

Fundamental decoherence and neutrino oscillations

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UNIVERSITÀ DEGLI STUDI
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 - Constraint from reactor neutrinos data
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QG-induced fundamental decoherence

Several QG models lead to decoherence mechanisms [A. Bassi et al, *Class. Quant. Grav.* 34, 193002 (2017)].

QG-Induced fundamental decoherence

Several QG models lead to decoherence mechanisms [S.A. Bassi et al, Class.](#)

[Quant. Grav. 34, 193002 \(2017\)](#)

Fundamental decoherence: no interaction with an environment.

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Several QG models lead to decoherence mechanisms. A. Bassi et al, Class. Quant. Grav. 34, 193002 (2017).

Fundamental decoherence: no interaction with an environment.

Decoherence modifies neutrino oscillations

Damping factor in oscillation probability

Quenching of neutrino fluxes

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Oscillation probability

States

$$|n_g\rangle = \sum_i U_{gi} |y_i\rangle \quad |n_i\rangle = \sum_i U_{gi} \int d^3p y_i(\mathbf{p}) |p_i\rangle \quad |n_i\rangle \quad (1)$$

Probability given by

$$P(b \leftarrow a; t) = \text{Tr} \{ r(t) |n_a\rangle \langle n_a| \}, \quad r(0) = |n_b\rangle \langle n_b| \quad (2)$$

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$$\left\{ \begin{array}{l} \int_t r = \int_{\{Z\}} i[H, r] \\ \text{Standard QM} \end{array} \right\} \quad \left\{ \begin{array}{l} \int_t r = \int_{\{Z\}} L[r] \\ \text{Decoherence} \end{array} \right\} \quad (3)$$

$$r(t) = \sum_{i,j} U_{bi} U_{bj} \int d^3p d^3q y_i(\mathbf{p}) y_j(\mathbf{q}) e^{it[E_i(\mathbf{p}) - E_j(\mathbf{q})]} e^{iL_{ij}(\mathbf{p}, \mathbf{q})} |p_i\rangle \langle q_j| \quad |n_i\rangle \langle n_j| \quad (4)$$

Oscillation Probability

Assumptions : one-dimensional reduction, wave-packets peaked around mean momenta p_i , only retain up to first order in Dm^2 terms.

$$P_{QG}(b \rightarrow a; L) \approx \sum_{i,j} U_{bi} U_{bj} U_{aj} U_{ai} e^{if_{ij} \frac{2p}{v_{g_{ij}}} z} \int dp e^{ip(1 - r_{ij})L} G_{ij}(p, r_{ij} p + DE_{ij}/v_{g_j}) e^{D_{ij} p + p_i, r_{ij} p + p_j / v_{g_j} DE_{ij}; L} \quad (5)$$

Oscillation Probability

Assumptions : one-dimensional reduction, wave-packets peaked around mean momenta p_i , only retain up to first order in Dm^2 terms.

$$P_{QG}(b \rightarrow a; L) \approx \sum_{i,j} U_{bi} U_{bj} U_{aj} U_{ai} e^{i f_{ij}} \int_{-\infty}^{+\infty} dp e^{i p(1 - r_{ij})L} G_{ij}(p, r_{ij}; p \pm DE_{ij}/v_{g_j}) e^{i D_{ij}(p \pm p_i, r_{ij}; p \pm p_j) L} \quad (5)$$

$$D_{ij}(p, q; L) = v_{g_j}^{-1} L L_{ij}(p, q), \quad r_{ij} = v_{g_i}^{-1} v_{g_j}^{-1}, \quad f_{ij} = L \frac{Dm_{ij}^2}{2p_{ij}}.$$

Two flavours probability

Propagation coherence condition Interaction coherence condition

$$L \ll \lambda_{\text{coh}} = s_X \frac{v_{g_{ij}}}{D v_{g_{ij}}} \quad (6) \qquad \text{DE}_{ij} \frac{s_X}{v_{g_{ij}}} \ll 1 \quad (7)$$

Probability simplifies to

$$P_{\text{QG}}(b \rightarrow a; L) = \sum_{i,j} \hat{a}_{ij} U_{bi} U_{bj} U_{aj} U_{ai} e^{i f_{ij}} e^{-D_{ij}(\rho_i, \rho_j; L)} \quad (8)$$

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Considering two flavours oscillations, probability further simplifies

$$P_{\text{QG}}(a \rightarrow a) = e^{-D} P_{\text{std}}(a \rightarrow a) + \frac{1}{2} (1 - e^{-D}) \sin^2 2q \quad (9)$$

with $P_{\text{std}}(a \rightarrow a) = \frac{1}{2} (1 + \sin^2 2q \sin^2 \frac{f}{2})$.

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Fundamental decoherence QG models

Deformation of symmetries: $D = \frac{L(Dm^2)^2}{8v_g E_{QG} p^2}$

[M. Arzano et al, accepted on Communication Physics]

Fluctuating minimal length: $D = \frac{16LE^4(Dm)^2}{v_g E_{QG}^5}$

[L. Petruzzello et al, Nat. Commun. 12, 1, 4449, (2021)]

Stochastic metric fluctuations: $D = \frac{L \left(1 + \frac{E^2}{m_i m_j}\right)^2 (Dm)^2}{8v_g E_{QG}}$

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Degenerate mass eigenstates: $m_i m_j = m^2, Dm^2 \ll (Dm)^2$.

