technische universität
dortmund

New Sources of Decoherence in Neutrino Oscillations - Challenges and Opportunities

Based on arXiv:2405.05000 [hep-ph]

D. Hellmann, S. Krieg, H. Päs, M. Tabet

BNL HET Seminar, 17.10.2024

Department of Physics
TU Dortmund

Outline

Motivation: Decoherence as a Probe for New Physics

Motivation

New physics in the neutrino sector:

- Coupling between neutrinos and non-SM degrees of freedom (DOFs)
- When only considering neutrino flavor DOFs: Decoherence arises due to interaction
- Decoherence leads to oscillation damping that might be observable
- But when are these new decoherence effects observable?

When are new Decoherence Effects Observable?

Two possible scenarios:

1. New effects lead to standard decoherence limit:

$$P_{ab} \to \bar{P}_{ab}^{\text{std}} := \sum_j |U_{aj}|^2 |U_{bj}|^2 \quad \text{(in vacuum)}$$

2. New effects lead to non-standard decoherence limit:

$$P_{ab} \to \bar{P}_{ab} \neq \bar{P}_{ab}^{\text{std}}$$

In case 1 standard decoherence effects must be avoided!

Brief Recap: Decoherence in Quantum Mechanics

Closed Quantum Systems

Consider system S coupled to environment E:

- Full system $S+E$: Closed Quantum system
- Hamiltonian:

$$\hat{H} = \hat{H}_S \otimes \mathbb{I}_E + \mathbb{I}_S \otimes \hat{H}_E + \hat{H}_{\text{int}}$$

- $|\psi(t), S+E\rangle$: Obeys Schrödinger equation

What if we are only interested in / able to measure subsystem S?

Open Quantum Systems

Interaction entangles degrees of freedom (DOFs) from S and E

$$\underbrace{|\psi(0), S+E\rangle}_{=|\psi_S(0),S\rangle\otimes|\psi_E(0),E\rangle} \quad \xrightarrow{\hat{H}_{\text{int}}\neq 0} \quad \underbrace{|\psi(t), S+E\rangle}_{\neq|\psi_S(t),S\rangle\otimes|\psi_E(t),E\rangle}$$

Solution: Density operator formalism

- Full system state: $\varrho(t) = |\psi(t), S+E\rangle\langle\psi(t), S+E|$
- Subsystem state: $\varrho_S = \mathrm{Tr}_E[\varrho]$
- Interactions / entanglement cause decoherence in S

$$\underbrace{\mathrm{Tr}[\varrho_S^2(0)] = 1}_{\text{pure state}} \quad \xrightarrow{\hat{H}_{\text{int}}\neq 0} \quad \underbrace{\mathrm{Tr}[\varrho_S^2(t)] < 1}_{\text{mixed state}}$$

Decoherence in Quantum Mechanics – Example

Two fermions form spin 0 bound state and are separated again:

$$\underbrace{e^-}_{S} + \underbrace{e^+}_{\subset E} \quad \rightarrow \quad \text{p-Ps} \quad \overset{+\gamma}{\rightarrow} \quad \underbrace{e^-}_{S} + \underbrace{e^+ + \gamma}_{E}$$

Initial vs final state:

$$|\psi(-\infty), S+E\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow, e^-\right\rangle + \left|\downarrow, e^-\right\rangle\right) \otimes \left|e^+, \gamma\right\rangle$$

$$\downarrow$$

$$|\psi(+\infty), S+E\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow, e^-\right\rangle \otimes \left|\downarrow, e^+\right\rangle - \left|\downarrow, e^-\right\rangle \otimes \left|\uparrow, e^+\right\rangle\right) \otimes |\gamma\rangle$$

Electron density matrices (in the spin up–down basis):

$$\varrho_S(-\infty) = \frac{1}{2}\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \quad \longrightarrow \quad \varrho_S(+\infty) = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix},$$

