Dated: July 22, 2022)

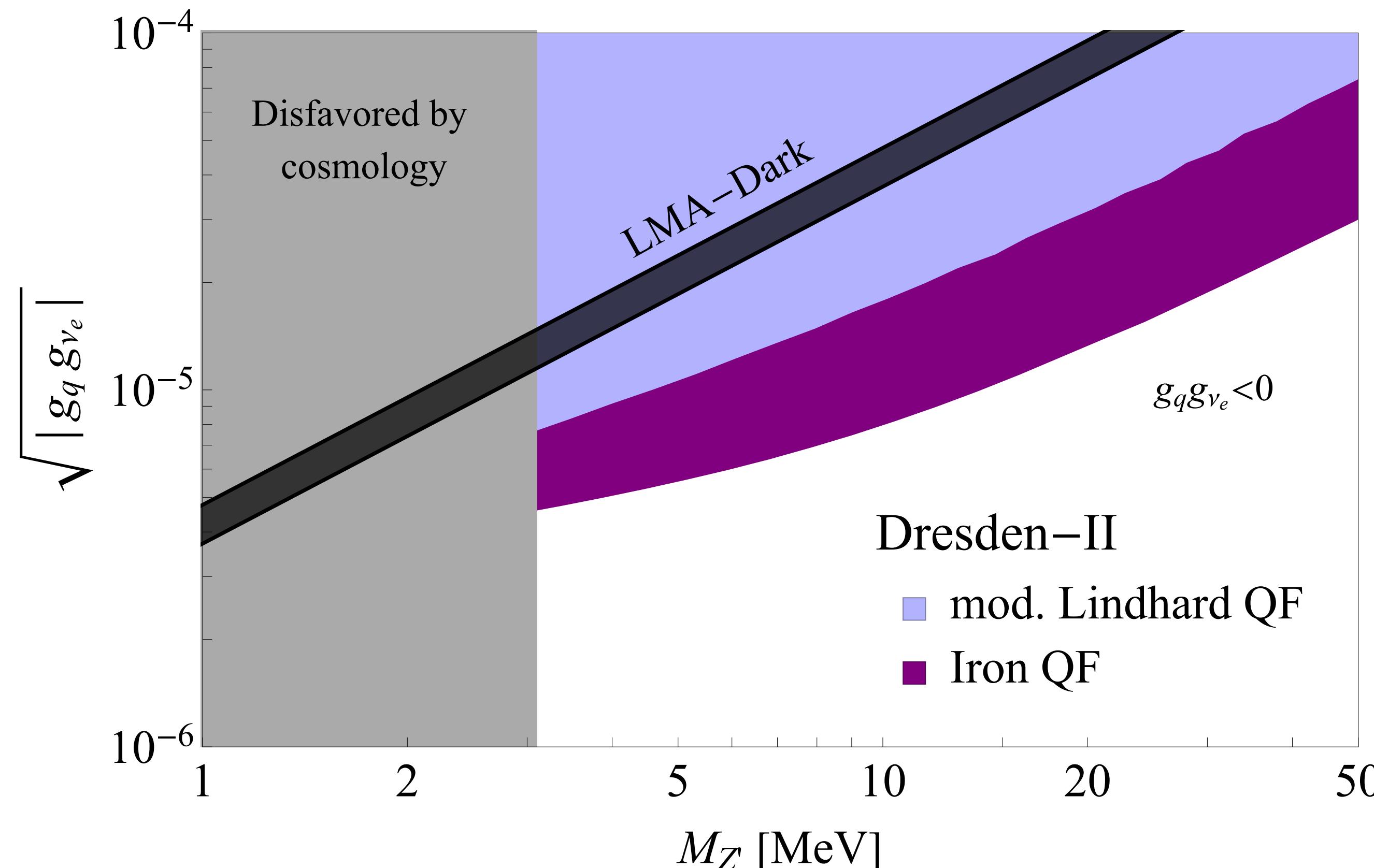
Phys. Rev. D 106 (2022) no.1, 015022  
arXiv: [2204.09060](#) [hep-ph]

# LMA-D degeneracy

Dresden-II data rules out remaining parameter space of LMA-D!

[Denton, JG [2204.09060](#)]

→ Degeneracy broken if NSI in electron sector!

