Open-System Effects in Neutrino Oscillations: From Decoherence to CPT/CP Symmetry Violation

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Open Quantum Systems: Dissipation and Decoherence from Subatomic to Cosmic Scales

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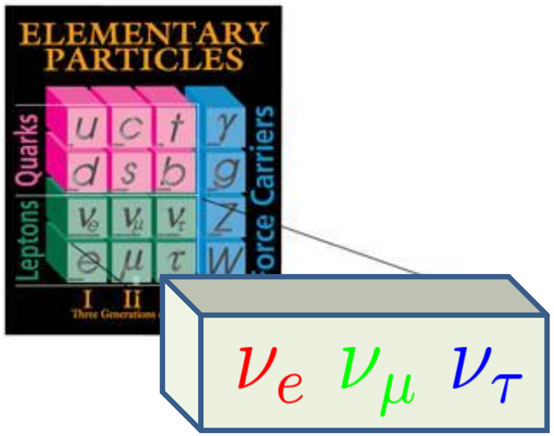
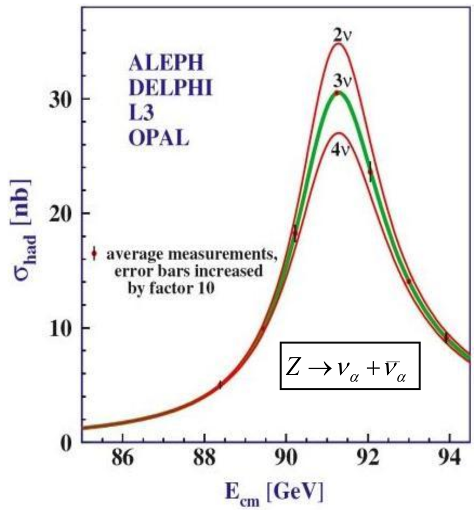
Outline

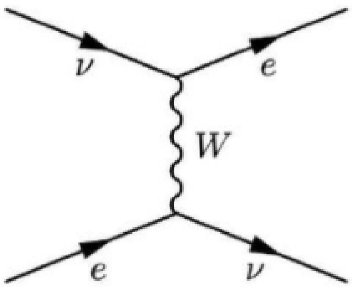
- Introduction
- ν-Quantum decoherence
- CPT and CP symmetry breaking
- Revealing Majorana phases
- Distortion in the Oscillation-Parameter measurements
- Open questions
- Conclusions

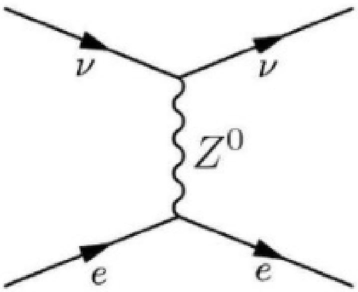
Neutrinos – Standard model





$$\boxed{N_\nu = 2.9963 \pm 0.0074}$$





$$m_\nu \bar{\nu}_L \cancel{\nu_R}$$

$$m_\nu = 0$$

in the Standard Model

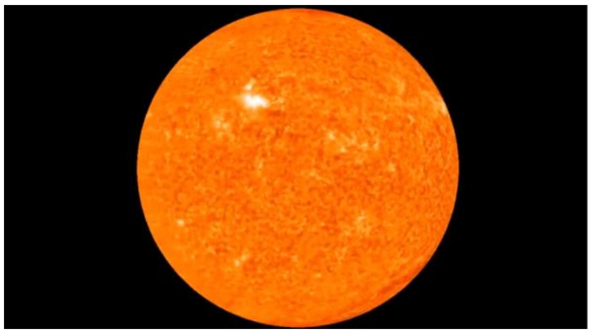
$$l = \frac{1}{n\sigma} = 10^{17}\ \mathrm{cm} = 10^8 D_{\mathrm{Earth}}$$

normal matter mean free path for 1 MeV neutrino

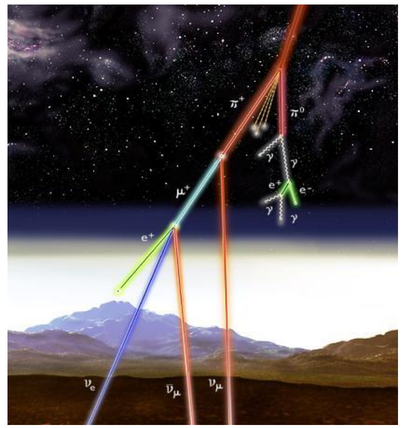
100 millions of Earth-diameters ~ 0.1 light years

Neutrinos interact weakly with matter

Neutrino Sources



Solar ν's - MeV



Atms ν's GeV- PeV

Extragalactic ν's PeV- EeV

Reactor ν's - MeV

Accelerator ν's - GeV

Standard Neutrino oscillation

(1957) *Bruno Pontecorvo*

suggested $\nu \to \bar{\nu}$

inspired on $K_0 \to \bar{K}_0$

Flavour eigenstates ***Mass eigenstates***

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}}_{\tilde{\nu}_\alpha} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \underbrace{\frac{1}{2E} U \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} U^\dagger}_{H_{osc}} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$i\frac{d}{dt}\tilde{\nu}_\alpha = H_{osc}\tilde{\nu}_\alpha$$

Oscillation amplitude ***Interference phase***

Disappearance

$$\boxed{P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{4E_\nu})}$$

$$\Delta m^2 = m_2^2 - m_1^2$$

Appearance

$$\boxed{P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{4E_\nu})}$$

Oscillation Wavelength

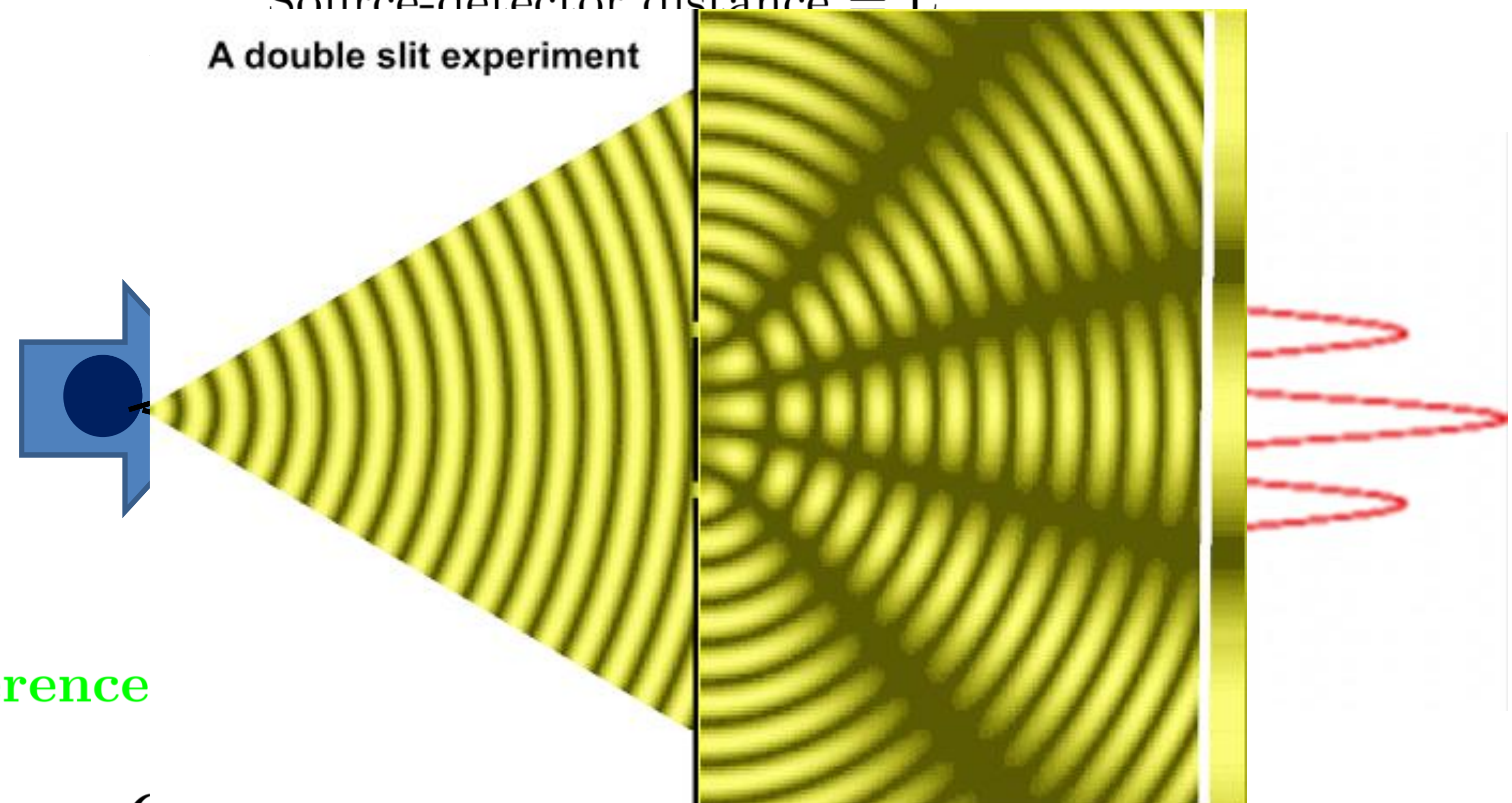
$$\boxed{L_{osc} = \frac{4\pi E_\nu}{\Delta m^2}}$$

