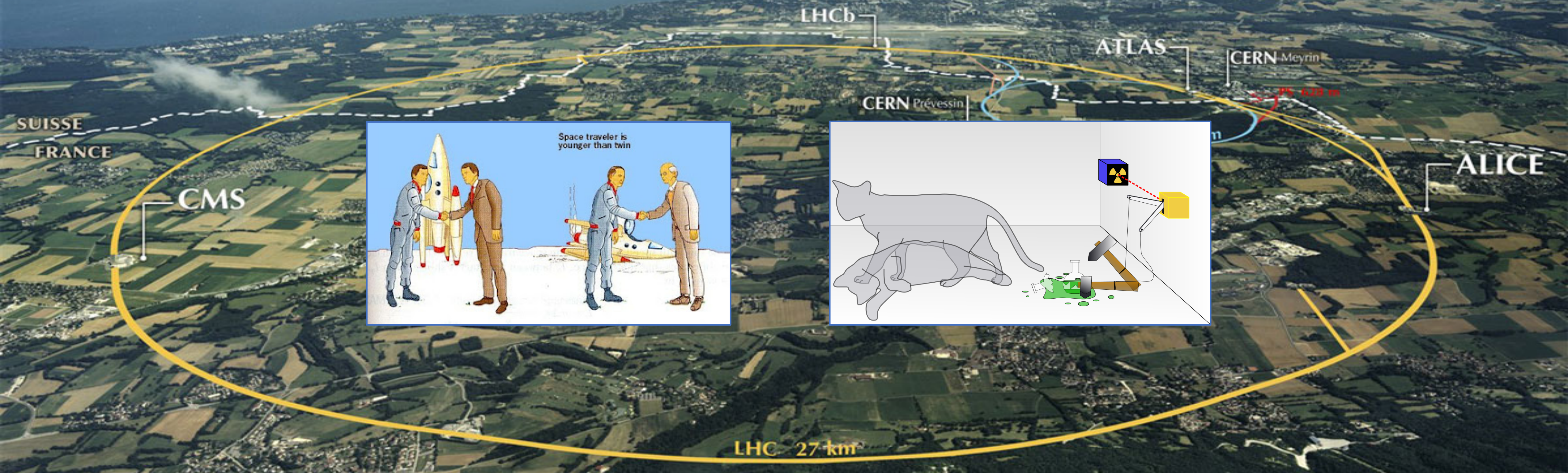
The Relativistic Quantum World

A lecture series on Relativity Theory and Quantum Mechanics

Marcel Merk



University of Maastricht, Sept 16 – Oct 14, 2020

The Relativistic Quantum World

Relativity

Sept. 16:
Lecture 1: The Principle of Relativity and the Speed of Light
Lecture 2: Time Dilation and Lorentz Contraction

Sept. 23:
Lecture 3: The Lorentz Transformation and Paradoxes
Lecture 4: General Relativity and Gravitational Waves

Quantum Mechanics

Sept. 30:
Lecture 5: The Early Quantum Theory
Lecture 6: Feynman's Double Slit Experiment

Oct. 7:
Lecture 7: Wheeler's Delayed Choice and Schrodinger's Cat
Lecture 8: Quantum Reality and the EPR Paradox

Standard Model

Oct. 14:
Lecture 9: The Standard Model and Antimatter
Lecture 10: The Large Hadron Collider

Lecture notes, written for this course, are available: www.nikhef.nl/~i93/Teaching/
Prerequisite for the course: High school level physics & mathematics.

Nobel Prize in Physics (Oct 6, 2020) – Black Holes

½ : Roger Penrose

For the discovery that black hole formation is a robust prediction of the general theory of relativity.

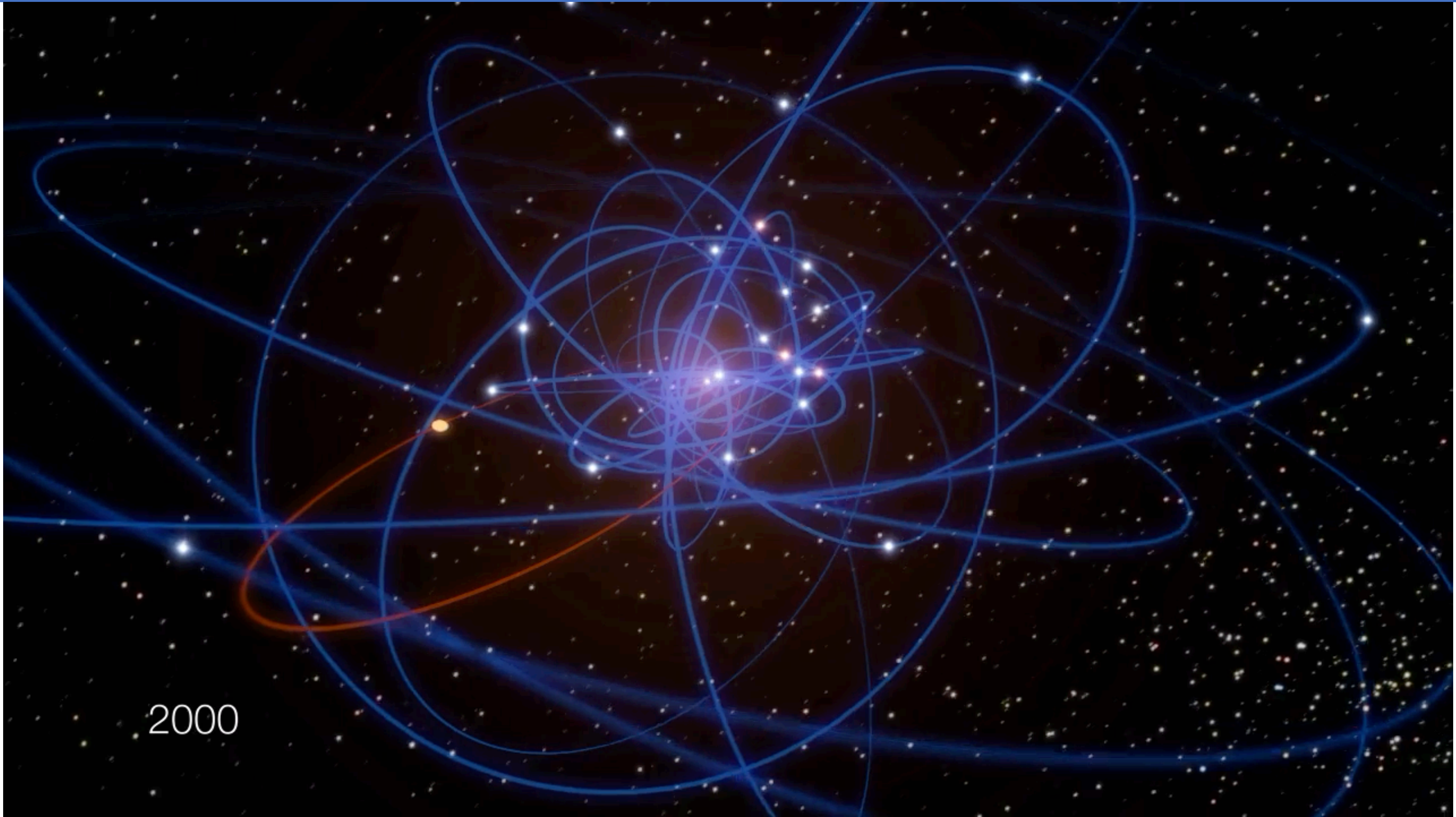
¼ : Reinhard Genzel

¼ : Andrea Ghez

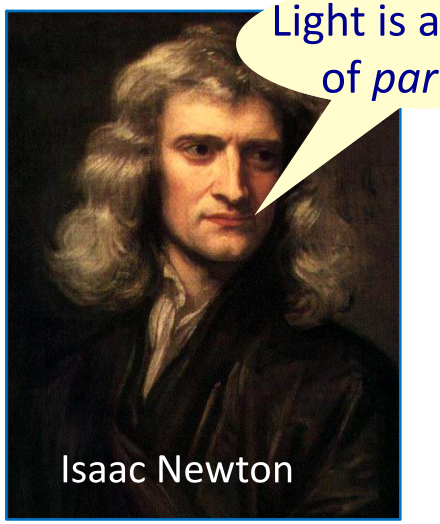
For the discovery of a supermassive compact object at the centre of our galaxy.

Center of our Milky Way Galaxy

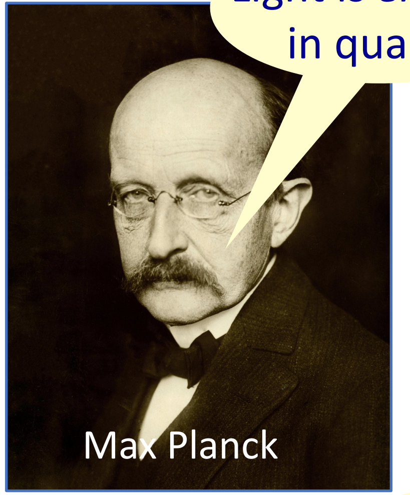
Supermassive Black Hole in the center of our Galaxy



Quantum Mechanics


Isaac Newton

Light is a stream of *particles*

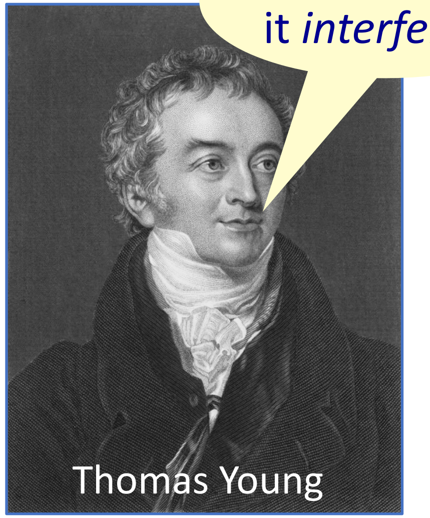

Max Planck

Light is *emitted* in quanta

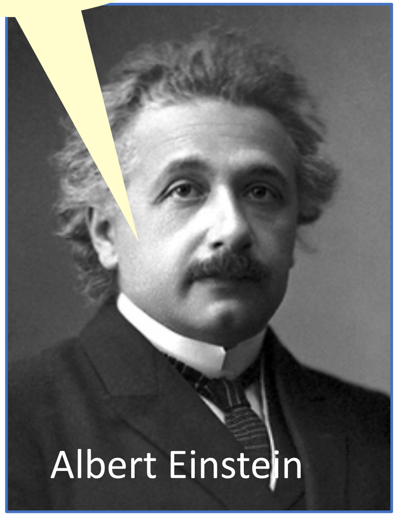
No, similar to sound light consists of *waves*


Christiaan Huygens

Yes, because it *interferes*


Thomas Young

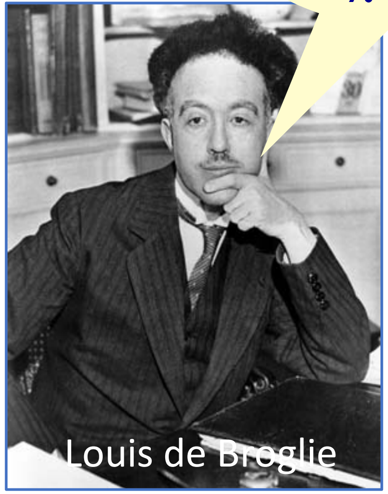
The *nature* of light is quanta


Albert Einstein

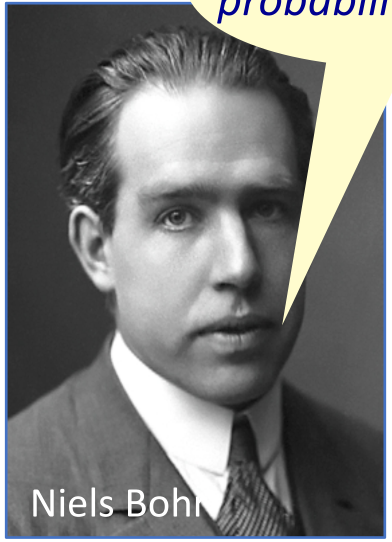
Yes, because photons collide!


Arthur Compton

Particles have a *wave nature*: $\lambda = h/p$

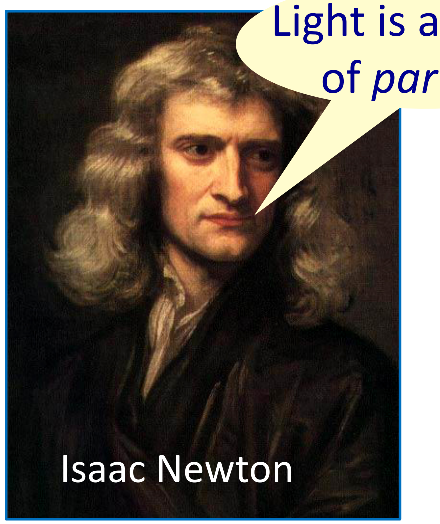

Louis de Broglie

Particles are *probability waves*


Niels Bohr

Quantum Mechanics

Light is a stream of *particles*



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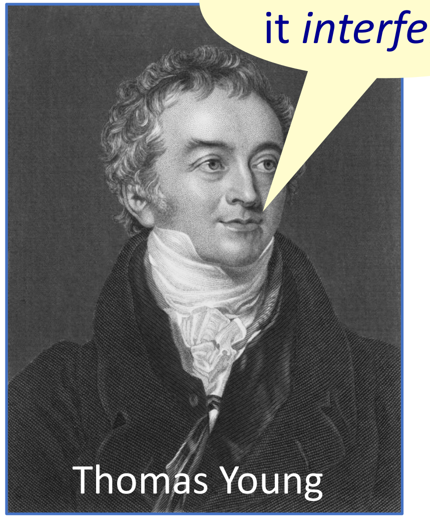
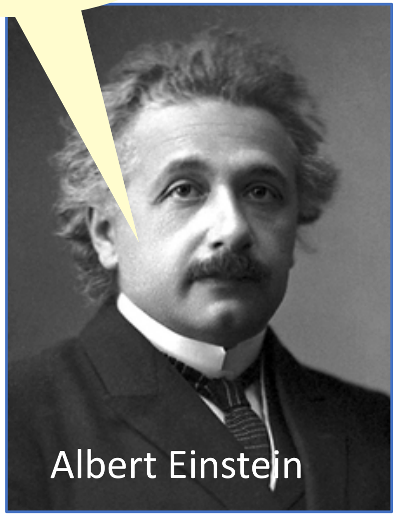


Thomas Young

"Particle" and "Wave" are complementary aspects.

The *nature* of light is quanta



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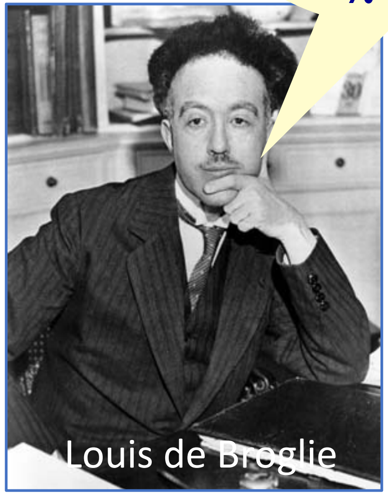
$\lambda = h/p$



Louis de Broglie

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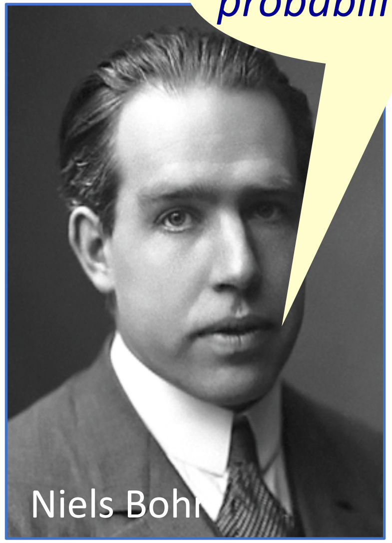


