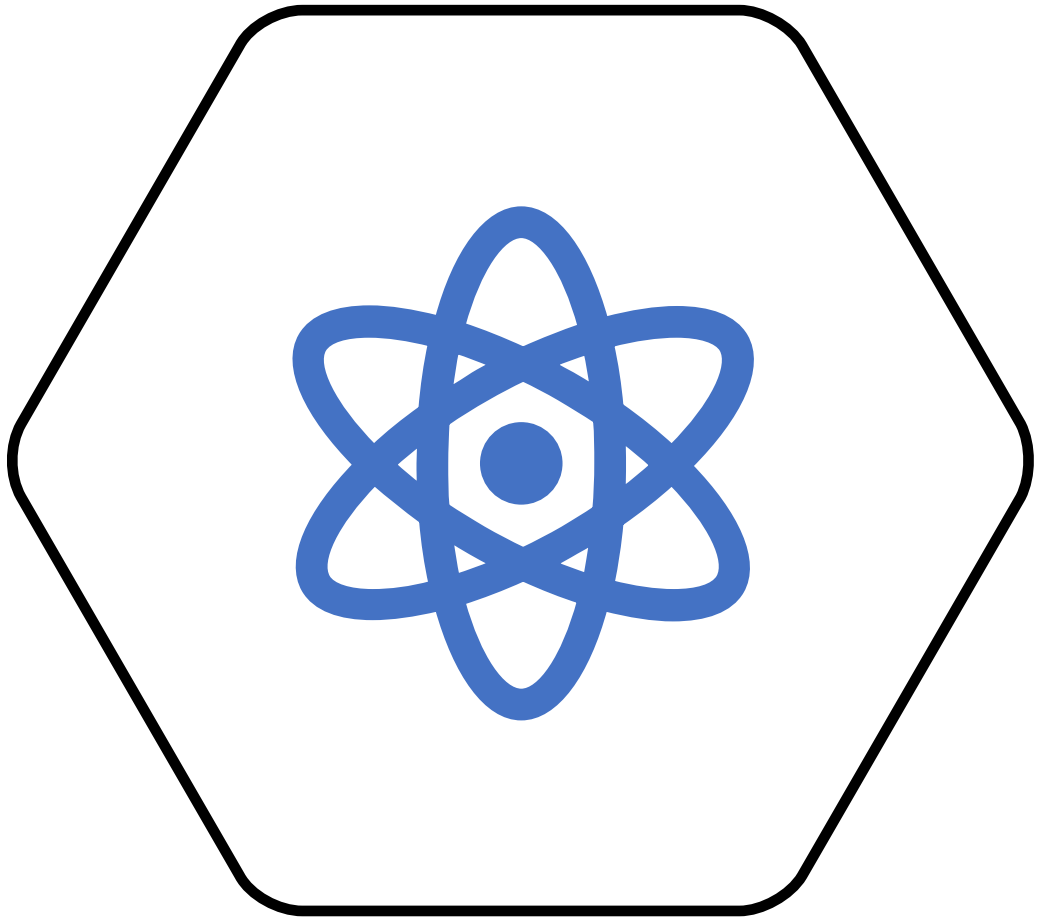
“What if…?”

Speculations about the Best of All Possible Quantum Worlds



International Conference on Advances in Pilot Wave Theory

Lisbon, July 26-30, 2021 // Online

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All the Pieces of the Quantum Puzzle

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- Quantum theory has outstanding predictive power
  - both in depth and in breath
- However, it has no explanatory power
  - scientific realists think it is incompatible with realism:
    - No coherent microscopic story
- Nonetheless, realists also think that one can provide such a picture by solving the measurement problem
  - unobserved macroscopic superpositions
  - Solutions:
    - von Neumann's collapse
    - GRW (more precise): nonlinear stochastic evolution for the wavefunction
    - De Broglie-Bohm: the complete description is given by the wavefunction and by particles' configurations

All the Pieces of the Quantum Puzzle

- My claim: **the measurement problem is a red herring**
  - No compelling rational reasons to consider it
  - Had people tried to provide the reductive understanding they used so far to explain the quantum rules, all the pieces would have fit together in a simple and straightforward schema:
    - Particles move according to highly non-classical trajectories and interact nonlocally