Experimental setup: $L \equiv$ source-detector distance $E_\nu \equiv$ neutrino energy

Standard Neutrino oscillation

Double slit interferometer

Source-detector distance = L



Interference

Quintessence of quantum mechanics

Long-distance Interferometry

Three-flavor neutrino oscillation

U_{PMNS}

Atmospheric **Solar**

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \overbrace{\boxed{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}} \times \boxed{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}}}^{\Delta m^2_{31}} \times \overbrace{\boxed{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}}^{\Delta m^2_{21}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

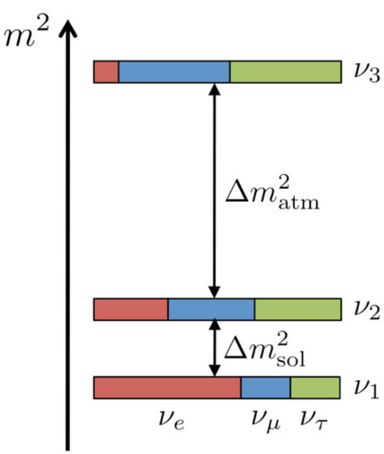
flavour ***LBL & atms*** ***Reactors & atms & LBL*** ***Solar & reactors*** ***mass***

PMNS =Pontecorvo-Maki-Nakagawa-Sakata ***LBL = Long BaseLine*** $c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$

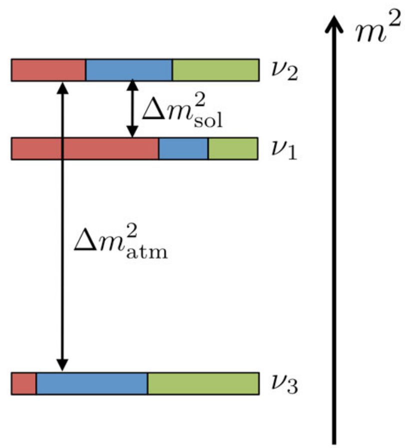
***Still barely known*:**

Mass hierarchy (ordering)

normal hierarchy (NH)



inverted hierarchy (IH)



δ -CP violation phase

$$\Delta P_{CP} = P(\nu_\alpha \to \nu_\beta) - P(\bar\nu_\alpha \to \bar\nu_\beta)$$

$$\boxed{\Delta P_{CP} \propto \sin\delta}$$

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar\nu_\alpha \to \bar\nu_\beta)$$

$$\textbf{when } \delta \neq n\pi$$

ν–Quantum decoherence

Beyond Standard Oscillation Physics

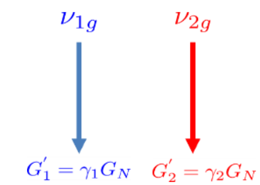
$$H_{\text{std-osc}} = \frac{1}{2E_\nu}\left(\mathbf{U}_{\text{PMNS}}\Delta\mathbf{M}^2\mathbf{U}_{\text{PMNS}}{}^\dagger + \mathbf{A}\right)$$ **flavor basis**

$\Delta\mathbf{M}^2 = \text{Diag}\left(0, \Delta m_{21}^2, \Delta m_{31}^2\right)$ $\quad \mathbf{A} = \text{Diag}\left(\text{A}_{\text{CC}}, 0, 0\right)$ $\quad \text{A}_{\text{CC}} = 2\sqrt{2}G_F n_e E_\nu$

matter potential

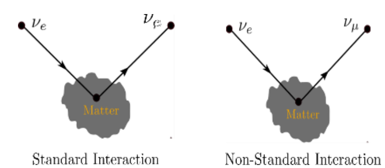
A phenomenologist's quest: **Is there a subleading beyond-the-Standard-Model effect, currently beyond the reach of existing experiments, co-existing with standard oscillations??**

