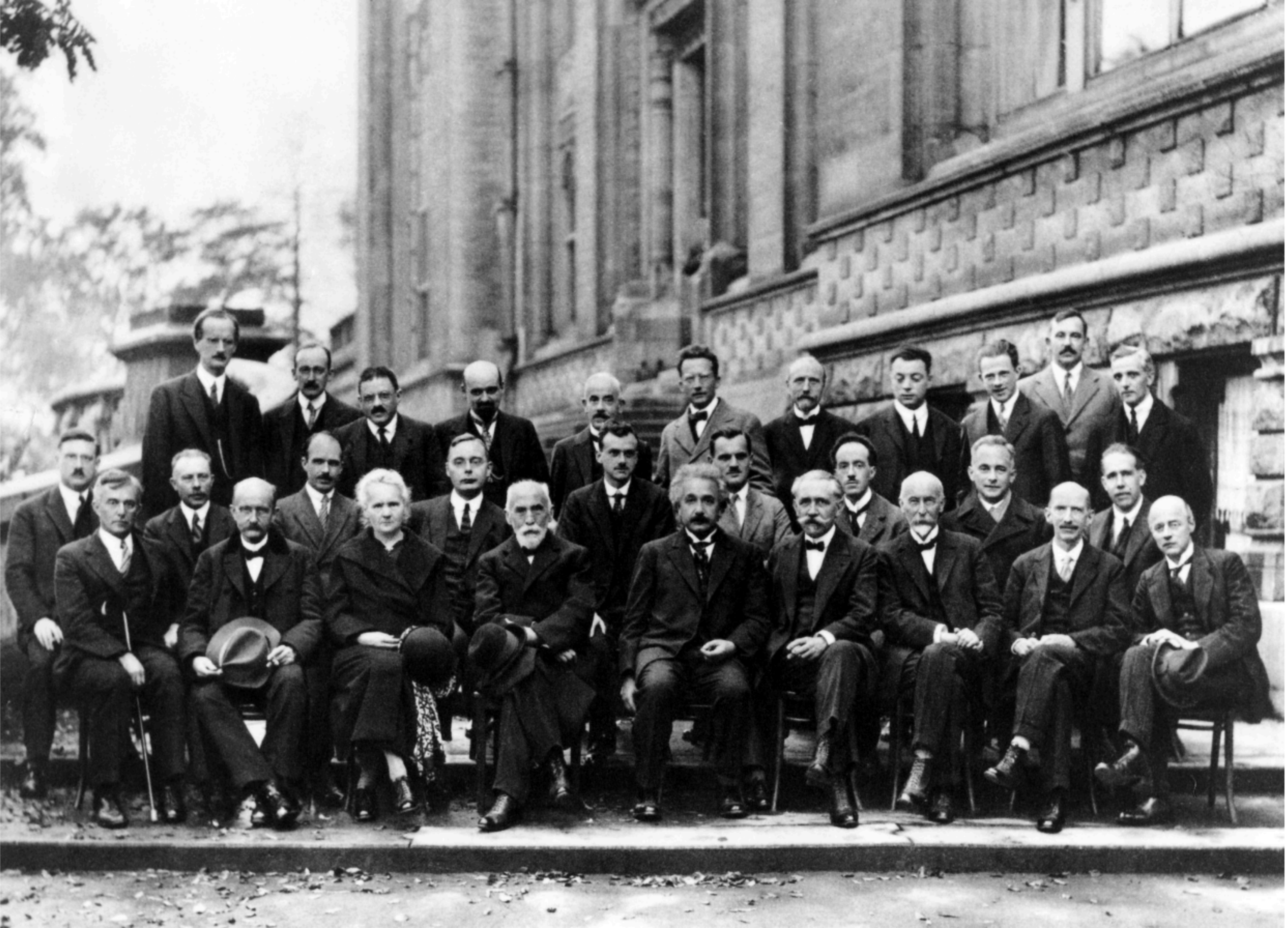


Philosophy of Physics

-

Lec. 7 - Making sense of quantum...

(Or trying at least!)

Recap!

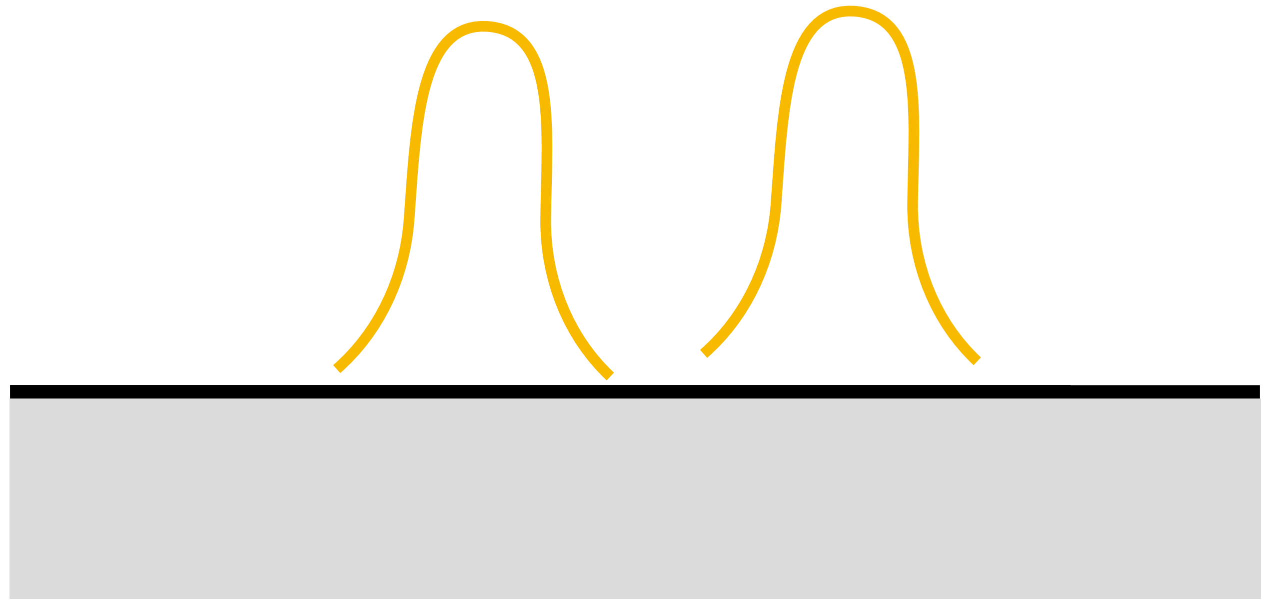
Seemingly, quantum mechanics has two types of evolution:

❋ **unitary:** following the Schrödinger equation: $\hat{H}\,\Psi(\vec{x},t) = i\hbar\frac{\partial}{\partial t}\Psi(\vec{x},t)$

- when the system is not “observed/measured/monitored"
- deterministic, reversible
- **yields/preserves** interference

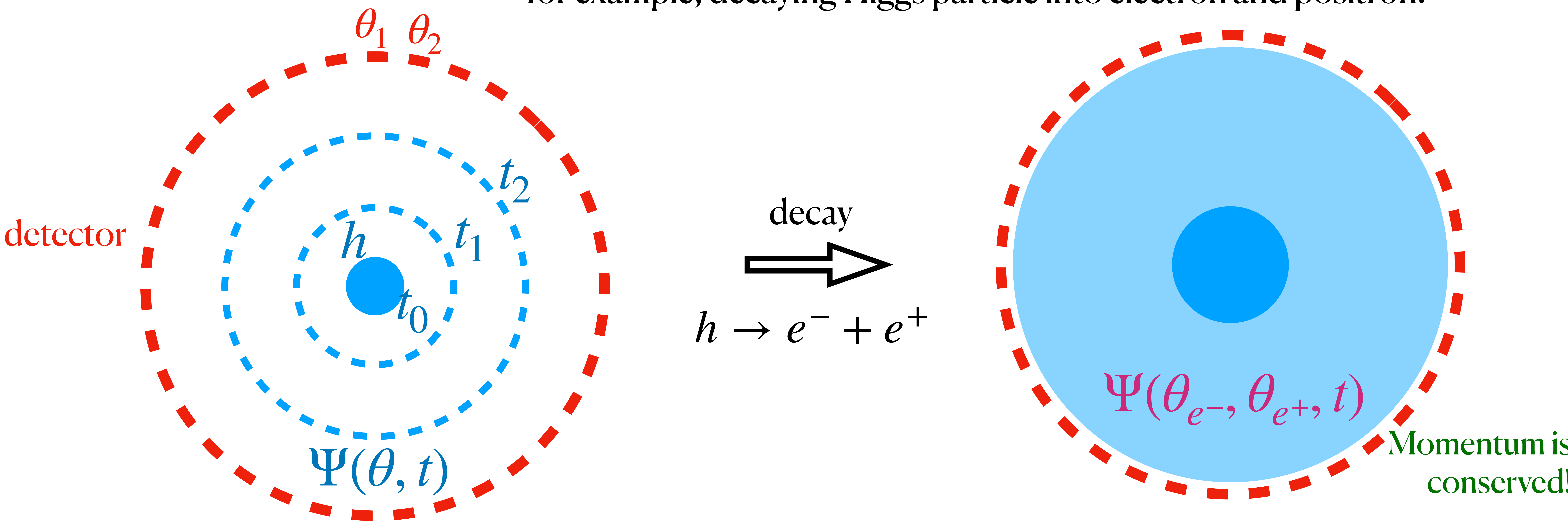
❋ **"collapse"**

- when measurements take place
- probabilistic, irreversible
- **destroys** interference



