Testing Quantum Aspects of Gravity at Low Energies

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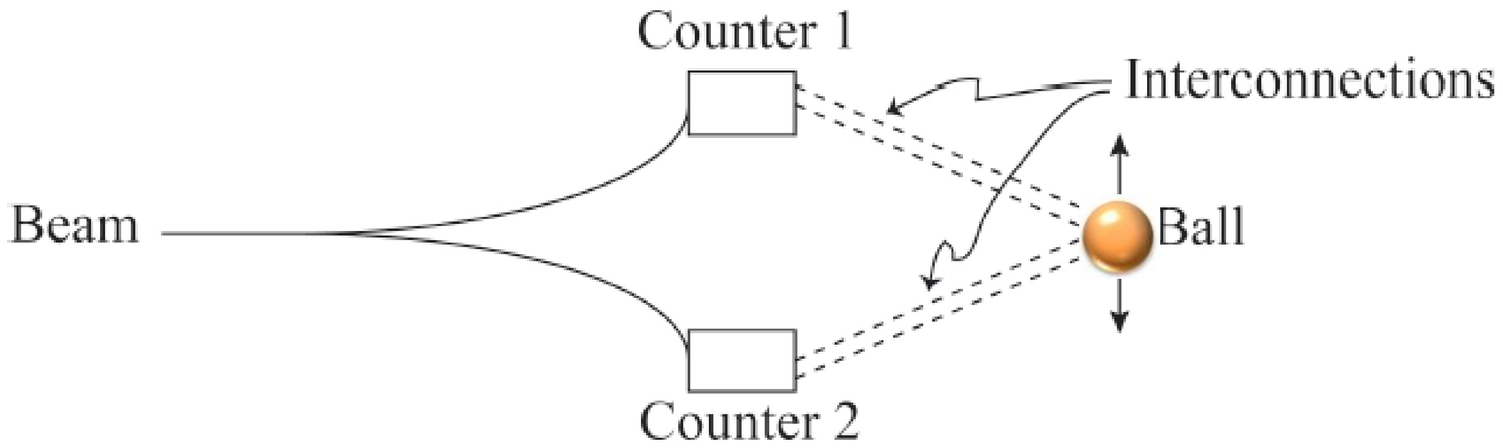
on joint work with
Ludovico Lami, Julen Pedernales,
Giovanni Spaventa & Kirill Streltsov



Test body

Feynman 1957
Lindner & Peres, PRA 2005
Kafri & Taylor, arXiv: 1311.4558
Kafri, Taylor, Milburn, NJP 2014
Krisnanda et al arXiv:1607.01140
....

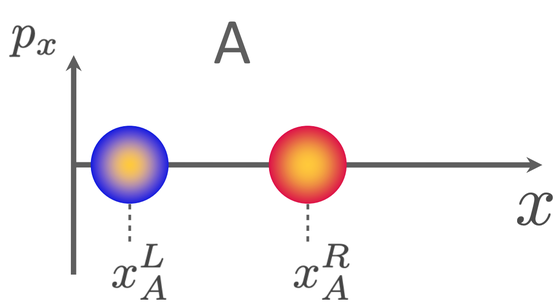
$$|z_B\rangle_B|z_T\rangle_T + |-z_B\rangle_B|-z_T\rangle_T$$ Q Gravity

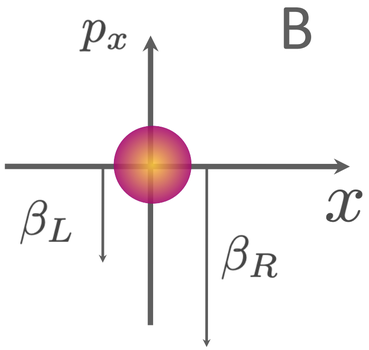
$$|z_B\rangle_B\langle z_B| \otimes |z_T\rangle_T\langle z_T| + |-z_B\rangle_B\langle -z_B| \otimes |-z_T\rangle_T\langle -z_T|$$ Classical Gravity

The presence of quantum correlations verifies the quantum character of the field mediating the interaction

R.P. Feynman, in a discussion at „The role of Gravitation in Physics“, 1957 Chapel Hill Conference (DeWitt and Rickles eds.)

Feynman





$$|\Psi\rangle = (|L\rangle_A + |R\rangle_A) \otimes |\chi\rangle_B \longrightarrow |\tilde{\Psi}\rangle = |L\rangle_A \otimes D(\beta_L)\,|\chi\rangle_B + |R\rangle_A \otimes D(\beta_R)\,|\chi\rangle_B$$

Entangled if $\quad {}_B\langle\chi|\, D(\beta_L)^\dagger D(\beta_R)\,|\chi\rangle_B < 1 \longrightarrow \beta_L - \beta_R > \Delta p_0$

Squeezed state

$$|\Psi\rangle = (|L\rangle_A + |R\rangle_A) \otimes |\xi\rangle \longrightarrow |\tilde{\Psi}\rangle = |L\rangle_A \otimes D(\beta_L)|\xi\rangle_B + |R\rangle_A \otimes D(\beta_R)|\xi\rangle_B$$