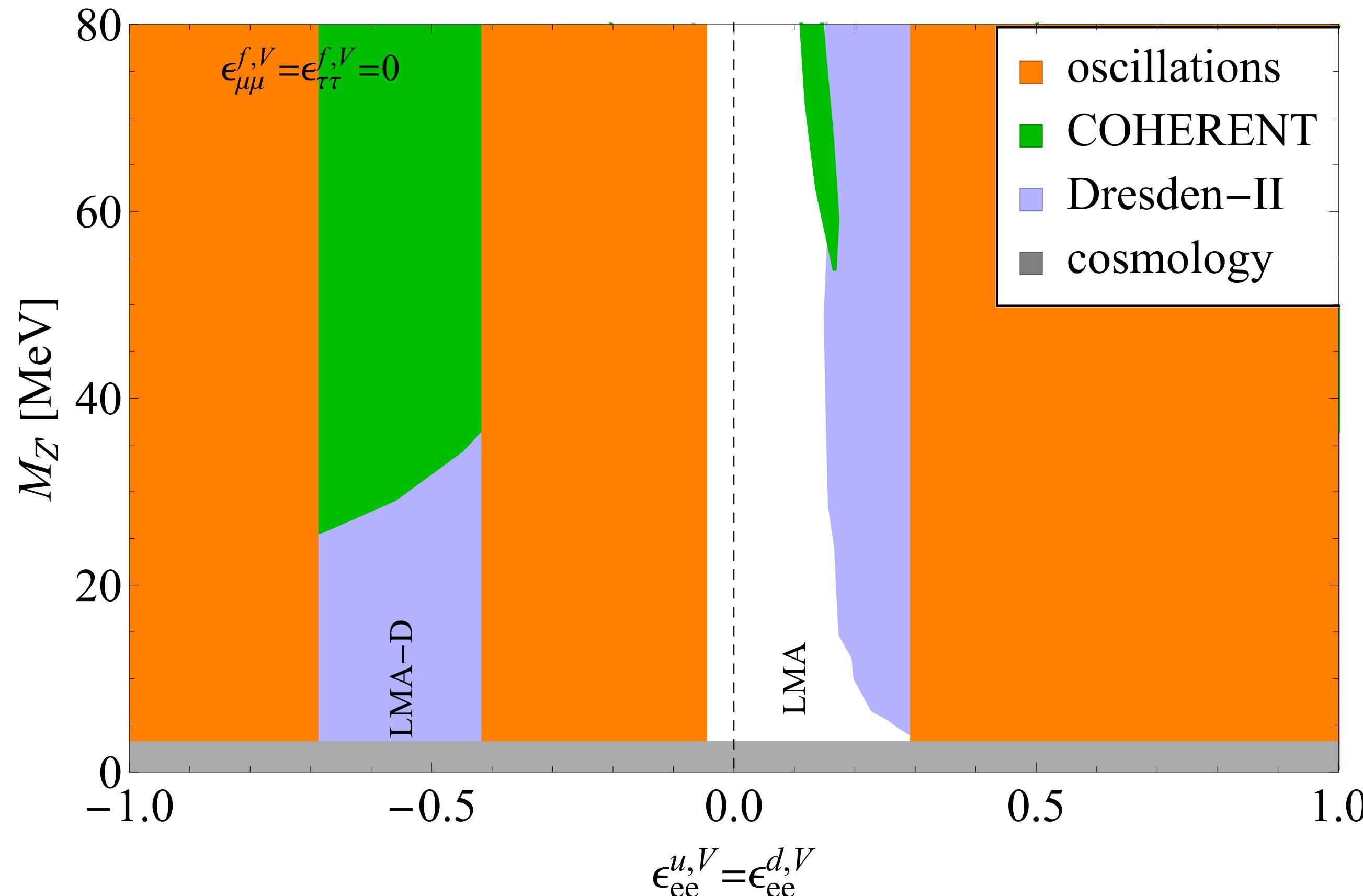


# LMA-D degeneracy

Dresden-II data rules out remaining parameter space of LMA-D!

[Denton, [JG 2204.09060](#)]

→ Degeneracy broken if NSI in electron sector!



