

# LMA-Dark: Large New Physics Effects in Neutrino Oscillations: I

Peter B. Denton

COHERENT Call

August 24, 2023

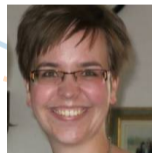
with Julia Gehrlein

P. Coloma, **PBD**, M. Gonzalez-Garcia, M. Maltoni, T. Schwetz [1701.04828](tel:1701.04828)

**PBD**, Y. Farzan, I. Shoemaker [1804.03660](tel:1804.03660)

**PBD**, J. Gehrlein [2008.06062](tel:2008.06062)

**PBD**, J. Gehrlein [2204.09060](tel:2204.09060)



Speaking from [Kumeyaay](#) land

# Strategy

1. Start broad: all BSM, then focus down
2. Understand why vector NSI with  $\nu_e$ 's is a curious example
3. The atmospheric mass ordering
4. Lots of indices for NSI: the role they play
5. Exactly what the degeneracy is and where it applies
6. Understand how to evade

Much of this talk will be about oscillations  
because LMA-Dark is an oscillation effect

# Many interesting new physics scenarios in oscillations

1. Sterile neutrinos
2. Non-standard neutrino interactions (NSI)  
with any Lorentz structure: SPVAT
3. Non-standard neutrino SELF interactions
4. Neutrino decay  
with visible or invisible final states
5. Unitarity violation
6. Neutrino – dark matter interactions
7. Decoherence
8. Lorentz invariance or CPT violation

# Many interesting new physics scenarios in oscillations

1. Sterile neutrinos PBD, Y. Farzan, I. Shoemaker [1811.01310](#)  
PBD [2111.05793](#)
2. Non-standard neutrino interactions (NSI)  
with any Lorentz structure: SPVAT PBD, J. Gehrlein, R. Pestes [2008.01110](#)  
P. Coloma, PBD, M. Gonzalez-Garcia, M. Maltoni, T. Schwetz [1701.04828](#)  
PBD, J. Gehrlein [2008.06062](#), [2204.09060](#)  
PBD, A. Giarnetti, D. Meloni [2210.00109](#)
3. Non-standard neutrino SELF interactions G. Barenboim, PBD, I. Oldengott [1903.02036](#)
4. Neutrino decay  
with visible or invisible final states PBD, I. Tamborra [1805.05950](#)  
PBD, A. Abdullahi [2005.07200](#)  
PBD [2109.14576](#)
5. Unitarity violation PBD, J. Gehrlein [2109.14575](#)
6. Neutrino – dark matter interactions A. Dev, et al. [2205.06821](#)  
C. Boehm, P. Fayet, R. Schaeffer [astro-ph/0012504](#)
7. Decoherence T. Stuttard, M. Jensen [2007.00068](#)  
A. Gouvêa, V. Romeri, C. Ternes [2104.05806](#)
8. Lorentz invariance or CPT violation S. Ge, H. Murayama [1904.02518](#)

New physics:  
Non-standard neutrino interactions  
(NSI)

# NSI at the Lagrangian Level

EFT Lagrangian:

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

$$\text{with } \Lambda = \frac{1}{\sqrt{2}\sqrt{2}\epsilon G_F}.$$

Simplified model Lagrangian:

$$\mathcal{L}_{\text{NSI}} = g_\nu Z'_\mu \bar{\nu} \gamma^\mu \nu + g_f Z'_\mu \bar{f} \gamma^\mu f$$

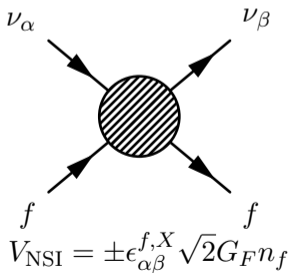
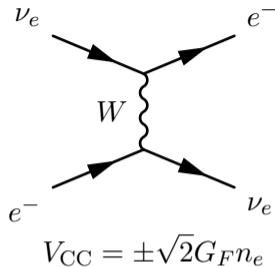
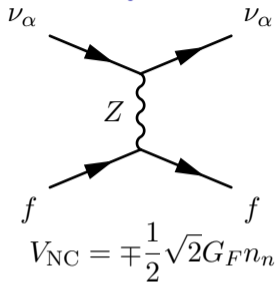
which gives a potential

$$V_{\text{NSI}} \propto \frac{g_\nu g_f}{q^2 + m_{Z'}^2}$$

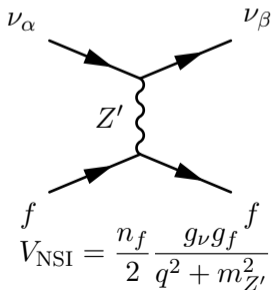
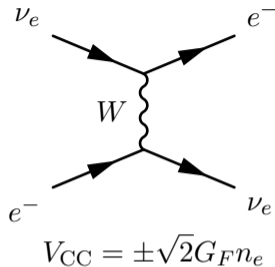
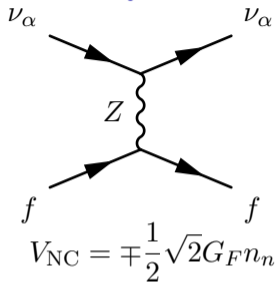
Models with large NSIs consistent with CLFV:

Y. Farzan, I. Shoemaker [1512.09147](#)   Y. Farzan, J. Heeck [1607.07616](#)   D. Forero and W. Huang [1608.04719](#)  
K. Babu, A. Friedland, P. Machado, I. Mocioiu [1705.01822](#) **PBD**, Y. Farzan, I. Shoemaker [1804.03660](#)  
U. Dey, N. Nath, S. Sadhukhan [1804.05808](#)   Y. Farzan [1912.09408](#)

# Matter Effects in Feynman Diagrams



# Matter Effects in Feynman Diagrams





## NSI at the Hamiltonian Level

$$H^{\text{vac}} = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix} U^\dagger$$

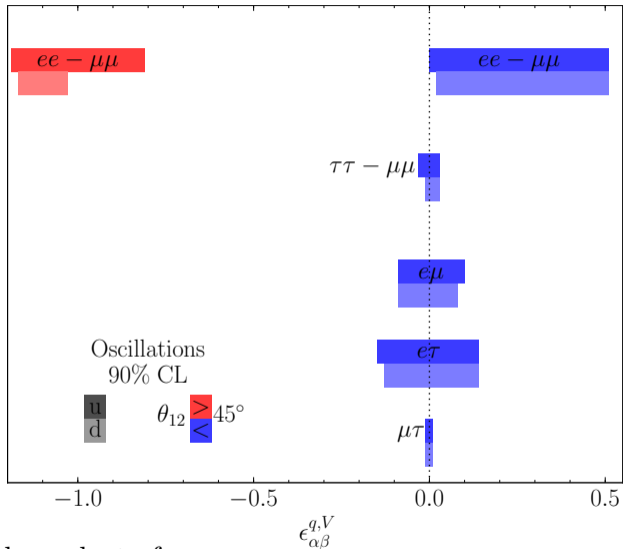
$$H^{\text{mat,SM}} = \frac{a}{2E} \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} \quad (\text{NC subtracted out})$$

$$H^{\text{mat,NSI}} = \frac{a}{2E} \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

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

$$H = H^{\text{vac}} + H^{\text{mat,SM}} + H^{\text{mat,NSI}}$$

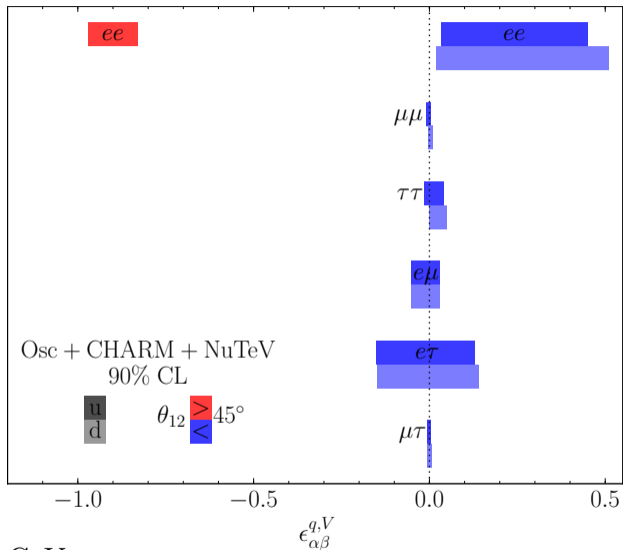
# NSI Global Fit: Oscillations



Oscillations are independent of  $m_{Z'}$ .

PBD, et al., [1701.04828](https://arxiv.org/abs/1701.04828)

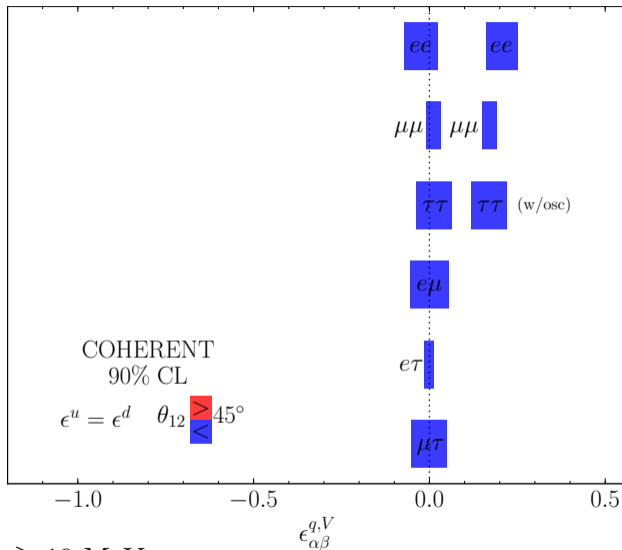
# Heavy NSI Global Fit: CHARM & NuTeV



Heavy  $\Rightarrow m_{Z'} \gtrsim 1 \text{ GeV}$ .