Krisnanda, Tham, Paternostro, Paterek., npj QI. 2020
Weiss, Roda-Llordes, Torrontegui, Aspelmeyer, Romero-Isart, PRL 2021
Cosco, Paternostro, Plenio., PRA 2021

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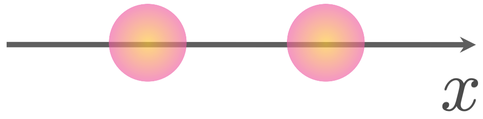
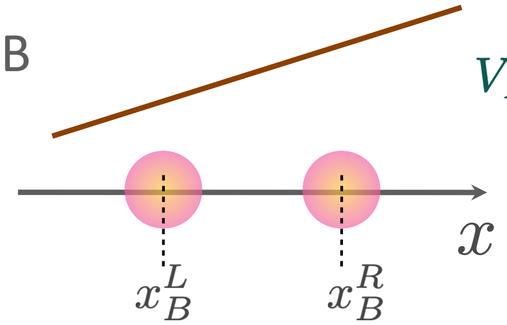
Cat state





$$\phi_{LR} = \frac{V_L(x_B^R) - V_L(x_B^L)}{\hbar}$$

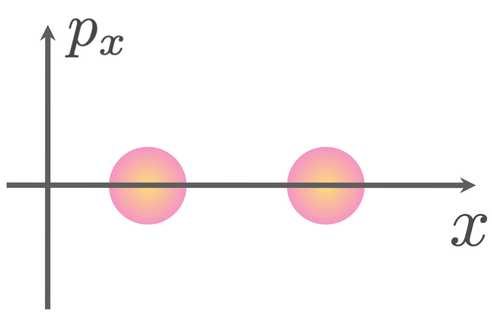
$$\phi_{RL} = \frac{V_R(x_B^R) - V_R(x_B^L)}{\hbar}$$

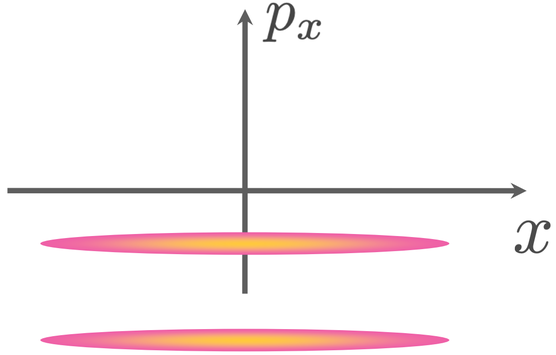
$$|\Psi\rangle = (|L\rangle_A + |R\rangle_A) \otimes (|L\rangle_B + |R\rangle_B) \longrightarrow |\tilde{\Psi}\rangle = |L\rangle_A \otimes (|L\rangle_B + e^{i\phi_{LR}t}|R\rangle_B) + |R\rangle_A \otimes (e^{i\phi_{RL}t}|L\rangle_B + |R\rangle_B)$$

Entangled if $\phi_{RL} \neq \phi_{LR}$

Bose, Mazumdar, Morley, Ulbricht, Toros, Paternostro, Geraci, Barker, Kim, Milburn, PRL **119**, 240401 (2017)
...

Squeezed state





$$|\Psi\rangle = (|L\rangle_A + |R\rangle_A) \otimes |\xi\rangle \longrightarrow |\tilde{\Psi}\rangle = |L\rangle_A \otimes D(\beta_L)|\xi\rangle_B + |R\rangle_A \otimes D(\beta_R)|\xi\rangle_B$$

Krisnanda, Tham, Paternostro, Paterek., npj QI. 2020
Weiss, Roda-Llordes, Torrontegui, Aspelmeyer, Romero-Isart, PRL 2021
Cosco, Paternostro, Plenio., PRA 2021

