Abstract

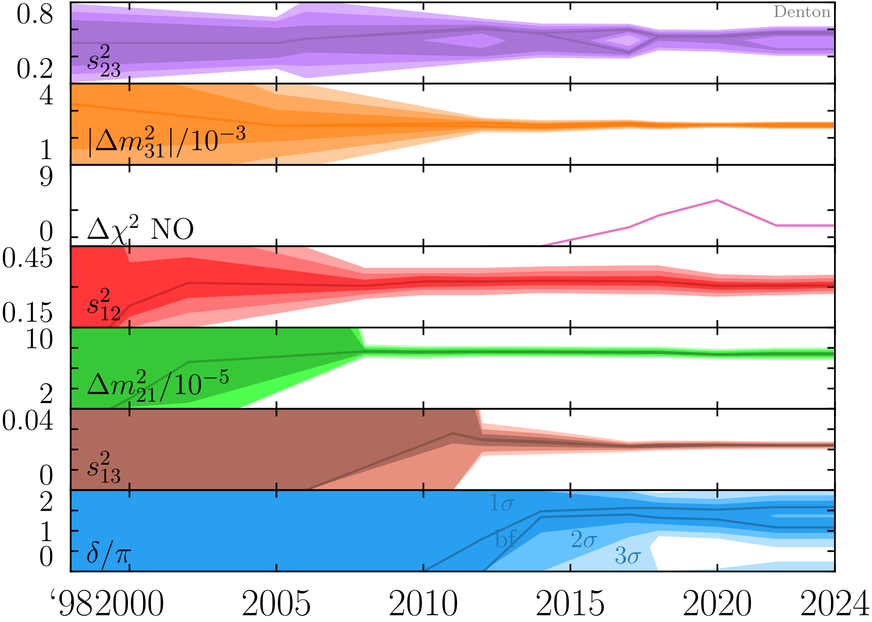
Scalar non-standard neutrino interactions (sNSI) is a scenario where neutrinos can develop a medium dependent contribution to their mass due to a new scalar mediator. This scenario differs from the commonly discussed vector mediator case in that the oscillation effect scales with density rather than density and neutrino energy. Thus the strongest oscillation constraint comes from solar neutrinos which experience the largest density in a neutrino oscillation experiment. We derive constraints on all the sNSI parameters as well as the absolute neutrino mass scale by combining solar and reactor data and find solar neutrinos to be >1 order of magnitude more sensitive to sNSI than terrestrial probes such as long-baseline experiments.

Solar Neutrinos and the Strongest Oscillation Constraints on Scalar NSI

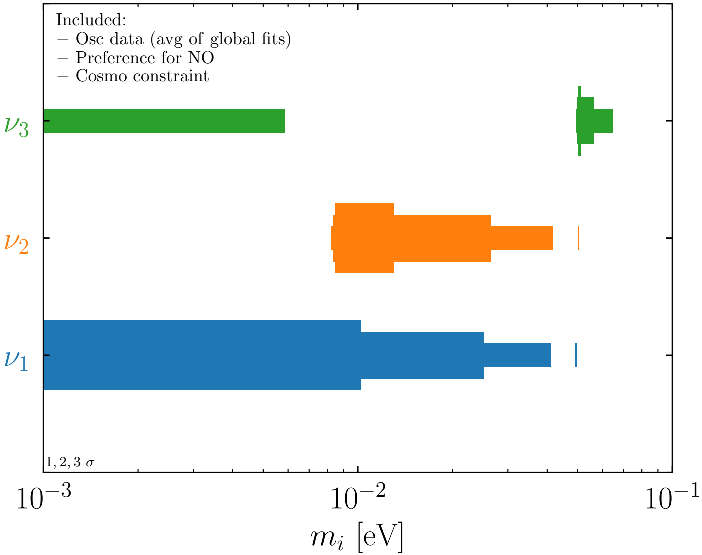
Peter B. Denton

August 25, 2025

2409.15411 with A. Giarnetti and D. Meloni


Denton
0.8
0.2
s_{23}^2
4
1
$|\Delta m_{31}^2|/10^{-3}$
9
0
$\Delta\chi^2$ NO
0.45
0.15
s_{12}^2
10
2
$\Delta m_{21}^2/10^{-5}$
0.04
0
s_{13}^2
2
1
0
δ/π
1σ
bf
2σ
3σ
'98
2000
2005
2010
2015
2020
2024

