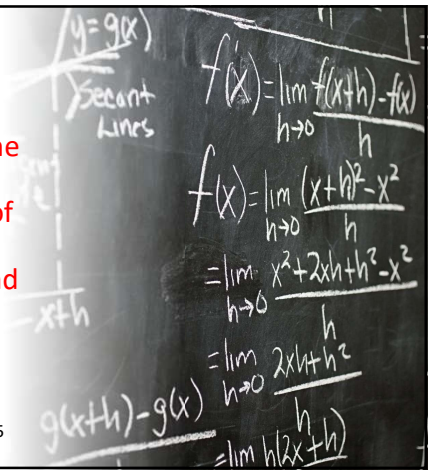
Relativistic Pilot-Wave Theories as the Rational Completion of Quantum Mechanics and Relativity



- Valia Allori, UniBg
- Bohm in Brazil Meeting, July 2025

1

Motivation & Central Thesis

- QM and relativity are in tension
  - QM: nonlocal, no clear spacetime entity to describe matter (ontology)
  - Relativity: local, spacetime-based
- Claims:
  - QM and relativity are both incomplete
    - QM needs a s-t ontology to explain the phenomena
    - Relativity needs a preferred frame to explain quantum nonlocality
  - Relativistic pilot-wave theories provide the minimal, simplest, most straightforward completion of both

2

Structure of the Talk

- 1. The problems with quantum theory
- 2. Pilot-wave theory
- 3. The spirit of relativity
- 4. Relativistic extensions
- 5. Why pilot-wave is the preferred way to go

3

Problems with Quantum Theory

- Measurement problem (Schrödinger's cat):
  - If the wf evolves according to the Schrödinger equation and it provides the complete description of physical systems, then the theory predicts unobserved macroscopic superposition (=it is falsified)
  - Usual (textbook) way out: collapse rule
  - Not ideal: imprecise… → solutions of the measurement problem:
    - dBB; GRW(P); Everett

4

Problems with Quantum Theory

- Deeper issue:
  - People usually focus on the measurement problem but even if one 'fixes' the problem of macro superposition, still there is **no spacetime fundamental entity** describing matter (ontology):
    - The wf lives in configuration space, not a real physical space
    - Lorentz, Schrödinger, **Einstein**, de Broglie, Heisenberg….: they were all aware of that, even if they reacted very differently

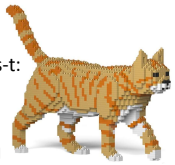
5

Problems with Quantum Theory

- A closer look…
- Einstein: QM is incomplete
- Several arguments (explained in more detail in the next slides):
  - 1926-Unphysical field arguments: QM is incomplete because there's nothing moving in 3d space
  - 1935 (EPR) Nonlocality arguments: QM is incomplete because quantum theory would be nonlocal
  - 1935-Macroscopic superpositions arguments (=the measurement problem): QM is incomplete because it predicts unobserved macro superpositions

6

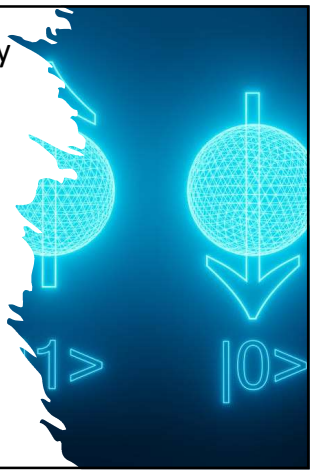
Problems with Quantum Theory



- What is wrong about a theory not grounded in s-t:
  - "It's crazy! It wouldn't be physics!"
    - But why?
  - Before QM physics has always explained macro phenomena in terms of the dynamics of fundamental micro objects – **reductionism/constructive/compositional explanation**
    - CM: Micro point particles moving in space evolving in time according to Newton's laws are what the world is made of at the fundamental level
    - In CM the phenomena and the fundamental entities both live in 3d space
  - If one think that what is fundamentally real in QM (its ontology) is the wf, since the wf is not in 3d, then strictly speaking **reductionism is inapplicable**
    - Need a s-t ontology at the fundamental level

7

Quantum Nonlocality



- Copenhagen people did not care about ontology or reductionism because they were (FAPP) positivists; so shifted gears to convince them QM is incomplete:
- Einstein (EPR): *by reductio*
  - Assume QM is complete, consider singlet state
    - If A measures her particle being spin +, the spin of B's particle (which was undetermined before A's measurement) becomes determined to be -
    - This is nonlocal action, which is absurd
    - Hence QM is incomplete:
      - Both spins always had definite values, even if QM does not give them to us, and measurements revealed them to us

8

Quantum Nonlocality

- Structure of the argument:
  - QM→ nonlocality: this is absurd (locality must be true)
    - That is
  - Locality + QM→ hidden variables (spin values)
    - That is
  - Locality implies that there are hidden variables
  - EPR correlations should be explained by hidden variables to avoid nonlocality