PBD, et al., [1701.04828](https://arxiv.org/abs/1701.04828)

# NSI Constraints: COHERENT



Valid down to  $m_{Z'} \gtrsim 10$  MeV

PBD, Y. Farzan, I. Shoemaker, [1804.03660](#)

# LMA-Dark Degeneracy Comes From Oscillations

Degeneracy: When two different physics scenarios look similar/identical in data

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Let's swap some oscillation parameters:

$$\Delta m_{21}^2 \rightarrow -\Delta m_{21}^2 \quad \Delta m_{31}^2 \rightarrow -\Delta m_{31}^2 \quad \delta \rightarrow -\delta \quad \epsilon_{ee} = 0 \rightarrow -2$$

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This changes the Hamiltonian:

$$H \rightarrow -H^*$$

The minus does time reversal and the complex conjugate does CP  
Under CPT this changes nothing.

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So a case with one mass ordering (sign  $\Delta m_{31}^2$ ), one value of  $\delta$ , and no new physics, looks *identical* to another with the opposite parameters and new physics



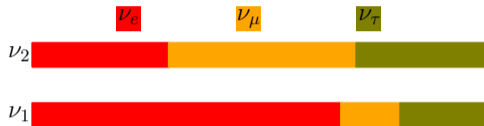
# Atmospheric mass ordering

# Mass ordering: what is it?

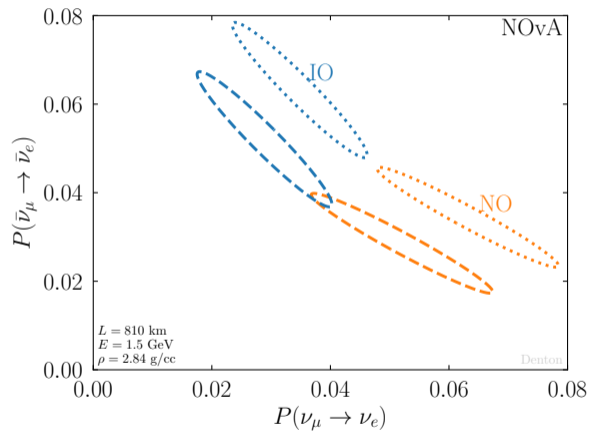
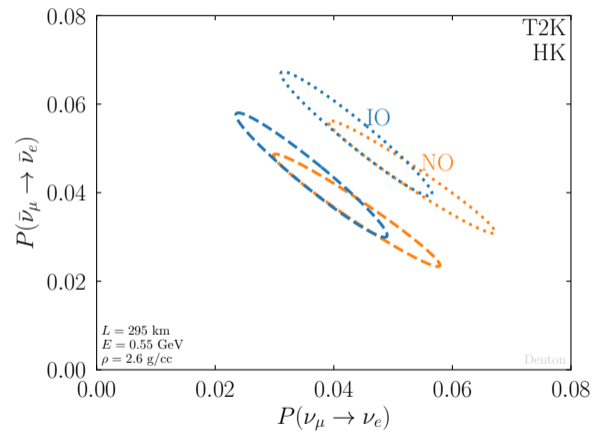
Normal



Inverted



# Mass ordering: what is it really?



## Mass ordering current status: oscillations

1. NOvA and T2K both prefer **NO** over **IO**
2. NOvA+T2K prefers **IO** over **NO**
3. SK still prefers **NO** over **IO**
4. NOvA+T2K+SK still prefers **NO** over **IO**
5. + Daya Bay & RENO  $\Rightarrow$  slight preference **NO**
6. =  $2.5 - 2.7\sigma$  in favor of the **NO**

K. Kelly, et al. [2007.08526](#)

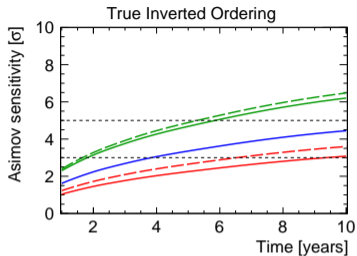
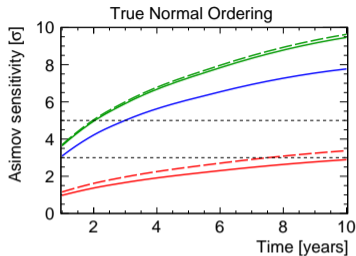
**PBD**, J. Gehrlein, R. Pestes [2008.01110](#)

I. Esteban, et al. [2007.14792](#)

F. Capozzi, et al. [2107.00532](#)

P. de Salas, et al. [2006.11237](#)

# Mass ordering: future oscillation sensitivities



Joint  
KM3NeT  
JUNO

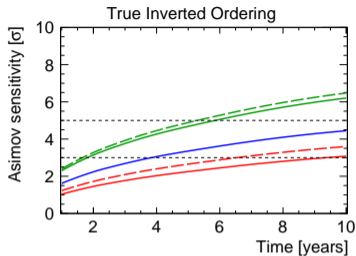
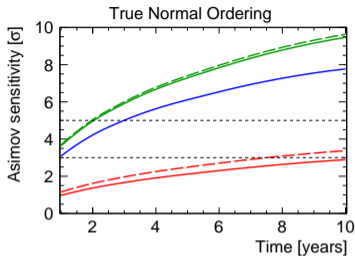
JUNO, KM3NeT [2108.06293](#)

JUNO, IceCube [1911.06745](#)

Note: if lower octant, KM3NeT is less sensitive

Joint is better than naive sum

# Mass ordering: future oscillation sensitivities



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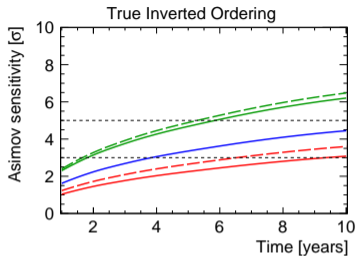
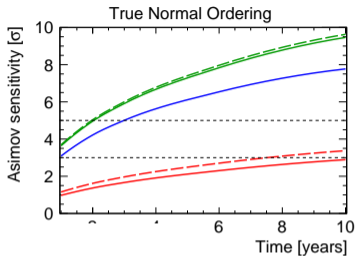
$$\Delta m_{ee}^2 = c_{12}^2 \Delta m_{31}^2 + s_{12}^2 \Delta m_{32}^2$$

$$\Delta m_{\mu\mu}^2 = s_{12}^2 \Delta m_{31}^2 + c_{12}^2 \Delta m_{32}^2 + \mathcal{O}(s_{13} \Delta m_{21}^2)$$

Differ by  $\pm \sim 1.5\%$  in each mass ordering

H. Nunokawa, S. Parke, R. Funchal [hep-ph/0503283](#)

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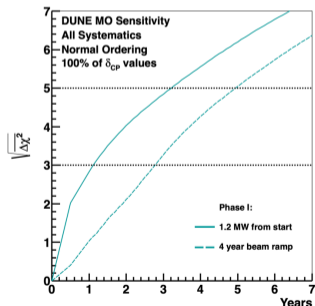
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Matter effect  $\Rightarrow$  DUNE [2203.06100](#)

H. Nunokawa, S. Parke, R. Funchal [hep-ph/0503283](#)

# Mass ordering current status: cosmology

Cosmology:  $m_1 + m_2 + m_3 < 90$  meV at 95% CL

E. Valentino, S. Gariazzo, O. Mena [2106.15267](#)

→ 20 meV precision with DESI, EUCLID, ...

From oscillations:

Normal :  $m_1 + m_2 + m_3 > 60$  meV

Inverted :  $m_1 + m_2 + m_3 > 100$  meV

See also KATRIN [2105.08533](#)



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## PRIORS?

Some claim “decisive” Bayesian evidence for normal ordering

R. Jimenez, et al. [2203.14247](#)

More general prior assumptions  $\Rightarrow$  no significant information from cosmology

S. Gariazzo, et al. [1801.04946](#)

S. Gariazzo, et al. [2205.02195](#)

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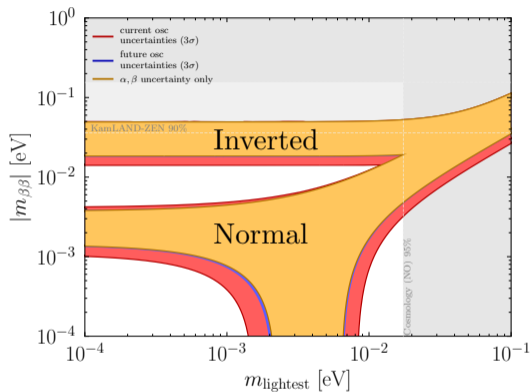
S. Gariazzo, et al. [2205.02195](#)

Not affected by NSI!

# Mass ordering: broad implications

- ▶ Affects cosmology
- ▶ Affects  $0\nu\beta\beta$
- ▶ Affects end point measurements
- ▶ Affects  $C\nu B$
- ▶ Flavor models insights

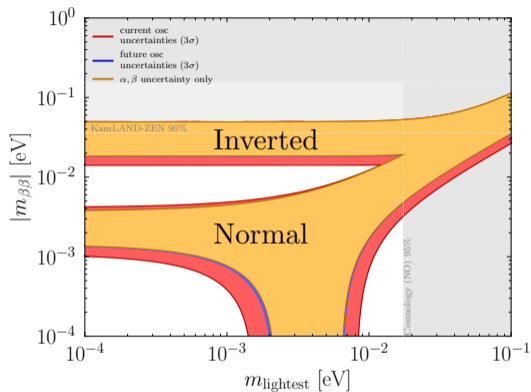
PBD, J. Gehrlein 2308.09737



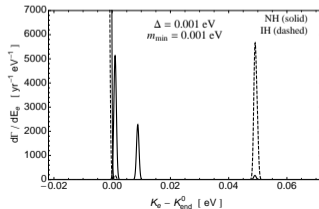
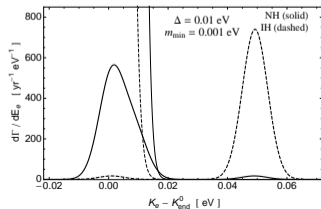
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PBD, J. Gehrlein [2308.09737](#)



A. Long, C. Lunardini, E. Sabancilar [1405.7654](#)



Peter B. Denton (BNL HET Group)

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Questions?

