

SN1987A bounds on neutrino quantum decoherence

Christoph A. Ternes^{1,*}, Giulia Pagliaroli^{1,†} and Francesco L. Villante^{1,2,‡}

¹*Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali del Gran Sasso,
67100 Assergi, L'Aquila (AQ), Italy*

²*Department of Physical and Chemical Sciences, University of L'Aquila, 67100 L'Aquila, Italy*



(Received 17 March 2025; accepted 10 September 2025; published 29 September 2025)

We obtain stringent bounds on neutrino quantum decoherence from the analysis of SN1987A data. We show that for the decoherence model considered here, which allows for neutrino loss along the trajectory, the bounds are many orders of magnitude stronger than the ones that can be obtained from the analysis of data from reactor neutrino oscillation experiments or neutrino telescopes.

DOI: [10.1103/4j6r-d2wx](https://doi.org/10.1103/4j6r-d2wx)

I. INTRODUCTION

The interpretation of current neutrino oscillation data relies on the so-called three-neutrino paradigm, where neutrinos propagate as superpositions of different mass or flavor eigenstates. During propagation, each component mass eigenstate evolves with a different frequency, thus resulting in the phenomenon of flavor conversion. In general, the study of neutrino oscillations considers the neutrino to be isolated from its environment, and the oscillation effects to be coherent. However, neutrinos may lose their quantum superposition, for example if the neutrino system interacts with a stochastic environment, thus resulting in a loss of coherence and in the damping of neutrino oscillation probabilities. Indeed, the possible loss of flavor coherence can also occur within standard quantum mechanics due to neutrino wave packet separation [1–18]. However, here we consider nonstandard decoherence effects, which can have different physical origins.

We work in the commonly used framework of open quantum systems [10,19–43] assuming that neutrino propagation can be affected by the interaction of the neutrino subsystem with the environment. The fluctuating nature of space time (the quantum foam) in a quantum theory of gravity is a commonly cited potential source of a stochastic background that might produce neutrino decoherence effects [40,44–47] via interactions of neutrinos with virtual black holes [40]. These Planck-length scale black holes

form from extreme fluctuations in the space time foam and almost immediately evaporate over Planck-time scales. Neutrinos might encounter these virtual black holes along their trajectories, which could induce a loss of quantum information.

Reference [40] discusses several models of neutrino quantum decoherence, in particular the so-called state-selection, phase-perturbation, and neutrino-loss models, which will be briefly introduced below. Experimental searches and future sensitivities for neutrino quantum decoherence have been performed with a variety of facilities using different neutrino sources [21,26,30,31,34,35,38,48–53]. These searches nearly always focus on state-selection and phase-perturbation models. The most stringent limits on decoherence parameters with positive energy dependence ($\Gamma \propto E^n$, $n > 0$, see discussion below) have been obtained using atmospheric neutrinos observed at the IceCube Neutrino Observatory [54], while for negative dependence they come from reactor neutrino experiments [55]. Using these experiments, the bounds for state selection and phase perturbation are nearly identical and it can be expected that the bound for neutrino loss is of similar strength, too. It should be noted, however, that very strong bounds are also obtained from the analysis of solar neutrino data [50], which can only be applied to state-selection models.

In this work we calculate the bounds on neutrino quantum decoherence from the analysis of SN1987A data collected in the Kamiokande-II [56], Baksan [57], and Irvine–Michigan–Brookhaven (IMB) [58] experiments for a decoherence model where neutrino loss is possible. Neutrinos that encounter a virtual black hole in their trajectory might be absorbed and immediately ejected as a different particle in a random direction, thus never reaching the detector. The fact that we observed neutrinos from SN1987A where neutrinos traveled a very long

* Contact author: christoph.ternes@lngs.infn.it

† Contact author: giulia.pagliaroli@lngs.infn.it

‡ Contact author: francesco.villante@lngs.infn.it

distance allows us to set very strong bounds on the parameters for the neutrino-loss model.

II. THE FORMALISM

We work in the open quantum systems framework. The time-evolution of the neutrinos is described through the Lindblad master equation [59,60]

$$\frac{\partial \rho_\nu(t)}{\partial t} = -i[H, \rho_\nu(t)] - \mathcal{D}[\rho_\nu(t)], \quad (1)$$

where $\rho_\nu(t)$ is a Hermitian density matrix describing the neutrino states in the mass basis and H is the Hamiltonian of the neutrino subsystem. Vacuum propagation and standard matter effects are encoded in H . The operator $\mathcal{D}[\rho_\nu(t)]$ describes the interaction of the neutrino with the environment and contains therefore all possible decoherence effects. The exact form of this operator depends on the decoherence model of interest. In general, it is also a Hermitian matrix which can be expressed as [20,21,40,61]

$$\mathcal{D}[\rho_\nu(t)] = \frac{1}{2} \sum_{j=1}^{N^2-1} ([\mathcal{O}_j, \rho_\nu(t) \mathcal{O}_j^\dagger] + [\mathcal{O}_j \rho_\nu(t), \mathcal{O}_j^\dagger]), \quad (2)$$

where N is the dimension of the $SU(N)$ Hilbert space defining the neutrino system (we will assume only the case $N=3$) and $\mathcal{O}_j$ are dissipative operators which characterize the coupling of the neutrino subsystem to its environment. Let us notice that, while being Hermitian, the matrix $\mathcal{D}[\rho_\nu(t)]$ can lead to nonunitary neutrino propagation due to the interactions of the neutrino subsystem with the environment as is the case when considering possible neutrino loss. We can expand the operators in Eq. (2) in terms of the generators from the $SU(N)$ group [20,36,37,40,61]

