Probing the impact of scalar-mediated non-standard interactions on the supernova neutrino flux

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Introduction

- A core collapse supernova (CCSN) in the coming decades could offer valuable insights into core collapse dynamics and shed new lights on neutrino physics.
- We probe the possible impact of scalar mediated non-standard interaction on the neutrinos from a core collapse supernova. Such interactions can modify matter-induced neutrino flavor conversion within the supernova core by introducing a new resonance
- We show the potential of next generation neutrino experiment DUNE and Hyper-K to probe such scenario.

Neutrinos from Supernova

- All flavors of neutrinos are produced during several stages of a core collapse supernova. We particularly focus on the neutronization burst phase, in which ν_e flux dominates over the other flavors.

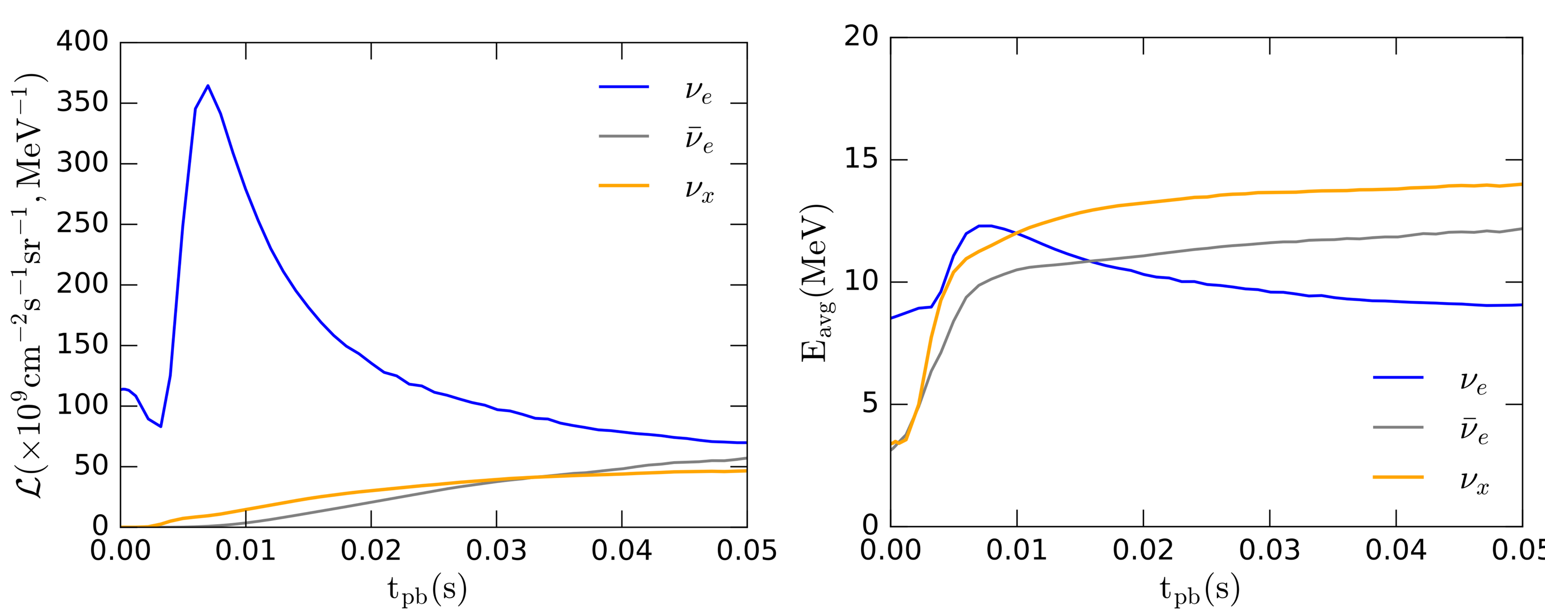

Fig 1: Expected neutrino luminosities (left) and average neutrino energy (right) from a core collapse supernova as a function of time after the core bounce. Data taken from 1D simulation of Supernova of progenitor mass $25_\odot$[2].

