

# ULDM signatures in neutrino oscillation experiments

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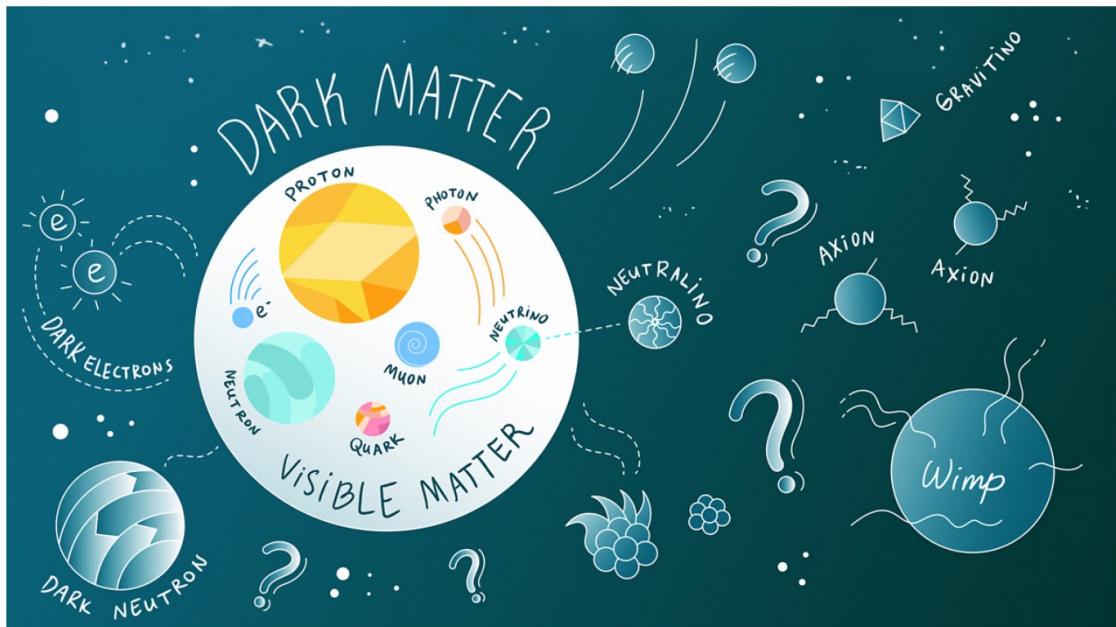
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July 2021

# Outline

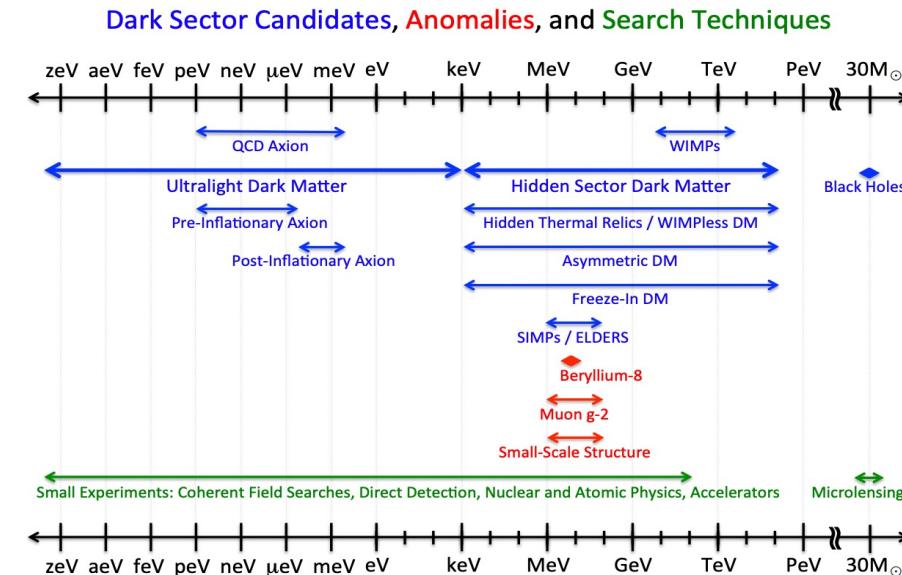
- Introduction
- ULDM effects on neutrino oscillations
- Relevant neutrino oscillation experiments
- Time averaged modulations
- CP Violation
- Time resolved modulations
- Pheno implications
- Conclusions

# Introduction

- Dark matter constitutes  $\sim 27\%$  of total energy density of the Universe
  - Plethora of candidates for DM
  - Focus today on Ultra Light Dark Matter (ULDM).



[Symmetry Magazine]



US Cosmic Visions 2017

# Main features of ULDM

- Small mass implies a large occupation number per de Broglie volume.
  - Must be a bosonic particle
- Consider a scalar field that will oscillate with a Compton frequency

$$\phi \approx \phi_0 \sin(m_\phi t)$$

- Local dark matter density defines:

$$\phi_0 \simeq \frac{\sqrt{2\rho_\phi^\oplus}}{m_\phi} \sim 2 \times 10^{10} \text{ GeV} \left( \frac{10^{-22} \text{ eV}}{m_\phi} \right)$$

# ULDM cont'd

- Oscillation period:

$$\tau_\phi = \frac{2\pi}{m_\phi} \approx 1.3 \text{ year} \times \left( \frac{10^{-22} \text{ eV}}{m_\phi} \right)$$

- Range of masses:

$$10^{-22} \text{ eV} \lesssim m_\phi \lesssim 10^{-12} \text{ eV}$$

# Theoretical set-up: SM + Scalar singlet

- Dim-5 and 6 terms in Lagrangian:

$$\mathcal{L}_{z,y} = \frac{z_{\alpha\beta}}{\Lambda} (L^\alpha)^T L^\beta H H + \frac{y_{\alpha\beta}}{\Lambda^2} \phi (L^\alpha)^T L^\beta H H$$

z and y are 3x3 symmetric matrices

$\Lambda$  scale of NP

$$H = \frac{1}{\sqrt{2}}(v + h)$$

- Generates neutrino mass terms and Yukawa couplings:

$$\mathcal{L}_{m_\nu} = \frac{z_{\alpha\beta} v^2}{2\Lambda} (\nu^\alpha)^T \nu^\beta + \frac{y_{\alpha\beta} v^2}{\Lambda^2} \phi (\nu^\alpha)^T \nu^\beta$$