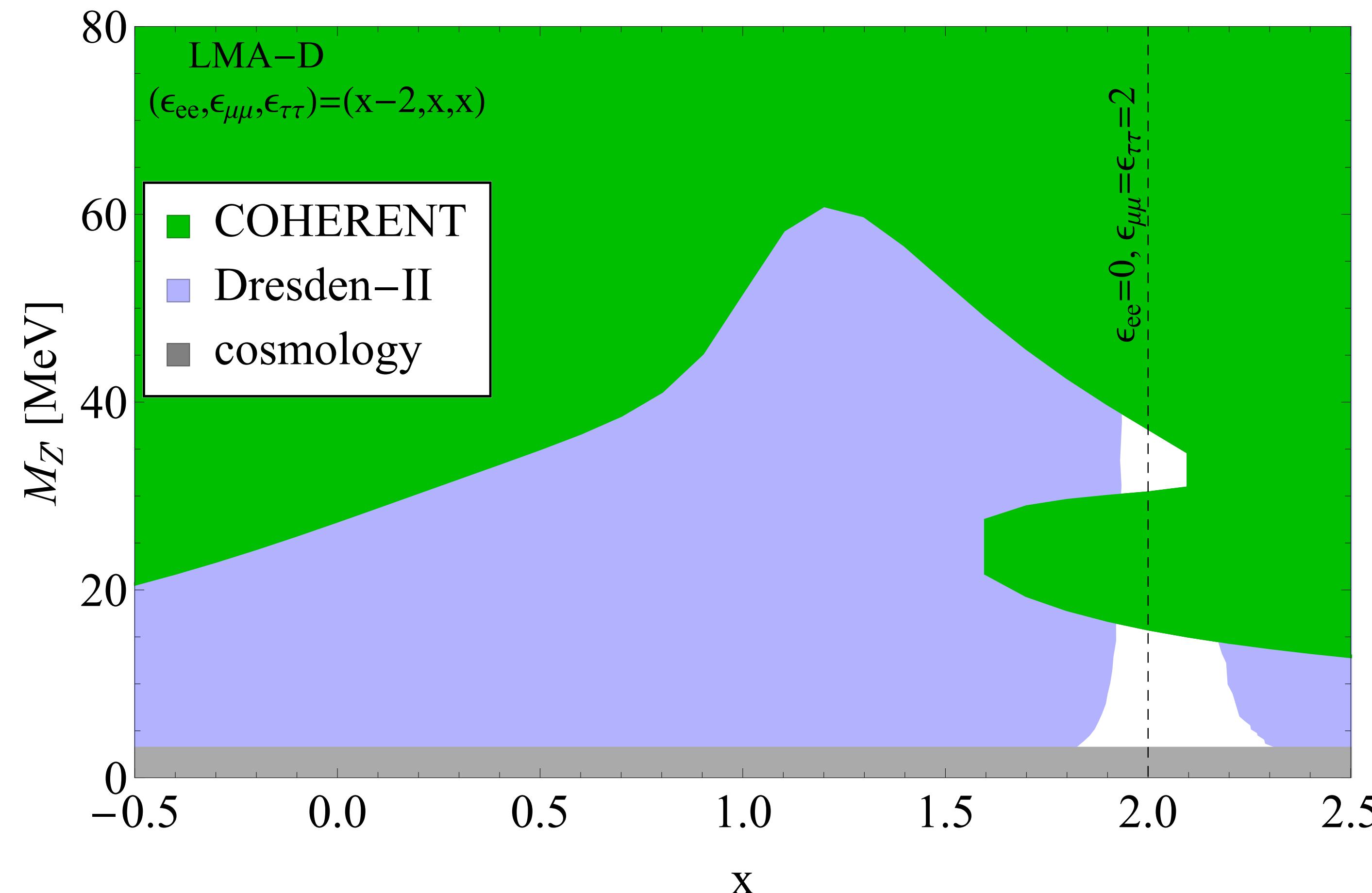
# LMA-D degeneracy

**Diagonal degeneracy of Hamiltonian:**

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

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

[Denton, [JG 2204.09060](#)]



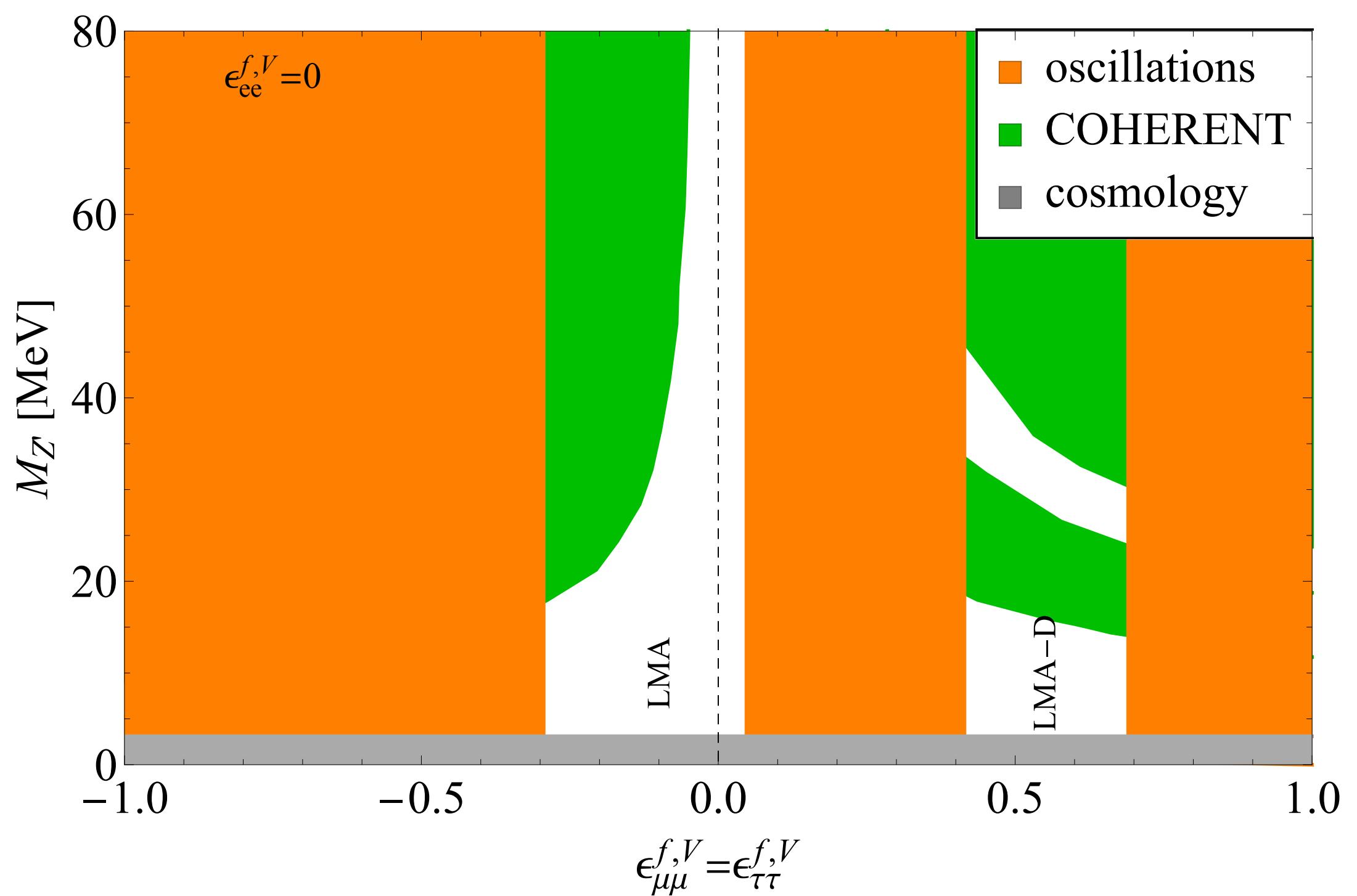
$x=0$ : LMA-D **only** in electron sector  
 $x=2$ : LMA-D **only** in muon and tau sector