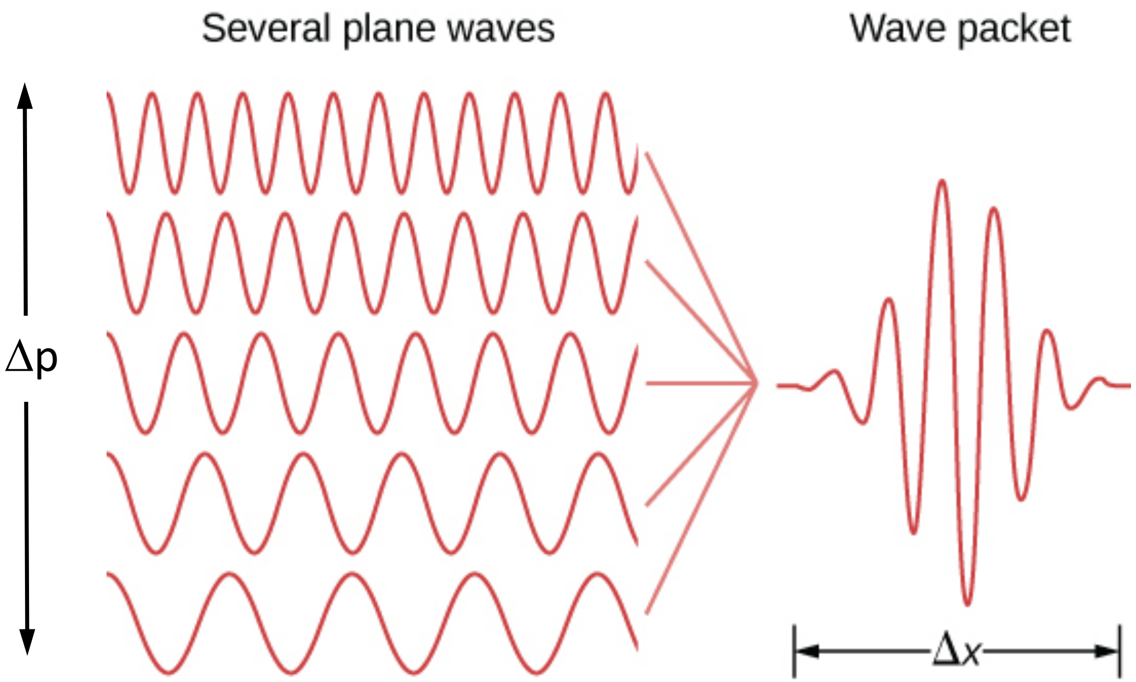
Niels Bohr

Uncertainty Relation

$$\Delta x \, \Delta p \geq \frac{\hbar}{2}$$

It is *not* possible to determine ***position*** and ***momentum*** at the same time:

Werner Heisenberg



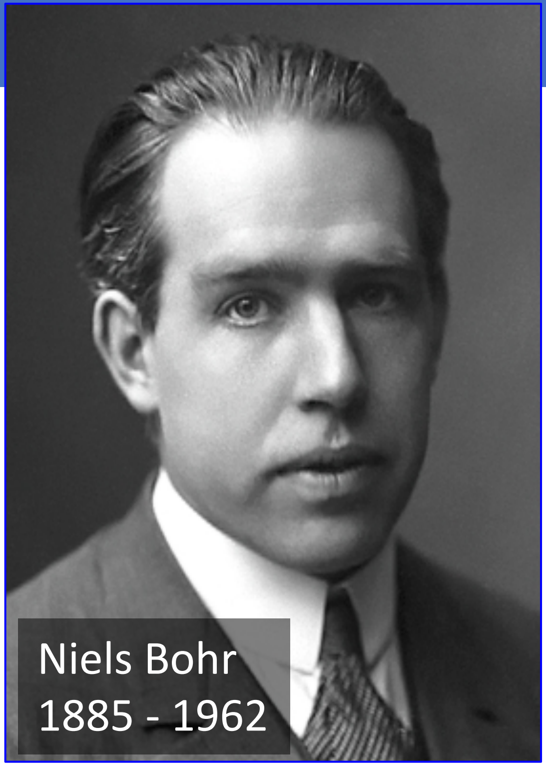
Erwin Schrödinger

$$p = \frac{h}{\lambda} = \frac{hf}{c}$$

A particle ***does not have*** well defined position and momentum at the same time.

Complementarity

Subatomic matter is not just waves and it is not just particles.
It is nothing we know from macroscopic world.



Niels Bohr
1885 - 1962

Copenhagen Interpretation (Niels Bohr, Max Born): $\boldsymbol{Prob(x,t) = |\psi(x,t)|^2}$

One can observe wave ***or*** particle characteristics of quantum objects, ***never both*** at the same time.

Particle and Wave aspects of a physical object are ***complementary***

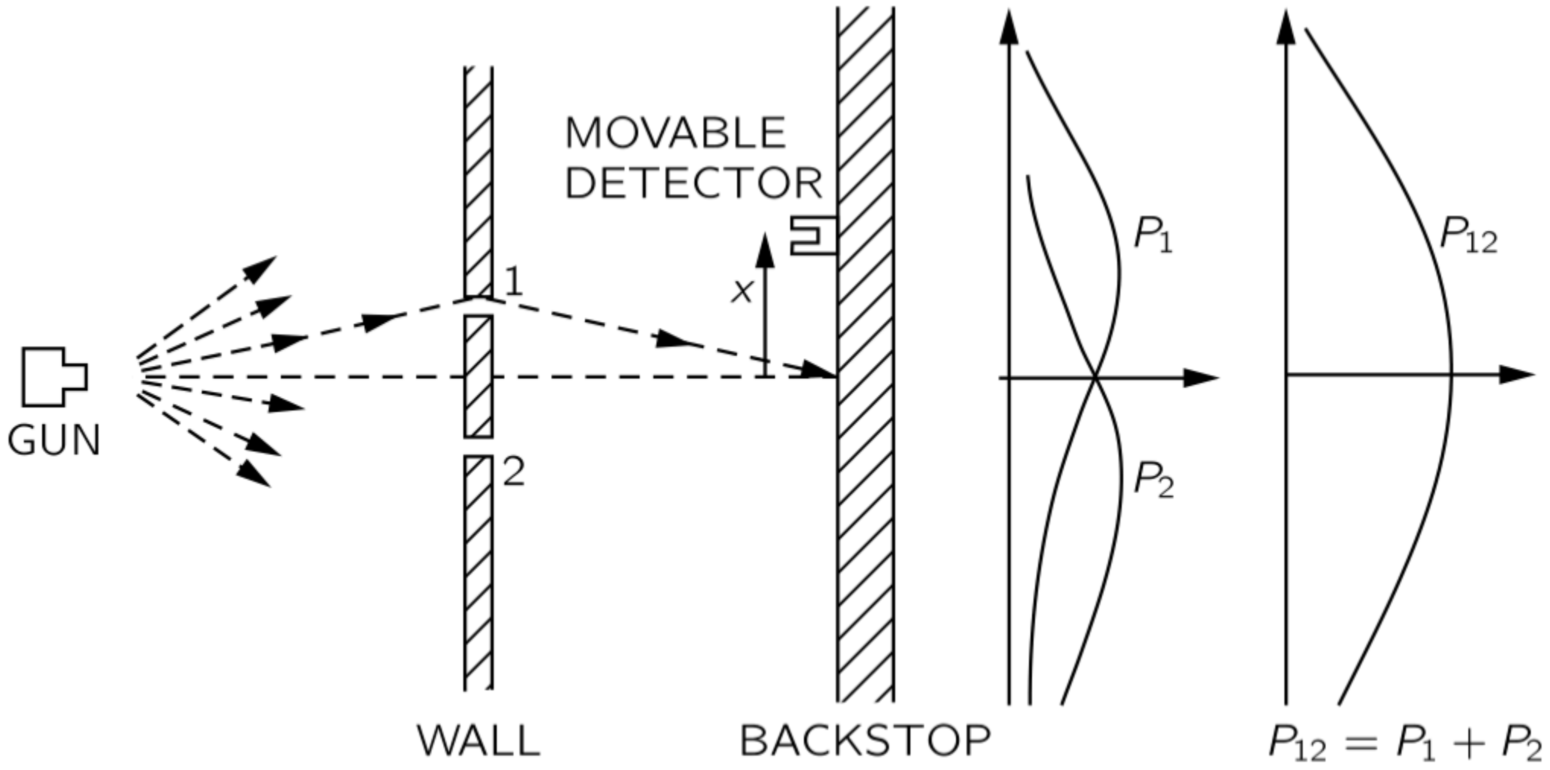
Similarly one can never determine from a quantum object at the same time:
energy and time, ***position and momentum*** and more (eg. ***spin components***).

Richard Feynman and the double slit experiment

The double slit experiment demonstrates the fundamental aspect of the quantum world.

Case 1: Experiment with Bullets

A gun fires bullets in random direction. Slits 1 and 2 are openings through which bullets can pass. A moveable detector "collects" bullets and counts them.



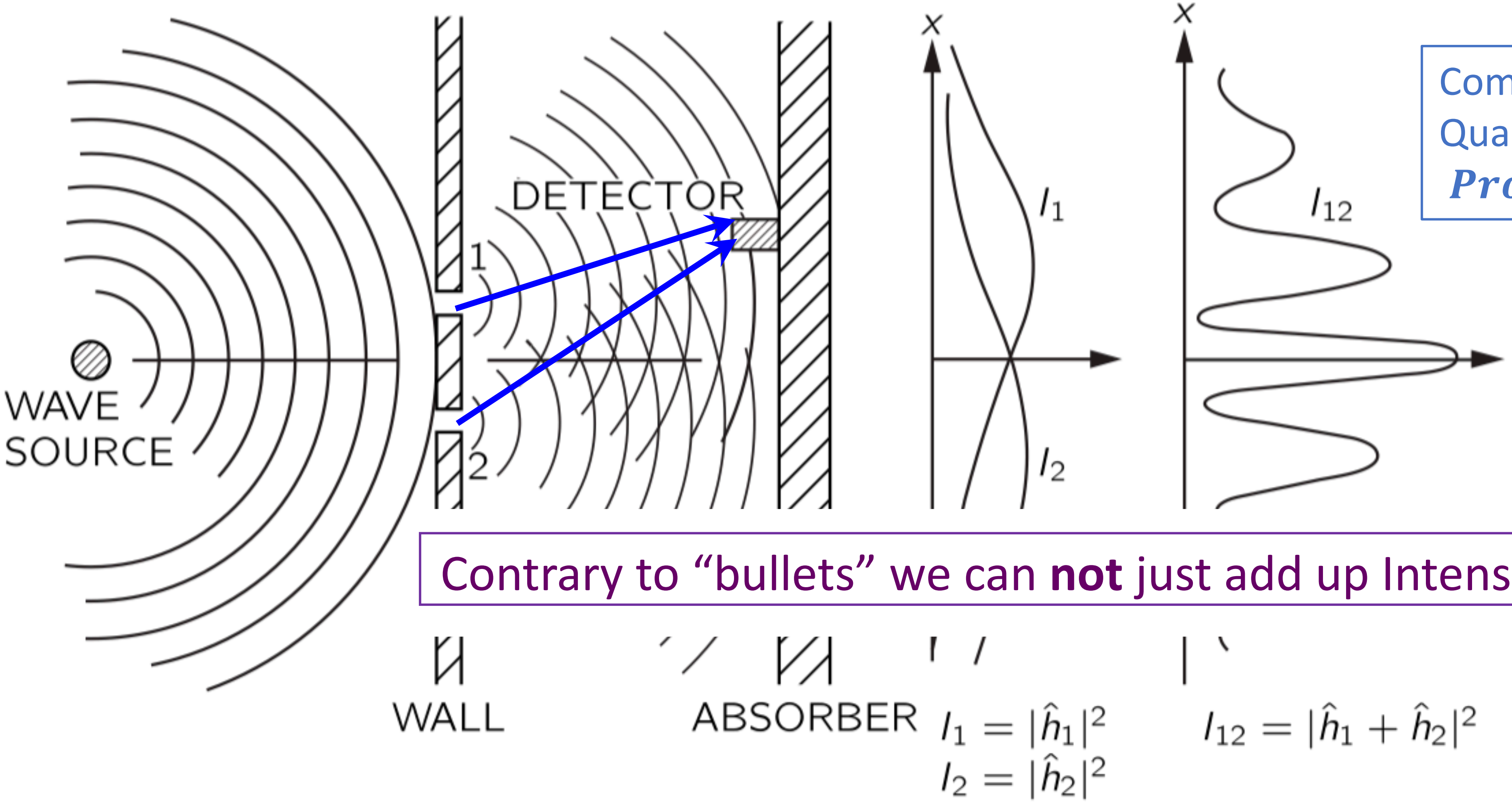
P_1 is the probability curve when only slit 1 is open
P_2 is the probability curve when only slit 2 is open

When both slits are open: $P_{12} = P_1 + P_2$

We can just add up the probabilities.

Case 2: Experiment with Waves

When both slits are open there are two contributions to the wave the oscillation at the detector: $R(t) = R_1(t) + R_2(t)$



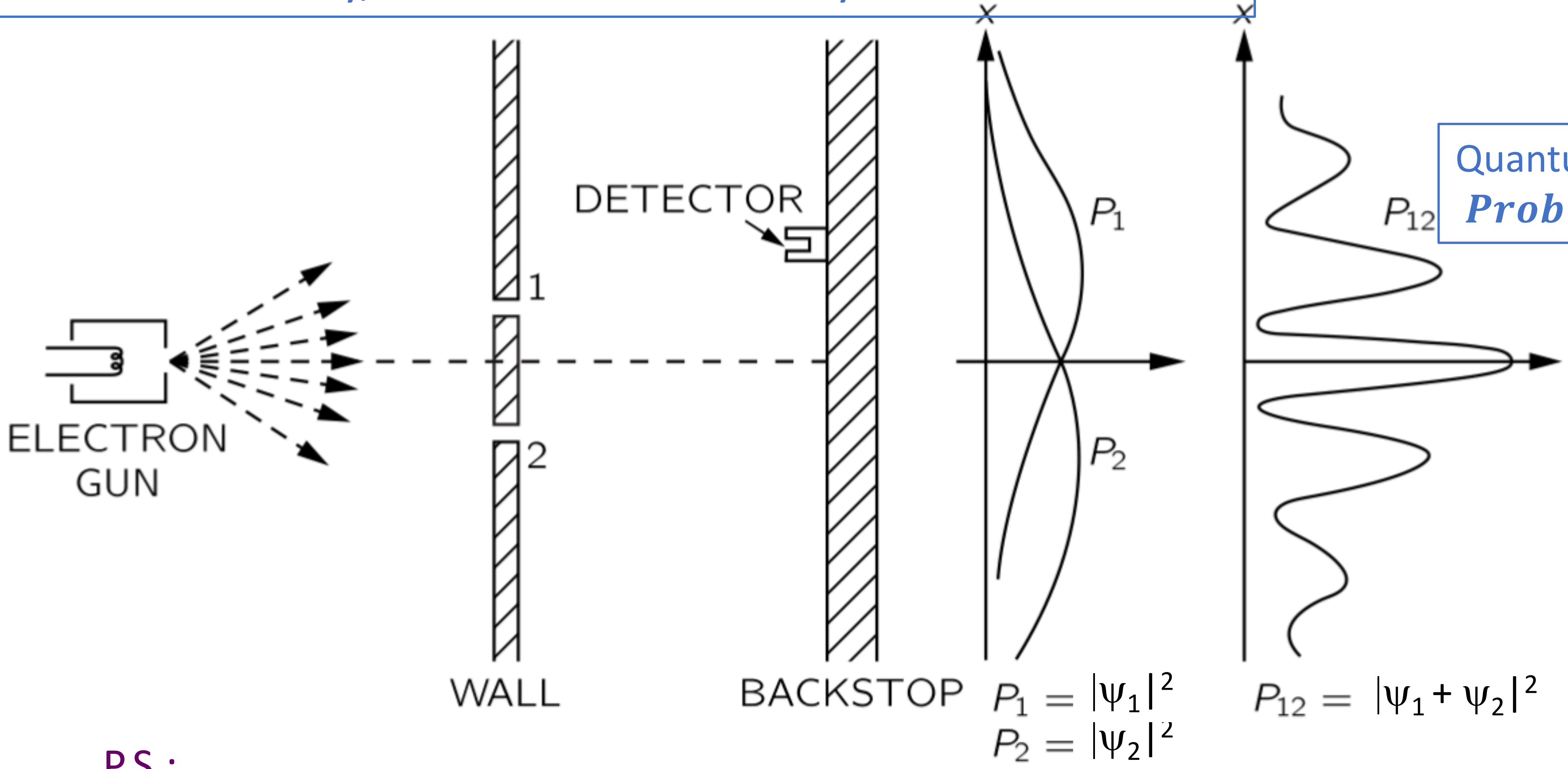
Compare to Quantum Waves:
$\boldsymbol{Prob(x,t) = |\psi(x,t)|^2}$

Contrary to “bullets” we can **not** just add up Intensities.

Interference pattern: $I_{12} = |R_1 + R_2|^2 = h_1^2 + h_2^2 + 2h_1h_2\cos(\Delta\phi)$
Regions where waves are *amplified* and regions where waves are *cancelled*.

Case 3: Experiment with Electrons

Perhaps the electrons interfere with each other.
Reduce the intensity, shoot electrons one by one: same result.



Quantum Waves:
$\boldsymbol{Prob(x,t) = |\psi(x,t)|^2}$

P.S.:
Classically, light behaves light waves. However, if you shoot light, photon per photon, it "comes in lumps", just like electrons.
Quantum Mechanics: for photons it is the same story as for electrons.

