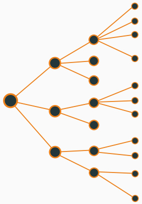
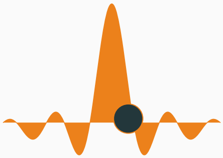
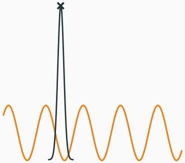
Some possible “non-romantic” foundations of quantum mechanics

an amateurish introduction







Autrans summer school
July 22, 2016
Antoine Tilloy, LPT-ENS

Stochastic Methods in Quantum Mechanics, summer school in Autrans, July 11-22 2016

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QUESTION

Is it possible to understand/interpret/reconstruct quantum mechanics from a down-to-earth/conservative/classic/boring theory?

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David Mermin 1981

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The only connexion between the **formalism** of quantum theory and **Nature** is through the measurement postulate.

"A **mathematically trivial** operation"

Measurement postulate

For a system "described" by $|\psi\rangle \in \mathscr{H}$ and a measurement of orthogonal projectors Π_i s. t. $\sum_i \Pi_i = \mathbb{1}$ one has:

Born rule :

Result " i " with probability $\mathbb{P}[i] = \langle\psi|\,\Pi_i\,|\psi\rangle$

Collapse :

$$|\psi\rangle \longrightarrow \frac{\Pi_i\,|\psi\rangle}{\sqrt{\mathbb{P}[i]}}$$

Max Born 1926

John von Neumann 1932

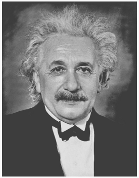
“A **physically subtle** endeavour”

- What is a measurement?
- How can measurement be a primitive concept?
- What is a measurement result made of?
- Can one deduce the measurement postulate from unitary evolution? (answer: NO, hint: decoherence does not help)

notions of ‘reversible’ and ‘irreversible’. Einstein said that it is theory which decides what is ‘observable’. I think he was right — ‘observation’ is a complicated and theory-laden business. Then that notion should not appear in the *formulation* of fundamental theory. *Information? Whose* information? Information about *what*?

On this list of bad words from good books, the worst of all is ‘measurement’. It must have a section to itself.

Physics World, Against Measurement



Albert Einstein 1935

John S. Bell 1989

What is quantum mechanics about?

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We would like more than an **interpretation** of the formalism, we would like a theory of how Nature could be giving rise to the formalism.

WHAT IS ROMANTIC

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A theory is "**romantic**" when it makes grandiose or counterintuitive claims about the universe without strong experimental support.

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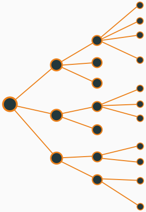
Example:
Many worlds
interpretation



Everett 1957

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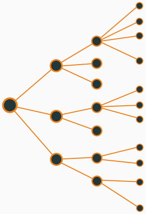

Everett 1957

We want to keep romanticism to a minimum.

A DEFINITION

Primitive ontology aka the “stuff” or “local beables”

The **ontology** is what the theory considers to be real. The **primitive ontology** is a local ontology living in **real space**.

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- The primitive ontology of a theory is not necessarily microscopically observable.
- Yet the macroscopic world (“tables and chairs”) should be understandable in terms of the primitive ontology.
- One can imagine theories with an ontology yet no primitive ontology, but its difficult to understand the emergence of tables and chairs.

Examples: particles, fields, flashes... (look up Valia Allori for excellent reviews)

WHAT WE WANT

Quantum theory without observer

A non-romantic theory with a clear primitive ontology which gives the operator formalism of quantum theory as a **theorem**.

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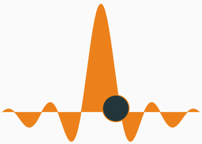
This excludes “interpretations” which are not theories of Nature:

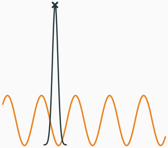
- Quantum Bayesianism
- Quantum Logic

OUTLINE

Study two mathematically well defined examples of non romantic foundations of quantum theory with a primitive ontology:

- Pilot Wave Theory
- Dynamical Reduction Models

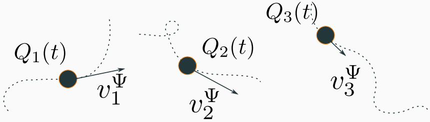




Bohm 1952

Ghirardi 1986

PILOT WAVE THEORY



Guiding equation

$$\frac{\mathrm{d}\,Q_k(t)}{\mathrm{d}t} = v_k^\Psi(Q_1(t), \cdots, Q_n(t))$$

Schrödinger equation

$$i\hbar\,\frac{\mathrm{d}\Psi}{\mathrm{d}t} = H\Psi$$

L. de Broglie 1927

D. Bohm 1952

It is a theory of the **universe**, Ψ is the wave function of all there is.