# LMA-D degeneracy

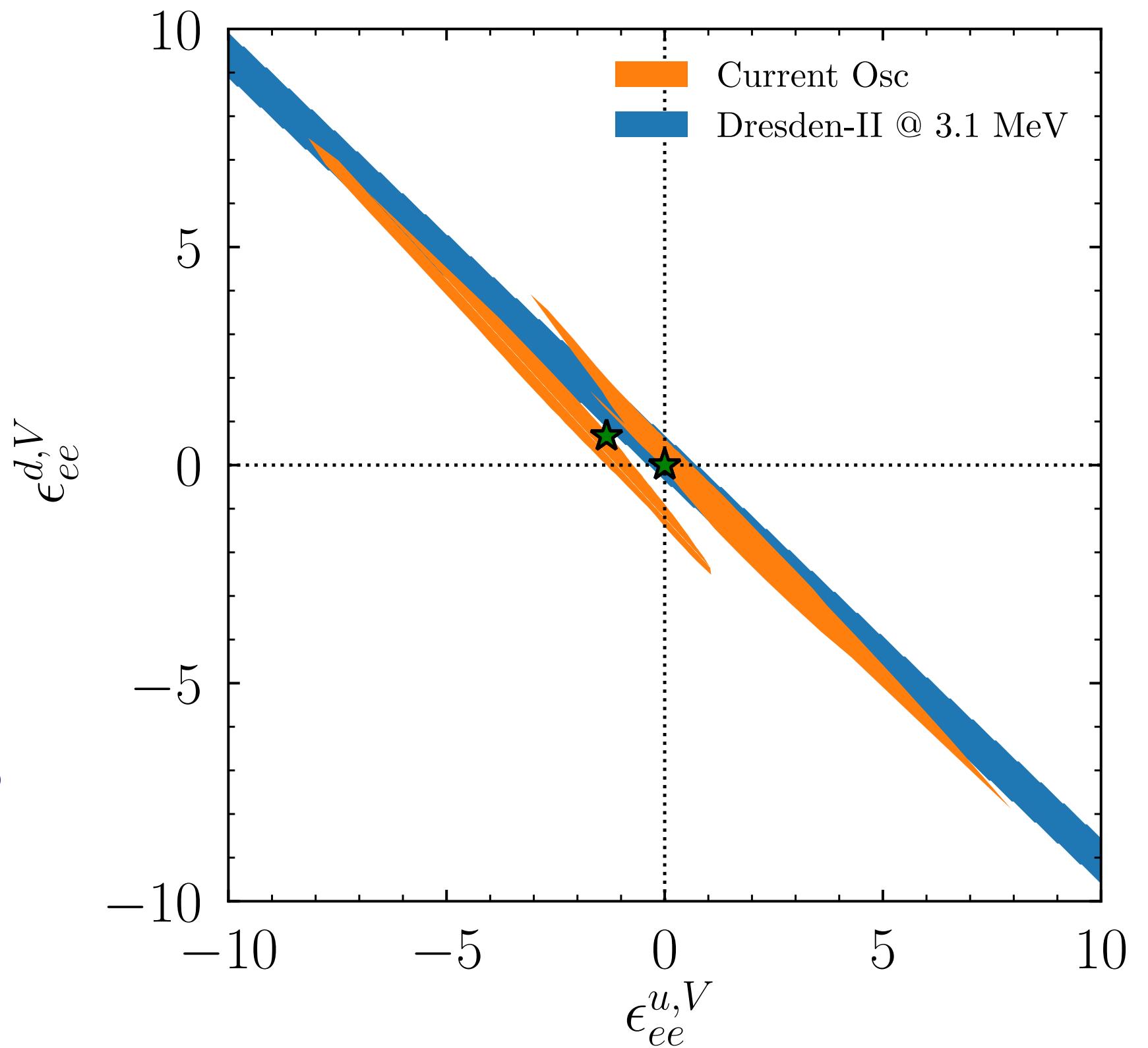
Can still evade constraints if  $\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$

[Denton, [JG 2204.09060](#)]

or certain  
u/d combinations



Probe  
 $\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$  at  
low threshold  
PiDAR experiments