Case 3: Experiment with Electrons

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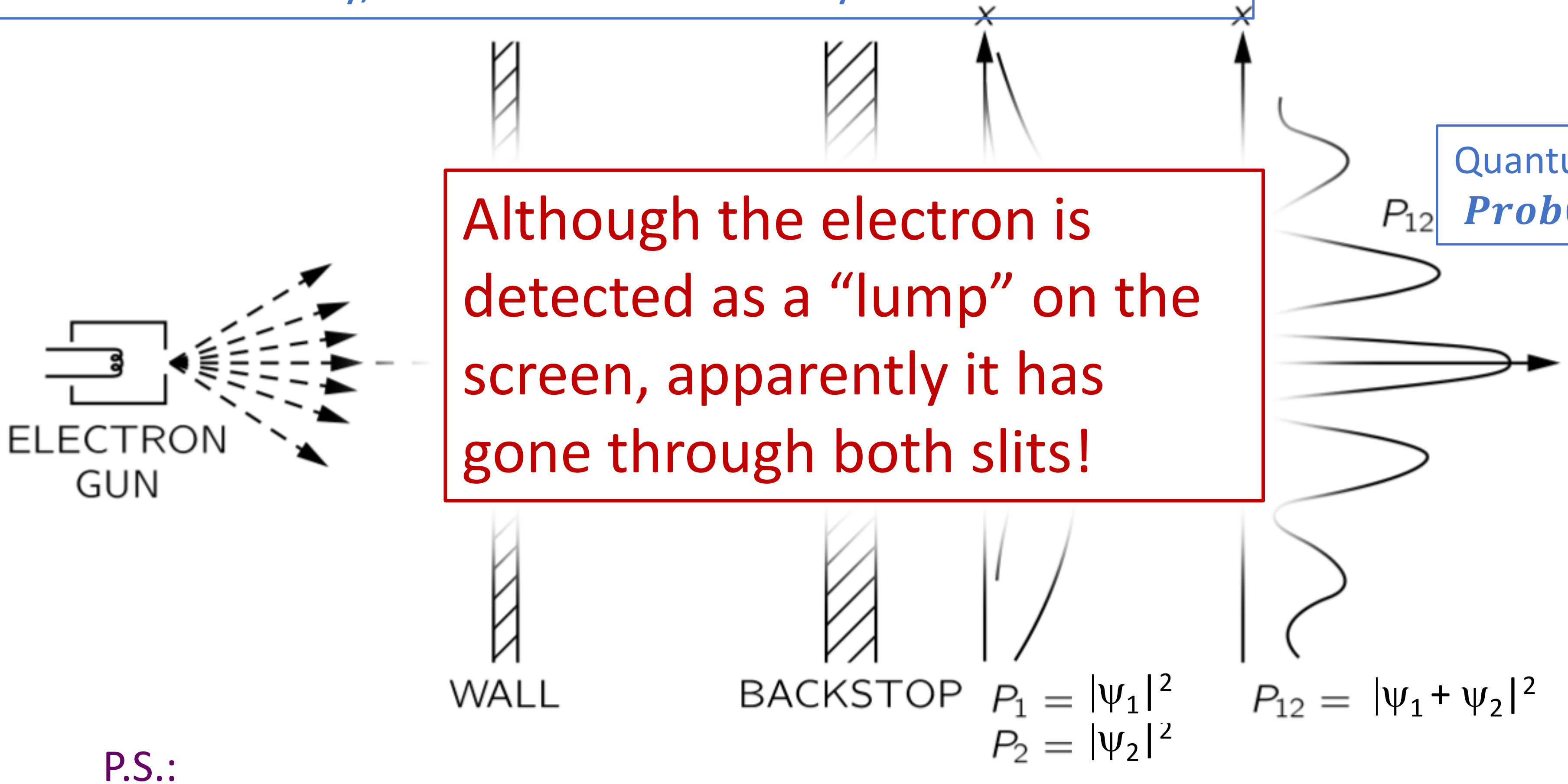


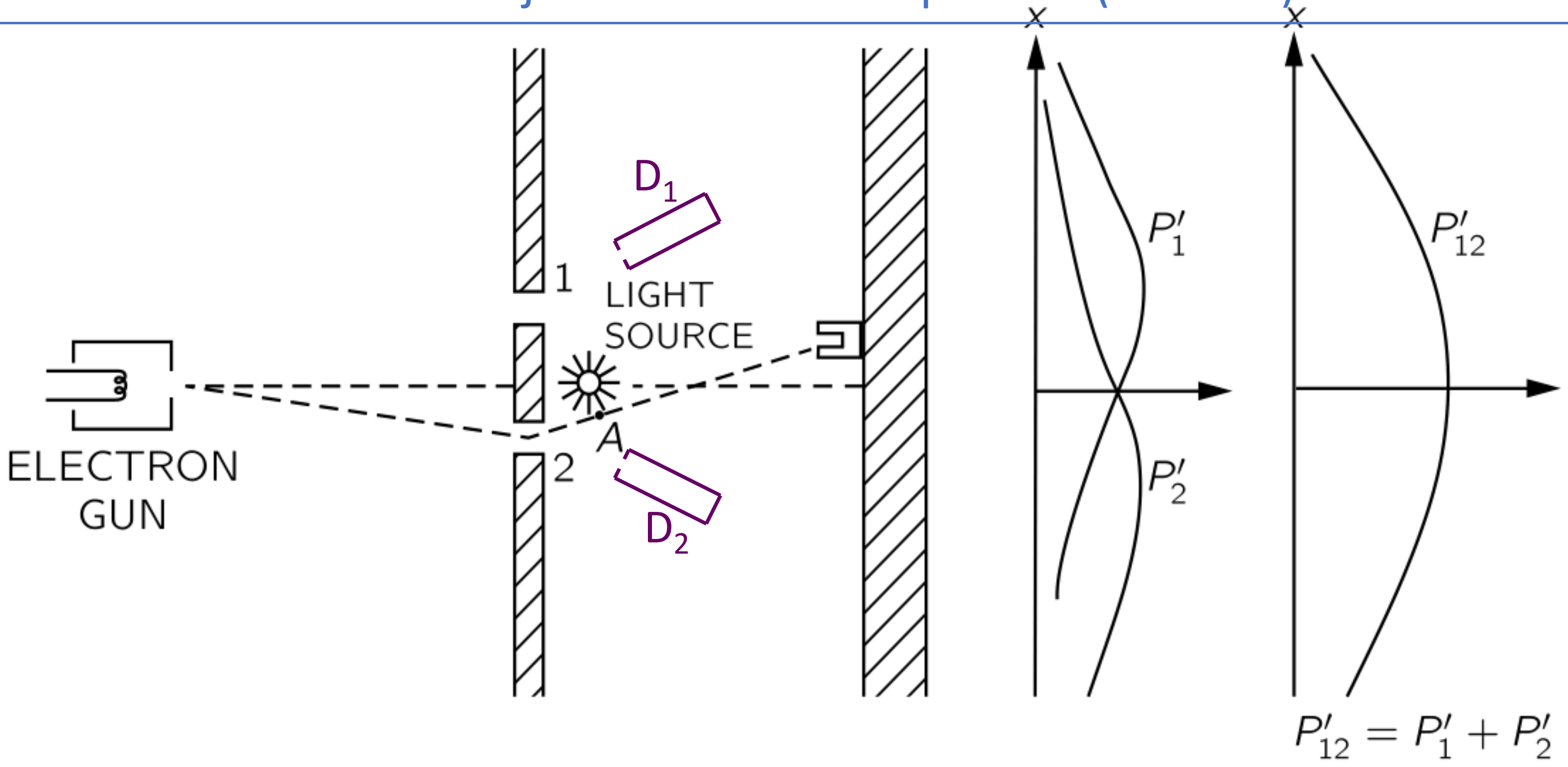
Although the electron is detected as a “lump” on the screen, apparently it has gone through both slits!

Quantum Waves:
$$\boldsymbol{Prob(x,t) = |\psi(x,t)|^2}$$

P.S.:
Classically, light behaves light waves. However, if you shoot light, photon per photon, it “comes in lumps”, just like electrons.
Quantum Mechanics: for photons it is the same story as for electrons.

Case 4: Watch the Electrons

When we watch through which slit the electrons go, we destroy the interference!
Now the electron behaves just like a classical particle (“bullet”).



If you watch ***half the time***; you only get the interference for the cases you ***did not watch***.

It requires an observation to let the quantum wave function “collapse” into reality.
As long as no measurement is made the wave function keeps “all options open”.

Lecture 7

Wheeler's Delayed Choice Experiment

"Your theory is crazy, but not crazy enough to be true."
- Niels Bohr

"Nothing exists, until it is measured."
- Niels Bohr

"I don't like it, and I'm sorry I ever had anything to do with it."
- Erwin Schrödinger

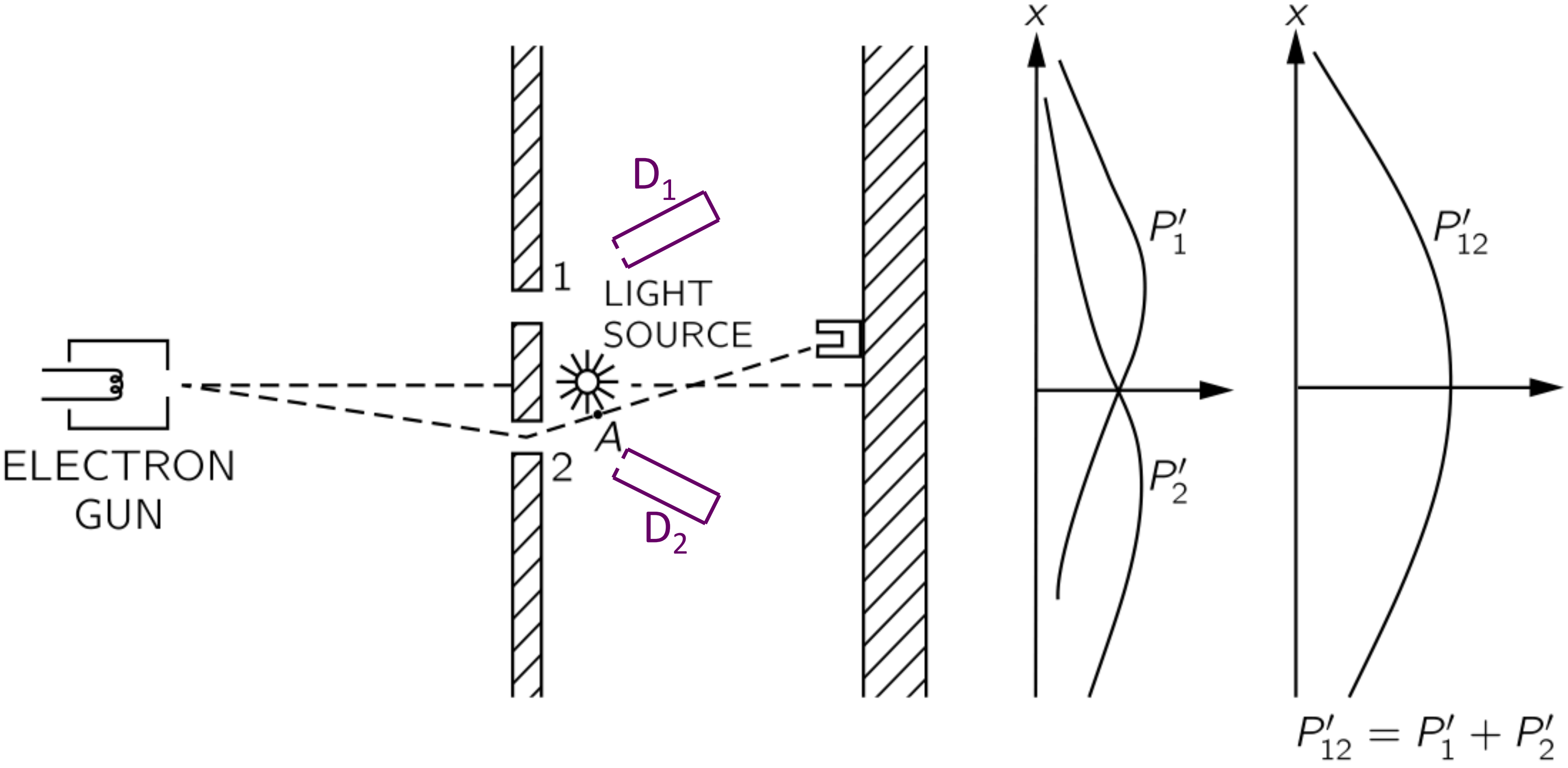
The Double Slit Experiment

Case 5:

The Delayed Choice Experiment

Case 4: Watch the Electrons

Consider again the double slit experiment in which we watch the electrons.

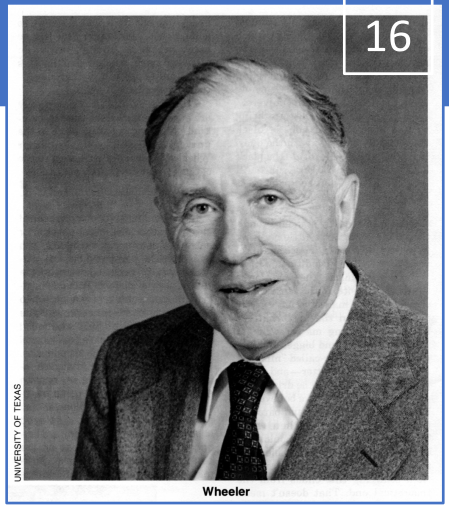


Can we try to “fool” the electron?

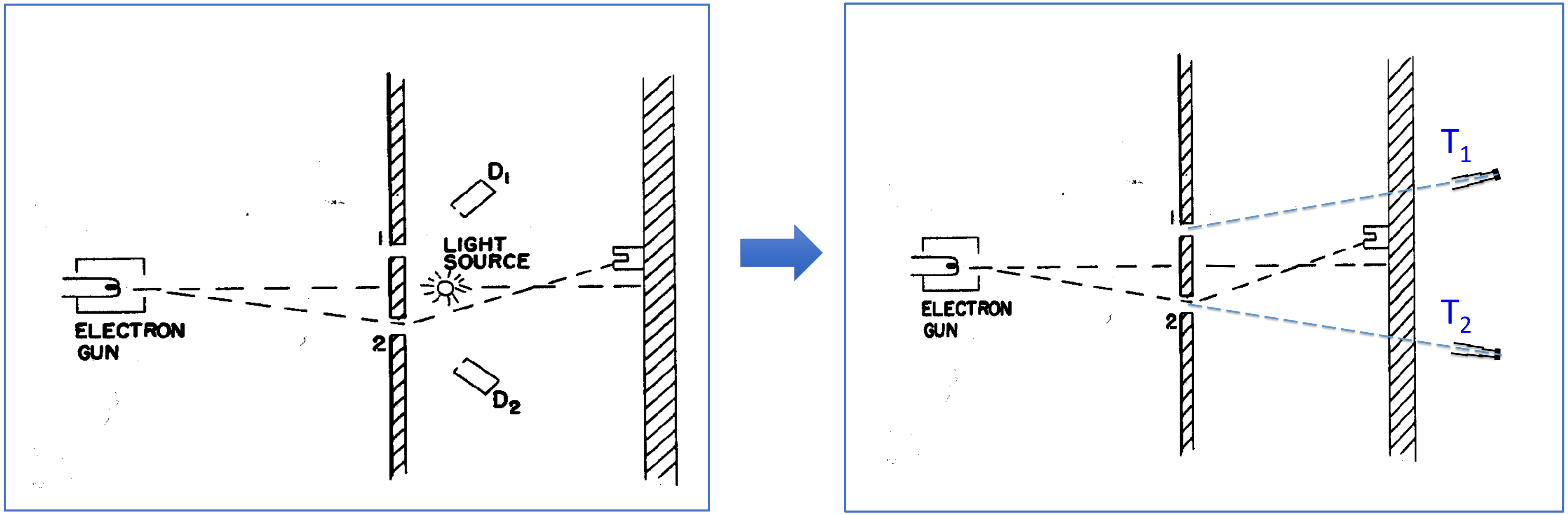
Wheeler's Suggestion (1978)

"The real reason universities have students is to educate the professors"
- John Archibald Wheeler

John Wheeler (1911 – 2008):
Famous for work on gravitation
(Black holes – quantum gravity)



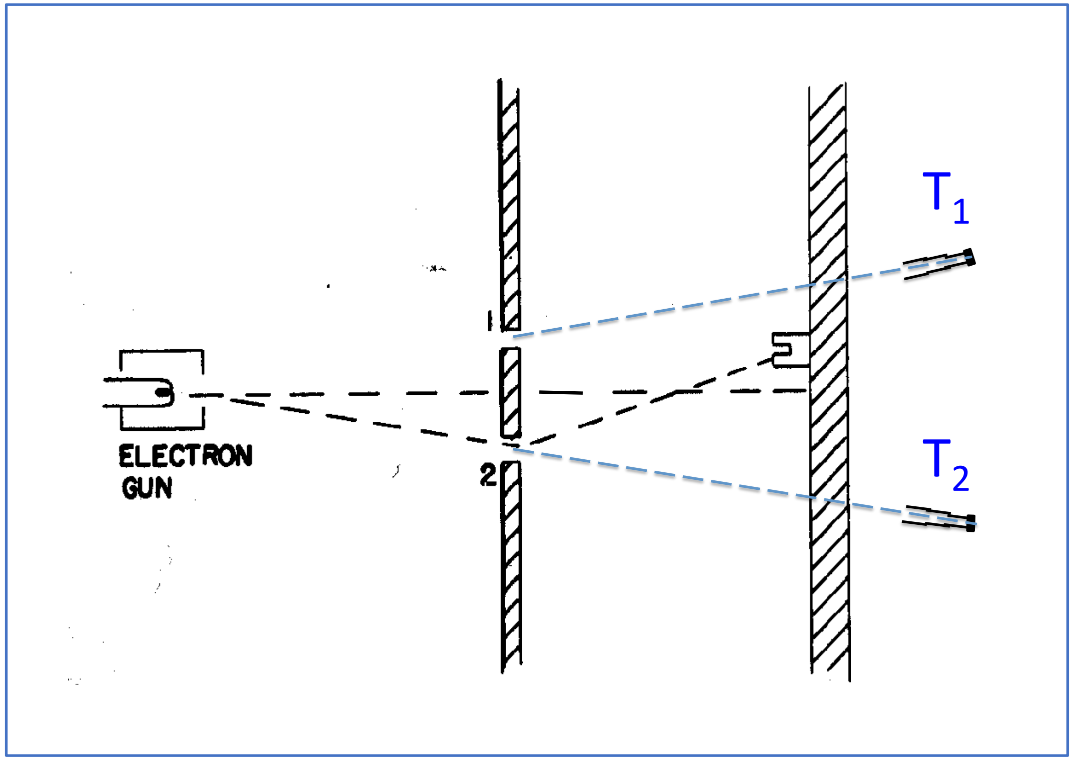
Replace detectors D_1 and D_2 with telescopes T_1 and T_2 which are focused on slits 1 and 2