On to professor Gehrlein

# Backups

# 1. Vacuum Oscillation Degeneracies

Vacuum oscillations described by:

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix} U^\dagger$$

1. Diagonal degeneracy  $\Rightarrow$  no sensitivity to  $m_1$ .
2. By CPT can send  $H \rightarrow -H^*$

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

Vacuum oscillations  $\Rightarrow$  impossible to determine either mass ordering

A. de Gouvea, A. Friedland, H. Murayama [hep-ph/0002064](#)  
P. Bakhti and Y. Farzan, [1403.0744](#)  
P. Coloma, T. Schwetz [1604.05772](#)  
**PBD**, S. Parke [2106.12436](#)

## 2. Solar Neutrinos



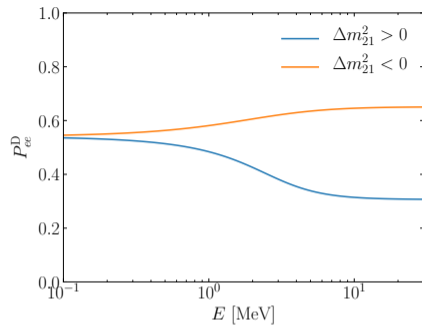
In matter

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

$$a \equiv 2\sqrt{2}G_F N_e E$$

Subtracted NC matter effect: diagonal degeneracy

Given KamLAND:





## 2. Solar Neutrinos ☺



In matter

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

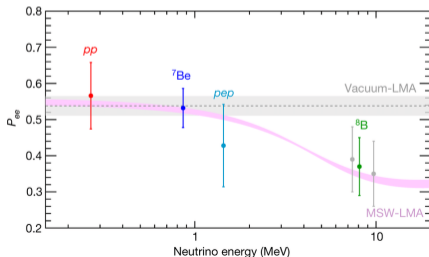
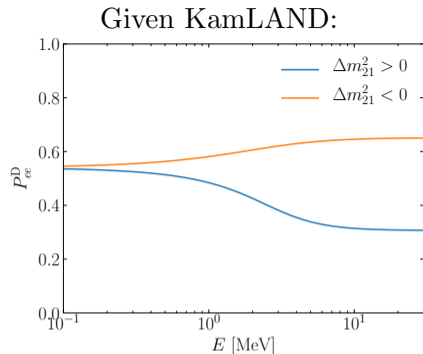
$$a \equiv 2\sqrt{2}G_F N_e E$$

Subtracted NC matter effect: diagonal degeneracy

We know  $\Delta m_{21}^2 > 0$  so degeneracy is broken by matter

Measuring the atmospheric mass ordering in DUNE also breaks the degeneracy

Unless ...



### 3. New Physics ☹️

In matter

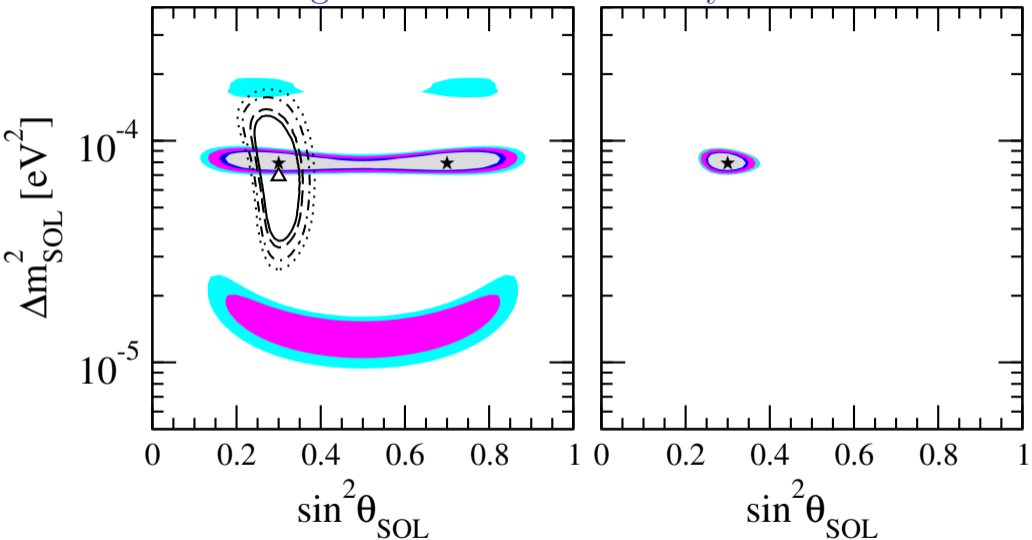
$$H = \frac{1}{2E} \left[ U \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix} U^\dagger + a \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} \right]$$

equivalent to:

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

This factor  $\epsilon_{ee} = -2$  restores the degeneracy even in matter

# Best Fit Assuming Standard Neutrino Physics



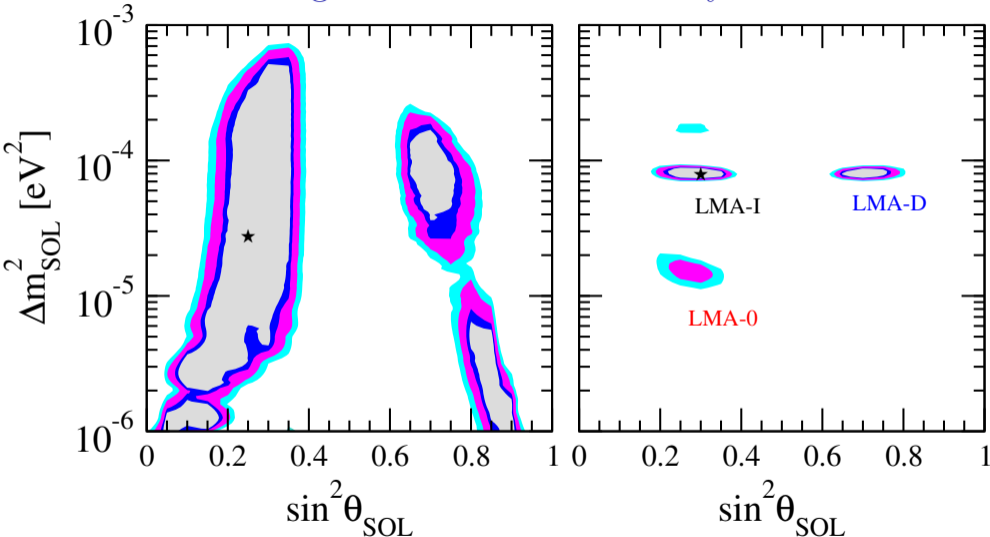
90%, 95%, 99% and 99.73% CL

O. Miranda, M. Tórtola, J. Valle, [hep-ph/0406280](https://arxiv.org/abs/hep-ph/0406280)

KamLAND (color), solar (black)

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# Best Fit Assuming Standard Neutrino Physics



90%, 95%, 99% and 99.73% CL

O. Miranda, M. Tórtola, J. Valle, [hep-ph/0406280](https://arxiv.org/abs/hep-ph/0406280)  
Solar (left), solar + KamLAND (right),  $\Delta\chi^2 = 80.2 - 79.7$ .

# Modern Global Analysis

A modern global fit reveals:

P. Coloma, [PBD](#), M. Gonzalez-Garcia, M. Maltoni, T. Schwetz [1701.04828](#)

- ▶ LMA-Dark solution is very much accommodated by oscillation data
- ▶  $\epsilon_{ee} = 0$  slightly disfavored
  - ▶ Solar upturn
- ▶ Slight information from quark composition
  - ▶ Due to different neutron fractions in the Sun and Earth

## 4. Quark Contribution in NSI

Need  $\epsilon_{ee} = -2$ ,

$$\epsilon_{ee} = (2 + Y_n)\epsilon_{ee}^{u,V} + (1 + 2Y_n)\epsilon_{ee}^{d,V} = -2$$

$Y_n = N_n/N_e$  and is  $\sim 1/3$  in the Sun and 1.05 in the Earth's crust

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**If**  $\epsilon^u = \epsilon^d$ , in the sun  $\epsilon_{ee}^{u,V} = -1/2$ .

For the same parameters in the Earth,  $\epsilon_{ee} = -3.1$  which is detectable!