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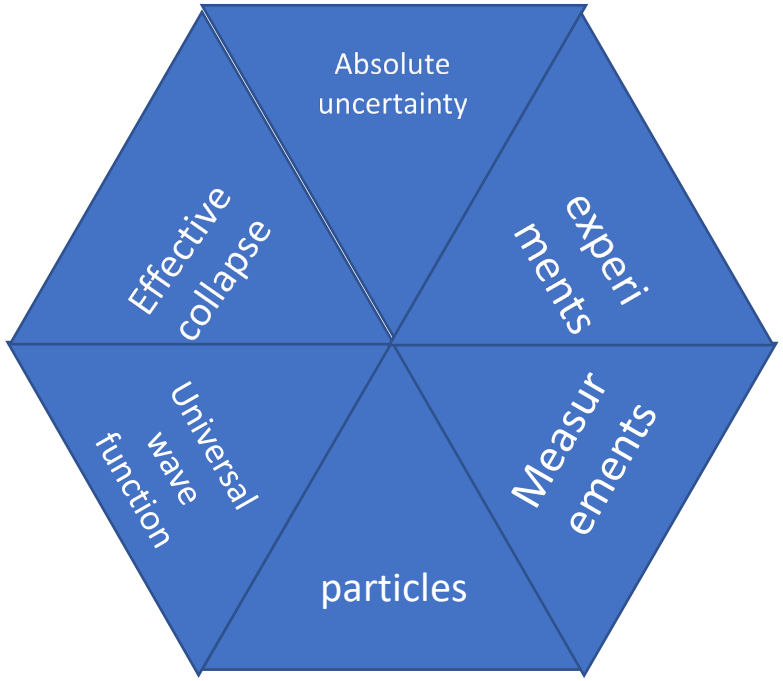
    - Particles move according to highly non-classical trajectories and interact nonlocally
  - No mention of:
    - Instrumentalism, measurements/observers being fundamental, the measurement problem, consciousness, wavefunction ontology, many-worlds, stochastic nonlinear modifications of the Schrödinger equation/contextuality …..



Classical Physics

- Matter
  - Microscopic massive 3d point-particles (trajectories)
  - Electromagnetism: add charge to particles
- Light
  - Wave oscillating in 3-d (interference and diffraction)

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- Matter
  - Microscopic massive 3d point-particles (trajectories)
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- Light
  - Wave oscillating in 3-d (interference and diffraction)
- Distinctive type of explanation (reductive, dynamical schema)
  - Macro properties are explained in terms of the motion of the microscopic particles composing them
    - Prototypical ex: statistical mechanics
- Classical physics is a constructive theory (Einstein terminology)
  - Dynamical reduction
- Opposed to a principle theory:
  - Principles constrain the possible processes (ex thermodynamics)

The Road to Quantum Theory

This is the quantum trajectory of a particle

This is also the actual ‘historical trajectory’ of quantum theory….

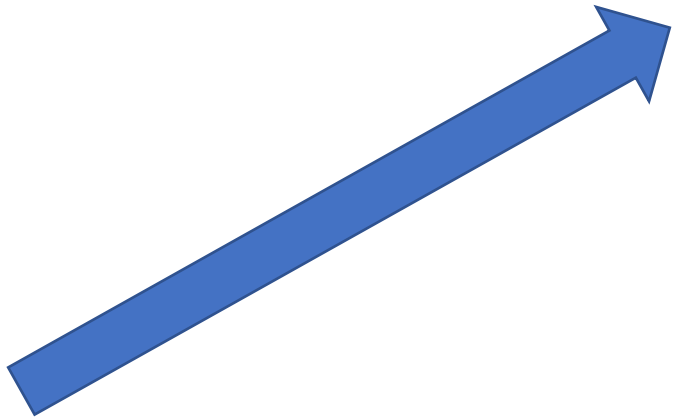
The road to quantum theory has been bumpy, convoluted, and full of ‘accidents’

