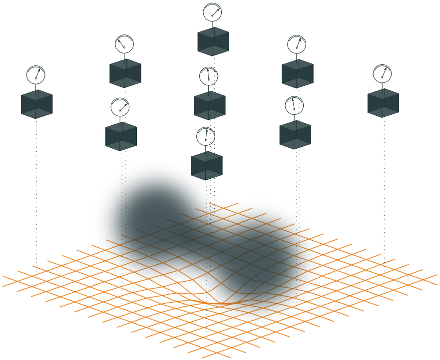
Does gravity have to be quantized?

Antoine Tilloy
Max Planck Institute of Quantum Optics, Garching, Germany



Colloquium
Max Planck Institute of Quantum Optics
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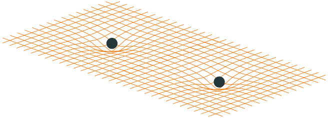
Alexander von Humboldt
Stiftung/Foundation

MPQ

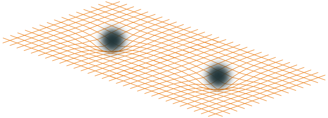
Prolegomena

Classical gravity



- **Matter** is classical
- Spacetime is classical

Semiclassical gravity



- **Matter** is quantum
- Spacetime is classical

Fully quantum gravity

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Main problem

No experimental evidence for the quantization of gravity
but
Romantic and counterintuitive consequences.

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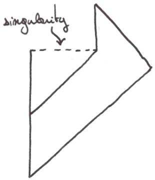
Romantic and counterintuitive consequences.

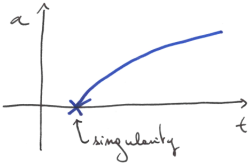
- Is semi-classical gravity really impossible?
- Can we construct simple toy models clarifying the alleged problems?

The shaky case for quantization I: smoothing out nastiness

Problematic divergences in known theories:

- Singularities in **General Relativity** (black-holes, Big-Bang) $R \to +\infty$ or $a \to 0^+$





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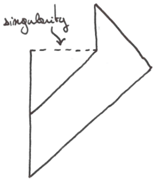
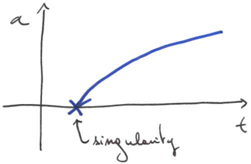
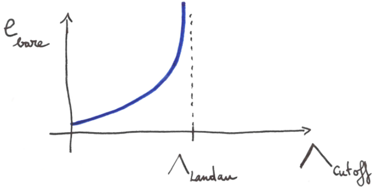




- Landau Pole in $U(1)$ sector of the **Standard Model** $\Lambda_{\text{cutoff}} \leqslant \Lambda_{\text{Landau}}$



BUT: Quantization is not snake oil

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- quantization did not save EM
- not even clear what singularities **mean** in QG
- many other ways to solve these problems
- what happens when there is nothing left to “quantize”?

The shaky case for quantization II: aesthetics

Quantum theory as a **meta theory**, as a procedure to transform the “old fashioned” into the “modern”:

- “Everything should be quantized”
- “Gravity is just like the other forces”
- “People tried to have the EM field classical and it turned out they were wrong”

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- "Everything should be quantized"
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Instance of **non-empirical confirmation** à la Dawid

BUT: Quantization is not a sausage machine

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- approaches that look universal are sometimes not:
  - geometrization of electrodynamics via Kaluza-Klein theories failed
  - $SU(5)$ and other GUT failed

BUT: Quantization is not a sausage machine

- gravity is **not** just a spin 2 Gauge field
- approaches that look universal are sometimes not:
  - geometrization of electrodynamics via Kaluza-Klein theories failed
  - $SU(5)$ and other GUT failed
- maybe gravity is just different (and it does look different)

The shaky case for quantization III: impossibles chimera

"Semi-classical theories are mathematically impossible."