Violation of Equivalence Principle

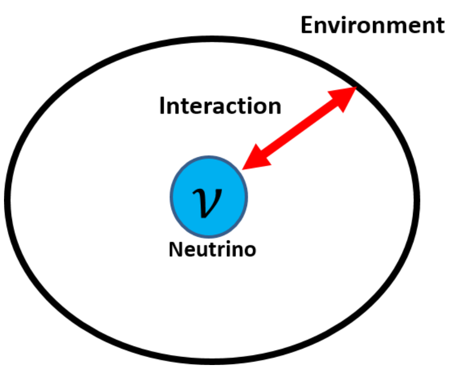


$$H_{\text{std-osc}} = H_{\text{std-osc}} + H_{\text{BSO}}$$

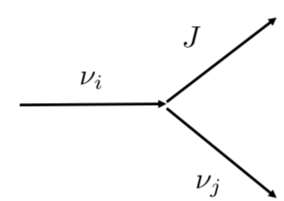
Non-standard neutrino interaction



ν-Quantum decoherence



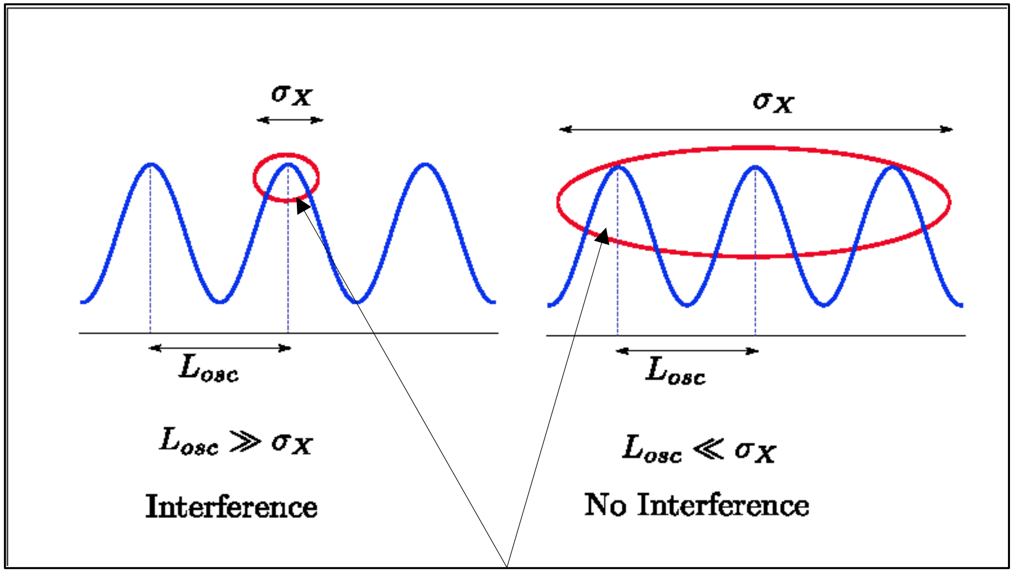
Neutrino Decay



Non-Hermitian contribution

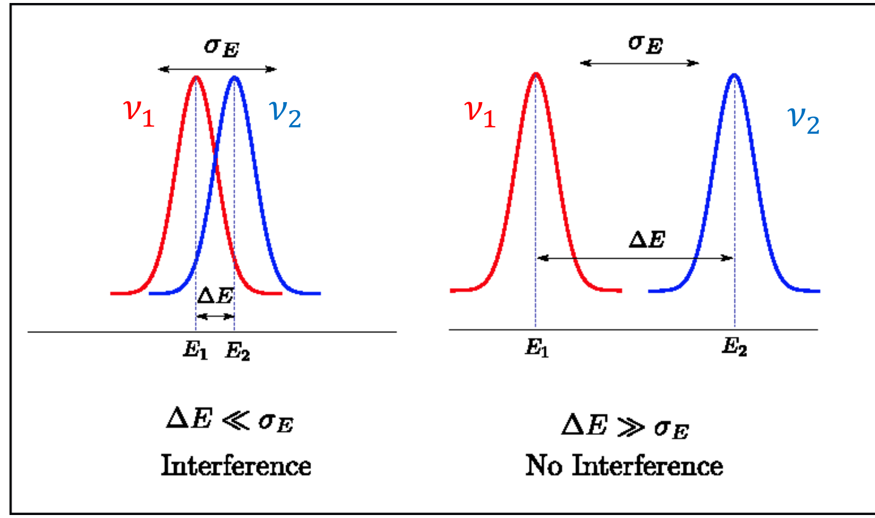
Decoherence in neutrino oscillation

Coherence (Decoherence) @Production/Detection

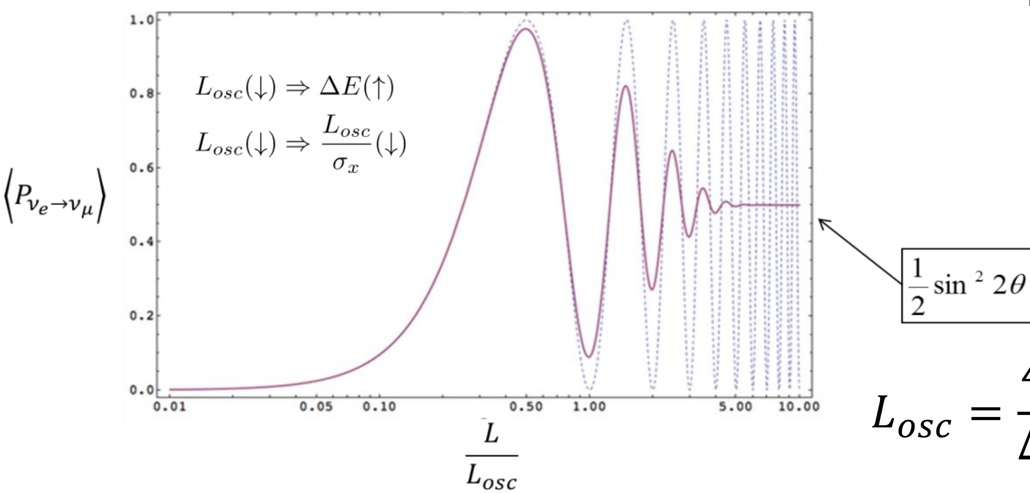


σ_x = size of the detection/production region

σ_E = QM energy uncertainty of the neutrino state



Decoherence destroys interference



$$L_{osc} = \frac{4\pi E}{\Delta m^2}$$

Coherence(decoherence)@ propagation

Δ_x **vs** $\sigma_{x(\mathbf{wps\text{-}spread})}$

$L_{coh} \gg L \ (\sigma_{x(\mathbf{wps\text{-}spread})} \gg \Delta x)$ *coherence*

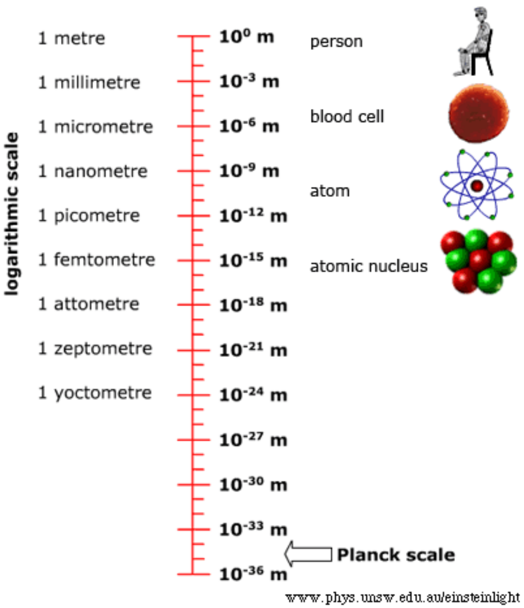
$L_{coh} \ll L \ (\sigma_{x(\mathbf{wps\text{-}spread})} \ll \Delta x)$ *decoherence*

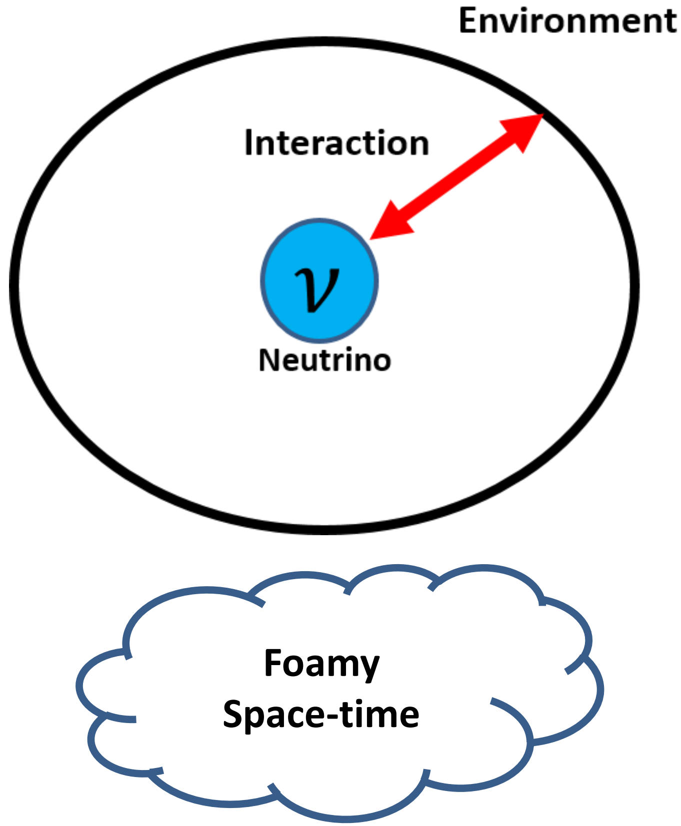
Δ_x = **wps center separation**

$$L_{coh} \simeq \frac{2E^2}{|\Delta m^2|}\sigma_{x(\mathbf{wps\text{-}spread})}$$

Quantum decoherence

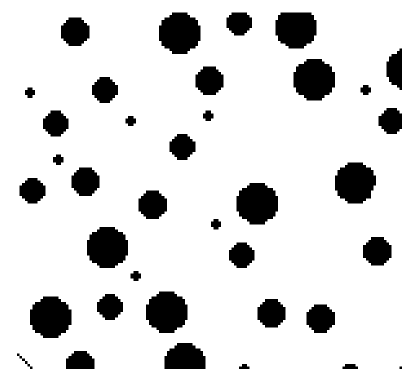
F. Benatti and R. Floreanini, JHEP 0002 (2000) 032





J. Ellis, et al., NPB241 (1984)
J. Ellis, N. E. Mavromatos, D. V. Nanopoulos PLB293 (1992)

Virtual Black -Holes

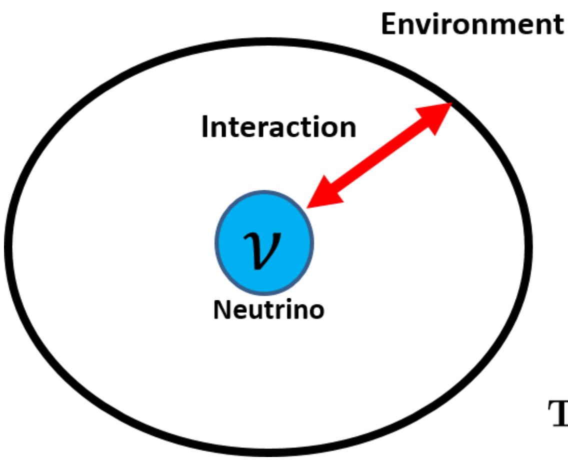


Pure state ***Mixed state***

$$\rho = |\psi><\psi| \rightarrow p_\phi|\phi><\phi| + p_\sigma|\sigma><\sigma| + \ldots$$

Non-Unitary Evolution (Decoherence)

Quantum decoherence –neutrino system



$$H = H_S + H_E + H_I$$

$S =$ **System** $\quad E =$ **Environment** $\quad I =$ **Interaction**

$$\rho_{SE}(t) = U(t,0)\,(\rho_S(0) \otimes \rho_E)\,U^\dagger(t,0)$$

Total unitary evolution of the system plus environment

$$\rho_S(t) = \mathrm{Tr}_E[U(t,0)\,(\rho_S(0) \otimes \rho_E)\,U^\dagger(t,0)]$$

Non-unitary reduced dynamics of the system after tracing

Under the **weak coupling limit** conditions we can get:

Born Approximation: $\rho_{SE}(t) \simeq \rho_S(t) \otimes \rho_E$

Weak coupling $S - E \Rightarrow$ negligible backreaction $\Rightarrow \rho_E$ almost stationary

Markovianity: $\tau_S \gg \tau_E$

τ_S : system evolution time scale $\quad \tau_E$: environment memory time

Lindblad Master equation

$$\frac{d\rho_S(t)}{dt} = -i[H_S + H_{LS}, \rho_S(t)] + \mathcal{D}[\rho_S(t)]$$

Dissipative term

LS : **Lamb shift**

The weak coupling limit typical regime considered in neutrinos

Quantum decoherence –neutrino system

Lindblad Master equation

$$\frac{d\rho_S(t)}{dt} = -i[H_{\text{std-osc}}, \rho_S(t)] + \mathcal{D}[\rho_S(t)]$$

H_{LS} **typically neglected**

gain/jump term

$$\mathcal{D}[\rho_S(t)] = \frac{1}{2}\sum_l \left([A_l, \rho_S(t)A_l^\dagger] + [A_l\rho_S(t), A_l^\dagger]\right) = \sum_l \left(A_l\rho_S(t)A_l^\dagger - \frac{1}{2}\{A_l^\dagger A_l, \rho_S(t)\}\right)$$

losses and damping of coherences

If we expand $A_l = \sum_{a=1}^{8} a_a^{(l)} F_a$ $\quad [F_a, F_b] = i f_{abc} F_c (c = 1, .., 8),\ \mathrm{Tr}[F_n] = 0$

A_l : effective operators describing how the environment acts on the neutrino subsystem.

