Link between non-Markovian collapse models and de Broglie-Bohm theory

Antoine Tilloy, with Howard M. Wiseman

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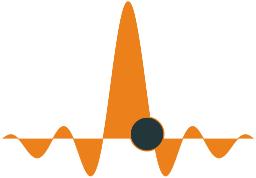

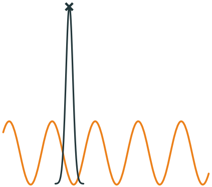

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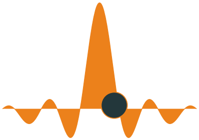
Two “realist” reconstructions of QM

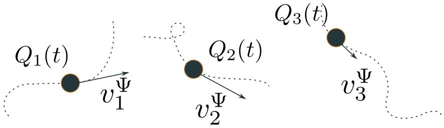
de Broglie - Bohm



- ♣ The wave-function ψ evolves unitarily

$$\partial_t|\psi\rangle = -iH|\psi\rangle$$

- ♠ *“Particles move”*



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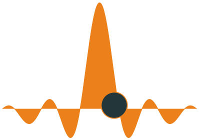

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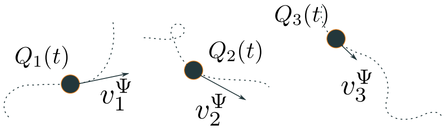
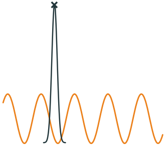


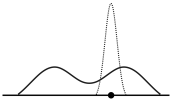
Objective collapse



- ♣ The wave-function does **not** evolve unitarily

$$\partial_t|\psi\rangle = -iH|\psi\rangle + \varepsilon\, f(\psi, w)\,|\psi\rangle$$

- ♠ The real world is made from ψ or collapse events (“flashes”)

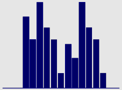


A connection on two levels

Weak inclusion

For a reasonably generic collapse model on a system S, there exists a bath of oscillators B and some (carefully chosen) unitary dynamics on $S + B$ such that the two models are **empirically** indistinguishable.

`Collapse` on S $\underset{\text{empirically}}{\Longleftrightarrow}$ `dBB` (or `MW` or ...) on $S + B$



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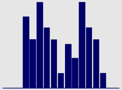
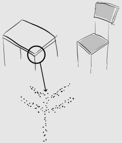


Strong inclusion

With the same choice of B, one can supplement the bath oscillators with Bohmian positions (hidden variables) q_B such that $\psi_S^{\text{collapse}}(\cdot) = \psi_{S+B}^{\text{dBB}}(\cdot, q_B)$, and the collapse model noise has the same law as a linear functional of q_B.

Collapse on S $\underset{\text{ontologically}}{\Longleftrightarrow}$ dBB on $S + B$



Plan

1. The principle and origin of collapse models (Ghirardi-Rimini-Weber)
2. The structure of collapse models (Gisin's theorem)
3. Modern collapse models (with colored noise)
4. Dilation and Bohmianization
5. Discussion

The principle and origin of collapse models (Ghirardi-Rimini-Weber)

The idea of collapse models

Other names : [Objective / spontaneous / dynamical] [reduction / collapse] [model / program]

Schödinger equation + tiny non-linear bit

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

H is the Standard Model Hamiltonian (or non-relativistic approx)

Careful : a priori *ad hoc*, the objective is primarily to show it's possible *possible*

Ghirardi Rimini Weber model

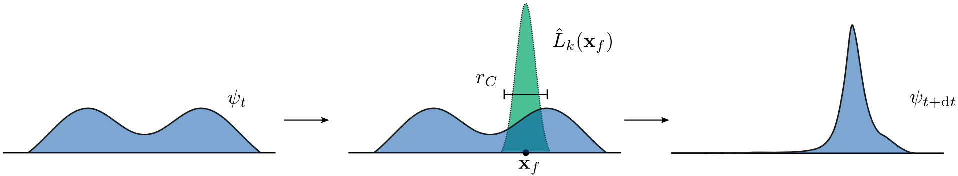
The GRW modification (1986)