Chimera

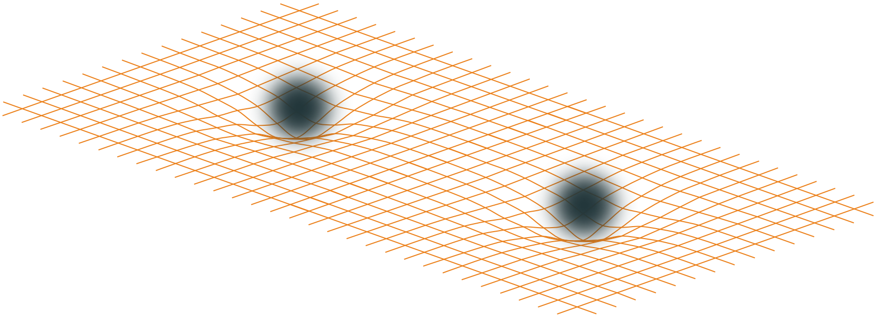
The shaky case for quantization III: impossibles chimera

"Semi-classical theories are mathematically impossible."

Chimera

If true, crippling argument $\Longrightarrow$ gravity needs to be quantized (or emerge from some purely quantum theory)

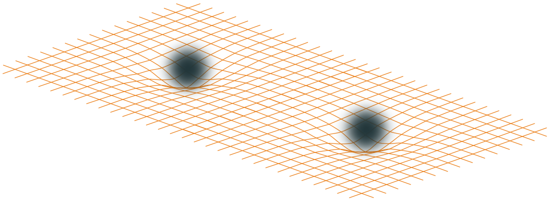
Standard semiclassical gravity



“Standard” semi-classical gravity

A semi-classical theory of gravity tells 2 stories:

1. Quantum matter moves in a curved classical space-time
2. The classical space time is curved by quantum matter



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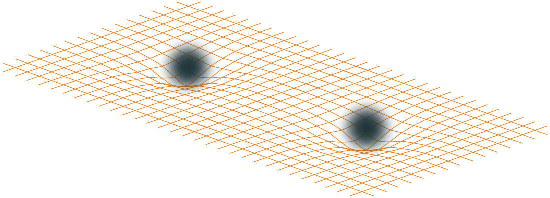


1 is known (QFTCST), **2** is not

The crucial question of semi-classical gravity is to know how quantum matter should source curvature.

Møller-Rosenfeld semi-classical gravity

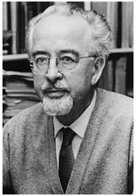
The **CHOICE** of Møller and Rosenfeld it to take:

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G \, \langle \hat{T}_{\mu\nu} \rangle$$

$\rightarrow$ source gravity via expectation values

There are:

- **technical relativistic** difficulties [renormalization of $\langle T_{\mu\nu} \rangle$]
- **conceptual non-relativistic** difficulties [Born rule,$\cdots$].



Christian Møller

Leon Rosenfeld

Schrödinger-Newton

1. Non-relativistic limit of the "sourcing" equation:

$$\nabla^2 \Phi(x, t) = 4\pi G \langle \psi_t | \hat{M}(x) | \psi_t \rangle$$

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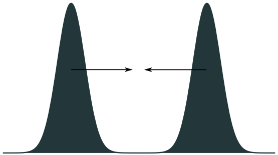
Putting the two together:

$$\frac{\mathrm{d}}{\mathrm{d}t} |\psi_t\rangle = -iH_0 |\psi_t\rangle + i\,G \int \mathrm{d}x \, \mathrm{d}y \, \frac{\langle \psi_t | \hat{M}(x) | \psi_t \rangle \, \hat{M}(y)}{|x-y|} |\psi_t\rangle.$$

The problems with Schrödinger-Newton

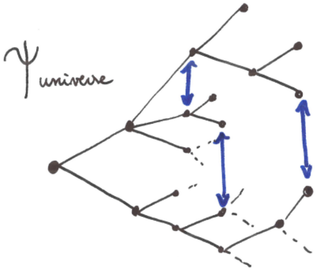


The SN equation is problematic for a fundamental theory because of its **deterministic non-linearity** (Gisin, Diósi, Polchinski)

- If there is **no fundamental collapse** [Many Worlds, Bohm,$\cdots$], super weird world unlike our own
- If there is **fundamental collapse** [Copenhaguen, Collapse models]: break down of the statistical interpretation of states & instantaneous signaling

The problems with Schrödinger-Newton

Without collapse upon measurement (Bohm, Many Worlds,$\cdots$)



