Faculty of Physics
Lomonosov Moscow
State University

Quantum field-theoretic framework for neutrino decoherence

Konstantin Stankevich

Quarks-2026

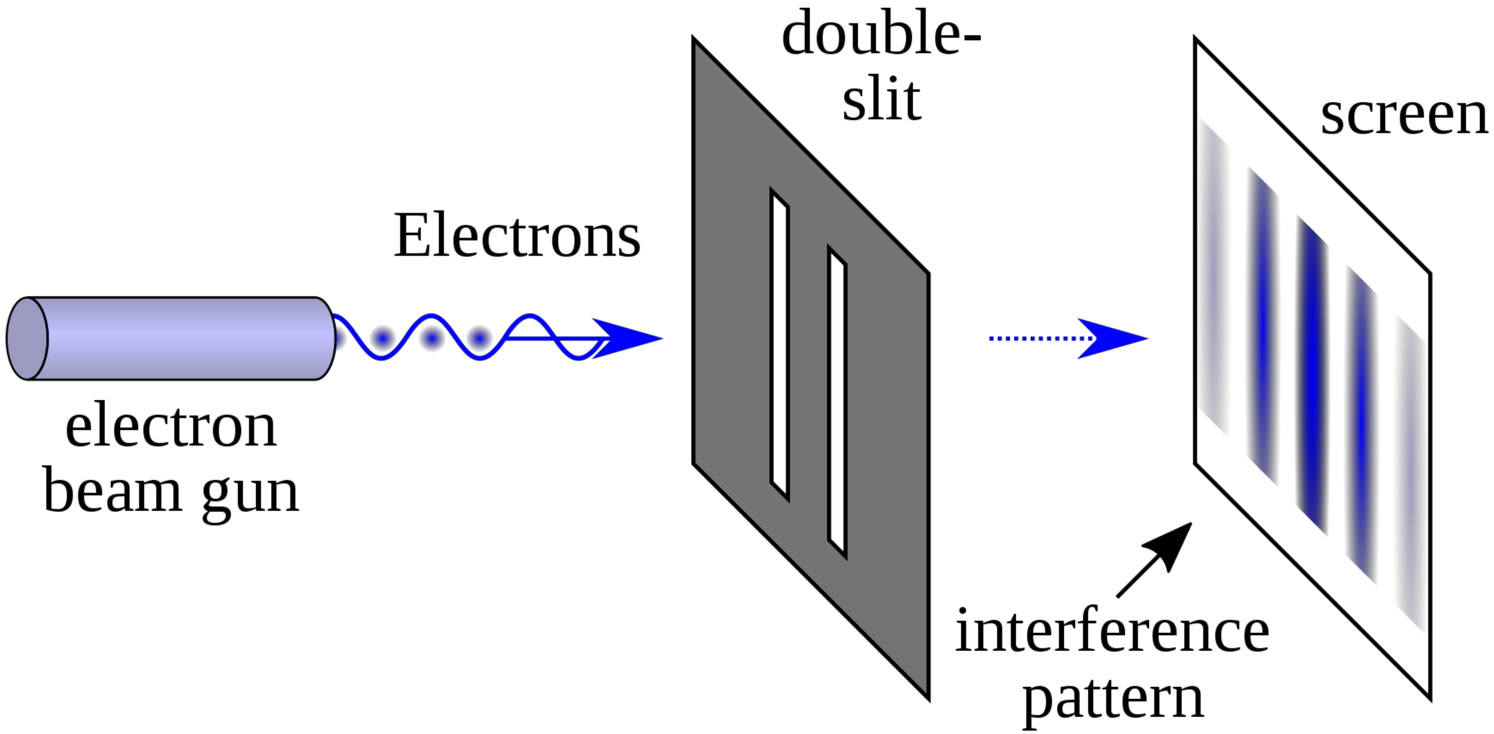
18-23 May, 2026 Petrozavodsk, Russia

This work was supported by the Russian Science Foundation (project no. 24-12-00084)

