

# Unlocking the Light(er) Sterile Neutrino Sector: Matter Effects and Mass Ordering

## INTRODUCTION

We analytically calculate the neutrino conversion probability  $P_{\mu e} \equiv P(\nu_\mu \rightarrow \nu_e)$  in the presence of sterile neutrinos, with:

- exact dependence on  $\Delta m_{41}^2$
- matter effects explicitly included.

We numerically calculate the sensitivity of DUNE to **Sterile Mass Ordering (SMO)**, and explain it.

## HAMILTONIAN

The Hamiltonian for the 3+1 neutrino system:

$$\mathcal{H}_{3+1} = \frac{1}{2E_\nu} U \cdot \text{diag} [(0, \Delta m_{21}^2, \Delta m_{31}^2, \Delta m_{41}^2)] \cdot U^\dagger + \text{diag} [(V_e + V_n, V_n, V_n, 0)]$$

- 4 × 4 PMNS matrix  $U = U_{34} U_{24} U_{14} U_{23} U_{13} U_{12}$ .
- Some useful dimensionless quantities:

$$\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}, \quad R \equiv \frac{\Delta m_{41}^2}{\Delta m_{31}^2}, \quad \Delta \equiv \frac{\Delta m_{31}^2 L}{4E_\nu},$$

$$A_e \equiv \frac{2E_\nu V_e}{\Delta m_{31}^2}, \quad A_n \equiv \frac{2E_\nu V_n}{\Delta m_{31}^2}.$$

- Expansion parameter  $\lambda \equiv 0.2$  (book-keeping).
- $\alpha \sim O(\lambda^2)$ ,  $s_{13} \sim O(\lambda)$ ,  $s_{14}, s_{24}, s_{34} \sim O(\lambda)$ .

## ANALYTIC PROBABILITY $P_{\mu e}$

Cayley-Hamilton theorem (with  $A_n = -A_e/2$ ) ⇒

$$P_{\mu e} = 4s_{13}^2 s_{23}^2 \frac{\sin^2[(A_e - 1)\Delta]}{(A_e - 1)^2} \quad [3\nu]$$

$$+ 2\alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\delta_{13} + \Delta)$$

$$\times \frac{\sin[(A_e - 1)\Delta] \sin[A_e \Delta]}{A_e - 1} \quad [3\nu]$$

$$+ 4s_{13}s_{14}s_{24}s_{23} \frac{\sin[(A_e - 1)\Delta]}{A_e - 1} \quad [4\nu]$$

$$\times [\sin(\delta'_{24})P_{24}^s + \cos(\delta'_{24})P_{24}^c]$$

$$+ 4s_{13}s_{14}s_{34}s_{23}^2 c_{23} \frac{\sin[(A_e - 1)\Delta]}{A_e - 1}$$

$$\times [\sin(\delta'_{34})P_{34}^s + \cos(\delta'_{34})P_{34}^c] + O(\lambda^4),$$

where the coefficient of  $\sin(\delta'_{24})$  is

$$P_{24}^s = R \left[ \frac{1}{2} A_e c_{23}^2 + (R - 1)(s_{23}^2 + 1) \right]$$

$$\times \frac{\sin \left[ \left( R - 1 + \frac{A_e}{2} \right) \Delta \right]}{R - 1 + \frac{A_e}{2}} \frac{\sin \left[ \left( R - \frac{A_e}{2} \right) \Delta \right]}{R - \frac{A_e}{2}}$$

$$+ c_{23}^2 R \sin \left[ \left( R - 1 - \frac{A_e}{2} \right) \Delta \right]$$

$$\times \frac{\sin \left[ \left( R + \frac{A_e}{2} \right) \Delta \right]}{R + \frac{A_e}{2}}.$$

