Gravity-related alterations of non-relativistic quantum theory

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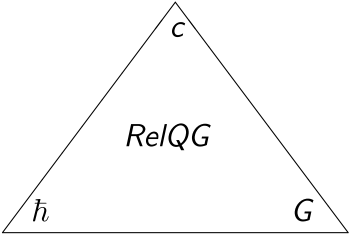
Why Newtonian Quantum Gravity? 1980's

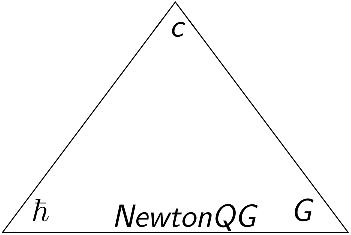
Quantum or Gravity is bottle-neck of Quantum Gravity?

That's just Gravity!



perturbativ QFT
Q-$\mathcal{G}^{(3)}$ dynamics
loops, strings, ... ???

1980s-: **That's Quantum!**



Bottle-neck: Schrödinger Cat
Let's go non-relativistic, first!
Hope: new QM comes from NQG

Spatial mass density $\hat{\varrho}(\mathbf{r})$, and resolution σ

Forget full energy-momentum $\hat{T}_{ab}$! Use $\hat{T}_{00}/c^2 = \hat{\varrho}$
Non-relativistic spatial mass distribution:

$$\hat{\varrho}(\mathbf{r}) = \sum_k m_k \delta_\sigma(\mathbf{r} - \hat{\mathbf{x}}_k)$$

mass density $\nearrow$ $\nwarrow$ *spatial resolution* σ

δ_σ: Gaussian of width σ

What are the sources of gravity?

	nuclei	...	bulk matter
σ resolution	$10^{-12} cm$	...	$10^{-5} cm$

No evidence!
Spatial resolution σ: **burning and lasting issue**

Standard Schrödinger Eq. with Newton gravity

That's standard QM with standard Newtonian pair-potential:

$$|\dot{\Psi}\rangle = -\frac{i}{\hbar}\left(\hat{H} - G\int \frac{\hat{\varrho}(\mathbf{r})\hat{\varrho}(\mathbf{s})}{|\mathbf{r}-\mathbf{s}|}d\mathbf{r}d\mathbf{s}\right)|\Psi\rangle$$

Justified in classical limit only.
Quantum regime - **tests are (currently) impossible**:
G is too small, massive d.o.f. would be influenced.
But massive d.o.f. decohere immediately by environment.

Open issue:

		nuclei	...	bulk matter
σ	resolution	$10^{-12}cm$	...	$10^{-5}cm$

Classical limit is insensitive to σ, **quantum tests are missing**.
We are free to speculate: to **alter QM**, to **choose** σ.

Semiclassical Schrödinger-Newton Equation 1984

Quantized matter in classical Newton-potential:

$$|\dot{\Psi}\rangle = -\frac{i}{\hbar}\left(\hat{H} - G\int \frac{\hat{\varrho}(\mathbf{r})\langle\!\langle\hat{\varrho}(\mathbf{s})\rangle\!\rangle_\Psi}{|\mathbf{r}-\mathbf{s}|} d\mathbf{r}d\mathbf{s}\right)|\Psi\rangle$$

Non-linearity generates **self-interaction**. For c.o.m. $\hat{\mathbf{x}}$ (at $\Delta x \ll \sigma$):

$$|\dot{\Psi}\rangle = -\frac{i}{\hbar}\left(\hat{H} + \frac{1}{2}M\omega_G^2(\hat{\mathbf{x}} - \langle\hat{\mathbf{x}}\rangle_\Psi)^2\right)|\Psi\rangle$$

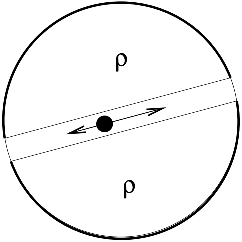
Solitonic solutions: **localized stationary states for bulk c.o.m.!**
No decoherence, no wave function collapse, of course!

