Neutrino NSI from Ultralight Scalars

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with

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Scalar Neutrino Non-standard Interactions (SNSI)

[2401.02107]

$$\mathcal{L}_S = \bar{\nu}\left(i\gamma^\mu \partial_\mu - m_\nu\right)\nu - (y_\nu)_{\alpha\beta}\bar{\nu}_\alpha \nu_\beta \phi - y_f \bar{f} f \phi - \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{m_\phi^2}{2}\phi^2$$

- We consider a light (< keV) to ultralight (<< eV) scalar ϕ

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- We consider a light (< keV) to ultralight (<< eV) scalar ϕ
- Phenomenology signatures:
  - Scattering in detector: light recoils $\propto \frac{y_f (y_\nu)_{\alpha\beta}}{q^2 - m_\phi^2}$ $\quad m_\phi << q \rightarrow \frac{y_f (y_\nu)_{\alpha\beta}}{q^2}$
  - Oscillation: in the forward, coherent scattering in-medium: $\rightarrow \frac{y_f (y_\nu)_{\alpha\beta}}{m_\phi^2}$

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- matter effect in **DUNE long-baseline beam neutrino oscillations**

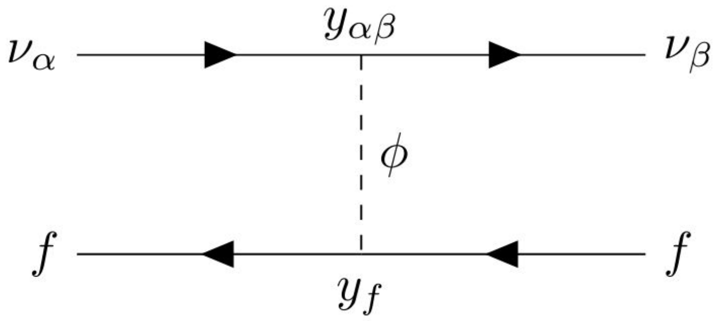
Scalar or Vector NSI?

[forward limit]

$$\mathcal{L}_S^6 \supset \frac{(y_\nu)_{\alpha\beta} y_f}{m_\phi^2} (\bar{f} f)(\bar{\nu}_\alpha \nu_\beta)$$

$$\frac{\delta \mathcal{L}_S}{\delta \bar{\nu}_\alpha} \propto \frac{1}{m_\phi^2} (\bar{f} f) \times \nu_\beta$$

$$\propto \frac{1}{m_\phi^2} \times \underbrace{(\bar{f} f)}_{\text{number density } n_f} \times \nu_\beta$$



See e.g.
Ge, Parke 1812.08376
Smirnov, Xu 1909.07505

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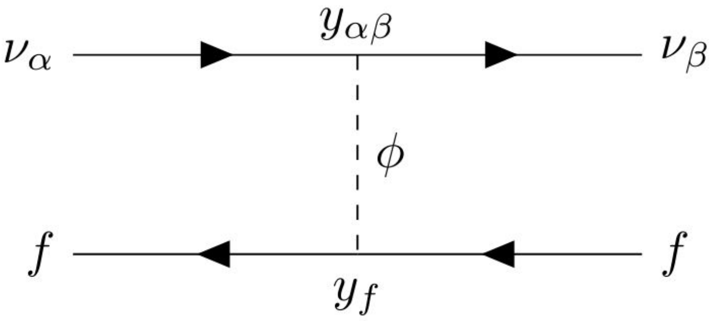


$$\bar{\nu}_\alpha \left[i\partial_\mu \gamma^\mu - \left(M_{\alpha\beta} + \frac{n_f y_f y_{\alpha\beta}}{m_\phi^2} \right) \right] \nu_\beta = 0$$

Propagation Hamiltonian

Realized as a **mass shift**

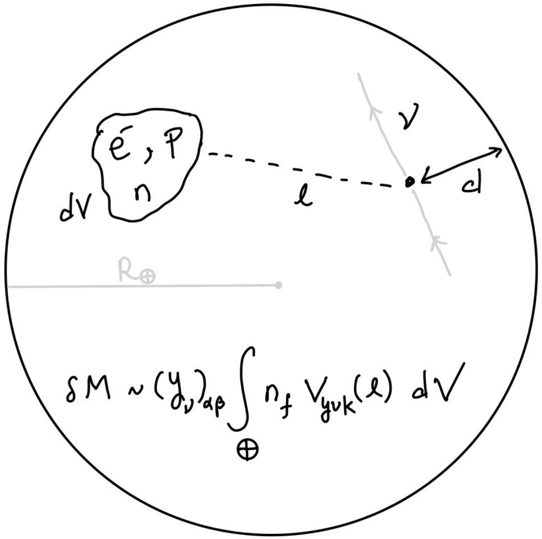
$$H_{\alpha\beta} = \frac{1}{2E_\nu} (\mathbb{M} + \delta\mathbb{M})^\dagger_{\alpha\beta} (\mathbb{M} + \delta\mathbb{M})_{\alpha\beta} + V_{CC}$$

