Title: Lee Smolin, Perimeter Institute for Theoretical Physics

Speakers: Lee Smolin

Collection: Perimeter Public Lectures

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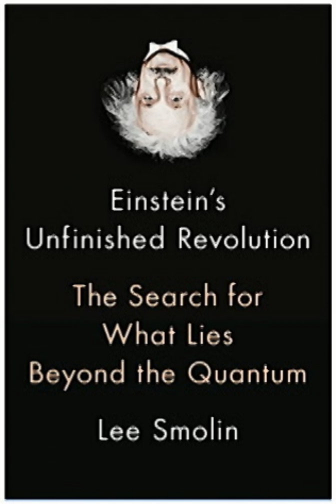
Abstract: Quantum physics is the golden child of modern science. It is the basis of our understanding of atoms, radiation, and so much else - from elementary particles and basic forces to the behaviour of materials. But for a century it has also been the problem child of science: it has been plagued by intense disagreements among its inventors, strange paradoxes, and implications that seem like the stuff of fantasy. Whether itâ€™s SchrÃ¶dingerâ€™s cat - a creature that is simultaneously dead and alive - or a belief that the world does not exist independently of our observations of it, quantum theory challenges our fundamental assumptions about reality.

On April 17, in a special webcast talk based on his latest book, Einsteinâ€™s Unfinished Revolution, Lee Smolin will argue that the problems that have bedeviled quantum physics since its inception are unsolved and unsolvable for the simple reason that the theory is incomplete. There is more to quantum physics waiting to be discovered. Smolin will take the audience on a journey through the basics of quantum physics, introducing the stories of the experiments and figures that have transformed our understanding of the universe.

Einstein's Unfinished Revolution

Lee Smolin
PI
April 17 2019


Einstein's
Unfinished Revolution
The Search for
What Lies
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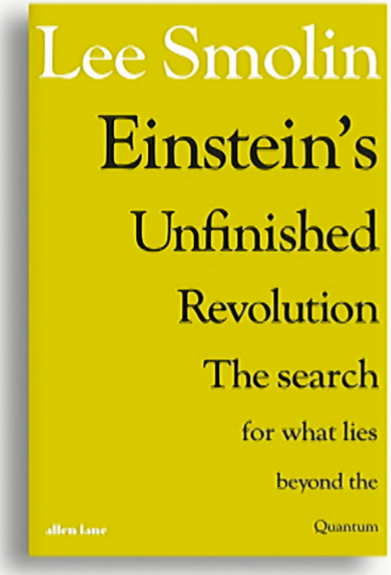
Lee Smolin
Einstein's
Unfinished
Revolution
The search
for what lies
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Quantum
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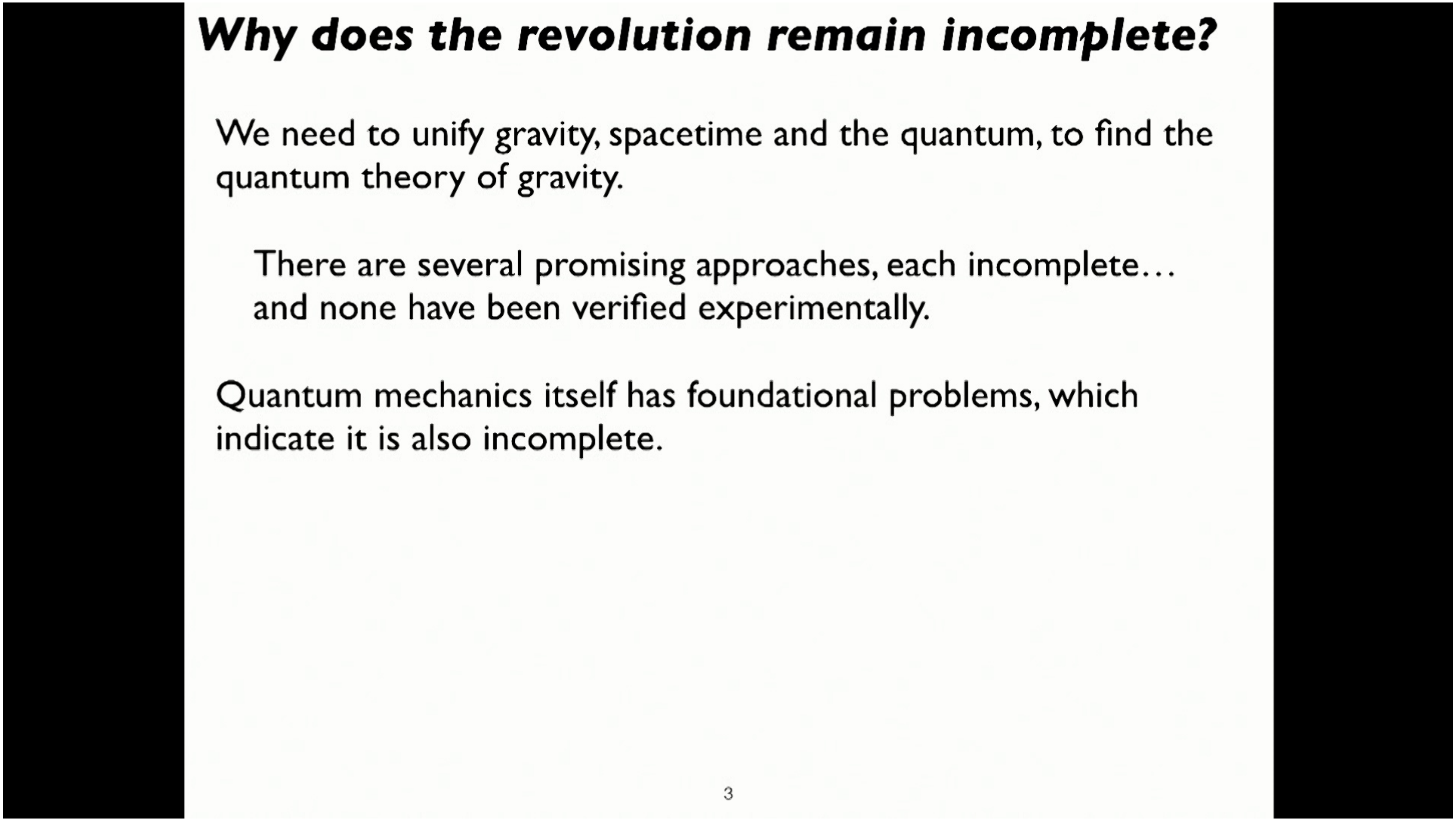
Einstein initiated two revolutions in 1905

Relativity theory

- Special relativity 1905
- General relativity 1915 A new theory of space and time, which incorporates gravity.

Quantum theory

- Wave particle duality for light Einstein 1905
- Atomic orbitals: Bohr 1911
- Wave-particle duality for matter de Broglie 1923
- In final form as Quantum Mechanics 1927

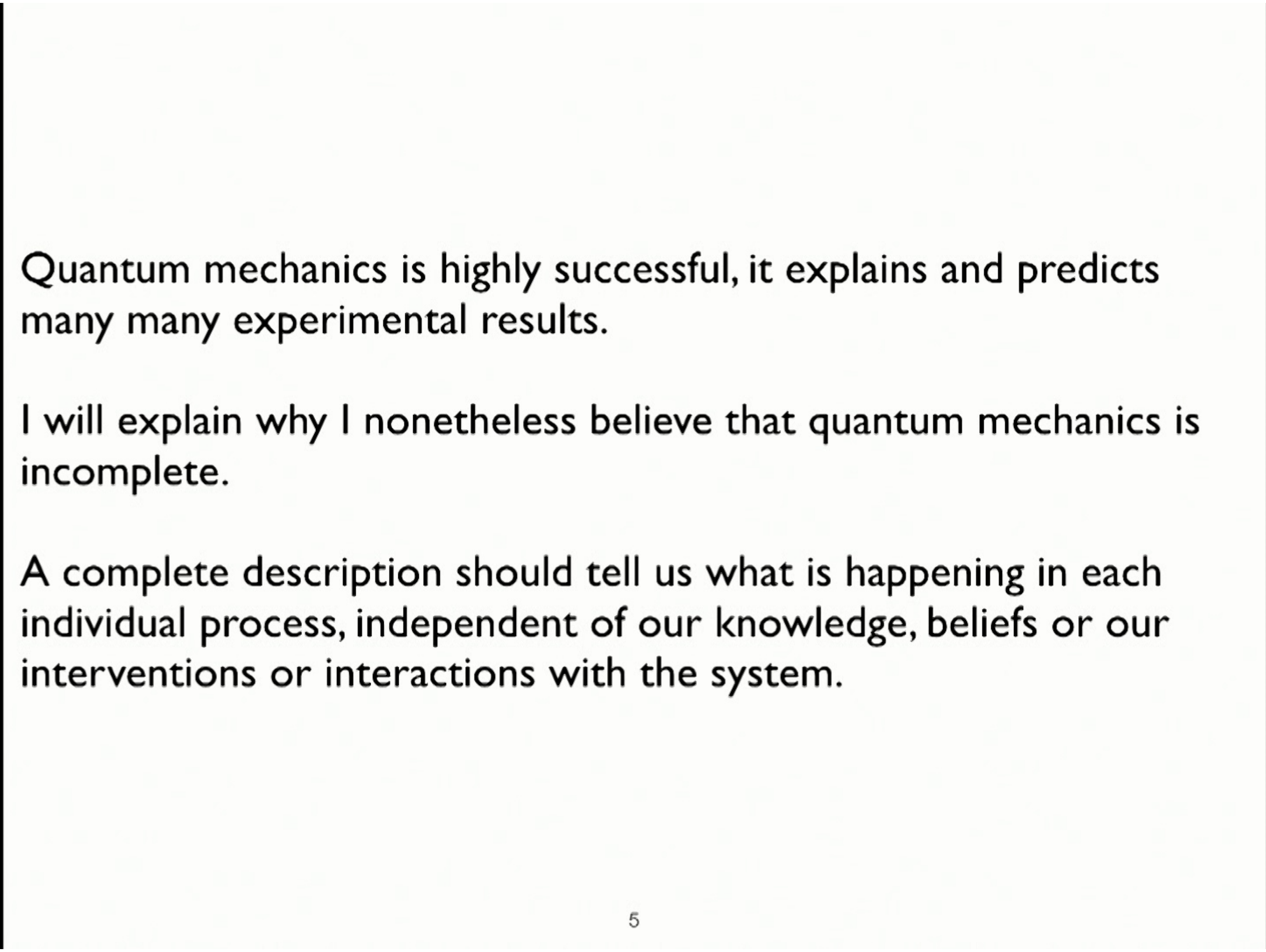


Why does the revolution remain incomplete?

We need to unify gravity, spacetime and the quantum, to find the quantum theory of gravity.

> There are several promising approaches, each incomplete… and none have been verified experimentally.

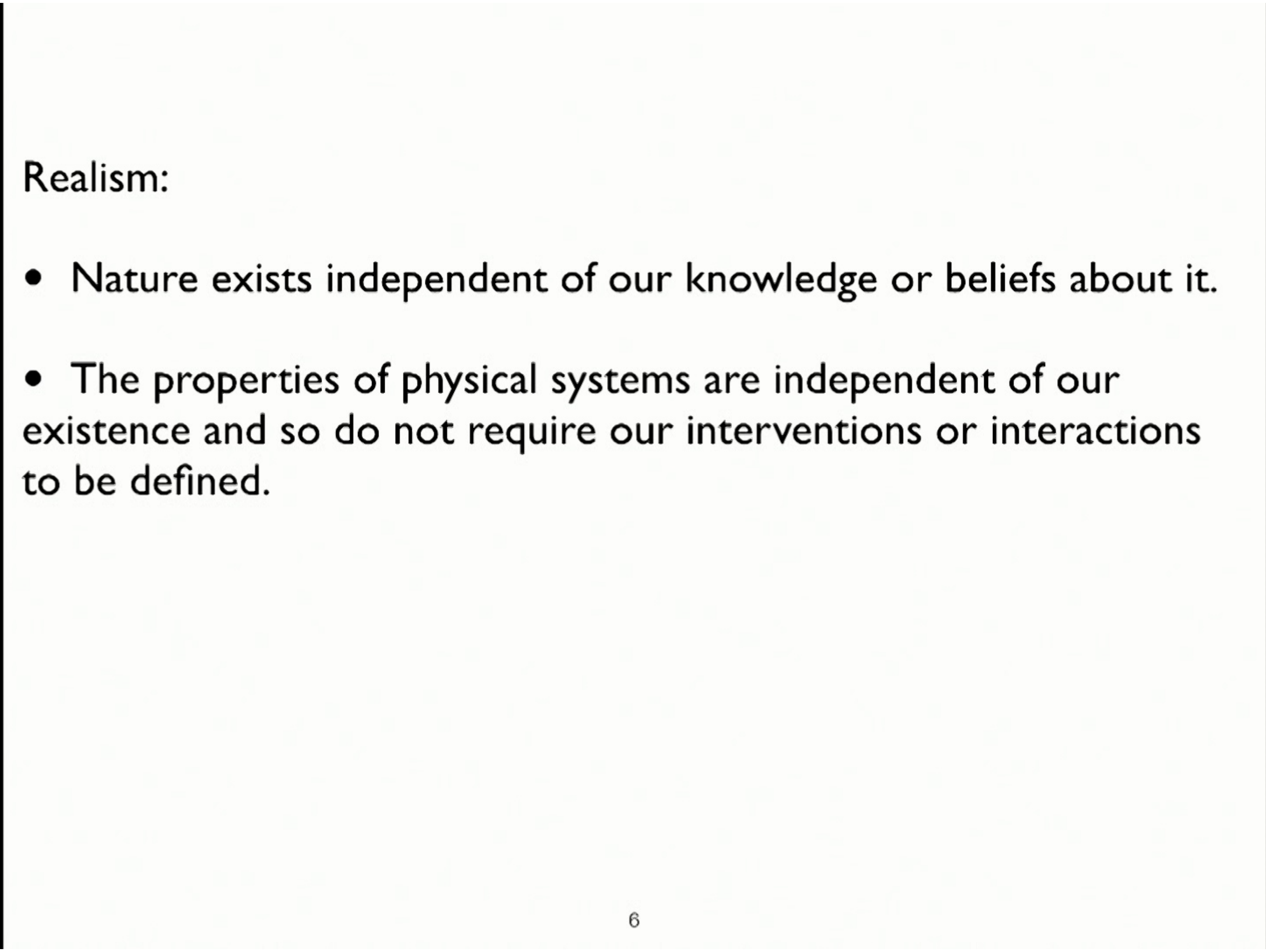
Quantum mechanics itself has foundational problems, which indicate it is also incomplete.



Quantum mechanics is highly successful, it explains and predicts many many experimental results.

I will explain why I nonetheless believe that quantum mechanics is incomplete.

