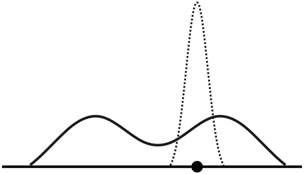
Ghirardi Rimini Weber model with massive flashes

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



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MPQ

No experimental evidence for the quantization of gravity

but

Romantic and counterintuitive consequences.

Introduction

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

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

Outline

1. The arguments for quantized gravity
2. "Standard" semi-classical gravity
3. Collapse models
4. GRW model with massive flashes
5. Conclusion

The shaky case for quantization

3 classes of arguments for **quantized** gravity:

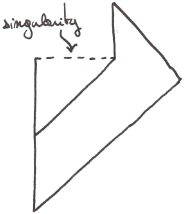
- to cure existing theories
- because of aesthetics of unification
- because semi-classical theories are inconsistent

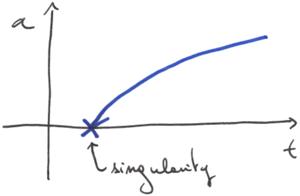
The **third** is the strongest $\rightarrow$ the one that really needs to be addressed

The shaky case for quantization I: smoothing out nastiness

Problematic divergences in known theories:

- Singularities in **GR** (black-holes, Big-Bang) $R \longrightarrow +\infty$





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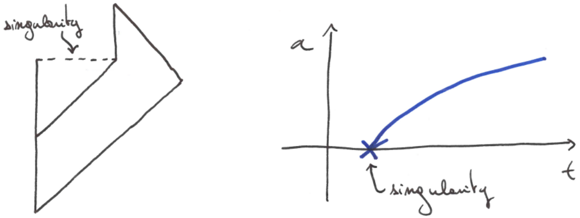


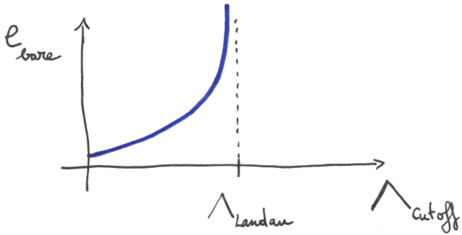
"However, the reason why a full model of quantum gravity is necessary is in order to resolve singularities at high curvature scales, in black holes and most importantly in the early universe, to understand the initial conditions for cosmology. The present model is not a step in this direction."

Referee B, for `arXiv:1709.03809`

The shaky case for quantization I: smoothing out nastiness

Problematic divergences in known theories:

- Landau Pole in $U(1)$ sector of the **SM** $\Lambda_{\text{cutoff}} \leq \Lambda_{\text{Landau}}$



"It is well known that quantum gravity is necessary to remove the ill-defined UV behavior of QFT, especially the Landau pole of the electroweak sector of the standard model. The author's proposal does not solve this issue." [quoted from memory]

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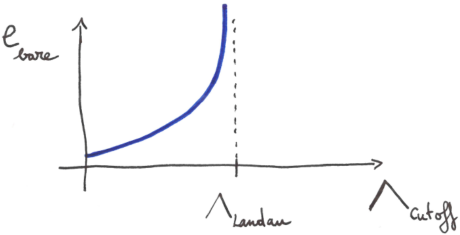

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Referee A, for `arXiv:1509.08705`

BUT: Quantization is not snake oil

- quantization did not save EM
- not even clear what singularities **mean** in QG
- many other ways to solve these problems
- pure wishful thinking?
- 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"

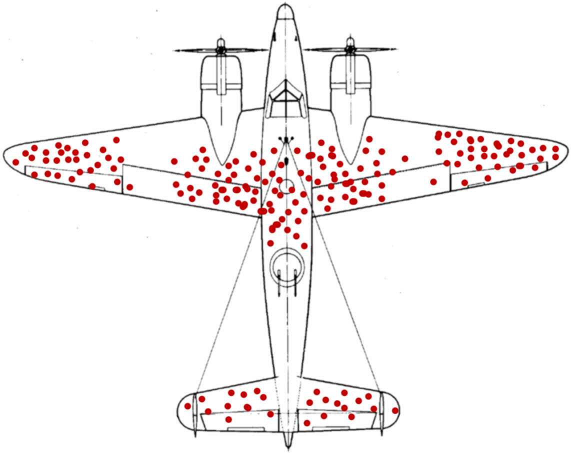
Unifying means **quantizing**

$$\{,\} \to [,] \;\; ; \;\; [x, p] = i$$

BUT: Quantization is not a sausage machine

- gravity is **not** just a spin 2 Gauge field
- unification $\neq$ quantization.
- 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 kind of looks different)

Aparté: Survival bias



The shaky case for quantization III: impossibles chimera

"Semi-classical theories are mathematically impossible."