See e.g.
Ge, Parke 1812.08376
Smirnov, Xu 1909.07505

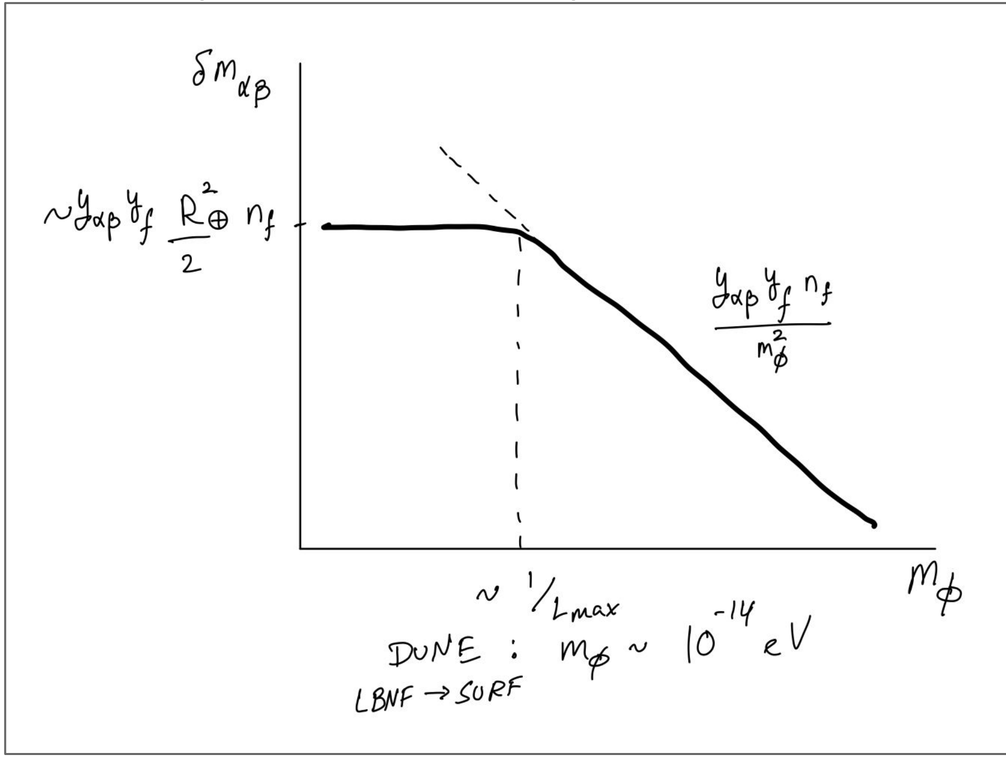
What about the long-ranged scalar potential?

Consider long-ranged ϕ potential from matter sources inducing a neutrino mass correction:

Wise, Zhang 1803.00591
Smirnov, Xu 1909.07505
Babu, Chauhan, Dev 1912.13488
Agarwalla, Bustamante, Singh, Swain 2404.02775



$$\rightarrow \frac{n_f\, y_{\alpha\beta}\, y_f}{m_\phi^2} \quad \text{for} \quad m_\phi\, \ell_{max}(R_\oplus, \text{depth}) \gg 1$$



Recovers the short-range description

Cutoff for DUNE beam depth: $m_\phi \sim 10^{-14}$ eV

How to parameterize the physics?

Flavor Basis: Normalize to one of the mass splittings

$$\delta\mathbb{M}_{\alpha\beta} \equiv \sqrt{|\Delta m_{31}^2|} \begin{pmatrix} \eta_{ee} & \eta_{e\mu}e^{i\phi_{e\mu}} & \eta_{e\tau}e^{i\phi_{e\tau}} \\ \eta_{e\mu}e^{-i\phi_{e\mu}} & \eta_{\mu\mu} & \eta_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \eta_{e\tau}e^{-i\phi_{e\tau}} & \eta_{\mu\tau}e^{-i\phi_{\mu\tau}} & \eta_{\tau\tau} \end{pmatrix} \quad \eta_{\alpha\beta} = \frac{n_f y_f y_{\alpha\beta}}{\sqrt{|\Delta m_{31}^2|}m_\phi^2}$$