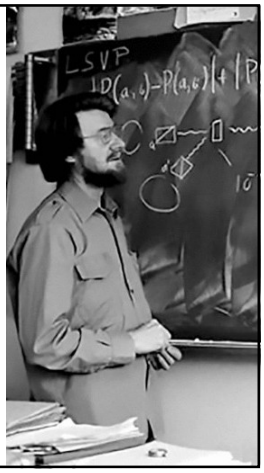
9

Quantum Nonlocality

- Why was nonlocality thought to be totally absurd?
  - locality←→ interaction travels at finite velocity
    - Throw a rock in a pond where a toy boat is floating. The boat will 'feel' the rock's presence after some time (when the waves created by the rock reach it)
  - Nonlocality ←→ instantaneous action at an arbitrary distance
    - Seems empirically false (objects can be thought of as isolated; it is possible to identify the cause of a phenomenon in its neighborhood; …)
    - Seems unexplainable/too mysterious (if interaction does not travel, how does that wok?)
    - Contradicts relativity: c is the maximum speed

10

Quantum Nonlocality



- Problem with the EPR argument: Bell (1964)
  - assume EPR conclusion and construct a local theory which has all spin values determined (spin-hidden-variables QM)
  - It makes predictions which are different from the ones of QM
    - Locality +QM→ predictions_1
    - QM→ predictions_2
  - We can make a "crucial experiment"

11

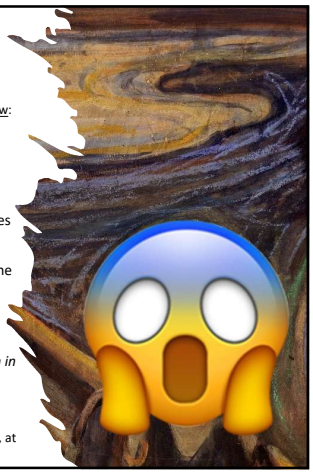
Quantum Nonlocality

- This crucial experiment has been performed by Aspect (1981):
  - Local Spin-hv-QM (the result of assuming locality) is falsified
- Conclusion:
  - Locality is false ←→ Nonlocality is essential to QM

12

Reactions

- Accept the conclusion: **nature is nonlocal**
  - However, this is a big conclusion to swallow:
- To try to save locality, some have rejected some other assumption in the overall argument
  - *Superdeterministic theories reject Statistical Independence*
    - They allow experimental outcomes to be determined by what the experimenter decide to measure (rather than the actual value of the property being measured)
      - Bell regarded these theories conspiratorial
  - *Retrocausal theories allow events to have causes in the future (rather than in the past)*
- **They seem worse than accepting nonlocality**
  - Just assume nature is nonlocal (in this talk, at least)



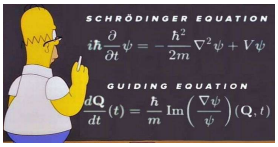
13

Where we are so far

- QM needs to have a s-t ontology if we want reductionism
  - (that is, matter needs to be made of 3d micro stuff moving in space)
- QM needs to be **nonlocal** if we want empirical adequacy
  - OPTIONS???

14

Pilot-Wave Theory (dBB, Bohmian mechanics)

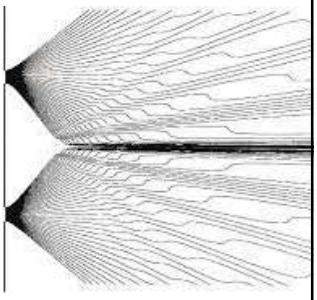


- Ontology (what fundamentally matter is made of): point particles in 3D space
- Particles guided by the wf (guidance equation):
  - The wf represents the interaction (objectively, like a potential), NOT matter
  - The wf evolves according to the Schrödinger equation

15

Features of Pilot-Wave Theory

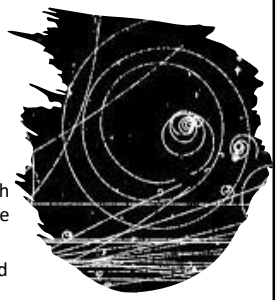
- ✅ Provides a spatiotemporal ontology
  - particles
- ✅ Solves the measurement problem
  - Matter is never in superposition
- ✅ Accepts nonlocality as fundamental
  - The interaction is mediated by the wf which lives in configuration space



16

Hidden Variables?

- Not EPR-style hidden variables:
  - In EPR: hv=spin property values
- Here:
  - Spin is not a property at all
  - Only positions are the 'true' properties of the particles
  - They are 'hidden' from QM (which is indeed incomplete) but they are clearly defined in dBB
- In dBB EPR correlations are explained not by hv but by nonlocality
- So what are they for?
  - To ground the theory in spacetime!



