Constraints on quantum spacetime-induced decoherence from neutrino oscillations

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INFN Istituto Nazionale di Fisica Nucleare

Università degli Studi di Napoli Federico II

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

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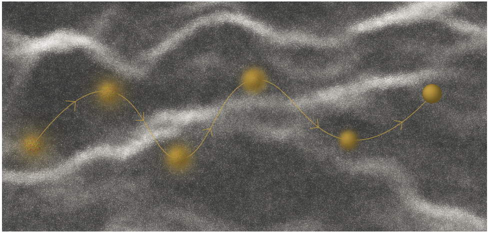
Fundamental decoherence: no interaction with an environment.



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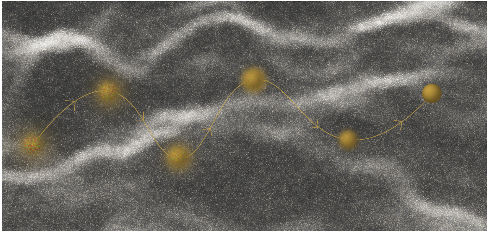

Decoherence modifies neutrino oscillations

- Damping factor in oscillation probability
- Quenching of neutrino fluxes

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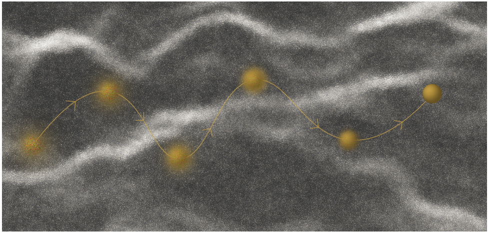

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Oscillation probability

States

$$|\nu_\gamma\rangle = \sum_i U^*_{\gamma i}\,|\psi_i\rangle \otimes |\nu_i\rangle = \sum_i U^*_{\gamma i} \int \mathrm{d}^3p\,\psi_i(\boldsymbol{p})\,|\boldsymbol{p}\rangle \otimes |\nu_i\rangle \qquad (1)$$

Probability given by

$$P(\beta \to \alpha; t) = \mathrm{Tr}\{\rho(t)\,|\nu_\alpha\rangle\langle\nu_\alpha|\}\,, \quad \rho(0) = |\nu_\beta\rangle\langle\nu_\beta| \qquad (2)$$

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$$\underbrace{\partial_t\rho = -i[H,\rho]}_{\text{Standard QM}} \longmapsto \underbrace{\partial_t\rho = \mathfrak{L}[\rho]}_{\text{Decoherence}} \tag{3}$$

$$\rho(t) = \sum_{i,j} U^*_{\beta i}U_{\beta j} \int \mathrm{d}^3p\,\mathrm{d}^3q\;\psi_i(\boldsymbol{p})\psi^*_j(\boldsymbol{q})e^{-it\left[E_i(\boldsymbol{p})-E_j(\boldsymbol{q})\right]}e^{-t\mathcal{L}_{ij}(\boldsymbol{p},\boldsymbol{q})}\,|\boldsymbol{p}\rangle\langle\boldsymbol{q}| \otimes |\nu_i\rangle\langle\nu_j| \tag{4}$$

Oscillation Probability

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

$$P_{QG}(\beta \to \alpha; L) \propto \sum_{i,j} U^*_{\beta i} U_{\beta j} U^*_{\alpha j} U_{\alpha i}\, e^{i\phi_{ij}} \frac{2\pi}{v_{g_{ij}}} \int_{-\infty}^{+\infty} \mathrm{d}p\, e^{ip(1-r_{ij})L} \cdot$$

$$\cdot G_{ij}(p, r_{ij}\, p + \Delta E_{ij}/v_{g_j}) e^{-D_{ij}\left(p+p_i, r_{ij}p+p_j-v_{g_j}^{-1}\Delta E_{ij}; L\right)} \tag{5}$$

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$$D_{ij}(p,q;L) = v_{g_{ij}}^{-1} L\, \mathcal{L}_{ij}(p,q),\ r_{ij} = v_{g_i} \cdot v_{g_j}^{-1},\ \phi_{ij} = -L\frac{\Delta m^2_{ij}}{2\, p_{ij}}.$$

Two flavours probability

Propagation coherence condition

$$L \ll l_{\mathrm{coh}} = \sigma_X \frac{v_{g_{ij}}}{\Delta v_{g_{ij}}} \quad (6)$$

