“What if…?”

Speculations about the Best of All Possible Quantum Worlds

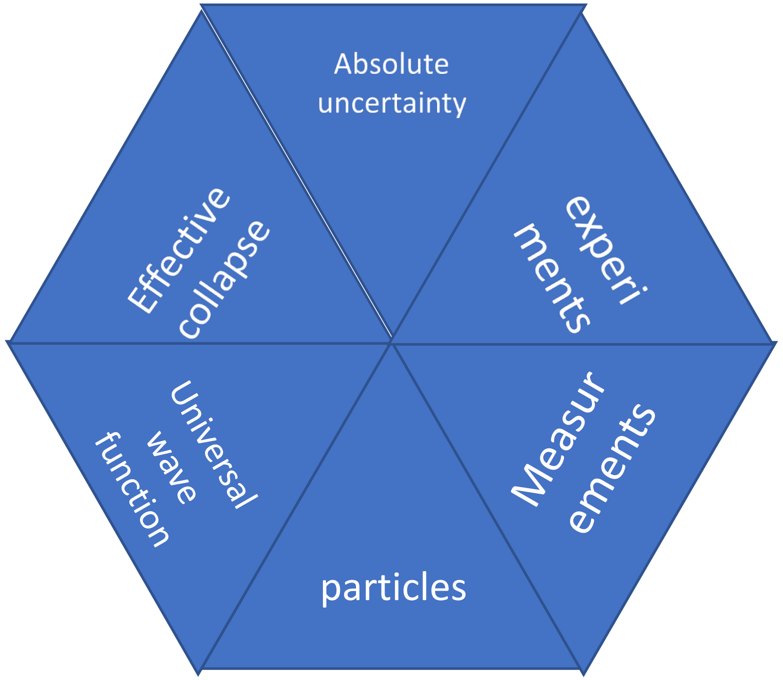
International Conference on Advances in Pilot Wave Theory

Lisbon, July 26-30, 2021 // Online

Valia Allori -- Philosophy, Northern Illinois University

All the Pieces of the Quantum Puzzle

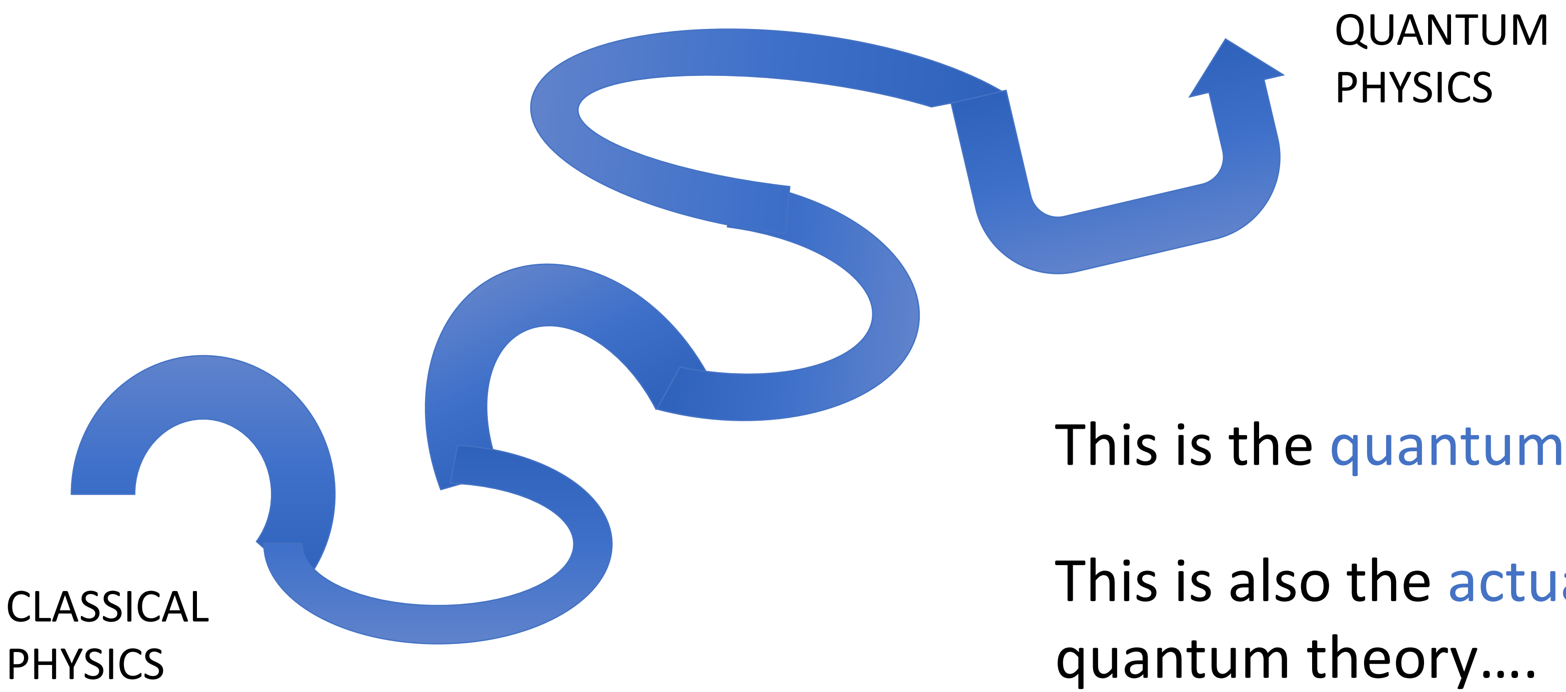
- My claim: **the measurement problem is a red herring**
  - No compelling rational reasons to consider it
  - Had people tried to provide the reductive understanding they used so far to explain the quantum rules, all the pieces would have fit together in a simple and straightforward schema:
    - Particles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