$$\mathcal{D}[\rho_\nu(t)] = c_k \lambda^k, \quad (3)$$

with $\rho_\nu = \sum \rho_\nu^k \lambda^k$ and $\mathcal{O}_j = \sum \mathcal{O}_j^k \lambda^k$. In the previous expression, c_k are the coefficients of the expansion, and the index k runs from 0 to 8 (for $N=3$), with λ^0 being the identity matrix and λ^k the Gell-Mann matrices satisfying $[\lambda^a, \lambda^b] = i \sum_c f_{abc} \lambda^c$, f_{abc} being the structure constants of $SU(3)$. We can then express the decoherence term as $\mathcal{D}[\rho_\nu(t)] = (\mathbf{D}_{k\ell} \rho_\nu^\ell) \lambda^k$, where ρ_ν^ℓ are the coefficients of the neutrino density matrix, and $\mathbf{D}_{k\ell} \rho_\nu^\ell = c_k$ contains the elements of a $N^2 \times N^2$ matrix representing the free parameters of the system, which in its most general form can be parametrized as

$$\mathbf{D} = \begin{pmatrix} \Gamma_0 & \beta_{01} & \beta_{02} & \beta_{03} & \beta_{04} & \beta_{05} & \beta_{06} & \beta_{07} & \beta_{08} \\ \beta_{01} & \Gamma_1 & \beta_{12} & \beta_{13} & \beta_{14} & \beta_{15} & \beta_{16} & \beta_{17} & \beta_{18} \\ \beta_{02} & \beta_{12} & \Gamma_2 & \beta_{23} & \beta_{24} & \beta_{25} & \beta_{26} & \beta_{27} & \beta_{28} \\ \beta_{03} & \beta_{13} & \beta_{23} & \Gamma_3 & \beta_{34} & \beta_{35} & \beta_{36} & \beta_{37} & \beta_{38} \\ \beta_{04} & \beta_{14} & \beta_{24} & \beta_{34} & \Gamma_4 & \beta_{45} & \beta_{46} & \beta_{47} & \beta_{48} \\ \beta_{05} & \beta_{15} & \beta_{25} & \beta_{35} & \beta_{45} & \Gamma_5 & \beta_{56} & \beta_{57} & \beta_{58} \\ \beta_{06} & \beta_{16} & \beta_{26} & \beta_{36} & \beta_{46} & \beta_{56} & \Gamma_6 & \beta_{67} & \beta_{68} \\ \beta_{07} & \beta_{17} & \beta_{27} & \beta_{37} & \beta_{47} & \beta_{57} & \beta_{67} & \Gamma_7 & \beta_{78} \\ \beta_{08} & \beta_{18} & \beta_{28} & \beta_{38} & \beta_{48} & \beta_{58} & \beta_{68} & \beta_{78} & \Gamma_8 \end{pmatrix}, \quad (4)$$

where all entries are real scalars. Given the large number of free parameters that this matrix contains, an analysis including all parameters is realistically not practical. Often focus is set on the diagonal parameters.¹ The abovementioned models correspond to [40]

$$\mathbf{D}_{\text{phase-pert}} = \text{diag}(0, \Gamma, \Gamma, 0, \Gamma, \Gamma, \Gamma, \Gamma, 0), \quad (5)$$

$$\mathbf{D}_{\text{state-select}} = \text{diag}(0, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma), \quad (6)$$

$$\mathbf{D}_{\nu\text{-loss}} = \text{diag}(\Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma). \quad (7)$$

It is assumed that the new parameter Γ can have the following energy dependence

$$\Gamma = \gamma_0 \left(\frac{E_\nu}{E_0} \right)^n, \quad (8)$$

where E_ν is the neutrino energy and E_0 is a reference energy. For easy comparison with existing literature we set $E_0 = 1$ GeV, even though this energy is far out of the range of the energies of supernova neutrinos.

Notice that if we consider $n = -1$ the phenomenology of neutrino decoherence is similar to that of neutrino decay [62]. The case $n = -2$ can arise naturally when considering a coupling among neutrinos and gravitational waves [63,64]. If the loss of coherence is related to quantum gravity, one could naturally expect n to be positive, but some models also predict negative values. For some concrete models, see Refs. [64–73]. For completeness and comparison with the literature, we consider the cases $n = -2, -1, 0, 1, 2$.

The leading bounds on γ_0 are obtained in Refs. [54,55], depending on the value of n . The bounds have been calculated for the phase-perturbation and state-selection models, and the numerical values are very similar. It can be expected that slightly stronger bounds would be obtained for the neutrino-loss model, since, in addition

¹Note, however, that the presence of nondiagonal parameters can lead to very interesting phenomenology, too [36,37].

to decoherence effects, we would observe an overall reduction of the neutrino flux at the detector. The state-selection and phase-perturbation models cannot be tested using supernova neutrinos from SN1987A, because they only lead to slightly different flux compositions, not sufficiently different from the standard case to be distinguished [74]. It was shown in Ref. [75] that even future experiments could place bounds on these models only for a relatively near supernova.

However, if neutrinos are lost along the trajectory, the overall flux of neutrinos at the detector is reduced, and strong bounds can be obtained from supernova data. Note that the same behavior can be observed when comparing the SN1987A bounds on invisible [76] and visible [77] neutrino decay. From here on we will focus only on this case where neutrino loss occurs. In this scenario, the oscillation probability is simply given by [75]

$$P_{\alpha\beta}^{\text{dec}}(L, E_\nu) = P_{\alpha\beta}^{\text{sm}} e^{-L\gamma_0(E_\nu/E_0)^n}, \quad (9)$$

where $P_{\alpha\beta}^{\text{sm}}$ is the standard model oscillation probability and L is the distance traveled by the neutrino.

III. DATA ANALYSIS

In order to provide very robust bounds we perform two different analyses of SN1987A data. We first consider a time-integrated (TI) analysis following the approach described in Ref. [78] and then we perform a time-dependent (TD) analysis based on the procedure outlined in Ref. [79], see also Ref. [80].

