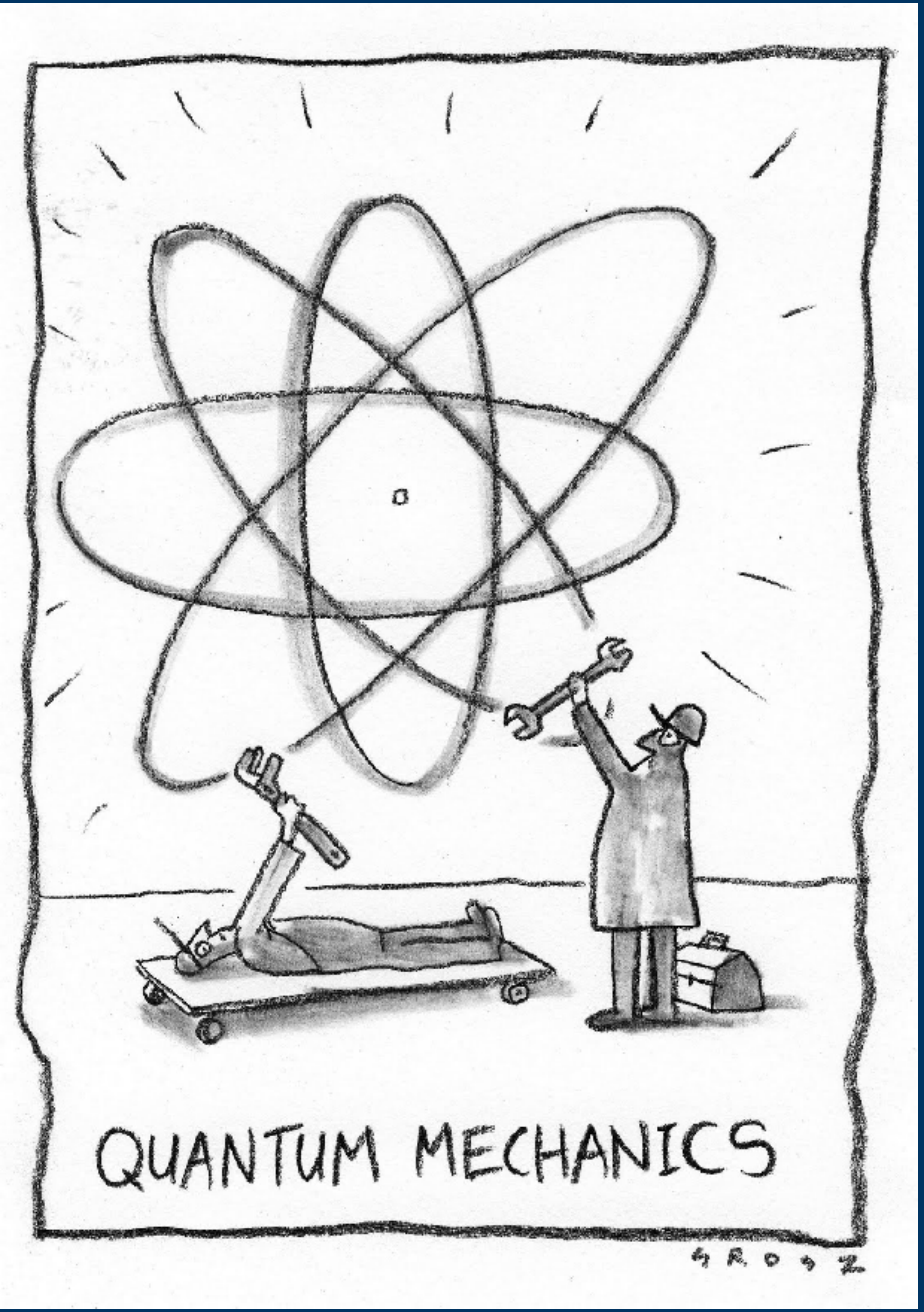
An Armchair Guide:

To Quantum Mechanics



The Armchair Guide

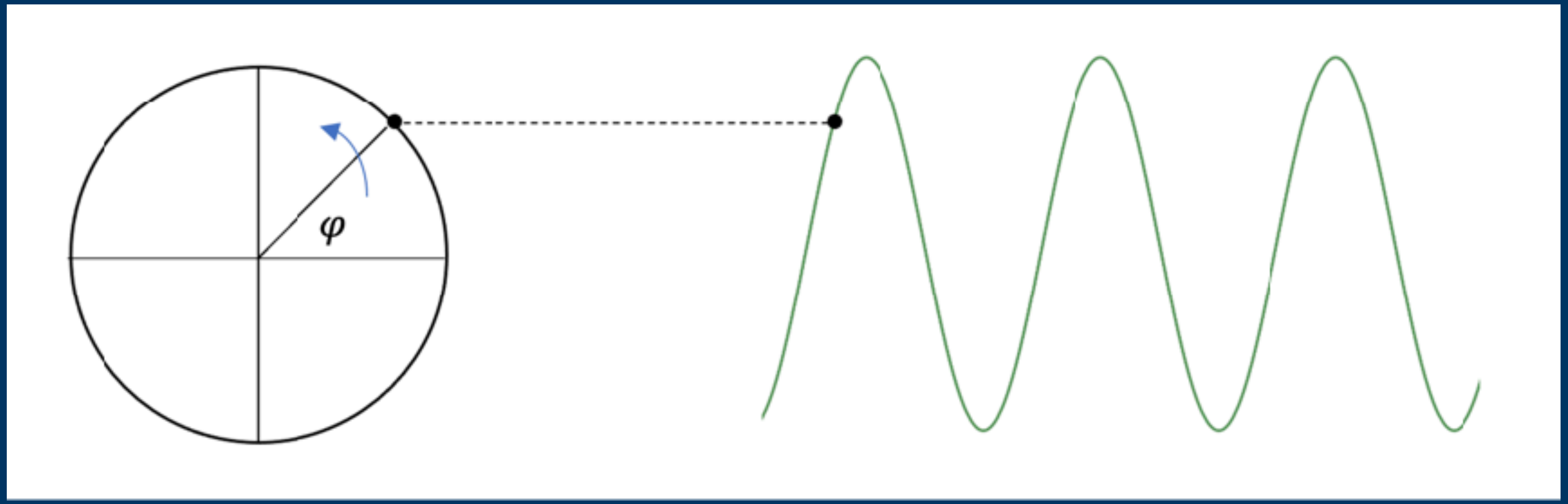
Jonathan Allday

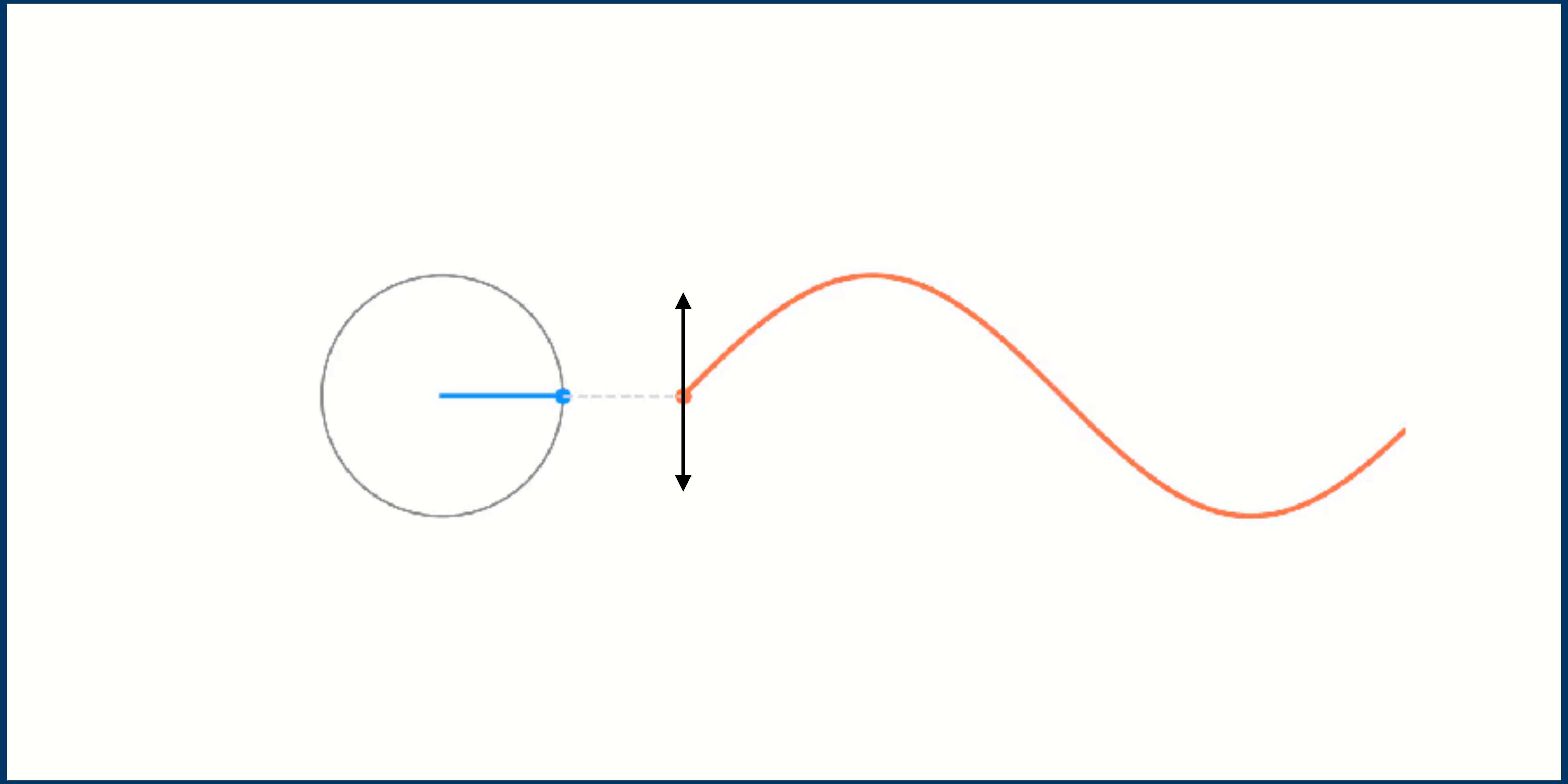
Session 4:

The Measurement Problem

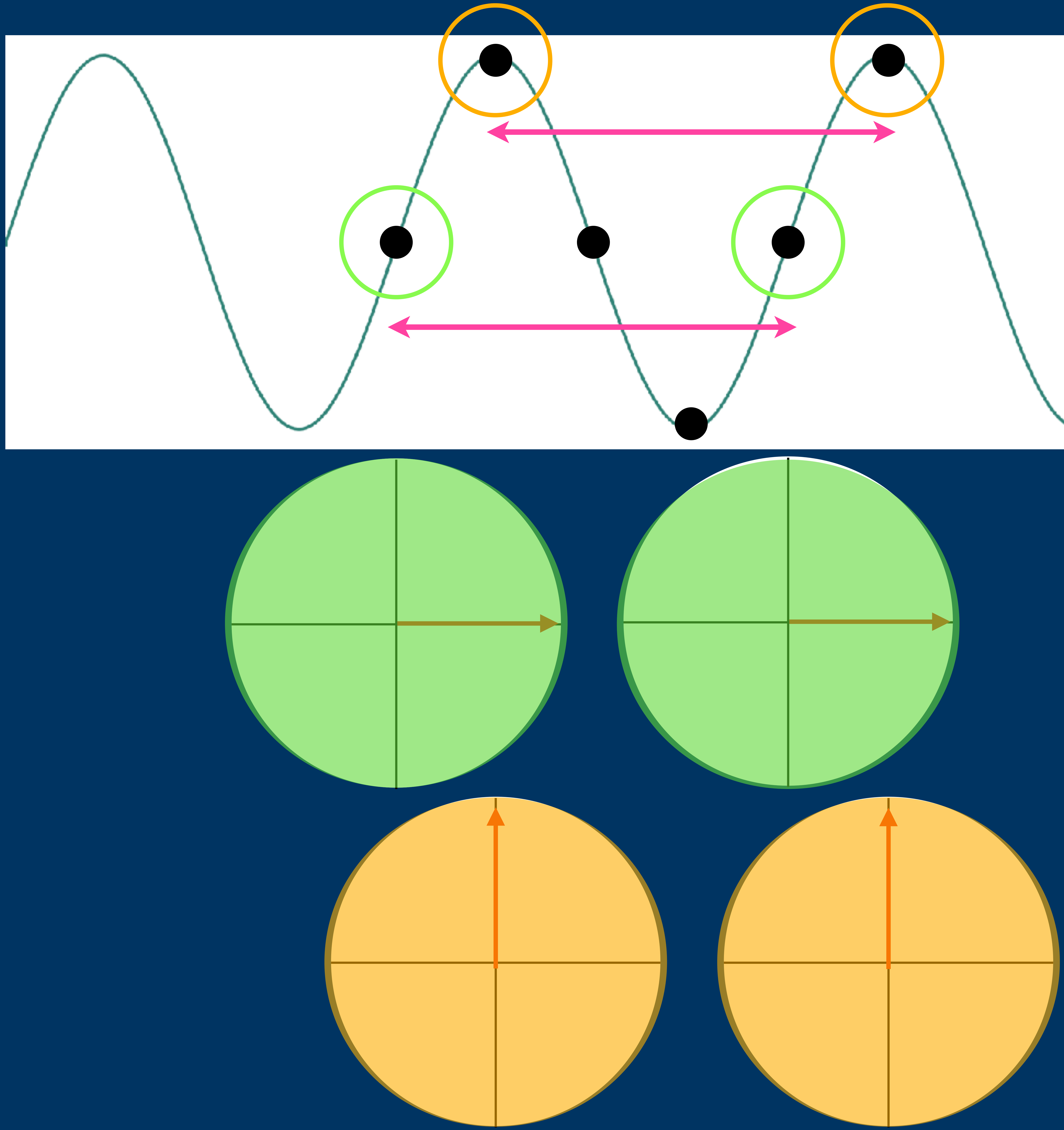
Wave phase - what part of the cycle

Specified as an angle…



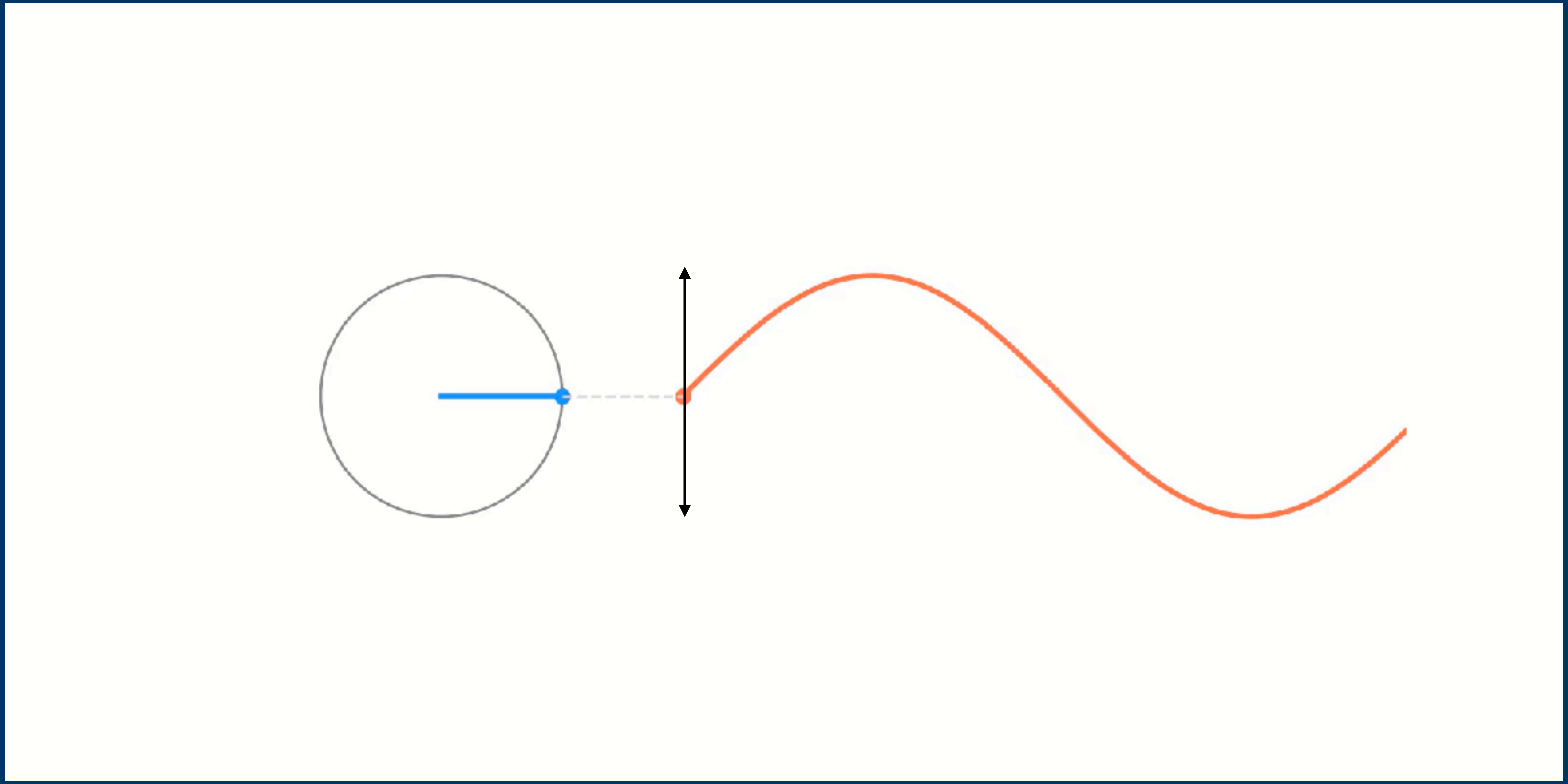


NB: wave frozen at a moment in time



Wavelength:

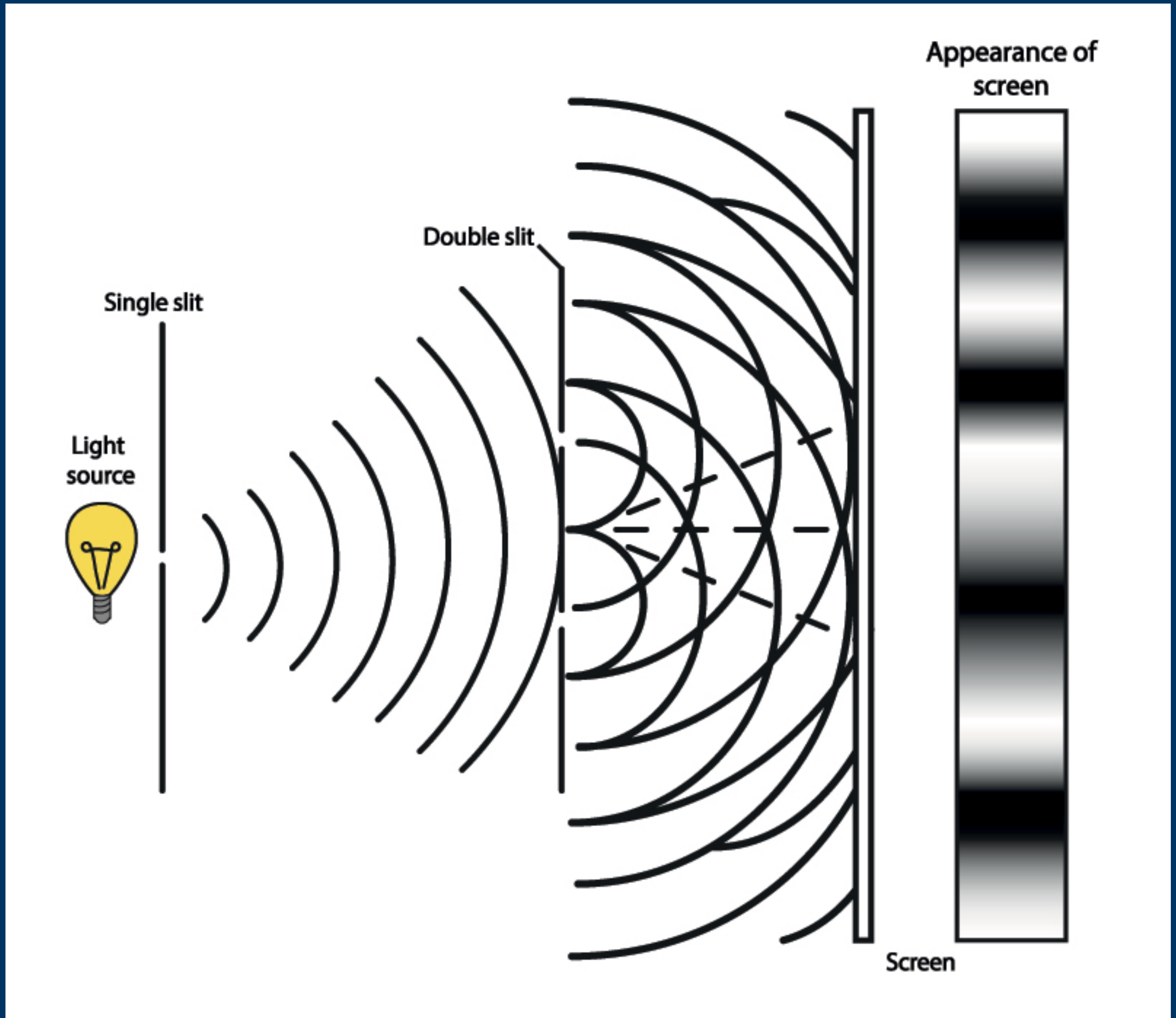
Shortest distance between two points of the same phase