Entanglement

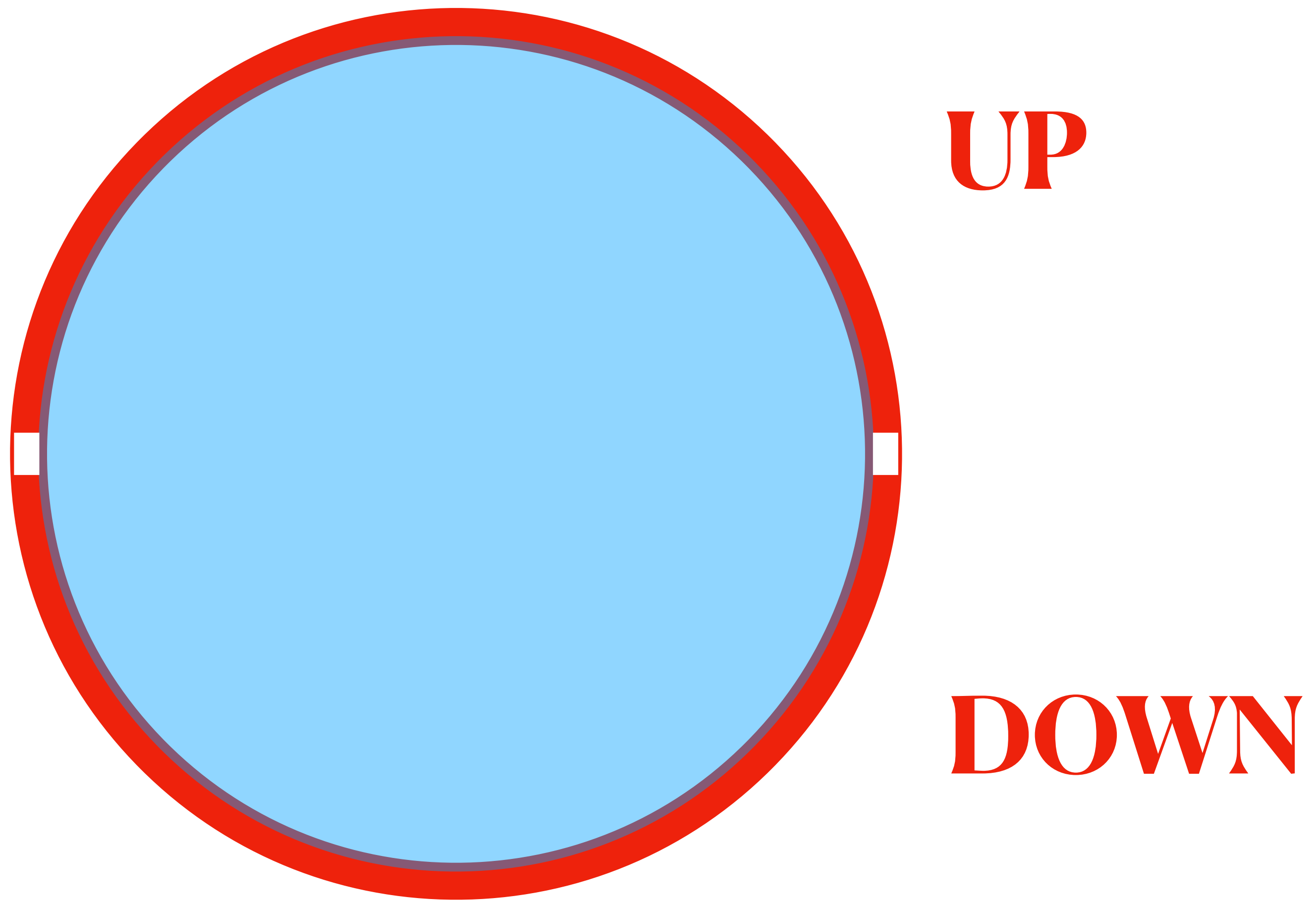
- what is the wavefunction $|\Psi\rangle$ representing?
  - ❖ it is associated with the probabilities of every possible outcome for any quantum system **as a whole!**
  - ❖ for example, decaying Higgs particle into electron and positron:



- wavefunction is defined over configuration space, not physical space: $\Psi(\cancel{x}, t)$, $\Psi(x, x_1, x_2, \ldots, t)$

- therefore, even though we typically consider simple quantum systems, in principle the whole world is quantum and there is a single wavefunction for the whole Universe!

- in the previous example, after the Higgs particle decayed, the wavefunction for the electron and positron has to conserve the initial vanishing momentum of the Higgs. Therefore, if our detector was even lower in resolution, it'd be like:



$$\Psi_{e^-,e^+} = \Psi(\theta_{e^-}, \theta_{e^+})$$
$$= \Psi(\mathrm{UP}, \mathrm{DOWN}) + \Psi(\mathrm{DOWN}, \mathrm{UP})$$

- so, if we detect the electron to be UP, then we know the positron will be detected in the DOWN part of the detector. The particles are ENTANGLED!

Measurement and Entanglement

- How does a measurement happen?

- things bumping on one another! BUT we know there are conservations laws, such as momentum conservation, governing how things bump!

- our measurement devices are also quantum systems! Thus, we expect that the overall wavefunction if also describing them. So, when a particle bumps on the upper part of the detector, we know the detector moves a bit up, and same for down:

Measurement and Entanglement

$$\Psi(\text{electron, apparatus}) : \begin{cases} \Psi(\text{UP, apparatus}) \implies \Psi(\text{UP, UP}) \\ \Psi(\text{DOWN, apparatus}) \implies \Psi(\text{DOWN, DOWN}) \end{cases}$$

therefore, if the electron is initially in superpositon , then:

$$[\Psi_{e^-}(\text{UP}) + \Psi_{\mathrm{e}^-}(\text{DOWN})] \times \Psi_{\text{apparatus}} \to \Psi(\text{UP, UP}) + \Psi(\text{DOWN, DOWN})$$

The electron and the measurement device are entangled!

On one hand, this has not involved the collapse of the wavefunction! On the other hand, now the apparatus is in a superimposed state!

But we do not observe that in the lab!