TI analysis. We consider the time-integrated event rate produced by electron antineutrinos interacting through inverse beta decay. The expected signal $\bar{R}(E_e)$ (differential in the positron energy E_e) is given by,

$$\bar{R}(E_e) = N_p \sigma_{\bar{\nu}_e p}(E_\nu) F_{\bar{\nu}_e}(E_\nu) \eta(E_e), \quad (10)$$

where E_ν is the neutrino energy, N_p is the number of free protons in the detector, $\sigma_{\bar{\nu}_e p}$ is the inverse beta decay (IBD) cross section [81], η is the detector dependent detection efficiency, and $F_{\bar{\nu}_e}$ is the electron antineutrino fluence. We neglect the (small) kinetic energy of the neutron in the final state and we relate the neutrino and positron energy by $E_e = E_\nu - (m_n - m_p)$, where m_n and m_p are neutron and proton masses, respectively. The number of target protons N_p is calculated by considering 2.14 kt (6.8 kt) of H_2O for Kamiokande-II (IMB) detectors and 280 tons of water equivalent for the Baksan scintillator. For the detection efficiencies we adopt the ones reported in Fig. 1 of Ref. [82]. The standard model electron antineutrino fluence, i.e., the time integrated neutrino flux, is assumed to be well described by a Maxwell-Boltzmann spectrum in the form

$$F_{\bar{\nu}_e}^{\text{sm}}(E_\nu) = \frac{1}{4\pi D^2} \frac{E_{\text{tot}}^{\bar{\nu}_e} (1 + \alpha)^{(1+\alpha)}}{\langle E_{\bar{\nu}_e} \rangle \Gamma[1 + \alpha]} \times \left(\frac{E_\nu}{\langle E_{\bar{\nu}_e} \rangle} \right)^2 e^{-\frac{(1+\alpha)E_\nu}{\langle E_{\bar{\nu}_e} \rangle}}, \quad (11)$$

where we set $\alpha = 2$ and $D = 50$ kpc is the distance to SN1987A. The two free parameters in this time-independent data analysis are: the total energy $E_{\text{tot}}^{\bar{\nu}_e}$ emitted in $\bar{\nu}_e$ and the average $\bar{\nu}_e$ energy $\langle E_{\bar{\nu}_e} \rangle$. Since the total energy and the time-integrated average energies of $\bar{\nu}_e$ and $\bar{\nu}_x$ are expected to be nearly the same, oscillations among different flavors (or state selection and phase-perturbation decoherence) do not alter the predicted $\bar{\nu}_e$ fluence at Earth. The effect of decoherence with neutrino loss is described as

$$F_{\bar{\nu}_e}^{\text{dec}}(E_\nu) = F_{\bar{\nu}_e}^{\text{sm}}(E_\nu) e^{-D\gamma_0(E_\nu/E_0)^n}, \quad (12)$$

where we propagated the decoherence term from the probability [see Eq. (9)] to the fluence at Earth. The individual likelihoods for each detector are given in this case by

$$\bar{\mathcal{L}}_d = e^{-\bar{R}} \prod_{i=1}^{N_d^*} \left[\int \bar{R}(E_e) G(E_e, E_i) dE_e \right], \quad (13)$$

where the $\bar{R}$ is the rate in Eq. (10) integrated over the total energy range, while

$$G(E_e, E_i) = \frac{1}{\sqrt{2\pi}\delta E_i} \exp\left(-\frac{(E_e - E_i)^2}{2\delta E_i^2}\right) \quad (14)$$

are the energy smearing functions with E_i and δE_i being the measured positron energies and uncertainties, respectively. In a TI analysis it is not clear how to treat backgrounds and for the present analysis we have not included them. Following Ref. [78] we define *a priori* the dataset of Kamiokande events N_d^* which we analyze excluding the events below the energy threshold. The list of events for all experiments is summarized in the Appendix.

TD analysis. The signal rate for each detector, triply differential in time t , positron energy E_e and cosine of the positron emission angle c_θ , is computed according to

$$R(t, E_e, c_\theta) = N_p \frac{d\sigma_{\bar{\nu}_e p}}{dc_\theta}(E_\nu, c_\theta) \Phi_{\bar{\nu}_e}(t, E_\nu) \times \xi(c_\theta) \eta(E_e) \frac{dE_\nu}{dE_e}, \quad (15)$$

where ξ is the angular bias (1 for Kamiokande-II and Baksan and $1 + 0.1c_\theta$ for IMB), and $\Phi_{\bar{\nu}_e}$ is the electron antineutrino flux. In the above equation, the neutrino and positron energies are related via

$$E_\nu = \frac{E_e + \delta_-}{1 - (E_e - p_e c_\theta)/m_p}, \quad (16)$$

where p_e is the positron momentum and $\delta_- = (m_n^2 - m_p^2 - m_e^2)/(2m_p) = 1.294$ MeV, with m_p , m_n , and m_e being the masses of the proton, neutron and electron, respectively. Regarding the differential IBD cross section we use the approximated formulas valid for the energies under consideration presented in Refs. [81,83].

The electron antineutrino flux is parametrized as a pure cooling emission phase, i.e., a thermal emission from the neutrinosphere,

$$\Phi_{\bar{\nu}_e}^0(t, E_\nu) = \frac{R_c^2 g_{\bar{\nu}_e}(t, T_c(t))}{8\pi^2 D^2} \quad (17)$$

with the Fermi-Dirac spectrum

$$g_{\bar{\nu}_e}(t, T_c(t)) = \frac{E_\nu^2}{1 + \exp(E_\nu/T_c(t))}, \quad (18)$$

which depends on

$$T_c(t) = T_c \exp(-t/(4\tau_c)). \quad (19)$$

The physical parameters in this scenario are the radius of the neutrinosphere R_c , the initial temperature T_c and the time constant of the process τ_c . The initial flux of muon and tau antineutrinos $\Phi_{\bar{\nu}_x}^0(t, E_\nu)$ is the same as for electron antineutrinos, but with the replacements $T_c \rightarrow 1.2T_c$ and $R_c \rightarrow R_c/1.2^2$. This prescription implements equipartition of emitted energy among different flavors. However, it takes into account that, due to reduced interactions, muon and tau neutrinos have a more internal neutrinosphere and a slightly larger average energy than electron neutrinos. Since emission spectra of $\bar{\nu}_e$ and $\bar{\nu}_x$ are not identical, we need to account for possible conversions among neutrino flavors. In the standard oscillation scenario the flux at the detector is given by

$$\Phi_{\bar{\nu}_e}^{\text{sm}}(t, E_\nu) = P_{ee} \Phi_{\bar{\nu}_e}^0(t, E_\nu) + P_{xe} \Phi_{\bar{\nu}_x}^0(t, E_\nu). \quad (20)$$

