Damping signatures at JUNO, a medium-baseline reactor neutrino oscillation experiment

The JUNO collaboration

E-mail: Juno_pub_comm@juno.ihep.ac.cn

ABSTRACT: We study damping signatures at the Jiangmen Underground Neutrino Observatory (JUNO), a medium-baseline reactor neutrino oscillation experiment. These damping signatures are motivated by various new physics models, including quantum decoherence, $\nu_3$ decay, neutrino absorption, and wave packet decoherence. The phenomenological effects of these models can be characterized by exponential damping factors at the probability level. We assess how well JUNO can constrain these damping parameters and how to disentangle these different damping signatures at JUNO. Compared to current experimental limits, JUNO can significantly improve the limits on $\tau_3/m_3$ in the $\nu_3$ decay model, the width of the neutrino wave packet $\sigma_x$, and the intrinsic relative dispersion of neutrino momentum $\sigma_{\text{rel}}$.

KEYWORDS: Neutrino Detectors and Telescopes (experiments)

ARXIV ePRINT: 2112.14450
1 Introduction

Neutrino oscillation was first proposed by Bruno Pontecovero in 1957 [1] and was invoked for the solution of atmospheric neutrino anomaly and solar neutrino puzzle. It was experimentally confirmed by the Super-Kamioka Neutrino Detection Experiment (Super-K, SK) [2] in 1998 and the Sudbury Neutrino Observatory (SNO) [3] in 2002; for further details see ref. [4]. Most neutrino oscillation experiments can be well explained in the Standard Model (SM) with three massive neutrinos. In the standard three-flavor neutrino oscillation framework, the three known neutrino flavor eigenstates ($\nu_e$, $\nu_\mu$, and $\nu_\tau$) can be written as quantum superpositions of three mass eigenstates ($\nu_1$, $\nu_2$, and $\nu_3$), and the neutrino oscillation probabilities are expressed in terms of six oscillation parameters: three mixing angles ($\theta_{12}$, $\theta_{13}$, and $\theta_{23}$), two mass-squared differences ($\Delta m^2_{21}$ and $\Delta m^2_{31}$), and one Dirac CP phase ($\delta_{\text{CP}}$). The Majorana CP phases play no role in neutrino oscillations if neutrinos are Majorana particles. Among these six observable oscillation parameters, $\Delta m^2_{21}$, $|\Delta m^2_{31}|$, $\theta_{12}$, and $\theta_{13}$ have been well determined to the few-percent level. However, the neutrino mass ordering (whether $\Delta m^2_{31}$ is positive or negative), the octant of $\theta_{23}$ (whether $\theta_{23}$ is larger or smaller than 45°) and the Dirac CP phase are still open questions. At present, the normal mass ordering (NMO) and the second octant of $\theta_{23}$ are both favored by less than 3σ confidence level (CL) [4–6], and $\delta_{\text{CP}}$ is in the range of [-3.41, -0.03] for the NMO and [-2.54, -0.32] for the inverted mass ordering (IMO) at the 3σ CL [7], respectively. The main physics goals of next-generation neutrino oscillation experiments, such as the...
Deep Underground Neutrino Experiment (DUNE) [8, 9], Hyper-Kamiokande [10] and the Jiangmen Underground Neutrino Observatory (JUNO) [11, 12], are to determine the mass ordering with a $3 - 5\sigma$ CL and to observe CP violation with a $3\sigma$ CL for $\sim 75\%$ of $\delta_{CP}$ values, etc. To reach these goals, the ability to achieve high-precision measurement of the oscillation spectrum is required for these experiments. In the meantime, these high-precision experiments will also reach sufficient sensitivity to probe new physics beyond the standard three-neutrino paradigm.

The presence of new physics in the neutrino sector would yield corrections to the standard three-flavor neutrino oscillation probabilities, thus leading to modifications to the spectrum measured in high-precision neutrino oscillation experiments. Among various possible new physics scenarios, a number of them lead to exponential damping in the neutrino oscillation probabilities [13, 14], which could yield a different number of neutrinos observed than expected [14–19] or a shift in the best fit values for neutrino oscillation parameters [13–17, 20–25]. These damping signatures can be treated as secondary effects relative to the standard three-neutrino oscillations in the neutrino flavor transitions. In this work, we present a systematic study of the possible damping effects at the JUNO detector.

JUNO is a medium-baseline reactor neutrino experiment with a 20kton liquid scintillator (LS) detector located in a laboratory at 700m underground in Jiangmen, China. The main physics goals of JUNO are to determine the mass ordering and perform high-precision measurements of the neutrino oscillation parameters $\sin^2\theta_{12}$, $\Delta m^2_{21}$ and $|\Delta m^2_{ee}|$ [11, 12]. Also, JUNO is expected to be sensitive to the tiny damping signatures due to its effective energy resolution of 3$\%$ at 1MeV and the capability of measuring multiple oscillation cycles [25].

This paper is organized as follows. In section 2, we discuss the damping signatures arising from different new physics models. In section 3, we discuss the damping signatures at medium-baseline reactor neutrino experiments. In section 4, we describe the statistical analysis method for JUNO used in this work. In section 5, we present the results of constraining and disentangling damping signatures at JUNO. We conclude in section 6.

## 2 Damping signatures from new physics models

Damping signatures can be induced by a class of new physics models. Here, we focus on the exponential damping framework [13, 14], i.e., they can be written in the form of multiplying each term of the neutrino oscillation probabilities with exponential factors, which can arise from an approximation of the first- or second-order perturbations to the standard neutrino oscillation probabilities from new physics scenarios [25–27]. In this framework, the general expression for the probability of $\nu_a$ oscillating into $\nu_b$ in vacuum is given by

$$P(\nu_a \rightarrow \nu_b) = \sum_{i,j=1}^{3} U_{ai} U_{bj}^{*} U_{ai}^{*} U_{bi} \exp \left( -i \frac{\Delta m^2_{ij} L}{2 E} \right) D_{ij}(\alpha_{ij}),$$

where $U$ is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix [3, 4], $\Delta m^2_{ij} = m_i^2 - m_j^2$, with $m_i$ being the eigenstate mass of $\nu_i$; $L$ is the baseline length, $E$ is the neutrino energy; $D_{ij}$ is an exponential damping factor and the specific form can be found in table 1.
| Type   | Damping effect | Reference                          | Damping factor $D_{ij}$ | Units of $\alpha$ |
|--------|----------------|------------------------------------|-------------------------|------------------|
| (1)    | QD I           | [20, 23, 28–33]                    | $\exp(-\alpha L/E^2)$  | MeV$^2 \cdot m^{-1}$ |
| (2)    | QD II          | [20, 23, 28–40]                    | $\exp(-\alpha L)$      | $m^{-1}$         |
| (3)    | QD III         | [13, 20, 23, 28–33, 35–39]         | $\exp(-\alpha LE^2)$  | MeV$^{-2} \cdot m^{-1}$ |
| (4)    | Absorption     | [13, 20, 23, 28–32, 40]            | $\exp(-\alpha LE)$     | MeV$^{-1} \cdot m^{-1}$ |
| (5)    | $\nu_3$ decay | [15–17, 19, 41–43]                 | $\{\exp\left(-\alpha \frac{L}{E}\right), \exp\left(-\alpha \frac{L^2}{E^2}\right)\}$ | MeV$ \cdot m^{-1}$ |
| (6)    | WPD I          | [13, 23, 24, 44–49]                | $\exp\left(-\alpha \frac{(\Delta m^2)^2 L^2}{E^4}\right)$ | MeV$^2$ |
| (7)    | WPD II         | [13, 25, 37, 50]                   | $\exp\left(-\alpha \frac{(\Delta m^2)^2 L^2}{E^4}\right)$ | dimensionless |
| (8)    | WPD III        | [21, 22, 25, 51, 52]               | $\exp(-R - iX)$         | dimensionless |

Table 1. List of new physics models with different exponential damping factors. The definitions of the parameters in the type (8) model are given in eq. (2.2).

and the $\alpha_{ij}$ are damping coefficients. Hereinafter, except for the $\nu_3$ decay case, we assume universal couplings, i.e., $\alpha_{ij} \equiv \alpha$, to describe the magnitudes of different damping effects.

