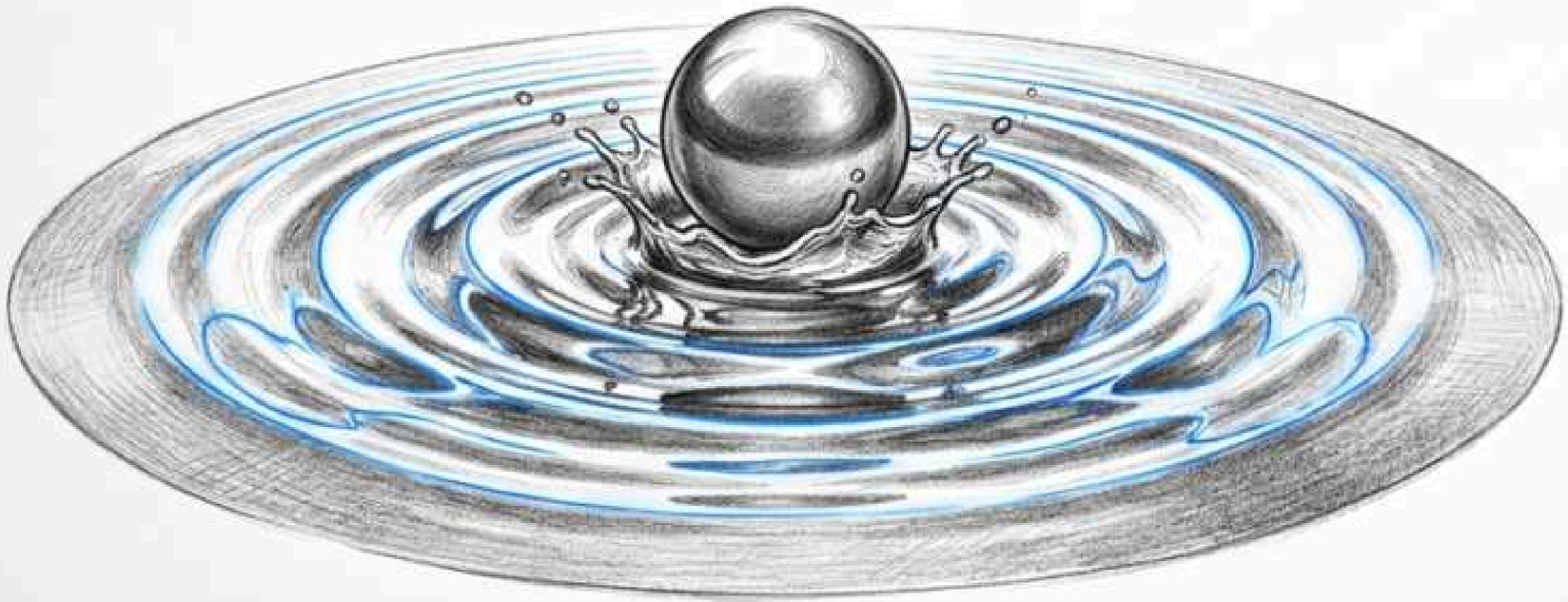


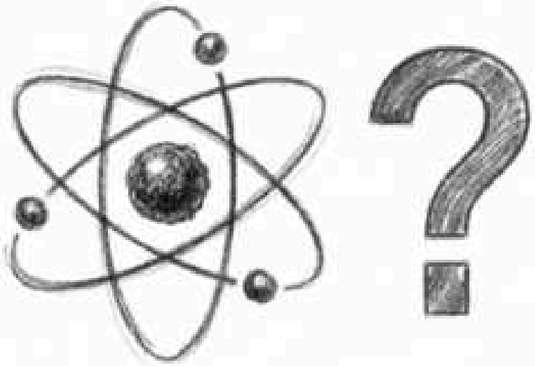
Lecture 2: Particles Are Waves Too

de Broglie and the Double Slit

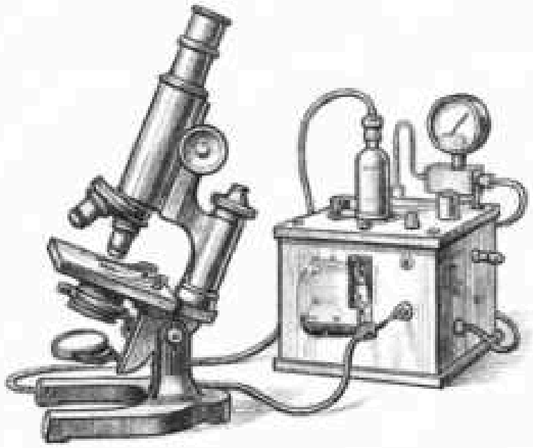
Quantum Mechanics for Everyone

Paragraph 2.1

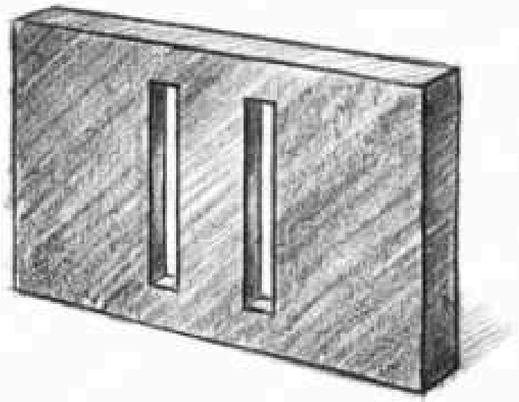
Three Questions for This Lecture



If light behaves like particles, could electrons—which we thought were particles—behave like waves?