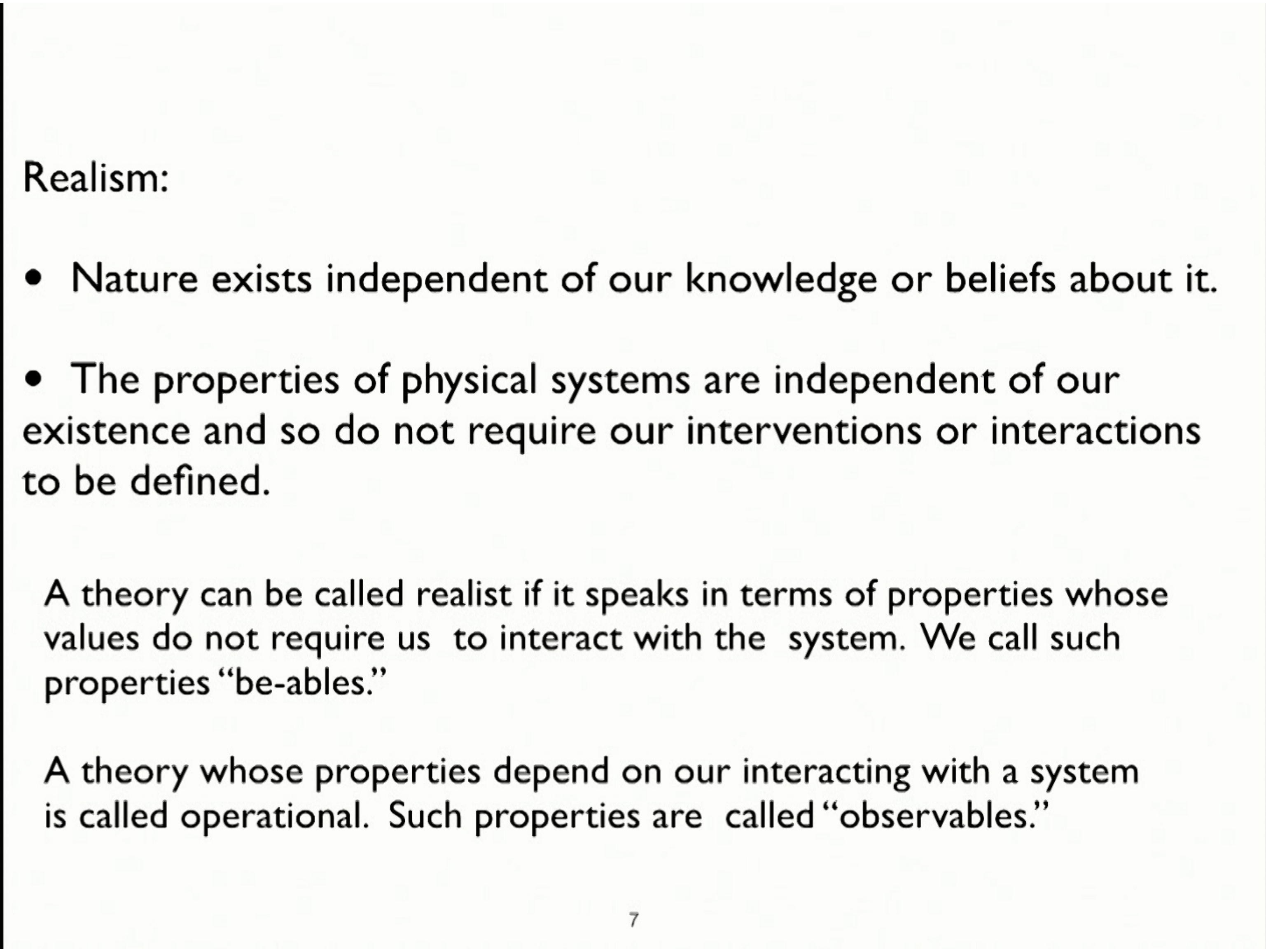
A complete description should tell us what is happening in each individual process, independent of our knowledge, beliefs or our interventions or interactions with the system.



Realism:

- Nature exists independent of our knowledge or beliefs about it.

- The properties of physical systems are independent of our existence and so do not require our interventions or interactions to be defined.



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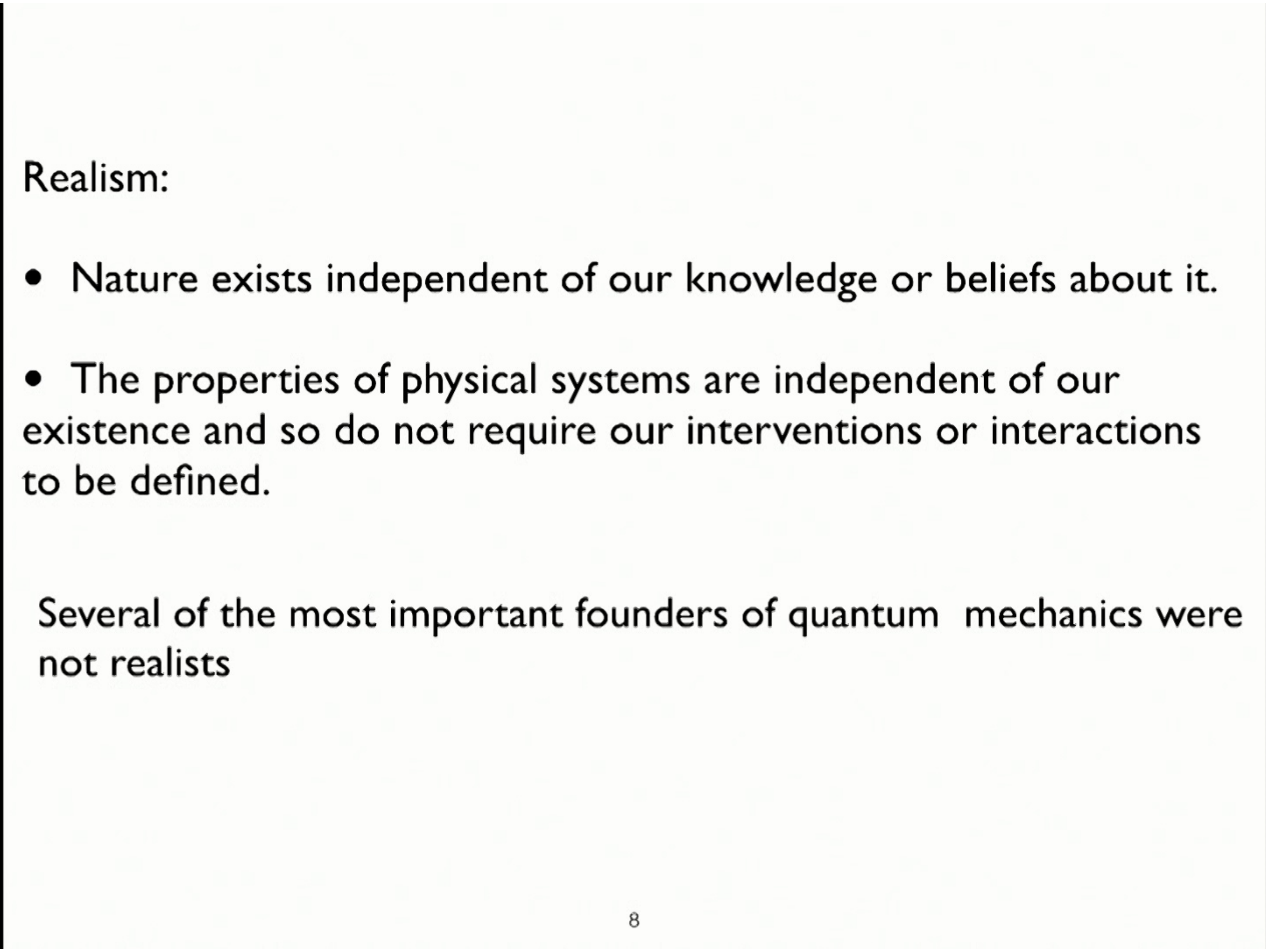
A theory can be called realist if it speaks in terms of properties whose values do not require us to interact with the system. We call such properties "be-ables."

A theory whose properties depend on our interacting with a system is called operational. Such properties are called "observables."



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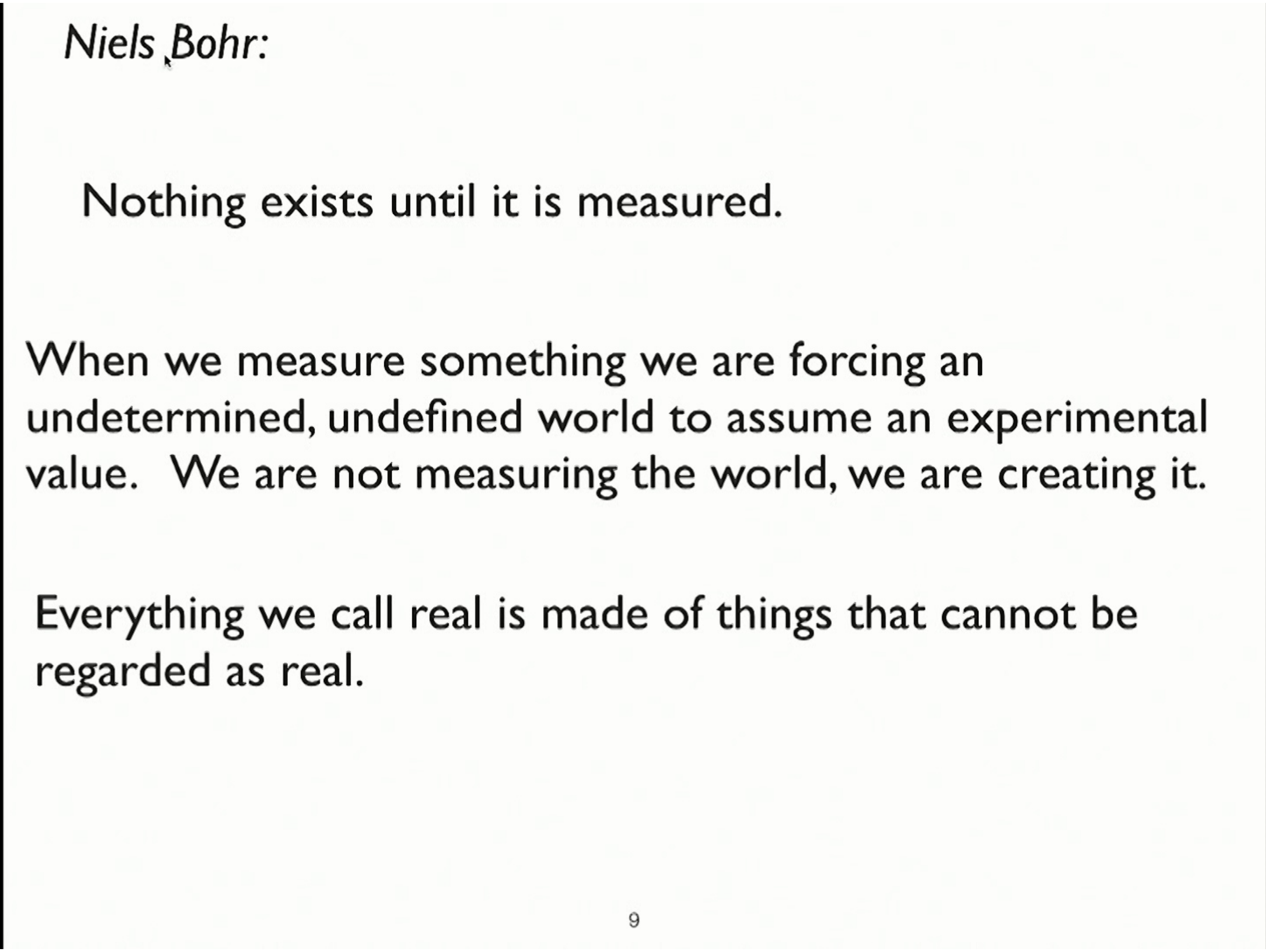
Several of the most important founders of quantum mechanics were not realists

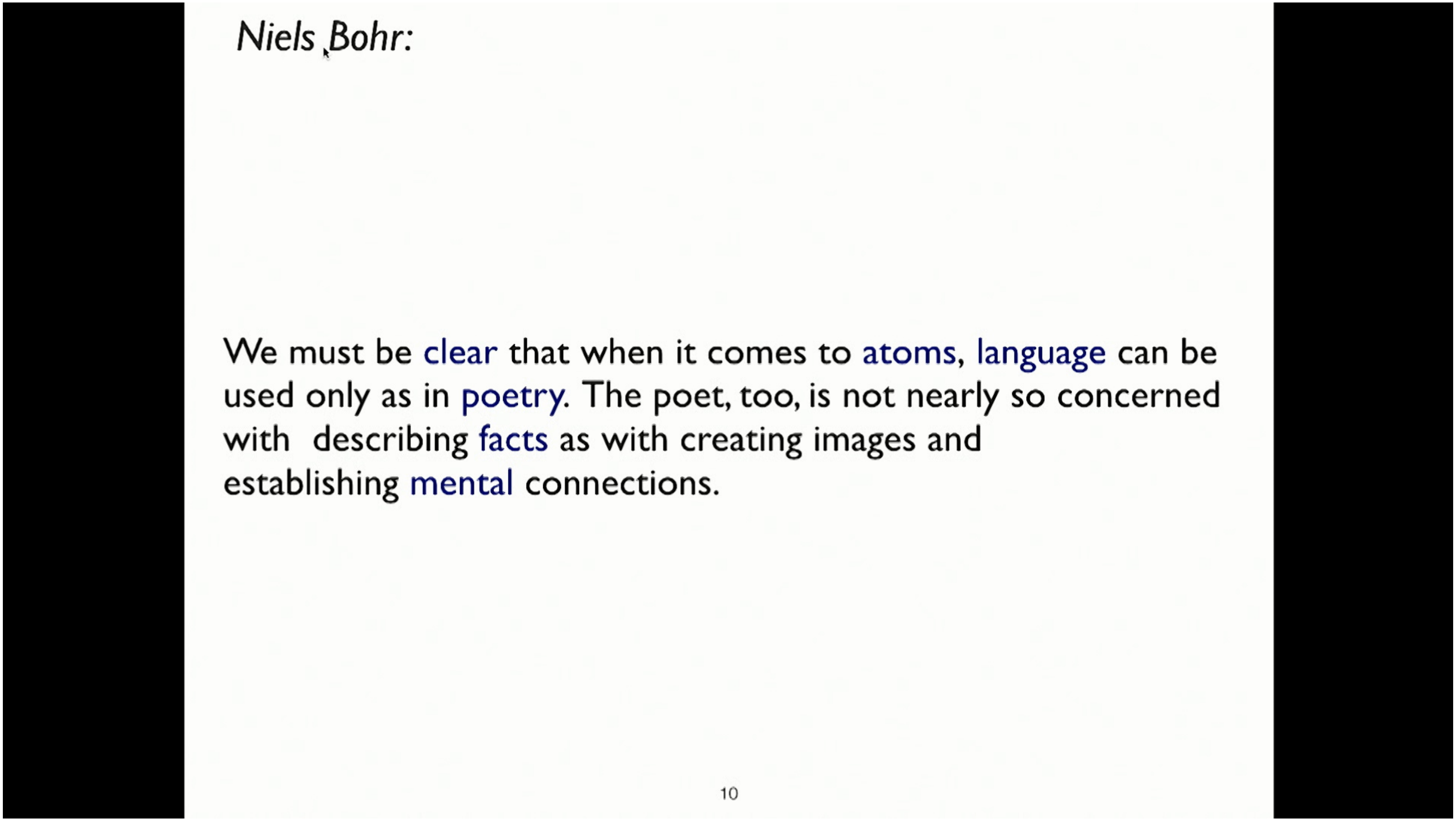


Niels Bohr:

Nothing exists until it is measured.