The damping signatures from various new physics models are summarized in table 1. These models include quantum decoherence (QD), neutrino absorption, $\nu_3$ decay, and wave packet decoherence (WPD). The new physics models of types (1) – (5) in table 1 are expressed as power-law dependencies of the exponential form, i.e., $\exp(-\alpha LE^n)$ with $n = 0, \pm 1, \pm 2$ [20, 23, 28–33, 35, 37, 39, 40]. Specifically, the type (1) model ($n = -2$) is demonstrated in ref. [20] that it has the same functional form as the effects induced by stochastic density fluctuations. Thus, it is used to probe QD effects that might be induced by matter density fluctuations. The corresponding constraints of this model can be interpreted as limits on possible matter density fluctuations in the Sun [20]. The most significant feature of the type (2) model ($n = 0$) is independent of neutrino energy. Many researchers have focused on this model since it is the simplest case of QD effects that might be induced by quantum gravity [20, 23, 28–40]. The type (3) model ($n = 2$) is used to probe QD effects that might be induced by the space-time “foam” configurations of quantum gravity or D-brane of the form $\alpha \propto E^2/M_{\text{Planck}}$ [20, 35, 53, 54], where $M_{\text{Planck}}$ is the Planck mass scale. The type (4) model ($n = 1$), which is called neutrino absorption in ref. [13], is used to describe the absorption effect when neutrinos propagate through matter. In this type of model, $\alpha \equiv \rho \sigma(E_0)/E_0$, where $\rho$ is the matter density and $\sigma(E_0)$ is the effective cross section for neutrinos with an energy of $E_0$. Currently, neither atmospheric, solar neutrino oscillation experiments nor the long-baseline reactor neutrino experiment Kamioka Liquid Scintillator Anti-Neutrino Detector (KamLAND) shows evidence in favor of the new physics effects described by the previous four models ($n = 0, 1$ and $\pm 2$) [20, 35], which also indicates that their damping parameter $\alpha$ can be strongly constrained. Furthermore, there are no significant changes in the best-fit neutrino oscillation parameters in these new physics scenarios [30, 31, 33, 40]. The fact that neutrinos are massive implies they could decay. The $n = -1$ case was used in refs. [13, 16, 18, 38, 55–62] to describe invisible neutrino decay scenarios, which lead to the violation of three-flavor neutrino unitarity. However,
ref. [18] has shown that astrophysical neutrinos are potentially the most powerful source for constraining the decay parameters of $\nu_1$ and $\nu_2$, which could lead to the lower bounds on $\tau/m \sim 10^{-4}$ ($10^6$) s/eV from the solar (supernova) neutrinos. Nevertheless, the constraints on $\nu_3$ decay is much weaker than those on $\nu_1$ and $\nu_2$ from the current data [16, 18, 19]. Here, in the type (5) model, we only consider the $\nu_3$ decay scenario [15–17, 19, 41–43]. The oscillation probability of $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ comprises two exponential forms derived from the case of $n = -1$, with $\alpha$ being the neutrino eigenstate mass divided by the corresponding lifetime, i.e., $\alpha \equiv m_3/\tau_3$.

Although the plane-wave approximation theory successfully interprets a wide range of neutrino experiments, it is not self-consistent and leads to many paradoxes [46, 51, 52, 63]. Therefore, the models of types (6) – (8) are proposed to form a consistent description of neutrino oscillations, which use the wave packet treatment of neutrino oscillation instead of the plane wave approximation for neutrino propagation [21, 22, 25, 46, 51, 52]. However, this description also induce some WPD effects, which have not been found in current experimental data [22, 24, 49]. Furthermore, the WPD effects and $\nu_3$ decay can shift the best-fit neutrino oscillation parameters if these effects are strong enough [13, 16, 17, 22, 24, 49]. Specifically, the type (6) model is used to describe the decoherence effect caused by wave packet separation [13, 23, 24, 44–49]. This effect is related to the characteristics of the neutrino source and detector. In the type (6) model, $\alpha \equiv 1/(4\sqrt{2}\sigma_x)^2$, where $\sigma_x$ is the spatial width of the neutrino wave packet. The type (7) model is used in ref. [50] to show that in the two-neutrino oscillation case, a Gaussian-averaged neutrino oscillation model with $\exp[-2\sigma^2(\Delta m^2)^2]$ and a neutrino decoherence model with $\exp(-d^2L)$ are equivalent if $d = \frac{\sqrt{2} \Delta m^2}{\sqrt{E}} \sigma$ is fulfilled, where $\sigma$ is the standard deviation of $L/E$ and $d$ is the decoherence parameter. The model with $\exp[-2\sigma^2(\Delta m^2)^2]$ is obtained by Gaussian average over the $L/E$ dependence for the oscillation probability under the plane-wave approximation due to uncertainties in the energy and oscillation length [37, 50]. Since under the condition of $(2\sigma^2 E^4/L^2) = 1/(4\sqrt{2}\sigma_x)^2$, the type (6) and type (7) models are equivalent, we refer to the type (7) model as WPD II.

The type (8) model systematically studies the quantum decoherence effects caused by wave packet separation, dispersion and delocalization. We rewrite the unified decoherence model as WPD II.

\[
\exp(-R - iX) = \exp \left\{ -\frac{1}{4} \ln(1 + y_{ij}^2) + \lambda_{ij} + \eta_{ij} \right\} - i \frac{1}{2} \tan^{-1}(y_{ij}) - \lambda_{ij} y_{ij} \right\}
\]

\[
\left( \frac{1}{1 + y_{ij}^2} \right)^{\frac{1}{4}} \exp(-\lambda_{ij}) \exp \left( -\frac{i}{2} \tan^{-1}(y_{ij}) \right) \exp(i\lambda_{ij} y_{ij}) \exp(-\eta_{ij}),
\]

where $\lambda_{ij} = \frac{x_i^2}{1 + y_{ij}^2}, x_i = \frac{\sqrt{2} \Delta m^2 L}{4E} \sigma_{\text{rel}}, y_{ij} = \frac{\Delta m^2 L}{E} \sigma_{\text{rel}}, \eta_{ij} = \frac{1}{2} \left( \frac{\Delta m^2 L}{4 \sigma_{\text{rel}} E} \right)^2$, and $\sigma_{\text{rel}} = (2\sigma_x E)^{-1}$. In this model, we define $\alpha \equiv \sigma_{\text{rel}}$, where $\sigma_{\text{rel}}$ represents the intrinsic relative dispersion of neutrino momentum. The $\exp(-\lambda_{ij})$ term corresponds to the conventional quantum decoherence effect caused by the gradual separation of different mass states traveling at different spatial propagation speeds, which causes them to stop interfering.
with each other, leading to damped oscillations. The terms containing $y_{ij}$ describe the dispersion effect, which includes two effects on the oscillations: wave packet spreading compensates for wave packet separation, and dispersion reduces the overlap fraction of the wave packets \cite{21,25}. The $\exp(-\eta_{ij})$ term corresponds to the quantum decoherence effect from delocalization, which is related to the neutrino production and detection processes and is independent of the baseline $L$. We find that $\exp(-\eta_{ij})$ is very close to 1 at JUNO if $\sigma_{rel} \gtrsim O(10^{-15})$. In ref. \cite{22}, the Daya Bay (DYB) collaboration published their first experimental limits, which are $10^{-14} < \sigma_{rel} < 0.23$ and $2.38 \times 10^{-17} < \sigma_{rel} < 0.23$ at a 95% CL when the dimensions of the reactor cores and detectors are and are not considered as constraints, respectively. Therefore, we neglect the $\exp(-\eta_{ij})$ term in eq. (2.2) in this work in the following text.\footnote{If we consider the decoherence effect caused by delocalization, the lower limit on $\sigma_{rel}$ at JUNO can reach $3.0 \times 10^{-17}$ at 95% CL. Although this expected lower limit is slightly better than the DYB limit of $\sigma_{rel} > 2.38 \times 10^{-17}$, the improvement from JUNO is not large due to the smaller IBD events compared with DYB and the baseline independence of delocalization \cite{22}.}

In addition, some works have discussed exponential damping models such as $\exp\left(-\alpha \frac{L^2}{(2E)^2}\right)$ and $\exp\left(-\alpha \frac{(\Delta m^2_{ij})^2 L}{E^2}\right)$. The former was adopted in ref. \cite{13} to approximately describe the mixing of three active neutrinos and a very light sterile neutrino in short-baseline reactor neutrino experiments. Here, $\alpha$ represents the magnitude of mixing between the three active neutrinos and the light sterile neutrino. Note that this approximate relationship does not hold for medium- or long-baseline neutrino experiments with an eV-scale sterile neutrino or for mixing scenarios involving three active neutrinos and multiple sterile neutrinos. The latter damping model was proposed to explain the decoherence effect caused by quantum gravity in the Super-Kamiokande experiment \cite{64}, and the coupling $\alpha$ can be related to $M_{\mathrm{Planck}}$. For a single-baseline experiment or an experiment with multiple identical baselines, the phenomenology of the former model above is the same as that of the type (1) model, and the phenomenology of the latter model above is the same as that of the type (7) model. Therefore, we will not discuss these two models in depth in this paper.

3 Damping signatures at medium-baseline reactor neutrino experiments

In this section, we first discuss the damping effects on the survival probability of $\bar{\nu}_e$ in medium-baseline reactor neutrino experiments. After that, we classify the damping effects in accordance with their different damping behaviors.

