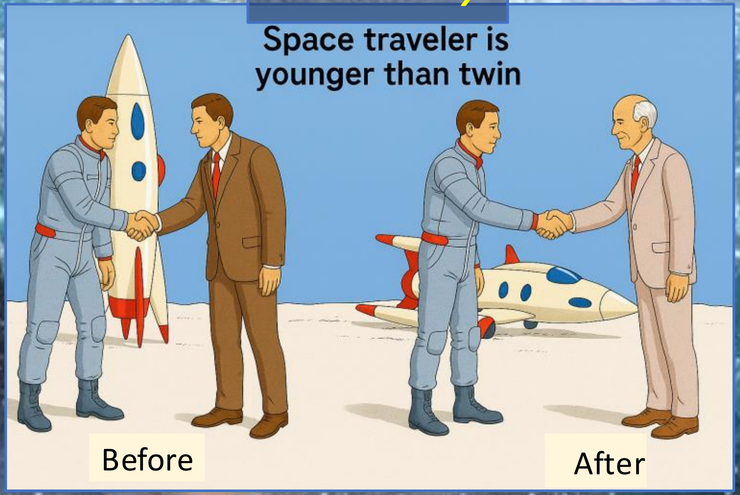
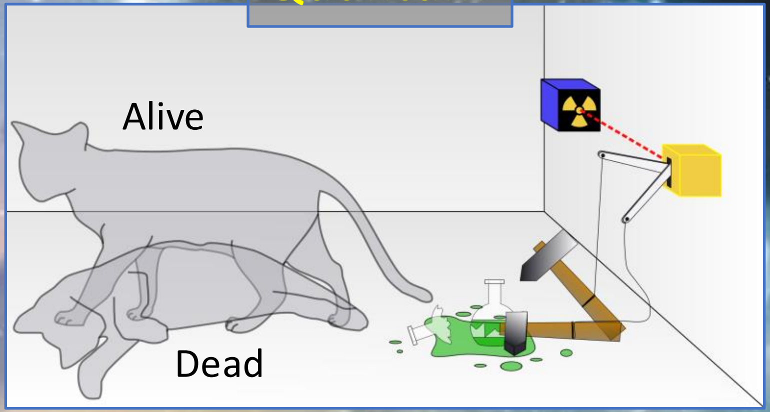
The Relativistic Quantum World

A lecture series on
Relativity Theory and Quantum Mechanics

Relativity



Quantum



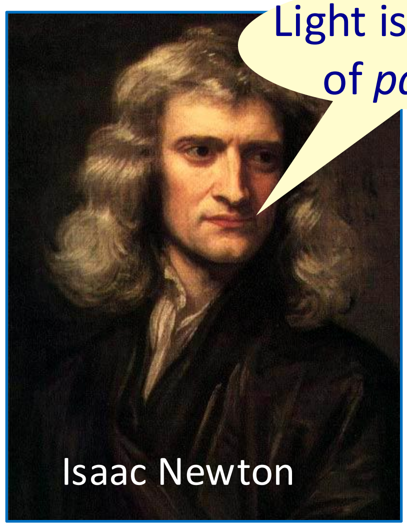
Marcel Merk
Studium Generale Maastricht
Sep 10 – Oct 8, 2025

The Relativistic Quantum World

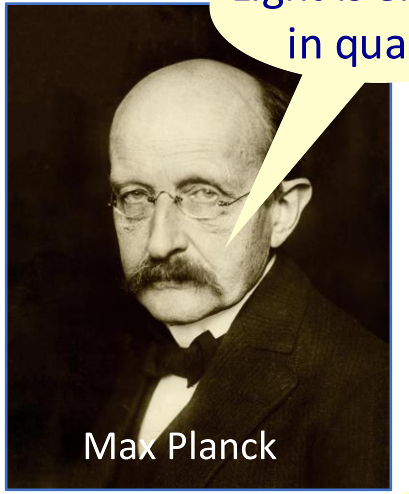
Relativity	Sep. 10:	Lecture 1: The Principle of Relativity and the Speed of Light Lecture 2: Time Dilation and Lorentz Contraction
	Sep. 17:	Lecture 3: The Lorentz Transformation and Paradoxes Lecture 4: General Relativity and Gravitational Waves
Quantum Mechanics	Sep. 24:	Lecture 5: The Early Quantum Theory Lecture 6: Feynman's Double Slit Experiment
	Oct. 1 :	Lecture 7: Wheeler's Delayed Choice and Schrodinger's Cat Lecture 8: Quantum Reality and the EPR Paradox
Standard Model	Oct. 8:	Lecture 9: The Standard Model and Antimatter Lecture 10: Why is there something rather than nothing?

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

Quantum Mechanics



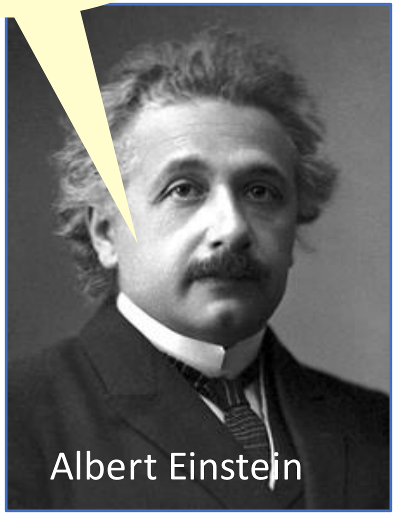
Light is a stream of *particles*



Light is *emitted* in quanta

No, similar to sound light consists of *waves*

Yes, because it *interferes*



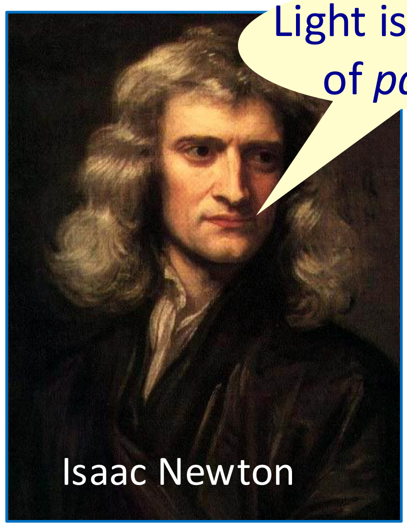
The *nature* of light is quanta

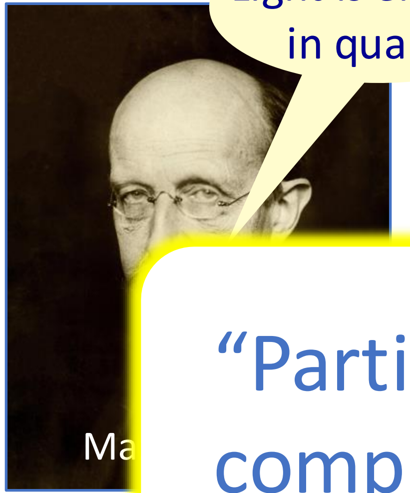
Yes, because photons collide!

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

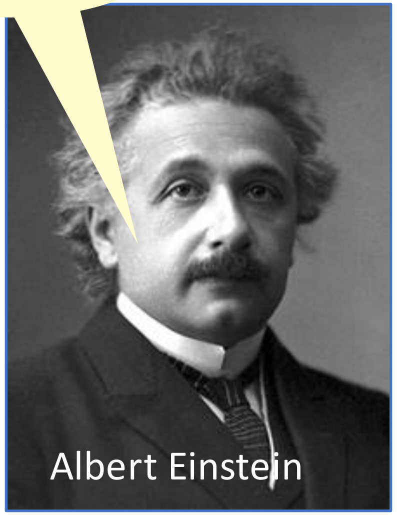
Particles are *probability waves*

Quantum Mechanics





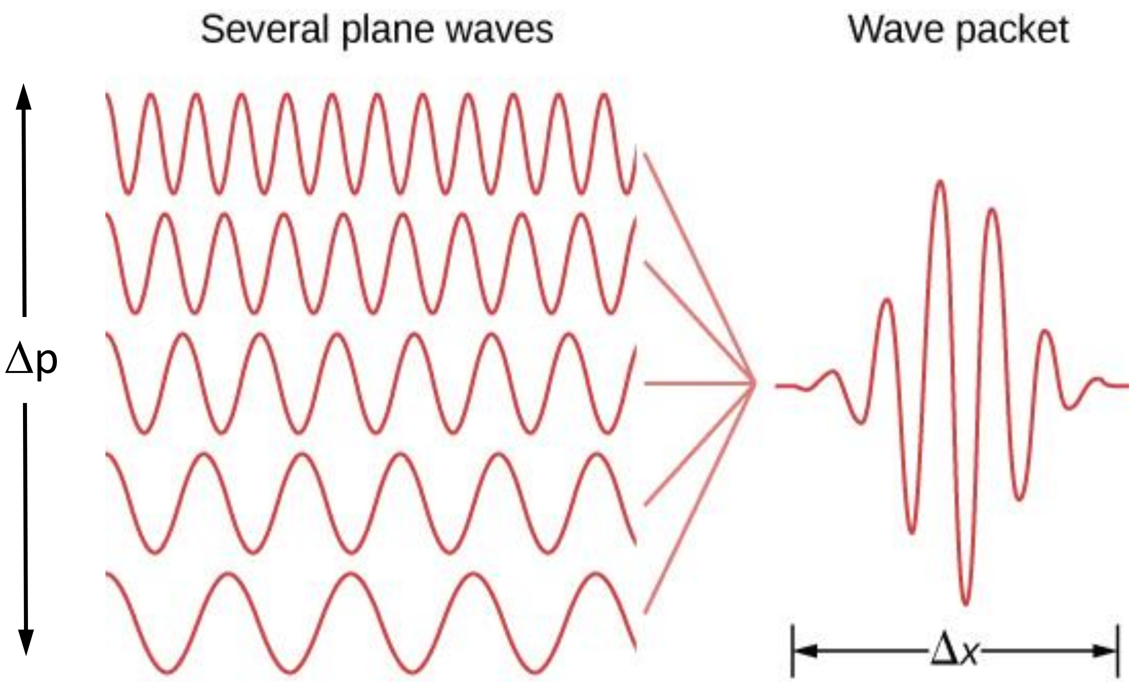
“Particle” and “Wave” are complementary aspects.



Uncertainty Relation

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

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



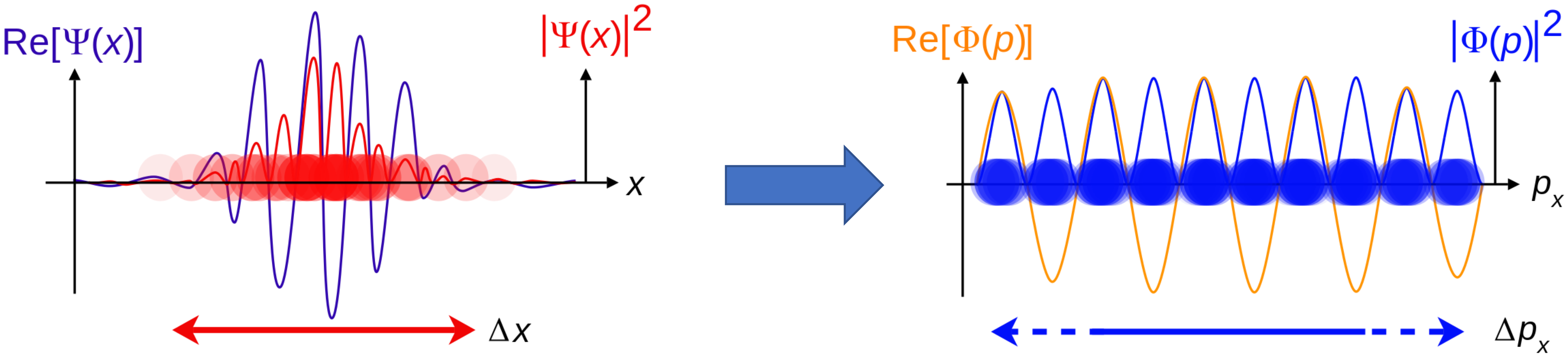
$$p = \frac{h}{\lambda} = \frac{hf}{c}$$

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

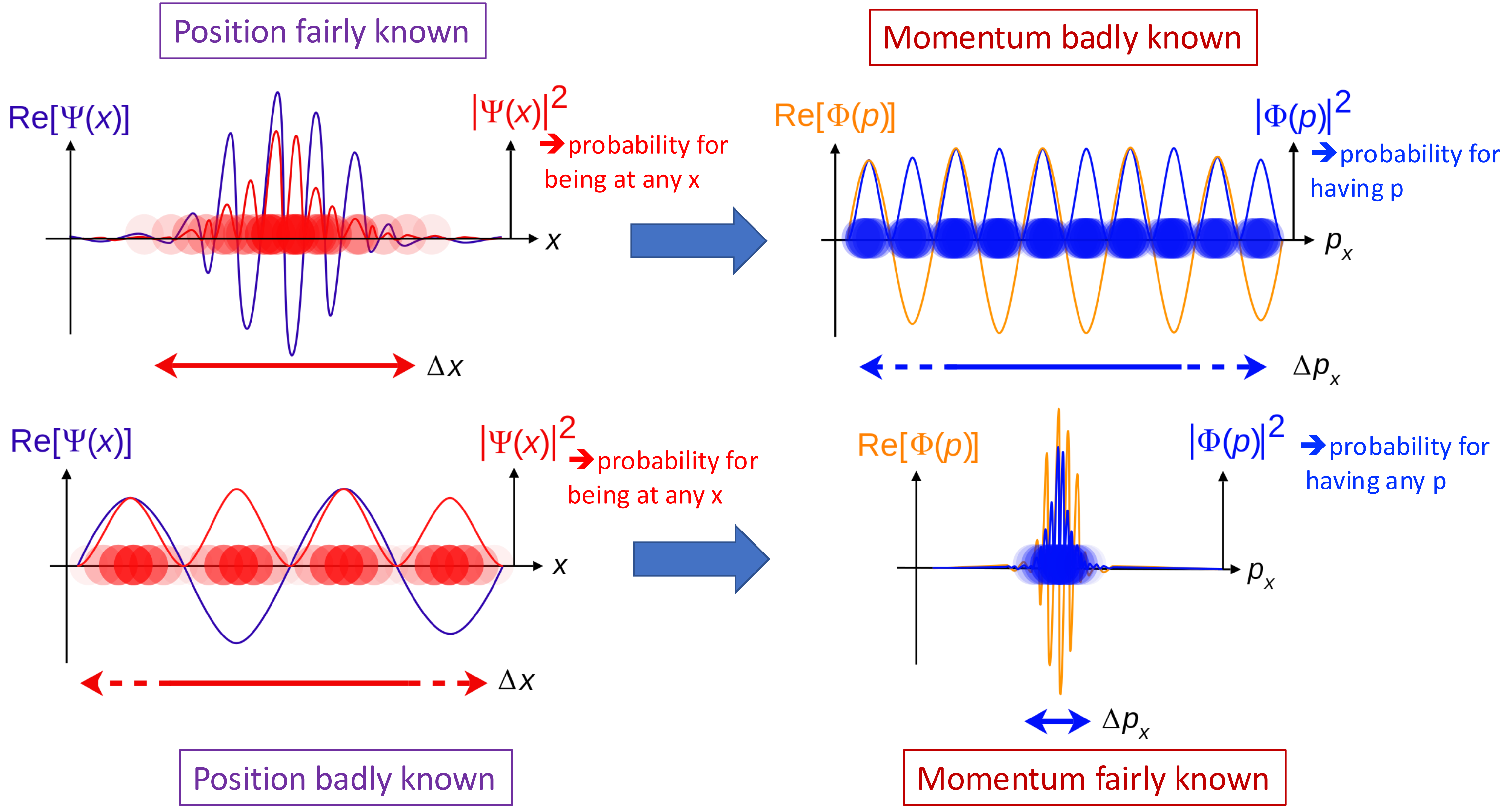
The wave function ψ

Position fairly known

Momentum badly known



The wave function ψ



Lecture 6

Feynman's Double Slit Experiment

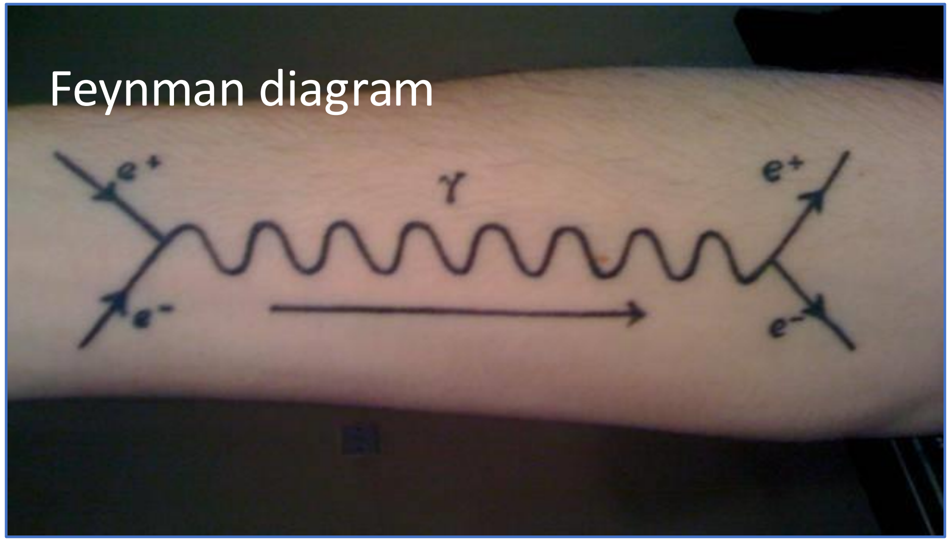
"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment it's wrong."