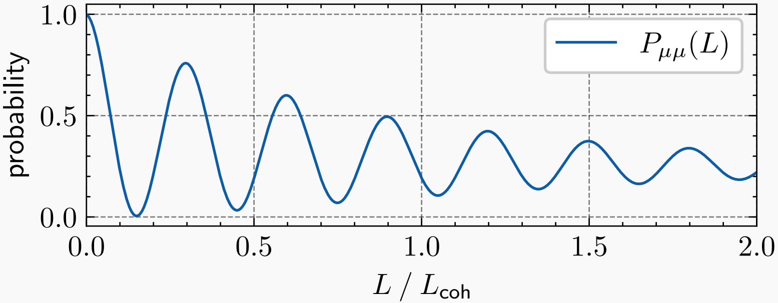
Decoherence in Neutrino Oscillations

Simple maximally mixed two flavor scenario

Without decoherence:

$$\varrho_\mu(L) = \frac{1}{2}\begin{pmatrix} 1 & e^{-i\frac{\Delta m^2_{21}L}{2E}} \\ e^{i\frac{\Delta m^2_{21}L}{2E}} & 1 \end{pmatrix} \rightarrow \frac{1}{2}\begin{pmatrix} 1 & e^{-i\frac{\Delta m^2_{21}L}{2E}-\Gamma(L)} \\ e^{i\frac{\Delta m^2_{21}L}{2E}-\Gamma(L)} & 1 \end{pmatrix}$$

Decoherence also leads to oscillation damping!



Standard Sources of Decoherence in Neutrino Oscillations

Standard Sources of Decoherence

Two kinds of decoherence:

1. Inherent QM sources of decoherence
2. Measurement related sources of decoherence

Only some sources can be interpreted as *actual* decoherence

Inherent Sources of Decoherence

Flavor transition probability in vacuum with (standard) decoherence

$$P_{ab}(L,E) = \sum_j |U_{aj}|^2 |U_{bj}|^2 + 2\sum_{j>k} \mathrm{Re}\left[U_{aj}^* U_{bj} U_{ak} U_{bk}^* e^{-i\frac{\Delta m_{jk}^2}{2E}L} e^{-\Gamma_{jk}^{\text{std}}(L)} \right]$$

Γ_{jk}^{std} contains

- Γ_{jk}^{WP}: Wave packet (WP) decoherence
- $\Gamma_{jk}^{\text{prod/det}}$: Production / Detection decoherence

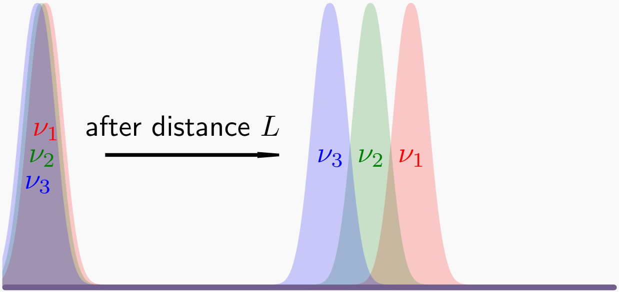
In matter: Incoherent scattering leads to decoherence!

Wave Packet Separation

Mass eigenstates propagate with different group velocities:

$$v_k^g = \frac{\mathrm{d}E_k}{\mathrm{d}p} \approx 1 - \frac{m_k^2}{2p^2}$$

$\Rightarrow$ Overlap vanishes after $L \gtrsim L_{jk}^{\mathrm{coh}} \propto \sigma_X \bar{v}^g / |\Delta v_{jk}^g|$



Wave Packet Separation

Coherence length:

$$L_{jk}^{\text{coh}} \propto \sigma_X \frac{E^2}{|\Delta m_{jk}^2|} = \left(\frac{\sigma_X}{\text{nm}}\right)\left(\frac{E}{\text{GeV}}\right)^2 \left(\frac{10^{-3}\text{eV}^2}{|\Delta m_{jk}^2|}\right) 10^9\text{km}$$

L_{jk}^{coh} vs typical scale: $(\sigma_X \sim 1\,\text{nm})$ [Argüelles et al., Phys. Rev. D 107 (2023)]

- Solar neutrinos:

$$L_{j3}^{\text{coh}}(100\,\text{keV}) < L_{12}^{\text{coh}}(100\,\text{keV}) \sim 130\,\text{km} \ll L_{\text{Earth}-\text{Sun}}$$

