The Foundations of Quantum Mechanics

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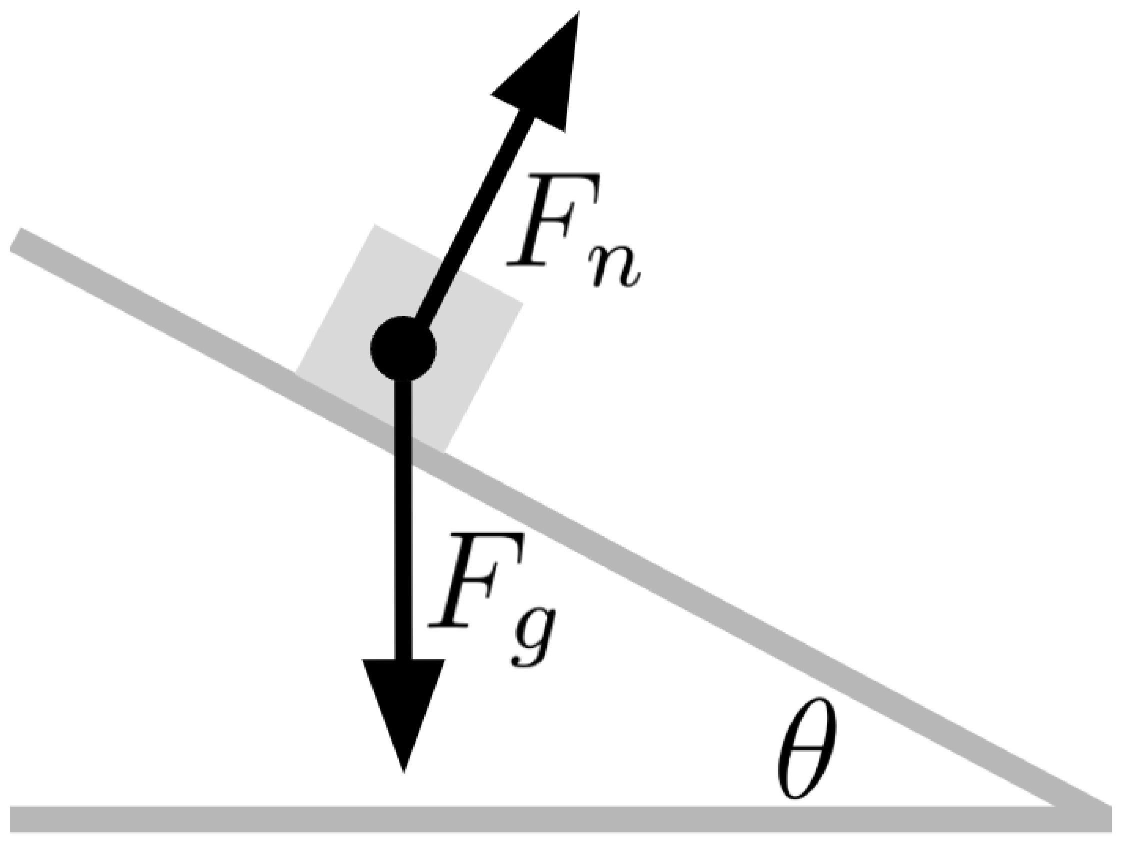
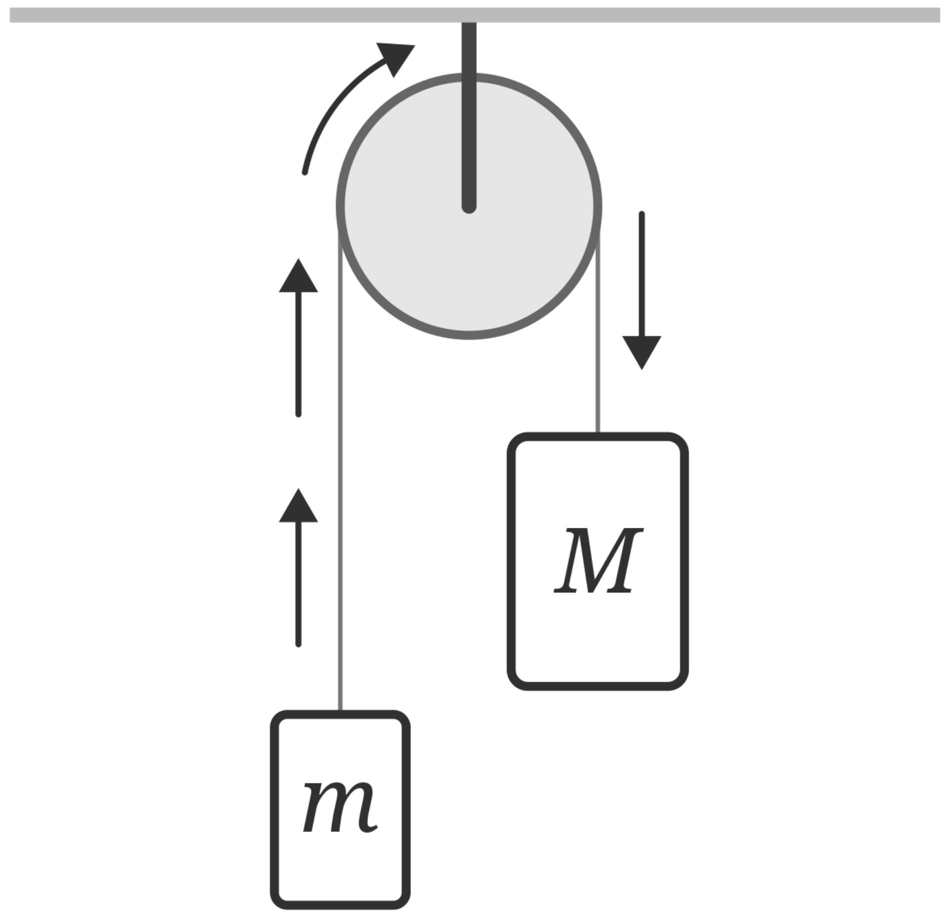
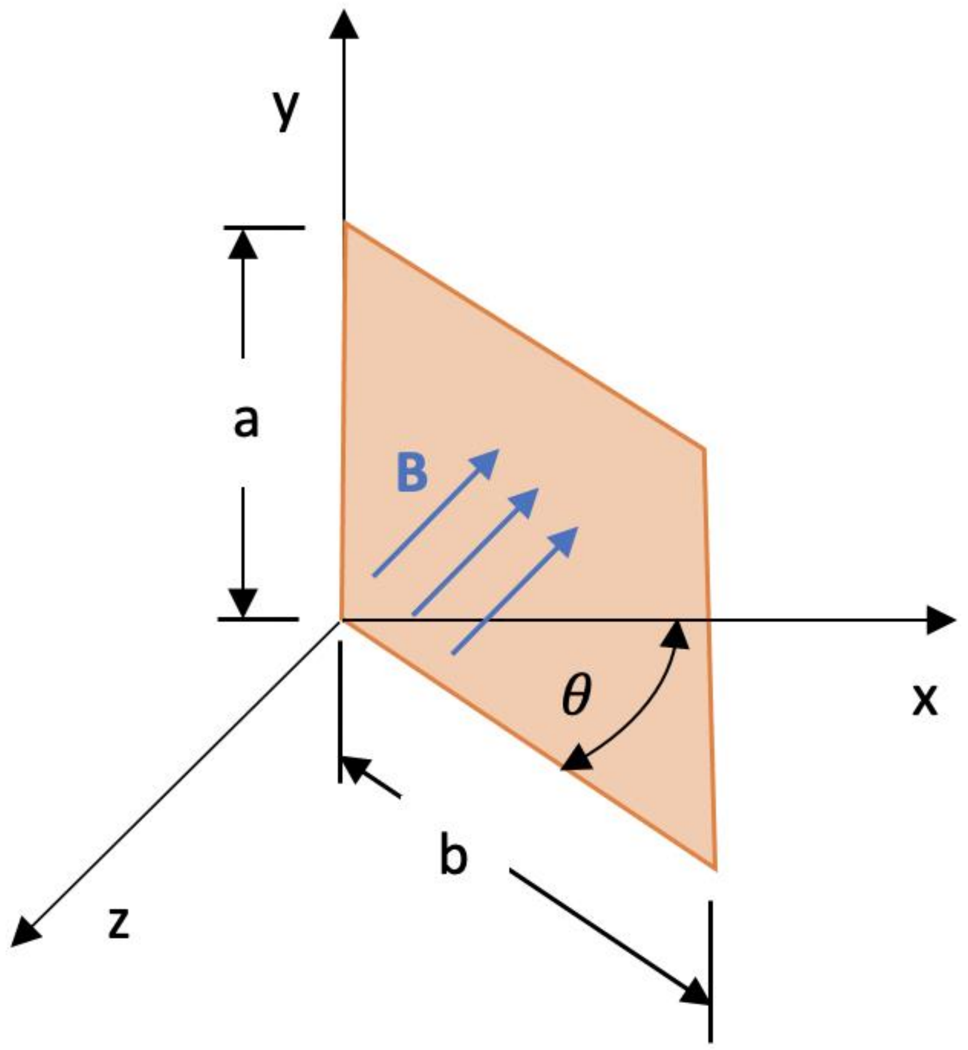
Pre-Quantum Era: Classical Physics Rules

“There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.”







Before the 20th century, physics was dominated by **Newtonian mechanics** and **Maxwell's electromagnetism**. These frameworks explained most macroscopic phenomena—but certain anomalies at atomic scales remained unresolved.