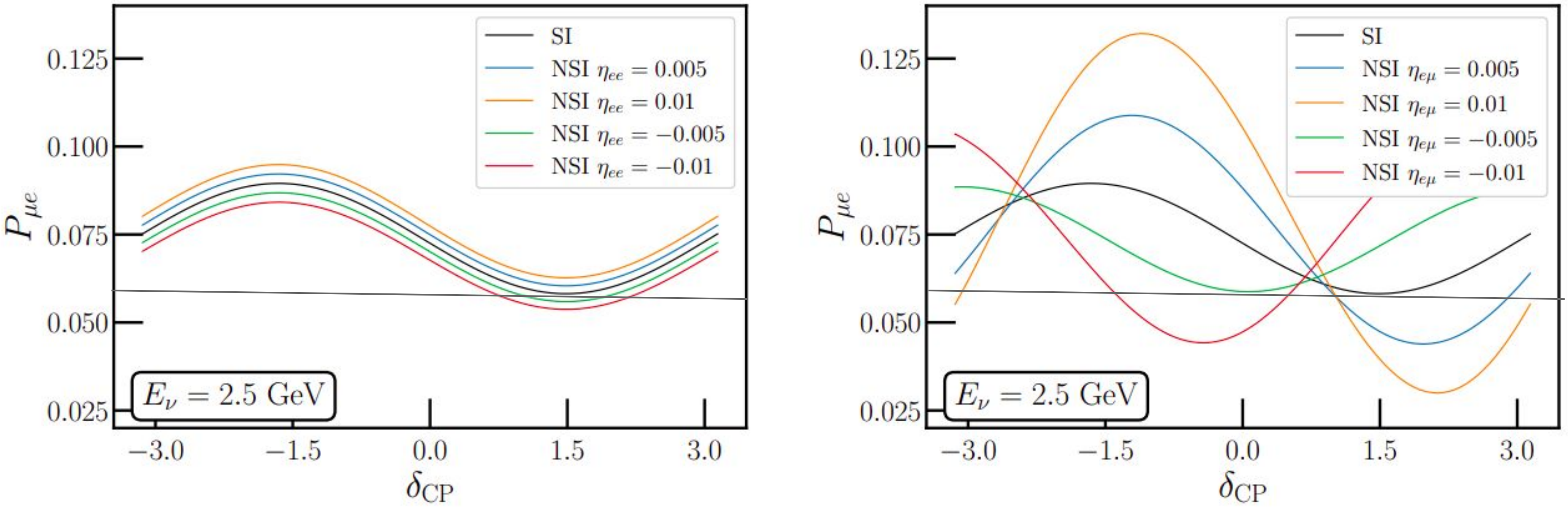
$$H \supset \mathbb{M}^\dagger \cdot \delta\mathbb{M} \supset m_1 \times \eta$$ [modulo PMNS elements]

- **Depends on choice for m_1**
- One choice: fixing Δm_{21}^2 and Δm_{31}^2 to measured values, and specify a choice of m_1 to constrain η's

Light SNSI Oscillations at DUNE Far Detector and δ_{CP} Extraction

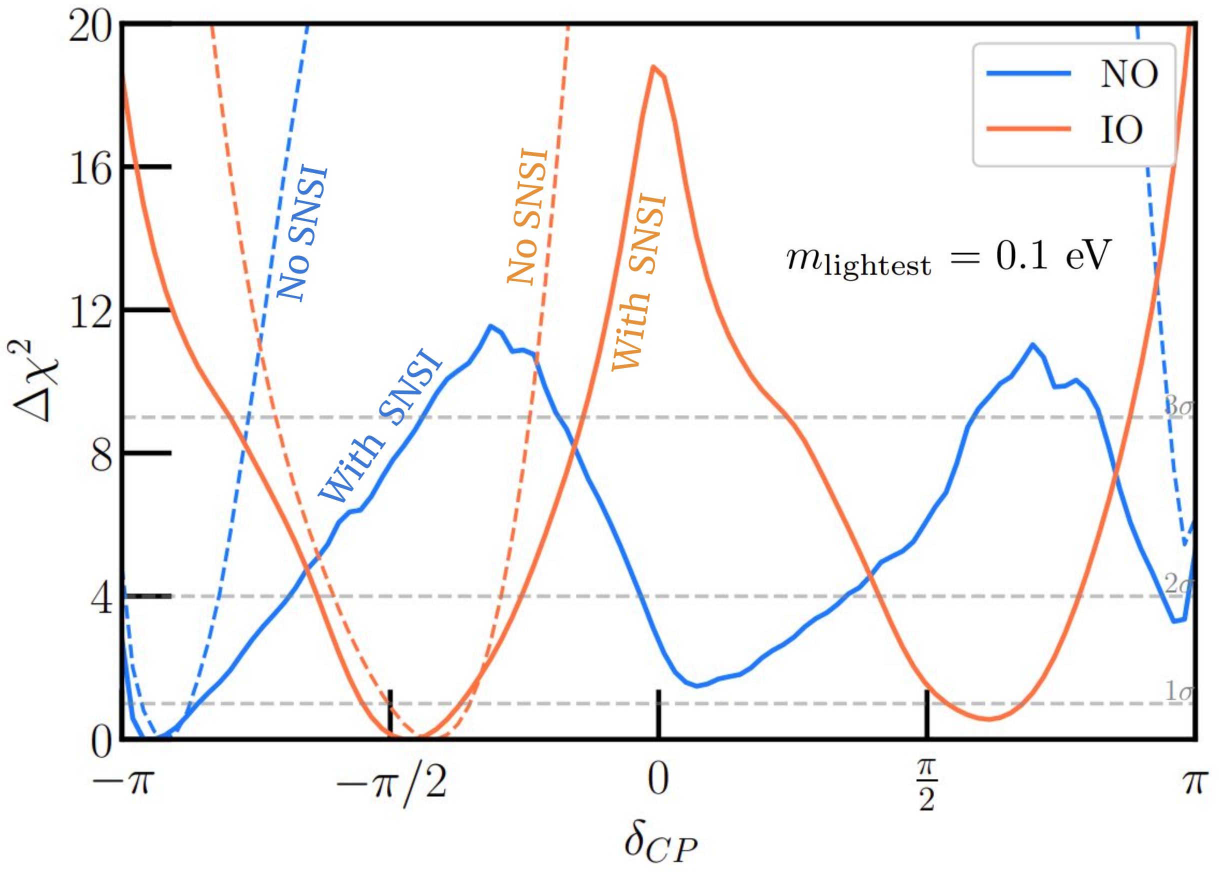
[2401.02107]