$F_0 \equiv \frac{1}{3}\mathbb{I}, \qquad F_a \equiv \frac{\lambda_a}{2}, \qquad a = 1, \ldots, 8.$

$$\mathcal{D}[\rho_S(t)] = \frac{1}{2}\sum_l \sum_{a,b=1}^{8} a_a^{(l)} a_b^{*(l)} \left([F_a, \rho_S(t)F_b^\dagger] + [F_a\rho_S(t), F_b^\dagger]\right)$$

Gorini–Kossakowski–Sudarshan-Lindblad form

$c_{ab} = \sum_l a_a^{(l)} a_b^{*(l)},\ C = (c_{ab}) \geq 0$ **positive semidefinite Hermitian Matrix**, $C = C^\dagger,\ \lambda_i(C) \geq 0$

Lindblad Structure ensures:

Trace preserving $\frac{d\mathrm{Tr}[\rho_S(t)]}{dt} = 0$ **Complete positivity** $C \geq 0 \Rightarrow \rho_S(t) \geq 0$

for all t

Quantum decoherence –neutrino system

In neutrino applications an extra condition is added

$A_l = A_l^\dagger \Rightarrow S = -\mathrm{Tr}[\rho \ln \rho]$ increases $(\Delta S \geq 0)$ **Irreversibility**

$D[\rho_S(t)]$ **is:**

now c_{ab} is symmetric and real

with $\rho_S = \rho_0 F_0 + \sum_1^8 \rho_n F_n$

$F_0 \propto \mathbb{I}$

$$\mathcal{D}[\rho_S(t)] = -\frac{1}{2} \sum_{n,m=1}^{8} \sum_{r,a,b=1}^{8} c_{ab}(f_{nbr} f_{arm}) \rho_n F_m$$

probability conservation

$$D_{0\mu} = D_{\mu 0} = 0$$

entropy-increasing

$$\boxed{\mathcal{D}_{mn} = -\frac{1}{2} \sum_{r,a,b=1}^{8} c_{ab}(f_{nbr} f_{arm})}$$

$\mathbf{D} \equiv D_{mn}$ **symmetric and real**

Dissipative/Decoherence Matrix

Quantum decoherence –neutrino system

$$\rho_S = \rho_0 F_0 + \sum_{n=1}^{8} \rho_n F_n, \qquad H_{\mathrm{std-osc}} = h_0 F_0 + \sum_{i=1}^{8} h_i F_i. \qquad A_\ell = \sum_{a=1}^{8} a_a^{(\ell)} F_a.$$

Lindblad Master Equation in components

$$\boxed{\dot{\rho}_0 = 0, \qquad \dot{\rho}_m = \sum_{n=1}^{8} \left(\mathcal{H}_{mn} + D_{mn}\right) \rho_n \equiv \sum_{n=1}^{8} M_{mn} \rho_n \;\Rightarrow\; \boldsymbol{\rho}(t) = e^{Mt} \boldsymbol{\rho}(0)}$$

$$\mathcal{H}_{mn} = \sum_{i=1}^{8} h_i f_{inm}.$$

$\boldsymbol{\rho}$ **eight-dimensional column vector**

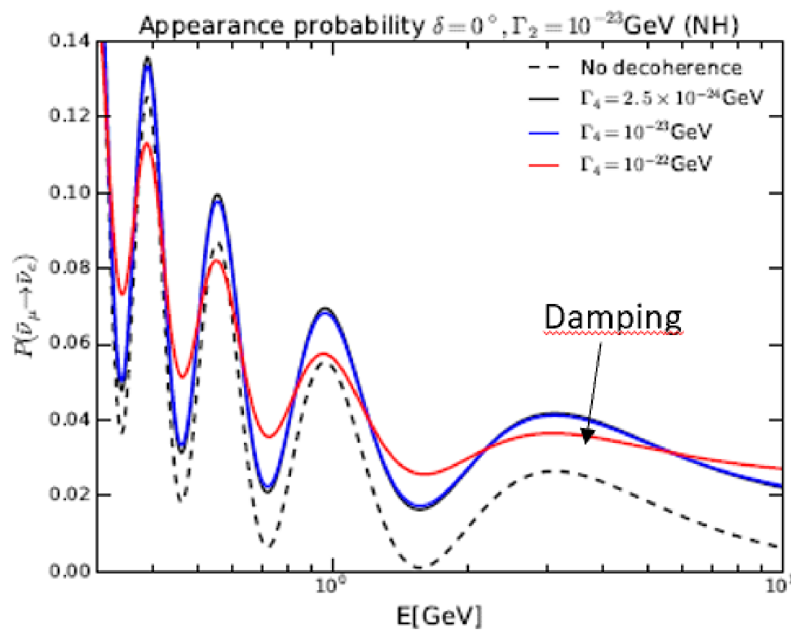
$$P_{\nu_\alpha \to \nu_\beta} = \mathrm{Tr}[\rho^\beta(0)\rho^\alpha(t)]$$

$$P_{\nu_\alpha \to \nu_\beta} = \frac{1}{3} + \frac{1}{2} \sum_{i,j=1}^{8} \rho_i^\beta(0) \left[e^{Mt}\right]_{ij} \rho_j^\alpha(0)$$

$$\rho_k^\alpha(0) = 2\,\mathrm{Tr}\left(\rho^\alpha F_k\right).$$

$$\rho^\alpha = |\nu_\alpha\rangle\langle\nu_\alpha|, \qquad (\rho^\alpha)_{nm} = U^*_{\alpha n} U_{\alpha m}.$$

connection with ν mixing matrix



Quantum decoherence –neutrino system

$M_{\mu\nu}$ in the two-neutrino system

$$\Delta = \frac{\Delta m^2}{4E}$$

oscillation frecuency

$$M_{\mu\nu} = -\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & a & b-\Delta & 0 \\ 0 & b+\Delta & \alpha & 0 \\ 0 & 0 & 0 & \gamma \end{pmatrix}$$

$$P_{\nu_\mu \to \nu_e}(t) = \frac{1}{2}\left\{\cos^2 2\theta\left[1 - e^{-2\gamma t}\right] + \sin^2 2\theta\left[1 - e^{-(a+\alpha)t}\left(\cos 2\Omega_0 t - \frac{a-\alpha}{2\Omega_0}\sin 2\Omega_0 t\right)\right]\right\},$$

$$\Omega_0 = \sqrt{\Delta^2 - \frac{4b^2 + (a-\alpha)^2}{4}}.$$

b off diagonals dissipative coefficient affects oscillation frecuencies.

a, α decoherence parameters destroy interference $(a+\alpha)$, modified oscillation frecuencies and amplitudes of the oscillatory terms $(a-\alpha)$

γ relaxation parameter tends to drive the system toward equipartition between the two oscillation channels.

F. Benatti and R. Floreanini, JHEP 0002 (2000) 032

CPT and CP symmetry breaking

CPT and CP symmetries and neutrino oscillations

$$\boxed{\begin{aligned} &\nu_{\alpha L} \to \nu_{\beta L} \overset{C}{\Rightarrow} \bar{\nu}_{\alpha L} \to \bar{\nu}_{\beta L} \\ &\nu_{\alpha L} \to \nu_{\beta L} \overset{P}{\Rightarrow} \nu_{\alpha R} \to \nu_{\beta R} \\ &\nu_{\alpha L} \to \nu_{\beta L} \overset{T}{\Rightarrow} \nu_{\beta L} \to \nu_{\alpha L} \end{aligned}}$$

$$\boxed{\nu_{\alpha L} \to \nu_{\beta L} \overset{CPT}{\Rightarrow} \bar{\nu}_{\beta R} \to \bar{\nu}_{\alpha R} \longrightarrow P_{\nu_{\alpha L} \to \nu_{\beta L}} = P_{\bar{\nu}_{\beta R} \to \bar{\nu}_{\alpha R}}}$$

$$\Delta P_{\mathrm{CPT}} = P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\beta \to \bar{\nu}_\alpha} \Rightarrow \Delta P_{\mathrm{CPT}} = P_{\nu_\alpha \to \nu_\alpha} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\alpha}$$

while $\Delta P_{\mathrm{CP}} = P_{\nu_\beta \to \nu_\alpha} - P_{\bar{\nu}_\beta \to \bar{\nu}_\alpha}$

CPT symmetry – Diagonal Decoherence Matrix (DDM)

$$\mathbf{D}_{\mathrm{DDM}} = -\mathrm{Diag}(\Gamma,\Gamma,\Gamma,\Gamma,\Gamma,\Gamma,\Gamma,\Gamma)$$

$$\boxed{P^{\mathrm{SO}\bigoplus\mathrm{DDM}}_{\nu_\alpha\nu_\alpha} = \frac{1}{3}(1-e^{-\Gamma t}) + e^{-\Gamma t} P^{\mathrm{SO}}_{\nu_\alpha\nu_\alpha}}$$

$\mathbf{SO = Standard\ Oscillations}$

$$\Delta P^{\mathrm{SO}\bigoplus\mathrm{DDM}}_{\mathrm{CPT}} = e^{-\Gamma t}\Delta P^{\mathrm{SO}}_{\nu_\alpha\nu_\alpha}$$

$$\Delta P^{\mathrm{SO}}_{\nu_\alpha\nu_\alpha} = P_{\nu_\alpha\to\nu_\alpha} - P_{\bar\nu_\alpha\to\bar\nu_\alpha}$$

