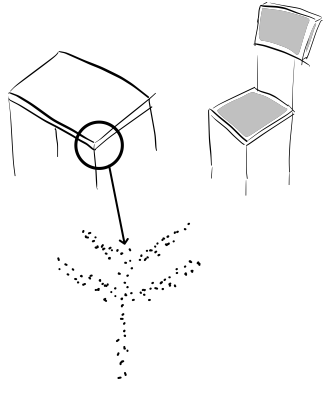
When metaphysics matters: the example of quantum-classical dynamics



Antoine Tilloy

January 9th, 2026

The ontology of fields – LMU

MINES PARIS | PSL ENS | PSL Inria erc

Prolegomena

Orthodox quantum mechanics is a prediction black box

Prolegomena

Obscurantist position: one should not look for more – that the black box works means that we need not look for more *and even cannot* look for more

Prolegomena

"We know that the moon is **demonstrably** not there when nobody looks"

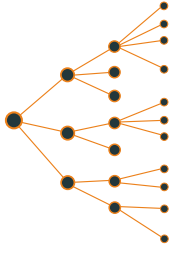


David Mermin - 1981

Having a clear ontology (at least) allows to disprove the inevitable nature of such claims!

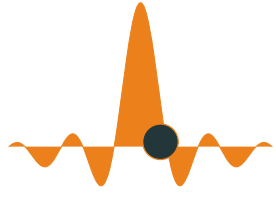
Prolegomena

- Accept that ψ describes a multiverse
- Add particles "choosing" the branch/macroscopic outcomes
- Add a non-linearity in the dynamics to kill macroscopic superpositions



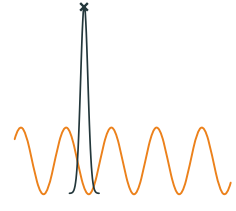


Everett 1957





Bohm 1952





Ghirardi 1986

Prolegomena

Actually: embarassment of riches

$\rightarrow$ some physicists say why bother? It's not falsifiable! It's not scientific!

Prolegomena

I want to illustrate the standard point that metaphysics is crucial for theory building

Totally standard point, for example:

> *In Popper's opinion it is not all that bad to be pre-scientifically metaphysical, for unfalsifiable metaphysics is often the speculative parent of falsifiable science.*
>
> *Ian Hacking*

Outline

Illustrate on collapse models, and their use in building consistent semiclassical theories

- The standard story of collapse models
- The more subtle story (can we hear the jumps?)
- Fundamentally semiclassical gravity
- Consistent versions from a "good" ontology

The standard story of collapse models

Main idea of collapse models

[objective / spontaneous / dynamical] [collapse / reduction] [models / program]

Schrödinger equation + tiny non-linear perturbation

$$\frac{\mathrm{d}}{\mathrm{d}t}\psi_t = -\frac{i}{\hbar}H\psi_t + \varepsilon(\psi)\,,$$

H is the standard model Hamiltonian (or a non-relativistic simplification)

The example of the Ghirardi-Rimini-Weber model

The GRW modification (1986)

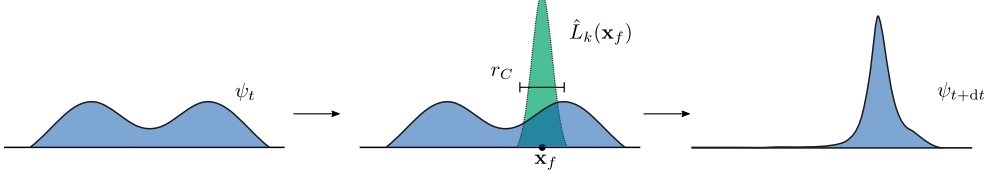
Every dt, with probability λdt particle k collapses around point x_f

$$\psi_t \longrightarrow \frac{\hat{L}_k(x_f)\psi_t}{\|\hat{L}_k(x_f)\psi_t\|} \quad \text{with proba} \quad P(x_f) = \|\hat{L}_k(x_f)\psi_t\|^2$$

with an envelope $\hat{L}_k(x_f) = \frac{1}{(\pi r_C^2)^{3/4}} e^{-(\hat{x}_k - x_f)^2/(2r_C^2)}$.