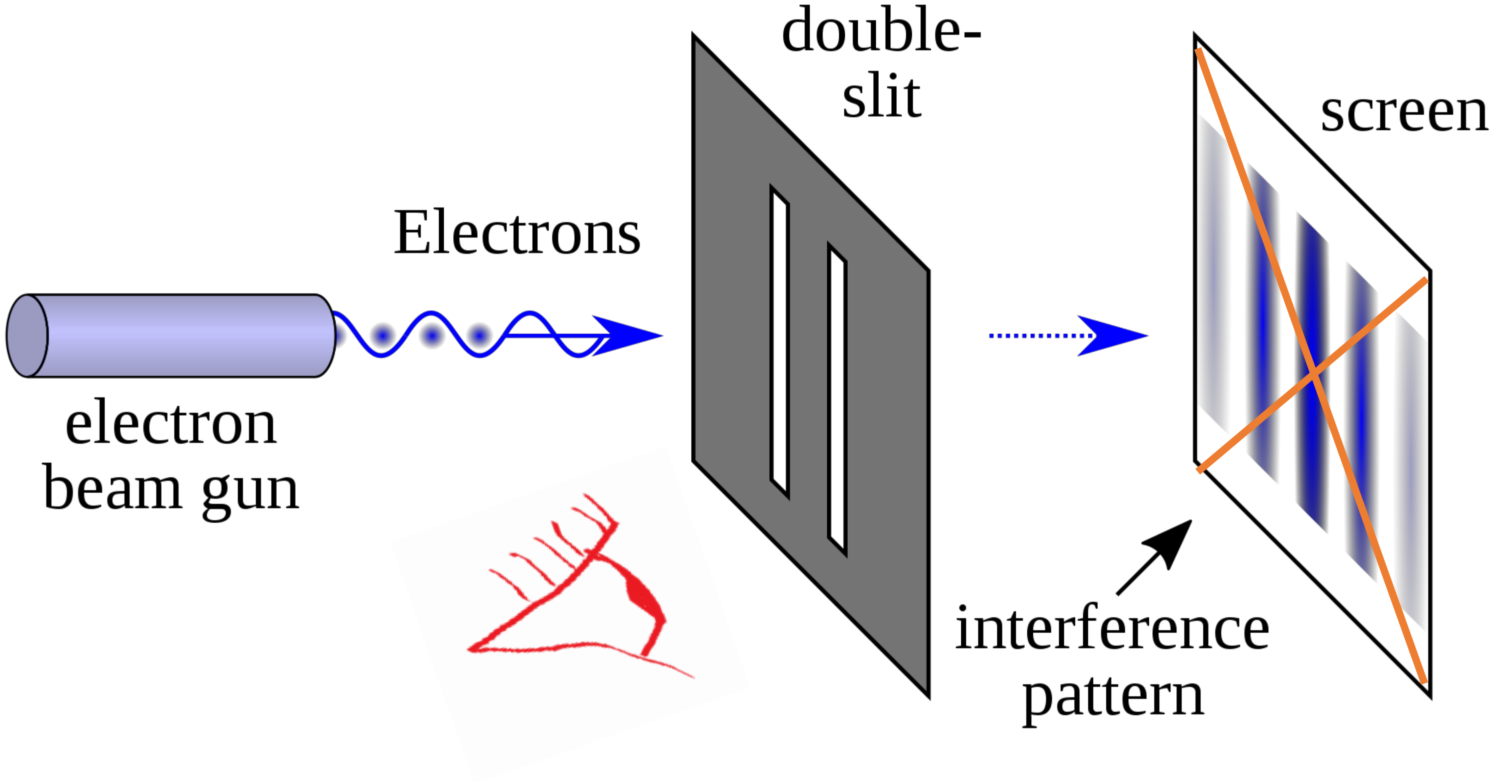
Part 1

The phenomenon of neutrino quantum decoherence

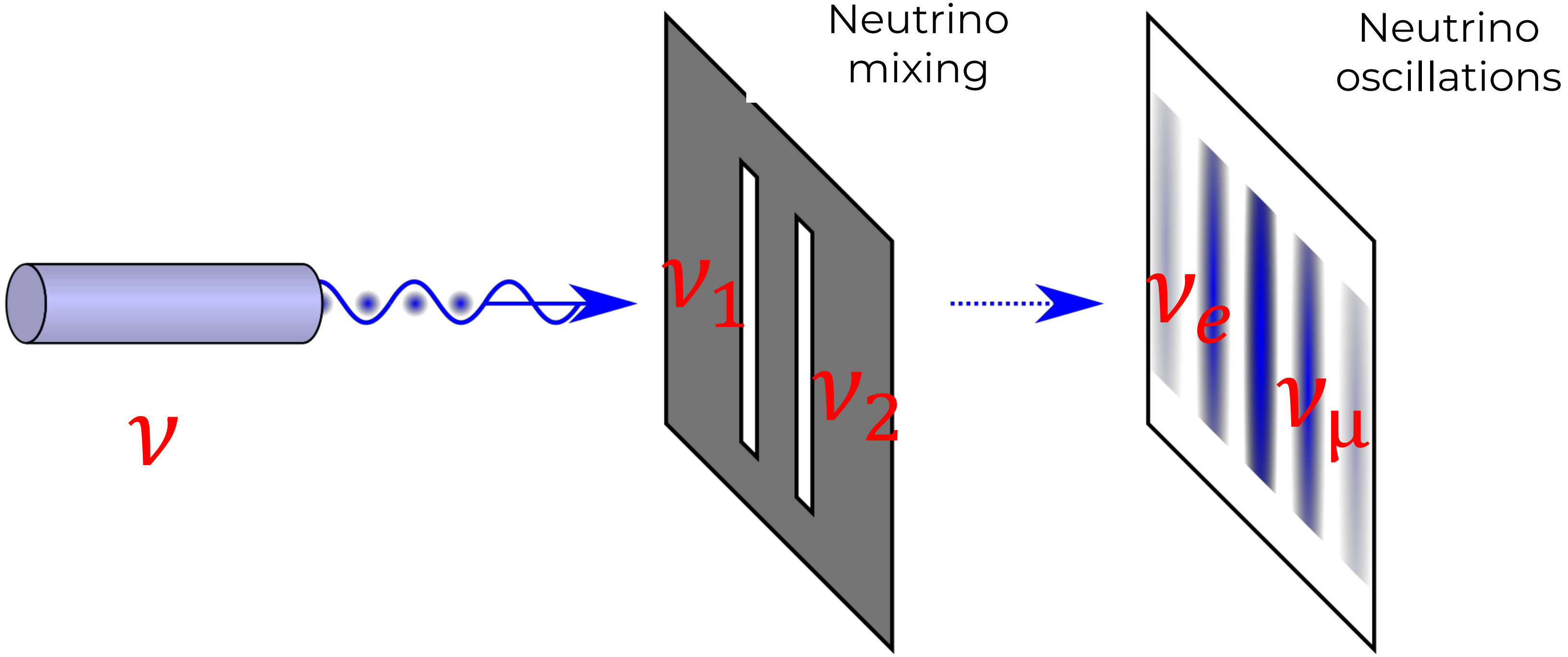
Quantum decoherence



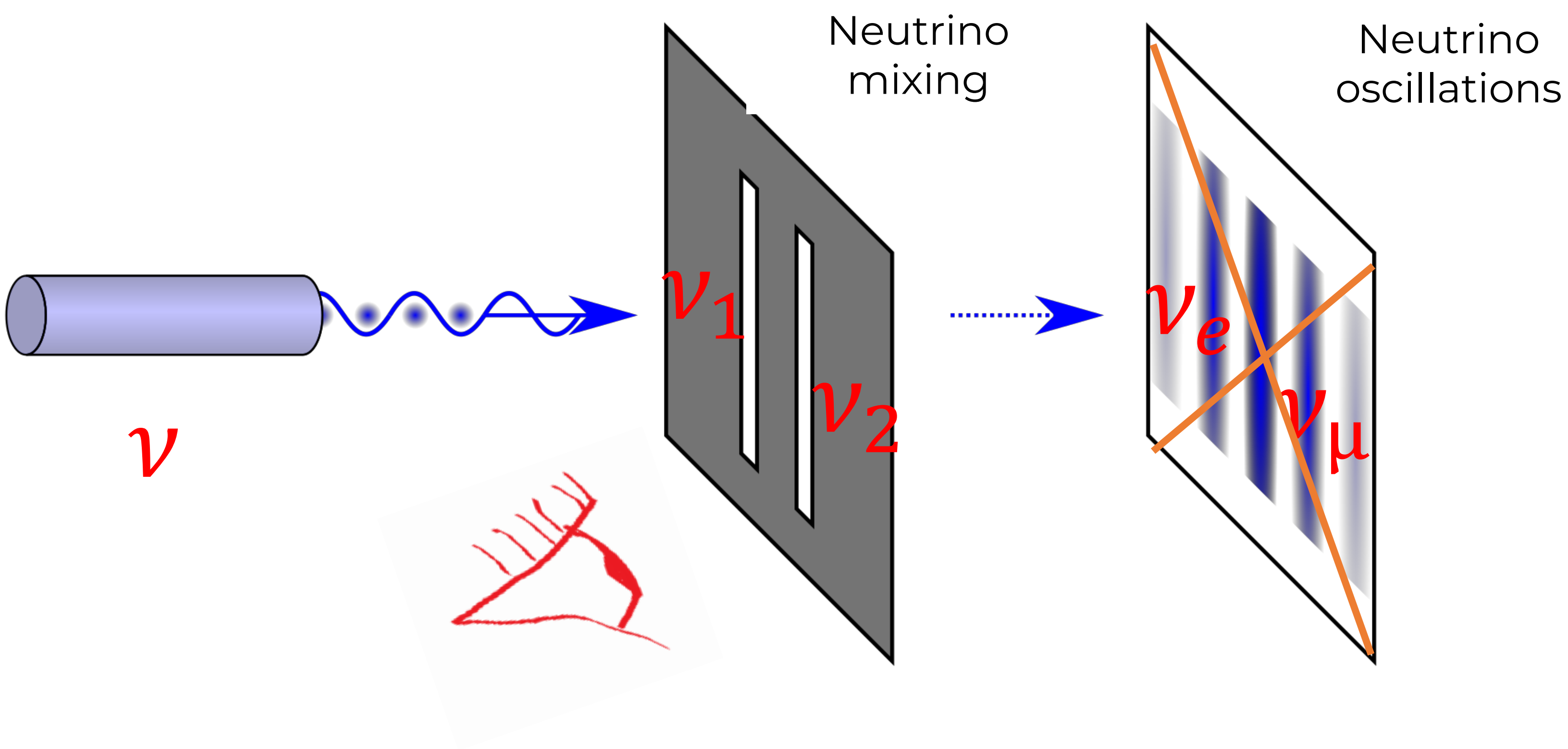
Quantum decoherence



Quantum decoherence



Quantum decoherence



Neutrino flavour oscillations

(two flavour approximation)

Probability to find ν_e

Wave function

Density matrix

flavour states

$$|\nu_f\rangle = \begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} \longrightarrow \rho = |\nu_f\rangle\langle\nu_f| = \begin{pmatrix}\nu_e\nu_e^* & \nu_e\nu_\mu^*\\ \nu_\mu\nu_e^* & \nu_\mu\nu_\mu^*\end{pmatrix}$$

Probability to find ν_μ

mass states

$$|\nu_m\rangle = \begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} \longrightarrow \rho = |\nu_m\rangle\langle\nu_m| = \begin{pmatrix}\nu_1\nu_1^* & \nu_1\nu_2^*\\ \nu_2\nu_1^* & \nu_2\nu_2^*\end{pmatrix}$$

Neutrino flavour oscillations

(two flavour approximation)

flavour states

Wave function

Density matrix

Coherence of two states

$$|\nu_f\rangle = \begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} \quad\longrightarrow\quad \rho = |\nu_f\rangle\langle\nu_f| = \begin{pmatrix}\nu_e\nu_e^* & \nu_e\nu_\mu^*\\ \nu_\mu\nu_e^* & \nu_\mu\nu_\mu^*\end{pmatrix}$$

Coherence of two states

mass states

$$|\nu_m\rangle = \begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} \quad\longrightarrow\quad \rho = |\nu_m\rangle\langle\nu_m| = \begin{pmatrix}\nu_1\nu_1^* & \nu_1\nu_2^*\\ \nu_2\nu_1^* & \nu_2\nu_2^*\end{pmatrix}$$

The evolution equation taking into account quantum decoherence

Liouville–von Neumann equation

$$\frac{\partial}{\partial t}\rho(t) = -i\left[\hat{H}, \rho(t)\right] \quad ?$$

The evolution equation taking into account quantum decoherence

~~Liouville–von Neumann equation~~

$$\xcancel{\frac{\partial}{\partial t}\rho(t) = -i\left[\hat{H}, \rho(t)\right]}$$

Requirements for the evolution equation:

(1) $T(t+s) = T(t)T(s) = T(s)T(t), \quad T(0) = \mathbb{1}, \qquad \forall\, t, s \geq 0,$ *(semigroup property)*

(2) $t \mapsto T(t)\rho$ is continuous, for all $\rho \in \mathcal{J}$. *(strong continuity)*

(3) $\|T(t)\rho\| \leq \|\rho\|$, for all $\rho \in \mathcal{J}$, *(contractivity)*

(4) $T(t)\rho \geq 0$, for all $t \geq 0$ and all $\rho \geq 0$,

(5) $\mathrm{Tr}(T(t)\rho) = \mathrm{Tr}(\rho)$, for all $\rho \in \mathcal{J}_1^{\mathrm{sa}}(\mathcal{H})$.

[1] M.Falconi, J.Faupin, J.Frohlich, B.Schubnel,
Communications in Mathematical Physics 350 (2017)

Lindblad equation

G. Lindblad, On the Generators of Quantum DynamicalSemigroups, Commun. Math. Phys. 48 (1976) 119.

Lindblad equation

$$\frac{\partial \rho_\nu(t)}{\partial t} = -i\left[H_S, \rho_\nu(t)\right] + D\left[\rho_\nu\right]$$

$\rho_\nu(t)$ - neutrino density matrix
H_s - neutrino Hamiltonian

Dissipative term

$$\frac{\partial \rho_\nu(t)}{\partial t} = -i[H(t), \rho_\nu(t)] + \sum_i \gamma_i \left(L_i \rho_\nu L_i^\dagger - \frac{1}{2}\{L_i^\dagger L_i, \rho_\nu\} \right)$$

Decomposition in terms of Pauli matrices σ_k :

$$\frac{\partial \rho_k(t)}{\partial t}\sigma_k = 2\epsilon_{ijk} H_i \rho_j(t)\sigma_k + D_{kl}\rho_l(t)\sigma_k$$

$$D_{ll} = -diag\{\Gamma_1, \Gamma_1, \Gamma_2\}$$

Γ_1 decoherence parameter
Γ_2 relaxation parameter

Lindblad equation

Lindblad equation

$$\frac{\partial \rho_\nu(t)}{\partial t} = -i\left[H_S, \rho_\nu(t)\right] + D\left[\rho_\nu\right]$$

$\rho_\nu(t)$ - neutrino density matrix
H_s - neutrino Hamiltonian

G. Lindblad, On the Generators of Quantum DynamicalSemigroups, Commun. Math. Phys. 48 (1976) 119.

$$D_{ll} = -diag\{\Gamma_1, \Gamma_1, \Gamma_2\}$$

Γ_1 decoherence parameter
Γ_2 relaxation parameter

Lindblad equation by components

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho_{11} & \rho_{12}\\ \rho_{21} & \rho_{22}\end{pmatrix} = -i[\hat{H}, \rho(t)] - \begin{pmatrix}\Gamma_2\rho_{11}(t) & \Gamma_1\rho_{12}(t)\\ \Gamma_1\rho_{21}(t) & \Gamma_2\rho_{22}(t)\end{pmatrix}$$

Lindblad equation

Lindblad equation

$$\frac{\partial \rho_\nu(t)}{\partial t} = -i\left[H_S, \rho_\nu(t)\right] + D\left[\rho_\nu\right]$$

$$D_{ll} = -diag\{\Gamma_1, \Gamma_1, \Gamma_2\}$$

Γ_1 decoherence parameter

Γ_2 relaxation parameter

The probability of flavor oscillations of neutrinos taking into account quantum decoherence

$$P_{\nu_\alpha \nu_\alpha} = \frac{1}{2}\left[1 + e^{-\Gamma_2 x}\cos^2 2\tilde{\theta} + e^{-\Gamma_1 x}\sin^2 2\tilde{\theta}\cos\left(\tilde{\Delta}x\right)\right]$$

Neutrino from reactors and accelerators

Lindblad master equation in case of three flavours expanded by Gell-Mann matrices:

$$\frac{\partial P_k(t)}{\partial t} F_k = 2\epsilon_{ijk} H_i P_j(t) F_k + D_{kl} P_k(t) F_l$$

V. De Romeri, C.Giunti, T.Stuttard, C.A.Ternes, Neutrino oscillation bounds on quantum decoherence, JHEP **09** (2023) 097

Neutrino from reactors and accelerators

Lindblad master equation in case of three flavours expanded by Gell-Mann matrices:

$$\frac{\partial P_k(t)}{\partial t} F_k = 2\epsilon_{ijk} H_i P_j(t) F_k + D_{kl} P_k(t) F_l$$

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

$$D = -\mathrm{diag}(\Gamma_{21}, \Gamma_{21}, 0, \Gamma_{31}, \Gamma_{31}, \Gamma_{32}, \Gamma_{32}, 0)$$

V. De Romeri, C.Giunti, T.Stuttard, C.A.Ternes, Neutrino oscillation bounds on quantum decoherence, JHEP **09** (2023) 097

Neutrino from reactors and accelerators

Lindblad master equation in case of three flavours by components:

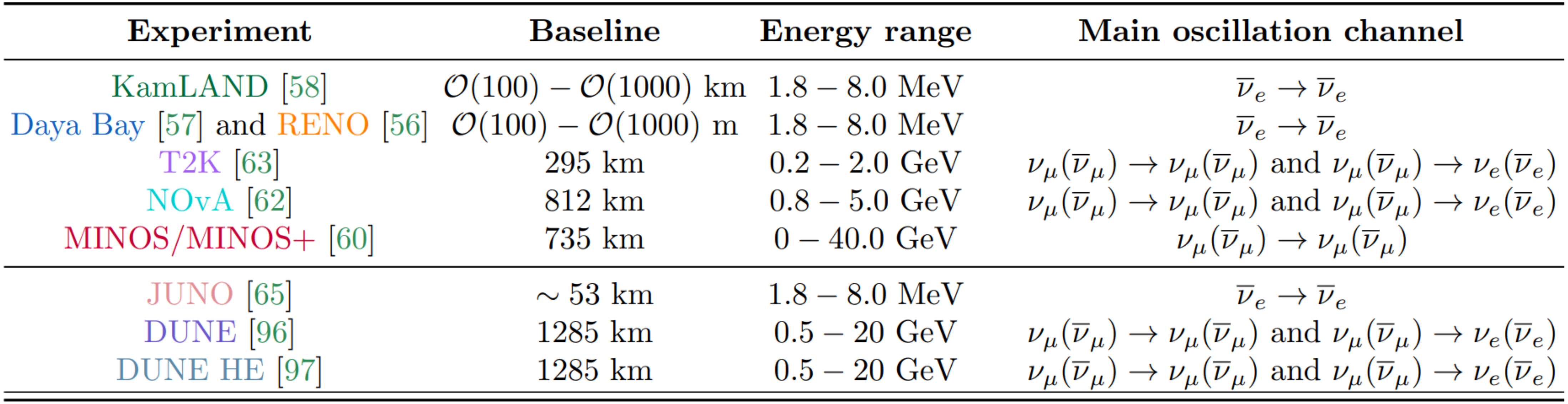
$$\frac{\partial}{\partial t}\begin{pmatrix}\rho_{11} & \rho_{12} & \rho_{13}\\ \rho_{31} & \rho_{22} & \rho_{23}\\ \rho_{31} & \rho_{32} & \rho_{33}\end{pmatrix} = -i\left[\hat{H},\rho(t)\right] - \begin{pmatrix}0 & \Gamma_{21}\rho_{12}(t) & \Gamma_{31}\rho_{13}(t)\\ \Gamma_{21}\rho_{21}(t) & 0 & \Gamma_{32}\rho_{23}(t)\\ \Gamma_{31}\rho_{31}(t) & \Gamma_{32}\rho_{32}(t) & 0\end{pmatrix}$$