## 4. Quark Contribution in NSI

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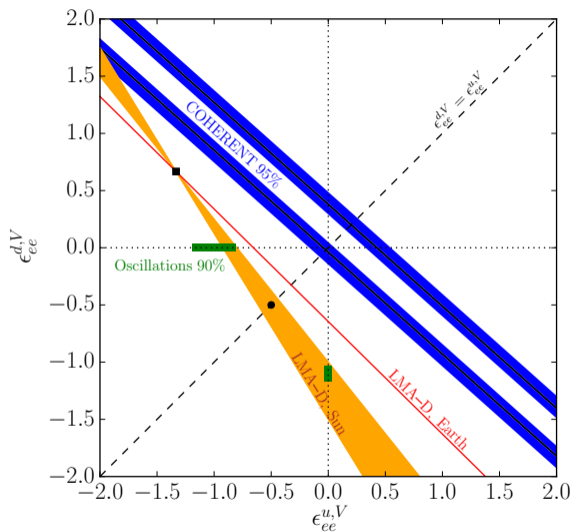
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Matter effect  $\Rightarrow \epsilon_{ee}$  has only been measured in the Sun,  
DUNE will make a  $\sim 30\%$  measurement in the crust

K. Kelly, S. Parke [1802.06784](#)



## 5. Quark Combinations



PBD, Y. Farzan, I. Shoemaker [1804.03660](#)

- ▶ Clear that matter effect measurement comes from solar
- ▶ Precision measurements can break this if
  - ▶  $\epsilon^u = 0$
  - ▶  $\epsilon^u = \epsilon^d$
  - ▶  $\epsilon^d = 0$
- ▶ No oscillation measurements in any materials and for any level of precision can break this if:

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

Oscillations can go no further

# NSI in Scattering Experiments Probe Different Scales

NSI affects:

- ▶ **Oscillation:**  $q^2 = 0$ , the effect is valid for any  $m_{Z'}$

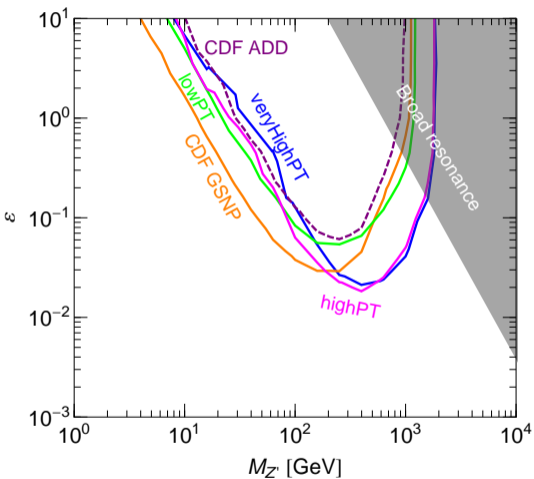
\*See e.g. M. Wise, Y. Zhang [1803.00591](#)

- ▶ **Scattering:** the NSI potential is suppressed if  $q^2 > m_{Z'}^2$

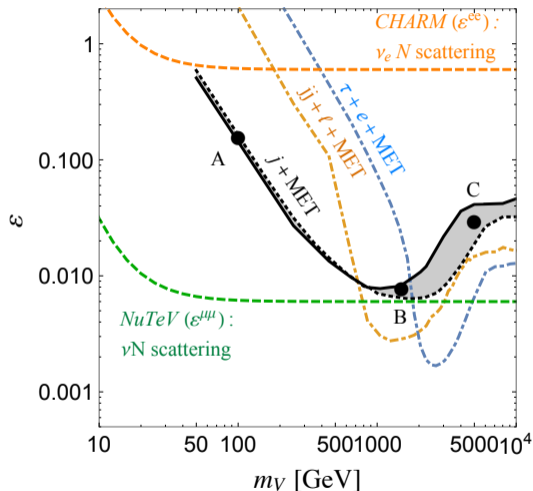
| Regime            | $m_{Z'}$               | Status |
|-------------------|------------------------|--------|
| Tevatron/LHC      | $\gtrsim 10 - 100$ GeV | Exists |
| CHARM/NuTeV (DIS) | $\gtrsim 1$ GeV        | Exists |
| COHERENT (CEvNS)  | $\gtrsim 50$ MeV       | Exists |
| Early universe    | $\lesssim 5$ MeV       | Exists |
| Reactor CEvNS     | $\gtrsim 1$ MeV        | New!   |
| Oscillation       | Any                    | Exists |

For  $m_{Z'} \gtrsim 1$  TeV,  $\epsilon \sim \mathcal{O}(1)$  is no longer perturbative.

# High Energy Collider Constraints



A. Friedland, et al., [1111.5331](#)



D. Franzosi, M. Frandsen, and I. Shoemaker, [1507.07574](#)

# CHARM

CHARM measured NC and CC  $\langle \bar{\nu}_e \rangle$  cross sections with nuclei,

$$R_{\text{NC/CC}} = (\tilde{g}_e^L)^2 + (\tilde{g}_e^R)^2 = 0.406 \pm 0.140$$

at  $\langle E_\nu \rangle = 54$  GeV on Fe.

CHARM Collaboration, [PLB180 \(1986\)](#)

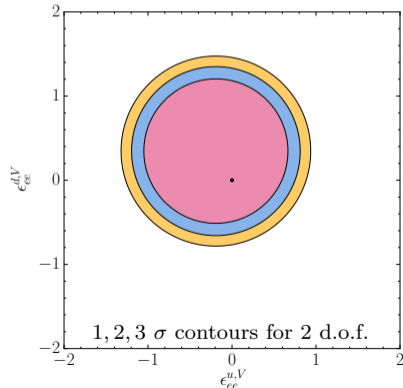
$$(\tilde{g}_e^P)^2 = \sum_{q=u,d} \left[ (g_q^P + \epsilon_{ee}^{q,P})^2 + \sum_{\alpha \neq e} |\epsilon_{e\alpha}^{q,P}|^2 \right]$$

2-loop radiative corrections for SM couplings

J. Erler, S. Su, [1303.5522](#)

$R_{e,\text{SM}} = 0.333$  for  $q^2 \sim 20$  GeV<sup>2</sup>.

[PBD](#), et al., [1701.04828](#)



NuTeV measured NC and CC  $\nu_\mu$  and  $\bar{\nu}_\mu$  cross sections with nuclei.

$$R_\mu^\nu = \frac{\sigma(\nu_\mu X \rightarrow \nu_\mu X)}{\sigma(\nu_\mu X \rightarrow \mu X)} = (\tilde{g}_\mu^L)^2 + r(\tilde{g}_\mu^R)^2 = 0.3919 \pm 0.0013$$

$$R_\mu^{\bar{\nu}} = \frac{\sigma(\bar{\nu}_\mu X \rightarrow \bar{\nu}_\mu X)}{\sigma(\bar{\nu}_\mu X \rightarrow \bar{\mu} X)} = (\tilde{g}_\mu^L)^2 + \frac{1}{r}(\tilde{g}_\mu^R)^2 = 0.4050 \pm 0.0027$$

at  $\langle E_\nu \rangle = 60$  GeV on Fe.

$$r = \frac{\sigma(\bar{\nu}_\mu X \rightarrow \bar{\mu} X)}{\sigma(\nu_\mu X \rightarrow \mu X)}$$

NuTeV Collaboration, [hep-ex/0110059](https://arxiv.org/abs/hep-ex/0110059)

G. P. Zeller PhD thesis

This leads to  $\chi_{\text{NuTeV,SM}}^2 \sim 9$  which is the NuTeV anomaly.

# NuTeV Corrected

Measurements need to be corrected,

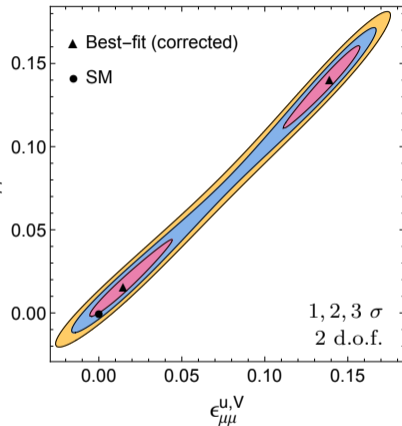
- ▶ Improved nuclear models
- ▶ Iron is not isoscalar
- ▶ Updated PDFs including the strange quark

NNPDF Collaboration, [0906.1958](#)  
W. Bentz, et al., [0908.3198](#)

$$\delta R_{\mu,\text{exp}}^{\nu} = 0.0017, \quad \delta R_{\mu,\text{exp}}^{\bar{\nu}} = -0.0016,$$

$$R_{\text{exp,true}} = R_{\text{exp,orig}} + \delta R$$

Corrected  $\chi_{\text{NuTeV,SM}}^2 \sim 2.3$ .



PBD, et al., [1701.04828](#)

# Coherent Elastic $\nu$ Nucleus Scattering: CE $\nu$ NS (“Sevens”)

CE $\nu$ NS :=  $\nu$  scattering off the weak charge of entire nucleus

The CE $\nu$ NS cross section is very high, but recoil energies are very low:

*Our suggestion may be **an act of hubris**, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.*

D. Freedman, [PRD 9 \(1974\)](#)

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D. Freedman, [PRD 9 \(1974\)](#)

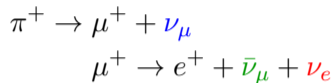
Thanks to DM direct detection efforts, this is now possible.



# COHERENT

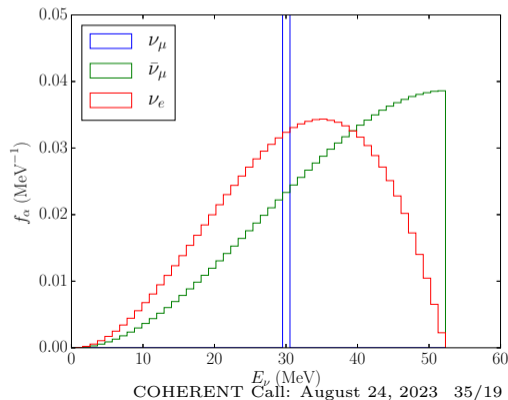
Spallation Neutron Source at Oak Ridge in a  $\pi$ -DAR configuration.

K. Scholberg, [hep-ex/0511042](https://arxiv.org/abs/hep-ex/0511042)



$$\begin{aligned}f_{\nu_\mu} &= \delta \left( E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi} \right), \\ f_{\bar{\nu}_\mu} &= \frac{64}{m_\mu} \left[ \left( \frac{E_\nu}{m_\mu} \right)^2 \left( \frac{3}{4} - \frac{E_\nu}{m_\mu} \right) \right], \\ f_{\nu_e} &= \frac{192}{m_\mu} \left[ \left( \frac{E_\nu}{m_\mu} \right)^2 \left( \frac{1}{2} - \frac{E_\nu}{m_\mu} \right) \right].\end{aligned}$$

Detector 22 m from source with  $E_{\text{tr}} = 5$  keV.



