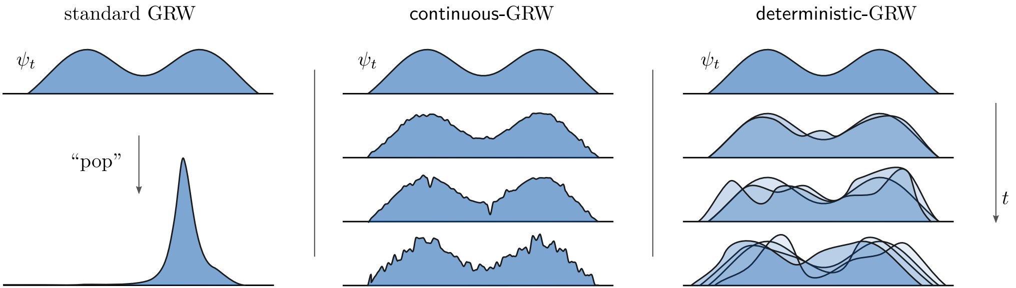
The sound of collapse

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



Seminar of Mathematical Physics
LMU
June 17th, 2020

Context

- Revisiting the old question of *quantum jumps* for the **FQXI** essay contest
  Essay can be found on their website (soon arxiv?)
- Inspired by a paper by Feldman and Tumulka `arXiv:1109.6579`

3.4 Spontaneous Sound Emission

For sufficiently small σ, every single GRW collapse would inject so much energy into the particle affected that a noticeable explosion would occur, which should lead to the emission of sound (besides radiation and heat). The fact that we do not hear spontaneous bangs leads to bounds on σ and λ as follows. One can hear a bang of energy 10^{-6} J (which corresponds to the click of a typewriter [36]) or more. If we assume that the energy injected by collapse into an electron bound in an atom is comparable to that for a free electron as in Eq. (13), and that a substantial fraction of it is emitted as sound, then we obtain that a single collapse will cause an audible noise for $\sigma < 10^{-16}$ m.

- Gives structure to my old ramblings about collapse models

Vague historical question

Do quantum jumps exist fundamentally? Can one hear/see them in any way?

A slightly more precise question

Can one hear the sound of collapse in a model in which collapse is real? If so what does it sound like? Is it specific? Could we deduce from this noise that a special form of randomness exists?

Idea of collapse models

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

Schrödinger equation + tiny non-linear bit

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

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

Completely *ad hoc*, the objective is mostly to see if it is *possible*

The Ghirardi-Rimini-Weber Model

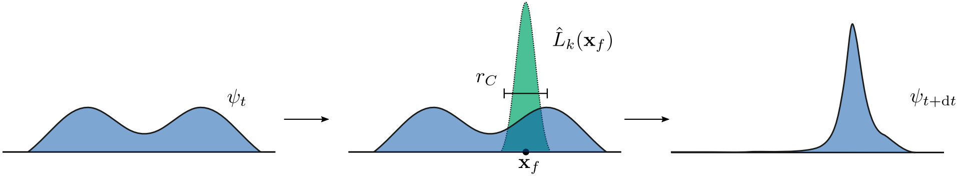
The GRW proposal (1986)

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

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

and 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

If we take for example $\lambda = 10^{-16}s^{-1}$ (historical proposal) :

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

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Long story short: it allows to derive the measurement postulate by applying the theory to macroscopic measurement apparatus.

Small things are collapsed not because they collapse fundamentally, but because the macroscopic device coupled to them collapses.

Metaphysics - ontology

What is the theory about? What is real in this approach? What is matter?