Decoherence parameters are taken as free parameters:

$$\Gamma_{ij}(E) = \Gamma_{ij}\left(E_0\right)\left(\frac{E}{E_0}\right)^n$$

V. De Romeri, C.Giunti, T.Stuttard, C.A.Ternes, Neutrino oscillation bounds on quantum decoherence, JHEP **09** (2023) 097

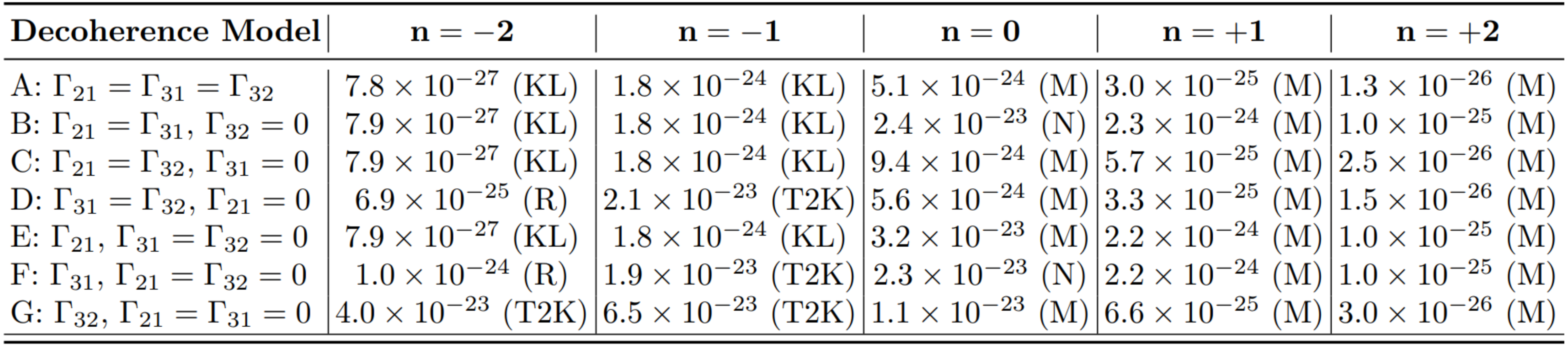
Neutrino from reactors and accelerators



Experiment	Baseline	Energy range	Main oscillation channel
KamLAND [58]	$\mathcal{O}(100) - \mathcal{O}(1000)$ km	$1.8 - 8.0$ MeV	$\overline{\nu}_e \to \overline{\nu}_e$
Daya Bay [57] and RENO [56]	$\mathcal{O}(100) - \mathcal{O}(1000)$ m	$1.8 - 8.0$ MeV	$\overline{\nu}_e \to \overline{\nu}_e$
T2K [63]	295 km	$0.2 - 2.0$ GeV	$\nu_\mu(\overline{\nu}_\mu) \to \nu_\mu(\overline{\nu}_\mu)$ and $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$
NOvA [62]	812 km	$0.8 - 5.0$ GeV	$\nu_\mu(\overline{\nu}_\mu) \to \nu_\mu(\overline{\nu}_\mu)$ and $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$
MINOS/MINOS+ [60]	735 km	$0 - 40.0$ GeV	$\nu_\mu(\overline{\nu}_\mu) \to \nu_\mu(\overline{\nu}_\mu)$
JUNO [65]	~ 53 km	$1.8 - 8.0$ MeV	$\overline{\nu}_e \to \overline{\nu}_e$
DUNE [96]	1285 km	$0.5 - 20$ GeV	$\nu_\mu(\overline{\nu}_\mu) \to \nu_\mu(\overline{\nu}_\mu)$ and $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$
DUNE HE [97]	1285 km	$0.5 - 20$ GeV	$\nu_\mu(\overline{\nu}_\mu) \to \nu_\mu(\overline{\nu}_\mu)$ and $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$

V. De Romeri, C.Giunti, T.Stuttard, C.A.Ternes, Neutrino oscillation bounds on quantum decoherence, JHEP **09** (2023) 097

Neutrino from reactors and accelerators



Decoherence Model	$\mathbf{n = -2}$	$\mathbf{n = -1}$	$\mathbf{n = 0}$	$\mathbf{n = +1}$	$\mathbf{n = +2}$
A: $\Gamma_{21} = \Gamma_{31} = \Gamma_{32}$	7.8×10^{-27} (KL)	1.8×10^{-24} (KL)	5.1×10^{-24} (M)	3.0×10^{-25} (M)	1.3×10^{-26} (M)
B: $\Gamma_{21} = \Gamma_{31},\ \Gamma_{32} = 0$	7.9×10^{-27} (KL)	1.8×10^{-24} (KL)	2.4×10^{-23} (N)	2.3×10^{-24} (M)	1.0×10^{-25} (M)
C: $\Gamma_{21} = \Gamma_{32},\ \Gamma_{31} = 0$	7.9×10^{-27} (KL)	1.8×10^{-24} (KL)	9.4×10^{-24} (M)	5.7×10^{-25} (M)	2.5×10^{-26} (M)
D: $\Gamma_{31} = \Gamma_{32},\ \Gamma_{21} = 0$	6.9×10^{-25} (R)	2.1×10^{-23} (T2K)	5.6×10^{-24} (M)	3.3×10^{-25} (M)	1.5×10^{-26} (M)
E: $\Gamma_{21},\ \Gamma_{31} = \Gamma_{32} = 0$	7.9×10^{-27} (KL)	1.8×10^{-24} (KL)	3.2×10^{-23} (M)	2.2×10^{-24} (M)	1.0×10^{-25} (M)
F: $\Gamma_{31},\ \Gamma_{21} = \Gamma_{32} = 0$	1.0×10^{-24} (R)	1.9×10^{-23} (T2K)	2.3×10^{-23} (N)	2.2×10^{-24} (M)	1.0×10^{-25} (M)
G: $\Gamma_{32},\ \Gamma_{21} = \Gamma_{31} = 0$	4.0×10^{-23} (T2K)	6.5×10^{-23} (T2K)	1.1×10^{-23} (M)	6.6×10^{-25} (M)	3.0×10^{-26} (M)

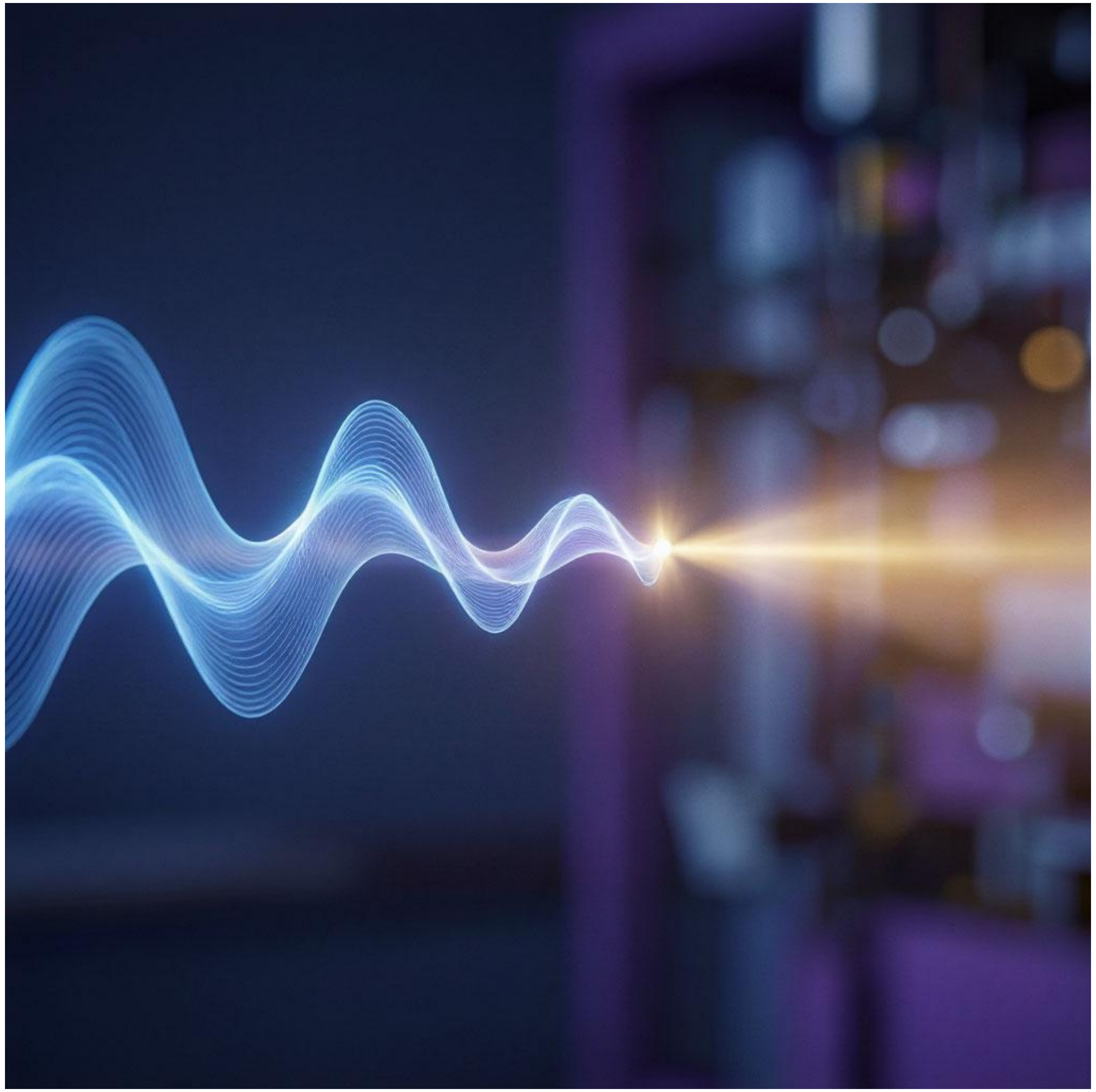
$$\Gamma_{ij}(E) = \Gamma_{ij}\left(E_0\right)\left(\frac{E}{E_0}\right)^n$$

V. De Romeri, C.Giunti, T.Stuttard, C.A.Ternes, Neutrino oscillation bounds on quantum decoherence, JHEP **09** (2023) 097