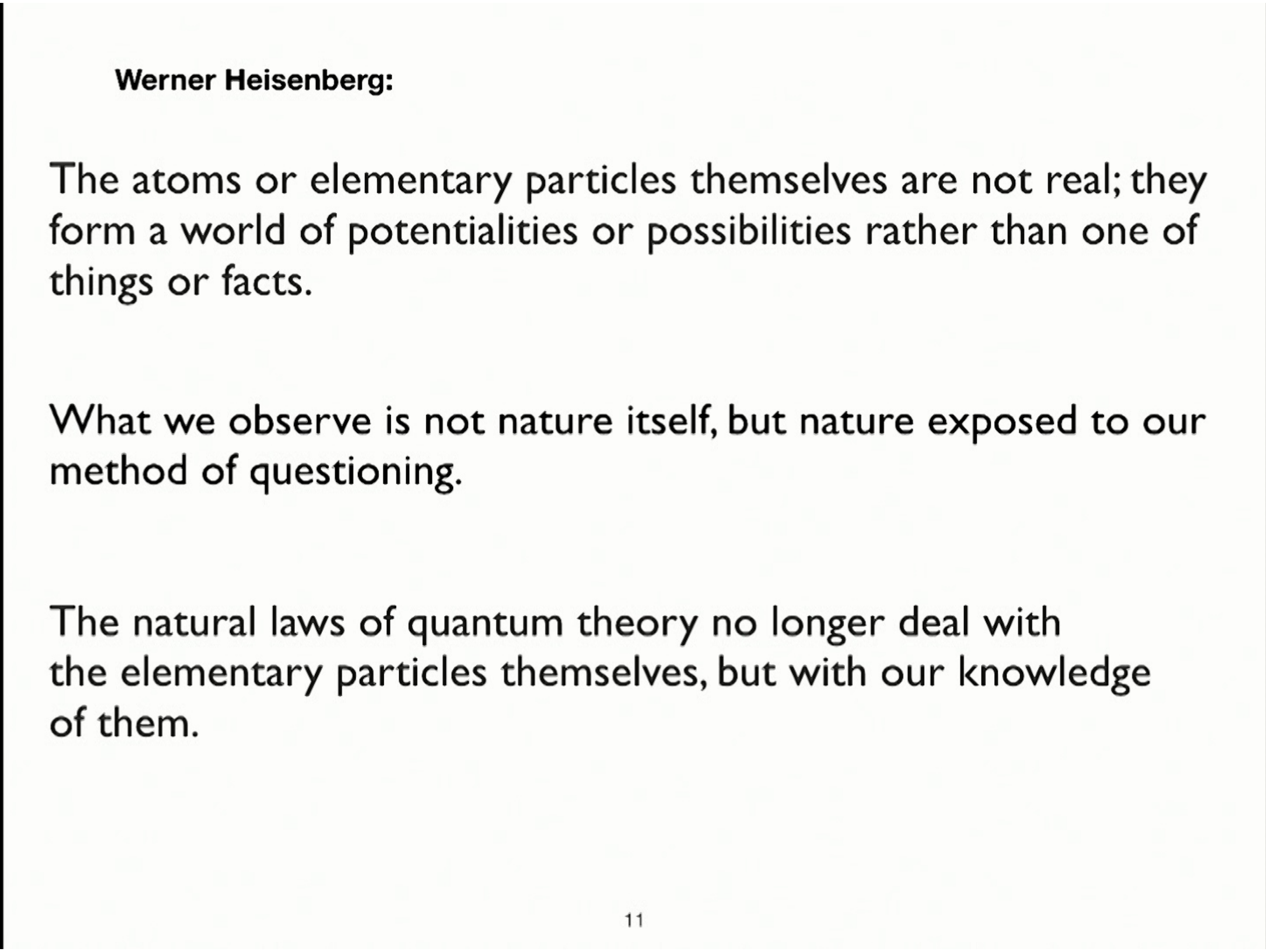
When we measure something we are forcing an undetermined, undefined world to assume an experimental value. We are not measuring the world, we are creating it.

Everything we call real is made of things that cannot be regarded as real.



Niels Bohr:

We must be clear that when it comes to atoms, language can be used only as in poetry. The poet, too, is not nearly so concerned with describing facts as with creating images and establishing mental connections.



Werner Heisenberg:

The atoms or elementary particles themselves are not real; they form a world of potentialities or possibilities rather than one of things or facts.

What we observe is not nature itself, but nature exposed to our method of questioning.

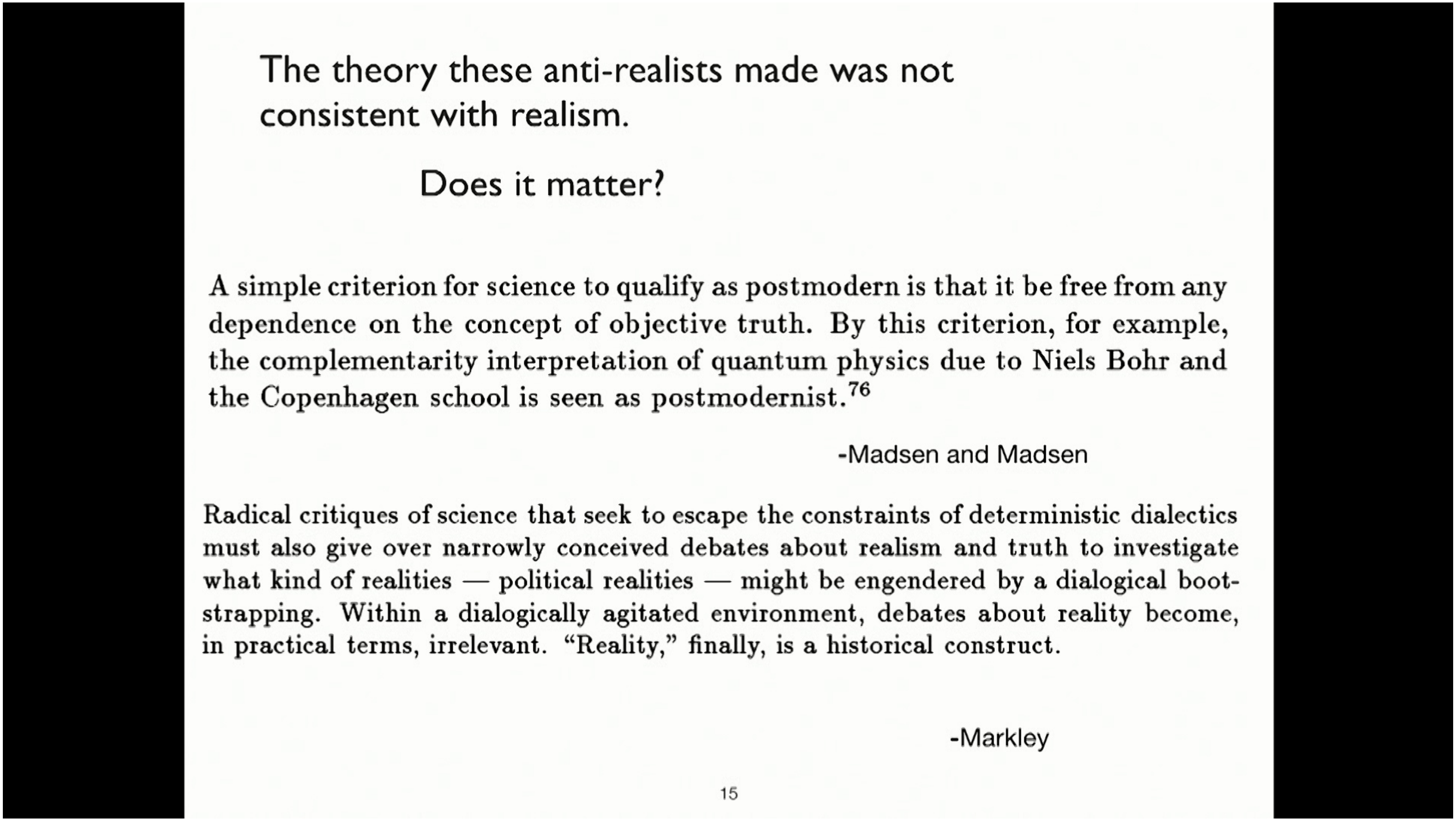
The natural laws of quantum theory no longer deal with the elementary particles themselves, but with our knowledge of them.

The theory these anti-realists made was not consistent with realism.

The properties QM uses to describe atoms depend on us to prepare and measure them. These are observables, not beables.

The theory these anti-realists made was not consistent with realism.

Does it matter?



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Does it matter?

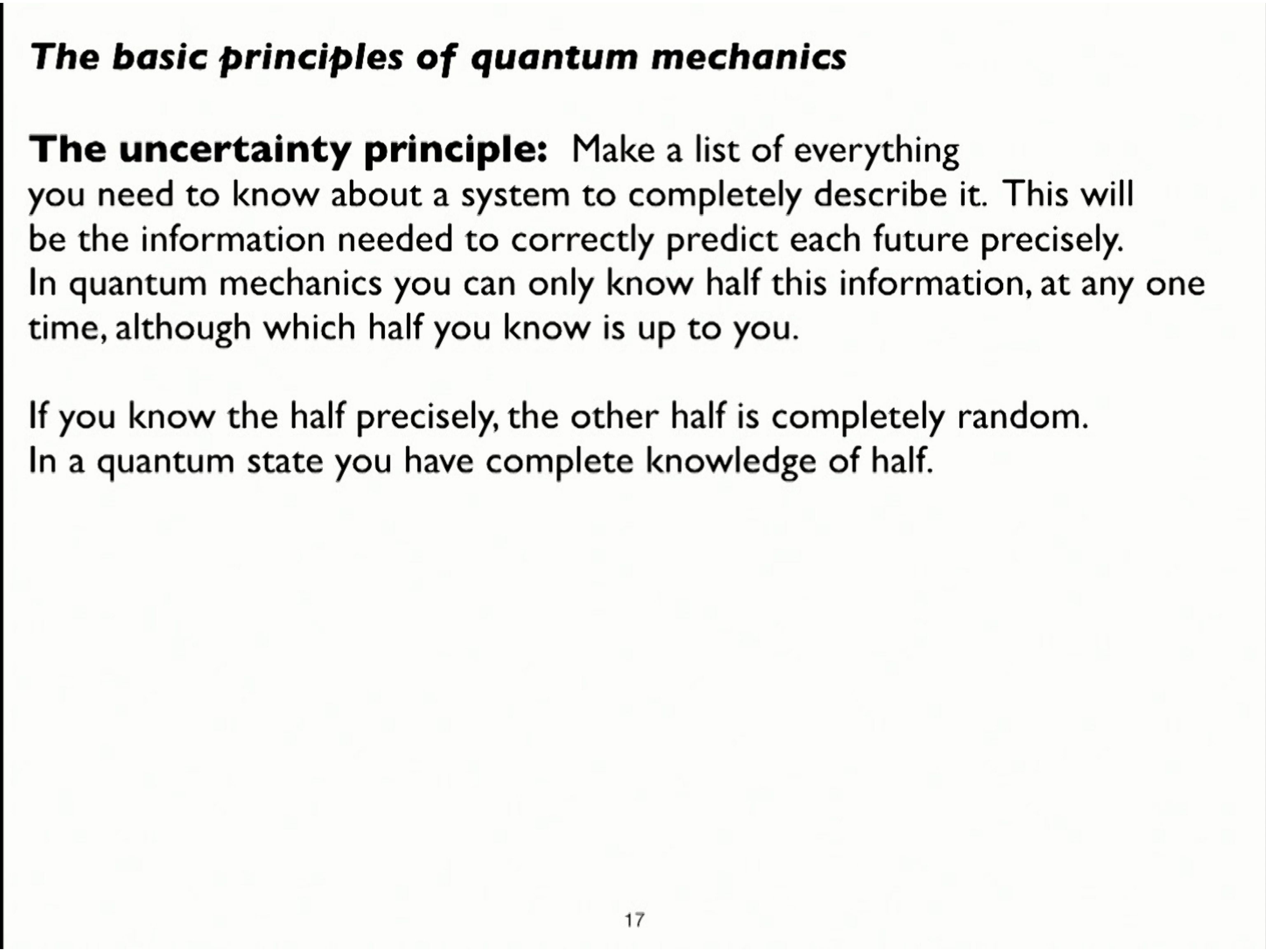
A simple criterion for science to qualify as postmodern is that it be free from any dependence on the concept of objective truth. By this criterion, for example, the complementarity interpretation of quantum physics due to Niels Bohr and the Copenhagen school is seen as postmodernist.[76]

-Madsen and Madsen

Radical critiques of science that seek to escape the constraints of deterministic dialectics must also give over narrowly conceived debates about realism and truth to investigate what kind of realities — political realities — might be engendered by a dialogical bootstrapping. Within a dialogically agitated environment, debates about reality become, in practical terms, irrelevant. "Reality," finally, is a historical construct.

-Markley

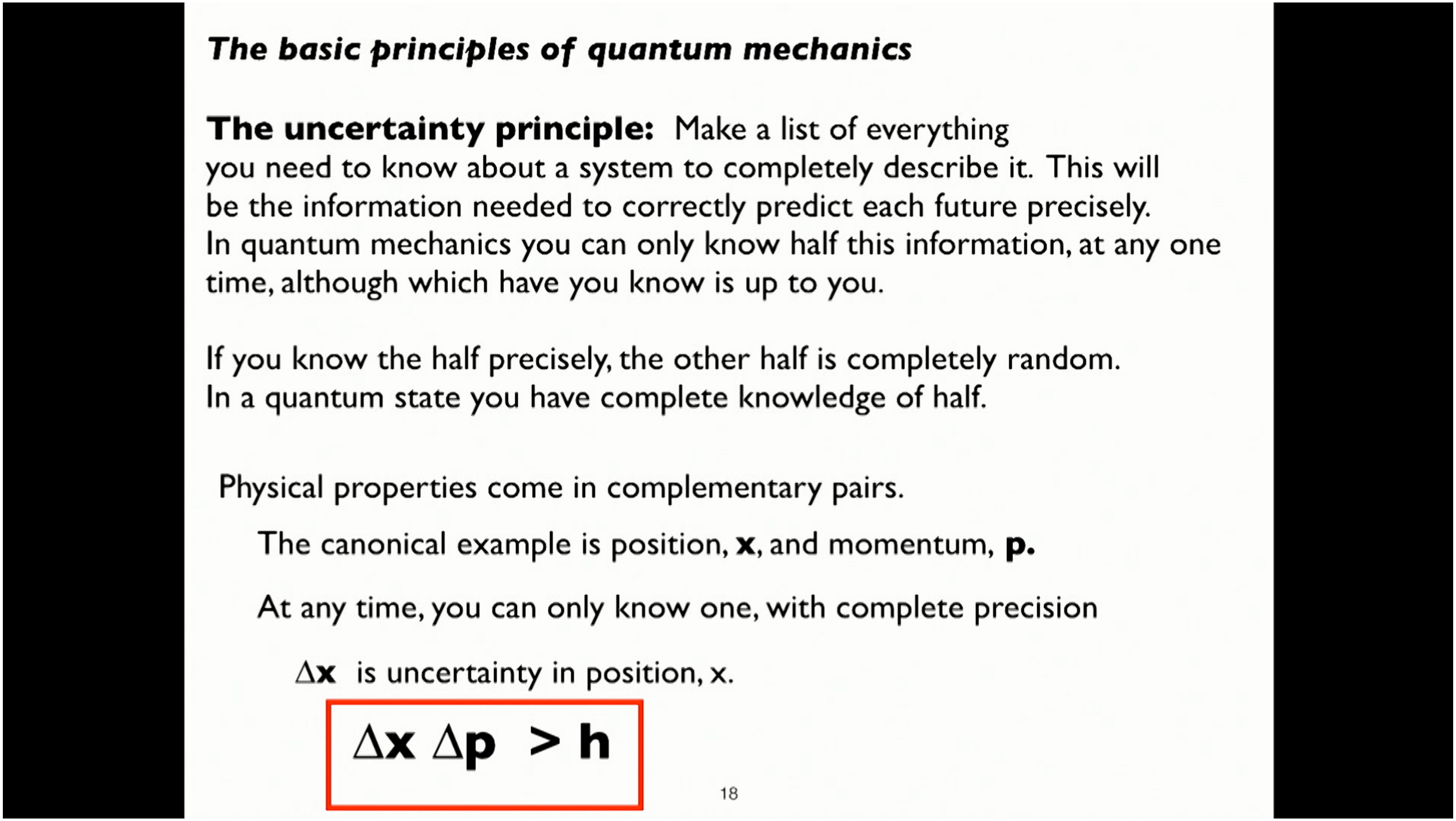
Quantum mechanics is based on simple principles.



The basic principles of quantum mechanics

The uncertainty principle: Make a list of everything you need to know about a system to completely describe it. This will be the information needed to correctly predict each future precisely. In quantum mechanics you can only know half this information, at any one time, although which half you know is up to you.

If you know the half precisely, the other half is completely random. In a quantum state you have complete knowledge of half.



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Physical properties come in complementary pairs.

