New Neutrino Interactions: Breaking Degeneracies and Relaxing Sterile Tensions

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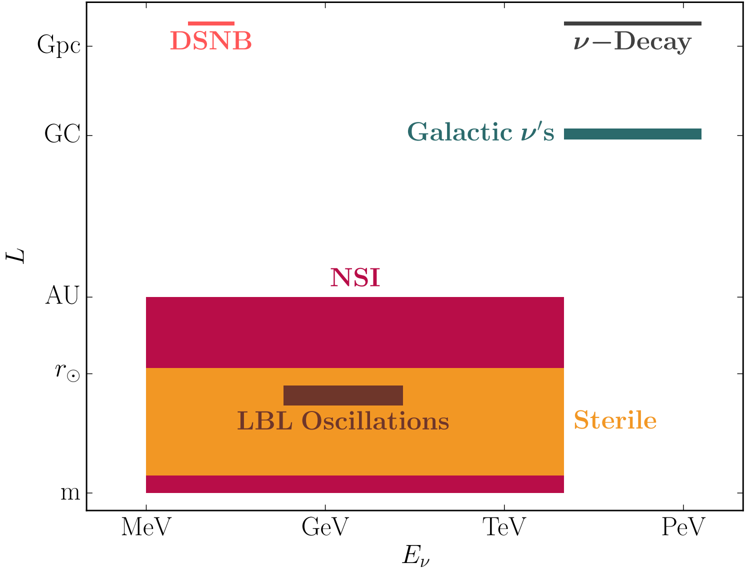
BNL

August 3, 2018

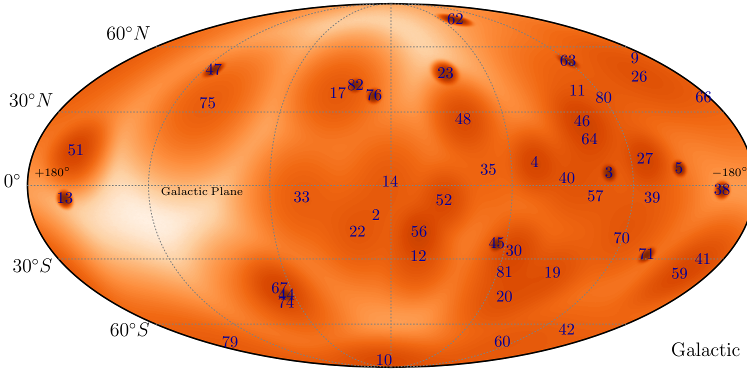
The Niels Bohr International Academy

VILLUM FONDEN

Neutrinos at All Scales



IceCube Neutrinos Origin



$< 9.5\%$ galactic fraction at 90% CL

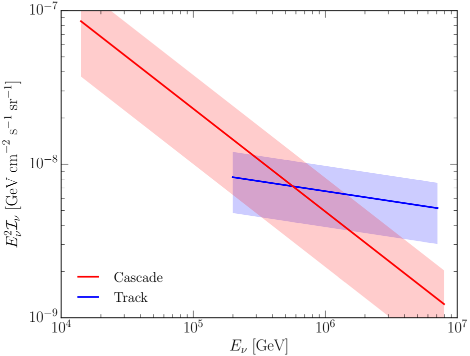
PBD, D. Marfatia, T. Weiler, 1703.09721

Consistent with IceCube, 1707.03416

IceCube's Tracks and Cascades

IceCube measures different spectra for tracks (ν_μ) and cascades (ν_e, ν_τ).

No standard model of sources describes the data.

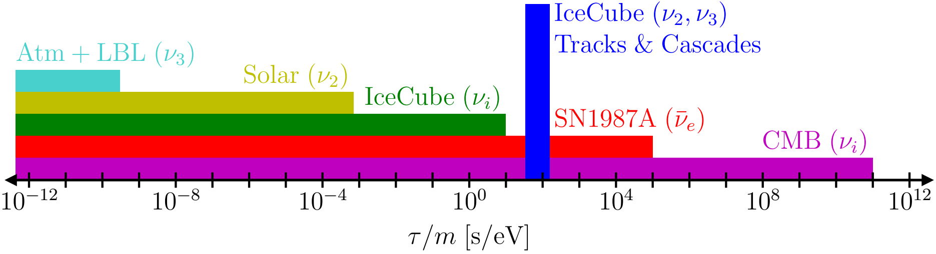


DM decay could work (early universe constraints)

Invisible ***ν*-decay** of ν_2 and ν_3 preferred at 3.4 σ.
Predict ~50% smaller ν_τ flux.

PBD, I. Tamborra, 1805.05950

Invisible ν Decay Constraints and Evidence



PBD, I. Tamborra, 1805.05950

S. Hannestad, G. Raffelt, hep-ph/0509278

Kamiokande-II, PRL 58 1490 (1987)

G. Pagliaroli, et al., 1506.02624

J. Berryman, A. de Gouvea, D. Hernandez, 1411.0308

M. Gonzalez-Garcia and M. Maltoni, 0802.3699

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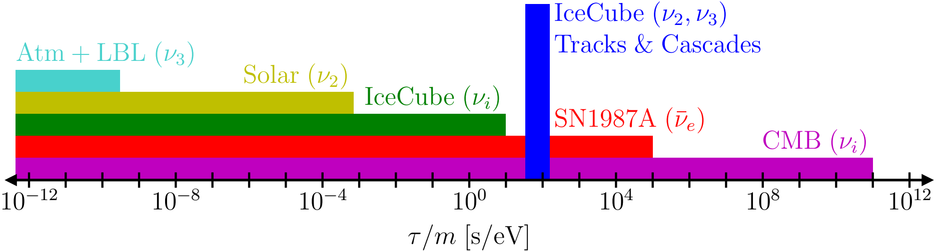

ν_2, ν_3 decay leads to 16% reduction in $\bar{\nu}_e$ flux:
SN 1987A doesn't apply

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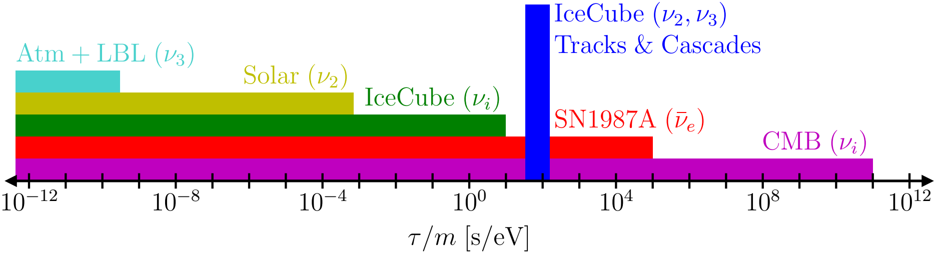

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CMB constraints assume all flavors decay, <3 decaying is allowed...

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J. Berryman, A. de Gouvea, D. Hernandez, `1411.0308`

M. Gonzalez-Garcia and M. Maltoni, `0802.3699`

N. Bell, E. Pierpaoli, K. Sigurdson, `astro-ph/0511410`

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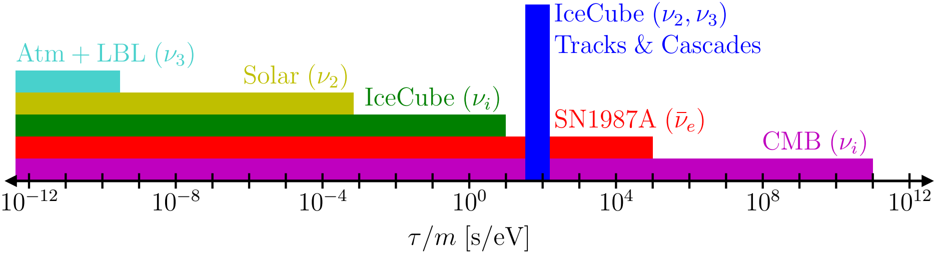


ν_2, ν_3 decay leads to 16% reduction in $\bar{\nu}_e$ flux: SN 1987A doesn't apply

CMB constraints assume all flavors decay, <3 decaying is allowed... and may be slightly preferred

PBD, I. Tamborra, 1805.05950

S. Hannestad, G. Raffelt, hep-ph/0509278

Kamiokande-II, PRL 58 1490 (1987)

G. Pagliaroli, et al., 1506.02624

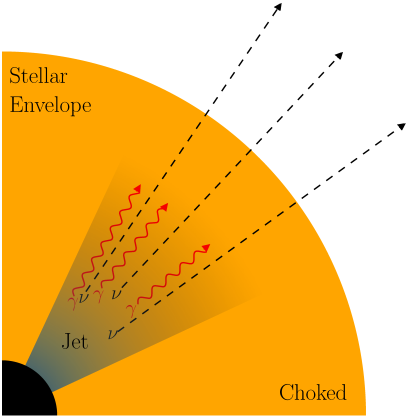
J. Berryman, A. de Gouvea, D. Hernandez, 1411.0308

M. Gonzalez-Garcia and M. Maltoni, 0802.3699

N. Bell, E. Pierpaoli, K. Sigurdson, astro-ph/0511410

M. Archidiacono, et al., 1404.5915

GRB - SN Connection with Neutrinos

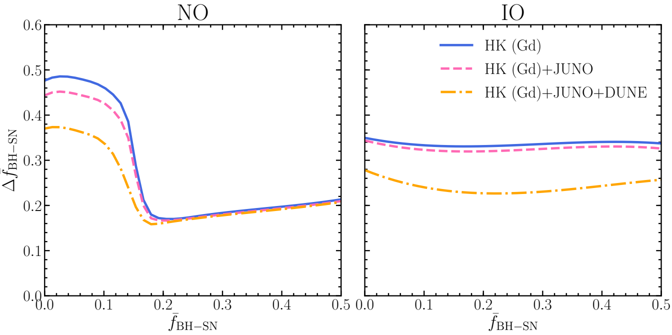


- Realistic jet structure
- Connect visible to invisible (choked) jets
- IC constrains fraction of SNe that form jets $\lesssim 1\%$