Part 2

Mechanisms of neutrino quantum decoherence

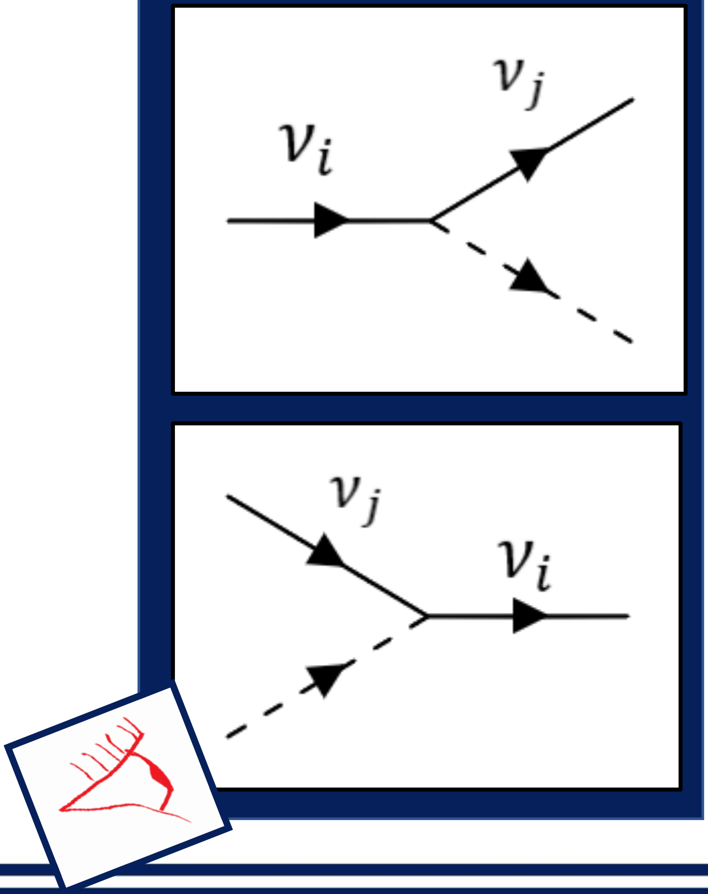
Neutrino decay

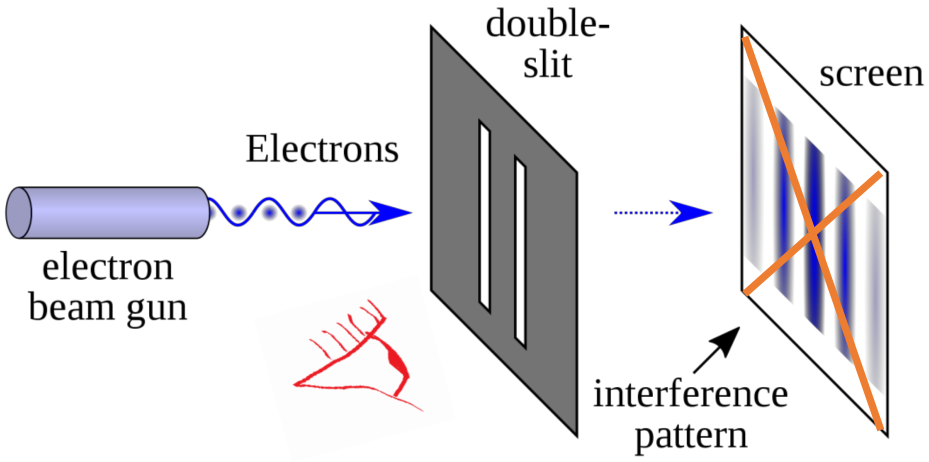


Mechanisms of neutrino quantum decoherence

Neutrino decay

Neutrino decay



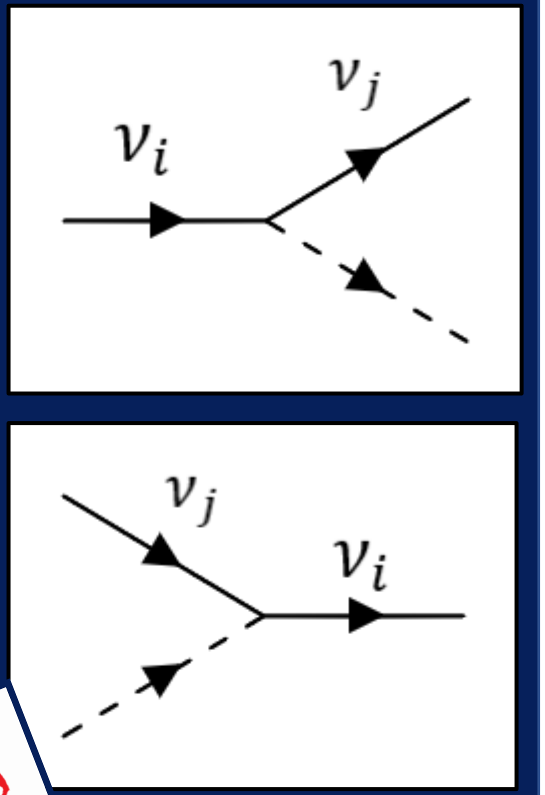


K.Stankevich, A.Studenikin, M.Vyalkov, Generalized Lindblad master equation for neutrino evolution, Phys.Rev.D 111 (2025) 3

Mechanisms of neutrino quantum decoherence

Neutrino decay

Neutrino decay



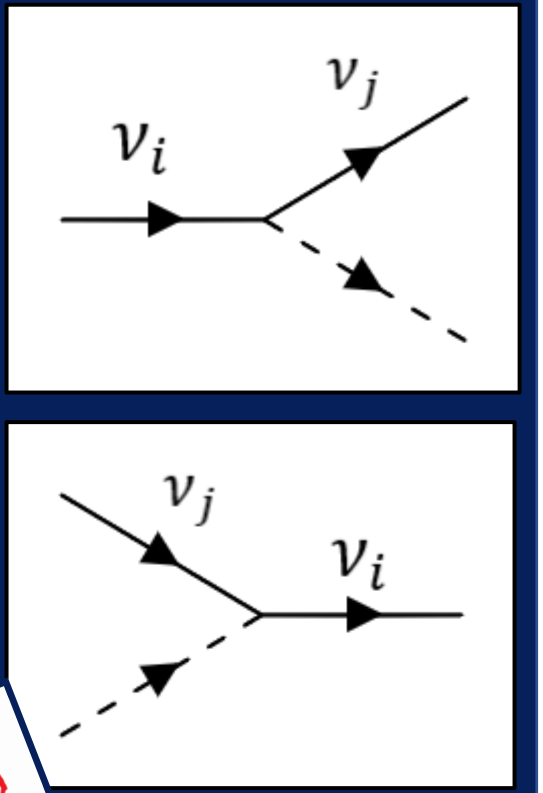
$$H(t) = \int d^3\mathbf{x} \sum_{\alpha} \bar{\nu}(x)\Gamma_{\alpha}\nu(x)\, A_{\alpha}(x)$$

K.Stankevich, A.Studenikin, M.Vyalkov, Generalized Lindblad master equation for neutrino evolution, Phys.Rev.D 111 (2025) 3

Mechanisms of neutrino quantum decoherence

Neutrino decay

Neutrino decay



$$H(t) = \int d^3\mathbf{x} \sum_{\alpha} \bar{\nu}(x)\Gamma_{\alpha}\nu(x)\, A_{\alpha}(x)$$

$$\varrho(t) = \rho_{\nu}(t_0) \otimes \rho_{\mathrm{A}}(t_0)$$

$$\varrho(t) = U(t_0, t)\varrho(t_0)U^{\dagger}(t_0, t)$$

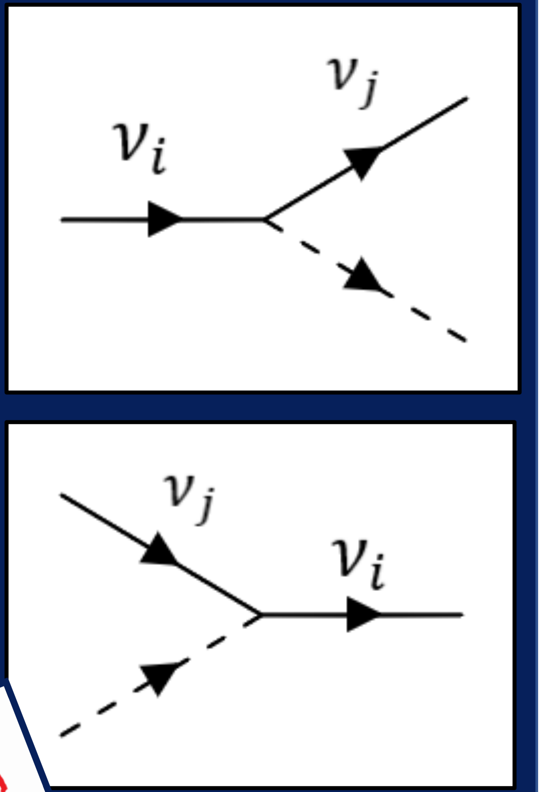
$$U(t_0, t) = Texp\left(-i\int_{t_0}^{t} H\,(t')dt'\right)$$

K.Stankevich, A.Studenikin, M.Vyalkov, Generalized Lindblad master equation for neutrino evolution, Phys.Rev.D 111 (2025) 3

Mechanisms of neutrino quantum decoherence

Neutrino decay

Neutrino decay



$$\rho_\nu(t) = \mathrm{Tr}_A\, \varrho(t)$$

$$\varrho(t) = \rho_\nu(t_0) \otimes \rho_{\mathrm{A}}(t_0)$$

$$\varrho(t) = U(t_0, t)\varrho(t_0)U^\dagger(t_0, t)$$

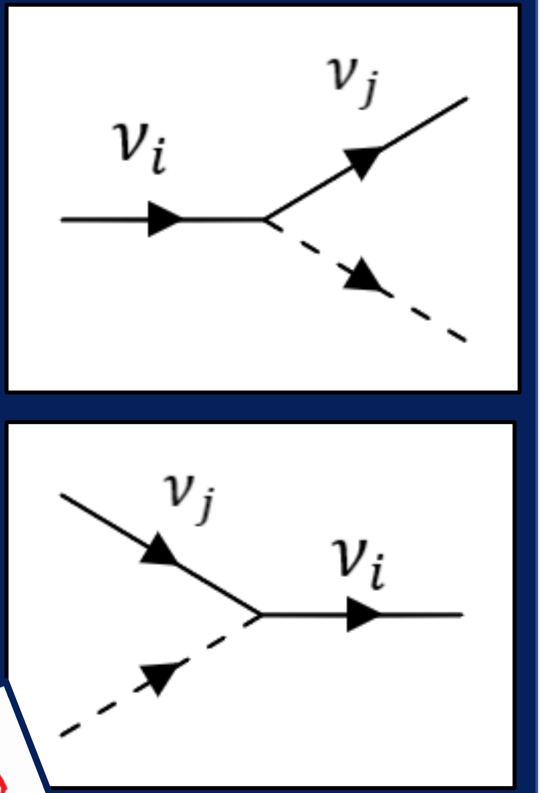
$$U(t_0, t) = Texp\left(-i\int_{t_0}^{t} H\,(t')dt'\right)$$

K.Stankevich, A.Studenikin, M.Vyalkov, Generalized Lindblad master equation for neutrino evolution, Phys.Rev.D 111 (2025) 3

Mechanisms of neutrino quantum decoherence

Neutrino decay

Neutrino decay



$$\rho_\nu(t) = \mathrm{Tr}_A\, \varrho(t)$$

$$\varrho(t) = \rho_\nu(t_0) \otimes \rho_A(t_0)$$

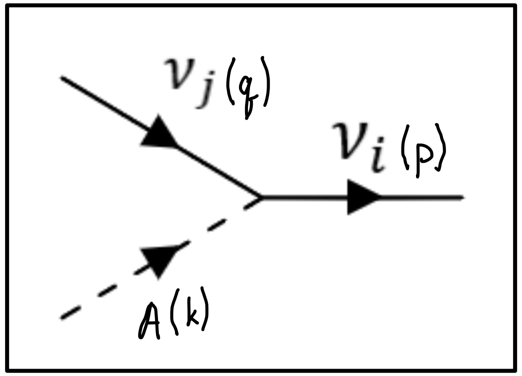
$$\varrho(t) = U(t_0, t)\varrho(t_0)U^\dagger(t_0, t)$$

$$U(t_0, t) = Texp\left(-i\int_{t_0}^{t} H\,(t')dt'\right)$$

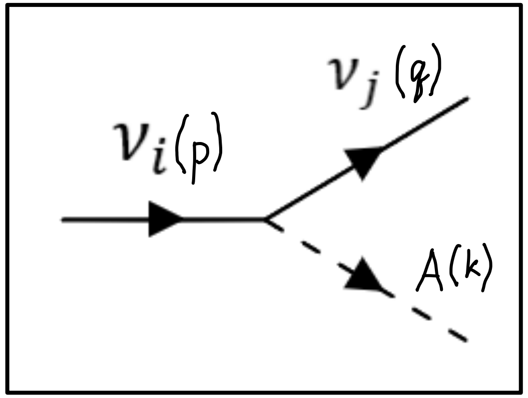
Two additional approximations:

1) rotating-wave approximation;
2) Markovian approximation.