Every $\mathrm{d}t$, with proba $\lambda \mathrm{d}t$ particle k collapses around point x_f

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

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

If one takes $\lambda = 10^{-16}\text{s}^{-1}$ (historical value) :

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

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

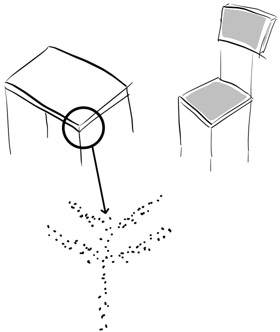
Metaphysics – Ontology

What is real ? What is the world made of ?

1. GRW0 The wave-function ψ_t itself (but infinite literature of subtleties)
2. GRWm The mass density $\langle \hat{M}(x) \rangle$

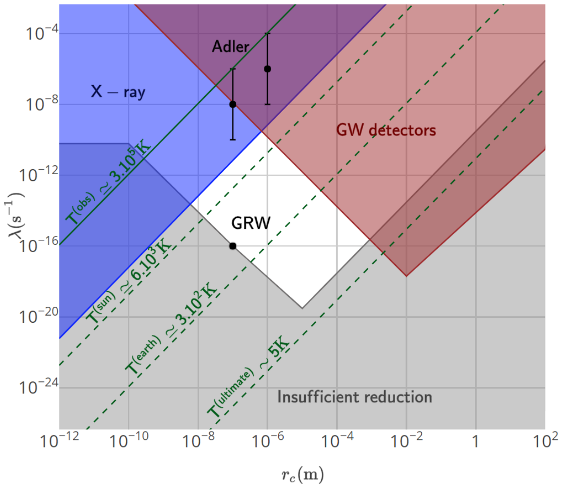
$$\langle \hat{M}(x) \rangle = \sum_k \int dx_1 \cdots dx_n \, |\psi(x_1, \cdots, \underbrace{x}_{x \text{ in } k^{\text{th}} \text{ position}}, \cdots, x_n)|^2$$

3. GRWf The events (t_f, x_f) where the wave-function collapse (the flashes) – [Bell's choice !]



Experimental consequences

1. Loss of interference pattern with macro-molecules
2. Matter heats up (slowly...)
3. Micro vibrations
4. Spontaneous emission of photons



Some candidates

1) Experiments of Markus Arndt 2) **Neutron stars** 3) Mirrors of LISA Pathfinder 4) Germanium crystals underground in Gran Sasso

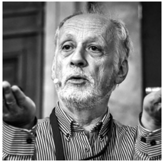
The structure of collapse models (Gisin's "theorem")

Could we do things differently ?

Steven Weinberg tried but ...

Gisin's theorem (1989)

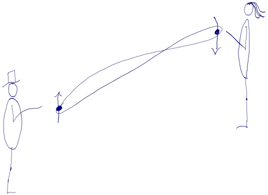
Non-linear deterministic modifications of Schrödinger's equation allow to send signals faster than light (or break Born's rule).



Nicolas Gisin

Reason : with such a modification, one can *empirically* distinguish

- a statistical mixture (Alice measured, Bob doesn't know the result)
- an entangled state (Alice didn't measure)



Linearity of the master equation

Empirical content of GRW

Crucial point : we can only measure frequencies in practice $\pi_k = \langle\psi|\widehat{\Pi}_k|\psi\rangle$, which are in addition averaged over jumps $\overline{\pi}_k = \mathbb{E}\left[\langle\psi|\widehat{\Pi}_k|\psi\rangle\right]$

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

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

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

GRW master equation

Everything is made such that $\mathbb{E}$ cancels away the non-linearity

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

Les modèles de collapse modernes (à bruit coloré)

Modern collapse models (with colored noise)