$$H = \beta x$$

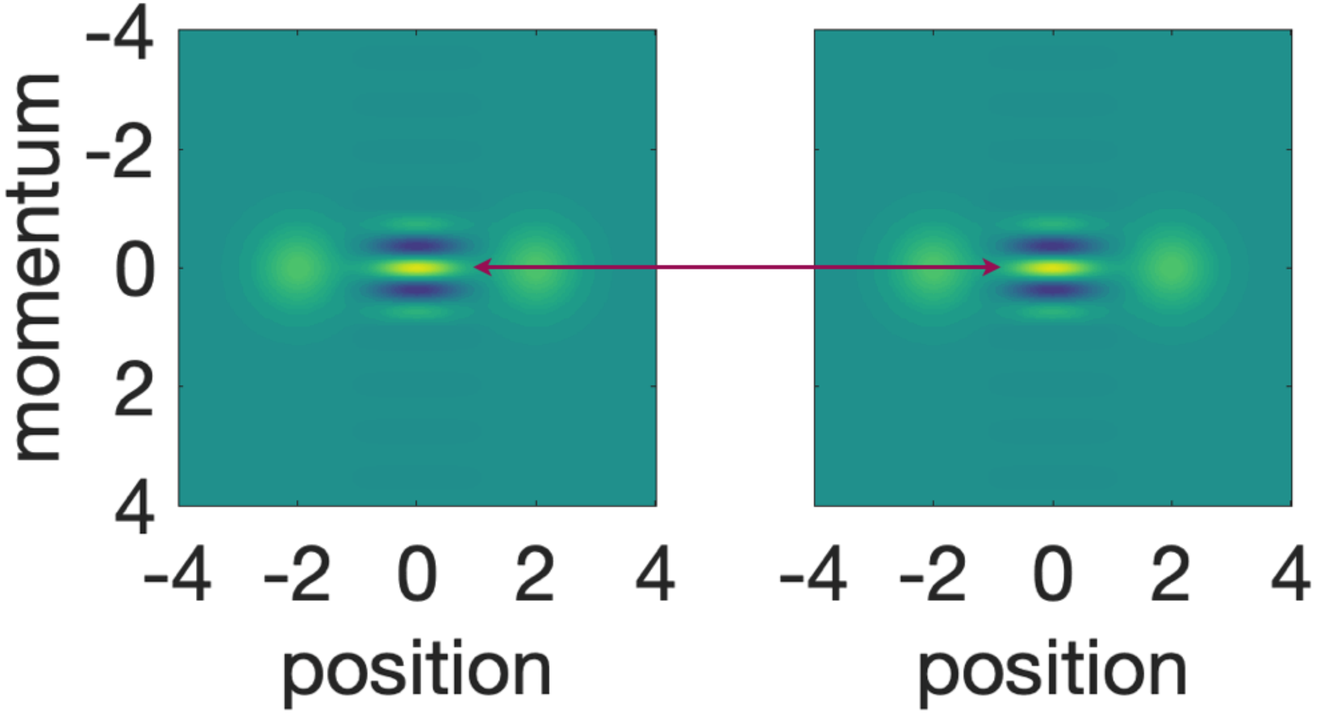
Change of relative phase

$$|\Psi(t)\rangle = |-\alpha\rangle + e^{-i\beta\Delta x t}\,|\alpha\rangle$$

$$|\Psi_0\rangle = |-\alpha\rangle + |\alpha\rangle$$

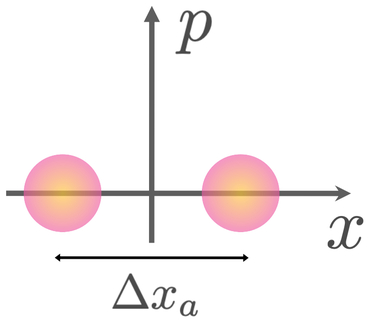
Displacement in momentum

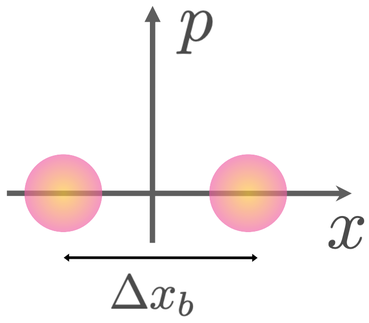
$$|\Psi(t)\rangle = D(\beta t/2)\,|\Psi_0\rangle$$



$$\text{Fidelity} \sim \int dx dp W_1(x,p) W_2(x,p)$$

Enhancing the signal by delocalization in phase space





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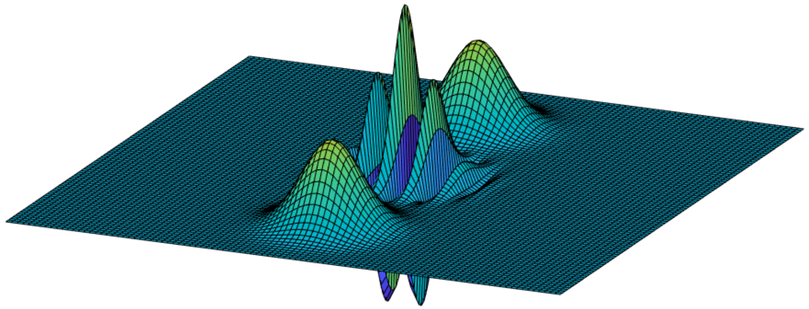
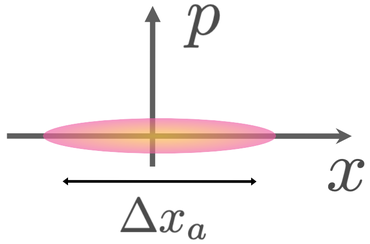
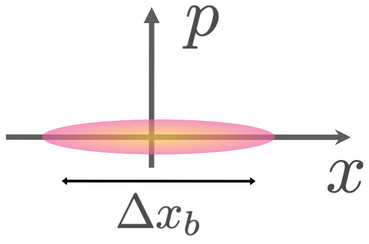
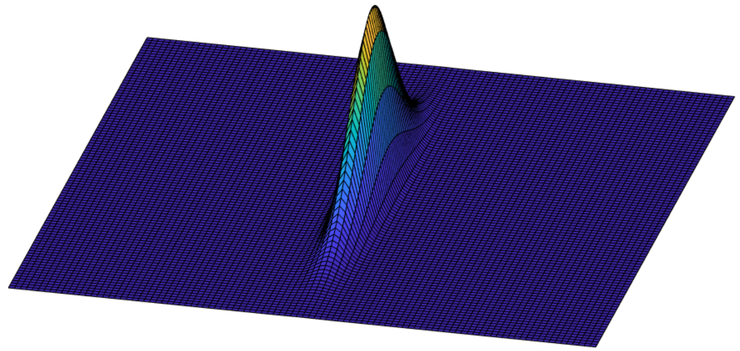


$$\Delta p \sim \frac{\hbar}{\Delta x}$$







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Cosco, Paternostro, Plenio., PRA 2021

What is needed ?