- Richard Feynman

Richard Feynman (1918 – 1988)

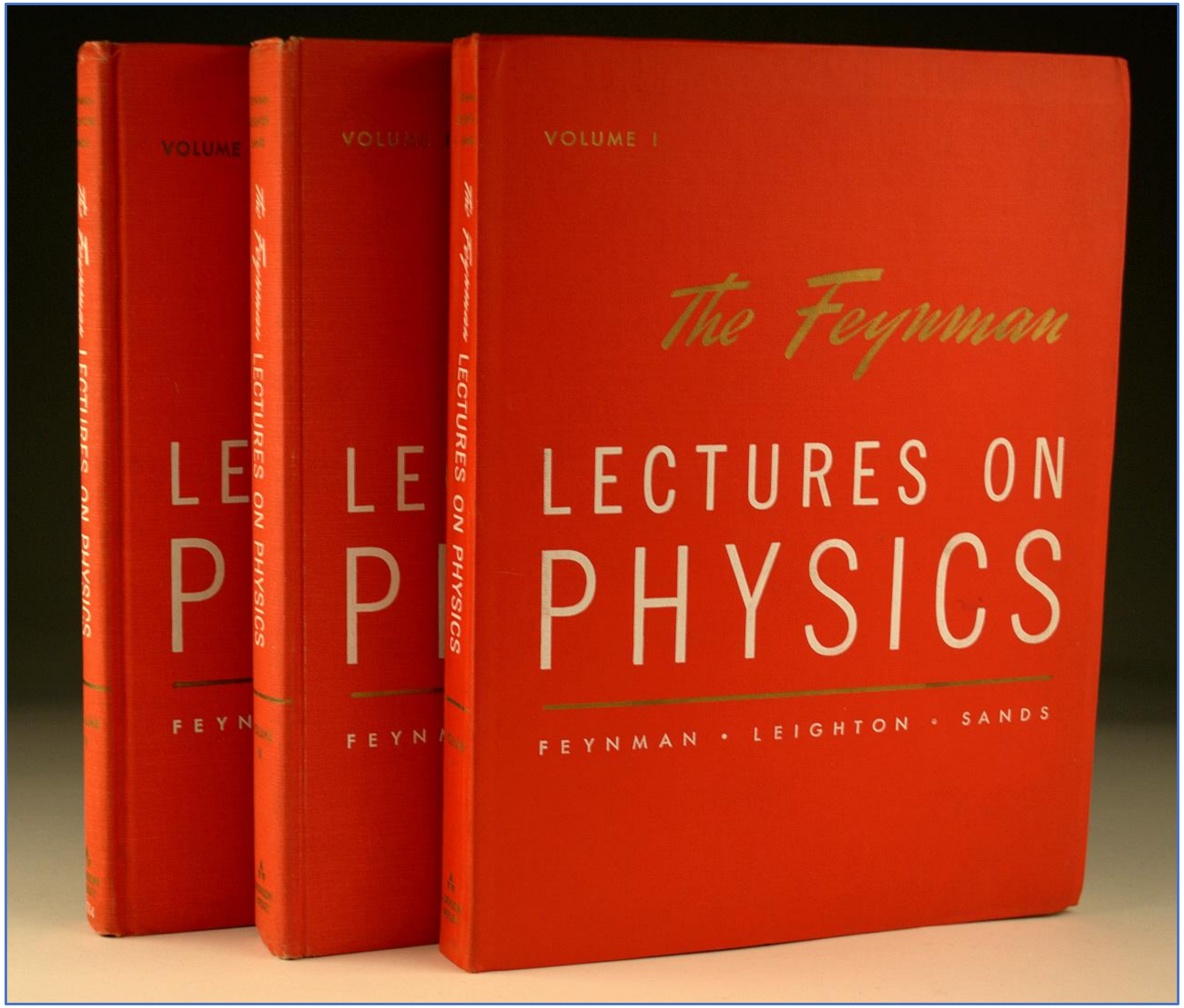
Nobelprize 1965: Quantum Electrodynamics
(Path Integral formulation of quantum mechanics)

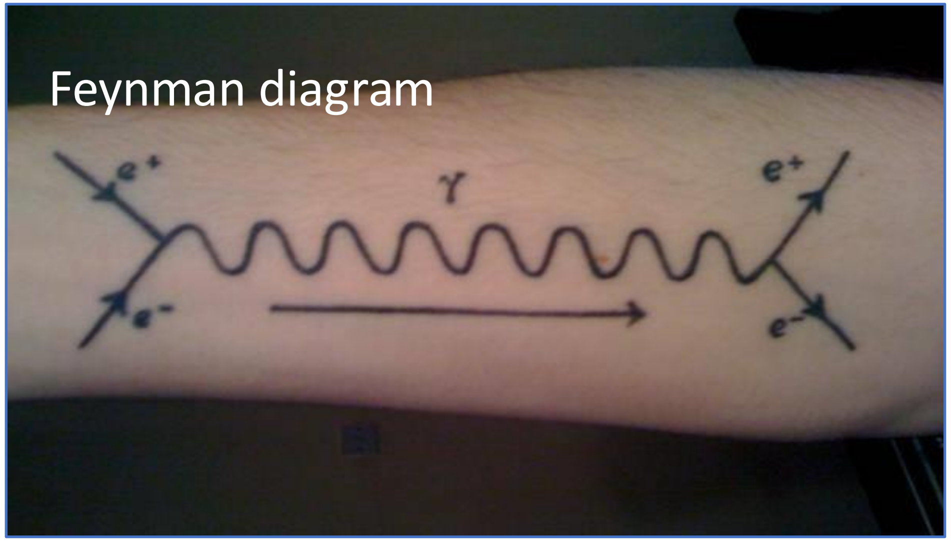
Mostly known from:
- Feynman diagrams
- Challenger investigation
- Popular books



Richard Feynman (1918 – 1988)

Nobelprize 1965: Quantum Electrodynamics
(Path Integral formulation of quantum mechanics)





Feynman diagram

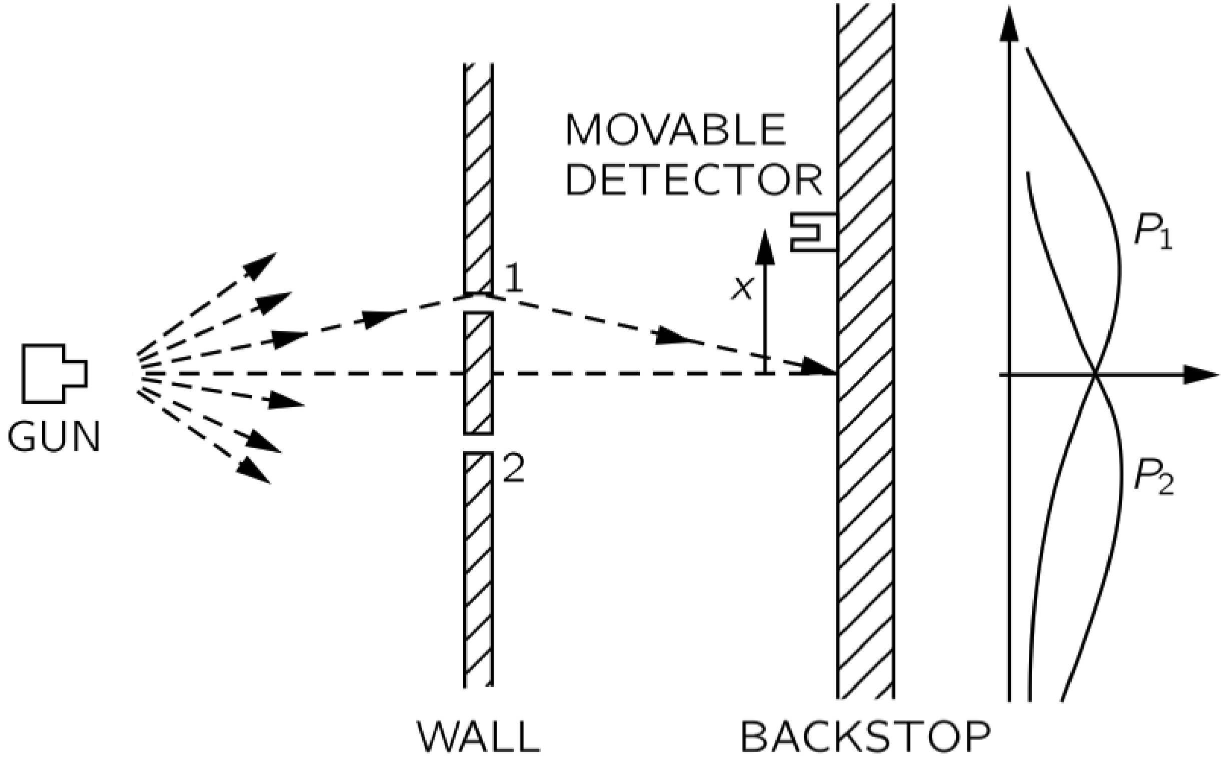
Richard Feynman and the double slit experiment

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

Case 1:
An Experiment with Bullets

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.



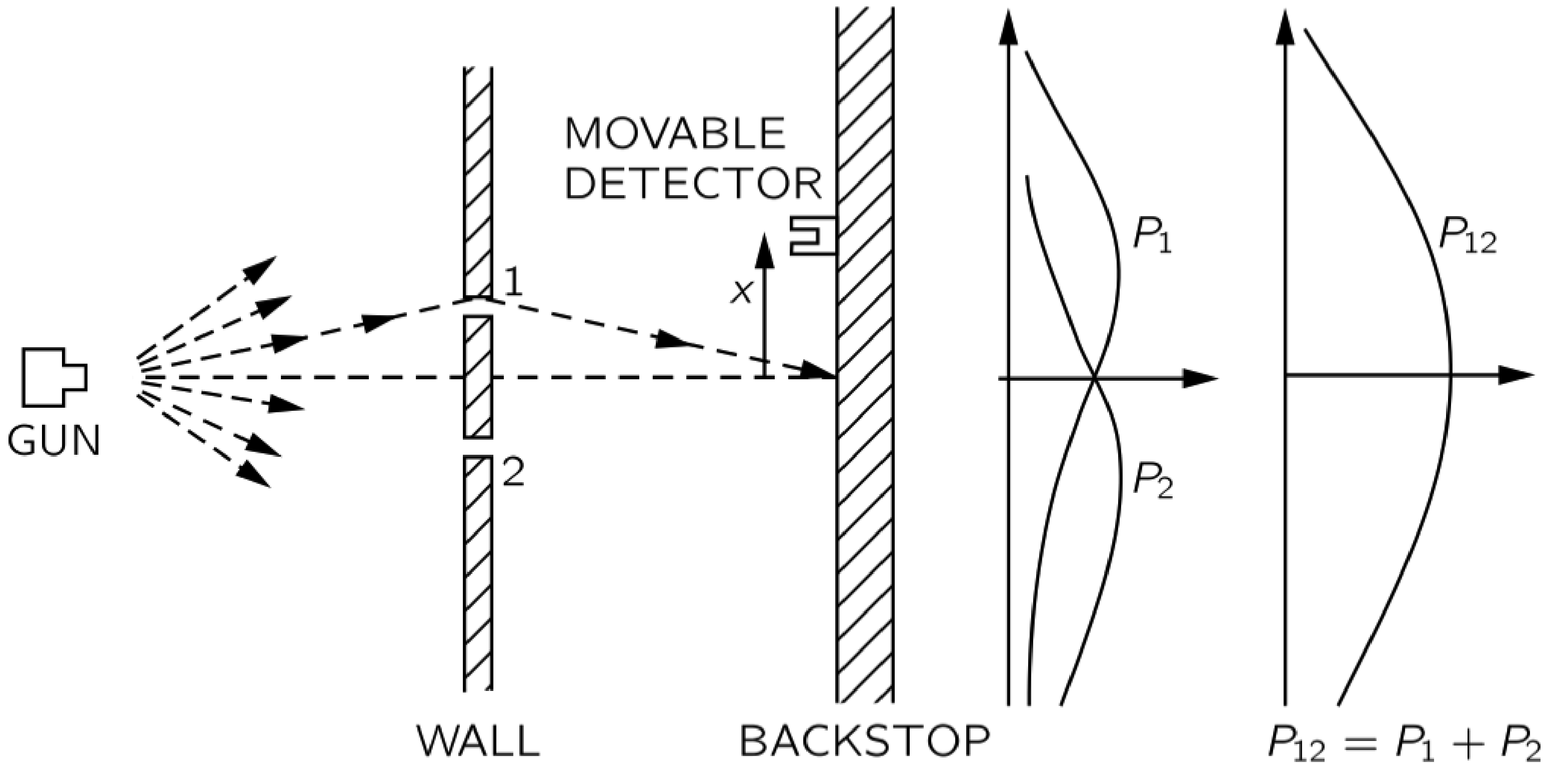
Observation:
Bullets come in “lumps”.

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

What is the probability curve when both slit 1 and slit 2 are open?

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

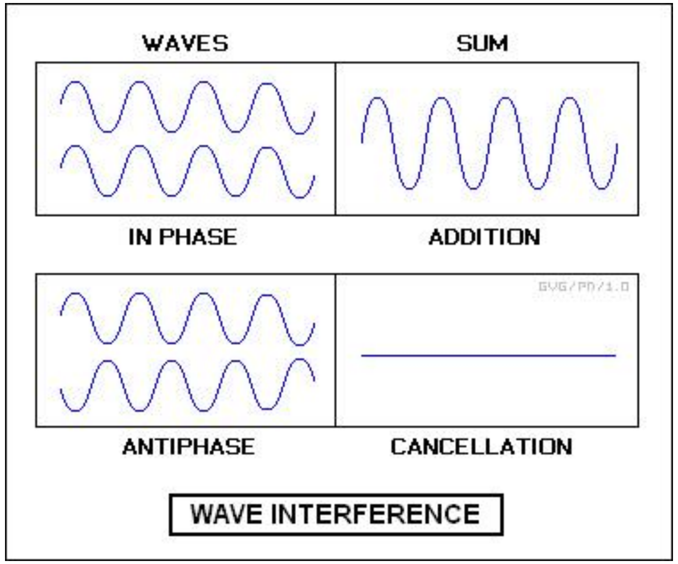
When both slits are open: $P_{12} = P_1 + P_2$

We can just add up the probabilities.

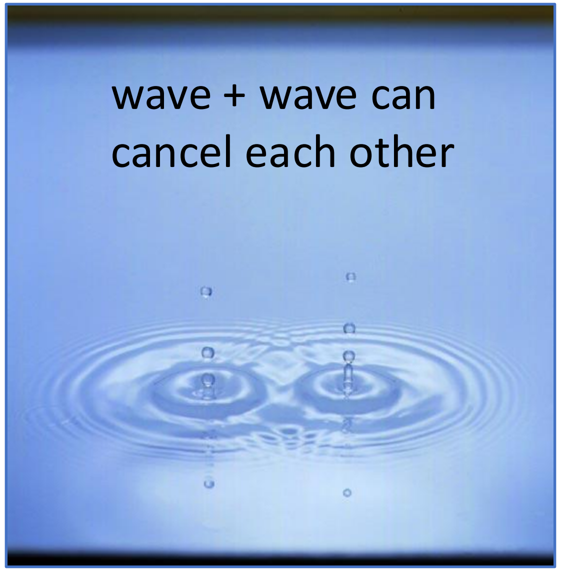
Case 2:
An Experiment with Waves

Waves & Interference : water, sound, light

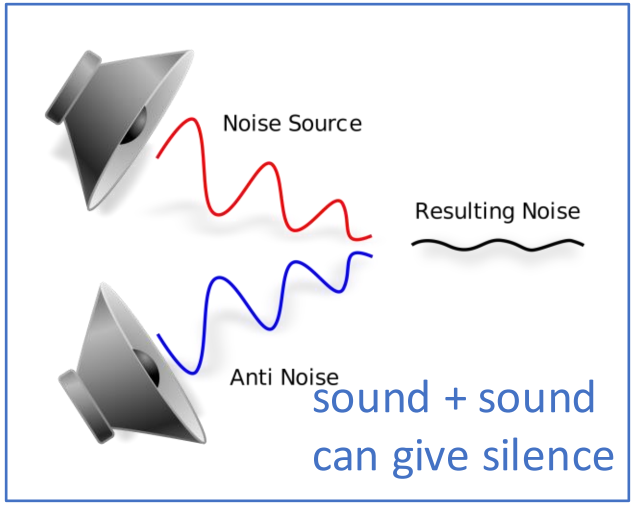
Waves: Interference principle:



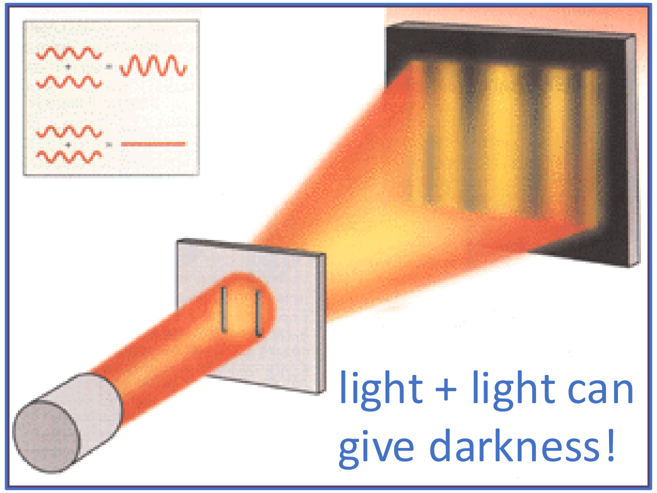
Water: Interference pattern:



Sound: Active noise cancellation:

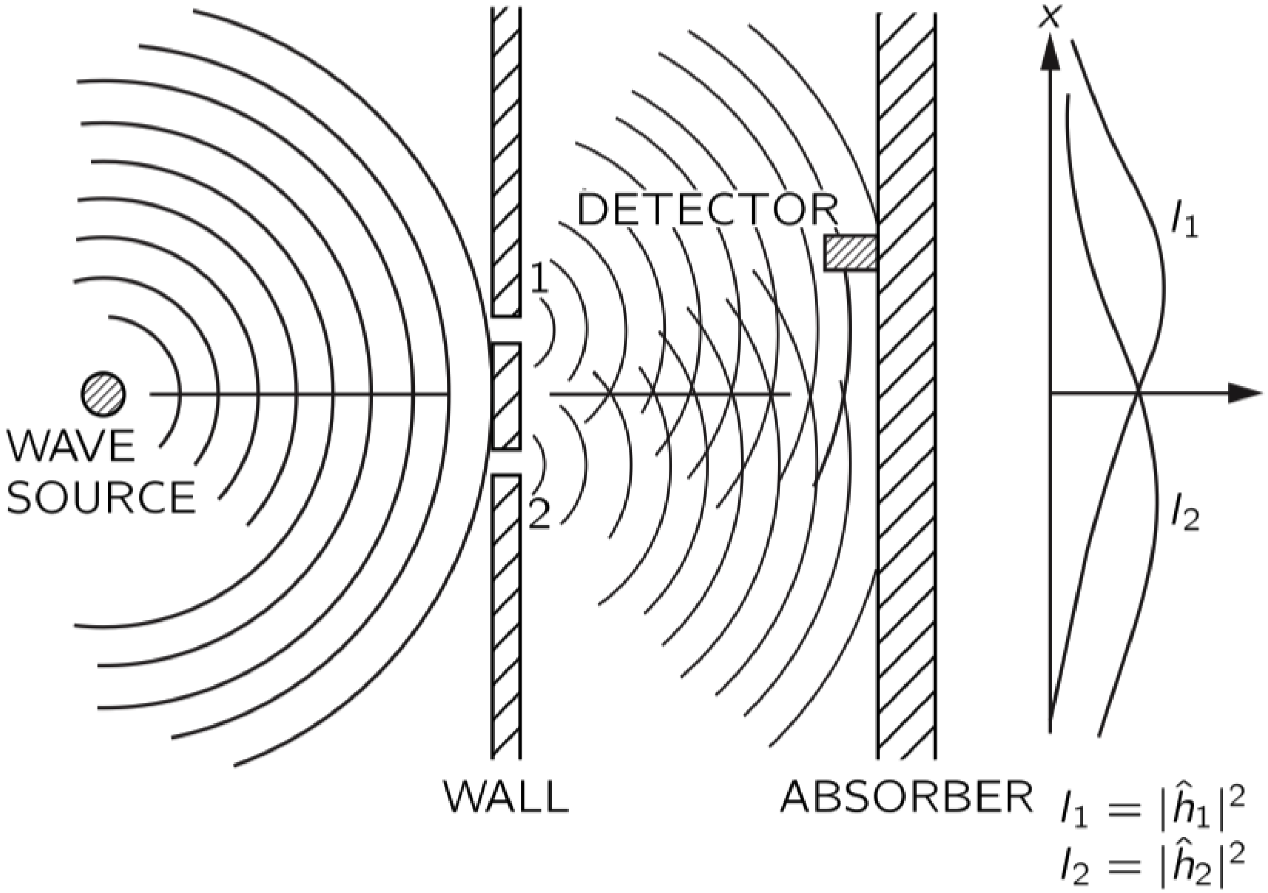


Light: Thomas Young experiment:



Case 2: Experiment with Waves

We replace the gun by a wave generator: think of water waves. Slits 1 and 2 act as new wave sources. The detector measures now the intensity (energy) in the wave.



Observation:
Waves do not Come in "lumps".

$I_1 = |h_1|^2$ ← Only 1 is open

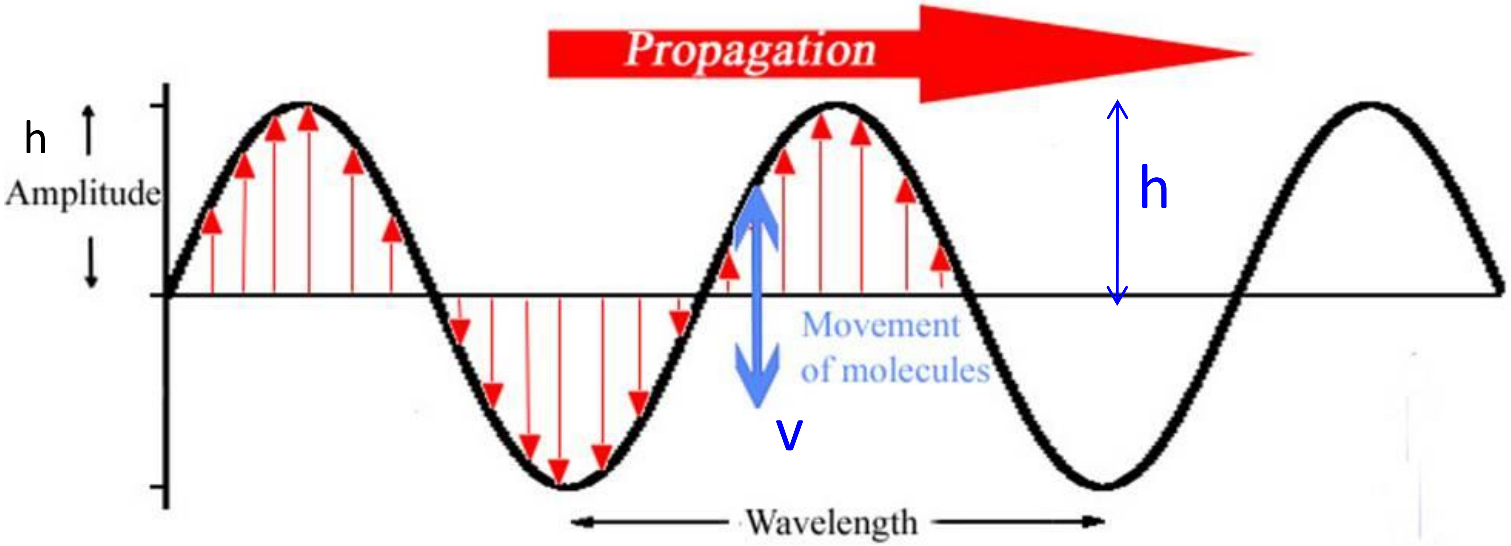
$I_2 = |h_2|^2$ ← Only 2 is open

$I_{12} = ??$ ← Both 1 and 2 open

The intensity of a wave is the square of the amplitude…

Intermezzo: Wave Oscillation & Intensity

Energy in the oscillation (up-down) movement of the molecules:
$E_{kin} = {}^1/_2\, mv^2$ and v is proportional to the amplitude or height: $v \approx h$
So that the intensity of the wave is: $I \approx h^2$



Formula for the resulting oscillation of a water molecule somewhere in the wave:

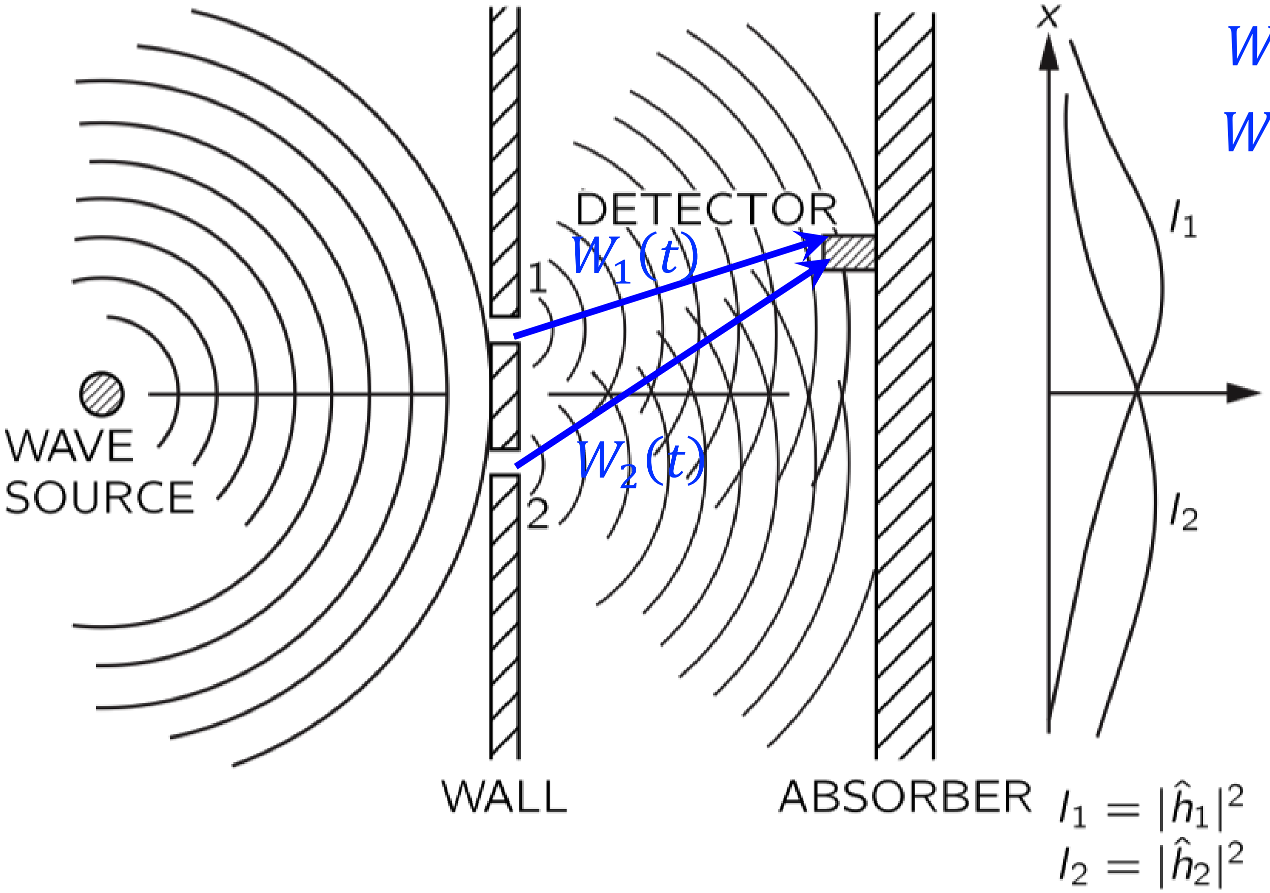
$$W(t) = h\cos(2\pi f t + \phi)$$

and the Intensity: $I = h^2$

f = frequency
ϕ = phase

Case 2: Experiment with Waves

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



$W_1(t) = h_1 \cos(2\pi f\ t + \phi_1)$

$W_2(t) = h_2 \cos(2\pi f\ t + \phi_2)$

ϕ_1 and ϕ_2 depend on distance to 1 and 2

$$I_1 = |h_1|^2$$
$$I_2 = |h_2|^2$$
$$I_{12} = ??$$

First combine: $W(t) = W_1(t) + W_2(t)$

Afterwards look at the amplitude and intensity of the resulting wave!

For math lovers: let's calculate

$$W_{12}(t) = h_1 \cos(2\pi f t + \phi_1) + h_2 \cos(2\pi f\, t + \phi_2)$$

Assume equal size waves: $h_1 = h_2 = h$

Find amplitude of sum wave $W_{12}(t)$.

From math textbook: $\cos(A) + \cos(B) = 2\cos\left(\frac{1}{2}(A-B)\right)\cos\left(\frac{1}{2}(A+B)\right)$

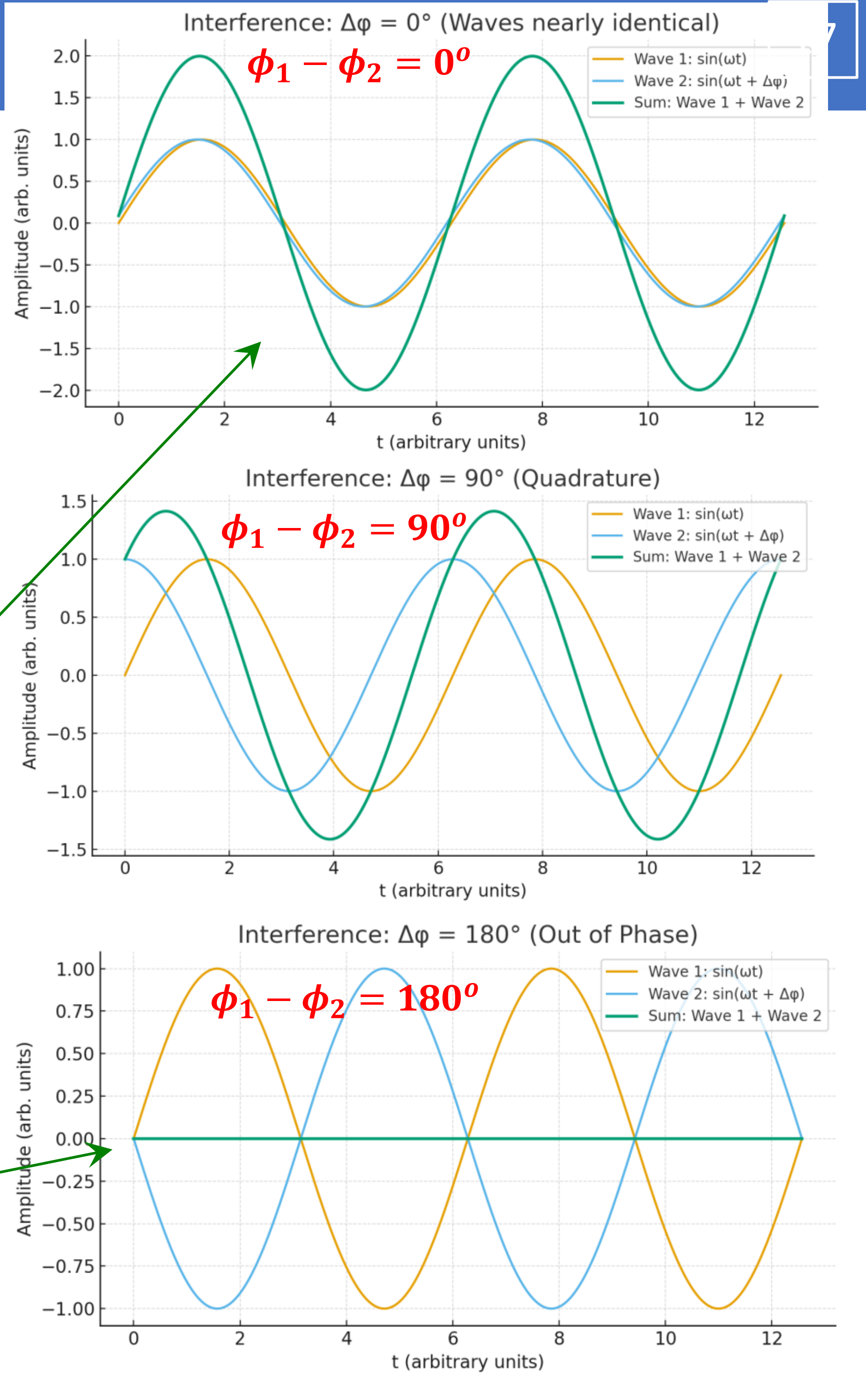
Use this to find:

$$W_{12}(t) = h' \cos\left(2\pi f t + \frac{1}{2}(\phi_1 + \phi_2)\right)$$

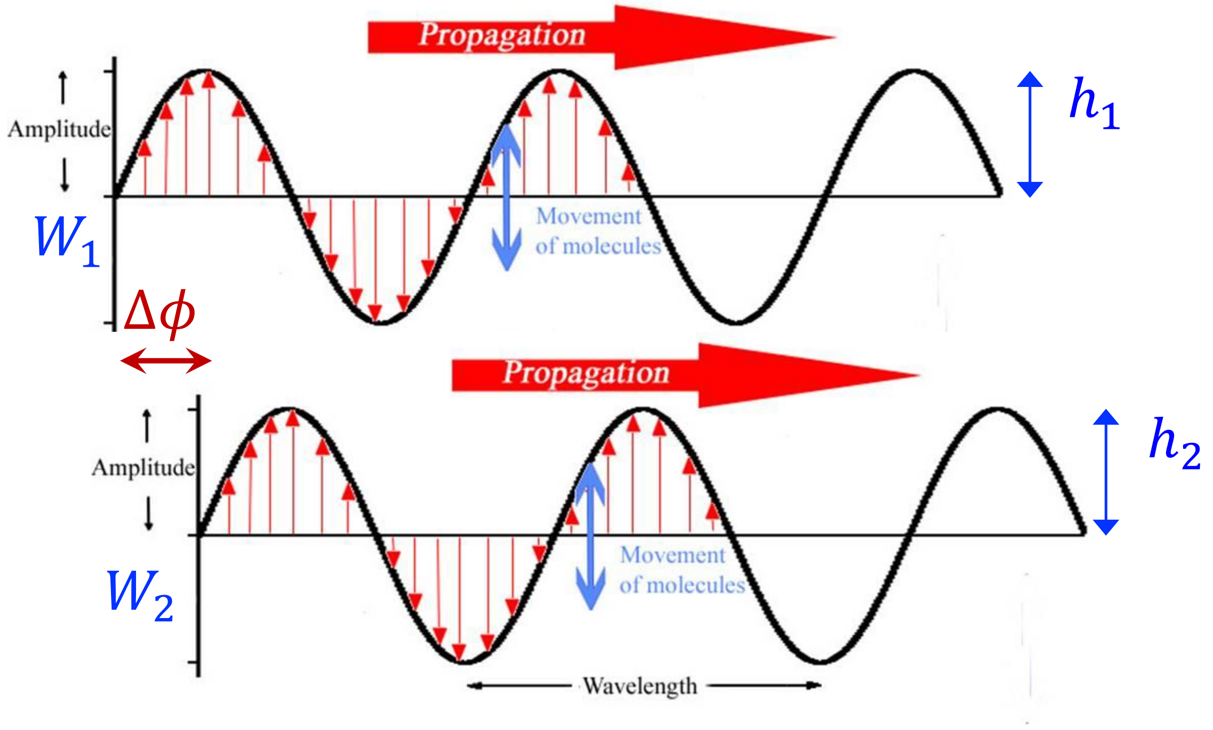
With $h' = 2h \cos\left(\frac{1}{2}(\phi_1 - \phi_2)\right)$