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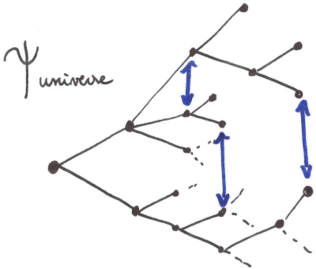
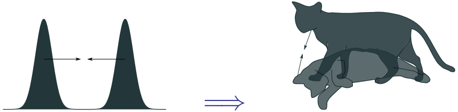


Decohered branches interact with each other $\rightarrow$ **empirically inadequate**



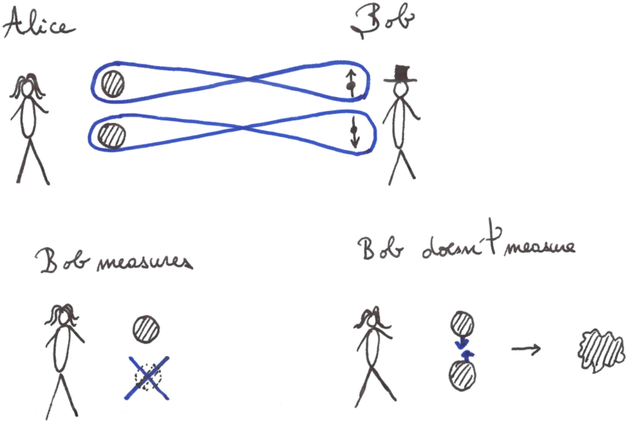
The problems with Schrödinger-Newton

With collapse upon measurement (either from pure Copenhaguen or collapse models).

Consider a mass entangled with a spin far away:

$$|\Psi\rangle \propto |\text{left}\rangle^{\text{Alice}} \otimes |\uparrow\rangle^{\text{Bob}} + |\text{right}\rangle^{\text{Alice}} \otimes |\downarrow\rangle^{\text{Bob}}.$$

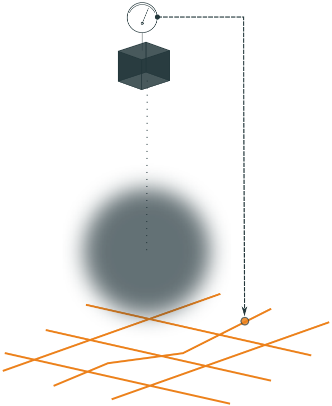
Bob can decide to whether or not he measures his spin:



The big question

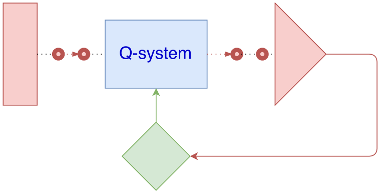
What mathematical object can one construct to source the gravitational field while keeping the Born rule?

Feedback approach



Measurement + feedback

Actually, in orthodox quantum theory, trivial way to do quantum-classical coupling: **measurement** & **feedback** [Diósi & Halliwell]



The state of the controler is the classical variable

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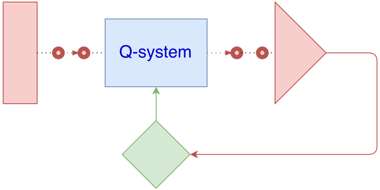


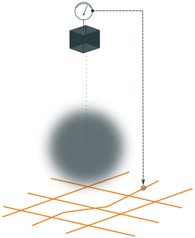
The state of the controler is the classical variable

Idea:

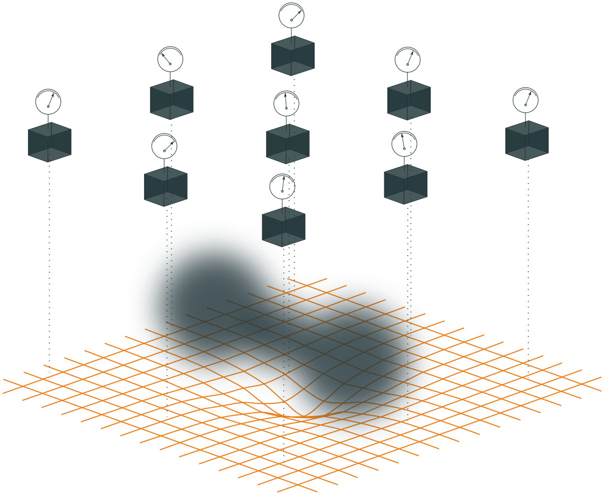
Source gravity by measuring the mass density:

$$\nabla^2\Phi(x) = 4\pi G \mathscr{S}_{\hat{M}}(x)$$

[Kafri, Taylor & Milburn 2014]
[Diósi & T 2015]

