Gravity related spontaneous decoherence: from Wheeler-Bekenstein-Hawking to optomechanics

Lajos Diósi

Wigner Center, Budapest

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The inception of a universal gravity-related irreversibility took place originally in quantum cosmology but it turned out soon that a universal non-unitary dynamics is problematic itself. Independent investigations of the quantum measurement postulate clarified that a non-unitary dynamics is of interest already in the non-relativistic context. An intricate relationship between Newton gravity and quantized bulk matter might result in universal non-relativistic violation of unitarity - also called spontaneous decoherence. The corresponding gravity-related spontaneous decoherence model is now on the verge of detectability in optomechanical experiments. It is also a toy-model of cosmic quantum-gravitational non-unitarity, illuminating that the bottle-neck of quantum-gravity is the quantum measurement postulate instead of quantum cosmology.

Irrev Quantum Gravity/Cosmology at Planck Scale

Heuristic Arguments **within** Standard Physics

- Wheeler (1955): foamy space-time at Planckian scale
  no compact dynamical eq.
- Bekenstein (1972): black-holes behave termodynamically

$$S_{BH} = \frac{k_B}{4}\frac{A_{BH}}{A_{Pl}}$$

  ... and even radiate thermally, Hawking (1973)
- Hawking (1983): unitarity is lost due to instantons

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

- Banks-Susskind-Peskin (1984): violation of conservations laws

$$\dot{\hat{\rho}} = -i[\hat{H},\hat{\rho}] - \int\int [\hat{Q}(x),[\hat{Q}(y),\hat{\rho}\,]]h(x-y)d^3xd^3y$$

  $\hat{Q}$ is relativistic quantum field, h is positive kernel.

Irrev Quantum Mechanics for Massive Objects

Heuristic **modifications** of Standard Physics

Purpose: massive Schrodinger Cats $|f_1\rangle + |f_2\rangle$ decay spontaneously

- Karolyhazy (1966): fluctuations of space-time at Planckian scale
  G-related qualitative eqs.
- GRW (1986): rare spontaneous localizations of constituents
  G-unrelated exact eqs.
- D. (1986): fluctuations of Newtonian gravitational field

$$\dot{\widehat{\rho}} = -\frac{i}{\hbar}[\widehat{H}, \widehat{\rho}] - \frac{G}{2\hbar}\iint [\widehat{f}(x), [\widehat{f}(y), \widehat{\rho}\,]]\frac{1}{|x-y|}d^3x d^3y$$

  $\widehat{f}$ is non-relativistic quantized mass density field

- Penrose (1996): uncertainty of time-flow

$$\frac{1}{\tau_{decay}} = \frac{G}{\hbar}\iint [f_1(x) - f_2(x)][f_1(y) - f_2(y)]\frac{1}{|x-y|}d^3x d^3y$$

  f_1, f_2 mass densities of Cat state

G-related spontaneous decoherence

Particular purpose: $|f_1\rangle + |f_2\rangle$ decay into mixture of $|f_1\rangle$ and $|f_2\rangle$.

Construction of G-related spontaneous decoherence
(with one eye on G-related spontaneous collapse):

- formal von Neumann measurements of local mass densities $f(x)$
- detectors are hidden this time!
- nobody reads out the measurement outcomes

Resulting Master Equation of G-related spontaneous decoherence:

$$\dot{\widehat{\rho}} = -\frac{i}{\hbar}[\widehat{H}, \widehat{\rho}] - \frac{G}{2\hbar}\int [\widehat{f}(x), [\widehat{f}(y), \widehat{\rho}\,]] \frac{1}{|x-y|} d^3x d^3y$$

$\widehat{f}$ is non-relativistic quantized mass density field: $\widehat{f}(x) = \sum_n m_n g_\sigma(x - \widehat{q}_n)$.
Note: same structure as BSP eq., interpretation is very different.