- We consider L~1300 km baseline oscillations from the DUNE beam neutrinos
- 4 component analysis: electron (anti)neutrino appearance, muon (anti)neutrino disappearance
- 5% flux normalization uncertainty



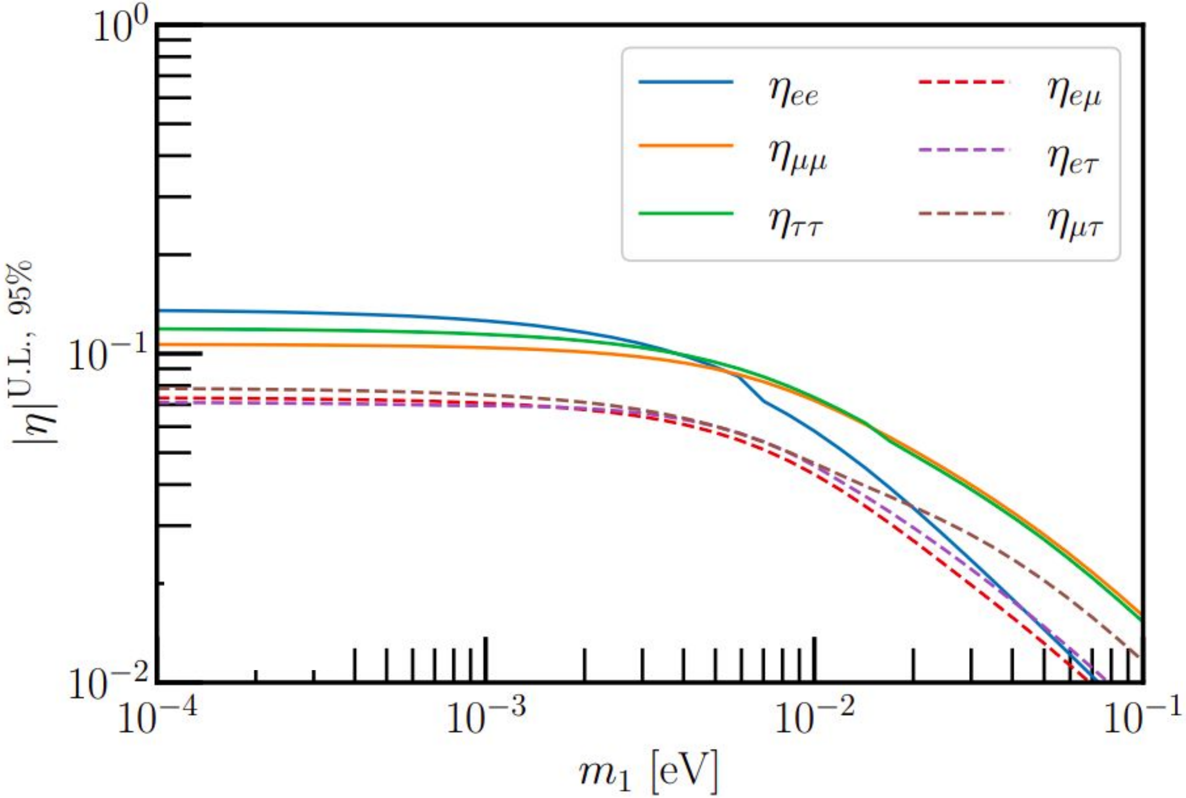
See also: Moon Moon's talk, [2309.12249], [2210.00109]

Resolving the CP Phase at DUNE



- Test for δ_{CP} at DUNE with scalar NSI (SNSI) in the long-baseline oscillations
- We marginalize over the all SNSI (η magnitudes and phases)
- We expect degeneracies to show up in the measurement just like vector NSI

Dependence on the lightest neutrino mass



- Generically get the best upper limit (U.L.) when m_1 is larger
  - Enhances the M·δM term
- To evaluate the best possible sensitivity, take the largest m_1 value

Other Constraints on Non-standard Oscillations (light scalars)

[1912.13488] Babu, Chauhan, Dev

In Medium Mass: Our Sun
- Long-ranged scalar potential induces **in-medium mass correction ~ $y\langle\phi\rangle$ in the sun**

Long-ranged mass correction should not exceed solar data :