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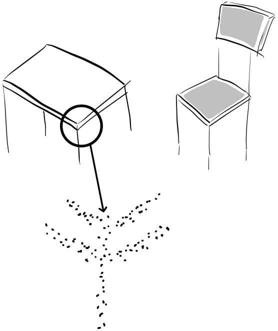

1. `GRW0` The wave function ψ_t itself
2. `GRWm` The mass density expectation value on the wavefunction $\langle \hat{M}(x) \rangle$

$$\langle \hat{M}(x) \rangle = \sum_k \int dx_1 \cdots dx_n \, |\psi(\underbrace{x_1, \cdots, x, \cdots, x_n}_{x \text{ in } k^{\text{th}} \text{ position}})|^2$$

3. `GRWf` The collapse space time points (t_f, x_f), aka "flashes"

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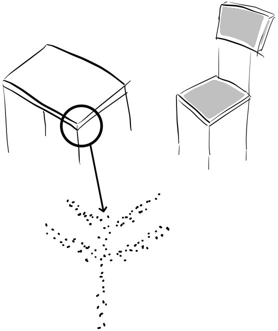
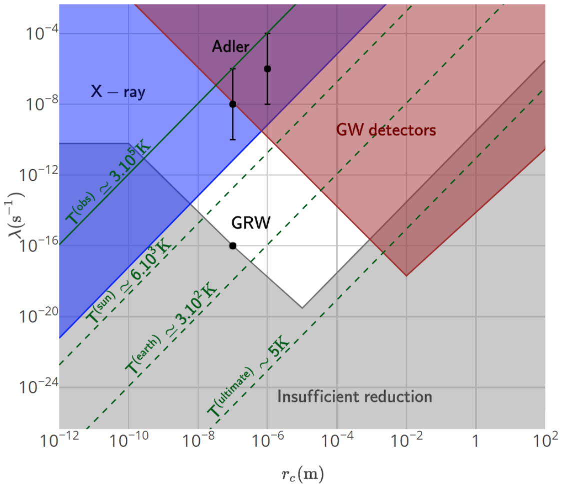


Often considered anecdotal / philosophical / secondary compared to the stochastic dynamics.

Some experimental consequences

1. Loss of interference constrast
2. Matter heats spontaneously
3. Matter jitters weirdly
4. Photons get emitted spontaneously



A few candidates

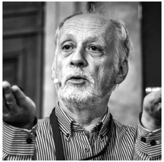
1) Experiments with macromolecules 2) Cold neutron stars 3) Mirors of LISA Pathfinder 4) Germanium crystals in Gran Sasso

Could we do differently? The stiff price of consistency

Steven Weinberg tried but...

Gisin's theorem (1989)

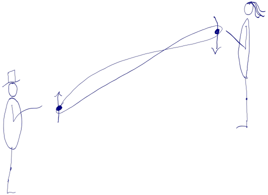
Non-linear deterministic modifications of the Schrödinger allow faster than light signaling (or destroy the Born rule)



Nicolas Gisin

Reason: in an EPR scenario, such a modification allows Bob to distinguish

- a proper mixture (statistical ensemble of pure states, obtained when Alice measured)
- an improper mixture (a mixed state obtained by tracing out Alice's state when she has not yet measured)



Linearity of the master equation

Empirical content of GRW

Crucial fact: we measure relative frequencies $\pi_k = \langle\psi|\hat{\Pi}_k|\psi\rangle$, and in fact only averaged over intrinsic randomness $\bar{\pi}_k = \mathbb{E}\left[\langle\psi|\hat{\Pi}_k|\psi\rangle\right]$

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

So **all** the falsifiable predictions we can ever make are in $\hat{\rho} = \mathbb{E}\left[|\psi\rangle\langle\psi|\right]$

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GRW master equation

Everything is made in such a way that $\mathbb{E}$ kills away non-linear terms:

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

Collapse models: 3 levels of description

Ontological content

"What the theory says the world is like"

$$(x_f, t_f)$$

State vector (?)

