Quantum control and semiclassical quantumgravity

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Abstract

Quantum gravity has not yet obtained a usable theory. We apply the semiclassical theory instead, where the space-time remains classical (i.e.: unquantized). However, the hybrid quantum-classical coupling is acausal, violates both the linearity of quantum theory and the Born rule as well. Such anomalies can go away if we modify the standard mean-field coupling, building on the mechanism of quantum measurement and feed-back well-known in, e.g., quantum optics. The newtonian limit can fully be worked out, it leads to the gravity-related spontaneous wave function collapse theory of Penrose and the speaker.

Fragments from history

Bronstein (1935): A sharp space-time structure is unobservable (because of Schwartzschild radii of test bodies). Quantization of gravity can not copy quantization of electromagnetism. We may be enforced to reject our ordinary concept of space-time.

1906-1938

Jánossy (1952): Quantum mechanics should be more classical. Expansion of the wave packet might be limited by

$$\dot{\psi}(x) = \frac{i\hbar}{2M}\psi''(x) - \gamma(x - \langle x \rangle)^2\psi(x) + \frac{1}{2}\gamma(\Delta x)^2\psi(x)$$

if we accept superluminality caused by the nonlinear term.

1912-1978

Károlyházy (1966): The ultimate unsharpness of space-time structure limits coherent expansion of massive objects' position (while individual particles can expand coherently with no practical limitations).

1929-2012

Semiclassical Gravity 1962-63: sharp metric

Sharp classical space-time metric (Møller, Rosenfeld 1962-63):

$$\mathrm{G}_{ab} = \frac{8\pi G}{c^4}\langle\Psi|\hat{\mathrm{T}}_{ab}|\Psi\rangle$$

Schrödinger equation on background metric g:

$$|\dot{\Psi}\rangle = -\frac{i}{\hbar}\hat{H}[\mathrm{g}]|\Psi\rangle$$

That's our powerful effective hybrid dynamics for $(\mathrm{g}_{ab}, |\Psi\rangle)$, but

- with fundamental anomalies (superluminality, no Born rule, ...)
- that are unrelated to relativity and even gravitation
- just related to quantum-classical coupling
- that makes Schrödinger eq. nonlinear

No deterministic hybrid dynamics is correct fundamentally!

Way out: metric cannot be sharp, must have fluctuations $\delta\mathrm{g}_{ab}$.

Sharp metric Newtonian limit

$$\mathrm{G}_{00} = 8\pi G c^{-4} \langle\Psi|\hat{\mathrm{T}}_{00}|\Psi\rangle \quad \Rightarrow \quad \Delta\Phi = 4\pi G \langle\Psi|\hat{\varrho}|\Psi\rangle$$
$$|\dot{\Psi}\rangle = -(i/\hbar)\hat{H}[\mathrm{g}]|\Psi\rangle \quad \Rightarrow \quad |\dot{\Psi}\rangle = -(i/\hbar)\left(\hat{H}_0 + \int \hat{\varrho}\Phi dV\right)|\Psi\rangle \quad \Rightarrow$$

$\Rightarrow$ Schrödinger-Newton Equation with self-attraction:

$$|\dot{\Psi}\rangle = -\frac{i}{\hbar}\left(\hat{H}_0 - G\iint \frac{\hat{\varrho}(\mathbf{x})\,\langle\Psi|\hat{\varrho}(\mathbf{y})|\Psi\rangle}{|\mathbf{x}-\mathbf{y}|} d\mathbf{x} d\mathbf{y}\right)|\Psi\rangle$$

Single "pointlike" body c.o.m. motion:

$$\dot{\psi}(\mathbf{x}) = \frac{i\hbar}{2M}\nabla^2\psi(\mathbf{x}) + \underbrace{\frac{i}{\hbar} G M^2 \int \frac{|\psi(\mathbf{y})|^2 d\mathbf{y}}{|\mathbf{x}-\mathbf{y}|}\psi(\mathbf{x})}_{\text{self-attraction}}$$

Solitonic solutions: $\Delta x \sim \hbar^2/GM^3$.

Irrelevant for atomic M, grow relevant for nano-M:

$$M \sim 10^{-15} g, \;\; \Delta x \sim 10^{-5} cm$$

That's quantumgravity in the lab [D. 1984].

Testing self-attraction

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Optomechanical test of the Schrödinger-Newton equation

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The Schrödinger-Newton equation has been proposed as an experimentally testable alternative to quantum gravity, accessible at low energies. It contains self-gravitational terms, which slightly modify the quantum dynamics. Here we show that it distorts the spectrum of a harmonic system. Based on this effect, we propose an optomechanical experiment with a trapped microdisc to test the Schrödinger-Newton equation, and we show that it can be realized with existing technology.