# COHERENT

Observed spectrum:

$$\frac{dN_\alpha}{dE_r} = N_t \Delta t \int dE_\nu \phi_\alpha(E_\nu) \frac{d\sigma_\alpha}{dE_r}(E_\nu),$$

Neutrino nucleon cross section:

$$\frac{d\sigma_\alpha}{dE_r} = \frac{G_F^2}{2\pi} \frac{Q_{w\alpha}^2}{4} F^2(2ME_r) M \left( 2 - \frac{ME_r}{E_\nu^2} \right),$$

Form factors from: C. Horowitz, K. Coakley, D. McKinsey, [astro-ph/0302071](#)

Electroweak charge:

$$\begin{aligned} \frac{1}{4} Q_{w\alpha}^2 = & \left[ Z(g_p^V + 2\epsilon_{\alpha\alpha}^{u,V} + \epsilon_{\alpha\alpha}^{d,V}) + N(g_n^V + \epsilon_{\alpha\alpha}^{u,V} + 2\epsilon_{\alpha\alpha}^{d,V}) \right]^2 \\ & + \sum_{\beta \neq \alpha} \left[ Z(2\epsilon_{\alpha\beta}^{u,V} + \epsilon_{\alpha\beta}^{d,V}) + N(\epsilon_{\alpha\beta}^{u,V} + 2\epsilon_{\alpha\beta}^{d,V}) \right]^2. \end{aligned}$$

$$Z = 32, N = 44.$$

$$g_p^V = \frac{1}{2} - 2 \sin^2 \theta_W, g_n^V = -\frac{1}{2}.$$

# SNS Beam Details

Pulsed beam: flavor discrimination

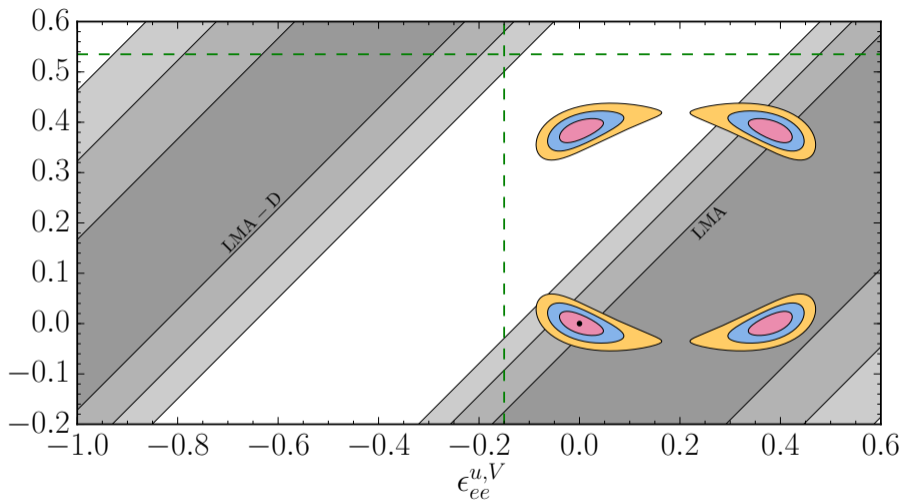
- ▶ The  $\nu_\mu$  from the  $\pi^+$  decay forms the prompt signal.
- ▶ The  $\nu_e$  and  $\bar{\nu}_\mu$  form the delayed signal.
- ▶ Probability that the muon decays within the pulse width,

$$P_c = \frac{1}{t_w} \int_0^{t_w} dt \left[ 1 - e^{-(t_w-t)/\Gamma\tau} \right] = 0.138$$

- ▶ We expect  $\sim 100$  prompt and  $\sim 200$  delayed.

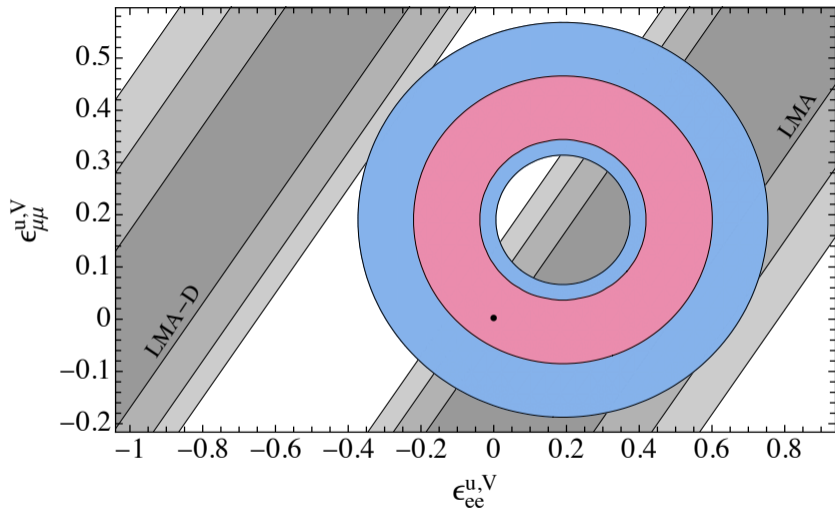
Systematics: beam normalization at 10% and 20% background.

# COHERENT Sensitivity to Exclude LMA-Dark



Predicted sensitivity measuring SM with 10 kg·yrs of  $^{76}\text{Ge}$ .

## 6. COHERENT Excludes LMA-Dark ☺

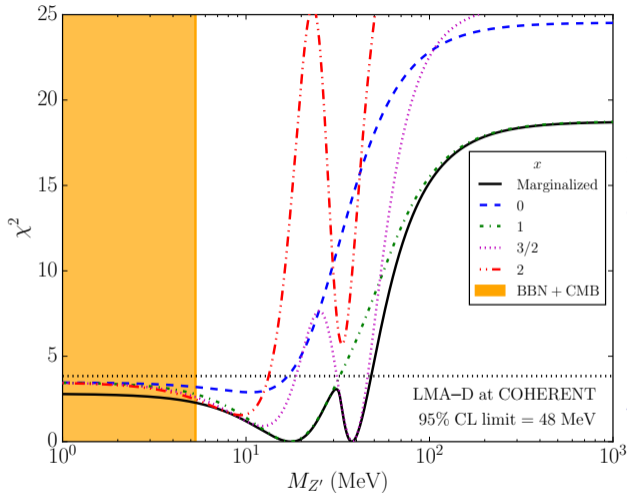


Counts only, no timing

P. Coloma, et al., [1708.02899](#)

Applies to  $m_{Z'} \gtrsim \mathcal{O}(50)$  MeV

## 7. General LMA-Dark Constraints from COHERENT ☹️



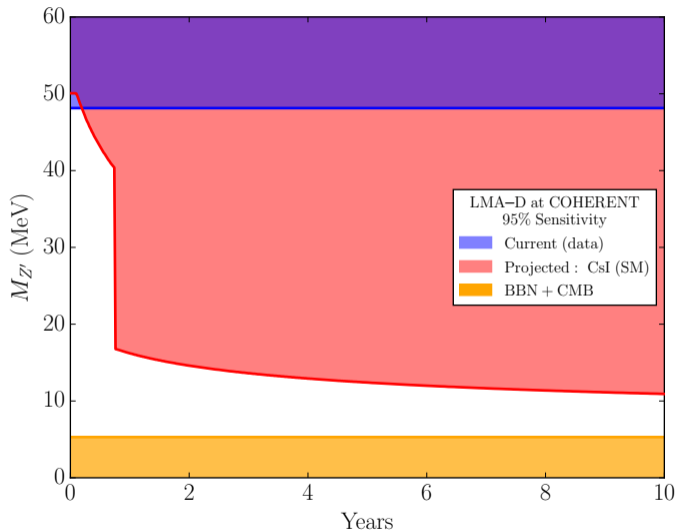
1. Assume  $\epsilon^u = \epsilon^d$
2. LMA-Dark ruled out for  $M_{Z'} > 17 \text{ MeV}$
3. Oscillations sensitive to diagonal degeneracy:  
General Oscillation Degeneracy:

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

4. LMA-Dark and diagonal degeneracy ruled out for  $M_{Z'} > 48 \text{ MeV}$

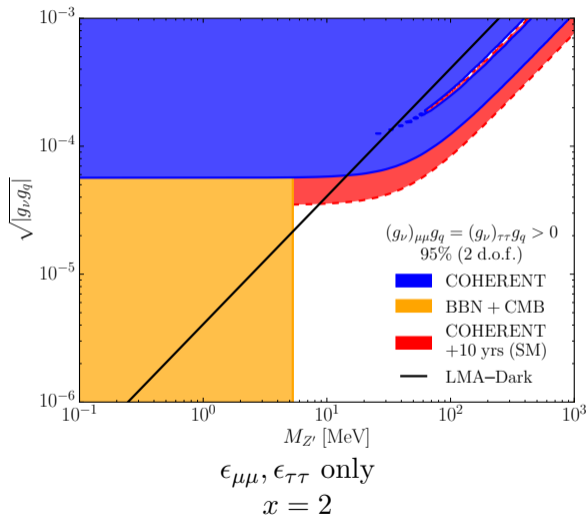
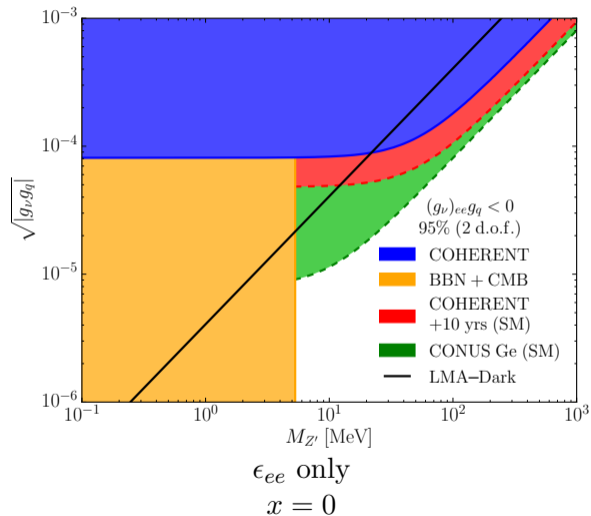
PBD, Y. Farzan, I. Shoemaker, [1804.03660](#)

