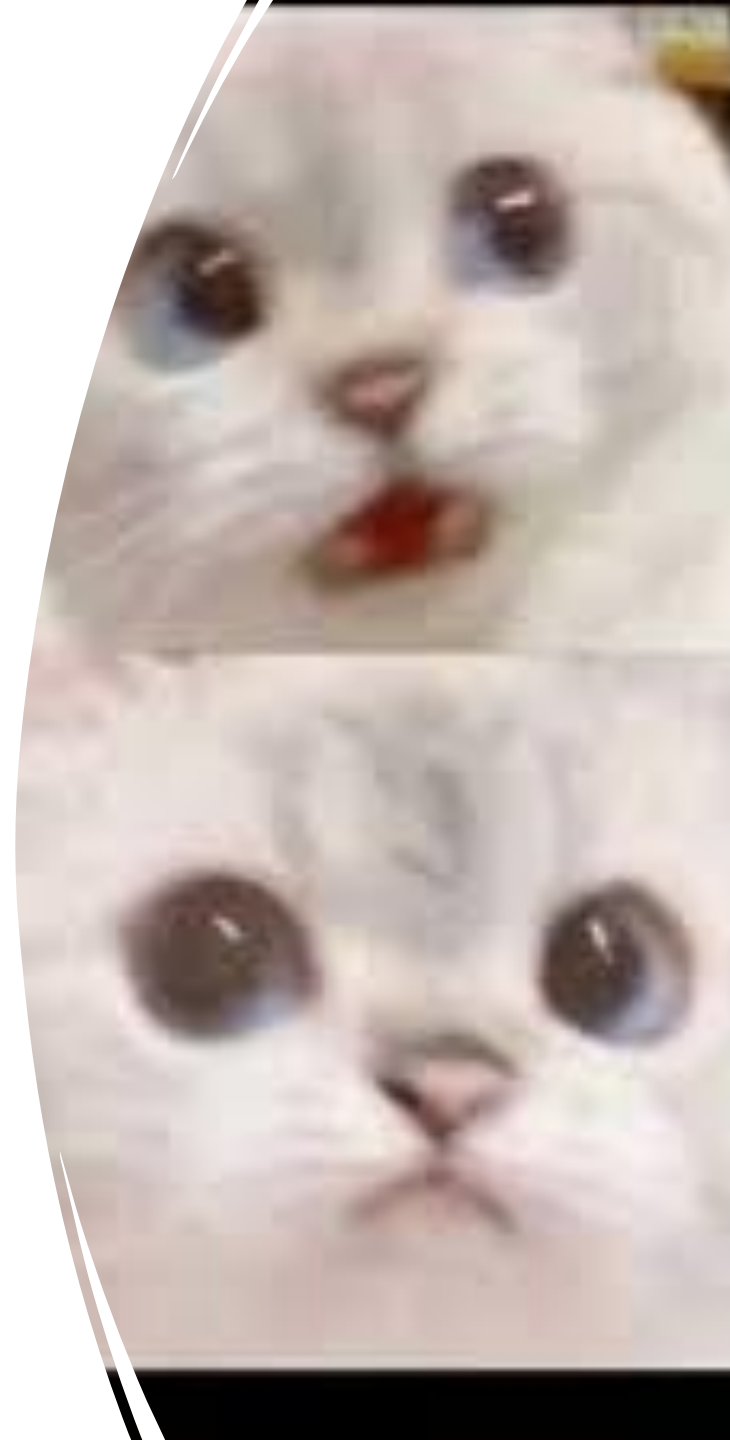


Who's Afraid of the Schrödinger Cat? On the Problem of Realism in Quantum Mechanics

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March 24, 2025

University of Geneva



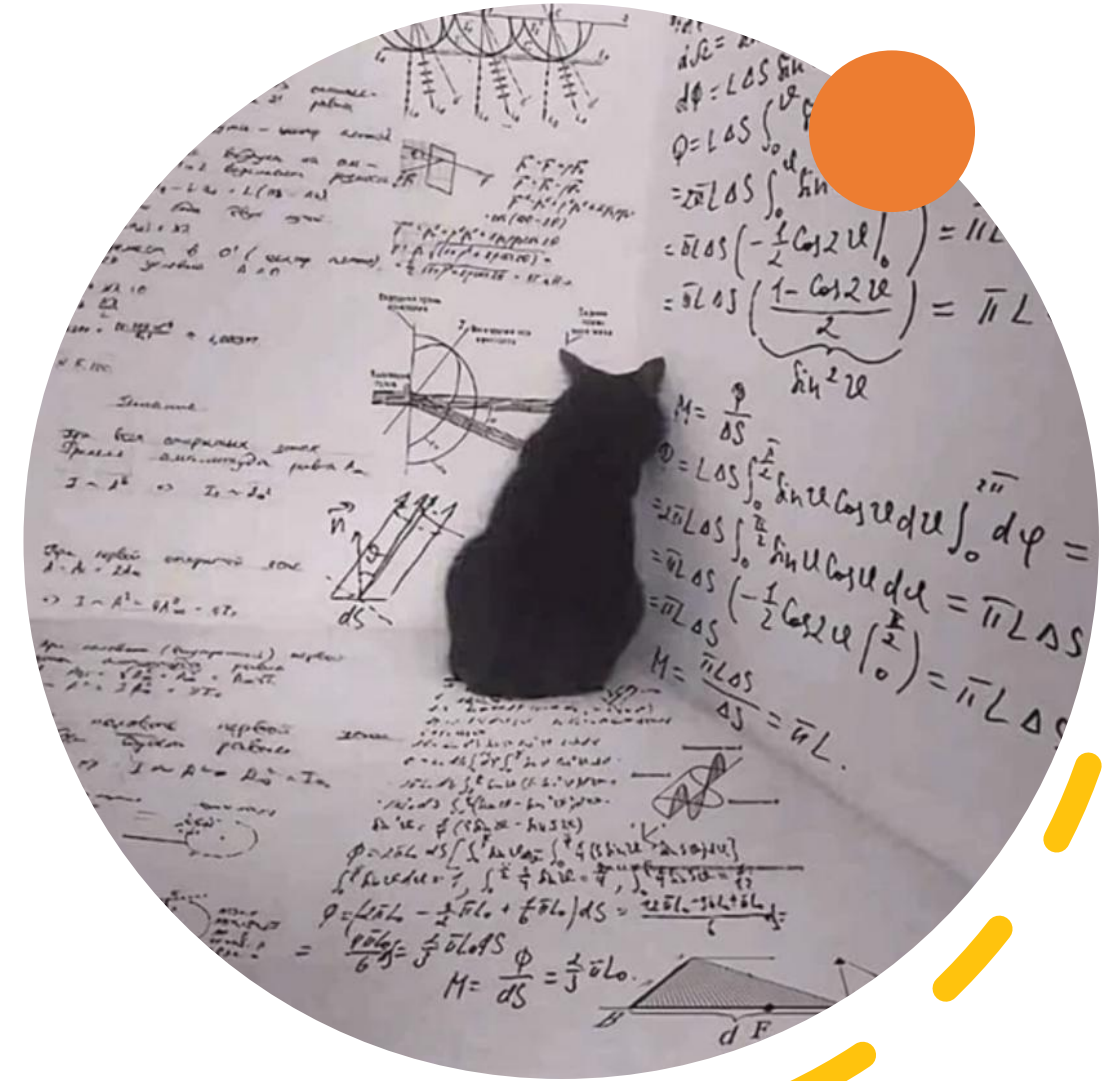
Schrodinger
puts you in a box

On the other hand, it's
a pretty good box.

IS IT???

Motivation

- A possible (probable?) attitude of a typical attendee of my talk: “Why on Earth do we need another talk about this problem, who’s been around for 100 years!?! Do we actually need this?”
- My reply: “Yes!”
- “Why’s that? I REALLY need a good reason...”
- “Because it’s the **WRONG** problem to look at, and people don’t realize that: they’ve spent the last 70+ years wasting energy by trying to solve it”



Isn't that bold? ;-)

A more precise outlook

- The **realism problem**: what problem(s) you need to solve if you are a scientific realist?
- Classical domain
 - “Nothing to worry about”
- Quantum domain
 - **“Incompatible” with scientific realism**
- How do we fix this (=how do we solve the realism problem=how do we make QM compatible with realism)?
 - Usual answer: solve the **measurement problem**
- My main question:



is that really so?

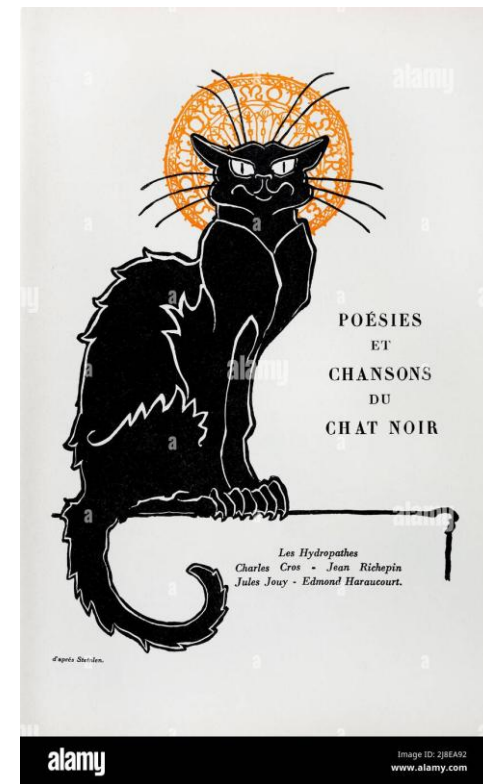
Spoiler

- I argue that this is **not** the case:
 - The measurement problem is a “shallower problem”, **mostly directed to empiricists** (i.e., usually anti-realists)
 - Scientific realists should worry about another problem which has to do with specifying what the **microscopic world** looks like....



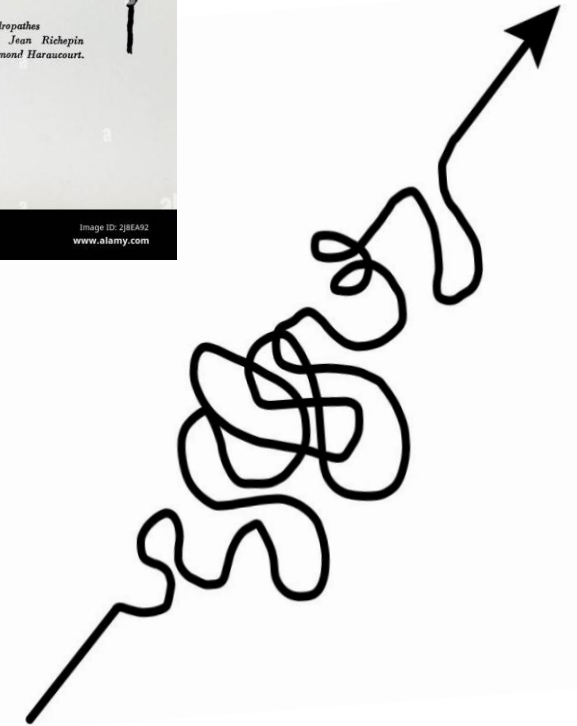
Spoiler

- If that's true, **why hadn't people seen it and done that? Why wasn't it clear since the start?**
 - This has to do with history:
 - The road to quantum theory has been bumpy, convoluted, and full of 'accidents'
 - It led people to problems and theories that a "classical realism" would never have looked at
 - (not in a good way)



QUANTUM
PHYSICS

CLASSICAL
PHYSICS



Scientific Realism

- Our best scientific theories can be taken as providing an **approximately true** description of the world, macro and micro → macro stuff (phenomenological) is accounted for in terms of micro stuff (fundamental)
- PRE-QUANTUM (CLASSICAL) ATTITUDE / WORK PLAN
- **Conditions (implicit because self-evident/undeniable and empirically founded):**
 1. **(empirical adequacy)** The theoretical predictions and the empirical data need to match
 2. **(spatiotemporality)** Fundamental entities are described mathematically by the appropriate mathematical objects in Euclidean 3d space
 3. **(locality)** Physical objects do not interact with one another instantaneously = interaction takes time



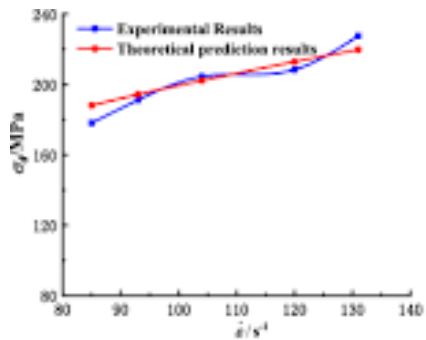
Empirical adequacy

• 1-(empirical adequacy)= theoretical predictions match experimental data

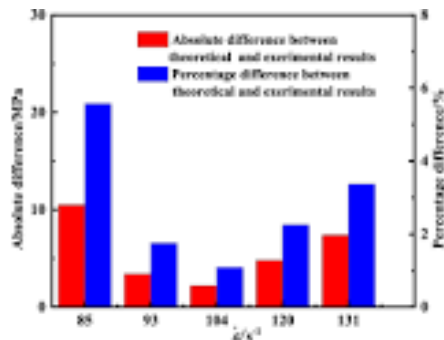
• Self-evident and empirically founded

- This is the “very essence” of science, if there is one
- A theory needs to “save the phenomena”
- Accepted by all “types” of scientist, realist or antirealists alike