Vacuum

$$\Delta P^{\mathrm{SO}\bigoplus\mathrm{DDM}}_{\mathrm{CPT}} = 0$$

in vacuum $\Delta P^{\mathrm{SO}}_{\nu_\alpha\nu_\alpha} = 0$

Matter

$$\Delta P^{\mathrm{SO}\bigoplus\mathrm{DDM}}_{\mathrm{CPT}} = \Delta P^{\mathrm{SO}}_{\nu_\alpha\nu_\alpha} \quad (\Gamma\to 0)$$

$$\Delta P^{\mathrm{SO}\bigoplus\mathrm{DDM}}_{\mathrm{CPT}} = 0 \quad (\Gamma\to\infty)$$

in matter $\Delta P^{\mathrm{SO}}_{\nu_\alpha\nu_\alpha} \neq 0$

J. C. Carrasco, F. N. Díaz, A. M. G, PRD 99, 075022 (2019).

CPT violation-Non Diagonal Decoherence Matrix

$$\boxed{\Delta P_{\mathrm{CPT}} = P_{\nu_\alpha \to \nu_\alpha} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\alpha}}$$

Δ_{12}, Δ_{23}

oscillation frecuencies

$$M_{kj} = \begin{pmatrix} -\Gamma & -\Delta_{12}+\beta_{12} & 0 & 0 & 0 & 0 & 0 & 0 \\ \Delta_{12}+\beta_{12} & -\Gamma & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\Gamma & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\Gamma & -\Delta_{13} & 0 & 0 & 0 \\ 0 & 0 & 0 & \Delta_{13} & -\Gamma & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\Gamma & -\Delta_{23} & 0 \\ 0 & 0 & 0 & 0 & 0 & \Delta_{23} & -\Gamma & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\Gamma \end{pmatrix}$$

$$U = U_{PMNS}$$

$$\rho_0^\alpha = \sqrt{2/3}$$
$$\rho_1^\alpha = 2\mathrm{Re}(U_{\alpha 1}^* U_{\alpha 2})$$
$$\rho_2^\alpha = -2\mathrm{Im}(U_{\alpha 1}^* U_{\alpha 2})$$
$$\rho_3^\alpha = |U_{\alpha 1}|^2 - |U_{\alpha 2}|^2$$
$$\rho_4^\alpha = 2\mathrm{Re}(U_{\alpha 1}^* U_{\alpha 3})$$
$$\rho_5^\alpha = -2\mathrm{Im}(U_{\alpha 1}^* U_{\alpha 3})$$
$$\rho_6^\alpha = 2\mathrm{Re}(U_{\alpha 2}^* U_{\alpha 3})$$
$$\rho_7^\alpha = -2\mathrm{Im}(U_{\alpha 2}^* U_{\alpha 3})$$
$$\rho_8^\alpha = \frac{1}{\sqrt{3}}(|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2 - 2|U_{\alpha 3}|^2)$$

$$\boxed{\Delta P_{\mathrm{CPT}} = \beta_{12} \left(\frac{e^{\Omega_{\beta_{12}} t} - e^{-\Omega_{\beta_{12}} t}}{\Omega_{\beta_{12}}} \right) \rho_i^\alpha \rho_j^\alpha \, e^{-\Gamma t}}$$

$$\Omega_{\beta_{12}} = \sqrt{\beta_{12}^2 - \Delta_{12}^2}$$

β_{12}, Δ_{12} corresponds to $(ij) = (12), (23), (28)$

For having $\Delta P_{\mathrm{CPT}} \neq 0$ we need:

$$\delta_{\mathrm{CP}} \neq n\pi,\ \beta_{ij} \neq 0 \text{ and } \rho_i^\alpha \rho_j^\alpha \xrightarrow{\mathrm{CPT}} -\rho_i^\alpha \rho_j^\alpha$$

Quantum decoherence and CPT violation

Decoherence Matrix

$$\mathbf{D} = \begin{pmatrix} -\Gamma & \beta_{12} & \beta_{13} & \beta_{14} & \beta_{15} & \beta_{16} & \beta_{17} & \beta_{18} \\ \beta_{12} & -\Gamma & \beta_{23} & \beta_{24} & \beta_{25} & \beta_{26} & \beta_{27} & \beta_{28} \\ \beta_{13} & \beta_{23} & -\Gamma & \beta_{34} & \beta_{35} & \beta_{36} & \beta_{37} & \beta_{38} \\ \beta_{14} & \beta_{24} & \beta_{34} & -\Gamma & \beta_{45} & \beta_{46} & \beta_{47} & \beta_{48} \\ \beta_{15} & \beta_{25} & \beta_{35} & \beta_{45} & -\Gamma & \beta_{56} & \beta_{57} & \beta_{58} \\ \beta_{16} & \beta_{26} & \beta_{36} & \beta_{46} & \beta_{56} & -\Gamma & \beta_{67} & \beta_{68} \\ \beta_{17} & \beta_{27} & \beta_{37} & \beta_{47} & \beta_{57} & \beta_{67} & -\Gamma & \beta_{78} \\ \beta_{18} & \beta_{28} & \beta_{38} & \beta_{48} & \beta_{58} & \beta_{68} & \beta_{78} & -\Gamma \end{pmatrix} .$$

CP and CPT violated symmetries

Non-diagonal element	CPV	CPTV
$\beta_{12}, \beta_{23}, \beta_{24}, \beta_{26}, \beta_{28}$ $\beta_{15}, \beta_{35}, \beta_{45}, \beta_{56}, \beta_{58}$ $\beta_{17}, \beta_{37}, \beta_{47}, \beta_{67}, \beta_{78}$	✓	✓

CPT violation symmetry

$$\Delta P_{CPT} = P_{\nu_\mu \to \nu_\mu} - P_{\bar{\nu}_\mu \to \bar{\nu}_\mu}$$