# Two neutrino case

Mass squared difference

$$\begin{aligned}\Delta \hat{m}^2 &= \Delta m^2 + 2(m_2 \hat{y}_{22} - m_1 \hat{y}_{11})\phi + \mathcal{O}(\hat{y}^2 \phi^2) \\ &\equiv \Delta m^2 [1 + 2\eta_\Delta \sin(m_\phi t)].\end{aligned}$$

Mixing angle

$$\begin{aligned}\hat{\theta} &= \theta + \frac{\hat{y}_{12}\phi}{\Delta m} + \mathcal{O}\left(\frac{\hat{y}^2 \phi^2}{m^2}\right) \\ &\equiv \theta + \eta_\theta \sin(m_\phi t).\end{aligned}$$

$$\eta_\Delta, \eta_\theta \sim \mathcal{O}\left(\frac{y}{z} \frac{\phi_0}{\Lambda}\right)$$

$\nu_\mu \rightarrow \nu_e$  appearance oscillation probability

$$P_{\mu e} = \sin^2 2\hat{\theta} \sin^2 \hat{x}_E \quad \hat{x}_E \equiv \frac{\Delta \hat{m}^2 L}{4E}$$

$\theta$ -modification

$$\hat{y}_{11} = \hat{y}_{22} = 0 \quad P_{\mu e} = \sin^2 x_E \sin^2 \{2 [\theta + \eta_\theta \sin(m_\phi t)]\}$$

$\Delta m^2$  modification

$$\hat{y}_{12} = 0 \quad P_{\mu e} = \sin^2 2\theta \sin^2 \{x_E [1 + 2\eta_\Delta \sin(m_\phi t)]\}$$

# Neutrino experiments

Pontecorvo 1959  
Schwartz 1960  
Danby et al 1962

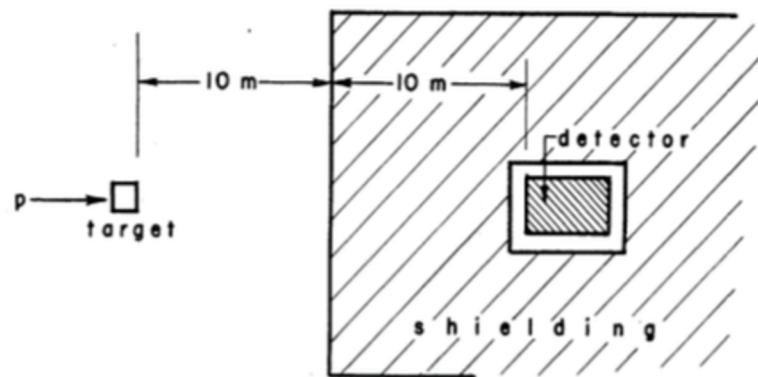


FIG. 1. Proposed experimental arrangement.

$$I = 5 \times 10^{12} \text{ protons/sec}$$

$I/10$  Pions produced at target,  $E > 2 \text{ GeV}$ , 2 steradians

$$c\tau = 7.8 \text{ m} \Rightarrow \text{Decay length } L = 111 \text{ m}$$

10% of pions decay

$$N_{\text{flux}} = 10^{-9} I$$

# events  $\sim I$  per hour

Led to first  $\nu$  beam and discovery of  $\nu_e \not\equiv \nu_\mu$

# Neutrino oscillation experiments

- Relevant Timescales  $\tau_\phi$ 
    - $\tau_d$  - the source-to-detector distance.
    - $\tau_r$  - the time-resolution of the detector.
    - $\tau_e$  - the running time of the experiment.
- $$\tau_d \lesssim \tau_\phi \lesssim \tau_e$$

	$\tau_d$	$\tau_r$	$\tau_e$	$N_\nu/\text{day}$	$P_{\alpha\beta}$
Daya Bay	$2.7 \times 10^{-6}$	$4 \times 10^3$	$5 \times 10^7$	800	$P_{\bar{e}\bar{e}}$
DUNE	$4.3 \times 10^{-3}$	$1 \times 10^6$	$2 \times 10^8$	16	$P_{\mu\mu}, P_{\mu e}$
JUNO	$1.8 \times 10^{-4}$	$1 \times 10^4$	$2 \times 10^8$	83	$P_{\bar{e}\bar{e}}$
KamLAND	$6.0 \times 10^{-4}$	$9 \times 10^5$	$3 \times 10^8$	2	$P_{\bar{e}\bar{e}}$
SK, SNO		$9 \times 10^4$	$3 \times 10^8$	10	$P_{ee}$
T2HK	$1.0 \times 10^{-3}$	$9 \times 10^4$	$9 \times 10^7$	56	$P_{\mu\mu}, P_{\mu e}$

# Time-averaged modulations ( $\tau_\phi < \tau_r$ )

- Mixing angles

$$\hat{\theta}_{ij} = \theta_{ij} + \eta_{\theta_{ij}} \sin(m_\phi t)$$

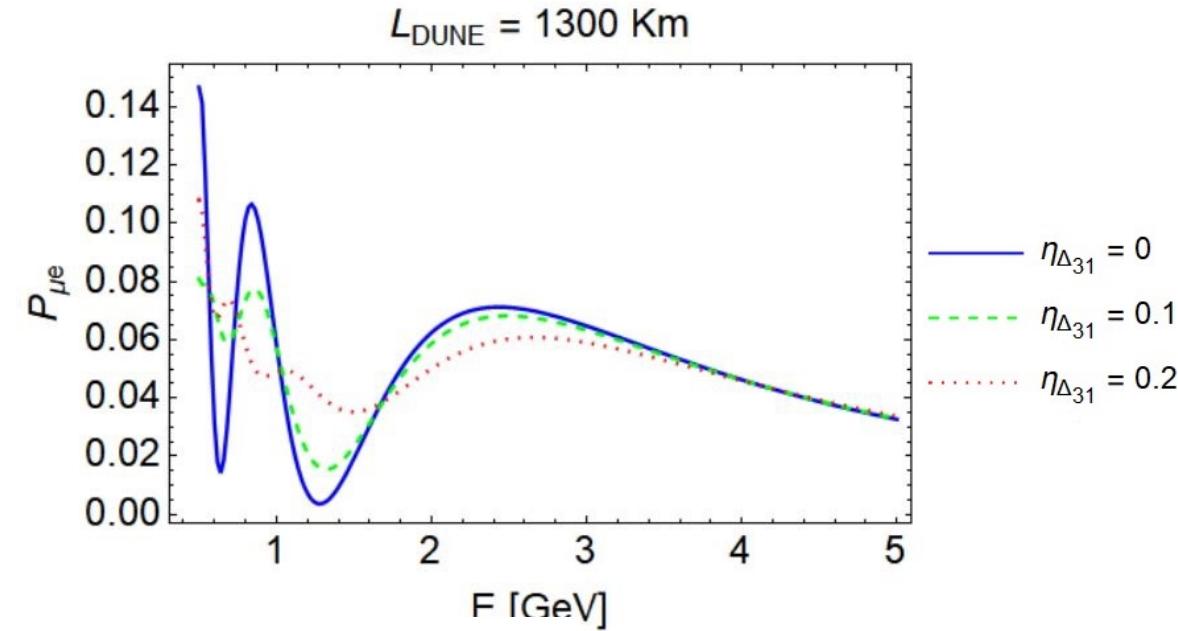
$$\begin{aligned}\langle \sin^2 2\hat{\theta}_{ij} \rangle &= \frac{1}{\tau_\phi} \int_0^{\tau_\phi} dt \sin^2[2\theta_{ij} + 2\eta_{\theta_{ij}} \sin(m_\phi t)] \\ &= \frac{1}{2} [1 - \cos(4\theta_{ij}) J_0(4\eta_{\theta_{ij}})] ,\end{aligned}$$