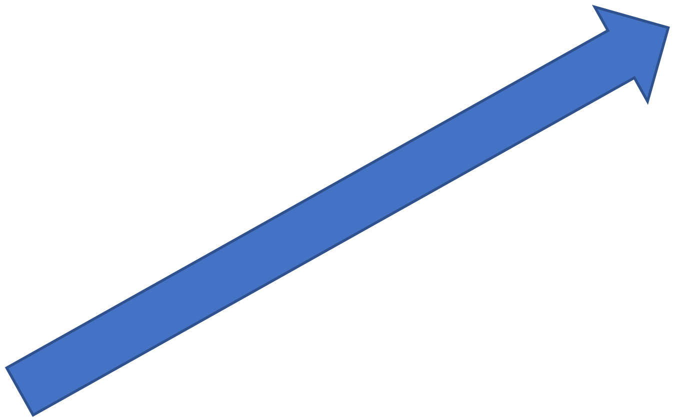
The road to quantum theory has been bumpy, convoluted, and full of 'accidents'

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)
      - PRINCIPLE-TYPE OF EXPLANATION
  - 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
    - Localized wave packets ← → they appear as particles
- 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.”
- 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
  - Evolution: deterministic evolution for the particles determined by the wavefunction + Schrödinger evolving wavefunction
  - Meaning of the wavefunction: not representing matter (because it's in configuration space), more similar to the Hamiltonian
- Avoids the problems of wave mechanics
  - 1-partcules don't 'spread' (obviously)
  - 2-superpostions of the wavefunction have no physical meaning
- 2011: **empirical confirmation** of the highly--nonclassical trajectories →

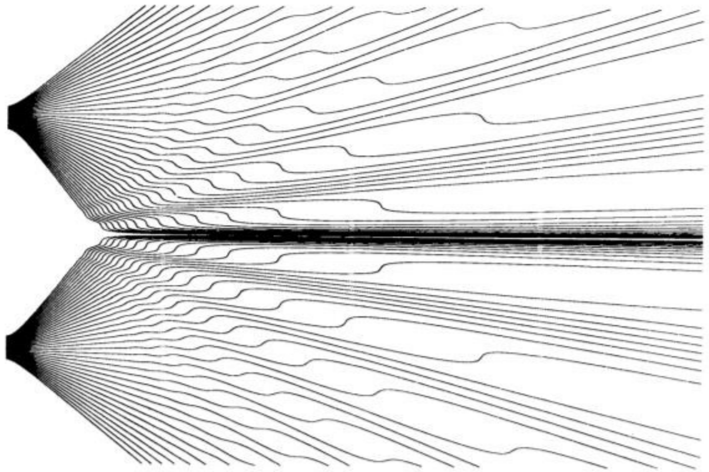


Figure 3.4: Particle trajectories in the interference region of a double slit apparatus. First theoretical calculation, by Philippidis et al. [22].