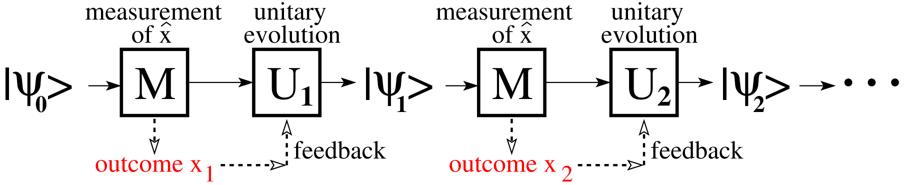
Schrödinger-Newton Equation for $1D$ motion of a Massive oscillator:

$$\dot{\psi}(x) = \frac{i\hbar}{2M}\psi''(x) - \frac{iM}{2\hbar}\left(\Omega^2 x^2 + \omega_G^2 (x - \langle x \rangle)^2\right)\psi(x)$$

$$\omega_G^2 = \text{const.} \times G \times \text{nuclear density in } M$$

Quantum control to generate potential (tutorial)

Sequential measurements of $\hat{x}$ plus feedback:



At ∞ repetition frequency: time-continuous monitoring+feedback.

$$\underbrace{x_t}_{signal} = \underbrace{\langle\Psi_t|\hat{x}|\Psi_t\rangle}_{mean} + \underbrace{\delta x_t}_{noise} \qquad \underbrace{\mathbb{E}\delta x_t \delta x_s}_{correlation} = \underbrace{\gamma^{-1}}_{\gamma=precision}\delta(t-s)$$

To generate a potential, take $\hat{H}_{fb}(t) = Rx_t\hat{x} = R(\langle\Psi_t|\hat{x}|\Psi_t\rangle + \delta x_t)\hat{x}$.

$$|\dot{\Psi}\rangle = \frac{-i}{\hbar}(\hat{H}_0 + \underbrace{\tfrac{1}{2}R\hat{x}^2}_{fb-generated})|\Psi\rangle - \frac{1}{8}\underbrace{[\gamma + 4\gamma^{-1}(R/\hbar)^2]}_{to\ be\ minimized}\underbrace{(\hat{x} - \langle\hat{x}\rangle)^2}_{localisation}|\Psi\rangle + \underbrace{\ldots\delta x}_{stochastic}|\Psi\rangle$$

$$\dot{\hat{\rho}} = \frac{-i}{\hbar}[\hat{H}_0 + \tfrac{1}{2}R\hat{x}^2, \hat{\rho}] - \frac{1}{2\hbar}R[\hat{x}, [\hat{x}, \hat{\rho}]]$$

Quantum control to generate potential (summary)

Assume $\hat{x}$ is being monitored, yielding signal $x_t = \langle\Psi_t|\hat{x}|\Psi_t\rangle + \delta x_t$. Apply feedback via the hybrid Hamiltonian

$$\hat{H}_{fb}(t) = R x_t \hat{x} = \underbrace{R\langle\hat{x}\rangle_t\hat{x}}_{sharp\ \ semiclassical\ \ coupling} + \underbrace{R\delta x_t\hat{x}}_{(white)noise\ \ part\ \ of\ \ coupling}$$

Sharp+noisy terms together cancel nonlinearity (and related anomalies) from the quantum dynamics:

$$\dot{\hat{\rho}} = \frac{-i}{\hbar}[\hat{H}_0 + \tfrac{1}{2}R\hat{x}^2, \hat{\rho}] - \frac{1}{2\hbar}R[\hat{x}, [\hat{x}, \hat{\rho}]]$$

New potential has been generated 'semiclassically' and consistently with quantum mechanics, but at the price of decoherence.

Decoherent Semiclassical Gravity: unsharp metric

- Assume $\hat{\mathrm{T}}_{ab}$ is spontaneously measured (monitored)
- Let T_{ab} be the measured value (called signal in control theory)
- Replace Møller-Rosenfeld 1962-63 by

$$\mathrm{G}_{ab} = \frac{8\pi G}{c^4}\mathrm{T}_{ab} = \frac{8\pi G}{c^4}(\langle\hat{\mathrm{T}}_{ab}\rangle + \delta\mathrm{T}_{ab})$$

i.e.: source Einstein eq. by the noisy signal (meanfield+noise)

- For backaction of monitoring, add terms to Schrödinger eq.:

$$\frac{d}{dt}|\Psi\rangle = -\frac{i}{\hbar}\hat{H}[\mathrm{g}]|\Psi\rangle + \mathrm{nonlinear} + \mathrm{stoch.\ terms}$$