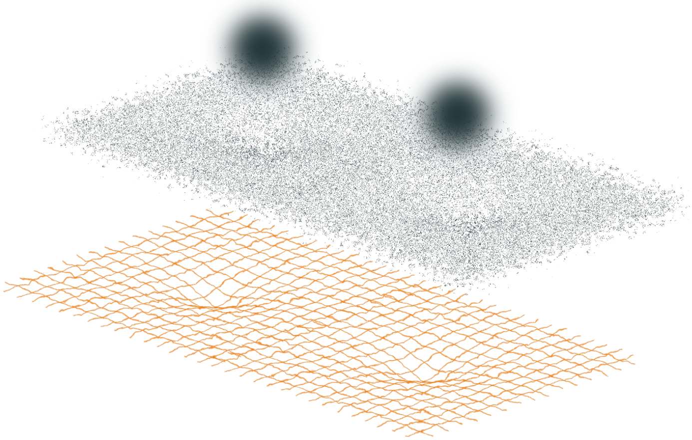


Formal / “intuition pump” picture



“There are detectors in space-time measuring the mass density continuously and curving space-time accordingly.” $\longrightarrow$ this is why it works

Ontological picture



"The gravitational interaction is mediated by a stochastic field, which is the **primitive ontology** of the theory" $\rightarrow$ this is how it should be understood physically

Continuous measurement

Stochastic Master Equation **($\sim$ 1987)**

Density matrix:

$$d\rho_t = \mathcal{L}(\rho_t)\,dt + \gamma\,\mathcal{D}[\mathcal{O}](\rho_t)\,dt + \sqrt{\gamma}\,\mathcal{H}[\mathcal{O}](\rho_t)\,dW_t$$

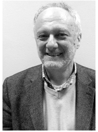
Signal:

$$dy_t = \sqrt{\gamma}\,\mathrm{tr}\left[\left(\mathcal{O} + \mathcal{O}^\dagger\right)\rho_t\right]\,dt + dW_t$$

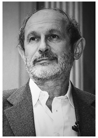
with:

- $\mathcal{D}[\mathcal{O}](\rho) = \mathcal{O}\rho\mathcal{O}^\dagger - \frac{1}{2}\left(\mathcal{O}^\dagger\mathcal{O}\rho + \rho\mathcal{O}^\dagger\mathcal{O}\right)$
- $\mathcal{H}[\mathcal{O}](\rho) = \mathcal{O}\rho + \rho\mathcal{O}^\dagger - \mathrm{tr}\left[\left(\mathcal{O} + \mathcal{O}^\dagger\right)\rho\right]\rho$
- $\frac{dW_t}{dt}$ “white noise”

V. Belavkin



A. Barchielli



L. Diósi

Model

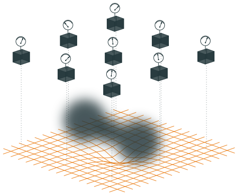
1. **Step 1: continuous mass density measurement**
   We **imagine** that space-time is filled with detectors weakly measuring the mass density:

The equation for matter is now as before with

$$\mathcal{O} \to \hat{M}(x), \ \ \forall x \in \mathbb{R}^3$$

$\gamma \to \gamma(x, y)$ coding detector strength and correlation

and there is a "mass density signal" $S(x)$ in every point.



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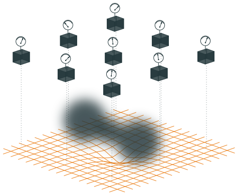
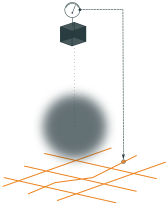


2. **Step 2: Feedback**

   We take the mass density signal $\mathsf{S}(x)$ to source the gravitational field φ:

$$\nabla^2 \varphi(x) = 4\pi G\, \mathsf{S}(x)$$

   which is **formally** equivalent to quantum feedback.



