Fundamental decoherence and neutrino oscillations

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11 July 2023

Based on arXiv:2306.14778 with Giulia Gubitosi

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QG-induced fundamental decoherence

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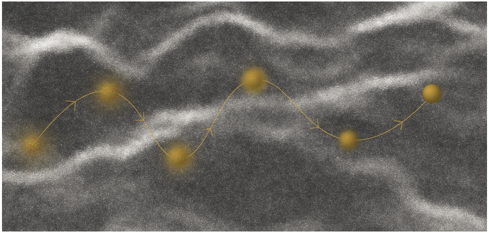
Fundamental decoherence: no interaction with an environment.



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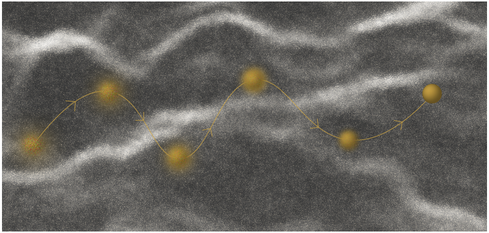

Decoherence modifies neutrino oscillations

- Damping factor in oscillation probability
- Quenching of neutrino fluxes

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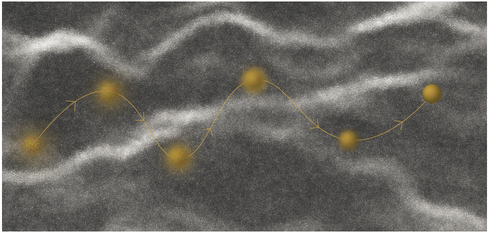

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Oscillation probability

States

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

Probability given by

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

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

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

Oscillation Probability

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

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

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

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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

$$L \ll l_{\text{coh}} = \sigma_X \frac{v_{g_{ij}}}{\Delta v_{g_{ij}}} \tag{6}$$

Interaction coherence condition

$$\Delta E_{ij} \frac{\sigma_X}{v_{g_{ij}}} \ll 1 \tag{7}$$

Probability simplifies to

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

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

Contents

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, accepted on Communication Physics*].

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

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Degenerate mass eigenstates: $m_i m_j \sim m^2$, $\Delta m^2 \sim (\Delta m)^2$.

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

$$(\Delta m)^2 = \left(-m_{\min} + \sqrt{m_{\min}^2 + \Delta m^2}\right)^2$$

Neutrino oscillations regimes

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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)*].

Astrophysical neutrinos

Standard probability damping for astrophysical neutrinos
[*C. Giunti et al, Phys. Rev. D 58, 017301 (1998)*].
With identical Gaussian wave-packets at production and detection probability reads

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

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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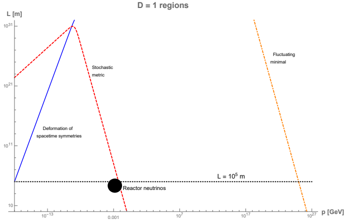
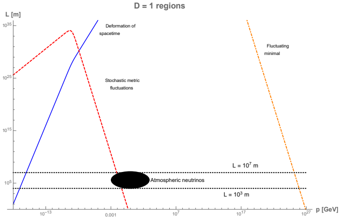
Stochastic metric fluctuations:

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





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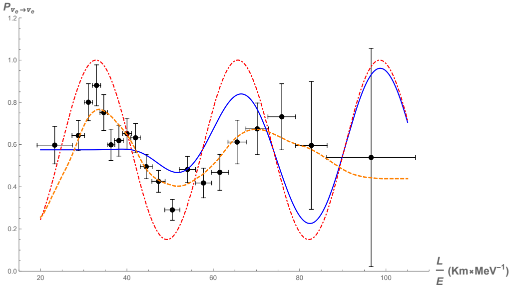
KamLAND



Data from [*KamLAND coll., Phys. Rev. Lett. 101, 119904 (2008)*]. $L = 180\,\text{Km}$, $m = 1\,\text{eV}$ (conservative choice), $E_{QG} = 10^{24}\,\text{GeV}$.
$\Delta m^2 = 7.53 \times 10^{-5}\,\text{eV}^2$, $\sin^2 2\theta = 0.85$ [*PDG coll., Rev. of Part. Phys., PTEP 2022 (2022) 083C01*].

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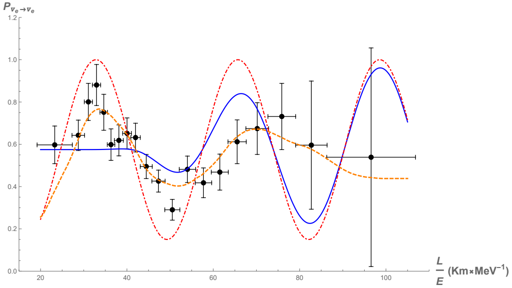

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Matter effects $\Rightarrow$ Focus on high energies ($\frac{L}{E} < 45\,\frac{\text{Km}}{\text{MeV}}$).