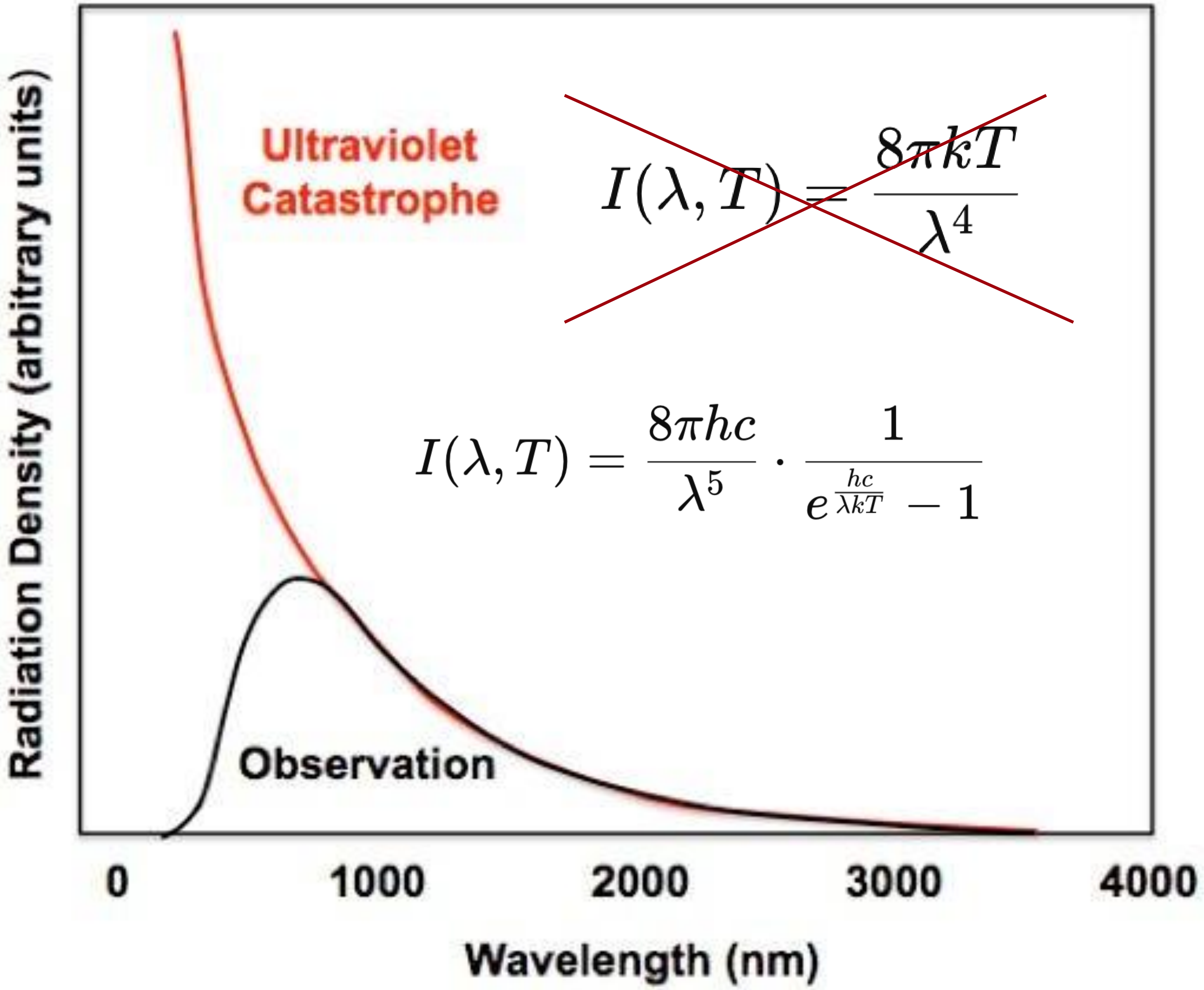
Anomalies Led To The Birth of Quantum Theory

Max Planck and Blackbody Radiation (1900)

Problem: Classical physics predicted that blackbody radiation would emit infinite energy at short wavelengths—a contradiction known as the **ultraviolet catastrophe**.

Planck's Solution: He proposed that energy is **quantized**, emitted in discrete packets called **quanta**.

$$E = h\nu$$



This was the first real hint that classical physics might not fully describe the microscopic world.

The Early Quantum Revolution

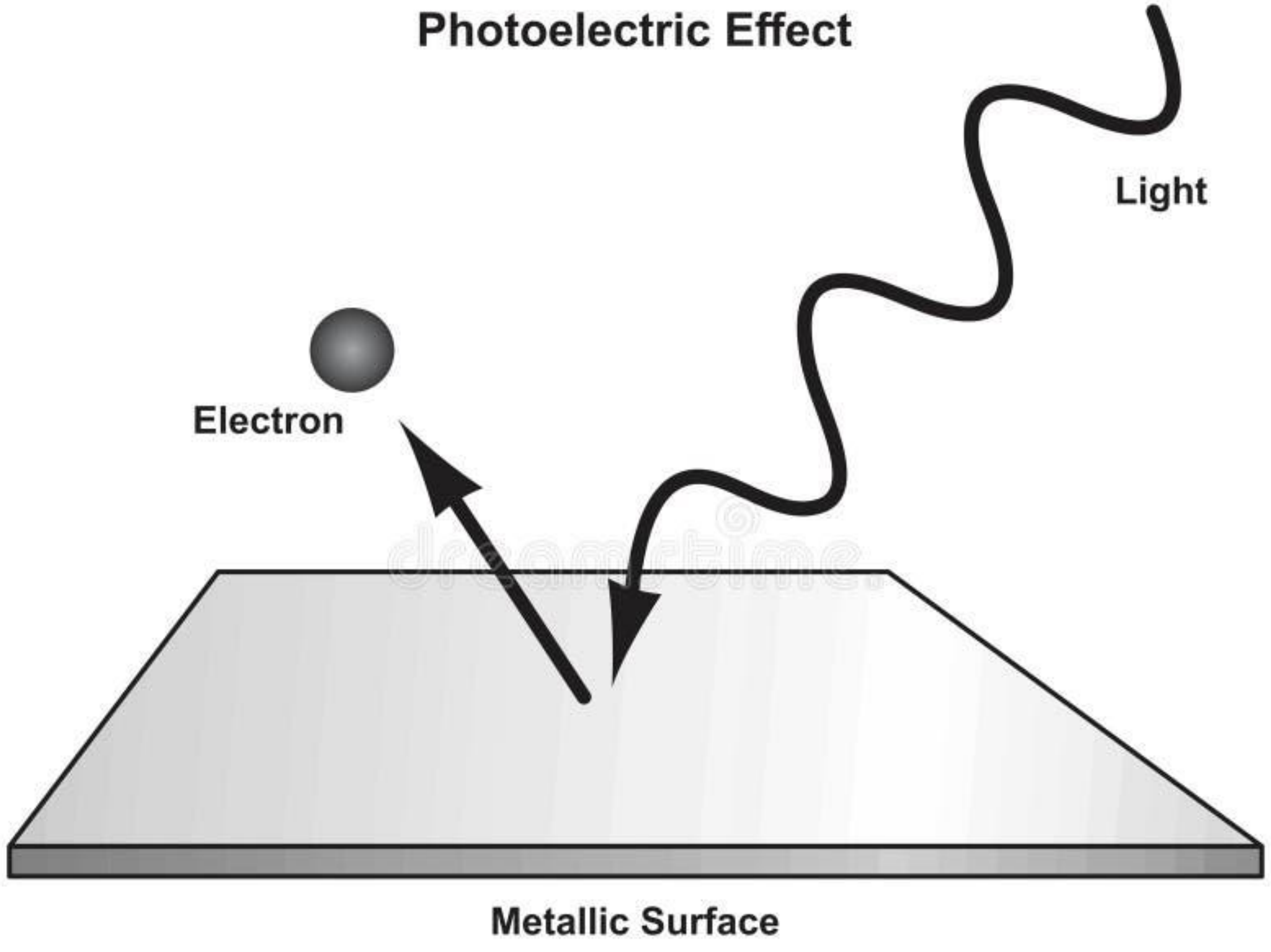
The Photoelectric effect (1905)

Problem: Under **classical wave theory of light**, here's what physicists expected that:

- **Light intensity** should control how much energy electrons gain.
- There should be a **delay**—electrons would gradually "soak up" energy and eventually be ejected.
- There should be **no threshold frequency**—even low-frequency light, if intense enough, should eventually cause ejection.

In short: brighter light = more energy, regardless of frequency.

All of this proved wrong.



The Early Quantum Revolution

The Photoelectric effect (1905)

Solution:

Einstein proposed a radical idea:

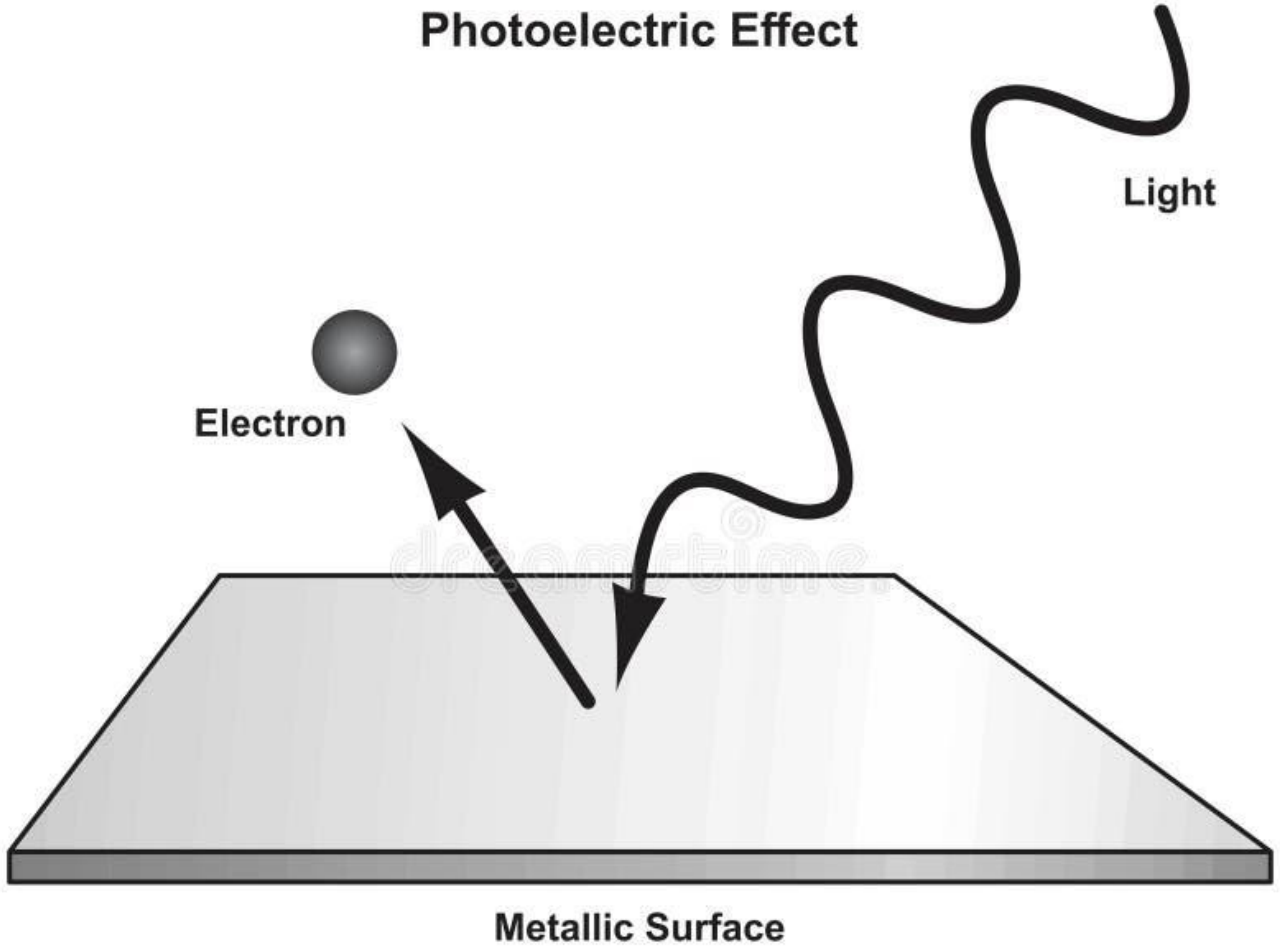
Light isn't just a wave—it comes in **particles** called **photons**, each with energy proportional to its frequency:

$$E = h\nu$$

One photon hits one electron.
If the photon's energy is **greater than the work function** (the energy needed to liberate an electron from the metal), the electron is ejected.

Any **extra energy** becomes **kinetic energy** of the electron.

$$K_{\max} = h\nu - \phi$$



Bohrs Model for Atoms

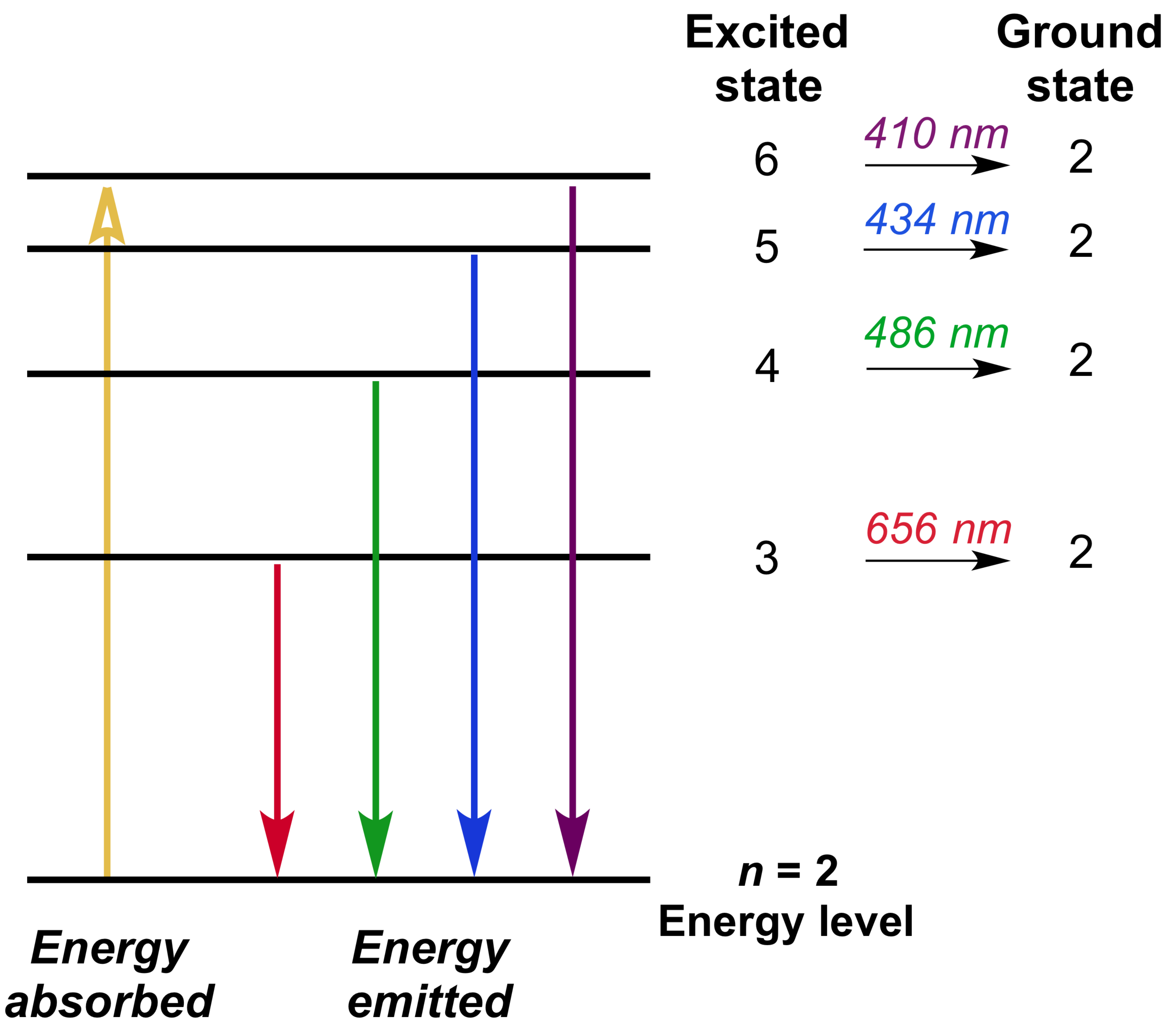
Bohr Model of the Atom (1913)

Problem: In the early 20th century, the classical models of the atom, like the Rutherford model, couldn't explain why atoms were stable or why they emitted light at specific wavelengths (like those seen in hydrogen's spectrum).

Bohr's Contribution: Electrons orbit the nucleus in quantized energy levels. Transitions between levels emit/absorb photons.

Success: Explained the spectral lines of hydrogen

$$E_{\text{photon}} = E_n - E_m = h\nu$$



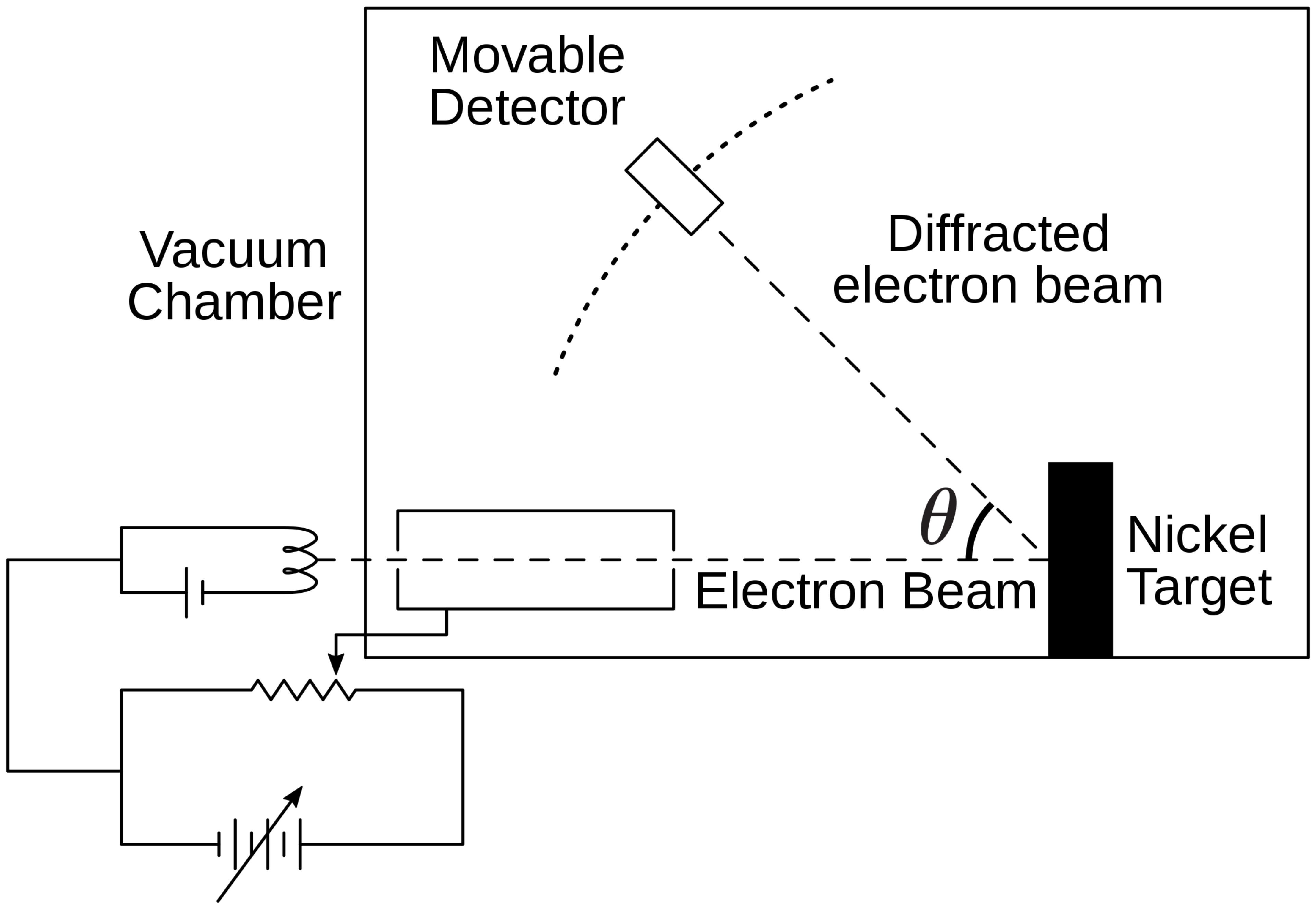
Wave-Particle Duality

Louis de Broglie and Matter Waves (1924)

Hypothesis: If light can behave like a particle, then particles (like electrons) should exhibit wave-like properties.