3.1 Damped neutrino oscillation probabilities

From the general expression in eq. (2.1), we can obtain four cases for the damped survival probability of reactor neutrinos ($\bar{\nu}_e$) in vacuum, as follows:

(I) The overall $\bar{\nu}_e$ survival probability is damped out. This case includes the QD I, QD II, QD III, and absorption damping effects.

$$
\begin{align*}
P(\bar{\nu}_e \to \bar{\nu}_e) &= D \left\{ 1 - c_{13}^4 \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) - c_{12}^2 \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\
&\quad - s_{12}^2 \sin^2(2\theta_{13}) \sin^2(\Delta_{32}) \right\}.
\end{align*}
$$

(3.1)
where the expression in curly brackets represents the $\bar{\nu}_e$ survival probability in vacuum without damping effects (i.e., the standard $\bar{\nu}_e$ survival probability), $D = D_{ij}$ because there are no relevant $\Delta m^2_{ij}$ terms in these damping factors, $c_{ij} = \cos \theta_{ij}$, $s_{ij} = \sin \theta_{ij}$, and the oscillation phase $\Delta_{ij}$ is defined as

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E} \simeq 1.267 \frac{\Delta m_{ij}^2 [\text{eV}^2] L [\text{km}]}{E [\text{GeV}]} = 1.267 \frac{\Delta m_{ij}^2 [\text{eV}^2] L [\text{m}]}{E [\text{MeV}]}.$$  \hspace{1cm} (3.2)

(II) Some oscillating and nonoscillating terms of the $\bar{\nu}_e$ survival probability are damped out. This case includes the $\nu_3$ decay damping effect.

$$P(\bar{\nu}_e \to \bar{\nu}_e) = c_{13}^4 [1 - \sin^2(2\theta_{12}) \sin^2(\Delta_{21})]$$

$$+ \frac{1}{2} \sin^2(2\theta_{13}) \exp \left( -\frac{\alpha L}{2E} \right) [c_{12}^2 \cos(2\Delta_{31}) + s_{12}^2 \cos(2\Delta_{32})]$$

$$+ \exp \left( -\frac{\alpha L}{E} \right) s_{13}^4.$$  \hspace{1cm} (3.3)

(III) Only the oscillating terms of the $\bar{\nu}_e$ survival probability are damped out, but there are no dispersion terms. This case includes the WPD I and WPD II damping effects.

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \frac{1}{2} [c_{13}^4 \sin^2(2\theta_{12}) + \sin^2(2\theta_{13})] + \frac{1}{2} c_{13}^4 \sin^2(2\theta_{12}) D_{21} \cos(2\Delta_{21})$$

$$+ \frac{1}{2} \sin^2(2\theta_{13}) [D_{31} c_{12}^2 \cos(2\Delta_{31}) + D_{32} s_{12}^2 \cos(2\Delta_{32})].$$  \hspace{1cm} (3.4)

(IV) Not only are the oscillating terms of the $\bar{\nu}_e$ survival probability damped out, but there are also dispersion terms. This case includes the WPD III damping effect.

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \frac{1}{2} c_{13}^4 \sin^2(2\theta_{12}) \left[ 1 - \left( \frac{1}{1 + y_{21}^2} \right)^{\frac{1}{2}} \exp(-\lambda_{21}) \cos(\phi_{21}) \right]$$

$$- \frac{1}{2} \sin^2(2\theta_{13}) c_{12}^2 \left[ 1 - \left( \frac{1}{1 + y_{31}^2} \right)^{\frac{1}{2}} \exp(-\lambda_{31}) \cos(\phi_{31}) \right]$$

$$- \frac{1}{2} \sin^2(2\theta_{13}) s_{12}^2 \left[ 1 - \left( \frac{1}{1 + y_{32}^2} \right)^{\frac{1}{2}} \exp(-\lambda_{32}) \cos(\phi_{32}) \right].$$  \hspace{1cm} (3.5)

where $\phi_{ij} = \frac{\Delta m^2_{ij} L}{2E} + \frac{1}{2} \arctan(y_{ij}) - \lambda_{ij} y_{ij}$ and is the sum of the plane wave phase and the phase shift introduced by wave packet dispersion.

In general, the $\bar{\nu}_e$ survival probability at JUNO is also affected by the Mikheyev-Smirnov-Wolfenstein (MSW) matter effect as the neutrinos travel through matter [65, 66]. We can treat this damping effect as a minor perturbation of the neutrino oscillations in matter [13]. For the standard three-neutrino oscillation scenarios, the corrections to the neutrino parameters due to matter effects do not exceed 1.1% [11, 67, 68]. In this work, we also ignore matter effects because they only slightly shift the central values of the neutrino oscillation parameters and do not affect the measurement precision.
3.2 Classification of damping effects

In figure 1, we plot the $\bar{\nu}_e$ survival probability $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ with different damping parameter values for each new physics model. The neutrino oscillation parameters are taken from ref. [4] and summarized in table 2. We assume the NMO in this analysis. We find that the results are quite similar for the IMO. We choose a few values for the damping parameters for illustration. In particular, $\alpha = 0$ indicates no damping effect, i.e., neutrino oscillation of the standard type. The farther the spectrum is from the no-damping curve, the stronger the intensity of the damping effect. The distortion of the standard $\bar{\nu}_e$ survival probability spectrum caused by damping is a combined phenomenon of an amplitude decrease and a phase shift, which can be regarded as a unique signature, as shown in figure 1. We find that the amplitude decrease behaviors of both the fast oscillation cycles (driven by $\Delta m^2_{31}$ and $\Delta m^2_{32}$) and the slow oscillation cycles (driven by $\Delta m^2_{21}$) are more significant than their phase shift behaviors in all damping effect scenarios. Therefore, damping effects mainly smear the fine structure of the standard $\bar{\nu}_e$ survival probability spectrum through amplitude-decreasing effects. Furthermore, the fine structure of the fast oscillation cycles is smeared more strongly than that of the slow oscillation cycles with increasing $\alpha$, which indicates that more spectral shape information is lost in the former than in the latter.

Based on the different smearing behaviors, we can divide the damping effects in table 1 into three categories. The first category is referred to as the QD-like effects, which include the QD I, QD II, QD III, and absorption damping effects. Although the details of the smearing behavior of each model are different, the fine structure is more completely preserved under increasing $\alpha$ for models in this category than for models in the other two categories. As $\alpha \rightarrow \infty$, the $\bar{\nu}_e$ survival probabilities of the models in this category approach zero, which means that the neutrinos do not propagate. The second category includes the $\nu_3$ decay effect. In this category, the fine structure of the fast oscillation cycles will be smeared more strongly as $\alpha$ increases until all details of the fast oscillation structure are lost. However, the damping effects of this category will not affect the fine structure of the slow oscillation cycles. Consequently, only the slow oscillation cycles will remain as $\alpha \rightarrow \infty$. The third category is referred to as WPD-like effects, which include the WPD I, WPD II, and WPD III damping effects. As $\alpha$ increases, the fine structures of both the fast and slow oscillation cycles will be strongly smeared under WPD-like effects, but the former will be smeared out before the latter. The $\bar{\nu}_e$ survival probabilities of these models approach a nonzero constant value as $\alpha \rightarrow \infty$, i.e., $1 - \frac{1}{2} c_{13}^4 \sin^2(2\theta_{12}) + \sin^2(2\theta_{13})$. Notably, the number of neutrinos will be lost in the damping models of the first and second categories, whereas they will keep the same in the third category.

4 Analysis method for JUNO

The damping effects on the reactor neutrino oscillations can be probed at JUNO by measuring the distortion of the neutrino inverse beta decay (IBD) event spectrum. The observed $\bar{\nu}_e$ distribution in terms of the reconstructed energy ($E_{\text{rec}}$) can be expressed as
Figure 1. The $\bar{\nu}_e$ survival probability $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ with different damping parameter values for each new physics model.
The neutrino oscillation parameters used in this work [4]. The input values $p^{\text{input}}$ and the corresponding 1σ uncertainty values $\delta p$ are taken from ref. [4]. For the case in which $\Delta m^2_{32}$ is negative, the corresponding $\delta p$ is the average value.

| $p$ | $\sin^2 \theta_{12}$ | $\sin^2 \theta_{13}$ | $\Delta m^2_{21}$ (eV$^2$) | $\Delta m^2_{32}$ (NMO, eV$^2$) | $\Delta m^2_{32}$ (IMO, eV$^2$) |
|-----|----------------------|----------------------|-----------------|-----------------|-----------------|
| $p^{\text{input}}$ | 0.307 | $2.18 \times 10^{-2}$ | $7.53 \times 10^{-5}$ | $2.453 \times 10^{-3}$ | $-2.546 \times 10^{-3}$ |
| $\delta p$ | 0.013 | $0.07 \times 10^{-2}$ | $0.18 \times 10^{-5}$ | $0.034 \times 10^{-3}$ | $0.037 \times 10^{-3}$ |

Table 2. The neutrino oscillation parameters used in this work [4]. The input values $p^{\text{input}}$ and the corresponding 1σ uncertainty values $\delta p$ are taken from ref. [4]. For the case in which $\Delta m^2_{32}$ is negative, the corresponding $\delta p$ is the average value.