The neutrino oscillation probabilities are given by $P_{ee} = \cos^2 \theta_{12} \cos^2 \theta_{13}$ and $P_{xe} = 1 - P_{ee}$, where we use [84] $\sin^2 \theta_{12} = 0.318$ and $\sin^2 \theta_{13} = 0.022$. Even though the neutrino mass ordering is not definitely determined yet [85], we consider here only normal mass ordering, slightly preferred by the data [84–87]. Phase-perturbation decoherence models do not alter this prediction because they have the same effects of kinematic decoherence that is already taken into account for supernova neutrinos. State-selection decoherence models lead to equipartition of flavors, corresponding to $P_{ee} = 1/3$ in the above expression. The different flux composition however, due to similarities among $\Phi_{\bar{\nu}_e}^0$ and $\Phi_{\bar{\nu}_x}^0$, cannot be constrained

by SN1987A data. Decoherence models with neutrino loss can instead have observable effects, since the flux at the detector becomes,

$$\Phi_{\bar{\nu}_e}^{\text{dec}}(t, E_\nu) = \Phi_{\bar{\nu}_e}^{\text{sm}}(t, E_\nu) e^{-D\gamma_0(E_\nu/E_0)^n}, \quad (21)$$

where we again propagated the decoherence term from the probability, Eq. (9), to the flux at Earth.

The statistical analysis is performed by evaluating

$$\chi^2 = -2 \sum_{d=K,I,B} \log \mathcal{L}_d \quad (22)$$

where the individual likelihoods for each detector are given by

$$\mathcal{L}_d = e^{-f_d \int R(t) dt} \prod_{i=1}^{N_d} e^{R(t_i) \tau_d} \times \left[\frac{B_i}{2} + \int R(t_i, E_e, c_\theta) G(E_e, E_i) dE_e \right], \quad (23)$$

where the product is taken over the N_d events observed in each detector, $R(t)$ is Eq. (15) integrated over E_e and c_θ , B_i are the background rates for each detector. The quantities with subscript i are the measured times (t_i), energies ($E_i \pm \delta E_i$), and angles (θ_i) of the i th event. Finally, f_d and τ_d are the live-time fraction and dead time of the detectors. We take $f_d = 0.9055$ ($f_d = 1$) and $\tau_d = 0.035$ s ($\tau_d = 0$ s) for IMB (Kamiokande-II and Baksan).

IV. RESULTS AND DISCUSSION

The bounds on the decoherence parameter γ_0 are obtained by marginalizing over the parameters used to describe SN1987A neutrino emission. Specifically, the total energy and the average energy of emitted electron antineutrinos, $E_{\text{tot}}^{\bar{\nu}_e}$ and $\langle E_\nu \rangle$, are considered in the TI analysis, while the radius and temperature of neutrinosphere, R_c and T_c , and the timescale τ_c for supernova cooling are adopted in the TD analysis. These parameters are varied in very conservative ranges. For the TI analysis the total energy emitted in $\bar{\nu}_e$ is bounded to be smaller than the neutron star binding energy, i.e., $E_{\text{tot}}^{\bar{\nu}_e} \leq 5 \times 10^{53}$ ergs, while the average energy of $\bar{\nu}_e$ is constrained to be $\langle E_\nu \rangle < 90$ MeV. Note that the upper limit for $E_{\text{tot}}^{\bar{\nu}_e}$ corresponds to the extreme assumption that all available energy is radiated in electron antineutrinos. For the TD analysis, we assume the following priors, $R_c < 100$ km, $2 \text{ MeV} < T_c < 8 \text{ MeV}$, and $1 \text{ s} < \tau_c < 10 \text{ s}$, based on general expectations from supernova theory and recent simulations [78,88,89].

The 90% confidence level (CL) bounds on the decoherence parameter γ_0 obtained with the TI and the TD approach are shown in Fig. 1 and Table I. Since our

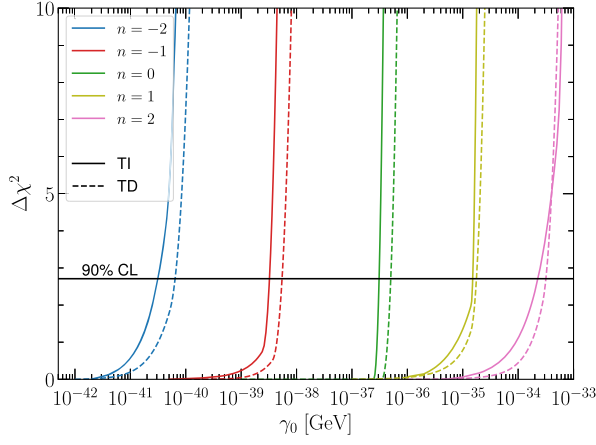


FIG. 1. χ^2 profiles for the decoherence parameter γ_0 for different values of n as indicated in the legend. The solid (dashed) lines correspond to the TI (TD) analyses.

reference energy in Eq. (8) is $E_0 = 1$ GeV while the average energy of supernova neutrinos is ~ 10 MeV, we find the strongest bound on γ_0 for $n = -2$, becoming then weaker as n increases. The bound from SN1987A is for all n many orders of magnitude larger than the previous bounds for which we only indicate an order of magnitude estimate,² since Refs. [50,54,55] did not consider neutrino-loss models.