The rest, especially what happens in situations when we deal with subsystems, should be derived through mathematical analysis.

The **primitive ontology** is simply the particle positions (as in classical mechanics).

HOW TO DETERMINE THE VELOCITY FIELD?

Equivariance

If the a priori probability on the particle positions is consistent with the Born rule, i.e.

$$\mathbb{P}(Q_1, \cdots, Q_n) = |\Psi(Q_1, \cdots, Q_n)|^2,$$

it should stay so as time flows.

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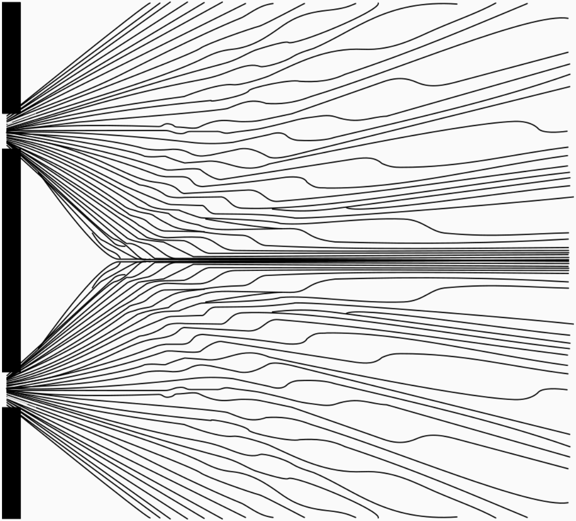
Velocity field

The simplest velocity field satisfying equivariance is:

$$v_k^\Psi = \frac{J_k^\Psi}{\Psi^* \Psi} = \frac{\hbar}{m_k} \Im\mathrm{m} \left(\frac{\nabla_k \Psi}{\Psi} \right)$$

DOUBLE SLIT EXPERIMENT



Conditional wave function

Consider a subsystem $X = (Q_1, \cdots, Q_k)$ of k particles of the universe. Then the **conditional wave function** of the subsystem is:

$$\psi_X(q_1, \cdots, q_k) = \Psi(q_1, \cdots, q_k, Q_{k+1}, \cdots, Q_n)$$

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The Bohmian conditional wave function corresponds to the "orthodox" wave function (especially, it effectively collapses during measurements).

FUNDAMENTAL RESULTS

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For “typical” initial conditions Q of the universe, we have **Quantum Equilibrium**, i.e. the Born rule is valid for subsystems using the conditional wave function.

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N. Zanghi, D. Dürr, S. Goldstein

IMPORTANT FACTS

- Spin can easily be included, it is a **property of the wave function** and not of the particles.
- Extensions to regularized QFTs are possible with field or particle primitive ontology.

CONCLUSION OF BOHM

- Reproduces predictions of Quantum theory as long as they are well defined.
- Fully deterministic (randomness comes from an impossibility to know the initial conditions).
- Explicitely non-local (which guided Bell towards his inequality) and **contextual**.
- Can be used to construct the only mathematically precise “Many Worlds” theory on the market (Hall-Deckert-Wiseman, PRX 2014)

DYNAMICAL REDUCTION MODELS

DISCRETE MODEL (1987)

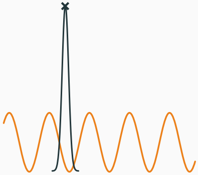
Ghirardi-Rimini-Weber model

Most of the time:

$$i\hbar \frac{\mathrm{d}\psi}{\mathrm{d}t} = H\psi$$

With probability $\mathbb{P}[x_c] = \lambda\,|\psi(x_c)|^2\,\mathrm{d}t$

$$\psi(x) \longrightarrow \psi_c(x) \propto e^{-(x-x_c)^2/(2\,\sigma)}\psi(x)$$

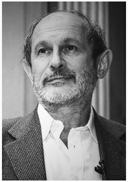


Quantum Mechanics with Universal Position Localization (QMUPL)

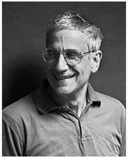
$$\mathrm{d}\rho_t = -i[H, \rho_t]\,\mathrm{d}t + \lambda \mathcal{D}[X](\rho_t)\,\mathrm{d}t + \sqrt{\lambda}\mathcal{M}[X](\rho_t)\,\mathrm{d}W_t$$