17

The Spirit of Relativity

- Two principles:
  - Constancy of the speed of light
  - Relativity principle (Lorentz invariance: the form of laws is frame-independent)
- Geometrical formulation: Minkowski spacetime
- No preferred frame or absolute simultaneity

18

The Tensions

- Relativity is local: interactions confined to light cones
- Quantum nonlocality violates this assumption: Aspect experiments confirm instantaneous correlations
- Relativity is a theory of spacetime
- The quantum wf is not in spacetime

19

Alleviating the Tensions

- My take:
- Recognize that quantum mechanics is incomplete:
  - It lacks a spatiotemporal ontology to 'fit well' with relativity as a theory of spacetime
- Recognize that (ALSO) relativity is incomplete:
  - It lacks structure to accommodate nonlocality

20

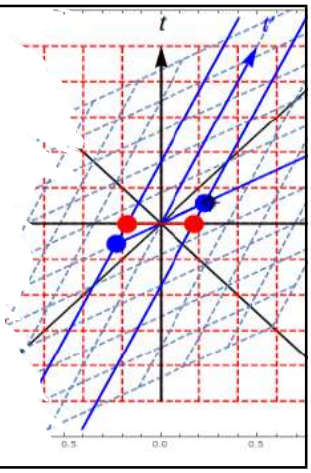
Alleviating the Tensions

- My take:
- Einstein was right to think QM was incomplete, but for the wrong reason:
  - He thought one needed to have BOTH a s-t ontology and local interaction
  - A s-t- ontology is needed and can be given but
  - Bell, Aspect have shown that local interaction is empirically falsified
  - Hence, since relativity is LOCAL, relativity needs to be modified too

21

Relativity as Spacetime Theory

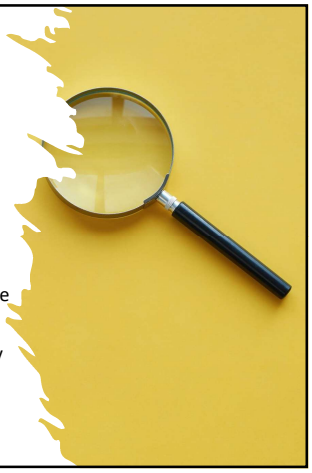
- Events lie in 4D Minkowski spacetime
- Simultaneity is relative
- Spacetime sliced into hypersurfaces differently by observers
- Lorentz transformations link perspectives



22

What is Required from a Relativistic Quantum Theory?

- (At least) it must combine:
  - 1 Spacetime
    - Why? Otherwise, reductionism would be impossible. Also, Relativity is a theory about spacetime
  - 2 Lorentz invariance
    - Why? Because of Relativity
  - 3 Nonlocality
    - Why? Because of QM



23

Relativistic Pilot-Wave Theories

- 1- They are in spacetime
  - Particles moving around
- 2- They are Lorentz invariant
  - Dirac or Klein-Gordon equations
- 3- They are nonlocal
  - They have a preferred foliation (=absolute simultaneity), which is undetectable (but one can explain why using 'quantum equilibrium')

24

Relativistic Quantum Theories

- Do we have any better alternative?
- I do not think so….

25

Comparing Alternatives

- Relativistic GRW-type theories (with a s-t ontology like GRWm, GRWf) change only QM trying to keep relativity as is
  - PROS: foliation-free, Lorentz-invariant
  - CONS: stochastic (and nonlinear) →
    - No cause-effect distinction, supernonlocality, no energy conservation, ad hoc…
- Relativistic pilot-wave theories: change them both
  - CONS: preferred foliation
  - PROS: Lorentz-invariant, deterministic, minimally nonlocal, energy conserving, not ad hoc, … AND preserves explanatory power

26

dBB as a Balanced Proposal

- ✅ QM is incomplete because it lacks a spacetime ontology
  - dBB gives one to QM
- ✅ Relativity is incomplete because it lacks structure for nonlocality
  - dBB gives one to Relativity

27

dBB as a Balanced Proposal

- That is….
- **dBB modifies QM and relativity MINIMALLY, MOST NATURALLY:**
  - Add s-t ontology of matter (particles)
  - Add foliation to spacetime
- By doing this, dBB retains:
  - Determinism (not always/not necessarily)
  - Lorentz-invariant dynamics
  - Compatibility with nonlocal dynamics
- Result: simple, coherent, explanatory, non-ad hoc theory

28

Final Thoughts

- Matter is real:
  - Just use the simplest one: particles
- Nonlocality is real:
  - Just embrace it explicitly
- How? Build spatiotemporal, Lorentz-invariant theories in which matter interacts nonlocally:
  - no advantage or need to do otherwise

29

Final Thoughts

- Looking for a relativistic dBB is **THE rational step forward**
  - It's not surely the final answer, there are many open issues
    - In physics (QFT?)
    - In philosophy (interaction?)
  - But that's what I think researchers should focus on
- *"That's one small step for man, one giant leap for mankind"*

30

Thank you for
your attention!

31