follows [69]:

$$
\frac{dN}{dE_{\text{rec}}} = \frac{N_p T}{4\pi L^2} \int_{m_n-m_p+m_e} dE \frac{W_{\text{th}}}{\sum_{u} f_u \varpi_u} \sum_{u} f_u S_u(E) P(\bar{\nu}_e \rightarrow \nu_e) \sigma_{\text{IBD}}(E) G(E_{\text{vis}} - E_{\text{rec}}, \delta E_{\text{vis}}),
$$

where $N_p$ is the total number of free target protons in the LS detector, $T$ is the total exposure time, and $W_{\text{th}}$ is the thermal power of the reactor. $f_u$, $\varpi_u$, and $S_u$ are the fission fraction, the mean energy released per fission, and the $\bar{\nu}_e$ energy spectrum per fission, respectively, for the isotope $u$, where $u = \{^{235}\text{U}, ^{238}\text{U}, ^{239}\text{Pu}, ^{241}\text{Pu}\}$. The values of $f_u$ and $\varpi_u$ are taken from ref. [70]. $S_{^{235}\text{U}}$, $S_{^{239}\text{Pu}}$, and $S_{^{241}\text{Pu}}$ are derived from ref. [71], and $S_{^{238}\text{U}}$ is derived from ref. [72]. $\sigma_{\text{IBD}}(E)$ is the cross section for IBD in a detector, taken from refs. [73, 74]; $E_{\text{vis}}$ is the visible energy ($E_{\text{vis}} \sim E_e + m_e \sim (E - 0.8)$ MeV), and $G(E_{\text{vis}} - E_{\text{rec}}, \delta E_{\text{vis}})$ is a normalized Gaussian function representing a detector response function with an energy resolution of $\delta E_{\text{vis}}$. This function is expressed as follows:

$$
G(E_{\text{vis}} - E_{\text{rec}}, \delta E_{\text{vis}}) \approx \frac{1}{\sqrt{2\pi} \delta E_{\text{vis}}} \exp \left\{ -\frac{(E_{\text{vis}} - E_{\text{rec}})^2}{2(\delta E_{\text{vis}})^2} \right\},
$$

where $\delta E_{\text{vis}}$ is taken from ref. [11]. The detector energy resolution can be described by a three-parameter function, i.e.,

$$
\frac{\delta E_{\text{vis}}}{E_{\text{vis}}} = \sqrt{ \left( \frac{p_0}{\sqrt{E_{\text{vis}}/\text{MeV}}} \right)^2 + p_1^2 + \left( \frac{p_2}{E_{\text{vis}}/\text{MeV}} \right)^2 },
$$

where the parameters $p_0$, $p_1$, and $p_2$ represent the contributions to the energy resolution from the photon statistics, detector-related residual energy nonuniformity, and photomultiplier tube (PMT)-related effects, respectively.

The effective energy resolution of 3% at 1 MeV of the JUNO detector, as discussed in refs. [12, 75], is considered, and we set $p_0 = 2.61\%$, $p_1 = 0.82\%$, and $p_2 = 1.23\%$. We also take the IBD detection efficiency of the detector to be 73% [11, 75]. The JUNO detector is located at equal distances of $\sim 53$ km from the Yangjiang and Taishan thermal power reactor complexes [11, 12, 75]. The thermal powers of these two reactor complexes are 17.4 GW$_{\text{th}}$ and 9.2 GW$_{\text{th}}$, respectively [75]. We consider the exposure of the JUNO detector to be $(26.6 \times 20 \times 6 \times 300)$ GW$_{\text{th}}$ · kton · years · days and assume the NMO scenario unless explicitly stated otherwise.
For the analysis, we adopt the least square method from refs. [11, 16, 18, 69, 76, 77] and define a \( \chi^2 \) function with proper nuisance parameters and penalty terms to quantify the sensitivity of \( \alpha \), as follows:

\[
\chi^2 = \sum_{i} N_{\text{bin}} \left[ M_i - T_i \left( (1 + \epsilon_R + \epsilon_d + \sum_r \omega_r \epsilon_r + \epsilon_b) - \sum_b B_{b,i}(1 + \epsilon_b) \right)^2 \right. \\
+ \left. \frac{\epsilon_R^2}{\sigma_R^2} + \frac{\epsilon_d^2}{\sigma_d^2} + \sum_r \frac{\epsilon_r^2}{\sigma_r^2} + \sum_b \frac{\epsilon_b^2}{\sigma_b^2} + \sum_k \left( \frac{p_{k,\text{input}} - p_{k,\text{fit}}}{\delta p_k} \right)^2 \right]
\]

where \( N_{\text{bin}} \) is the number of energy bins, \( M_i \) is the number of measured total events (the summation of signal and background) in the \( i \)-th bin, \( T_i \) is the predicted number of IBD events, \( B_b \) is the \( b \)-th kind of estimated background (the main background spectra for the JUNO detector are taken from ref. [11]), and the quantities \( \sigma \) and \( \epsilon \) with different indices represent systematic uncertainties and the corresponding pull parameters, respectively. The considered systematic uncertainties include the correlated reactor uncertainty (\( \sigma_R=2\% \)), the detector-related uncertainty (\( \sigma_d=1\% \)), the uncorrelated reactor uncertainty (\( \sigma_r=0.8\% \)), the uncorrelated spectrum shape uncertainty (\( \sigma_{\text{shape}}=1\% \)), the correlated spectrum shape uncertainty (\( \sigma_{\text{shape}}=1\% \)), the shape uncertainties of the backgrounds (\( \sigma_b \)), and the relative rate uncertainties of the backgrounds (\( \sigma_b \)). Specifically, the \( \sigma_{\text{shape}} \) values for accidental coincidences, fast neutrons, \(^9\text{Li}/^8\text{He}, ^{13}\text{C}(\alpha,\text{n})^{16}\text{O}\) and geoneutrinos at JUNO are negligible (i.e., 0%), 20%, 10%, 50%, and 5%, respectively; the corresponding \( \sigma_b \) values are 1%, 100%, 20%, 50%, and 30%, respectively. Additionally, \( \omega_r \) is a fraction representing the \( r \)-th reactor’s contribution to the corresponding pull parameter \( \epsilon_r \). Finally, \( p_k \) and \( \delta p_k \) denote the \( k \)-th neutrino oscillation parameter (\( \sin^2 \theta_{12}, \sin^2 \theta_{13}, \Delta m_{21}^2 \), or \( \Delta m_{32}^2 \)) and the corresponding uncertainty, respectively, at a 1\( \sigma \) CL; these values are given in table 2.

5 Results

In this section, we present the results of probing the damping signatures of different new physics models at JUNO. We firstly study the constraints on the damping parameters for the eight new physics models at JUNO. Then, we show that JUNO can also help to disentangle the damping model from each other.

5.1 Constraints on the damping parameters at JUNO

To obtain the constraints on the damping parameters at JUNO, we scan the damping parameter of each damping model by marginalizing over other parameters, and fit the simulated no-damping JUNO data to obtain the exclusion sensitivities of the damping parameters. We list the constraints on the damping parameter of each damping model from this work in table 3. The current bounds on the damping parameters in the literature are also listed for comparison. The damping factors of the first seven damping models in
Table 3. The limits on the damping parameters for each damping model at JUNO. The experimental and phenomenological limits in the literature are also shown for comparison.

Table 3 can be unified into a general form [13, 14],

\[
D_{ij} = \exp \left( -\alpha \frac{|\Delta m^2_{ij}|^{\xi} L^{\beta}}{E^\gamma} \right),
\]

where the parameters \( \xi, \beta, \) and \( \gamma \) are the power numbers in the damping factor of interest. The strength of neutrino oscillation experiments to probe the damping effects is strongly dependent on the specific values of \( \xi, \beta, \) and \( \gamma \) [13, 14].

Compared to current experimental limits, we find that JUNO will improve the limits on \( \tau_3/m_3 \) in the \( \nu_3 \) decay model by a factor of \( \sim 36 \). The limits on \( \sigma_{\text{rel}} \) (or \( \sigma_x \)) in the WPD III...
Figure 2. The ratio of the $\bar{\nu}_e$ survival probabilities between the WPD II and WPD III scenarios as a function of the neutrino energy. Here the oscillation parameters are taken from table 2 and the damping parameter $\sigma_{\text{rel}}$ is set to $2.08 \times 10^{-2}$, which corresponds to a $5\sigma$ CL limit obtained from this work.

model can be also improved by a factor of $\sim 22$ (23). After taking into account the previous limits from phenomenological analysis, we find that JUNO will also impose stronger limits on the damping parameters in WPD I and WPD III. However, the improvement of the bounds on the damping parameters in the QD I, QD II, QD III, $\nu_3$ decay and neutrino absorption scenarios from JUNO is not significant compared to other phenomenological analysis. This is mainly due to the fact that JUNO has a smaller value of $|\Delta m^2_{ij}| \xi_L \beta / E_\gamma$.

From table 3, we see that a global joint analysis can be more restrictive in terms of these limits, which provides a promising future direction for JUNO to study these damping effects.

In the WPD II model, we also replace $\alpha$ with $\left(\sqrt{2}\sigma_{\text{rel}}/4\right)^2$ to study the effect of limit on $\sigma_{\text{rel}}$ in the absence of the quantum decoherence caused by the dispersion effect. We find that the upper limits on $\sigma_{\text{rel}}$ for the WPD II and WPD III are about the same, which means that the quantum decoherence caused by the dispersion effect is negligible on the limits on the damping parameters at JUNO. This can be understood from figure 2, which shows that the $\bar{\nu}_e$ survival probabilities described by eq. (3.4) and eq. (3.5) are very close at JUNO, and the modification to the $\bar{\nu}_e$ survival probability due to the dispersion effect is less than 0.5%.

5.2 Disentangling damping signatures at JUNO

To compare these eight damping effects, we follow the analysis method described in ref. [13]. For a fixed set of oscillation parameters and $\alpha$ values in the simulated damping model, we marginalize over the oscillation parameters, $\alpha$ values and all pull parameters in the fitted model. Then, we define a threshold $\alpha_{\text{th}}$ as the sensitivity limit for the simulated $\alpha$, i.e., the simulated $\alpha$ must be above this threshold for the simulated damping model to be
distinguishable from the fitted model at JUNO. The corresponding sensitivity limits at a 95% (3σ) CL obtained through this work are shown in table 4, where we specifically include the no-damping model among the fitted models. For instance, the QD I model could be distinguished from the no-damping model at the 95% CL if \( \alpha > 4.62 \times 10^{-6} \text{ MeV}^2/\text{m} \).