- Do we need to study entanglement to determine the quantum character of the gravitational interaction ?

  Lami, Pedernales, Plenio, arxiv:2302.03075

- Are there loopholes in currently proposed tests ?

  - What if quantum mechanics is replaced by GPTs?

    Rexamination in GPTs by Galley, Giacomini, Selby, arxiv:2012.01441

  - What if quantum mechanics is non-linear ?

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We call the gravitational interaction quantum mechanical if

If it can entangle distant test masses

Feynman 1957
Lindner & Peres, PRA 2005
Kafri & Taylor, arXiv: 1311.4558
Kafri, Taylor, Milburn, NJP 2014
Krisnanda et al arXiv:1607.01140
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We call the gravitational interaction
classical if its action can be modelled by
local quantum operations and classical communication

If it **cannot** entangle
distant test masses

Feynman 1957
Lindner & Peres, PRA 2005
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Kafri, Taylor, Milburn, NJP 2014
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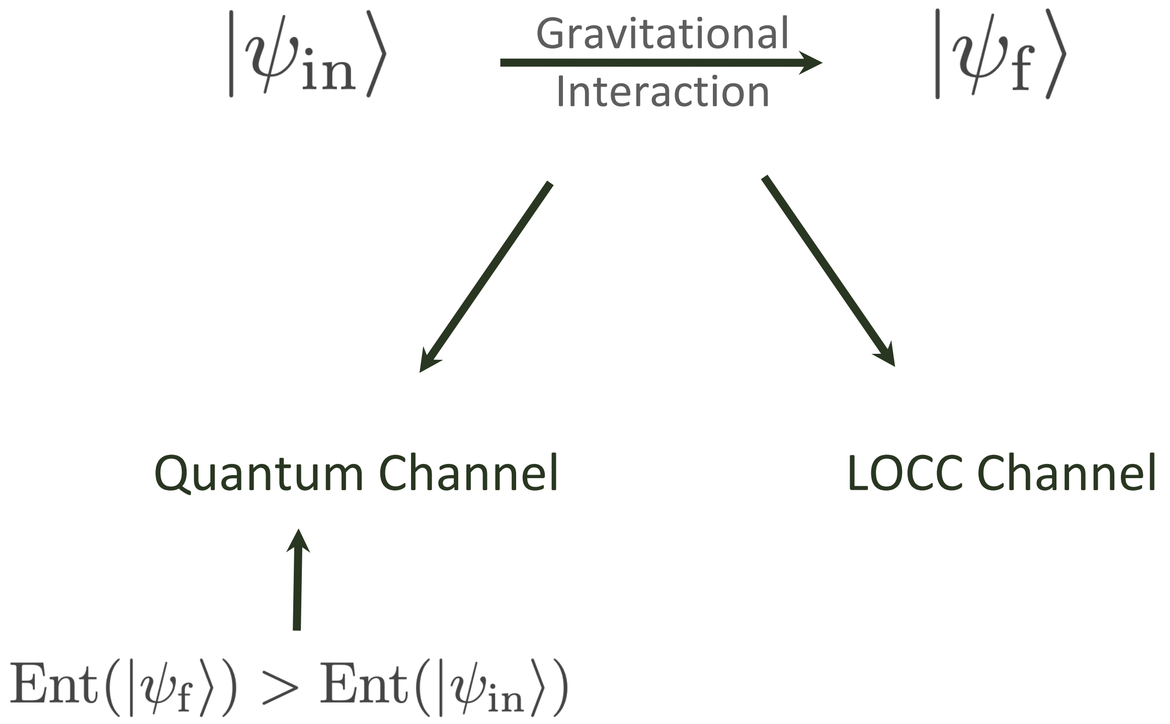
Do we need entanglement ?