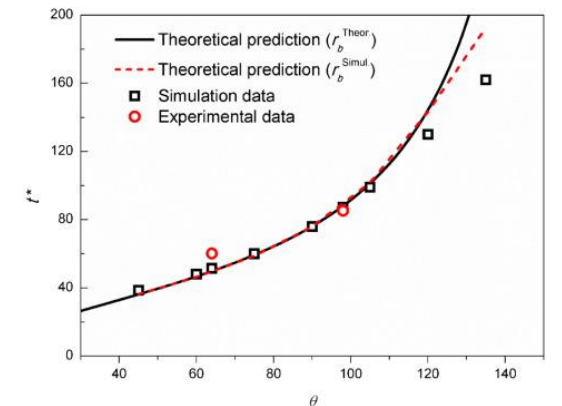
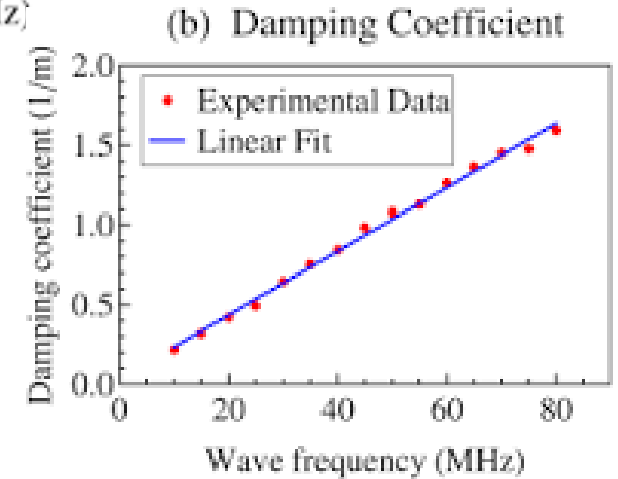
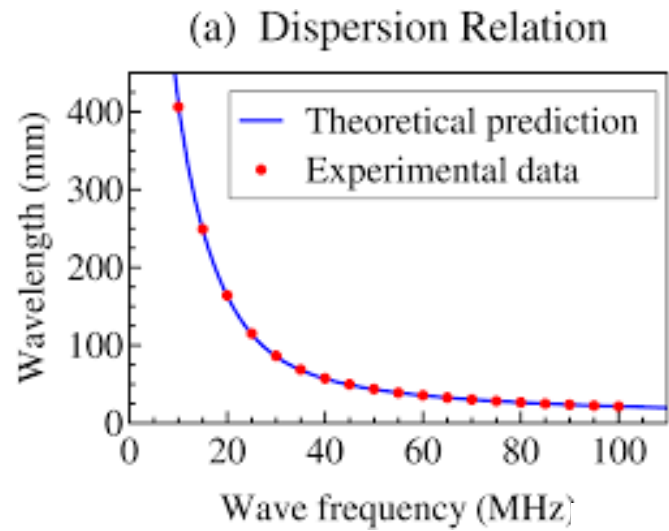
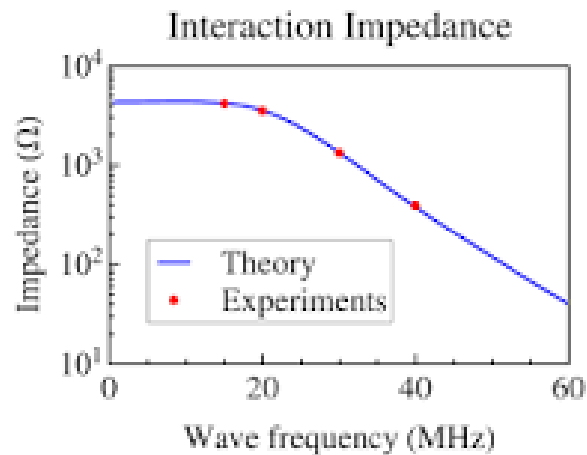
Evidence?



(a) Change trends of theoretical and experimental results



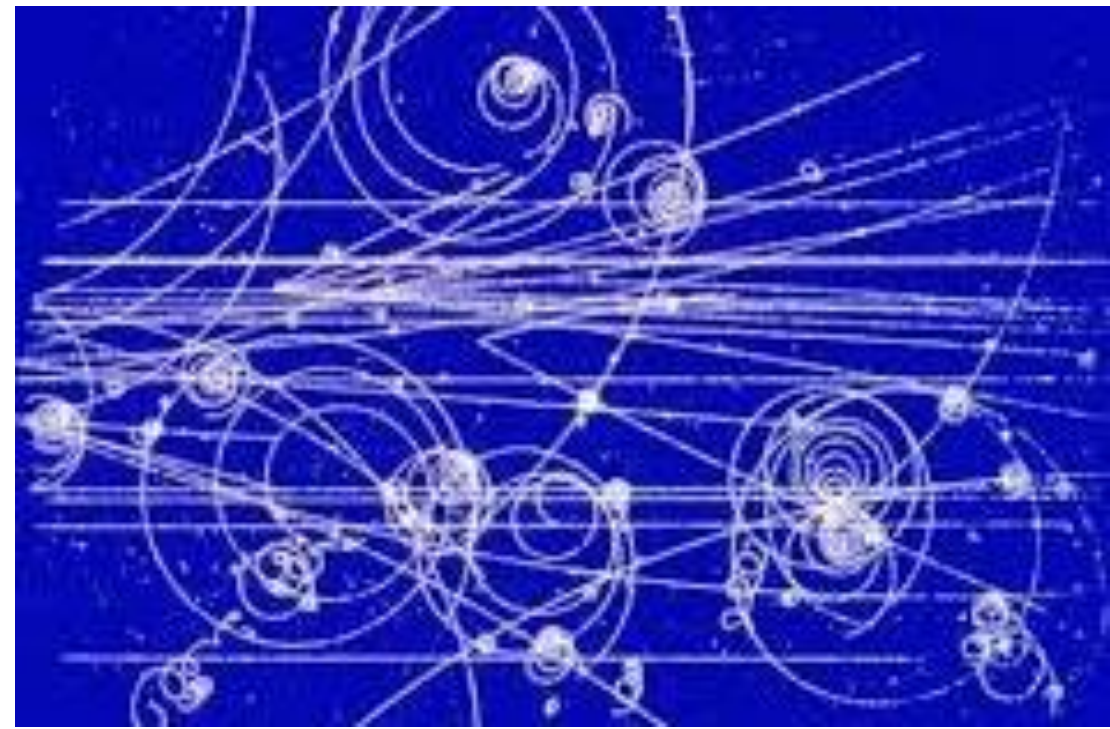
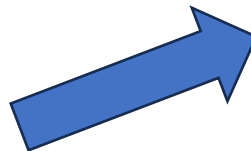
(b) Difference between theoretical and experimental results



Spatiotemporality

- **2-(spatiotemporality) Fundamental entities are in 3d**
- Self-evident and empirically founded
 - Possible ontologies = **possible ontologies in 3d**
 - Point-articles = dimensionless corpuscles **in 3d** → points in 3d Euclidean space
 - Newton's theory of matter
 - Waves = 'disturbances' propagating and oscillating **in 3d** → fields in 3d Euclidean space
 - Maxwell's theory of light
 - No evidence against it

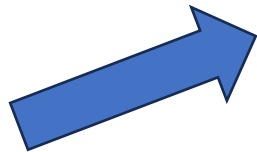
Evidence



Locality

- **3-(locality = local causality) = interactions propagate continuously at finite velocity**
 - Self-evident and empirically founded
 - We successfully describe systems as isolated
 - We successfully identify causes nearby and after their effects
 - Past nonlocal theories were seen as mysterious and “to be fixed” locally:
 - Newtonian gravity → Einsteinian general relativity
 - Electromagnetic forces → electromagnetic fields propagating at c
 - Einsteinian relativity sets a limit to the possible velocities
 - No evidence against it

Evidence

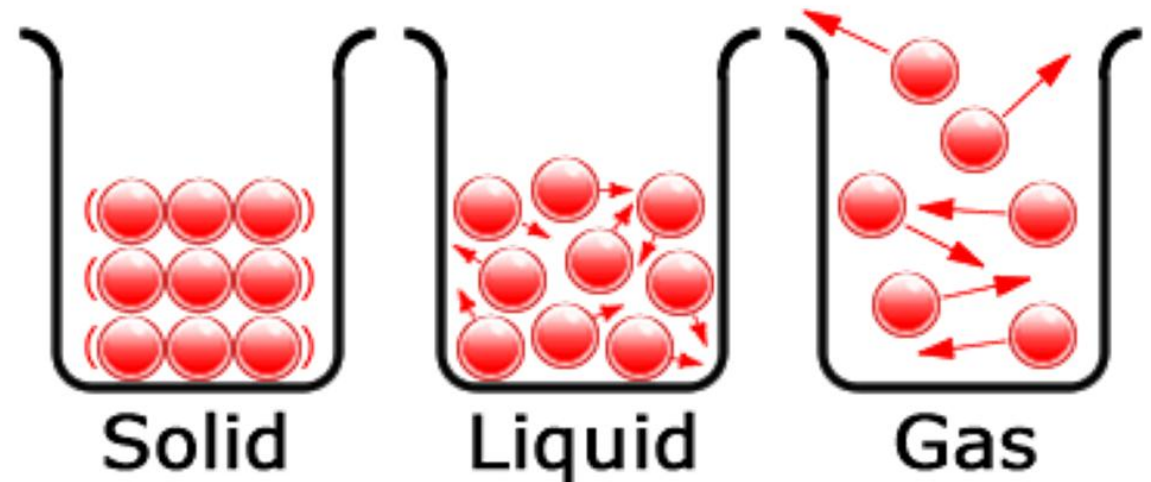


“Classical Reductionism”

- If the theory is **micro**, the realist also “wants”:
- **(Local) compositionality** = everything is composed of 3d stuff interacting locally in an empirically adequate way (1+2+3)
- → **Macro properties** = understood in terms of micro local dynamics
- **Visualizability** = you can draw pictures about the unobservable microscopic world



Evidence?
It worked!

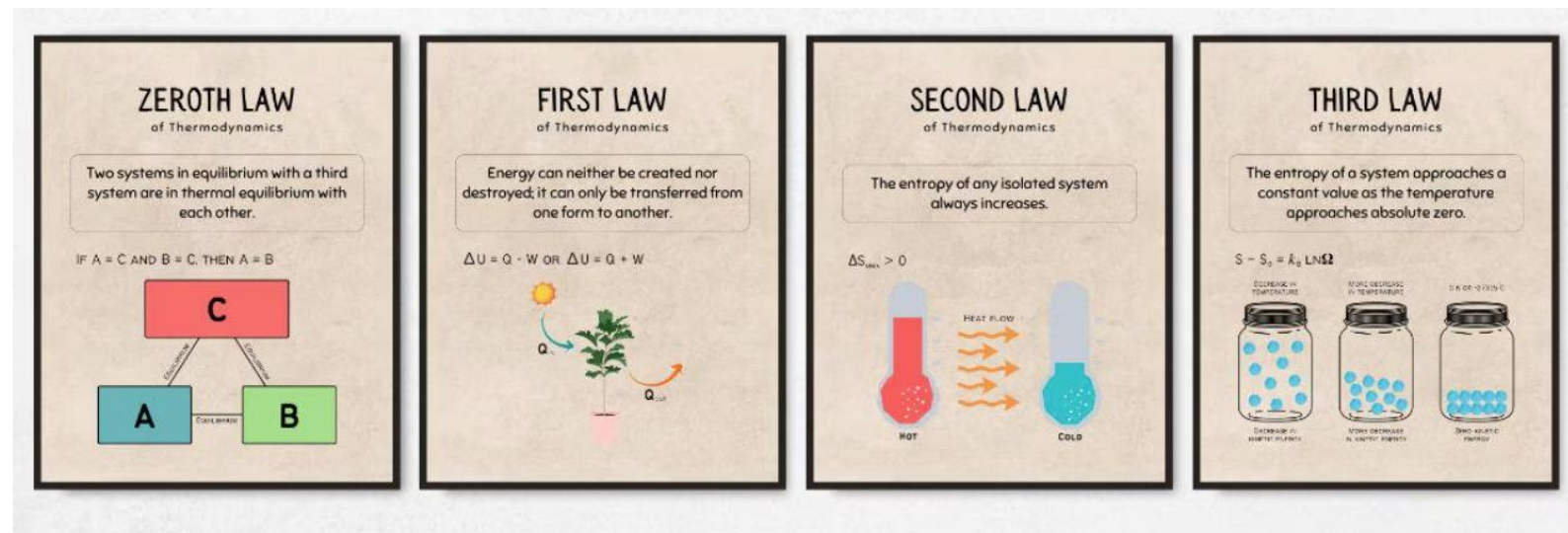


Constructive Theories

- Einstein's classification about type of theories/explanations
 - **Constructive vs Principle theories**
 - $\leftarrow \rightarrow$ Constructive and Principle explanations
- Constructive theories (Lego style)
 - **Spatiotemporal micro** ontology \rightarrow fundamental building blocks
 - Interacting **locally**
 - Macro objects made of micro objects (**compositionality**)
 - Macro behavior completely specified in terms of the microscopic dynamics (**dynamical** explanation)
 - Essentially "bottom-up"
 - Classical mechanics is like this



Principle Theories



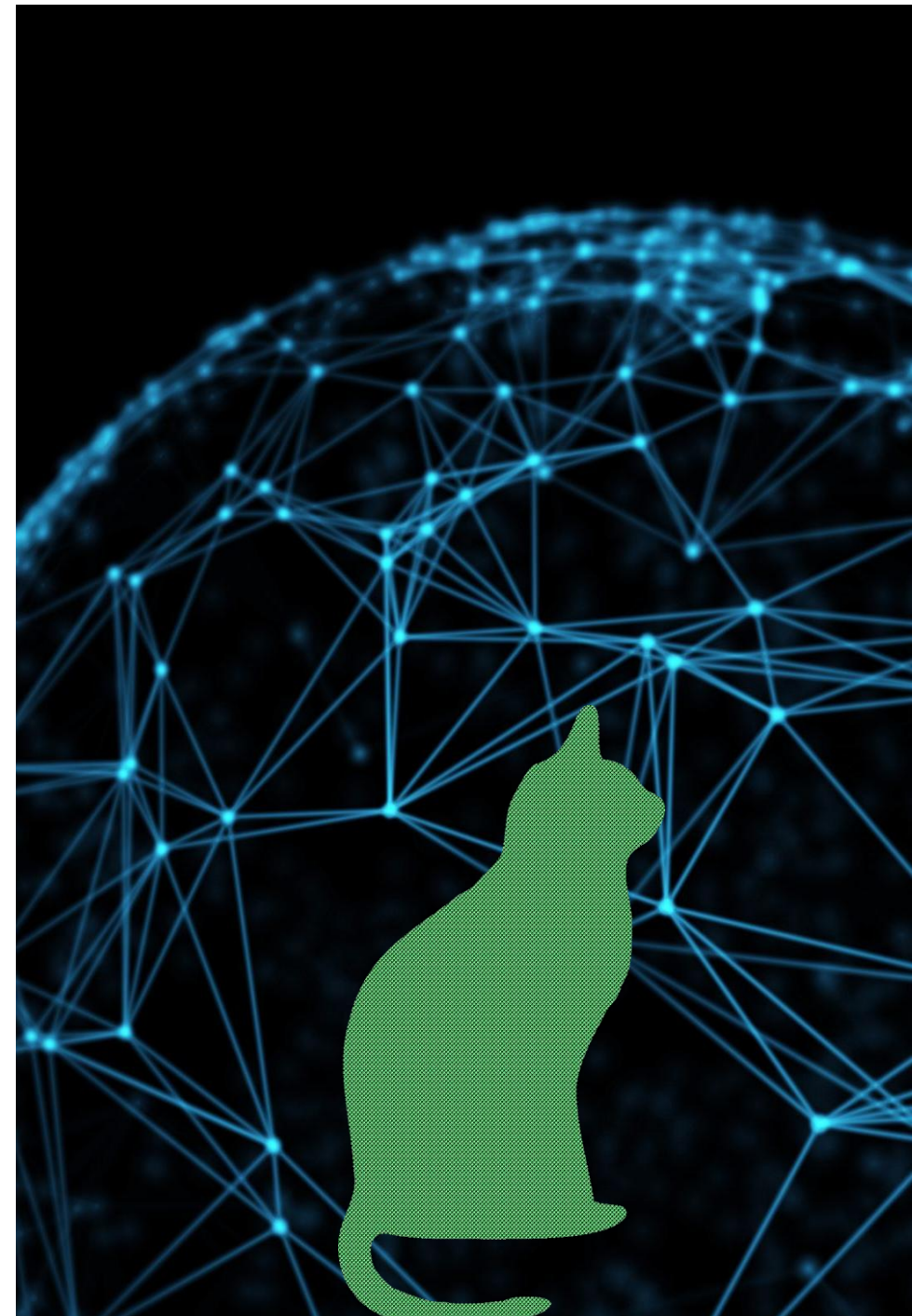
- **Principle theories:**
 - Principles to constrain possible processes
 - Kinematic theories = they are **not in terms of the dynamics and do not involve interactions**
 - Essentially “top-down”
- Prototypical example : *thermodynamics*
- Einstein:
 - Principle theories are provisional
 - We accept them only if there is nothing else
 - We should look for constructive theories “to explain” the principles
 - Ex: kinetic theory explains the principles of thermodynamics



Back to scientific realism...