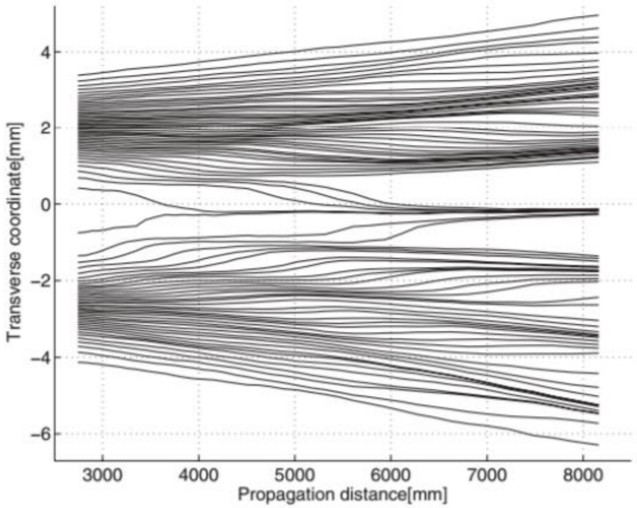


Figure 3.5: Average trajectories of single photons observed in the interference region of a double slit apparatus. First experimental reconstruction, by Kocsis et al. [46].

PREDCITED

MEASURED

Consequences: Collapse of the Wavefunction

- Schrödinger evolving wavefunction: wavefunction of the universe
- In general systems do not have a Schrödinger evolving wavefunction
- In suitable situations, however they do:
  - ‘Effective (Schrödinger evolving) wavefunction’ of a system
  - → it may evolve into a superposition
  - However, in experimental situations (=when interacting in a sufficiently strong it effectively ‘collapses’ (=stops evolving according to Schrödinger's eq)
    - 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

Consequences: Uncertainty Principle

- What we can know ←→ whether systems can correlate with one another
  - Equilibrium → Independent systems → no correlation → no knowledge (since nothing changes)
- The wavefunction is not in equilibrium
- The configurations of the particles are in 'quantum' equilibrium
  - All we can know about a system is given by the system's wavefunction
  - ← → Heisenberg's 1927 indeterminacy or 'uncertainty principle'
    - There are limitations to what we can know about a system

Consequences: The Born Rule

- Experimental results are statistical because we do not know where the particles were
- Equivariance:
  - Assuming a given initial universal wavefunction, if the particles are initially randomly arranged according to a distribution given by the square module of the initial universal wavefunction $|\psi_{t=0}(x)|^2$, then they will continue to be distributed that way $|\psi_t(x)|^2$
- 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
    - $A\,\psi_i = a_i\,\psi_i$
  - And one can write the wavefunction as a linear combination of the eigenstates ψ_i
    - $\psi = c_1\,\psi_1 + \ldots + c_i\,\psi_i + \ldots$
  - 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 : $|c_i|^2$

Consequences: Experiments vs Measurements

- No-go theorem against 'genuine measurements' (von Neumann 1932): most experiments are not genuine measurements
  - Genuine measurement: experiment in which the system is not too much disturbed
  - Destructive experiment: experiment in which the system is very much perturbed
    - They measure nothing
- This happens because experiments are physical processes
  - Ex: to determine the velocity of an unmoving particle inside of a box, we need to remove the box, but then the particle will start moving
- AKA 'contextuality' proofs: whether an experiment is destructive or not depends on the context
- 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

Consequences: Quantum nonlocality

- The wavefunction is on configuration space → by acting on a particle here, one affects a particle over there instantaneously → nonlocality
- Problem: this is in contrast with relativity
- 1964: Bell worked out a LOCAL reductive understanding of the quantum phenomena with a generic ‘hidden’ ontology
- Its empirical predictions differ from the ones of the dBB theory→ crucial test
- 1982: Crucial test falsified the local theory and confirmed dBB
- Open question: what does this mean for relativity?
- This is where we are right now
  - Or better, this is where we would be, had things had gone differently than it actually did