$\Delta m_{Sun} = n^{Sun}_f y_f y_\nu / m_\phi^2 < 7.4$ meV

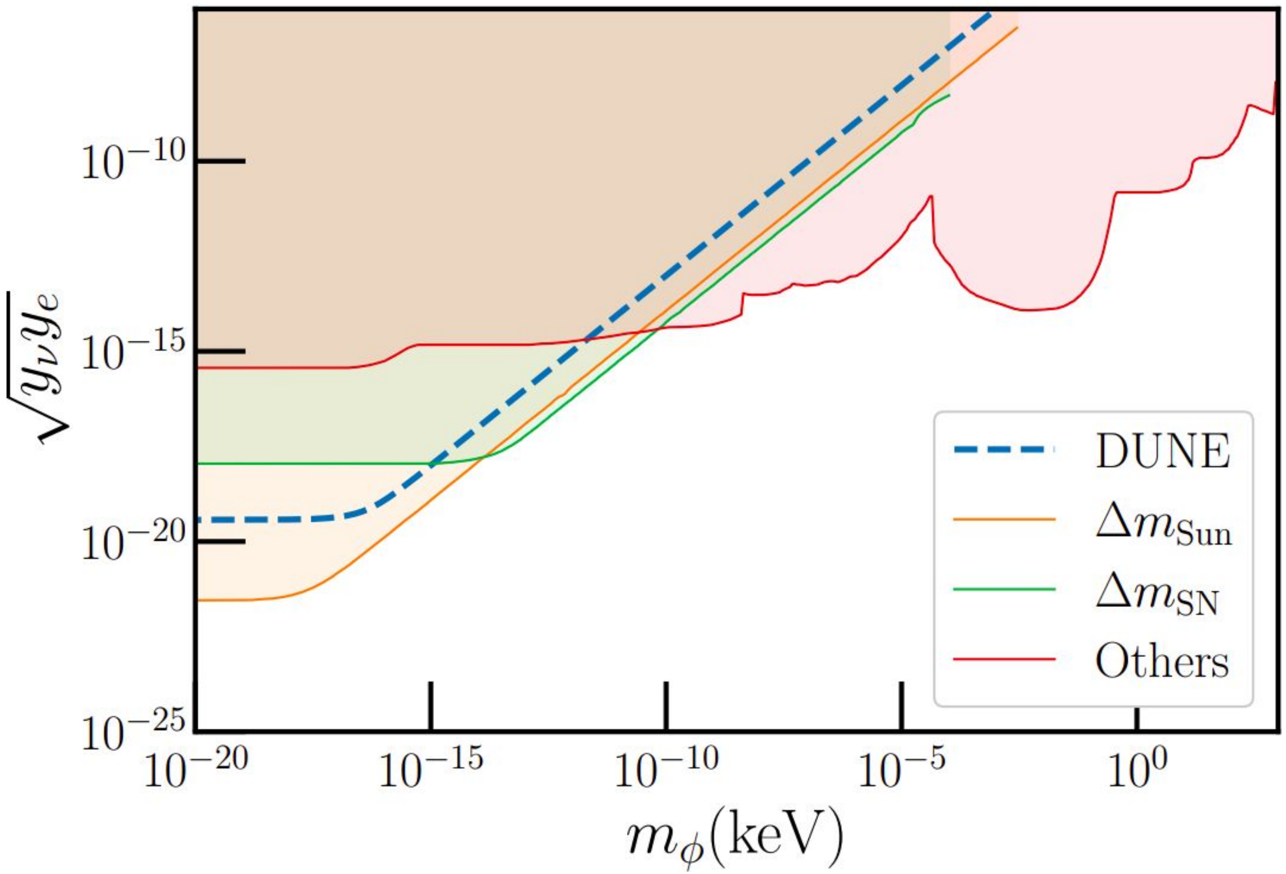
In Medium Mass: Supernova
- Likewise, the long ranged potential in supernova

Long-ranged mass correction should not modify neutrino free streaming :

$\Delta m_{SN} = n^{SN}_f y_f y_\nu / m_\phi^2 < T_\nu \sim 5$ MeV

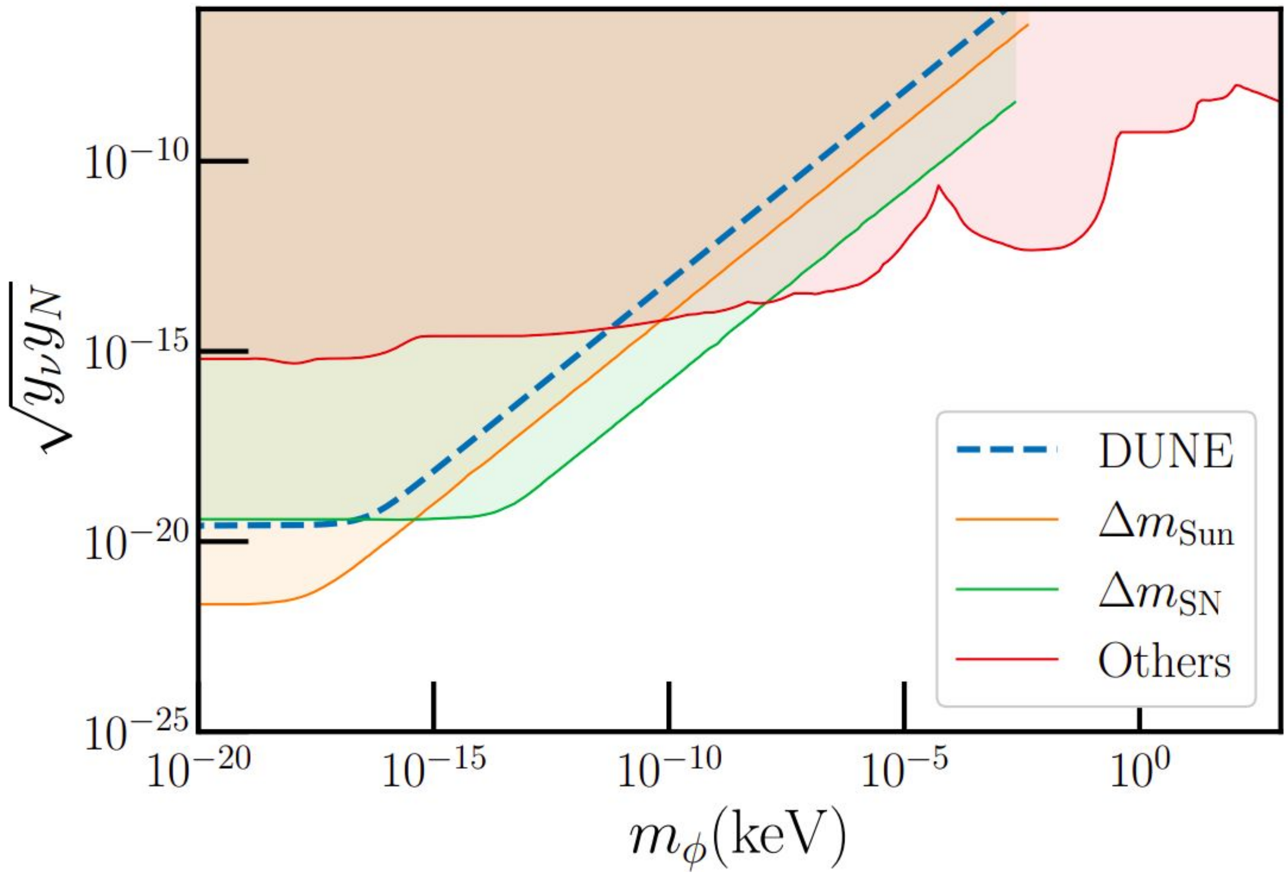
Additional constraints from, e.g.
- BBN
- ΔNeff and CMB
- Scattering experiments (high masses)