# Future LMA-Dark Sensitivity at COHERENT



PBD, Y. Farzan, I. Shoemaker, [1804.03660](#)

# 8. Present and Future LMA-Dark Bounds ☹️



PBD, Y. Farzan, I. Shoemaker, [1804.03660](#)



# Light Mediator Coverage

1. **Early universe:**  $m_{Z'} \lesssim 0.1 - 1 \text{ MeV}$   
 $\Rightarrow Z'$  is relativistic at BBN,  $\Delta N_{\text{eff}} = 3 \times 4/7 = 1.7$

$N_{\text{eff}}$ -BBN measurements require  $m_{Z'} > \mathbf{5.3 \text{ MeV}}$  and  $g_\nu < 10^{-9} \frac{m_{Z'}}{\text{MeV}}$

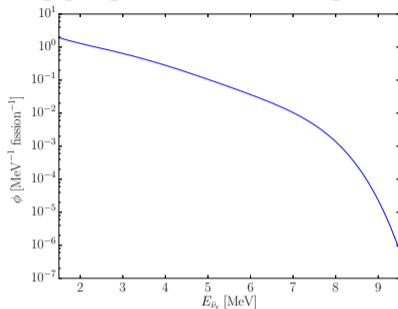
A. Kamada, H. Yu, [1504.00711](#)

Relevant  $\sqrt{g_\nu g_q} \sim 10^{-5}$

2. **Reactor CEvNS:** Sensitive to  $M_{Z'} \gtrsim 1 \text{ MeV}$

# Reactor CEvNS Experiments

Upcoming program of measuring CEvNS with reactors:

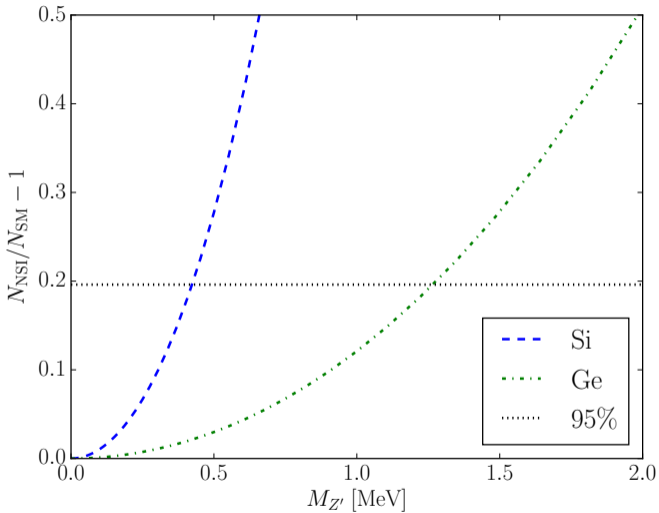


- ▶ High statistics
- ▶ Low  $q^2 \Rightarrow$  “more coherent”
  - ▶ Less form factor uncertainty
- ▶ Flux uncertainty
  - ▶ Reactor anti-neutrino anomaly
  - ▶ 5 MeV bump

Experimental program includes:

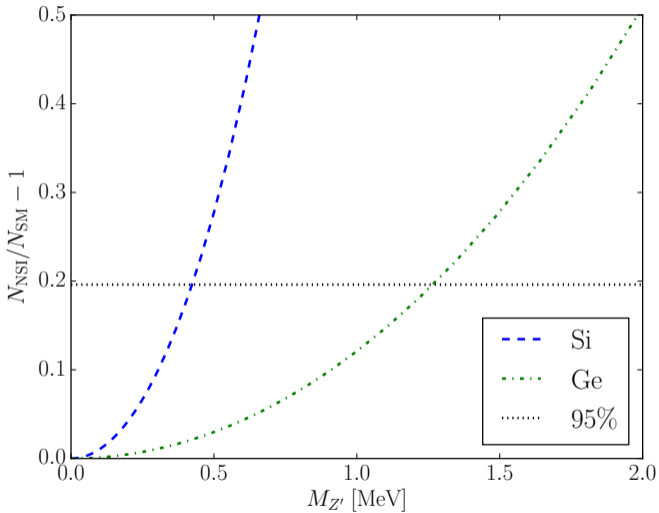
- ▶ NOSTOS [hep-ex/0503031](#)
- ▶ TEXONO [hep-ex/0511001](#)
- ▶ GEMMA [1411.2279](#)
- ▶  $\nu$ GeN [JINST 10 \(2015\)](#)
- ▶ CONNIE [1604.01343](#)
- ▶ MINER [1609.02066](#)
- ▶ CONUS [1612.04150](#)
- ▶ Ricochet [1612.09035](#)
- ▶  $\nu$ -cleus [1704.04320](#)
- ▶  $\vdots$

## 9. Reactor Sensitivity for CONUS



PBD, Y. Farzan, I. Shoemaker, [1804.03660](#)

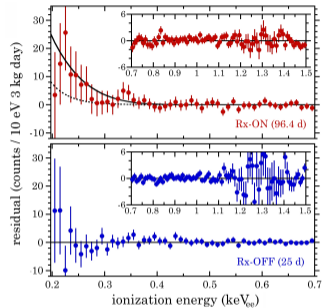
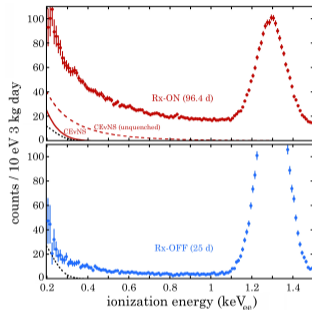
## 9. Reactor Sensitivity for CONUS



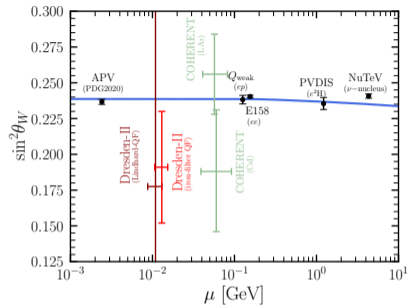
$\bar{\nu}_e$  only  $\Rightarrow$  LMA-Dark at  $x = 0$  only

PBD, Y. Farzan, I. Shoemaker, [1804.03660](#)

# Actual reactor CEvNS data from Dresden-II



Dresden-II [2202.09672](#)



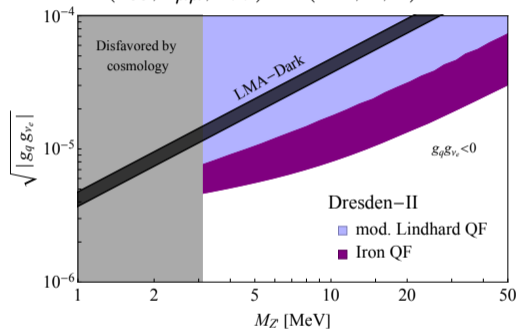
D. Sierra, V. De Romeri,  
D. Papoulias [2203.02414](#)

## Quenching factors?

# Actual reactor CEvNS data from Dresden-II

$$\epsilon_{ee}^{u,V} = \epsilon_{ee}^{d,V}$$

$$(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (-2, 0, 0)$$



Covers region for either quenching factor!

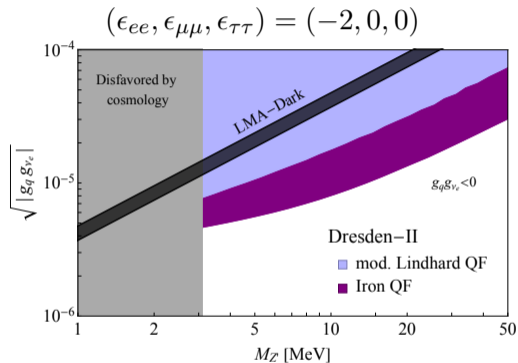
PBD, J. Gehrlein 2204.09060

Peter B. Denton (BNL HET Group)

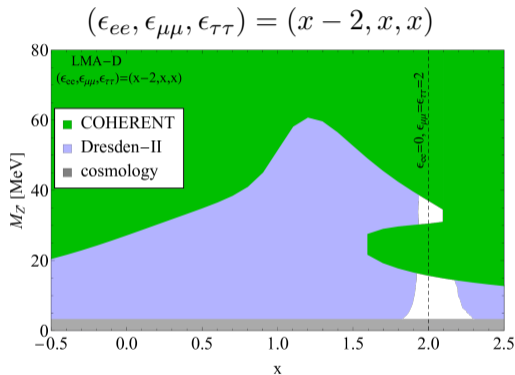
COHERENT Call: August 24, 2023 47/19

# Actual reactor CEvNS data from Dresden-II

$$\epsilon_{ee}^{u,V} = \epsilon_{ee}^{d,V}$$



Covers region for either quenching factor!