Unoscillated neutrino flux at Earth : $\Phi(E,t) = \frac{1}{4\pi L^2}\frac{L(t)}{E_{\rm avg}}\phi(E)$

$$\phi(E) \propto \left(\frac{E}{E_{\rm avg}}\right)^{\alpha} \mathrm{Exp}[-(\alpha+1)\frac{E}{E_{\rm avg}}]$$

Neutrino mixing effect:

$f_{\nu_e}(E,t) = |U_{e3}|^2\Phi_{\nu_e}(E,t) + (1-|U_{e3}|^2)\Phi_{\nu_x}(E,t)$ … Normal mass ordering (NMO)

$f_{\nu_e}(E,t) = |U_{e2}|^2\Phi_{\nu_e}(E,t) + (1-|U_{e2}|^2)\Phi_{\nu_x}(E,t)$ … Inverted mass ordering (IMO)

Scalar non-standard interaction (SNSI)

- Effective interaction term [3]: $L_{\rm eff}^{SNSI} = \frac{y_f Y_{\alpha\beta}}{m_\varphi^2}[\bar{\nu}_\alpha(p_3)\nu_\beta(p_2)][\bar{f}_\alpha(p_1)f(p_4)]$
- SNSI modifies the neutrino mass term: $M_{\alpha\beta} \to M_{\alpha\beta}^{\rm eff} = M_{\alpha\beta} + \frac{\sum_f n_f y_f Y_{\alpha\beta}}{m_\varphi^2}$
- Neutrino Hamiltonian in the presence of scalar NSI: $H = \frac{M^{\rm eff}M^{\rm eff\,\dagger}}{2E} \pm V_{\rm SI}$

$$M^{\rm eff} = M + \delta M = M + \delta\tilde{M}\frac{n_f}{n_{f,s}} \qquad M = \mathrm{Diag.}\,[0, \Delta m_{21}^2, \Delta m_{31}^2]$$

$$\delta\tilde{M} = \sqrt{\Delta m_{31}^2}\begin{bmatrix}\eta_{ee} & \eta_{e\mu} & \eta_{e\tau}\\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\mu\tau}\\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau}\end{bmatrix} \qquad \eta_{\alpha\beta} \propto \sum_f \frac{n_{f,s}\,y_f Y_{\alpha\beta}}{m_\varphi^2}$$

Neutrino flavor evolution in presence of SNSI

- Neutrino Hamiltonian in terms of effective neutrino mixing parameters

$$H = U^{\rm eff}.\left[\frac{m_{1,m}^2}{2E}, \frac{m_{2,m}^2}{2E}, \frac{m_{3,m}^2}{2E}\right].U^{\rm eff\,\dagger} \qquad U^{\rm eff} \to \text{effective mixing matrix}$$