Decoherence

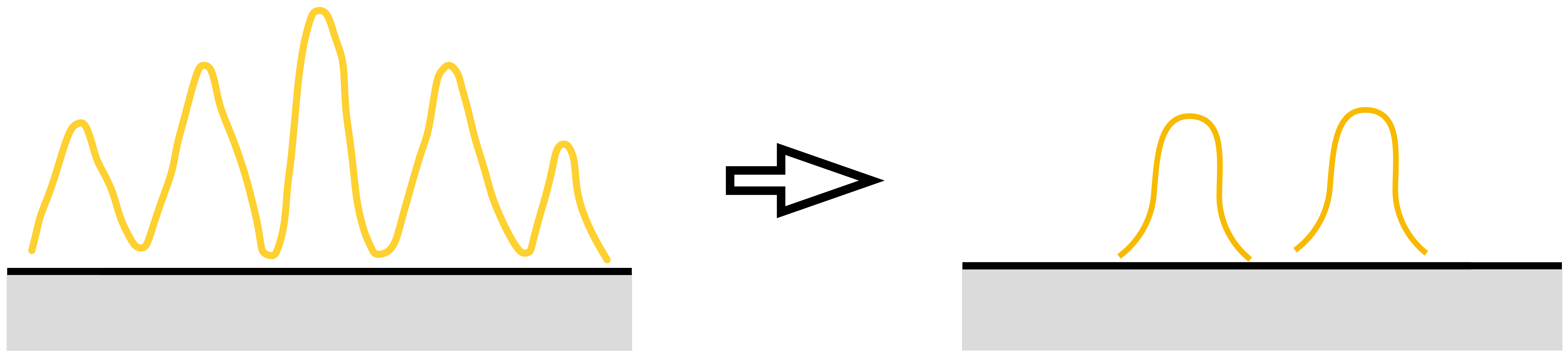
- But the world is not just the electron and the apparatus! There is a whole environment around any experiment! If the detector says UP or DOWN, some of the photons in the lab will literally scatter differently!

- As we said, if there is just a single wavefunction for everything, then we also have to describe the environment as we just did with the apparatus! But that means the environment alos gets entangled!

$$\Psi(e^-, \text{app}, \text{environment}) \longrightarrow \Psi(\text{UP}, \text{UP}, \text{UP}) + \Psi(\text{DOWN}, \text{DOWN}, \text{DOWN})$$

But now it seems that we just got worse off! The electron, the apparatus, and the environment are entangled and superimposed!

- However, we do not (and cannot in practice) control the whole environment! So we ignore it (tehnically, we trace it out) and by doing that, what is left is a classical mixture of having measured either UP or DOWN, but without any superposition/interference! This is what is called **decoherence**!



- This makes some progress towards understanding why we do not see macroscopic interference from quantum systems, since decoherence happens quite fast the larger the environment is.

- BUT, it still does not explain how we go from multiple outcomes to a single one at every run of the experiment! The measurement problem remains!

Interpretations of Quantum Mechanics

- As we saw, QM seems to imply two different evolutions of the quantum state, leading to
  - ❖ Interference: the quantum state is a physical description of the system's indefinite state
  - ❖ Collapse: the quantum state is a probabilistic description of the system's unknown but definite states
- Thus, despite the mathematical formalism of QM being well established, its philosophical foundations are not!
- Naturally, one way out is to be instrumentalist and reject the idea that the quantum state reflect pre-existing properties of the system — it's simply a mathematical tool! To talk about the system prior to measurements is meaningless!

What do you think?

Copenhagen Interpretation (Instrumentalist)

- Mostly championed by Bohr; textbook tacit interpretation
- Statistical element of QM due to the collapse of the wavefunction:
    - ❖ Born rule: probability density of collapse happening somewhere
    - ❖ Instanteneous and triggered by measurement
- QM is complete; intrinsically stochastic
- Measurements are described by classical physics, introducing a classical/quantum interface

What about outside the lab?!

BUT: the divide between what is observed and theoretical is blurred! And measurement devices are assumed to be working under QM principles, so without understanding their workings, we don't know what a measurement is! — need QM to understand measurement devices, and vice-versa!

Dynamical Collapse Theories

- Dynamical equartion different than Schrödinger that leads to collapse before measurement happens. Thus, it's a physical process!
- Collapse happens objectively and instantaneously
- If collapses happens too fast, no interference! If too slow, it fails to prevent Schrödinger cats! So it's testable!
- Collapse rarely happens for a single particle, but if there are many, they quickly get entangled and the collapse of one collapses the whole system's state!

  So no Schrödinger cats macroscopically!

BUT: how can it be instantaneous without invoking a preferred frame of reference?

Hidden variables theory

- Maybe there are hidden variables that represent measurement outcomes. Then the wavefunction can remain indefinite and serve as a guide
- Pilot-wave theory is the most famous model and can lead to different predictions than quantum mechanics

- Due to Bell's inequalities and experimental data, these hidden-variable theories have to be nonlocal. They imply:
    - ❖ Fully deterministic evoltuion of the system
    - ❖ Hidden variables are not fully epistemically accessible
    - ❖ Pilot wave (wavefunction) control the movement of particles nonlocally
    - ❖ No energy is transferred faster than the speed of light

BUT:

1. Still special role in the measurement unveilling only hidden variables, not quantum -state
2. Relativistic attempts are very contrived
3. Nothing in QM suggests hidden variables; it's mostly our desire to keep some elements of the classical ontology

Many-worlds Interpretation

- Maybe we don't need to add, but remove things from QM (e.g. ~~collapse of the wavefunction~~), and have just Schrödinger evolution
- We saw how the environment gets entangled with the system and measurement device. But we are part of the environment!!