Result

Standard quantum feedback like computations give for $\rho_t = \mathbb{E}[|\psi_t\rangle\langle\psi_t|]$:

$$\partial_t \rho = -i\left[H_0 + \frac{1}{2}\iint \mathrm{d}x\mathrm{d}y \mathscr{V}(x,y)\hat{M}(x)\hat{M}(y), \rho_t\right] - \frac{1}{8}\iint \mathrm{d}x\mathrm{d}y\, \mathscr{D}(x,y)\left[\hat{M}(x), \left[\hat{M}(y), \rho_t\right]\right],$$

with the **gravitational pair-potential**

$$\mathscr{V} = \left[\frac{4\pi G}{\nabla^2}\right](x,y) = -\frac{G}{|x-y|},$$

and the **positional decoherence**

$$\mathscr{D}(x,y) = \left[\frac{\gamma}{4} + \mathscr{V} \circ \gamma^{-1} \circ \mathscr{V}^{\top}\right](x,y)$$

Hence the expected pair potential has been generated consistently at the price of more decoherence.

Principle of least decoherence

$$\mathscr{D}(x,y) = \left[\frac{\gamma}{4} + \mathscr{V} \circ \gamma^{-1} \circ \mathscr{V}^{\top}\right](x,y)$$

There is still a (functional) degree of freedom $\gamma(x,y)$:

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Diagonalizing in Fourier, one gets a global minimum for

$$\gamma = 2\sqrt{\mathscr{V} \circ \mathscr{V}^\top} = -2\mathscr{V}$$

Hence:

$$\mathscr{D}(x,y) = -\mathscr{V}(x,y) = \frac{G}{|x-y|}$$

This is just the decoherence kernel of the Diósi-Penrose model (erstwhile heuristically derived)!

Regularization

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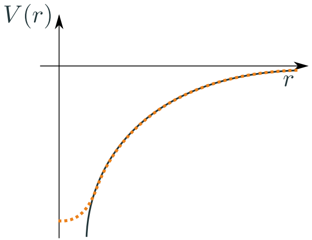
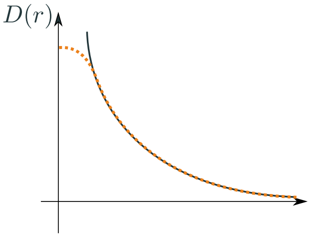
$\Longrightarrow$ there is a **trade-off**.





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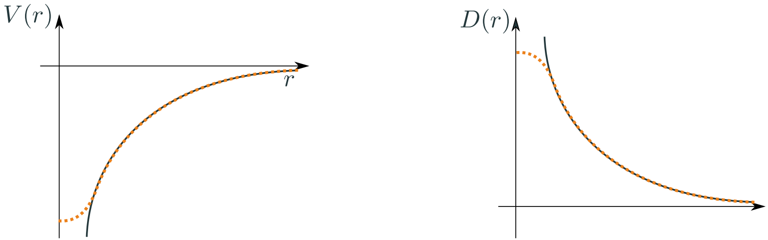


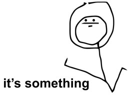
Experimentally:

$$\underbrace{10^{-15}m}_{\text{decoherence constraint}} \ll \sigma \leqslant \underbrace{10^{-4}m}_{\text{gravitational constraint}}$$

Importantly $\sigma > \ell_{\text{Compton}} \gg \ell_{\text{Planck}}$.

Summary of the approach

1. **Most importantly**: Constructing consistent models of semiclassical gravity is possible... in the Newtonian limit



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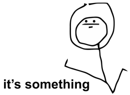
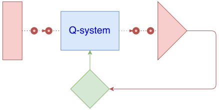


2. The intuition is to use measurement based **Markovian feedback**



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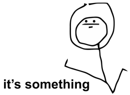

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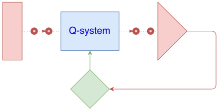

3. The price to pay for semiclassical coupling is intrinsic and gravitational decoherence

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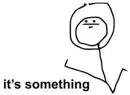

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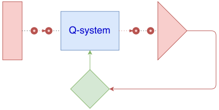
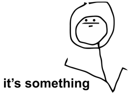


3. The price to pay for semiclassical coupling is intrinsic and gravitational decoherence
4. Minimizing total decoherence gives a parameter free model

Summary of the approach

1. **Most importantly**: Constructing consistent models of semiclassical gravity is possible... in the Newtonian limit



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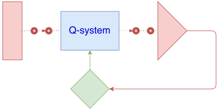