PBD, I. Tamborra, 1711.00470

PBD, I. Tamborra, 1802.10098

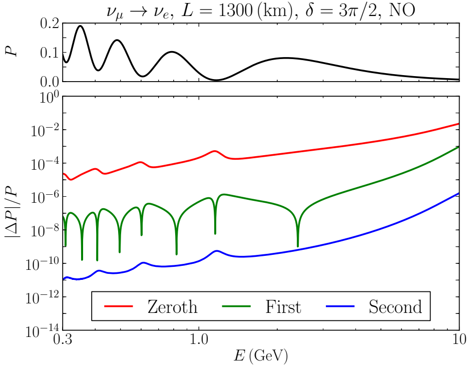
Supernova Properties with Neutrinos

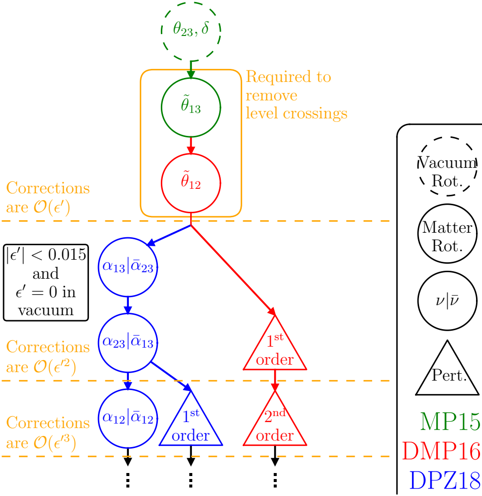


Hyper-K, JUNO, and DUNE measure the DSNB
Constrain BH/NS fraction

K. Møller, A. Suliga, I. Tamborra, PBD, 1804.03157

What are neutrino oscillation probabilities in matter?



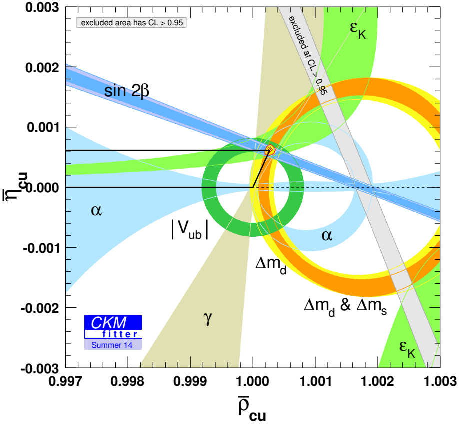


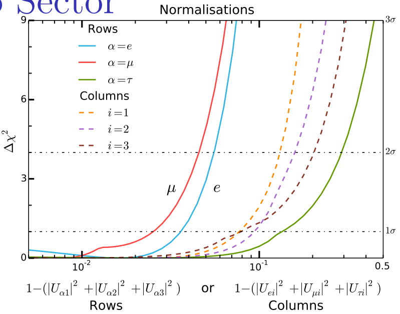
PBD, H. Minakata, S. Parke, 1604.08167, 1801.06514

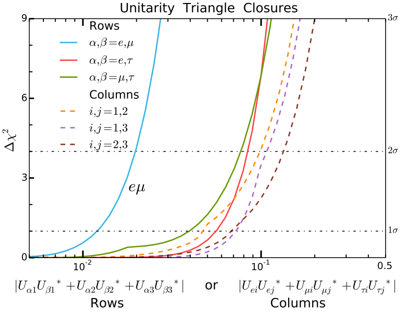
PBD, S. Parke, X. Zhang, 1806.01277

PBD, S. Parke, in prep.

Over Constrain the Neutrino Sector







J. Charles, et al., 1501.05013

S. Parke, M. Ross-Lonergan, 1508.05095

Not Just Under Constrained

arXiv.org > hep-ph > arXiv:hep-ph/0406280

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High Energy Physics - Phenomenology

Are solar neutrino oscillations robust?

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

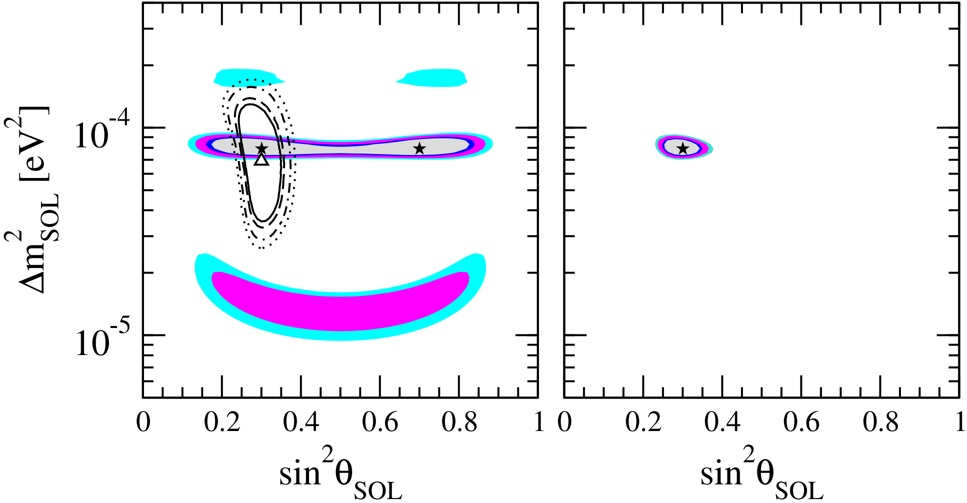
(Submitted on 24 Jun 2004 (v1), last revised 7 Sep 2006 (this version, v3))

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 ^13C(\alpha,n) ^16O. 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_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_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

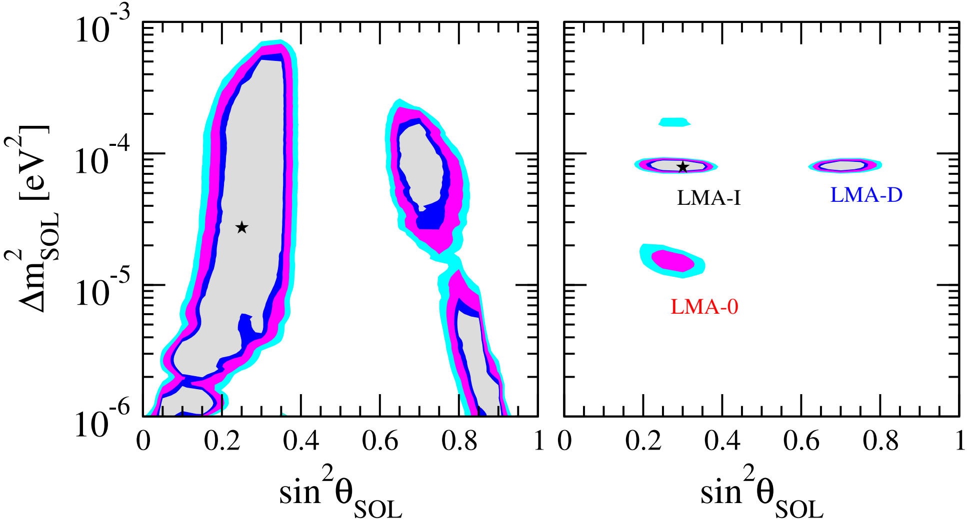
Best Fit Assuming Standard Neutrino Physics



90%, 95%, 99% and 99.73% CL O. Miranda, M. Tórtola, J. Valle, hep-ph/0406280

KamLAND (color), solar (black).

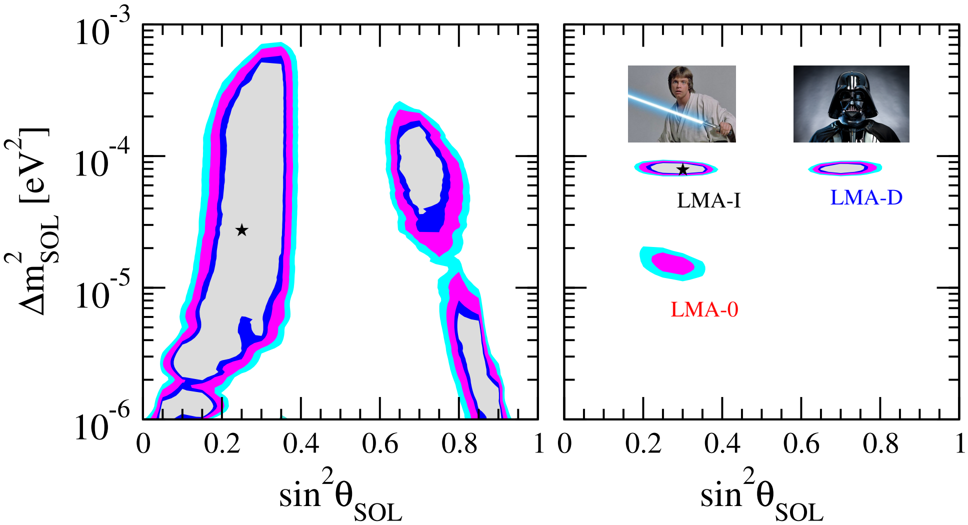
Allowing For New Neutrino Interactions



O. Miranda, M. Tórtola, J. Valle, hep-ph/0406280

Solar (left), solar + KamLAND (right), $\Delta\chi^2 = 80.2 - 79.7$.

Allowing For New Neutrino Interactions



O. Miranda, M. Tórtola, J. Valle, hep-ph/0406280

Solar (left), solar + KamLAND (right), $\Delta\chi^2 = 80.2 - 79.7$.