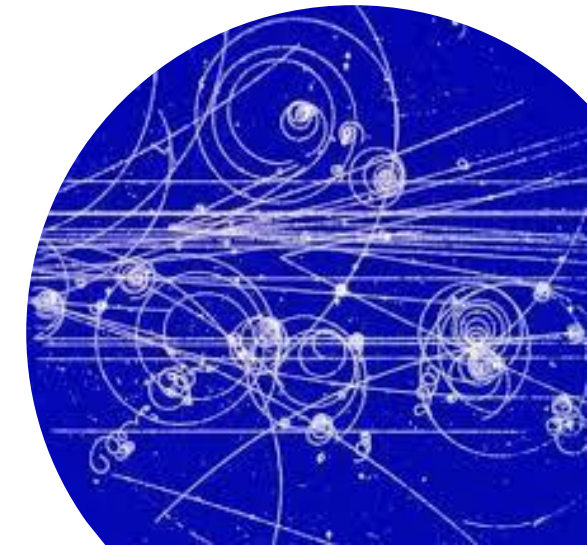
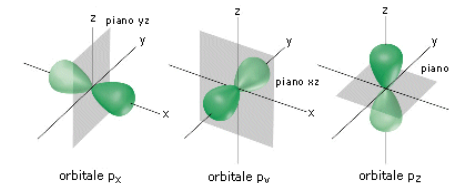
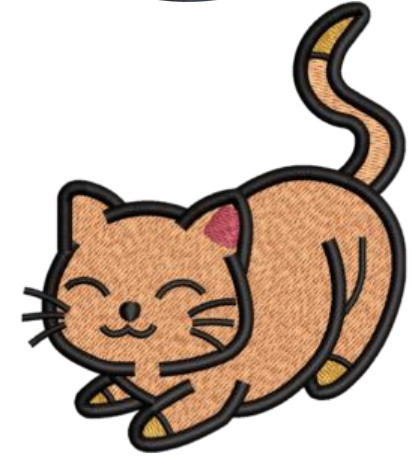
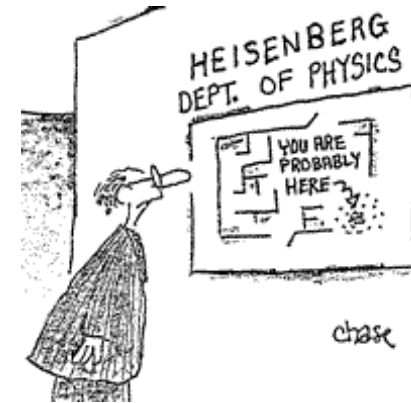
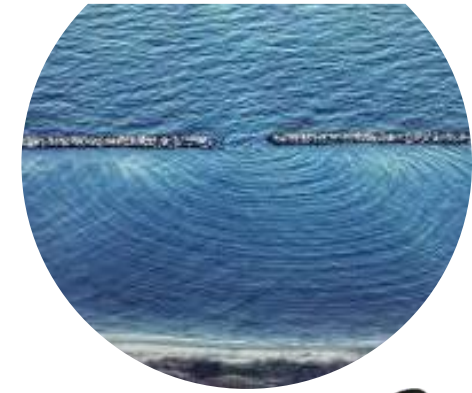
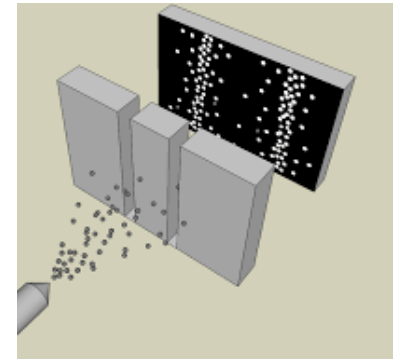
- **Principle theory explanations** tell you **WHAT** to expect: expect to see what satisfies the principles
- **Constructive theories explanations** tell you **WHY** we should expect that
- → **constructive theories are deeper** (Einstein)
- Scientific realism:
 - our best theories tell us **what the world is like microscopically**, not only what we should expect in the next experiment
- So, realists should care about **finding constructive** rather than principle theories
- This is at least what they were looking for pre-quantum....

What happened?



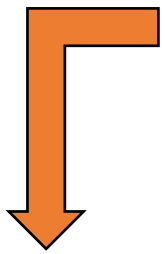
Origins of Quantum “Antirealism”

- (A brief history of Quantum Mechanics)
- Late 1800s: matter as made of particles; light as a wave
 - Particle: localized entity that leaves a well-defined trajectory
 - Wave: non-localized entity that interferes and diffracts
- **The wave nature of light (classically accepted) challenged:**
 - Photoelectric and Compton effects [...]
- **The particle nature of matter (classically accepted) challenged:**
 - **1-Experiments:** interference and diffraction of particles
 - **2-Theoretical aspects**
 - Heisenberg's uncertainty principle
 - Schrödinger's wave mechanics

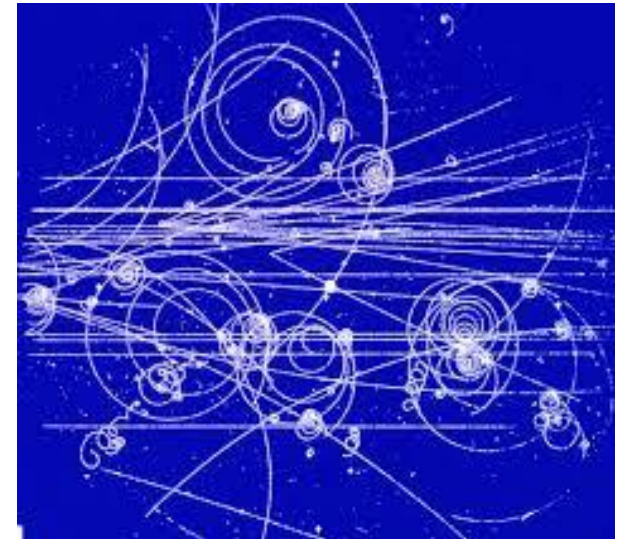
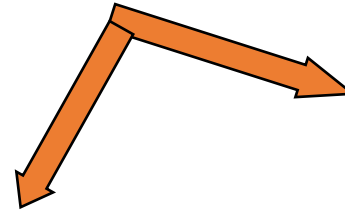
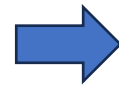
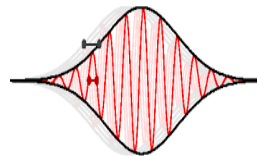
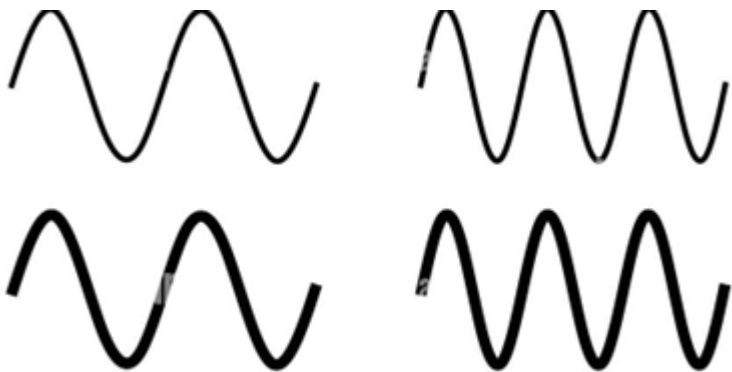


The “resistance” of the realist

- Realist inclined physicists (Schrödinger, Einstein, de Broglie, Lorentz...) did not give it up immediately
- Schrödinger (1926):

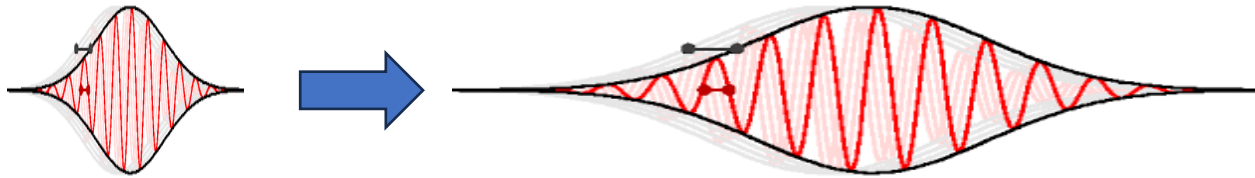


- **Fundamental ontology of everything**
(light and matter) : **waves**
- **Tracks? → ‘particles’ = wave packets**

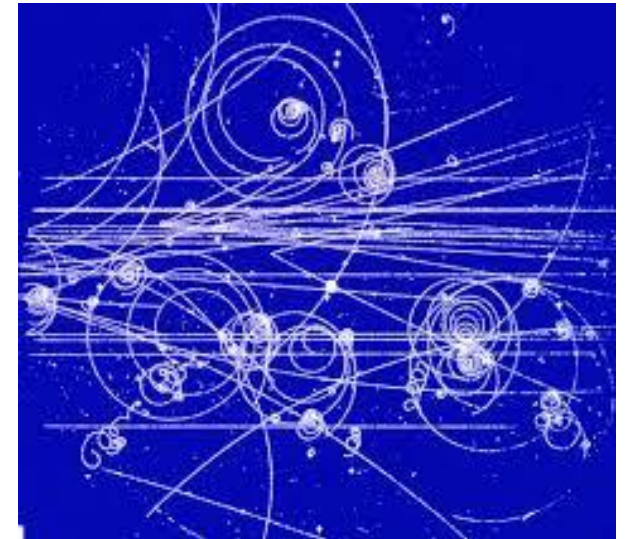


“Resistance is futile”

- **Challenges** of Schrödinger’s realist “everything is a wave” hypothesis
- **A - Spreading** (Schrödinger 1926)
 - The packet quickly gets bigger and loses localization →
 - We should not see definite tracks (which we instead do)



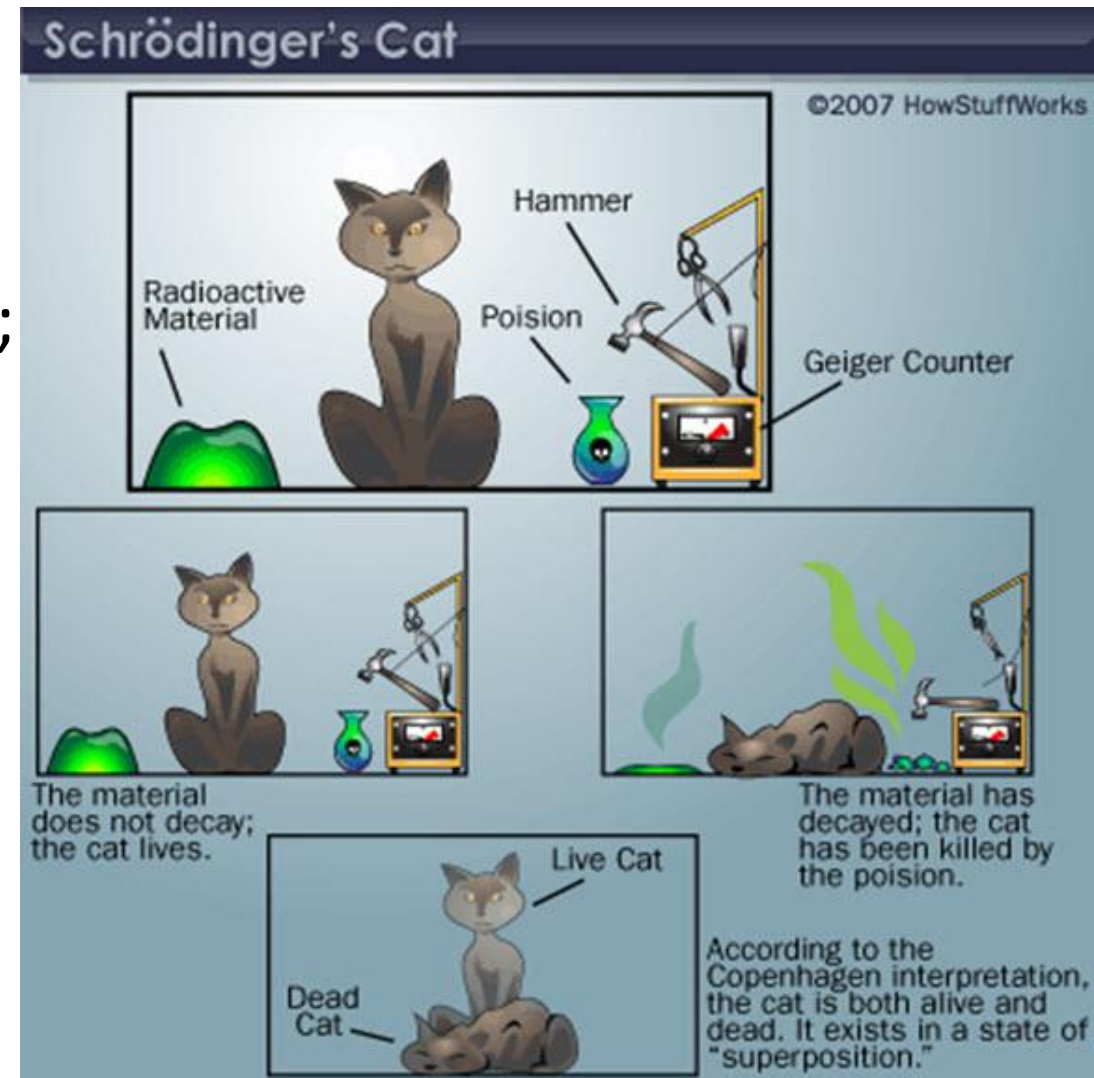
???