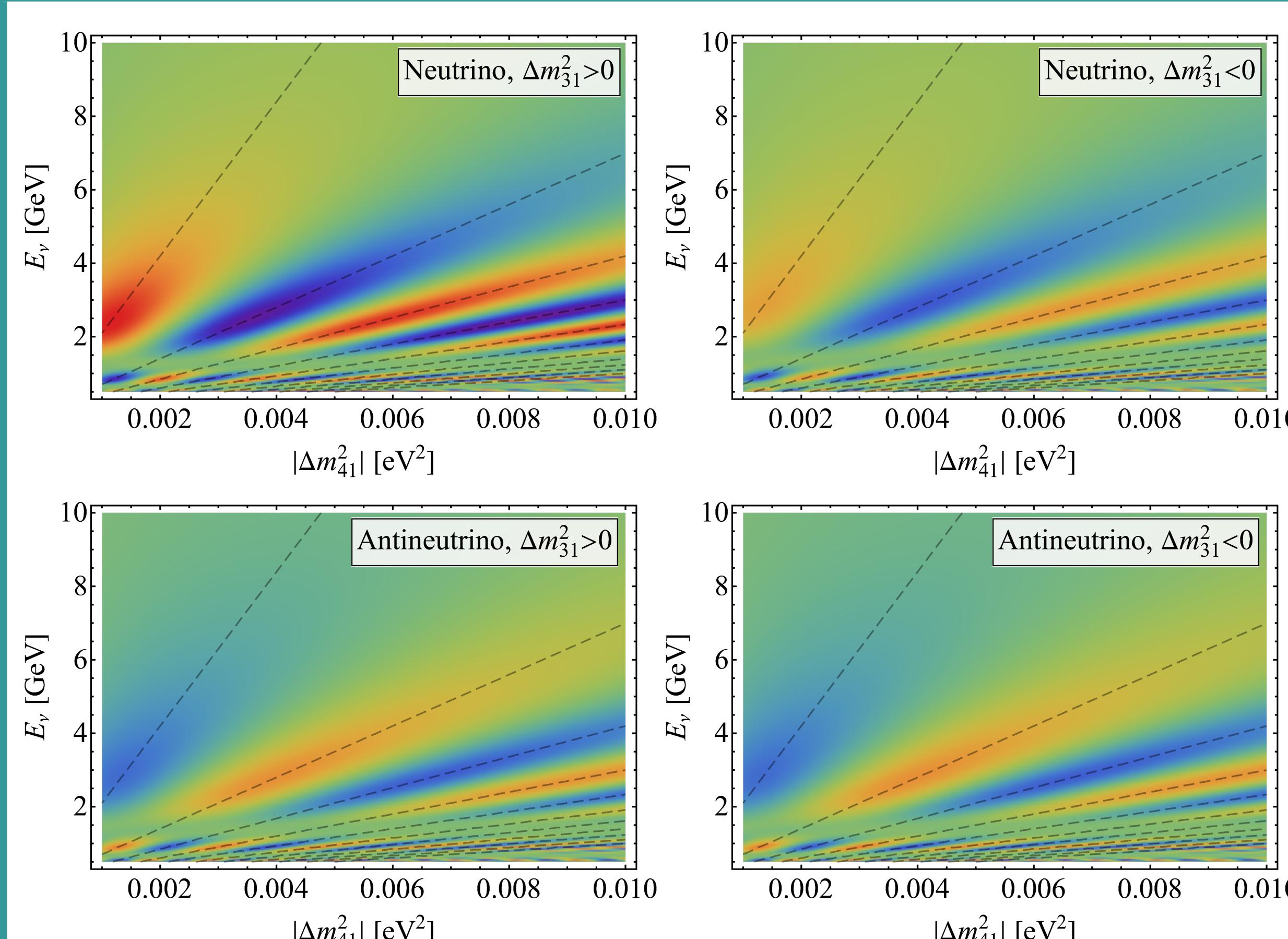
Here,  $\delta'_{ij} \equiv \delta_{ij} + \delta_{13}$ . Similar expressions for  $P_{24}^c$ ,  $P_{34}^s$  and  $P_{34}^c$  are derived in [1].

Expressing  $P_{\mu e}$  in the  $\sin(x)/x$  form helps identify possible **resonance-like** regions due to **sterile-matter interplay**.

## REFERENCES

- [1] D. S. Chattopadhyay, M. M. Devi, A. Dighe, D. Dutta, D. Pramanik and S. K. Raut, "Sterile neutrinos: propagation in matter and sensitivity to sterile mass ordering", JHEP 02 (2023) 044, (arXiv: 2211.03473 [hep-ph]).