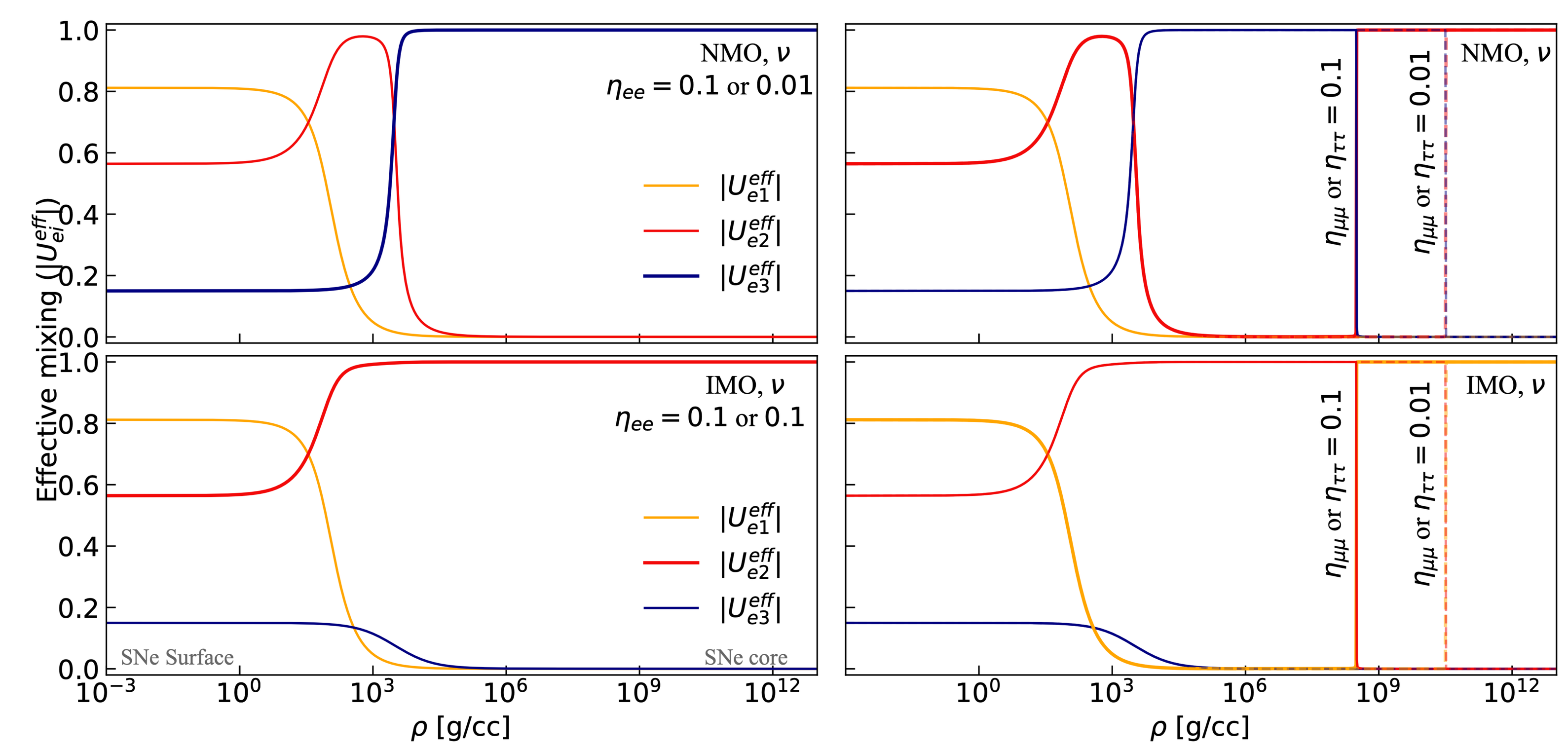

Fig. 2: Evolution of the effecting mixing parameters with of matter density inside a supernova for neutrino with E = 10 MeV.

- Electron neutrino flux at Earth:

$f_{\nu_e}(E,t) = |U_{e2}|^2\Phi_{\nu_e}(E,t) + (1-|U_{e2}|^2)\Phi_{\nu_x}(E,t)$ … Normal mass ordering (NMO)

$f_{\nu_e}(E,t) = |U_{e1}|^2\Phi_{\nu_e}(E,t) + (1-|U_{e1}|^2)\Phi_{\nu_x}(E,t)$ … Inverted mass ordering (IMO)

	NMO	IMO
ν_e (SI)	$\nu_e \approx \nu_{3,m}$	$\nu_e \approx \nu_{2,m}$
ν_e ($\eta_{\mu\mu}$ or $\eta_{\tau\tau}$)	$\nu_e \approx \nu_{2,m}$	$\nu_e \approx \nu_{1,m}$
$\bar{\nu}_e$(SI)	$\bar{\nu}_e \approx \bar{\nu}_{1,m}$	$\bar{\nu}_e \approx \bar{\nu}_{3,m}$
$\bar{\nu}_e$($\eta_{\mu\mu}$ or $\eta_{\tau\tau}$)	$\bar{\nu}_e \approx \bar{\nu}_{1,m}$	$\bar{\nu}_e \approx \bar{\nu}_{3,m}$

Table 1: effective mass states in which ν_e and $\bar{\nu}_e$ aligns at the supernova core in standard interaction case and in the presence of SNSI

SNSI induced resonance

- Two flavor neutrino Hamiltonian at large matter density (relevant for the new resonance)

$$H_{2\times 2} = \frac{1}{2E}\begin{bmatrix}2EV_{CC} & M_{e\mu}\delta M_{\mu\mu}\\ M_{e\mu}^*\delta M_{\mu\mu} & (\delta M_{\mu\mu})^2\end{bmatrix} \qquad \begin{matrix}M_{\alpha\beta} \to \text{Elements of vacuum Hamiltonian}\\ \delta M_{\alpha\beta} \to \text{Elements of interaction Hamiltonian}\end{matrix}$$

- The new resonance condition : $2EV_{CC} = (\delta M_{\mu\mu})^2 \;\to \rho_{\rm res} = \frac{2\sqrt{2}G_F Y_e E}{m_n|\Delta m_{31}^2|\eta_{\mu\mu}^2}\rho_s^2$