- Atmospheric Neutrinos:

$$L_{12}^{\text{coh}}(10\,\text{GeV}) > L_{j3}^{\text{coh}}(10\,\text{GeV}) \sim 4.2 \times 10^{11}\,\text{km} \gg R_{\text{Earth}}$$

Production / Detection Coherence

Neutrino oscillations rely on coherent production of flavor eigenstates:

$$|\nu_a\rangle = \sum_j U^*_{aj} |\nu_j\rangle$$

If experimental energy resolution is too good, i.e.

$$\sigma_E \lesssim \Delta E_{jk} \propto \Delta m^2_{jk} \,,$$

mass eigenstates can be resolved $\Rightarrow$ Oscillations are damped!
Fulfilled in all scenarios since $\sigma_E \gg \Delta m^2_{jk}$!

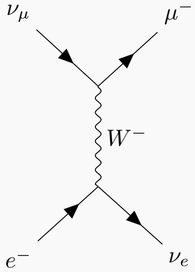
Incoherent Scattering in a Medium

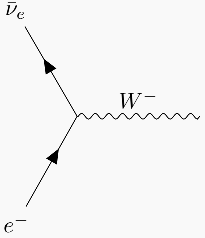
Incoherent scattering effects:

- Neutrino absorption in matter
- Scattering to different energies

Condition: Mean free path much bigger than prop. distance

$$\lambda_{\text{int}} \gg L_{\text{in medium}}$$





The Full Density Operator Evolution

Density Operator evolution equation:

$$\frac{\partial \rho(x,E)}{\partial x} = -i[H(x,E), \rho(x,E)] + D_{\mathrm{WP}}[x,E,\rho] + \mathcal{C}[x,E,\rho,\bar{\rho}]$$

$$\rho(x_0,E) \equiv \rho_0(E)$$

- Prod. / Det. Coherence $\leftrightarrow$ Encoded in initial / final state
- WP separation $\leftrightarrow$ Linear dissipator D_{WP}
- Incoherent scattering $\leftrightarrow$ Collision term $\mathcal{C}$ (matter only)

Measurement Related Sources of Decoherence

Experiments only measure averaged probabilities

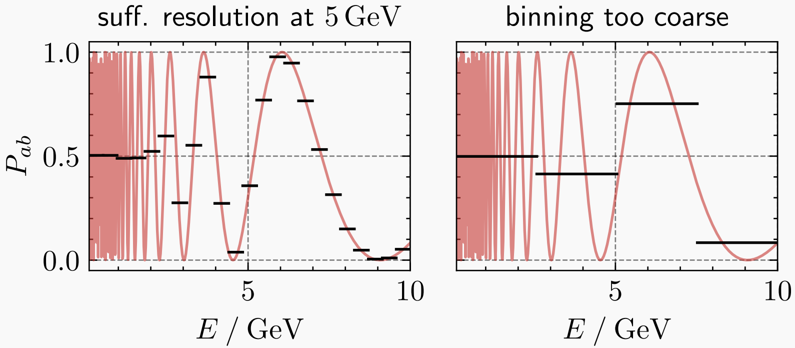
$$\langle P_{ab} \rangle \propto \int_{E_i}^{E_{i+1}} \int_0^{T_{\text{exp}}} \int_{L(t)-\frac{\Sigma_L}{2}}^{L(t)+\frac{\Sigma_L}{2}} \frac{\mathrm{d}\phi_a^{\text{prod}}}{\mathrm{d}E}(E)\mathbf{P_{ab}}(\ell, \mathbf{E})\sigma_b^{\text{det}}(E)\varepsilon(E)\frac{\mathrm{d}\ell}{\Sigma_L}\frac{\mathrm{d}t}{T_{\text{exp}}}\mathrm{d}E$$

- Average over energy bin $[E_i, E_{i+1}]$
- If time not tracked: Time average
- Average over production region (e.g. solar neutrinos)