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

Confirmed: Later validated by electron diffraction experiments in 1927.



Formalizing Quantum Mechanics

Heisenberg's Matrix Mechanics (1925)

-> A mathematical formulation using matrices to represent observable quantities like position and momentum

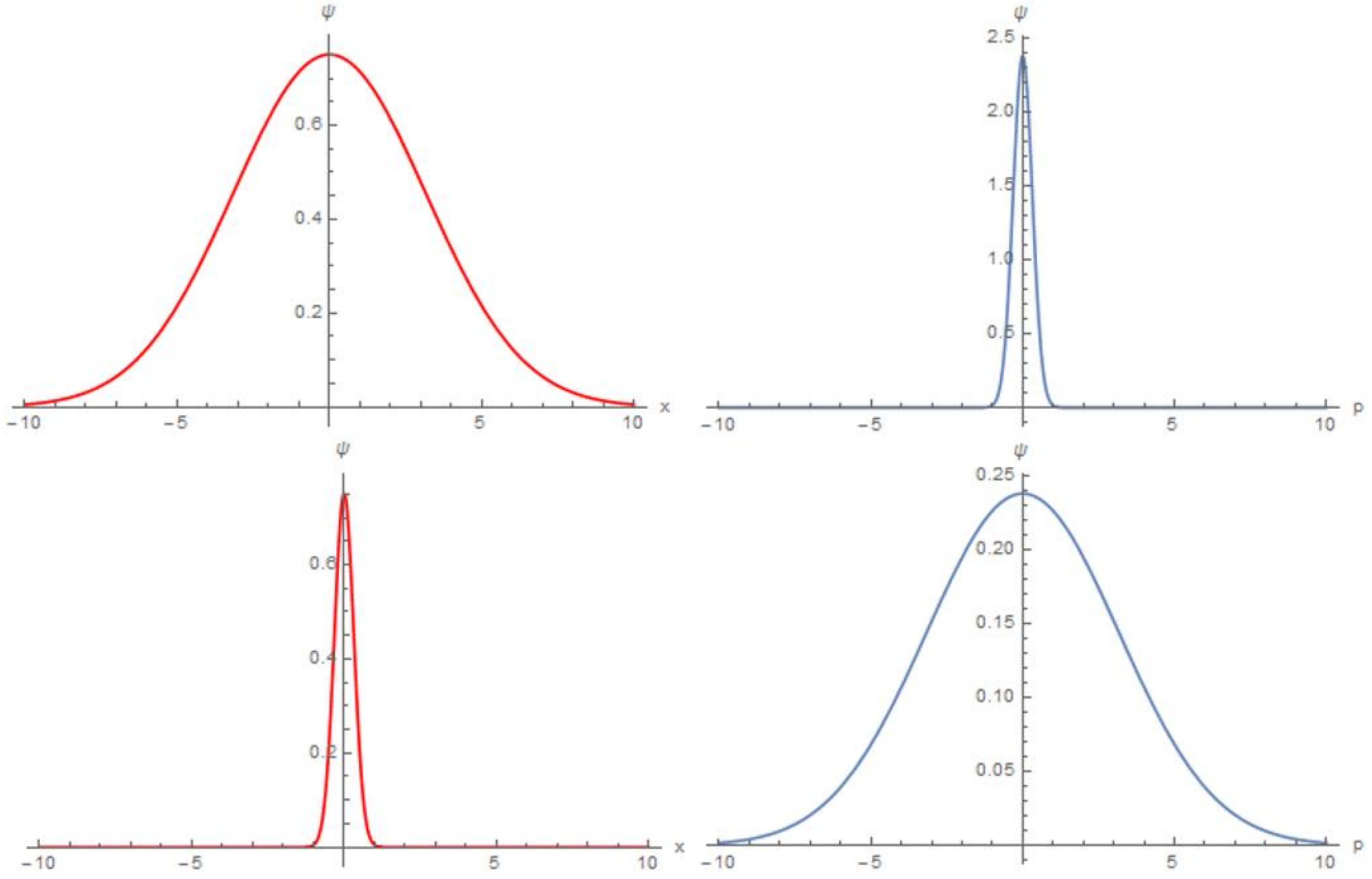
$$XP \neq PX$$

$$[X, P] = i\hbar$$

$$\frac{dA}{dt} = \frac{i}{\hbar}[H, A] + \frac{\partial A}{\partial t}$$

Position

Momentum



Revolutionary because:

- Abstract mathematics (matrices!) now described physical reality.
- Uncertainty was baked into the theory—no more deterministic trajectories.
- Physical observables were not numbers but operators acting on states

Formalizing Quantum Mechanics

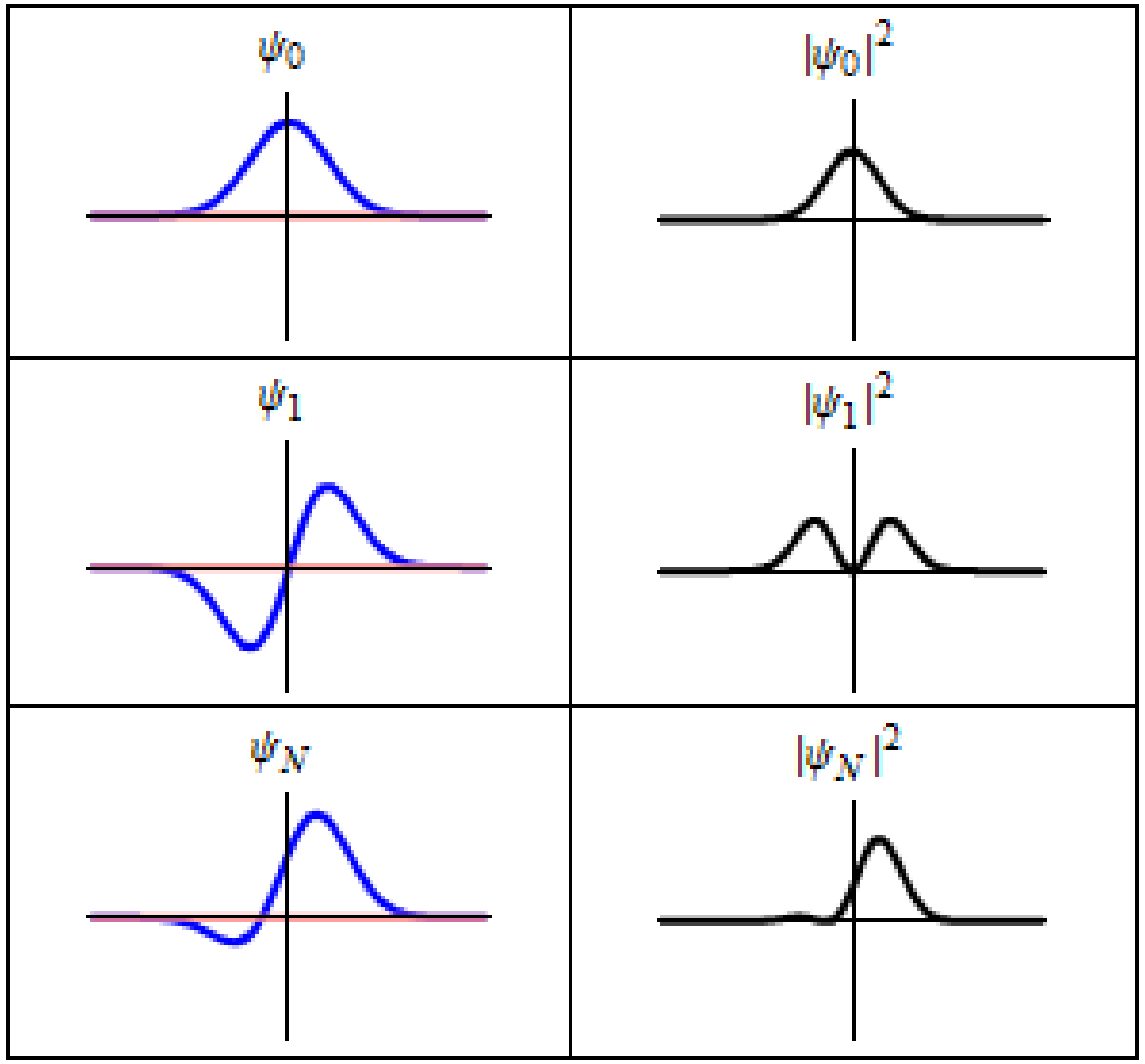
Schrödinger's Wave Mechanics (1926)

•Developed the **Schrödinger equation**, describing how the quantum state (wavefunction) evolves over time.

•Interpreted particles as **wavefunctions**, encapsulating all measurable information.