So far…

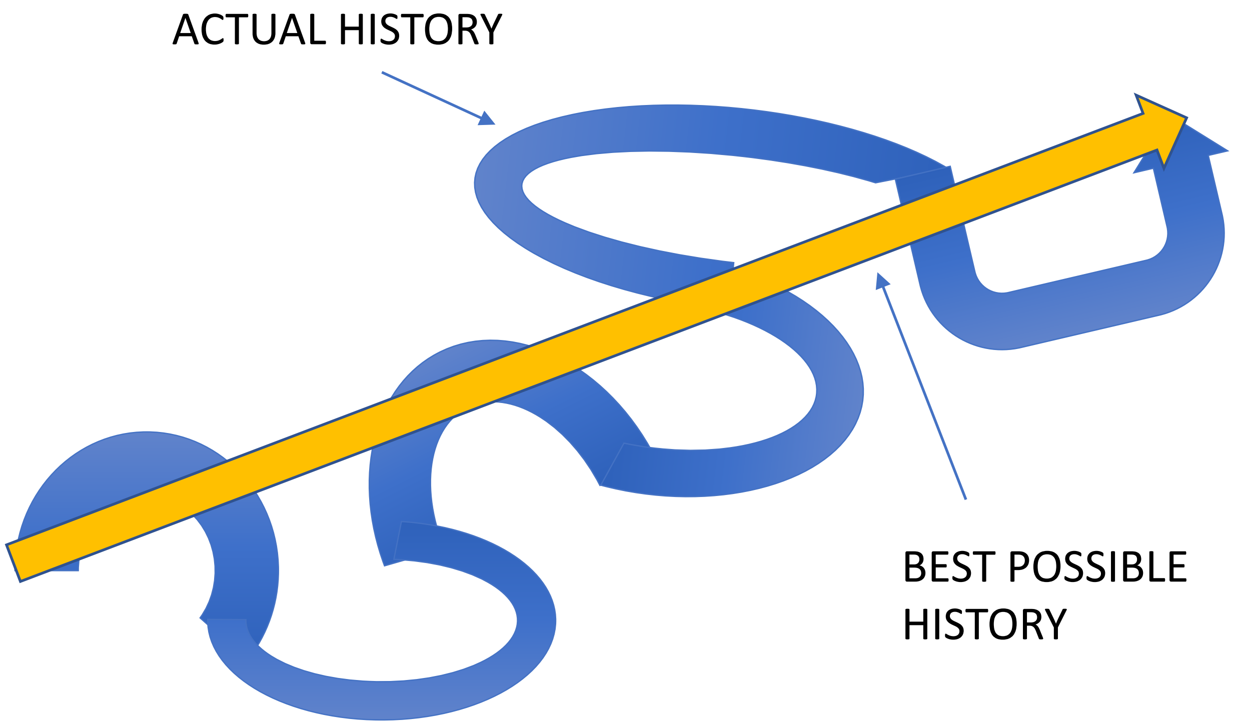
- … we have seen:
  - No measurements/observers being fundamental
  - No instrumentalism
  - No complementarity
  - No unobserved macroscopic superpositions
  - No high dimensional field ontology
  - No stochastic modifications of the Schrödinger equation
  - No undetectable infinity of non-interacting worlds
  - No consciousness
  - … none of the quantum 'weirdness' has come up!

So far…

- Everything got shut down when people focused on keeping the reductive schema ← → a 3d ontology
  - **WHY WOULD HAVE THEY GIVEN UP ON IT, WTHOUT EVEN TRYING?**
  - **SO THEY TRIED, AND THEY SUCCEDED!**
    - We have a clear and simple picture of the world, according to which particles move around in 3d following highly nonclassical laws, and in which the main discovery of modern science, namely nonlocality, is explicit
  - **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



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
- Schrödinger acknowledged and proposed a charge density 3d-field ontology
- However, macroscopic superpositions + spreading of the wave packet

→ inadequate

Nonlocality Arguments against Quantum Mechanics

- **1927-1935: Quantum mechanics is incomplete otherwise locality is false - we haven't seen it before**