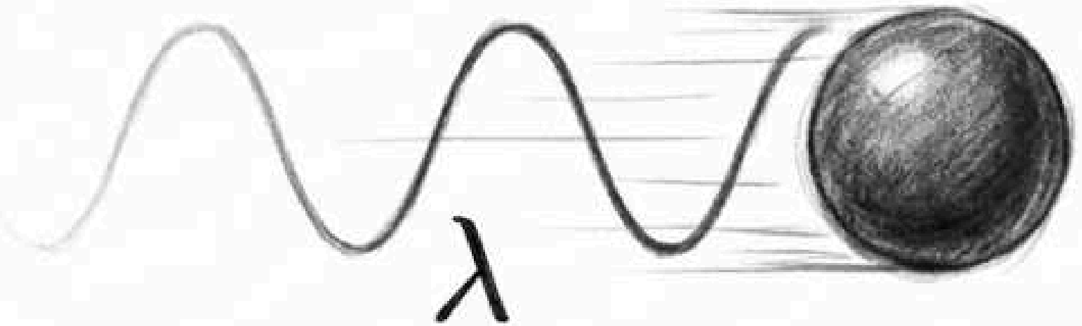


How was that radical idea tested?



What does the double slit experiment, done with one electron at a time, reveal about the quantum world?

De Broglie's Bold Suggestion (1924)



wavelength

p

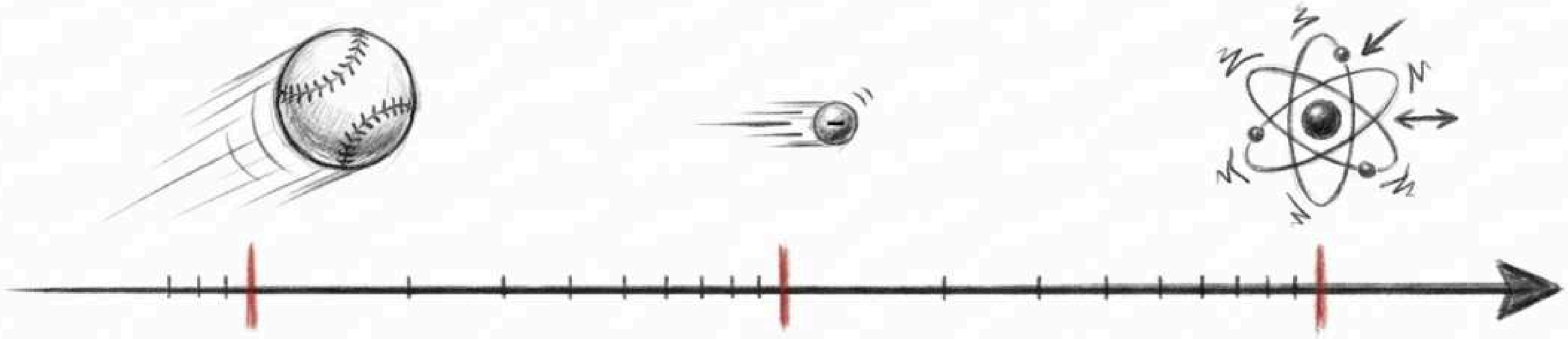
momentum
(mass × velocity)

Planck's constant (very small)

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

If photons have wave and particle properties, all matter does.
The heavier or faster an object, the shorter its wave.

Why Didn't We Notice Matter Waves?



10^{-34} meters

145g baseball at 40 m/s. Far too small for any instrument to detect.

0.12 nanometers

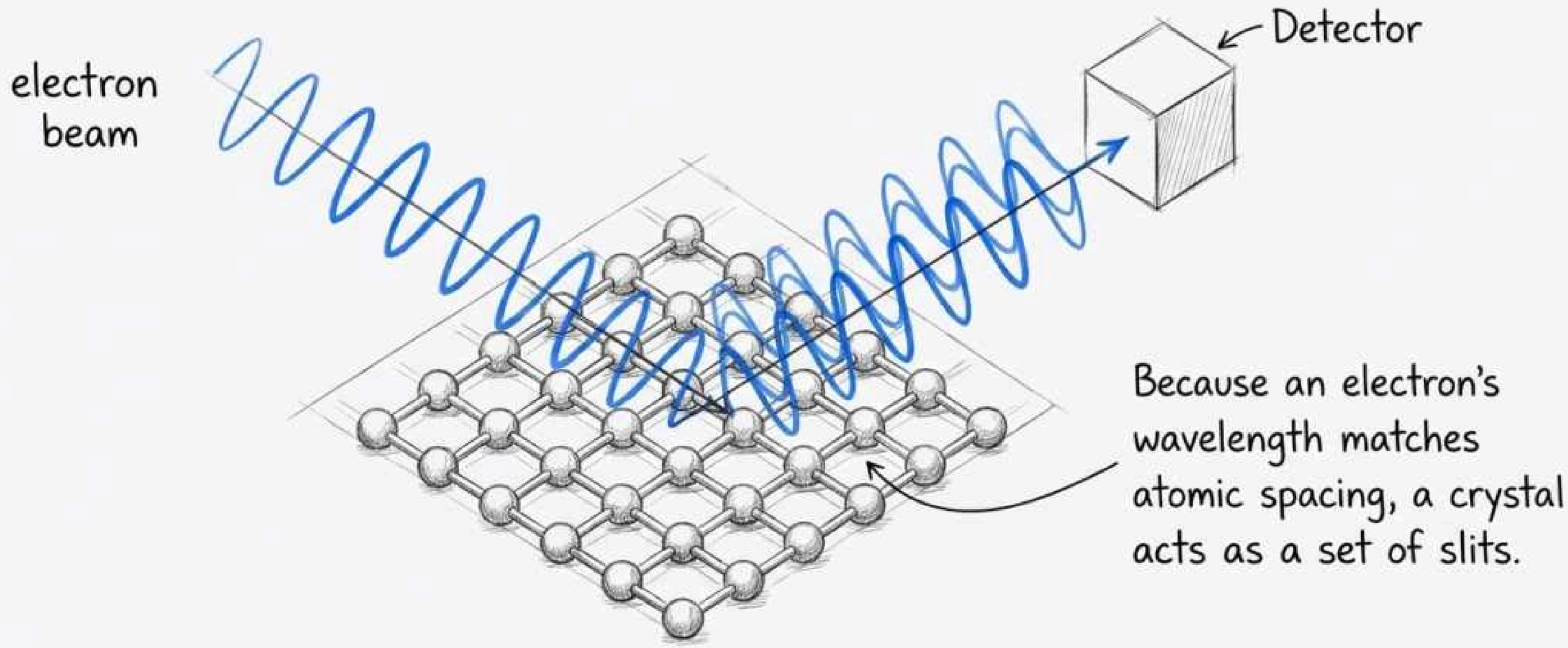
Electron sped up through 100 volts. Roughly the spacing between atoms.