K.Stankevich, A.Studenikin, M.Vyalkov, Generalized Lindblad master equation for neutrino evolution, Phys.Rev.D 111 (2025) 3



Generalized Lindblad master equation

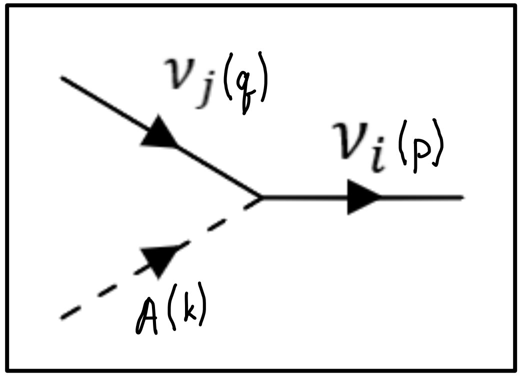


$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t),\rho_{\mathbf{p}}(t)] - \frac{1}{2}\sum_i \left(\Gamma^d_{\mathbf{ip}} + \Gamma^a_{\mathbf{ip}}\right)\{\Pi_{ii},\rho_{\mathbf{p}}(t)\} +$$

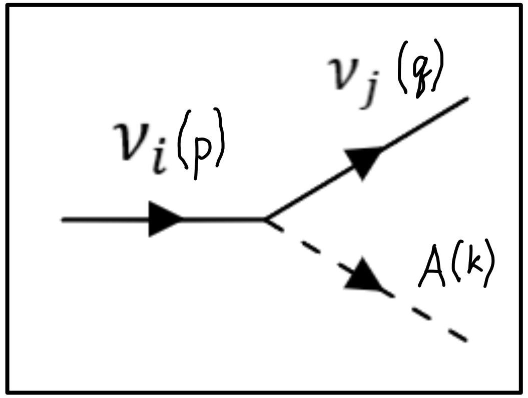
$$+\sum_i \int \frac{d^3\mathbf{k}}{2(2\pi)^3\omega}\left[\sum_{j:\{m_j>m_i\}}\int \frac{d^3\mathbf{q}}{2(2\pi)^3 E_{\mathbf{q}j}}\Gamma^d_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji} + \sum_{j:\{m_j<m_i\}}\int \frac{d^3\mathbf{q}}{2(2\pi)^3 E_{\mathbf{q}j}}\Gamma^a_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji}\right]$$

Lindblad master equation

$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t),\rho_{\mathbf{p}}(t)] + \sum_i \gamma_i\left(L_i\rho_{\mathbf{p}}L_i^\dagger - \frac{1}{2}\{L_i^\dagger L_i,\rho_{\mathbf{p}}\}\right)$$



Generalized Lindblad master equation

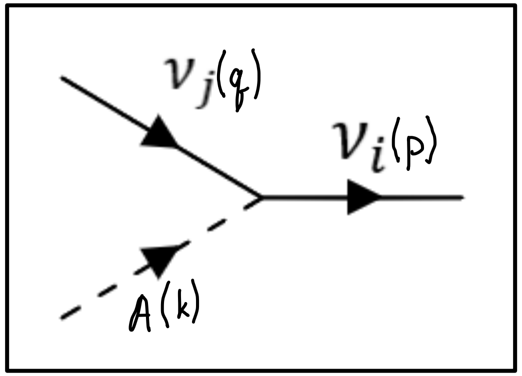


$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t),\rho_{\mathbf{p}}(t)] - \frac{1}{2}\sum_i \left(\Gamma^d_{\mathbf{ip}} + \Gamma^a_{\mathbf{ip}}\right)\{\Pi_{ii},\rho_{\mathbf{p}}(t)\} +$$

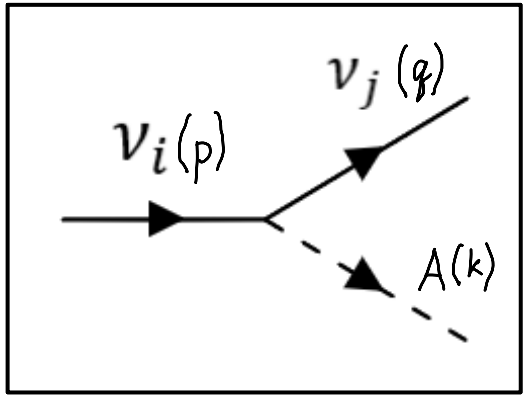
$$+\sum_i \int \frac{d^3\mathbf{k}}{2(2\pi)^3\omega}\left[\sum_{j:\{m_j>m_i\}}\int \frac{d^3\mathbf{q}}{2(2\pi)^3 E_{\mathbf{q}j}}\Gamma^d_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji} + \sum_{j:\{m_j<m_i\}}\int \frac{d^3\mathbf{q}}{2(2\pi)^3 E_{\mathbf{q}j}}\Gamma^a_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji}\right]$$

Lindblad master equation

$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t),\rho_{\mathbf{p}}(t)] + \sum_i \gamma_i\left(L_i\rho_{\mathbf{p}}L_i^\dagger - \frac{1}{2}\{L_i^\dagger L_i,\rho_{\mathbf{p}}\}\right)$$



Generalized Lindblad master equation



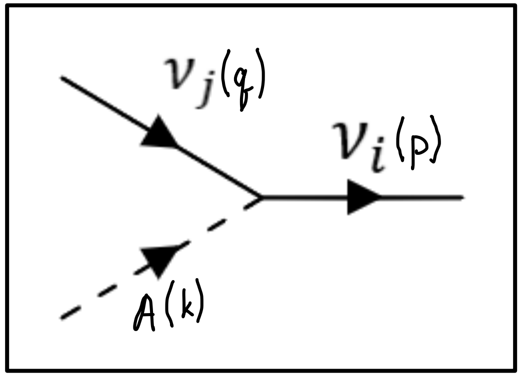
$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t), \rho_{\mathbf{p}}(t)] - \frac{1}{2}\sum_i (\Gamma^d_{i\mathbf{p}} + \Gamma^a_{i\mathbf{p}})\{\Pi_{ii}, \rho_{\mathbf{p}}(t)\} +$$

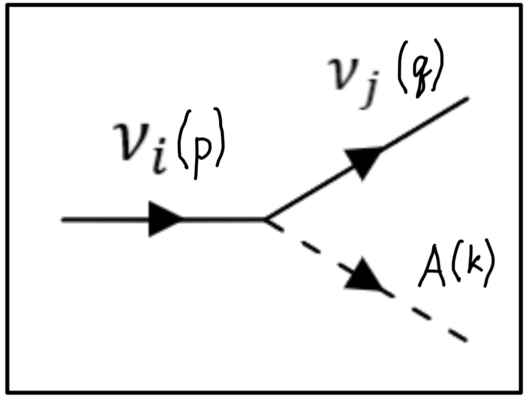
$$+\sum_i \int \frac{d^3\mathbf{k}}{2(2\pi)^3\omega}\left[\sum_{j:\{m_j>m_i\}} \int \frac{d^3\mathbf{q}}{2(2\pi)^3 E_{\mathbf{q}j}} \Gamma^d_{j\mathbf{q}\to i\mathbf{p}} \Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji} + \sum_{j:\{m_j<m_i\}} \int \frac{d^3\mathbf{q}}{2(2\pi)^3 E_{\mathbf{q}j}} \Gamma^a_{j\mathbf{q}\to i\mathbf{p}} \Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji}\right]$$

Lindblad master equation

$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t), \rho_{\mathbf{p}}(t)] + \sum_i \gamma_i \left(L_i \rho_{\mathbf{p}} L_i^\dagger - \frac{1}{2}\{L_i^\dagger L_i, \rho_{\mathbf{p}}\} \right)$$

Generalized Lindblad master equation





$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t),\rho_{\mathbf{p}}(t)] - \frac{1}{2}\sum_i \left(\Gamma^d_{\mathbf{ip}} + \Gamma^a_{\mathbf{ip}}\right)\{\Pi_{ii},\rho_{\mathbf{p}}(t)\} +$$

$$+\sum_i \int \frac{d^3\mathbf{k}}{2(2\pi)^3\omega}\left[\sum_{j:\{m_j>m_i\}}\int\frac{d^3\mathbf{q}}{2(2\pi)^3E_{\mathbf{q}j}}\Gamma^d_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji} + \sum_{j:\{m_j<m_i\}}\int \frac{d^3\mathbf{q}}{2(2\pi)^3E_{\mathbf{q}j}}\Gamma^a_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji}\right]$$

Γ^d_{ip} - decay width of the neutrino stationary state $|i\mathbf{p}>$ to all possible neutrino states

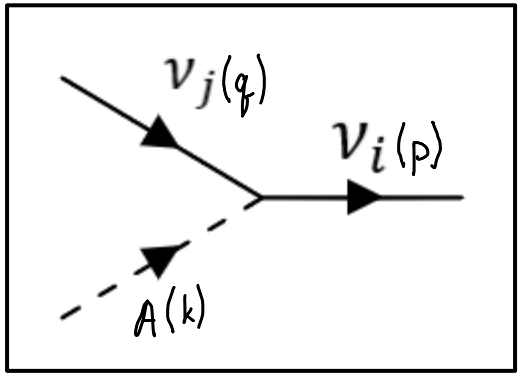
Γ^a_{ip} - absorption width associated with transitions from all possible states into the neutrino state $|\, i\mathbf{p}\rangle$

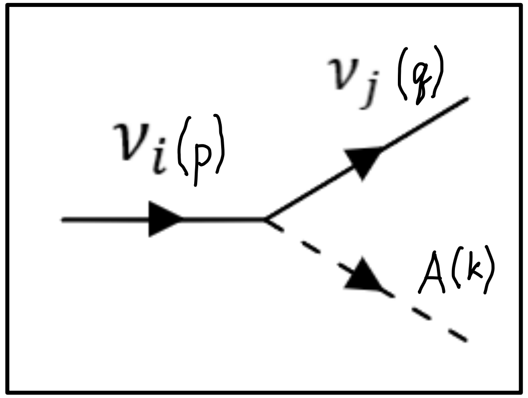
$\Gamma^d_{j\mathbf{q}\to i\mathbf{p}}$ - decay widths associated with transition between neutrino states $|j\mathbf{q}> \to |i\mathbf{p}>$