- 1927: Einstein proposed a deterministic particle theory, which later retracted because nonlocal
- 1927 (Solvay): particle through one slit diffracts, so it is everywhere, while we observe only one spot → nonlocality
  - Misunderstood by Bohr
  - Heisenberg granted nonlocality but denied contradiction with relativity (no superluminal signaling)
- 1930 (Solvay): a photon in energy states superposition leaves box and travels far away. By measuring the box's weight, one 'creates' the photon's energy → nonlocality
  - Misunderstood by Bohr
- 1935 (letter to Schrödinger): a wavefunction in a box is divided into two halves. The boxes are sent in opposite direction. By opening one box, one affects the other → nonlocality
- 1935, EPR: A pair of entangled particles travel in opposite directions; results of experiments on each particle are anticorrelated → nonlocality
- Thus, there have to be 'hidden' variables, representing the pre-existing properties revealed by the experiment.
  - Again, misunderstood by Bohr

Impossibility Proofs against the Possibility of a Quantum Reductive Schema

- More legitimate reasons to discard the project of completing quantum theory
  - 1932 von Neumann's impossibility proofs:
    - He assumed there are preexisting properties, whose values are revealed by experiments
    - Then he showed that these properties have to stand into mathematically contradictory relations
    - Therefore, he concluded that **we cannot complete quantum theory**
- 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

The Measurement Problem against Quantum Theory

- A final argument against quantum theory (=wave mechanics)
- 1935: Quantum mechanics is incomplete otherwise there are unobserved macroscopic superpositions
- 1935, Schrödinger cat paper:
  - a radioactive nucleus in decayed-not decayed superposition is coupled with a vial of poison to be released in a box where there's a cat. Thus, the cat is in a dead-alive superposition. However, when we open the box, the cat is either alive or dead.
  - The theory is not empirically adequate
- 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."
- 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
- The wavefunction never collapses but there are no macroscopic superpositions:
  - 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

Contextuality of the de Broglie-Bohm Theory

- People dismissed the theory based on the impossibility proofs
- 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

Bell’s Theorem

- 1964: Bell showed that the impossibility proofs assumed non-contextuality (=that one can measure properties without modifying the system), which is however unwarranted.→ you **can** complete quantum theory
- The de Broglie-Bohm theory does this, but it was also nonlocal, so Bell started to wonder whether one could complete quantum theory while also preserving locality,
- 1964: Bell started from the EPR argument, concluded that a local theory would have to have preexisting values, and then derived an inequality which holds for his theory but not for quantum mechanics → experimental tests
- 1980s: the quantum mechanical predictions are correct, locality is false
  - This is what he wanted to argue but **he was misunderstood**
    - People thought he proved that hidden variables as predicted by Einstein (local or not) are impossible
- 1975: Bell reformulated his inequality without passing from EPR, showing nonlocality
  - Nonetheless, controversies are still open about what Bell did or did not prove

The Rise of Many-Worlds

- Slowly, the attention shifted from the problem of keeping the reductive schema (completing quantum theory) to solving the measurement problem
- 1957: Everett started from the measurement problem and argued against the von Neumann collapse as unsatisfactory – what is a measurement?
  - He proposed a many-worlds picture to make minimal sense of the unobserved macroscopic superpositions
  - Bohr ultimately destroyed Everett's career
- 1970s: DeWitt and Graham book on many-worlds ←→in cosmology there is no observer
- 1985: Deutsch paper on quantum computers making sense only in a many-worlds setting
- The many-world theory, not adding anything to the standard theory and not modifying the Schrödinger equation seemed to many as the best compromise among the solutions of the measurement problem.
  - If one forgets about the inflated metaphysics, that is.

The Rise of Many-Worlds

- Slowly, the attention shifted from the problem of keeping the reductive schema (completing quantum theory) to solving the measurement problem
- 1957: Everett started from the measurement problem and argued against the von Neumann collapse as unsatisfactory – what is a measurement?
  - He proposed a many-worlds picture to make minimal sense of the unobserved macroscopic superpositions
  - Bohr ultimately destroyed Everett's career
- 1970s: DeWitt and Graham book on many-worlds ←→in cosmology there is no observer
- 1985: Deutsch paper on quantum computers making sense only in a many-worlds setting
- The many-world theory, not adding anything to the standard theory and not modifying the Schrödinger equation seemed to many as the best compromise among the solutions of the measurement problem.
  - If one forgets about the inflated metaphysics, that is.
- Because of this, it slowly grew in the sympathies of physicists

Dynamical Collapse

- 1970 Varenna, 1973 Erice: the first conferences on quantum foundations were focusing on the measurement problems
- 1980s: unifying dynamics projects (incorporate the collapse into the dynamical equation of the wavefunction)
- 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