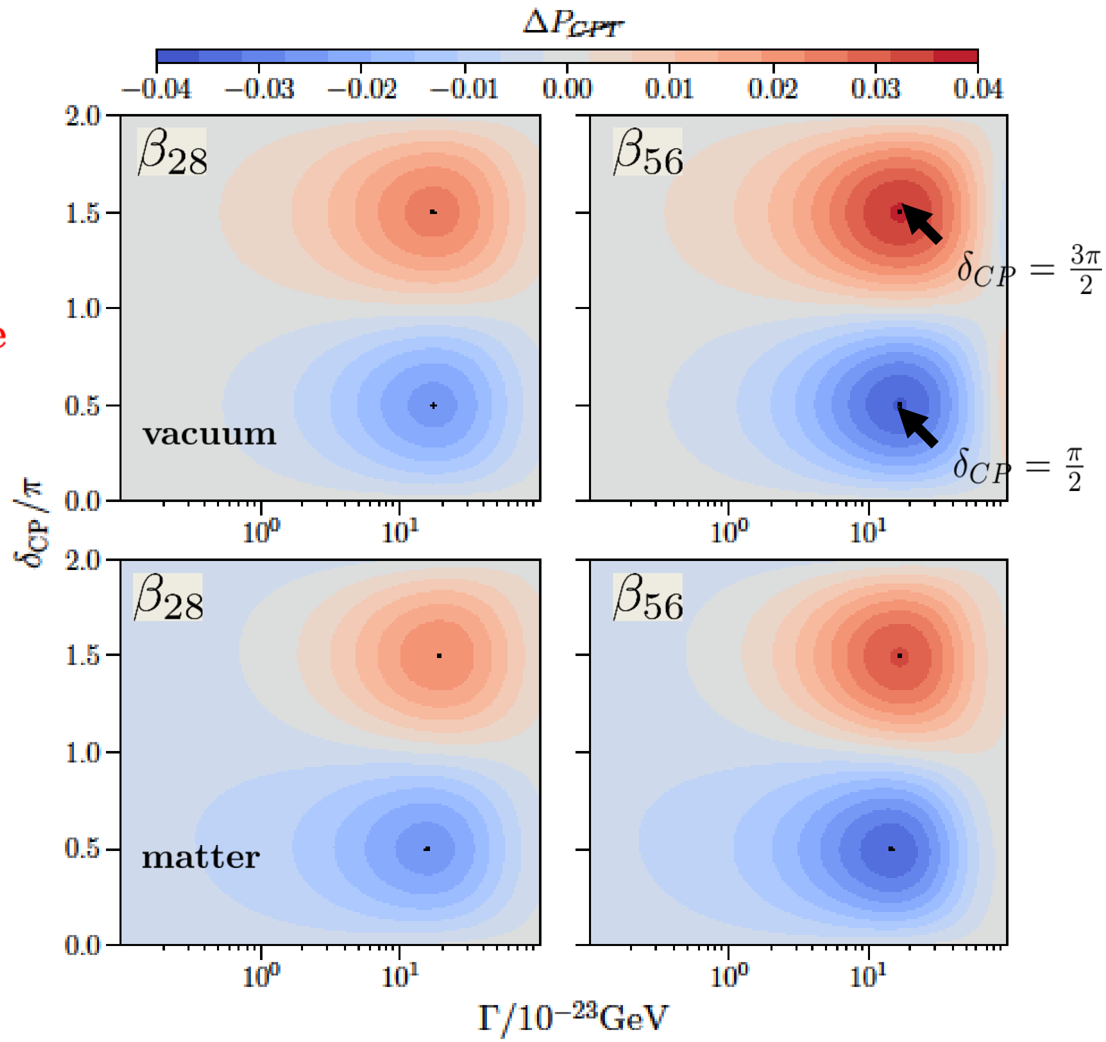
CPT violation with Dirac Phase

$$\beta_{28} = \beta_{56} = \frac{\Gamma}{\sqrt{3}}$$

$$E_\nu = 2.6\,\mathrm{GeV}$$

$$L = 1300\,\mathrm{km}$$

Compatible with DUNE experiment



J. C. Carrasco, F. N. Díaz, A. M. G, PRD 99, 075022 (2019).

CPT violation symmetry

$$\Gamma_{E_\nu} = \Gamma \left(\frac{E_\nu}{\text{GeV}} \right)^n$$

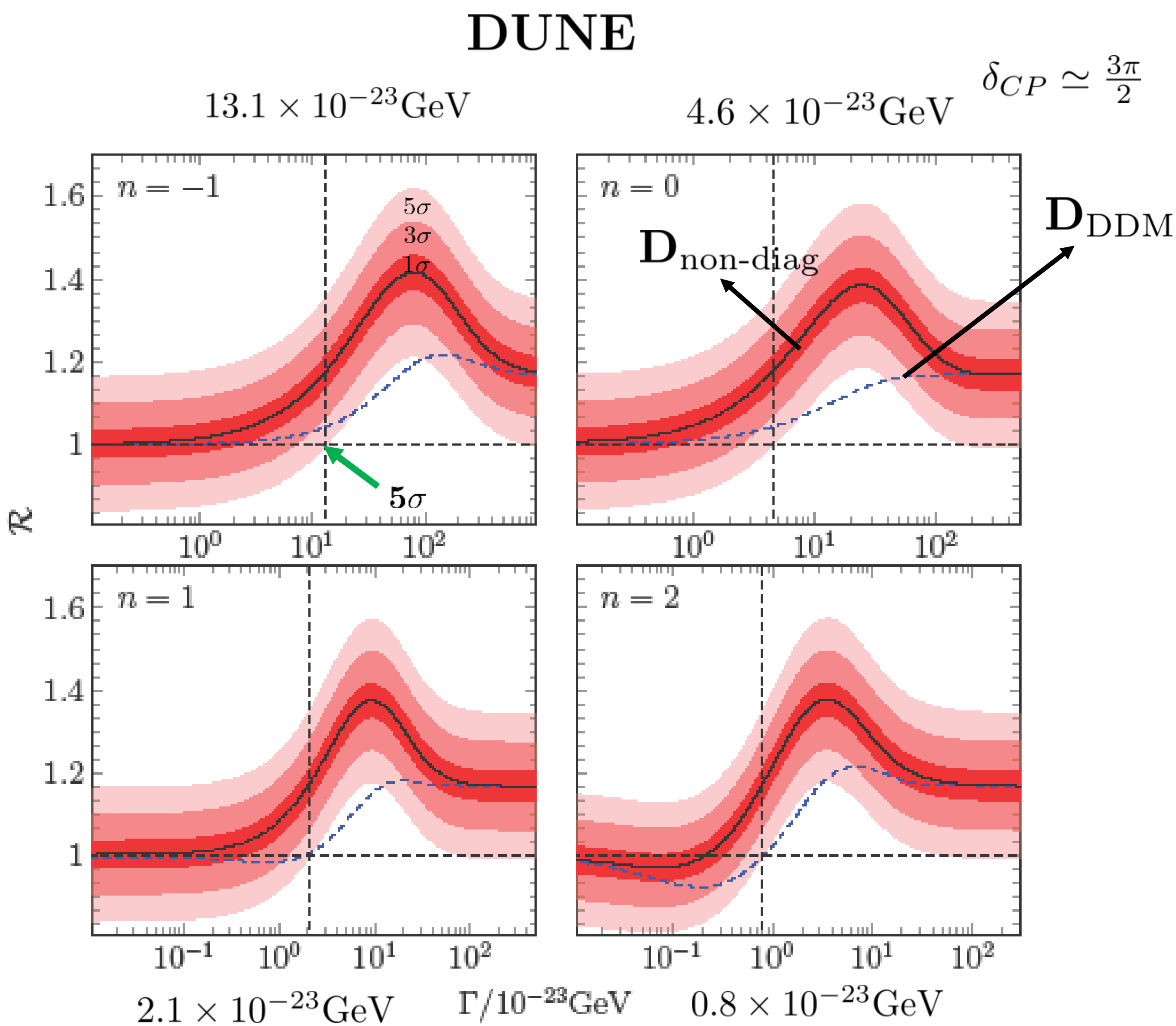
$n = -1$ **standard oscillation**
$n = 1$ **quantum gravity**
$n = 2$ **string theory**

$$\mathcal{R} = \frac{\Delta N^{\text{SO} \bigoplus \text{DEC}}}{\Delta N^{\text{SO}}}$$

$$\Delta N^{\text{SO} \ (\text{SO} \bigoplus \text{DEC})} = N_{\nu_\mu} - N_{\bar{\nu}_\mu}$$

$\mathbf{D}_{\text{DDM}} \equiv$ Diagonal decoherence matrix

J. C. Carrasco, F. N. Díaz, A. M. G, PRD 99, 075022 (2019).



Revealing Majorana phases

Quantum Decoherence and Majorana Phases

Majorana condition

$$\nu = \nu^C = C\bar{\nu}^{\mathrm{T}}$$

Neutrino= Antineutrino

$$U_{\text{Majorana}} = U_{\text{PMNS}}.\text{diag}(1, \exp -i\phi_1, \exp -i\phi_2)$$

Majorana phases are unobservable in standard neutrino oscillation

However...

$$\rho_1^\alpha \to \rho_1^\alpha \cos\phi_1 - \rho_2^\alpha \sin\phi_1$$
$$\rho_2^\alpha \to \rho_2^\alpha \cos\phi_1 + \rho_1^\alpha \sin\phi_1$$
$$\rho_3^\alpha \to \rho_3^\alpha$$
$$\rho_4^\alpha \to \rho_4^\alpha \cos\phi_2 - \rho_5^\alpha \sin\phi_2$$
$$\rho_5^\alpha \to \rho_5^\alpha \cos\phi_2 + \rho_4^\alpha \sin\phi_2$$
$$\rho_6^\alpha \to \rho_6^\alpha \cos\Delta\phi - \rho_7^\alpha \sin\Delta\phi$$
$$\rho_7^\alpha \to \rho_7^\alpha \cos\Delta\phi + \rho_6^\alpha \sin\Delta\phi$$
$$\rho_8^\alpha \to \rho_8^\alpha,$$

$$\Delta P_{\text{CP}} \neq 0$$

CP violated symmetries:

$\delta_{\text{CP}} \neq 0$, **or** $\phi_1 \neq 0$ **or** $\phi_2 \neq 0$ **or** $\Delta\phi = \phi_1 - \phi_2 \neq 0$

CPV	Non-null Majorana phase
$\beta_{13}, \beta_{23}, \beta_{18}, \beta_{28}, \beta_{12}$	ϕ_1
$\beta_{34}, \beta_{35}, \beta_{48}, \beta_{58}, \beta_{45}$	ϕ_2
$\beta_{37}, \beta_{36}, \beta_{68}, \beta_{67}, \beta_{78}$	$\Delta\phi$
$\beta_{14}, \beta_{24}, \beta_{15}, \beta_{25}$	ϕ_1, ϕ_2
$\beta_{16}, \beta_{17}, \beta_{26}, \beta_{27}$	$\phi_1, \Delta\phi$
$\beta_{46}, \beta_{47}, \beta_{56}, \beta_{57}$	$\phi_2, \Delta\phi$

$$\Delta\phi = \phi_1 - \phi_2$$

*F. Benatti and R. Floreanini, PRD **64**, 085015(2001).*
*A. Capolupo, S. M. Giampaolo and G. Lambiase, PLB **792**, 298 (2019).*
*R.L. N. De Oliveira, M.M. Guzzo, P.C. De Holanda, PRD **89**, 053002(2014).*
*J. C. Carrasco, F. N. Díaz, A. M. G, PRD **105**, 035010 (2022)*