Localization heavily depends on gravity's spatial resolution σ:

		nuclei	...	bulk matter
σ	resolution	$10^{-12}cm$	...	$10^{-5}cm$
ω_G		$10^3/s$	...	$10^{-3}/s$

The strong-effect-edge may become falsifiable in coming years.

ω_G: Classical Newton oscillator frequency 2007



[Named as "SN-frequency" (2013-): incorrect name, ω_G has no $\hbar$!]

$$\omega_G = \sqrt{\frac{4\pi}{3} G \varrho_0}$$

$$\frac{\omega_G \text{ in nuclear matter}}{\omega_G \text{ in common matter}} \sim 10^6$$

		nuclei	...	bulk matter
σ	resolution	$10^{-12} cm$	...	$10^{-5} cm$
ω_G		$10^3/s$	...	$10^{-3}/s$

SN self-interaction $\frac{1}{2}M\omega_G^2(\hat{\mathbf{x}} - \langle\hat{\mathbf{x}}\rangle)^2$ becomes **10^{12}-times stronger** if nucleus-size resolution is taken.

G-related spontaneous decoherence (DP) 1987

Master equation to decohere mass-density superpositions:

$$\dot{\hat{\rho}} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] - \frac{G}{2\hbar} \int [\hat{\varrho}(\mathbf{r}), [\hat{\varrho}(\mathbf{s}), \hat{\rho}]] \frac{d\mathbf{r}d\mathbf{s}}{|\mathbf{r}-\mathbf{s}|}$$

Fast **decoherence of bulk d.o.f.**. For c.o.m. $\hat{\mathbf{x}}$ (at $\Delta x \ll \sigma$):

$$\dot{\hat{\rho}} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] - \frac{1}{2\hbar} M\omega_G^2 [\hat{\mathbf{x}}, [\hat{\mathbf{x}}, \hat{\rho}]]$$

$\nwarrow$ *decoherence rate*

Universal **heating of all d.o.f.**: $\dot{\epsilon} = \frac{1}{2}\hbar\omega_G^2 / d.o.f.$

		nuclei	...	bulk matter
σ	resolution	$10^{-12} cm$	...	$10^{-5} cm$
ω_G	decoh. rate	$10^3/s$	...	$10^{-3}/s$
$\dot{\epsilon}$	heating rate	$10^{-21} erg/s/d.o.f.$	...	$10^{-33} erg/s/d.o.f.$

At strong-effect-edge heating is 10μK/s, much too high! **Ruled out?**

LISA Pathfinder experiment 2016

$$\dot{\hat{\rho}} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] - \frac{1}{2\hbar}M\omega_G^2[\hat{\mathbf{x}},[\hat{\mathbf{x}},\hat{\rho}]]$$

↖ *decoherence rate*

Free falling test mass $M = 2kg$ on satellite
C.o.m. acceleration noise $\leq 5.2fms^{-2}/\sqrt{Hz}$ in range 0.7 − 20mHz.
Most precise control of c.o.m. ever!
A most direct test of spontaneous decoherence.
Seems to rule out DP strong-edge version (finest resolution 10^{-12}cm).

		nuclei	...	bulk matter
σ	resolution	$10^{-12}cm$	...	$10^{-5}cm$
ω_G	decoh. rate	$10^3/s$	...	$10^{-3}/s$
$\dot{\epsilon}$	heating rate	$10^{-21}erg/s/d.o.f.$	...	$10^{-33}erg/s/d.o.f.$

LISA 2016: $\sigma \not< \mathbf{4}{*}10^{-12}$cm.

Helou-Slagmolen-McClelland-YanbeiChen, arXiv:1606.03637.