$\Gamma^a_{j\mathbf{q}\to i\mathbf{p}}$ - absorption width associated with transitions between neutrino states $|j\mathbf{q}> \to |i\mathbf{p}>$

$\Pi_{ij} = |i><j|$ - projector to the neutrino mass states

Generalized Lindblad master equation





$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t),\rho_{\mathbf{p}}(t)] - \frac{1}{2}\sum_i \left(\Gamma^d_{\mathbf{ip}} + \Gamma^a_{\mathbf{ip}}\right)\{\Pi_{ii},\rho_{\mathbf{p}}(t)\} +$$

$$+\sum_i \int \frac{d^3\mathbf{k}}{2(2\pi)^3\omega}\left[\sum_{j:\{m_j>m_i\}}\int\frac{d^3\mathbf{q}}{2(2\pi)^3E_{\mathbf{q}j}}\Gamma^d_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji} + \sum_{j:\{m_j<m_i\}}\int\frac{d^3\mathbf{q}}{2(2\pi)^3E_{\mathbf{q}j}}\Gamma^a_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji}\right]$$

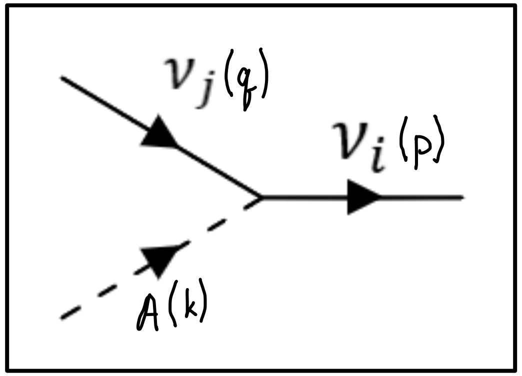
$\Gamma^d_{\mathbf{ip}}$ - decay width of the neutrino stationary state $|i\mathbf{p}>$ to all possible neutrino states

$\Gamma^a_{\mathbf{ip}}$ - absorption width associated with transitions from all possible states into the neutrino state $|\,i\mathbf{p}\rangle$

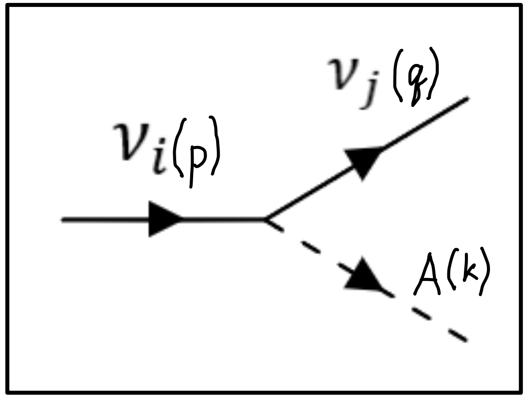
$\Gamma^d_{j\mathbf{q}\to i\mathbf{p}}$ - decay widths associated with transition between neutrino states $|j\mathbf{q}>\to|i\mathbf{p}>$

$\Gamma^a_{j\mathbf{q}\to i\mathbf{p}}$ - absorption width associated with transitions between neutrino states $|j\mathbf{q}>\to|i\mathbf{p}>$

$\Pi_{ij} = |i><j|$ - projector to the neutrino mass states



Generalized Lindblad master equation



$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t), \rho_{\mathbf{p}}(t)] - \frac{1}{2}\sum_{i}(\Gamma^{d}_{\mathbf{ip}} + \Gamma^{a}_{\mathbf{ip}})\{\Pi_{ii}, \rho_{\mathbf{p}}(t)\} +$$

$$+\sum_{i}\int\frac{d^3\mathbf{k}}{2(2\pi)^3\omega}\left[\sum_{j:\{m_j>m_i\}}\int\frac{d^3\mathbf{q}}{2(2\pi)^3E_{\mathbf{q}j}}\Gamma^{d}_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji} + \sum_{j:\{m_j<m_i\}}\int\frac{d^3\mathbf{q}}{2(2\pi)^3E_{\mathbf{q}j}}\Gamma^{a}_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji}\right]$$

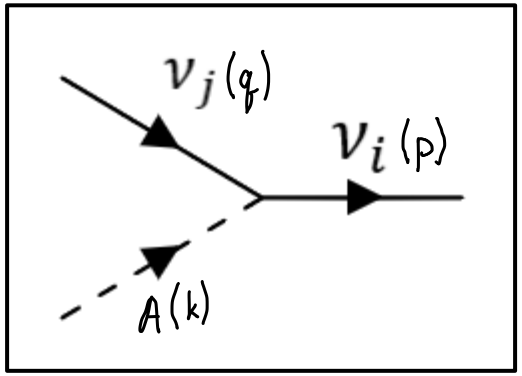
Γ^{d}_{ip} - decay width of the neutrino stationary state $|i\mathbf{p}>$ to all possible neutrino states

Γ^{a}_{ip} - absorption width associated with transitions from all possible states into the neutrino state $|\, i\mathbf{p}\rangle$

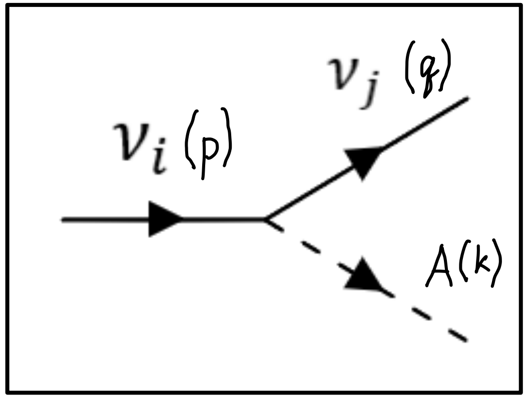
$\Gamma^{d}_{j\mathbf{q}\to i\mathbf{p}}$ - decay widths associated with transition between neutrino states $|j\mathbf{q}>\to|i\mathbf{p}>$

$\Gamma^{a}_{j\mathbf{q}\to i\mathbf{p}}$ - absorption width associated with transitions between neutrino states $|j\mathbf{q}>\to|i\mathbf{p}>$

$\Pi_{ij} = |i><j|$ - projector to the neutrino mass states



Generalized Lindblad master equation

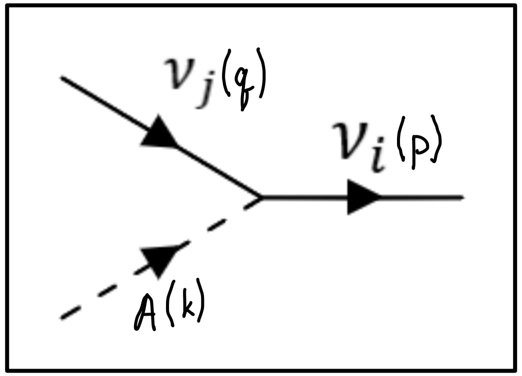


$$\frac{\partial\rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t),\rho_{\mathbf{p}}(t)] - \frac{1}{2}\sum_{i}\left(\Gamma^{d}_{\mathbf{ip}} + \Gamma^{a}_{\mathbf{ip}}\right)\{\Pi_{ii},\rho_{\mathbf{p}}(t)\} +$$

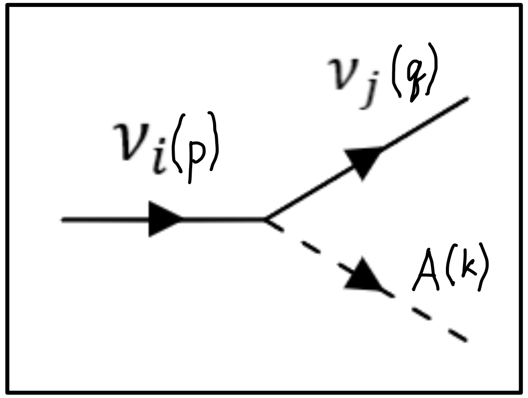
$$+\sum_{i}\int\frac{d^{3}\mathbf{k}}{2(2\pi)^{3}\omega}\left[\sum_{j:\{m_j>m_i\}}\int\frac{d^{3}\mathbf{q}}{2(2\pi)^{3}E_{\mathbf{q}j}}\Gamma^{d}_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji} + \sum_{j:\{m_j<m_i\}}\int\frac{d^{3}\mathbf{q}}{2(2\pi)^{3}E_{\mathbf{q}j}}\Gamma^{a}_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji}\right]$$

Lindblad master equation

$$\frac{\partial\rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t),\rho_{\mathbf{p}}(t)] + \sum_{i}\gamma_i\left(L_i\rho_{\mathbf{p}}L_i^{\dagger} - \frac{1}{2}\{L_i^{\dagger}L_i,\rho_{\mathbf{p}}\}\right)$$



Generalized Lindblad master equation



$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t),\rho_{\mathbf{p}}(t)] - \frac{1}{2}\sum_i \left(\Gamma^d_{\mathbf{ip}} + \Gamma^a_{\mathbf{ip}}\right)\{\Pi_{ii},\rho_{\mathbf{p}}(t)\} +$$

$$+\sum_i \int \frac{d^3\mathbf{k}}{2(2\pi)^3\omega}\left[\sum_{j:\{m_j>m_i\}}\int\frac{d^3\mathbf{q}}{2(2\pi)^3E_{\mathbf{q}j}}\Gamma^d_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji} + \sum_{j:\{m_j<m_i\}}\int \frac{d^3\mathbf{q}}{2(2\pi)^3E_{\mathbf{q}j}}\Gamma^a_{j\mathbf{q}\to i\mathbf{p}}\Pi_{ij}\rho_{\mathbf{q}}(t)\Pi_{ji}\right]$$

$$\Bigg\downarrow \; p_\nu \gg m_\nu$$

Lindblad master equation

$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t),\rho_{\mathbf{p}}(t)] + \sum_i \gamma_i\left(L_i\rho_{\mathbf{p}}L_i^\dagger - \frac{1}{2}\{L_i^\dagger L_i,\rho_{\mathbf{p}}\}\right)$$

Mechanisms of neutrino quantum decoherence

Neutrino decay

$$\frac{\partial P_k(t)}{\partial t} F_k = 2\epsilon_{ijk} H_i P_j(t) F_k + D_{kl} P_k(t) F_l$$

$$D_{kl}^{(3)} = -\frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & -\frac{1}{3}\left(2\Gamma_{21}^{S} + \Gamma_{31}^{S} - \Gamma_{32}^{S}\right) & 0 & 0 & 0 & 0 & -\frac{1}{\sqrt{3}}\left(\Gamma_{32}^{S} + \Gamma_{31}^{S}\right) \\ 0 & \Gamma_{21}^{S} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \Gamma_{21}^{S} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2\Gamma_{21}^{S} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \Gamma_{32}^{S} + \Gamma_{31}^{S} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \Gamma_{32}^{S} + \Gamma_{31}^{S} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \Gamma_{32}^{S} + \Gamma_{31}^{S} + \Gamma_{21}^{S} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \Gamma_{32}^{S} + \Gamma_{31}^{S} + \Gamma_{21}^{S} & 0 \\ 0 & 0 & 0 & -\frac{2}{\sqrt{3}}\left(\Gamma_{21}^{S} + \Gamma_{32}^{S} - \Gamma_{31}^{S}\right) & 0 & 0 & 0 & 0 & 2\left(\Gamma_{32}^{S} + \Gamma_{31}^{S}\right) \end{pmatrix}$$