The canonical example is position, **x**, and momentum, **p.**

At any time, you can only know one, with complete precision

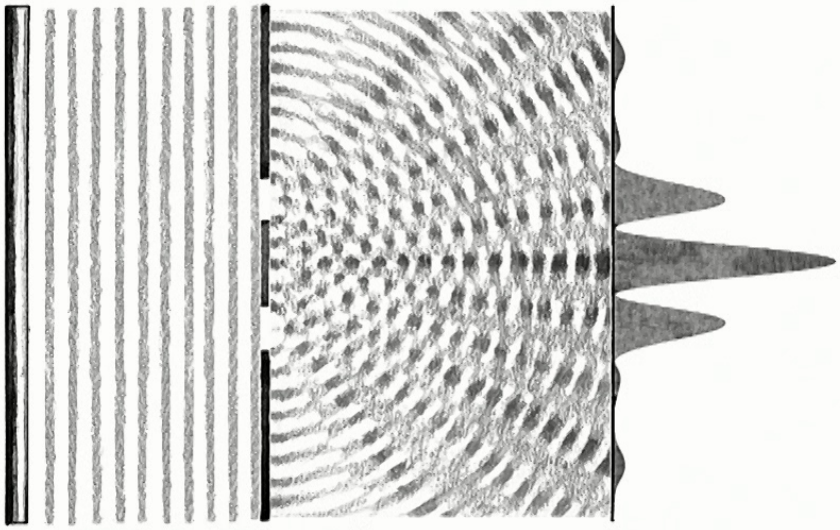
$\Delta \mathbf{x}$ is uncertainty in position, x.

$$\boxed{\Delta \mathbf{x}\ \Delta \mathbf{p} > \mathbf{h}}$$

The basic principles of quantum mechanics

The superposition principle: If A and B are quantum states, so is x A + y B, where x and y are complex numbers.

This is familiar as a property of waves. In QM it applies universally.



Summary: the two most basic principles of quantum mechanics

The uncertainty principle: Make a list of everything you need to know about a system to completely describe it. This will be the information needed to correctly predict each future precisely. In quantum mechanics you can only know half this information, at any one time, although which have you know is up to you.

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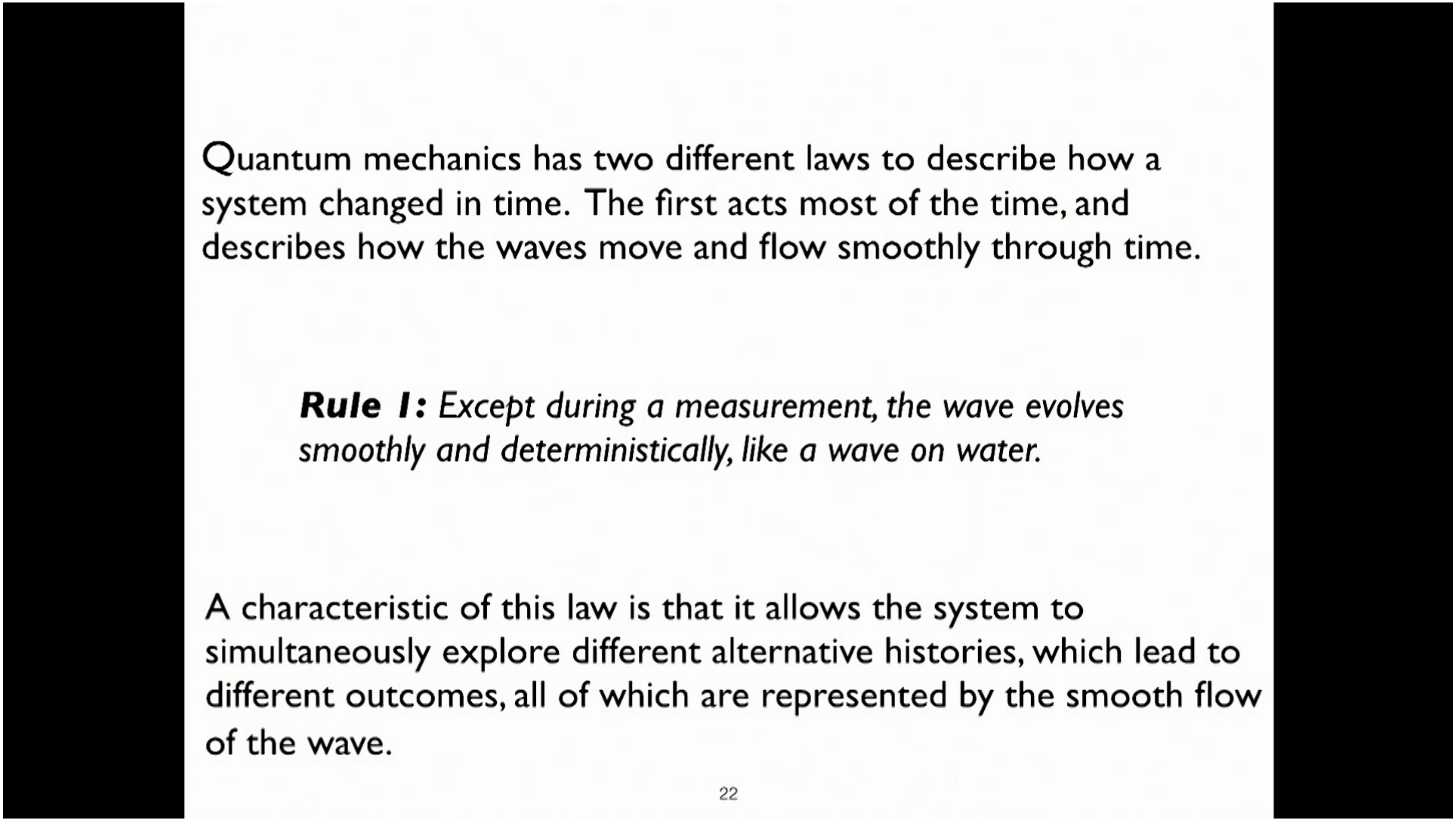
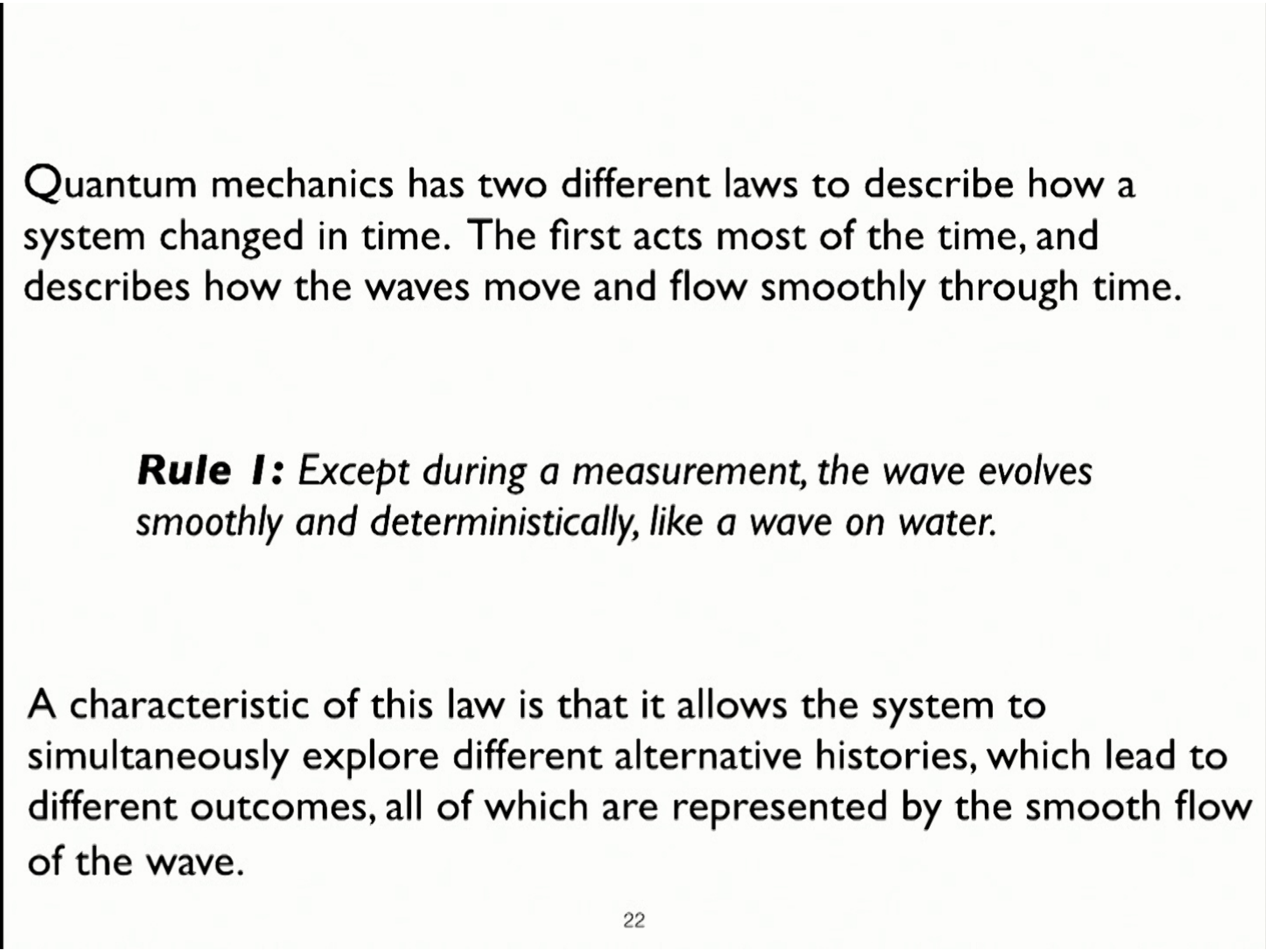
How quanta change in time:



Quantum mechanics has two different laws to describe how a system changed in time. The first acts most of the time, and describes how the waves move and flow smoothly through time.

Rule 1: *Except during a measurement, the wave evolves smoothly and deterministically, like a wave on water.*

A characteristic of this law is that it allows the system to simultaneously explore different alternative histories, which lead to different outcomes, all of which are represented by the smooth flow of the wave.



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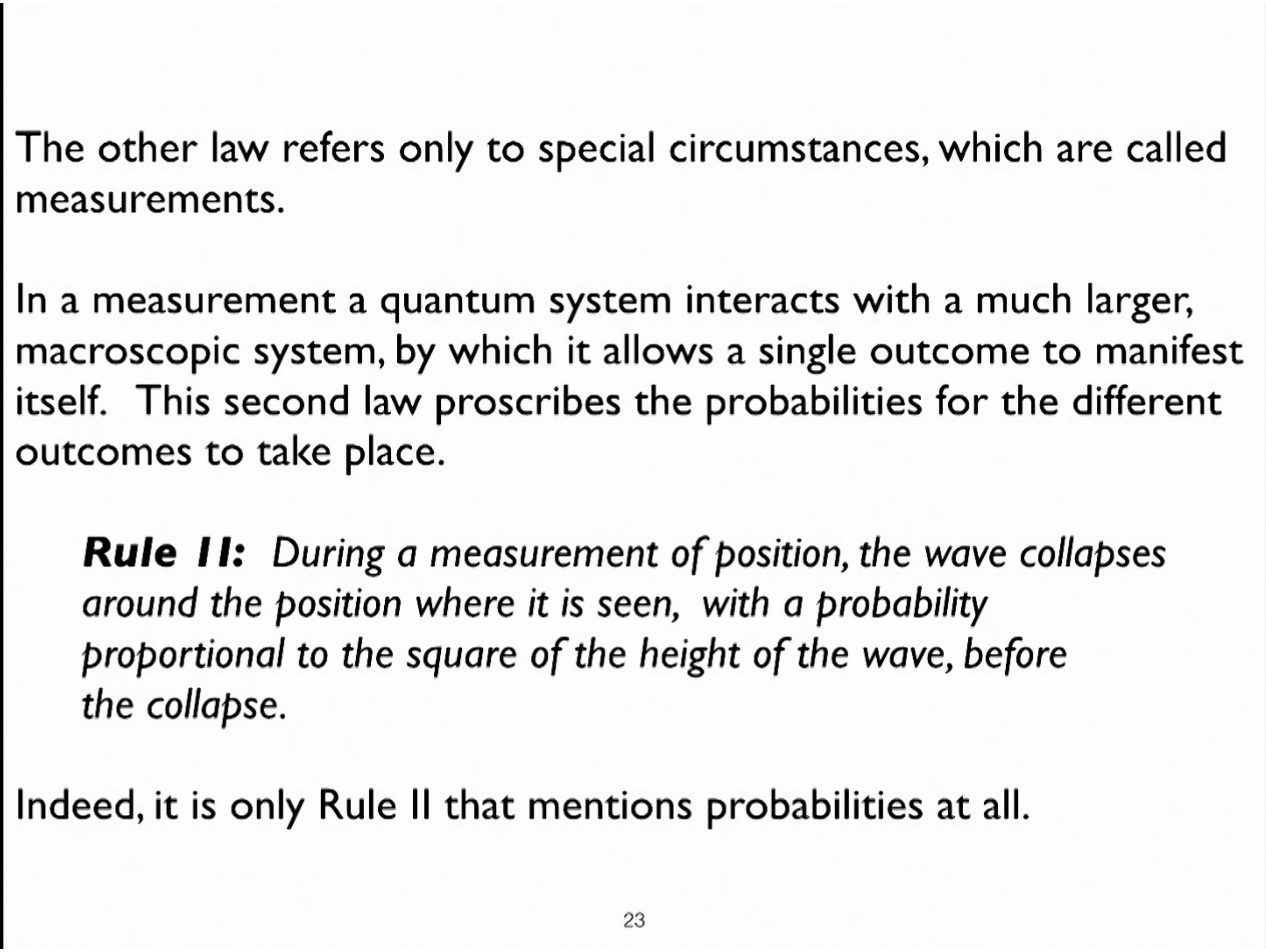


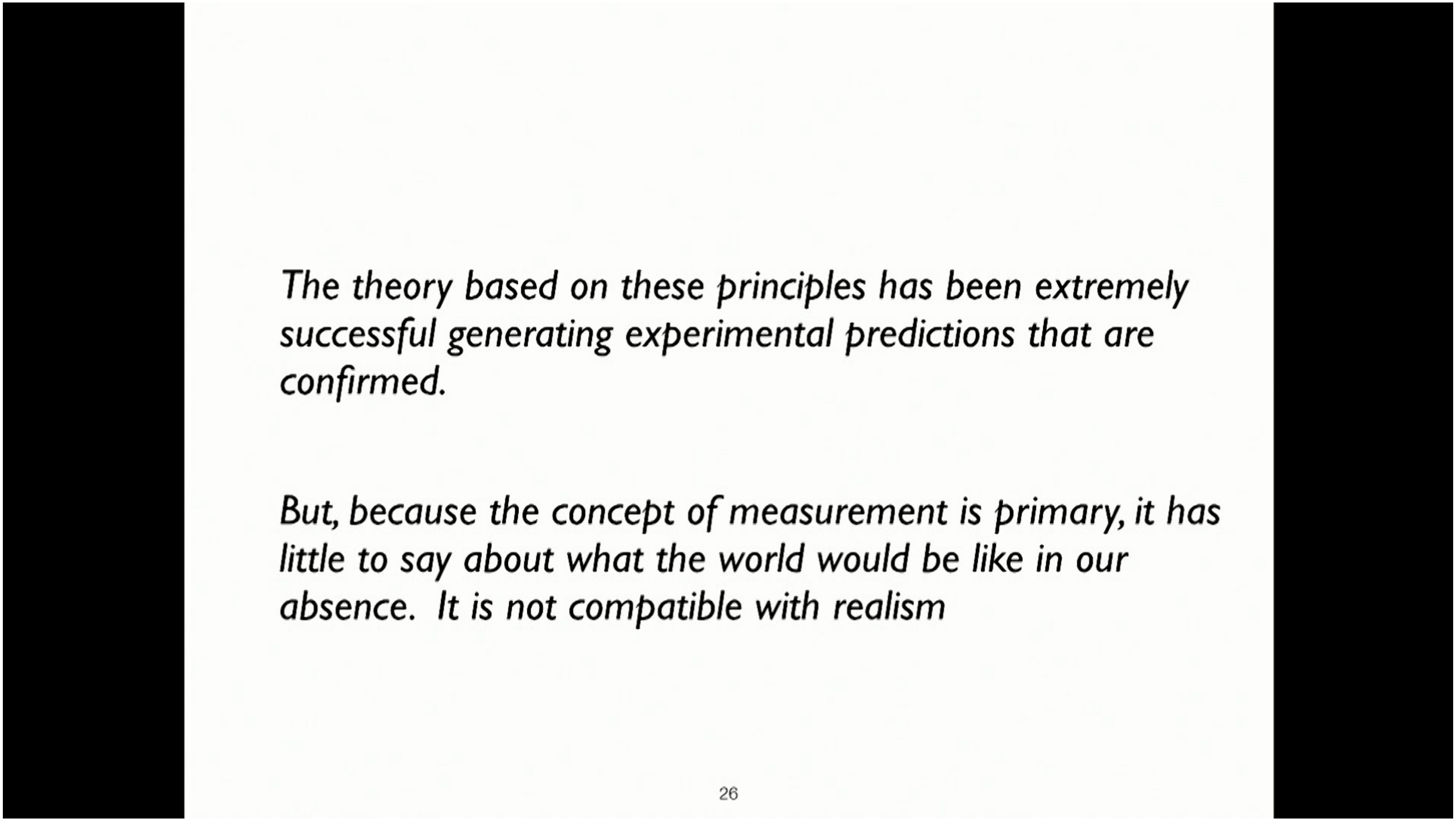
The other law refers only to special circumstances, which are called measurements.