Use best experimental results on mixing angles

# Time-averaged modulations | DUNE

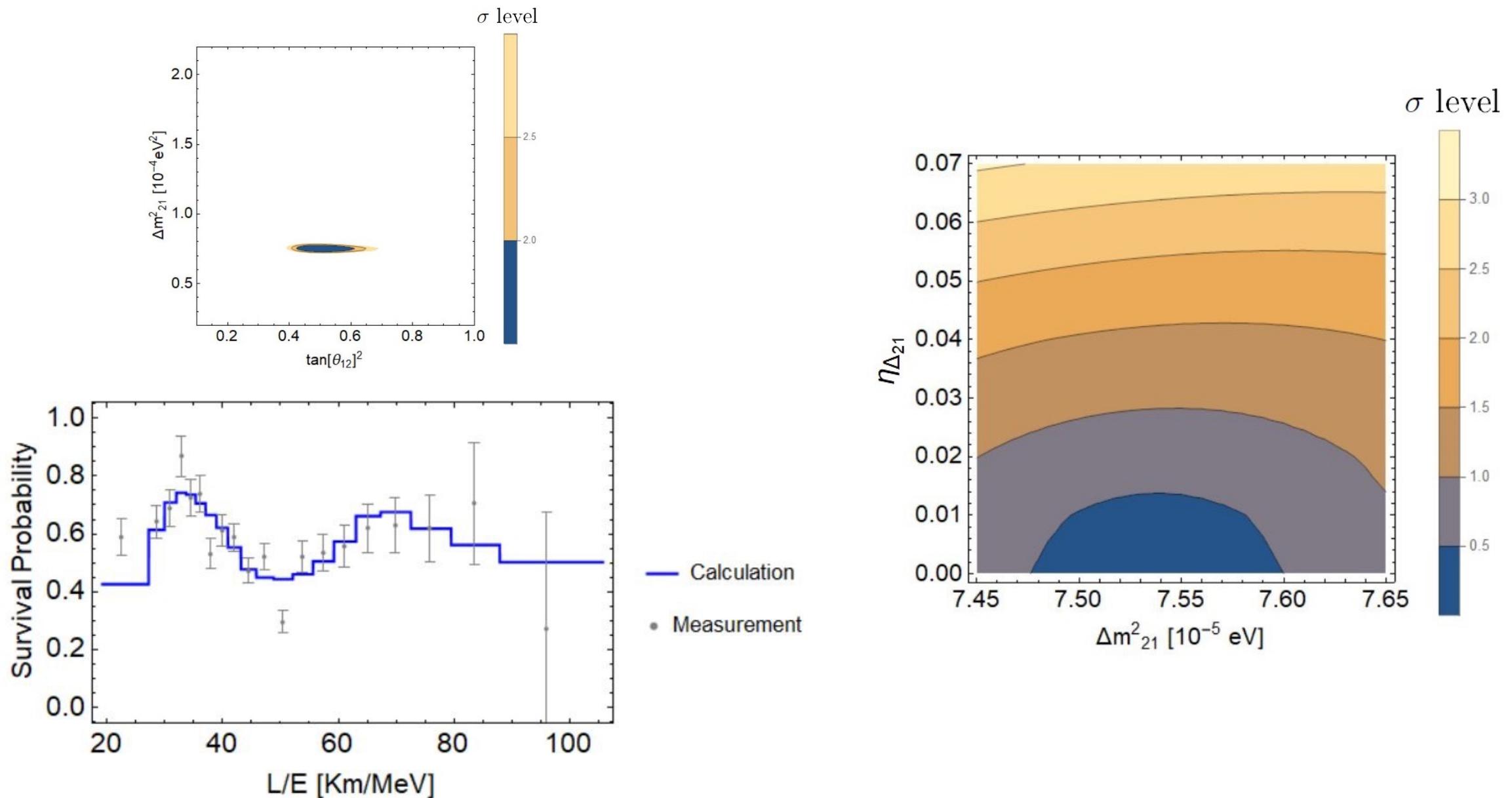
Mass modulation

$$\Delta \hat{m}_{ij}^2 = \Delta m_{ij}^2 [1 + 2\eta_{\Delta_{ij}} \sin(m_\phi t)]$$



$$\begin{aligned} \langle \sin^2[\Delta \hat{m}_{ij}^2 L / (4E)] \rangle &= \frac{1}{\tau_\phi} \int_0^{\tau_\phi} dt \sin^2 \left\{ x_{Eij} [1 + 2\eta_{\Delta_{ij}} \sin(m_\phi t)] \right\} \\ &= \sin^2(x_{Eij}) + 2x_{Eij}^2 \eta_{\Delta_{ij}}^2 \cos(2x_{Eij}) + \mathcal{O}\left(x_{Eij}^4 \eta_{\Delta_{ij}}^4\right) \end{aligned}$$