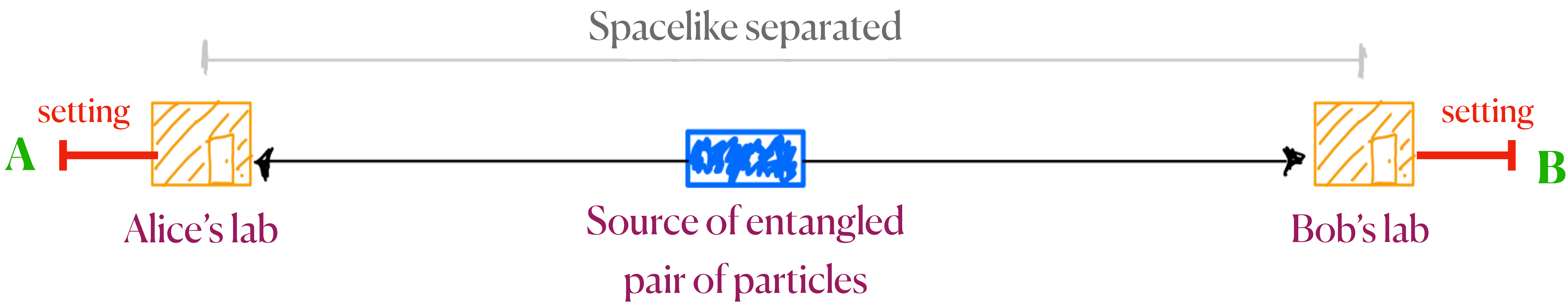
$$(|\text{ALIVE} + |\text{DEAD}\rangle) \times |\text{IGNORANT}\rangle \longrightarrow |\text{ALIVE, SEES ALIVE}\rangle + |\text{DEAD, SEES DEAD}\rangle)$$

So we evolve into a state which is at once two ordinary, definite outcomes.

- Due to decoherence, each of these branches evolve independently, definining independent classical worlds with definite outcomes
- This happens universally, not only for the cat example, but all the way down to electrons going through one or the other slit in the double-slit experiment
- It requires no modification of QM, no change of philosophy of science, but with astonishing prediction (not postulated!) of a branching reality

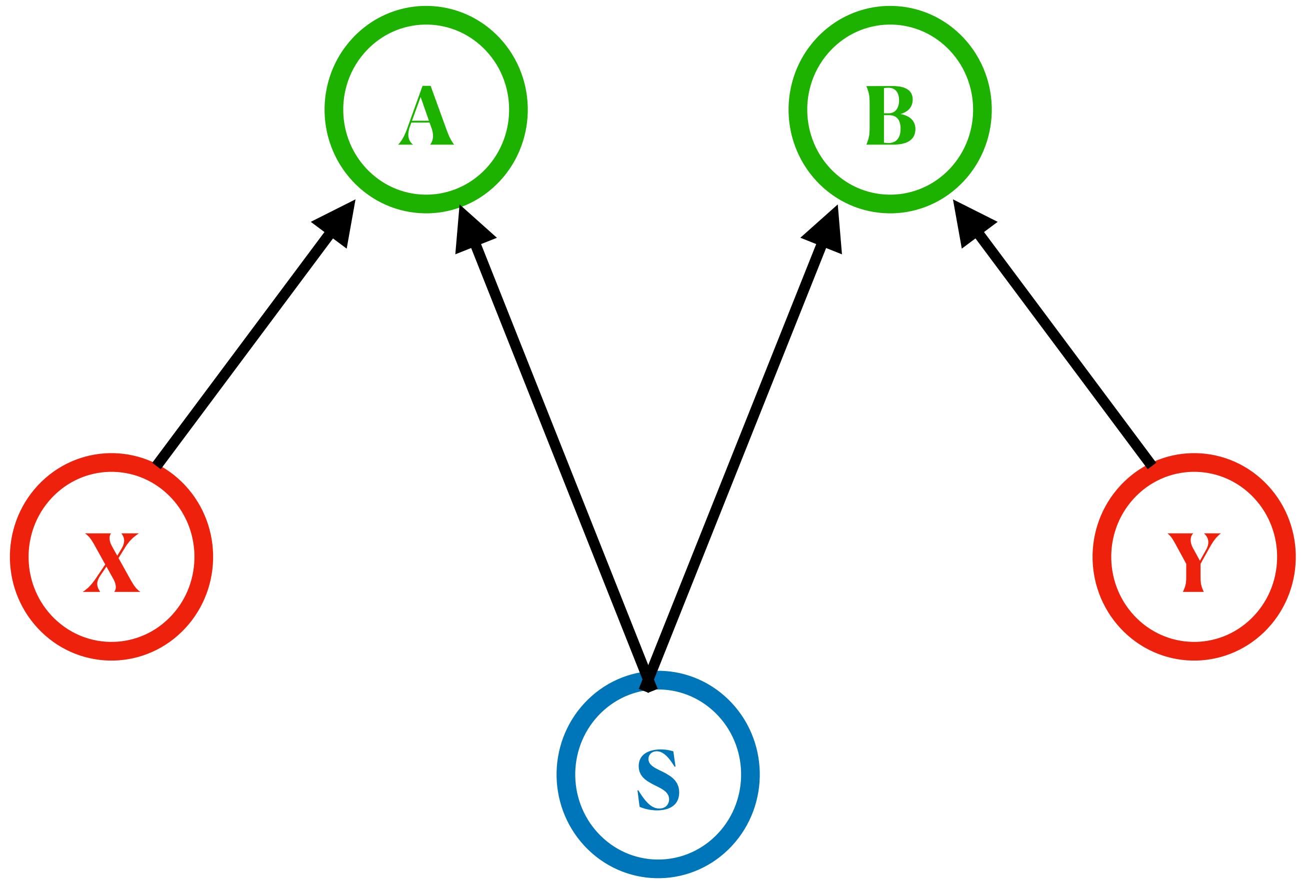
BUT: one of the main challenges is to make sense of the Born rule and probabilities if everything that can happen <u>WILL</u> happen!

What if we avoid commitments?!



- Each lab has two settings **x, y** with possible outcomes **A, B**
- Repeat the experiment many times, with independent settings, record outcomes
- Question: what correlations do we expect to find between outcomes?

Causal Diagram



Seemingly looking natural assumptions?!