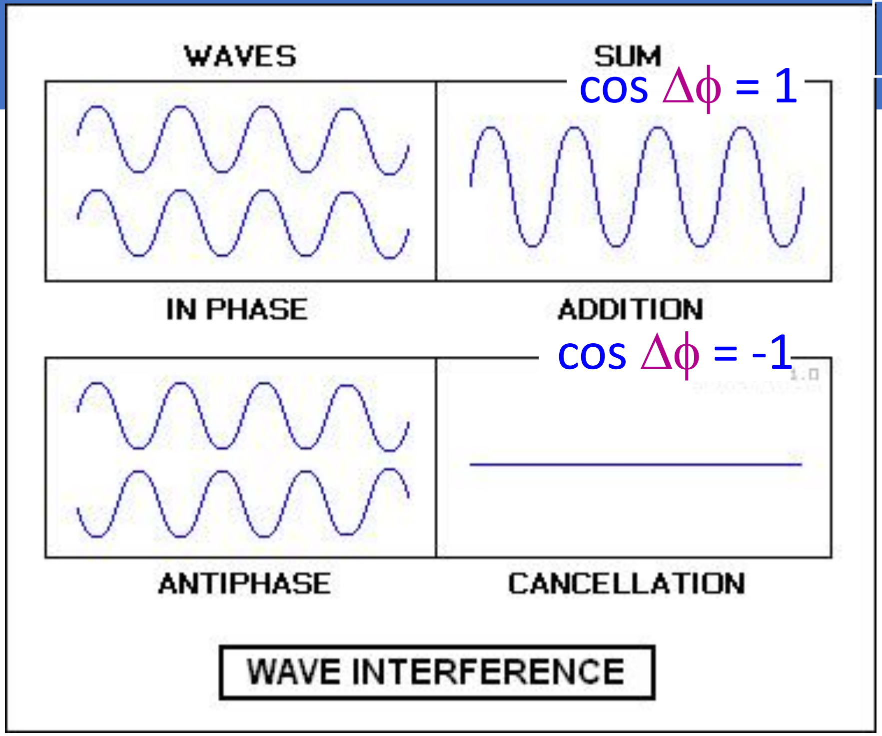
If $\phi_1 - \phi_2 = 0^o$ then double resulting amplitude: ***constructive* interference**

If $\phi_1 - \phi_2 = 180^o$ then zero resulting amplitude: ***destructive* interference**



Interference of Waves





Interfering waves: $\Delta\phi = \phi_1 - \phi_2$

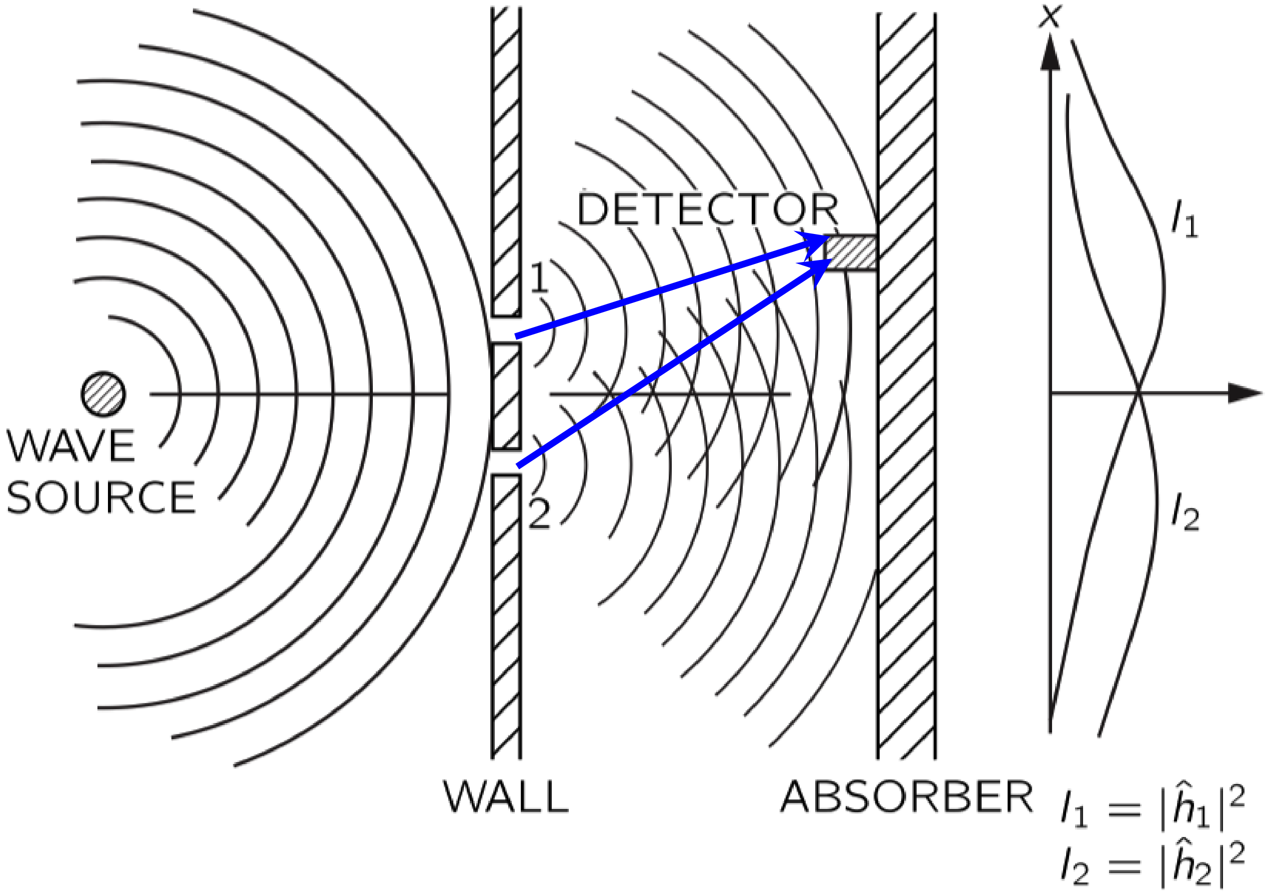
$$I_{12} = |W_1 + W_2|^2 = h_1^2 + h_2^2 + 2h_1 h_2 \cos(\Delta\phi)$$

Regions of *constructive* interference: $I_{12} = 2 \times (I_1 + I_2)$

Regions of *destructive* interference: $I_{12} = 0$

Case 2: Experiment with Waves

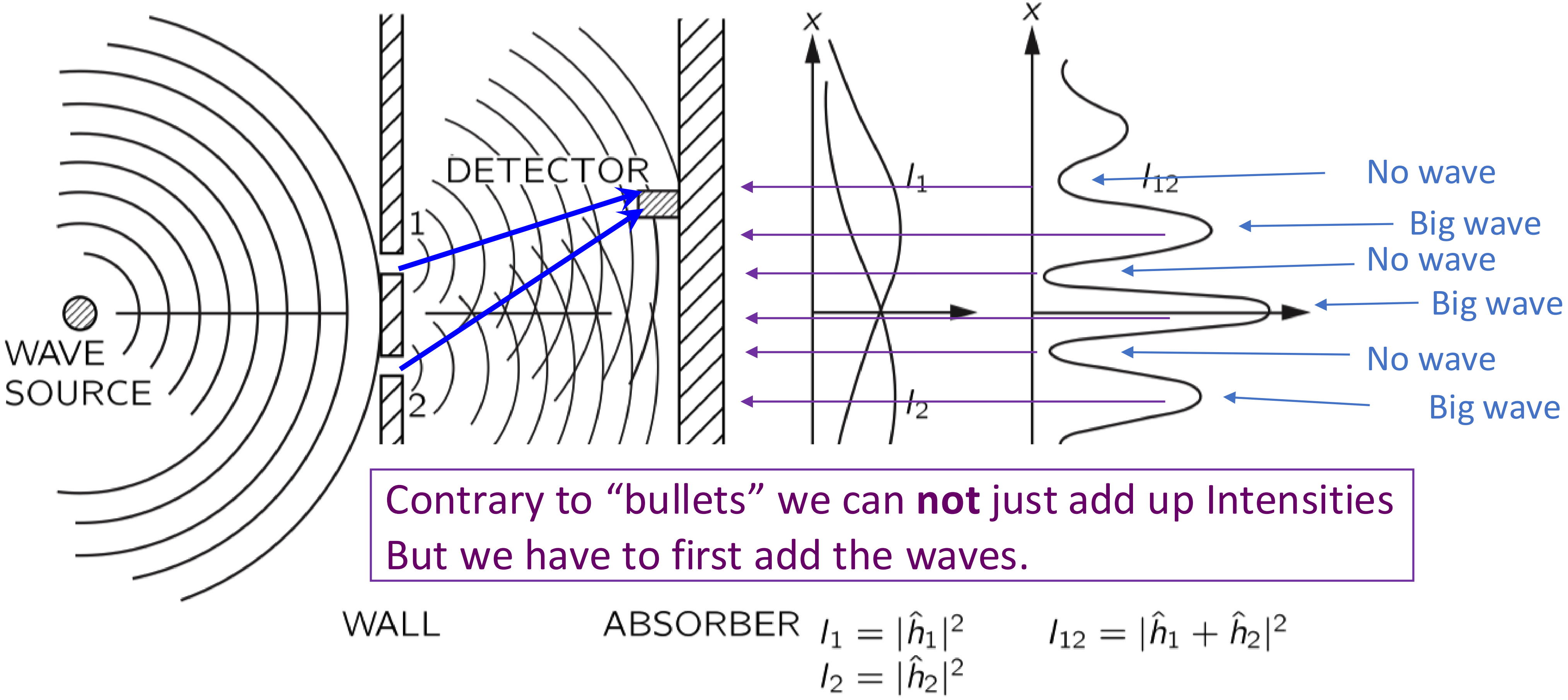
When both slits are open there are two contributions to the wave the oscillation at the detector: $W(t) = W_1(t) + W_2(t)$



First combine: $W(t) = W_1(t) + W_2(t)$
Afterwards look at the amplitude and intensity of the resulting wave!

Case 2: Experiment with Waves

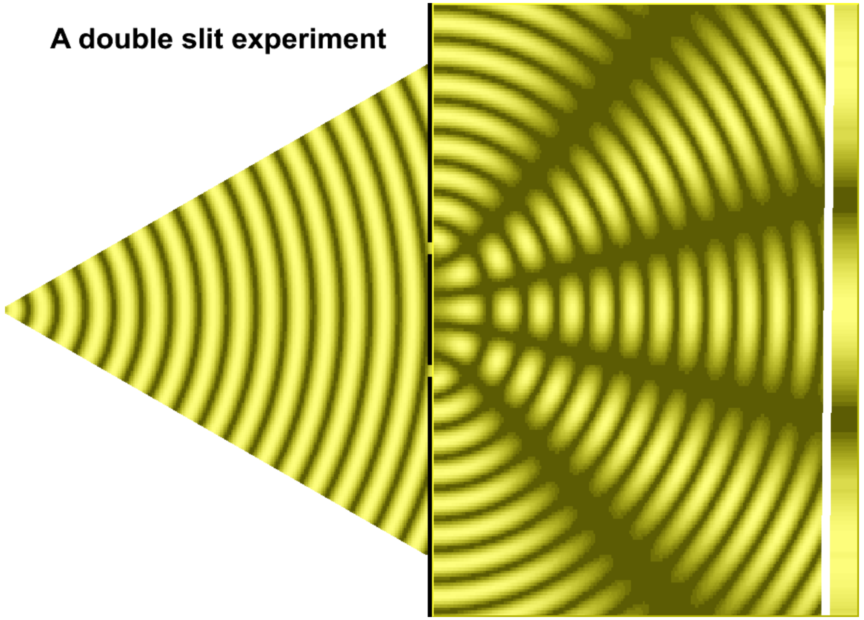
When both slits are open there are two contributions to the wave the oscillation at the detector: $W(t) = W_1(t) + W_2(t)$

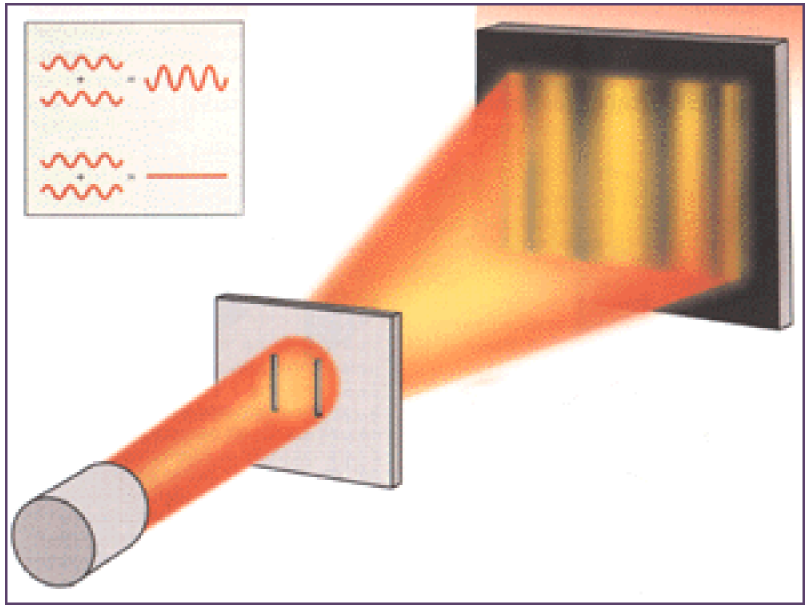


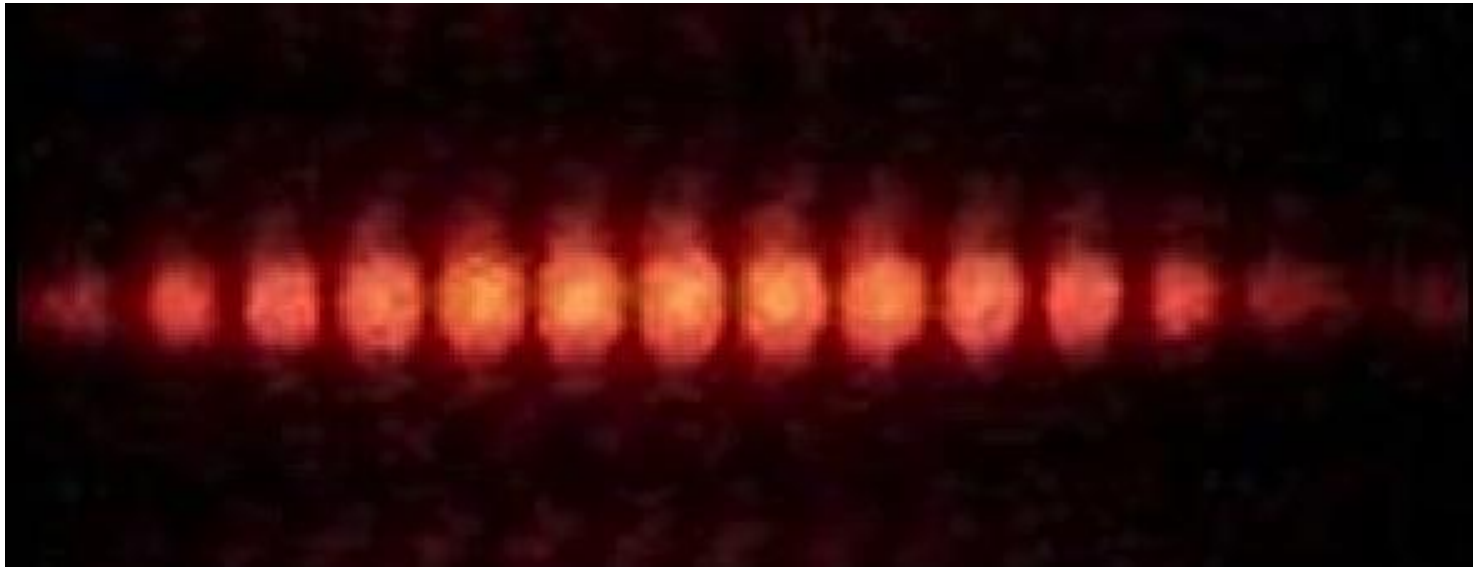
Contrary to “bullets” we can **not** just add up Intensities But we have to first add the waves.