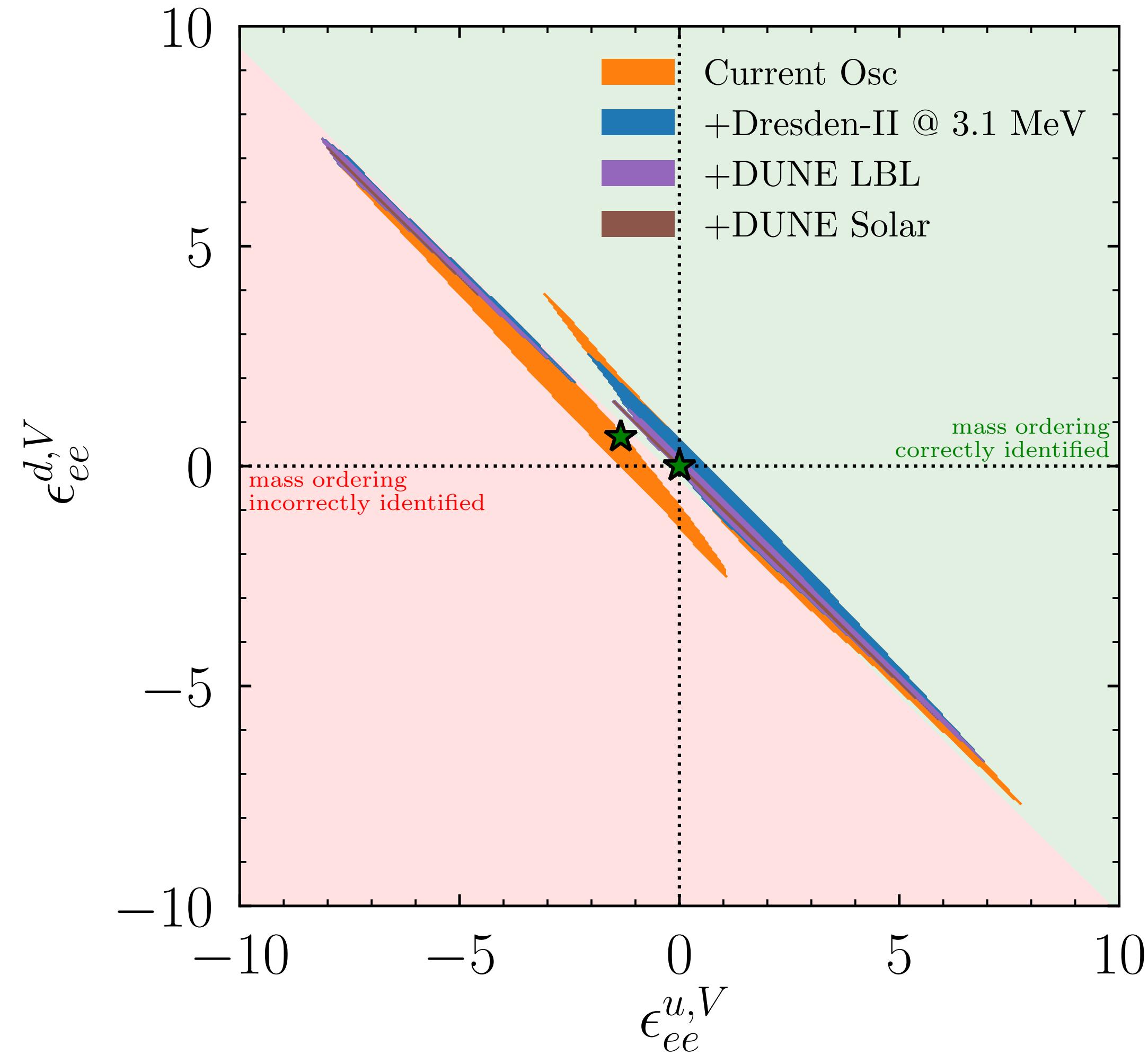


Test with materials with very  
different neutron/proton ratios

# LMA-D degeneracy

## Future of LMA-D

[Denton, JG [2204.09060](#)]



# Neutrino mass ordering determination

## Summary & Conclusion

- Neutrino mass ordering currently unknown
- Want to ensure unambiguous determination at next generation experiments
- New neutrino interactions **appear naturally** in extensions of SM with new mediators, can prevent determination of MO (LMA-D degeneracy if  $\epsilon_{ee} = -2$ )
- **Excluded LMA-D degeneracy** in electron sector → mass ordering determination possible assuming only non-zero  $\epsilon_{ee}$
- Future experiments will continue to probe NSI
- **Theory effort** needed to build consistent NSI models