The agreement between the results obtained by using different approaches is striking and shows us that the adopted parametrization for the supernova emission is not relevant for the final results. Indeed, the TI approach is mainly based on the spectral shape of the supernova signal observed in the numerical simulation without taking into account the temporal evolution of the emission and the temporal distribution of the observed events. Since the neutrino average energy can be constrained by the observed signal, the total number of observed events translates into a constraint on γ_0 , once an upper limit on the total energy emitted in electron antineutrinos is given. This, however, can be conservatively estimated as $E_{\text{tot}}^{\bar{\nu}_e} \leq 5 \times 10^{53}$ ergs, as was explained above. The number of free parameters in this analysis is smaller (only 3); however, background rejection is not possible, requiring that a reduced dataset (where background events are expected to be absent) is defined “*a priori*.” On the other hand, the TD analysis is more complex. The signal is parametrized according to a phenomenological description of the neutrino emission during the cooling phase and the number of free parameters is larger (4). However, the time (and angular) distribution of the expected supernova neutrino events can be used to separate signal and background contributions. In this case, considering that the energy and time distribution of observed events can be used to constrain T_c and τ_c

²We have numerically verified by using the analysis method of Ref. [55] that bounds for neutrino-loss are only about a factor 4–5 stronger than the bounds for the phase-perturbation model, justifying the order-of-magnitude estimate.

TABLE I. Bounds on the decoherence parameter γ_0 in GeV at 90% CL obtained in this paper with the TI and the TD approach. For comparison we also show an order-of-magnitude estimate from the leading bounds from other experiments, Ref. [55] for $n < 0$, Ref. [50] for $n = 0$, and Ref. [54] for $n > 0$.

n	Previous bound	This work (TI)	This work (TD)
−2	$\mathcal{O}(10^{-27})$	3.1×10^{-41}	6.4×10^{-41}
−1	$\mathcal{O}(10^{-24})$	3.2×10^{-39}	5.5×10^{-39}
0	$\mathcal{O}(10^{-28})$	3.1×10^{-37}	5.0×10^{-37}
1	$\mathcal{O}(10^{-28})$	1.5×10^{-35}	1.8×10^{-35}
2	$\mathcal{O}(10^{-32})$	2.3×10^{-34}	3.2×10^{-34}

parameters, the bound on γ_0 is connected with the assumed radius of the neutrinosphere, for which the very conservative upper bound $R_c < 100$ km is adopted. We checked that the best-fit obtained in absence of decoherence is in perfect agreement with the ones obtained in previous analysis of SN1987A, i.e., Ref. [78] for the TI approach and Ref. [79] for the TD analysis. Note that, a future observation of a supernova can further improve the bounds obtained here. In Ref. [75] it was shown that future detectors could achieve a similar bound to ours for a supernova already at less than 10 kpc distance.

Finally, we comment on the specific case of $n = 2$: the Γ parameter can be expressed relative to the Planck scale as $\Gamma = \xi_{\text{Planck}} E^n / M_{\text{Planck}}^{n-1}$ with $M_{\text{Planck}} \simeq 1.2 \times 10^{19}$ GeV and ξ_{Planck} being a relative strength for ν -virtual black hole interactions [40]. Our bound on γ_0 can be converted into a limit on this strength, giving $\xi_{\text{Planck}} < 2.8 \times 10^{-15}$ (to be compared with the ones reported in [54] from IceCube of $\xi_{\text{Planck}} < 1.2 \times 10^{-13}$).

For even larger values of n than those considered here, the bound from Ref. [54] becomes stronger than the bound from SN1987A, since in these cases the shorter distance of atmospheric neutrinos becomes compensated for by their much larger energies. In principle, the strongest bounds could be obtained by looking at extremely high energy events from far away sources. However, since sources are not easily identified (or modeled), we chose to discuss SN1987A here, for which we have a clear theoretical description. We will discuss the case of high-energy neutrinos in a future work.

ACKNOWLEDGMENTS

The work of G. P. and F. L. V. is partially supported by Grant No. 2022E2J4RK “PANTHEON: Perspectives in Astroparticle and Neutrino THEory with Old and New messengers” under the program PRIN 2022 funded by the Italian Ministero dell’Università e della Ricerca (MUR) and by the European Union—Next Generation EU.

DATA AVAILABILITY

No data were created or analyzed in this study.

APPENDIX: SN1987A EVENTS

We summarize the experimental data used in the analysis of the present paper in Table II for Kamiokande-II, in Table III for Baksan, and in Table IV for IMB.

TABLE II. The Kamiokande-II data set. For the TI data analysis only the data indicated with a * are considered, while in the TD analysis we include the entire data set. Energies are given in MeV and times are relative times with respect to the bounce in seconds.

δt_i	$E_i \pm \delta E_i$	$\theta_i \pm \delta \theta_i$	B_i
0.0*	20.0 ± 2.9	18 ± 18	1.0×10^{-5}
0.107*	13.5 ± 3.2	40 ± 27	5.4×10^{-4}
0.303*	7.5 ± 2.0	108 ± 32	3.1×10^{-2}
0.324*	9.2 ± 2.7	70 ± 30	8.5×10^{-3}
0.507*	12.8 ± 2.9	135 ± 23	5.3×10^{-4}
0.686	6.3 ± 1.7	68 ± 77	7.1×10^{-2}
1.541*	35.4 ± 8.0	32 ± 16	5.0×10^{-6}
1.728*	21.0 ± 4.2	30 ± 18	1.0×10^{-5}
1.915*	19.8 ± 3.2	38 ± 22	1.0×10^{-5}
9.219*	8.6 ± 2.7	122 ± 30	1.8×10^{-2}
10.433*	13.0 ± 2.6	49 ± 26	4.0×10^{-4}
12.439*	8.9 ± 1.9	91 ± 39	1.4×10^{-2}
17.641	6.5 ± 1.6	103 ± 50	7.2×10^{-3}
20.257	5.4 ± 1.4	110 ± 50	5.2×10^{-2}
21.355	4.6 ± 1.3	120 ± 50	1.8×10^{-2}
23.814	6.5 ± 1.6	112 ± 50	7.3×10^{-2}

TABLE III. The Baksan data set. No information on the angle was provided and it is assumed to be 90° for all events.