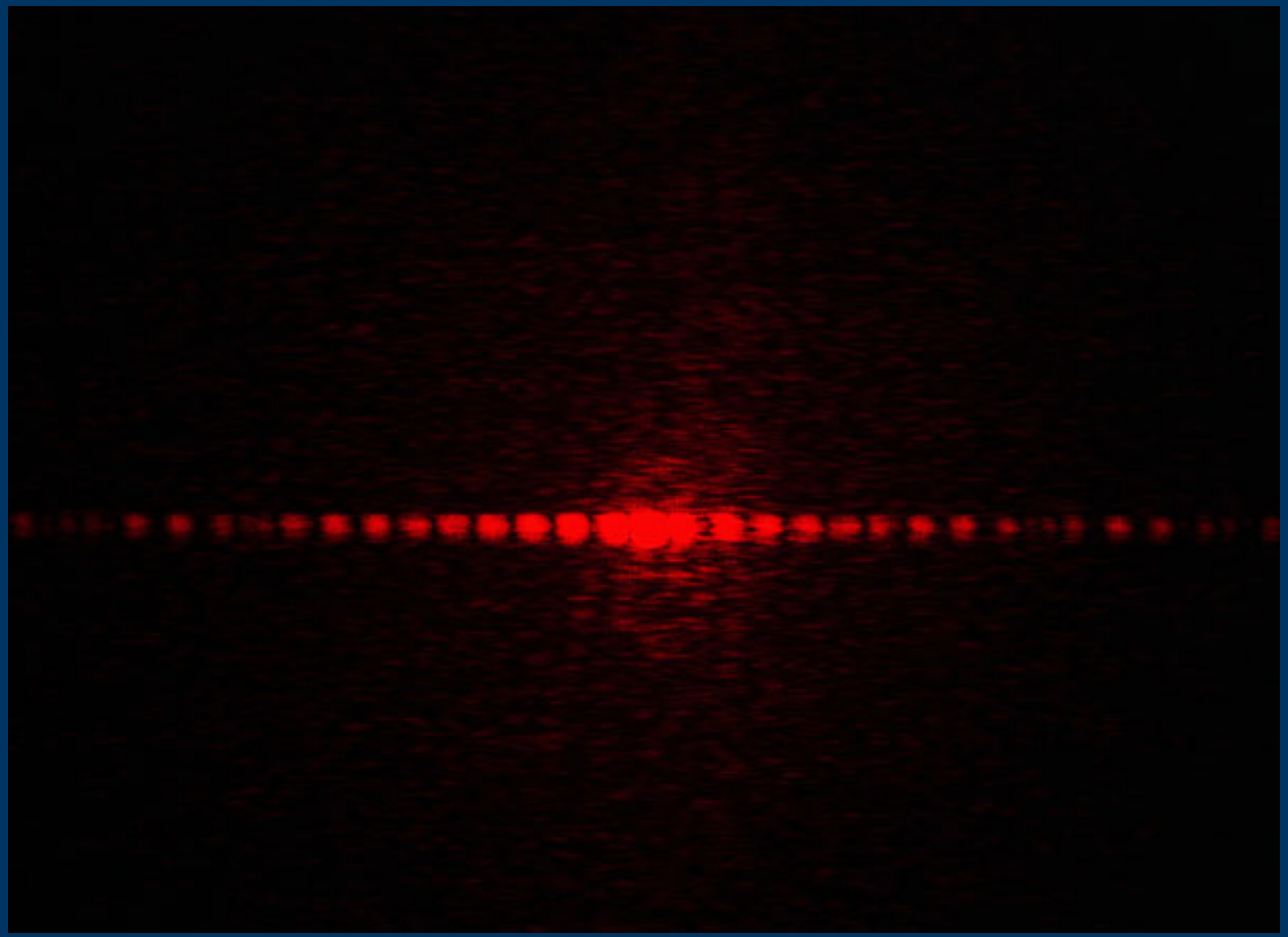


Frequency: shortest time taken to reach the same phase again

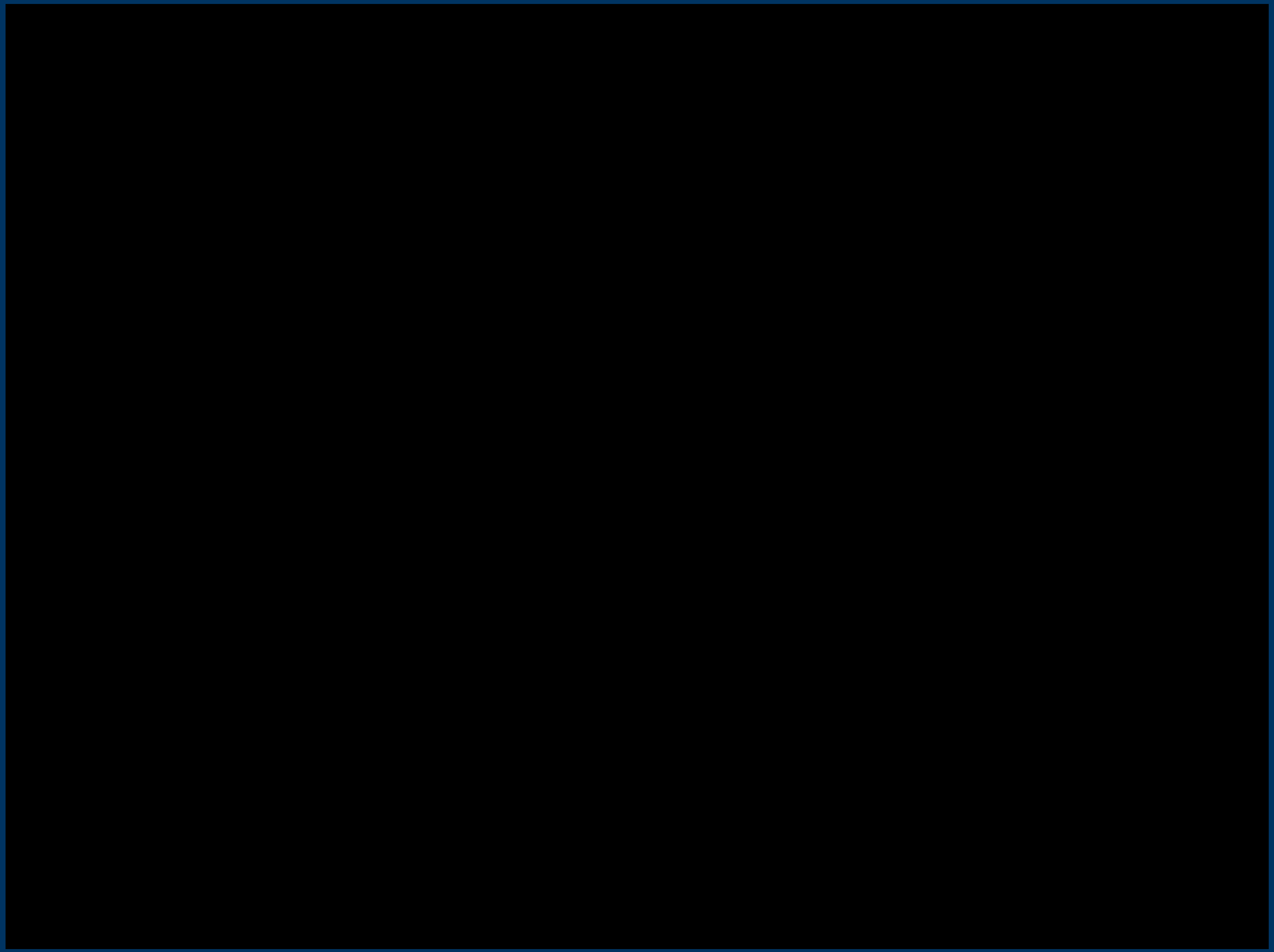
NB: single place on the wave over time

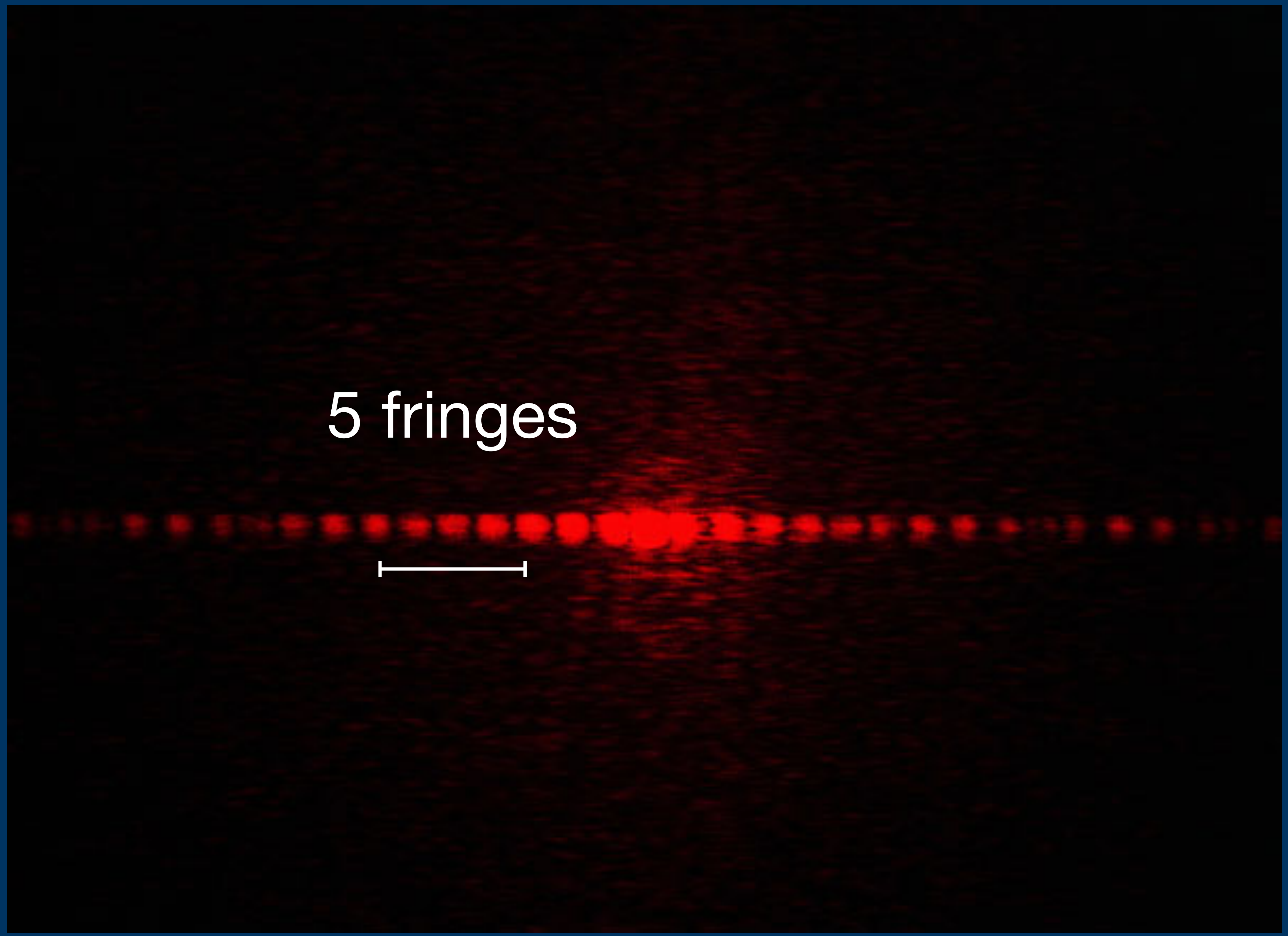
Double slit experiment with light