Absolute masses



New Physics in Oscillations

- Oscillation picture is starting to converge, is that it?
- Neutrino mass generation is still not understood, new physics?
- Many oscillation measurements upcoming, optimal time to search for new physics

Scalar NSI in the Sun Outline

1. Scalar NSI theory
2. Scalar NSI phenomenology
3. Scalar NSI experimental constraints

Scalar NSI theory

Scalar Non-Standard Interaction Theory

Similar to vector NSI

L. Wolfenstein PRD 1978

but with scalar mediator:

$$\mathcal{L}^{eff}_{\text{scalar NSI}} = \frac{y_f y_{\alpha\beta}}{m_\phi^2}(\bar{\nu}_\alpha \nu_\beta)(\bar{f} f)$$

$f = e, u, d$

Could be related to neutrino mass generation

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Focus on the case where $1/m_\phi \lesssim L$
Dirac equation:

$$\bar{\nu}_\beta \left[i\partial_\mu \gamma^\mu + \left(M_{\beta\alpha} + \frac{\sum_f N_f y_f y_{\alpha\beta}}{m_\phi^2} \right) \right] \nu_\alpha = 0$$

Parameterize the Effect

Dimensionless parameter

$$\eta_{\alpha\beta} = \frac{y_{\alpha\beta}}{m_\phi^2 \sqrt{|\Delta m^2_{21,\mathrm{KL}}|}} \sum_f N_f y_f$$

Like the ϵ's for vNSI
Rescale by Δm^2_{21} as we are focused on solar

$$\delta M = \sqrt{\Delta m^2_{21,\mathrm{KL}}} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta^*_{e\mu} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta^*_{e\tau} & \eta^*_{\mu\tau} & \eta_{\tau\tau} \end{pmatrix}$$

New Hamiltonian in the flavor basis in matter:

$$H_f = \frac{1}{2E} \left[\left(UMU^\dagger + \delta M \right)^2 + \begin{pmatrix} a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right]$$

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

Scalar NSI Literature

- sNSI at Daya Bay, Borexino, and JUNO

  S-F. Ge, S. Parke 1812.08376

- Mediator mass in different enviroments

  K. Babu, G. Chauhan, B. Dev 1912.13488

- Ultralight mediators

  A. Smirnov, X-J. Xu 1909.07505

- sNSI with protons

  A. Suliga, S. Shalgar, G. Fuller 2012.11620

- BBN

  J. Venzor, A. Pérez-Lorenzana, J. De-Santiago 2009.08104

- DUNE+δ

  A. Medhi, D. Dutta, M. Devi 2111.12943

- Differentiating sNSI, vNSI, & steriles at DUNE

  PBD, A. Giarnetti, D. Meloni 2210.00109

- Absolute neutrino mass scale

  A. Medhi, A. Sarker, M. Devi 2307.05348

- Others

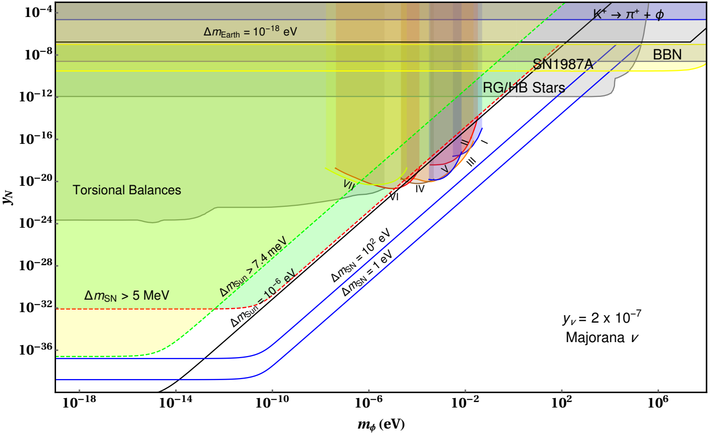
  J. Liao, D. Marfatia, K. Whisnant 1506.03013
  A. Medhi, M. Devi, D. Dutta 2209.05287
  T. Sarkar 2209.10233
  B. Dutta, et al. 2209.13566
  A. Gupta, D. Majumdar, S. Prakash 2306.07343
  D. Singha, et al. 2308.10789
  A. Sarker, et al. 2309.12249
  ESSnuSB 2310.10749
  A. Sarker, et al. 2406.15307
  B. Dutta, et al. 2401.02107

Scalar NSI phenomenology

The Big Picture

Effect increases with density, but not E

Solar neutrinos best in a lot of parameter space!



