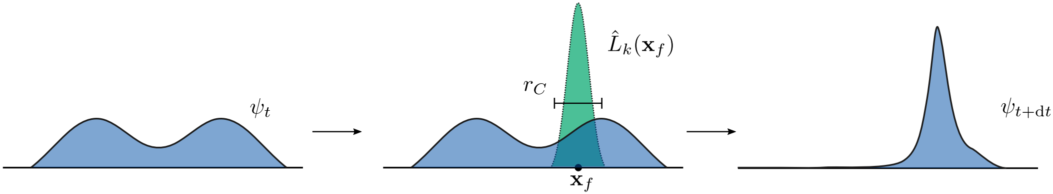
The sound of quantum jumps

and other consequences of Gisin's 42nd theorem



Antoine Tilloy

May 31st, 2022
Nicolas Gisin turns 70!

MINES PARIS | PSL | Inria

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)

First consistent equation of this type: [Gisin 1984]

The easier Ghirardi-Rimini-Weber model

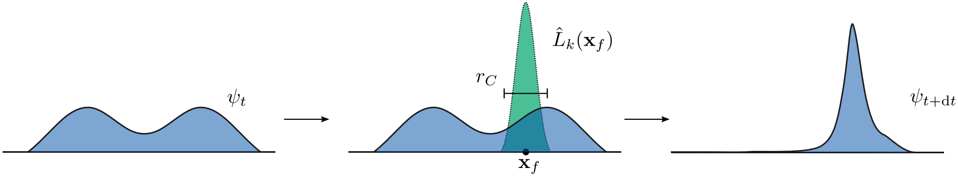
The GRW modification (1986)

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.* $\lambda = 10^{-16}\text{s}^{-1}$ (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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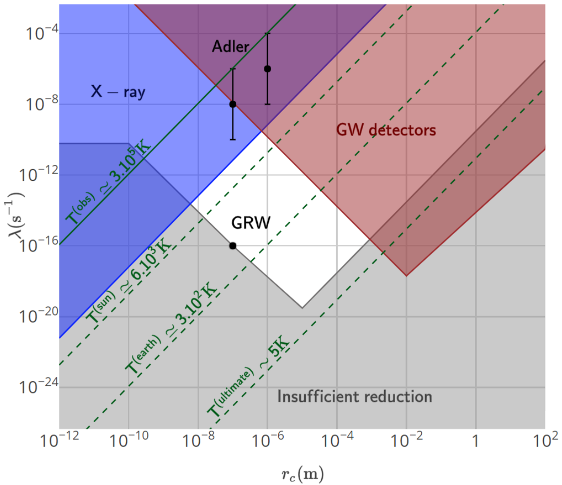
In brief: one can semi-rigorously derive the measurement postulate by studying the stochastic dynamics of measurement devices

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

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

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Steven Weinberg tried...

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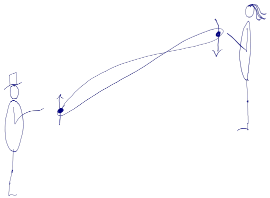
Reason: such a modification makes

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.

Timeline:

1. Gisin's theorem 1989
2. Weinberg's proposal 1989
3. Gisin's explicit rebuttal 1990



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

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

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

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Master equation of GRW

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

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

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

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

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Unraveling

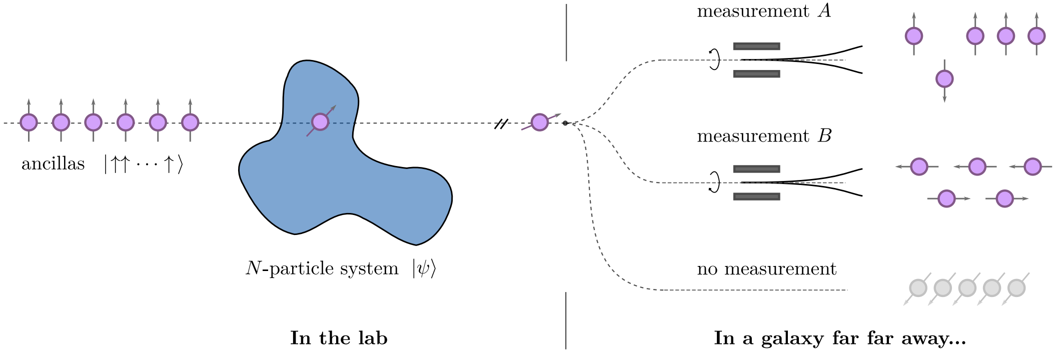
For ρ verifying (1), $\exists$ infinitely many stochastic equations for $|\psi\rangle$ such that $\rho = \mathbb{E}|\psi\rangle\langle\psi|$. [*e.g.* Dalibard, Castin, Mølmer]

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:

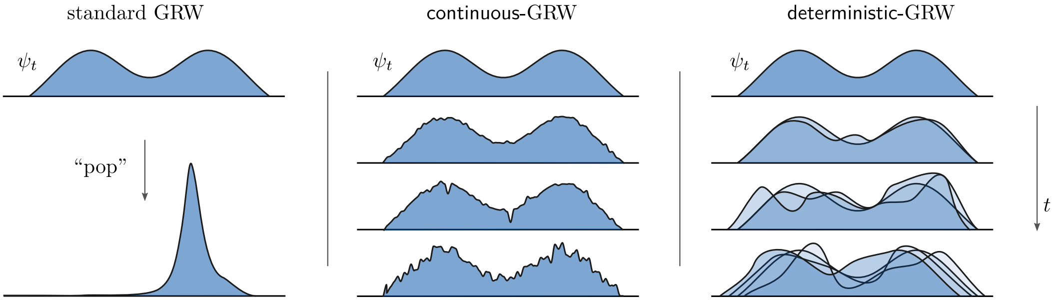


If measurement A gives a discretized GRW, measurement B gives an alternative stochastic evolution, and non-measurement a unitary one.

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.
$\longrightarrow$ Each collapse makes an **audible** bang!

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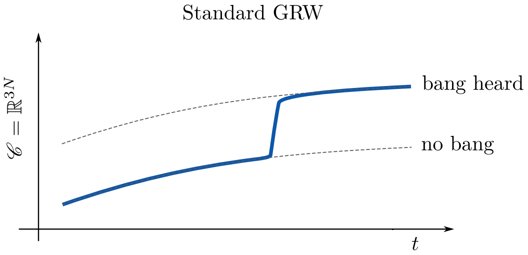
Or does it make:

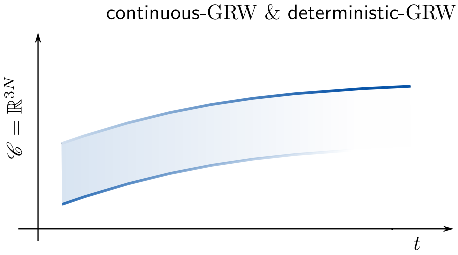
- A constant buzzing (continuous unraveling)
- No noise at all? (unitary dilation)

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.
$\Longrightarrow$ impossible to distinguish this objective randomness from quantum randomness

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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?