New Physics: Phenomenology

The simplest/clearest phenomenological description of NSI is,

$$H_\nu = H_\nu^{\rm vac} + H_\nu^{\rm mat}\,,$$

with

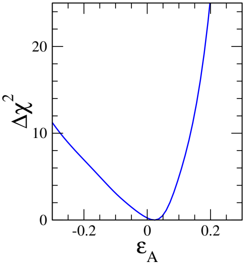
$$H_\nu^{\rm vac} = \frac{1}{2E} U_{\rm PMNS} \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U_{\rm PMNS}^\dagger$$

$$H_\nu^{\rm mat} = H_\nu^{\rm mat,SM} + H_\nu^{\rm mat,NSI}$$

$$H_\nu^{\rm mat,SM} = \sqrt{2} G_F n_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

$$H_\nu^{\rm mat,NSI} = \sqrt{2} G_F n_e \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

NSI: The Epsilons



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

with

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

- We constrain ourselves to only consider vector NSI.
- Generically, axial-vector NSI may exist as well.
- This doubles the number of free parameters.
- Axial is not constrained by oscillations, only scattering.

Axial constraints from SNO-NC by O. Miranda, M. Tórtola, J. Valle, hep-ph/0406280

Lagrangian

EFT Lagrangian:

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

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

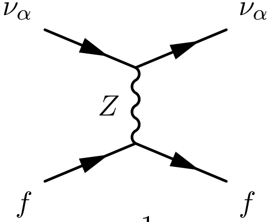
Simplified model Lagrangian:

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

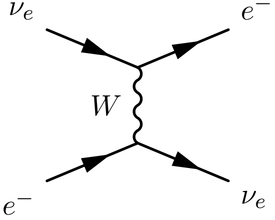
which gives a potential

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

Matter Effects in Feynman Diagrams

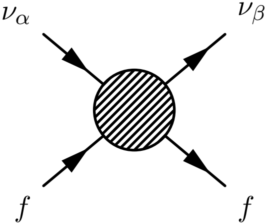


$$V_{\mathrm{NC}} = \mp\frac{1}{2}\sqrt{2}G_F n_n$$



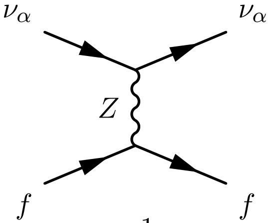
$$V_{\mathrm{CC}} = \pm\sqrt{2}G_F n_e$$

L. Wolfenstein, PRD 17 (1978)



$$V_{\mathrm{NSI}} = \pm\epsilon_{\alpha\beta}^{f,X}\sqrt{2}G_F n_f$$

Matter Effects in Feynman Diagrams



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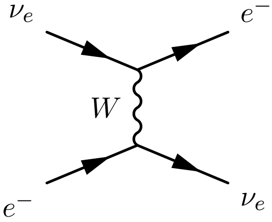

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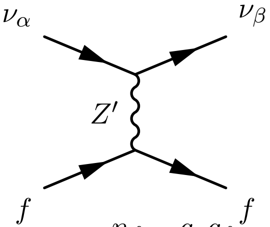


$$V_{\mathrm{NSI}} = \frac{n_f}{2}\frac{g_\nu g_f}{q^2 + m_{Z'}^2}$$

Generalized Mass Ordering Degeneracy (GMOD)

CPT symmetry $\Rightarrow$ that oscillations are invariant under $H \to -H^*$.

In vacuum, change:

- Switch mass ordering: $\Delta m^2_{31} \to -\Delta m^2_{32}$,
- $\sin\theta_{12} \to \cos\theta_{12}$,
- $\delta \to \pi - \delta$.

In vacuum, this degeneracy is exact.

In matter, the degeneracy can be restored with NSI with changes,

- $\epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta}$,
- $\epsilon_{ee} \to -\epsilon_{ee} - 2 \Rightarrow \epsilon_{ee} = -2$.

This can be broken by varying or different neutron densities.
The degeneracy can be restored by setting $\epsilon^u_{\alpha\beta} = -2\epsilon^d_{\alpha\beta}$.
Setting $\epsilon^u_{ee} = -4/3$ and $\epsilon^d_{ee} = 2/3$ yields an exact degeneracy $\forall\, Y_n$.

P. Coloma, T. Schwetz, 1604.05772

NSI in Scattering Experiments Probe Different Scales

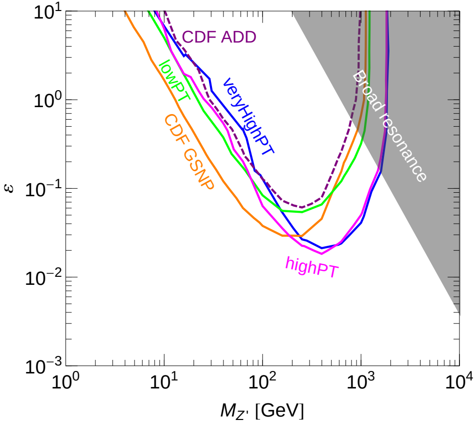
NSI affects:

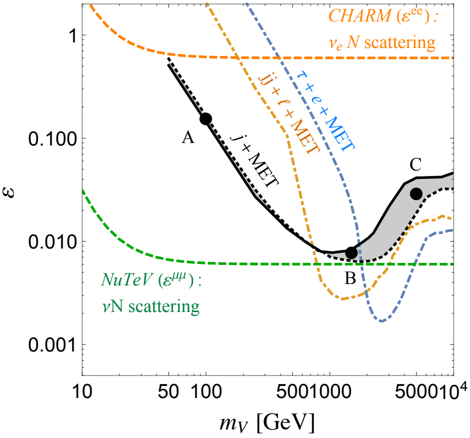
- Oscillation: $q^2 = 0$, the effect is valid for any $m_{Z'}$.
- Scattering: the NSI potential is suppressed if $q^2 > m_{Z'}^2$.

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

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 $\overset{(-)}{\nu}_e$ cross sections with nuclei,

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

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

CHARM Collaboration, PLB180 (1986)

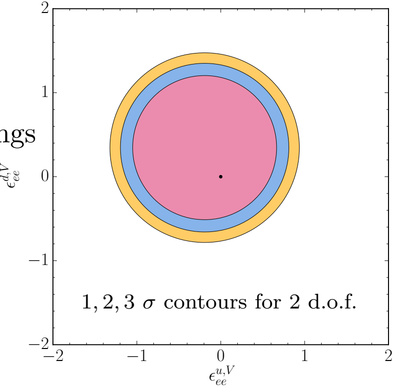
$$(\tilde{g}_e^P)^2 = \sum_{q=u,d} \left[(g_q^P + \epsilon_{ee}^{q,P})^2 + \sum_{\alpha \neq e} |\epsilon_{e\alpha}^{q,P}|^2 \right]$$

2-loop radiative corrections for SM couplings

J. Erler, S. Su, 1303.5522

$R_{e,\mathrm{SM}} = 0.333$ for $q^2 \sim 20$ GeV^2.

PBD, et al., 1701.04828



NuTeV

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

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

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

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

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

NuTeV Collaboration, hep-ex/0110059

G. P. Zeller PhD thesis

This leads to $\chi^2_{\mathrm{NuTeV,SM}} \sim 9$ 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

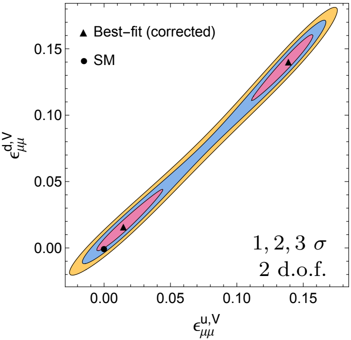
NNPDF Collaboration, 0906.1958

W. Bentz, et al., 0908.3198

$$\delta R^{\nu}_{\mu,\mathrm{exp}} = 0.0017\,, \quad \delta R^{\bar{\nu}}_{\mu,\mathrm{exp}} = -0.0016\,,$$

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

Corrected $\chi^2_{\mathrm{NuTeV,SM}} \sim 2.3$.



PBD, et al., 1701.04828

Coherent Elastic ν Nucleus Scattering: CEvNS ("Sevens")

CEvNS := ν scattering off the weak charge of entire nucleus

The CEvNS 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.

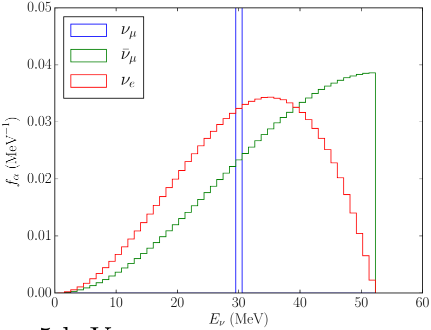
COHERENT

Spallation Neutron Source at Oak Ridge National Laboratory in a **π-DAR** configuration.

K. Scholberg, hep-ex/0511042

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

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



Detector 22 m from source with $E_{\rm tr} = 5$ 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:

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

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

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

SNS Beam Details

Pulsed beam: flavor discrimination

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

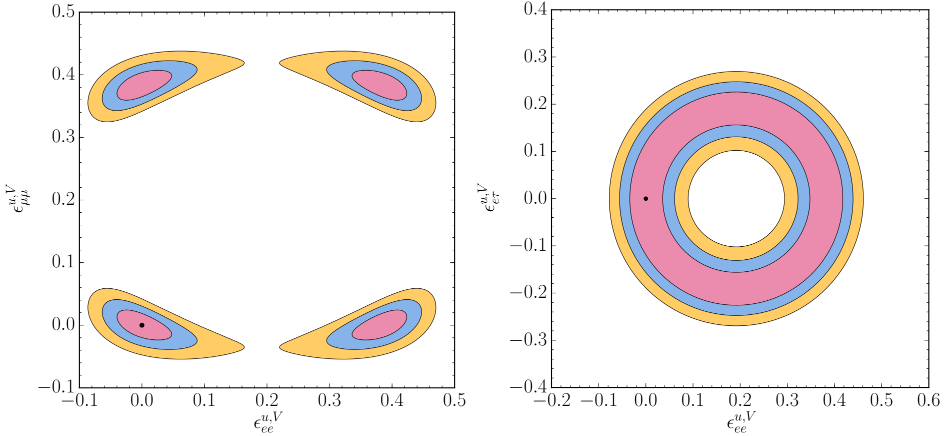
$$P_c = \frac{1}{t_w} \int_0^{t_w} dt \left[1 - e^{-(t_w - t)/\Gamma\tau}\right] = 0.138$$

- We expect ~ 100 prompt and ~ 200 delayed.