In a measurement a quantum system interacts with a much larger, macroscopic system, by which it allows a single outcome to manifest itself. This second law proscribes the probabilities for the different outcomes to take place.

> ***Rule II:*** *During a measurement of position, the wave collapses around the position where it is seen, with a probability proportional to the square of the height of the wave, before the collapse.*

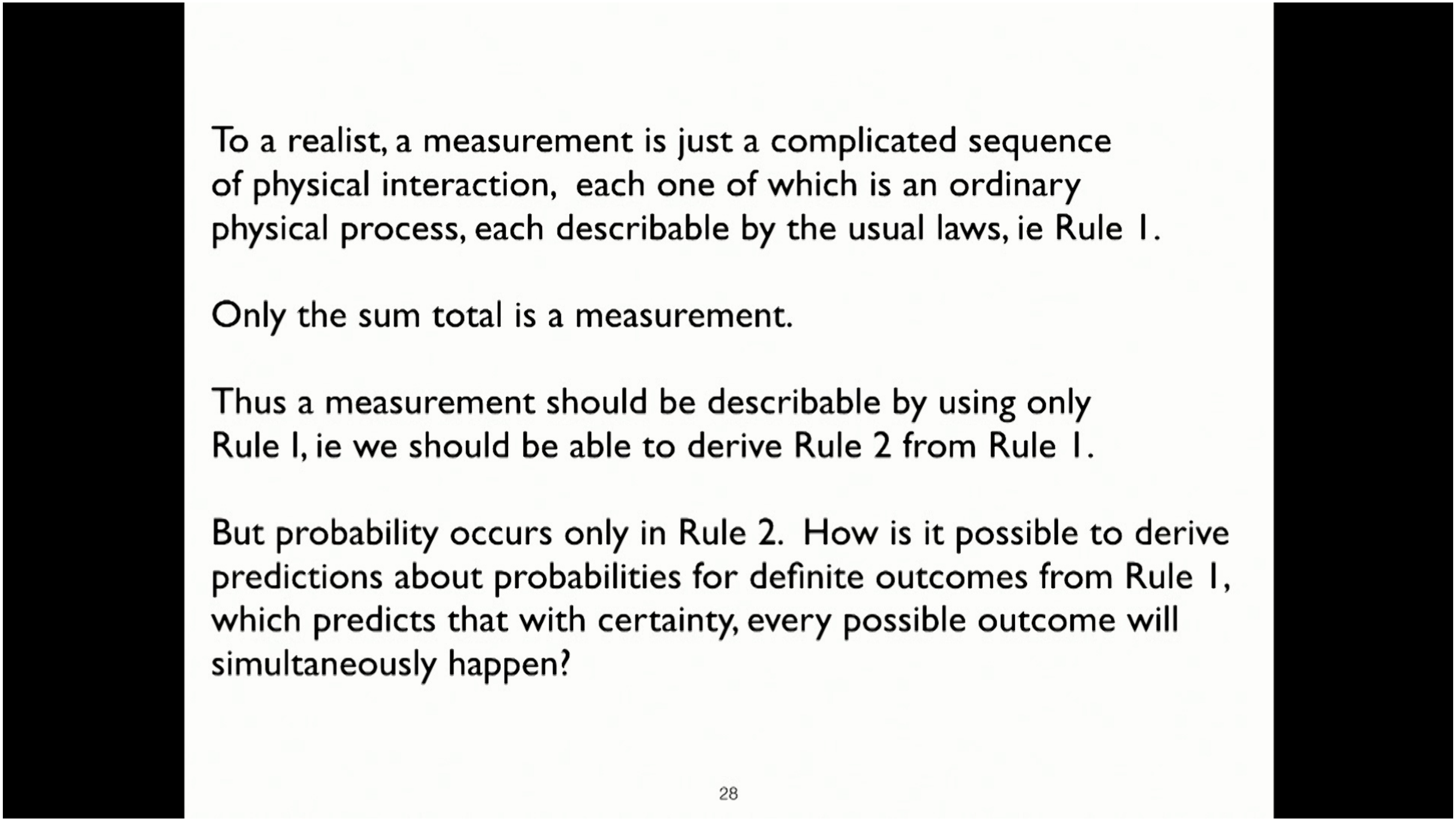
Indeed, it is only Rule II that mentions probabilities at all.

The theory based on these principles has been extremely successful generating experimental predictions that are confirmed.



The theory based on these principles has been extremely successful generating experimental predictions that are confirmed.

But, because the concept of measurement is primary, it has little to say about what the world would be like in our absence. It is not compatible with realism

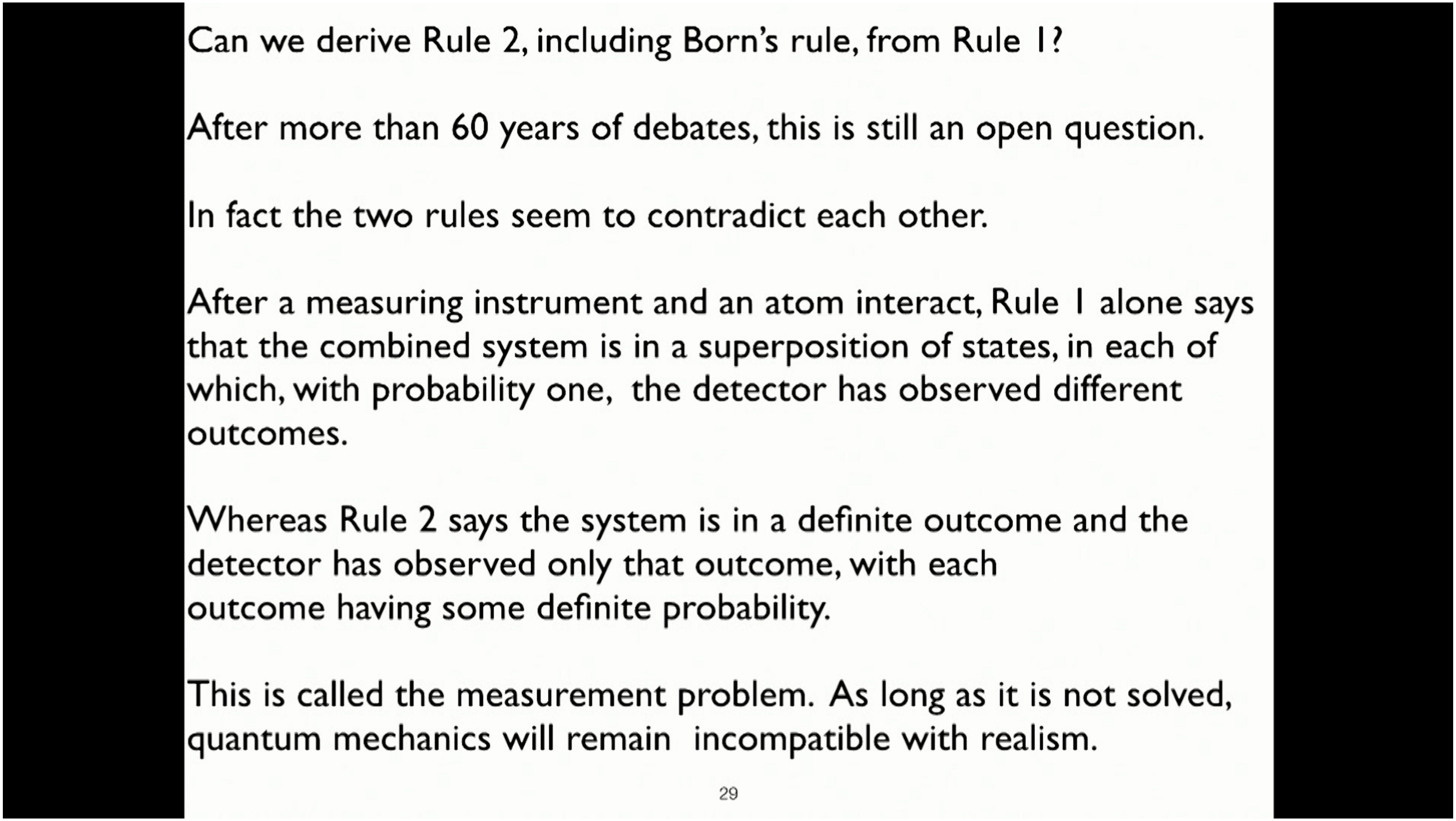


To a realist, a measurement is just a complicated sequence of physical interaction, each one of which is an ordinary physical process, each describable by the usual laws, ie Rule 1.

Only the sum total is a measurement.

Thus a measurement should be describable by using only Rule I, ie we should be able to derive Rule 2 from Rule 1.

But probability occurs only in Rule 2. How is it possible to derive predictions about probabilities for definite outcomes from Rule 1, which predicts that with certainty, every possible outcome will simultaneously happen?



Can we derive Rule 2, including Born's rule, from Rule 1?

After more than 60 years of debates, this is still an open question.

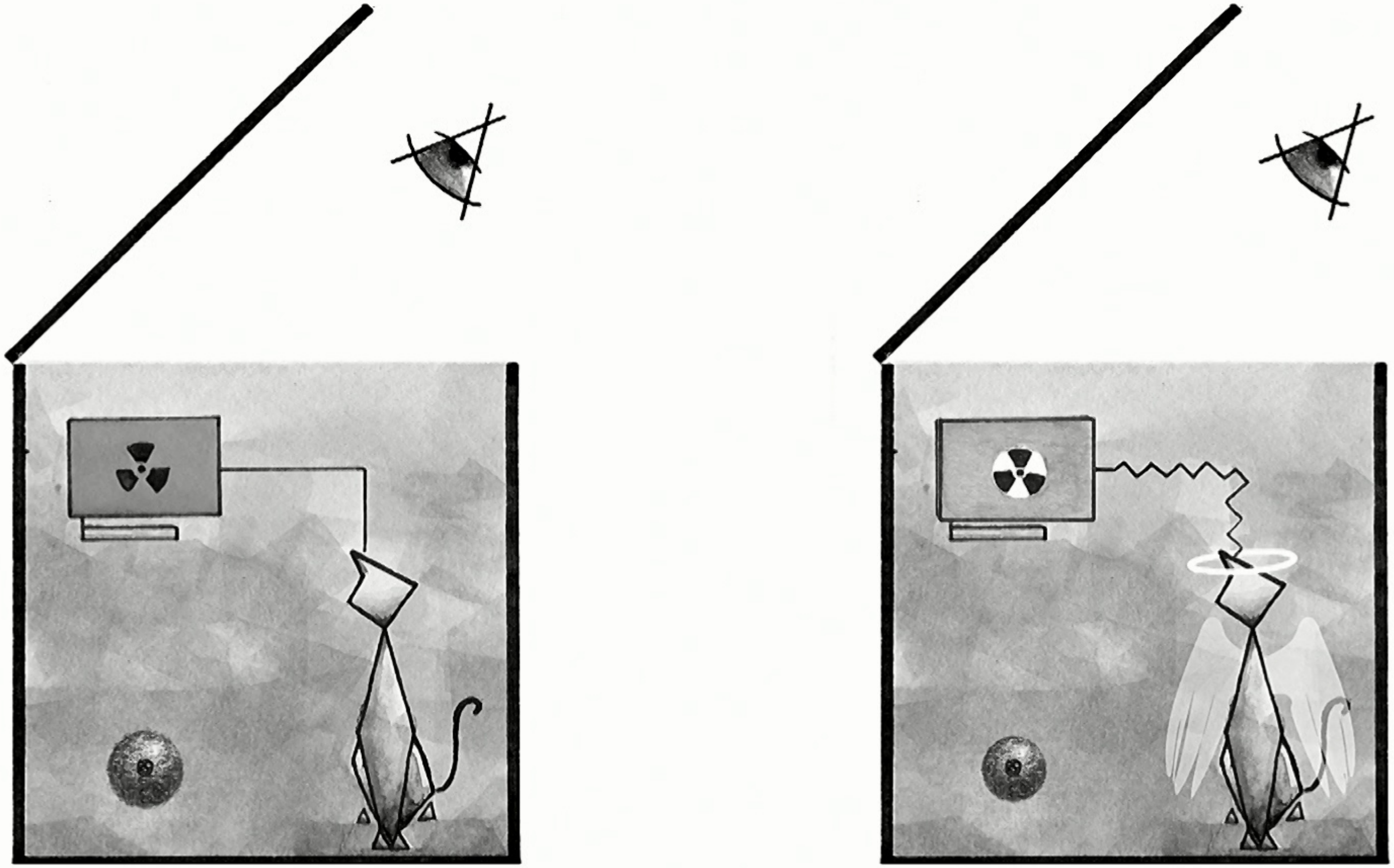
In fact the two rules seem to contradict each other.

After a measuring instrument and an atom interact, Rule 1 alone says that the combined system is in a superposition of states, in each of which, with probability one, the detector has observed different outcomes.

Whereas Rule 2 says the system is in a definite outcome and the detector has observed only that outcome, with each outcome having some definite probability.

This is called the measurement problem. As long as it is not solved, quantum mechanics will remain incompatible with realism.