Double slit experiment with light



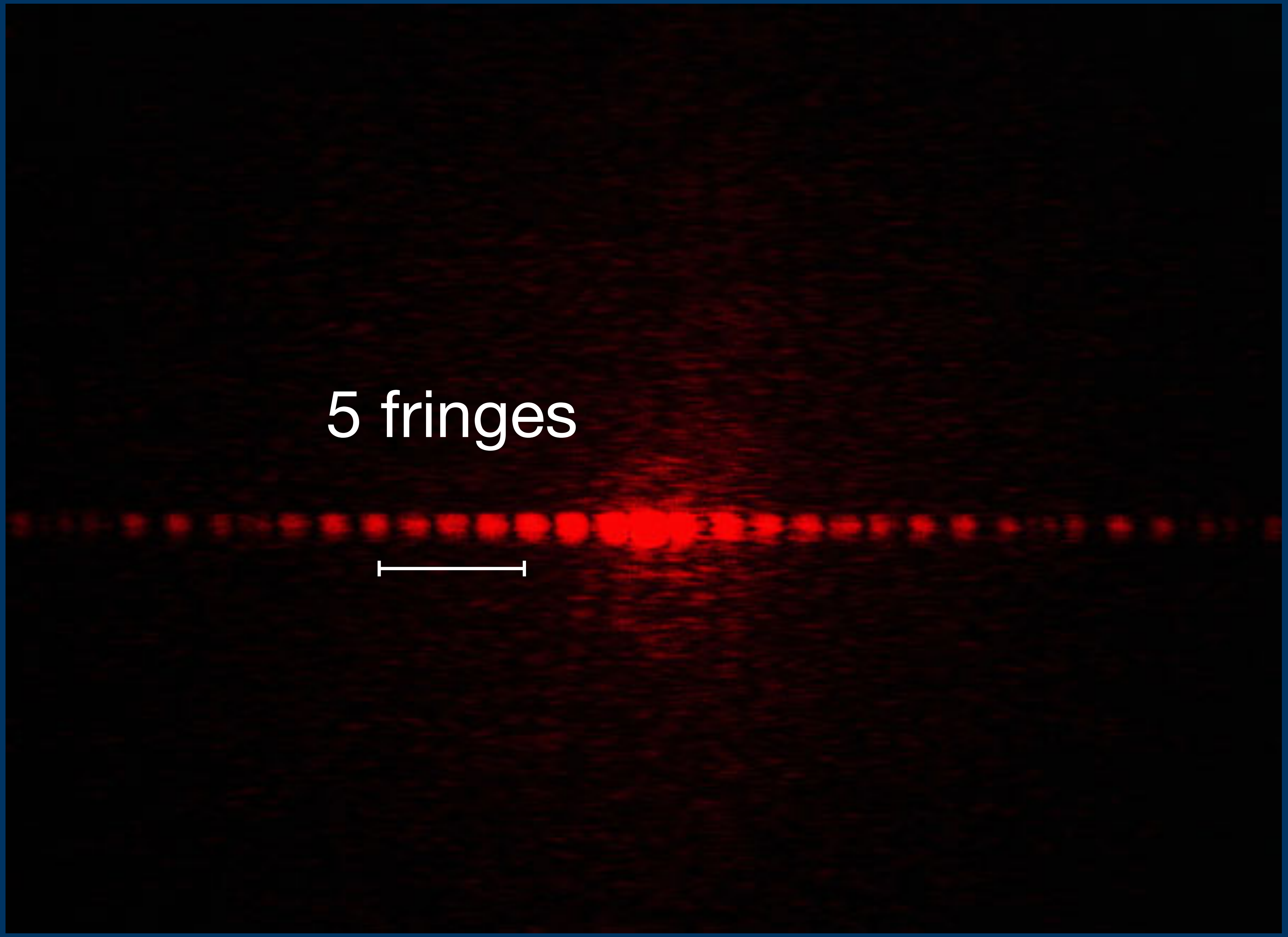


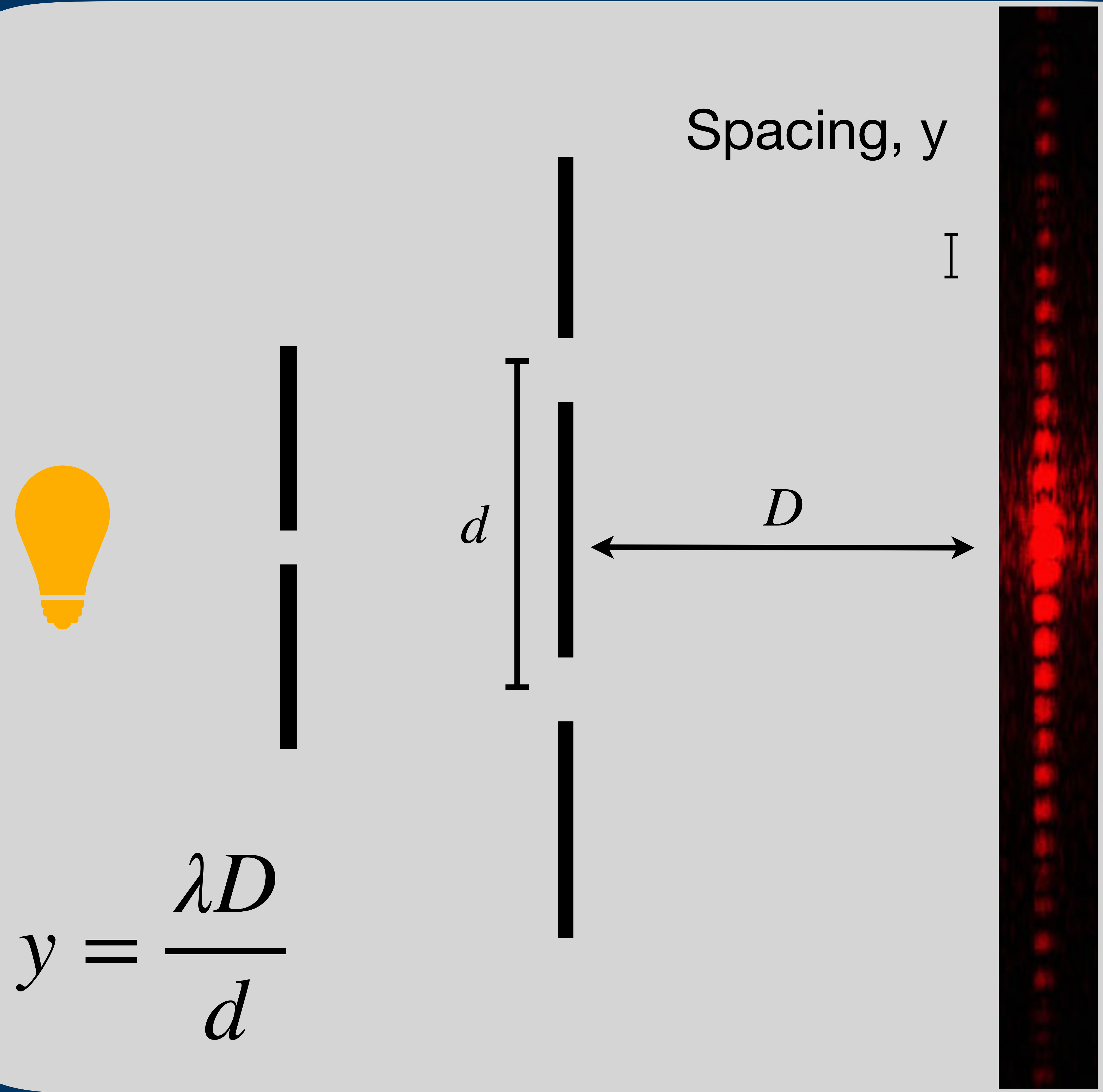
Get the fringe spacing

Gives us the wavelength of the wave

How the wavelength of light first measured…

Double slit experiment with light