3. The price to pay for semiclassical coupling is intrinsic and gravitational decoherence
4. Minimizing total decoherence gives a parameter free model
5. $\cdots$ up to regularization σ, which is upper bounded and lower bounded experimentally:

$$\underbrace{10^{-15}m}_{\text{decoherence constraint}} \ll \sigma \leqslant \underbrace{10^{-4}m}_{\text{gravitational constraint}}$$

Experimental final word

PRL **119,** 240401 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

Spin Entanglement Witness for Quantum Gravity

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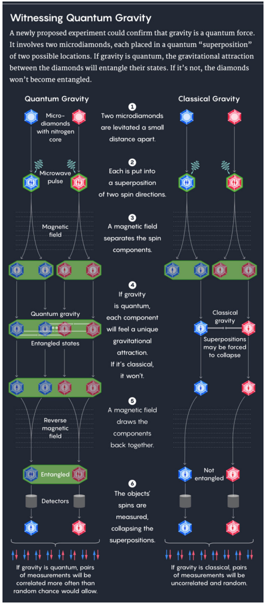
(Received 6 September 2017; revised manuscript received 6 November 2017; published 13 December 2017)

Understanding gravity in the framework of quantum mechanics is one of the great challenges in modern physics. However, the lack of empirical evidence has lead to a debate on whether gravity is a quantum entity. Despite varied proposed probes for quantum gravity, it is fair to say that there are no feasible ideas yet to test its quantum coherent behavior directly in a laboratory experiment. Here, we introduce an idea for such a test based on the principle that two objects cannot be entangled without a quantum mediator. We show that despite the weakness of gravity, the phase evolution induced by the gravitational interaction of two micron size test masses in adjacent matter-wave interferometers can detectably entangle them even when they are placed far apart enough to keep Casimir-Polder forces at bay. We provide a prescription for witnessing this entanglement, which certifies gravity as a quantum coherent mediator, through simple spin correlation measurements.

DOI: 10.1103/PhysRevLett.119.240401



Lucy Reading-Ikkanda/Quanta Magazine

How seriously should we take it?

Antoine, do you seriously believe the world is like in your theory?

Sheldon Goldstein

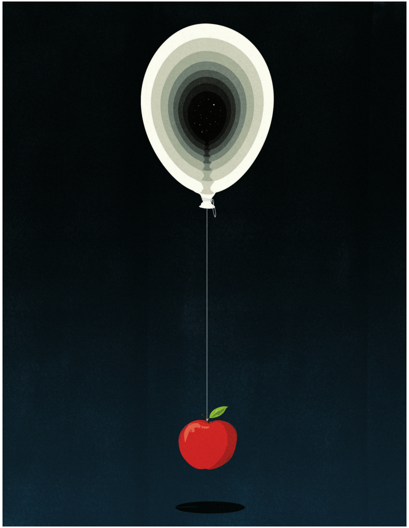
How seriously should we take it?

Antoine, do you seriously believe the world is like in your theory?

Sheldon Goldstein

I bet 99 to one that the outcome will be consistent with gravity having quantum properties.

Carlo Rovelli



NewScientist — 14 April 2018

Conclusion

Does gravity need to be quantized? No

- Weak arguments grounded on **hope** and **aesthetics**
- Strong argument: standard approach to semiclassical gravity **empirically inadequate**

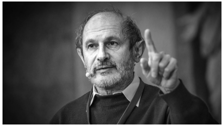
Counter example

- Semiclassical coupling $\equiv$ Measurement based feedback
- Parameter free model up to regularization

Experimentally

- Quantitatively: additional decoherence with a very specific form
- Qualitatively: cannot entangle

Acknowledgments



Lajos Diósi

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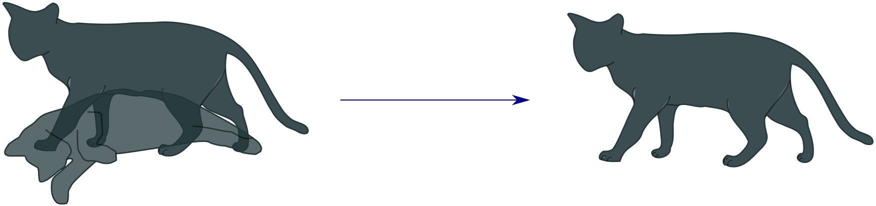
2. **T, Diósi** *Sourcing semiclassical gravity from spontaneously localized quantum matter* PRD 2016 and *Principle of least decoherence for Newtonian semiclassical gravity* PRD 2017
3. **T**, *Ghirardi Rimini Weber model with massive flashes* PRD 2018 and *Binding quantum matter and space time without romanticism*