The End of the Reductive Schema

- We are told that quantum theory forces us to abandon this idea of explanation
  - Our language is hopelessly incomplete
  - We will never be able to understand what lies beyond the phenomena
  - The classical and the quantum world are complementary
  - Experiments change (or even create!) the reality beyond the phenomena
  - There is a paradigm shift
- However, most of it was propaganda (Bohr's 'rhetoric of inevitability')

The Road to Quantum Theory

QUANTUM PHYSICS



CLASSICAL PHYSICS

This is the classical trajectory of a particle
This is also the "what if?" 'historical trajectory' of quantum theory….
(=the history of what would have likely happened if certain misunderstandings, propaganda, political opposition […] did not happen)

Let's tell a story about what it could have been in the best of all possible quantum worlds!

Quantum Theory as Thermodynamics

- ~1900: Uncooperating experiments
  - Blackbody radiation, atomic spectra, stability of the atom, … → quantization
    - Project (Bohr-Sommerfeld): determine the right quantization rules for the various quantities within the classical understating (matter=particles; light=wave)
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  - Compton and photoelectric effects→ particle aspect of light
    - Einstein (1905): photon
  - Particle interference → wave aspect of particles
    - de Broglie (1923): wave & particle
    - Light has a particle associated with it (photon); matter has a wave associated with it too (matter wave)
    - However: no equation for the matter wave

First Attempt to a Constructive Theory: Wave Mechanics

- 1926: Schrödinger's wave mechanics to reductively explain the quantization rules
  - Fundamental object (ontology): a wave (the wavefunction)
  - Evolution: deterministic linear equation (Schrödinger's equation)
  - Successes of reduction:
    - Hydrogen spectrum ← → nodes of the wavefunction
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- Objections (de Broglie, Lorentz and Einstein)
  - 1-wave packet spreading → no stable 'particle' trajectories
  - 2-for 2 or more 'particles' the wavefunction is an object in (high dimensional) configuration space→ unphysical
    - For the reductive schema to work we need 3d things

First Attempt to a Constructive Theory: Wave Mechanics

- Some quotes:
  - Lorentz: “If I had to choose now between your wave mechanics and the matrix mechanics, I would give the preference to the former, because of its greater intuitive clarity, so long as one only has to deal with the three coordinates x, y, z. If, however, there are more degrees of freedom, then I cannot interpret the waves and vibrations physically, and I must therefore decide in favor of matrix mechanics.”
  - Einstein: “Schrödinger’s conception of the quantum rules makes a great impression on me; it seems to me to be a bit of reality, however unclear the sense of waves in n-dimensional q-space remains.” “Schrödinger’s works are wonderful – but even so one nevertheless hardly comes closer to a real understanding. The field in a many-dimensional coordinate space does not smell like something real.”

First Attempt to a Constructive Theory: Wave Mechanics

- Schrödinger acknowledged this was a problem:
  - “The direct interpretation of this wave function of six variables in three-dimensional space meets, at any rate initially, with difficulties of an abstract nature.”
  - “Of course this use of the q-space is to be seen only as a mathematical tool, as it is often applied also in the old mechanics; ultimately [...] the process to be described is one in space and time.”

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- His response: charge density 3d-field ontology
- However:
  - Wave packets still quickly spread (however, later: decoherence)
  - Unobserved macroscopic charged density superpositions → not empirically adequate

The dBB Theory as the Constructive Counterpart

- 1952: Bohm used the results of de Broglie and Schrödinger to construct a new theory (the de Broglie-Bohm theory)
  - Fundamental object (ontology): particles
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- 2011: **empirical confirmation** of the highly--nonclassical trajectories →