K. Babu, G. Chauhan, B. Dev 1912.13488

Shift to the Oscillation Parameters

Consider a two-flavor limit and vary only η_{ee}, the corrections are:

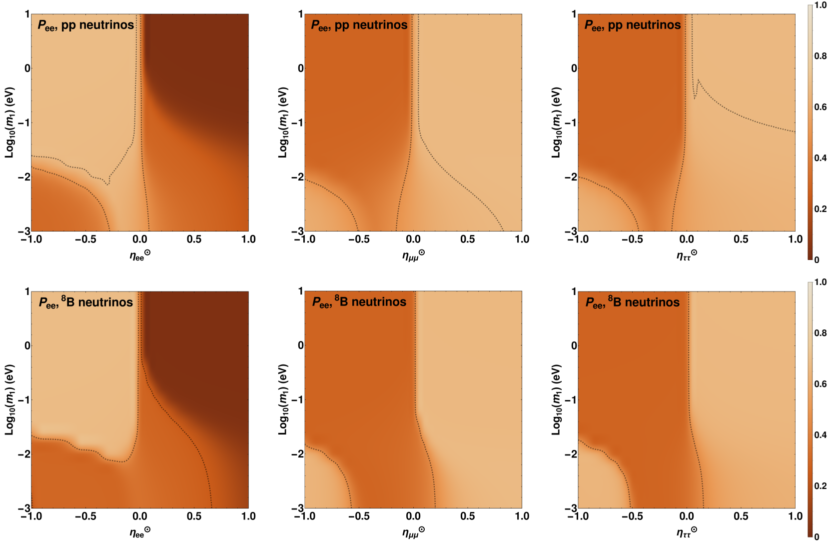
$$\delta(\Delta m^{2\odot}_{21}) = 2\sqrt{\Delta m^2_{21,\text{KL}}}\eta_{ee}\frac{(\tilde{A}-1)m_1\cos^2\theta_{12}+(\tilde{A}+1)m_2\sin^2\theta_{12}}{\sqrt{(\cos 2\theta_{12}-\tilde{A})^2+\sin^2 2\theta_{12}}}$$

$$\delta(\cos 2\theta^{\odot}_{12}) = \sqrt{\Delta m^2_{21,\text{KL}}}\eta_{ee}\sin^2 2\theta_{12}\frac{(\tilde{A}+1)m_1-(\tilde{A}-1)m_2}{\Delta m^2_{21}[(\cos 2\theta_{12}-\tilde{A})^2+\sin^2 2\theta_{12}]^{3/2}}$$