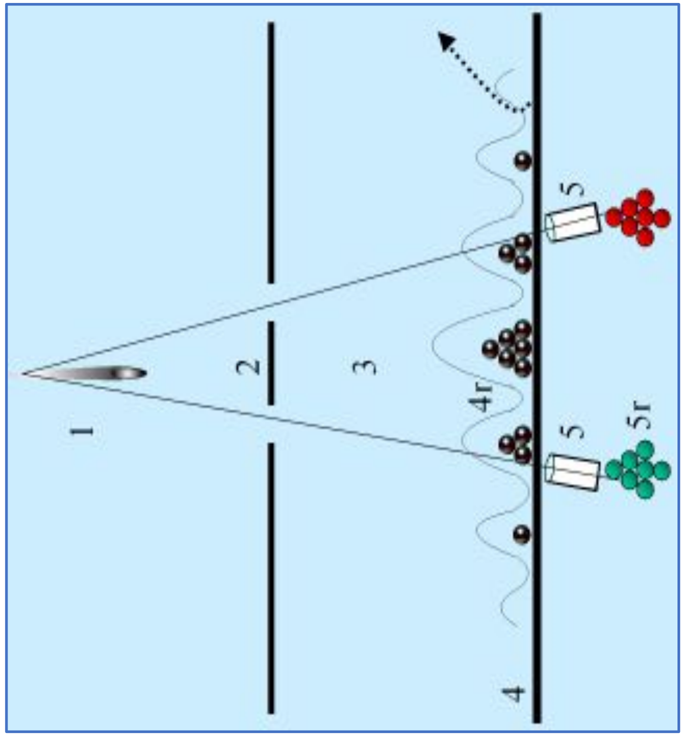


What happens if we ***afterwards check*** whether the electron went through slit 1 or slit 2?

Wheeler’s Delayed Choice Experiment

Even better: we can ***suddenly decide*** to look at the electrons or not.
We decide whether or not to look ***after*** the electrons passed the slits!

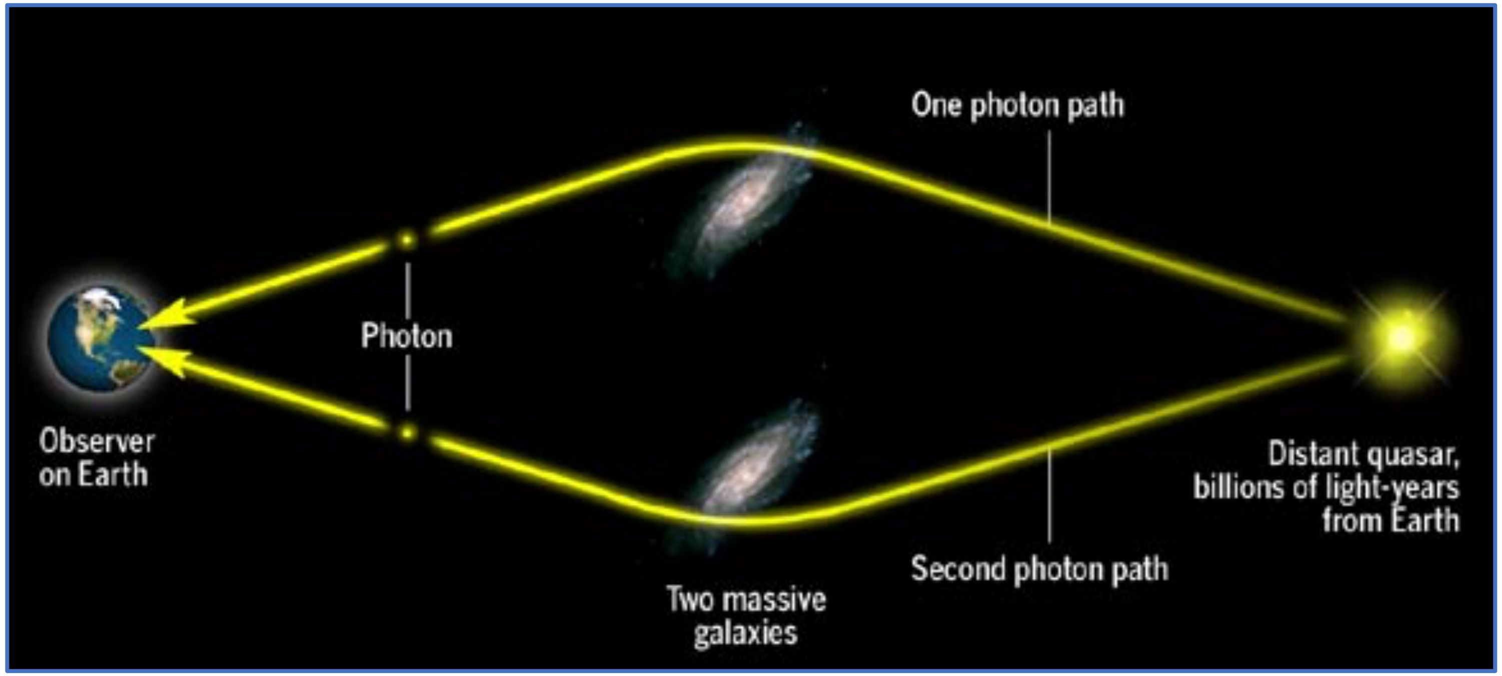


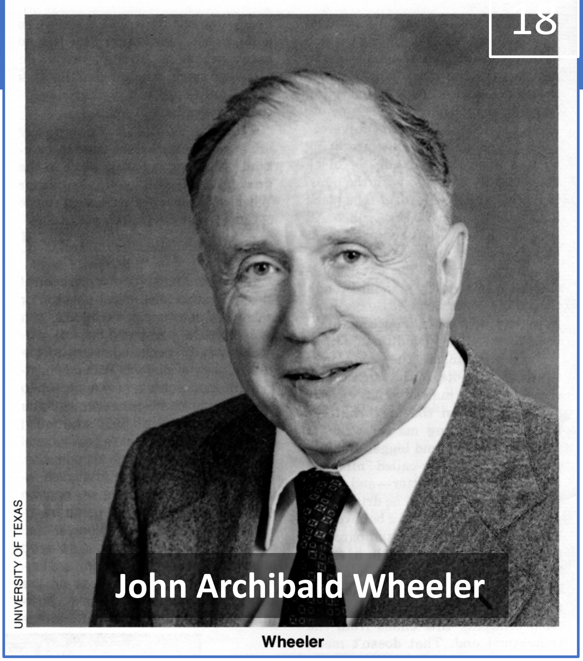


What will we see?
An wave interference (black) pattern or a bullet-like non-interference (red-green) pattern?

Thought Experiment with Gravitational Lensing

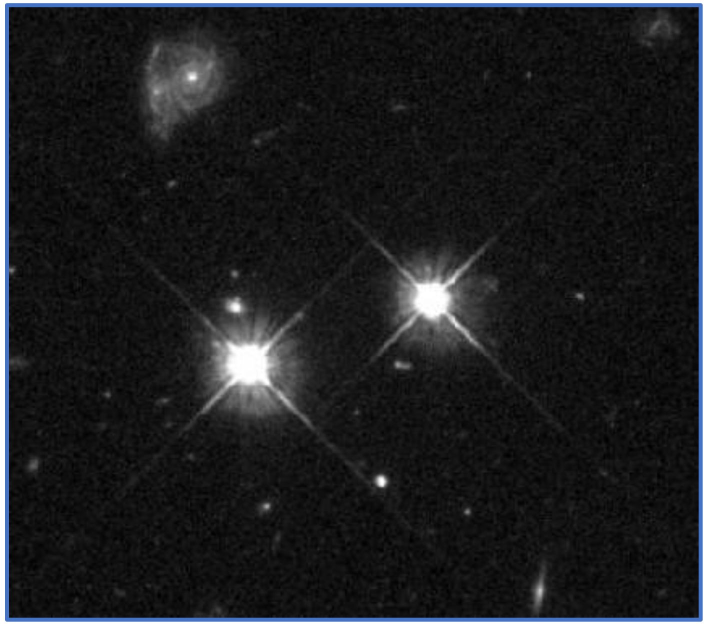
What if we make the distance from slits to screen ***very long***?





- Light beams bend in gravitation field.
- Two different light-paths can arrive in the same position in our eyes/telescope.
- We then see the same object in two locations.

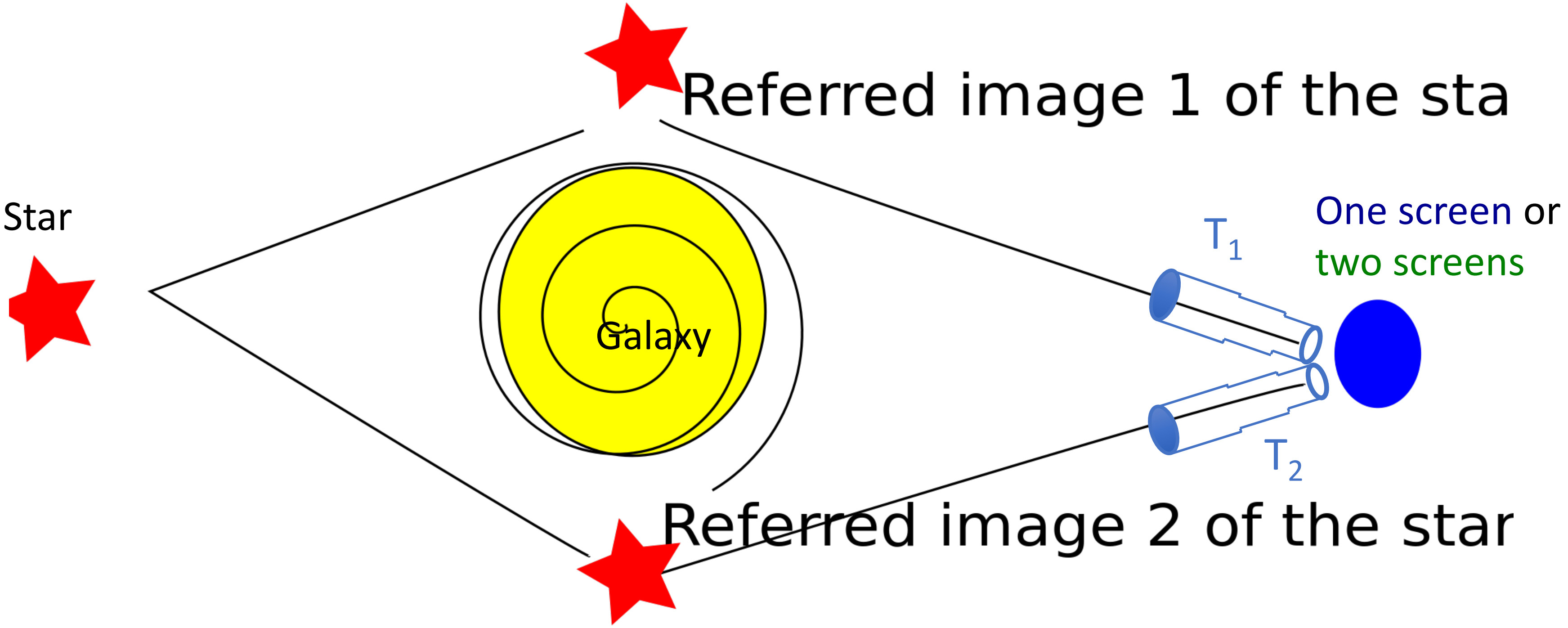
➔ We can make a “double slit” experiment



Wheeler's idea

What if we make the distance from slits to screen ***very long***?

Wheeler uses *"gravitational lensing"* as a "double slit".
In this case the electrons are replaced by photons.



Then, either: Project image of T_1 and T_2 on separate screens, → QM: no interference!
Or: Combine the image of T_1 and T_2 on one screen → QM: interference!

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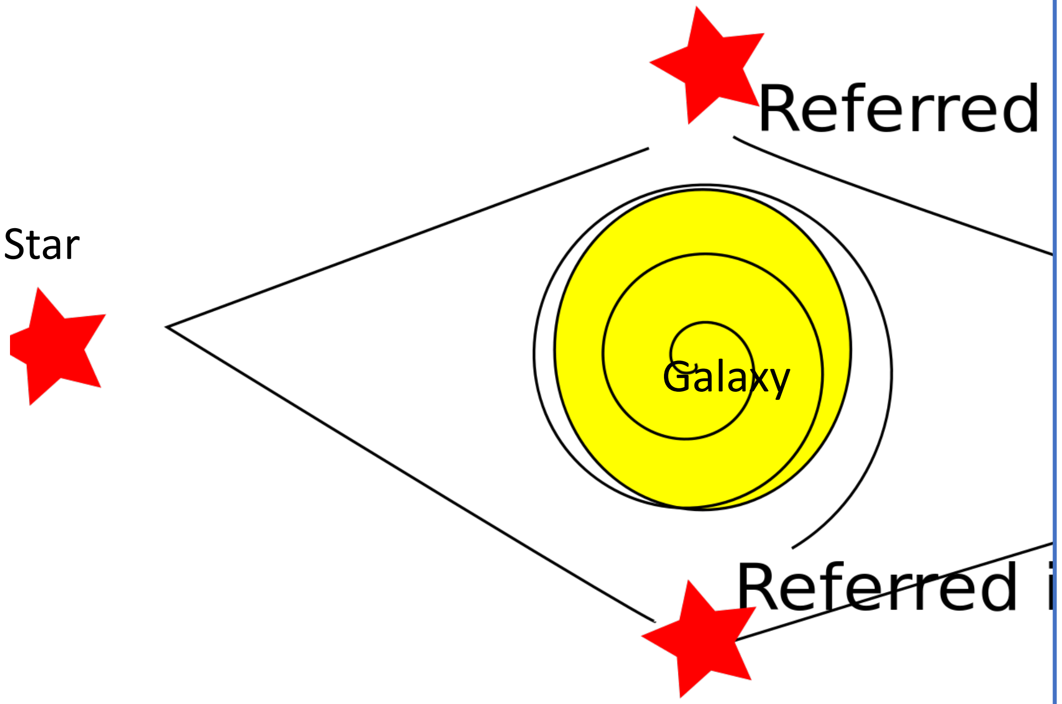