In the rows representing \( \nu_3 \) decay versus WPD-like models, there are no corresponding \( \alpha \) values at the 3σ CL since the \( \chi^2 \) are below 6.4 for all \( \alpha \) values in the simulated \( \nu_3 \) decay model. This can be attributed to the distortion of the standard \( \bar{\nu}_e \) survival probability spectrum caused by the \( \nu_3 \) decay, which can be easily compensated for by shifting the neutrino oscillation parameters and \( \alpha \) in the fitted WPD-like models. In the columns representing WPD-like models, the values with other WPD-like or \( \nu_3 \) decay scenarios are several orders of magnitude greater than the values with QD-like models. Thus, if a WPD-like model exists in nature, it will be much more difficult to distinguish it from other WPD-like scenarios or from a \( \nu_3 \) decay scenario as compared to a QD-like model.

**Table 4.** The sensitivity limits on \( \alpha \) for which a certain simulated damping model (in columns) could be distinguished from a certain fitted model (in rows) at JUNO.

| JUNO 95% (3σ) | Simulated damping model | Fitted model | QD I | QD II | QD III | Absorption | \( \nu_3 \) decay | WPD I | WPD II | WPD III |
|---------------|-------------------------|--------------|------|-------|--------|-------------|--------|--------|--------|
|               |                         | No damping   | 4.62 | 0.99  | 1.51   | 1.28        | 0.55   | 0.22   | 0.14   | 1.05   |
|               |                         | (7.2)        | (1.54)| (2.35)| (1.99) | (0.93)      | (0.44) | (0.24) | (1.39) |
|               |                         | QD I         | —    | 1.05  | 1.51   | 1.28        | 0.55   | 0.22   | 0.14   | 1.05   |
|               |                         | (1.62)       | (2.35)| (1.99) | (0.93) | (0.44)      | (0.24) | (1.39) |
|               |                         | QD II        | 4.82 | —     | 1.75   | 1.84        | 0.55   | 0.22   | 0.14   | 1.05   |
|               |                         | (7.5)        | (1.8) | (2.71)| (2.84) | (0.93)      | (0.44) | (0.24) | (1.39) |
|               |                         | QD III       | 4.62 | 1.16  | —      | 4.54        | 0.55   | 0.22   | 0.14   | 1.05   |
|               |                         | (7.2)        | (1.8) | (2.24)| (8.21) | (0.93)      | (0.44) | (0.24) | (1.39) |
|               |                         | Absorption   | 4.62 | 1.43  | 5.26   | —           | 0.55   | 0.22   | 0.14   | 1.05   |
|               |                         | (7.2)        | (1.8) | (2.24)| (8.21) | (0.93)      | (0.44) | (0.24) | (1.39) |
|               |                         | \( \nu_3 \) decay | 4.62 | 0.99  | 1.51   | 1.28        | —      | 4.03   | 10.48  | 8.88   |
|               |                         | (7.2)        | (1.54)| (2.35)| (1.99) | (0.93)      | (0.44) | (0.24) | (1.39) |
|               |                         | WPD I        | 4.62 | 0.99  | 1.51   | 1.28        | 4.4    | 10.48  | 8.88   |
|               |                         | (7.2)        | (1.54)| (2.35)| (1.99) | (0.93)      | (0.44) | (0.24) | (1.39) |
|               |                         | WPD II       | 4.62 | 0.99  | 1.51   | 1.28        | —      | 3.2    | 4.72   |
|               |                         | (7.2)        | (1.54)| (2.35)| (1.99) | (0.93)      | (0.44) | (0.24) | (1.39) |
|               |                         | WPD III      | 4.62 | 0.99  | 1.51   | 1.28        | —      | 9.12   | 66.8   |
|               |                         | (7.2)        | (1.54)| (2.35)| (1.99) | (0.93)      | (0.44) | (0.24) | (1.39) |

In the rows representing \( \nu_3 \) decay versus WPD-like models, there are no corresponding \( \alpha \) values at the 3σ CL since the \( \chi^2 \) are below 6.4 for all \( \alpha \) values in the simulated \( \nu_3 \) decay model.
6 Conclusions

In this paper, we systematically study the phenomenology of damping signatures at JUNO, a medium-baseline reactor neutrino oscillation experiment. As the benchmark models in this work, we analyze several new physics scenarios, including quantum decoherence, $\nu_3$ decay, neutrino absorption, and wave packet decoherence. Based on a six-year exposure and five main background sources for the JUNO detector, we demonstrate how to test and disentangle the fine-scale spectral structure caused by the damping effects. The exclusion sensitivities on the damping parameters at JUNO for each benchmark model are listed in table 3. Compared to current experimental limits, JUNO will significantly improve the limits on $r_3/m_3$ in the $\nu_3$ decay model, the width of the neutrino wave packet $\sigma_x$, and the intrinsic relative dispersion of neutrino momentum $\sigma_{\text{rel}}$ by a factor of $\sim 36, 23$ and $22$, respectively. Furthermore, we find that the quantum decoherence caused by the dispersion effect is negligible at JUNO. Finally, we find that compared to the QD-like models, the WPD-like and $\nu_3$ decay models are much more difficult to distinguish from each other at JUNO.

Acknowledgments

We are grateful for the ongoing cooperation from the China General Nuclear Power Group. This work was supported by the Chinese Academy of Sciences, the National Key R&D Program of China, the CAS Center for Excellence in Particle Physics, Wuyi University, and the Tsung-Dao Lee Institute of Shanghai Jiao Tong University in China, the Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) in France, the Istituto Nazionale di Fisica Nucleare (INFN) in Italy, the Italian-Chinese collaborative research program MAECI-NSFC, the Fond de la Recherche Scientifique (F.R.S-FNRS) and FWO under the “Excellence of Science — EOS” in Belgium, the Conselho Nacional de Desenvolvimento Científico e Tecnológico in Brazil, the Agencia Nacional de Investigacion y Desarrollo en Chile, the Charles University Research Centre and the Ministry of Education, Youth, and Sports in Czech Republic, the Deutsche Forschungsgemeinschaft (DFG), the Helmholtz Association, and the Cluster of Excellence PRISMA+ in Germany, the Joint Institute of Nuclear Research (JINR) and Lomonosov Moscow State University in Russia, the joint Russian Science Foundation (RSF) and National Natural Science Foundation of China (NSFC) research program, the MOST and MOE in Taiwan, the Chulalongkorn University and Suranaree University of Technology in Thailand, and the University of California at Irvine in U.S.A.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

[1] B. Pontecorvo, *Inverse beta processes and nonconservation of lepton charge*, Zh. Eksp. Teor. Fiz. 34 (1957) 247 [spire]

[2] Super-Kamiokande collaboration, *Evidence for oscillation of atmospheric neutrinos*, Phys. Rev. Lett. 81 (1998) 1562 [hep-ex/9807003] [spire]
3] C. Giganti, S. Lavignac and M. Zito, Neutrino oscillations: The rise of the PMNS paradigm, *Prog. Part. Nucl. Phys.* 98 (2018) 1 [arXiv:1710.00715] [SPIRE].

4] Particle Data Group collaboration, Review of Particle Physics, *PTEP* 2020 (2020) 083C01 [SPIRE].

5] NOV A collaboration, Measurement of the neutrino mixing angle $\theta_{23}$ in NOV A, *Phys. Rev. Lett.* 118 (2017) 151802 [arXiv:1701.05891] [SPIRE].

6] Super-Kamiokande collaboration, Atmospheric neutrino oscillation analysis with external constraints in Super-Kamiokande I-IV, *Phys. Rev. D* 97 (2018) 072001 [arXiv:1710.09126] [SPIRE].

7] T2K collaboration, Constraint on the matter-antimatter symmetry-violating phase in neutrino oscillations, *Nature* 580 (2020) 339 [Erratum ibid. 583 (2020) E16] [arXiv:1910.03887] [SPIRE].

8] DUNE collaboration, Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE): Conceptual Design Report, Volume 2: The Physics Program for DUNE at LBNF, arXiv:1512.06148 [SPIRE].

9] DUNE collaboration, Long-baseline neutrino oscillation physics potential of the DUNE experiment, *Eur. Phys. J. C* 80 (2020) 978 [arXiv:2006.16043] [SPIRE].

10] Hyper-Kamiokande collaboration, Hyper-Kamiokande Design Report, arXiv:1805.04163 [SPIRE].

11] JUNO collaboration, Neutrino Physics with JUNO, *J. Phys. G* 43 (2016) 030401 [arXiv:1507.05613] [SPIRE].

12] JUNO collaboration, JUNO Physics and Detector, arXiv:2104.02565 [SPIRE].

13] M. Blennow, T. Ohlsson and W. Winter, Damping signatures in future neutrino oscillation experiments, *JHEP* 06 (2005) 049 [hep-ph/0502147] [SPIRE].