One wonders which type of non-linear stochastic Schrödinger equations one can write :

$$\partial_t|\psi\rangle = -iH|\psi\rangle + \varepsilon \underbrace{f(\psi, w)}_{\text{non-linear}} |\psi\rangle \tag{1}$$

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- Equation (1) reduces superpositions in a certain basis (typically position)
- The master equation on $\rho_t = \mathbb{E}\left[\, |\psi_t\rangle\langle\psi_t| \,\right]$ is **linear** :

$$\rho_t = \Phi_t \cdot \rho_0$$ **C**ompletely **P**ositive **T**race **P**reserving

Necessary to stay safe from Nicolas Gisin's anger.

Recipe – step 1 : start from a linear equation

Linear Stochastic differential equation

$$\frac{\mathrm{d}}{\mathrm{d}t}|\phi_w(t)\rangle = \Big[-iH + \underbrace{\sqrt{\gamma}\, w_i(t)}_{\text{noise}} A_i \underbrace{- 2\sqrt{\gamma}\, A_i \int_0^t \mathrm{d}s\, D_{ij}(t,s) \frac{\delta}{\delta w_j(s)}}_{\text{non-trivial yet necessary memory term}} \Big] |\phi_w(t)\rangle,$$

with Gaussian **colored** noise : $\mathbb{E}\left[w_i(t) w_j(s)\right] = D_{ij}(t,s)$ où $D > 0$

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- **Master equation** : For $\rho_t = \mathbb{E}\Big[|\phi_w(t)\rangle\langle\phi_w(t)| \Big]$, one gets $\rho_t = \Phi_t \cdot \rho_0$ with Φ_t (CPTP) thanks to the memory term

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- **Dilation** : the master equation admits a unitary dilation by adding a bath of harmonic oscillators $\to$ weak inclusion is intuitive

Recipe – step 2 : normalize ϕ and cook the noise

Normalize

The norm of $|\phi_w(t)\rangle$ is not constant, one needs to normalize

$$|\psi_w(t)\rangle := \frac{1}{\sqrt{\langle\phi_w(t)|\phi_w(t)\rangle}}|\phi_w(t)\rangle$$

but, horror ! $|\psi_w(t)\rangle$ does not give a linear master equation upon $\mathbb{E}$

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Cook the noise

One restores the linearity by continuously changing the law of the noise

$$\forall t \geqslant 0, \quad w_j^{[t]}(s) = w_j(s) + 2\sqrt{\gamma}\int_0^t \mathrm{d}\tau\, D_{ij}(\tau, s)\langle A_i\rangle_\tau,$$

to get a new noise that depends on the complete trajectory $|\phi_w\rangle$

The collapse model is contained in the evolution of $|\psi_{w^{[t]}}(t)\rangle$.

Salient points to remember

Generic collapse models *i.e.* with colored noise, are more subtle than they seem.
In particular, 2 difficulties :

1. **Memory term** :

$$2\sqrt{\gamma}\,A_i \int_0^t \mathrm{d}s\, D_{ij}(t,s)\frac{\delta}{\delta w_j(s)}|\phi_w(t)\rangle$$

   necessary to maintain consistency but extremely not intuitive

2. **Cooking / noise redefinition** :

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→ Equivalent in dBB : **conditioning** for 1 and **piloting equation** for 2

Dilation and Bohmianization

Explicit dilation

Objective : find an explicit bath B such that

tracing over bath $\text{tr}_B[|\psi_{S+B}\rangle\langle\psi_{S+B}|]$ $=$ **average over noise** $\mathbb{E}[|\psi_w\rangle\langle\psi_w|]$

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Solution : continuum of harmonic oscillators $[\hat{x}_{j,\omega}, \hat{p}_{j',\omega'}] = i\delta_{j,j'}\delta(\omega-\omega')$

$$H_B = \sum_j \int_{\mathbb{R}} \mathrm{d}\omega\ \omega\, a^\dagger_{j,\omega} a_{j,\omega} \quad \text{and} \quad H_{B\leftrightarrow S} = \sum_{j,k} A_j \otimes \int_{\mathbb{R}} \mathrm{d}\omega\ \kappa_{j,k,\omega}\, \hat{p}_{k,\omega}$$

with $\kappa_{k,\ell,\omega} = \kappa_{k,\ell,-\omega}$.