## STERILE MASS ORDERING AT DUNE

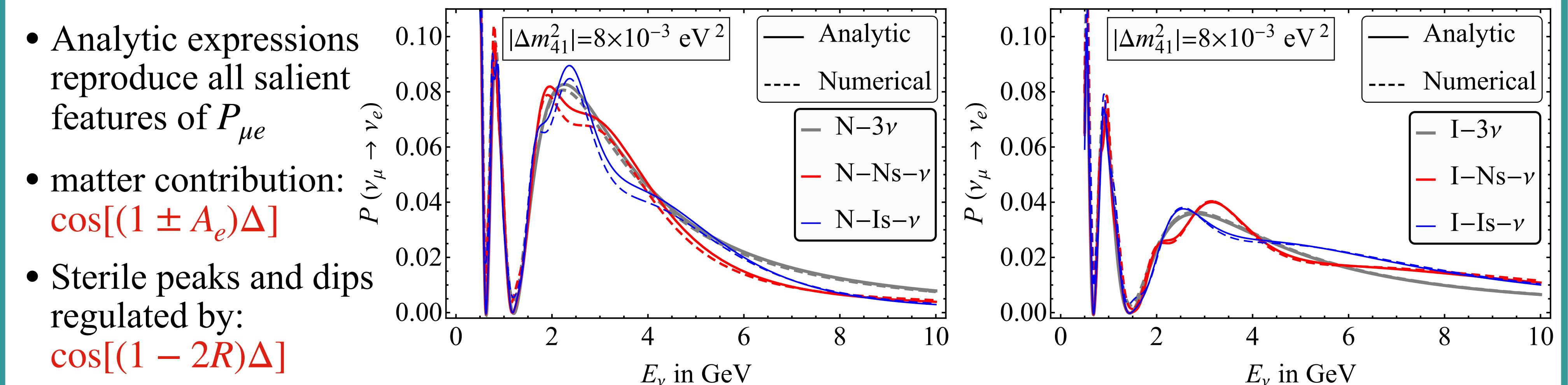


Active mass ordering	Sterile mass ordering	Combination
$\Delta m_{31}^2 > 0$ (N)	$\Delta m_{41}^2 > 0$ (Ns)	N-Ns
$\Delta m_{31}^2 < 0$ (Is)	$\Delta m_{41}^2 < 0$ (Is)	N-Is
$\Delta m_{31}^2 < 0$ (I)	$\Delta m_{41}^2 > 0$ (Ns)	I-Ns
	$\Delta m_{41}^2 < 0$ (Is)	I-Is

Quantifying effects of Sterile Mass Ordering

$$\delta P_{\mu e} = P_{\mu e}(R) - P_{\mu e}(-R)$$

• Max. sensitivity to SMO expected at  $E_\nu \sim (2 - 4)$  GeV, for  $|\Delta m_{41}^2| \sim (10^{-4} - 10^{-2})$  eV<sup>2</sup>.