# Time-averaged modulations | Kamland



# CP Violation | Toy model

- z matrix is real,  $y$  matrix is complex
- Only off-diagonal elements of  $y$  are non-zero and purely imaginary
- CP-conserving parameters are quadratic in  $\eta$

$$U_0^T M U_0 = \begin{pmatrix} m_1 & i\mu & 0 \\ i\mu & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

$$\epsilon \equiv -\frac{\mu}{m_1 + m_2}$$

$$|\epsilon| \ll 1$$

# Modified PMNS matrix

$$U = U_0 V, \quad V = \begin{pmatrix} 1 - \frac{1}{2}\epsilon^2 & i\epsilon & 0 \\ i\epsilon & 1 - \frac{1}{2}\epsilon^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathcal{O}(\epsilon^3)$$

$$\hat{\theta}_{12} = \theta_{12} + \frac{\epsilon^2}{\tan 2\theta_{12}}$$

$$\hat{\theta}_{13} = \theta_{13}$$

$$\hat{\theta}_{23} = \theta_{23}$$

$$J = \frac{\epsilon}{4} \cos \hat{\theta}_{13} \sin 2\hat{\theta}_{23} \sin 2\hat{\theta}_{13}$$

$$\delta_{\text{CP}} = \frac{\epsilon}{\cos \theta_{12} \sin \theta_{12}} + \mathcal{O}(\epsilon^3)$$

$$\Delta \hat{m}_{21}^2 = \Delta m_{21}^2 (1 + 2\epsilon^2)$$

$$\Delta \hat{m}_{31}^2 = \Delta m_{31}^2 - 2m_1 (m_1 + m_2) \epsilon^2$$

# CP Violation

$$\epsilon = \epsilon_0 \sin(m_\phi t)$$

$$\delta_{CP} = \eta_\delta \sin(m_\phi t) + \mathcal{O}(\eta_\delta^3), \quad \eta_\delta = \frac{2\epsilon_0}{\sin 2\theta_{12}}$$

$$P_{\mu e} = P_{\bar{\mu} \bar{e}}$$

Time-averaged effect not because CPV is zero

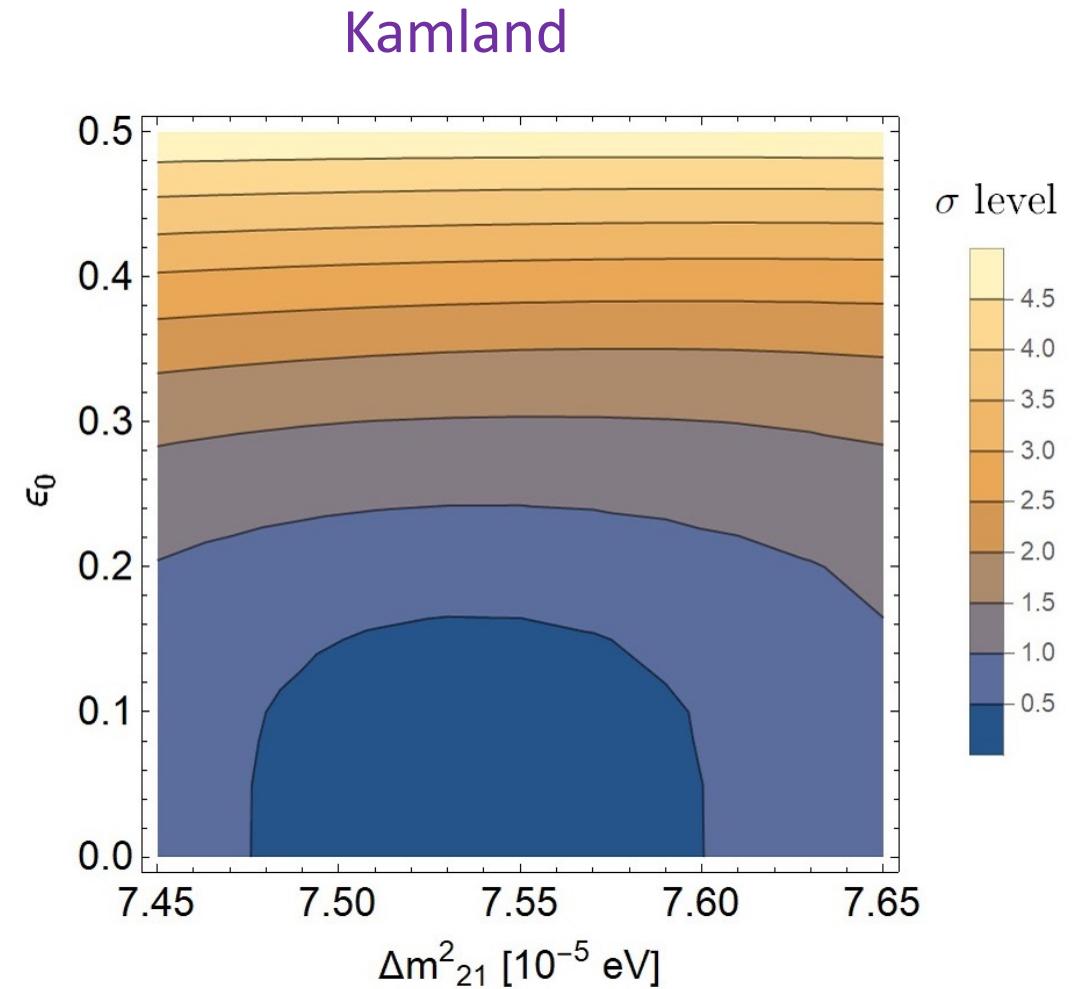
# CP Violation

- Current Bound from

$$\theta_{12} \rightarrow \theta_{12} - \epsilon_0^2 / [2 \tan(2\theta_{12})]$$

$$\Delta m_{21}^2 \rightarrow \Delta m_{21}^2 / (2 + 2\epsilon_0^2)$$

$$\epsilon_0 < 0.34 \implies \eta_\delta < 0.74$$



# Probing time-averaged CP violation

Complex perturbation

$$U_0^T M U_0 = \begin{pmatrix} m_1 & \mu e^{i\varphi} & 0 \\ \mu e^{i\varphi} & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

Modified PMNS matrix

$$V = \begin{pmatrix} 1 - \frac{1}{2}\epsilon^2 & \epsilon e^{i\varphi} & 0 \\ -\epsilon e^{-i\varphi} & 1 - \frac{1}{2}\epsilon^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathcal{O}(\epsilon^3)$$

$$P_{\alpha\alpha} = 1 - 4C_{\alpha\alpha}^{21} \sin^2 x_{21} - 4C_{\alpha\alpha}^{31} \sin^2 x_{31} - 4C_{\alpha\alpha}^{32} \sin^2 x_{32}$$

$$P_{\mu e} = C_{\mu e}^{21} \sin^2 x_{21} + C_{\mu e}^{31} \sin^2 x_{31} + C_{\mu e}^{32} \sin x_{31} \sin x_{21} \cos x_{32}$$

# Probing TA CPV

$$\xi_{\mu e} = \frac{(C_{\mu e}^{32})^2}{C_{\mu e}^{21} C_{\mu e}^{31}} = 1 - \frac{(U_{e2} U_{\mu 1} + U_{e1} U_{\mu 2})^2}{2 U_{e2}^2 U_{\mu 2}^2} \epsilon_0^2 + \mathcal{O}(\epsilon_0^4)$$

$$\xi_{\alpha\alpha} = \sqrt{\frac{C_{\alpha\alpha}^{21} C_{\alpha\alpha}^{31}}{C_{\alpha\alpha}^{32}}} + \sqrt{\frac{C_{\alpha\alpha}^{21} C_{\alpha\alpha}^{32}}{C_{\alpha\alpha}^{31}}} + \sqrt{\frac{C_{\alpha\alpha}^{31} C_{\alpha\alpha}^{32}}{C_{\alpha\alpha}^{21}}} = 1 - (1 - 2 U_{\alpha 3}^2) \epsilon_0^2 \cos^2 \varphi$$

Real part pert.