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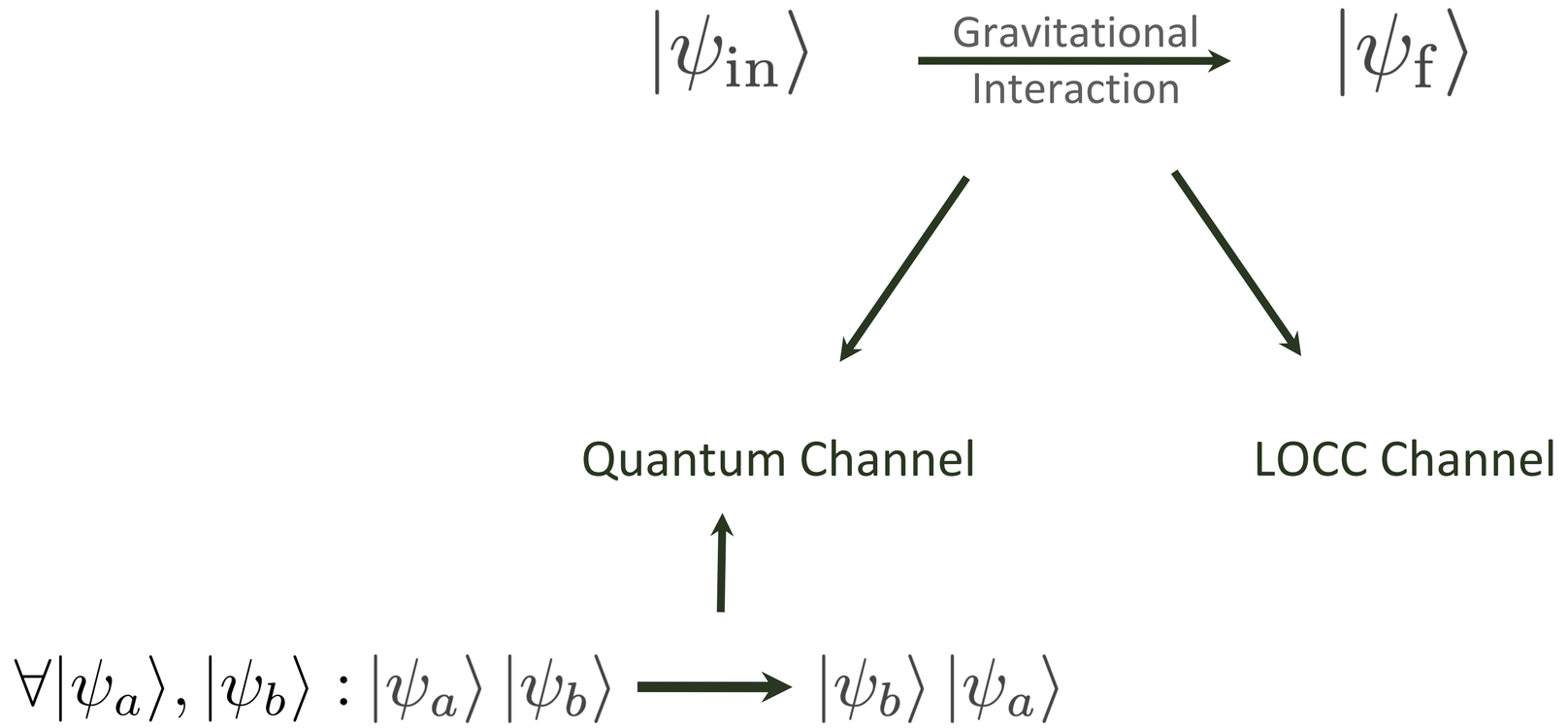
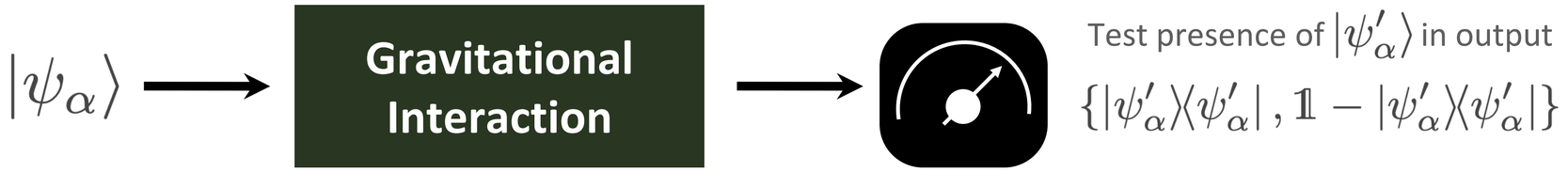


Lami, Pedernales, Plenio, arXiv:2307.03075

Do we need entanglement ?

$$\mathcal{E} = \{p_\alpha, |\psi_\alpha\rangle\}_\alpha$$

$$|\psi'_\alpha\rangle = U_{\text{grav}} |\psi_\alpha\rangle$$



Gravitational interaction is quantum mechanical:

$$P(Q|U_{\text{grav}}) = \sum_\alpha p_\alpha \,\text{Tr}\left[|\psi'_\alpha\rangle\langle\psi'_\alpha| \, U_{\text{grav}} \, |\psi_\alpha\rangle\langle\psi_\alpha| \, U^\dagger_{\text{grav}}\right] = 1$$

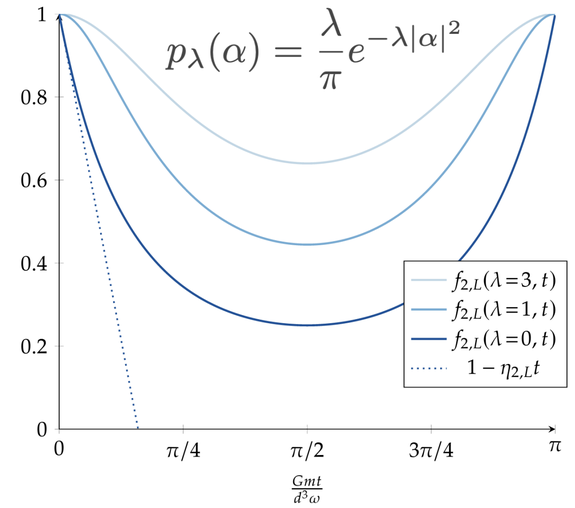
Gravitational interaction is LOCC (or even PPT)

$$P(Q|LOCC) = \sum_\alpha p_\alpha \,\text{Tr}[|\psi'_\alpha\rangle\langle\psi'_\alpha| \, \Lambda_{\text{LOCC}}(|\psi_\alpha\rangle\langle\psi_\alpha|)] < P(Q|U_{grav})$$