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

COHERENT Sensitivity

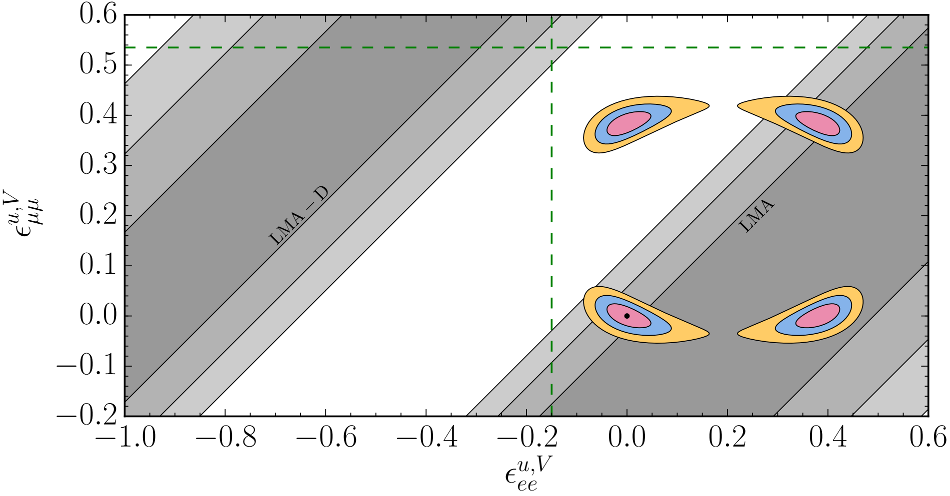
$\epsilon_{e\tau}$ is poorly constrained.



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

LHS shape is due to prompt + delayed. PBD, et al., 1701.04828

COHERENT Sensitivity to Exclude LMA-Dark



Predicted sensitivity measuring SM with 10 kg·yrs of ^{76}Ge.
Dashed lines are the locations of another exact degeneracy.

PBD, et al., 1701.04828

Early Universe

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

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

A. Kamada, H. Yu, 1504.00711

Oscillations and the Diagonal Terms

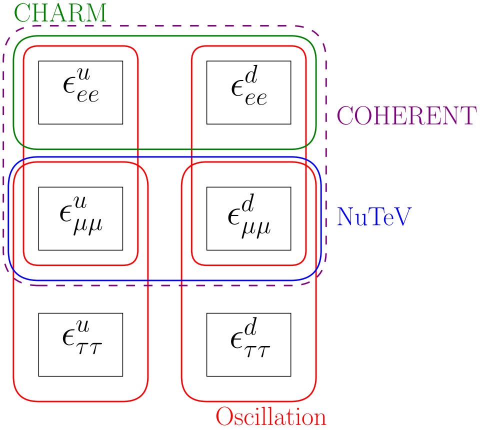
Solar
Chlorine, Gallex/GNO, SAGE, Super-K, Borexino, and SNO.

Atmospheric
Super-K, MINOS, and T2K.

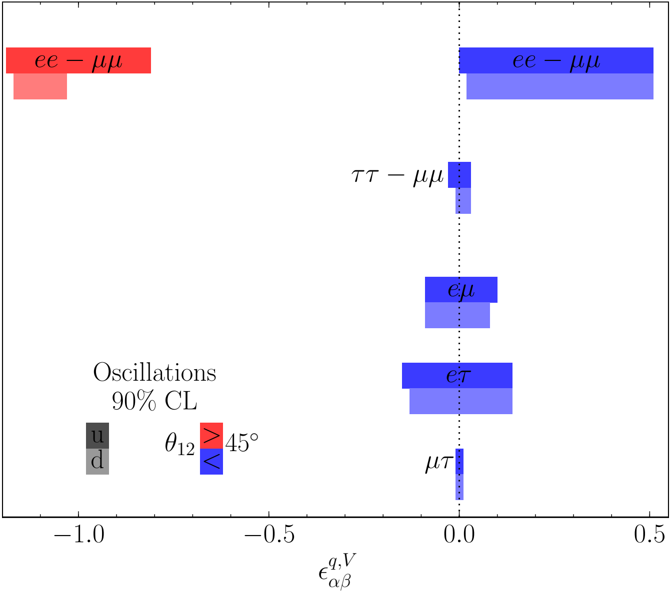
Reactor
CHOOZ, Palo Verde, Double CHOOZ, Daya Bay, and RENO.

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

Global fit to oscillation data



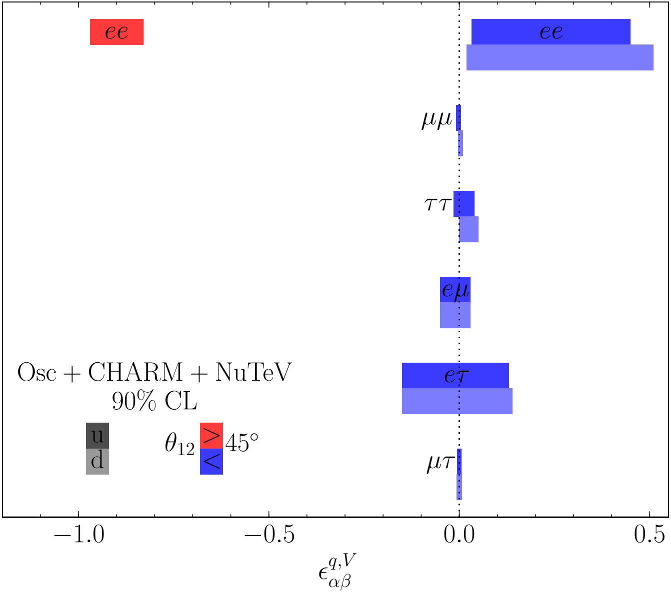
NSI Global Fit: Oscillations



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

PBD, et al., 1701.04828

Heavy NSI Global Fit: CHARM & NuTeV

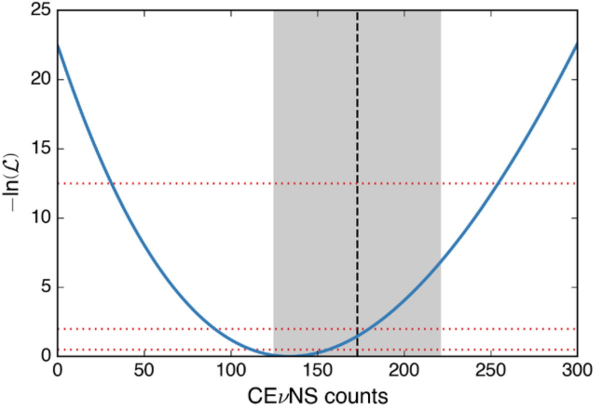


Heavy $\Rightarrow m_{Z'} \gtrsim 1$ GeV.

PBD, et al., 1701.04828

COHERENT Results Last Year

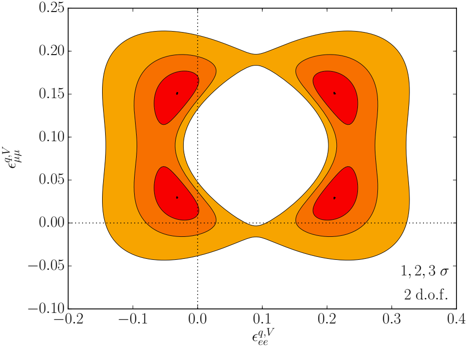
COHERENT measured CEvNS at 6.7σ.
14.6 kg CsI (Na doped) for 15 months.



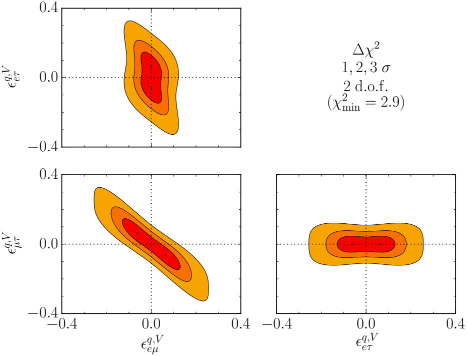
COHERENT Collaboration, 1708.01294 Science

NSI Projections: COHERENT

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



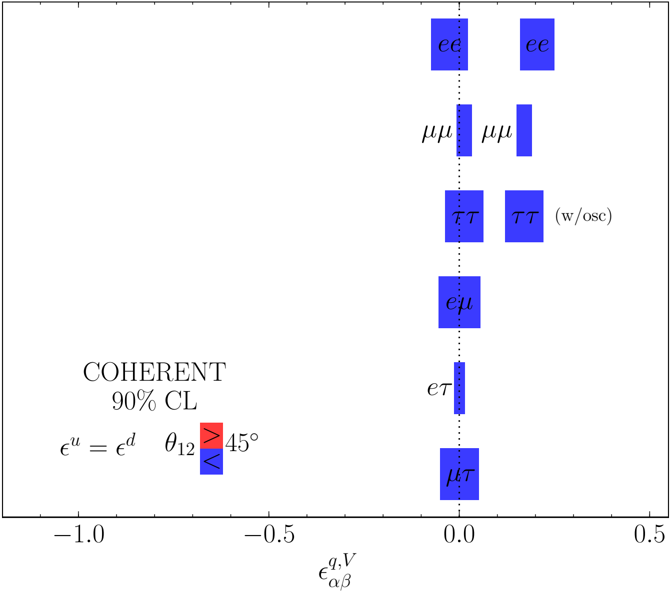
Diagonal



Off-Diagonal

PBD, Y. Farzan, I. Shoemaker, 1804.03660

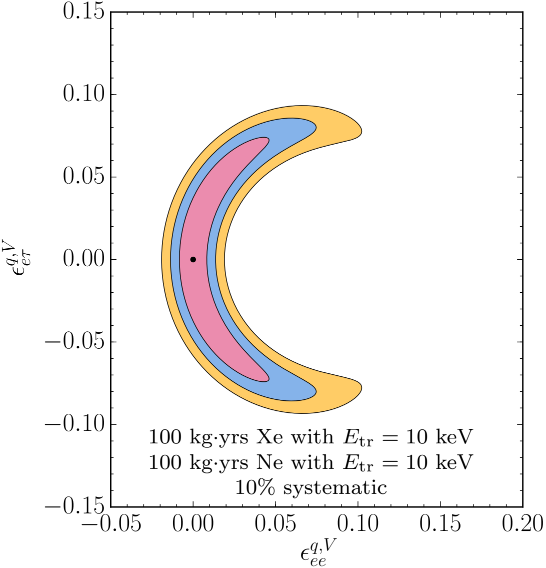
NSI Constraints: COHERENT



Valid down to $m_{Z'} \gtrsim 10$ MeV PBD, Y. Farzan, I. Shoemaker, 1804.03660

Looking to the COHERENT Future

Interference of different materials is powerful.