Schrodinger's cat



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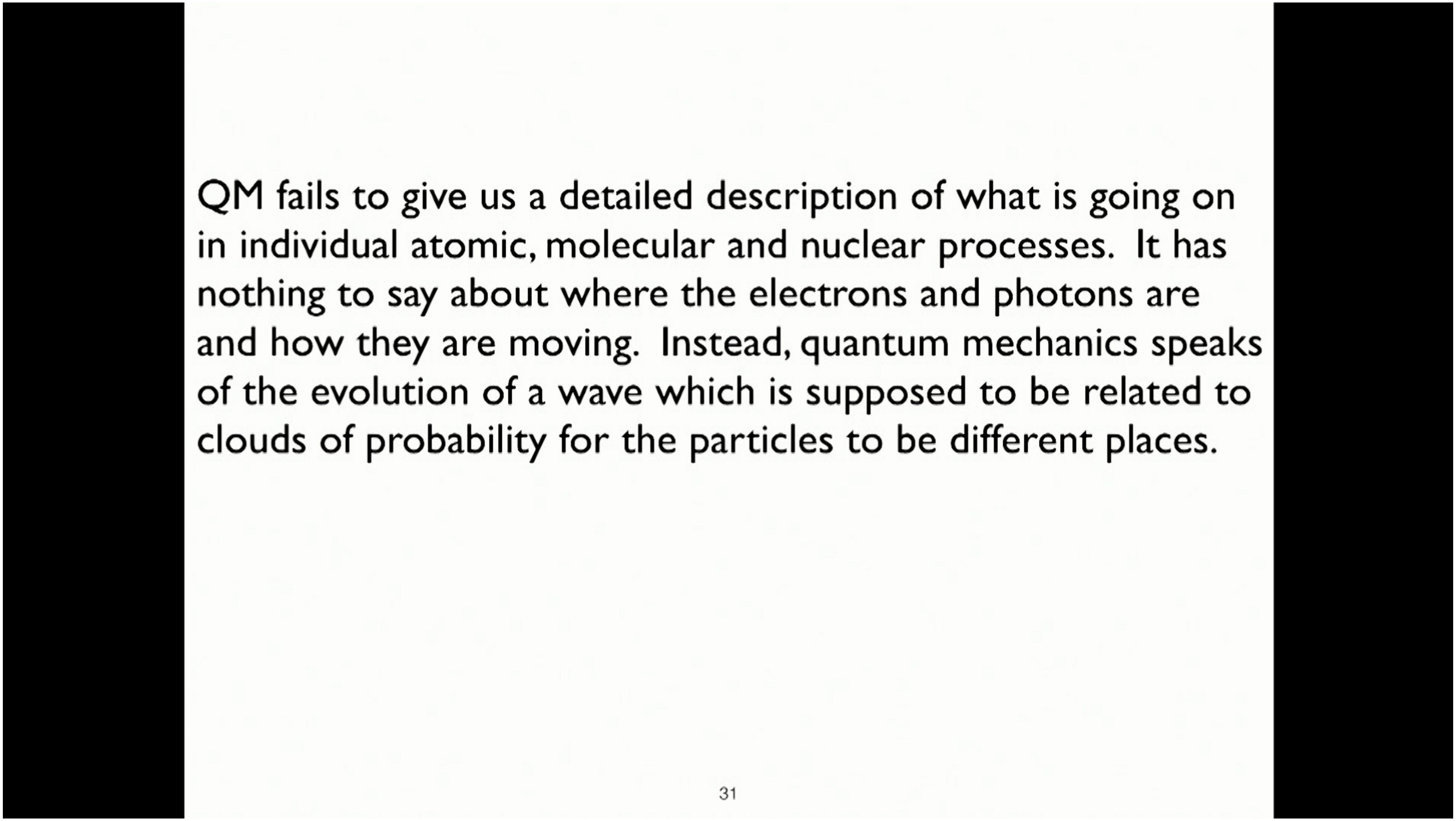
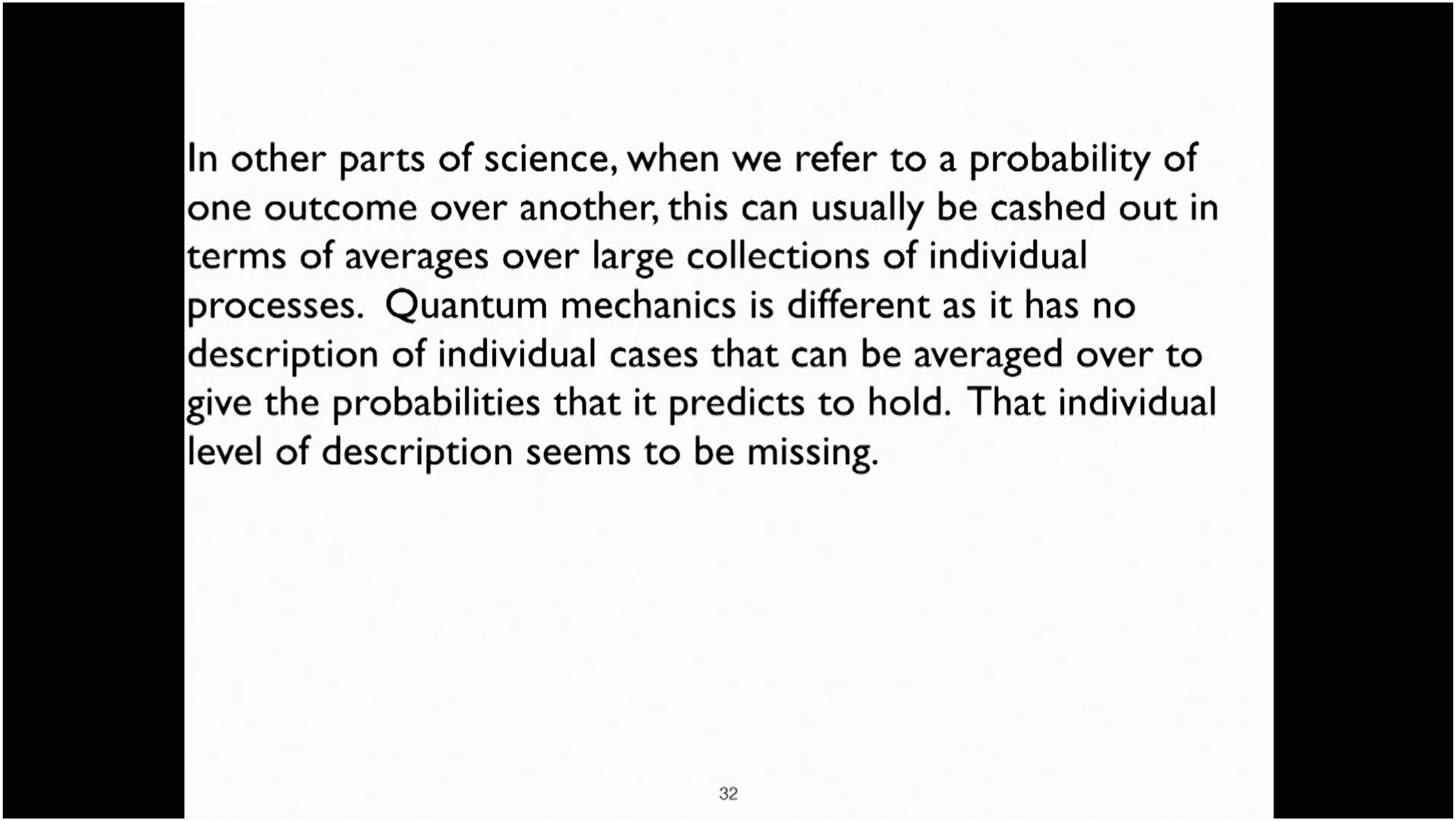
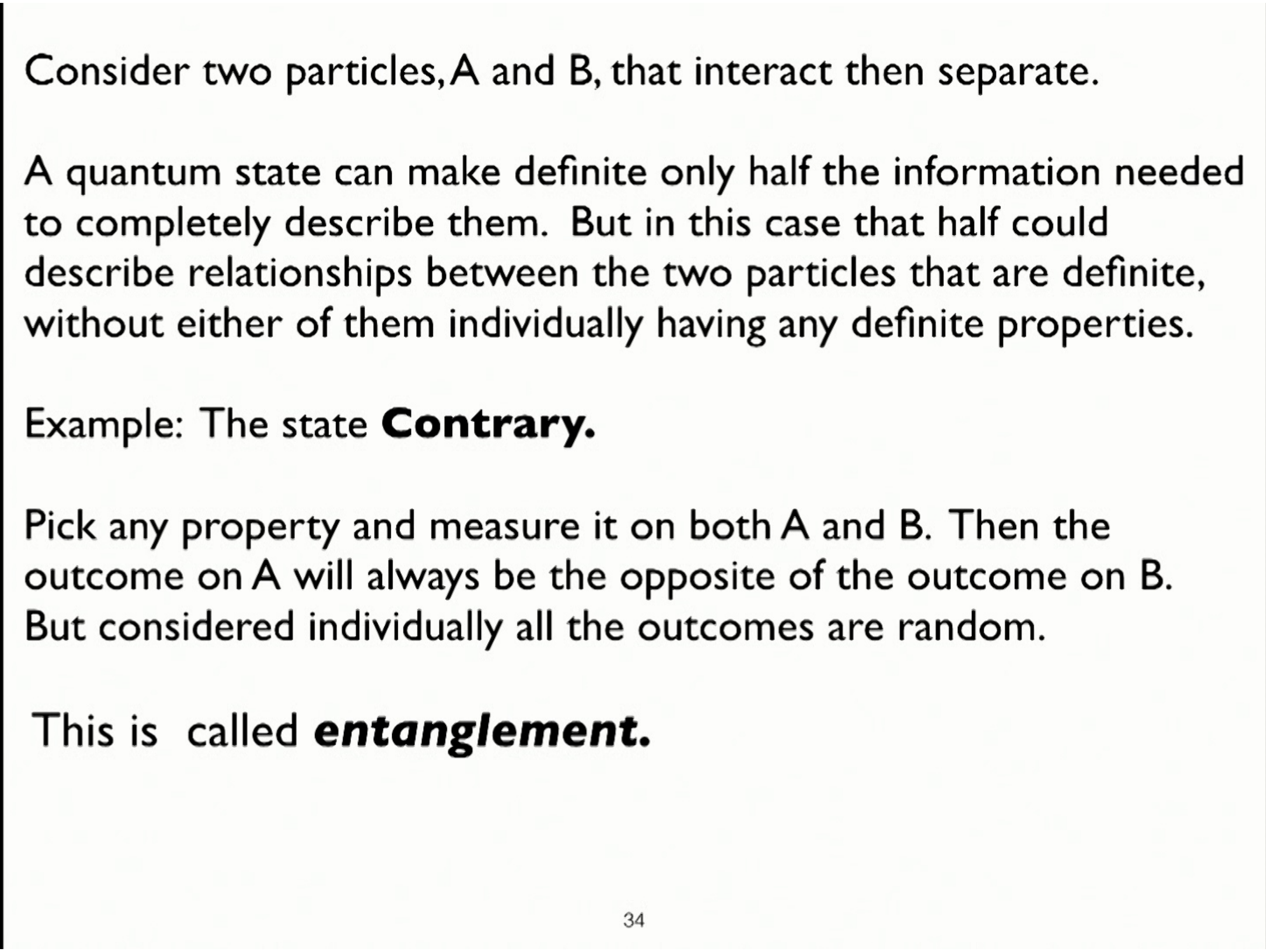


QM fails to give us a detailed description of what is going on in individual atomic, molecular and nuclear processes. It has nothing to say about where the electrons and photons are and how they are moving. Instead, quantum mechanics speaks of the evolution of a wave which is supposed to be related to clouds of probability for the particles to be different places.



In other parts of science, when we refer to a probability of one outcome over another, this can usually be cashed out in terms of averages over large collections of individual processes. Quantum mechanics is different as it has no description of individual cases that can be averaged over to give the probabilities that it predicts to hold. That individual level of description seems to be missing.

The big clue: non-locality and entanglement



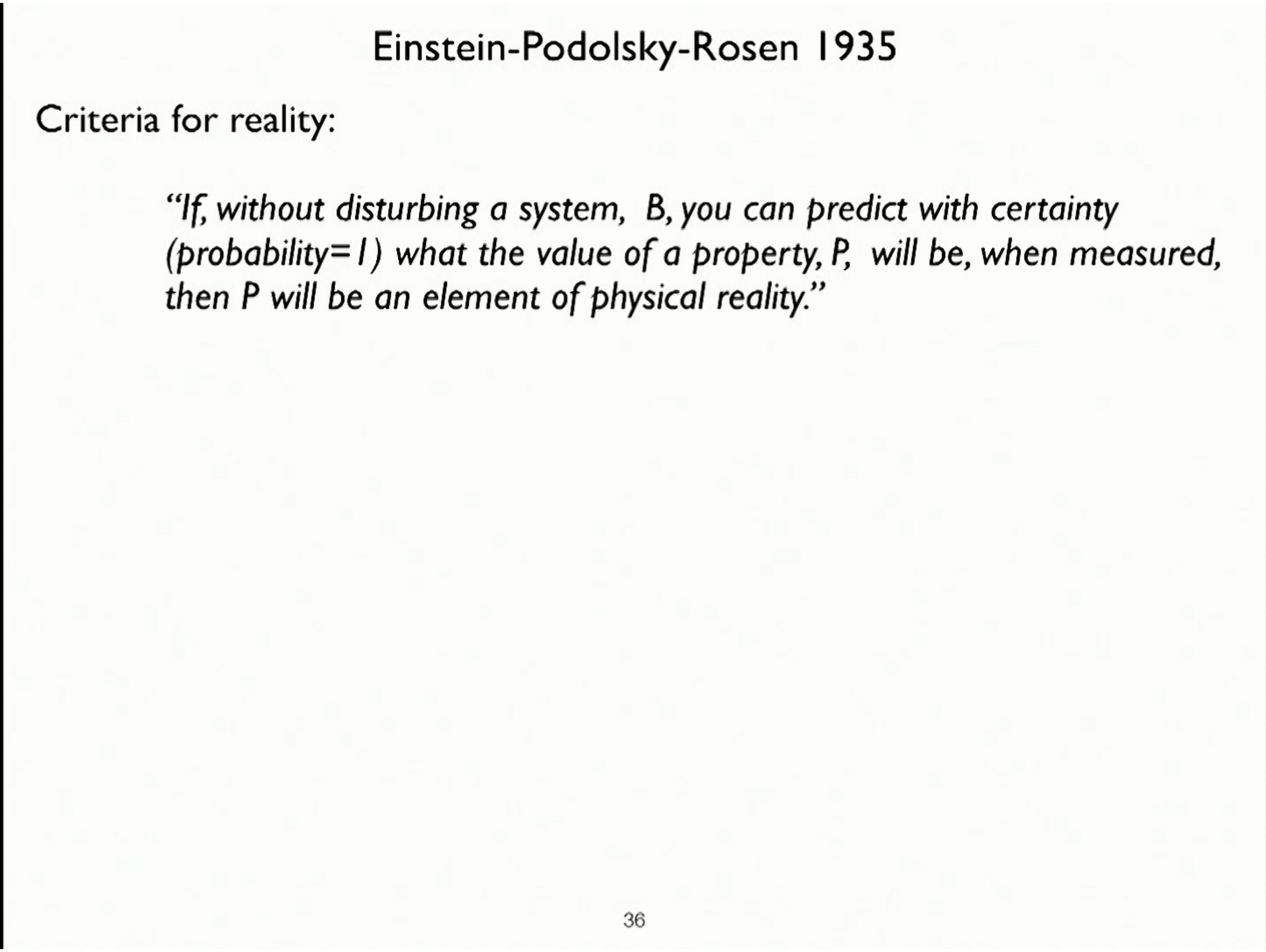
Consider two particles, A and B, that interact then separate.

A quantum state can make definite only half the information needed to completely describe them. But in this case that half could describe relationships between the two particles that are definite, without either of them individually having any definite properties.

Example: The state **Contrary.**

Pick any property and measure it on both A and B. Then the outcome on A will always be the opposite of the outcome on B. But considered individually all the outcomes are random.