IV – Link with collapse models



Collapse models

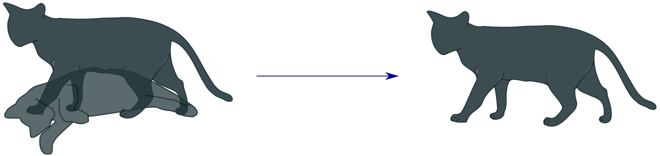
Naive definition

Collapse models are an attempt to solve the measurement problem of quantum mechanics through an *ad hoc*, non-linear, and stochastic modification of the Schrödinger equation.

$$\partial_t|\psi_t\rangle = -iH|\psi_t\rangle + \varepsilon\, f_\xi(|\psi_t\rangle)$$

A few names:

Pearle, Ghirardi, Rimini, Weber, Diósi, Adler, Gisin, Tumulka, Bedingham, Penrose, Percival, Bassi, Ferialdi, Weinberg ...



Collapse models

The modification is such that:

Weak collapse

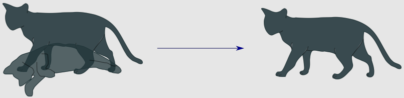
A single particle *extremely rarely* collapses in the position basis

- Microscopic dynamics unchanged

Amplification

The effective collapse rate is renormalized for macroscopic superpositions:

- Macroscopic superpositions almost instantly collapse



We have a collapse model!

Actually, the continuous measurement of the regularized mass density gives:

- The Continuous Spontaneous Localization (CSL) model for $\gamma(x, y) \propto \delta(x, y)$ i.e. maximally local (up to regularization)
- The Diósi-Penrose (DP) model for $\gamma(x, y)$ minimizing decoherence

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Consequences

1. Our model **solves the measurement problem**. There are no macroscopic superpositions

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Consequences

1. Our model **solves the measurement problem**. There are no macroscopic superpositions
2. It is tempting make an analog construction for GRW

The GRW model

GRW model for N spinless particles

- Standard linear evolution between jumps

$$\partial_t|\psi_t\rangle = -iH|\psi_t\rangle$$

- Jump hitting particle k in x_f at a rate λ

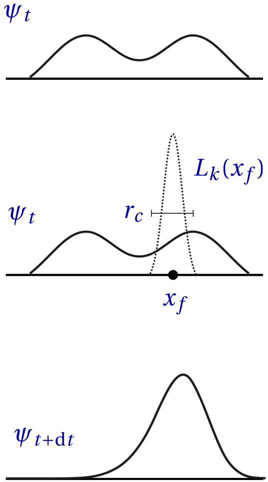
$$|\psi_t\rangle \to \frac{\hat{L}_k(x_f)|\psi_t\rangle}{\|\hat{L}_k(x_f)|\psi_t\rangle\|}$$

with

$$\mathbb{P}(x_f) = \|\hat{L}_k(x_f)|\psi_t\rangle\|^2$$

and

$$\hat{L}_k(x_f) = \frac{1}{(\pi r_c^2)^{3/2}} \mathrm{e}^{(\hat{x}_k - x_f)^2/(2r_c^2)}$$



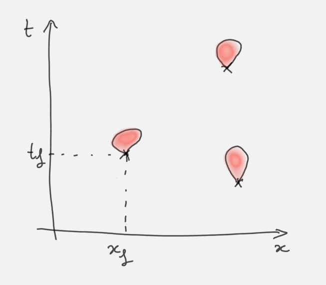
Ghirardi, G. C., Rimini, A., & Weber, T. (1986) Phys. Rev. D, **34**(2), 470.