Interaction coherence condition

$$\Delta E_{ij} \frac{\sigma_X}{v_{g_{ij}}} \ll 1 \quad (7)$$

Probability simplifies to

$$P_{QG}(\beta \to \alpha; L) = \sum_{i,j} U^*_{\beta i} U_{\beta j} U^*_{\alpha j} U_{\alpha i}\, e^{i\phi_{ij}} e^{-D_{ij}(p_i, p_j; L)} \quad (8)$$

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Considering two flavours oscillations, probability further simplifies

$$P_{QG}(\alpha \to \alpha) = e^{-D} P_{\text{std}}(\alpha \to \alpha) + \left(1 - e^{-D}\right)\left(1 - \frac{1}{2}\sin^2 2\theta\right) \tag{9}$$

with $P_{\text{std}}(\alpha \to \alpha) = 1 - \sin^2 2\theta \sin^2 \frac{\phi}{2}$.

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Fundamental decoherence QG models

Deformation of symmetries: $D = \frac{L\left(\Delta m^2\right)^2}{8 v_g E_{QG}\, p^2}$

[*M. Arzano et al, Commun.Phys. 6 (2023) 1, 242*].

Fluctuating minimal length: $D = \frac{16 L E^4 (\Delta m)^2}{v_g E_{QG}^5}$

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

Stochastic metric fluctuations: $D = \frac{L\, E^6 \left(\Delta m^2\right)^2}{4 v_g E_{QG}\, m_i^4 m_j^4}$

[*H. Breuer et al, Class. Quant. Grav. 26, 105012, (2009)*, VDE and G. Gubitosi, arXiv:2306.14778].

Neutrino oscillations regimes

Neutrino oscillations regimes

Astrophysical neutrinos.

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Astrophysical neutrinos.

Solar neutrinos.

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Atmospheric neutrinos.

Neutrino oscillations regimes

Astrophysical neutrinos.

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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

$$P(\beta \to \alpha) \propto e^{-\frac{L}{l_{\mathrm{coh}}}} \tag{10}$$

Oscillations are washed out by propagation over such huge distances.

Solar neutrinos

$\cos\phi$ rapidly oscillating. $\Rightarrow$ Averaged probability is observed.

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$$\langle P_{\text{std}}(\alpha \to \alpha)\rangle = 1 - \frac{1}{2}\sin^2 2\theta \Rightarrow \left\langle P_{QG}(\alpha \to \alpha)\right\rangle = \langle P_{\text{std}}(\alpha \to \alpha)\rangle \tag{11}$$

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 $D \gtrsim 1$.

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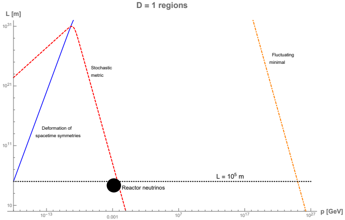

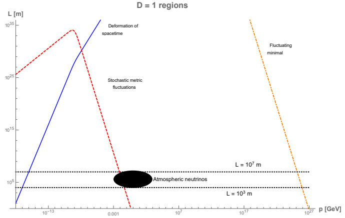

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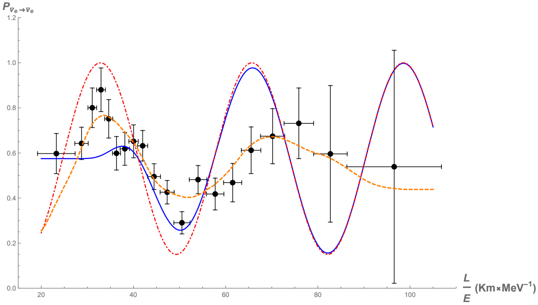
KamLAND



Data from [*KamLAND coll., Phys. Rev. Lett. 101, 119904 (2008)*]. $L = 180\,\text{Km}$, $m = 1\,\text{eV}$ (conservative choice), $E_{QG} = 10^{34}\,\text{GeV}$.
$\Delta m^2 = 7.53 \times 10^{-5}\,\text{eV}^2$, $\sin^2 2\theta = 0.85$ [*PDG coll., Rev. of Part. Phys., PTEP 2022 (2022) 083C01*].

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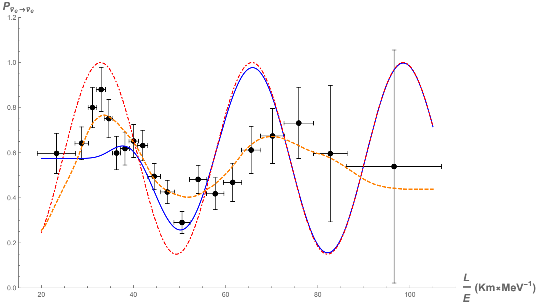

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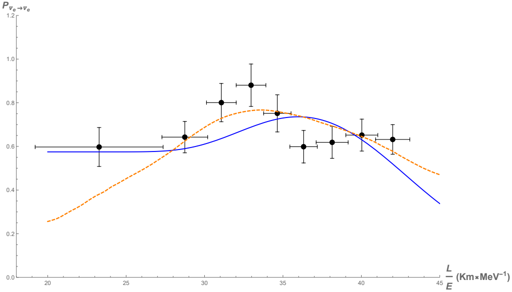
Several reactors $\Rightarrow$ Focus on high energies ($\frac{L}{E} < 45\,\frac{\text{Km}}{\text{MeV}}$).