Non-degenerate mass eigenstates: $m_i m_j = m_{\min}^2 + Dm^2$,

$$(Dm)^2 = m_{\min}^2 + \frac{q}{m_{\min}^2 + Dm^2}^2$$

Introduction

Neutrino oscillations and decoherence

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Sensitivity to different regimes

Neutrino oscillations regimes

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Astrophysical neutrinos.

Neutrino oscillations regimes

Astrophysical neutrinos.

Solar neutrinos.

Neutrino oscillations regimes

Astrophysical neutrinos.

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Atmospheric neutrinos.

Neutrino oscillations regimes

Astrophysical neutrinos.

Solar neutrinos.

Atmospheric neutrinos.

Reactor and accelerator neutrinos.

Astrophysical neutrinos

Standard probability damping for astrophysical neutrinos

[C. Giunti et al, Phys. Rev. D 58, 017301 (1998)]

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With identical Gaussian wave-packets at production and detection probability reads

$$P(b \rightarrow a) \propto e^{-\frac{L}{l_{\text{coh}}}} \quad (10)$$

Oscillations are washed out by propagation over such huge distances.

Solar neutrinos

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$$\langle P_{\text{std}}(a \rightarrow a) \rangle = 1 - \frac{1}{2} \sin^2 2q \quad P_{\text{QG}}(a \rightarrow a) = \langle P_{\text{std}}(a \rightarrow a) \rangle \quad (11)$$

Averaged oscillations **not sensitive** to QG-induced decoherence.

Neutrino oscillations regimes

~~Astrophysical neutrinos.~~

~~Solar neutrinos.~~

Atmospheric neutrinos.

Reactor and accelerator neutrinos.

Sensitivity to QG models

Observable effect when $D \ll 1$.

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Observable effect when $D \ll 1$.

Deformation of symmetries:

$$D = \frac{L (Dm^2)^2}{8v_g E_{QG} p^2}$$

Fluctuating minimal length:

$$D = \frac{16LE^4 (Dm)^2}{v_g E_{QG}^5}$$

Stochastic metric fluctuations:

$$D = \frac{L \left(1 + \frac{E^2}{m_i m_j}\right)^2 (Dm)^2}{8v_g E_{QG}}$$

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KamLAND

Data from [KamLAND coll., Phys. Rev. Lett. 101, 119904 (2008)] $L = 180$ Km,
 $m = 1$ eV (conservative choice), $E_{QG} = 10^{24}$ GeV.
 $\Delta m^2 = 7.53 \cdot 10^{-5} \text{ eV}^2$, $\sin^2 2\theta = 0.85$ [PDG coll., Rev. of Part. Phys., PTEP 2022
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Matter effects) Focus on high energies ($\frac{L}{E} < 45 \frac{\text{Km}}{\text{MeV}}$).

QG decoherence **not stronger** than matter decoherence (conservative choice)) $E_{\text{QG}} > E_{\text{QG}}^{c^2} : Dc^2 = c_{\text{QG}}^2 \quad c_{\text{KL}}^2 = 2.7.$

QG decoherence **not stronger** than matter decoherence (conservative choice)) $E_{\text{QG}} > E_{\text{QG}}^{c^2} : Dc^2 = c_{\text{QG}}^2 \quad c_{\text{KL}}^2 = 2.7.$

$$E_{\text{QG}} > 4.1 \cdot 10^{24} \text{ GeV} \quad (12)$$

Super-Kamiokande

Data from [SK, Phys. Rev. Lett. 93, 221803 (2004)] $L = 10 \text{ Km}$, $m_{\text{min}} = 1 \text{ eV}$ (both conservative choices), $E_{\text{QG}} = 10^{30} \text{ GeV}$. $Dm^2 = 2.45 \cdot 10^3 \text{ eV}^2$, $\sin^2 2q = 0.99$ [PDG coll., Rev. of Part. Phys., PTEP 2022 (2022) 083C01]

Super-Kamiokande

Data from [SK, Phys. Rev. Lett. 93, 221803 (2004)] $L = 10 \text{ Km}$, $m_{\text{min}} = 1 \text{ eV}$ (both conservative choices), $E_{\text{QG}} = 10^{30} \text{ GeV}$. $\Delta m^2 = 2.45 \cdot 10^3 \text{ eV}^2$, $\sin^2 2\theta = 0.99$ [PDG coll., Rev. of Part. Phys., PTEP 2022 (2022) 083C01] **Fast oscillations**) Focus on high energies ($\frac{L}{E} < 1000 \frac{\text{Km}}{\text{GeV}}$).

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No significant damping from QG decoherence)

$$E_{QG} > E_{QG}^{c^2} : Dc^2 = c_{QG}^2 \quad c_{std}^2 = 2.7.$$

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$$E_{QG} > 4.2 \cdot 10^{34} \text{ GeV} \quad (13)$$

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Conclusions

- Derived a general formalism for decoherence effects in neutrino oscillations that can be applied to any Lindblad-type evolution.

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- Derived a general formalism for decoherence effects in neutrino oscillations that can be applied to any Lindblad-type evolution.
- **Strong constraints** on the stochastic metric fluctuations scale from long baseline reactor and atmospheric neutrinos.

Conclusions

Thank you!