Interference pattern: $I_{12} = |W_1 + W_2|^2 = h_1^2 + h_2^2 + 2h_1h_2\cos(\Delta\phi)$
Regions where waves are *amplified* and regions where waves are *cancelled*.

Double Slit Experiment with Light (Young)







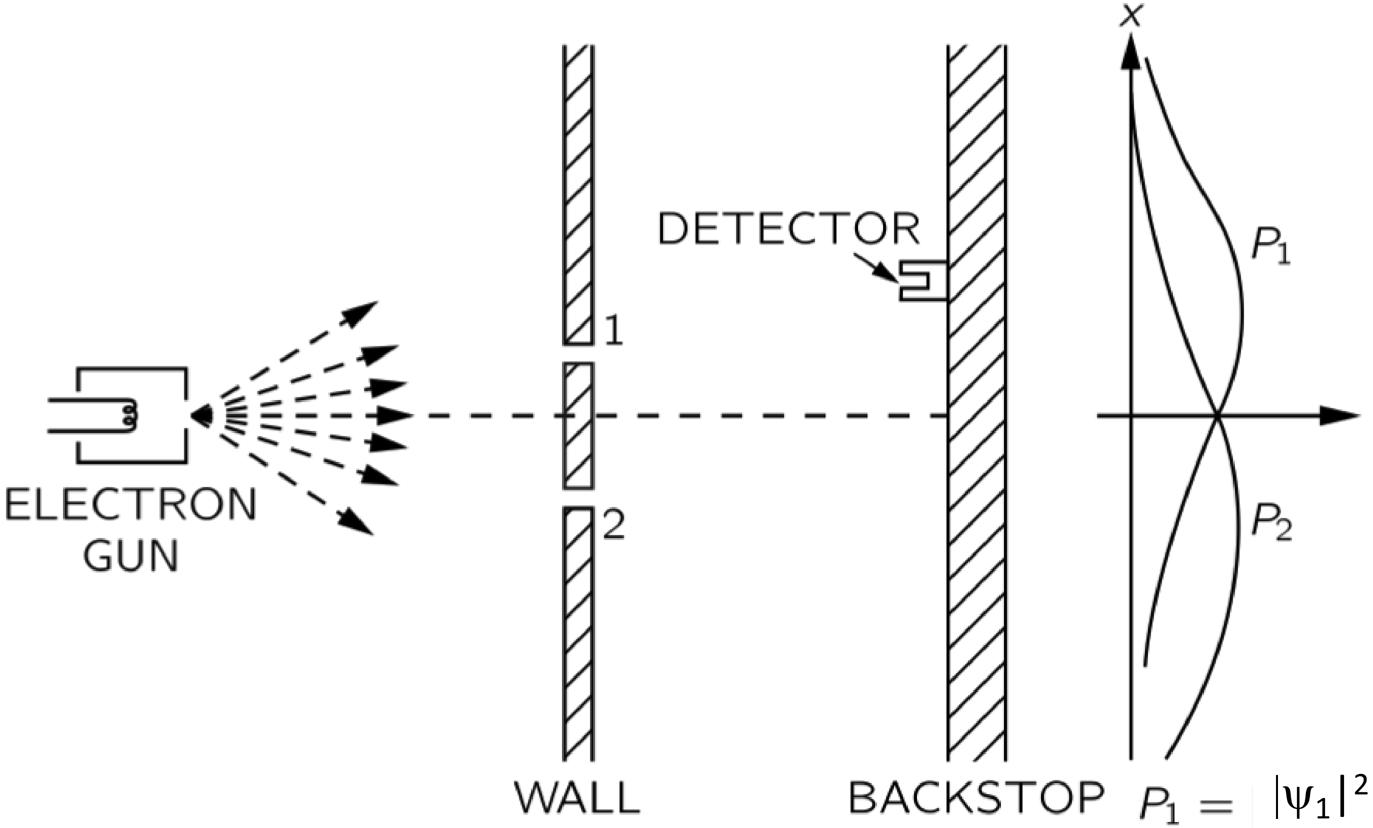
The Double Slit Experiment

Case 3:

An Experiment with Electrons

Case 3: Experiment with Electrons

From the detector counts deduce again the probabilities P_1 and P_2

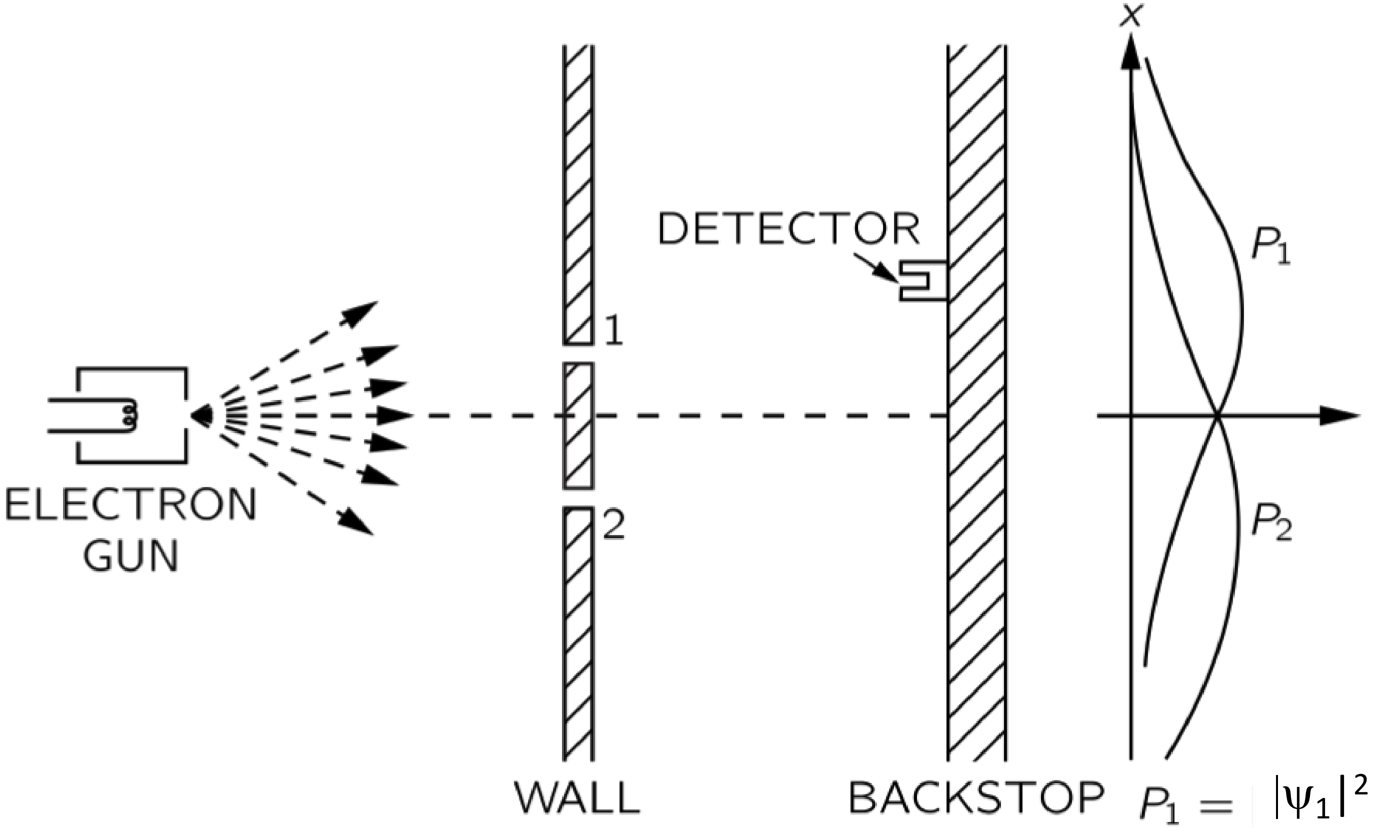


$$P_1 = |\psi_1|^2$$
$$P_2 = |\psi_2|^2$$

Observation:
Electrons come in "lumps", like bullets

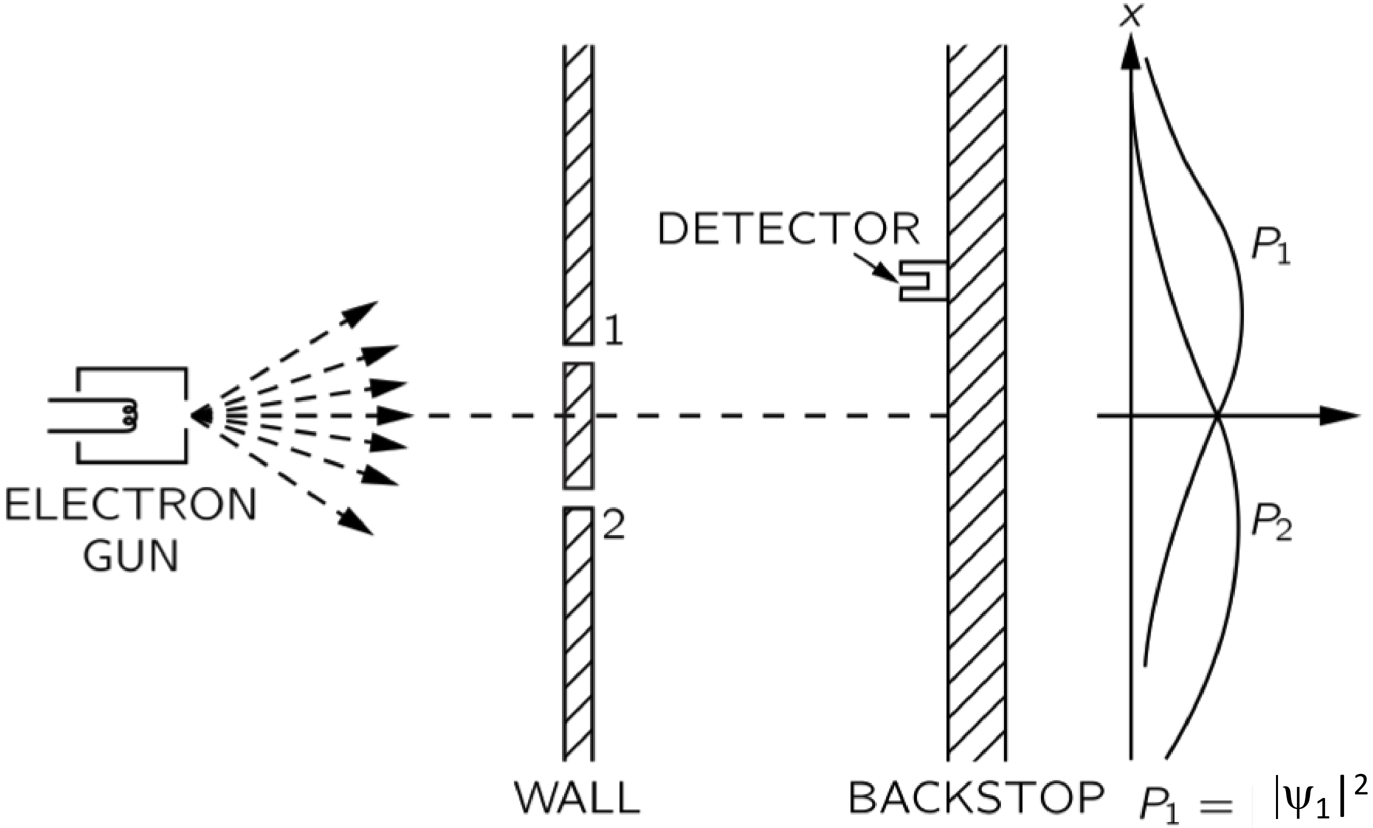
What do we expect when both slits are open?

Case 3: Experiment with Electrons



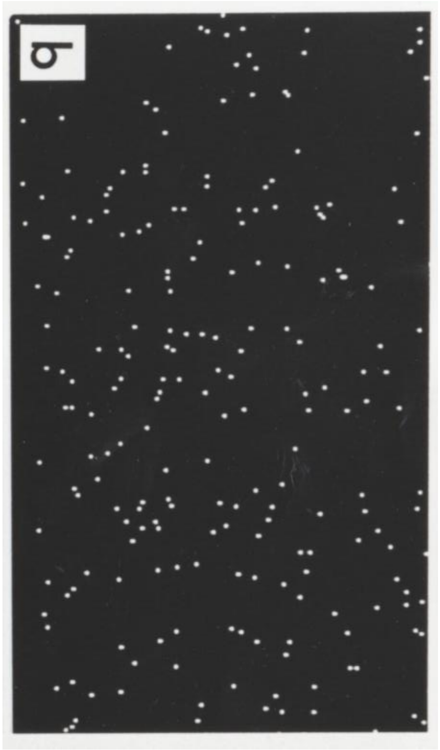
$$P_1 = |\psi_1|^2$$
$$P_2 = |\psi_2|^2$$