KamLAND



QG decoherence **not stronger** than standard decoherence (conservative choice) $\Rightarrow E_{QG} > E_{QG}^{\chi^2} \; : \; \Delta\chi^2 = \chi^2_{QG} - \chi^2_{\text{KL}} = 2.7.$

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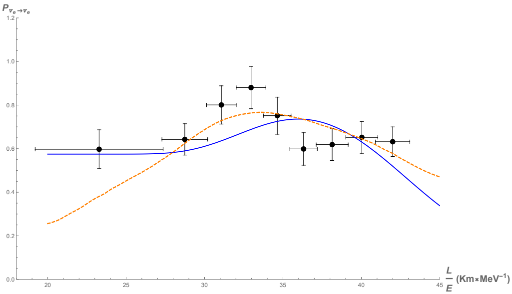

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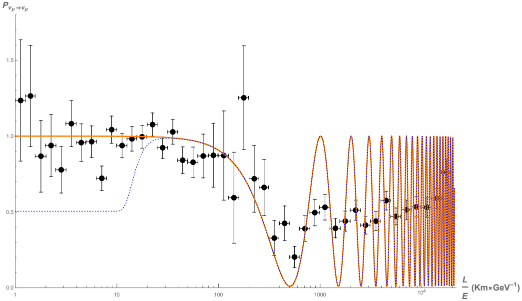
$$E_{QG} > 2.6 \times 10^{34}\,\mathrm{GeV} \tag{12}$$

Super-Kamiokande



Data from [*SK, Phys. Rev. Lett. 93, 221803 (2004)*]. $L = 10\,\mathrm{Km}$, $m_{\min} = 1\,\mathrm{eV}$ (both conservative choices), $E_{QG} = 10^{49}\,\mathrm{GeV}$. $\Delta m^2 = 2.45 \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2 2\theta = 0.99$ [*PDG coll., Rev. of Part. Phys., PTEP 2022 (2022) 083C01*].

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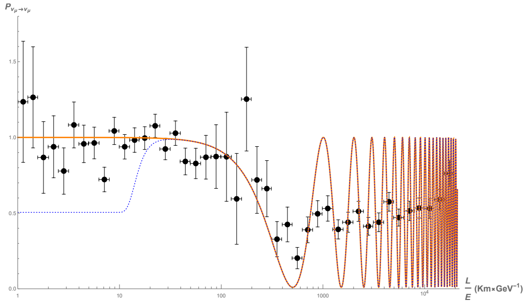

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Fast oscillations $\Rightarrow$ Focus on high energies ($\frac{L}{E} < 1000\,\frac{\text{Km}}{\text{GeV}}$).

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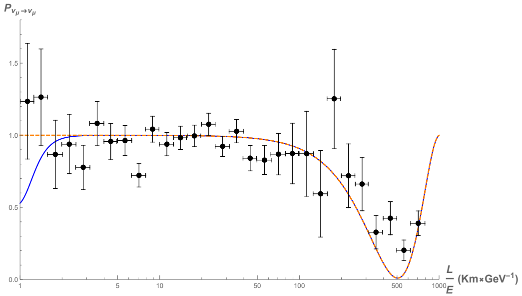

No significant damping from QG decoherence ⇒

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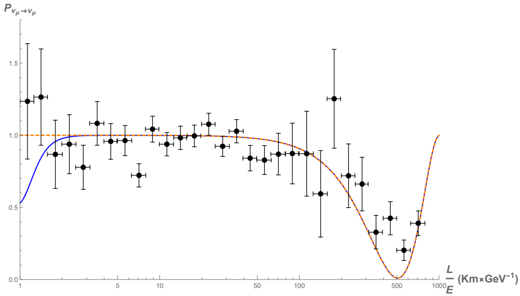

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$$E_{QG} > 2.5 \times 10^{55}\,\text{GeV} \tag{13}$$

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- **Strong constraints** on the stochastic metric fluctuations scale from long baseline reactor and atmospheric neutrinos.

Thank you!