1 micrometer

Very cold atoms (few mm/s). Long enough to measure directly.

Takeaway: Matter waves only matter for very light or incredibly slow objects.

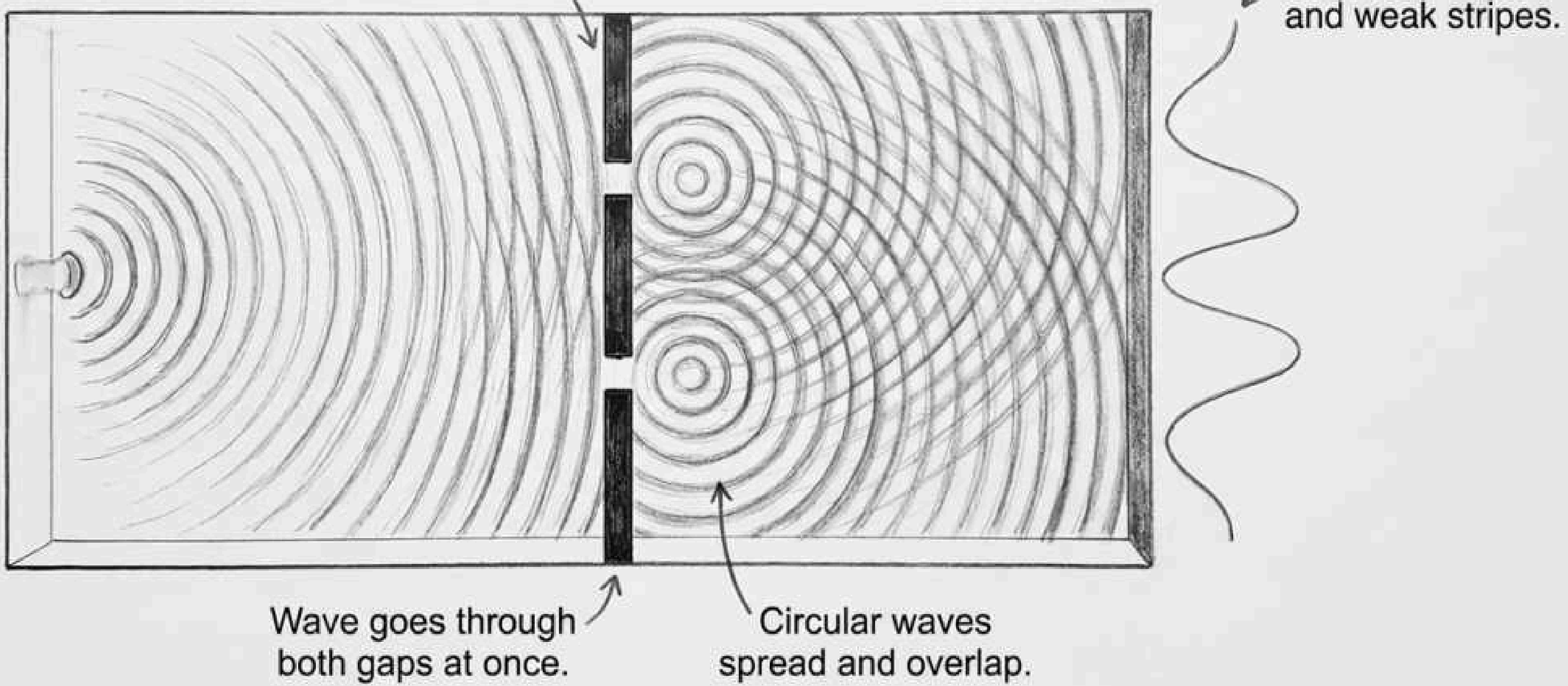
The Evidence: Crystal Diffraction



1927: Davisson & Germer (nickel crystal) and G.P. Thomson (thin metal films) saw rings of interference, proving de Broglie right. (Shared 1937 Nobel Prize).