Seeing the full picture: translating to neutrino/electron Yukawas



- Marginalize over all η's and δ_{CP}
- Take the best constraint on $\eta_{\alpha\beta}$ (and the associated Yukawa) after marginalizing all others

...and the neutrino/nucleon Yukawas



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Key Points

- Light-mediator scalar NSI modify the effective mass matrix in the propagation Hamiltonian
- Degeneracies with the absolute neutrino masses
- Degeneracies with oscillation parameters, e.g. δ_{CP}
- However DUNE appears to only be sensitive to SNSI already ruled out by more powerful long-ranged effects : Δm_{SN} and Δm_{Sun}

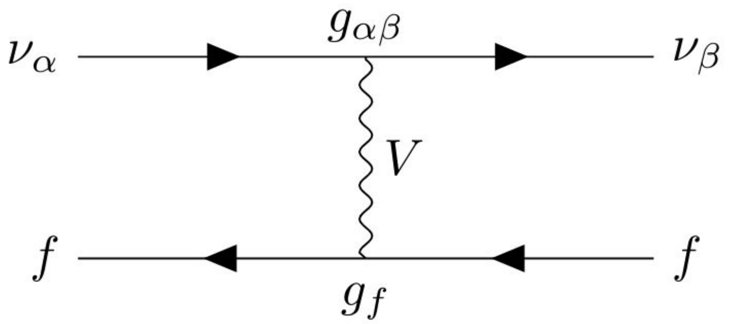
Backup Deck

Scalar or Vector NSI?

$$\frac{\delta \mathcal{L}_\nu}{\delta \bar{\nu}_\alpha} \propto \frac{1}{m_V^2}(\bar{f}\gamma_\mu f) \times (\gamma^\mu \nu_\beta)$$

$$\propto \frac{1}{m_V^2} \times \underbrace{(\bar{f}\gamma_0 f)}_{\text{number density } n_f} \times (\gamma^0 \nu_\beta)$$

[forward limit]



$$\bar{\nu}_\alpha \left[\gamma^0 \left(i\partial_0 - V_{\alpha\beta} - \frac{n_f g_f g_{\alpha\beta}}{m_V^2}\right) - i\gamma \cdot \nabla - M_{\alpha\beta}\right] \nu_\beta = 0$$

Propagation Hamiltonian

Realized as a **potential energy shift**

$$H_{\alpha\beta} = \frac{1}{2E_\nu}\mathbb{M}^\dagger_{\alpha\beta}\mathbb{M}_{\alpha\beta} + (V_{\rm CC} + V^{\rm NSI}_{\alpha\beta})$$