Case 3: Experiment with Electrons

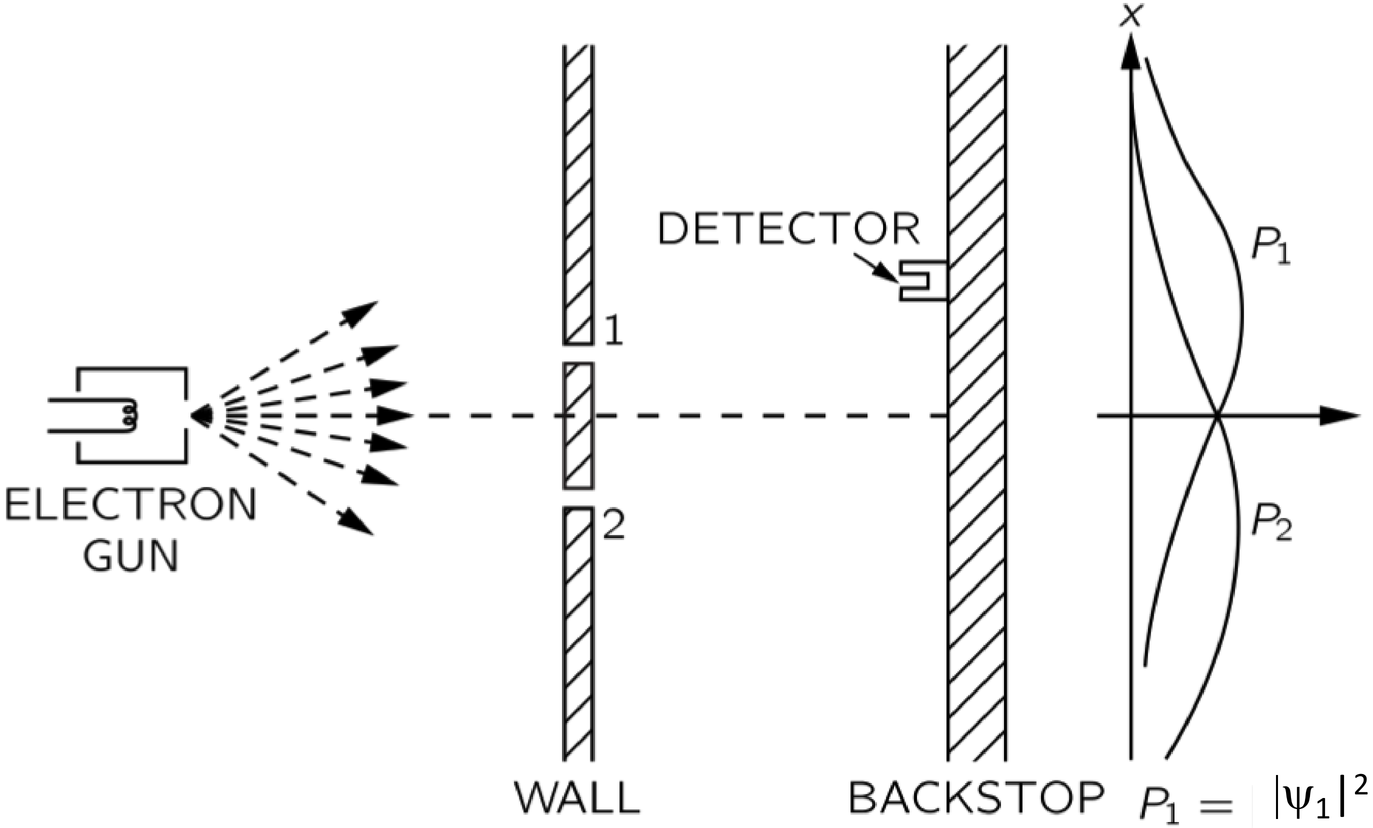


$P_1 = |\psi_1|^2$

$P_2 = |\psi_2|^2$

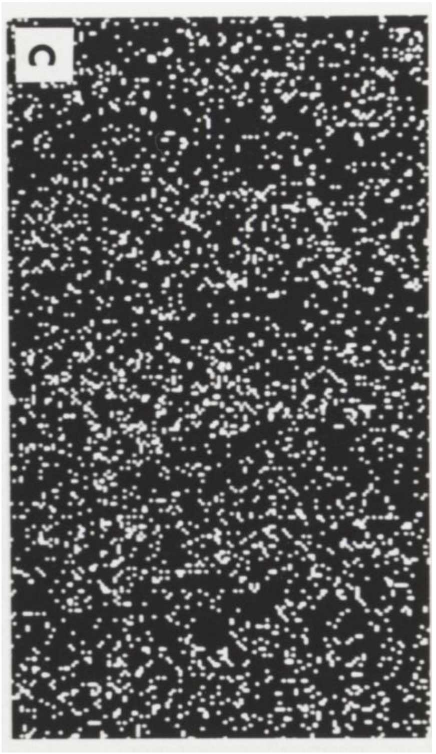


Case 3: Experiment with Electrons

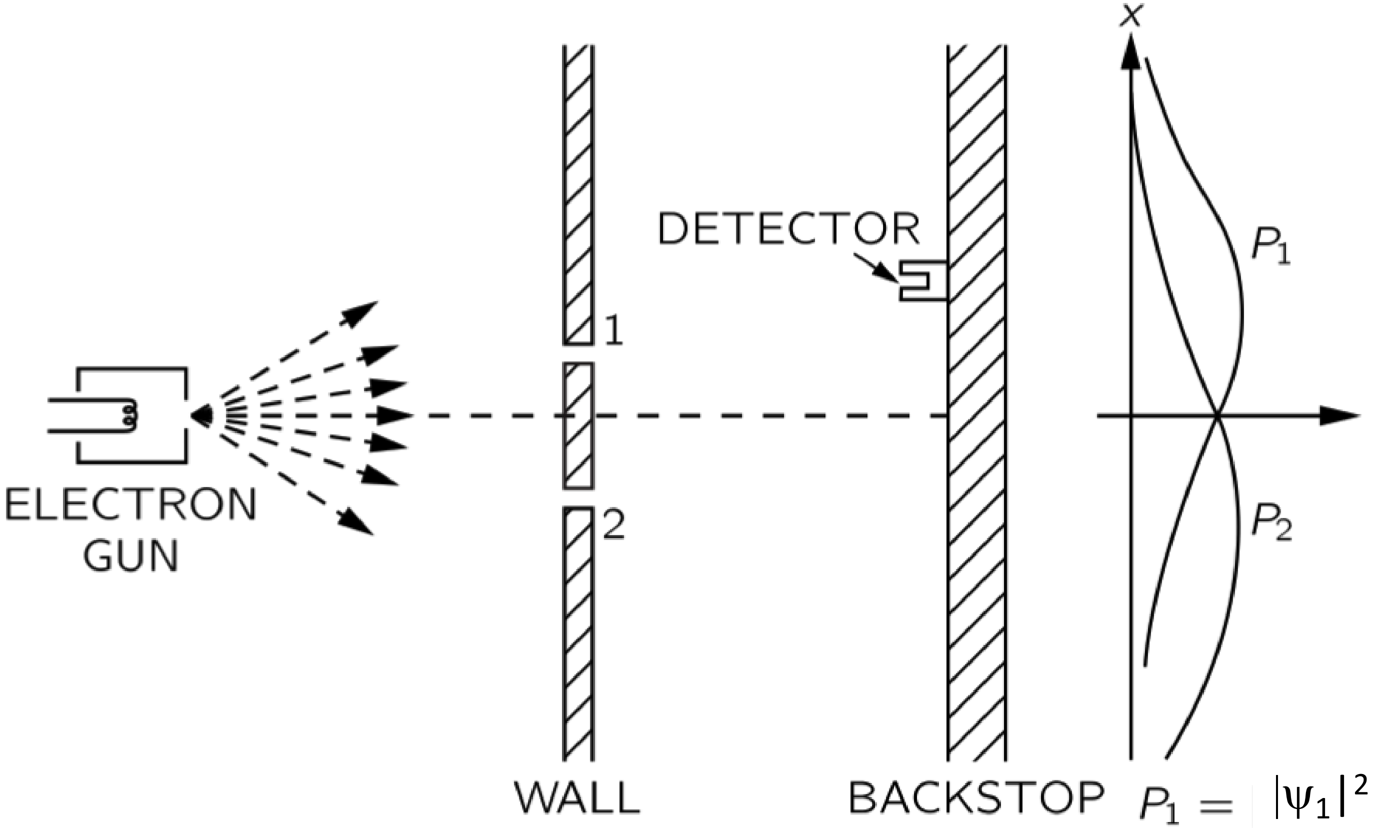


$P_1 = |\psi_1|^2$

$P_2 = |\psi_2|^2$

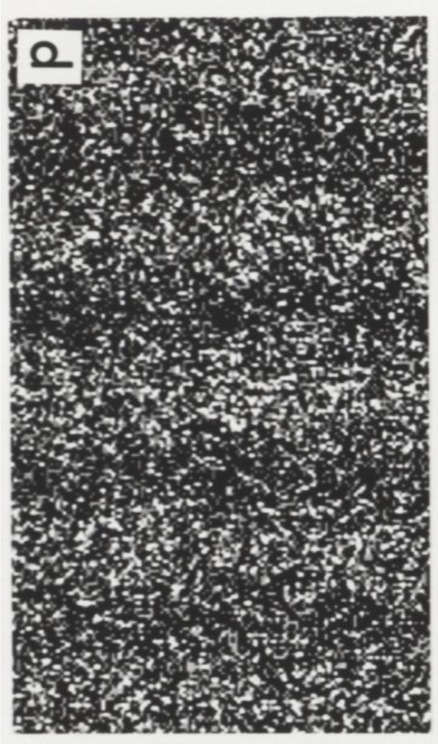


Case 3: Experiment with Electrons

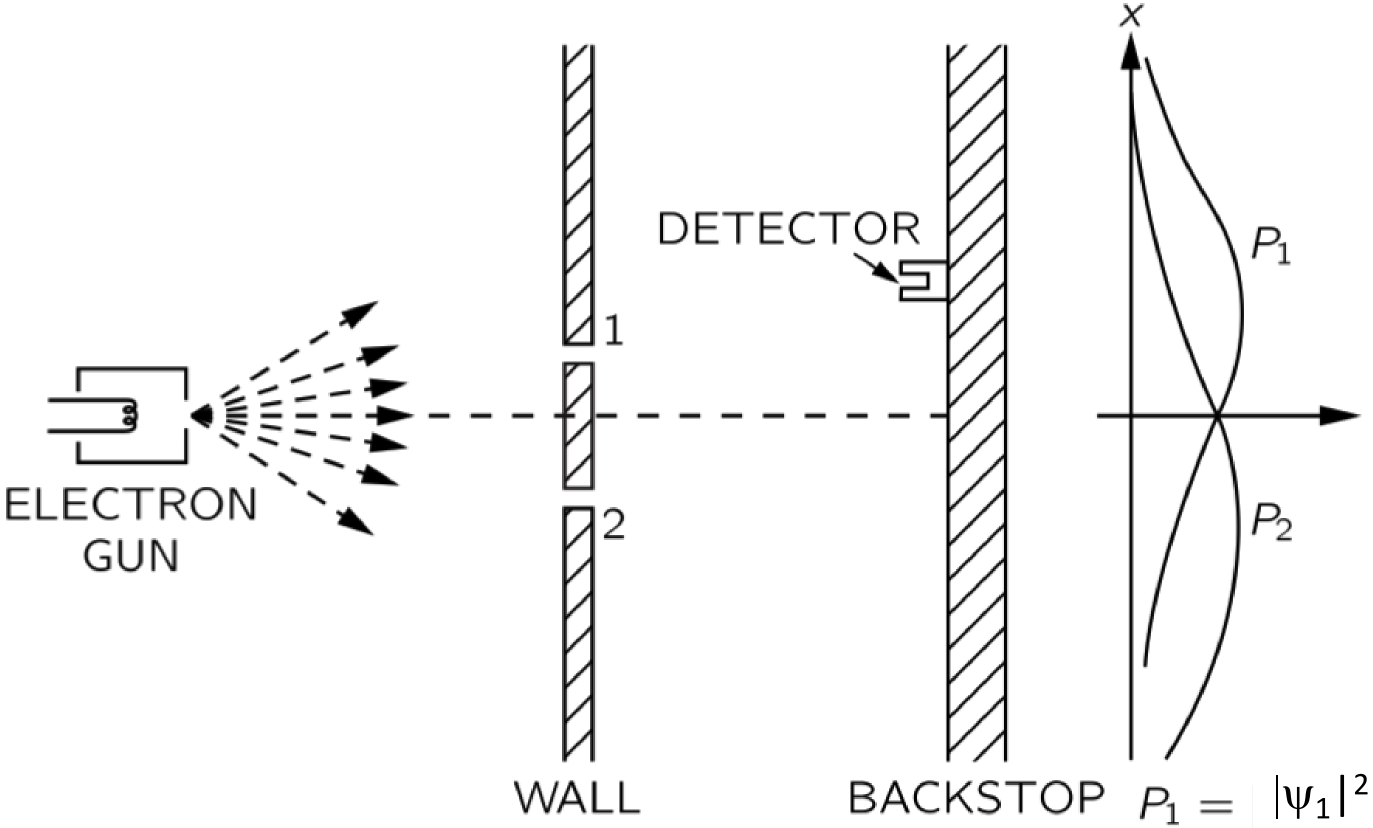


$P_1 = |\psi_1|^2$

$P_2 = |\psi_2|^2$

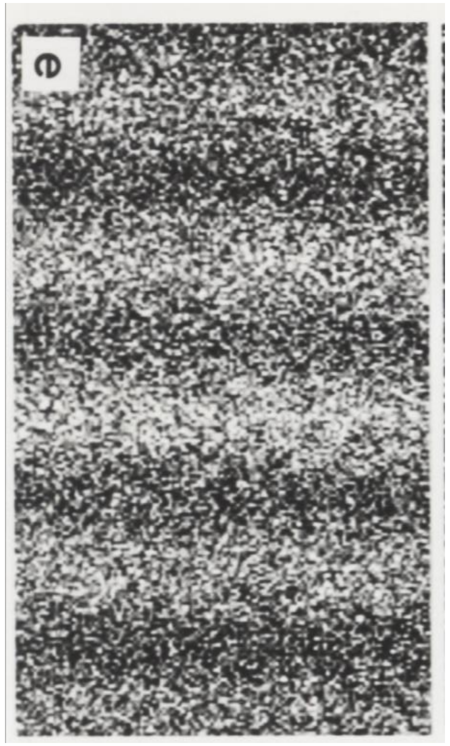


Case 3: Experiment with Electrons

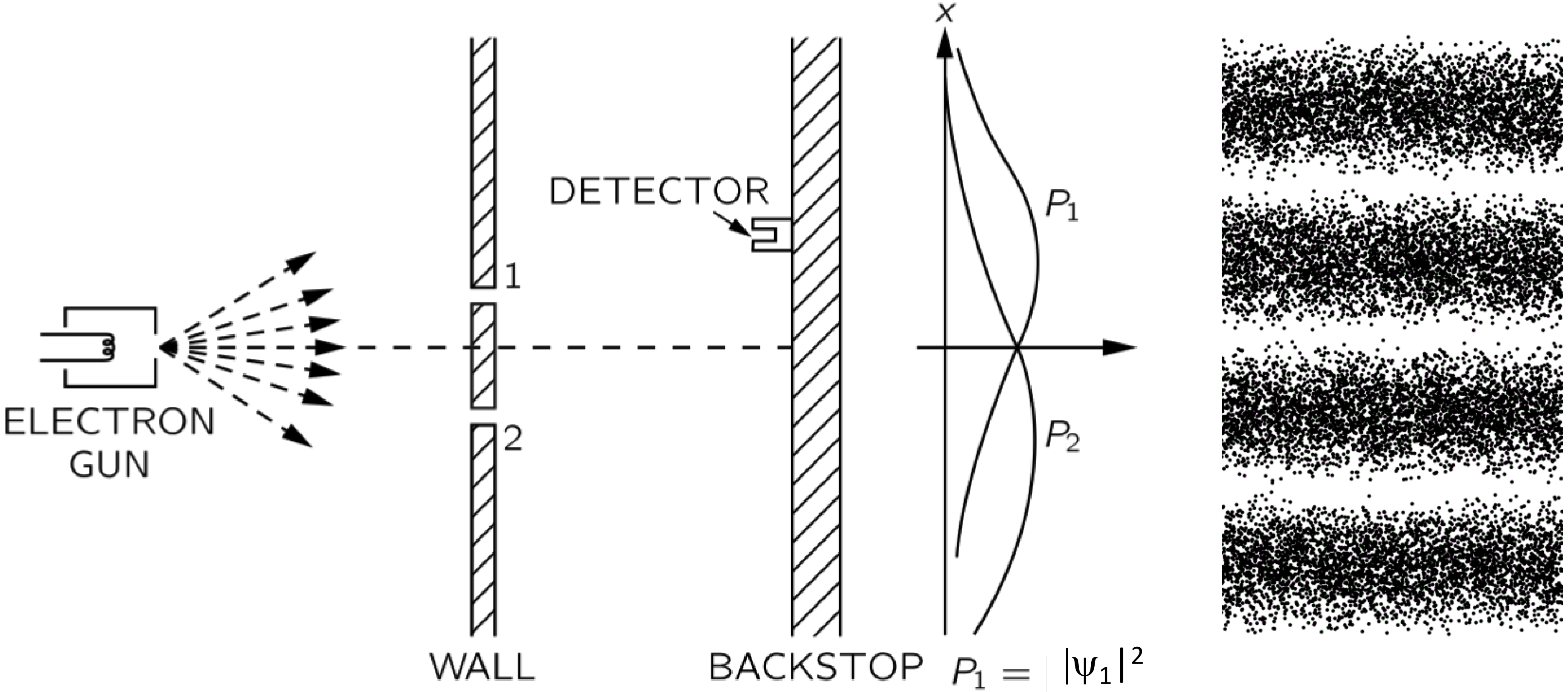


$P_1 = |\psi_1|^2$

$P_2 = |\psi_2|^2$



Case 3: Experiment with Electrons



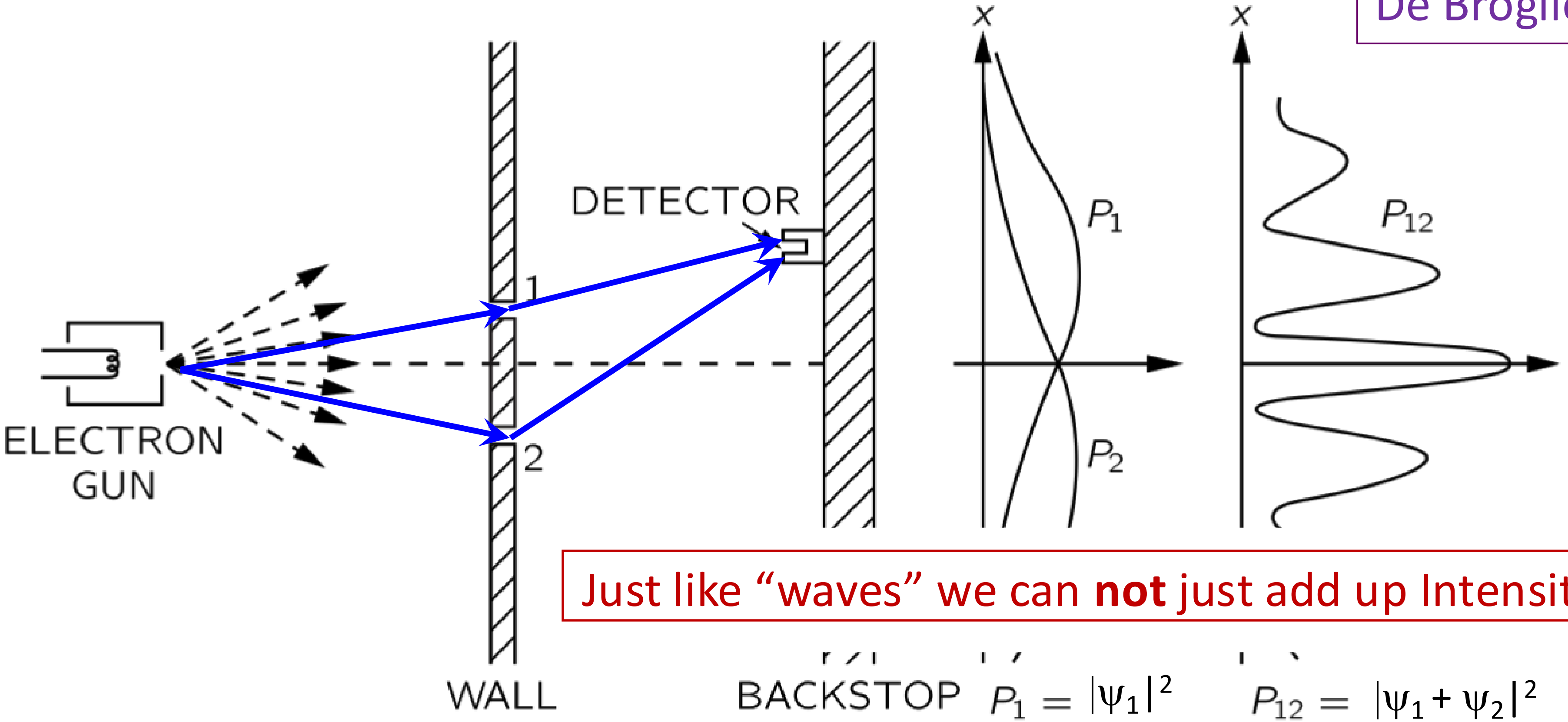
$$P_1 = |\psi_1|^2$$
$$P_2 = |\psi_2|^2$$

Case 3: Experiment with Electrons

An Interference pattern!