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

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

$$\epsilon^{q,V}_{ee,\rm deg} \in [0.15, 0.18]$$

Solar upturn?

Looking to the Long Baseline Future

- DUNE

P. Coloma, 1511.06357

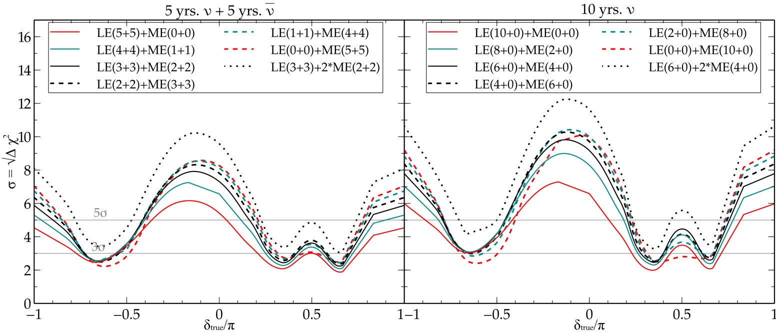
M. Masud, M. Bishai, P. Mehta, 1704.08650

- T2HK, T2HKK

J. Liao, D. Marfatia, K. Whisnant, 1612.01443

- ESSνSB

M. Blennow, et al., 1507.02868



Two NSI Generalizations

1. NSI with mediator mass

$$\epsilon_{\alpha\beta}^{f,V}(q) = \frac{(g_\nu)_{\alpha\beta}\, g_f}{2\sqrt{2}G_F(q^2 + m_{Z'}^2)}$$

   Oscillations is the $q \to 0$ limit.

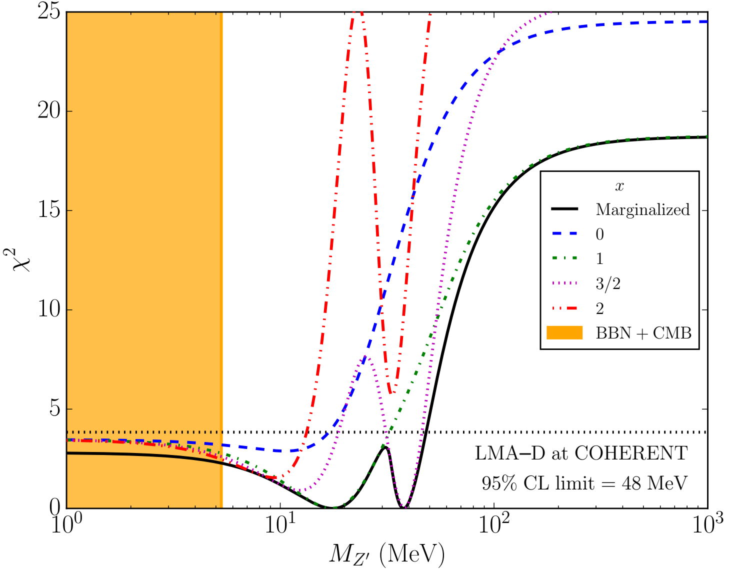
2. Diagonal degeneracy for oscillations

$$H \to H + x\mathbb{1}$$

   General Oscillation Degeneracy

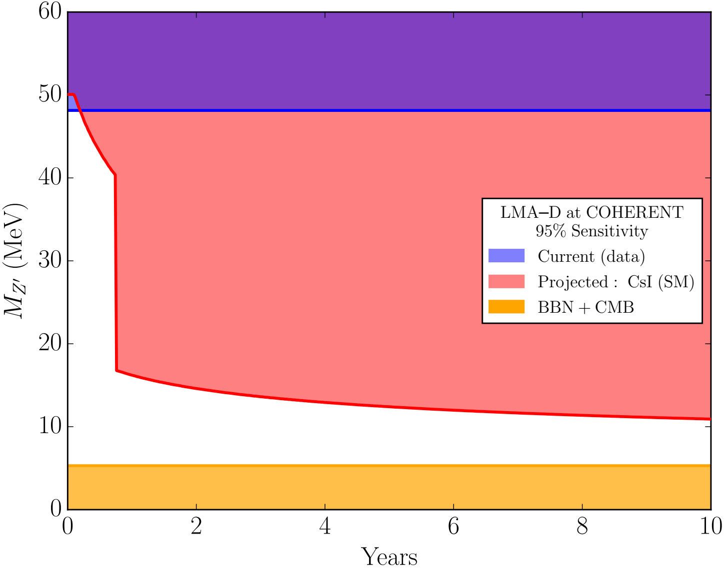
$$(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (x-2, x, x)$$

General LMA-Dark Constraints from COHERENT



PBD, Y. Farzan, I. Shoemaker, 1804.03660

Future LMA-Dark Sensitivity at COHERENT

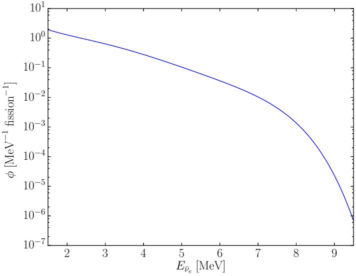


← Gap?

PBD, Y. Farzan, I. Shoemaker, 1804.03660

Reactor CEvNS Experiments

Upcoming program of measuring CEvNS with reactors:



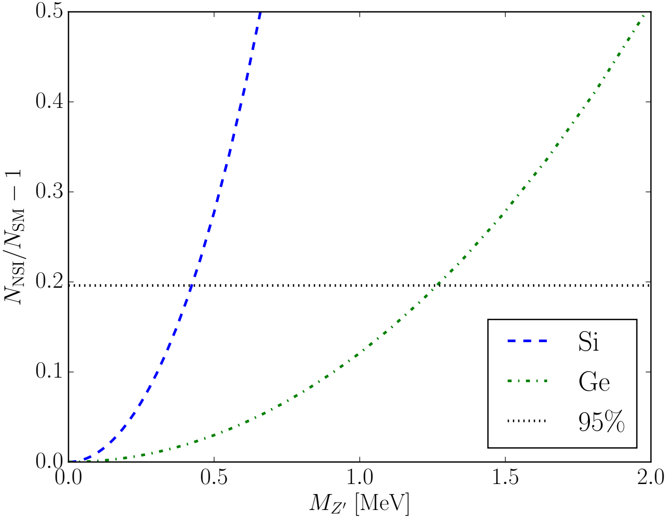
- High statistics
- Low $q^2 \Rightarrow$ "more coherent"
  - Less form factor uncertainty
- Flux uncertainty
  - Reactor anti-neutrino anomaly
  - 5 MeV bump

Experimental program includes:

- NOSTOS hep-ex/0503031
- TEXONO hep-ex/0511001
- GEMMA 1411.2279
- νGeN JINST 10 (2015)
- CONNIE 1604.01343
- MINER 1609.02066
- CONUS 1612.04150
- Ricochet 1612.09035
- ν-cleus 1704.04320

$\vdots$

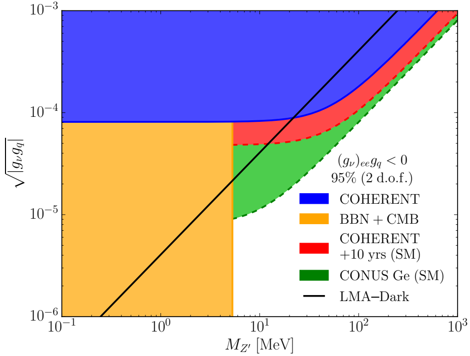
Reactor Sensitivity for CONUS



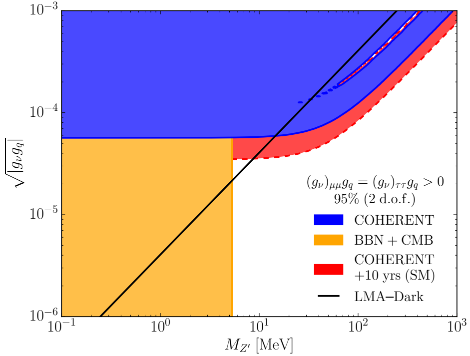
$\bar{\nu}_e$ only $\Rightarrow$
LMA-Dark
at $x = 0$ only.