Many-parameters vs. one-at-a-time

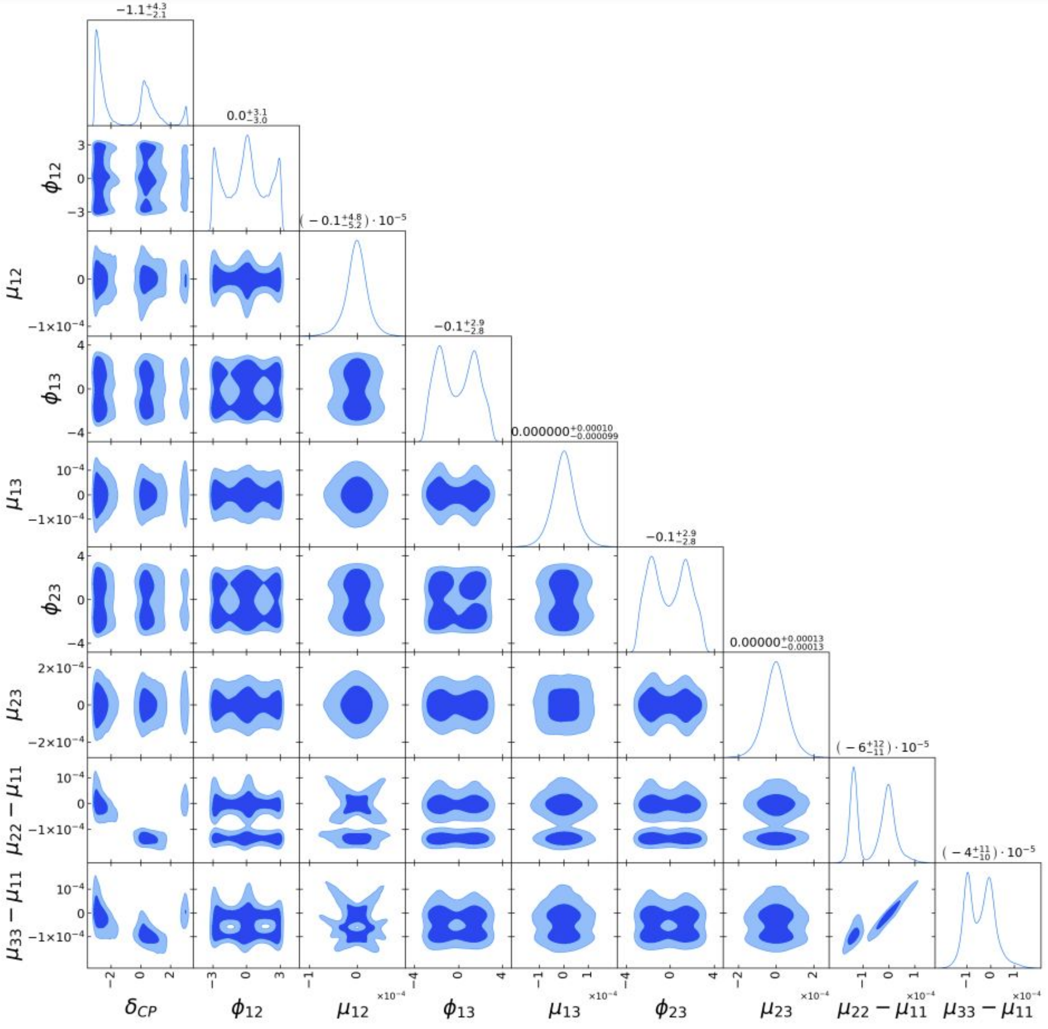
One-at-a-time

NSI	NO ($m_1 = 0.1$ eV)	IO ($m_3 = 0.1$ eV)
η_{ee}	$[-0.006, 0.006]$	$[-0.0077, 0.0059]$
$\eta_{\mu\mu}$	$[-0.004, 0.004]$	$[-0.0036, 0.004]$
$\eta_{\tau\tau}$	$[-0.004, 0.004]$	$[-0.0037, 0.0036]$
$\|\eta_{e\mu}\|$	[0,0.0017]	[0,0.0017]
$\|\eta_{e\tau}\|$	[0,0.0019]	[0,0.0015]
$\|\eta_{\mu\tau}\|$	[0,0.0042]	[0,0.0035]