The electron wave function behaves exactly like classical waves.

De Broglie waves



Just like "waves" we can **not** just add up Intensities.

$P_1 = |\psi_1|^2$ $\quad P_{12} = |\psi_1 + \psi_2|^2$

$P_2 = |\psi_2|^2$

Add the wave amplitudes:

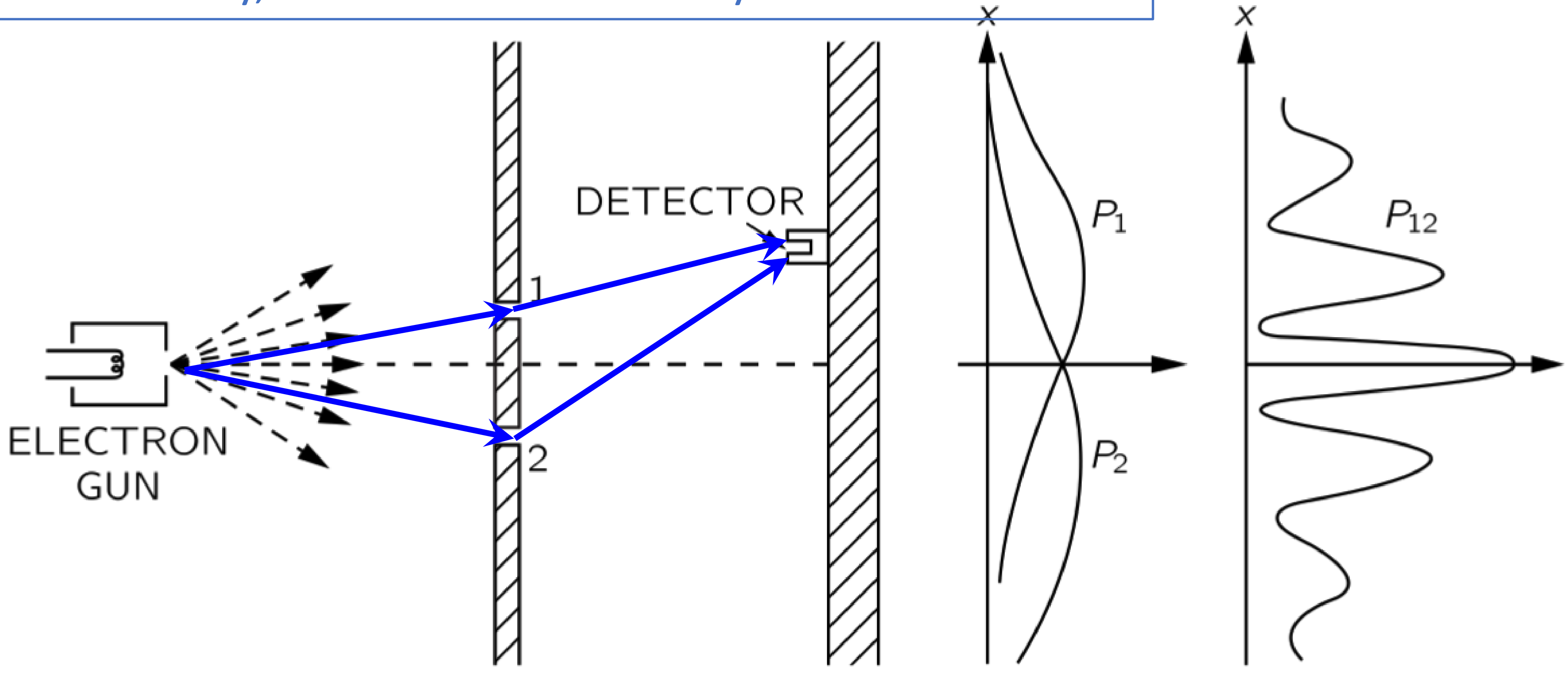
$\psi_{12} = \psi_1 + \psi_2$

The probability is the square of the sum:

$P_{12} = |\psi_{12}|^2 = |\psi_1 + \psi_2|^2 = |\psi_1|^2 + |\psi_2|^2 + 2\psi_1\psi_2^*$

Case 3: Experiment with Electrons

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

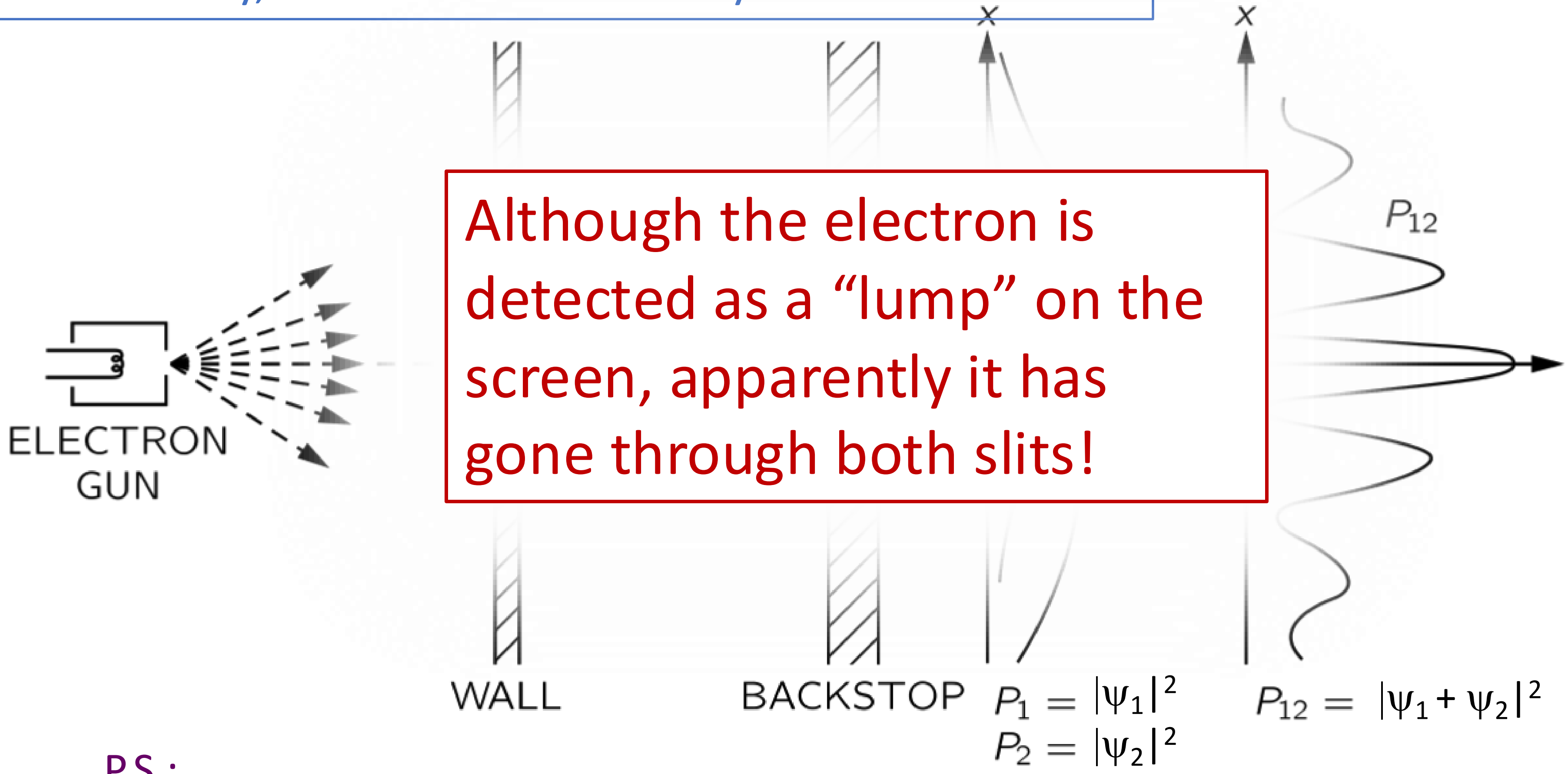


$P_1 = |\psi_1|^2$
$P_2 = |\psi_2|^2$

$P_{12} = |\psi_1 + \psi_2|^2$

Case 3: Experiment with Electrons

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

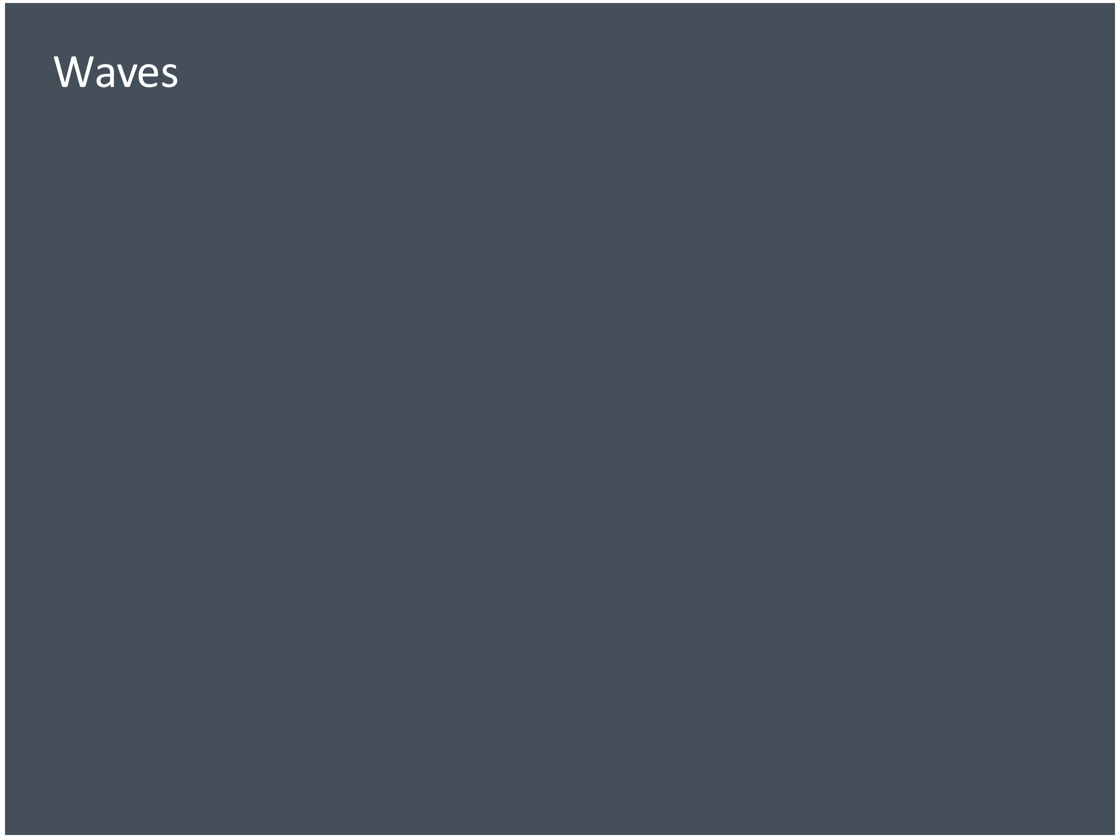


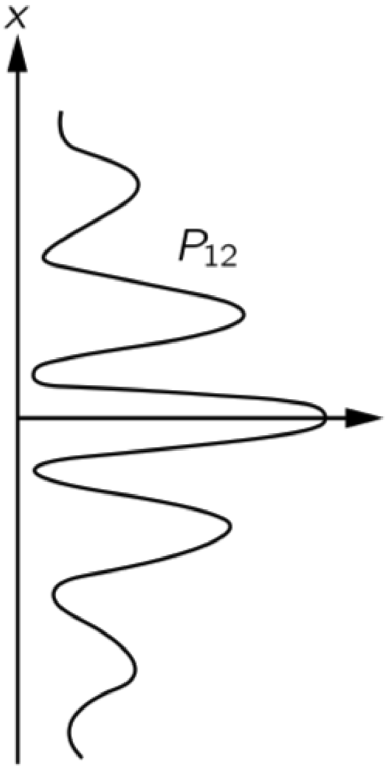
Although the electron is detected as a "lump" on the screen, apparently it has gone through both slits!

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

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





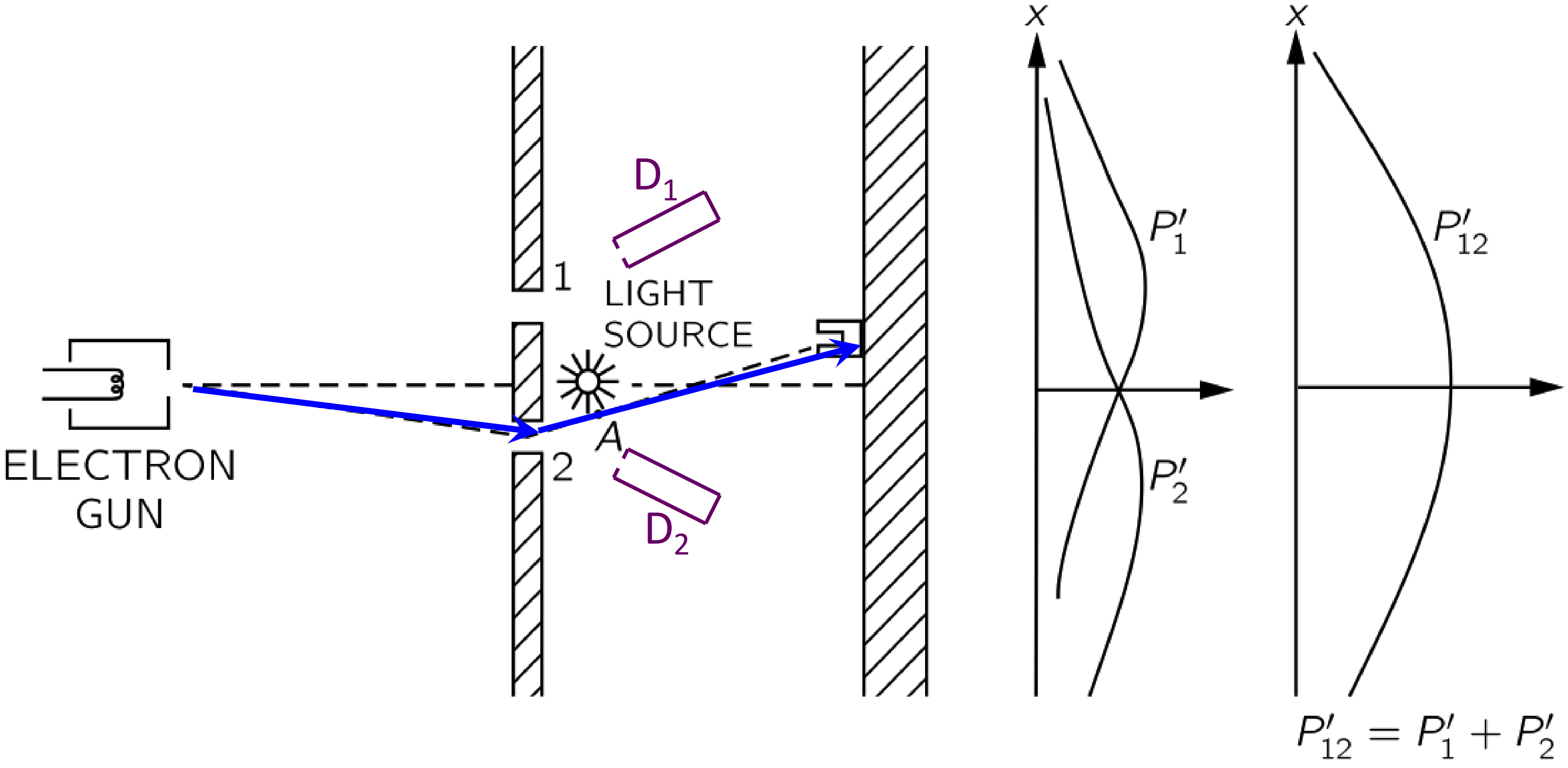
$$P_{12} = |\psi_1 + \psi_2|^2$$

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:
A Different Experiment with Electrons