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Link with the 2-point function of the noise :

$$D_{jk}(t-s) = \int_{\mathbb{R}^+} \mathrm{d}\omega\ \kappa_{j,\ell,\omega} \kappa_{k,\ell,\omega}\ \cos(t-s)$$

$\rightarrow$ explicit version of the weak inclusion [proof : Wick's theorem]

Technical subtlety

For what follows we need to change of basis for B

1. go into interaction representation for the bath (rotating basis)
2. define new oscillator variables

$$\hat{x}^+_{j,\omega} = \frac{\hat{x}_{j,\omega} + \hat{x}_{j,-\omega}}{\sqrt{2}} \qquad \hat{p}^+_{j,\omega} = \frac{\hat{p}_{j,\omega} + \hat{p}_{j,-\omega}}{\sqrt{2}}$$

$$\hat{x}^-_{j,\omega} = \frac{\hat{p}_{j,\omega} - \hat{p}_{j,-\omega}}{\sqrt{2}} \qquad \hat{p}^-_{j,\omega} = \frac{-\hat{x}_{j,\omega} + \hat{x}_{j,-\omega}}{\sqrt{2}}$$

This new basis is still a legitimate oscillator basis, with canonical commutation relations

$$[\hat{x}^+_{j,\omega}, \hat{p}^+_{j,\omega}] = i \qquad [\hat{x}^+_{j,\omega}, \hat{p}^-_{j,\omega}] = 0$$

$$[\hat{x}^-_{j,\omega}, \hat{p}^+_{j,\omega}] = 0 \qquad [\hat{x}^-_{j,\omega}, \hat{p}^-_{j,\omega}] = i,$$

Bohmianizing the bath : 1 conditioning

Step 1 : condition the state of $S + B$ for **fixed** particle positions in B

$$\psi_{S,x_B}(t, x_S) := \psi_{S+B}(t, x_S, x_B) \quad \Leftrightarrow \quad |\psi_{S,x_B}(t)\rangle := \langle x_B|\psi_{S+B}(t)\rangle$$

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Observation 1

$|\psi_{S,x_B}(t)\rangle$ obeys the same differential equation as $|\phi_w(t)\rangle$ with the "noise"

$$\widetilde{w}_k(t) = \int_{\mathbb{R}^+} \mathrm{d}\omega\ \kappa_{k,\ell,\omega}\left[\cos(\omega t)\, x^+_{\ell,\omega} + \sin(\omega t)\, x^-_{\ell,\omega}\right]$$

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Observation 2

If the system $S+B$ is initially in the state $|\psi_{S+B}\rangle = |\psi_S\rangle \otimes |0\rangle_B$ and if initial Bohmian variables B are drawn from Born's rule, $\widetilde{w}$ (which is deterministic !) has the same law as the noise w the collapse model before cooking

Bohmianizing the bath : 2 evolve the particles

Step 2 : condition not on x_B fixed in B, but on positions $x_B(t)$ evolving according to `Bohmian` dynamics

$$|\psi_{S,x_B}(t)\rangle \longrightarrow |\psi_{S,x_B(t)}(t)\rangle \quad \text{with} \quad \frac{\mathrm{d}x_B(t)}{\mathrm{d}t} = \mathcal{V}_{\mathtt{dBB}}^{\psi_{S+B}}[x_B(t)]$$

i.e. the standard conditional wavefunction in `dBB`

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Observation 3

The field $\widetilde{w}^{[t]}$ obtained from $x_B(t)$ is linked to $\widetilde{w}$ through the same non-trivial transformation linking $w^{[t]}$ and w.