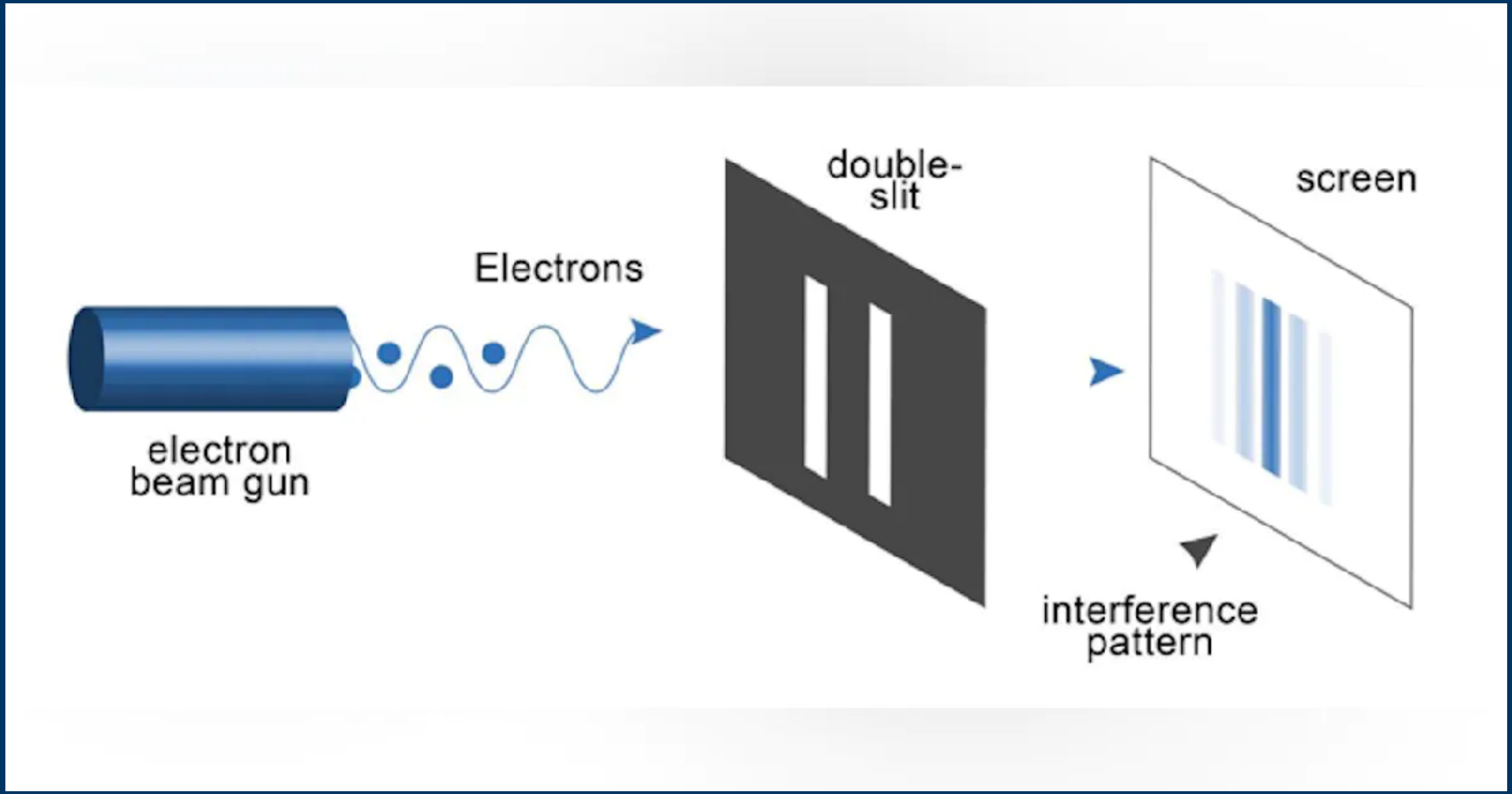


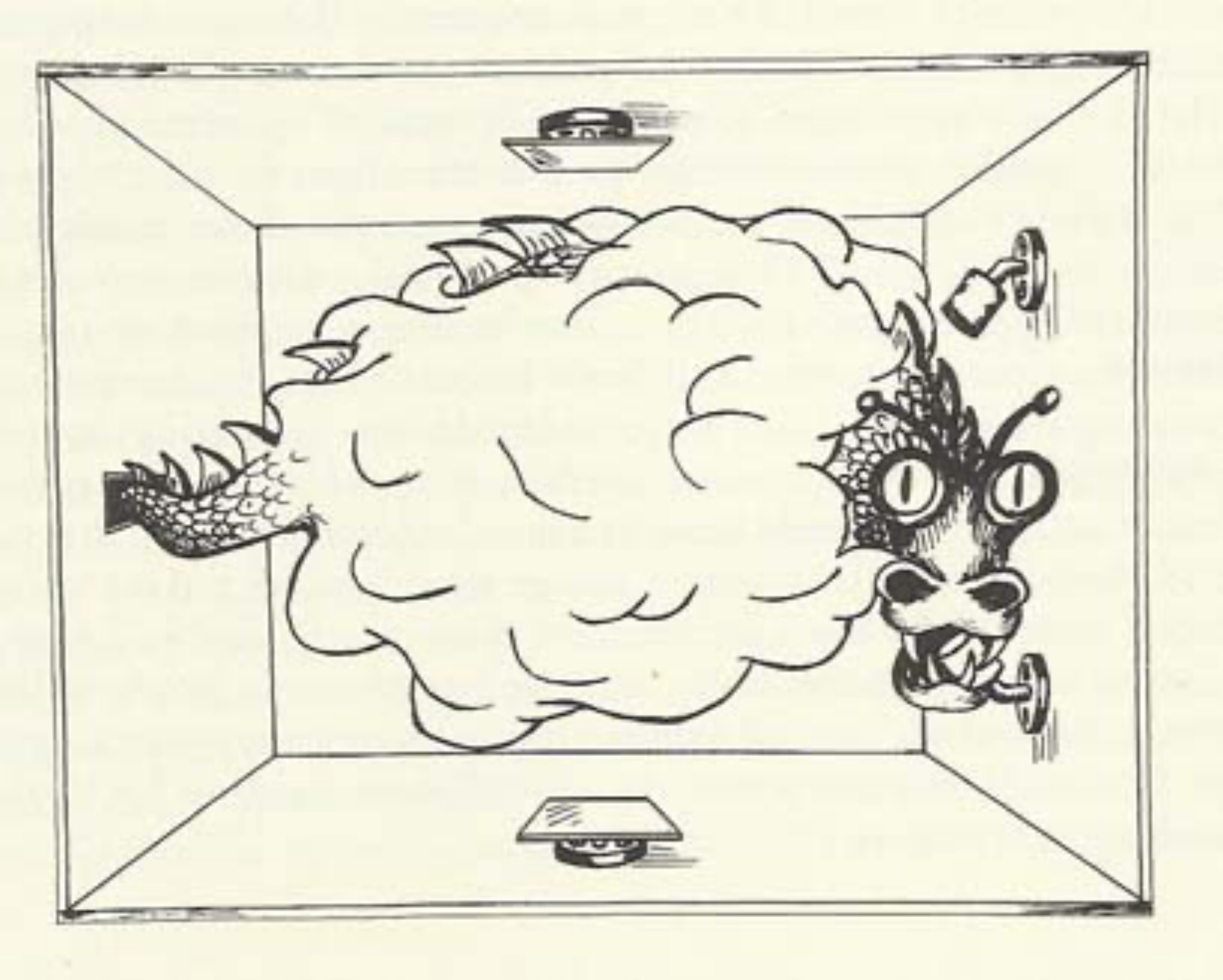


$$y = \frac{\lambda D}{d}$$

That’s how we could measure something so small…back in 1800s

Double slit with electrons



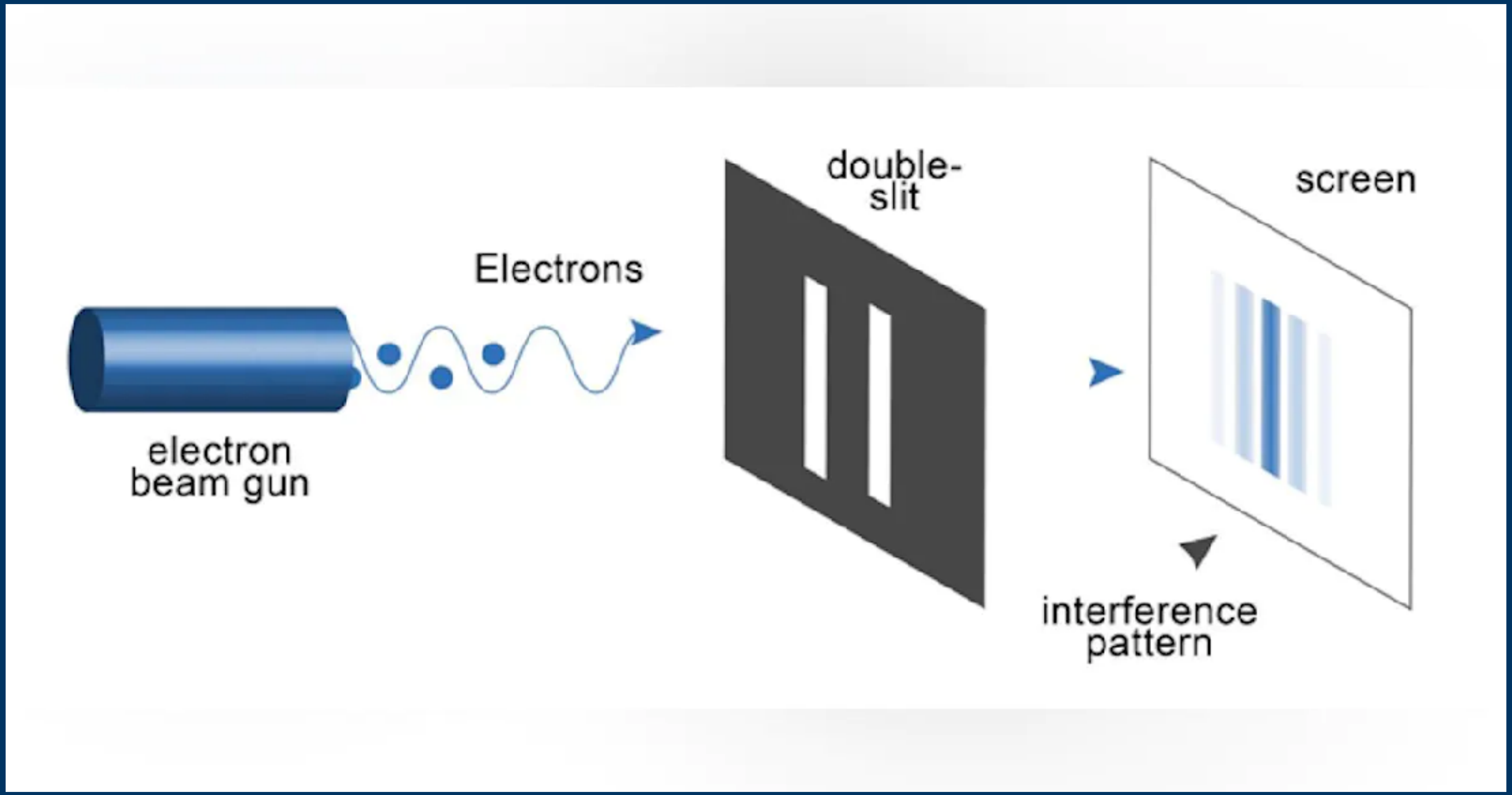


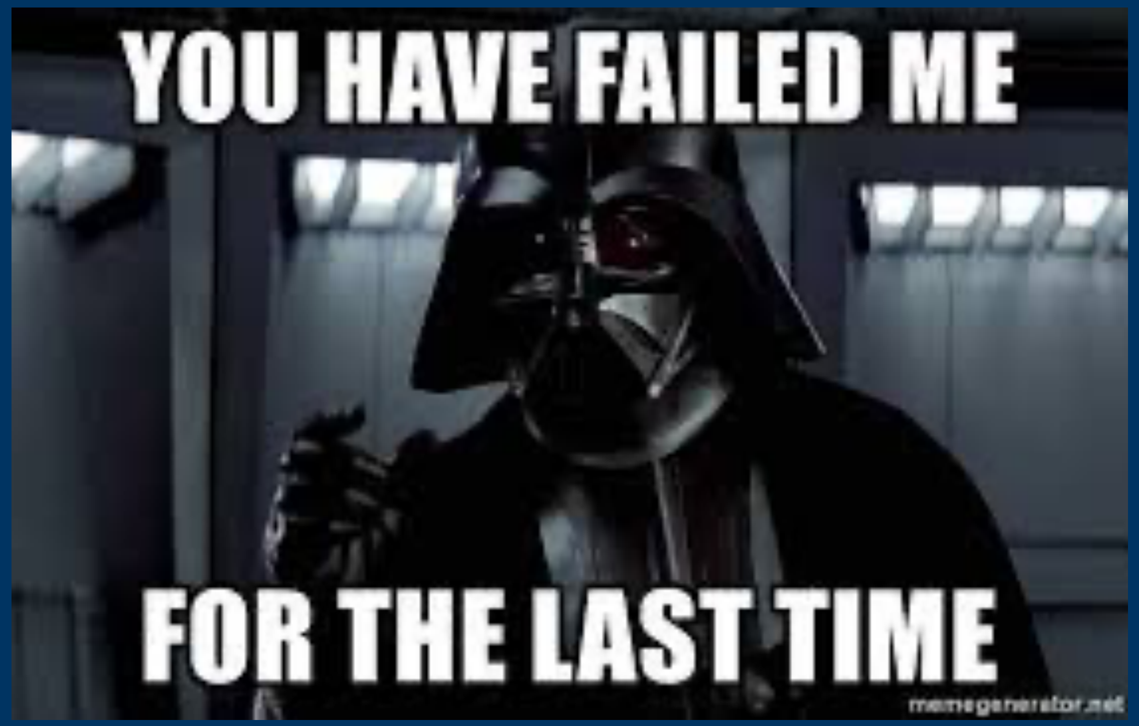