# Thank you for your attention!



# Appendix: NSI models

## NSI models

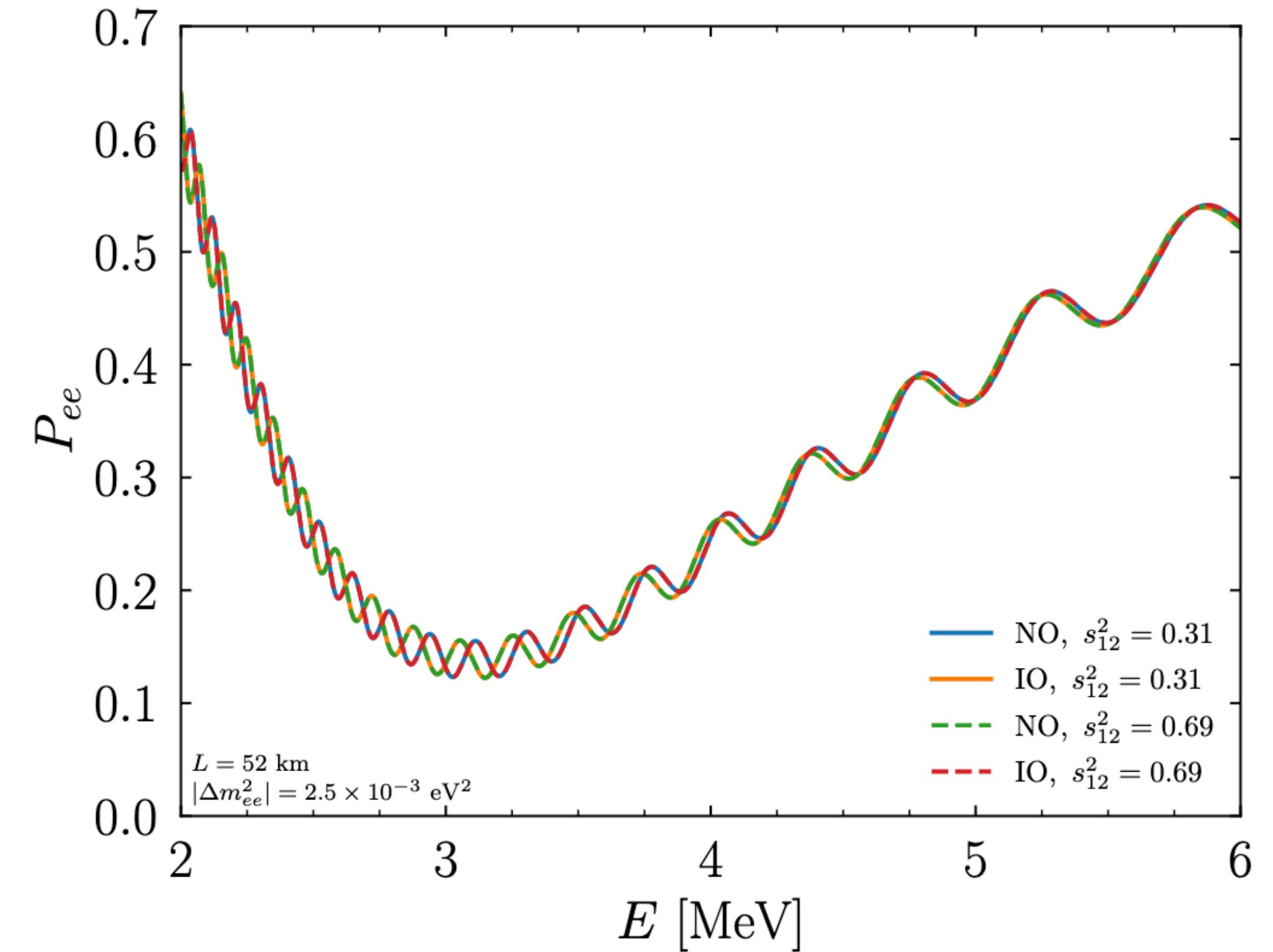
general idea to allow for sizable NSI: constraining the direct coupling of the NSI mediator to the heavier generations or to sterile neutrinos that mix with the active ones

- D. V. Forero and W.-C. Huang, JHEP 03, 018 (2017), arXiv:1608.04719 [hep-ph].
- P. B. Denton, Y. Farzan, and I. M. Shoemaker, Phys. Rev. D 99, 035003 (2019), arXiv:1811.01310 [hep-ph].
- U. K. Dey, N. Nath, and S. Sadhukhan, Phys. Rev. D 98, 055004 (2018), arXiv:1804.05808 [hep-ph].
- K. Babu, A. Friedland, P. Machado, and I. Mocioiu, JHEP 12, 096 (2017), arXiv:1705.01822 [hep-ph].
- Y. Farzan and J. Heeck, Phys. Rev. D 94, 053010 (2016), arXiv:1607.07616 [hep-ph].
- Y. Farzan and I. M. Shoemaker, JHEP 07, 033 (2016), arXiv:1512.09147 [hep-ph].
- Y. Farzan, Phys. Lett. B 748, 311 (2015), arXiv:1505.06906 [hep-ph].
- K. Babu, P. B. Dev, S. Jana, and A. Thapa, JHEP 03, 006 (2020), arXiv:1907.09498 [hep-ph].

# Appendix: MO determination at JUNO

JUNO relies on input from solar experiments to determine MO

1. JUNO needs to know if  $\theta_{12} < 45^\circ$  or  $\theta_{12} > 45^\circ$   
( $\Delta m_{21}^2 < 0$  or  $\Delta m_{21}^2 > 0$ ) however reactor  
experiments sensitive to  $\sin^2 2\theta_{12} \leftrightarrow$  solar  
experiments sensitive to  $\sin^2 \theta_{12}$
2. JUNO will measure  $\Delta m_{31}^2$  and  $\Delta m_{32}^2$ : determine  
which one is larger  $\rightarrow$  MO determination  
  
Size of oscillation  
 $\propto \sin^2 \theta_{12} \sim 1/3$  for  $\Delta m_{32}^2$   
 $\propto \cos^2 \theta_{12} \sim 2/3$  for  $\Delta m_{31}^2$   
 $\Rightarrow$  with only knowledge of  $\sin^2 2\theta_{12}$ : possible to swap  
MO and octant of  $\theta_{12}$ : exact degeneracy!



# Appendix: NSI

Affect neutrino oscillations as a new matter effect

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

- Parameters related to parameters in Hamiltonian as  $\epsilon_{\alpha\beta} = \sum_f \epsilon_{\alpha\beta}^{f,V} \langle N_f(x)/N_e(x) \rangle$
- Real diagonal NSI parameters  $\epsilon_{\alpha\alpha}$ ,  
complex off-diagonal parameters  $\epsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}| e^{i\phi_{\alpha\beta}}$
- Can subtract one term on the diagonal  $\Rightarrow$  **8 free parameters** probed by oscillations  
 $(|\epsilon_{\alpha\beta}|, \phi_{\alpha\beta}, \epsilon_{ee} - \epsilon_{\mu\mu}, \epsilon_{\tau\tau} - \epsilon_{\mu\mu})$
- Focus on diagonal NSI parameters  $\rightarrow$  affect mass splittings