Quantum Theories without Observers

- Bell: three ways of making realist sense of quantum theory
  - "Either the wave-function, as given by the Schrödinger equation, is not everything, or it is not right"
- This legitimized the many-worlds theory and the dynamical collapse models
  - dBB, many-worlds, and GRW started to be considered equally plausible, each with pros and cons
- Wavefunction realism:
  - It became natural to think of the wavefunction as the ontology of the theory (which was initially thought impossible)
    - Argument from the formalism:
      - Classical mechanics had an equation for particles, so particles are the ontology; here there is an equation for the wavefunction, so the wavefunction is the ontology
      - (However, this is putting the cart -the equation- in front of the horse -the ontology-)
    - Locality argument:
      - Bell showed reality is nonlocal, and this is the only way to make the theory local again (in configuration space)
      - (However, why would one care about such a locality? Einstein was interested in 3d locality to separate the universe into roughly independent physical subsystems)
  - Abandonment of the reductive schema (no 3d ontology)

Which Problem Should the Realist Look at?

- Historically three arguments for incompleteness of quantum theory were proposed:
  - Unphysical field arguments: Quantum mechanics is incomplete otherwise reductionism is false (because there's nothing moving in three-dimensional space)
  - Nonlocality arguments: Quantum mechanics is incomplete otherwise relativity is false (because quantum theory is nonlocal
  - Macroscopic superpositions arguments (aka measurement problem): Quantum mechanics is incomplete otherwise it is empirically inadequate (because it predicts unobserved macroscopic superpositions)

Which Problem Should the Realist Look at?

- The unphysical field problem is the strongest of these arguments:
  - It was proposed to show that one needs to complete the theory if we wish to preserve the reductive schema
  - It tells us how to complete it: add some 3d ontology
- The nonlocality argument is weaker:
  - It does not tell us how to complete it, just to make it in such a way that the theory is local
    - To convince the instrumentalists, who at least should care about relativity
    - However, Heisenberg responded that the theory is not incompatible with relativity (instrumentally understood as a theory of signals)
- The measurement problem is the weakest:
  - It does not say how to complete it, or whether to make it local, just be sure to make the theory empirically adequate!
    - This is the only thing instrumentalist cared about!
    - This allows for ad hoc, nonlocal, imprecise solutions like the von Neumann collapse
- But why should a realist be interested in such a problem????
- They should care about the unphysical field problem:
  - The problem to solve is to find the correct 3d ontology

Which 3d Ontology Should we Use?

- Natural choice: either particles or fields
  - Try fields (like Schrödinger's charge density):
    - (assuming we can control the wave packet’s spreading through decoherence)
    - There are unobserved macroscopic superpositions, no interference between macroscopic matter
    - What’s the most sensible conclusion?
      - OPTION 1: WE WERE WRONG, MATTER IS MADE OF PARTICLES (moving in non-classical ways)
      - → de Broglie Bohm pilot-wave theory
      - OPTION 2: WE WERE RIGHT, MATTER IS WAVE-LIKE BUT THERE ARE MANY-WORLDS, ONE FOR EACH TERM OF THE SUPERPOSION, AND THESE WORLDS DO NOT INTERACT
    - Which option is the most plausible?
      - Option 1: simple, clear, reductively explanatory
      - Option 2: ad hoc, unfalsifiable, not reductive
    - Option 1 provide a ‘statistical mechanics’ for quantum theory, seen equivalent to thermodynamics
    - Instead, Option 2 provides a more complex thermodynamics, in which the principles apply to unobserved and unobservable worlds….

Are There Other Options?

- No, if one is looking at the unphysical field problem to preserve the reductive schema
  - The (nonlinear stochastic) modification of the Schrödinger equation (GRW) comes about only when we look at the measurement problem
    - Why would someone want to modify the equation, given that one would still have a 3d ontology to add?
  - No reason to consider consciousness
  - …

Conclusion

- Realists should have tried to keep the reductive schema by solving the unphysical field problem
  - By focusing on the measurement problem, they ended up giving too much credit to ideas that would have never been considered
- We can keep the reductive schema in terms of the motion of microscopic 3d objects composing macroscopic bodies
- 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!

Valia Allori…. Wave and Particle ;-)