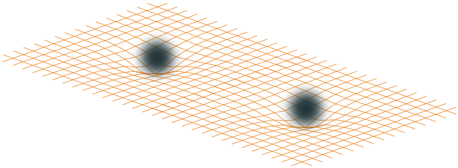
Chimera

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

"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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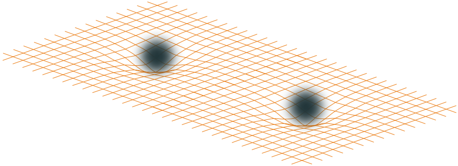

1 is known (QFTCST), **2** is not

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

Christian Møller

There are:

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

Leon Rosenfeld

Schrödinger-Newton

1. Non-relativistic limit of the “sourcing” equation:

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

2. Non-relativistic limit of QFTCST (just external field)

$$\frac{\mathrm{d}}{\mathrm{d}t} |\psi\rangle = -i \left(H_0 + \int \mathrm{d}x \, \Phi(x,t) \hat{M}(x) \right) |\psi_t\rangle,$$

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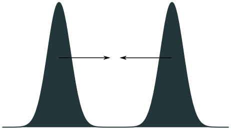
Putting the two together:

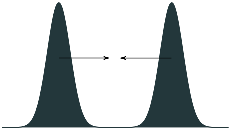
$$\frac{\mathrm{d}}{\mathrm{d}t} |\psi_t\rangle = -iH_0 |\psi_t\rangle + i\, G \int \mathrm{d}x \, \mathrm{d}y \, \frac{\langle \psi_t | \hat{M}(x) | \psi_t \rangle \, \hat{M}(y)}{|x-y|} |\psi_t\rangle.$$

The problems with Schrödinger-Newton



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

The problems with Schrödinger-Newton

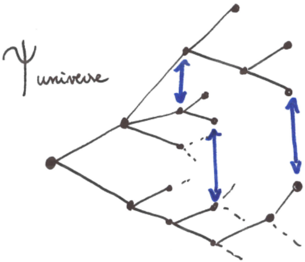


The SN equation is problematic for a fundamental theory because of its **deterministic non-linearity** (Gisin, Diósi, Polchinski)

- 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, $\cdots$)



Decohered branches interact with each other $\rightarrow$ **totally ridiculous**

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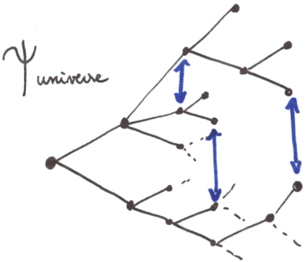

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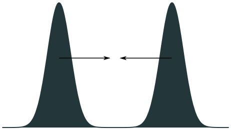
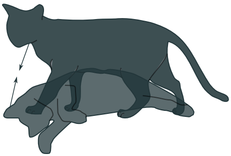


$\Longrightarrow$



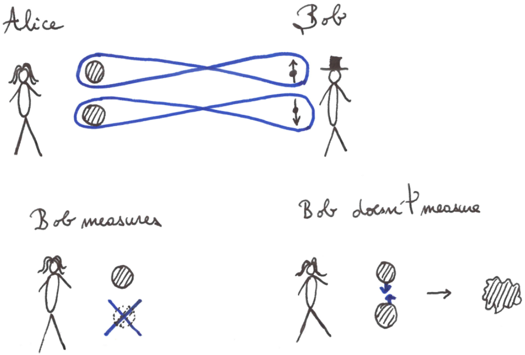
The problems with Schrödinger-Newton

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:



Two first steps

- Via Bohmian mechanics
  Couple with **the particle trajectories** $\rightarrow$ Struyve 2015-2017
- Via Collapse models
  Add an objective collapse $\rightarrow$ Derakhshani 2014

In both cases, destroy the statistical interpretation of the state vector $\rightarrow$ extract predictions only via the **primitive ontology**.

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In both cases, destroy the statistical interpretation of the state vector $\rightarrow$ extract predictions only via the **primitive ontology**.

Maybe there is no way out and gravity has to break the statistical interpretation of states. But **if possible, it would be better not to screw everything**.