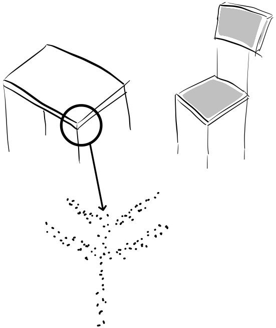
"An intermediary object in the theory"

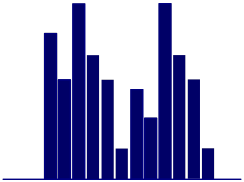
$$\frac{d}{dt}\psi_t = -\frac{i}{\hbar} H \psi_t + \varepsilon(\psi)$$

Empirical content

"What the theory predicts"

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





Consequences of linearity

All the collapse models so far proposed are good with Gisin's theorem and have a linear master equation:

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

It's the thing we test experimentally. What does it tell us about the underlying jumps?

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Unraveling

For ρ verifying (1), $\exists$ infinitely many SDEs for $|\psi\rangle$ such that $\rho = \mathbb{E}|\psi\rangle\langle\psi|$.

Dilation

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

An expample of alternative unraveling

Continuous non-collapsing GRW model

This model is given by the stochastic Schrödinger equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\psi_t = -\frac{i}{\hbar} H \psi_t + i\sqrt{\lambda} \sum_k \int \mathrm{d}x_f \, w_t^k(x_f) \, \hat{L}_k(x_f) \, \psi_t,$$

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This model has the **same master equation as GRW**. But it is

1. continuous (no-jumps)
2. unitary
3. non-collapsing (macroscopic superpositions remained superposed)

An example of unitary dilation

Deterministic unitary GRW model

This model is given by $\frac{\mathrm{d}}{\mathrm{d}t}|\Psi_t\rangle = -\frac{i}{\hbar}H_{\text{tot}}|\Psi_t\rangle$ with $H_{\text{tot}} = H + H_{\text{bath}} + H_{\text{int}}$

$$H_{\text{bath}} = \int_{\mathbb{R}^4} \mathrm{d}\omega\, \mathrm{d}x\, \hbar\, \omega\, a_k^\dagger(\omega, x) a_k(\omega, x)\,,$$

$$H_{\text{int}} = \int_{\mathbb{R}^4} \mathrm{d}\omega\, \mathrm{d}x\, \hbar \sqrt{\lambda}\, \hat{L}_k(x) \otimes \left[a_k^\dagger(\omega, x) + a_k(\omega, x)\right]\,,$$

where the a's are simply annihilators for standard harmonic oscillators

$$[a_k(\omega, x), a_{k'}^\dagger(\omega', x')] = \delta^3(x - x')\delta(\omega - \omega')\delta_{k,k'}\,.$$

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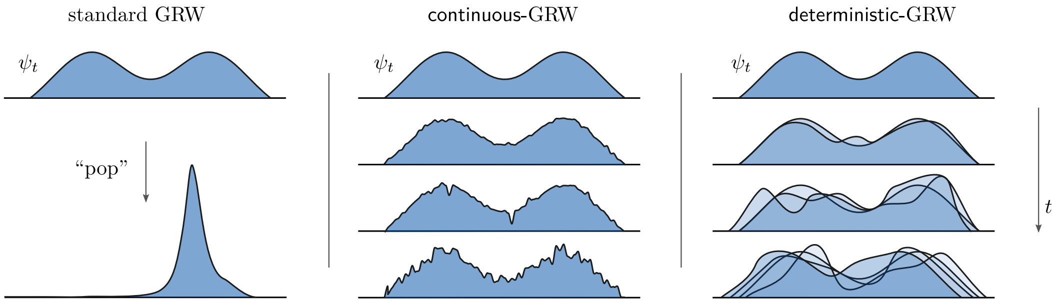
This model has the same master equation as GRW but it is

1. Unitary and deterministic
2. Fully orthodox quantum mechanics

Summary: 50 shades of models

GRW has cousins with the same empirical content but wildly different dynamics

- Stochastic and continuous, but doesn't collapse cats
- Unitary and orthodox, just with an additional "dark matter"



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Imagine a world in which it is the case, or even that λ and r_c are such that roughly once per day, a huge bang is heard throughout the world.