All may result in further oscillation damping
$\rightarrow$ **Decoherence**

Energy Average – Why Cosmics don't Oscillate

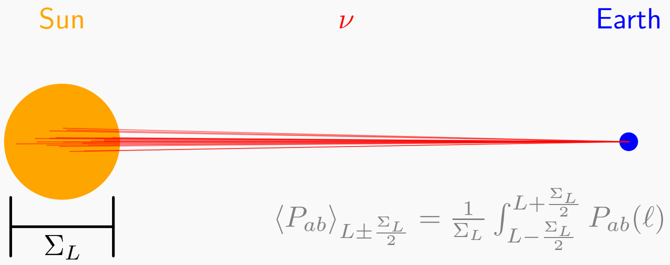
Energy binning should fulfill $\Delta E \sim 2E^2/\Delta m_{jk}^2 L$



Here we use $L \sim 3 \times 10^5$ km and $\Delta m_{12}^2 = 7.5 \times 10^{-5}\,\mathrm{eV}^2$

Neutrino Origin Averaging

Famous example: Solar neutrinos



$$\langle P_{ab} \rangle_{L \pm \frac{\Sigma_L}{2}} = \frac{1}{\Sigma_L} \int_{L-\frac{\Sigma_L}{2}}^{L+\frac{\Sigma_L}{2}} P_{ab}(\ell)\,\mathrm{d}\ell$$

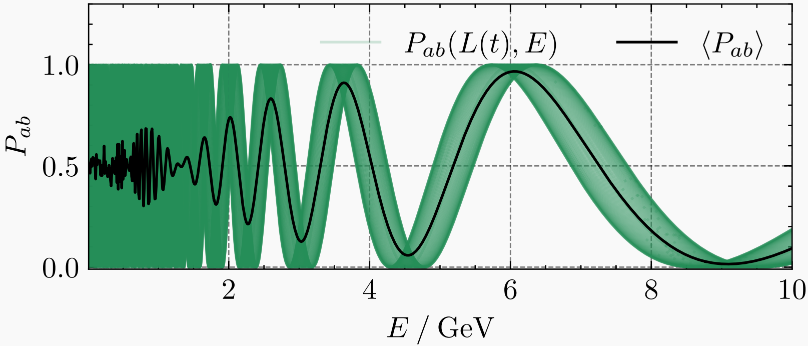
Oscillation damping if $\mathbf{L^{osc}_{jk}} \lesssim \mathbf{\Sigma_L}$ where $L^{osc}_{jk} := 4\pi E/|\Delta m^2_{jk}|$

Neutrino Baseline Averaging

Same effect can arise due to $L(t) \neq$ const.:

$$\langle P_{ab} \rangle_{T_{\text{exp}}} = \int_0^{T_{\text{exp}}} P_{ab}(L(t), E) \frac{\mathrm{d}t}{T_{\text{exp}}}$$

If $\mathbf{L}_{\mathbf{jk}}^{\text{osc}} \lesssim \mathbf{\Delta L} := \max(L(t)) - \min(L(t))$ oscillations are damped!



Summary: Set of Criteria

Criteria to resolve Δm^2_{jk} oscillation:

(i) WP separation:

$$\mathbf{L} \lesssim \mathbf{L}^{\text{coh}}_{\mathbf{jk}} \propto \sigma_{\mathbf{X}} \frac{\mathbf{E^2}}{|\boldsymbol{\Delta}\mathbf{m^2_{jk}}|}$$

(ii) Baseline / production region averaging:

$$\boldsymbol{\Delta}\mathbf{L}, \boldsymbol{\Sigma}_{\mathbf{L}} \ll \mathbf{L}^{\text{osc}}_{\mathbf{jk}} = \mathbf{4}\pi \frac{\mathbf{E}}{\boldsymbol{\Delta}\mathbf{m^2_{jk}}}$$

(iii) Energy resolution:

$$\frac{\boldsymbol{\Delta}\mathbf{E}}{\mathbf{E}} \lesssim \frac{\mathbf{2E}}{|\boldsymbol{\Delta}\mathbf{m^2_{jk}}|\mathbf{L}}$$

In matter: $\lambda_{\text{int}} \gg L_{\text{in medium}}$ to observe oscillations!