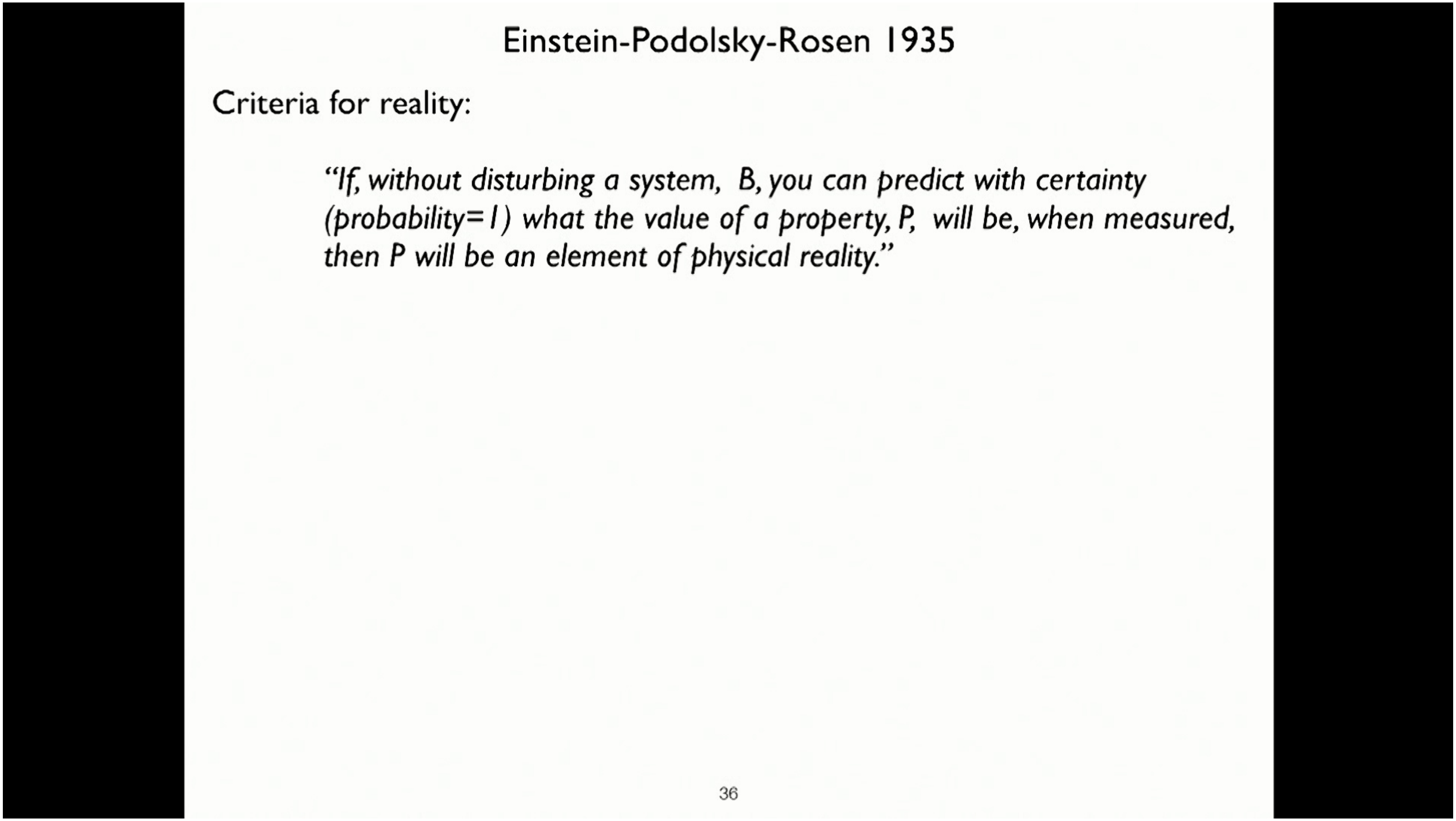
This is called ***entanglement.***



Einstein-Podolsky-Rosen 1935

Criteria for reality:

> *"If, without disturbing a system, B, you can predict with certainty (probability=1) what the value of a property, P, will be, when measured, then P will be an element of physical reality."*



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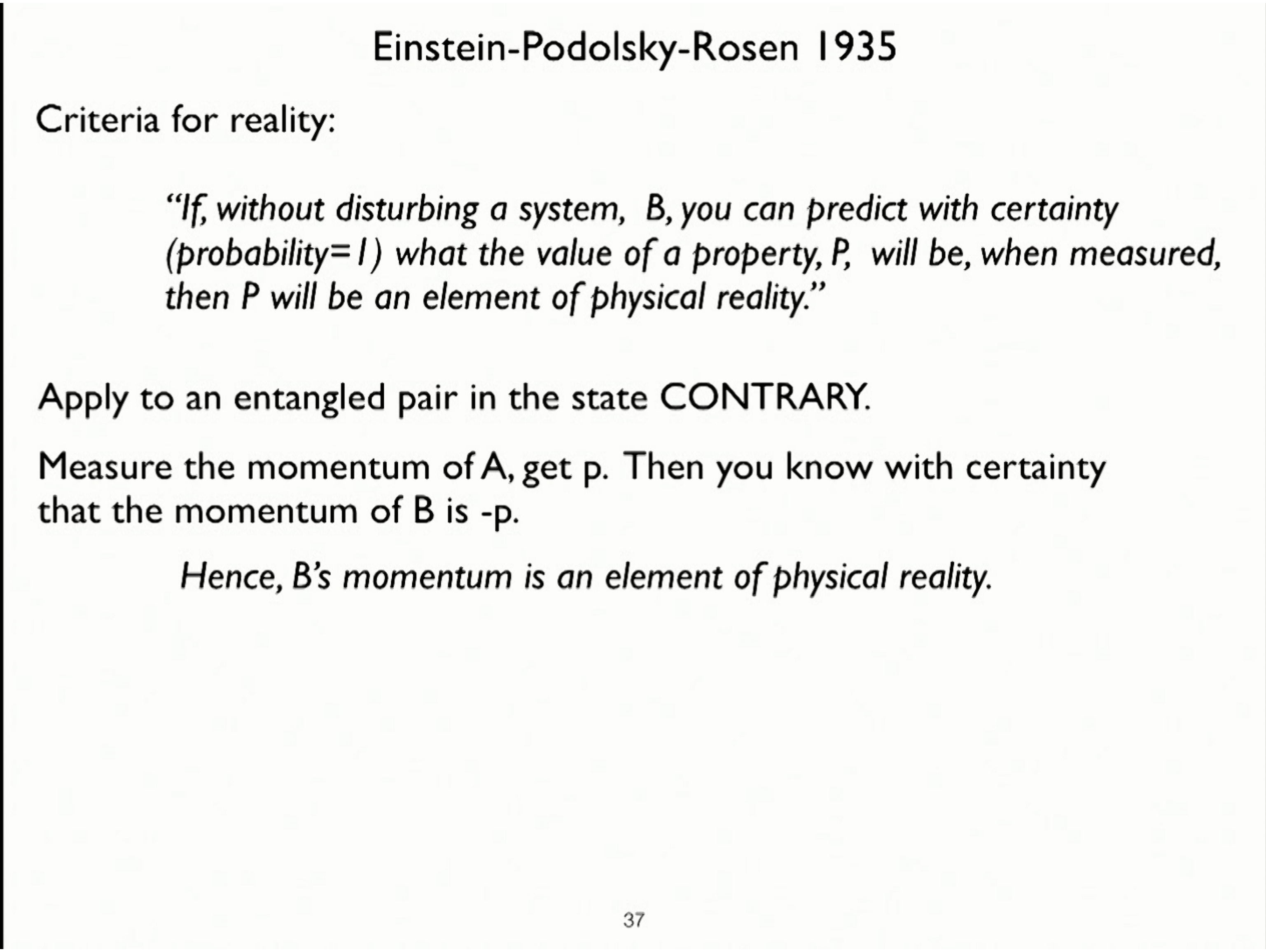

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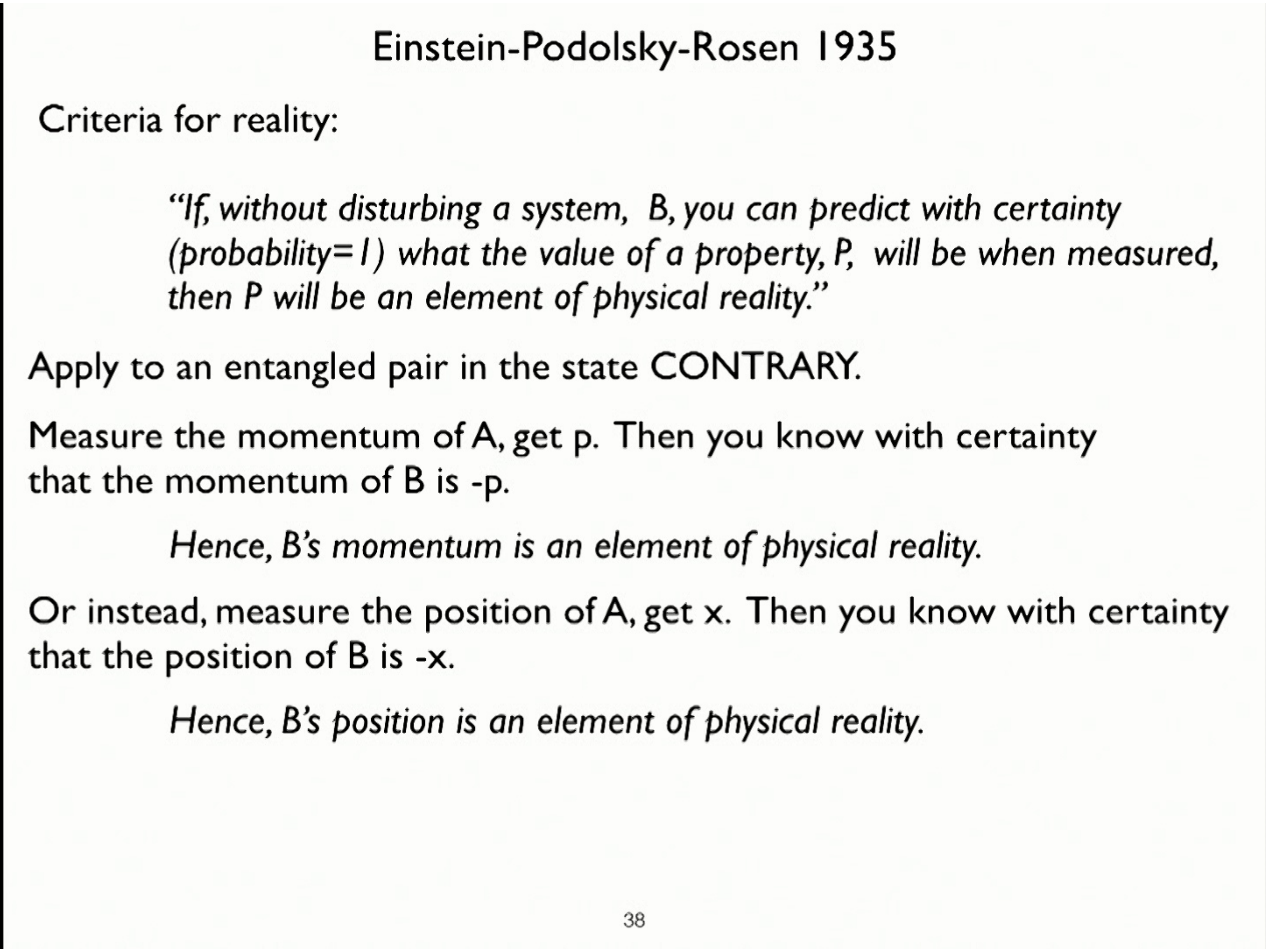
Apply to an entangled pair in the state CONTRARY.

Measure the momentum of A, get p. Then you know with certainty that the momentum of B is -p.

Hence, B's momentum is an element of physical reality.



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Or instead, measure the position of A, get x. Then you know with certainty that the position of B is -x.

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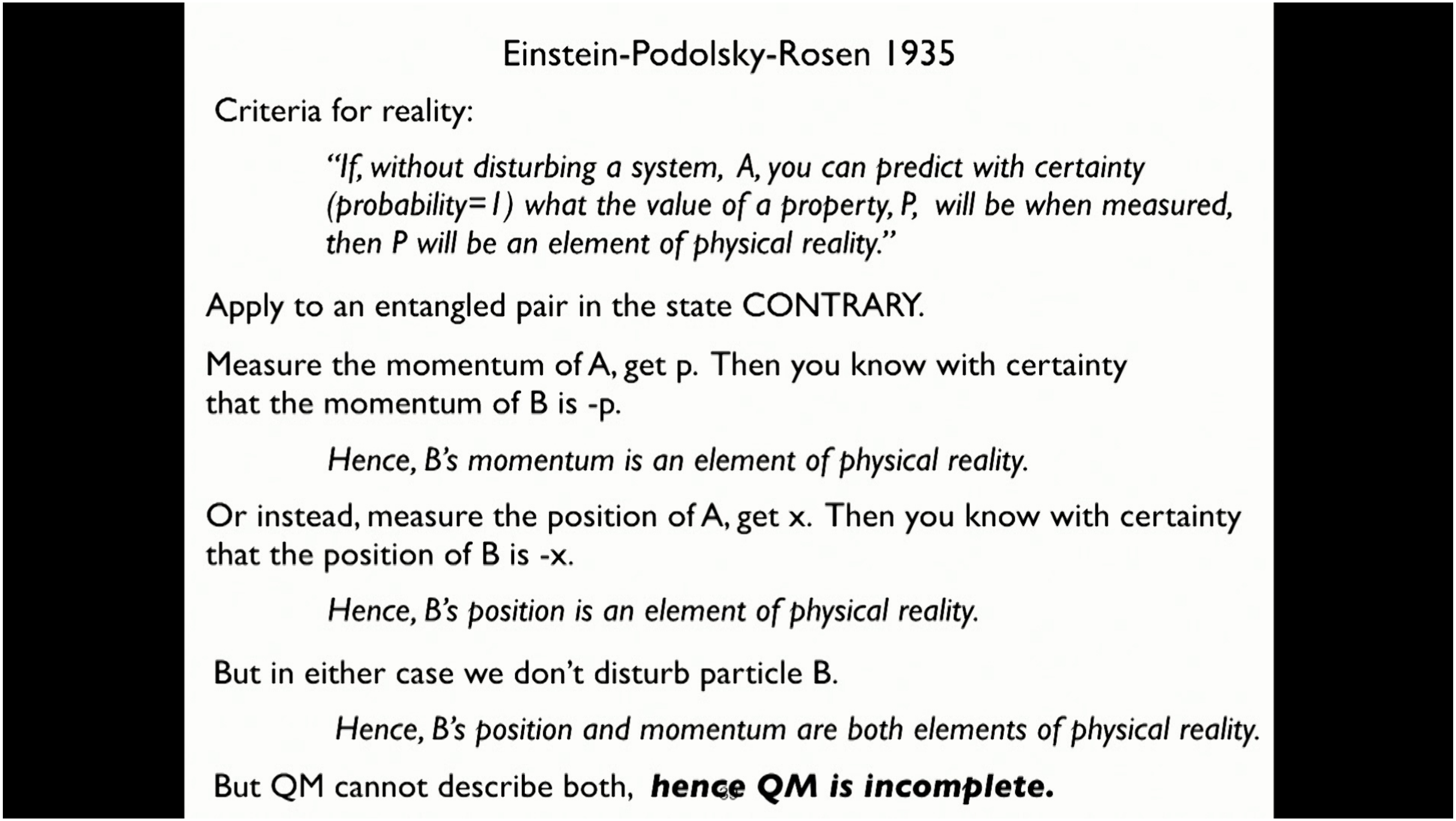