“Resistance is futile”

- **B - The “cat problem”** (Schrödinger 1935; measurement problem=macroscopic superposition problem)
 - Waves superimpose
 - In suitable circumstances, they produce unobserved **macroscopic superpositions**
 - “DEAD and ALIVE” CAT

$$\frac{1}{\sqrt{2}} |\text{Live Cat}\rangle + \frac{1}{\sqrt{2}} |\text{Dead Cat}\rangle$$



The “lesson” of quantum theory

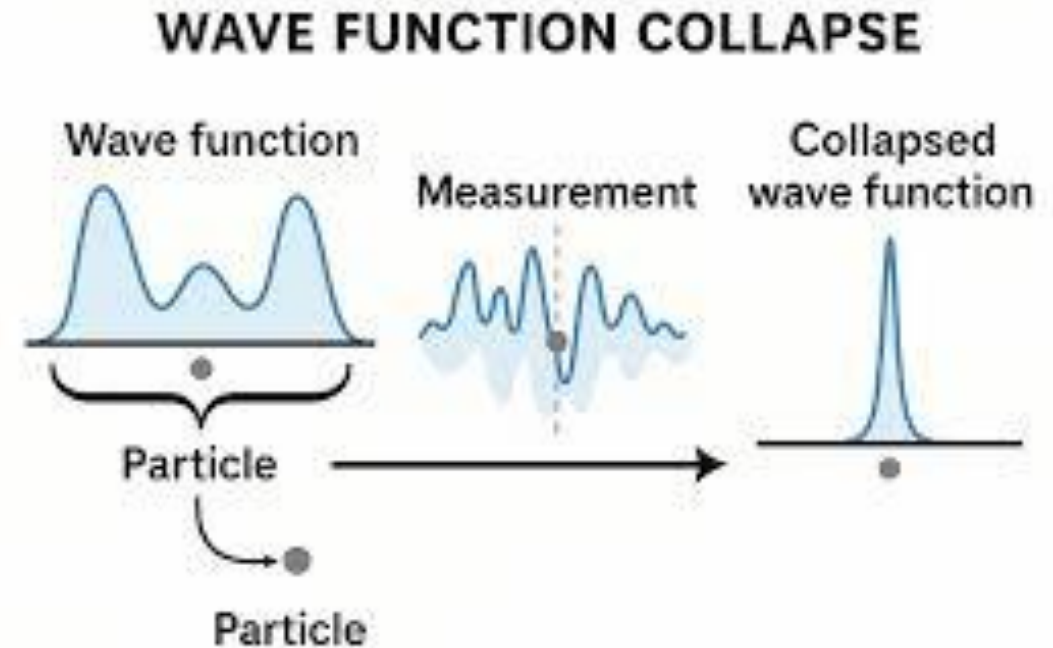
- **“Quantum theory is incompatible with scientific realism”** (they say in physics textbooks etc.):
 - We can only have access to experimental data:
 - Microscopic, unobservable, reality is
 - **Not knowable**
 - “Experience never allows us to affirm that a physical quantity has a definite value, but only that a physical quantity has a definite value *for an observer*” (von Neumann)
 - We have inadequate concepts (Bohr’s complementarity/duality)
 - **Not existing**
 - The observer creates what they observe: “The Moon doesn't exist when I don't look at it” (semi-quote from Einstein)
 - **Not interesting**
 - Describing the unobservable microscopic reality is not necessary/not one of the aims of physics

Realism is doomed



Axiomatic Quantum Mechanics

- How to **effectively systematize the empirical data** in **one** simple framework (von Neumann 1932)
 - **1- state (instantaneous complete description) = quantum state**
 - **2- observables = measurable properties** → **self-adjoint operators**
 - **3a- WHEN NO MEASUREMENT, Schrödinger equation**
 - **3b- WHEN MEASUREMENT, von Neumann collapse rule** – when “measuring operator A”:
 - → possible values = eigenvalues of A
 - → collapsed the wf= corresponding eigenstate of A
 - **4- Born rule = “Prob (some eigenvalue) = |coeff_eigenstate|²”**
- This framework is **empirically adequate**



Axiomatic Quantum Mechanics

- **Realists' protests:** "But what is a measurement? Why when a measurement happens, physical laws change? Why isn't a measurement just a particular type of interaction? When does the wf stop obeying the Schrödinger equation and actually collapses?"
- **Reply (vN):** "We cannot do better than this; realism is impossible. So don't ask too many questions about what you cannot observe. Stop asking this type of questions."

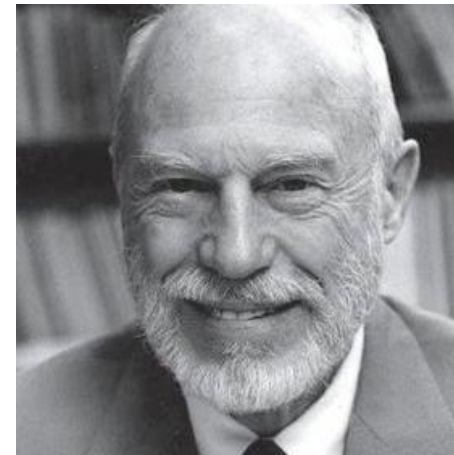


The observer?



Fast forward: “realist” quantum proposals

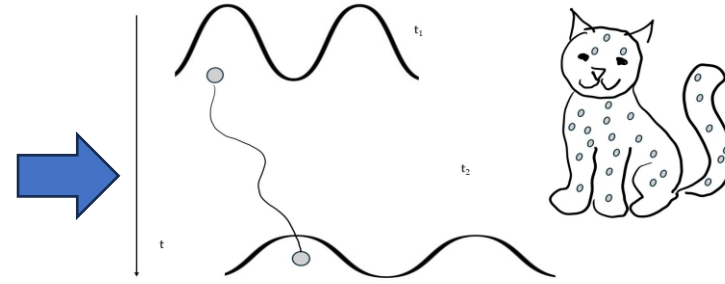
- Many years passed.... **“Now we know better: quantum theory CAN be compatible with scientific realism”**
- In fact, in the period between 1920s and 1980s, **various theories** have been proposed to account for the quantum phenomena which are **“more satisfactory”** than von Neumann’s axiomatization:
 - 1920s: (Schrödinger wave theory); de Broglie pilot-wave theory
 - 1952: Bohm pilot-wave theory
 - 1957: Everett relative state formulation of qm
 - 1970s: de Witt Graham (Everettian) many worlds theory
 - 1980s: Ghirardi Rimini Weber (+Diosi+Pearle) collapse theory



Quick description of the main ideas

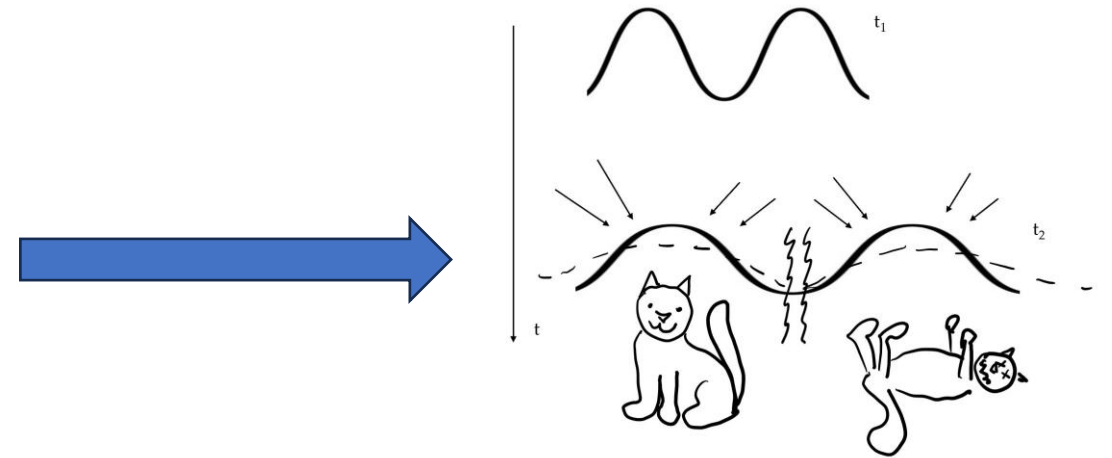
- **Pilot wave theory (de Broglie-Bohm):**

- “There ‘are’ both particles and waves, each with their own deterministic evolution equation; the wave ‘acts’ on the particle, not the other way around”



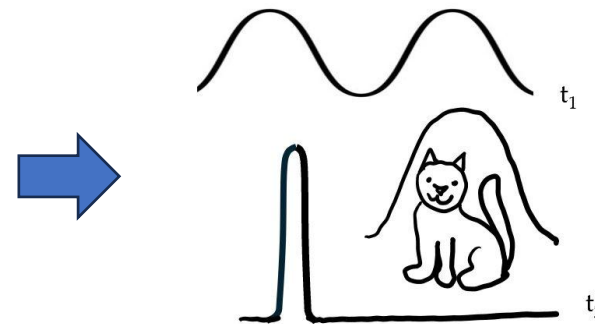
- **Many Worlds (Everett, de Witt):**

- “The world is ‘wave-like’, deterministically evolving and such that there ‘is’ a ‘world’ for each term of the superposition; worlds are mutually invisible because they effectively they do not mutually interact”



- **Spontaneous collapse (Ghirardi-Rimini-Weber, Pearle, Diosi):**

- The world is ‘wave-like’, and such that, spontaneously but as a ‘matter of law’, superpositions collapse into definite states ‘when suitably’”



“More satisfactory” ?

- These theories are “more satisfactory” than vN’s axiomatization because (usual answer)
 - 1-their ontology is not vague: there is no “observer/measurement” vague notion needed in their formulation
 - 2-they have a precise dynamics: every mathematical object in the theory obeys a single equation
- BECAUSE OF THESE FEATURES, ALL THESE THEORIES ARE EQUALLY COMPATIBLE WITH REALISM



A posteriori systematization

- What do these theories have in common? Can they be seen as different responses to the same question/ different solutions to the same problem?
- They are different solutions of the MEASUREMENT PROBLEM (the macroscopic superposition problem/the cat problem), when reformulated like this (Maudlin 1991):
 - The three following claims are incompatible:
 1. The wf provides a **complete** description
 2. The wf evolves according to the **Schrödinger** equation
 3. Measurements have **unique outcomes**

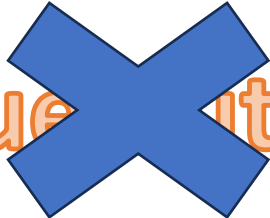


A posteriori systematization

- **Indeed:**
- If (1) is true and the wf provides the complete description, and (2) is true, and so it evolves according to the Schrödinger equation, then there are macroscopic superpositions and (3) is false: measurements do not have unique outcomes

Wf complete

Schrödinger wf

Unique  outcomes

A posteriori systematization

- Indeed:

- If (2) is true, and so the wf evolves according to the Schrödinger equation, and (3) is true, and measurements have unique outcomes, then (1) cannot be true, thus the wf cannot be complete

Wf complete

Schrödinger wf

Unique outcomes

A posteriori systematization

- Indeed:

- If (1) is true and the wf provides the complete description, and (3) is true, and measurements have unique outcomes, then (2) cannot be true, thus the wf cannot evolve according to Schrödinger's evolution.

Wf complete

Schrödinger wf

Unique outcomes

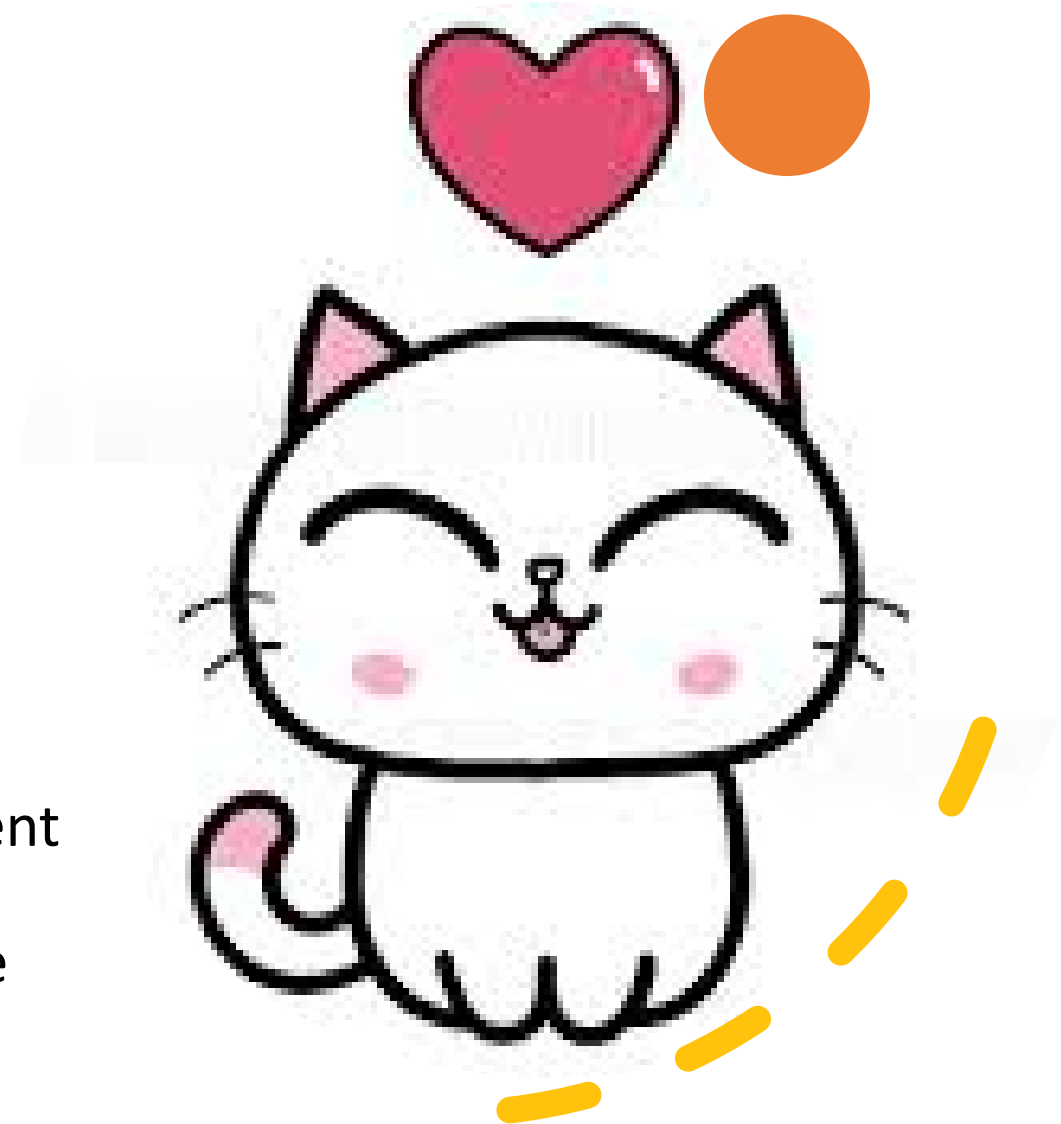
Compatibility with Realism

- The “DOGMA” (I will argue) of naturalized quantum:
- **A quantum theory is compatible with realism if it solve the measurement problem**
- And one can do that by denying at least one of the three premises:
 - Completeness
 - Pilot wave theory denies this (particle AND waves)
 - Schrödinger evolution
 - Spontaneous collapse theory denies this (collapse IN the law)
 - Unique outcomes
 - Many-worlds theory denies this (one outcome for one world)