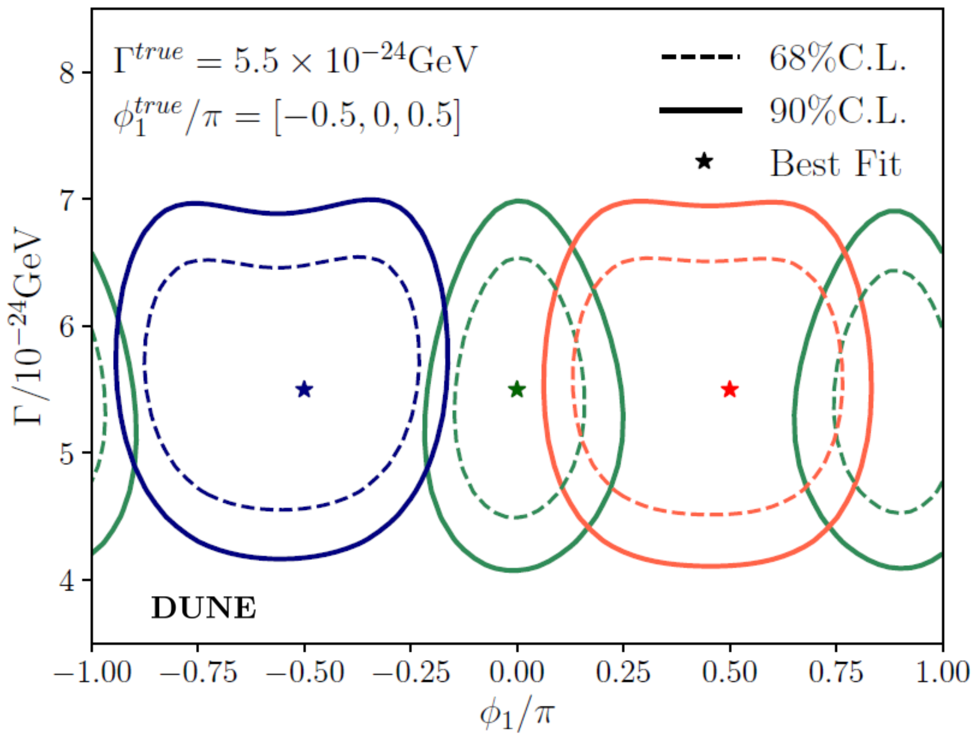
Quantum Decoherence and Majorana phases

Then we have:

$$P^{\mathrm{SO}\bigoplus\mathrm{DE}}_{\nu_\mu\to\nu_e} = \frac{(1-e^{-\bar{\Gamma}})}{3} + P^{\mathrm{SO}}_{\nu_\mu\to\nu_e} e^{-\bar{\Gamma}}$$

$$-\frac{\bar{\Gamma}_{28}}{\sqrt{3}} \sin 2\theta_{12} \sin^2\theta_{23} \sin\phi_1 e^{-\bar{\Gamma}} + \mathcal{O}(\bar{\Gamma}_{28}\theta_{13}) + \ldots$$

the Majorana phase can be revealed



☞ **Non-zero Majorana CP-phase (+0.5/-0.5) can be differentiated from zero at more than 1σ.**

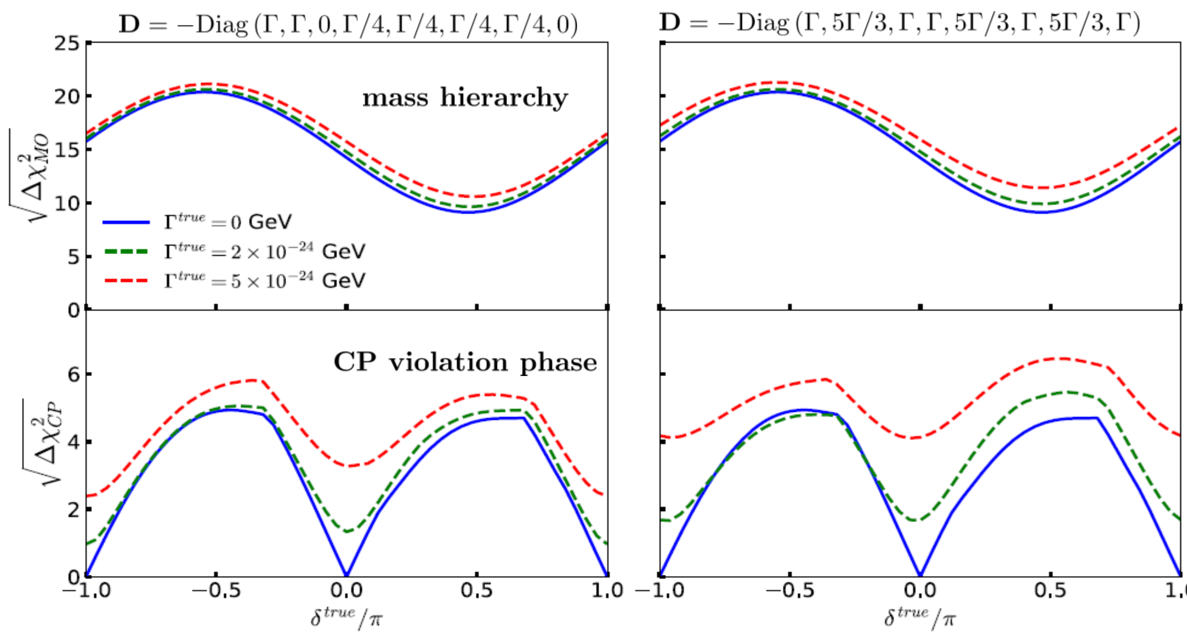
J. C. Carrasco, F. N. Díaz, A. M. G, PRD 105, 035010 (2022)

$$\phi_1/\pi = -0.50(+0.50) \pm 0.32 \text{ for } \Gamma = (5.50 \pm 1.42) \times 10^{-24} \text{ GeV}$$

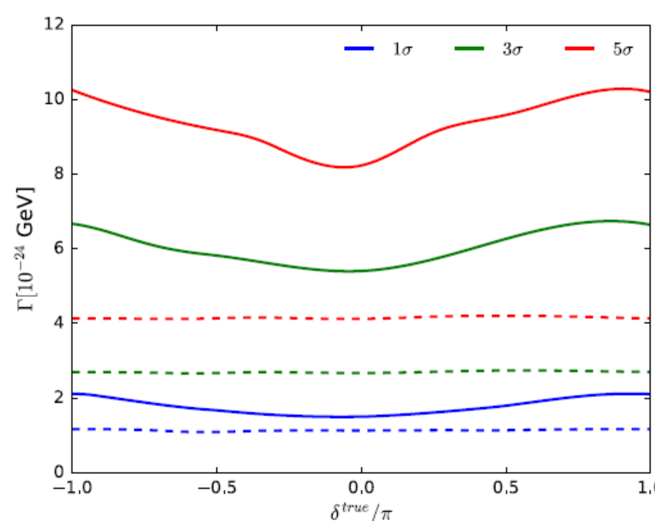
Distortion in the Oscillation-Parameter measurements

Quantum Decoherence -DUNE sensitivities

DUNE projected sensitivities for Quantum Decoherence



DUNE projected bounds for QD



—— $\mathbf{D} = -\mathrm{Diag}\,(\Gamma, \Gamma, 0, \Gamma/4, \Gamma/4, \Gamma/4, \Gamma/4, 0)$

– – $\mathbf{D} = -\mathrm{Diag}\,(\Gamma, 5\Gamma/3, \Gamma, \Gamma, 5\Gamma/3, \Gamma, 5\Gamma/3, \Gamma)$

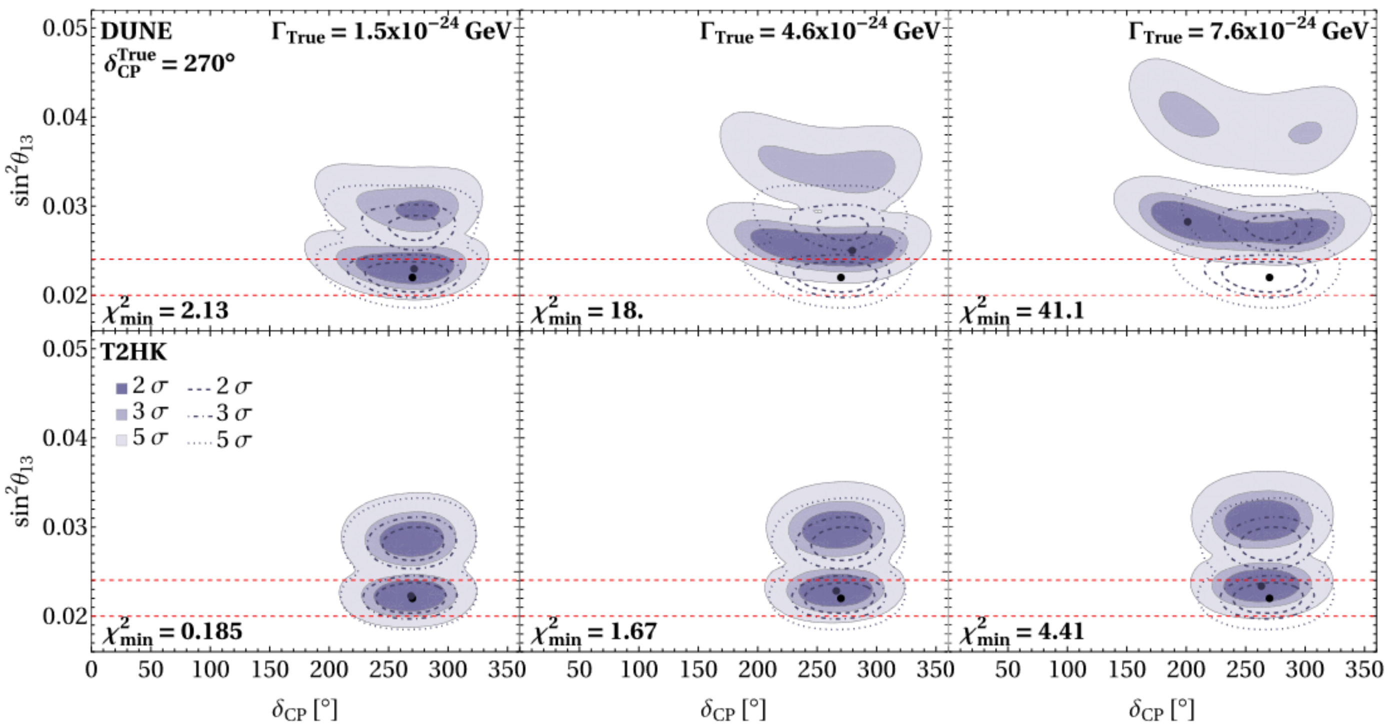
J. A. Carpio, E. Massoni, A. M. G
PRD 100, 015035 (2019)