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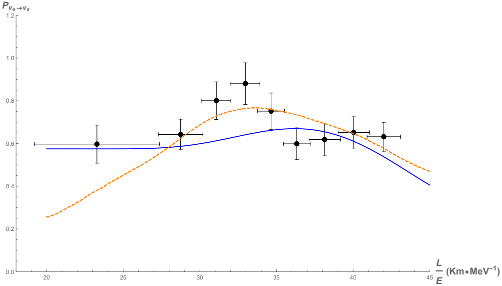

QG decoherence **not stronger** than matter decoherence (conservative choice) $\Rightarrow E_{QG} > E_{QG}^{\chi^2} \; : \; \Delta\chi^2 = \chi^2_{QG} - \chi^2_{\mathrm{KL}} = 2.7.$

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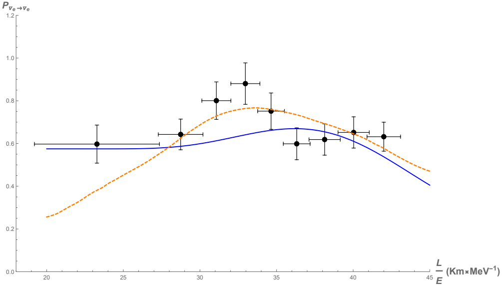

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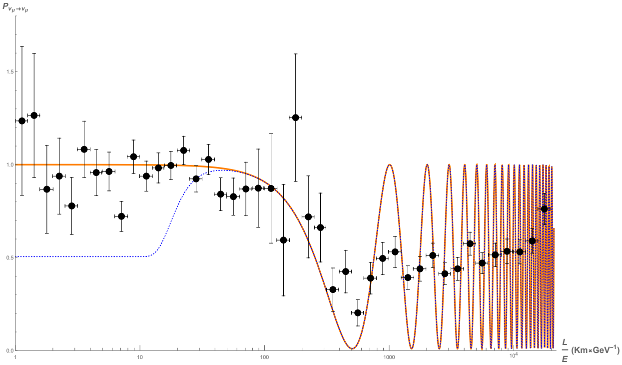
$$E_{QG} > 4.1 \times 10^{24}\,\mathrm{GeV} \tag{12}$$

Super-Kamiokande



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

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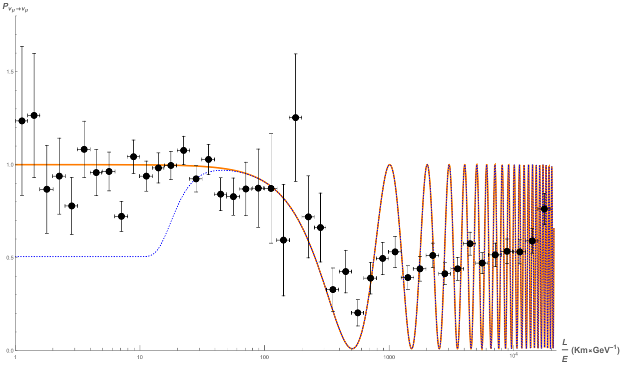

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Fast oscillations $\Rightarrow$ Focus on high energies ($\frac{L}{E} < 1000\,\frac{\text{Km}}{\text{GeV}}$).

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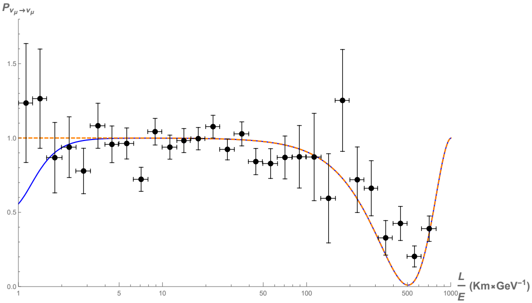

No significant damping from QG decoherence ⇒

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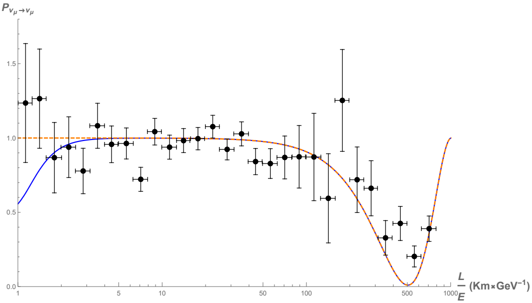

No significant damping from QG decoherence ⇒

$E_{QG} > E_{QG}^{\chi^2}$: $\Delta\chi^2 = \chi^2_{QG} - \chi^2_{\rm std} = 2.7$.

$$E_{QG} > 4.2 \times 10^{34}\,\mathrm{GeV} \tag{13}$$

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

Conclusions

Thank you!