Continuous Spontaneous Localization (CSL)

$$\mathrm{d}\rho_t = -\,i[H, \rho_t]\,\mathrm{d}t + \gamma \int \mathrm{d}^3x\,\mathcal{D}[\hat{M}_\sigma(x)](\rho_t)\,\mathrm{d}t + \sqrt{\gamma}\int \mathrm{d}^3x\,\mathcal{M}[\hat{M}_\sigma(x)](\rho_t)\,\mathrm{d}W_t^{(x)}$$



L. Diósi



P. Pearle

HOW REDUCTION WORKS

The additional collapse term:

- barely changes the microscopic dynamics
- collapses macroscopic superpositions in position

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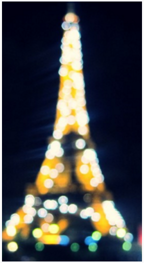
GRWm: mass density ontology

$$\varrho(x) = m|\psi(x)|^2$$



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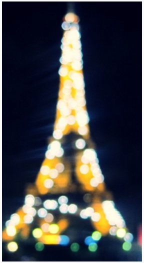

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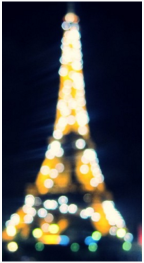

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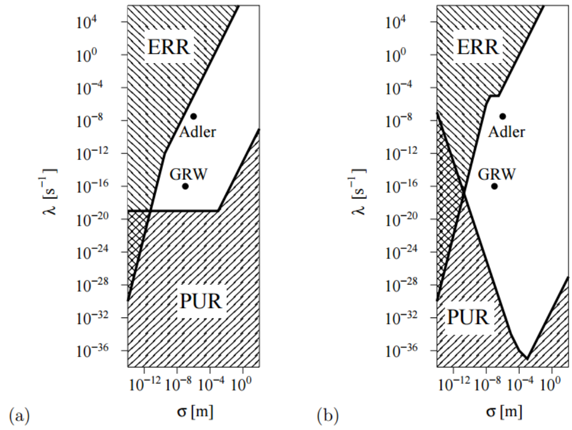
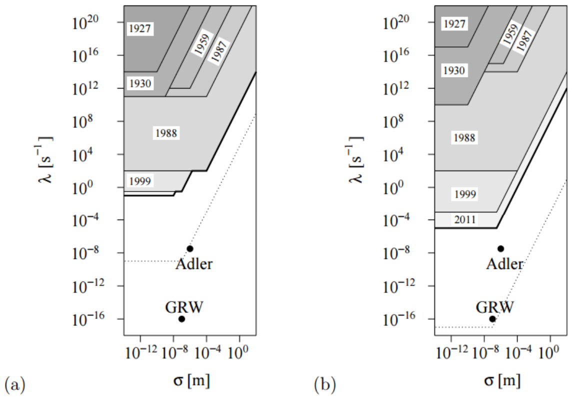
This gives two different theories which make the same predictions.

Dynamical reduction models make different predictions from quantum mechanics, yet are not falsified by experiments:



GRW and CSL parameter space. ERR: empirically refuted region, PUR: philosophically unsatisfactory region – **Feldman & Tumulka**, 2011

We will soon know if dynamical reduction models are compatible with reality!



GRW and CSL parameter space. **Feldman & Tumulka**, 2011

CONCLUSION ABOUT THE DYNAMICAL REDUCTION PROGRAM

- Dynamical reduction models can be made relativistic (see Tumulka for GRW, Pearle and Bedingham for CSL).
- CSL can be used to explore paradoxes (cosmological fluctuations, black hole info, see Sudarsky's group)
- CSL can be used to couple matter and gravity in the Newtonian limit (see Diosi and myself)

CONCLUSION

SOME LESSONS ABOUT QUANTUM THEORY

In practice, we should use the orthodox formalism to do computations!

The previous constructions are likely not the final word about Nature, yet they provide counter examples to common misconceptions such as:

- Quantum mechanics (or Bell inequality) implies that Nature is intrinsically random.
- The cat is dead and alive
- It is not possible to talk about the position and the velocity of particles at the same time
- In the double slit experiment, one cannot even define where the particle went through.

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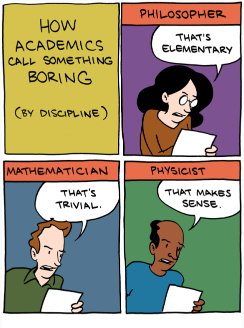
– **Do we really understand Quantum Mechanics**
Frank Laloë (2012)
– **Quantum theory without observers**
Sheldon Goldstein (1998)



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