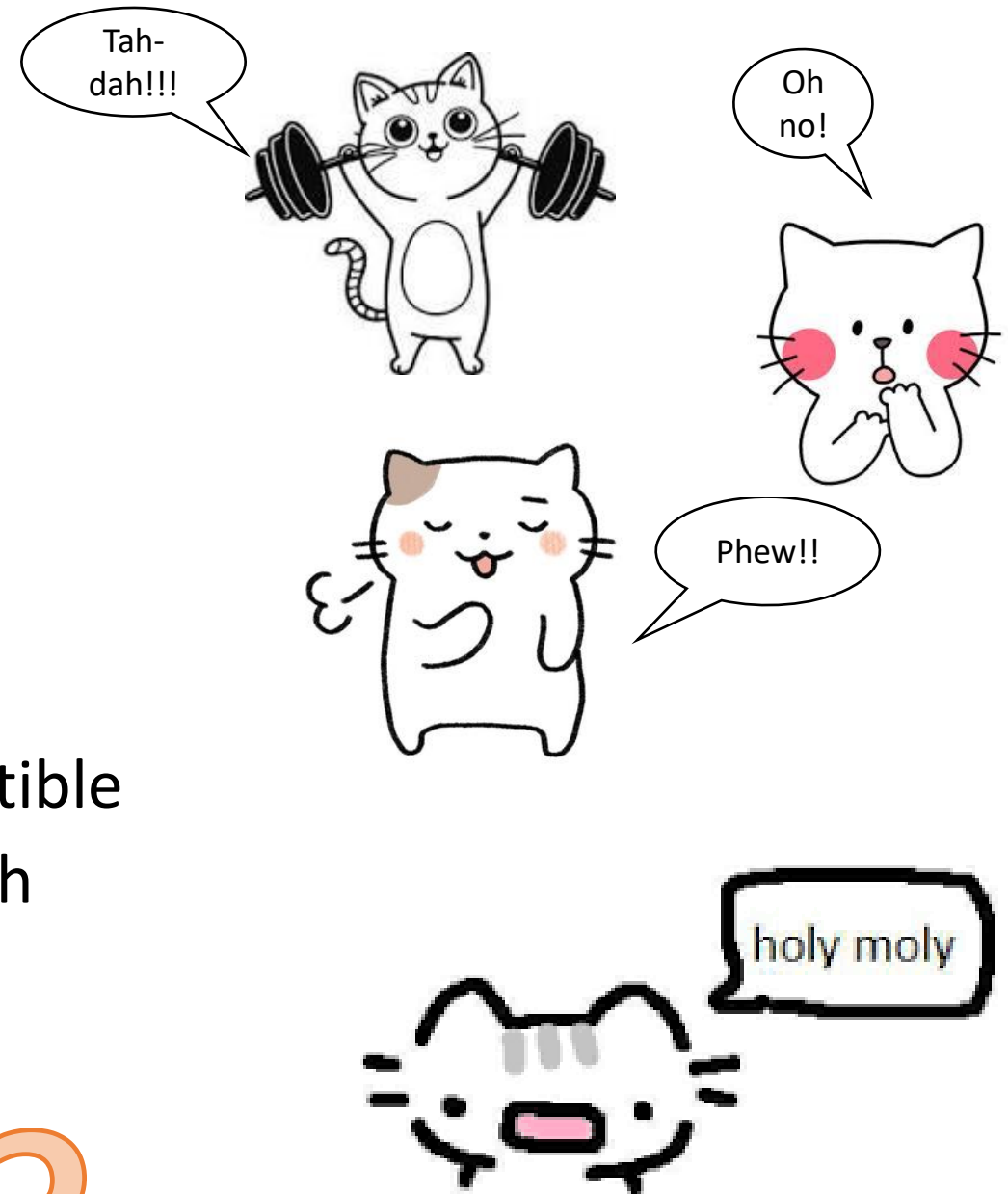
Compatibility with Realism

- THE ARGUMENT:
 - The measurement problem is **THE** problem to solve to make qm compatible with realism
 - Pilot wave, spontaneous collapse and many-worlds are **ALL** solutions of the measurement problem
 - Thus, they are all **EQUALLY** compatible with realism
- Consequence
 - These theories are all **effectively empirically equivalent** (spontaneous collapse makes different predictions but they are hard to test)
 - Therefore, the preference criteria for one or the other solution are **EXTRA-empirical**
 - (For many physicists that means that these theory are worthless)



The story, so far

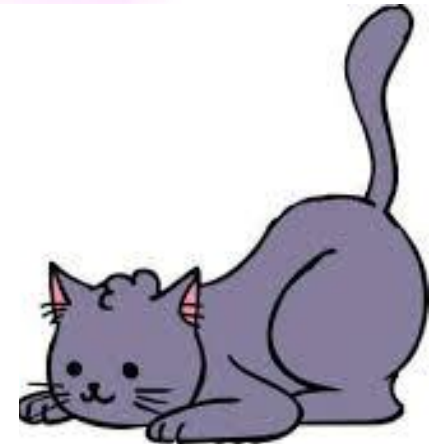
- Classical mechanics: realism was successful
- Success until quantum theory: realism is impossible
- No, that was too pessimistic: just solve the measurement problem
- Indeed, not only quantum theory is compatible with realism, but we can even choose which quantum theory we prefer!!!!



OR NOT?????

Back to realism, again

- What realists really wanted, up to quantum phenomena:
 - Empirical adequacy, yes
 - but also spatiotemporality, locality, compositionality and visualizability
- Why?
 - To get them a constructive theory instead of a principle theory
- Why?
 - Because constructive theories are deeper, and we know how to explain things constructively
 - We called this classical realism; another good name is constructive realism or **“Lego style” realism**



Lego style realism

- **Constructive realism** (in short):
 - Empirical adequacy
 - Spatiotemporality of micro objects
 - Locality of interaction
 - Compositionality of macro objects
 - (as a consequence) visualizable picture of the micro phenomena
- Can we **extend** this type of explanation in quantum theory?
- Realists: we should *at least try ...*



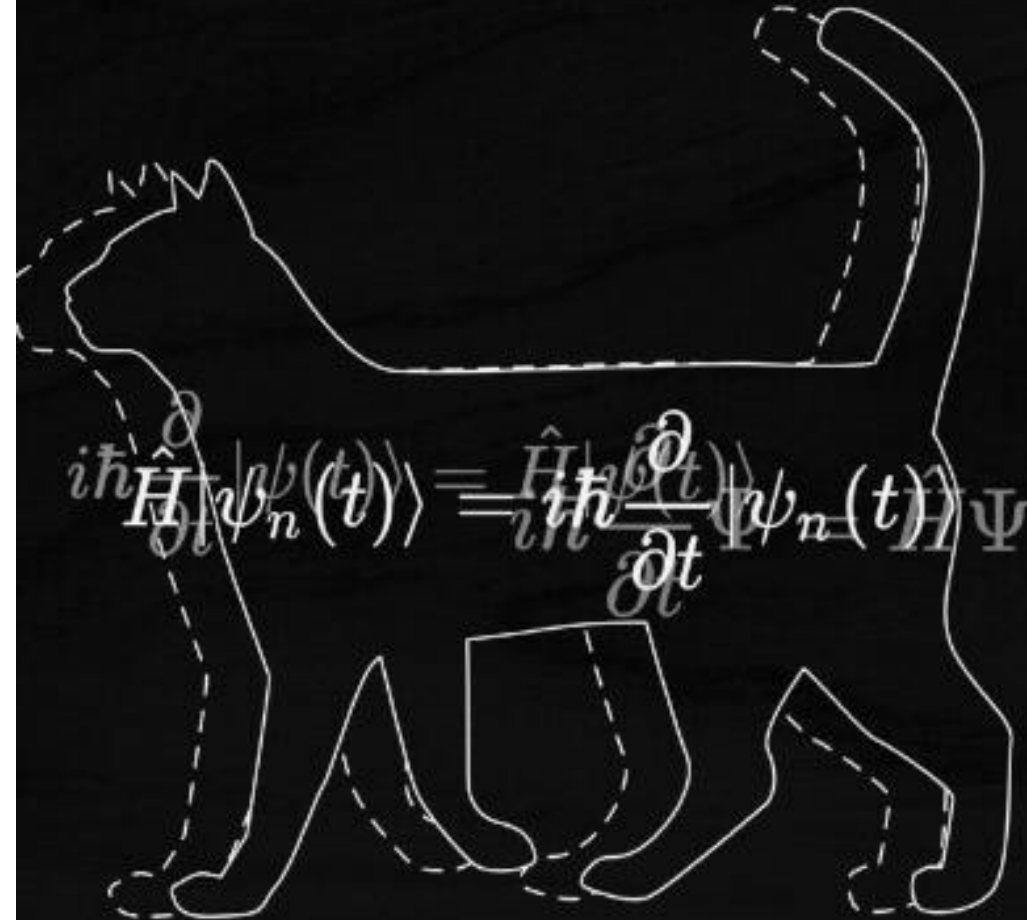
The First Comprehensive and Coherent Formalism: Matrix Mechanics

- Heisenberg, Born, Jordan (1925) : matrix mechanics
 - The first **COMPLETE and COHERENT systematization** of experimental results using matrices/operators
 - BUT: No dynamics, no spacetime, no objects
- Therefore, it was **NOT A VIABLE STARTING POINT** for the realist: it is **not a constructive realist theory**
 - Schrödinger: “I knew of his [Heisenberg’s] theory, of course, but felt discouraged — not to say repelled — by the methods ... and by the lack of visualizability (Anschaulichkeit).”
 - Lorentz: “The fact that the coordinates, the potential energy, etc., are now represented by matrices shows that these magnitudes have lost their original meaning, and that a tremendous step has been taken towards increasing abstraction.”
 - Schrödinger: “My method was inspired by L. de Broglie and by brief, yet infinitely far-seeing remarks of Einstein.”
 -



A First Attempt to a Constructive Theory

- **Schrödinger's wave mechanics** (1926) was a conscious, deliberate attempt to a **constructively realist quantum theory**:
 - He was not satisfied with systematizations; he wanted to understand where they come from in terms of a visualizable microscopic picture
- His theory can **constructively explain** the quantization rules described by matrix mechanics in terms of a
 - Fundamental wave picture (the wavefunction)
 - Evolving deterministically and linearly linear equation (Schrödinger's equation)

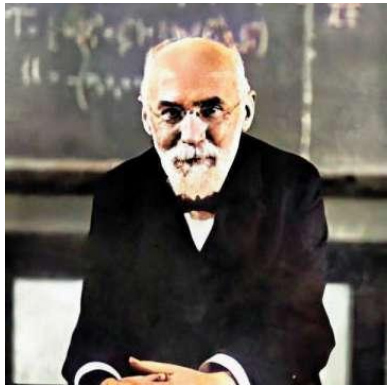


The Realists' Concerns

- **Realists** (Schrödinger, de Broglie, Einstein) **weren't happy** with wave mechanics for various reasons:
 - ANTICIPATION
 - 1- It has **no spatiotemporal ontology**
 - “**unphysical field**” arguments: if the theory were complete, then matter would be a wave oscillating, but not in 3d
 - Regardless, if one tries to fix the theory otherwise, then:
 - 2-Either the interaction is **nonlocal**
 - “**Nonlocality**” arguments (1926 onwards, culminating in Einstein Podolsky Rosen, EPR, 1935): if the theory were complete, then there would be nonlocal interaction
 - 3-Or the theory would become empirically inadequate= it would be **falsified**
 - The “**measurement**” problem (1935): if wave mechanics were complete, then there would be unobserved macroscopic **superpositions**



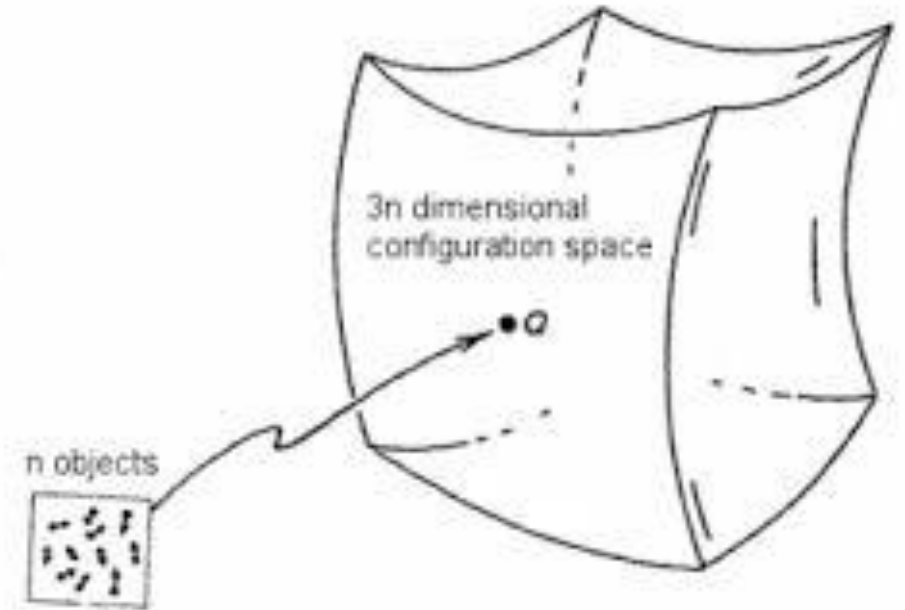
The Realists' Concerns



- Wave mechanics was **immediately criticized** by the realists
- 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.**”
 - De Broglie: “if the propagation of a wave in space has a clear physical meaning, it is not the same as the propagation of a wave in the **abstract configuration space**, for which the number of dimensions is determined by the number of degrees of freedom of the system”