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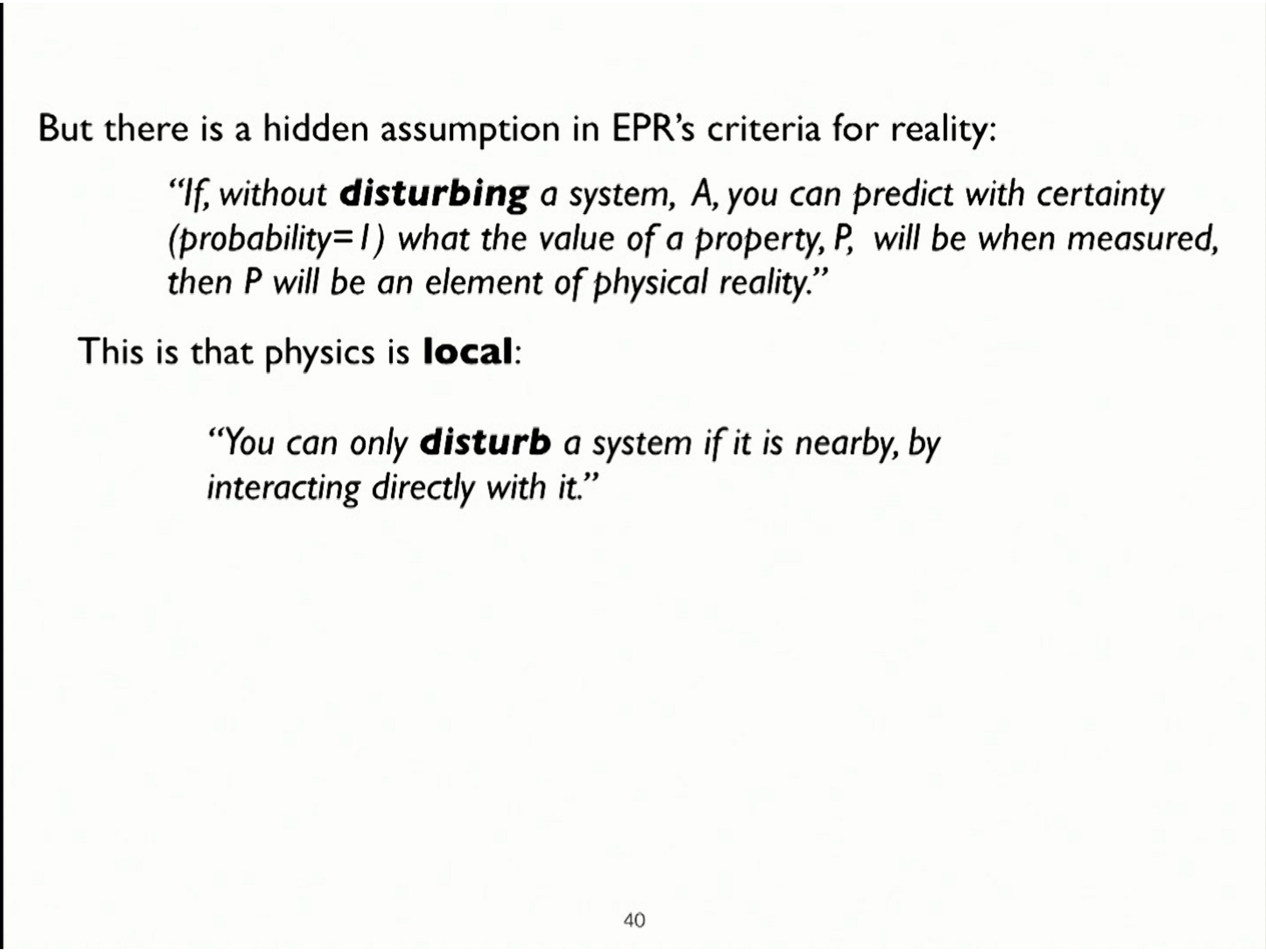
But in either case we don't disturb particle B.

> *Hence, B's position and momentum are both elements of physical reality.*

But QM cannot describe both, ***hence QM is incomplete.***



But there is a hidden assumption in EPR's criteria for reality:

> *"If, without* ***disturbing*** *a system, A, you can predict with certainty (probability=1) what the value of a property, P, will be when measured, then P will be an element of physical reality."*

This is that physics is **local**:

> *"You can only* ***disturb*** *a system if it is nearby, by interacting directly with it."*

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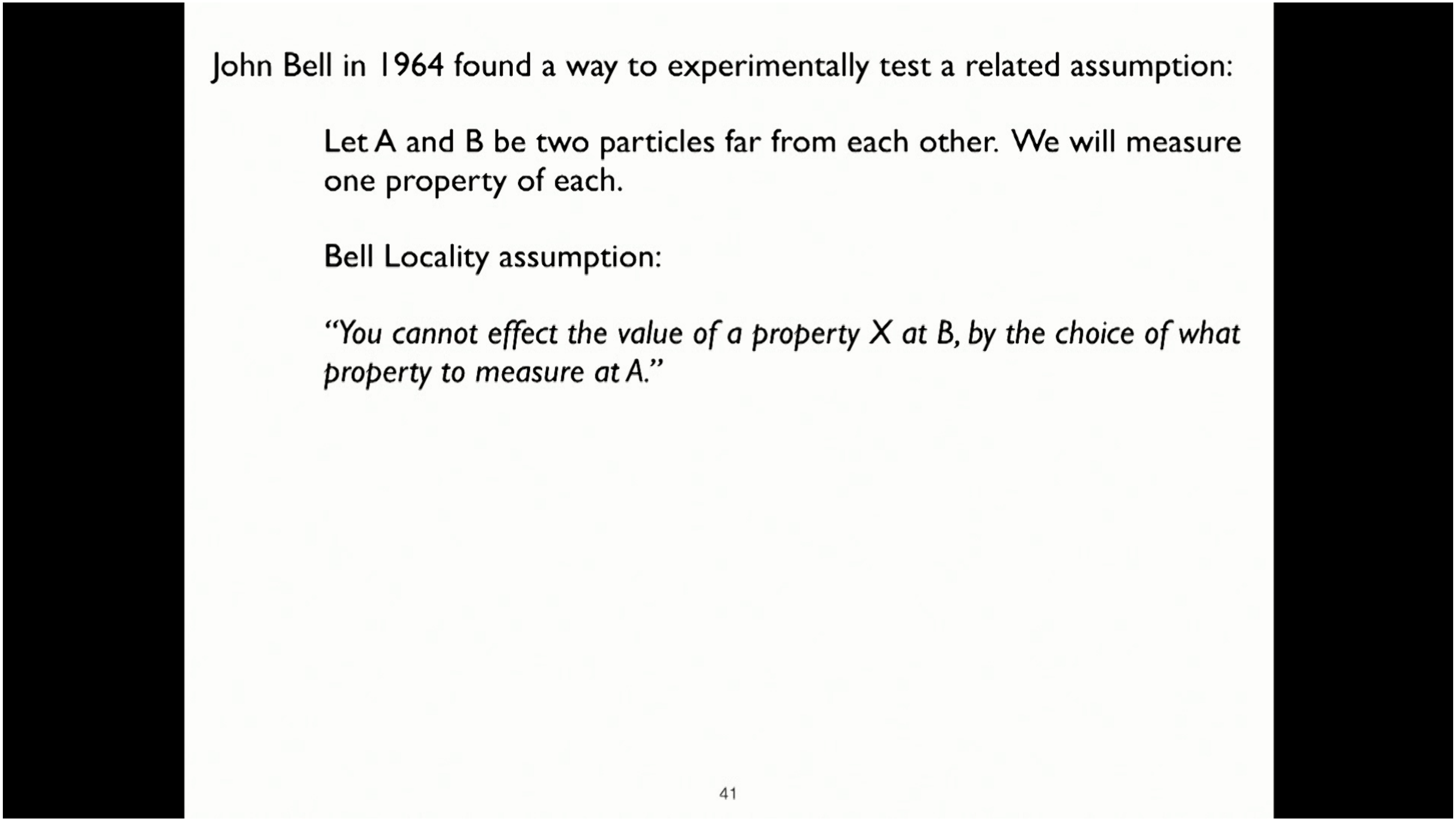
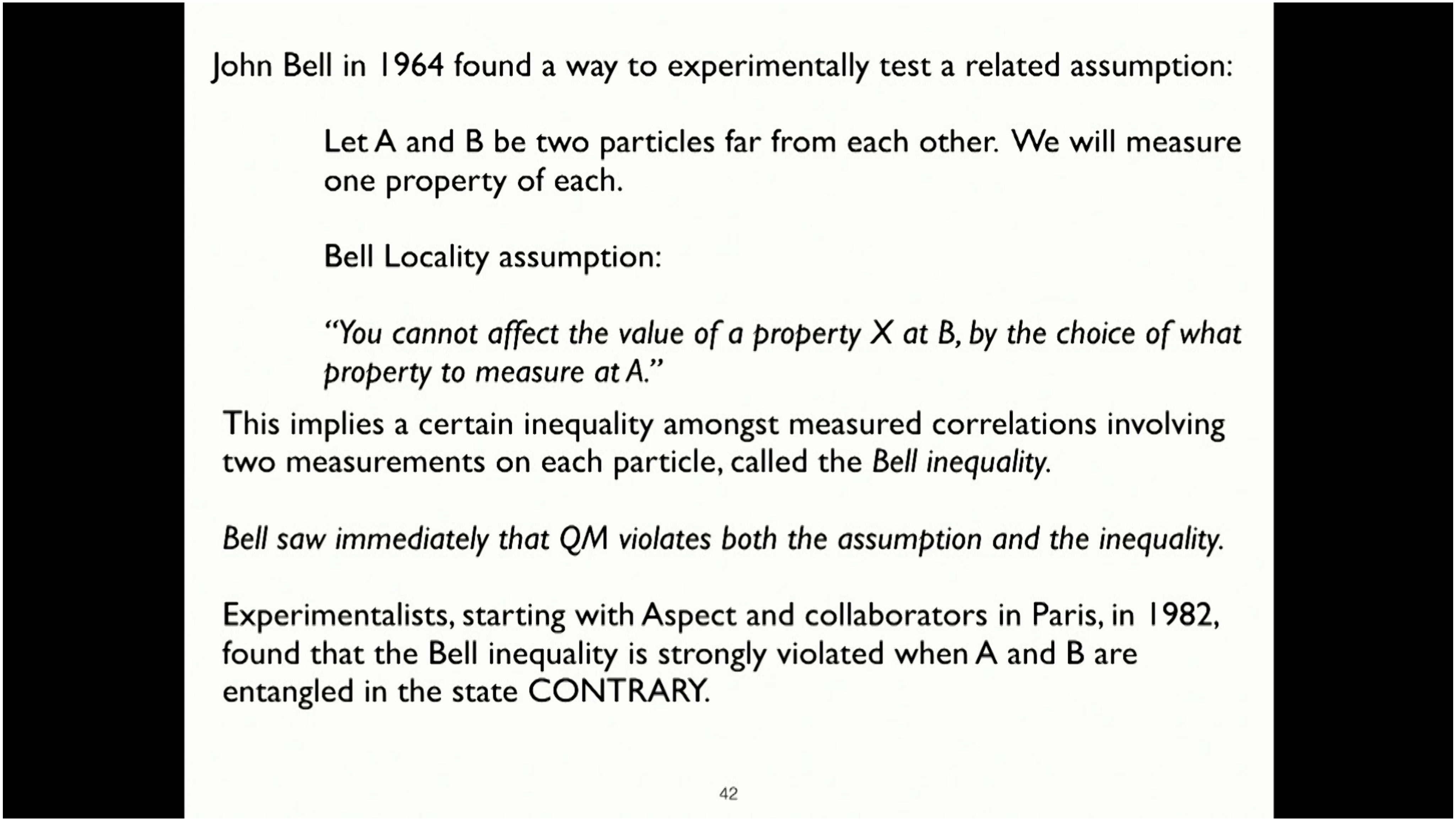


John Bell in 1964 found a way to experimentally test a related assumption:

Let A and B be two particles far from each other. We will measure one property of each.

Bell Locality assumption:

"You cannot effect the value of a property X at B, by the choice of what property to measure at A."



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> Bell Locality assumption:
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> *"You cannot affect the value of a property X at B, by the choice of what property to measure at A."*

This implies a certain inequality amongst measured correlations involving two measurements on each particle, called the *Bell inequality.*

Bell saw immediately that QM violates both the assumption and the inequality.

Experimentalists, starting with Aspect and collaborators in Paris, in 1982, found that the Bell inequality is strongly violated when A and B are entangled in the state CONTRARY.

HENCE: The Bell Locality assumption is false:

> *"You* **can** *affect the value of a property X at B, by the choice of what property to measure at A."*
>
> *Not just in QM but in nature:*

HENCE: The Bell Locality assumption is false:

> *"You **can** affect the value of a property X at B, by the choice of what property to measure at A."*
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> *Not just in QM but in nature:*

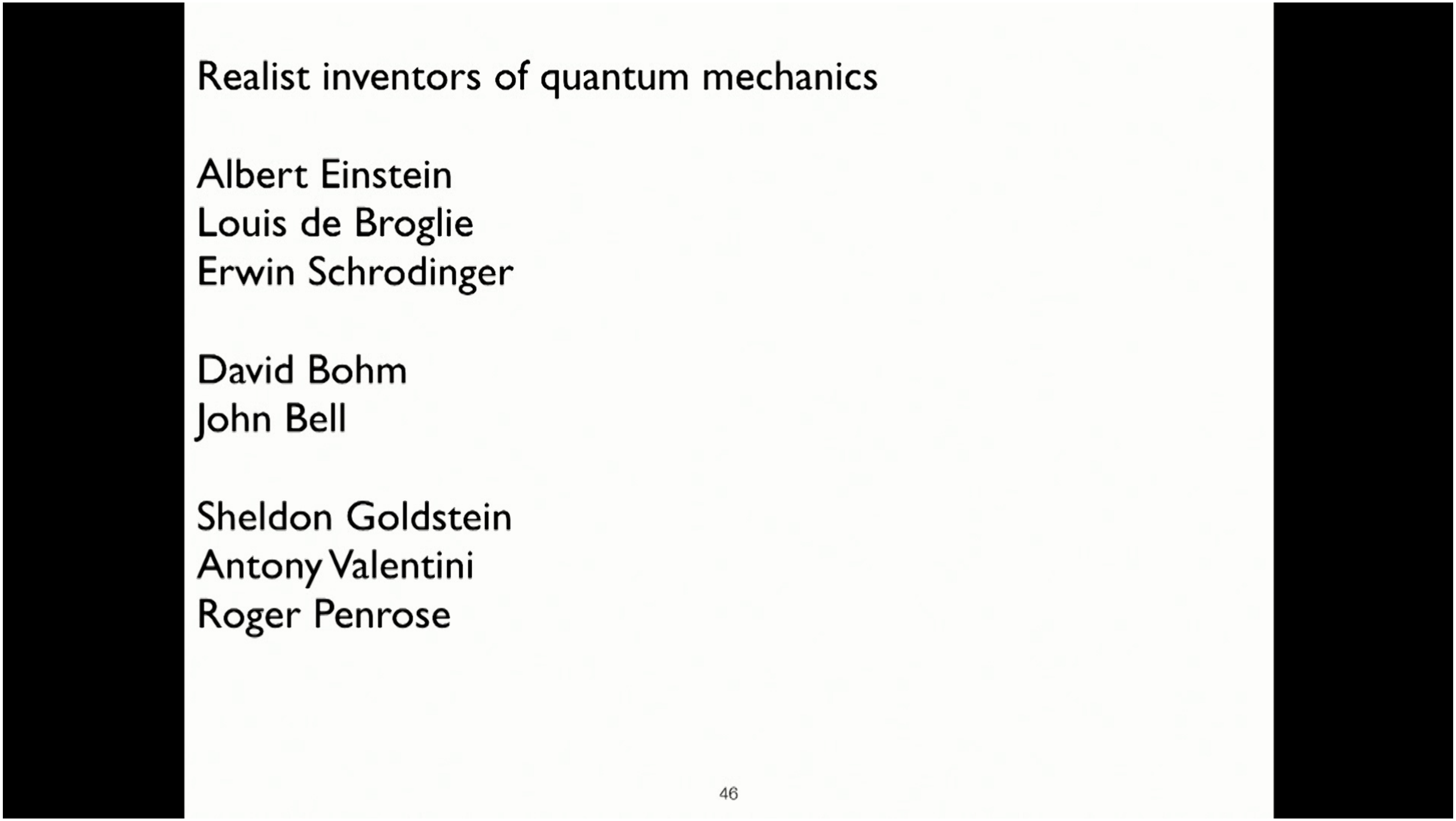
HENCE: Any completion of QM which gives a detailed description of the non-local correlations in entangled pairs will have to include explicit non-local interactions.

This is true in all the examples of realist completions of QM.

Many of the inventors of quantum mechanics were anti-realists

Niels Bohr
Werner Heisenberg
John von Neumann
Wolfgang Pauli

Their writings are grouped loosely as the Copenhagen interpretation



Realist inventors of quantum mechanics

Albert Einstein
Louis de Broglie
Erwin Schrodinger

David Bohm
John Bell

Sheldon Goldstein
Antony Valentini
Roger Penrose