PBD, Y. Farzan, I. Shoemaker, 1804.03660

Present and Future LMA-Dark Bounds



ϵ_{ee} only
$x = 0$



$\epsilon_{\mu\mu}, \epsilon_{\tau\tau}$ only
$x = 2$

PBD, Y. Farzan, I. Shoemaker, 1804.03660

Sterile Neutrino Motivation

- Probably required for neutrino mass generation
- $m_4 \gtrsim 1$ keV $\Rightarrow$ DM (also 7 keV sterile from X-ray line)

S. Dodelson, L. Widrow, hep-ph/9303287

E. Bulbul, et al., 1402.2301

- Experimental evidence for $m_4 \sim 1$ eV
  - LSND + MiniBooNE: 6.1 σ

    LSND, hep-ex/0104049

    MiniBooNE, 1805.12028
  - Reactor Antineutrino Anomaly: 3 σ

    G. Mention, et al., 1101.2755

    A. Hayes, E. McCutchan, A. Sonzogni, et al., 1707.07728
  - Gallium anomaly: 3 σ

    C. Giunti, M. Laveder, 1006.3244
  - NEOS & DANSS: $\sim 3\ \sigma$ & 2.8 σ

    NEOS, Neutrino, '18

    DANSS, Neutrino, '18

1 eV Steriles: Constraints

Experimental constraints from:

- IceCube 1605.01990
- MINOS/MINOS+ 1710.06488
  See also W. Louis, 1803.11488
- Super-K 1410.2008
- KARMEN hep-ex/0203021
- CDHS PLB 134, 281 (1984)
- Daya Bay, MINOS, Bugey-3 1607.01177
- OPERA 1303.3953
- ICARUS 1209.0122
- NOvA 1706.04592
- PROSPECT 1806.02784

⋮

The Sterile NSI Model

Main components:

- $m_s \sim 1$ eV
- $m_{Z'} \sim 10$ eV

New $U_X(1)$ where fermions carry charge

$$B + a_e L_e + a_\mu L_\mu + a_\tau L_\tau$$

Need $\sum_\alpha a_\alpha = -3$ for chiral anomaly cancellation

This leads to negligible NSI among active neutrinos.

Sterile is charged under $U_X(1)$ with $a_s = g_s/g_B$.

Active-sterile mixing breaks gauge invariance.

The Sterile NSI Model

Add $U_X(1)$ charged Higgs doublet H'

- vev $\langle H' \rangle$
- Same charge as ν_s
- Mixing $U_{\alpha 4} = y_\alpha \langle H' \rangle / m_{\nu_s}$
- Contributes to the Z' mass $\langle H' \rangle < 10\text{ keV}\left(\frac{m_{Z'}}{10\text{ eV}}\right)\left(\frac{10^{-3}}{g_s}\right)$

Heavy H' with small vev?
New singlet scalar S with same $U_X(1)$ charge

$$\mathcal{L} \supset -m_S^2|S|^2 + \lambda_S|S|^4 + \mu S^\dagger H' \cdot H$$

$$\langle H' \rangle = -\langle S \rangle \frac{\mu \langle H \rangle}{2m_{H'}^2}$$

The S vev comes from m_S and $\langle S \rangle$ gives the Z' its mass.

Sterile NSI Model: Oscillations

$$V_s = 3(2\sqrt{2})G_F n_n \epsilon_{ss}$$

$$\epsilon_{ss} = \frac{g_s g_B}{m_{Z'}^2}\frac{1}{6\sqrt{2}G_F}$$

$$H_\nu^{\mathrm{mat}} = \begin{pmatrix} V_{\mathrm{CC}} + V_{\mathrm{NC}} & & & \\ & V_{\mathrm{NC}} & & \\ & & V_{\mathrm{NC}} & \\ & & & V_{\mathrm{s}} \end{pmatrix}$$

Sterile NSI Model Bounds

$Z - Z'$ mixing constrained to $\delta \lesssim 0.01$

H. Davoudiasl, H. Lee, W. Marciano, 1203.2947

We have $\delta < 7 \times 10^{-8} \left(\frac{m_{Z'}}{10\text{ eV}}\right)\left(\frac{10^{-3}}{g_s}\right)$

Consistent with fifth force and stellar cooling constraints.

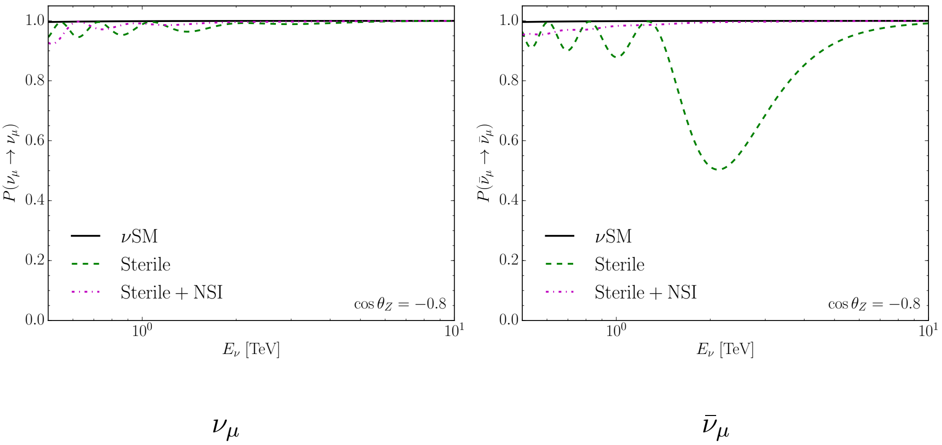
M. Bordag, U. Mohideen, V. Mostepanenko, quant-ph/0106045

E. Hardy, R. Lasenby, 1611.05852

Negligible contribution to $N_{\rm eff}$.

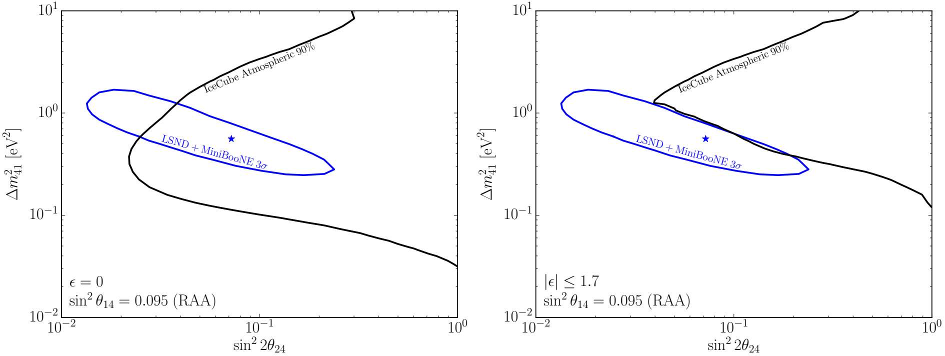
IceCube Oscillation Probabilities

Resonant MSW conversion of $\Delta m^2_{41} \simeq 1$ eV^2 through the core



PBD, Y. Farzan, I. Shoemaker, in prep.

Removing IceCube Sterile Constraints with NSI



Sterile

Sterile + Interaction

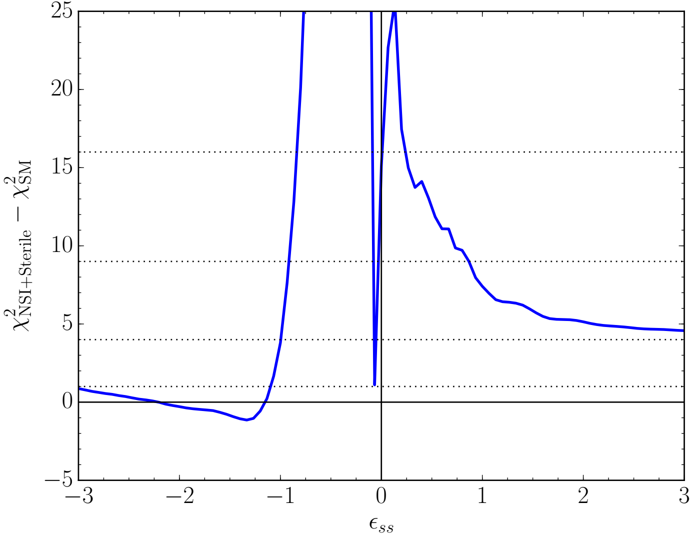
PBD, Y. Farzan, I. Shoemaker, in prep.

M. Dentler, et al., 1803.10661

See also J. Liao, D. Marfatia, 1602.08766

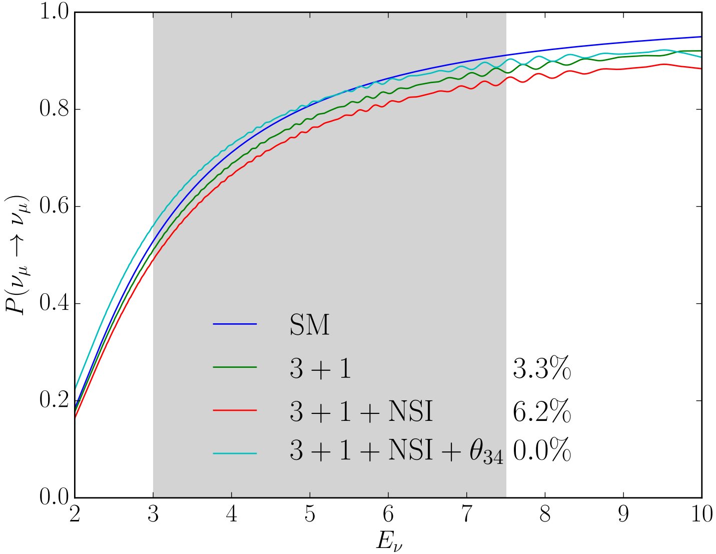
Removing IceCube Sterile Constraints with NSI

Sterile parameters fixed to global best fit



PBD, Y. Farzan, I. Shoemaker, in prep.