Case 4: Watch the Electrons

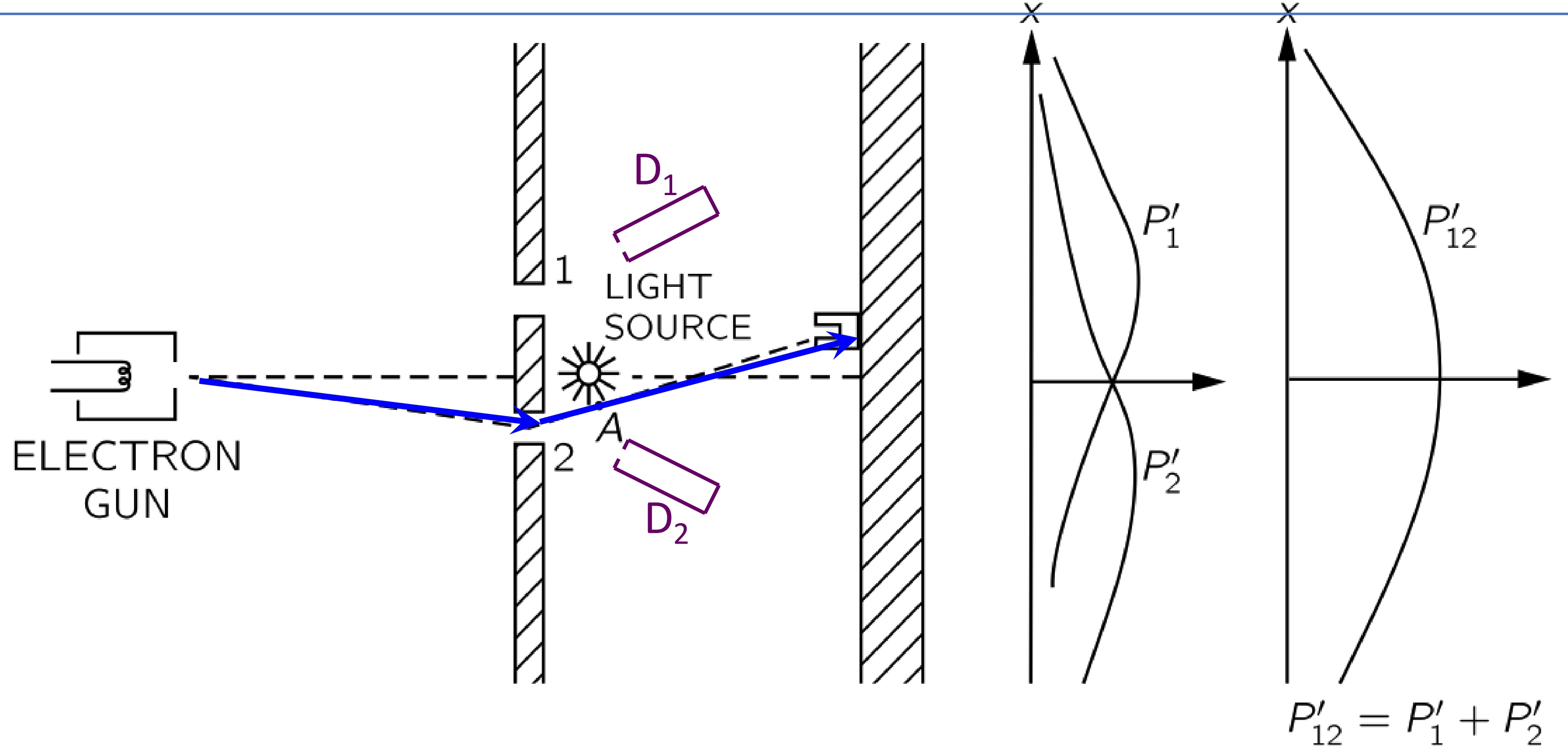
Let us try to out-smart the electron: just watch through which slit it goes!



D_1 and D_2 are two "microscopes" looking at the slits 1 and 2, respectively.

Case 4: Watch the Electrons

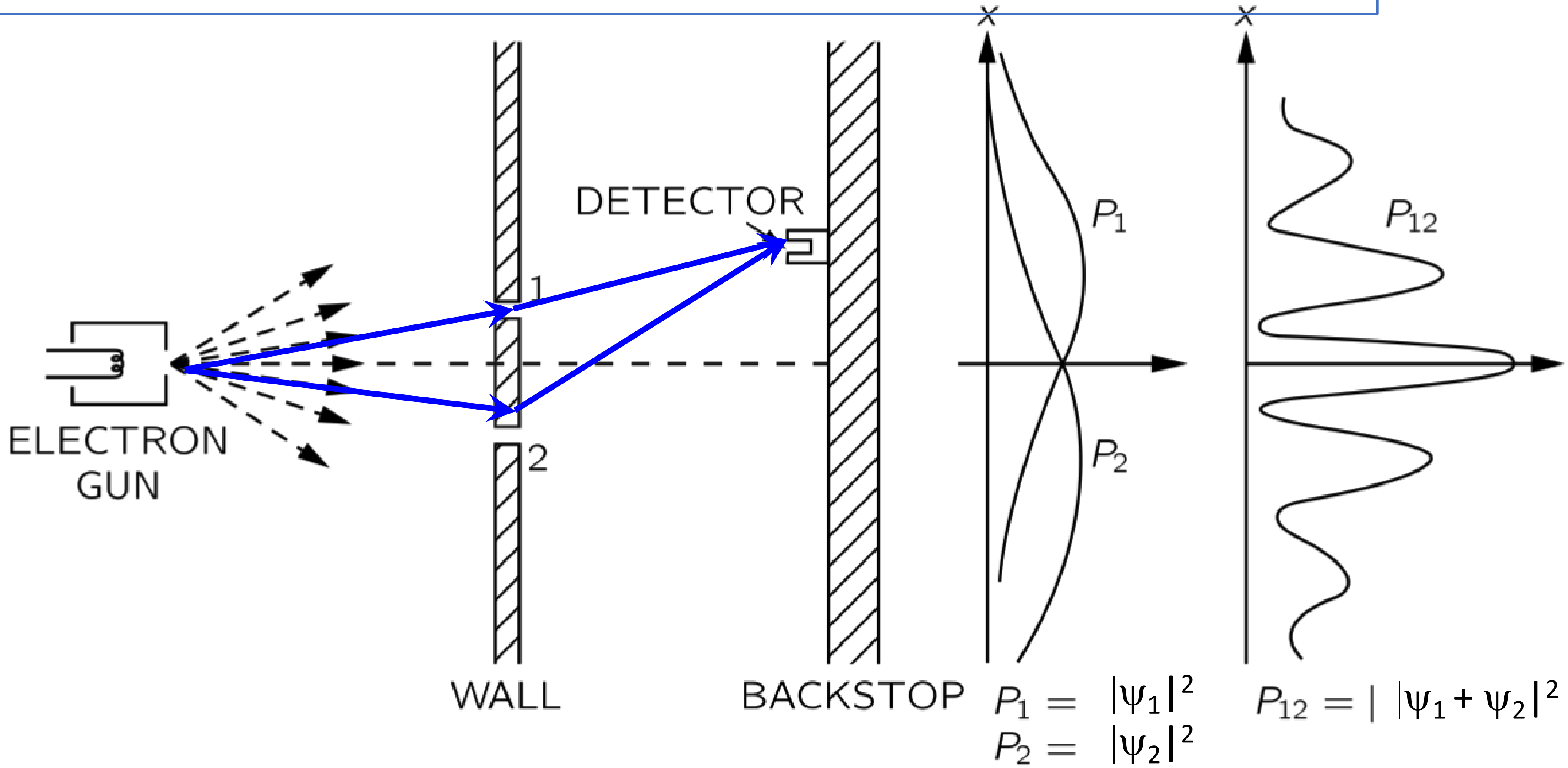
When we watch through which slit the electrons go, we destroy the interference!
Now the electron behaves just like a classical particle (“bullet”).



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”.

Case 3: Don't Watch the Electrons

When we don't watch through through which slit the electrons go, the electron is an object that interferes with itself!



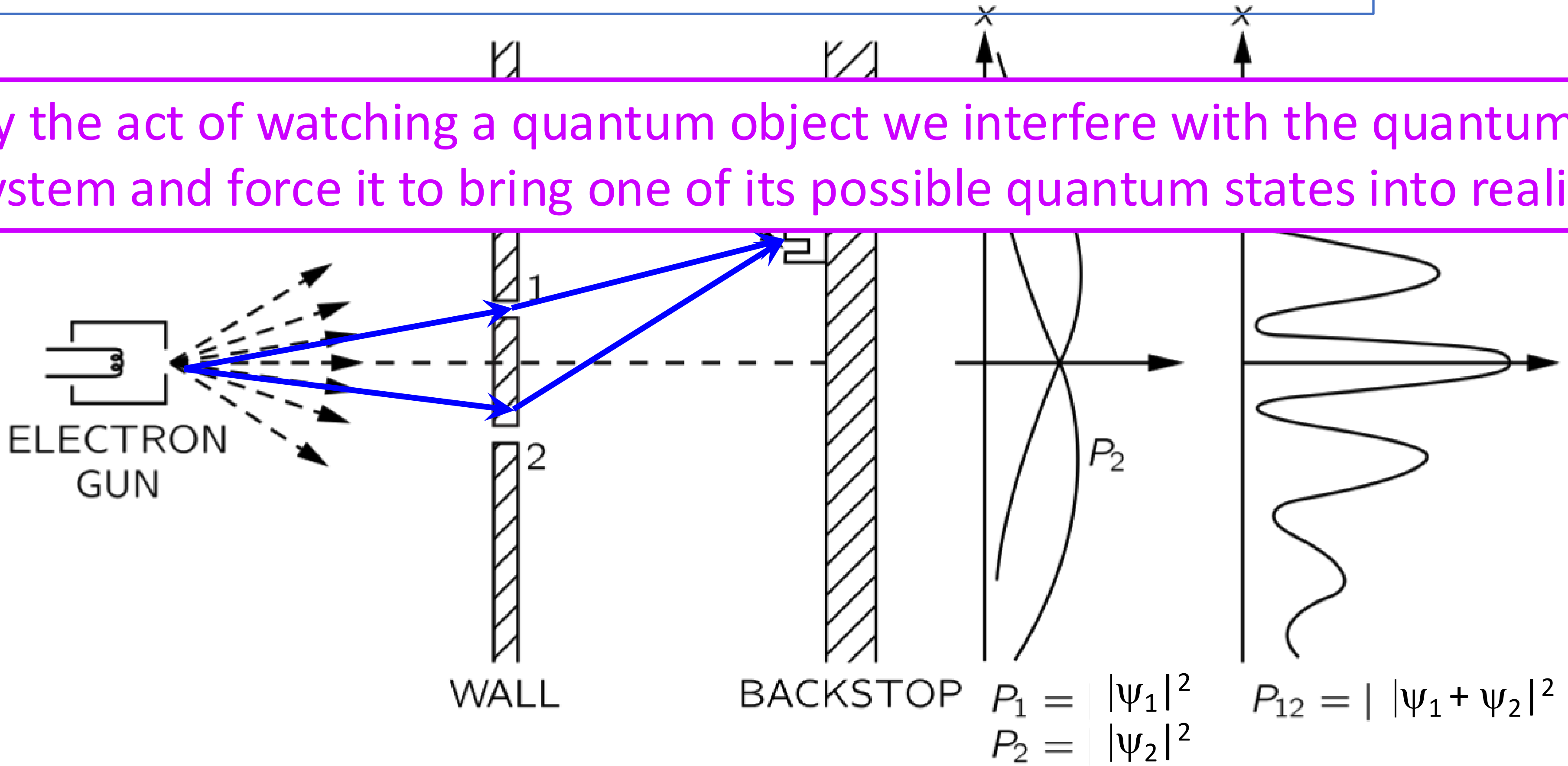
It requires an observation to let the quantum wave function "collapse" into reality. As long as no measurement is made the wave function keeps "all options open".

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

Case 3: Don't Watch the Electrons

When we don't watch through through which slit the electrons go, the electron is an object that interferes with itself!

By the act of watching a quantum object we interfere with the quantum system and force it to bring one of its possible quantum states into reality.



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".

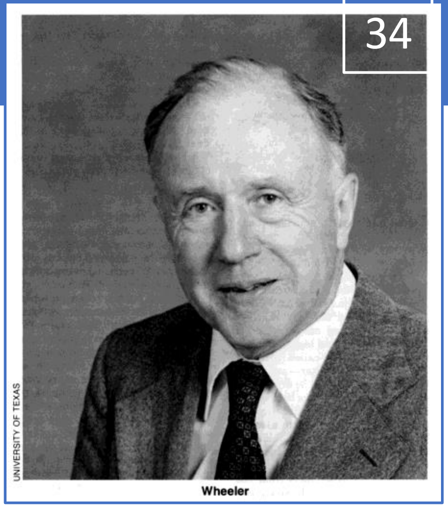
If you watch ***half the time***; you only get the interference for the cases you ***did not watch***.

Wave Particle Duality

Next lecture we will try to out-smart nature one step further…
… and face the consequences.

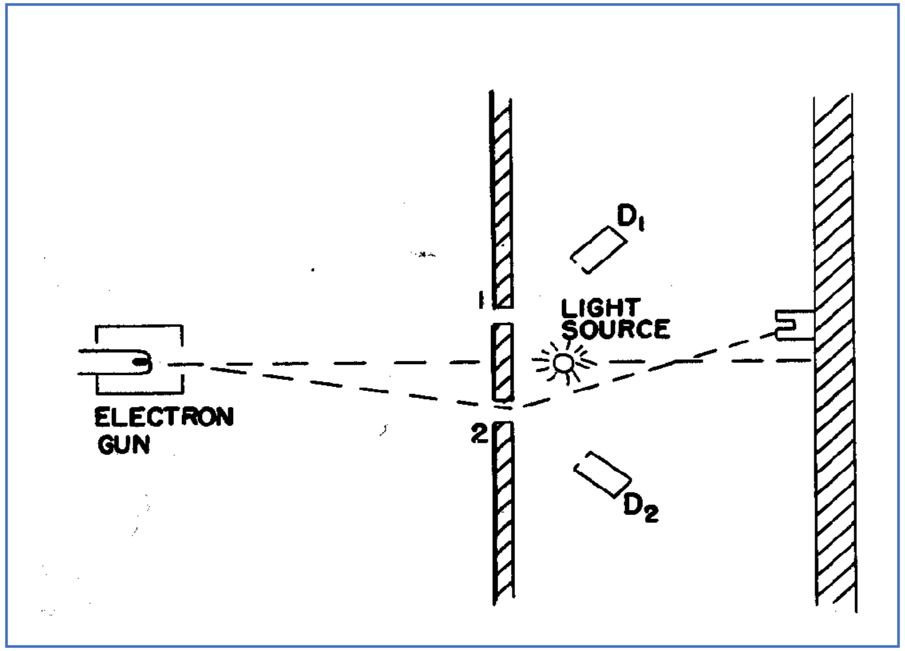
Next Lecture: Wheeler's Delayed Choice

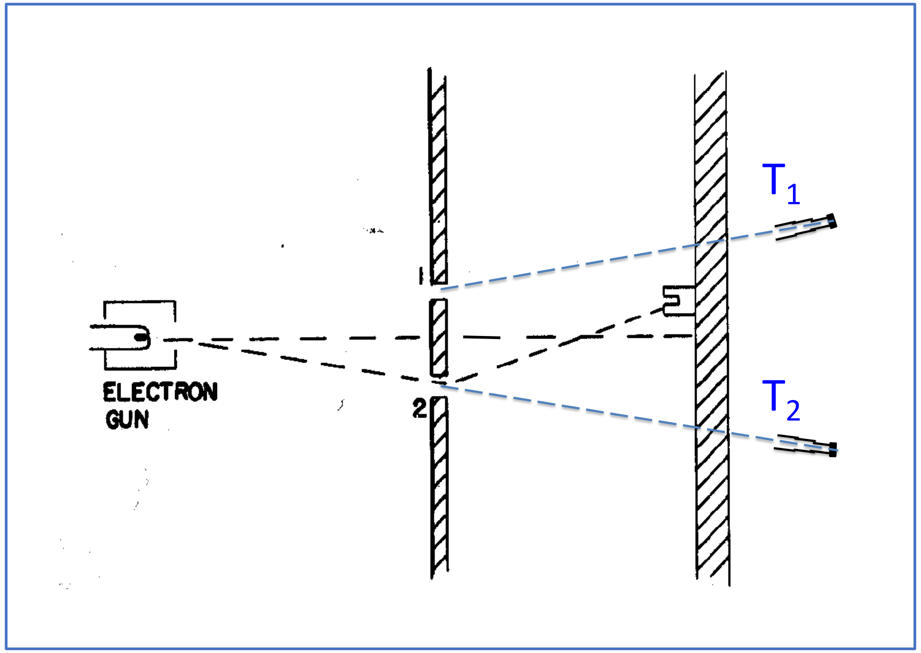
John Wheeler (1911 – 2008):
Famous for work on gravitation
(Black holes – quantum gravity)



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 would reconstruct*** whether the electron went through slit 1 or slit 2?





Try to out-smart nature one step further… and face the consequences: Schrödinger's cat.

Next Lecture…