G-related spontaneous decoherence: test

Effect on massive harmonic oscillator: spontaneous heating (D. 2015)

$$\Delta T_{sp} = \frac{\hbar\omega_G^2}{2k_B}\tau_{ring-down},$$

$$\omega_G = 1.3kHz(\text{decoherence/collapse rate})$$

$$\mathbf{Q} = \mathbf{\Omega}\tau_{\mathbf{ring-down}}$$

Ω		10^2	10^3	10^4	10^5	10^6
	10^5Hz	[10^{-8}K]	[10^{-7}K]	[10^{-6}K]	10^{-5}K	10^{-4}K
	10^4Hz	[10^{-7}K]	10^{-6}K	10^{-5}K	10^{-4}K	10^{-3}K
	10^3Hz	10^{-6}K	10^{-5}K	10^{-4}K	10^{-3}K	**10^{-2}**K
	10^2Hz	10^{-5}K	10^{-4}K	10^{-3}K	**10^{-2}**K	**10^{-1}**K
	10Hz	10^{-4}K	10^{-3}K	**10^{-2}**K	**10^{-1}**K	**1**K
	1Hz	10^{-3}K	**10^{-2}**K	**10^{-1}**K	**1**K	**10**K

Table : Magnitudes of spontaneous heating effect ΔT_{sp} of the DP-model. Data above the millikelvin range are enhanced (typed in boldface).

G-related spontaneous decoherence - recall

Particular purpose: $|f_1\rangle + |f_2\rangle$ decay into **mixture** of $|f_1\rangle$ and $|f_2\rangle$.

Construction of G-related spontaneous decoherence
(with one eye on G-related spontaneous collapse):

- formal von Neumann measurements of local mass densities $\widehat{f}(x)$
- detectors are hidden this time!
- **nobody reads out the measurement outcomes**

Master equation for $\widehat{\rho}$:

$$\dot{\widehat{\rho}} = -\frac{i}{\hbar}[\widehat{H}, \widehat{\rho}] - \frac{G}{2\hbar}\int [\widehat{f}(x), [\widehat{f}(y), \widehat{\rho}\,]]\frac{1}{|x-y|}d^3x d^3y$$

$\widehat{f}$ is non-relativistic quantized mass density field: $\widehat{f}(x) = \sum_n m_n g_\sigma(x - \widehat{q}_n)$.

G-related spontaneous collapse

Particular purpose: $|f_1\rangle + |f_2\rangle$ decay into **either** $|f_1\rangle$ **or** $|f_2\rangle$.

Construction of G-related spontaneous decoherence:

- formal von Neumann measurements of local mass densities $\widehat{f}(x)$
- detectors are **still hidden** but:
- **measurement outcomes** $f_{signal}(x,t)$ **are supposed to be read out**

Resulting in Stochastic Schrodinger equation for Ψ:

$$\dot{\Psi} = -\frac{i}{\hbar}\widehat{H}\Psi - \frac{G}{2\hbar}\int[\widehat{f}(x) - \langle\widehat{f}(x)\rangle][\widehat{f}(y) - \langle\widehat{f}(y)\rangle]\frac{d^3xd^3y}{|x-y|}\Psi + \text{stoch. term.}$$

where the stoch. term. depends uniquely (not indicated here) on the measured values:

$$f_{signal}(x,t) = \langle\Psi_t|\widehat{f}(x)|\Psi_t\rangle + \sqrt{\frac{\hbar}{G}}w(x,t)$$

w is a certain (well-defined) white-noise.

G-related spontaneous collapse: test?

If $f_{signal}(x,t)$ is not accessible (e.g.: left out of the theory) spontaneous collapse remains untestable, the only testable effect is spontaneous decoherence:

$|f_1\rangle + |f_2\rangle$ decay into **mixture** of $|f_1\rangle$ and $|f_2\rangle$.

If $f_{signal}(x,t)$ is "read out" (accessible), spontaneous collapse is testable:

$|f_1\rangle + |f_2\rangle$ decay into **either** $|f_1\rangle$ **or** $|f_2\rangle$.

We should postulate $f_{signal}(x,t)$ is experimentally acccesible, we can record it, couple it, or it is even coupled to somewhere.

G-related spontaneous collapse: casue of gravity!

A very vague hypothesis (D. 2009):
Newton field $-GM/r$ of mass M emerges because, and at rate, of G-related collapses of the center-of-mass Ψ.

Rate of G-related spontaneous decoherence/collapse: $\omega_G = 1.3kHz$.
When M is accelerated, its Newton field follows it at a delay $\tau_{delay} \sim 1ms$.
No laboratory/astrophysical/cosmological evidence against $\tau_{delay} \sim 1ms$.