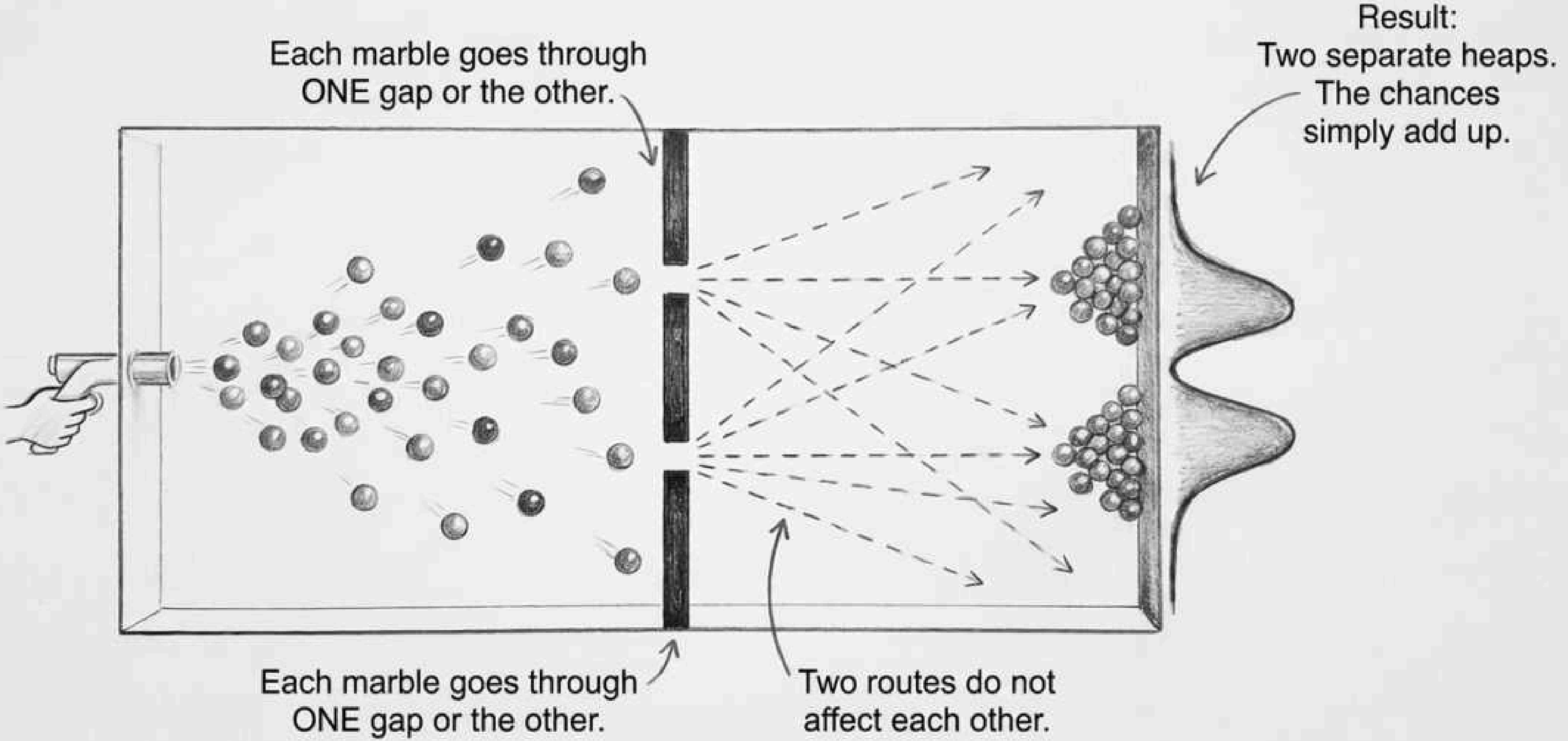
Paragraph 2.5

The Double Slit, Part 1: Water



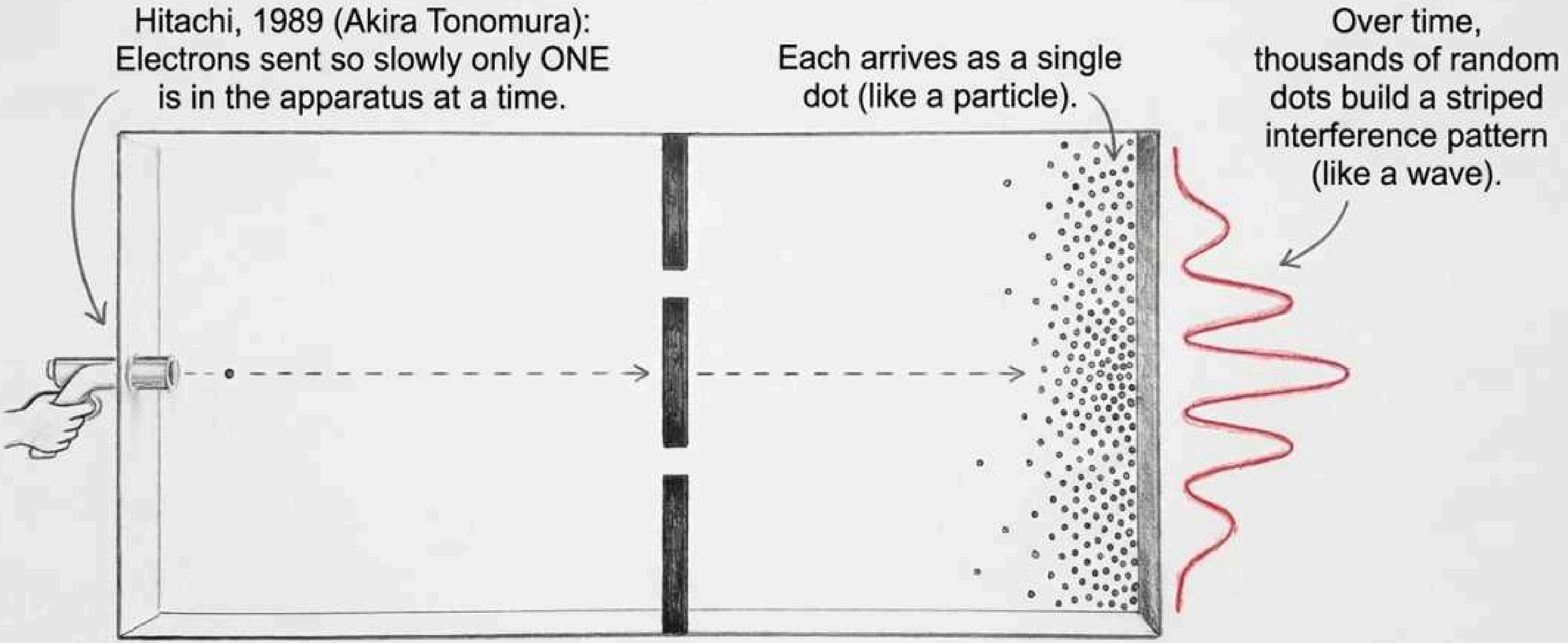
Paragraph 2.6

The Double Slit, Part 2: Marbles



Paragraph 2.7

The Double Slit, Part 3: Electrons

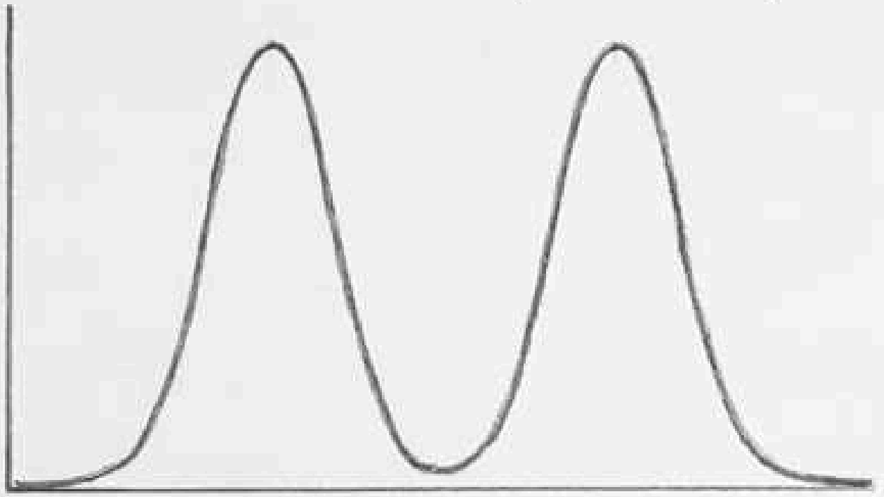


Takeaway: No half-electrons ever arrive.

Paragraph 2.8

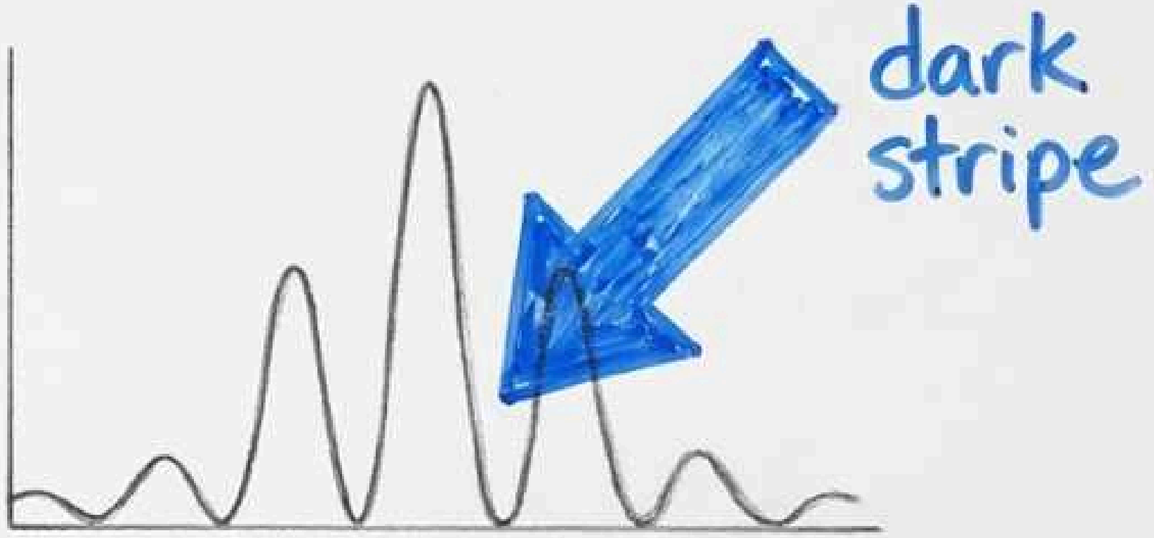
The Interference Surprise

Classical Expectation
detector screen (back wall)



Two separate heaps.

Quantum Reality



Opening a second path makes arrival here LESS likely.

There are places on the screen where electrons land often when only one slit is open. But when BOTH slits are open, almost zero electrons reach those spots. Something about each individual electron depends on both slits being open.

Paragraph 2.9

The Heart of Quantum Mechanics



"[It is] a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics."

— Richard Feynman

Almost everything else in quantum mechanics is a variation on what this single experiment shows.

Paragraph 2.10

Adding Amplitudes

$$P = |\phi_1 + \phi_2|^2$$



ϕ_1
(positive amplitude)

ϕ_2
(negative amplitude)

Zero Probability
(Cancellation)