•Introduced the interpretation that the square of the wavefunction $|\psi|^2$ represents a **probability density**.

$$|\psi(x)|^2$$



$$i\hbar\frac{\partial}{\partial t}|\Psi\rangle = \hat{H}|\Psi\rangle$$

Key Quantum Component #1: Superposition

Heisenberg didn't explicitly talk about superposition, but his use of **matrices** to describe transitions between energy states involved **adding** contributions from different states.

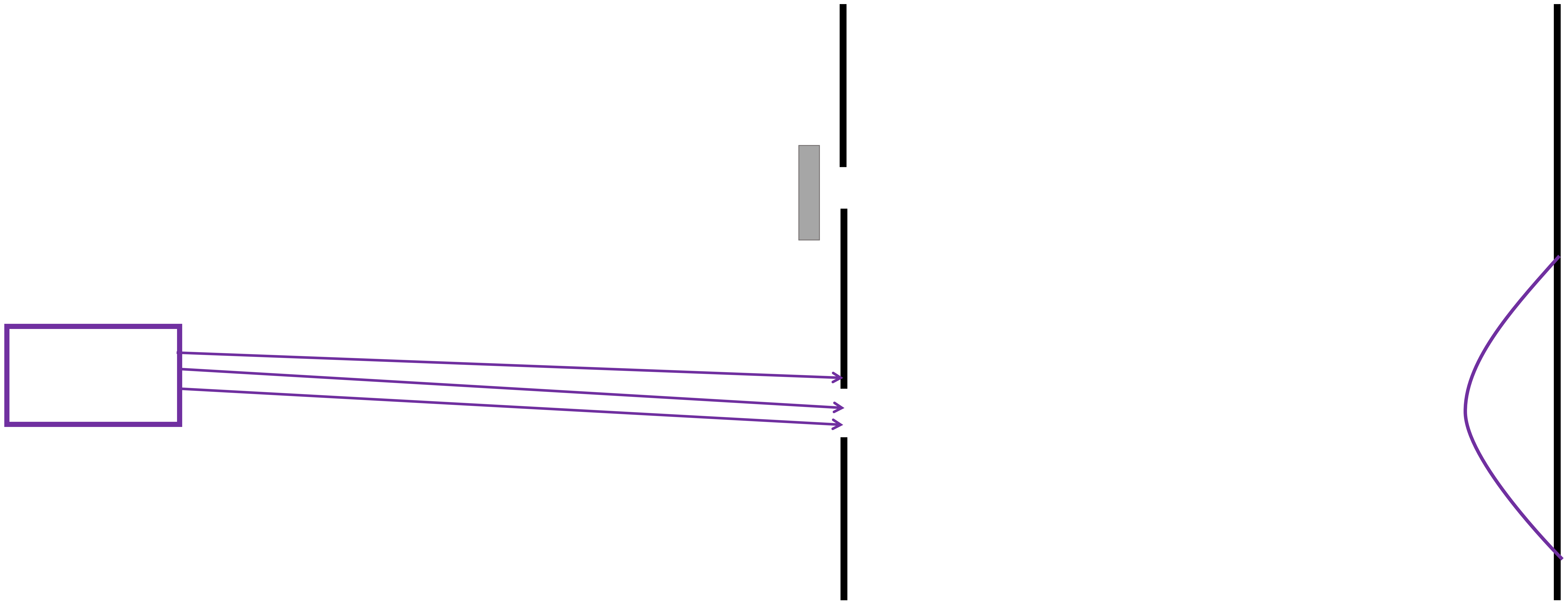
- The Schrödinger equation is **linear**, which means:
- If ψ1 and ψ2 are solutions, then linear superpositions are also solutions:

$$\psi = a\psi_1 + b\psi_2$$

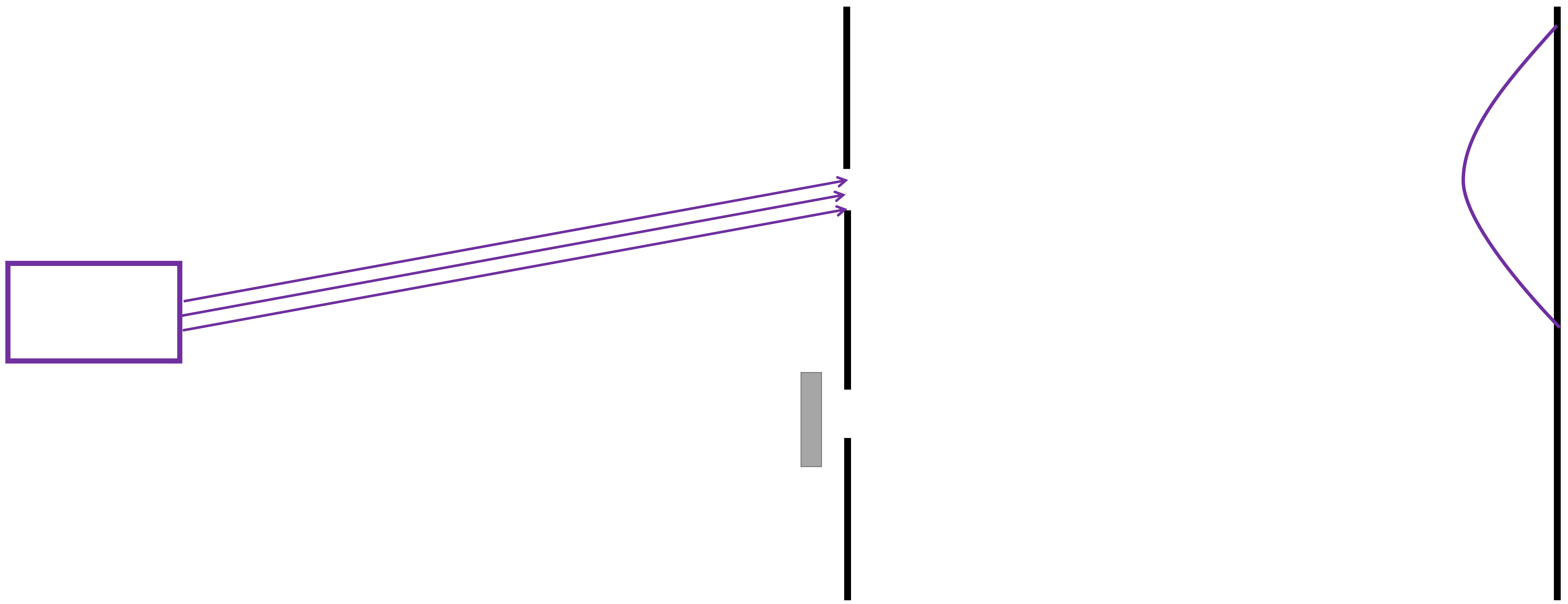
- This is the **superposition principle**: quantum states can exist as **linear combinations of other states**.

Schrödinger himself recognized this: in one of his early papers, he described particles in overlapping or mixed wave states—laying out the principle clearly.

Superposition



Superposition



Superposition

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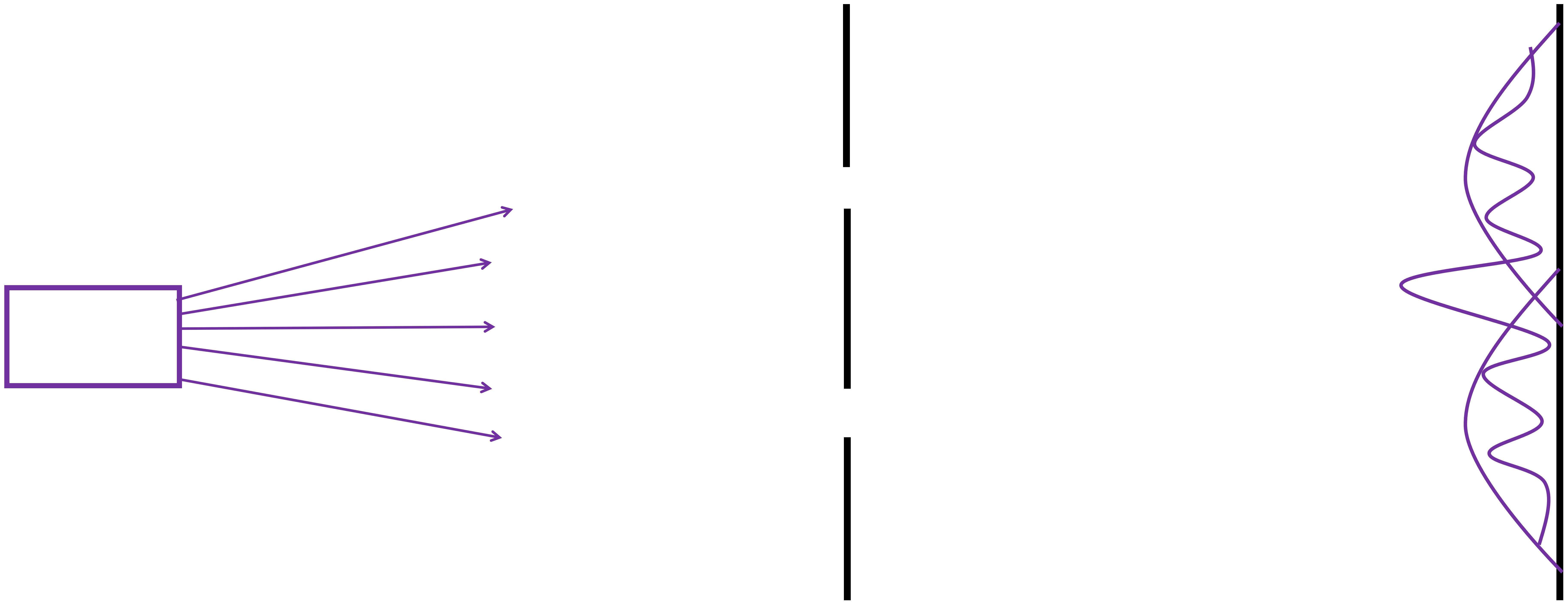