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Imagine a world in which it is the case, or even that λ and r_c are such that roughly once per day, a huge bang is heard throughout the world.

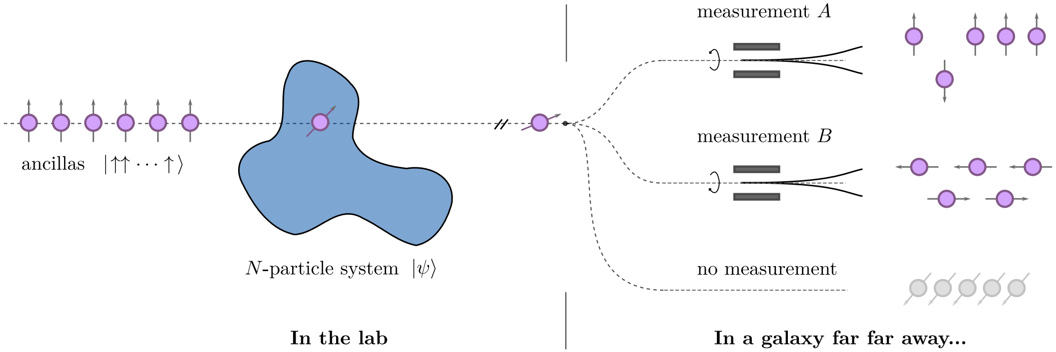
But, intuitively

- continuousGRW would predict a constant buzzing
- deterministicGRW would predict some continuous sound (??)

So what is it?

Repeated interactions

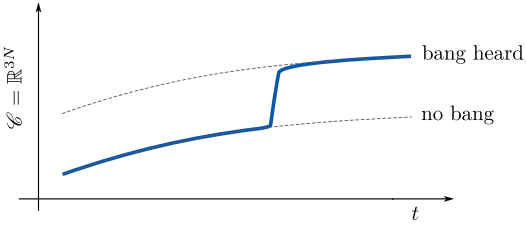
In discrete time, the multiplicity of unraveling, dilations, and their empirical equivalence, is easier to understand

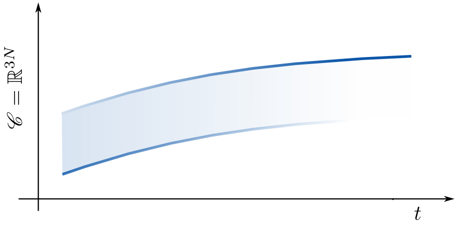


correspond to doing different operations on the ancillas

The sound of collapse: resolution

Decoherence is remarkably efficient for all practical purposes. It carves the wavefunction into branches corresponding to bang and no bang, even without collapse





The collapse paints the branch chosen.

Decoherence vs collapse

But it does a lot! It is sufficient to explain everything for all practical purposes

- It carves the wave function into branches
- It makes position fundamental because interactions are local in position space in QFT
- It tells us what is macroscopic, and tells us why we don't see superposed cats

On the other hand **collapse models**:

- Also carve the wave function into branches (but marginally compared to QED) `[redundant]`
- Also single out position in their dynamics (negligibly compared to the H of the SM) `[redundant]`
- **Define precise local things that are real**
- **They tell us why superposed cats don't exist**

Summary

There are no *specific* signatures of the quantum jumps of collapse.

The main steps of the argument are

1. We start from a stochastic non-linearity in the Schrödinger equation
2. Consistency conditions require non-linearity to vanish upon averaging
3. The linear averaged equation contains all the empirical content of the model
4. This equation can be reproduced by many other models that tell a very different story
5. Hence, the stochastic description is as metaphysical as the choice of ontology

The main achievement of collapse models is **metaphysical** (it's already a lot!). What they bring empirically (reduction of the coherence of a Schrödinger cat for example) is redundant with what decoherence already does.