Quantum-gravity spontaneous decoherence? 1983

Hawking 1983: unitarity is lost due to space-time fluctuations (instantons) on Planck scale

$$\hat{\rho} \to \widehat{\$}\hat{\rho} \neq \hat{S}\hat{\rho}\hat{S}^\dagger$$

Banks-Susskind-Peskin 1984: master equation to detail Hawking's $\widehat{\$}$. Violation of conservations laws (cf. **heating**):

$$\dot{\hat{\rho}} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] - \int [\hat{Q}(\mathbf{r}),[\hat{Q}(\mathbf{s}),\hat{\rho}]]h(\mathbf{r}-\mathbf{s})d\mathbf{r}d\mathbf{s}$$

D 1987: unitarity is lost due to gravitational fluctations much before the Planck scale, same strucure as BSP's:

$$\dot{\hat{\rho}} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] - \frac{G}{2\hbar}\int [\hat{\varrho}(\mathbf{r}),[\hat{\varrho}(\mathbf{s}),\hat{\rho}]]\frac{d\mathbf{r}d\mathbf{s}}{|\mathbf{r}-\mathbf{s}|}$$

Reznik&Oppenheim 2009: to conserve total momentum, decohere relational variables:

$$\dot{\hat{\rho}} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] - \frac{1}{2}\sum_{k,l}\gamma_{kl}[\hat{\mathbf{x}}_k - \hat{\mathbf{x}}_l,[\hat{\mathbf{x}}_k - \hat{\mathbf{x}}_l,\hat{\rho}]]$$

Semiclassical gravity + DP collapse 2016

Master equation to decohere mass-density superpositions:

$$\dot{\hat{\rho}} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] - \frac{G}{2\hbar}\int[\hat{\varrho}(\mathbf{r}),[\hat{\varrho}(\mathbf{s}),\hat{\rho}]]\frac{d\mathbf{r}d\mathbf{s}}{|\mathbf{r}-\mathbf{s}|}$$

Straightforward underlying mechanism: spontaneous monitoring of $\hat{\varrho}$:

$$\text{monitoring of } \hat{\varrho} \Rightarrow \left\{ \begin{array}{l} \text{stochastic Q-trajectory } \Psi(t) \\ \text{measured signal } \varrho(\mathbf{r},t) \end{array} \right\}$$

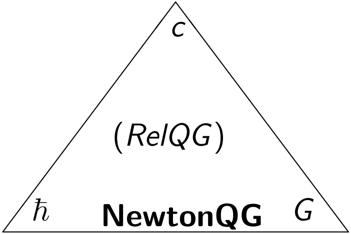
$$\varrho(\mathbf{r},t) = \langle\hat{\varrho}(\mathbf{r})\rangle_{\Psi(t)} + \text{noise}$$

Let's source Newton field by $\varrho(\mathbf{r},t)$! Tilloy&D 2016 (cf. D 1990):

$$\dot{\hat{\rho}} = -\frac{i}{\hbar}\left[\hat{H} - G\int\hat{\varrho}(\mathbf{r})\hat{\varrho}(\mathbf{s})\frac{d\mathbf{r}d\mathbf{s}}{|\mathbf{r}-\mathbf{s}|}\ ,\hat{\rho}\right] - \frac{G}{\hbar}\int[\hat{\varrho}(\mathbf{r}),[\hat{\varrho}(\mathbf{s}),\hat{\rho}]]\frac{d\mathbf{r}d\mathbf{s}}{|\mathbf{r}-\mathbf{s}|}$$

Newtonian pair-potential emerges, self-interaction & non-linearity gone, DP decoherence doubles.

Why Newtonian Quantum Gravity? 1980's-2010's-...



- **Standard QM with pair-potential:** too small, far from testability.
- **Non-standard SNE, DP, ...**: New effects depend heavily on σ. In strong-effect regime $\sigma \sim 10^{-12}cm$ SN self-attraction, DP-heating become testable in coming years.

If Schrödinger Cats are **bottle-neck** of Quantum Gravity:

Newtonian Quantum Gravity might be the key first.

G-related Newtonian alterations of QM are still uncomplete.

They can yet encode a piece of truth.

Experiments will decide if NQG concerns new physics at all.