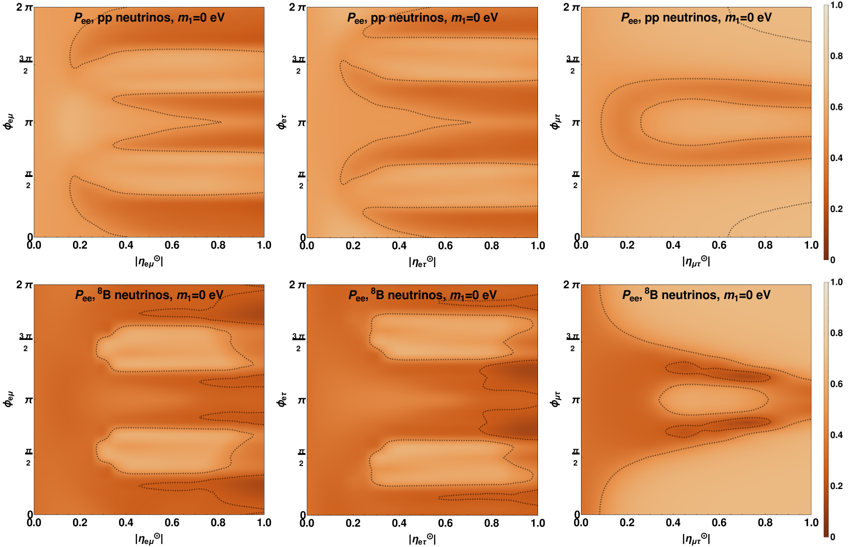
$\tilde{A}\equiv a/\Delta m^2_{21}$

1. Depends on absolute neutrino mass scale!
2. Effect depends on density, not energy $\Rightarrow$ solar neutrinos are best
3. For m_1 small, the shift is the same (opposite) sign for Δm^2_{21} ($\cos 2\theta_{12}$)
4. Since we see a depletion of ^{8}B neutrinos, Δm^2_{21} sets an upper limit on η_{ee}
5. Similar arguments for other sNSI parameters

Effect on Solar Flux



Effect on Solar Flux



Scalar NSI experimental constraints

Experimental Data

Borexino:

$$P_{ee}(\mathrm{pp}) = 0.57 \pm 0.09$$
$$P_{ee}(^7\mathrm{Be}) = 0.53 \pm 0.05$$
$$P_{ee}(\mathrm{pep}) = 0.43 \pm 0.11$$
$$P_{ee}(^8\mathrm{B}) = 0.37 \pm 0.08$$

BOREXINO Nature 2018

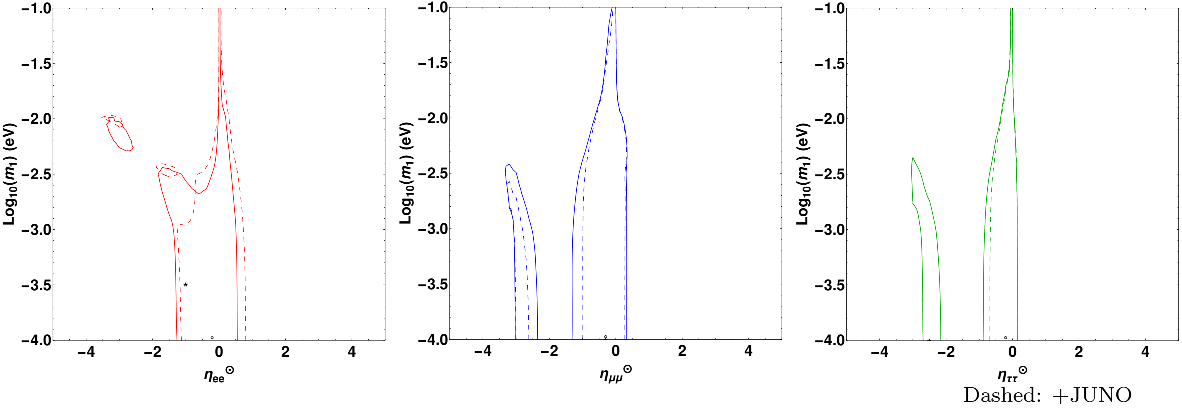
Spectral information from SNO

SNO 1109.0763

KamLAND now and JUNO in the future to measure the oscillation parameters

$$\text{KamLAND}: \quad \Delta m^2_{21} = 7.41 \pm 0.21 \times 10^{-5}\ \mathrm{eV}^2$$
$$\text{JUNO}: \quad \Delta m^2_{21} = 7.53 \pm 0.024 \times 10^{-5}\ \mathrm{eV}^2, \ \sin^2\theta_{12} = 0.307 \pm 0.0016$$