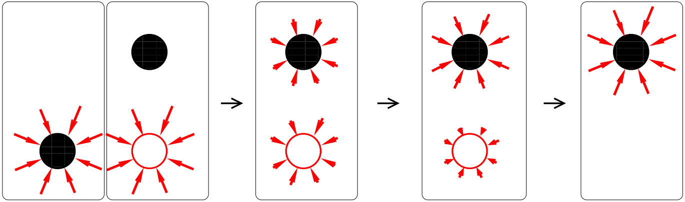
Model of "lazy" Newton gravity (D. 2013):

$$\Phi(x,t) = -GM \int_0^\infty \frac{\exp(-\tau/\tau_{delay})}{|x - q(t-\tau)|} \frac{d\tau}{\tau_{delay}}$$

to be evaluated in the co-moving-falling frame.

Testable predictions of gravity's laziness I.

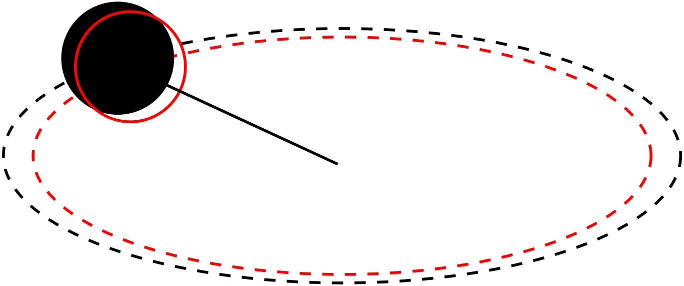
Large delay effect after sudden displacement



If the source is sudddenly displaced by a non-gravitational force, it's Newton field follows it with the time-delay $\tau_{delay} \sim 1$ms.

Testable predictions of gravity's laziness II.

Small effect under moderate non-gravitational force

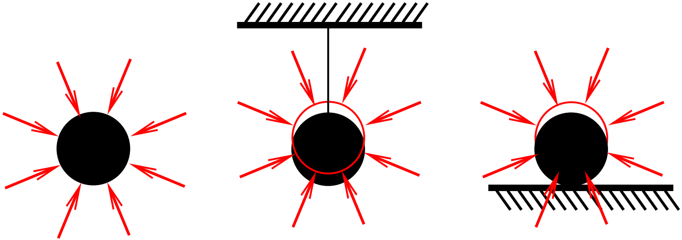


Revolving at (small) angular frequency Ω under non-gravitational force (e.g. of a rope), the accelerated source yields an enhanced Newton force in the center, by the factor

$$1+\frac{1}{2}\Omega^2\tau_{delay}^2 \qquad (\Omega \ll 1/\tau_{delay} \sim 1\mathrm{kHz})$$

Testable predictions of gravity's laziness III.

Universal effect in Earth field



Free falling objects create standard instantaneous Newton forces.
All static objects create Newton forces as if they were higher than their static position, by

$$-g\tau_{delay}^2 \sim 10^{-3}\mathrm{cm} = 10\mu\mathrm{m}$$

Cavendish test of gravity's laziness III.

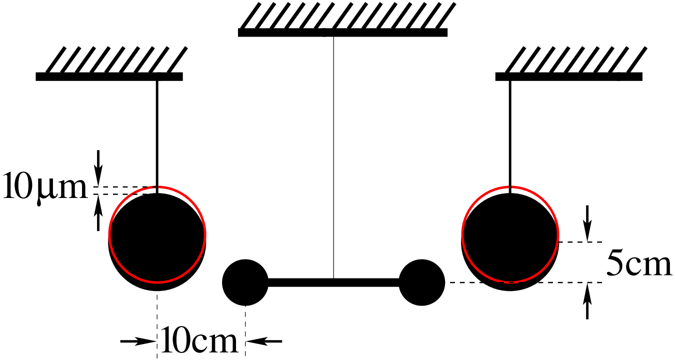


Figure : Schematic view of a Cavendish experiment where the delay $\tau_{delay} \sim 1$ms would shift the $5th$ digit of the measured G by -8.

Summary

- Quantum-gravity 1950's- departure from unitarity
  - Standard Quantum Theory
  - Relativistic approach
  - Quantum measurement, collapse: not discussed
- Quantum Mechanics 1960's - departure from unitarity
  - Modified Quantum Theory, to kill Cats
  - Non-relativistic context
  - Intrinsic link between G and quantum measurement, collapse
  - G-related spontaneous measurement of mass density $f(x)$
    - Master eq. for ρ: spontaneous decoherence
    - Test: spontaneous ΔT_{sp} in quantum optomechanical oscillators
    - Stoch. Sch. eq. for Ψ: spontaneous collapse
    - Test: only if collapse imposes physical effects
  - If spontaneous collapse cause gravity
    - Delayed Newton force
    - Test: Cavendish?