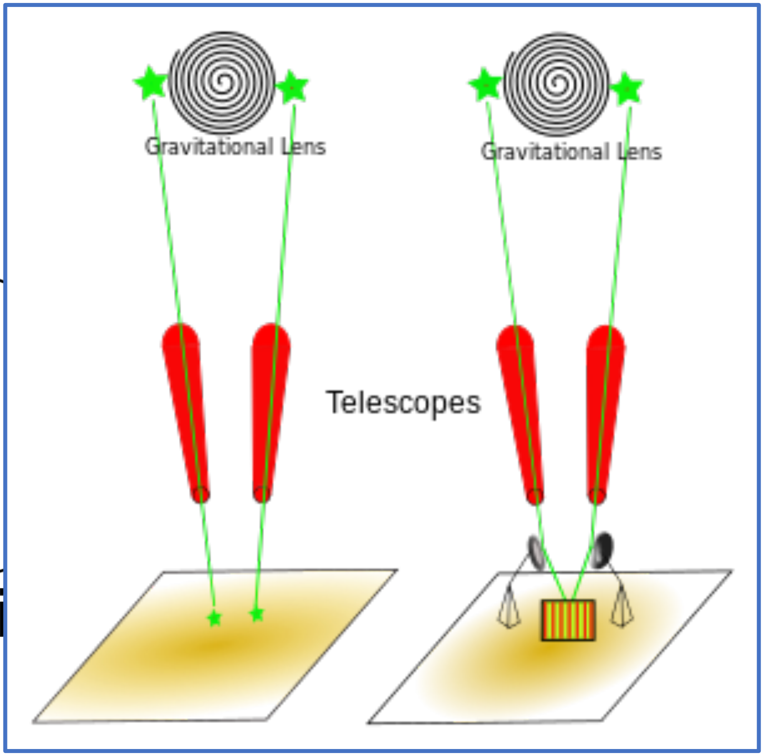

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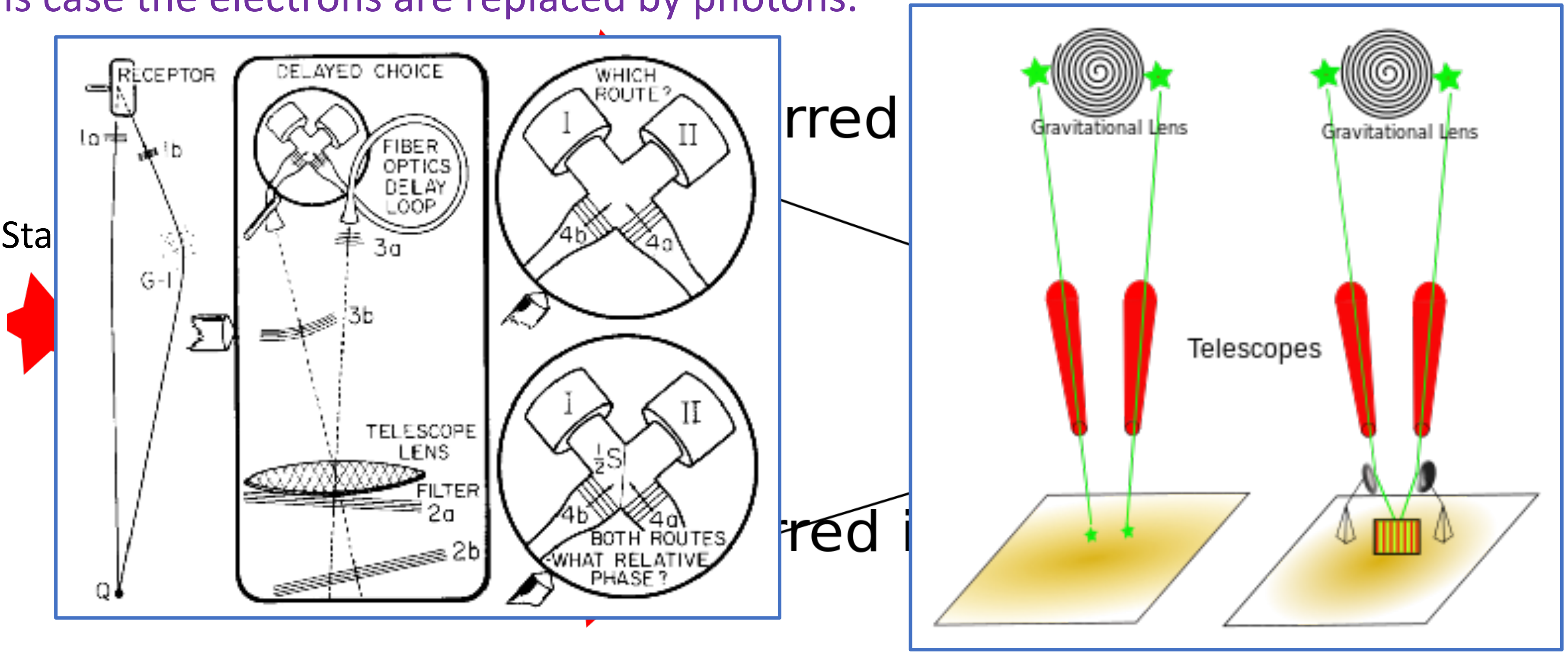
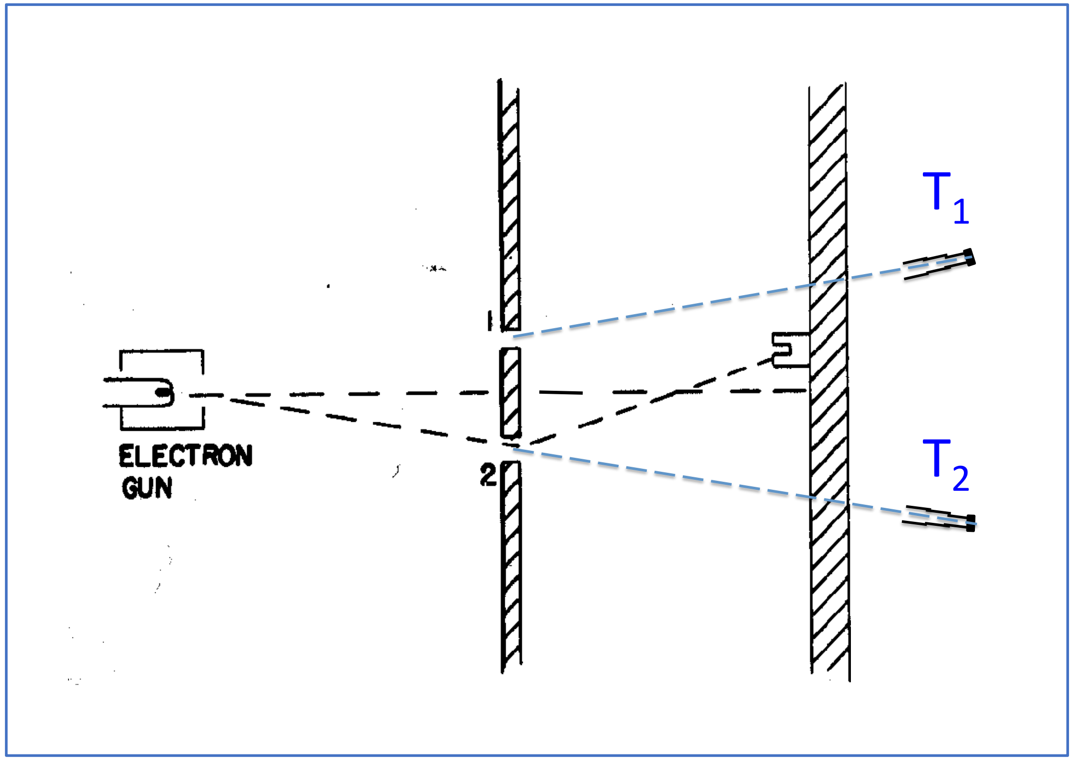


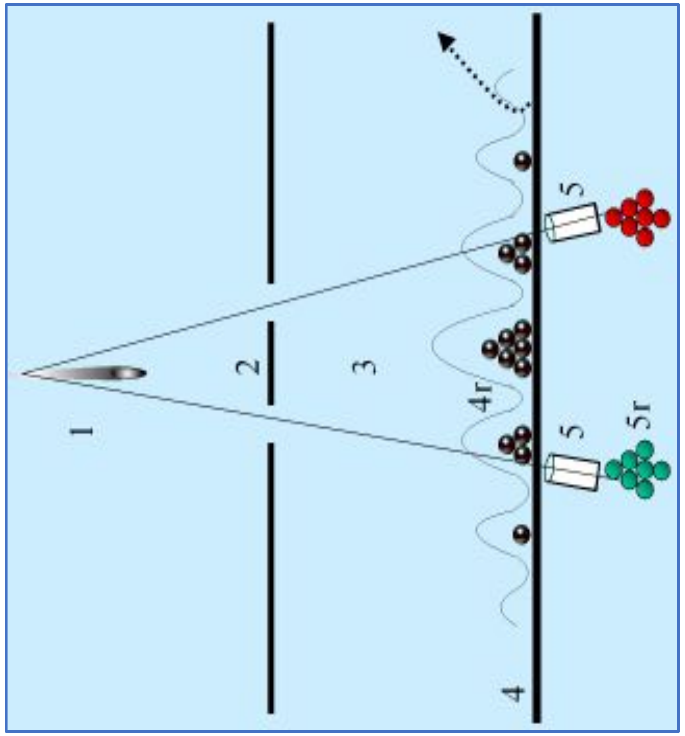
Then, either: Project image of T_1 and T_2 on separate screens, → QM: no interference!
Or: Combine the image of T_1 and T_2 on one screen → QM: interference!

Crucial point: **it must be *impossible* to know which path the photon took!**

Wheeler’s Delayed Choice Experiment

Even better: we can ***suddenly decide*** to look at the electrons.
Suppose we decide (random) to look ***after*** the electrons passed the slits!





What will we see?
An wave interference (black) pattern or a bullet-like non-interference (red-green) pattern?

Answer: “Bullets”. We still have killed the interference by measuring!!!

Delayed Choice…?

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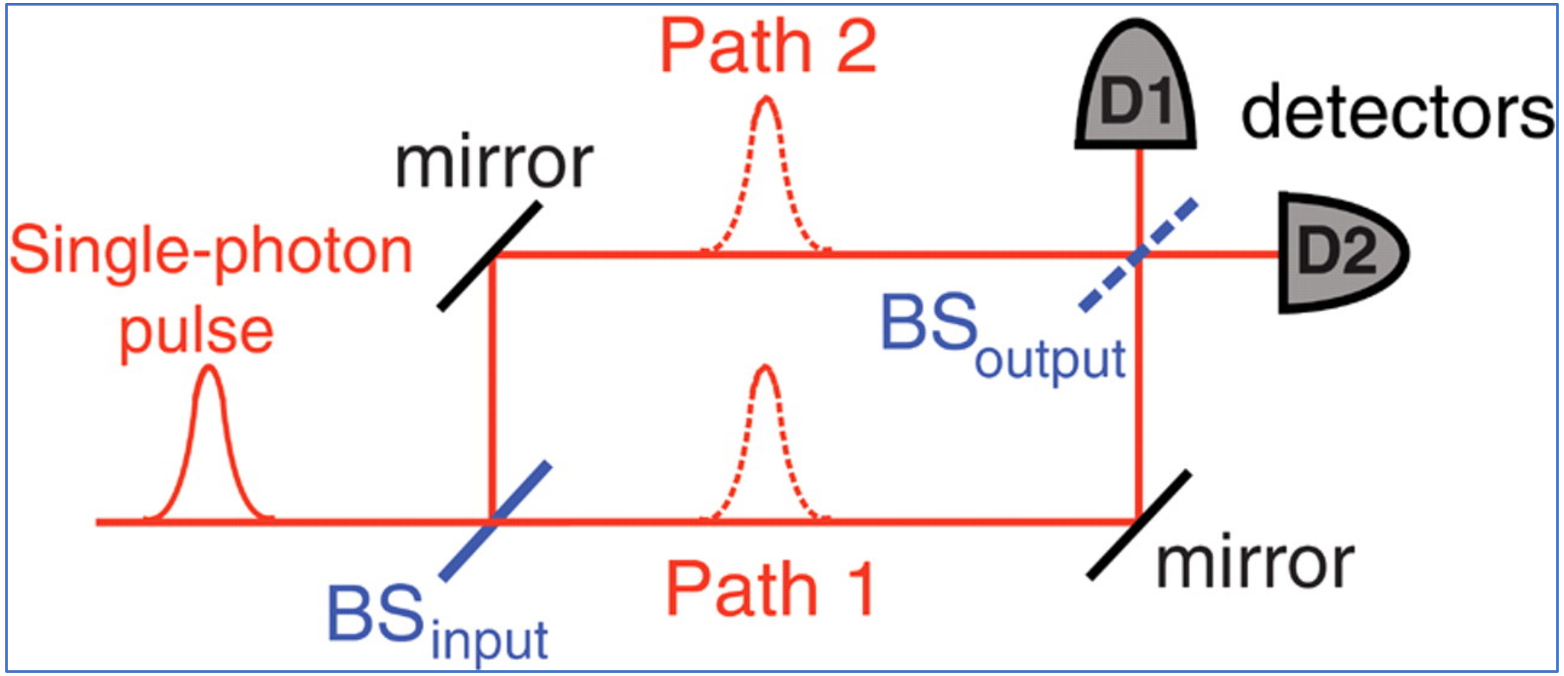
THIS IS EXACTLY HOW WAVE-PARTICLE DUALITY WORKS

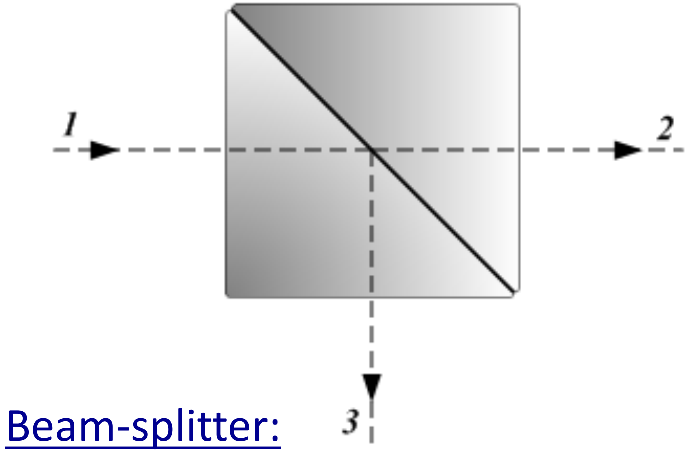
GODSOFTHEMOON.COM

The Experiment of Aspect (2007)

Alain Aspect and his team have done the experiment!
In yet another way: using photons in the lab.

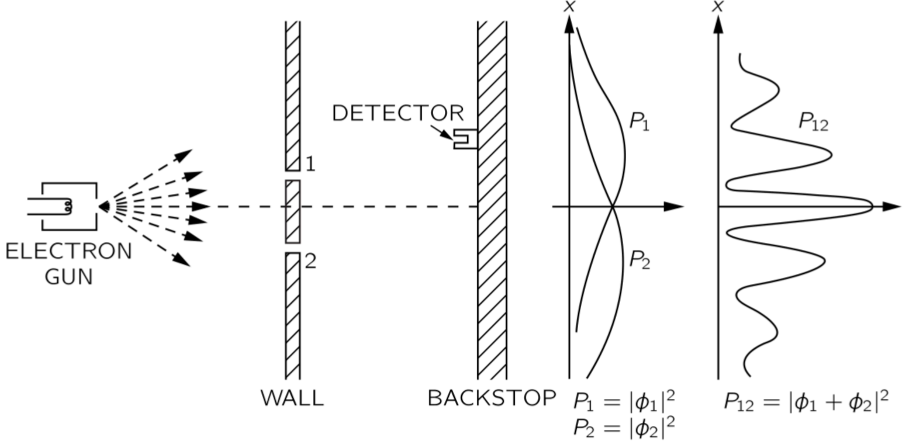
They used beam-splitters to create two alternative routes for a photon to the same place. Path 1 = Path 2 = 48 m

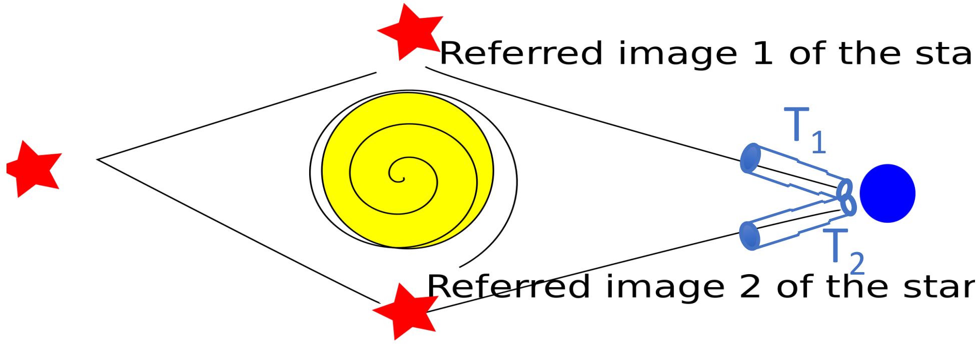


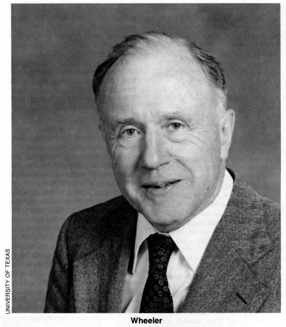


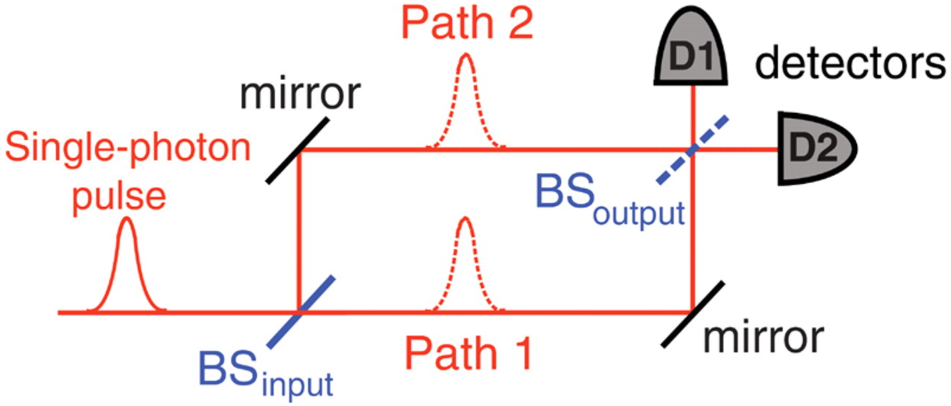
Beam-splitter:
Photon has 50% chance to pass through and 50% chance to reflect.
Like 2-slits: the quantum can do both!