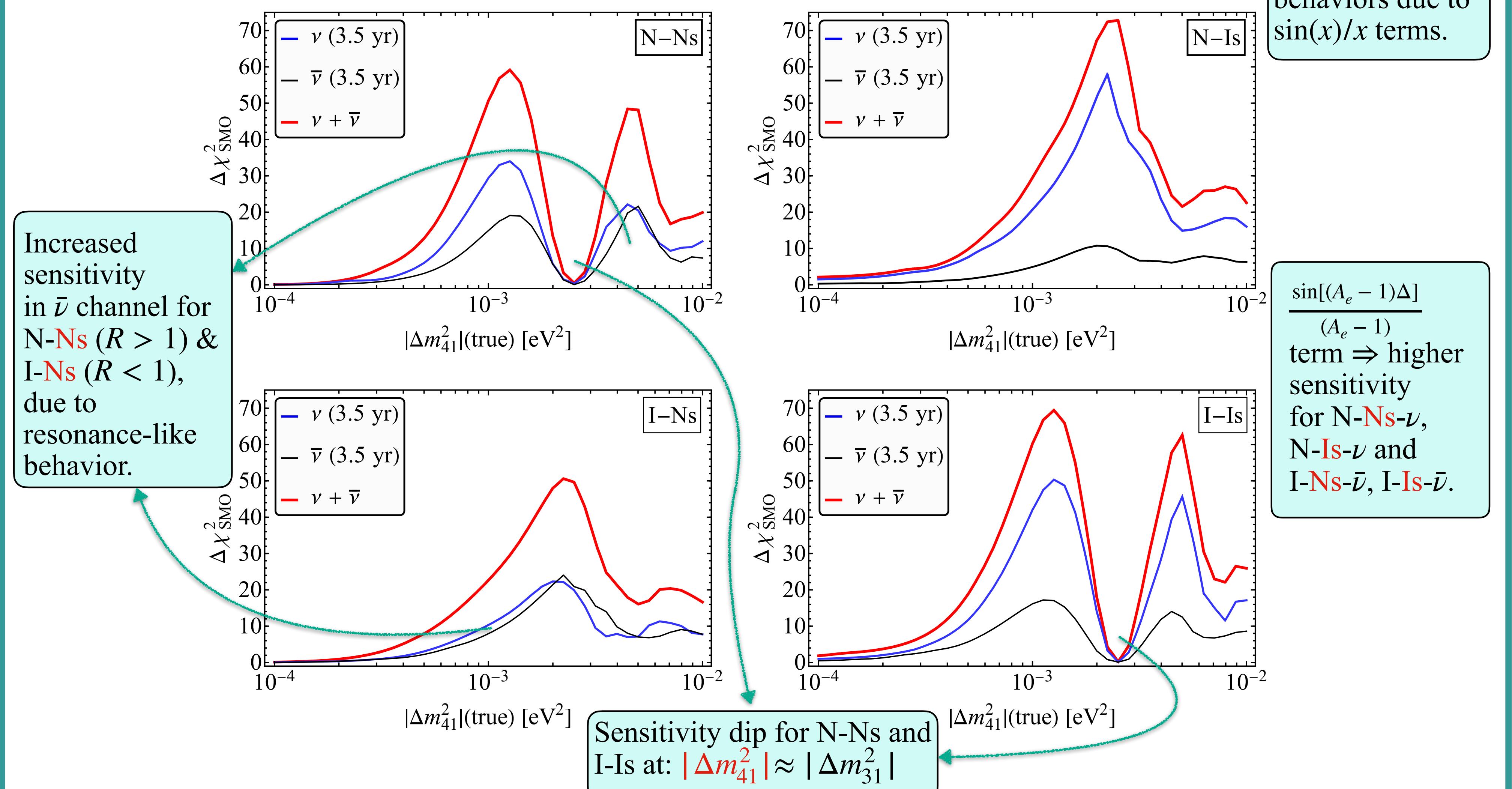
$$\Delta m_{21}^2 = 7.5 \times 10^{-5} \text{ eV}^2, \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2, \theta_{12} = 33.56^\circ, \theta_{23} \simeq 45^\circ, \theta_{13} \simeq 8.46^\circ, \delta_{CP} = -90^\circ,$$

Benchmark values  $\theta_{14} = 5^\circ, \theta_{24} = 10^\circ, \theta_{34} = 0^\circ, \delta_{24} = 0^\circ, \delta_{34} = 0^\circ$ .

## SENSITIVITY TO STERILE MASS ORDERING AT DUNE

In general:  $\Delta\chi^2_{\text{SMO}}(\nu) \gtrsim \Delta\chi^2_{\text{SMO}}(\bar{\nu})$

$\Delta\chi^2_{\text{SMO}} \gtrsim 25 \Rightarrow 5\sigma$  identification of SMO



sign of $A_e$	sign of $R$	Combinations		$ R  < 1$	$ R  > 1$
		$\nu$	$\bar{\nu}$		
+	+	N-Ns-ν	I-Is- $\bar{\nu}$	✓	—
-	+	I-Is-ν	N-Ns- $\bar{\nu}$	✓	✓✓
+	-	N-Is-ν	I-Ns- $\bar{\nu}$	✓✓	—
-	-	I-Ns-ν	N-Is- $\bar{\nu}$	—	—

- Disentangling of the complex interplay between matter effects and sterile contribution.
- Identifying the Resonance-like behavior in the  $P_{24}^s$  term which affects the sensitivity for all mass ordering combinations.

## TAKE HOME MESSAGE

Within constant average density approximation, our expressions for  $P_{\mu e}$  is valid for all long-baseline and atmospheric  $\nu$  experiments.

We show that DUNE is sensitive to **Sterile Mass Ordering** for  $|\Delta m_{41}^2| \sim (10^{-4} - 10^{-2})$  eV<sup>2</sup>.

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