$$\forall t \geqslant 0, \quad \widetilde{w}_j^{[t]}(s) = \widetilde{w}_j(s) + 2\sqrt{\gamma}\int_0^t \mathrm{d}\tau\, D_{ij}(\tau, s)\langle A_i\rangle_\tau,$$

Technical subtlety

Expressing the velocity field (guiding law or pilot equaiton) for a generic dBB theory with a Hamiltonian at most order 2 in $\hat{p}$

$$\frac{\mathrm{d}}{\mathrm{d}t}x(t) = \mathcal{V}[x(t)] = \frac{\mathfrak{Re}\left[\langle\psi_t|\widehat{\Pi}_x(t)\widehat{\mathcal{V}}|\psi_t\rangle\right]}{\langle\psi_t|\widehat{\Pi}_x(t)|\psi_t\rangle},$$

with

$$\widehat{\mathcal{V}} = -i[H, \hat{x}]$$

which extends the standard

$$\mathcal{V}(x(t), |\psi_t\rangle] = \frac{1}{m}\mathfrak{Im}\left[\frac{\partial_x\psi_t(x)}{\psi_t(x)}\right]\Big|_{x=x(t)}$$

to generic Hilbert spaces (not just $L^2(\mathbb{R})$)

Bohmianizing the bath : conclusion

The 3 observations

1. The wavefunction of $S + B$ where we fix bath particles has the same dynamics as $|\phi_w\rangle$ if we assume the linear field $\widetilde{w}$ has the same value as the noise w.
2. If Bohmian positions of the bath are initially drawn from the Born rule (which is the case at equilibrium in dBB), then $\widetilde{w}$ indeed has the same law as w.
3. Letting the bath particle evolve according to the standard Bohmian guiding laws transforms the field in the same way that cooking cooking changes the collapse field.

Bohmianizing the bath : conclusion

The 3 observations

1. The wavefunction of $S + B$ where we fix bath particles has the same dynamics as $|\phi_w\rangle$ if we assume the linear field $\widetilde{w}$ has the same value as the noise w.
2. If Bohmian positions of the bath are initially drawn from the Born rule (which is the case at equilibrium in dBB), then $\widetilde{w}$ indeed has the same law as w.
3. Letting the bath particle evolve according to the standard Bohmian guiding laws transforms the field in the same way that cooking cooking changes the collapse field.

imply the strong result

- The wavefunction ψ_S by fixing the bath positions to their real-time dBB value $x_B(t)$ *i.e.* $\psi_{S+B}(x_B(t), \cdot)$ is a stochastic process with the same law as $\psi_w^{[t]}$ the wavefunction of the collapse model
- The law of the field $\widetilde{w}^{[t]}$ (linear functional of the Bohmian positions) is the same as the law of the cooked noise $w^{[t]}$ in the full collapse model.

Discussion

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- *Collapse models bring nothing to foundations then ?*
  $\rightarrow$ they do, they solve the measurement problem, which is an empirical problem

Implications du résultat fort – inclusion ontologique

Pot pourri :

- Des dynamiques **aléatoire** et **déterministe** peuvent être **identiques** – la différence est alors *nomologique* (dans l'écriture de la loi, *i.e.* la filtration)

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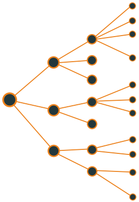
  $\rightarrow$ restreindre l'appellation aux modèles Markoviens comme GRW ?
- Il est tentant de répéter les mêmes constructions à des « bains » existants (comme les photons)
  $\rightarrow$ description dBB partielle équivalente à leur « *unraveling* » stochastique

Conclusion



Il n'y a qu'une manière de choisir une branche

Les deux approches les plus précises et explicites pour choisir une branche de la fonction d'onde – pour éviter *Many World* en étant *réaliste* – utilisent en fait de manière cachée la même dynamique.

Peut-on faire autrement ?