Mechanisms of neutrino quantum decoherence

Neutrino decay

Comparing the obtained dissipative matrix with experimental constants on neutrino decoherence parameters we get the following estimation on neutrino lifetime:

$$\frac{\tau_2}{m_2} > 1.83 \times 10^{-10} \frac{s}{eV}$$

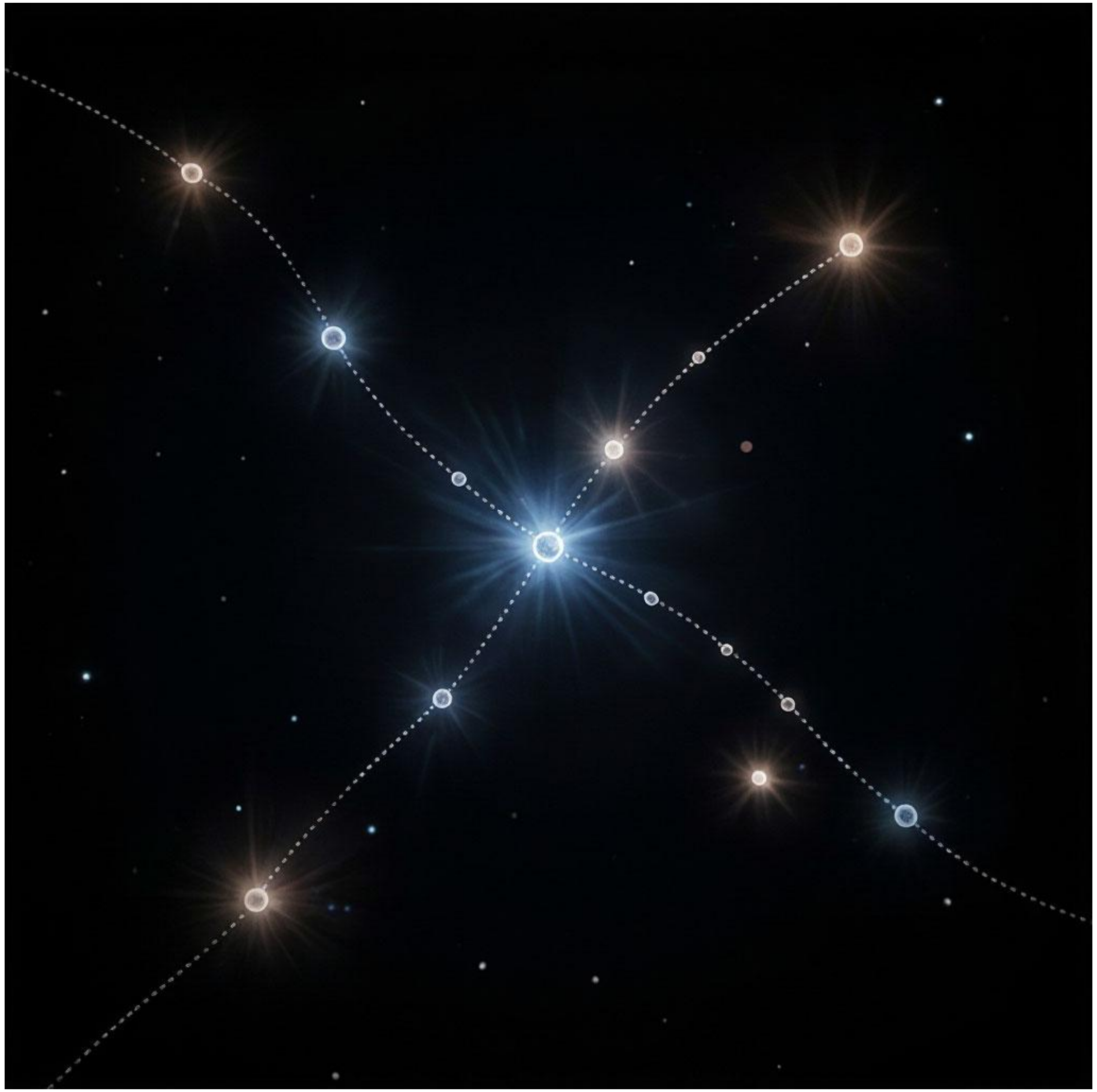
The current constraint on neutrino lifetime from oscillation data is:

$$\frac{\tau_2}{m_2} > 1.18 \times 10^{-11} \frac{s}{eV}$$

Part 3

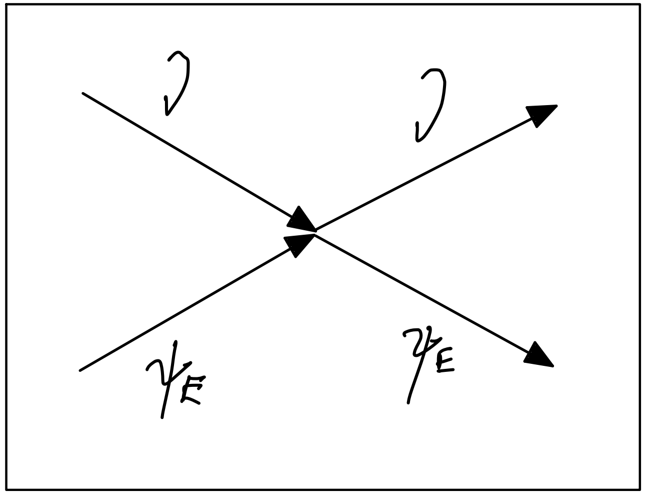
Mechanisms of neutrino quantum decoherence

Neutrino elastic scattering



Mechanisms of neutrino quantum decoherence

Neutrino elastic scattering



Neutrino interaction is given by

$$H_I(t) = \int d^3\boldsymbol{x}\, j_\mu(x) J^\mu(x)$$

where neutrino current

$$j_\mu(x) = \bar{\nu}(x)\Gamma_\mu \nu(x)$$

and external matter current

$$J_\mu(x) = \overline{\Psi}_{\mathrm{E}}(x)\Gamma'_\mu \psi_E(x)$$

K.Stankevich, A.Studenikin, M.Vyalkov, Quantum field-theoretic framework for neutrino decoherence from scattering in a medium, sent to Phys.Rev.D

Mechanisms of neutrino quantum decoherence

Neutrino elastic scattering

$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = \left[H(t), \rho_{\mathbf{p}}(t)\right] - \sum_{i,j=1}^{3} \langle \sigma_{ij\mathbf{p}} \rangle \{\Pi_{ii}, \rho_{\mathbf{p}}(t)\} + 2\left[\sum_{i,j=1}^{3} \int \frac{d^3\mathbf{q}}{2(2\pi)^3 E_{\mathbf{q}j}} \left\langle \frac{d\sigma_{j\mathbf{q}\to i\mathbf{p}}}{dq} \right\rangle \Pi_{ij} \rho_{\mathbf{q}}(t) \Pi_{ji}\right]$$

$\langle \sigma_{ij\mathbf{p}} \rangle$ - scattering cross section for neutrino from state $|\boldsymbol{ip}\rangle$ to $\sum_{\boldsymbol{q}} |\boldsymbol{jq}\rangle$

$\left\langle \frac{d\sigma_{j\mathbf{q}\to i\mathbf{p}}}{dq} \right\rangle$ - scattering cross section for neutrino from state $|\boldsymbol{jq}\rangle$ to state $|\boldsymbol{ip}\rangle$

K.Stankevich, A.Studenikin, M.Vyalkov, Quantum field-theoretic framework for neutrino decoherence from scattering in a medium, sent to Phys.Rev.D

Mechanisms of neutrino quantum decoherence

Neutrino elastic scattering

$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = \left[H(t), \rho_{\mathbf{p}}(t)\right] - \sum_{i,j=1}^{3} \langle \sigma_{ij\mathbf{p}} \rangle \left\{\Pi_{ii}, \rho_{\mathbf{p}}(t)\right\} + 2\left[\sum_{i,j=1}^{3} \int \frac{d^3\mathbf{q}}{2(2\pi)^3 E_{\mathbf{q}j}} \left\langle \frac{d\sigma_{j\mathbf{q}\to i\mathbf{p}}}{dq} \right\rangle \Pi_{ij} \rho_{\mathbf{q}}(t) \Pi_{ji} \right]$$

$$\Big\downarrow \; p_\nu \ll m_s$$

Lindblad master equation

$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial t} = -i[H(t), \rho_{\mathbf{p}}(t)] + \sum_{i} \gamma_i \left(L_i \rho_{\mathbf{p}} L_i^\dagger - \frac{1}{2}\{L_i^\dagger L_i, \rho_{\mathbf{p}}\} \right)$$

K.Stankevich, A.Studenikin, M.Vyalkov, Quantum field-theoretic framework for neutrino decoherence from scattering in a medium, sent to Phys.Rev.D

Mechanisms of neutrino quantum decoherence

Neutrino elastic scattering

1) Neutrino scattering on electrons leads to quantum Zeno effect

$$D_{kl}^{fl} = -\frac{\mathrm{\sigma_{ee}N_e}}{2}\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

K.Stankevich, A.Studenikin, M.Vyalkov, Quantum field-theoretic framework for neutrino decoherence from scattering in a medium, sent to Phys.Rev.D

Mechanisms of neutrino quantum decoherence

Neutrino elastic scattering

2) Estimations on neutral current NSI parameters

$$\mathcal{L} \ = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{f}\left(\overline{\nu_\alpha}\gamma^{\mu}P_L\nu_\beta\right)\left(\bar{f}\gamma_\mu P_L f\right),$$

$$-4.47 < \epsilon_{ee}^{p,n} < 4.47$$

$$-4.47 < \epsilon_{e\mu}^{p,n} < 4.47$$

Global fit: $-0.13 < \epsilon_{ee}^{p,n} < 0.12$

Global fit: $-2.3 \times 10^{-3} < \epsilon_{e\mu}^{p,n} < 2.3 \times 10^{-3}$

K.Stankevich, A.Studenikin, M.Vyalkov, Quantum field-theoretic framework for neutrino decoherence from scattering in a medium, sent to Phys.Rev.D

Mechanisms of neutrino quantum decoherence

Neutrino elastic scattering

2) Estimations on neutral current NSI parameters

$$\mathcal{L} = -2\sqrt{2}G_F\epsilon^{f}_{\alpha\beta}(\overline{\nu_\alpha}\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_L f),$$

$-4.47 < \epsilon^{p,n}_{ee} < 4.47$

$-4.47 < \epsilon^{p,n}_{e\mu} < 4.47$

Global fit: $-0.13 < \epsilon^{p,n}_{ee} < 0.12$

Global fit: $-2.3 \times 10^{-3} < \epsilon^{p,n}_{e\mu} < 2.3 \times 10^{-3}$

K.Stankevich, A.Studenikin, M.Vyalkov, Quantum field-theoretic framework for neutrino decoherence from scattering in a medium, sent to Phys.Rev.D

Mechanisms of neutrino quantum decoherence

Neutrino elastic scattering

3) Neutrino interaction with dark matter fermions

$$H_{\text{int}} = \int d^3x \, \frac{g_\chi g_\nu}{m_{Z'}^2} \bar{\chi}_L \gamma^\mu \chi_L \overline{\nu_e} \gamma_\mu \nu_e .$$

Theoretical prediction of the neutrino quantum decoherence parameter:
$\Gamma_{DM} < 10^{-44}$ GeV

