The sound of quantum jumps

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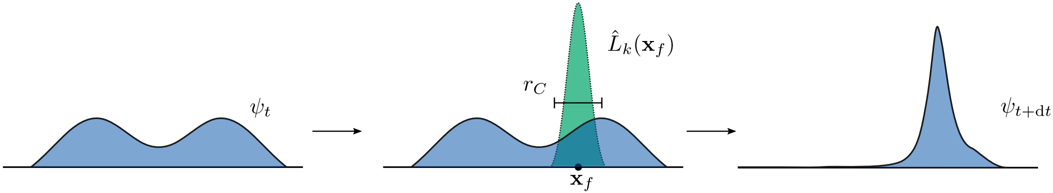
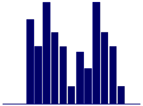


October 15th, 2021

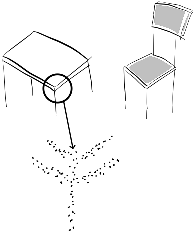
Objective

Clarify what in collapse models

1. Is a quantitative prediction



2. Is a useful metaphysical simplification



To understand in what sense collapse models differ from quantum theory

Inspired from an essay for **FQXI** "*The subtle sound of quantum jumps*"
`arXiv:2007.15420`

Main idea of collapse models

Other names: [objective / spontaneous / dynamical] [collapse / reduction] [models / program]

Schrödinger equation + peanut 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)

at this stage somehow ad hoc

The Ghirardi-Rimini-Weber model

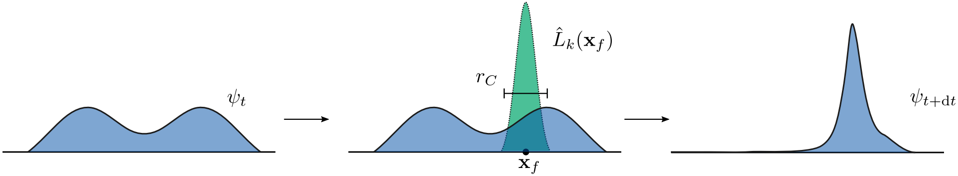
The GRW modification (1986)

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

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

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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

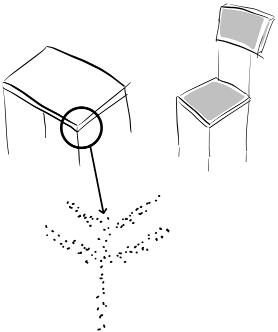
Metaphysics - ontology

What is real? What is the world made of?

1. `GRW0` The wavefunction ψ_t itself (but endless literature of subtleties, *tail problem*...)
2. `GRWm` The mass density $\langle \hat{M}(x) \rangle$

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

3. `GRWf` The points (t_f, x_f) where the wavefunction collapses (the "flashs") – [Bell's choice!]



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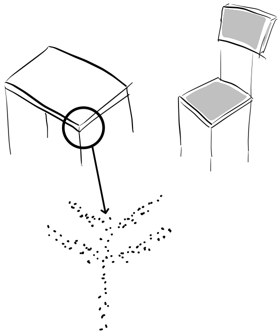
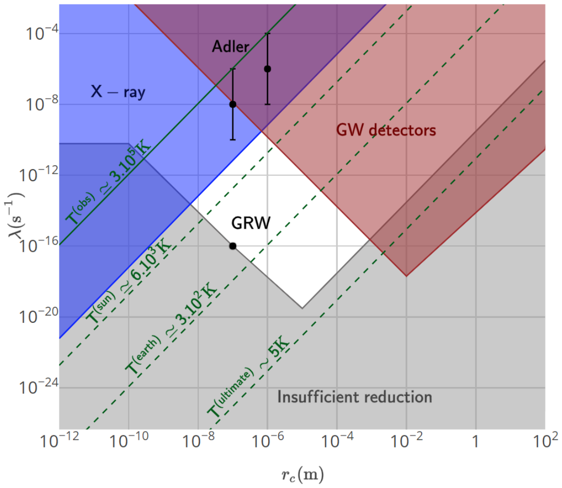


often deemed anecdotal, redundant, or “worse” philosophical

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

Could one have done things differently?

Steven Weinberg tried...

Gisin's theorem (1989)

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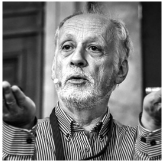
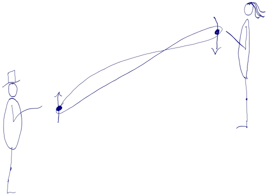


Nicolas Gisin

Reason: such a modification makes

1. a **proper** statistical mixture (Alice measured but Bob does not know the result)
2. an **improper** mixture, from an entangled state (Alice did not measure)

locally distinguishable by Bob.



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* $\bar{\pi}_k = \mathbb{E}\left[\pi_k\right]$

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

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

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Master equation of GRW

Collapse probabilities are chosen exactly so that $\mathbb{E}$ removes the non-linearity

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

3 levels of description

Ontology

"What the theory says about the world"

e.g. flashes (x_f, t_f)

The wave-function

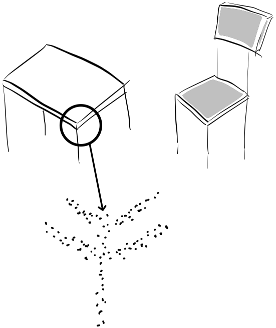
"An intermediary object"

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

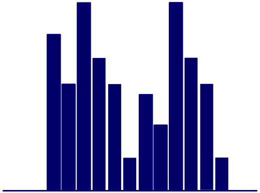
The empirical content

"Quantitative testable predictions of the theory"

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



ψ?



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.