Quantum Decoherence – T2HK and DUNE

Distorsion in the extraction of oscillation parameters at T2HK and DUNE

Feature	DUNE (USA)	T2HK (Japan)
Fiducial mass	40 kton (LAr)	374 kton (Water)
Baseline length	1,300 km	295 km
Mean energy	$\sim$ 2.5–3.0 GeV	$\sim$ 0.6 GeV

Decoherence matrix $\mathbf{D} = -\mathrm{Diag}\left(\Gamma, 5\Gamma/3, \Gamma, \Gamma, 5\Gamma/3, \Gamma, 5\Gamma/3, \Gamma\right)$



- **Measurement of SO parameters mostly unaffected at T2HK.**
- **Large distortions could be expected at DUNE.**

G.Barenboim, A.M. Calatayud-Cadenillas, A. M. G, C.A.Ternes
PLB 852, 138626 (2024)

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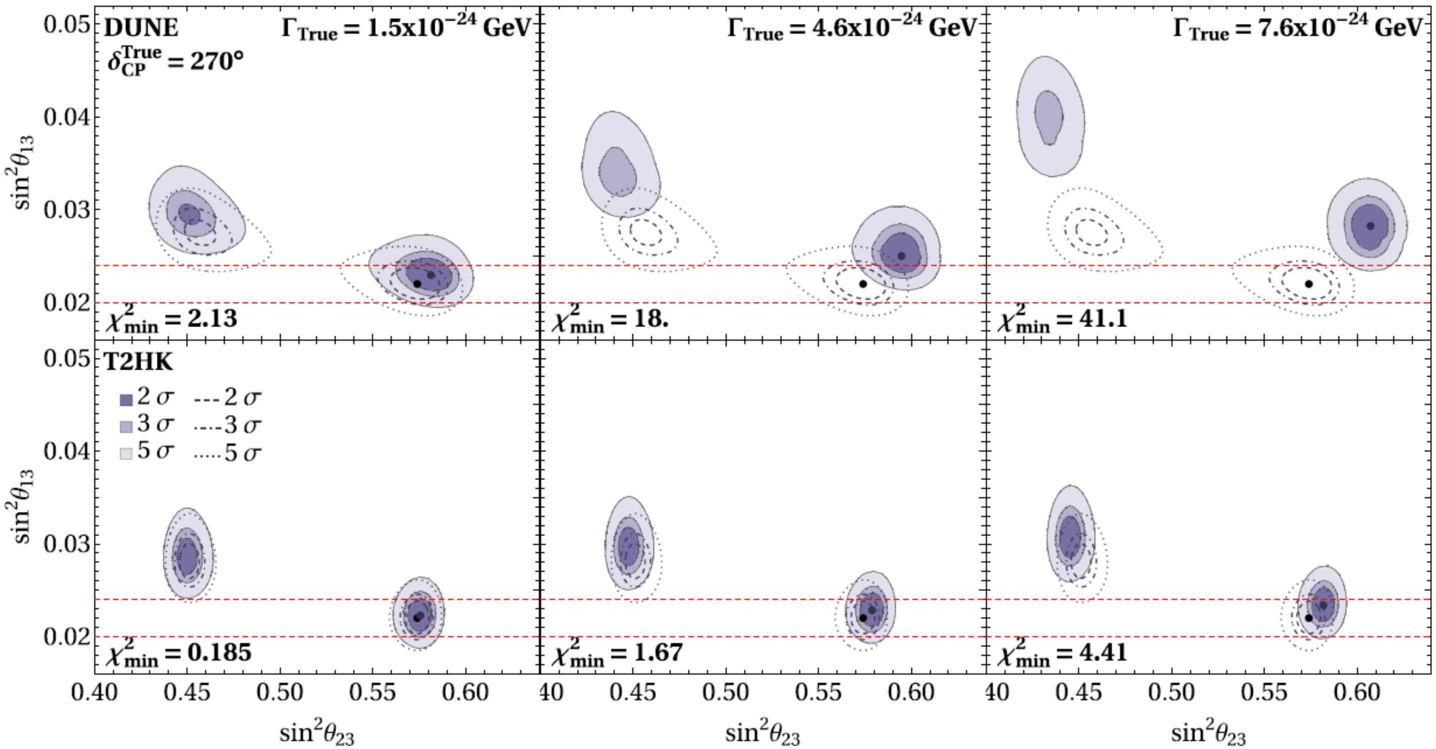

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PLB 852, 138626 (2024)

Open Questions

Open questions
(from the perspective of neutrino applications)

$$A_j = A_j^\dagger \Rightarrow \textbf{unital dynamics} \Rightarrow \Delta S \geq 0$$

with $S(\rho) = -\mathrm{Tr}[\rho \ln \rho] \geq 0$

measures the degree of mixedness

unital dynamics

$$\rho(0) = \mathbb{I} \to \rho(t) = \mathbb{I} \equiv \mathcal{L}(\mathbb{I}) = 0$$

where $\dot{\rho} = \mathcal{L}(\rho)$

Liouvillian Superoperator

stationary state (maximal entropy)

$$P_{\nu_\alpha \to \nu_\beta} = \frac{1}{n} \equiv \rho = \frac{\mathbb{I}}{n}$$

$(\alpha, \beta = e, \mu, \tau)$

$n = 3$

asymptotic behavior

Question: Is there a physical scenario that motivates to relax the condition $A_j = A_j^\dagger$?

Open questions
(from the perspective of neutrino applications)

$$\frac{d\rho(t)}{dt} = -i[H_{\text{eff}}, \rho(t)] + \mathcal{D}[\rho(t)]$$

$$\Delta = \frac{\Delta m^2}{4E} \qquad H_{\text{eff}} = \begin{pmatrix} \Delta & \lambda e^{i\phi} \\ \lambda e^{-i\phi} & -\Delta \end{pmatrix}$$

λ **modifies both the oscillation amplitudes and frequencies**

A natural hypothesis is that the same system-environment interaction generates both the off-diagonal coherent term and the decoherence parameters.

G.Barenboim and A. M. G, PRD 110, 095005 (2024)

In the weak-coupling limit, one obtains a Lamb-shift contribution:

$$H_{\text{eff}} = H_{\text{std-osc}} + H_{\text{LS}} \text{ with } [H_{\text{std-osc}}, H_{\text{LS}}] = 0$$

Corrects the oscillation frequencies

Question: Is there any physical scenario in which the system-environment interaction generates a non-diagonal coherent term while the evolution remains completely positive and trace preserving?

Open questions
(from the perspective of neutrino applications)

$$\frac{d\langle H_{\text{std-osc}}\rangle}{dt} = -i\,\mathrm{Tr}\left(H_{\text{std-osc}}[H_{\text{eff}},\rho(t)]\right) + \mathrm{Tr}\left(H_{\text{std-osc}}\mathcal{D}[\rho(t)]\right)$$

$$\frac{d\langle H_{\text{std-osc}}\rangle}{dt} = 0 \quad \Longrightarrow \quad [H_{\text{std-osc}}, H_{\text{eff}}] = 0, \; \sum_i D_{ik} h_i = 0$$

Energy conservation of the system

For instance, $D_{33} = 0$ only in the two-generation case and in the mass basis, assuming known how the decoherence is written in this basis.

Question: Which physical environments justify non-conservation of the neutrino subsystem energy?

Pure decoherence: no energy exchange with the environment

Dissipative dynamics: energy exchange with environment.

Conclusions

- **Open-system effects are not simply damping factors:** the non-trivial structure of the dissipator can encode novel physical effects beyond dephasing or dissipation.

- **CP/CPT symmetry violation and Majorana phases:** Non-diagonal terms in the decoherence matrix can generate CP- and CPT-violating contributions to the oscillation probability, and may also make Majorana CP phases observable.

- **Distortion in the oscillation-parameter measurements:** Open-system effects may distort the extraction of standard oscillation parameters, making decoherence a cause of misleading future precision measurements.

- **Open questions:** Identify physical scenarios in which standard assumptions of open neutrino dynamics can be challenged or relaxed.