Can be rigorously bounded away from unity and can be tested experimentally

Coherent state ensemble subject to beam-splitter type of Hamiltonian

– There is never any entanglement in the entire experiment



Lami, Pedernales, Plenio, arXiv:2307.03075

Do we need entanglement ?

Potential advantages: Disproves larger set of theories as inequality holds for

LOCC

Separable superoperators

$$\Phi(\rho) = \sum_i A_i \otimes B_i \rho A_i^\dagger \otimes B_i^\dagger$$

Require entanglement to be generated
Bennett et al PRA 2001

PPT-preserving operations

Any protocol that cannot be achieve by LOCC/SEPP/PPT will serve the purpose of unveiling the different levels of non-classicality of gravity

E.g. prepare GHZ and manipulate by gravitational interaction and transform to W-state.

$$p_{succ}^{LOCC} = 0 \qquad p_{succ}^{PPT} = 0.75463... \qquad p_{succ}^{QM} = 1$$

Dür,Vidal, Cirac, PRA 2000 Ishizaki & Plenio, PRA 2005

Lami, Pedernales, Plenio, arXiv:2307.03075

Are there loopholes ?

- Do we need to study entanglement to determine the quantum character of the gravitational interaction ?

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  - What if quantum mechanics is non-linear ?

    Spaventa, Lami, Plenio, arxiv:2302.00365

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Are there loopholes ?

PHYSICAL REVIEW
LETTERS

VOLUME 63 4 SEPTEMBER 1989 NUMBER 10

Test of the Linearity of Quantum Mechanics by rf Spectroscopy of the $^9Be^+$ Ground State

J. J. Bollinger, D. J. Heinzen, Wayne M. Itano, S. L. Gilbert, and D. J. Wineland
National Institute of Standards and Technology, Boulder, Colorado 80303
(Received 15 May 1989)

A hyperfine transition in the ground state of $^9Be^+$ was used to test a nonlinear generalization of quantum mechanics recently formulated by Weinberg. We searched for a dependence of the frequency of a coherent superposition of two hyperfine states on the populations of the states. We are able to set a limit of 4×10^{-27} on the fraction of binding energy per nucleon of the $^9Be^+$ nucleus that could be due to nonlinear corrections to quantum mechanics.

Linearity of quantum mechanics has been tested extremely well at low masses, but **not** for massive particles deep in the quantum regime

Testing Quantum Mechanics

STEVEN WEINBERG*

Theory Group, Department of Physics,
University of Texas, Austin, Texas 78712

Received March 6, 1989

This paper presents a general framework for introducing nonlinear corrections into ordinary quantum mechanics, that can serve as a guide to experiments that would be sensitive to such corrections. In the class of generalized theories described here, the equations that determine the time-dependence of the wave function are no longer linear, but are of Hamiltonian type. Also, wave functions that differ by a constant factor represent the same physical state and satisfy the same time-dependence equations. As a result, there is no difficulty in combining separated subsystems. Prescriptions are given for determining the states in which observables have definite values and for calculating the expectation values of observables for general states, but the calculation of probabilities requires detailed analysis of the method of measurement. A study is presented of various experimental possibilities, including the precession of spinning particles in external fields, experiments of Stern–Gerlach type, and the broadening and de-tuning of absorption lines. © 1989 Academic Press, Inc.

Coupling classical gravity to matter can give rise to non-linear equations of motion, see e.g. Kibble & Randjbar-Daemi, J. Phys. A: Math. Gen. 1980