Great smoky dragon - Wheeler

Passes through the experiment as a wave

Manifests at the screen as a particle

Double slit

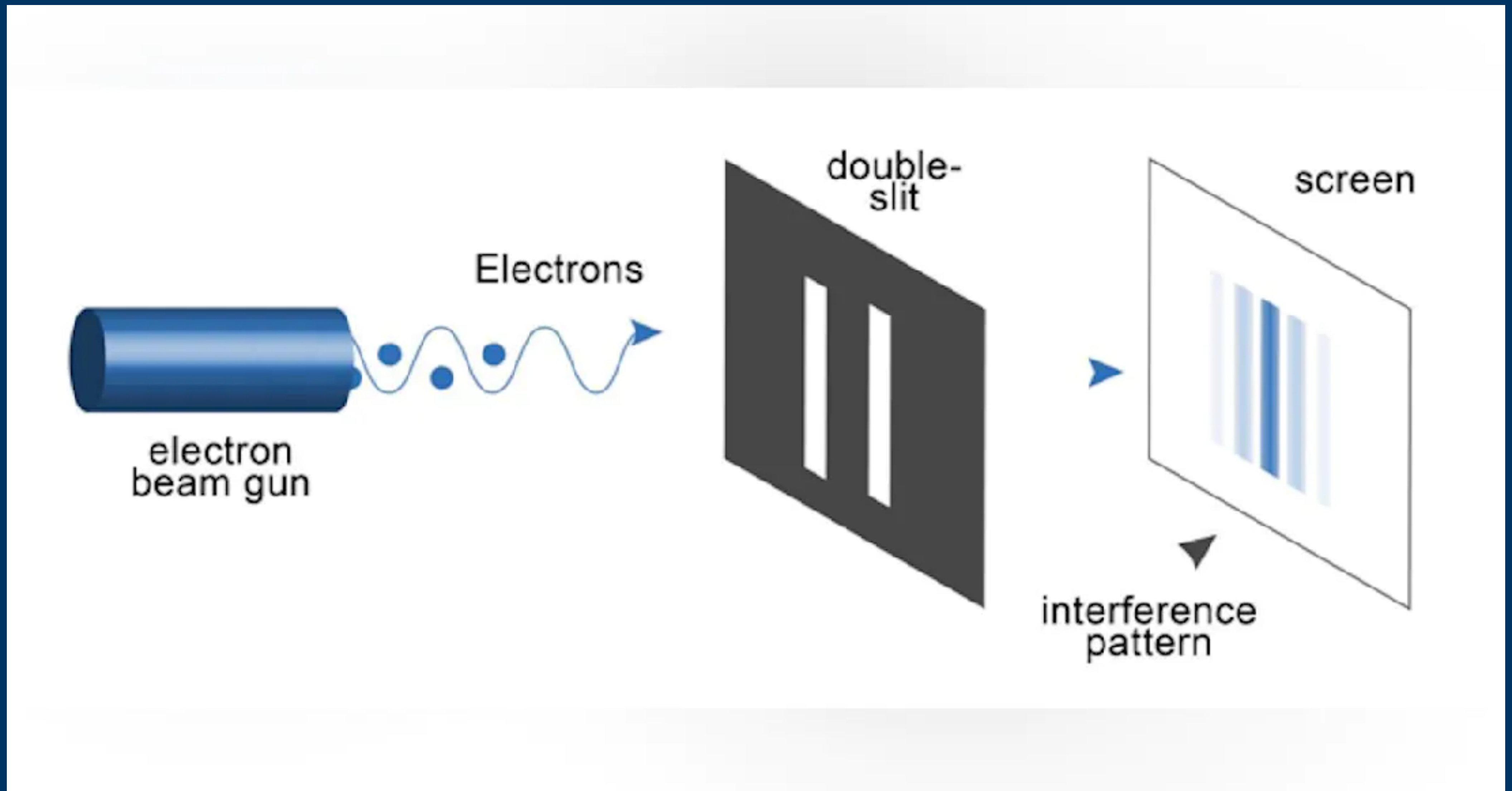




There are no paths in QM!

How does a particle passing through one slit ‘know about’ the other?