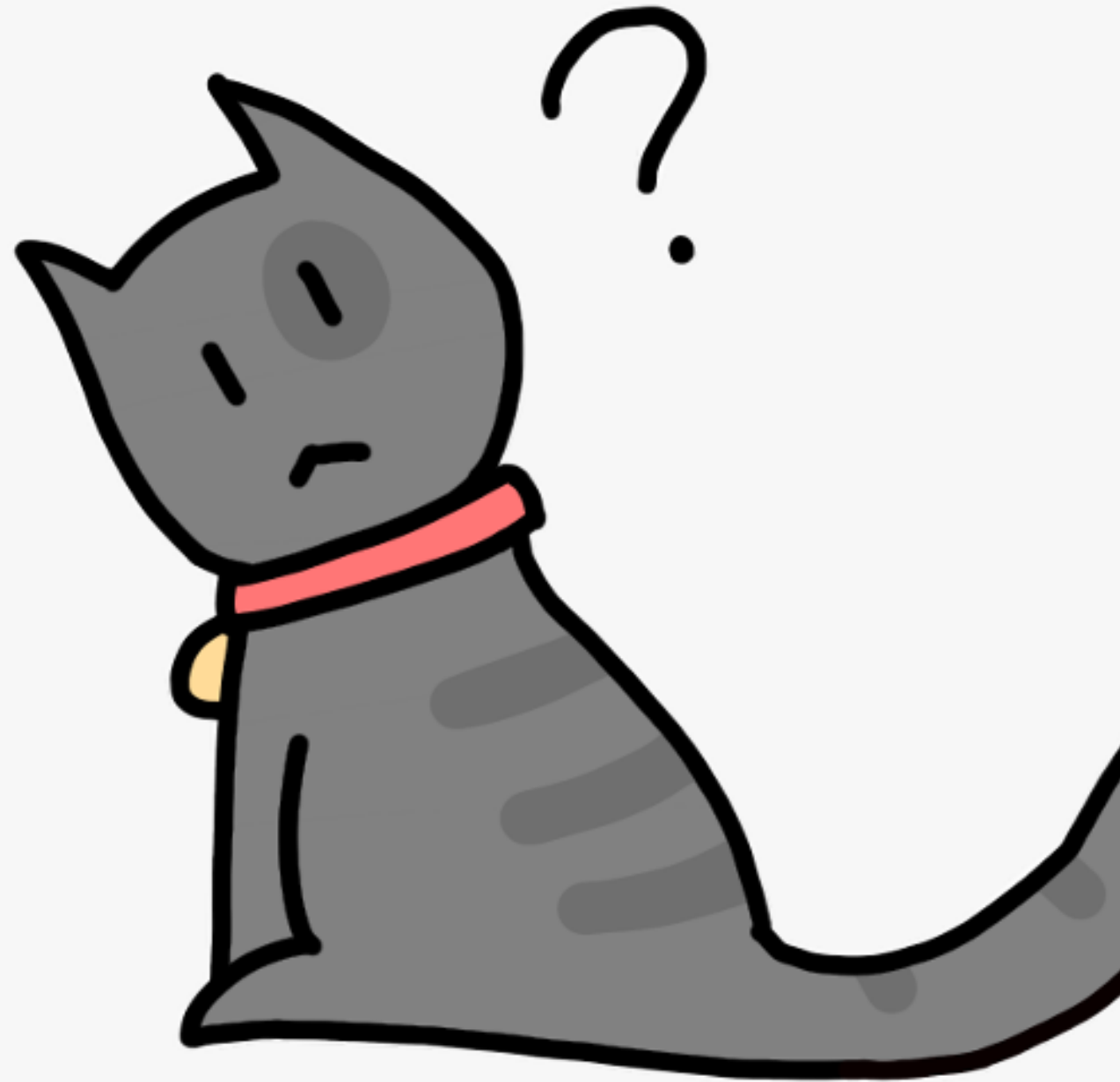
1-Unphysical Field Argument

- **1-The unphysical field argument**, spelled out (which they did not):
 - If the theory were complete, then matter would be represented by the wf, a wave
 - The wf is *not* defined in 3d
 - $\psi_{composite} = \psi(X); X = (x_1, \dots, x_N)$; a field in configuration space
 - Something not defined in 3d is not (does not represent) a physical field
 - So, the wf is (represents) an unphysical field
 - There is nothing else in the theory to represent matter
 - Thus, the theory is not complete:
 - **The theory needs a spatiotemporal ontology**



1-Unphysical Field Argument

- A legitimate question: **“Why didn’t realists spell this argument out in a paper?”**
- Because
 - 1-**Antirealists did not care** about (thought it was impossible to have) a **microscopic** understanding: so, they did not care about what represents micro stuff
 - 2- **No realist at the time actually questioned it**: it was ASSUMED TO BE OBVIOUS; it was one of the ACCEPTED PREMISES
- That is, **realists were talking among one another**, and understandably they did not give arguments for the premises everyone of their group (=realists) already assumed



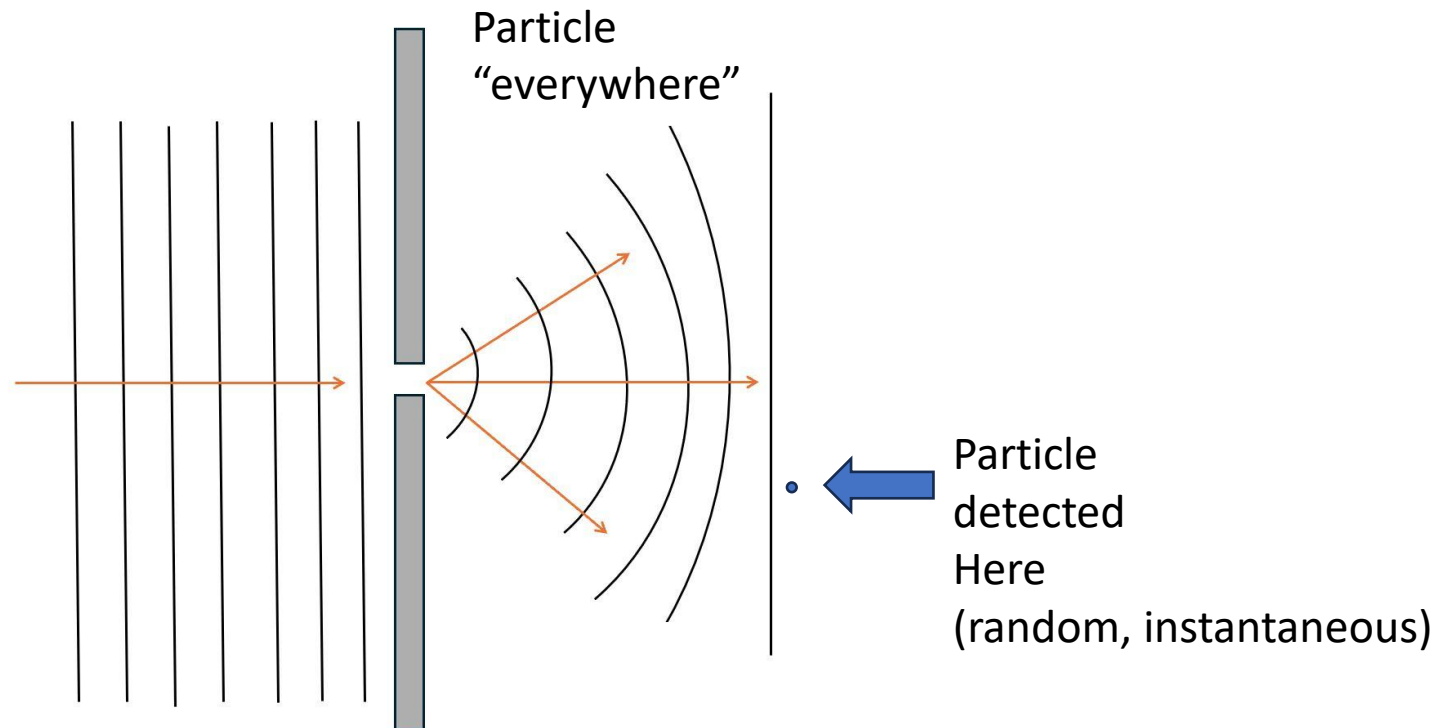
1-Unphysical Field Argument

- Indeed, **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 needs to be described is one **in space and time**.”
 - “..it has even been doubted whether what goes on in an atom can be described within a scheme of space and time. From a philosophical standpoint, I should consider a conclusive decision in this sense as equivalent to a complete surrender. For **we cannot really avoid our thinking in terms of space and time**, and what we cannot comprehend within it, we cannot comprehend at all. There *are* such things but I do not believe that atomic structure is one of them.”
- His “fix”(1926): charge density **3d-field ontology**
- However, it didn't work for other problems we already saw:
 - 1-wave packet spreading → no stable ‘particle’ trajectories
 - (2- Unobserved macroscopic charged density superpositions → not empirically adequate)



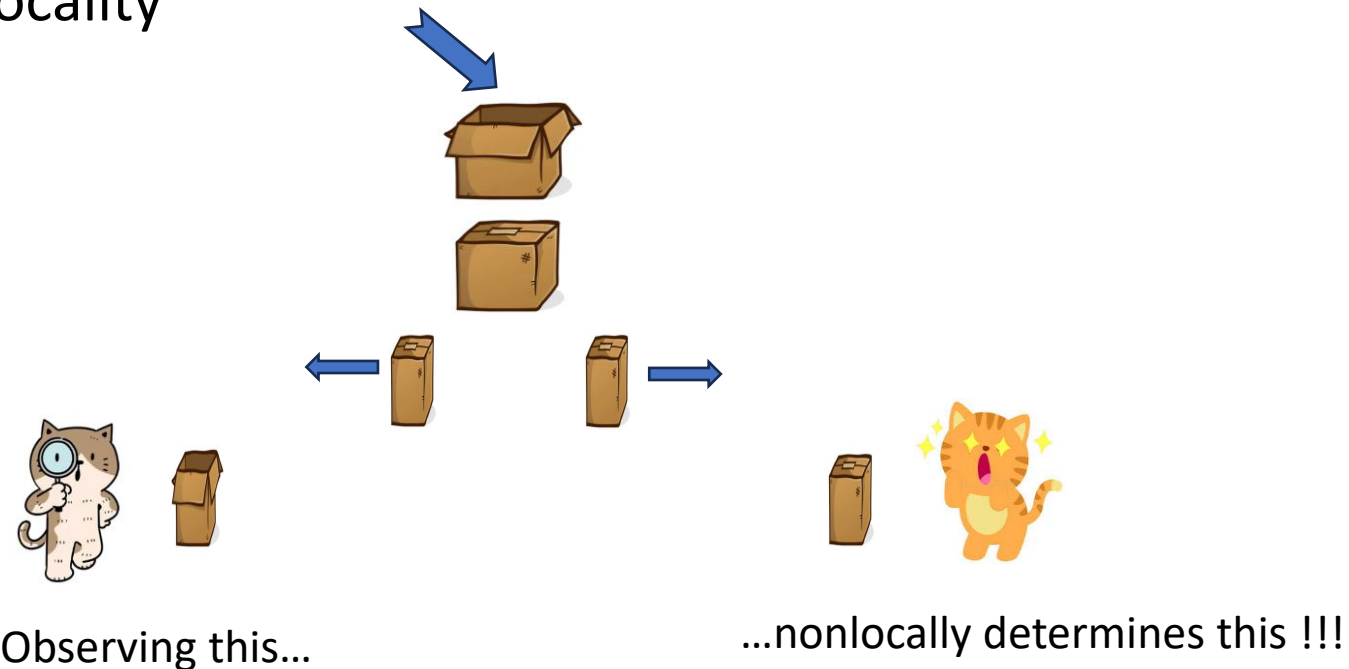
2-Nonlocality Arguments

- **1927-1935: if the theory were complete, locality would be false**
 - 1927: Einstein completed qm with particles but 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 as to be about the uncertainty principle)



2-Nonlocality Arguments

- **1927-1935: if the theory were complete, locality would be false (cont'd)**
 - 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 Einstein's two boxes (letter to Schrödinger): a wf in a box is divided into two halves. The boxes are sent in opposite direction. By opening one box, one affects the other → nonlocality



2-Nonlocality Arguments

- 1927-1935: if the theory were complete, locality would be false (cont'd)

- **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)

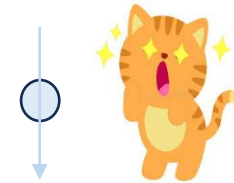


$$|S\rangle = \frac{1}{\sqrt{2}} \left(\begin{array}{c} \uparrow \\ \circ \end{array} \otimes \begin{array}{c} \downarrow \\ \circ \end{array} - \begin{array}{c} \downarrow \\ \circ \end{array} \otimes \begin{array}{c} \uparrow \\ \circ \end{array} \right)$$

Spin property
of each particle
“undetermined”



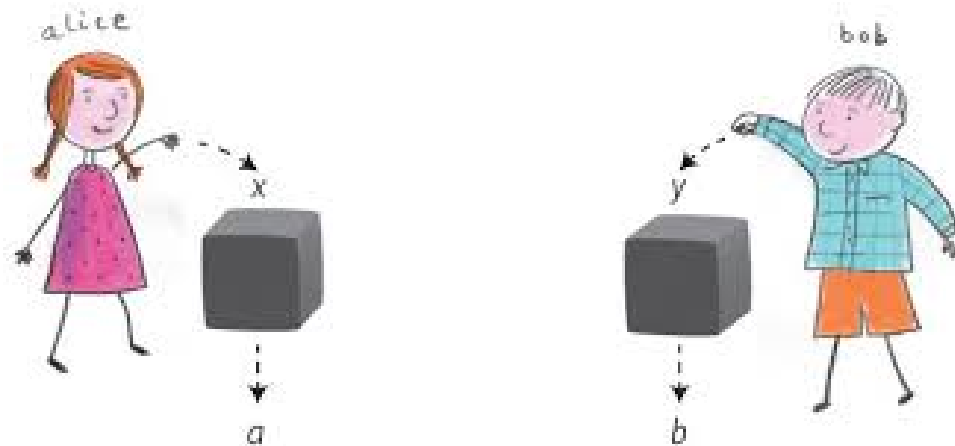
Observing this, “creates”
its spin property; BUT
ALSO ...



...nonlocally determines
the spin of this one !!!

2-Nonlocality Argument

- The schema of the various nonlocality arguments:
 - If the theory were complete, then interaction between matter would be nonlocal
 - A nonlocal interaction is impossible
 - If we assume that the theory is not complete (hidden variables) this nonlocality would go away
 - Thus, the theory is not complete



So far....