δt_i	$E_i \pm \delta E_i$	$\theta_i \pm \delta \theta_i$	B_i
0.0	12.0 ± 2.4	90 ± 0	8.4×10^{-4}
0.435	17.9 ± 3.6	90 ± 0	1.3×10^{-3}
1.710	23.5 ± 4.7	90 ± 0	1.2×10^{-3}
7.687	17.5 ± 3.5	90 ± 0	1.3×10^{-3}
9.099	20.3 ± 4.1	90 ± 0	1.3×10^{-3}

TABLE IV. The IMB data set. The background is assumed to be negligible.

δt_i	$E_i \pm \delta E_i$	$\theta_i \pm \delta \theta_i$	B_i
0.0	38.0 ± 7.0	80 ± 10	0
0.412	37.0 ± 7.0	44 ± 15	0
0.650	28.0 ± 6.0	56 ± 20	0
1.141	39.0 ± 7.0	65 ± 20	0
1.562	36.0 ± 9.0	33 ± 15	0
2.684	36.0 ± 6.0	52 ± 10	0
5.010	19.0 ± 5.0	42 ± 20	0
5.582	22.0 ± 5.0	105 ± 20	0

- [1] 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**, 87 (1992).
- [2] K. Kiers, S. Nussinov, and N. Weiss, Coherence effects in neutrino oscillations, *Phys. Rev. D* **53**, 537 (1996).
- [3] T. Ohlsson, Equivalence between neutrino oscillations and neutrino decoherence, *Phys. Lett. B* **502**, 159 (2001).
- [4] M. Beuthe, Towards a unique formula for neutrino oscillations in vacuum, *Phys. Rev. D* **66**, 013003 (2002).
- [5] C. Giunti, Coherence and wave packets in neutrino oscillations, *Found. Phys. Lett.* **17**, 103 (2004).
- [6] M. Blennow, T. Ohlsson, and W. Winter, Damping signatures in future neutrino oscillation experiments, *J. High Energy Phys.* **06** (2005) 049.
- [7] Y. Farzan and A. Y. Smirnov, Coherence and oscillations of cosmic neutrinos, *Nucl. Phys. B* **805**, 356 (2008).
- [8] B. Kayser and J. Kopp, Testing the wave packet approach to neutrino oscillations in future experiments, [arXiv:1005.4081](https://arxiv.org/abs/1005.4081).
- [9] D. V. Naumov, On the theory of wave packets, *Phys. Part. Nucl. Lett.* **10**, 642 (2013).
- [10] B. J. P. Jones, Dynamical pion collapse and the coherence of conventional neutrino beams, *Phys. Rev. D* **91**, 053002 (2015).
- [11] E. Akhmedov, Quantum mechanics aspects and subtleties of neutrino oscillations, in *International Conference on History of the Neutrino: 1930–2018* (2019).
- [12] W. Grimus, Revisiting the quantum field theory of neutrino oscillations in vacuum, *J. Phys. G* **47**, 085004 (2020).
- [13] D. V. Naumov and V. A. Naumov, Quantum field theory of neutrino oscillations, *Phys. Part. Nucl.* **51**, 1 (2020).
- [14] A. de Gouvêa, V. De Romeri, and C. A. Ternes, Probing neutrino quantum decoherence at reactor experiments, *J. High Energy Phys.* **08** (2020) 018.
- [15] A. de Gouvêa, V. De Romeri, and C. A. Ternes, Combined analysis of neutrino decoherence at reactor experiments, *J. High Energy Phys.* **06** (2021) 042.
- [16] E. Akhmedov and A. Y. Smirnov, Damping of neutrino oscillations, decoherence and the lengths of neutrino wave packets, *J. High Energy Phys.* **11** (2022) 082.
- [17] R. Krueger and T. Schwetz, Decoherence effects in reactor and Gallium neutrino oscillation experiments—A QFT approach, *Eur. Phys. J. C* **83**, 578 (2023).
- [18] A. de Gouvêa, V. De Romeri, and C. A. Ternes, Addendum to: Combined analysis of neutrino decoherence at reactor experiments, *J. High Energy Phys.* **11** (2024) 095.
- [19] A. M. Gago, E. M. Santos, W. J. C. Teves, and R. Zukanovich Funchal, Quantum dissipative effects and neutrinos: Current constraints and future perspectives, *Phys. Rev. D* **63**, 073001 (2001).
- [20] F. Benatti and R. Floreanini, Open system approach to neutrino oscillations, *J. High Energy Phys.* **02** (2000) 032.
- [21] E. Lisi, A. Marrone, and D. Montanino, Probing possible decoherence effects in atmospheric neutrino oscillations, *Phys. Rev. Lett.* **85**, 1166 (2000).
- [22] F. Benatti and R. Floreanini, Massless neutrino oscillations, *Phys. Rev. D* **64**, 085015 (2001).
- [23] H. P. Breuer and F. Petruccione, *The Theory of Open Quantum Systems* (Oxford University Press, 2002).
- [24] D. Morgan, E. Winstanley, J. Brunner, and L. F. Thompson, Probing quantum decoherence in atmospheric neutrino oscillations with a neutrino telescope, *Astropart. Phys.* **25**, 311 (2006).
- [25] L. A. Anchordoqui, H. Goldberg, M. C. Gonzalez-Garcia, F. Halzen, D. Hooper, S. Sarkar, and T. J. Weiler, Probing Planck scale physics with IceCube, *Phys. Rev. D* **72**, 065019 (2005).
- [26] 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**, 033006 (2007).
- [27] Y. Farzan, T. Schwetz, and A. Y. Smirnov, Reconciling results of LSND, MiniBooNE and other experiments with soft decoherence, *J. High Energy Phys.* **07** (2008) 067.
- [28] R. L. N. Oliveira and M. M. Guzzo, Dissipation and θ_{13} in neutrino oscillations, *Eur. Phys. J. C* **73**, 2434 (2013).
- [29] R. L. N. Oliveira, Dissipative effect in long baseline neutrino experiments, *Eur. Phys. J. C* **76**, 417 (2016).
- [30] G. Balieiro Gomes, M. M. Guzzo, P. C. de Holanda, and R. L. N. Oliveira, Parameter limits for neutrino oscillation with decoherence in KamLAND, *Phys. Rev. D* **95**, 113005 (2017).
- [31] J. A. B. Coelho, W. A. Mann, and S. S. Bashar, Nonmaximal θ_{23} mixing at NOvA from neutrino decoherence, *Phys. Rev. Lett.* **118**, 221801 (2017).
- [32] J. A. B. Coelho and W. A. Mann, Decoherence, matter effect, and neutrino hierarchy signature in long baseline experiments, *Phys. Rev. D* **96**, 093009 (2017).
- [33] J. Carpio, E. Massoni, and A. M. Gago, Revisiting quantum decoherence for neutrino oscillations in matter with constant density, *Phys. Rev. D* **97**, 115017 (2018).
- [34] P. Coloma, J. Lopez-Pavon, I. Martinez-Soler, and H. Nunokawa, Decoherence in neutrino propagation through matter, and bounds from IceCube/DeepCore, *Eur. Phys. J. C* **78**, 614 (2018).
- [35] J. A. Carpio, E. Massoni, and A. M. Gago, Testing quantum decoherence at DUNE, *Phys. Rev. D* **100**, 015035 (2019).
- [36] J. C. Carrasco, F. N. Díaz, and A. M. Gago, Probing *CPT* breaking induced by quantum decoherence at DUNE, *Phys. Rev. D* **99**, 075022 (2019).
- [37] L. Buoninfante, A. Capolupo, S. M. Giampaolo, and G. Lambiase, Revealing neutrino nature and *CPT* violation with decoherence effects, *Eur. Phys. J. C* **80**, 1009 (2020).
- [38] A. L. G. Gomes, R. A. Gomes, and O. L. G. Peres, Quantum decoherence and relaxation in neutrinos using long-baseline data, *J. High Energy Phys.* **10** (2023) 035.
- [39] T. Ohlsson and S. Zhou, Density matrix formalism for PT-symmetric non-Hermitian Hamiltonians with the Lindblad equation, *Phys. Rev. A* **103**, 022218 (2021).
- [40] T. Stuttard and M. Jensen, Neutrino decoherence from quantum gravitational stochastic perturbations, *Phys. Rev. D* **102**, 115003 (2020).
- [41] T. Stuttard, Neutrino signals of lightcone fluctuations resulting from fluctuating spacetime, *Phys. Rev. D* **104**, 056007 (2021).
- [42] I. K. Banerjee and U. K. Dey, Neutrino decoherence from generalised uncertainty, *Eur. Phys. J. C* **83**, 428 (2023).
- [43] G. Barenboim and A. M. Gago, Quantum decoherence effects: A complete treatment, *Phys. Rev. D* **110**, 095005 (2024).