==> In principle, we can extract phase of perturbation from these quantities.

$$\varphi \neq 0$$

Implies time-averaged CPV

# Time-resolved modulations ( $\tau_\phi > \tau_r$ )

Probe time dependence of  $P_{\alpha\beta}(E)$

$$P_{\alpha\beta}(E, t) \approx P_{\alpha\beta}^0(E) + \epsilon_{\alpha\beta}(E) \sin(m_\phi t) + \mathcal{O}(\epsilon_{\alpha\beta}^2)$$

$$\epsilon_{\mu e} = 2\eta_\theta \sin 2\theta \sin^2 x_E + 2\eta_\Delta x_E \sin^2 2\theta \sin 2x_E$$

→ Generate CL

$$CL = \left[ 1 - \exp \left( -\frac{1}{4} \frac{N_\nu^{\text{tot}}(E) \text{sinc}^2(m_\phi t/2) |\langle \epsilon_{\alpha\beta}(E) \rangle|^2}{\langle P_{\alpha\beta}^0(E) \rangle (1 - \langle P_{\alpha\beta}^0(E) \rangle)} \right) \right]^{n_{\text{tb}}}$$

# SK and SNO

- Search for periodic time variations < 10%

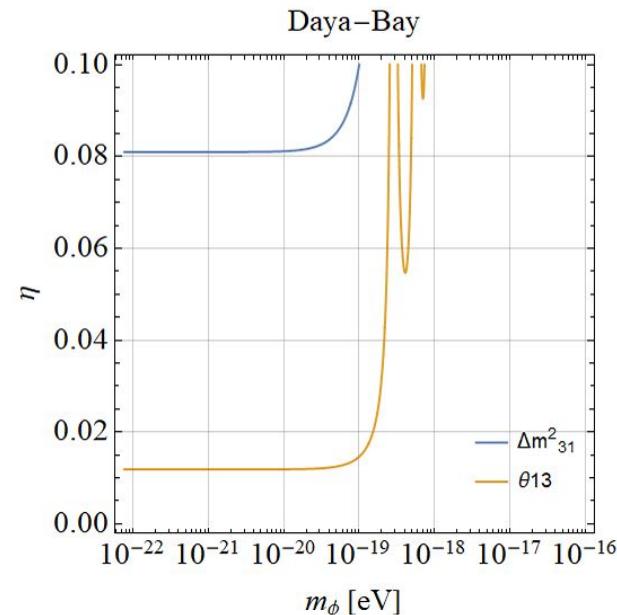
$$\begin{aligned}\eta_{\theta_{12}} &< 0.03 \\ \eta_{\theta_{13}} &< 0.3\end{aligned}$$

$$10 \text{ minutes} < \tau_\phi < 10 \text{ years} \Rightarrow 10^{-23} \text{ eV} < m_\phi < 7 \times 10^{-18} \text{ eV}$$

## Daya-Bay

Search for time variations in

$$P_{\overline{e}e}$$

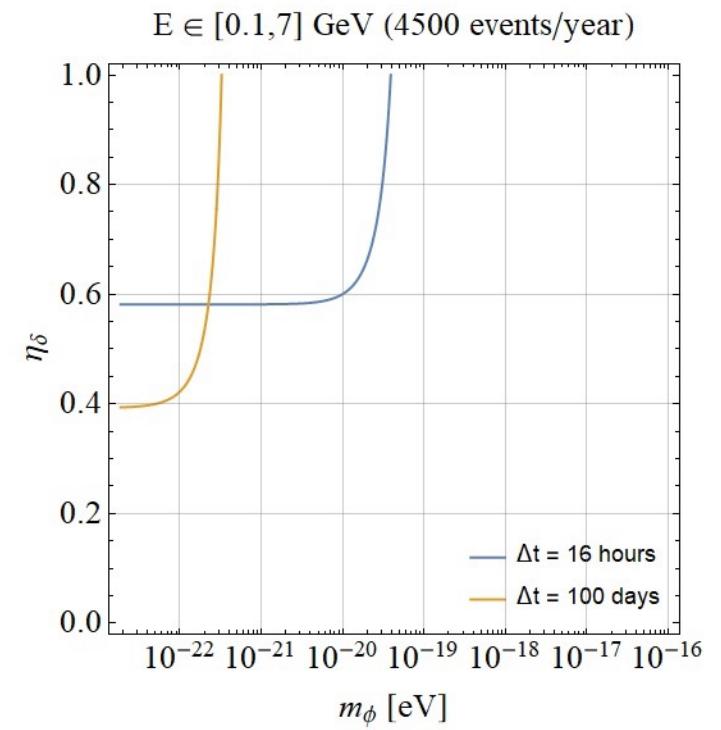
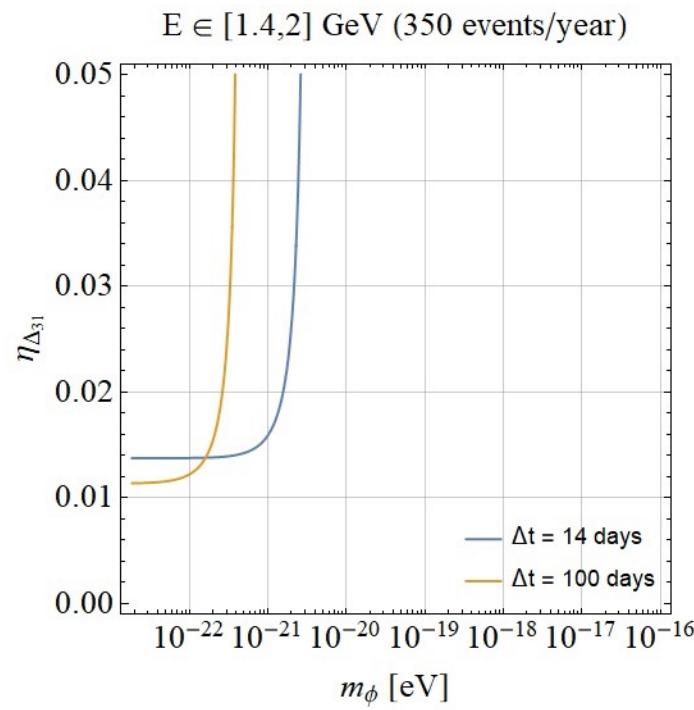
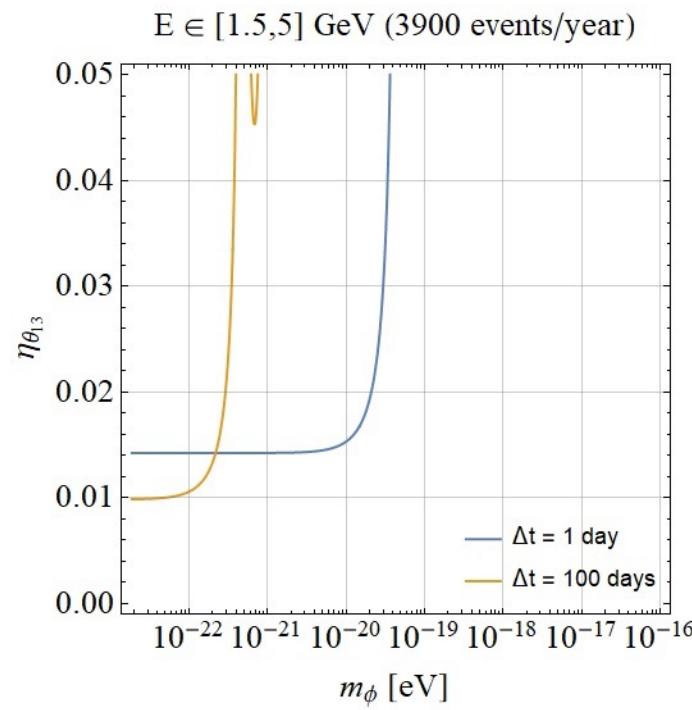