Where to Look for Non-Standard Decoherence

- Terrestrial experiments:
  - All coherence criteria (mostly) fulfilled
  - No signs for non-standard decoherence yet
- Cosmic neutrinos:
  - Coherence criteria difficult to fulfill
  - Great sensitivity to non-standard decoherence (large distances)
  - (No signs for non-standard decoherence yet)

If Decoherence Limit not modified

Ultra high energy (UHE) neutrinos are needed for cosmic decoherence searches. Neutrinos from galactic pulsars potentially interesting.

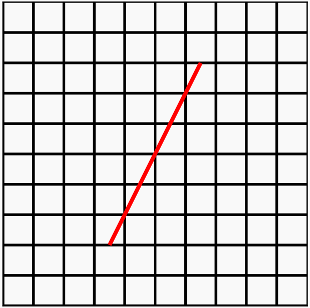
Non-standard sources of Decoherence: Examples

Outline

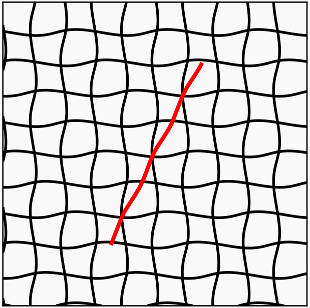
Motivation and Main Idea

- Neutrino oscillation phase depends on physical distance
- Gravitational waves (GWs) modify physical distance
- Idea: Stochastc GW background (SGWB) can induce Decoherence [Dvornikov, Phys. Rev. D 104 (2021)], [Lambiase et al., Phys. Rev. D 108 (2023)], [DH et al., arXiv:2405.05000 [hep-ph]]

ν path in flat spacetime



ν path in GW spacetime



Decoherence from the SGWB

Standard decoherence limit not modified

$$\Gamma_{jk}^{\text{std}}(L) \to \Gamma_{jk}^{\text{std}}(L) + \Gamma_{jk}^{\text{SGWB}}(L)$$

$$\Gamma_{jk}^{\text{SGWB}}(L) \propto \int_{f_{\text{min}}}^{f_{\text{max}}} \frac{\sin^2(\pi f L)}{f^5} \Omega_{\text{SGWB}}(f)\, \mathrm{d}f$$

[Dvornikov, Phys. Rev. D 104 (2021)]

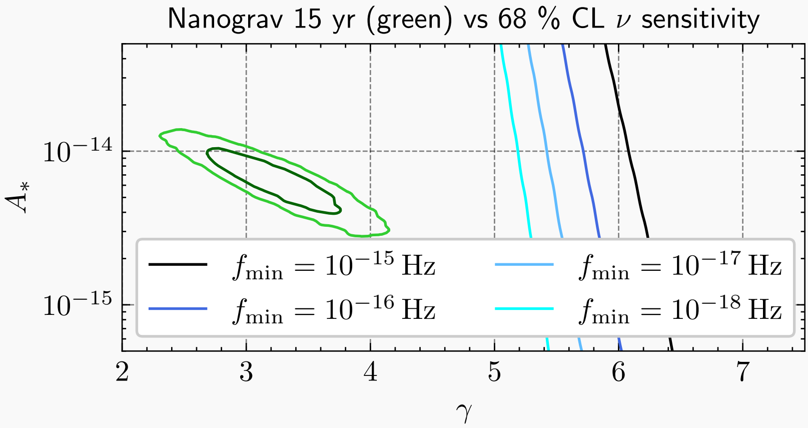
- $\Omega_{\text{SGWB}}(f)$: Fractional GW energy density (per frequency)
- $f_{\text{max/min}}$: Max. / Min. frequency of SGWB spectrum

Assume SGWB powerlaw spectrum:

$$\Omega_{\text{SGWB}}(f) = A_* \left(\frac{f}{f_{\text{yr}}}\right)^{\frac{3-\gamma}{2}}$$

[NANOGrav, Astrophys. J. Lett. 905 (2020)], [Ellis, Lewicki, Phys. Rev. Lett. 126 (2021)]

Sensitivity of Neutrinos to the SGWB



- Best sensitivity for ultra low frequency spectra
- Competition: CMB, Pulsar Timing Array Experiments

Drawbacks and Challenges

- Need large L
- Oscillations must be resolvable

Oscillations conditions need to be satisfied:

- Production region smaller than L_{jk}^{osc}
- Energy resolution sufficient $\Delta E/E \lesssim 2E/(\Delta m_{jk}^2 L)$
- WP decoherence negligible

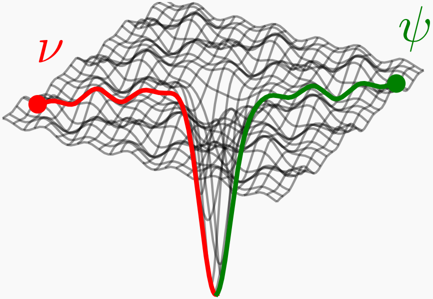
Neutrinos from galactic pulsars! Are statistics high enough?

Outline

Neutrino Entanglement with Spacetime Foam

Motivation / Main Idea:

- Spacetime itself may be “quantum” (foamy)
- Spacetime state interacts/entangles with propagating particles
- Cannot observe Quantum Gravitational (QG) DOFs
  - $\Rightarrow$ Decoherence
- This interaction could be flavor violating!



Flavor Violation in Quantum Gravity

Extended No Hair Theorem (Assumption!)

Interactions with virtual black holes conserve unbroken gauge quantum numbers.
Conservation of quantum numbers associated with global symmetries is violated.

No-Hair Theorem: [Israel, Phys. Rev. 164 (1967)], [Hawking, Commun. Math. Phys. 46 (1976)]
No-Hair Theorem in AdS CFT: [Harlow, Ooguri, PRL 122 (2019)]

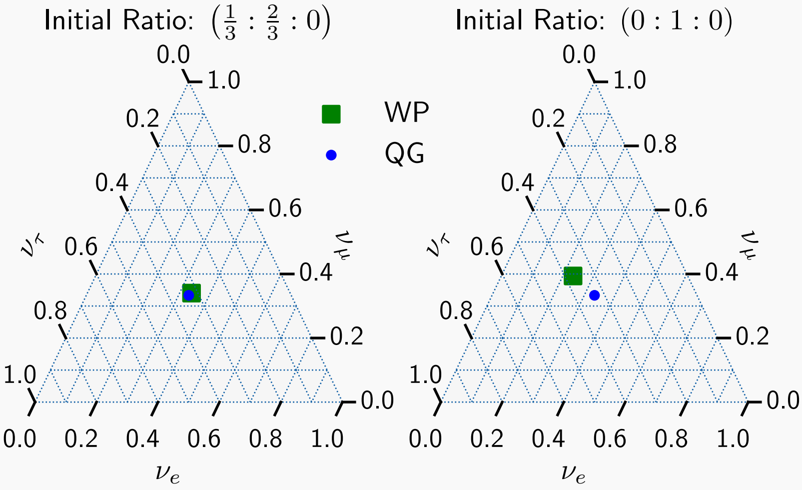
Consequence:

$$P_{ab}(L \to \infty) \longrightarrow \frac{1}{n_f}$$

n_f: Number of neutrino-like flavors (fermionic dark matter?)

Flavor Ratios

Final flavor ratios are always $\left(\frac{1}{3} : \frac{1}{3} : \frac{1}{3}\right)$ at $E \gg E_{\mathrm{QG}}^{\mathrm{coh}}$



QG vs Standard Decoherence

For $\Gamma_{\mathrm{QG}} \propto E^n$ with $n > 0$

- UHE neutrinos of cosmic origin most promising
- Decoherence limit is modified!
- Standard decoherence need not be avoided

Promising perspectives at future ν telescopes [DH et al., Phys. Rev. D 105 (2021)], [DH et al., Phys. Rev. D 106 (2022)], [DH et al., 2409.12633 [hep-ph]]

Summary and Outlook

Summary and Outlook

Main Take-Aways:

1. New physics scenarios can be probed using decoherence
2. It is mandatory that either
   - The decoherence limit changes
   - Or non-standard decoherence is not hidden by standard decoherence
3. Non-standard decoherence not observed in experiments yet

   $\Rightarrow$ Improve detectors **or**

   $\Rightarrow$ Consider cosmic neutrinos

Cosmic neutrinos:

- Barely oscillate
- Potential exceptions: UHE neutrinos from galactic pulsars