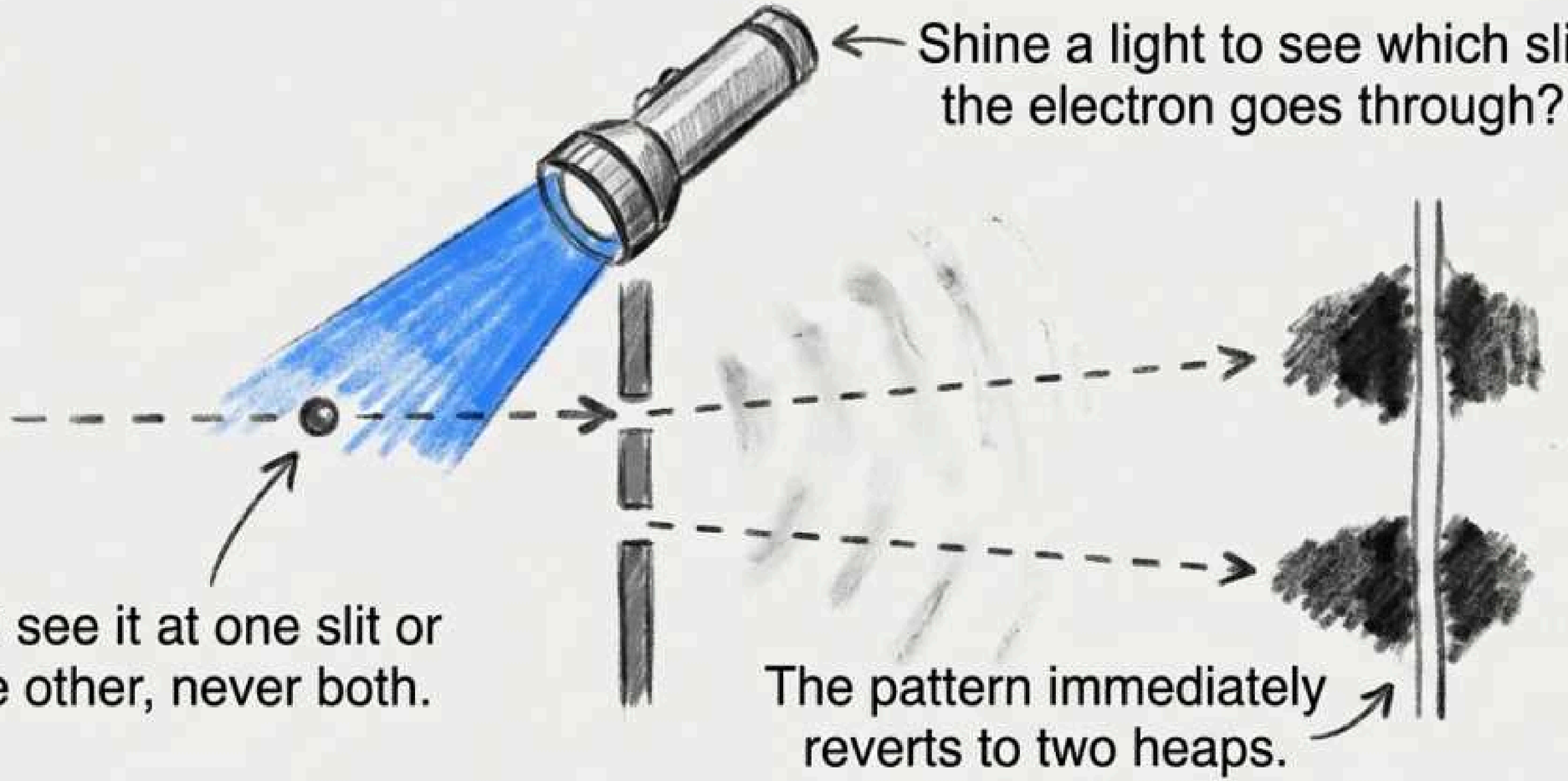


Rules: 1. Every path gets a probability amplitude (ϕ).
2. Add the amplitudes first.
3. Square the result to get the actual probability (P).

Because amplitudes can be positive or negative complex numbers, they can cancel out. This cancellation produces the dark stripes. Close one slit? Nothing to cancel against.

Paragraph 2.11

The Catch: Observation Destroys Interference



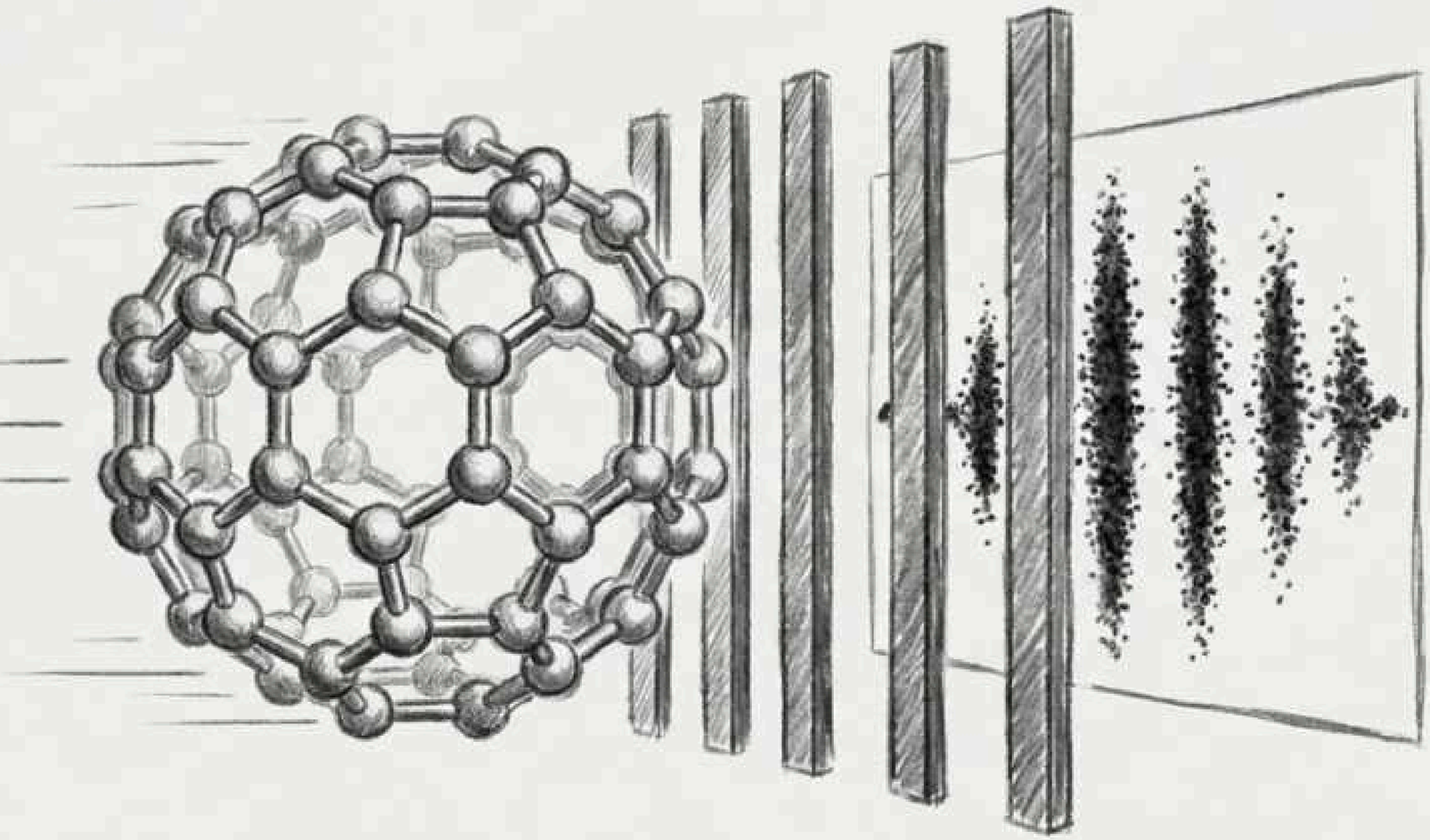
Takeaway: Any arrangement that records WHICH PATH was taken—even in principle—destroys the interference.