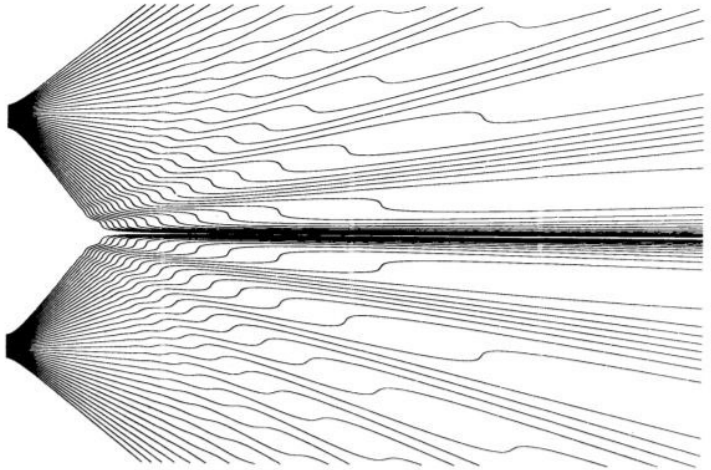

Figure 3.4: Particle trajectories in the interference region of a double slit apparatus. First theoretical calculation, by Philippidis et al. [22].

PREDCITED

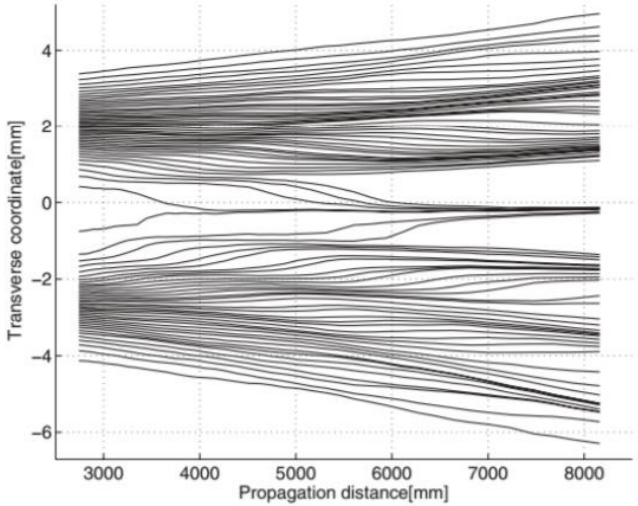

Figure 3.5: Average trajectories of single photons observed in the interference region of a double slit apparatus. First experimental reconstruction, by Kocsis et al. [46].

MEASURED

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    - The particle motion is governed by the 'collapsed' wavefunction (FAPP)
  - The term of the superposition in which the wavefunction will 'collapse' is determined
  - But we cannot predict it because that depends on the initial positions of the particles, and we have no access to them

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  - ← → Heisenberg’s 1927 indeterminacy or ‘uncertainty principle’
    - There are limitations to what we can know about a system

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- Born rule:
  - The probability P(x) of finding a particle in x is given by the square module of the wavefunction $|\psi(x)|^2$
    - In statistical mechanics the system likely evolves towards a greater entropy
    - In dBB the system likely evolves towards a greater value of $|\psi(x)|^2$

Consequences: Matrix Mechanics

- Bell: all measurements are position measurements
- Nonetheless, operators effectively summarize experimental results (Heisenberg, Born and Jordan, 1926)
  - To each experiment one can associate an operator, A, and the possible experimental results are given by their eigenvalues a_i
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    - $\psi = c_1\,\psi_1 + \ldots + c_i\,\psi_i + \ldots$
  - Generalized Born rule
    - The probability $P(a_i)$ of obtaining a possible results, a_i , is given by the square of the coefficient c_i : $|c_i|^2$

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- No-go theorem against ‘genuine measurements’ (von Neumann 1932): most experiments are not genuine measurements
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- Destructive experiments are associated with non-commuting operators
  - Since they are destructive, the order matters (obviously)
    - you read a message and then you burn it =/= you burn it and then you read it

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- This is where we are right now
  - Or better, this is where we would be, had things had gone differently than it actually did

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  - No consciousness
  - … none of the quantum ‘weirdness’ has come up!