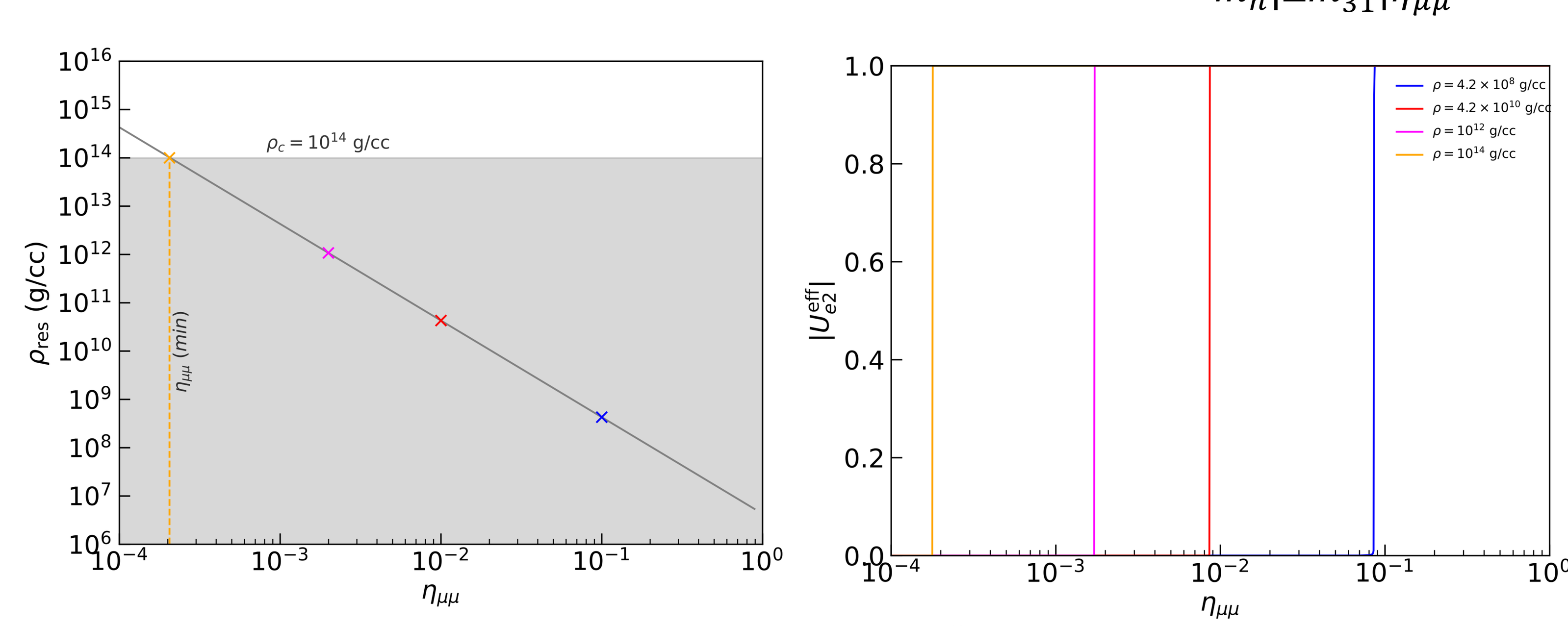

Fig. 3: Resonance density as a function of $\eta_{\mu\mu}$ (left). Evolution of $|U_{e2}^{\rm eff}|$ with $\eta_{\mu\mu}$ for different benchmark densities (right).

Expected event rate at DUNE and Hyper-K

- Expected number of neutrino events at the detector from a future SNe:

$$\frac{d^2N_{\nu_\alpha}}{dt\,dE^{rec}} = N_t\int_{E_{min}^{tr}}^{E_{max}^{tr}} dE^{tr} f_{\nu_\alpha}(E^{tr})\times\sigma(E^{tr})\times\epsilon(E^{rec},E^{tr})$$

- DUNE → 40 kt LArTPC detector, measure ν_e flux via ν_e CC interaction
- Hyper-K → 187 kt water Cherenkov detector, measure $\bar{\nu}_e$ flux via IBD process