The big question

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

Collapse models

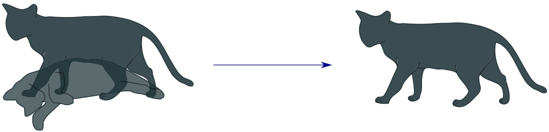
Naive definition

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 ...



The GRW model

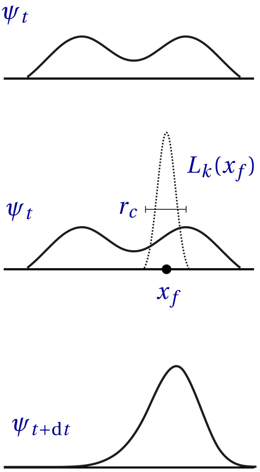
GRW model for N spinless particles

- 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.

The GRW model

The new parameters λ and r_c can be fixed in such a way that:

Weak collapse

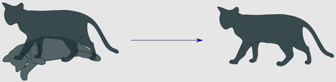
A single particle *extremely rarely* collapses in the position basis

- Microscopic dynamics unchanged

Amplification

The effective collapse rate is renormalized for macroscopic superpositions:

- Macroscopic superpositions almost instantly collapse



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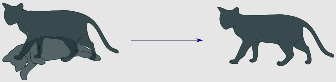

Still two questions:

- What is the theory about?
- What does it predict?

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

The GRW model: ontological content

Question 1: What is the theory about?

The theory is about **stuff** aka "**local beables**" aka "**primitive ontology**"

The GRW model: ontological content

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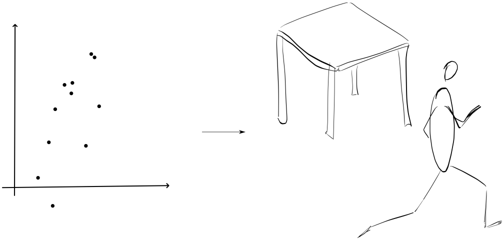
The theory is about **stuff** aka “**local beables**” aka “**primitive ontology**”

2 simple options:

- Collapse space-time events aka “**flashes**” (x_f, t_f)
- Mass density field: $\langle\psi_t|\hat{M}(x)|\psi_t\rangle$, i.e. morally $|\psi|^2$



Bell, J. S. (1987) in Schrödinger: Centenary of a polymath.
Tumulka, R. (2011) arXiv:1102.5767.
AT, L Diósi, Phys. Rev. D 93 (2), 024026

The GRW model: empirical content

Question 2: What does the theory predict?

The empirical content lies in the **master equation** obeyed by $\rho_t = \mathbb{E}\Big[\, |\psi_t\rangle\langle\psi_t| \,\Big]$:

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

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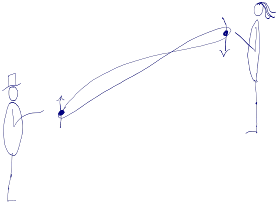
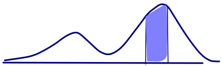
It is:

- linear
- of the Lindblad form

This prevents:

- faster than light signalling
- break down of the Born rule





Gisin, N. (1990) Phys. Lett. A, 143(1), 1-2.
Polchinski, J. (1991) Phys. Rev. Lett., 66(4), 397.

The GRW model: 3 levels of analysis

Ontological content

"What the theory says the world is like"

$$(x_f, t_f)$$

State vector (?)

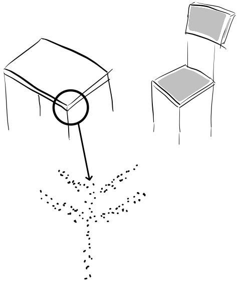
"An intermediary object in the theory"

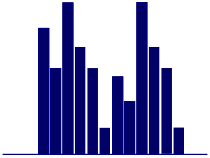
$$\partial_t|\psi_t\rangle = -\,iH|\psi_t\rangle + \varepsilon\, f_\xi(|\psi_t\rangle)$$

Empirical content

"What the theory predicts"

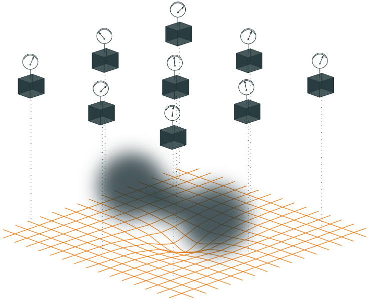
$$\partial\rho_t = \mathscr{L}(\rho_t)$$





Orthodox reformulation of GRW: why does it work?