Need a low-threshold  $\pi$ -DAR:  
Coherent Captain Mills

PBD, J. Gehrlein 2204.09060

CCM 2105.14020

# Future: relax quark couplings

## Future matter effect measurements at DUNE

- ▶ LBL: measure matter effect in Earth

K. Kelly, S. Parke [1802.06784](#)

- ▶ Solar: measure matter effect in Sun and Earth

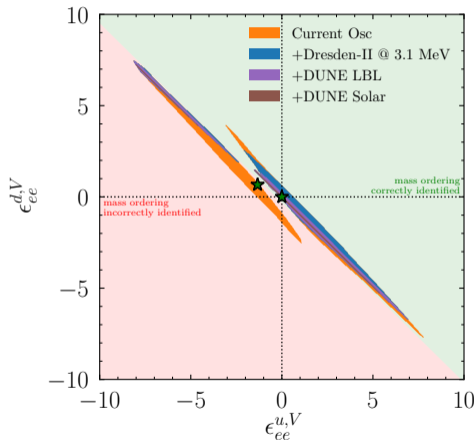
F. Capozzi, et al. [1808.08232](#)

- ▶ Atmospheric: measure matter effect in Earth

PBD, R. Pestes [2110.01148](#)

A sliver remains for certain quark combinations even for  $\epsilon_{ee} = -2$  ( $x = 0$ )  
Need better solar and long-baseline oscillations

$$(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (-2, 0, 0)$$



PBD, J. Gehrlein [2204.09060](#)












# Summary

- ▶ Exact degeneracies will be present in every oscillation experiment
- ▶ Measuring the sign of  $\Delta m_{ij}^2$  *requires* the matter effect
- ▶ The sign of  $\Delta m_{31}^2$  shows up in many neutrino searches
- ▶ New physics makes probing the mass ordering impossible with oscillations
- ▶ Oscillation experiments in different materials (Earth, Sun) helps, somewhat
- ▶ Scattering experiments help a lot, but only for heavy enough mediators
- ▶ Early universe constrains light mediators
- ▶ Gap ~~will be~~ has been covered by reactor CEvNS experiments
- ▶ Two regions remain:
  - ▶ Mostly in  $\epsilon_{\mu\mu}, \epsilon_{\tau\tau}$  sector
  - ▶ Mostly couples to protons not neutrons

# Oscillating Oscillation Degeneracies

There is a degeneracy that can be repeatedly broken and restored:

1. Can't determine mass orderings 
2. Matter effect breaks this 
3. NSIs restore the degeneracy 
4. Quark contribution breaks this 
5. Specific NSIs restores the degeneracy 
6. Scattering experiments breaks this 
7. The degeneracy is restored for light mediators 
8. LMA-Dark, light mediator, diagonal degeneracy restore the degeneracy 
9. BBN and CMB cover light mediators 

## Neutrino Mass Eigenstate Definition: Aside

The mass eigenstates can be numbered in a number of different ways

1.  $|U_{e1}| > |U_{e2}| > |U_{e3}|$
2.  $m_1 < m_2 < m_3$
3.  $m_1 < m_2$  and  $|U_{e3}| < |U_{e1}|$  and  $|U_{e3}| < |U_{e2}|$
4.  $\vdots$

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4.  $\vdots$

- ▶ #3 was commonly used in solar neutrinos
- ▶ We know that in the solar sector all three are equivalent
- ▶ We take #1 as our definition

Under definition #3 the LMA-Dark degeneracy is

$$\sin \theta_{12} \leftrightarrow \cos \theta_{12} \quad , \quad \Delta m_{31}^2 \rightarrow -\Delta m_{32}^2 \quad , \quad \delta \rightarrow \pi - \delta$$

Less symmetric  $\Rightarrow$  more errors

## NSI: The Epsilons

The  $\epsilon_{\alpha\beta}$  have 9 dof's, it's actually must worse

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The  $\epsilon_{\alpha\beta}$  have 9 dof's, it's actually must worse

$$\epsilon_{\alpha\beta} = \sum_{f=e,u,d} Y_f \epsilon_{\alpha\beta}^{f,V}$$

with

$$Y_f = \frac{n_f}{n_e}$$

dof's =  $9 \times 3 \times 2 = 54$

If SPVAT then 135

In SNe/early universe  $\nu\nu$  NSSI as well

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The  $\epsilon_{\alpha\beta}$  have 9 dof's, it's actually must worse

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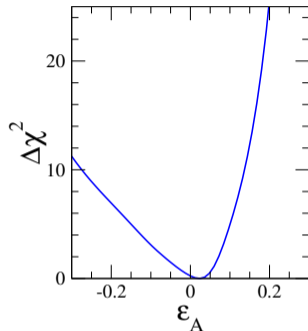
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dof's =  $9 \times 3 \times 2 = 54$

If SPVAT then 135

In SNe/early universe  $\nu\nu$  NSSI as well



- ▶ Axial is not constrained by oscillations, only scattering

Axial constraints from SNO-NC by O. Miranda, M. Tórtola, J. Valle, [hep-ph/0406280](https://arxiv.org/abs/hep-ph/0406280)

- ▶ Limit to just vector, up, down, real: dof=12

## High Energy Physics - Phenomenology

# Are solar neutrino oscillations robust?

O. G. Miranda, M. A. Tortola, J. W. F. Valle

(Submitted on 24 Jun 2004 (v1), last revised 7 Sep 2006 (this version, v3))

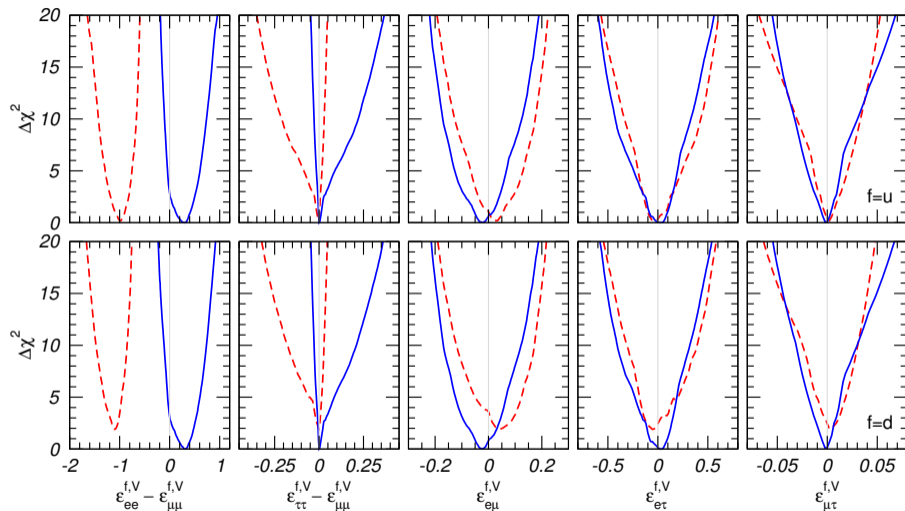
The robustness of the large mixing angle (LMA) oscillation (OSC) interpretation of the solar neutrino data is considered in a more general framework where non-standard neutrino interactions (NSI) are present. Such interactions may be regarded as a generic feature of models of neutrino mass. The 766.3 ton-yr data sample of the KamLAND collaboration are included in the analysis, paying attention to the background from the reaction  $^{13}\text{C}(\alpha, n)^{16}\text{O}$ . Similarly, the latest solar neutrino fluxes from the SNO collaboration are included. In addition to the solution which holds in the absence of NSI (LMA-I) there is a 'dark-side' solution (LMA-D) with  $\sin^2 \theta_{\text{Sol}} = 0.70$ , essentially degenerate with the former, and another light-side solution (LMA-0) allowed only at 97% CL. More precise KamLAND reactor measurements will not resolve the ambiguity in the determination of the solar neutrino mixing angle  $\theta_{\text{Sol}}$ , as they are expected to constrain mainly  $\Delta m^2$ . We comment on the complementary role of atmospheric, laboratory (e.g. CHARM) and future solar neutrino experiments in lifting the degeneracy between the LMA-I and LMA-D solutions. In particular, we show how the LMA-D solution induced by the simplest NSI between neutrinos and down-type-quarks-only is in conflict with the combination of current atmospheric data and data of the CHARM experiment. We also mention that establishing the issue of robustness of the oscillation picture in the most general case will require further experiments, such as those involving low energy solar neutrinos.

Comments: 13 pages, 6 figures; Final version to appear in JHEP

“Dark Side” from: A. de Gouvêa, A. Friedland, H. Murayama, [hep-ph/0002064](https://arxiv.org/abs/hep-ph/0002064)

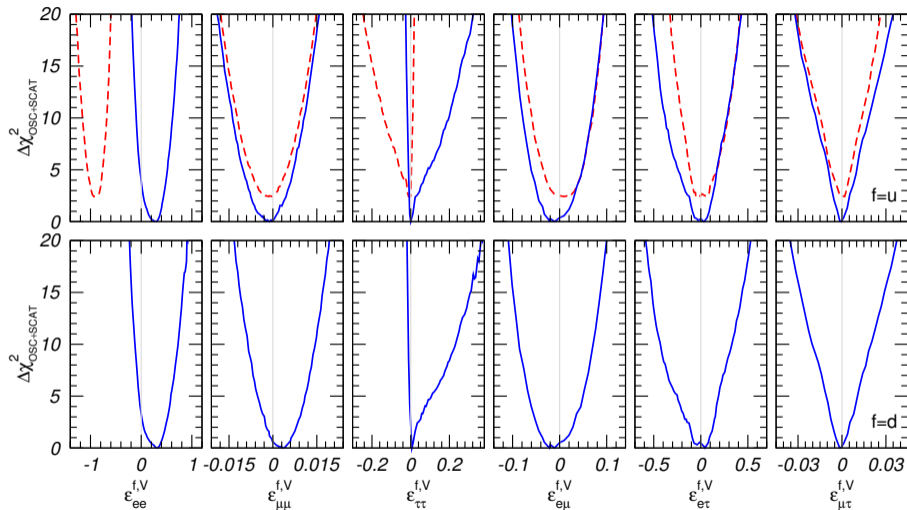


# NSI Global Fit Oscillation Data



Blue:  $\Delta m_{21}^2 > 0$ , Red:  $\Delta m_{21}^2 < 0$      P. Coloma, [PBD](#), M. Gonzalez-Garcia, M. Maltoni, T. Schwetz [1701.04828](#)

# Heavy NSI Constraints



Heavy  $\Rightarrow m_{Z'} \gtrsim 1$  GeV. All oscillation experiments, CHARM, and NuTeV.