GianCarlo Ghirardi
1935 - 2018



Why it works (solves the measurement problem)

Fixing *e.g.* $\lambda = 10^{-16}\mathrm{s}^{-1}$ (historical value) :

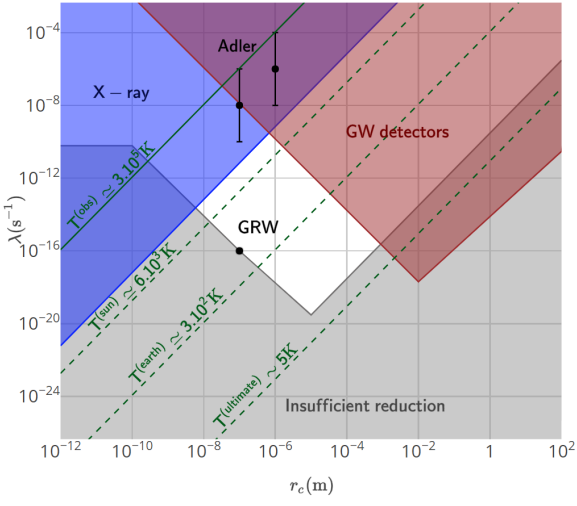
1. An electron collapses every 300 million years
2. A cat made of $\simeq 10^{28}$ electrons is localized up to r_c in less than a picosecond

In brief: one can semi-rigorously derive the measurement postulate by studying the stochastic dynamics of measurement devices

Microscopic degrees of freedom (spin, photon, etc.) do not collapse because of their intrinsic dynamics, but when they are coupled to something macroscopic

Experimental consequences

1. Loss of interferences for big molecules
2. Matter slowly heats up
3. Stuff vibrates
4. Photons spontaneously get emitted



Some candidates

1) Markus Arndt's experiments 2) Neptune / neutron stars 3) Mirors of LISA pathfinder 4) Germanium crystals in Gran Sasso

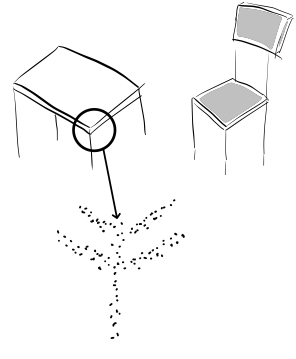
Metaphysics

What is the world made of?

1. `GRW0` The wave function ψ_t itself
2. `GRWm` The mass density $\langle \hat{M}(x) \rangle$

$$\langle \hat{M}(x) \rangle = \sum_k \int \mathrm{d}x_1 \cdots \mathrm{d}x_n \, |\psi(x_1, \cdots, x, \cdots, x_n)|^2$$
x in k^{th} position

3. `GRWf` The space-time points (t_f, x_f) where the wavefunction collapses (the "flashes")



Physicists see it sometimes as redundant, useless...

Can we hear the collapses?

The sound of collapse

If collapse models are true, and even with absurdly frequent and intense collapse, would we know for sure they are true? [inspired from Feldman & Tumulka]

- *The subtle sound of quantum jumps* – 2007.15420

Linearity of the master equation

Empirical content of GRW

Crucial point: one can only measure frequencies $\pi_k = \langle\psi|\hat{\Pi}_k|\psi\rangle$, averaged over jumps not knowable *a priori* $\bar{\pi}_k = \mathbb{E}[\pi_k]$

$$\bar{\pi}_k = \mathbb{E}\left[\langle\psi|\hat{\Pi}_k|\psi\rangle\right] = \mathrm{tr}\left(\hat{\Pi}_k\,\mathbb{E}\big[|\psi\rangle\langle\psi|\big]\right) = \mathrm{tr}\left(\hat{\rho}\,\hat{\Pi}_k\right).$$