- [44] S. W. Hawking, Breakdown of predictability in gravitational collapse, *Phys. Rev. D* **14**, 2460 (1976).
- [45] J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos, and M. Srednicki, Search for violations of quantum mechanics, *Nucl. Phys.* **B241**, 381 (1984).
- [46] S. B. Giddings and A. Strominger, Loss of incoherence and determination of coupling constants in quantum gravity, *Nucl. Phys.* **B307**, 854 (1988).
- [47] A. Addazi *et al.*, Quantum gravity phenomenology at the dawn of the multi-messenger era—A review, *Prog. Part. Nucl. Phys.* **125**, 103948 (2022).
- [48] R. L. N. de Oliveira, M. M. Guzzo, and P. C. de Holanda, Quantum dissipation and CP violation in MINOS, *Phys. Rev. D* **89**, 053002 (2014).
- [49] G. Balieiro Gomes, D. V. Forero, M. M. Guzzo, P. C. De Holanda, and R. L. N. Oliveira, Quantum decoherence effects in neutrino oscillations at DUNE, *Phys. Rev. D* **100**, 055023 (2019).
- [50] P. C. de Holanda, Solar neutrino limits on decoherence, *J. Cosmol. Astropart. Phys.* **03** (2020) 012.
- [51] J. Wang *et al.* (JUNO Collaboration), Damping signatures at JUNO, a medium-baseline reactor neutrino oscillation experiment, *J. High Energy Phys.* **06** (2022) 062.
- [52] G. Barenboim, A. M. Calatayud-Cadenillas, A. M. Gago, and C. A. Ternes, Quantum decoherence effects on precision measurements at DUNE and T2HK, *Phys. Lett. B* **852**, 138626 (2024).
- [53] S. Aiello *et al.* (KM3NeT Collaboration), Search for quantum decoherence in neutrino oscillations with six detection units of KM3NeT/ORCA, *J. Cosmol. Astropart. Phys.* **03** (2025) 039.
- [54] R. Abbasi *et al.* (ICECUBE Collaboration and IceCube Collaboration), Search for decoherence from quantum gravity with atmospheric neutrinos, *Nat. Phys.* **20**, 913 (2024).
- [55] V. De Romeri, C. Giunti, T. Stuttard, and C. A. Ternes, Neutrino oscillation bounds on quantum decoherence, *J. High Energy Phys.* **09** (2023) 097.
- [56] K. Hirata *et al.* (Kamiokande-II Collaboration), Observation of a neutrino burst from the supernova SN 1987a, *Phys. Rev. Lett.* **58**, 1490 (1987).
- [57] E. N. Alekseev, L. N. Alekseeva, I. V. Krivosheina, and V. I. Volchenko, Detection of the neutrino signal from SN1987A in the LMC using the Inr Baksan underground scintillation telescope, *Phys. Lett. B* **205**, 209 (1988).
- [58] R. M. Bionta *et al.*, Observation of a neutrino burst in coincidence with supernova SN 1987a in the large magellanic cloud, *Phys. Rev. Lett.* **58**, 1494 (1987).
- [59] G. Lindblad, On the generators of quantum dynamical semigroups, *Commun. Math. Phys.* **48**, 119 (1976).
- [60] V. Gorini, A. Kossakowski, and E. C. G. Sudarshan, Completely positive dynamical semigroups of N level systems, *J. Math. Phys. (N.Y.)* **17**, 821 (1976).
- [61] A. M. Gago, E. M. Santos, W. J. C. Teves, and R. Zukanovich Funchal, A study on quantum decoherence phenomena with three generations of neutrinos, [arXiv: hep-ph/0208166](https://arxiv.org/abs/hep-ph/0208166).
- [62] K. Stankevich, A. Studenikin, and M. Vyalkov, Generalized Lindblad master equation for neutrino evolution, *Phys. Rev. D* **111**, 036014 (2025).
- [63] M. Dvornikov, Interaction of supernova neutrinos with stochastic gravitational waves, *Phys. Rev. D* **104**, 043018 (2021).
- [64] A. Domi, T. Eberl, M. J. Fahn, K. Giesel, L. Hennig, U. Katz, R. Kemper, and M. Kobler, Understanding gravitationally induced decoherence parameters in neutrino oscillations using a microscopic quantum mechanical model, *J. Cosmol. Astropart. Phys.* **11** (2024) 006.
- [65] J. R. Ellis, N. E. Mavromatos, and D. V. Nanopoulos, String theory modifies quantum mechanics, *Phys. Lett. B* **293**, 37 (1992).
- [66] J. R. Ellis, N. E. Mavromatos, and D. V. Nanopoulos, Valleys in string foam suppress quantum coherence, *Mod. Phys. Lett. A* **10**, 425 (1995).
- [67] 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**, 243 (1997).
- [68] R. Gambini, R. A. Porto, and J. Pullin, Decoherence from discrete quantum gravity, *Classical Quantum Gravity* **21**, L51 (2004).
- [69] F. N. Loreti and A. B. Balantekin, Neutrino oscillations in noisy media, *Phys. Rev. D* **50**, 4762 (1994).
- [70] F. Benatti and R. Floreanini, Dissipative neutrino oscillations in randomly fluctuating matter, *Phys. Rev. D* **71**, 013003 (2005).
- [71] P. Nandi and T. Bhattacharyya, Unearthing neutrino decoherence from quantum spacetime: An open quantum systems perspective, [arXiv:2410.03808](https://arxiv.org/abs/2410.03808).
- [72] A. Domi, T. Eberl, D. Hellmann, S. Krieg, and H. Päs, Potential of neutrino telescopes to detect quantum gravity-induced decoherence in the presence of dark fermions, *J. Cosmol. Astropart. Phys.* **01** (2025) 063.
- [73] C. Burrage and C. Kading, Fock state probability changes in open quantum systems, [arXiv:2502.07673](https://arxiv.org/abs/2502.07673).
- [74] P. Dedin Neto, M. V. d. Santos, P. C. de Holanda, and E. Kemp, SN1987A neutrino burst: Limits on flavor conversion, *Eur. Phys. J. C* **83**, 459 (2023).
- [75] M. V. dos Santos, P. C. de Holanda, P. Dedin Neto, and E. Kemp, Effects of quantum decoherence in a future supernova neutrino detection, *Phys. Rev. D* **108**, 103032 (2023).
- [76] P. Martnez-Mirave, I. Tamborra, and M. Tortola, The Sun and core-collapse supernovae are leading probes of the neutrino lifetime, *J. Cosmol. Astropart. Phys.* **05** (2024) 002.
- [77] P. Ivanez Ballesteros and M. C. Volpe, SN1987A and neutrino non-radiative decay, *Phys. Lett. B* **847**, 138252 (2023).
- [78] D. F. G. Fiorillo, M. Heinlein, H.-T. Janka, G. Raffelt, E. Vitagliano, and R. Bollig, Supernova simulations confront SN 1987A neutrinos, *Phys. Rev. D* **108**, 083040 (2023).
- [79] G. Pagliaroli, F. Vissani, M. L. Costantini, and A. Ianni, Improved analysis of SN1987A antineutrino events, *Astropart. Phys.* **31**, 163 (2009).
- [80] R. M. Bozza, V. di Risi, G. Matteucci, V. Oliviero, G. Ricciardi, and F. Vissani, The flux of electron antineutrinos from supernova SN1987A data, *J. Cosmol. Astropart. Phys.* **05** (2025) 027.
- [81] A. Strumia and F. Vissani, Precise quasielastic neutrino/nucleon cross-section, *Phys. Lett. B* **564**, 42 (2003).