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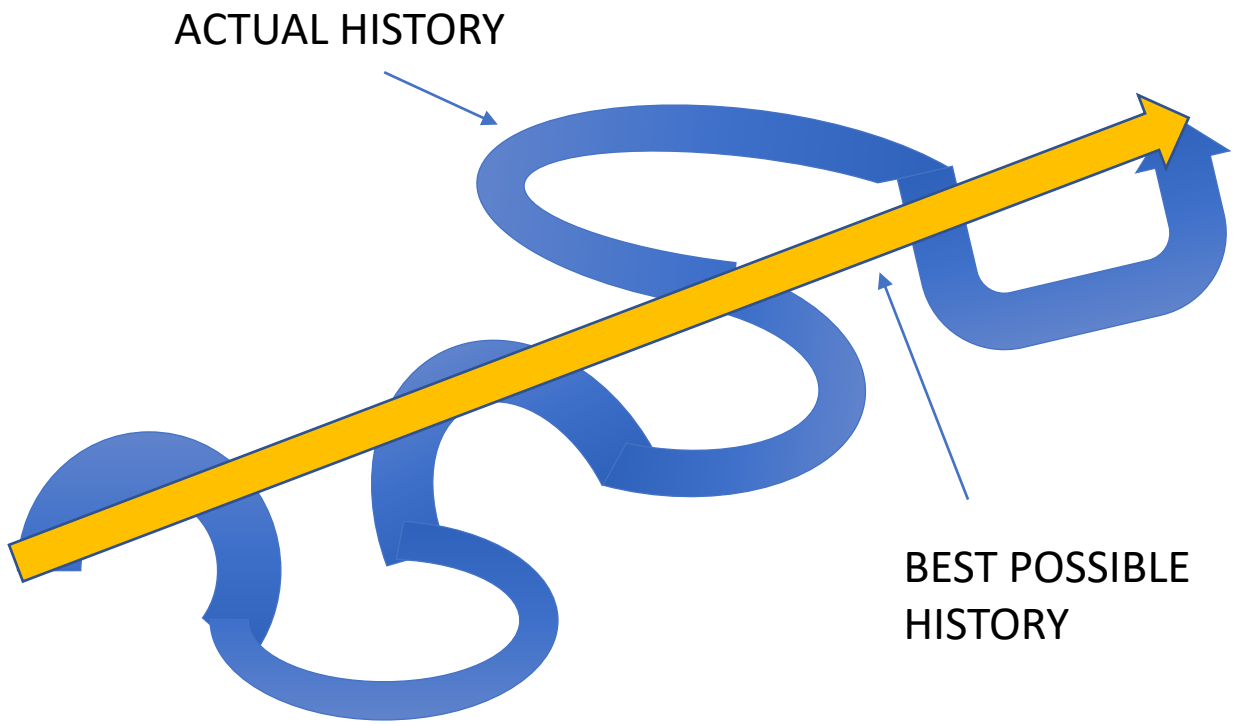
  - **THE THEORY WAS EVEN EMPIRICALLY CONFIRMED!**

Resistance is Futile

- But this is not what had happened…
- What actually happened is not as linear or as ‘rational’ as the one just presented
  - Filled of misunderstandings
  - People talking past each other
  - Ignoring arguments
  - Silencing unwanted objections
  - Politics
  - Propaganda …..
- Here is a short overview



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- Initial internal disagreement within the Copenhagen school (Bohr favored particles, in 1927's Como lectures Bohr's complementarity came as a compromise)
- Later, they formed a compact front against Schrödinger's wave mechanics
  - Accused not being able to explain quantum jumps, even if he did
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Matrix and Wave Mechanics

- 1900: quantum rules
- 1925 Heisenberg (with Born and Jordan) developed 'matrix mechanics'
  - Unified model to systematize experimental results using matrices/operators
  - No dynamics, no spacetime, no objects,
  - Initially (positivistic influence): No unobservables → the reductive schema has to go
- 1926 Schrödinger (to their dismay) proved them wrong by proposing wave mechanics:
  - Aimed at a reductive explanation of the quantum rules in terms of vibrations
  - Equivalent to matrix mechanics but also visualizable
- 1927 Heisenberg discovered the uncertainty relation:
  - No simultaneous position-momentum measurement → No trajectories
- Initial internal disagreement within the Copenhagen school (Bohr favored particles, in 1927's Como lectures Bohr's complementarity came as a compromise)
- Later, they formed a compact front against Schrödinger's wave mechanics
  - Accused not being able to explain quantum jumps, even if he did
  - de Broglie's preliminary proposal for a complete quantum theory in terms of particles and waves was effectively shut down by a harsh criticism by Pauli (1927 Solvay)
- Nonetheless, people started to use Schrödinger's formalism as the quantum formalism