Three Equivalent Experiments



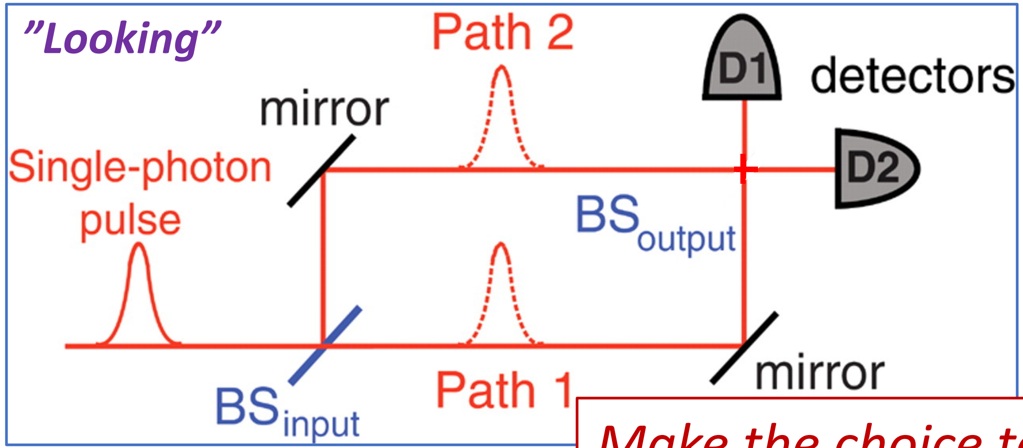




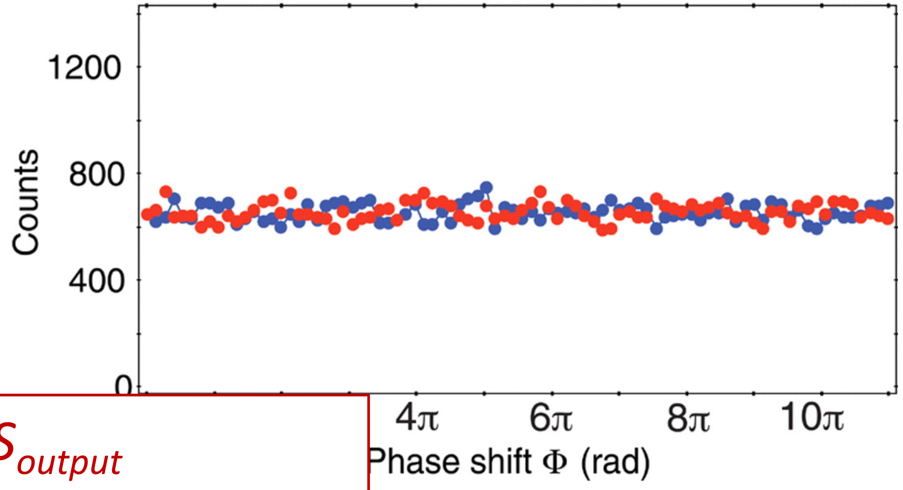


The Experiment of Aspect (2007)

Situation 1: “Are you a ***particle***?” (***open*** $\text{BS}_{\text{output}}$)

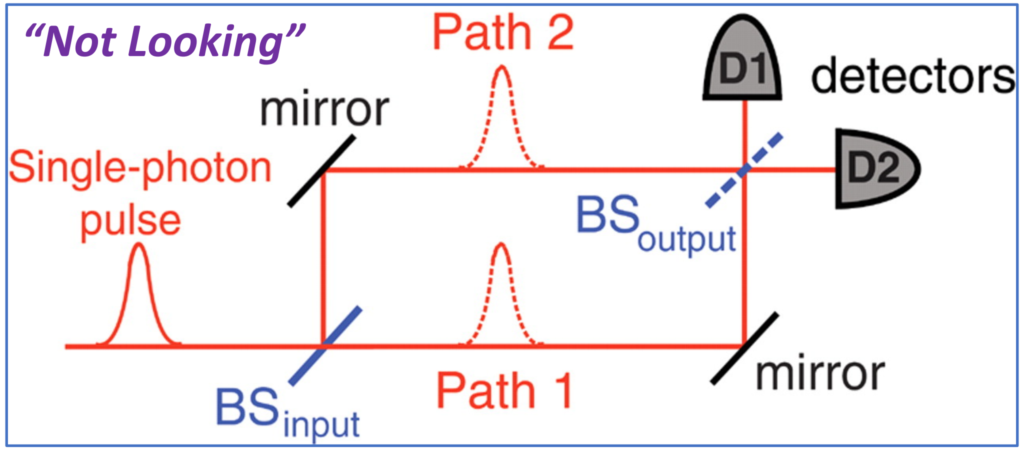


Answer: “Yes!” (Photon never on 2 paths)



*Make the choice to **close** $\text{BS}_{\text{output}}$*
***well after** the photon has passed BS_{input}!*

Situation 2: “Are you a ***wave***?” (***closed*** $\text{BS}_{\text{output}}$)



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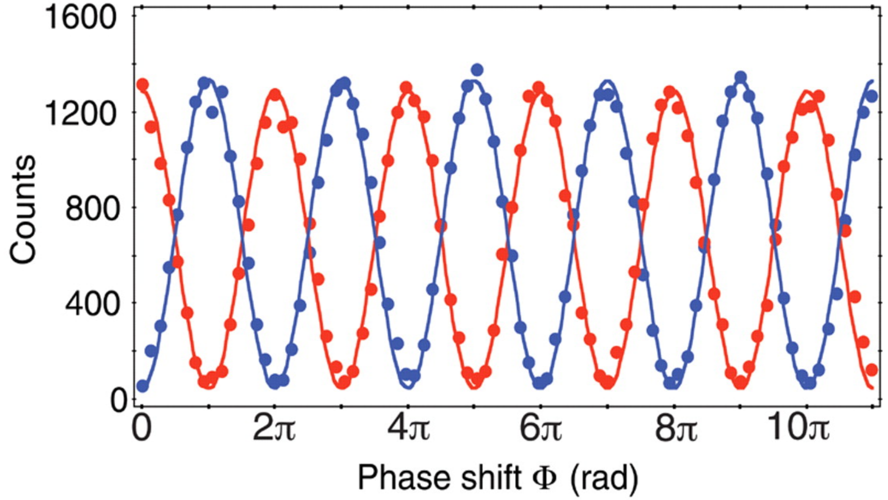

The Experiment of Aspect (2007)

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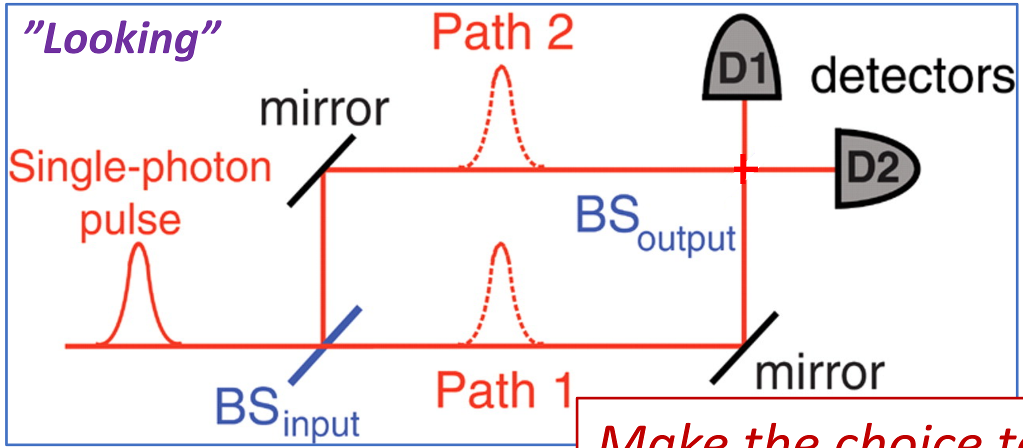
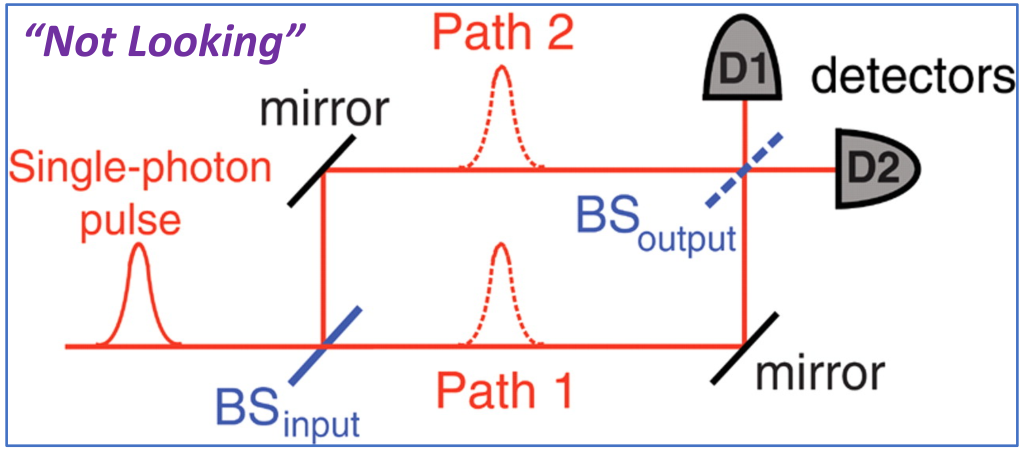
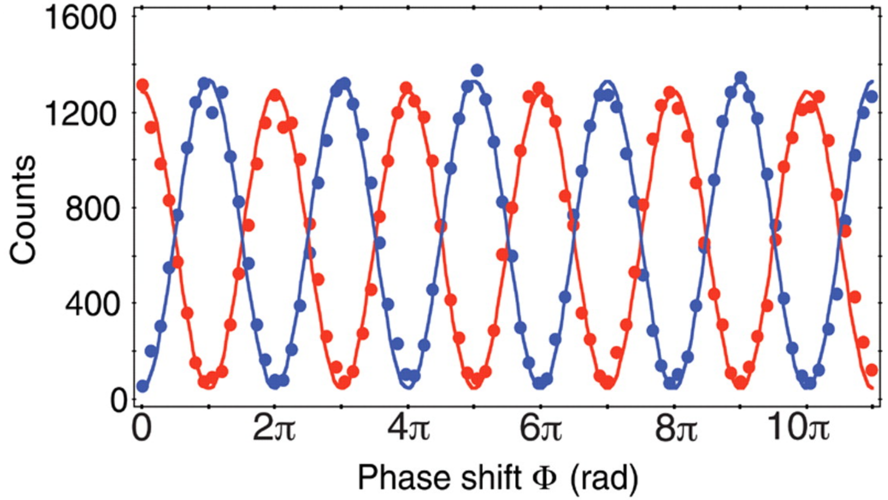


*Make the choice to **close** BS$_{output}$*
***well after** the photon has passed BS$_{input}$!*

Situation 2: “Are you a ***wave***?” (***closed*** BS$_{output}$)



Answer: “Yes!” (Photon on 2 paths)



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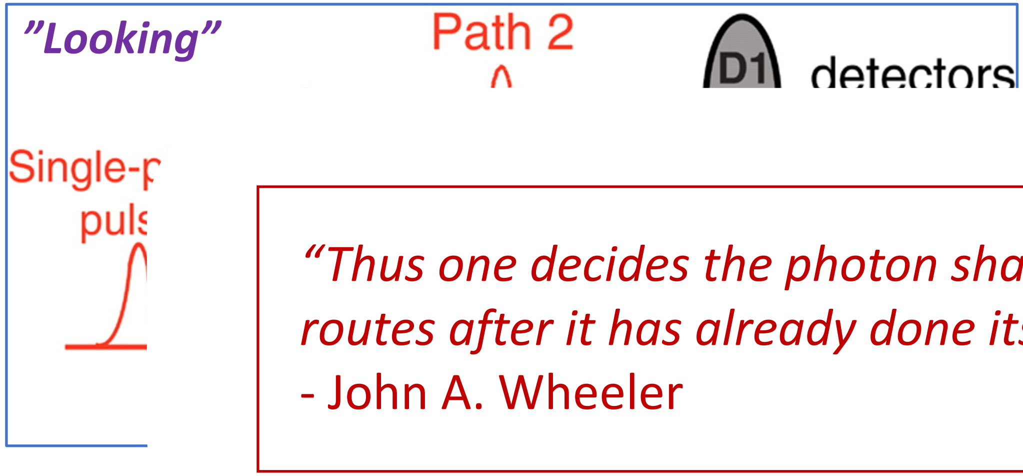
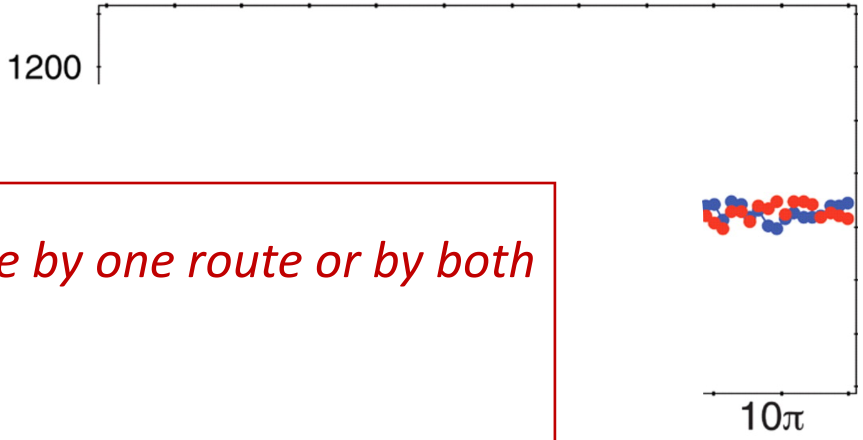


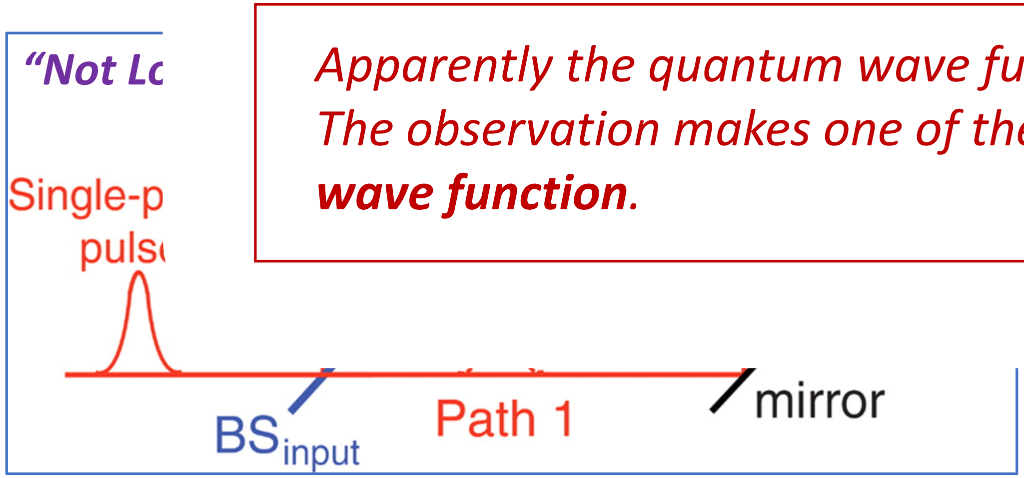


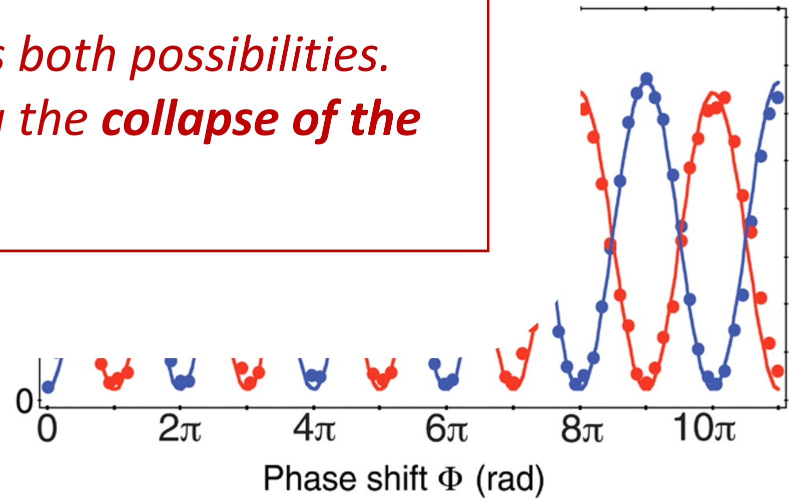
"Thus one decides the photon shall have come by one route or by both routes after it has already done its travel"
- John A. Wheeler