All floating, 1-D marginals

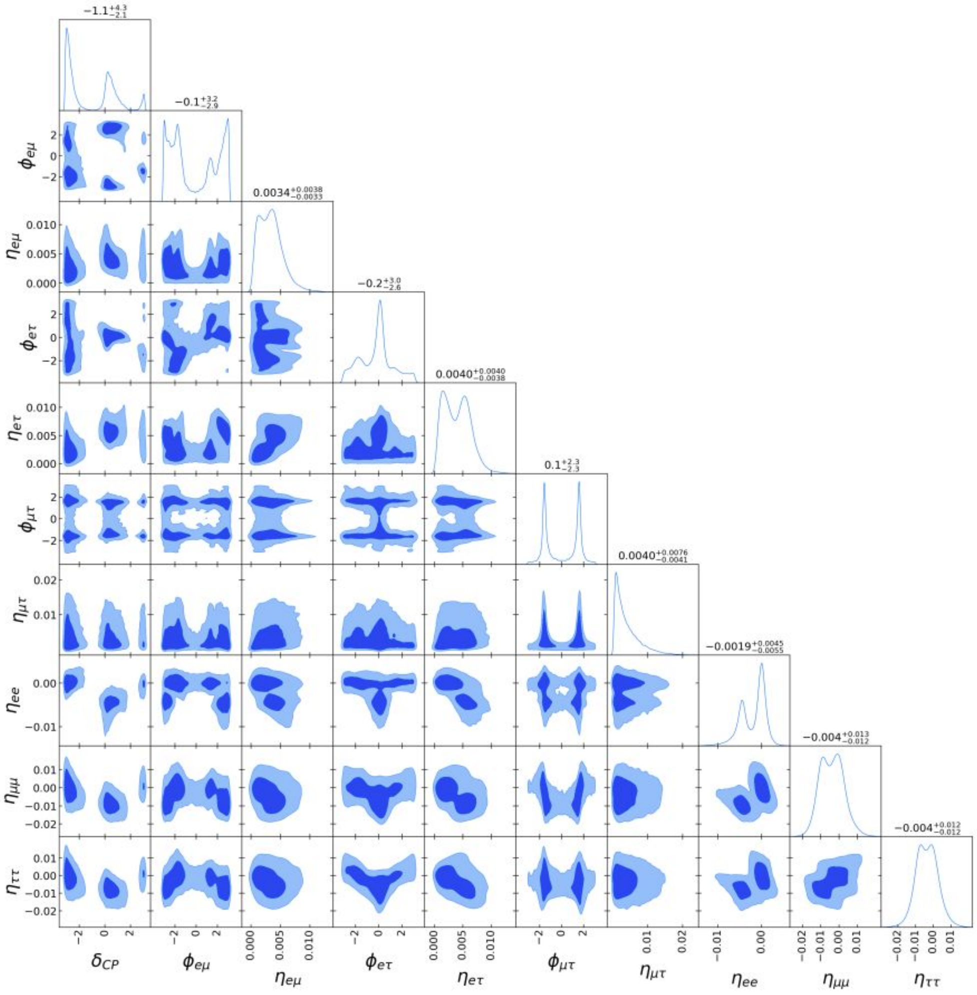
$m_{\text{lightest}} = 0.1$ eV

MO	NSI	$\eta_{\alpha\beta}$
NO	η_{ee}	$[-0.0074, 0.0026]$
	$\eta_{\mu\mu}$	$[-0.016, 0.009]$
	$\eta_{\tau\tau}$	$[-0.016, 0.008]$
	$\eta_{e\mu}$	$[0, 0.007]$
	$\eta_{e\tau}$	$[0, 0.008]$
	$\eta_{\mu\tau}$	$[0, 0.016]$
IO	η_{ee}	$[-0.0077, 0.0082]$
	$\eta_{\mu\mu}$	$[-0.011, 0.0067]$
	$\eta_{\tau\tau}$	$[-0.0081, 0.0096]$
	$\eta_{e\mu}$	$[0, 0.0073]$
	$\eta_{e\tau}$	$[0, 0.0077]$
	$\eta_{\mu\tau}$	$[0, 0.012]$



Multi-dimensional parameter scan

MultiNest



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$$\delta\mathbb{M}_{ij} = U^\dagger \delta\mathbb{M}_{\alpha\beta} U = \begin{pmatrix} \epsilon_{11} & \epsilon_{12} & \epsilon_{13} \\ \epsilon^*_{12} & \epsilon_{22} & \epsilon_{23} \\ \epsilon^*_{13} & \epsilon^*_{23} & \epsilon_{33} \end{pmatrix}$$

$$\epsilon_{11} \to -\epsilon_{11} - 2m_1$$
$$\epsilon_{22} \to -\epsilon_{22} - 2m_2$$
$$\epsilon_{33} \to -\epsilon_{33} - 2m_3$$
$$\epsilon_{ij} \to -\epsilon_{ij}; \quad i \neq j$$

Physical Degrees of Freedom

$$\mathbb{M}^2_{\text{eff}} \equiv \begin{pmatrix} m_1^2 + \mu_{11} & \mu_{12} & \mu_{13} \\ \mu_{12}^* & m_2^2 + \mu_{22} & \mu_{23} \\ \mu_{13}^* & \mu_{23}^* & m_3^2 + \mu_{33} \end{pmatrix}$$

$$\to \begin{pmatrix} 0 & \mu_{12} & \mu_{13} \\ \mu_{12}^* & \Delta m_{12}^2 - \mu_{11} + \mu_{22} & \mu_{23} \\ \mu_{13}^* & \mu_{23}^* & \Delta m_{13}^2 - \mu_{11} + \mu_{33} \end{pmatrix}$$

- **Depends on choice for *m*$_1$**
- One choice: fixing $\Delta m_{21}{}^2$ and $\Delta m_{31}{}^2$ to measured values, and specify a choice of *m*$_1$ to constrain η's

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[9-1=8 physical oscillation parameters; subtract constant times identity matrix]

$$\begin{aligned} \mu_{11} &= 2m_1\epsilon_{11} + |\epsilon_{11}|^2 + |\epsilon_{12}|^2 + |\epsilon_{13}|^2 , \\ \mu_{22} &= 2m_2\epsilon_{22} + |\epsilon_{22}|^2 + |\epsilon_{12}|^2 + |\epsilon_{23}|^2 , \\ \mu_{33} &= 2m_3\epsilon_{33} + |\epsilon_{33}|^2 + |\epsilon_{13}|^2 + |\epsilon_{23}|^2 , \\ \mu_{12} &= (m_1 + m_2 + \epsilon_{11} + \epsilon_{22})\,\epsilon_{12} + \epsilon_{13}\epsilon_{23}^* , \\ \mu_{13} &= (m_1 + m_3 + \epsilon_{11} + \epsilon_{33})\,\epsilon_{13} + \epsilon_{12}\epsilon_{23}^* , \\ \mu_{23} &= (m_2 + m_3 + \epsilon_{22} + \epsilon_{33})\,\epsilon_{23} + \epsilon_{13}\epsilon_{12}^* . \end{aligned}$$

See also: Denton, Giarnetti, Meloni [2210.00109]

DUNE Spectra