The Interpretation

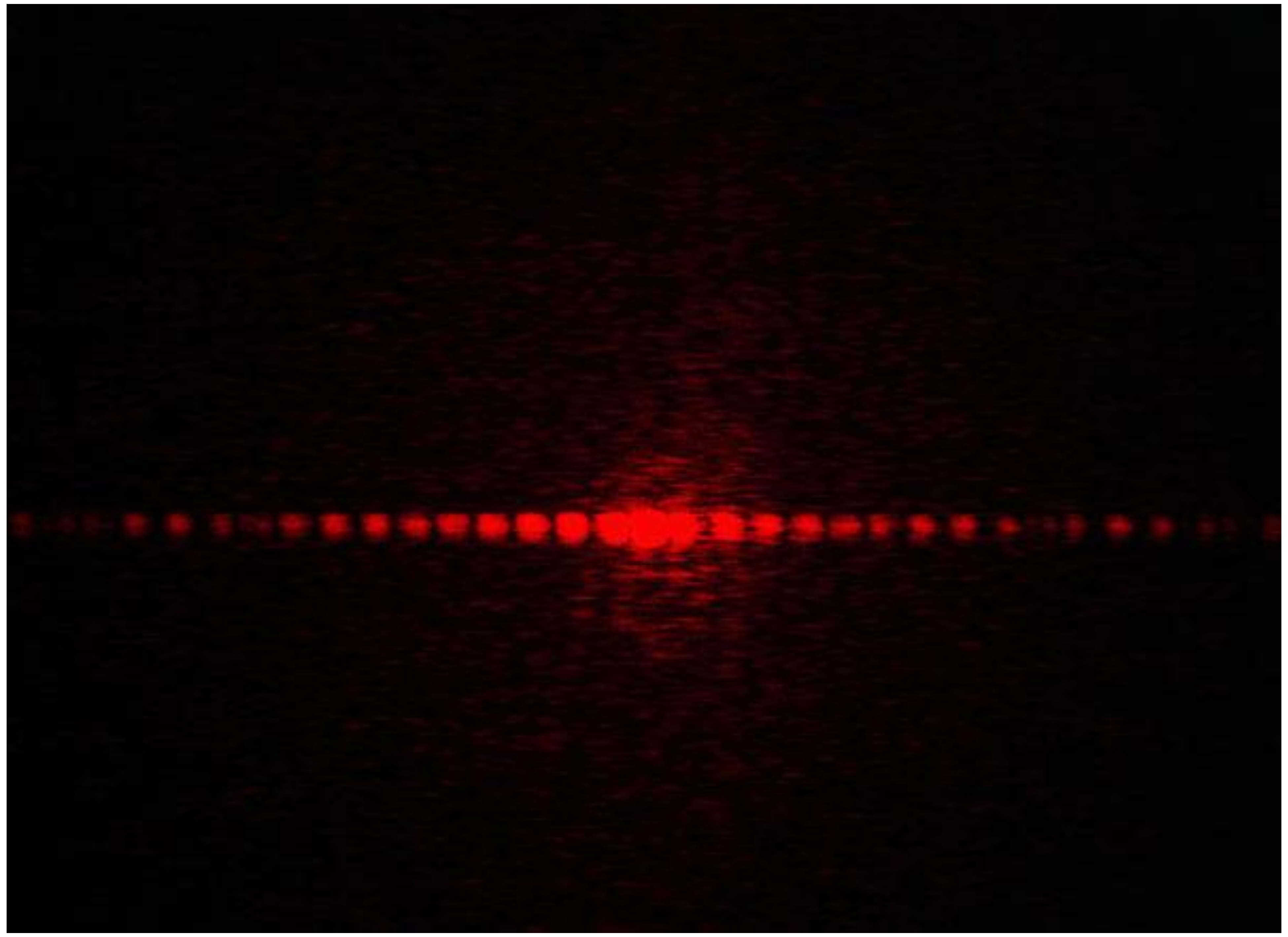
When unobserved, the particle doesn't "choose" a slit. It exists in a superposition of going through both slits at once:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\mathrm{Left}\rangle + |\mathrm{Right}\rangle)$$

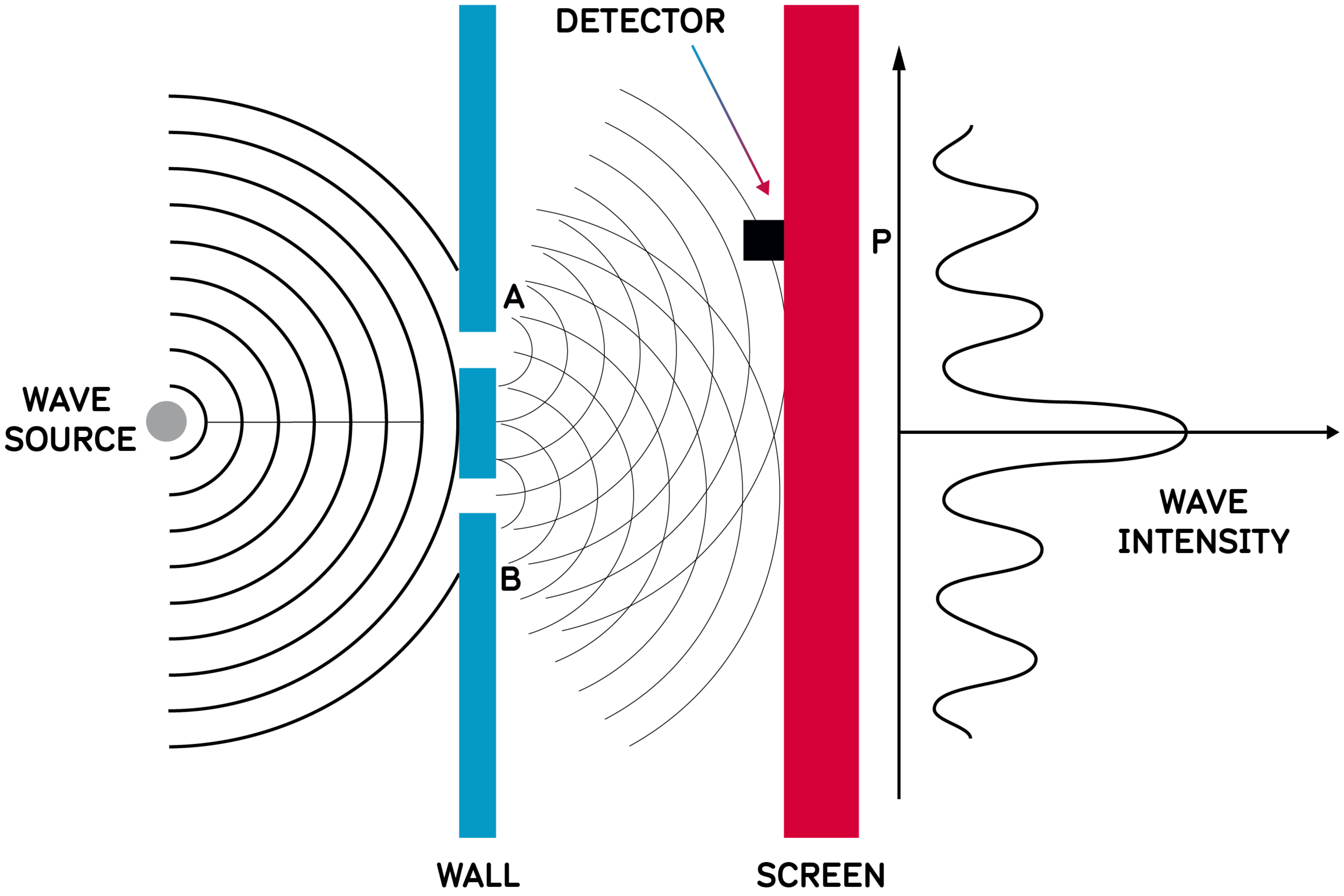
The interference pattern is the result of these two paths interfering with each other—a hallmark of superposition.

But when we measure "which slit," we collapse the wavefunction into just one path, destroying the interference.

→ The double-slit experiment *shows* what superposition **means physically**



Key Quantum Component #2: Interference



Coming up with Entanglement

Einstein, Podolsky, and Rosen (EPR Paradox, 1935)

•Proposed a thought experiment showing that quantum mechanics predicts "spooky action at a distance."

•Claimed this indicated the theory was incomplete.

Schrödinger's Response (1935)

•Coined the term entanglement (Verschränkung).

•Described how quantum states of two particles could become correlated in such a way that their individual states become meaningless apart from the whole.

You can't visualize quantum entanglement!