14] M. Blennow, Damping signatures in future neutrino oscillation experiments, *Nucl. Phys. B Proc. Suppl.* 155 (2006) 195 [SPIRE].

15] MINOS collaboration, Search for sterile neutrino mixing in the MINOS long baseline experiment, *Phys. Rev. D* 81 (2010) 052004 [arXiv:1001.0336] [SPIRE].

16] T. Abrahão, H. Minakata, H. Nunokawa and A.A. Quiroga, Constraint on Neutrino Decay with Medium-Baseline Reactor Neutrino Oscillation Experiments, *JHEP* 11 (2015) 001 [arXiv:1506.02314] [SPIRE].

17] S. Choubey, D. Dutta and D. Pramanik, Invisible neutrino decay in the light of NOV A and T2K data, *JHEP* 08 (2018) 141 [arXiv:1805.01848] [SPIRE].

18] Y.P. Porto-Silva, S. Prakash, O.L.G. Peres, H. Nunokawa and H. Minakata, Constraining visible neutrino decay at KamLAND and JUNO, *Eur. Phys. J. C* 80 (2020) 999 [arXiv:2002.12134] [SPIRE].

19] A. Ghoshal, A. Giarnetti and D. Meloni, Neutrino Invisible Decay at DUNE: a multi-channel analysis, *J. Phys. G* 48 (2021) 055004 [arXiv:2003.09012] [SPIRE].

20] G.L. Fogli, E. Lisi, A. Marrone, D. Montanino and A. Palazzo, Probing non-standard decoherence effects with solar and KamLAND neutrinos, *Phys. Rev. D* 76 (2007) 033006 [arXiv:0704.2568] [SPIRE].

21] Y.-L. Chan, M.C. Chu, K.M. Tsui, C.F. Wong and J. Xu, Wave-packet treatment of reactor neutrino oscillation experiments and its implications on determining the neutrino mass hierarchy, *Eur. Phys. J. C* 76 (2016) 310 [arXiv:1507.06421] [SPIRE].
[22] Daya Bay collaboration, Study of the wave packet treatment of neutrino oscillation at Daya Bay, \textit{Eur. Phys. J. C} 77 (2017) 606 [arXiv:1608.01661] [inSPIRE].

[23] J.A.B. Coelho, W.A. Mann and S.S. Bashar, Nonmaximal $\theta_{23}$ mixing at NOvA from neutrino decoherence, \textit{Phys. Rev. Lett.} 118 (2017) 221801 [arXiv:1702.04738] [inSPIRE].

[24] A. de Gouvêa, V. de Romeri and C.A. Ternes, Probing neutrino quantum decoherence at reactor experiments, \textit{JHEP} 08 (2020) 018 [arXiv:2005.03022] [inSPIRE].

[25] Z. Cheng, W. Wang, C.F. Wong and J. Zhang, Studying the neutrino wave-packet effects at medium-baseline reactor neutrino oscillation experiments and the potential benefits of an extra detector, \textit{Nucl. Phys. B} 964 (2021) 115304 [arXiv:2009.06450] [inSPIRE].

[26] Y. Liu, J.-L. Chen and M.-L. Ge, A constraint on EHNS parameters from solar neutrino problem, \textit{J. Phys. G} 24 (1998) 2289 [hep-ph/9711381] [inSPIRE].

[27] S. Shafaq, T. Kushwaha and P. Mehta, Investigating Leggett-Garg inequality in neutrino oscillations — role of decoherence and decay, \textit{arXiv:2112.12726} [inSPIRE].

[28] N.C. Ribeiro, H. Nunokawa, T. Kajita, S. Nakayama, P. Ko and H. Minakata, Probing Nonstandard Neutrino Physics by Two Identical Detectors with Different Baselines, \textit{Phys. Rev. D} 77 (2008) 073007 [arXiv:0712.4314] [inSPIRE].

[29] Y. Farzan, T. Schwetz and A.Y. Smirnov, Reconciling results of LSND, MiniBooNE and other experiments with soft decoherence, \textit{JHEP} 07 (2008) 067 [arXiv:0805.2098] [inSPIRE].

[30] P.A.N. Machado, H. Nunokawa, F.A. Pereira dos Santos and R. Zukanovich Funchal, Testing Nonstandard Neutrino Properties with a Mössbauer Oscillation Experiment, \textit{JHEP} 11 (2011) 136 [arXiv:1108.3339] [inSPIRE].

[31] R.L.N. de Oliveira, M.M. Guzzo and P.C. de Holanda, Quantum Dissipation and CP Violation in MINOS, \textit{Phys. Rev. D} 89 (2014) 053002 [arXiv:1401.0033] [inSPIRE].

[32] P. Coloma, J. Lopez-Pavon, I. Martinez-Soler and H. Nunokawa, Decoherence in Neutrino Propagation Through Matter, and Bounds from IceCube/DeepCore, \textit{Eur. Phys. J. C} 78 (2018) 614 [arXiv:1803.04438] [inSPIRE].

[33] A.L.G. Gomes, R.A. Gomes and O.L.G. Peres, Quantum decoherence and relaxation in neutrinos using long-baseline data, \textit{arXiv:2001.09250} [inSPIRE].

[34] Y. Liu, L.-z. Hu and M.-L. Ge, The effect of quantum mechanics violation on neutrino oscillation, \textit{Phys. Rev. D} 56 (1997) 6648 [inSPIRE].

[35] E. Lisi, A. Marrone and D. Montanino, Probing possible decoherence effects in atmospheric neutrino oscillations, \textit{Phys. Rev. Lett.} 85 (2000) 1166 [hep-ph/0002053] [inSPIRE].

[36] D. Morgan, E. Winstanley, J. Brunner and L.F. Thompson, Probing quantum decoherence in atmospheric neutrino oscillations with a neutrino telescope, \textit{Astropart. Phys.} 25 (2006) 311 [astro-ph/0412618] [inSPIRE].

[37] N.E. Mavromatos and S. Sarkar, Methods of approaching decoherence in the flavour sector due to space-time foam, \textit{Phys. Rev. D} 74 (2006) 036007 [hep-ph/0606048] [inSPIRE].

[38] P. Mehta and W. Winter, Interplay of energy dependent astrophysical neutrino flavor ratios and new physics effects, \textit{JCAP} 03 (2011) 041 [arXiv:1101.2673] [inSPIRE].

[39] P. Bakhti, Y. Farzan and T. Schwetz, Revisiting the quantum decoherence scenario as an explanation for the LSND anomaly, \textit{JHEP} 05 (2015) 007 [arXiv:1503.05374] [inSPIRE].

[40] G. Balicier Gomes, M.M. Guzzo, P.C. de Holanda and R.L.N. Oliveira, Parameter Limits for Neutrino Oscillation with Decoherence in KamLAND, \textit{Phys. Rev. D} 95 (2017) 113005 [arXiv:1603.04126] [inSPIRE].
[41] M.C. Gonzalez-Garcia and M. Maltoni, Status of Oscillation plus Decay of Atmospheric and Long-Baseline Neutrinos, Phys. Lett. B 663 (2008) 405 [arXiv:0802.3699] [INSPIRE].
[42] R.A. Gomes, A.L.G. Gomes and O.L.G. Peres, Constraints on neutrino decay lifetime using long-baseline charged and neutral current data, Phys. Lett. B 740 (2015) 345 [arXiv:1407.5640] [INSPIRE].
[43] G. Pagliaroli, N. Di Marco and M. Mannarelli, Enhanced tau neutrino appearance through invisible decay, Phys. Rev. D 93 (2016) 113011 [arXiv:1603.08696] [INSPIRE].
[44] C. Giunti, C.W. Kim and U.W. Lee, Coherence of neutrino oscillations in vacuum and matter in the wave packet treatment, Phys. Lett. B 274 (1992) 87 [hep-ph/9711363] [INSPIRE].
[45] C. Giunti, Coherence of neutrino oscillations in the wave packet approach, Phys. Rev. D 58 (1998) 017301 [hep-ph/9711363] [INSPIRE].
[46] C. Giunti, Coherence and wave packets in neutrino oscillations, Found. Phys. Lett. 17 (2004) 103 [hep-ph/0302026] [INSPIRE].
[47] M. Blasone, F. Dell’Anno, S. De Siena and F. Illuminati, Flavor entanglement in neutrino oscillations in the wave packet description, EPL 112 (2015) 20007 [arXiv:1510.06761] [INSPIRE].
[48] J. Kersten and A.Y. Smirnov, Decoherence and oscillations of supernova neutrinos, Eur. Phys. J. C 76 (2016) 339 [arXiv:1512.09068] [INSPIRE].
[49] A. de Gouvêa, V. De Romeri and C.A. Ternes, Combined analysis of neutrino decoherence at reactor experiments, JHEP 06 (2021) 042 [arXiv:2104.05806] [INSPIRE].
[50] T. Ohlsson, Equivalence between neutrino oscillations and neutrino decoherence, Phys. Lett. B 502 (2001) 159 [hep-ph/0012272] [INSPIRE].
[51] D.V. Naumov and V.A. Naumov, A diagrammatic treatment of neutrino oscillations, J. Phys. G 37 (2010) 105014 [arXiv:1008.0306] [INSPIRE].
[52] D.V. Naumov and V.A. Naumov, Quantum Field Theory of Neutrino Oscillations, Phys. Part. Nucl. 51 (2020) 1 [INSPIRE].
[53] J.R. Ellis, N.E. Mavromatos, D.V. Nanopoulos and E. Winstanley, Quantum decoherence in a four-dimensional black hole background, Mod. Phys. Lett. A 12 (1997) 243 [gr-qc/9602011] [INSPIRE].
[54] J.R. Ellis, N.E. Mavromatos and D.V. Nanopoulos, Quantum decoherence in a D foam background, Mod. Phys. Lett. A 12 (1997) 1759 [hep-th/9704169] [INSPIRE].
[55] M. Lindner, T. Ohlsson and W. Winter, A combined treatment of neutrino decay and neutrino oscillations, Nucl. Phys. B 607 (2001) 326 [hep-ph/0103170] [INSPIRE].
[56] A.S. Joshipura, E. Masso and S. Mohanty, Constraints on decay plus oscillation solutions of the solar neutrino problem, Phys. Rev. D 66 (2002) 113008 [hep-ph/0203181] [INSPIRE].
[57] J.F. Beacom and N.F. Bell, Do Solar Neutrinos Decay?, Phys. Rev. D 65 (2002) 113009 [hep-ph/0204111] [INSPIRE].
[58] G.L. Fogli, E. Lisi, A. Marrone and D. Montanino, Status of atmospheric $\nu_\mu \to \nu_\tau$ oscillations and decoherence after the first K2K spectral data, Phys. Rev. D 67 (2003) 093006 [hep-ph/0303064] [INSPIRE].
[59] P. Baerwald, M. Bustamante and W. Winter, Neutrino Decays over Cosmological Distances and the Implications for Neutrino Telescopes, JCAP 10 (2012) 020 [arXiv:1208.4600] [INSPIRE].
[60] R. Picoreti, M.M. Guzzo, P.C. de Holanda and O.L.G. Peres, *Neutrino Decay and Solar Neutrino Seasonal Effect*, Phys. Lett. B 761 (2016) 70 [arXiv:1506.08158] [INSPIRE].