- Single outcomes for **A** and **B**
- No arrow between **x** and **B** is because spacelike separated
- No arrow between **x** and **y** because we assume we can arrange the experiment with devices uncorrelated
- No arrow between **S** and **x, y** because we assume devices and source uncorrelated

- A or B alone will come out as RANDOM with some probability distribution over the possible outcomes. YET, somehow "they know each other" (contrast with gloves that will be random but fundamentally deterministic)

- Now let's work the probabilities:

$$P(AB\,|\,xy) = \sum_S P(A\,|\,X, S)\, P(B\,|\,Y, S)\, P(S)$$

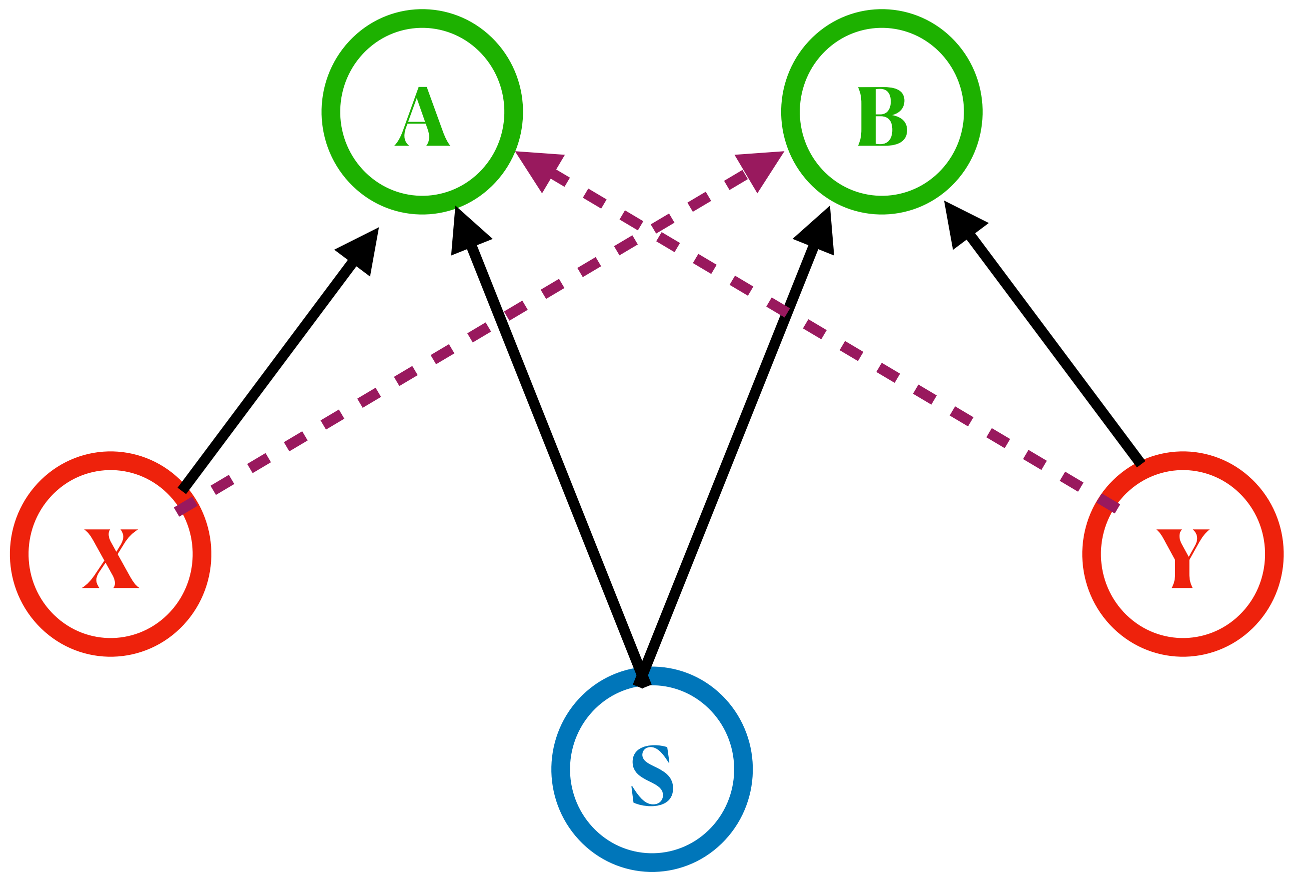
- **BELL'S INEQUALITIES** impose constraints on these probabilities. The most famous one is the Clauser-Horn-Shimony-Holt inequality: CHSH ≤ 2 but experiments get $2\sqrt{2}$! That means that our causal story cannot be the case! Thus, one or more assumptions have to go!

COPENHAGEN: $\cancel{P(AB\,|\,xy) = \sum_S P(A\,|\,X, S)\, P(B\,|\,Y, S) P(S)}$

Because in QM, the source is represented by the quantum state which can be entangled and violating the condition above!