Non-linear extensions to QM have manifold problems such as signalling

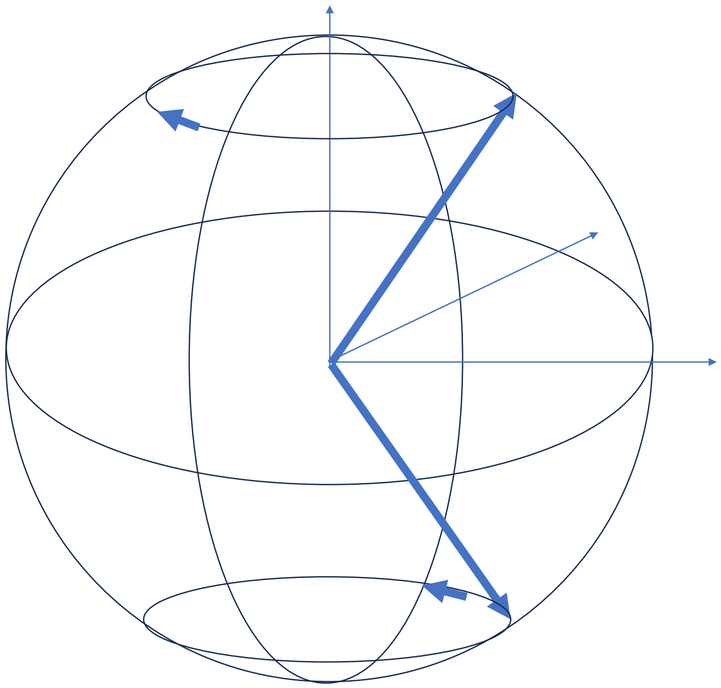
Gisin, PLA 1989; Polchinski PRL 1989

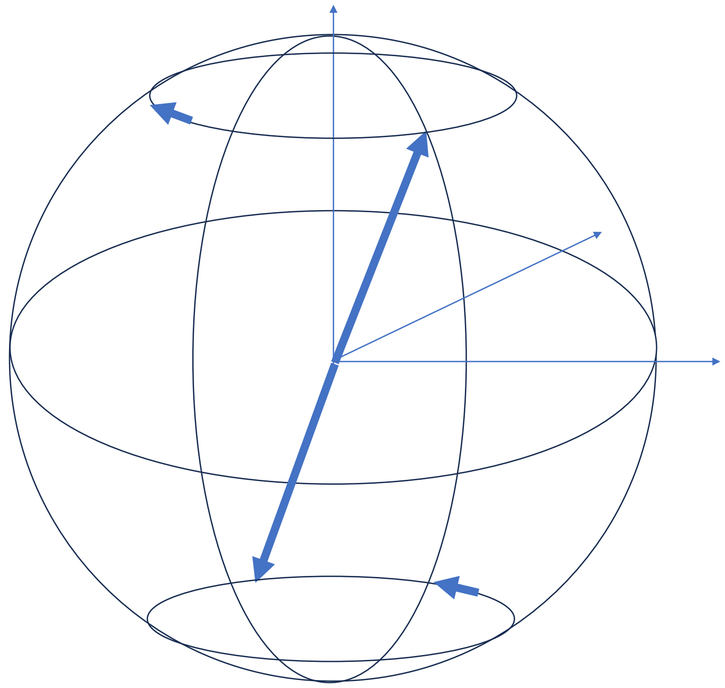
but maybe this can be fixed with clever variations?

Kent, PRA 2005, Kaplan, Rajendran 2106.10576.pdf

Testing Quantum Aspects of Gravity at Low Energies

Are there loopholes ?





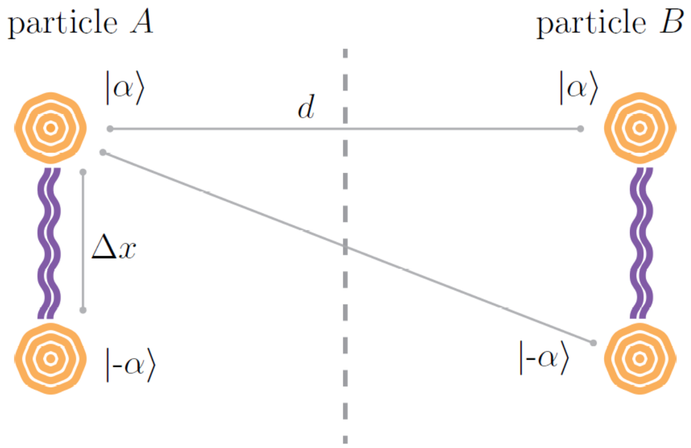
$$\frac{d}{dt}|\psi\rangle = -2i\langle\sigma_z\rangle\sigma_z|\psi\rangle$$

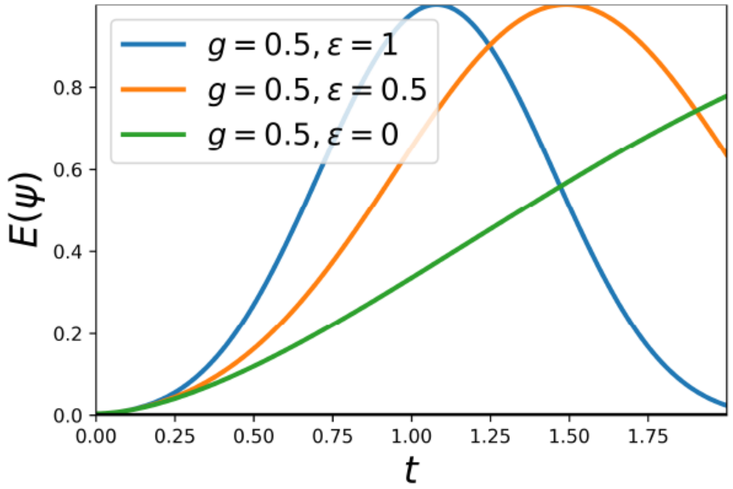
$$h(|\psi\rangle\langle\psi|) = \frac{\langle\psi|\sigma_z|\psi\rangle^2}{\langle\psi|\psi\rangle}$$

$$|\psi_{AB}\rangle = |0\rangle|\phi_0\rangle + |1\rangle|\phi_1\rangle$$

$$|\psi_{AB}\rangle = |0\rangle|\phi\rangle + |1\rangle|\phi^{\perp}\rangle$$

Are there loopholes ?





$$h(|\psi\rangle, \langle\psi|) = g \langle\psi| H_{\text{int}} |\psi\rangle + \epsilon \frac{\langle\psi| \sigma_y^a |\psi\rangle^2}{\langle\psi|\psi\rangle}$$

$$\frac{d}{dt} |\psi\rangle = -i \frac{\partial h}{\partial \langle\psi|}$$

Assume presence of very weak non-gravitational coupling, e.g. Casimir force, much smaller than the strength that gravity would have and observe resulting dynamics

Testing Quantum Aspects of Gravity at Low Energies

Are there loopholes ?