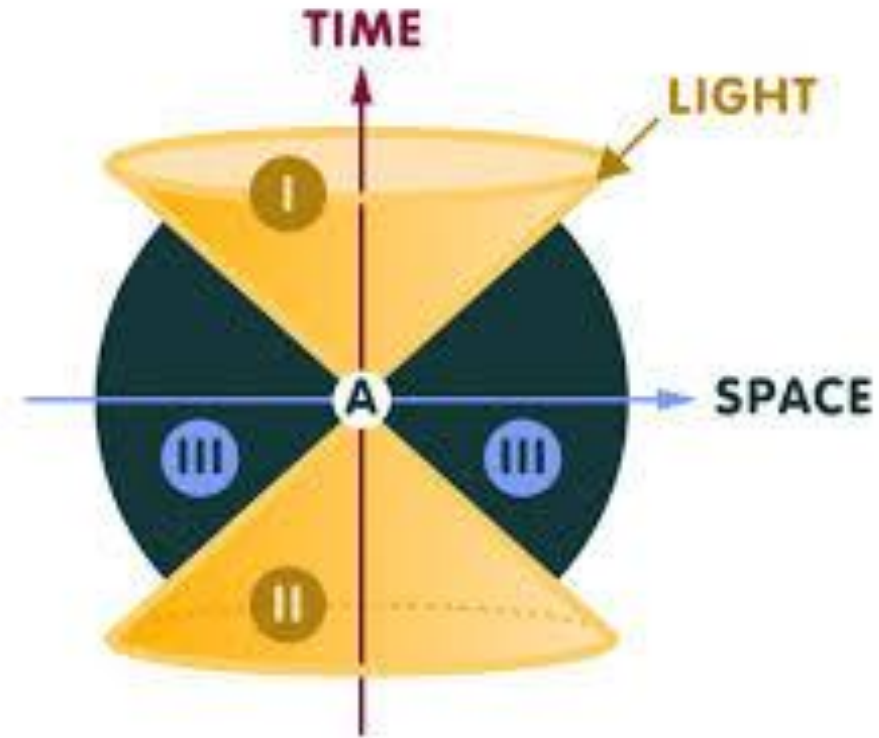
MISS
YOU
something



- Arguments 1 and 2 (unphysical field and nonlocality) **show INCOMPLETENESS** of quantum theory
- Both are **reductio ad absurdum** arguments
- The fact that the theory appears to have these absurd features shows that the theory is mistaken:
 - The theory turns out to be non-spatiotemporal? This is **evidence** that what matter consists of, is not specified by the theory → incomplete
 - The theory turns out to be nonlocal? This nonlocality is **evidence** of something missing “somewhere” → incomplete
- The nonlocality argument is weaker than the non-spatiotemporal/unphysical field argument):
 - the unphysical field argument specifies where the problem is (no spatiotemporal ontology); the nonlocality arguments second merely says that it’s somewhere
- But if we take them together, they say: **you need to add something in spacetime SUCH that the interaction would remain local**

The failure of nonlocality arguments

- Heisenberg (1928) dismissed nonlocality arguments by thinking of **relativity instrumentally** as a theory of signals
 - He accepted the argument that QM is nonlocal
 - But since you **cannot use quantum nonlocality to send faster-than light signals**, then it is not in contrast with relativity!

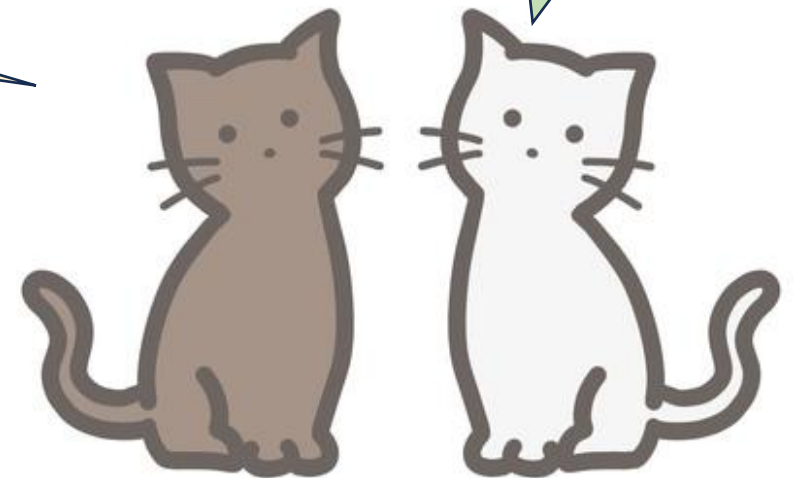


The failure of “microscopic”-type of arguments

Realist: “Wait! Nonlocality is ALSO bad because we can’t understand how it works, and we can’t understand why we seem to be able to isolate systems, and we seem to be able to identify causes, and so on...?!”

Antirealist: “The microscopic world is not understandable; stop asking this type of questions!”

- This type of response is **THE response** to ANY argument focused on micro stuff
- So, arguably realists, to resist accepting antirealism, had to move their arguments to the **macroscopic** domain



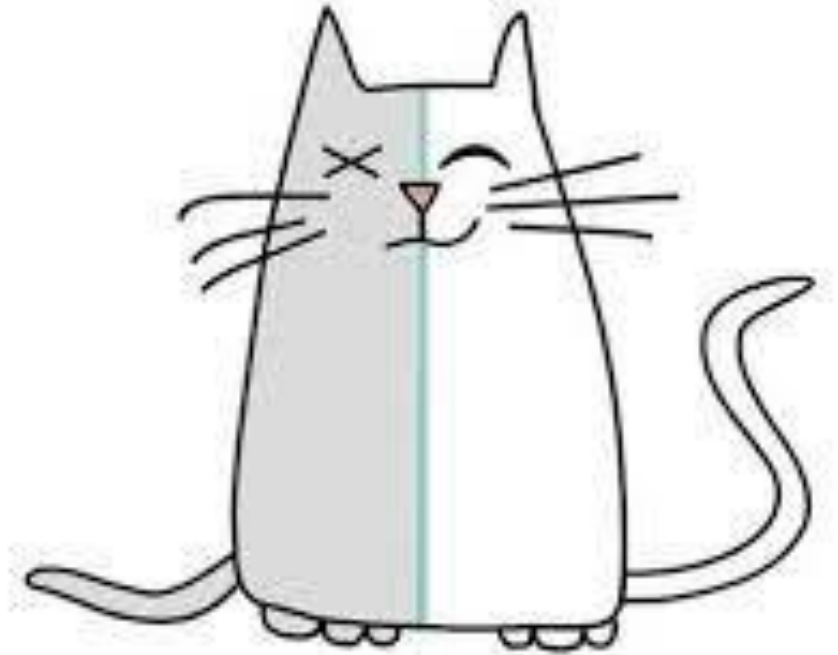
3-The Measurement Problem



- ... and here comes the measurement problem!
- **1935: the theory is incomplete otherwise it would be empirically inadequate/falsified - it predicts unobserved macroscopic superpositions**
- Einstein **bomb** example in a 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.”
- 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**

3-The Measurement Problem

- **The macro superposition argument:**
 - If the theory were complete, then it would predict the observation of macroscopic superpositions
 - Such macroscopic superpositions are not observed
 - So, the theory is empirically inadequate
 - It needs to be completed to make it adequate



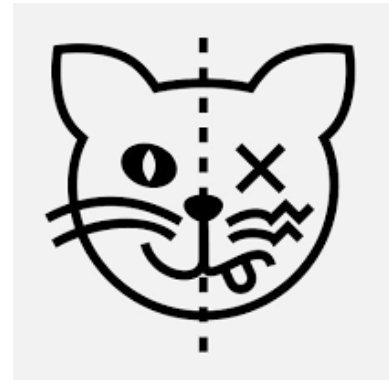
The measurement problem was directed to antirealists

- 1950 from Einstein:
- “Dear Schrödinger,

You are the only contemporary physicist, besides Laue, who sees that one cannot get around the assumption of reality—if only one is honest. Most of them simply do not see what sort of risky game they are playing with reality—reality as something independent of what is experimentally established. **They somehow believe that the quantum theory provides a description of reality, and even a complete description;** this interpretation is, however, **refuted, most elegantly by your system of radioactive atom + Geiger counter + amplifier + charge of gun powder + cat in a box,** in which the ψ -function of the system contains the cat both alive and blown to bits. Is the state of the cat to be created only when a physicist investigates the situation at some definite time? Nobody really doubts that the presence or absence of the cat is something independent of the act of observation. But then **the description by means of the ψ -function is certainly incomplete, and there must be a more complete description.** If one wants to consider the quantum theory as final (in principle), then one must believe that a more complete description would be useless because there would be no laws for it. If that were so then physics could only claim the interest of shopkeepers and engineers; the whole thing would be a wretched bungle”



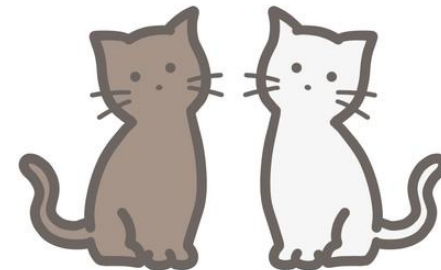
3-The Measurement Problem



- This argument is NOT to convince **realists**:
 - Realists (at the time) were **already convinced** that there was something missing (unphysical field and nonlocality arguments)
- Those left to be convinced were the **antirealists**:
 - **They do not care about the micro world** (and thus is insensitive to the unphysical field argument), and they do not care about nonlocality (because it does not contradict relativity if understood instrumentally)
- However, they **DO care about empirical adequacy**:
 - They care about their theory being confirmed/making correct predictions/being empirically adequate/...
- They **should care about the measurement problem** because it shows that either QM makes no prediction (what does it mean the cat is dead and alive?) or if it does, they are false (the cat is observed being either dead or alive, not in a superposition state)
- **Nonetheless, not even this argument worked: von Neumann's collapse rule took care of it**

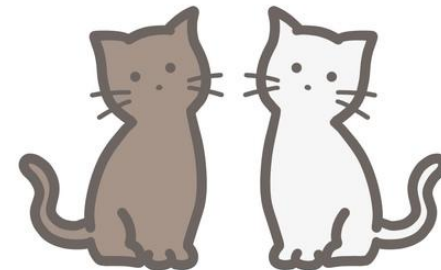
Another dialogue

- **Antirealist (von Neumann):** “No, no, no! The theory isn’t falsified! When a measurement is performed, the wave function collapses in one of the terms of the superpositions: either a dead cat or a living cat. The collapse solves the measurement problem”
- **Realist (Schrödinger, EPR):** “if you assume that, then it’s nonlocal!”
- **Antirealist (Heisenberg):** “Fine, since the nonlocality cannot be used to send superluminal signals”
- **Realist:** “...but the micro picture.... ”
- **Antirealist:** “STOP asking this type of questions!”
- → SAME RESPONSE AS BEFORE



Another dialogue

- **DOES IT GET DIFFERENT?**
- **Realist (~1990s onward):** "...but the collapse rule is not as satisfactory as the other solutions of the measurement problem (the pilot-wave, the spontaneous collapse, the many-worlds theory) because its ontology is vague (what's a measurement?) and its dynamics imprecise (two evolution laws)"
- **Antirealist:** "We do not need either a microscopic ontology, vague or otherwise, or a microscopic dynamics, precise or otherwise. We just need an empirically adequate systematization of the phenomena. This is BECAUSE WE DO NOT CARE ABOUT MICRO STUFF. Stop asking this type of questions."
- **....HERE WE GO AGAIN: THEY TALK PAST EACH OTHER**



Where are we at

- Who is the measurement problem a problem for?
 - It was never a problem intended for the realist: they were already convinced qm was problematic (precisely, incomplete)
 - It was proposed (I have argued) as a problem for the antirealist (it is about MEASUREMENTS, after all), which however solve it already (even if in a way the realists dislike)
- But if it was never a problem for the realist.... **WHY DID THE REALISTS EVEN and EVER TRY TO SOLVE IT?**



Historical “accidents”: dismissal of the pilot-wave theory

- 1932: von Neumann’s **impossibility proof** - completing quantum theory as EPR wanted (to make it “locally complete”) led to contradiction
 - This effectively destroyed the search for a constructive quantum theory for a long time
- 1952: Bohm’s improved (wrt de Broglie’s) **pilot-wave theory**
 - Nonetheless, **realists were still not happy**:
 - Einstein, initially supportive, did not like its explicit nonlocality of the theory
 - de Broglie was upset and initially dismissive
 - Schrödinger did not even bother to write Bohm (unclear why)
 - **Antirealists were even harsher**
 - Bohm was **effectively ostracized** by everybody else
 - Oppenheimer: “if we cannot prove him wrong, we must agree to ignore him”
 - Pauli: he is “beyond help”
 - Moreover, his sympathies towards **communism** got him exiled in Brazil
 - No passport → no travels to defend his theory
 - More generally, **people dismissed the theory based on the impossibility proofs** (even if he proved that his theory was immune to them)



Historical “accidents”: misunderstanding of Bell’s theorem

- 1964: Bell showed that the vN impossibility proof was unsound and thus you **can** complete QM
- The pilot-wave theory does this, but it was also nonlocal, so Bell started to **wonder whether one could complete QM while also preserving locality**
- 1964: Bell started from the EPR argument, concluded that a local theory would have to have preexisting values, and then showed **it makes different predictions than QM** → **experimental tests**
- 1980s (**Aspect et al**) : the quantum mechanical predictions are correct, thus **locality is false**
 - This is what he wanted to argue but he was misunderstood
 - **People thought he proved that completing QM is impossible, hence the pilot-wave is wrong**



Historical “accidents”: the rise of many-worlds

- Lack of consensus → Slowly, the attention **shifted from the problem of completing QM to solving the measurement problem**
- 1957: contrary to Bohm, Everett started from the measurement problem. He argued that the vN collapse was unsatisfactory – what is a measurement?
 - He proposed **a relative state picture** to make minimal sense of the unobserved macroscopic superpositions
 - Wheeler (his advisor) was excited and wanted him to meet Bohr; however, Bohr/Rosenfeld dismissed his work ... In any case, Everett went to work for the Army
- 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 physicists as the **best (=least costly) compromise** among the solutions of the measurement problem, at least when pressed on by realist questions
 - If one forgets about the inflated metaphysics, that is....
- Because of this, **it slowly grew in the sympathies of physicists**



Historical “accidents”: the beginning of spontaneous collapse theory

- 1970 Varenna, 1973 Erice: **at the first conferences on quantum foundations** people were focusing on the measurement problem
- 1980s: **unifying dynamics projects** - incorporate the collapse into the dynamical equation of the state to find a single equation for radioactive decay etc. (Ghirardi, Rimini, Weber; Pearle; Diosi; ...)
- 1986, **GRW theory**:
 - The quantum state 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
 - This theory was proposed as **phenomenological** at first (to make the evolution law precise)
 - But later (Bell) it was understood as **foundational**, to be understood from a realist perspective
 - It **precisely** solves the measurement problem



No-observer solutions of the measurement problem

- The *a posteriori classification* of the solutions of the measurement problem that we saw ...
 - (Pilot-wave denies completeness, spontaneous collapse denies S 's evolution, many-worlds denies outcome uniqueness)
- ... is universally accepted but it is also **misleading**:
 - It is indeed a posteriori
 - It **does not reflect the reason why these theories were proposed**
 - Only Everett explicitly proposed his theory as a solution of the measurement problem
 - GRW proposed it for making the vN rule precise, not guided by the concerns of the early realists
 - De Broglie-Bohm instead developed the pilot-wave theory coming from a realist understanding which required completing the wf



No-observer solutions of the measurement problem

- However, accepting such classification is not costless: it effectively **legitimized** as realist ALL the proposals:
 - The spontaneous collapse theory is just as legitimate as the many-worlds theory, which is just as legitimate as the pilot-wave theory
- They are **ALL EQUALLY SATISFACTORY**
 - They all are empirically adequate
 - They are all precise: they have a well-defined ontology and a unique dynamics
- Just chose the one that best fits your ***extra-empirical desiderata***



No-observer solutions of the measurement problem

- But if we **remember** what the realists were originally (pre-quantum) looking for, these theories ARE NOT on the same footing:

- Realists were **looking for a constructive quantum theory**

- That is, something that:

- (Is empirically adequate)
- Has a spatiotemporal ontology
- Which interact locally
- in which compositionality holds
- And which is visualizable

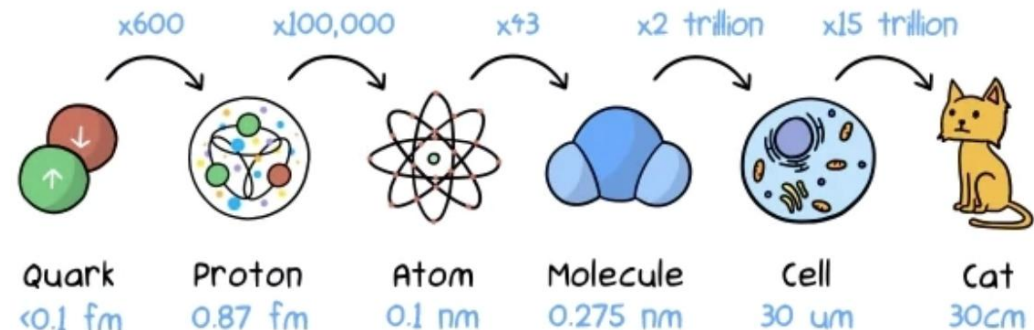
- **ONLY the pilot-wave theory** has them all:

- In the others, matter is represented by the wf, which does NOT live in 3d

- ... **the pilot-wave theory** has them all **except locality**, that is...