Paragraph 2.12

Scaling Up: There is No Known Size Limit

Data points:

- 1999 (Vienna): Interference seen with Carbon-60 buckyballs.
- 2019: Phenomenon shown with molecules made of ~2,000 atoms.



Takeaway: Physicists keep pushing to larger objects to test if the quantum rules ever stop applying. So far, they haven't.

Paragraph 2.13

Why Don't Baseballs Make Stripes?

Point 1: Absurdly small wavelengths (as seen in Slide 4).

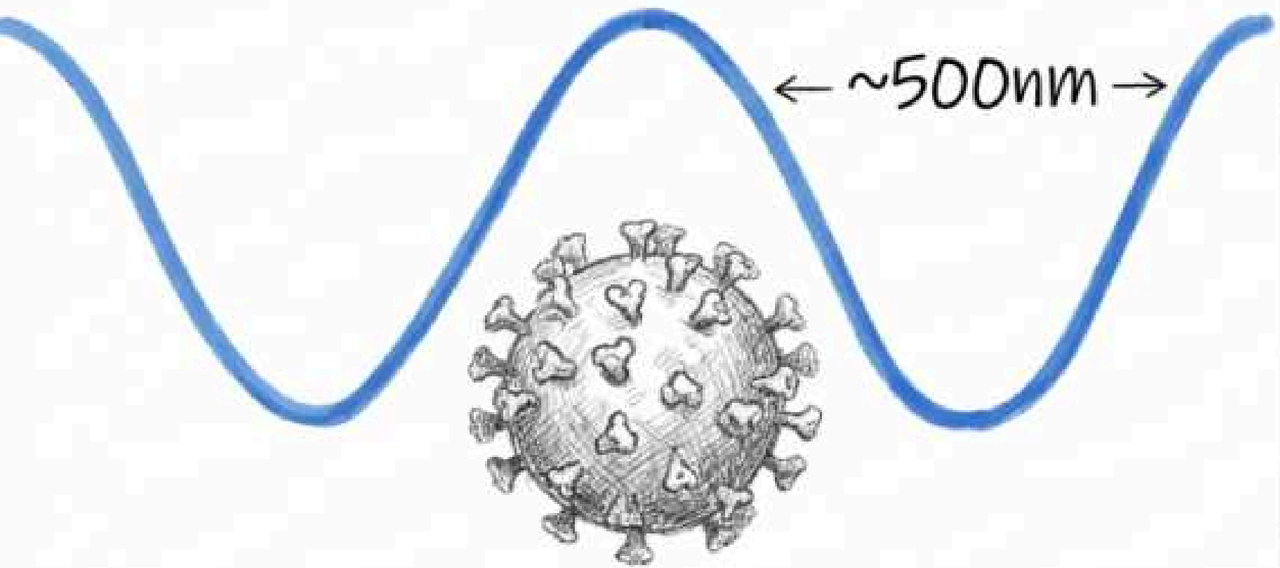
Point 2: Decoherence. Large objects constantly bump into air molecules and light.

Every bump leaves a record of where the object went in the environment. This constant recording of the path destroys interference.



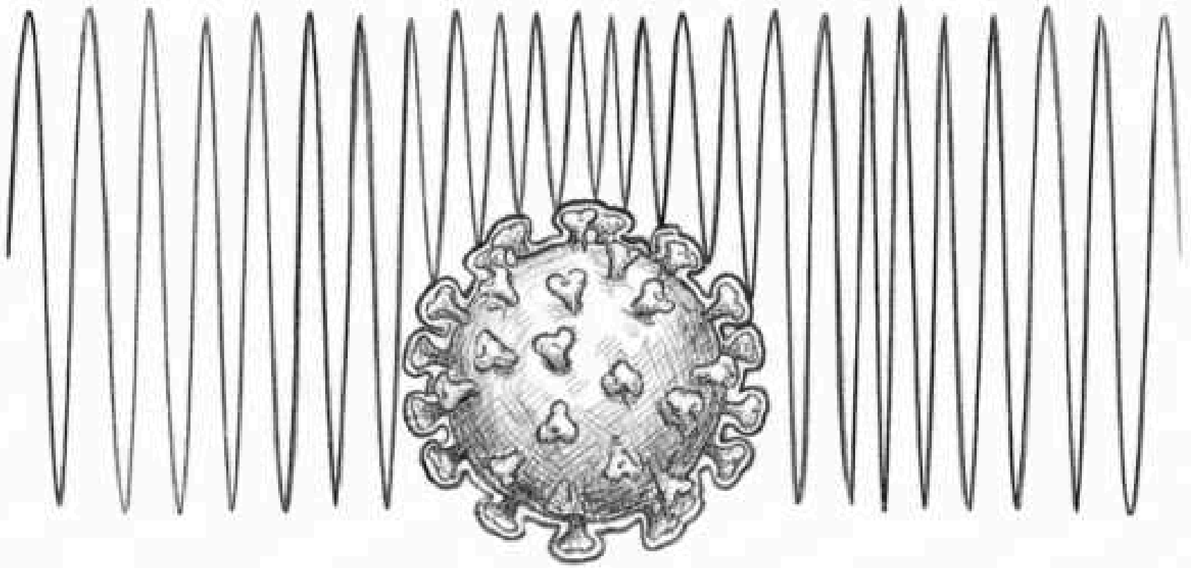
Real-World Application: The Electron Microscope

Light Microscope



Cannot see details smaller than the wavelength.