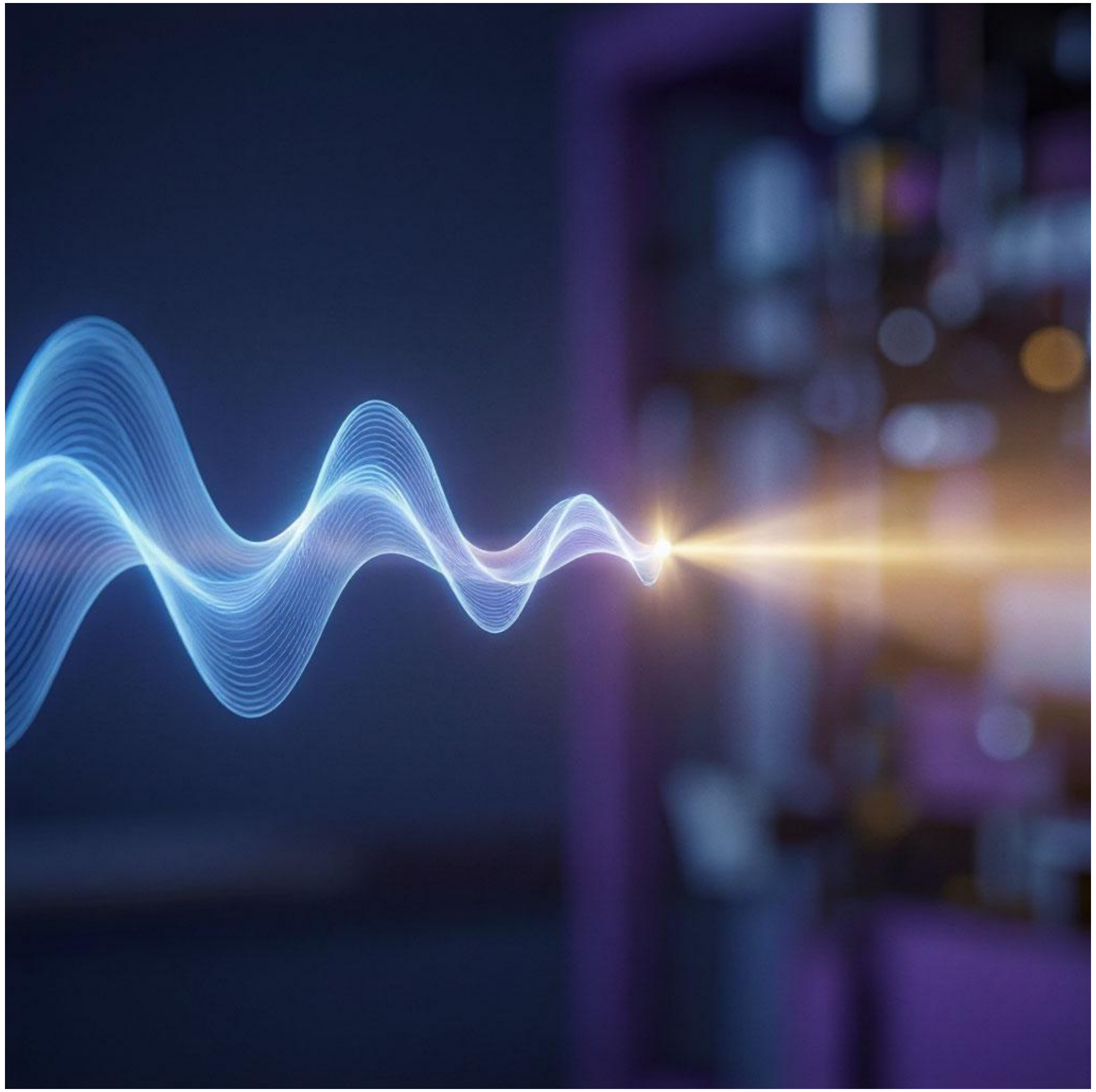
Experimental constraints on neutrino quantum decoherence parameter:
$\Gamma_{exp} < 10^{-26}$ GeV

K.Stankevich, A.Studenikin, M.Vyalkov, Quantum field-theoretic framework for neutrino decoherence from scattering in a medium, sent to Phys.Rev.D

Part 4

Mechanisms of neutrino quantum decoherence

Fluctuations of classical ALPs field



Mechanisms of neutrino quantum decoherence

Fluctuations of external classical environment

- Magnetic Field and matter
  - F. N. Loreti, A. B. Balantekin, Neutrino oscillations in noisy media, Phys. Rev. D 50 (1994).
  - C. P. Burgess, D. Michaud, Neutrino propagation in a fluctuating sun, Annals Phys. 256 (1997).
  - F. Benatti, R. Floreanini, Dissipative neutrino oscillations in randomly fluctuating matter, Phys. Rev. D 71 (2005).

- Gravity
  - P.Nandi, T.Bhattacharyya, A.S.Majumdar, G.Pleasance, F.Petruccione, Decoherence from quantum spacetime noise: An open-system framework with application to neutrino oscillations, Phys.Rev.Res. 8 (2026).
  - M. Dvornikov, Interaction of supernova neutrinos with stochastic gravitational waves, Phys. Rev. D 104 (2021).

Mechanisms of neutrino quantum decoherence

Fluctuations of classical ALPs field

Neutrino interaction with neutrinophilic axion-like dark matter is given by the Hamiltonian

$$H(t) = \int d^3\mathbf{x} j(x) a(x),$$

where the neutrino current

$$j(x) = i\bar{\nu}(x)\left(g_V + g_A\gamma_5\right)\nu(x)$$

with constants defined as

$$g_V^{ij} = C_V^{ij}\frac{m_i - m_j}{F},$$
$$g_A^{ij} = C_A^{ij}\frac{m_i + m_j}{F},$$

where the field is given by

$$a(x) \approx \alpha(t)\frac{\sqrt{2\rho}}{m_a}\cos\left(m_a t\right).$$

where $\alpha(t)$ is positive random variable following the Rayleigh distribution

$$f(\alpha) = \alpha \exp\left(-\frac{\alpha^2}{2}\right).$$

A.Lichkunov, K.Stankevich, A.Studenikin, Neutrino quantum decoherence in a fluctuating ALPs field, Phys. Rev. D 112, 123007 (2025).

Mechanisms of neutrino quantum decoherence

Fluctuations of classical ALPs field

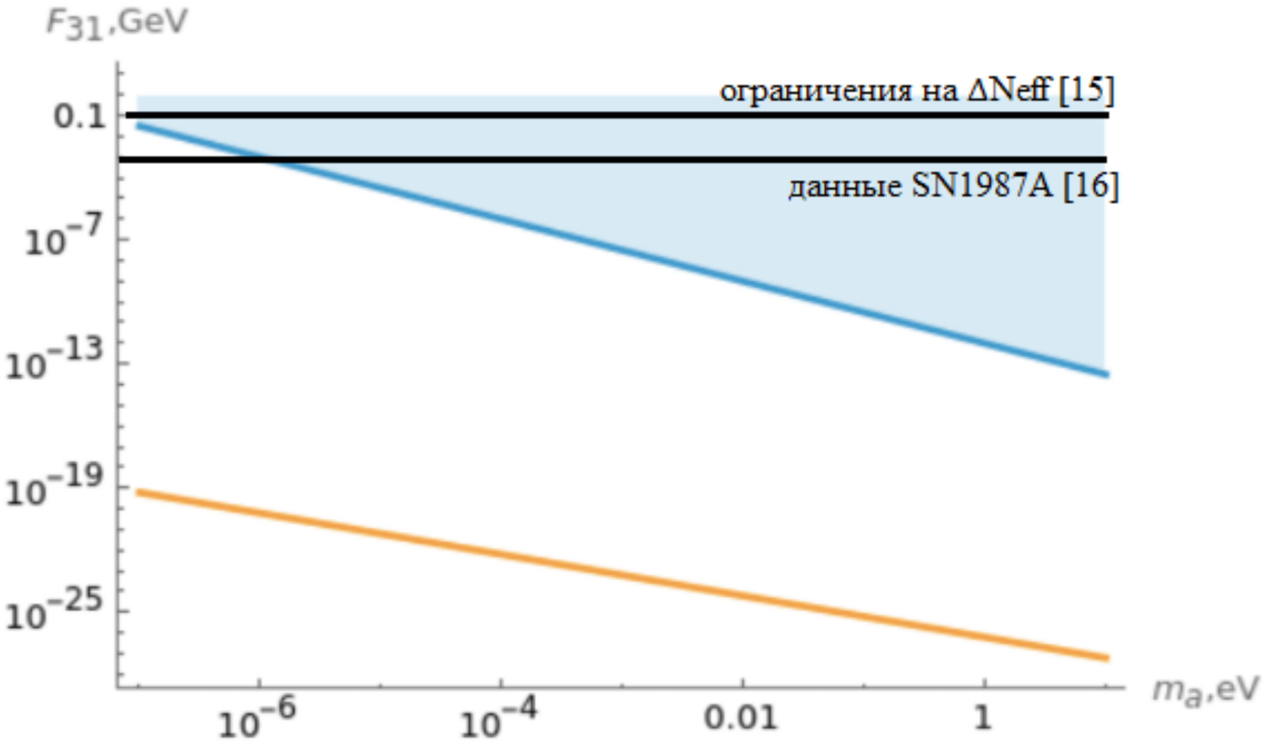
$$D = -\frac{(4-\pi)\rho}{8m_a^2}\tau \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 4h_2^2+h_5^2+h_7^2 & 0 & 0 & 3h_2h_5 & 0 & -3h_2h_7 & 0 & 2\sqrt{3}h_5h_7 \\ 0 & 0 & h_5^2+h_7^2 & 0 & 0 & -h_2h_5 & 0 & -h_2h_7 & 0 \\ 0 & 0 & 0 & 4h_2^2+h_5^2+h_7^2 & -3h_2h_7 & 0 & -3h_2h_5 & 0 & \sqrt{3}(h_5^2-h_7^2) \\ 0 & 3h_2h_5 & 0 & -3h_2h_7 & h_2^2+4h_5^2+h_7^2 & 0 & 3h_5h_7 & 0 & \sqrt{3}h_2h_7 \\ 0 & 0 & -h_2h_5 & 0 & 0 & h_2^2+h_7^2 & 0 & -h_5h_7 & 0 \\ 0 & -3h_2h_7 & 0 & -3h_2h_5 & 3h_5h_7 & 0 & h_2^2+h_5^2+4h_7^2 & 0 & -\sqrt{3}h_2h_5 \\ 0 & 0 & -h_2h_7 & 0 & 0 & -h_5h_7 & 0 & h_2^2+h_5^2 & 0 \\ 0 & 2\sqrt{3}h_5h_7 & 0 & \sqrt{3}(h_5^2-h_7^2) & \sqrt{3}h_2h_7 & 0 & -\sqrt{3}h_2h_5 & 0 & 3(h_5^2+h_7^2) \end{pmatrix}$$

$$h_2 = \frac{\Delta m_{21}^2 \left(C_V^{21} - C_A^{21}\right)}{E_\nu F}, \qquad h_5 = \frac{\Delta m_{31}^2 \left(C_V^{31} - C_A^{31}\right)}{E_\nu F}, \qquad h_7 = \frac{\Delta m_{32}^2 \left(C_V^{32} - C_A^{32}\right)}{E_\nu F}.$$

A.Lichkunov, K.Stankevich, A.Studenikin, Neutrino quantum decoherence in a fluctuating ALPs field, Phys. Rev. D 112, 123007 (2025).

Mechanisms of neutrino quantum decoherence

Fluctuations of classical ALPs field



$$\frac{F}{C_V^{ij} - C_A^{ij}} \geq \frac{\Delta m_{ij}^2 \sqrt{3(4-\pi)\rho\tau}}{2 m_a E_0 \sqrt{\gamma_0}}.$$

A.Lichkunov, K.Stankevich, A.Studenikin, Neutrino quantum decoherence in a fluctuating ALPs field, Phys. Rev. D 112, 123007 (2025).

Conclusions

We have developed a novel quantum field-theoretic framework for describing neutrino quantum decoherence. Within this approach we reveal three distinct mechanisms of decoherence:

- via neutrino decay
- via neutrino scattering
- via neutrino interaction with classical fluctuation of axion-like field

We have also shown that these results open a unique new possibility to use neutrinos as a window to new physics

Thank you for your attention