# Appendix: Degeneracies

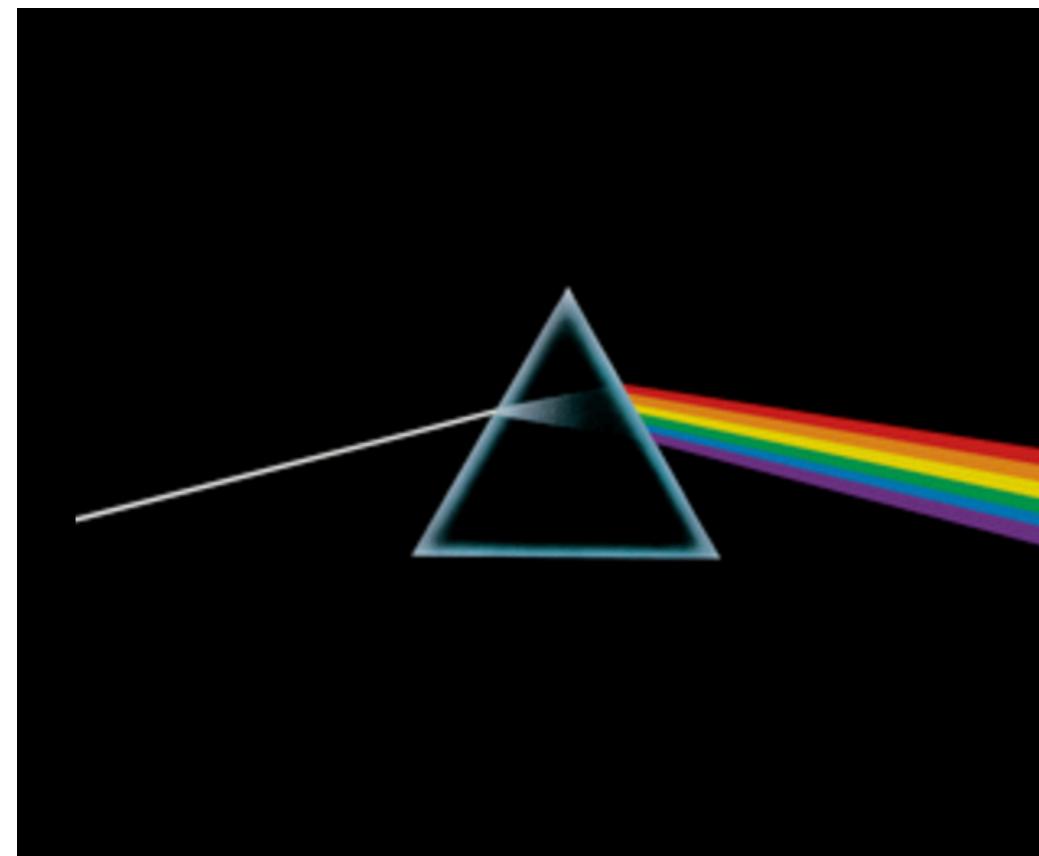
## 1. Without new physics & in vacuum:

Miranda, Tortola, Valle '04

Hamiltonian invariant under  
 $\Delta m_{21}^2 \rightarrow -\Delta m_{21}^2, \Delta m_{31}^2 \rightarrow -\Delta m_{31}^2, \delta \rightarrow -\delta$   
 $H_{\text{vac}} \rightarrow -H_{\text{vac}}^*$  leaves all observables invariant

Dark side of oscillations

LMA-Dark



# Appendix: Degeneracies

1. Without new physics & in vacuum:

Hamiltonian invariant under  
 $\Delta m_{21}^2 \rightarrow -\Delta m_{21}^2, \Delta m_{31}^2 \rightarrow -\Delta m_{31}^2, \delta \rightarrow -\delta$

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

Matter term does not change sign together with other parameters

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

# Appendix: Degeneracies

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Hamiltonian invariant under  
 $\Delta m_{21}^2 \rightarrow -\Delta m_{21}^2, \Delta m_{31}^2 \rightarrow -\Delta m_{31}^2, \delta \rightarrow -\delta$   
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2. Degeneracy broken when considering oscillations in matter  $\Rightarrow$  possibility to determine MO in vacuum