Electron Microscope



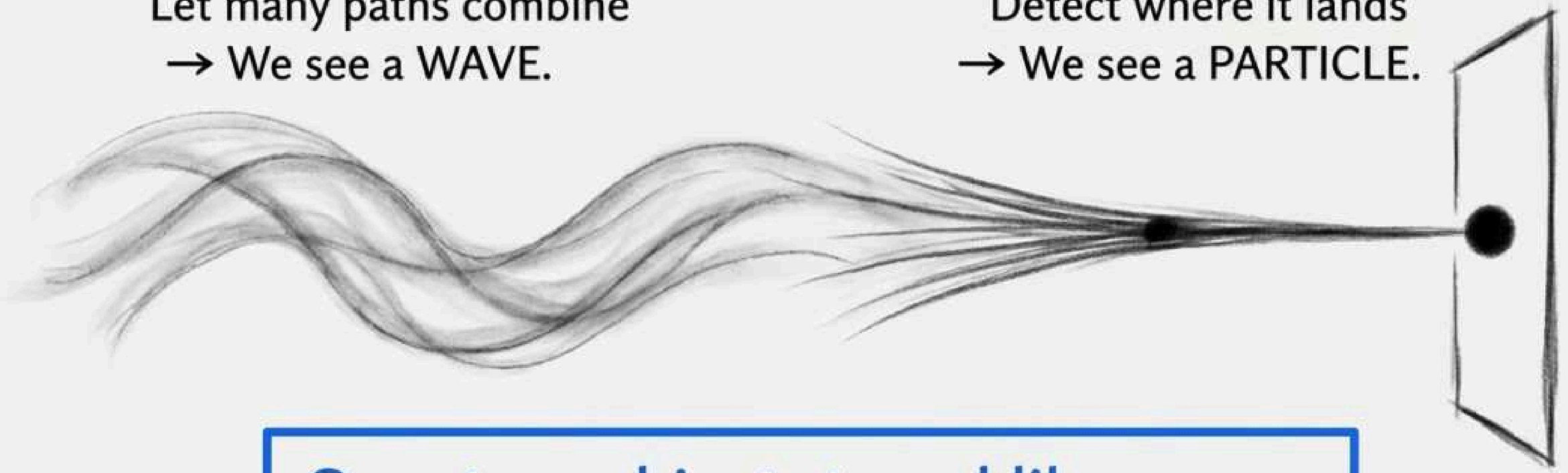
Invented in 1930s (Ruska & Knoll). Because fast electrons have wavelengths thousands of times shorter than visible light, they can resolve viruses, cell structures, and individual protein shapes (Cryo-EM).

Paragraph 2.15

The Dual Nature of Reality

Let many paths combine
→ We see a WAVE.

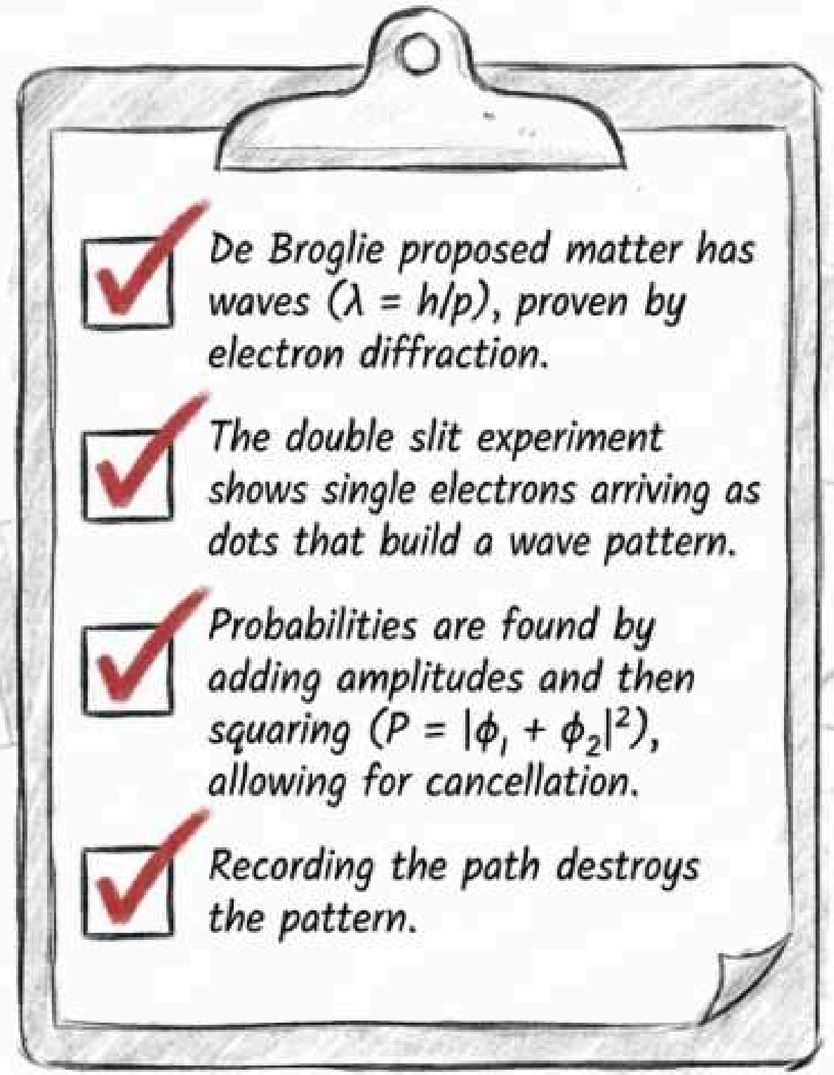
Detect where it lands
→ We see a PARTICLE.



Quantum objects travel like waves, but arrive like particles.

Both light and matter obey exactly the same quantum rules.

Lecture 2 Summary



Next up: Lecture 3 — Using matter waves to understand the atom.