Gravitational

$$\omega_g = \frac{GM_1M_2}{\hbar r}$$

Casimir interaction

$$\omega_c = \frac{23cR_1^3R_2^3}{4\pi r^7}\left(\frac{\epsilon_d - 1}{\epsilon_d + 2}\right)^2$$

For definiteness assume diamond

$$\epsilon_d = 5.7 \qquad \rho = 3.51 \times 10^3 \qquad R_1 = R_2 = 1.307\mu\text{m}, \qquad r = \Delta x = 200\,\mu\text{m},$$

$$|\psi(t)\rangle = |00\rangle + e^{i\omega_g/c\,t}(|01\rangle + |10\rangle) + |11\rangle$$

$$\omega_g = 1 \text{ Hz}$$

Spaventa, Lami, Plenio, arXiv:2302.00365

Testing Quantum Aspects of Gravity at Low Energies

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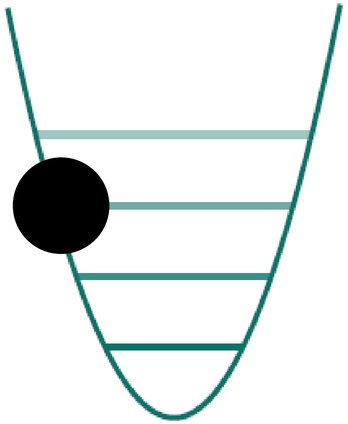
$$|\psi(t)\rangle = |00\rangle + e^{i\omega_g/c\,t}(|01\rangle + |10\rangle) + |11\rangle$$

$$\omega_g = 1 \text{ Hz} \qquad \omega_c = 0.096 \text{ Hz}$$

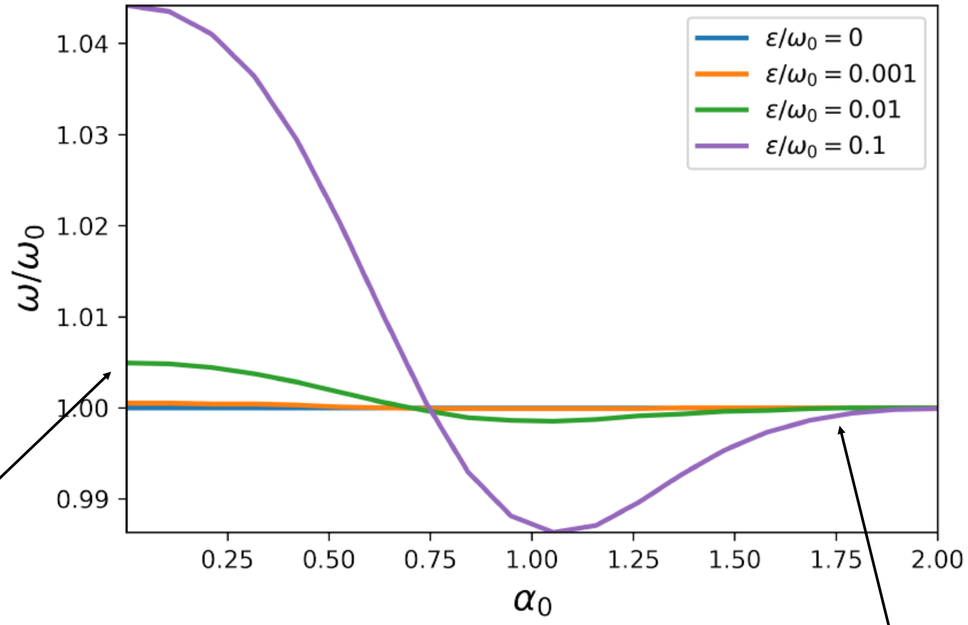
$$\boxed{\epsilon \sim 2.26 \text{ Hz}}$$

Spaventa, Lami, Plenio, arXiv:2302.00365

Are there loopholes ?



$$\frac{\delta\omega_0}{\omega_0} = 4e^{-\frac{\pi^2}{4}}(1-\frac{\pi^2}{4})\frac{\epsilon}{\omega_0} \cong \frac{\epsilon}{2\omega_0}$$



$$-4(\epsilon/\omega_0)e^{-4|\alpha_0|^2}$$

Such small non-linearities seem challenging to verify on the single particle level

A complete test of the quantum character of the gravitational interaction requires at least

Verification of quantum coherent gravitational coupling between two heavy masses

&

Experimental bounds non-linearities in the quantum mechanics of the same masses

Spaventa, Lami, Plenio, arXiv:2302.00365

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