- Tune precision of monitoring by Principle of Least Decoherence

D 1990, Kafri, Taylor & Milburn 2014, Tilloy & D 2016-17

Unsharp metric Newtonian limit

- Assume $\hat{\varrho}$ is spontaneously measured (monitored)
- Let ϱ_t be the measured value (called signal in control theory)
- Source classical Newtonian gravity by the signal:

$$\Phi_t(\mathbf{x}) = -G\int\frac{d\mathbf{y}}{|\mathbf{x}-\mathbf{y}|}\ \varrho_t(\mathbf{y})$$

- Introduce $\hat{H}_{fb}=\int\hat{\varrho}\Phi dV$ to induce Newton interaction
- For backaction of monitoring, add terms to Schrödinger eq.:

$$\frac{d}{dt}|\Psi\rangle = -\frac{i}{\hbar}\hat{H}_0|\Psi\rangle + \mathrm{nonlinear} + \mathrm{stoch.\ terms}$$

- Tune precision of monitoring by Principle of Least Decoherence

Such theory of unsharp semiclassical gravity coincides with ...

... coincides with DP wavefunction collapse theory

Unique ultimate unsharpness of Newton potential Φ (metric):

$$\mathbb{E}\delta\Phi_t(\mathbf{r})\delta\Phi_s(\mathbf{y}) = \frac{\hbar G}{2|\mathbf{x}-\mathbf{y}|}\delta(t-s)$$

By averaging over the stochastic Φ (metric), master eq. (D. 1986):

$$\frac{d\hat\rho}{dt} = -\frac{i}{\hbar}\Bigg[\hat H_0 + \underbrace{\frac{G}{2}\iint\frac{d\mathbf{x}d\mathbf{y}}{|\mathbf{x}-\mathbf{y}|}\hat\varrho(\mathbf{x})\hat\varrho(\mathbf{y})}_{Newton\ \ pairpotential}, \hat\rho\Bigg] \underbrace{-\frac{G}{2\hbar}\iint\frac{d\mathbf{x}d\mathbf{y}}{|\mathbf{x}-\mathbf{y}|}[\hat\varrho(\mathbf{x}),[\hat\varrho(\mathbf{y}),\hat\rho]]}_{DP\ \ decoherence}$$

Double merit:

- Semiclassical theory of gravity, a hybrid dynamics of $(\Phi, |\Psi\rangle)$ free of anomalies (no superluminality, valid Born rule).
- Theory of G-related spontaneous collapse (Schrödinger's Cats go collapsed).

Testing DP: LISA Pathfinder

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LISA pathfinder appreciably constrains collapse models

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Spontaneous collapse models are phenomenological theories formulated to address major difficulties in macroscopic quantum mechanics. We place significant bounds on the parameters of the leading collapse models, the continuous spontaneous localization (CSL) model, and the Diosi-Penrose (DP) model, by using LISA Pathfinder's measurement, at a record accuracy, of the relative acceleration noise between two free-falling macroscopic test masses. In particular, we bound the CSL collapse rate to be at most (2 … competitive bound explores a ne… nd
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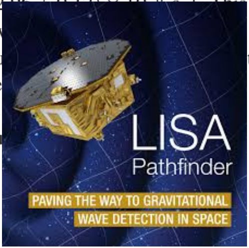
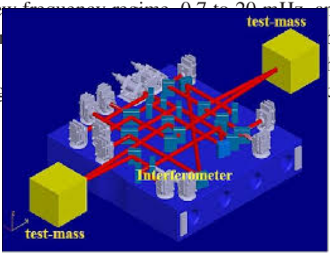
re… in the DP model to prevent diverg… ch
is… nucleus. Thus, we rule out the … a
fu…





MAQRO

- a medium-sized space mission, with a launch in 2025 (ESA)
- harnesses quantum optomechanics, high-M matter-wave interferometry
- testing quantum physics for truly macroscopic objects
- testing so-called collapse models

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Macroscopic Quantum Resonators (MAQRO): 2015 update

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Abstract

Summary

Møller-Rosenfeld (sharp) Semiclassical Gravity is quantum-nonlinear, with related fundamental anomalies and particular effects:

- superluminality, fall of Ψ's statistical interpretation (anomaly)
- self-attraction (main effect for tests)

These fundamental anomalies and self-attraction are missing in (unsharp) Decoherent Semiclassical Gravity. But new anomalies and effects arise:

- non-conservation of energy, momenta, etc. (anomaly)
- decoherence, c.o.m. Brownian motion, ... (effects for tests)
- submicron cutoff against diverging decoherence (open problem)
- submicron breakdown of Newton force (effect for tests)

Decoherent Semiclassical Gravity wouldn't have been realized without ...

background in standard quantum control—monitoring, feedback, etc. — and its various formalisms —master eqs., Ito-stochastic eqs., path integrals, time-ordered exponentials, double-time-superoperators (Keldysh), etc.

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