Unphysical Field Argument against Wave Mechanics

- Wave mechanics was also attacked by the realists (de Broglie, Einstein, Lorentz) – we've already seen this
- 1927: Quantum mechanics (=wave mechanics) is incomplete otherwise the reductive schema is false
  - The wavefunction is an unphysical fields (it's not in 3d) and to implement the reductive schema we need to complete the description with a 3d ontology

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- However, macroscopic superpositions + spreading of the wave packet

→ inadequate

Nonlocality Arguments against Quantum Mechanics

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Impossibility Proofs against the Possibility of a Quantum Reductive Schema

- More legitimate reasons to discard the project of completing quantum theory
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- This proof was not sound, but this was not clear until later:
  - Preexisting properties are not measured (Bell 1964, anticipated by Grete Hermann)
- So, these impossibility proof effectively gave the final blow to the proposals to complete quantum theory following the reductive schema
- The logic of inevitability:
  - We cannot do better than what the Copenhagen school is offering us
  - The impossibility proofs force us to give up our dream of reductive explanation

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- 1935, Einstein bomb example letter to Schrödinger:
  - "The system is a substance in chemically unstable equilibrium, perhaps a charge of gunpowder that, by means of intrinsic forces, can spontaneously combust, and where the average life span of the whole setup is a year. In principle this can quite easily be represented quantum-mechanically. In the beginning the ψ-function characterizes a reasonably well-defined macroscopic state. But, according to your equation, after the course of a year this is no longer the case at all. Rather, the ψ-function then describes a sort of blend of not-yet and of already-exploded systems."

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- However, this argument did not work: von Neumann collapse is a response to it…

Bohm's Rediscovery of de Broglie

- 1952, Bohm (Princeton): he rediscovered de Broglie's work, expanding it
  - He developed his theory as a microscopic understanding of quantum mechanics, not as a solution of the measurement problem
  - He wrote Newton's equation of motion and showed that one can reproduce the quantum predictions if one adds a quantum potential
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  - Matter is made of particles
- Bohm was effectively ostracized by everybody else
- Moreover, his sympathies towards communism got him exiled in Brazil
  - No passport → no travels to defend his theory
- Einstein, initially supportive, did not like the explicit nonlocality of the theory

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- Regardless, people though the theory has a high cost: contextual properties
  - Properties whose value changes depending on how you measure them
- Even if (Bohm 1952) contextual properties do not exist
  - The experimental results are not the preexisting values of some property

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- 1975: Bell reformulated his inequality without passing from EPR, showing nonlocality
  - Nonetheless, controversies are still open about what Bell did or did not prove

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- Because of this, it slowly grew in the sympathies of physicists

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- 1986, GRW theory:
  - The wavefunction evolves according to a stochastic nonlinear equation
  - It collapses at random times, into random places with a frequency that depends on how big the system is, so that macroscopic objects collapse almost instantly

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  - Abandonment of the reductive schema (no 3d ontology)

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  - Macroscopic superpositions arguments (aka measurement problem): Quantum mechanics is incomplete otherwise it is empirically inadequate (because it predicts unobserved macroscopic superpositions)

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- They should care about the unphysical field problem:
  - The problem to solve is to find the correct 3d ontology

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    - What's the most sensible conclusion?
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      - → de Broglie Bohm pilot-wave

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    - Instead, Option 2 provides a more complex thermodynamics, in which the principles apply to unobserved and unobservable worlds….

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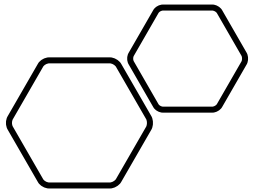
- The locality problem asks us to complete the theory in a local way, but Bell's theorem shows that we cannot have that
- This creates a true conflict with relativity (understood as a theory about reality rather than signals)
- This is the true quantum revolution, and this is what we should be thinking about



Thank you for your attention!