# Current Bounds

$\eta$	$\tau_\phi < \tau_r$			$\tau_\phi > \tau_r$		
	Bound	$P_{\alpha\beta}$	Exp.	Bound	$P_{\alpha\beta}$	Exp.
$\eta_{\theta_{12}}$	<b>0.29</b>	$P_{ee}$	$\nu_{\text{sol}}$	0.03	$P_{ee}$	SK,SNO
$\eta_{\theta_{13}}$	0.21	$P_{\bar{e}\bar{e}}$	$\nu_{\text{rea}}$	<b>0.01</b>	$P_{\bar{e}\bar{e}}$	DB
$\eta_{\theta_{23}}$	0.09	$P_{\mu\mu}$	$\nu_{\text{atm}}$	—	—	—
$\eta_\delta$	<b>0.74</b>	$P_{\bar{e}\bar{e}}$	KL	—	—	—
$\eta_{\Delta_{31}}$	—	—	—	<b>0.08</b>	$P_{\bar{e}\bar{e}}$	DB
$\eta_{\Delta_{21}}$	0.05	$P_{\bar{e}\bar{e}}$	KL	0.3	$P_{\bar{e}\bar{e}}$	DB

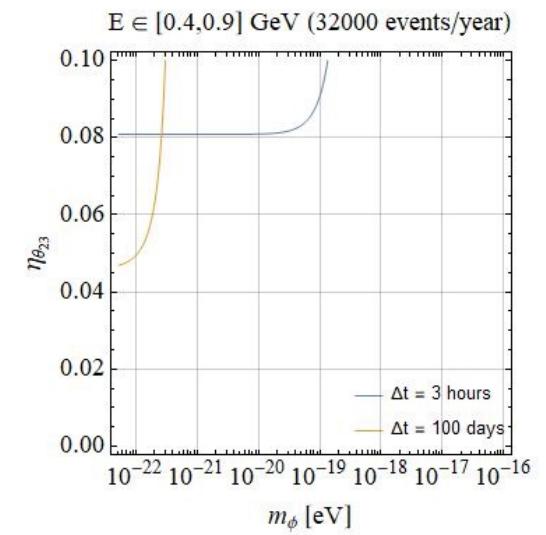
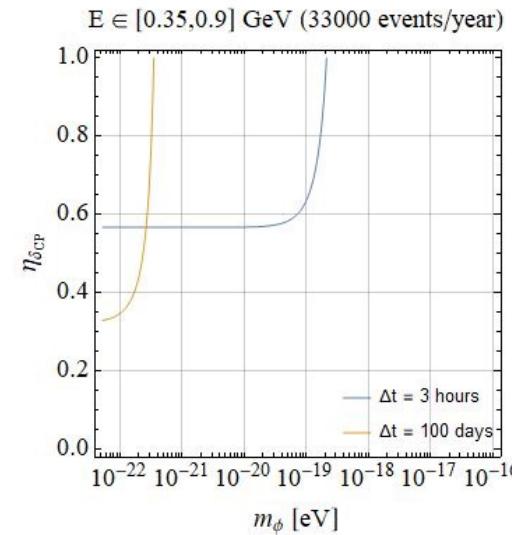
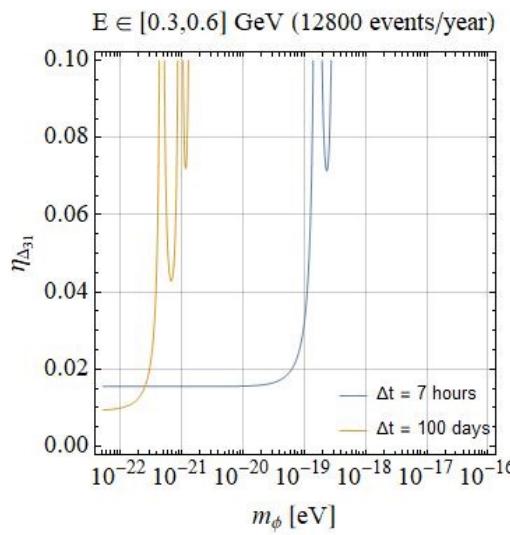
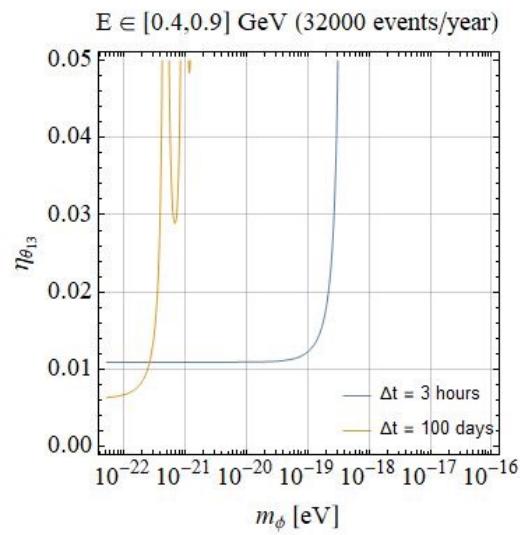
# Future sensitivities | DUNE