The **mathematics** of the collapse can be reproduced by iterating weak (orthodox) position measurements.

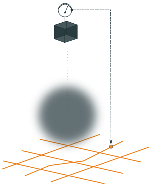


The flashes are just weak position measurement "results" in this orthodox analog model.

Intuition for gravity

Two arguments for sourcing gravity with the GRW flashes:

1. **Ontological intuition**: if the flashes are real (and the only real thing), they would naturally source the gravitational field
2. **Empirical consistency**: if flashes are formally measurement results, then making the dynamics depend on them is just **feedback** $\Longrightarrow$ linear average evolution by construction



GRW with massive flashes

Sourcing equation –general case–

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

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

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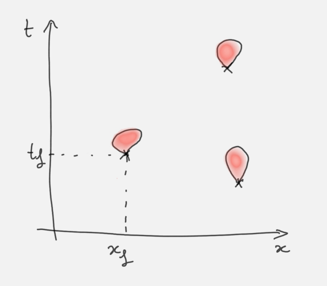
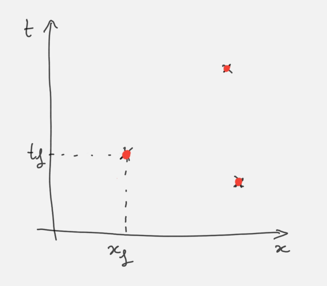


Sourcing equation –sharp limit–

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

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

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

GRW with massive flashes

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

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!

GRW with massive flashes

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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

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

It obeys:

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

with

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

GRW with massive flashes: phenomenology

Single particle master equation

Consider the density matrix

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

It obeys:

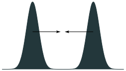
$$\partial_t \rho_t(x, y) = \lambda \left(\Gamma(x, y) - 1\right) \rho(x, y)$$

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:

- $-\lambda(\Gamma(x, y) - 1)$ has a local minimum in λ
- 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)

GRW model with massive flashes

Summary:

We have a crude non-relativistic model that is:

1. not plagued with inconsistencies:
   - Clear ontology
   - Clear empirical content (computable with standard methods)
2. falsifiable for all values of its parameters
3. not yet in conflict with experiments (behavior of gravity unknown at short distances)

Conclusions

1. **About this model**
   - Two birds one shot: solve the measurement problem and semi-classical gravity with the same tool, pay the price once
   - Makes collapse models falsifiable in all their parameter diagram
2. **About semi-classical gravity**
   - Schrödinger-Newton is a straw-man, easy to do better
   - No real objection to semi-classical gravity
3. **About physics in general**
   - Discussion of primitive ontology is not just philosophical BS

Final word: experimental

A Spin Entanglement Witness for Quantum Gravity

Sougato Bose,[1] Anupam Mazumdar,[2] Gavin W. Morley,[3] Hendrik Ulbricht,[4] Marko Toroš,[4]
Mauro Paternostro,[5] Andrew Geraci,[6] Peter Barker,[1] M. S. Kim,[7] and Gerard Milburn[7,8]

[1] *Department of Physics and Astronomy, University College London, Gower Street, WC1E 6BT London, UK*
[2] *Van Swinderen Institute University of Groningen 9747 AG Groningen, The Netherlands*
[3] *Department of Physics, University of Warwick, Gibbet Hill Road, Coventry CV4 7AL, UK*
[4] *Department of Physics and Astronomy, University of Southampton, SO17 1BJ, Southampton, UK*
[5] *CTAMOP, School of Mathematics and Physics, Queen's University Belfast, BT7 1NN Belfast, UK*
[6] *Department of Physics, University of Nevada, Reno, USA, 89557*
[7] *QOLS, Blackett Laboratory, Imperial College, London SW7 2AZ, UK*
[8] *Centre for Engineered Quantum Systems, School of Mathematics and Physics, The University of Queensland, QLD 4072 Australia.*

Understanding gravity in the framework of quantum mechanics is one of the great challenges in modern physics. Along this line, a prime question is to find whether gravity is a quantum entity subject to the rules of quantum mechanics. It is fair to say that there are no feasible ideas yet to test the quantum coherent behaviour of gravity 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 correlation measurements between two spins: one embedded in each test mass. Fundamentally, the above entanglement is shown to certify the presence of non-zero off-diagonal terms in the coherent state basis of the gravitational field modes.