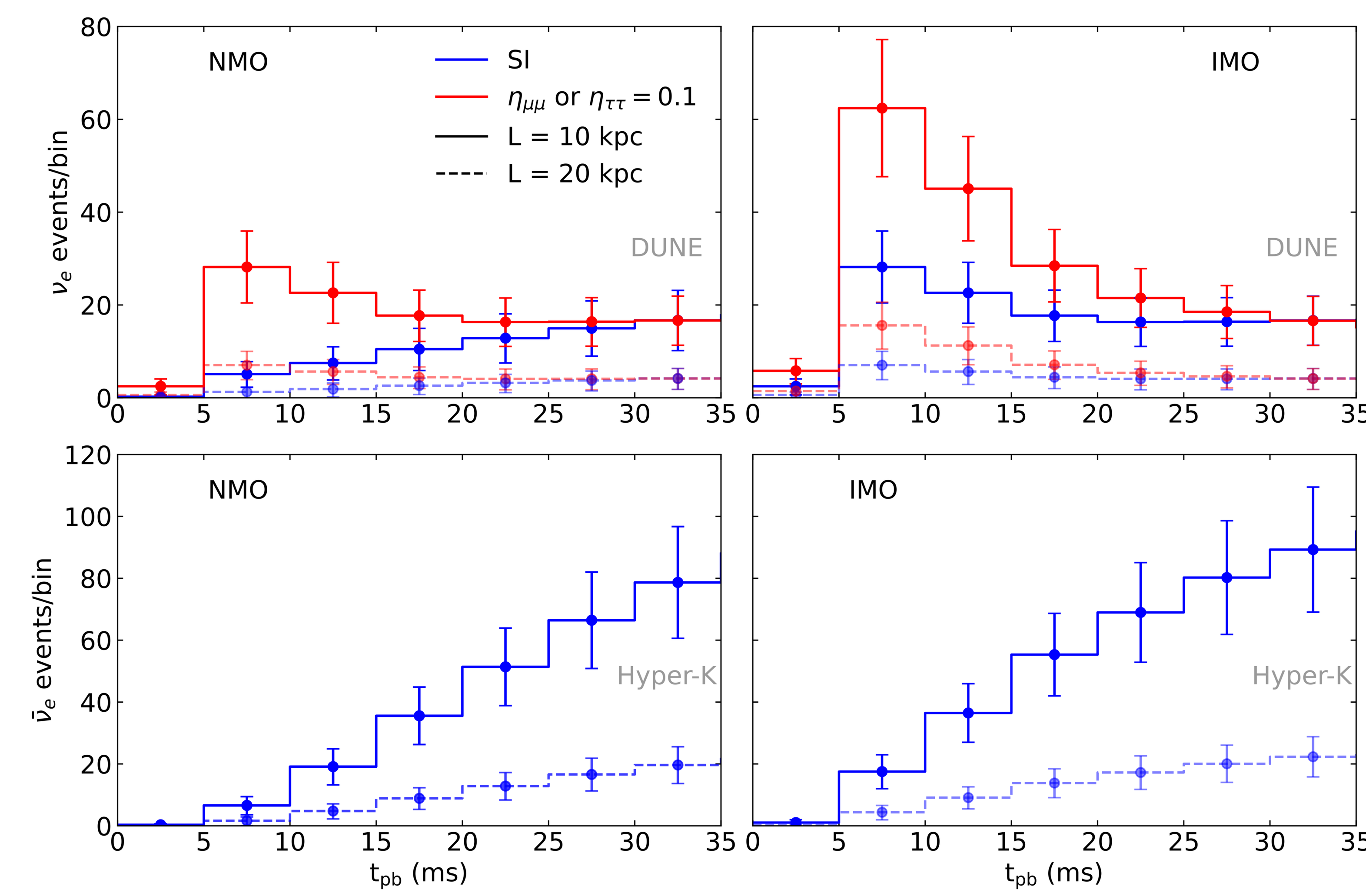

Fig. 4: Expected event rate at DUNE (top panels) and Hyper-K (bottom panels) as function of the time after core bounce considering NMO (left panels) and IMO (right panels) scenario.

Conclusion

- We probe the impact of a possible scalar mediated NSI on neutrino propagation inside a core collapse supernova.
- The new interaction induces a new resonance at the inner region of the supernova, inverting the mass states in ν_e aligns at the SNe core, which also depend on the neutrino mass ordering
- We estimate expected event rate from a future core collapse supernova at next-generation neutrino detector DUNE and Hyper-K. Combine results from both the experiment may help to probe such BSM scenarios

References

1. This poster is based on *JCAP* 02 (2026) 076 →
2. https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/
3. K. S. Babu, G. Chauhan, and P. S. Bhupal Dev, *Phys.Rev.D* 101 (2020) 9, 095029