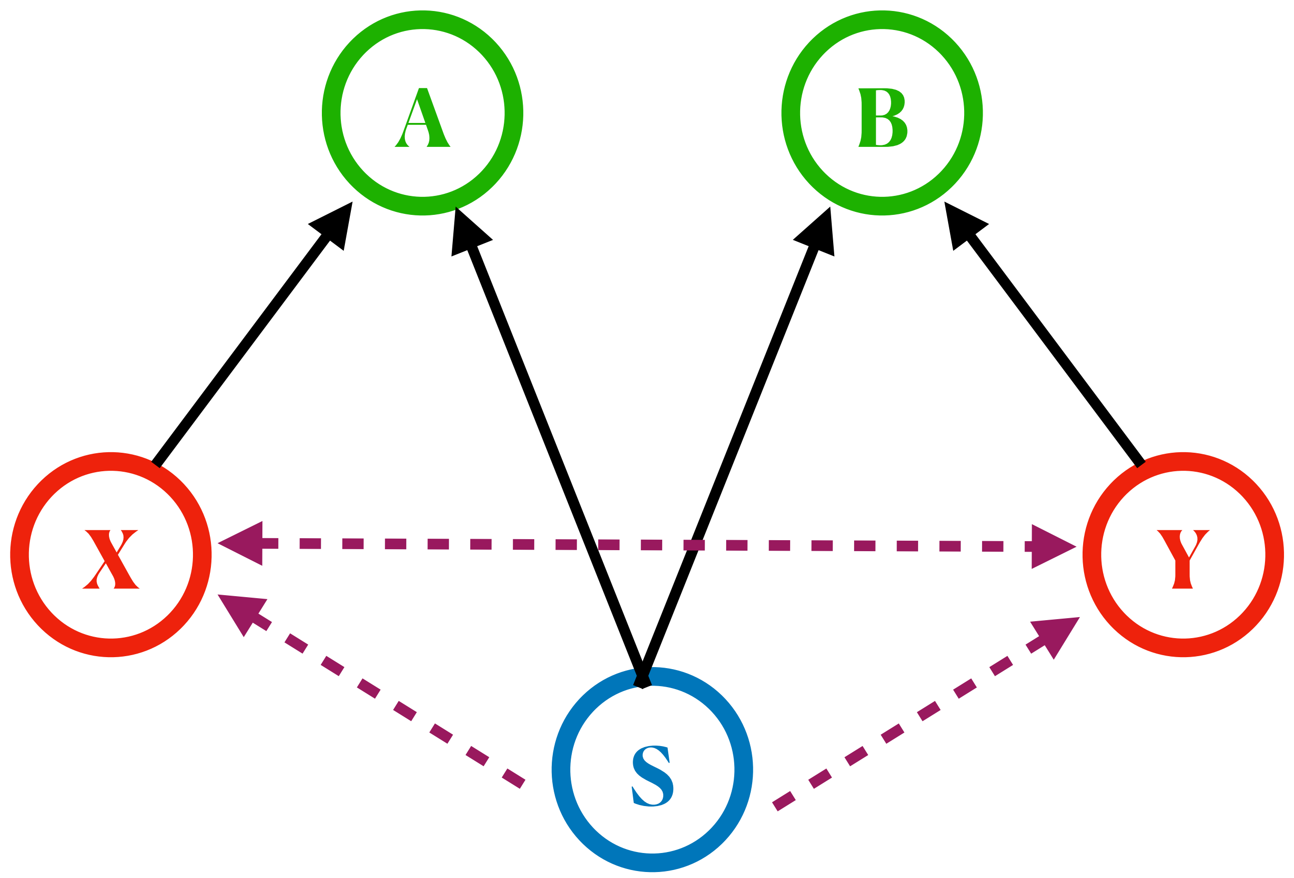
MANY-WORLDS: Not single outcomes!

HIDDEN VARIABLES THEORY: wavefunction guides the motion of particles instantaneously and nonlocally!



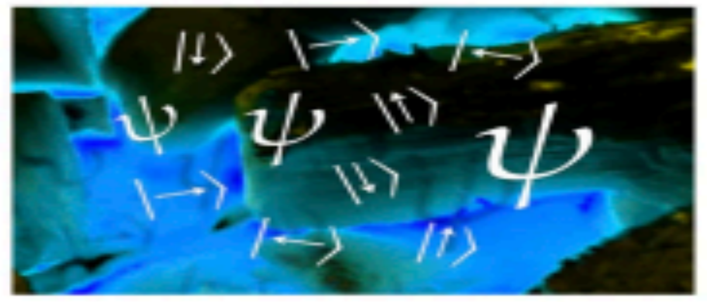
- Single outcomes for A and B
- ~~No arrow between x and B is because spacelike separated~~
- No arrow between x and y because we assume we can arrange the experiment with devices uncorrelated
- No arrow between S and x, y because we assume devices and source uncorrelated

SUPERDETERMINISM:



- Single outcomes for A and B
- No arrow between x and B is because spacelike separated
- ~~No arrow between x and y because we assume we can arrange the experiment with devices uncorrelated~~
- ~~No arrow between S and x, y because we assume devices and source uncorrelated~~

Hidden-Variable Theory



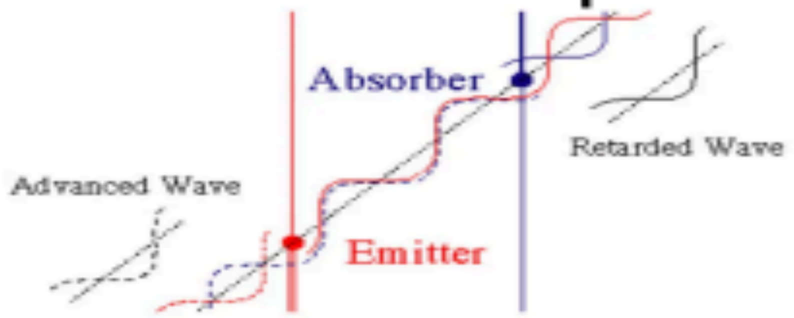
we just don't know (yet)

deterministic

God does not play dice!