# Mass ordering: new physics degeneracies

In the presence of new physics such as NSI we have:

$$[\text{NO}] + [\epsilon = 0] \equiv [\text{IO}] + [\epsilon_{ee} = -2]$$

$$[\text{IO}] + [\epsilon = 0] \equiv [\text{NO}] + [\epsilon_{ee} = -2]$$

Equivalences hold even if all oscillation probabilities are *perfectly* measured

P. Bakhti, Y. Farzan [1403.0744](#)

P. Coloma, T. Schwetz [1604.05772](#)

[PBD](#), S. Parke [2106.12436](#)

[PBD](#), J. Gehrlein [2204.09060](#)



This is known as the **LMA-Dark** solution

# Is the mass ordering robust?

Need **scattering** to break



Can probe same NC  $\epsilon = -2$  process in scattering, but...

CHARM and NuTeV for  $M_{Z'} \gtrsim 10$  GeV

PBD, et al. [1701.04828](#)

COHERENT for  $M_{Z'} \gtrsim 50$  MeV and cosmology for  $M_{Z'} \lesssim 5$  MeV

PBD, Y. Farzan, I. Shoemaker [1804.03660](#)

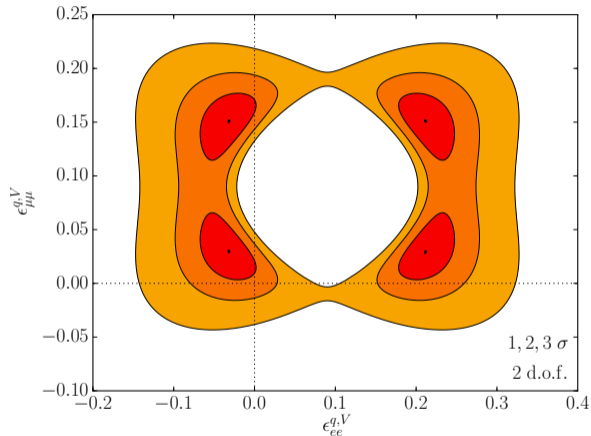
Dresden-II for any mediator mass

PBD, J. Gehrlein [2204.09060](#)

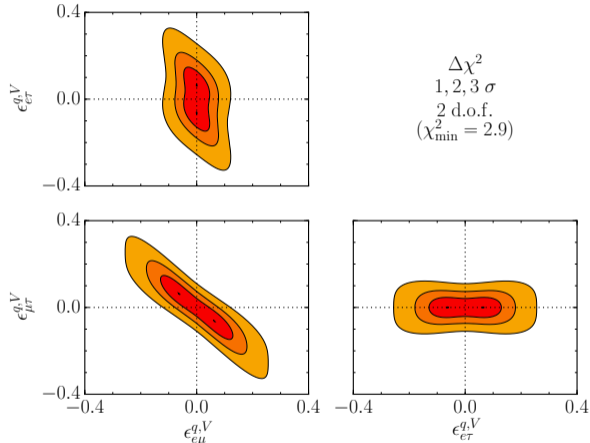
Can still evade with  $\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$  or certain  $u / d$  combinations

# NSI Projections: COHERENT

Limit ourselves to  $\epsilon^u = \epsilon^d$



Diagonal

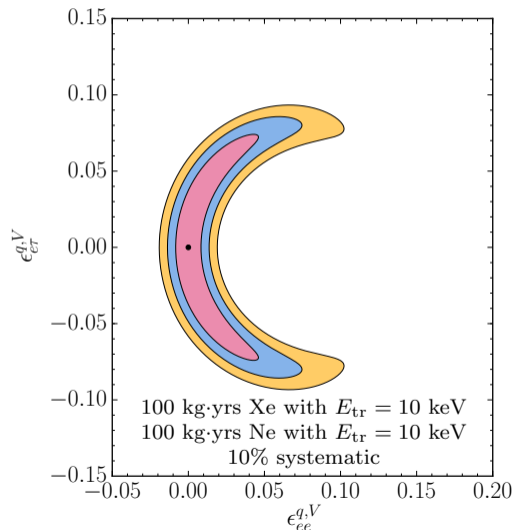


Off-Diagonal

PBD, Y. Farzan, I. Shoemaker, [1804.03660](#)

# Looking to the COHERENT Future

Interference of different materials is powerful.



$$\epsilon_{ee,\text{deg}}^{q,V} = \frac{1}{3} \frac{Y_n - (1 - 4 \sin^2 \theta_W)}{Y_n + 1}$$

$$Y_n \in [1, 1.43]$$

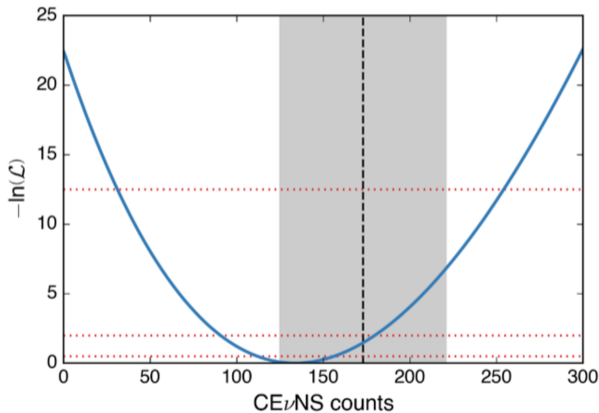
$$\epsilon_{ee,\text{deg}}^{q,V} \in [0.15, 0.18]$$

Solar upturn?

# COHERENT Results Last Year

COHERENT measured CE $\nu$ NS at  $6.7\sigma$ .

14.6 kg CsI (Na doped) for 15 months.



## Further LMA-Dark Degeneracy

There is a further exact degeneracy with scattering.

$$Q_{w\alpha}^2 \propto (X_q - \epsilon_{\alpha\alpha}^{q,V})^2,$$

with

$$X_u = -\frac{Zg_p^V + Ng_n^V}{2Z + N}, X_d = -\frac{Zg_p^V + Ng_n^V}{Z + 2N}.$$

This leads to an exact degeneracy at

$$\epsilon_{ee}^{u,V} = \begin{cases} -0.15 \\ 0.842 \end{cases}, \quad \epsilon_{ee}^{d,V} = \begin{cases} -0.224 \\ 0.886 \end{cases}.$$

- ▶ In this case a scattering experiment cannot break the degeneracy.
- ▶ Multiple materials can break this degeneracy in theory, in practice this is hard.
- ▶ Best fit points seem to be far from these points, so there is no problem.



# Recap: Oscillations and the Diagonal Terms

## Solar

Chlorine, Gallex/GNO, SAGE,  
Super-K, Borexino, and SNO.

## Atmospheric

Super-K, MINOS, and T2K.

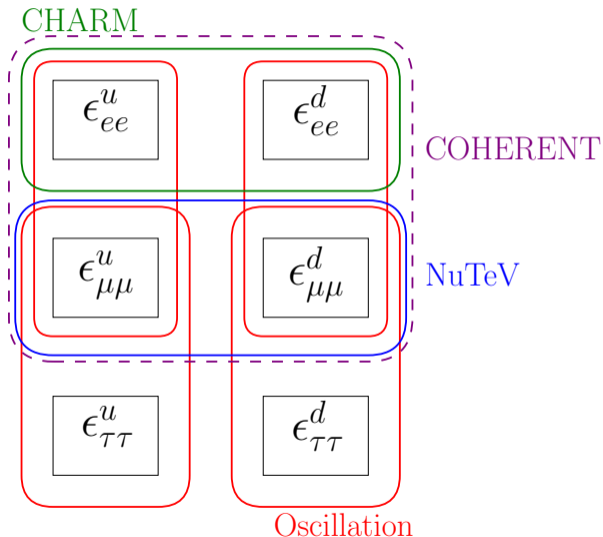
## Reactor

CHOOZ, Palo Verde, Double CHOOZ,  
Daya Bay, and RENO.

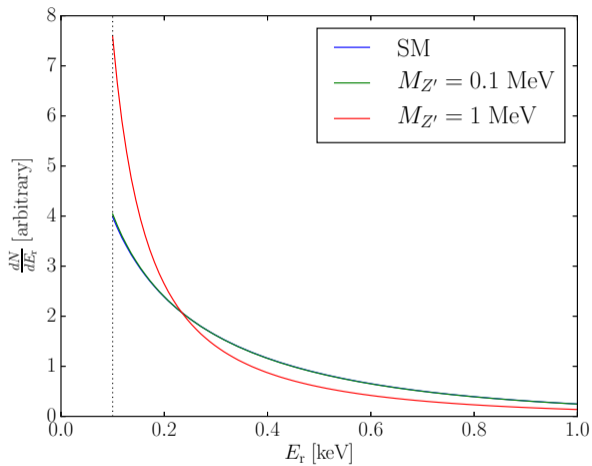
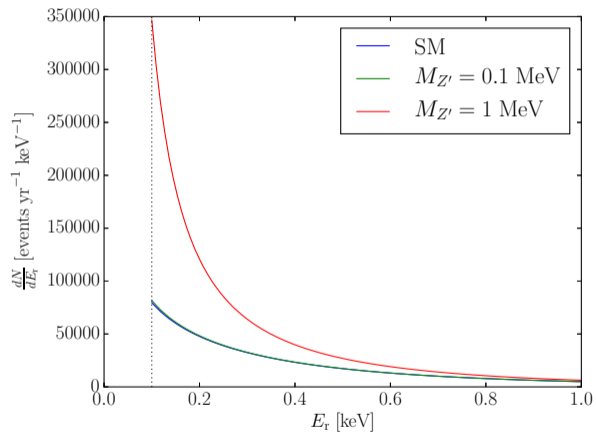
## Short baseline

Bugey, ROVNO, Krasnoyarsk, ILL,  
Gösgen, and SRP.

Global fit to oscillation data



# Reactor Spectrum Shape Analysis



LMA-Dark  $x = 0$  shape sensitivity down to  $\sim 1$  MeV.