- [82] T. J. Loredo and D. Q. Lamb, Bayesian analysis of neutrinos observed from supernova SN-1987A, *Phys. Rev. D* **65**, 063002 (2002).
- [83] F. Vissani, Comparative analysis of SN1987A antineutrino fluence, *J. Phys. G* **42**, 013001 (2015).
- [84] P. F. de Salas, D. V. Forero, S. Gariazzo, P. Martínez-Miravé, O. Mena, C. A. Ternes, M. Tórtola, and J. W. F. Valle, 2020 global reassessment of the neutrino oscillation picture, *J. High Energy Phys.* **02** (2021) 071.
- [85] S. Gariazzo *et al.*, Neutrino mass and mass ordering: No conclusive evidence for normal ordering, *J. Cosmol. Astropart. Phys.* **10** (2022) 010.
- [86] F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri, and A. Palazzo, Unfinished fabric of the three neutrino paradigm, *Phys. Rev. D* **104**, 083031 (2021).
- [87] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. a. P. Pinheiro, and T. Schwetz, NuFit-6.0: Updated global analysis of three-flavor neutrino oscillations, *J. High Energy Phys.* **12** (2024) 216.
- [88] H. T. Janka, Long-term multidimensional models of core-collapse supernovae: Progress and challenges, *arXiv*: 2502.14836.
- [89] Garching core-collapse supernova research archive, <https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/>.