MINOS+

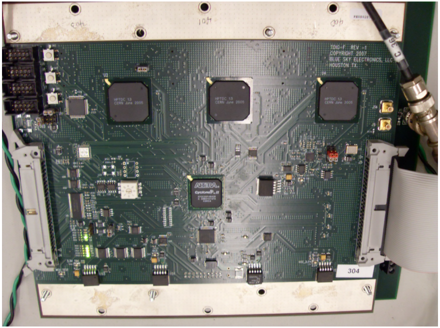


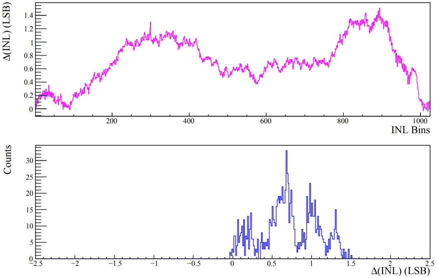
PBD, Y. Farzan, I. Shoemaker, in prep.

Wrap-up

- NSI parameterizes **generic** BSM pheno in the neutrino sector
- Large NSI $\gtrsim \mathcal{O}$(electroweak) **always allowed** by oscillation data
  - LMA-Dark
  - Diagonal degeneracy
- For heavy mediators $m_{Z'} \gtrsim 50$ MeV
  - CHARM, NuTeV, and COHERENT
  - With COHERENT LMA-Dark is completely ruled out
- For light mediators 5 MeV $\lesssim m_{Z'} \lesssim 50$ MeV
  - COHERENT can shrink the gap
  - Reactor CEvNS is needed to close it (ϵ_{ee} only)
- Anticipate future COHERENT and LBL results
- Making progress on constraining BSM ν physics
- Evidence **for** and **against** the $3+1$ sterile picture
- Adding an **interaction** to the **sterile sector** alleviates tension

STAR-TOF TDIG Boards Calibration in 2008

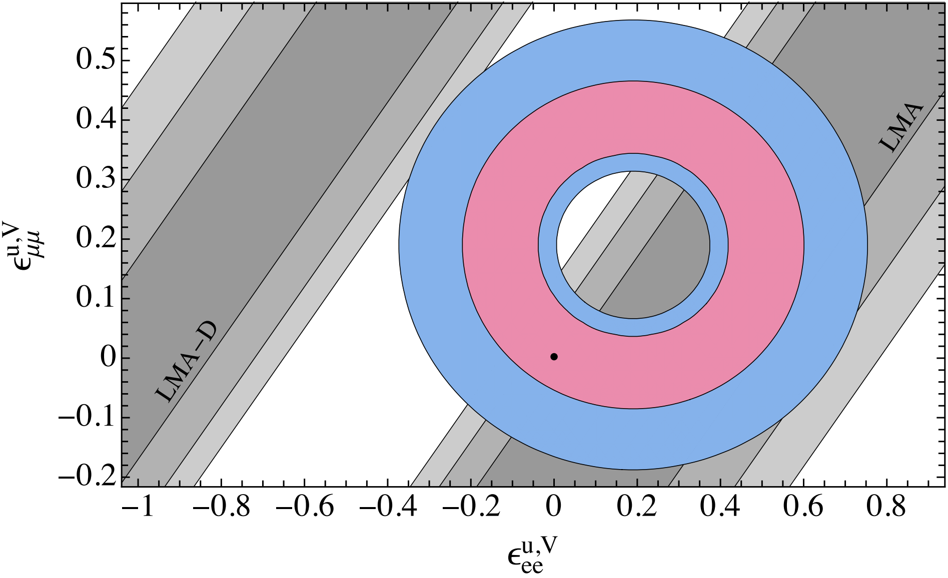




Thank you!

Backups

Light NSI Constraints: Count Only



P. Coloma, et al., 1708.02899

NSI Constraints for All Masses
Oscillations

$\epsilon_{ee}^{u,V} - \epsilon_{\mu\mu}^{u,V}$	$[-1.19, -0.81] \oplus [0.00, 0.51]$
$\epsilon_{\tau\tau}^{u,V} - \epsilon_{\mu\mu}^{u,V}$	$[-0.03, 0.03]$
$\epsilon_{e\mu}^{u,V}$	$[-0.09, 0.10]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.14]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.01, 0.01]$
$\epsilon_{ee}^{d,V} - \epsilon_{\mu\mu}^{d,V}$	$[-1.17, -1.03] \oplus [0.02, 0.51]$
$\epsilon_{\tau\tau}^{d,V} - \epsilon_{\mu\mu}^{d,V}$	$[-0.01, 0.03]$
$\epsilon_{e\mu}^{d,V}$	$[-0.09, 0.08]$
$\epsilon_{e\tau}^{d,V}$	$[-0.13, 0.14]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.01, 0.01]$

90% CL

NSI Constraints for Heavy Mediators
Oscillations + CHARM + NuTeV

$\epsilon_{ee}^{u,V}$	$[-0.97, -0.83] \oplus [0.033, 0.450]$
$\epsilon_{\mu\mu}^{u,V}$	$[-0.008, 0.005]$
$\epsilon_{\tau\tau}^{u,V}$	$[-0.0015, 0.04]$
$\epsilon_{e\mu}^{u,V}$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.13]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.006, 0.005]$
$\epsilon_{ee}^{d,V}$	$[0.02, 0.51]$
$\epsilon_{\mu\mu}^{d,V}$	$[-0.003, 0.009]$
$\epsilon_{\tau\tau}^{d,V}$	$[-0.001, 0.05]$
$\epsilon_{e\mu}^{d,V}$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{d,V}$	$[-0.15, 0.14]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.007, 0.007]$

90% CL

NSI Predictions for Heavy Mediators
Oscillations + CHARM + NuTeV + COHERENT(SM)

$\epsilon_{ee}^{u,V}$	$[0.014, 0.032] \oplus [0.24, 0.41]$
$\epsilon_{\mu\mu}^{u,V}$	$[-0.007, 0.005]$
$\epsilon_{\tau\tau}^{u,V}$	$[-0.006, 0.04]$
$\epsilon_{e\mu}^{u,V}$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.13]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.006, 0.004]$
$\epsilon_{ee}^{d,V}$	$[0.26, 0.38]$
$\epsilon_{\mu\mu}^{d,V}$	$[-0.003, 0.009]$
$\epsilon_{\tau\tau}^{d,V}$	$[-0.001, 0.05]$
$\epsilon_{e\mu}^{d,V}$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{d,V}$	$[-0.15, 0.14]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.007, 0.007]$

90% CL

NSI Constraints for Light Mediators
Oscillations + COHERENT(data)

$\epsilon_{ee}^{u,V}$	$[0.028, 0.60]$
$\epsilon_{\mu\mu}^{u,V}$	$[-0.088, 0.37]$
$\epsilon_{\tau\tau}^{u,V}$	$[-0.090, 0.38]$
$\epsilon_{e\mu}^{u,V}$	$[-0.073, 0.044]$
$\epsilon_{e\tau}^{u,V}$	$[-0.15, 0.13]$
$\epsilon_{\mu\tau}^{u,V}$	$[-0.01, 0.009]$
$\epsilon_{ee}^{d,V}$	$[0.03, 0.55]$
$\epsilon_{\mu\mu}^{d,V}$	$[-0.075, 0.33]$
$\epsilon_{\tau\tau}^{d,V}$	$[-0.075, 0.33]$
$\epsilon_{e\mu}^{d,V}$	$[-0.07, 0.04]$
$\epsilon_{e\tau}^{d,V}$	$[-0.13, 0.12]$
$\epsilon_{\mu\tau}^{d,V}$	$[-0.009, 0.008]$

90% CL from P. Coloma, et al., 1708.02899

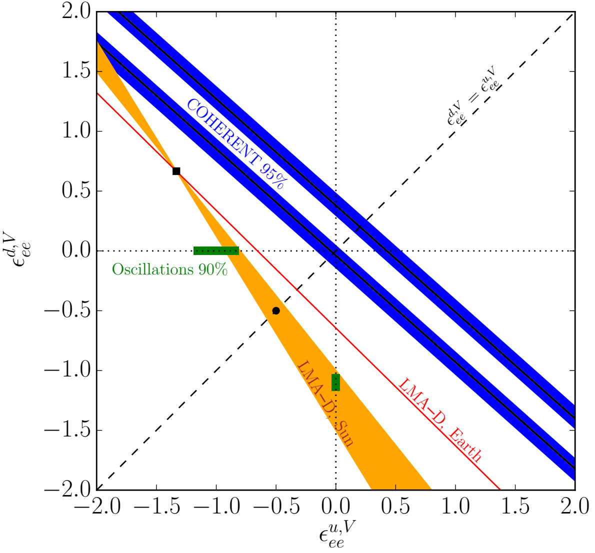
NSI Constraints for Light Mediators
Oscillations + COHERENT(data)

$$\epsilon^u = \epsilon^d$$

$\epsilon_{ee}^{q,V}$	$[-0.073, 0.023] \oplus [0.16, 0.25]$
$\epsilon_{\mu\mu}^{q,V}$	$[-0.007, 0.033] \oplus [0.15, 0.19]$
$\epsilon_{\tau\tau}^{q,V}$	$[-0.0015, 0.05]$
$\epsilon_{e\mu}^{q,V}$	$[-0.05, 0.03]$
$\epsilon_{e\tau}^{q,V}$	$[-0.014, 0.014]$
$\epsilon_{\mu\tau}^{q,V}$	$[-0.007, 0.007]$

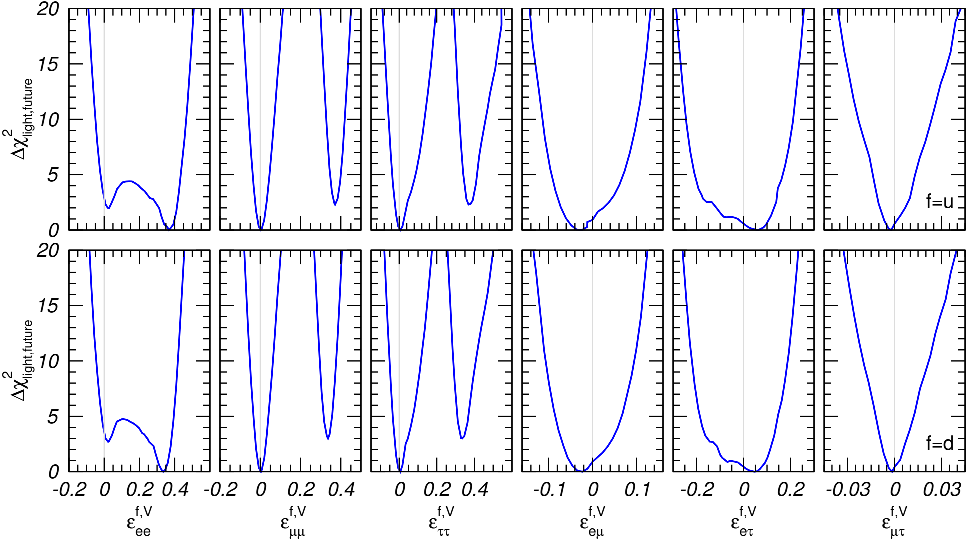
PBD, Y. Farzan, I. Shoemaker, 1804.03660

LMA-Dark Picture



COHERENT constraints for large $m_{Z'}$.