Situatio

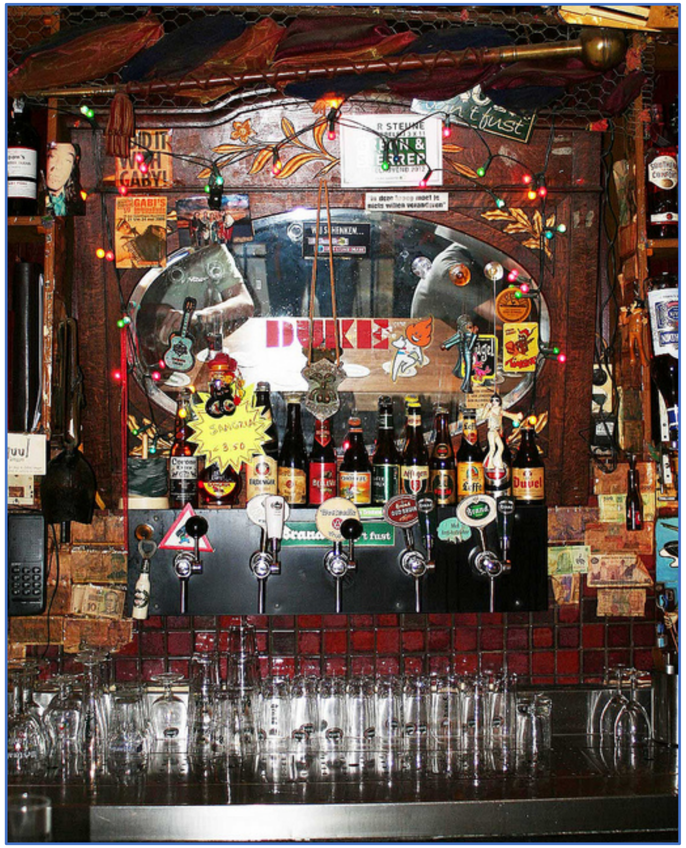
on 2 paths)

Apparently the quantum wave function includes both possibilities. The observation makes one of them a reality via the ***collapse of the wave function****.*





Schrödinger's Cat



The Copenhagen Interpretation

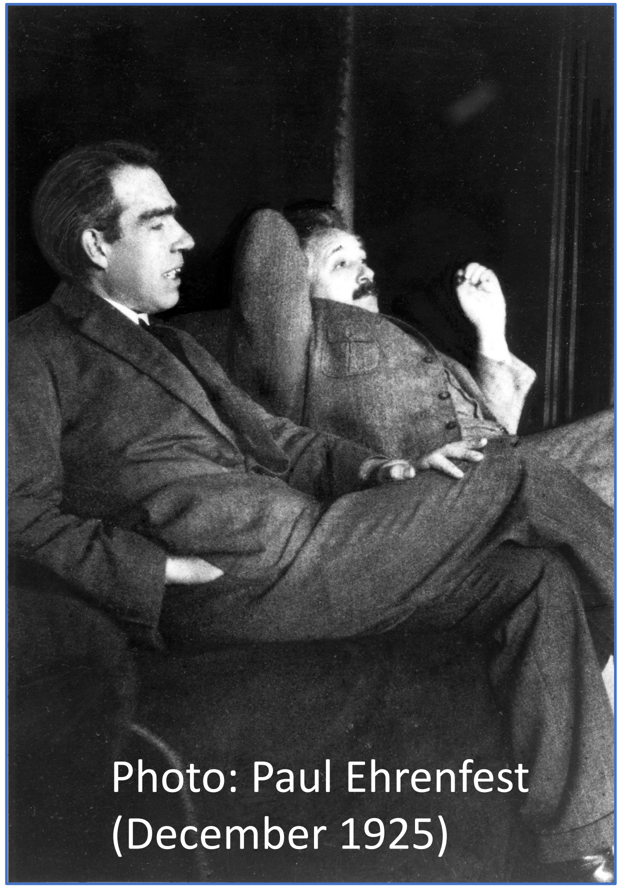
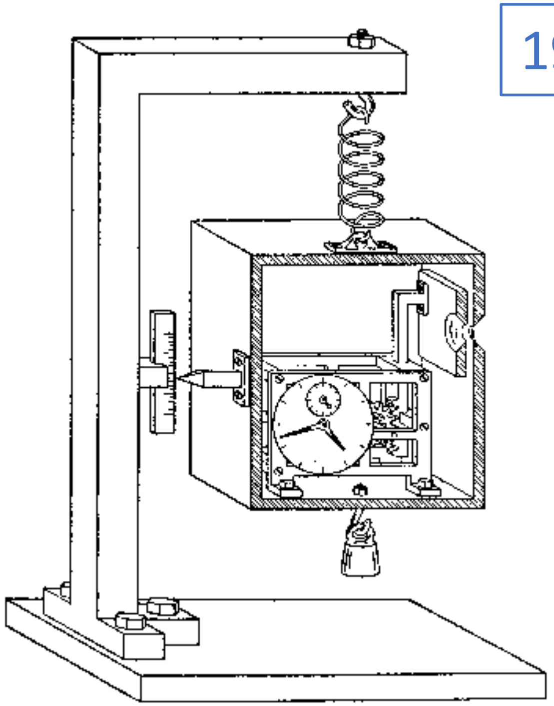


Photo: Paul Ehrenfest
(December 1925)

Niels Bohr and Albert Einstein debates at Solvay conf.

1927



Niels Bohr:

- Uncertainty relation
- Complementary, collapse of the wave function.

Albert Einstein:

- "God does not play dice"
- Objective Reality

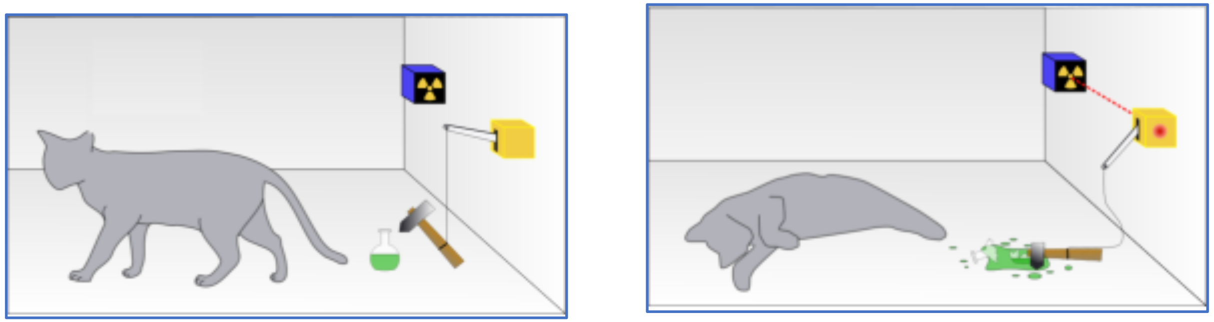
Particle-Wave duality: one of the great mysteries of quantum mechanics.

Complementarity: A quantum object is **both** a particle and a wave.
A measurement can illustrate **either** particle **or** wave nature but not both at the same time, because the object is affected by the act of measurement.

Schrodinger's Cat


E. Schrödinger

Paradox (thought experiment) invented by Erwin Schrödinger in 1935 to demonstrate that the Copenhagen interpretation makes no sense.



Compare quantum choice with double slit situation.

In a radioactive source, a single random quantum event has 50% probability to trigger a lever arm and break a flask containing deadly poison.

Schrodinger's Cat


E. Schrödinger

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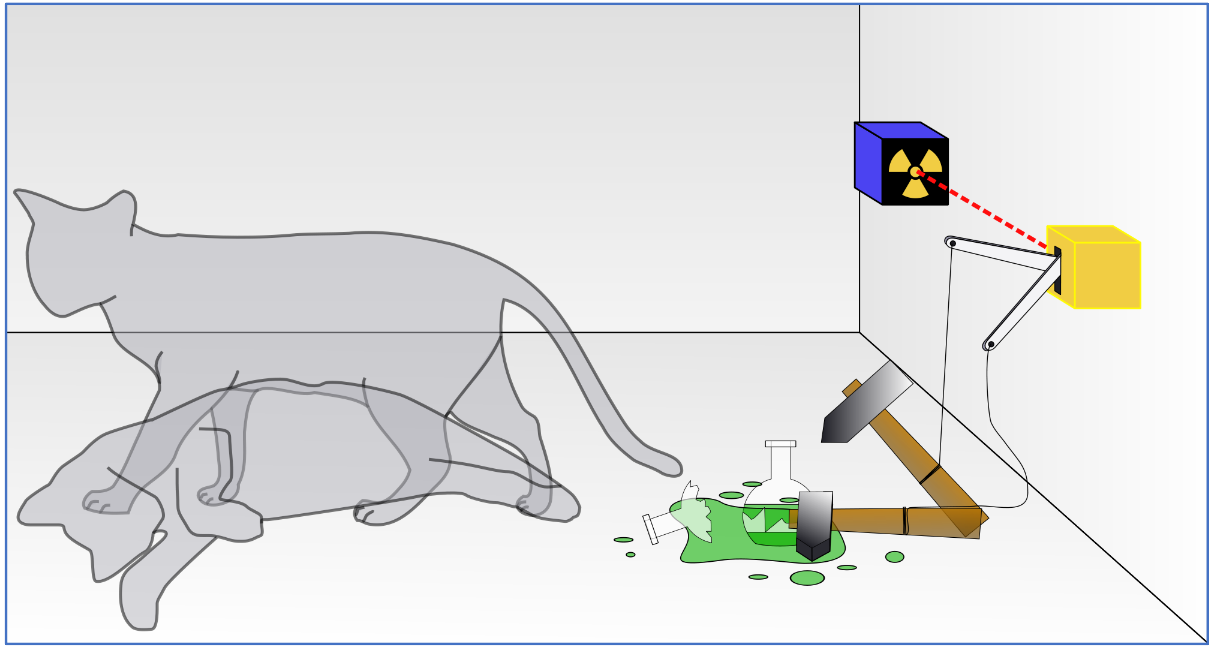

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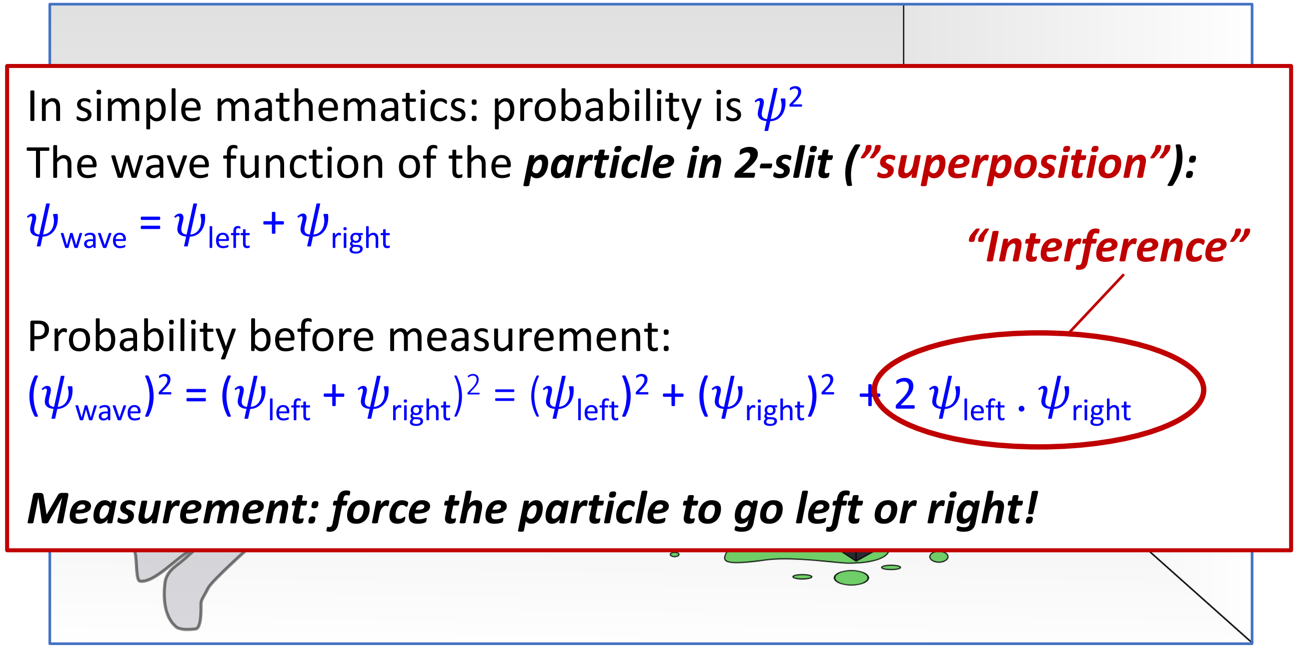

In simple mathematics: probability is ψ^2

The wave function of the ***particle in 2-slit (”superposition”):***

$\psi_{\text{wave}} = \psi_{\text{left}} + \psi_{\text{right}}$

“Interference”

Probability before measurement:

$(\psi_{\text{wave}})^2 = (\psi_{\text{left}} + \psi_{\text{right}})^2 = (\psi_{\text{left}})^2 + (\psi_{\text{right}})^2 + 2\, \psi_{\text{left}} \cdot \psi_{\text{right}}$

Measurement: force the particle to go left or right!

In a radioactive source, a single random quantum event has 50% probability to trigger a lever arm and break a flask containing deadly poison.

Schrodinger's Cat

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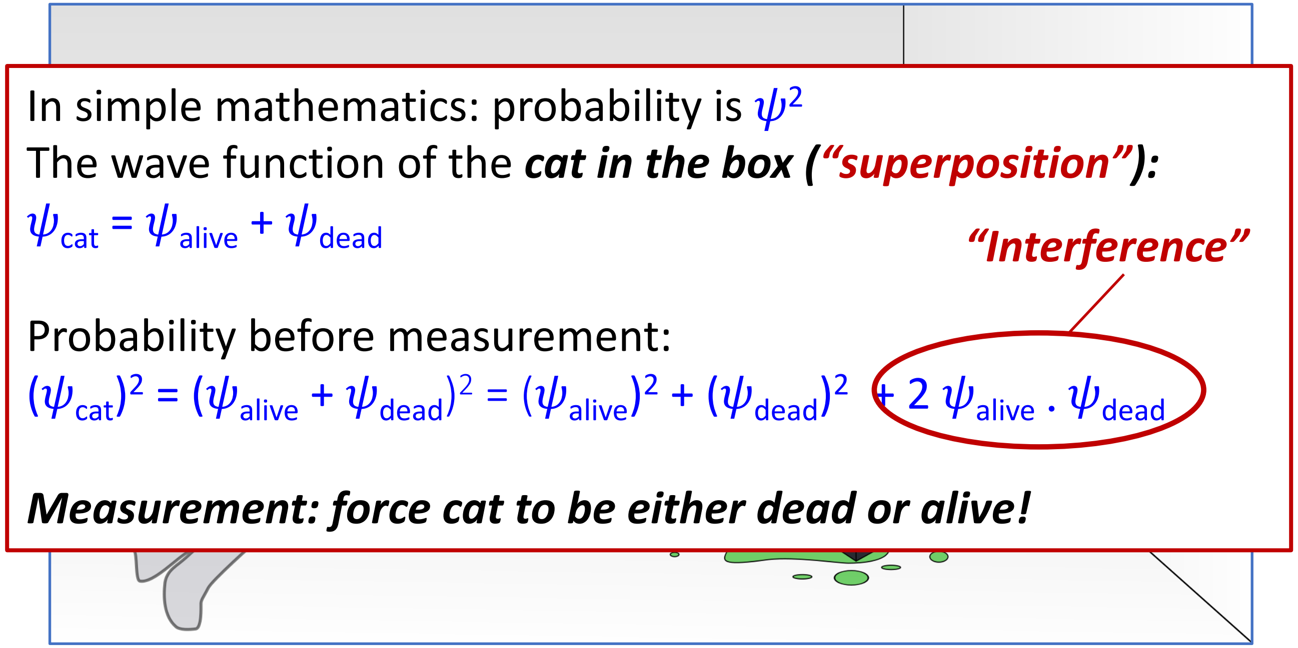

In simple mathematics: probability is ψ^2

The wave function of the ***cat in the box (“superposition”):***

$\psi_{cat} = \psi_{alive} + \psi_{dead}$

“Interference”

Probability before measurement:

$(\psi_{cat})^2 = (\psi_{alive} + \psi_{dead})^2 = (\psi_{alive})^2 + (\psi_{dead})^2 + 2\,\psi_{alive} \cdot \psi_{dead}$

Measurement: force cat to be either dead or alive!

In a radioactive source, a single random quantum event has 50% probability to trigger a lever arm and break a flask containing deadly poison.

Is the cat both dead and alive before we open the box to observe?

”Wigner's Friend” problem: ***Who*** is observer? ***When*** does the wave function collapse? Is it the cat? The Experimenter? The press reporter? Or you when you hear the news? Does it require consciousness?