GRW with massive flashes

Sourcing equation –general case–

Gravitational Φ field created by a single flash (x_f, t_f):

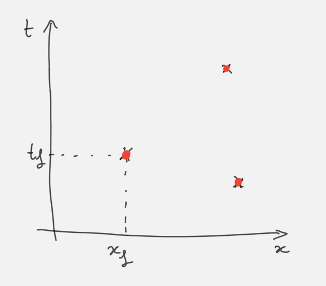
$$\nabla^2\Phi(x,t) = 4\pi G m_k \lambda^{-1} f(t - t_f, x - x_f)$$



Sourcing equation –sharp limit–

Gravitational Φ field created by a single flash (x_f, t_f):

$$\nabla^2\Phi(x,t) = 4\pi G m_k \lambda^{-1} \delta(t - t_f, x - x_f)$$



GRW with massive flashes

Add the gravitational field in the Schrödinger equation

$$\hat{V}_G = \int \mathrm{d}x \; \Phi(x) \hat{M}(x)$$
$$= -G\lambda^{-1} \sum_{\ell=1}^{N} m_k m_l \int \mathrm{d}x \frac{f(t - t_f, x - x_f)}{|x - \hat{x}_\ell|}$$

with $\hat{M}(x) = \sum_{\ell=1}^{N} m_\ell \delta(x - \hat{x}_\ell)$.

In the limit of sharp sources, $\hat{V}_G$ is ill-defined but the corresponding unitary is fine:

$$\hat{U}_k(x_f) = \exp\left(-\frac{i}{\hbar} \int_{t_f}^{+\infty} \mathrm{d}t \, \hat{V}_G(t)\right)$$
$$= \exp\left(i \frac{G}{\lambda\hbar} \sum_{\ell=1}^{N} \frac{m_k m_\ell}{|x_f - \hat{x}_\ell|}\right)$$

GRW with massive flashes

Just after a jump, a **jump dependent** unitary is applied to the N-particle system:

$$|\psi_t\rangle \to \hat{U}_k(x_f)\frac{\hat{L}_k(x_f)|\psi_t\rangle}{\|\hat{L}_k(x_f)|\psi_t\rangle\|} = \frac{\hat{U}_k(x_f)\hat{L}_k(x_f)|\psi_t\rangle}{\|\hat{U}_k(x_f)\hat{L}_k(x_f)|\psi_t\rangle\|} := \frac{\hat{B}_k(x_f)|\psi_t\rangle}{\|\hat{B}_k(x_f)|\psi_t\rangle\|}$$

It is just like changing the collapse operators to non self-adjoint ones!

In the end, all the empirical content lies in the master equation:

$$\partial_t\rho_t = -\frac{i}{\hbar}[H,\rho_t] + \lambda\sum_{k=1}^{n}\int \mathrm{d}x_f\ \hat{B}_k(x_f)\rho_t\hat{B}_k(x_f) - \rho_t$$

GRW with massive flashes: phenomenology

Single particle master equation

Consider the density matrix

$$\begin{aligned}\rho : \mathbb{R}^3 \times \mathbb{R}^3 &\longrightarrow \mathbb{C} \\ (x, y) &\longmapsto \rho(x, y)\end{aligned}$$

It obeys:

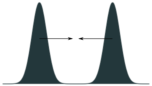
$$\partial_t \rho_t(x, y) = \lambda \left(\Gamma(x, y) - 1\right) \rho(x, y)$$

with

$$\Gamma(x, y) = \int \frac{dx_f}{(\pi r_C^2)^{3/2}} \exp\left(i \frac{Gm^2}{\lambda \hbar} \left[\frac{1}{|x - x_f|} - \frac{1}{|y - x_f|}\right]\right) \times \exp\left(-\frac{(x - x_f)^2 + (y - x_f)^2}{2 r_C^2}\right)$$

Lemma 1:

- $\Gamma(x, y)$ is **real** $\rightarrow$ pure decoherence
- No self-attraction



Lemma 2:

- The model is falsifiable for "all" values of λ

GRW with massive flashes: recovering Newtonian gravity

Two lengths scales in the problem:

- r_c the collapse regularization radius
- $r_G = Gm^2/(\hbar\lambda)$ a new gravitational length scale

For distances d larger than these two length scales:

- One can neglect the Gaussian smearing of the collapse
- The fact that gravity "kicks" instead of being continuous can be neglected on the average evolution:

$$U_k(x_f) \simeq 1 + i\frac{G}{\lambda\hbar}\sum_{\ell=1}^{N}\frac{m_k m_\ell}{|x_f - \hat{x}_\ell|}$$

We then recover Newton's potential! (+ decoherence)

Bonus: Survival bias