Lawful Good

Transactional Interpretation



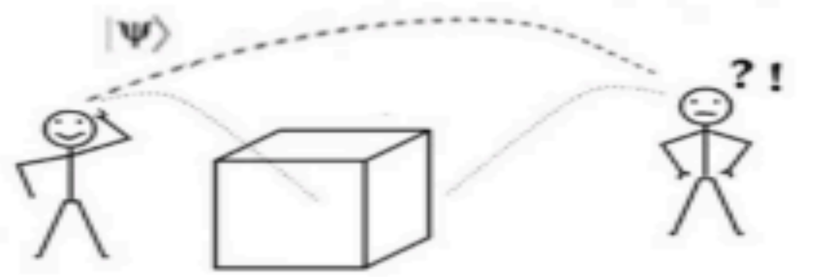
waves through time

quantum handshakes

explicitly non-local

Neutral Good

QBism



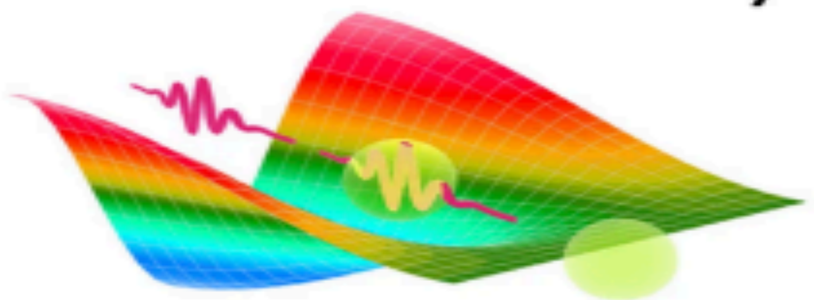
reality is observation

participatory realism

subjective Bayesianism

Chaotic Good

Pilot Wave Theory



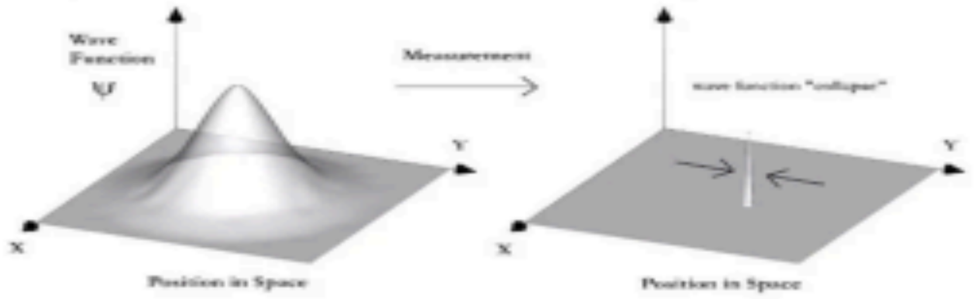
wave function & actual state

deterministic

explicitly non-local

Lawful Neutral

Copenhagen Interpretation



probabiltity wave → collapse

inderterministic

playing dice, but that's okay

True Neutral

Many Worlds Interpretation

every state a new world

decoherent

infinite universes

Chaotic Neutral

Superdeterminism

everything is predetermined

Bell's theorem loophole

quantum fuzziness is not real

Lawful Evil

Ensamble Interpretation

probabilities in groups

minimalist

statistics go brrr

Neutral Evil

Quantum Mysticism

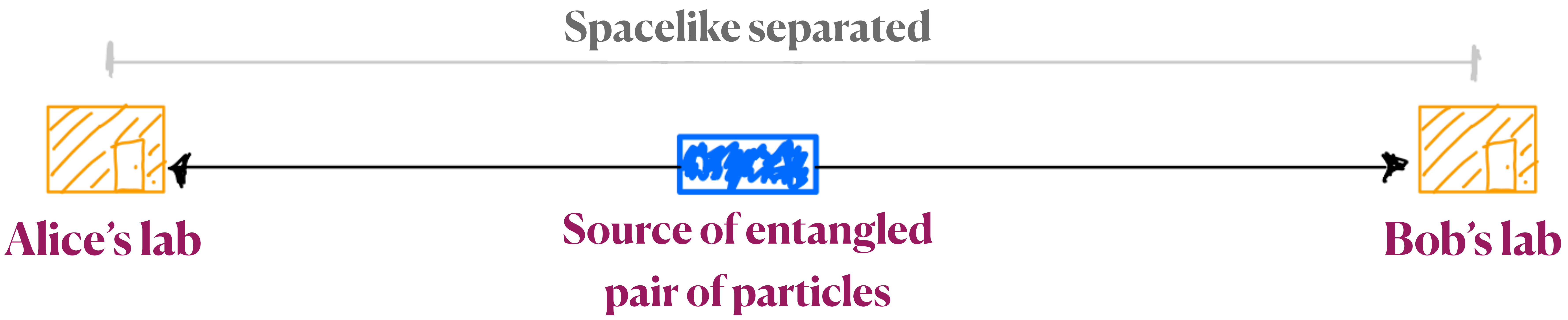
consciousness causes collapse

spooky

Philosophy > Physics

Chaotic Evil

EPR “Paradox"



Alice makes a measurement and “collapses" the state, but Bob doesn’t know, so from his point of view, the outcome’s probabilities haven’t changed!

=> The posited that when we can say with certainty what the measurement outcome will be, there must be an element of reality corresponding to that property. Thus, if Alice measures UP in the z-direction, there is an element of reality: “Bob's is DOWN in the z-direction.” But Alice could have measured UP in the x-direction, and then there would be another element of reality for Bob in the x-direction! And because of relativity, these elements should have been there all along! But that violates the uncertainty principle! So, it cannot be the case, and QM is incomplete!