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Unraveling

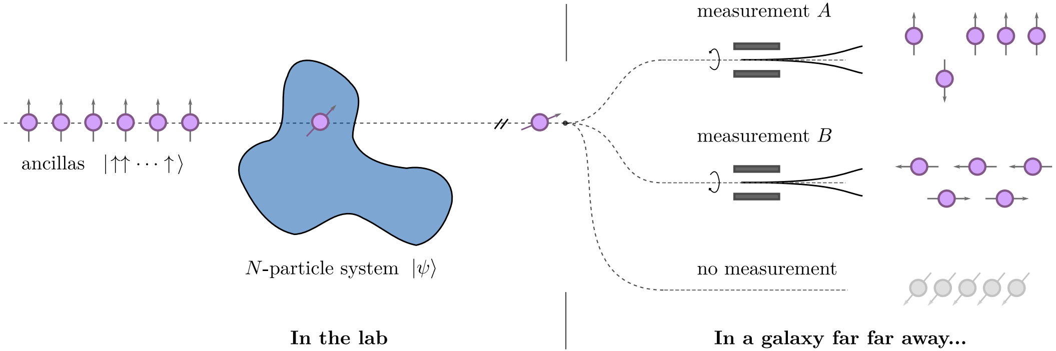
For ρ verifying (1), $\exists$ infinitely many stochastic equations for $|\psi\rangle$ such that $\rho = \mathbb{E}|\psi\rangle\langle\psi|$. [*e.g.* Dalibard, Castin, Mølmer]

Dilation

For ρ verifying (1) one can find a bigger Hilbert space $\mathscr{H}_{\text{big}} = \mathscr{H} \otimes \mathscr{H}_{\text{aux}}$ such that $|\Psi\rangle \in \mathscr{H}_{\text{big}}$ verifies a standard linear Schrödinger equation and $\rho = \text{tr}_{\text{aux}}[|\Psi\rangle\langle\Psi|]$.

Repeated interactions

In discrete time, *unravelings* and *dilations* are trivial to understand:

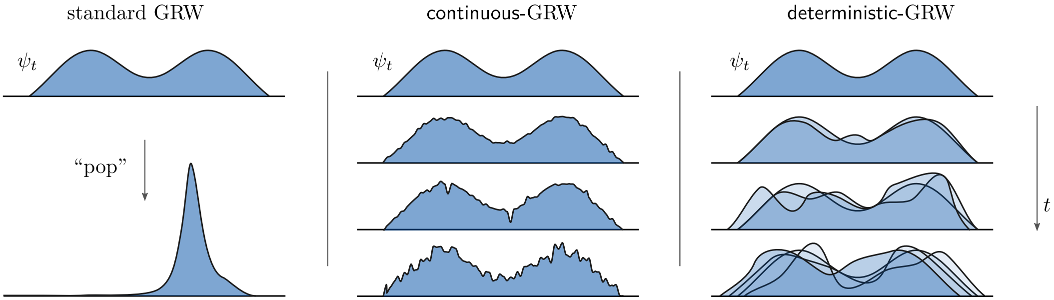


If measurement A gives a discretized GRW, measurement B gives an alternative stochastic evolution, and non-measurement a unitary one.

Many shades of models with identical predictions

For example for **GRW**.
On can construct empirically equivalent models that are:

- stochastic but continuous, and that do not collapse cats
- deterministic but with an added peculiar dark sector in the Standard Model



A counterexample?

Interesting thought experiment inspired from Feldmann & Tumulka
`arXiv:1109.6579`

Imagine we live in a world where $r_C \ll 10^{-16}$m.
$\rightarrow$ Each collapse makes an **audible** bang!

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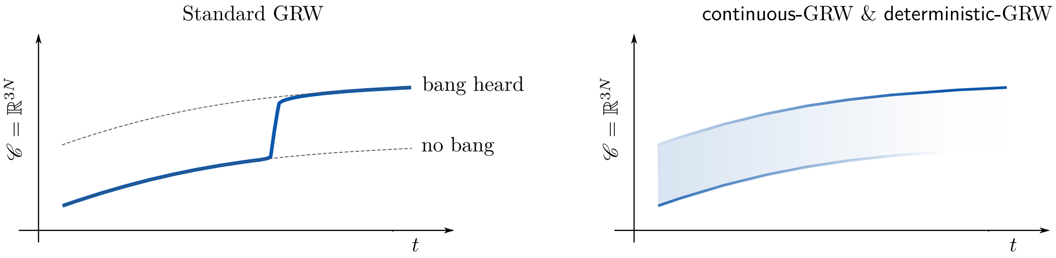
Or does it make:

- A constant buzzing (continuous unraveling)
- No noise at all? (unitary dilation)

Resolution

Empirically, all the models have to agree: we would hear bangs

Support of ψ in configuration space:



Same as the usual explanation of “discrete” photon clicks standard QED.

Summary of the reasoning

1. One introduces non-linear modifications of quantum mechanics to solve the measurement problem
2. These modifications have experimental consequences (advantage or inconvenient)
3. But these modification are strongly constrained by the need for a linear master equation
4. The master equation contains all the empirical predictions of the model (but not the metaphysics)
5. Infinitely many stochastic models or even unitary ones can reproduce the same master equation, and thus the empirical content of these models
6. **In fine**: collapse models solve the measurement problem, but their empirical content does not differ from quantum theory understood broadly, but rather from the standard model

What if the predictions of GRW are verified

- **Logically**, one could still defend some orthodox view of quantum mechanics, introducing a peculiar non-relativistic dark sector
- The standard GRW account would have had the great advantage of having predicted it

What would the community choose?

Main lessons of the collapse program

Very good illustration of:

- Naive realism (the world is made of stuff that moves) is tenable and not so contrived
- Metaphysics is underdetermined by experiments (always true, but particularly clear here)

Also an excellent starting point for theory building