E. Schrödinger

Eugene Wigner

Schrodinger's Cat

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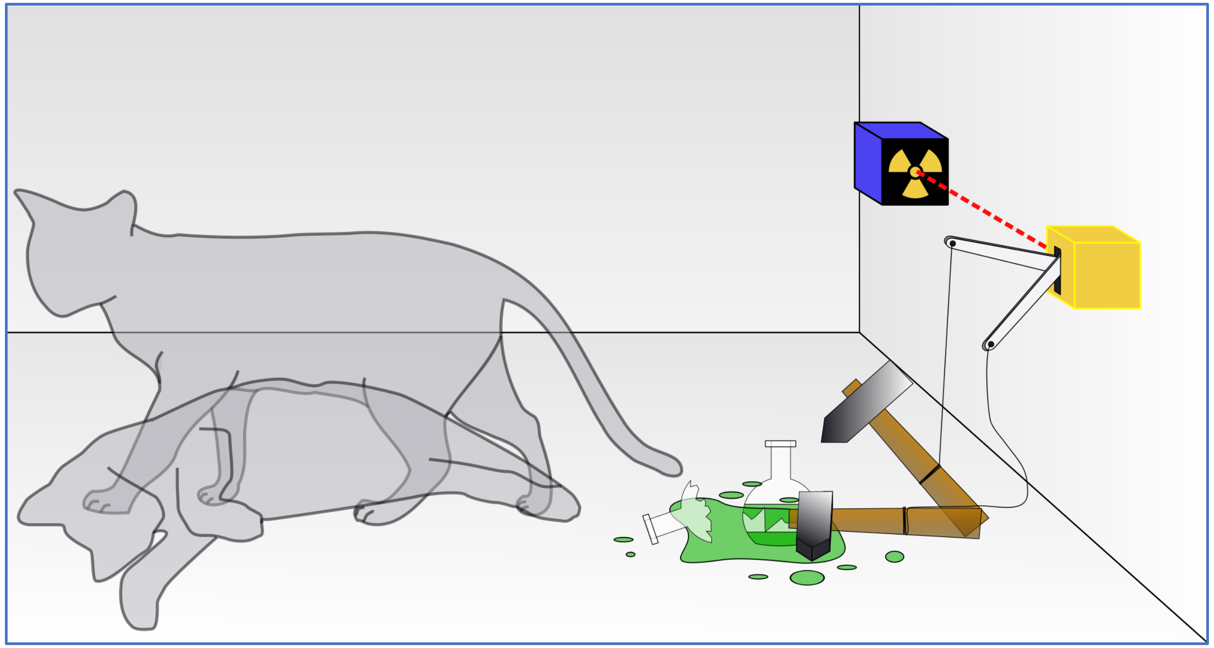
E. Schrödinger



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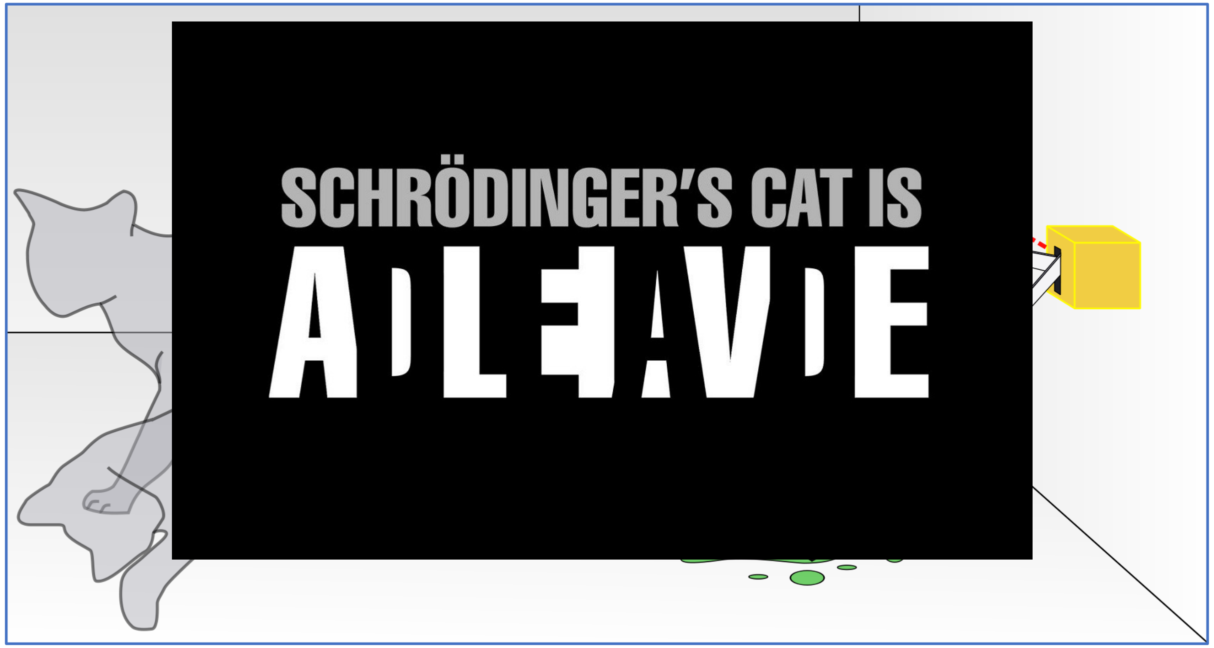

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Eugene Wigner

Wheeler: 20 Questions Analogy

A Word Game:

- At a party one guest has to guess a word that is agreed upon by the others asking questions to be answered with “yes”/”no”.

➔ The pre-existing word is guessed.

Alternative game:

- No word is agreed at beginning. Each person in turn answers yes/no consistently with all previous “yes”/”no” answers.
- Gets more and more difficult
- Finally the person guessing says: “Is it a cloud?” Answer: “Yes!”

➔ There was no pre-existing word. The final word was ***brought into being*** by the questions asked.

The “20-Q” game

Analogy:

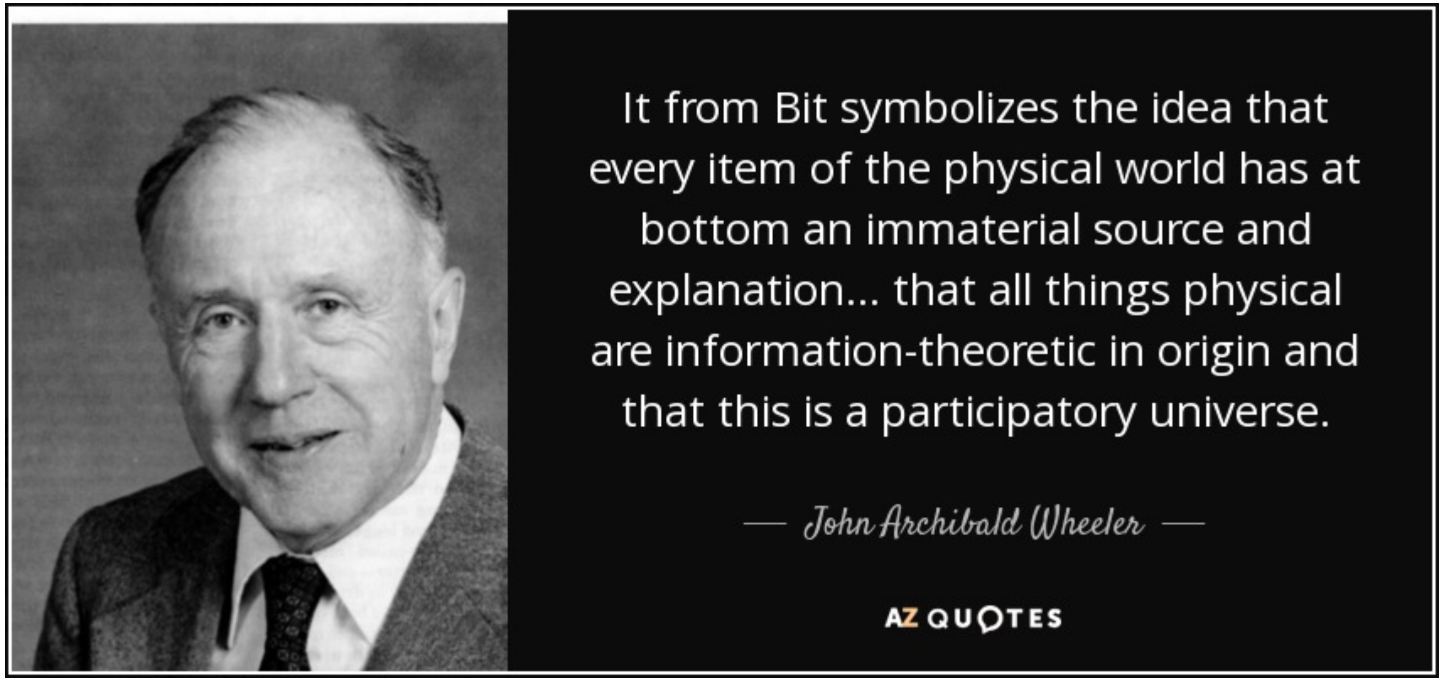
- Nature gives consistent answers on quantum questions asked by the “collapse of the wave function”

➔ The observer ***creates reality*** by making an observation.

“No phenomenon is a real phenomenon until it is an observed phenomenon.”

\- John Archibald Wheeler

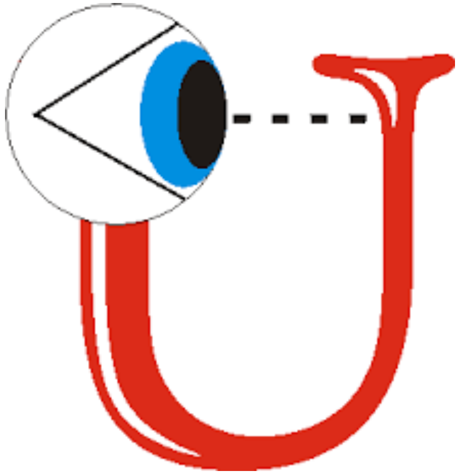
“It from Bit” and “Participatory Universe”

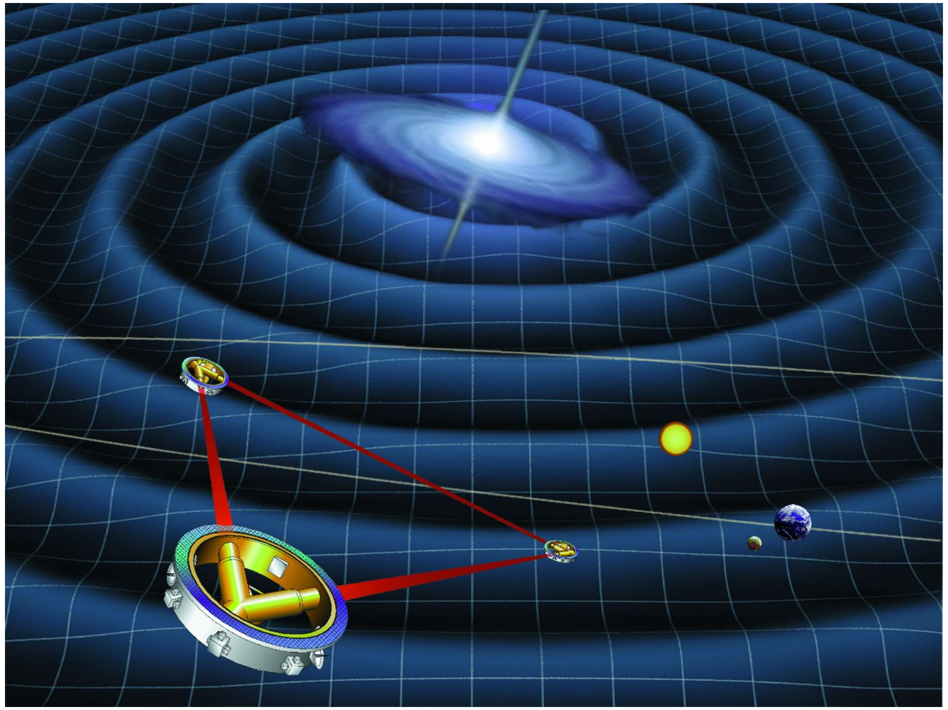


It from Bit symbolizes the idea that every item of the physical world has at bottom an immaterial source and explanation… that all things physical are information-theoretic in origin and that this is a participatory universe.

— *John Archibald Wheeler* —

AZ QUOTES

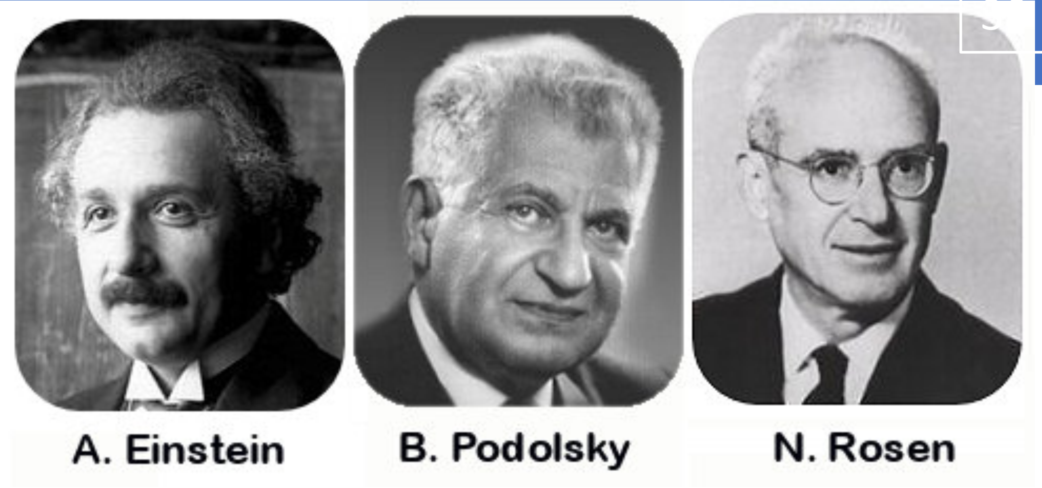


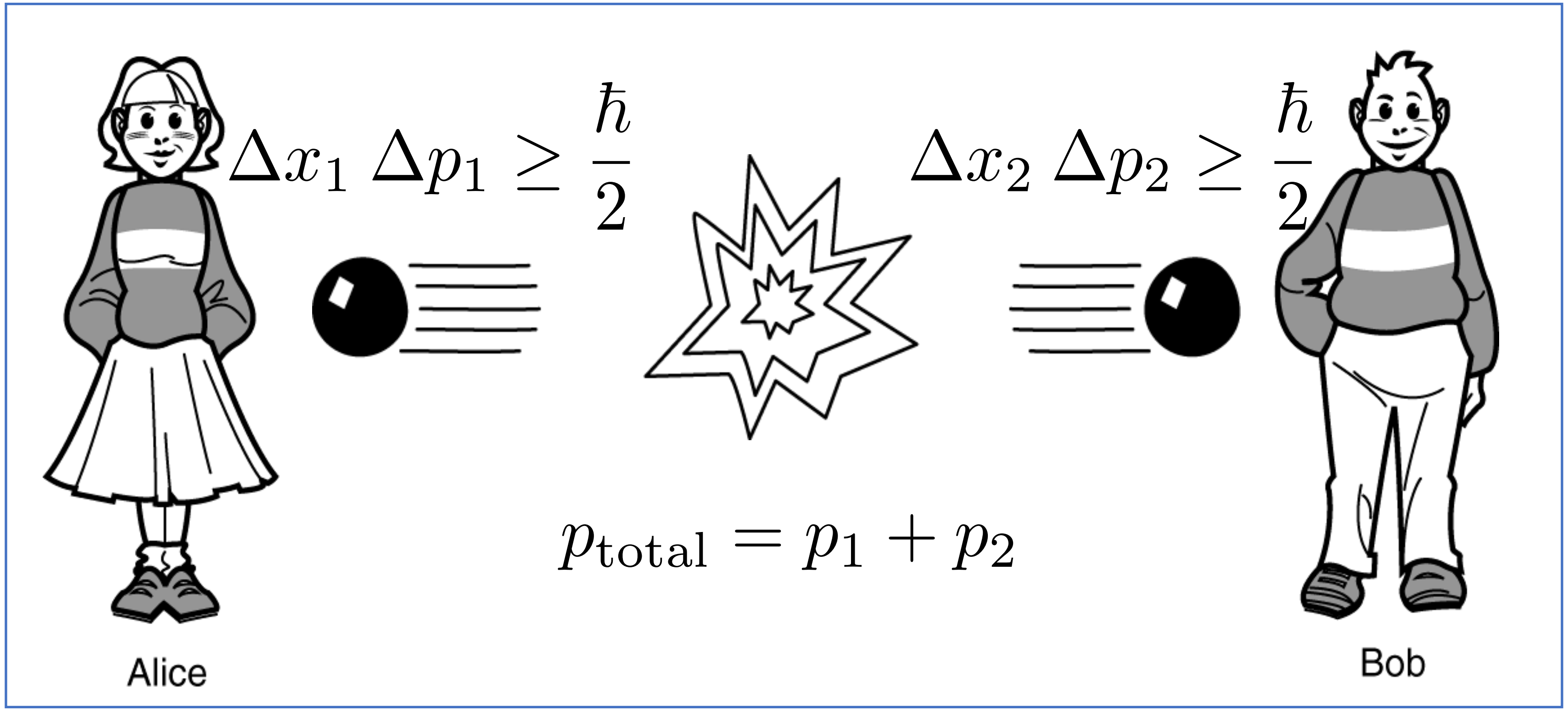


Build a gravitational wave detector
and look back directly at the big bang…. ?

Next Lecture: Einstein's Objection

The EPR paradox





$$\Delta x_1 \, \Delta p_1 \geq \frac{\hbar}{2}$$

$$\Delta x_2 \, \Delta p_2 \geq \frac{\hbar}{2}$$

$$p_{\mathrm{total}} = p_1 + p_2$$