[61] A.M. Gago, R.A. Gomes, A.L.G. Gomes, J. Jones-Perez and O.L.G. Peres, *Visible neutrino decay in the light of appearance and disappearance long baseline experiments*, JHEP 11 (2017) 022 [arXiv:1705.03074] [INSPIRE].

[62] SNO collaboration, *Constraints on Neutrino Lifetime from the Sudbury Neutrino Observatory*, Phys. Rev. D 99 (2019) 032013 [arXiv:1812.01088] [INSPIRE].

[63] E.K. Akhmedov and A.Y. Smirnov, *Paradoxes of neutrino oscillations*, Phys. Atom. Nucl. 72 (2009) 1363 [arXiv:0905.1903] [INSPIRE].

[64] S.L. Adler, *Comment on a proposed Super-Kamiokande test for quantum gravity induced decoherence effects*, Phys. Rev. D 62 (2000) 117901 [hep-ph/0005220] [INSPIRE].

[65] L. Wolfenstein, *Neutrino Oscillations in Matter*, Phys. Rev. D 17 (1978) 2369 [INSPIRE].

[66] S.P. Mikheyev and A.Y. Smirnov, *Resonance Amplification of Oscillations in Matter and Spectroscopy of Solar Neutrinos*, Sov. J. Nucl. Phys. 42 (1985) 913 [INSPIRE].

[67] Y.-F. Li, Y. Wang and Z.-z. Xing, *Terrestrial matter effects on reactor antineutrino oscillations at JUNO or RENO-50: how small is small?*, Chin. Phys. C 40 (2016) 091001 [arXiv:1605.00900] [INSPIRE].

[68] A.N. Khan, H. Nunokawa and S.J. Parke, *Why matter effects matter for JUNO*, Phys. Lett. B 803 (2020) 135354 [arXiv:1910.12900] [INSPIRE].

[69] S.-F. Ge, K. Hagiwara, N. Okamura and Y. Takaesu, *Determination of mass hierarchy with medium baseline reactor neutrino experiments*, JHEP 05 (2013) 131 [arXiv:1210.8141] [INSPIRE].

[70] Daya Bay collaboration, *Improved Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay*, Chin. Phys. C 41 (2017) 013002 [arXiv:1607.05378] [INSPIRE].

[71] P. Huber, *On the determination of anti-neutrino spectra from nuclear reactors*, Phys. Rev. C 84 (2011) 024617 [Erratum ibid. 85 (2012) 029901] [arXiv:1106.0687] [INSPIRE].

[72] T.A. Mueller et al., *Improved Predictions of Reactor Antineutrino Spectra*, Phys. Rev. C 83 (2011) 054615 [arXiv:1101.2663] [INSPIRE].

[73] A. Strumia and F. Vissani, *Precise quasielastic neutrino/nucleon cross-section*, Phys. Lett. B 564 (2003) 42 [astro-ph/0302056] [INSPIRE].

[74] A.S. Dighe, M.T. Keil and G.G. Raffelt, *Detecting the neutrino mass hierarchy with a supernova at IceCube*, JCAP 06 (2003) 005 [hep-ph/0303210] [INSPIRE].

[75] JUNO collaboration, *Calibration Strategy of the JUNO Experiment*, JHEP 03 (2021) 004 [arXiv:2011.06405] [INSPIRE].

[76] F. Capozzi, E. Lisi and A. Marrone, *Neutrino mass hierarchy and electron neutrino oscillation parameters with one hundred thousand reactor events*, Phys. Rev. D 89 (2014) 013001 [arXiv:1309.1638] [INSPIRE].

[77] H. Wang, L. Zhan, Y.-F. Li, G. Cao and S. Chen, *Mass hierarchy sensitivity of medium baseline reactor neutrino experiments with multiple detectors*, Nucl. Phys. B 918 (2017) 245 [arXiv:1602.04442] [INSPIRE].
The JUNO collaboration