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

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

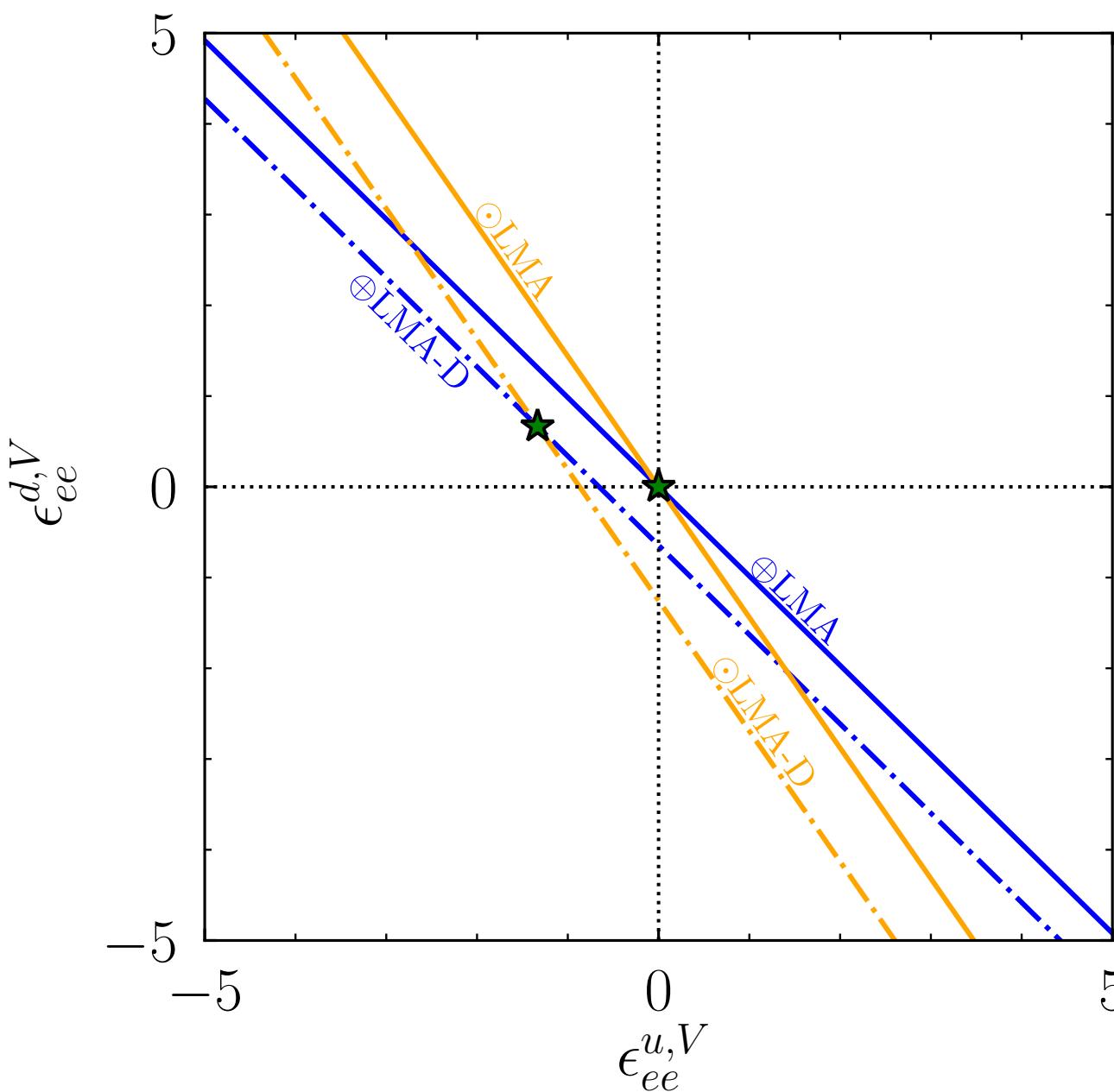
$$P_{\alpha\beta}(\text{IO}, L, E, \rho, \epsilon = 0) = P_{\alpha\beta}(\text{NO}, L, E, \rho, \epsilon = -2)$$

In **all** oscillation channels!

# Appendix: Degeneracies

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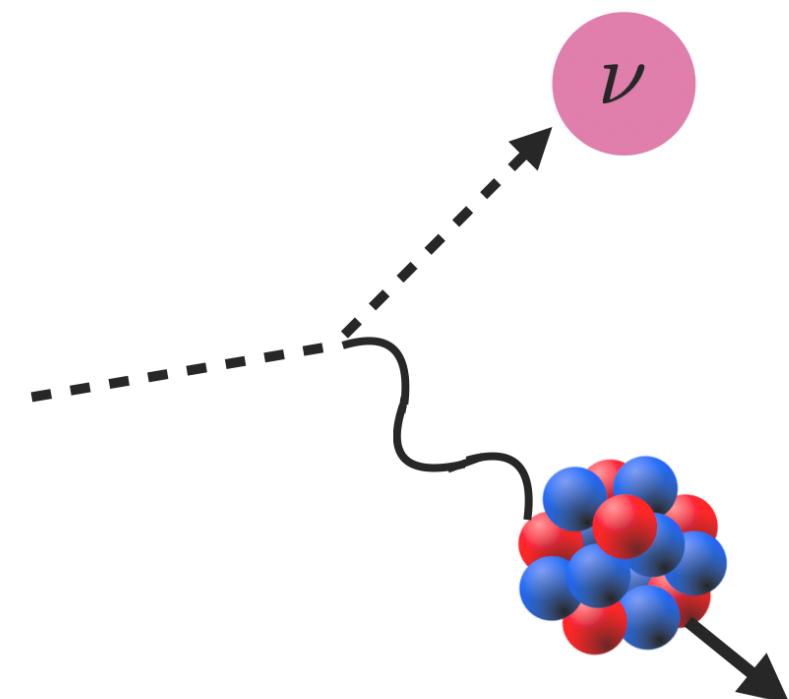
4. **Precise measurement** of  $\epsilon_{ee}$  in **different materials** can lift  
degeneracy unless new mediator is coupled to electrons only or specific  
combination to up and down quarks



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

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



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5. Scattering experiments don't suffer from LMA-D degeneracy  
 $\Rightarrow$  provide probes of LMA-D parameter space
6. NSI in oscillations not sensitive to mediator masses  
 $\Leftrightarrow$  NSI in scattering depends on **mediator mass**  
 $\rightarrow$  lower bound on mediator mass which can be probed

Neutrino scattering experiment with lowest momentum transfer: **CEvNS**