Hence all falsifiable predictions of the model are contained in $\hat{\rho} = \mathbb{E}\big[|\psi\rangle\langle\psi|\big]$

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Hence all falsifiable predictions of the model are contained in $\hat{\rho} = \mathbb{E}\big[|\psi\rangle\langle\psi|\big]$

Master equation of GRW

Collapse probabilities are chosen exactly so that $\mathbb{E}$ removes the non-linearity [required by Gisin's theorem]

$$\frac{\mathrm{d}}{\mathrm{d}t}\hat{\rho}_t = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}_t] + \lambda \sum_{k=1}^{N} \left\{ \int \mathrm{d}x_f \hat{L}_k(x_f)\hat{\rho}_t\hat{L}_k(x_f) \right\} - \hat{\rho}_t$$

Consequences of the linearity of the master equation

All collapse models proposed so far obey a linear master equation *e.g.* for Markovian collapse models

$$\frac{\mathrm{d}}{\mathrm{d}t}\hat{\rho}_t = \mathcal{L}\hat{\rho}_t \tag{1}$$

It is the only thing one can probe experimentally. What does it tell about the underlying non-linear model?

Unraveling

For ρ verifying (1), $\exists$ infinitely many stochastic equations for $|\psi\rangle$ such that $\rho = \mathbb{E}|\psi\rangle\langle\psi|$. [*e.g.* Dalibard, Castin, Mølmer]

Alternative GRW models

Empirically equivalent but weird GRW models:

- **Continuous collapsing GRW model**
- **Continuous unitary GRW model**

If you hear a jump, this jump need not be the fundamental GRW jump even if the model is empirically exact!

3 levels of description

Ontology

"What the theory says about the world"

e.g. flashes (x_f, t_f)

The wave-function

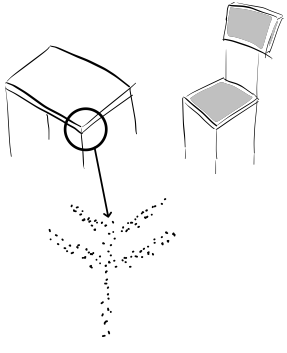
"An intermediary object with some intuition"

$$\frac{\mathrm{d}}{\mathrm{d}t}\psi_t = -\frac{i}{\hbar}H\psi_t + \varepsilon(\psi)$$

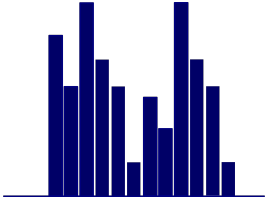
The empirical content

"Quantitative testable predictions of the theory"

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



ψ?



Local summary

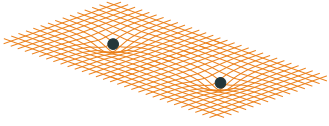
1. Both the standard choices of ontology *and* stochastic ψ could be dismissed as *metaphysical*
2. Collapse models make predictions that differ from our known *instance* of quantum mechanics (the standard model)
3. Collapse models cannot be distinguished from another (fully linear) quantum theory (*e.g.* with an extra dark sector)

Seems the skeptical physicists are even more right to dismiss all this!