DUNE: Total 6000 events/year,  $\tau_e = 7$  years



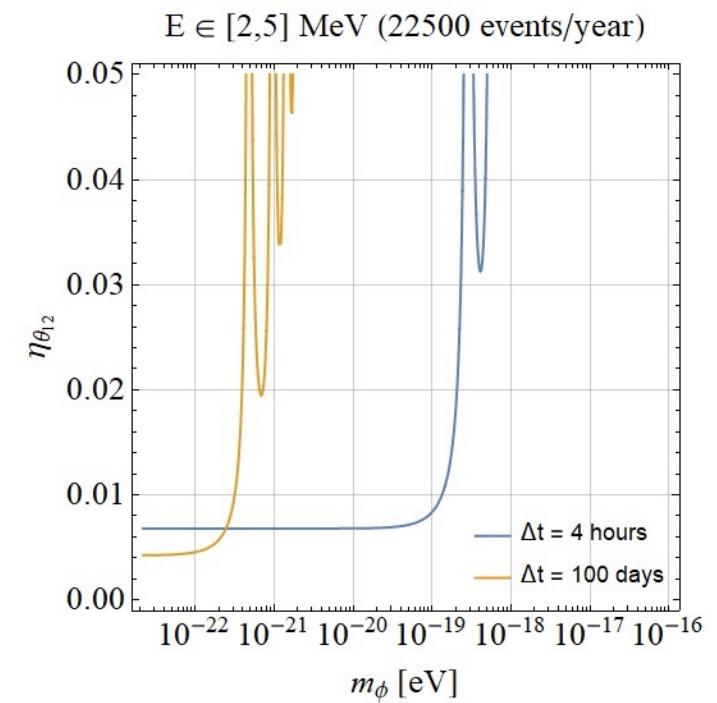
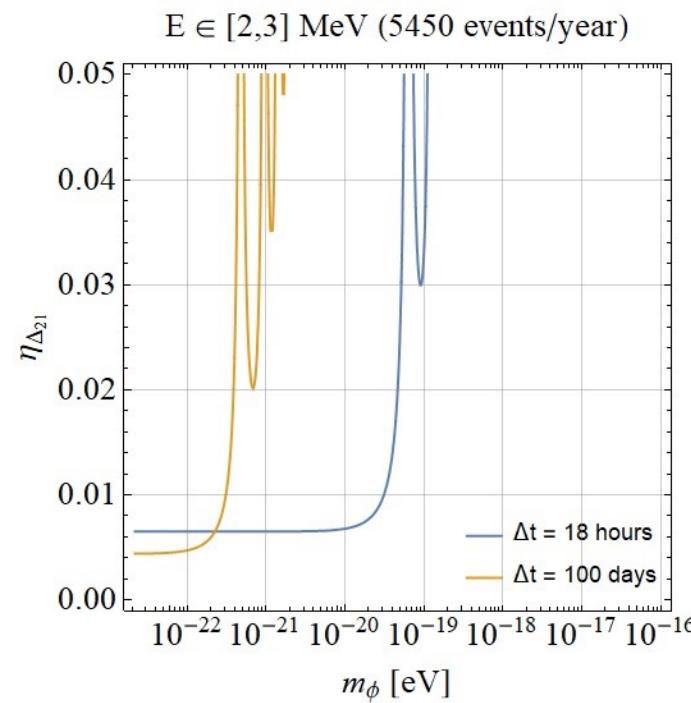
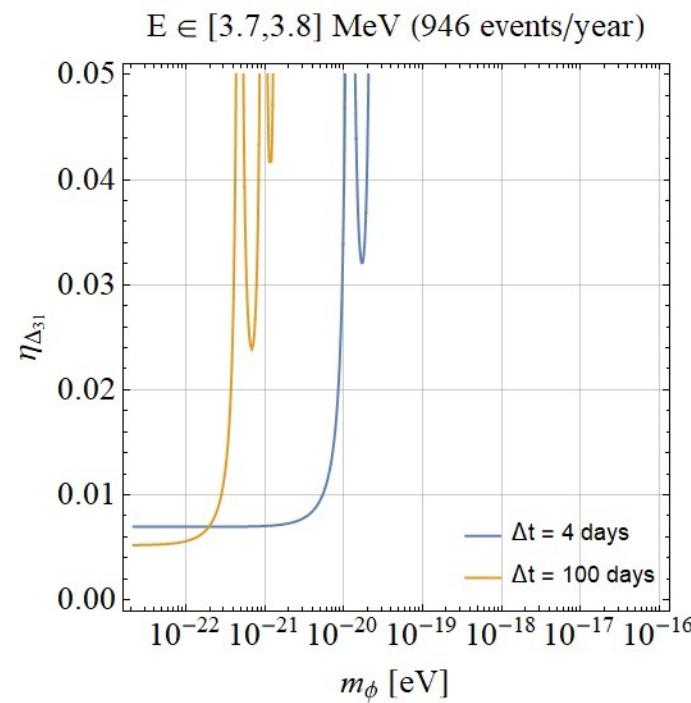
# Future Sensitivities | HK