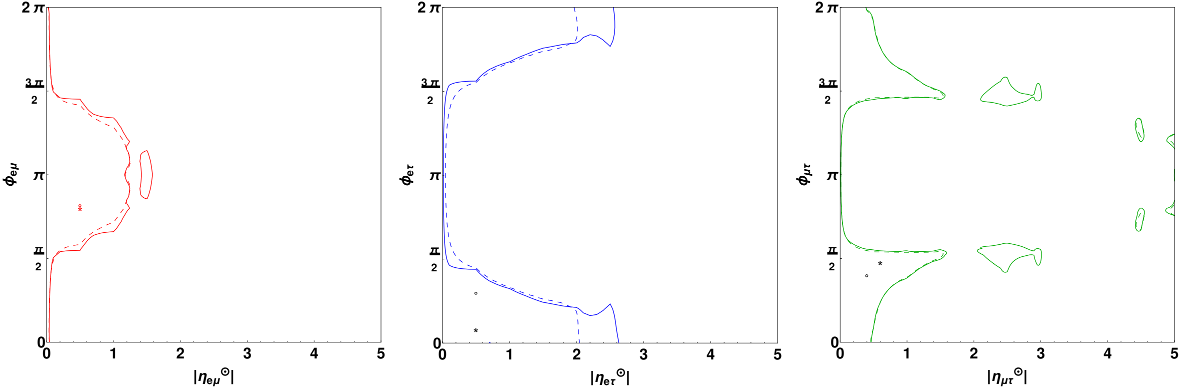
Combine Solar and KamLAND/JUNO: Diagonal sNSI



Combining data sets is essential

Absolute mass scale accessible in oscillation experiments with new physics

Combine Solar and KamLAND/JUNO: Off-Diagonal sNSI



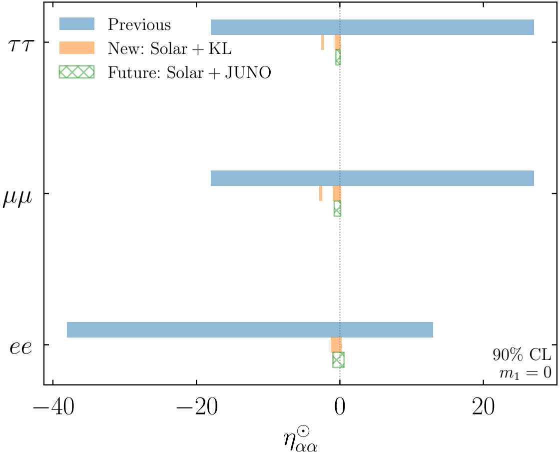
Dashed: +JUNO

Improved Constraints

1. Previous calculation $|\Delta m^\odot| < 7.4$ meV

S-F. Ge, S. Parke 1812.08376
K. Babu, G. Chauhan, B. Dev 1912.13488

2. New result: $|\Delta m^\odot| < 0.8$ meV



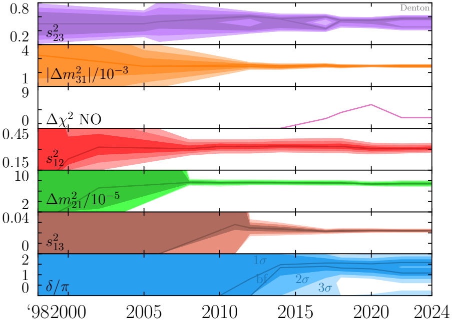
Neutrino oscillation summary

- Scalar non-standard neutrino interactions is an important BSM scenario
- Effect scales with matter density $\Rightarrow$ look to the Sun!
- Sensitivity to the absolute neutrino mass scale
- Combining solar experiments with KamLAND/JUNO provides the strongest constraints

Thanks for listening!

Backups

References



SK hep-ex/9807003

M. Gonzalez-Garcia, et al. hep-ph/0009350

M. Maltoni, et al. hep-ph/0207227

SK hep-ex/0501064

SK hep-ex/0604011

T. Schwetz, M. Tortola, J. Valle 0808.2016

M. Gonzalez-Garcia, M. Maltoni, J. Salvado 1001.4524

T2K 1106.2822

D. Forero, M. Tortola, J. Valle 1205.4018

D. Forero, M. Tortola, J. Valle 1405.7540

P. de Salas, et al. 1708.01186

F. Capozzi et al. 2003.08511

vNSI review

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

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 N. Bernal, Y. Farzan 2211.15686
S. Abbaslu, Y. Farzan 2407.13834

Affects oscillations via new matter effect

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

Matter potential $a \propto G_F \rho E$

B. Dev, K. Babu, PBD, P. Machado, et al. 1907.00991