Jun Wang, Jiajun Liao, Wei Wang, Angel Abusleme, Thomas Adam, Shakeel Ahmad, Rizwan Ahmed, Sebastiano Aiello, Muhammad Akram, Fengpeng An, Qi An, Giuseppe Andronico, Nikolay Anfinov, Vito Antonelli, Tatiana Antoshkina, Burin Asavapibhop, João Pedro Athayde Marcondes de André, Didier Auguste, Andrej Babic, Eric Baussan, Marco Bellato, Antonio Berguoli, Thilo Birkenfeld, Sylvie Blin, David Blum, Simon Blyth, Anastasia Bolshakova, Mathieu Bongrand, Clément Bordereau, Dominique Breton, Augusto Brigatti, Riccardo Brugnera, Riccardo Bruno, Antonio Budano, Mario Buscemi, Jose Busto, Ilya Butorov, Anatael Cabrera, Hao Cai, Xiao Cai, Yanke Cai, Zhiyan Cai, Riccardo Callegari, Antonio Cammi, Agustin Campeny, Chuanya Cao, Guo Fu Cao, Jun Cao, Rosella Caruso, Cédric Corna, Jinfan Chang, Yun Chang, Pingping Chen, Po-An Chen, Shaomin Chen, Xurong Chen, Yi-Wen Chen, Yixue Chen, Yu Chen, Zhang Chen, Jie Cheng, Yaping Cheng, Alexey Chetverikov, Davide Chiesa, Pietro Chimienti, Artem Chukunov, Gérard Claverie, Catia Clementi, Barbara Clerbaux, Selma Conforti Di Lorenzo, Daniele Corti, Flavio Dal Corso, Olivia Dalager, Christophe De La Taille, Jiawei Deng, Zhi Deng, Ziyi Deng, Wilfried Depnering, Xuefeng Ding, Yiyun Ding, Bayu Dirgantara, Sergey Dmitrievsky, Tadeas Dohnal, Dmitriy Dolzhikov, Georgy Donchenko, Jianmeng Dong, Evgeny Doroshkevich, Marcos Dracos, Frédéric Druillolle, Ran Du, Shuxian Du, Stefano Dusini, Martin Dvorak, Timo Enqvist, Heike Enzmann, Andrea Fabbris, Lukas Fajt, Donghua Fan, Lei Fan, Jian Fang, Wenxing Fang, Marco Fargetta, Vladko Fekete, Li-Cheng Feng, Qichun Feng, Richard Ford, Amédée Forriner, Haoran Gan, Feng Gao, Alberto Garfagnini, Arsenii Gavrikov, Marco Giannamarchi, Agnese Giaz, Nunzio Giudice, Maxim Gonchar, Guanghua Goung, Hui Gou, Yong Gou, Yui Gornushkin, Alexandre Götte, Marco Grassi, Christian Grewing, Vasily Gromov, Minghao Gu, Xiaofei Gu, Yu Gu, Mengyun Guan, Nunzio Guardone, Maria Guia, Cong Guo, Jingyuan Guo, Wanlei Guo, Xinheng Guo, Yuhang Guo, Paul Hackschacher, Caren Hagner, Han Han, Yang Han, Muhammad Sohaib Hassan, Miao He, Wei He, Tobias Heinz, Patrick Hellmuth, Yuekun Heng, Rafael Herrera, YuenKeung Hor, Shaojing Hou, Yee Hsiung, Bei-Zhen Hu, Hang Hu, Jiarrun Hu, Jun Hu, Shuyang Hu, Tao Hu, Zhaohan Hu, Guihong Huang, Hanxiong Huang, Wenhao Huang, Xin Huang, Xingtao Huang, Yongbo Huang, Jiaqi Hui, Lei Hui, Wenyu Hu, Cédric Huss, Safer Hussian, Ara Ioannisian, Roberto Iscratie, Beatrice Jelmini, Kuo-Lun Jen, Ignacio Jeria, Xiaohu Ji, Xingzhao Ji, Huilui Jia, Junji Jia, Siyu Jian, Di Jiang, Wei Jiang, Xiaoshan Jiang, Ruiyin Ji, Xiaoping Jing, Cécile Jollet, Jari Joutsenvaara, Silichok Junghwahn, Leonidas Kalousis, Philipp Kampmann, Li Kang, Rebin Kararapambili, Arineh Kazarian, Khanchai Khosonthongkaj, Denis Korahlev, Konstantin Kouzakov, Alexey Kransopirov, Andre Kruth, Nikolay Kutsovskiy, Pasi Kuusiniemi, Tobias Lachenmaier, Cecilia Landini, Sébastien Leblanc, Victor Lebrin, Frederic Lefevre, Ruiting Lei, Rupert Leitner, Jason Leung, Demin Li, Fei Li, Fule Li, Haitao Li, Huiling Li, Jiaqi Li, Mengzhao Li, Min Li, Nan Li, Nan Li, Qingliang Li, Ruhui Li, Shanfeng Li, Tao Li, Weidong Li, Weijing Li, Xiaomei Li, Xiaonan Li, Xinglong Li, Yi Li, Yufeng Li, Zhaohan Li, Zhiling Li, Ziyuan Li, Hao Liang, Xiao Li, Daniel Lieban, Ayut Limphirat, Sukit Limpijumnong, Guey-Lin Lin, Shengxin Lin, Tao Lin, Jiajie Ling, Ivanovich Lipp, Fang Liu, Haidong Liu, Hongbang Liu, Hongjuan Liu, Hongtao Liu, Hui Liu, JHEP06(2022)062
Steven Chan-Fai Wong, Bjoern Wonsak, Diru Wu, Qun Wu, Zhi Wu, Michael Wurm, Jacques Wurtz, Christian Wysotzki, Yufei Xi, Dongmei Xia, Xiaochuan Xie, Yuguang Xie, Handong Xu, Jie Li, Ying Xu, Meihang Xu, Yin Xu, Yu Xu, Baojun Yan, Taylor Yan, Wenqi Yan, Xiongbo Yan, Yuguang Xie, Changgen Yang, Chengfeng Yang, Huan Yang, Jie Yang, Lei Yang, Xiaoyu Yang, Yifan Yang, Yifan Yang, Haifeng Yao, Zafar Yasin, Jiaxuan Ye, Mei Ye, Zeping Ye, Ugur Yegiu, Frédéric Yermia, Peihuai Yi, Na Yin, Xiangwei Yin, Zhengyun You, Boxiang Yu, Chiye Yu, Chunxu Yu, Hongzhao Yu, Miao Yu, Xianghui Yu, Zeyuan Yu, Zehong Yu, Chengzhao Yuan, Ying Yuan, Zhenxiong Yuan, Zhiyi Yuan, Baobiao Yue, Noman Zafar, Andre Zambanini, Vitalii Zavadskiy, Shan Zeng, Tingxuan Zeng, Yuda Zeng, Liang Zhan, Aiqiang Zhang, Feiyang Zhang, Guoqing Zhang, Haiqiong Zhang, Honghao Zhang, Jiawen Zhang, Jie Zhang, Jin Zhang, Jingbo Zhang, Jinnan Zhang, Peng Zhang, Qingmin Zhang, Shiqi Zhang, Shun Zhang, Tao Zhang, Xiaomei Zhang, Xuantong Zhang, Xueyao Zhang, Yan Zhang, Yinhong Zhang, Yiyun Zhang, Yongpeng Zhang, Yuanyuan Zhang, Yunmei Zhang, Zhenyu Zhang, Zhijian Zhang, Fengyi Zhao, Jie Zhao, Rong Zhao, Shujun Zhao, Tianchi Zhao, Dongjin Zheng, Hua Zheng, Minshan Zheng, Yangheng Zheng, Weirong Zhong, Ming Zhou, Lan Zhou, Nan Zhou, Shun Zhou, Tong Zhou, Xiang Zhou, Jiang Zhu, Kangfu Zhu, Kejun Zhu, Zhihang Zhu, Bo Zhuang, Honglin Zhuang, Liang Zong, Jiaheng Zou.

* Corresponding author.

+ Sun Yat-Sen University, Guangzhou, China
+ Yerevan Physics Institute, Yerevan, Armenia
+ Université Libre de Bruxelles, Brussels, Belgium
+ Universidade Estadual de Londrina, Londrina, Brazil
+ Pontifícia Universidade Católica do Rio de Janeiro, Rio, Brazil
+ Pontifícia Universidade Católica de Chile, Santiago, Chile
+ Universidade Tecnica Federico Santa Maria, Valparaiso, Chile
+ Beijing Institute of Spacecraft Environment Engineering, Beijing, China
+ Beijing Normal University, Beijing, China
+ China Institute of Atomic Energy, Beijing, China
+ Institute of High Energy Physics, Beijing, China
+ North China Electric Power University, Beijing, China
+ School of Physics, Peking University, Beijing, China
+ Tsinghua University, Beijing, China
+ University of Chinese Academy of Sciences, Beijing, China
+ Jilin University, Changchun, China
+ College of Electronic Science and Engineering, National University of Defense Technology, Changsha, China
+ Chongqing University, Chongqing, China
+ Dongguan University of Technology, Dongguan, China
+ Jinan University, Guangzhou, China
+ Harbin Institute of Technology, Harbin, China
+ University of Science and Technology of China, Hefei, China
+ The Radiochemistry and Nuclear Chemistry Group in University of South China, Hengyang, China
+ Wuyi University, Jiangmen, China
+ Shandong University, Jinan, China, and Key Laboratory of Particle Physics and Particle Irradiation of Ministry of Education, Shandong University, Qingdao, China
+ Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China
Nanjing University, Nanjing, China
Guangxi University, Nanning, China
East China University of Science and Technology, Shanghai, China
School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China
Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai, China
Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, Shijiazhuang, China
Nankai University, Tianjin, China
Wuhan University, Wuhan, China
Xi’an Jiaotong University, Xi’an, China
Xiamen University, Xiamen, China
School of Physics and Microelectronics, Zhengzhou University, Zhengzhou, China
Institute of Physics, National Yang Ming Chiao Tung University, Hsinchu
National United University, Miaoli
Department of Physics, National Taiwan University, Taipei
Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
University of Jyvaskyla, Department of Physics, Jyvaskyla, Finland
IJC Lab, Université Paris-Saclay, CNRS/IN2P3, 91405 Orsay, France
Univ. Bordeaux, CNRS, LP2i Bordeaux, UMR 5797, F-33170 Gradignan, France
IPHC, Université de Strasbourg, CNRS-IN2P3, F-67037 Strasbourg, France
Aix-Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
SUBATECH, Nantes Université, IMT Atlantique, CNRS-IN2P3, Nantes, France
III. Physikalisches Institut B, RWTH Aachen University, Aachen, Germany
Institute of Experimental Physics, University of Hamburg, Hamburg, Germany
Forschungszentrum Jülich GmbH, Nuclear Physics Institute IKP-2, Jülich, Germany
Forschungszentrum Jülich GmbH, Central Institute of Engineering, Electronics and Analytics — Electronic Systems (ZEA-2), Jülich, Germany
Institute of Physics, Johannes-Gutenberg Universität Mainz, Mainz, Germany
Technische Universität München, München, Germany
Eberhard Karls Universität Tübingen, Physikalisches Institut, Tübingen, Germany
INFN Catania and Dipartimento di Fisica e Astronomia dell’Università di Catania, Catania, Italy
Department of Physics and Earth Science, University of Ferrara and INFN Sezione di Ferrara, Ferrara, Italy
INFN Sezione di Milano and Dipartimento di Fisica dell’Università di Milano, Milano, Italy
INFN Milano Bicocca and University of Milano Bicocca, Milano, Italy
INFN Milano Bicocca and Politecnico di Milano, Milano, Italy
INFN Sezione di Padova, Padova, Italy
Dipartimento di Fisica e Astronomia dell’Università di Padova and INFN Sezione di Padova, Padova, Italy
INFN Sezione di Perugia and Dipartimento di Chimica, Biologia e Biotecnologie dell’Università di Perugia, Perugia, Italy
Laboratori Nazionali di Frascati dell’INFN, Roma, Italy
University of Roma Tre and INFN Sezione Roma Tre, Roma, Italy
Institute of Electronics and Computer Science, Riga, Latvia
Pakistan Institute of Nuclear Science and Technology, Islamabad, Pakistan
Joint Institute for Nuclear Research, Dubna, Russia
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
Lomonosov Moscow State University, Moscow, Russia
Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia
Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
National Astronomical Research Institute of Thailand, Chiang Mai, Thailand
Suranaree University of Technology, Nakhon Ratchasima, Thailand
Department of Physics and Astronomy, University of California, Irvine, California, U.S.A.