Hyper Kamiokande: Total 20580 events/year,  $\tau_e = 2.5$  years



# Future sensitivities | JUNO

JUNO: Total 30500 events/year,  $t_{\text{exp}} = 6$  years



# Summary of current bounds and future sensitivities

$\eta$	$\tau_\phi < \tau_r$			$\tau_\phi > \tau_r$			JUNO		DUNE		HK	
	Bound	$P_{\alpha\beta}$	Exp.	Bound	$P_{\alpha\beta}$	Exp.	Bound	$P_{\alpha\beta}$	Bound	$P_{\alpha\beta}$	Bound	$P_{\alpha\beta}$
$\eta_{\theta_{12}}$	<b>0.29</b>	$P_{ee}$	$\nu_{\text{sol}}$	0.03	$P_{ee}$	SK,SNO	<b>0.004</b>	$P_{\bar{e}\bar{e}}$				
$\eta_{\theta_{13}}$	0.21	$P_{\bar{e}\bar{e}}$	$\nu_{\text{rea}}$	<b>0.01</b>	$P_{\bar{e}\bar{e}}$	DB			<b>0.01</b>	$P_{\mu e}$	<b>0.01</b>	$P_{\mu e}$
$\eta_{\theta_{23}}$	0.09	$P_{\mu\mu}$	$\nu_{\text{atm}}$	—							<b>0.03</b>	$P_{\mu e}$
$\eta_\delta$	<b>0.74</b>	$P_{\bar{e}\bar{e}}$	KL	—					<b>0.4</b>	$P_{\mu e}$	<b>0.23</b>	$P_{\mu e}$
$\eta_{\Delta_{31}}$	—			<b>0.08</b>	$P_{\bar{e}\bar{e}}$	DB	<b>0.005</b>	$P_{\bar{e}\bar{e}}$	<b>0.01</b>	$P_{\mu e}$	<b>0.005</b>	$P_{\mu e}$
$\eta_{\Delta_{21}}$	0.05	$P_{\bar{e}\bar{e}}$	KL	0.3	$P_{\bar{e}\bar{e}}$	DB	<b>0.004</b>	$P_{\bar{e}\bar{e}}$				

# Pheno implications and bounds

1. Effective potential for ULDM field and consistency with neutrino masses, visible signal and naturalness requires:

$$\Lambda_\nu \lesssim \frac{4\pi m_\phi}{\hat{y}} \lesssim 10^2 \sqrt{\frac{\rho_{\text{DM}}}{m_\nu^2}} \sim 10 \text{ eV}$$

→ Requires a new degree of freedom coupled to ULDM

2. Scalar mixing

$$\theta_{H\phi} \sim \frac{\hat{y}\Lambda_\nu^2 m_\nu}{16\pi^2 v m_H^2} \gtrsim \frac{0.1 m_\phi m_\nu}{\sqrt{\rho_{\text{DM}}}} \frac{\Lambda_\nu^2 m_\nu}{16\pi^2 v m_H^2} \sim 10^{-54} \frac{m_\phi}{10^{-18} \text{ eV}} \times \left(\frac{\Lambda_\nu}{\text{eV}}\right)^2$$

Consistent with ep and atomic clocks experiments

3. CMB bound

$$\sum m_\nu \lesssim 0.2 \text{ eV}$$

$$\eta_{\Delta_{31}} \lesssim 3 \times 10^{-2}$$

Does not constrain mixing angles or CP phase

# Conclusions

- Constraints on ULDM form neutrino oscillations.
- Time-averaged and time-resolved modulations of neutrino masses and mixings.
- Model which has a leading CP violating effect and modulation of CP conserving parameters is suppressed.
- Presented a unique imprint of TA-CPV in neutrino oscillations.
  - ▶ The bound on  $\eta_{\theta_{12}}$  from time-averaged modulations: Previous bounds from time-resolved modulations hold only for  $m_\phi \lesssim 7 \times 10^{-18}$  eV.
  - ▶ The bound on  $\eta_{\theta_{13}}$  from time-resolved modulations: It is the strongest bound for  $m_\phi \lesssim 7 \times 10^{-18}$  eV.
  - ▶ The bound on  $\eta_{\Delta_{31}}$  from time-resolved modulations: This constitutes the first bound on this parameter.
  - ▶ The bound on  $\eta_\delta$  from time-averaged modulations from KamLAND: This is the first bound on this parameter.
  - ▶ The expected sensitivities to various  $\eta$ 's of the different neutrino mass and mixing parameters from JUNO, DUNE and HK.

# Backup slides

$$C_{ee}^{21} = U_{e1}^2 U_{e2}^2 + \frac{1}{2} \epsilon_0^2 \left( U_{e1}^4 - 4U_{e1}^2 U_{e2}^2 + U_{e2}^4 \right) - U_{e1}^2 U_{e2}^2 \epsilon_0^2 \cos 2\varphi,$$

$$C_{ee}^{31} = U_{e3}^2 U_{e1}^2 + \frac{1}{2} \epsilon_0^2 U_{e3}^2 \left( U_{e2}^2 - U_{e1}^2 \right),$$

$$C_{ee}^{32} = U_{e3}^2 U_{e2}^2 - \frac{1}{2} \epsilon_0^2 U_{e3}^2 \left( U_{e2}^2 - U_{e1}^2 \right),$$

$$C_{\mu\mu}^{21} = U_{\mu 1}^2 U_{\mu 2}^2 + \frac{1}{2} \epsilon_0^2 \left( U_{\mu 1}^4 - 4U_{\mu 1}^2 U_{\mu 2}^2 + U_{\mu 2}^4 \right) - U_{\mu 1}^2 U_{\mu 2}^2 \epsilon_0^2 \cos 2\varphi,$$

$$C_{\mu\mu}^{31} = U_{\mu 3}^2 U_{\mu 1}^2 + \frac{1}{2} \epsilon_0^2 U_{\mu 3}^2 \left( U_{\mu 2}^2 - U_{\mu 1}^2 \right),$$

$$C_{\mu\mu}^{32} = U_{\mu 3}^2 U_{\mu 2}^2 + \frac{1}{2} \epsilon_0^2 U_{\mu 3}^2 \left( U_{\mu 1}^2 - U_{\mu 2}^2 \right),$$

$$C_{\mu e}^{21} = U_{e2}^2 U_{\mu 2}^2 + \frac{1}{2} \epsilon_0^2 \left[ U_{e2}^2 U_{\mu 1}^2 + U_{e1}^2 U_{\mu 2}^2 - 2U_{e2}^2 U_{\mu 2}^2 + 2U_{e1} U_{e2} U_{\mu 1} U_{\mu 2} (1 + \cos 2\varphi) \right],$$

$$C_{\mu e}^{31} = U_{e3}^2 U_{\mu 3}^2,$$

$$C_{\mu e}^{32} = U_{e2} U_{e3} U_{\mu 2} U_{\mu 3} - \frac{1}{2} \epsilon_0^2 U_{e2} U_{e3} U_{\mu 2} U_{\mu 3} + \frac{1}{2} \epsilon_0^2 U_{e1} U_{e3} U_{\mu 1} U_{\mu 3} \cos 2\varphi$$