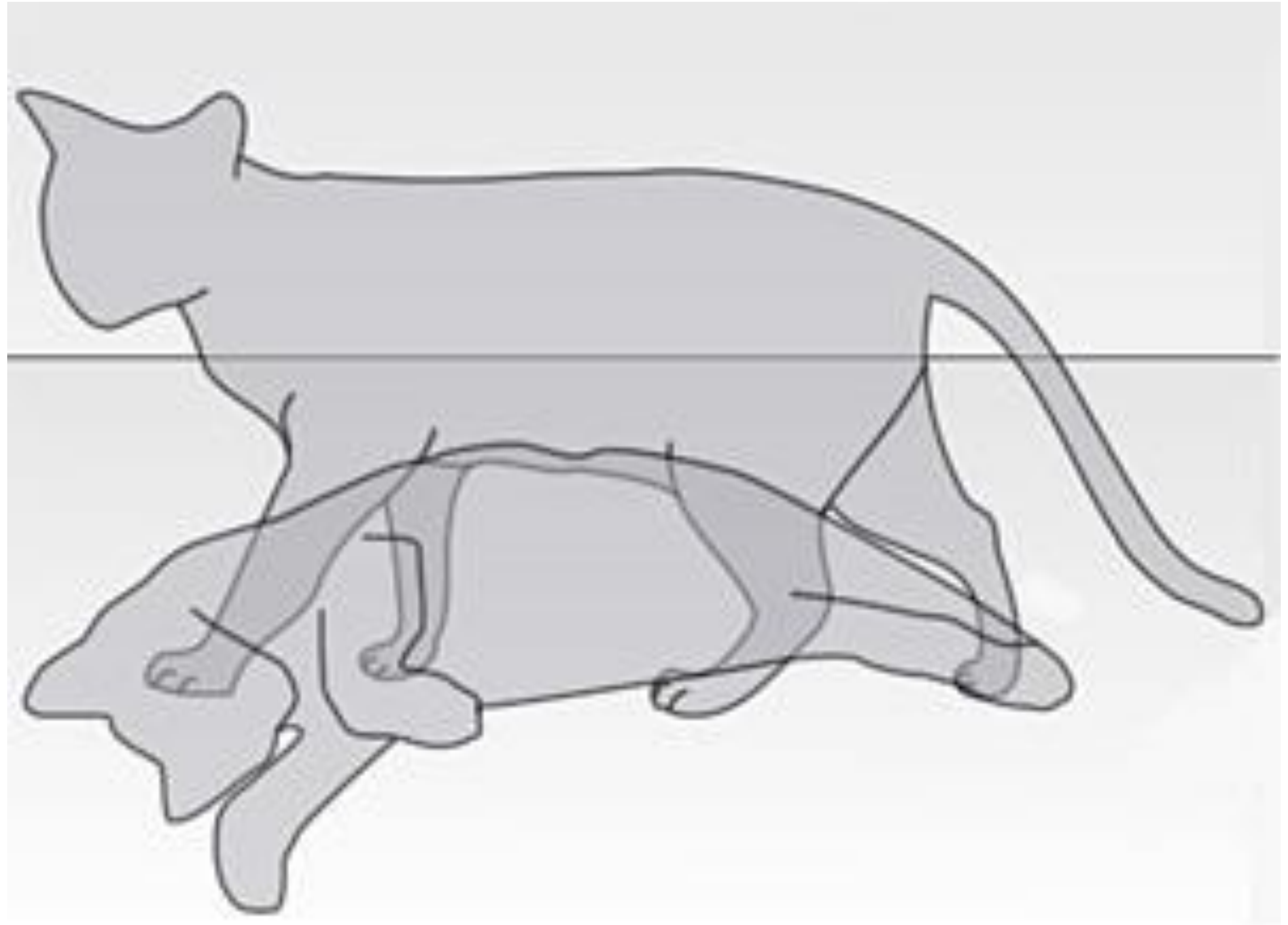
Key Quantum Component #3: Entanglement

"The combined system becomes entangled to the point that the states of the individual subsystems are no longer independently describable."

•Described how quantum states of two particles could become correlated in such a way that their individual states become meaningless apart from the whole.

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_A |\downarrow\rangle_B - |\downarrow\rangle_A |\uparrow\rangle_B\right)$$

$$\Psi(x_A, x_B) \neq \psi_A(x_A) \times \psi_B(x_B)$$

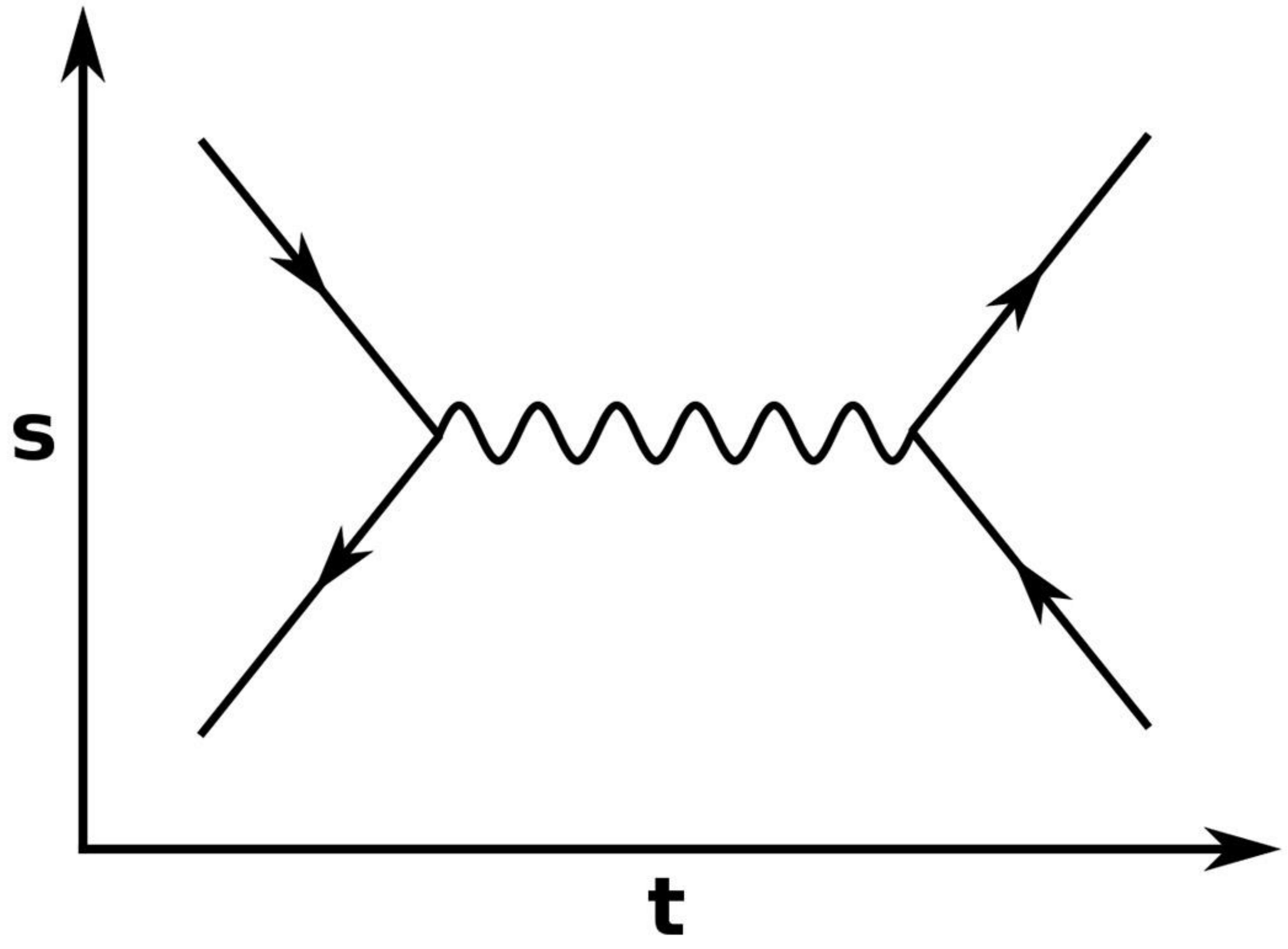


“Shut up and calculate” era

- After the intense philosophical debates of the 1930s (EPR, Schrödinger's cat, etc.), most physicists **stopped worrying about quantum weirdness**.

- Instead, they adopted a **"shut up and calculate"** attitude:
  - Use quantum mechanics to make precise predictions.
  - Stop debating its philosophical implications.

➔ Result: Tremendous advances in understanding atoms, nuclei, and fundamental forces.
  - QED
  - Feynman diagrams
  - Nuclear physics

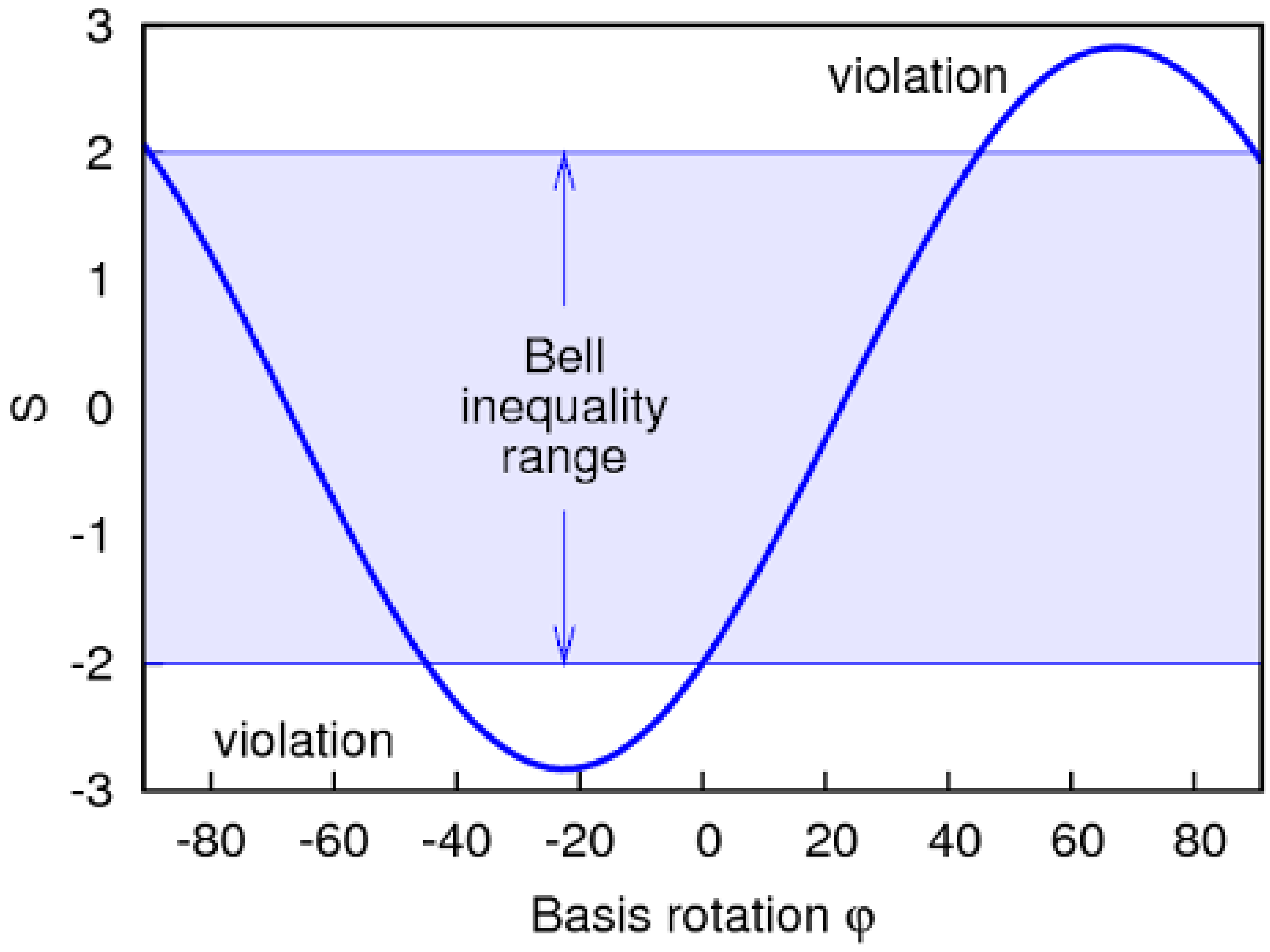


Bell's Theorem (1964)

•John Bell showed that no local hidden variable theory can reproduce all quantum predictions.
•Introduced Bell inequalities, which were later violated in experiments.