- But given Bell and Aspect, **ALL quantum theories are nonlocal...!!!**

- **Everyone has to figure out what that implies**



The best of all possible quantum worlds

- In a world full of “**constructive realists**”:
 - A quantum theory would have had a 3d fundamental ontology (particle, waves/fields) interacting locally
 - That is, a satisfactory constructive quantum theory would have had to solve problems 1 (unphysical field/spatiotemporality) and 2 (locality)
 - Bell+Aspect: problem 2 cannot be solved...
 - But at least we can solve problem 1, no?
 - Regardless, problem 3, **the measurement problem, would have never been mentioned!**



The best of all possible quantum worlds

- **Thus, NO antirealist attitudes:**
 - No measurements/observers being fundamental
 - No instrumentalism
 - No complementarity/duality
 - No unobserved macroscopic superpositions
 - No consciousness
- **But also**, since there was no need to invoke the measurement problem to convince the realists:
 - No high dimensional field ontology
 - No stochastic modifications of the Schrödinger equation
 - No undetectable infinity of non-interacting worlds
- **... none of the quantum 'weirdness' would have actually come up! 😊**



The best of all possible quantum worlds

- We can avoid quantum weirdness
- We can still (almost) understand things the way we did before, classically
- Why shouldn't we?
- **Why should realists give up on this, without even trying?**
- **Indeed, realists did try, and they did succeed**
 - The pilot-wave theory provides a clear and simple picture of the world, according to which particles move around in 3d following highly nonclassical laws



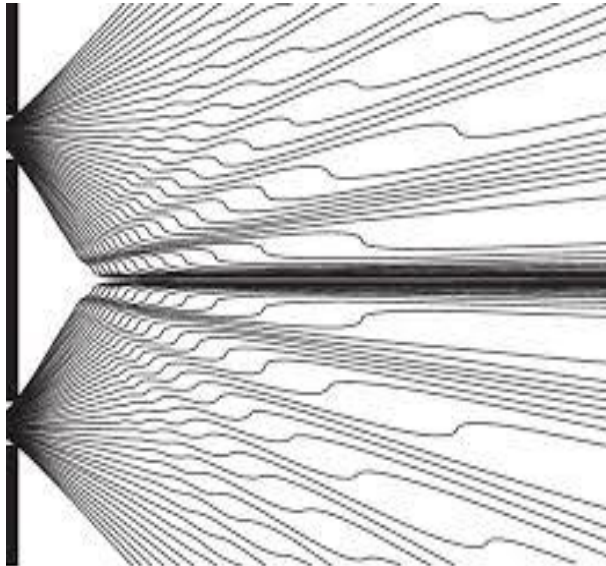
The best of all possible quantum worlds

- Another dialogue
- **Objection:** “WAIT! It’s nonlocal, remember?”
- Reply: “Oh, yes, it is explicitly nonlocal, but that is a virtue rather than a defect, given that reality is nonlocal (after Bell and Aspect)”
- **Objection:** “Mhm... what’s your evidence of this theory? “
- Reply: “It is empirically equivalent to axiomatic qm, so whatever confirms that, confirms the pilot-wave theory”
- **Objection:** “ No, that’s too cheap. I mean, can it make some new predictions?”
- Reply: “Technically, de Broglie proposed it in 1923, so before von Neumann’s axiomatization. So, by your reasoning, it would be the latter that needs to make different predictions. Regardless, what would you want to see as a proof?”
- **Objection:** “Something that shows or strongly indicates the correctness of the theory. Something for instance that would show that particles with trajectories exist”
- Reply: “I mean, if you see something that looks like a particle leaving a track, would you believe it’s left by a particle? That’s what we did classical, didn’t we?”
- **Objection:** “Yes...”

The best of all possible quantum worlds

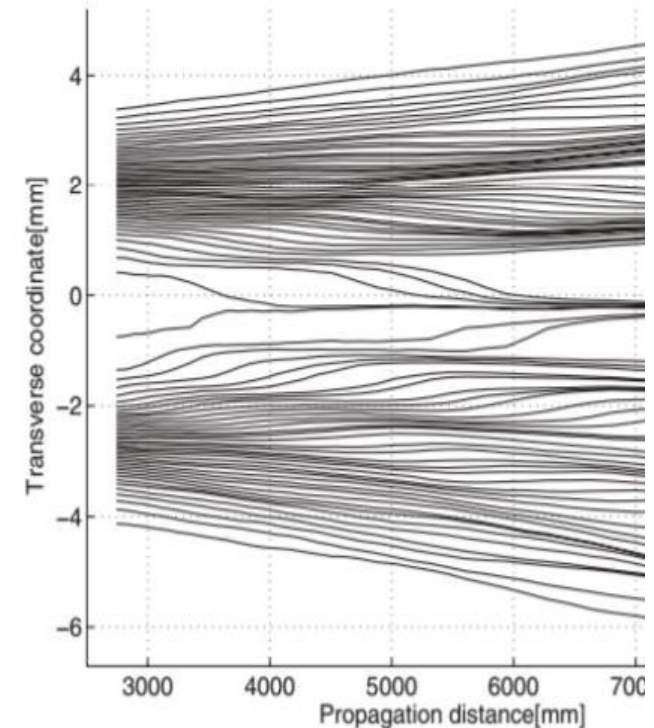
- Reply: “so here you are!”

PREDICTED



(I am cheating a little, because the observed trajectories (by weak measurements) are for photons, which is not what the predictions are about. Nonetheless, it seems fair to say that the observed data **STRONGLY SUGGESTS** that there are particles involved!

OBSERVED



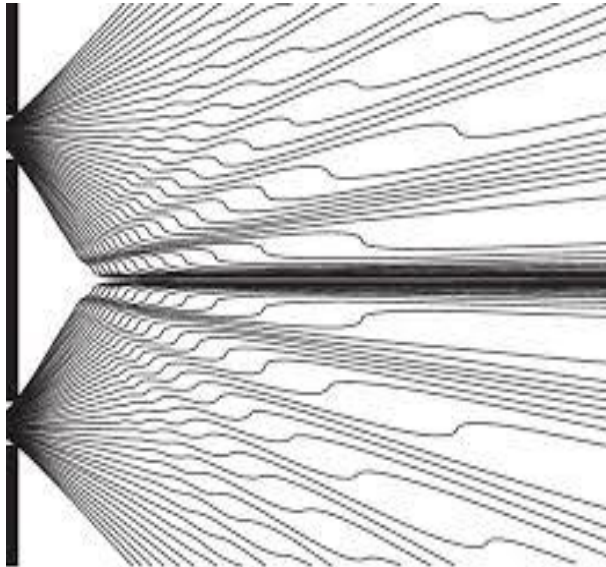
Average trajectories of single photons observed in the experiment. First experimental reconstruction, by Kocsis et al.

The best of all possible quantum worlds

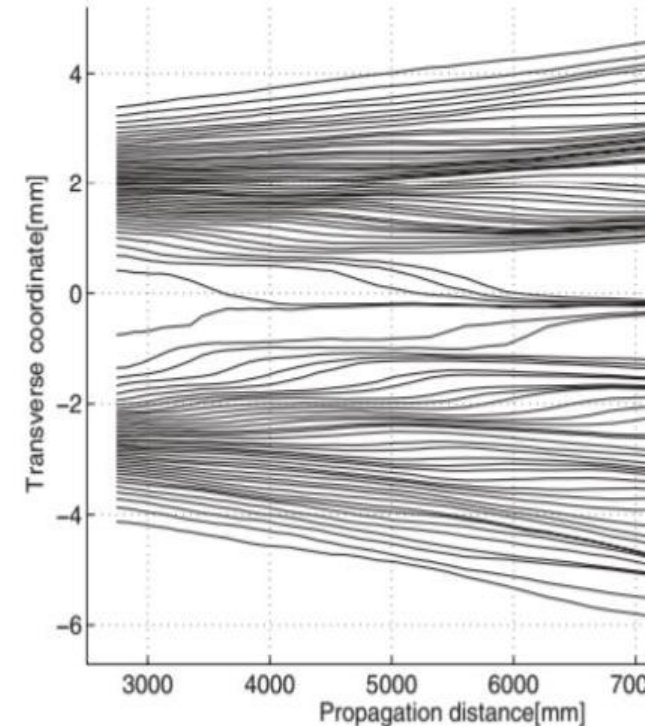
- Reply: “so here you are!”

I rest my case...

PREDICTED



OBSERVED



...almost

Average trajectories of single photons observed in the experiment. First experimental reconstruction, by Kocsis et al.

The best of all possible quantum worlds

- **Objection:** “WAIT AGAIN! But if the pilot-wave were the constructive theory behind axiomatic quantum mechanics, wouldn't that suggest that the pilot-wave theory has a larger domain? In other words, it seems that a constructive theory should be able to make more predictions than axiomatic quantum theory because it has more resources. I mean, when we do statistical mechanics to constructively explain the laws of thermodynamics, we end up discovering that they are approximate. For instance, the second law, which is exceptionless in thermodynamics, is instead understood only probabilistically: 'entropy most likely does not increase.' Can the resources of the pilot-wave be used to make new predictions?”
- **Reply:** “I am glad that you asked! This is indeed a very nice thing to notice. In axiomatic quantum theory observables are given by self adjoint operators, and results by their eigenvalues. In the pilot-wave theory instead the self adjoint operators simply are a convenient way of systematizing the data but do not represent any property. So, if we find a property which isn't represented by a self adjoint operator, then we might find experimental conditions in which the two theory differ. To cut a long story short, there is no self adjoint operator to represent time. However, sometimes we believe we are measuring time, like how long does it take for a particle to fly from its source to a screen (“time of arrival” experiments). Since there's not time operator, this type of time measurements are accounted for indirectly by axiomatic quantum theory. Instead, the pilot-wave theory just looks at the particle trajectories, so there is no need of such an operator to predict what will happen. It has therefore been proposed that in very specific situations the two theories may make different predictions. If so, one can actually show that the pilot-wave theory can indeed go beyond the predictions of the axiomatic theory.”

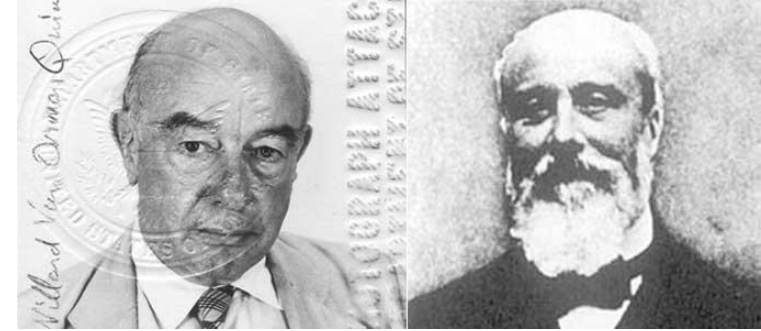
Abstract

The arrival time statistics of spin-1/2 particles governed by Pauli's equation, and defined by their Bohmian trajectories, show unexpected and very well articulated features. Comparison with other proposed statistics of arrival times that arise from either the usual (convective) quantum flux or from semiclassical considerations suggest testing the notable deviations in an arrival time experiment, thereby probing the predictive power of Bohmian trajectories. The suggested experiment, including the preparation of the wave functions, could be done with present-day experimental technology.

Summary and conclusion

- Which Problem Should the Realist Look at?
- The **unphysical field** problem is the **strongest** of the arguments we saw:
 - It tells us how to complete it: add some 3d ontology → no power over antirealists
- The **nonlocality** argument is **weaker**:
 - It does not tell us how to complete it, just do it locally → no power over antirealists
- The **measurement problem** is the **weakest**:
 - It does not say how to complete it, not even locally; it just says that BARE MINIMUM, the theory has to be **empirically adequate!**
 - → it has power over antirealists, but limited (they keep vN collapse)
 - → is just confuses realists because it allows all kinds of empirically adequate theories, not only constructive realist ones
 - **Why should we do this to ourselves?**
 - **...Just solve problem 1!**

Which 3d Ontology Should we Use? The Role of the Measurement Problem



- How do we solve problem 1? Either particles or fields/waves
- The measurement problem **rules out waves** for a linear evolving wf (unobserved macro 3d superpositions)
- Then? Various options
 - **OPTION 1:** WE WERE WRONG, MATTER IS MADE OF PARTICLES (moving in non-classical ways) → The pilot-wave theory
 - **OPTION 2:** WE WERE RIGHT, MATTER IS WAVE-LIKE BUT THE EVOLUTION EQUATION IS NONLINEAR AND STOCHASTIC → The spontaneous collapse theory
 - However, this is unmotivated: why insist on having matter waves if with particles you can keep determinism and linearity?
 - **OPTION 3:** WE WERE RIGHT, MATTER IS WAVE-LIKE BUT THERE ARE MANY-WORLDS, ONE FOR EACH TERM OF THE SUPERPOSITION, AND THESE WORLDS DO NOT INTERACT AND ARE UNDETECTABLE → The many-worlds theory
 - Option 3 looks like a case of **Quine-Duhem thesis** (anything can be held true if you have enough imagination)
 - But not all that is possible is equally plausible!

Conclusion



- Realists should have tried to keep the constructive 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 in other contexts/had things gone differently
- As a matter of fact, we can keep the constructive 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 and Aspect show that we cannot do 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!