Fundamentally semiclassical gravity

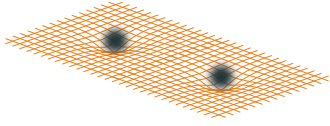
Prolegomena

Classical gravity



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

Semiclassical gravity



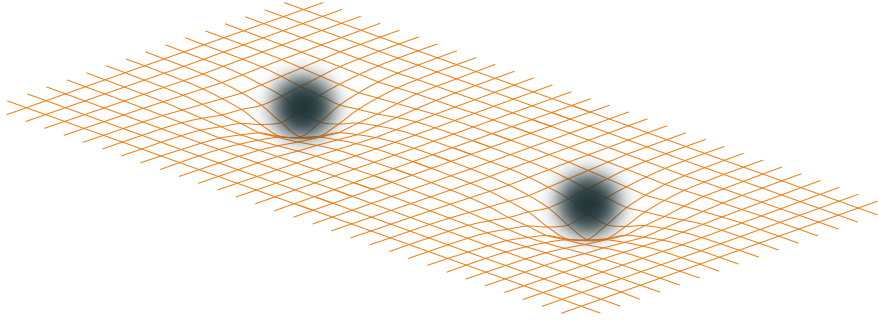
- **Matter** is quantum
- Spacetime is classical

Fully quantum gravity



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

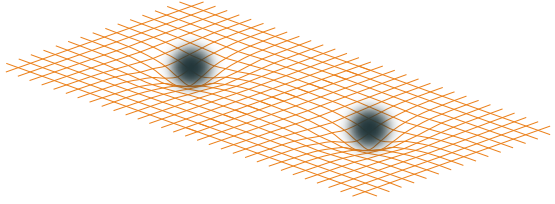
Standard semiclassical gravity



“Standard” semi-classical gravity

A semi-classical theory of gravity tells 2 stories:

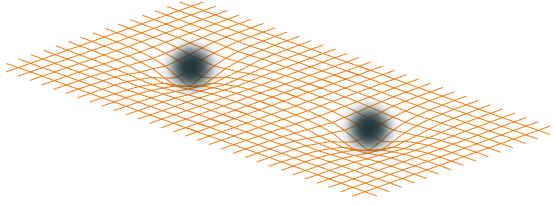
1. Quantum matter moves in a curved classical space-time
2. The classical space time is curved by quantum matter



“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



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

A poor choice of ontology:

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

Møller-Rosenfeld semi-classical gravity

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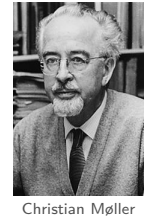
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$\rightarrow$ source gravity via expectation values

There are:

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



Christian Møller



Leon Rosenfeld

Examples of ‘good’ hybrid quantum-classical dynamics

Make what's real the source of gravity!

In the Newtonian limit:

$$\nabla^2\varphi = 4\pi G \times \text{whatever proxy to the mass there is in the ontology}$$

Several previous options:

1. Bohmian positions
2. GRWm

Not as bad as Møller-Rosenfeld, but flaws (equivariance broken, Gisin's theorem broken)...

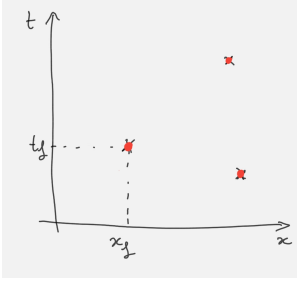
GRW with massive flashes

Make the flashes the source of the gravitational field

Sourcing equation –sharp limit–

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

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



As weird as it may seem, testable but compatible with current experiments!

Continuous spontaneous localization based gravity

The discussion is even more rich for CSL:

- Standard CSL has a continuous flash equivalent $\rightarrow$ gives a consistent semiclassical gravity (L. Diósi, AT)
- CSL also admits a jump unraveling and associated discrete flash ontology (Piccione and Bassi)
- Consistent dynamics, but empirically inadequate: flash density proportional to mass density *squared*
- Extend CSL, add $\sqrt{\cdot}$ everywhere, so that the flashes are proportional to the mass density $\rightarrow$ gives yet another model of gravity! (Piccione and Bassi)
- All these models have subtly different decoherence!

The ontology is central!

Conclusion 1

A black box is not easy to consistently extend, but a theory of the world is.

Conclusion 2

Favoring a world made of fields, particles, flashes, can at least very partially be based on what makes the next steps most natural and empirically adequate.

A small peculiarity in this example: making consistent (in my sense) possibly fundamental semiclassical theories is easy with fields and flashes, but not so much with particles.