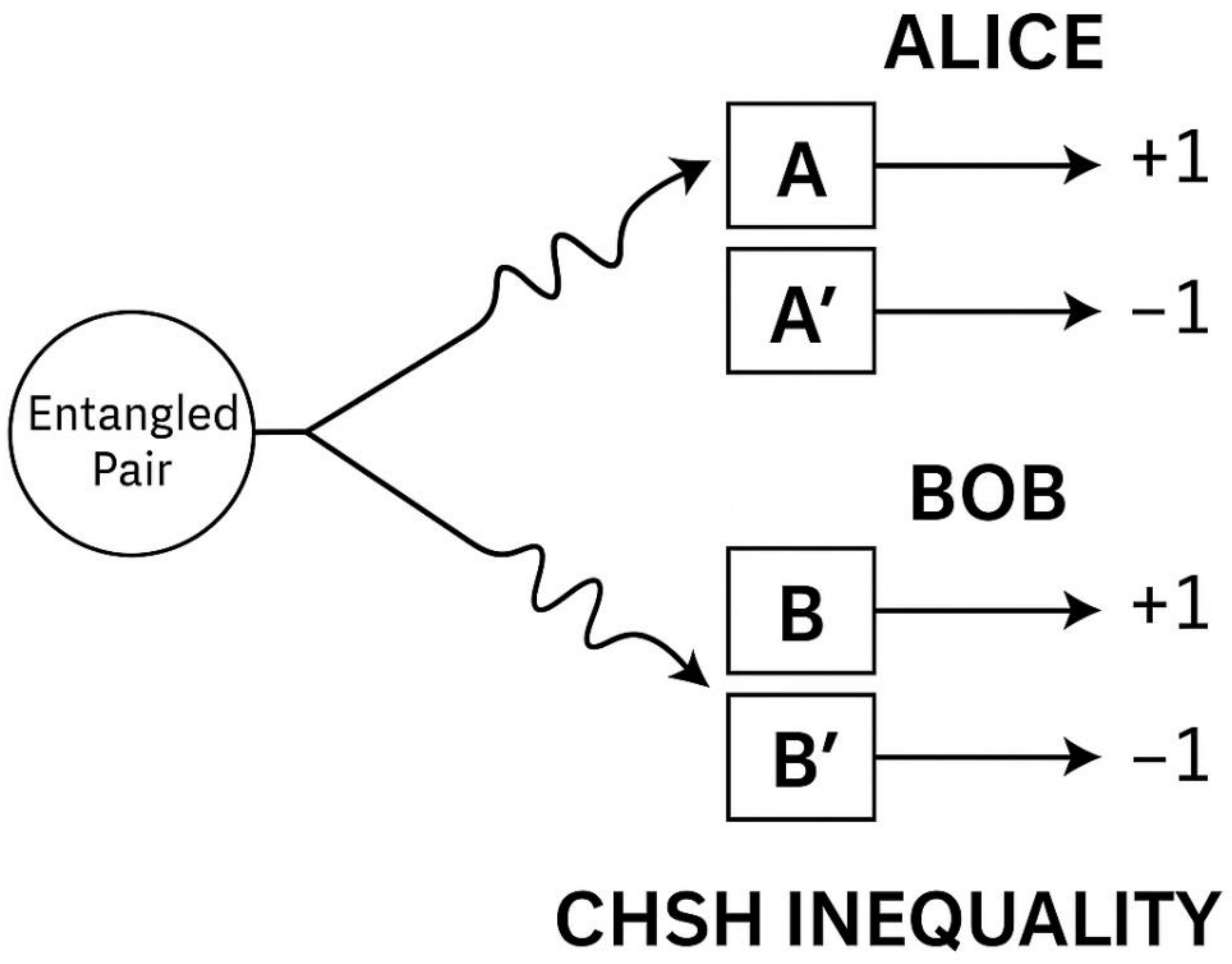
Experimental Confirmation of Entanglement

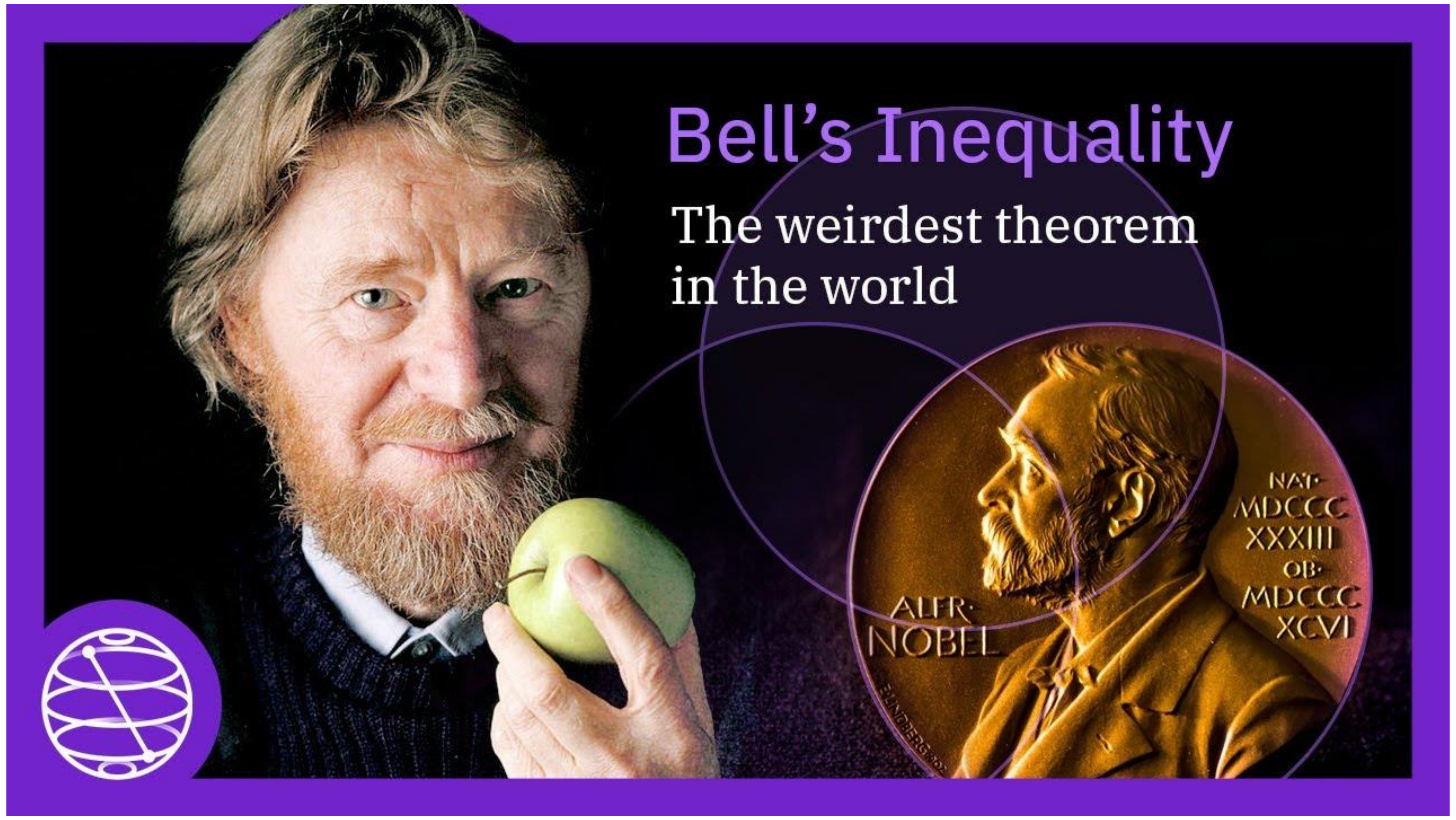
- Early experiments by John Clauser and others in the 1970s
- Alain Aspect (1981–1982) performed experiments showing Bell inequality violations, confirming entanglement and the non-locality of quantum mechanics.



CHSH Inequality

$$S = E(a,b) - E(a,b') + E(a',b) + E(a',b')$$
$$|S| \leq 2$$





Birth of Quantum Information Science (1990s onward)

- Researchers realized quantum phenomena could be harnessed:
  - Shor’s algorithm (1994) and Grover’s algorithm (1994)
  - DiVincenzo’s Criteria for a quantum computer (1996)
  - First realization of qubits begin to emerge

-> Impact:
  - Quantum weirdness isnt a bug — its a feature.
  - Instead of resisting quantum behavior, scientists began engineering it.

"If I have seen further, it is by standing on the shoulders of giants.” –Sir Isaac Newton