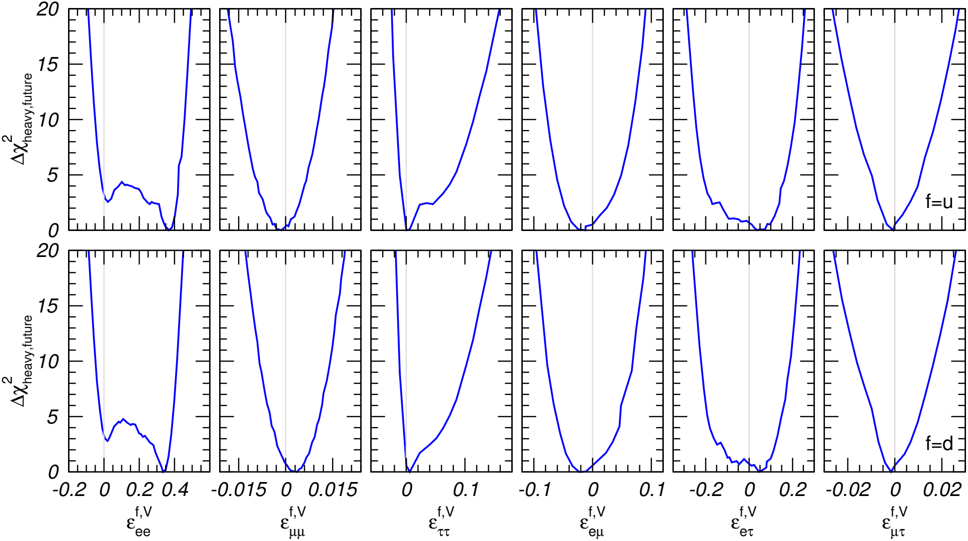
Predicted Light NSI Constraints



Assume that COHERENT measures SM: $\epsilon = 0$.

Oscillation plus COHERENT (no CHARM or NuTeV).

Predicted Heavy NSI Constraints



Heavy $\Rightarrow m_{Z'} \gtrsim 1$ GeV. All oscillation experiments, CHARM, and NuTeV. Assumes COHERENT measures SM: $\epsilon = 0$.

COHERENT χ^2

The COHERENT χ^2,

$$\chi^2_{\rm COH}=\min_\xi\sum_{k=p,d}\left(\frac{(1+\xi)N_{k,\rm NSI}-N_{k,\rm obs}}{\sqrt{N_{k,\rm obs}+0.2N_{k,\rm obs}}}\right)^2+\left(\frac{\xi}{0.1}\right)^2\,,$$

where 20% is the background rate and 10% is a normalization uncertainty covering various systematics including fast neutrons and CR and radioactive backgrounds.

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

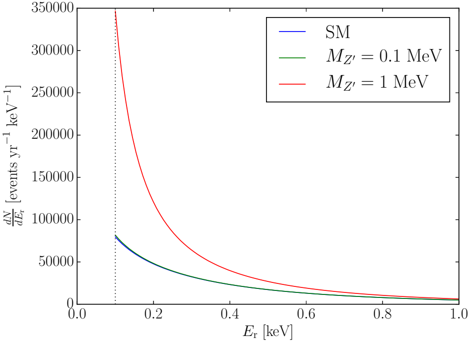
$$X_u = -\frac{Zg_p^V + Ng_n^V}{2Z+N} \,, X_d = -\frac{Zg_p^V + Ng_n^V}{Z+2N} \,.$$

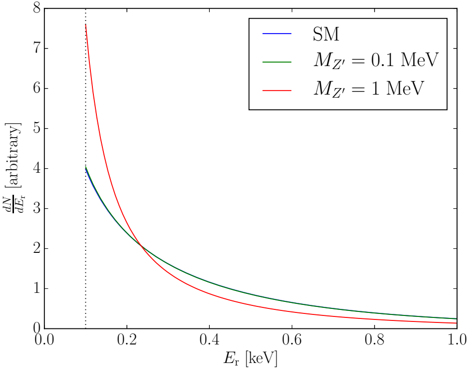
This leads to an exact degeneracy at

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

- 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.

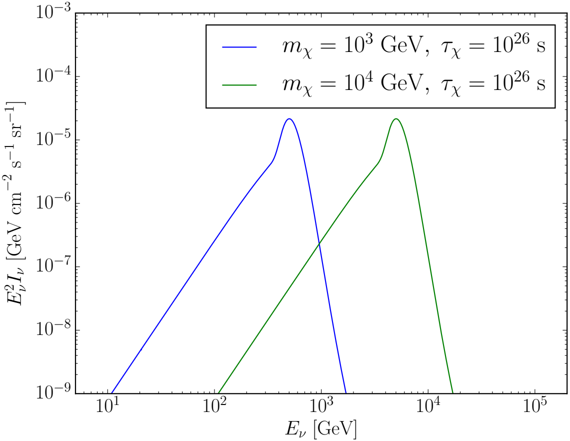
Reactor Spectrum Shape Analysis





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

BνSM Effects



Dark Matter Decay:

Prefer decay over annihilation due to anisotropy constraints

PBD, D. Marfatia, T. Weiler, 1703.09721

Consider couplings to ν_α (+ charged lepton, SU(2)).

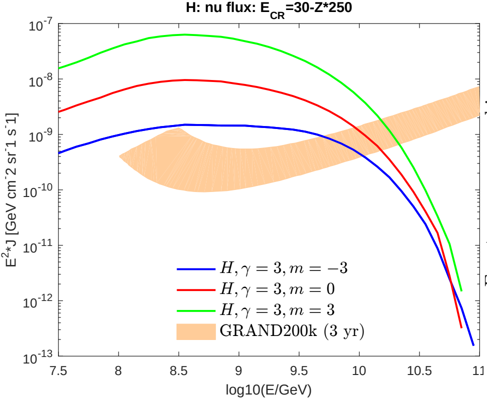
Radiative corrections with PYTHIA 8.2, NFW galactic profile.

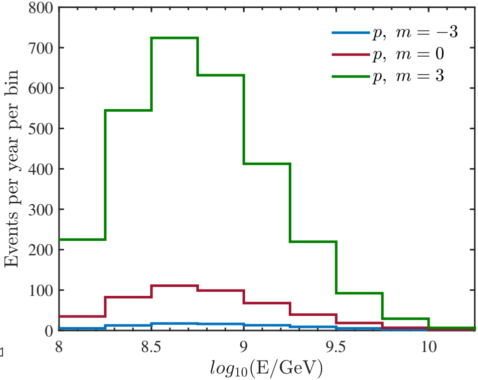
T. Sjöstrand, et al., 1410.3012, J. Navarro, C. Frenk, S. White, astro-ph/9508025

Good fit to the IceCube data; bad fit to CMB and reionization

H. Liu, T. Slatyer, J. Zavala, 1604.02457, T. Slatyer, C.-L. Wu, 1610.06933

UHECR Properties with Neutrinos

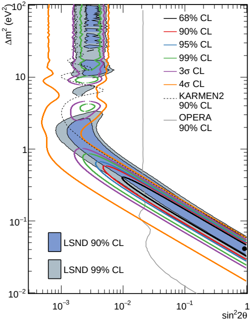


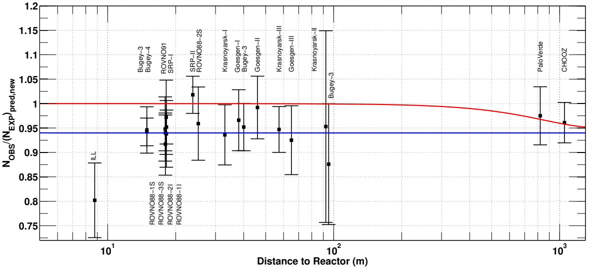


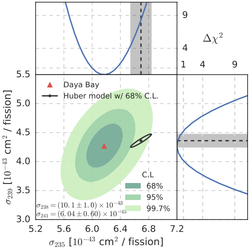
PBD, K. Møller, I. Tamborra, in prep.

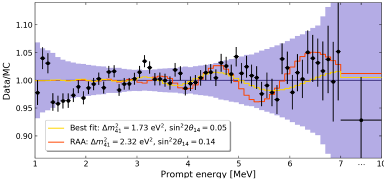
GRAND Collaboration white paper, in prep.

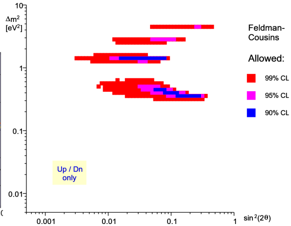
1 eV Steriles: Evidence











Daya Bay, 1704.01082