So how can electrons generate interference patterns?

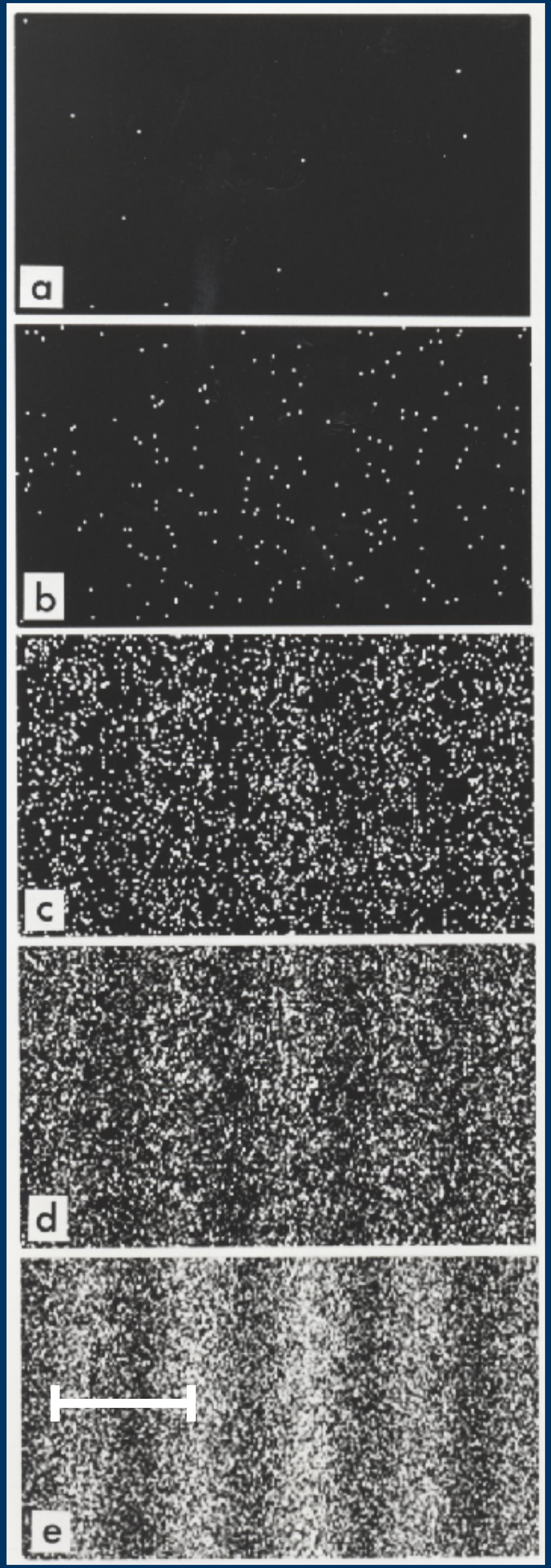


Means we can calculate

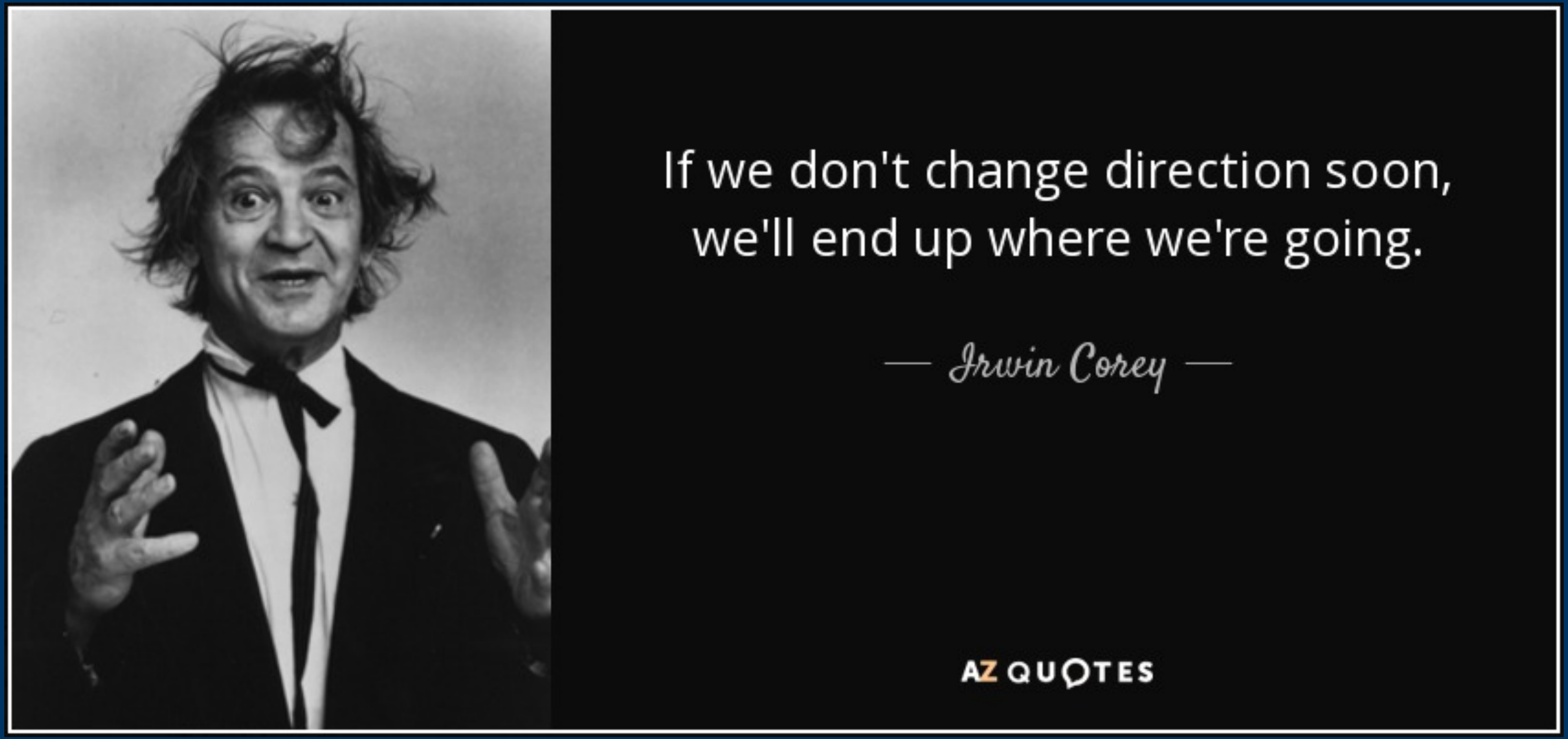
The ‘wavelength’ of the electrons

Turns out to be proportional to the momentum of the particles in the beam

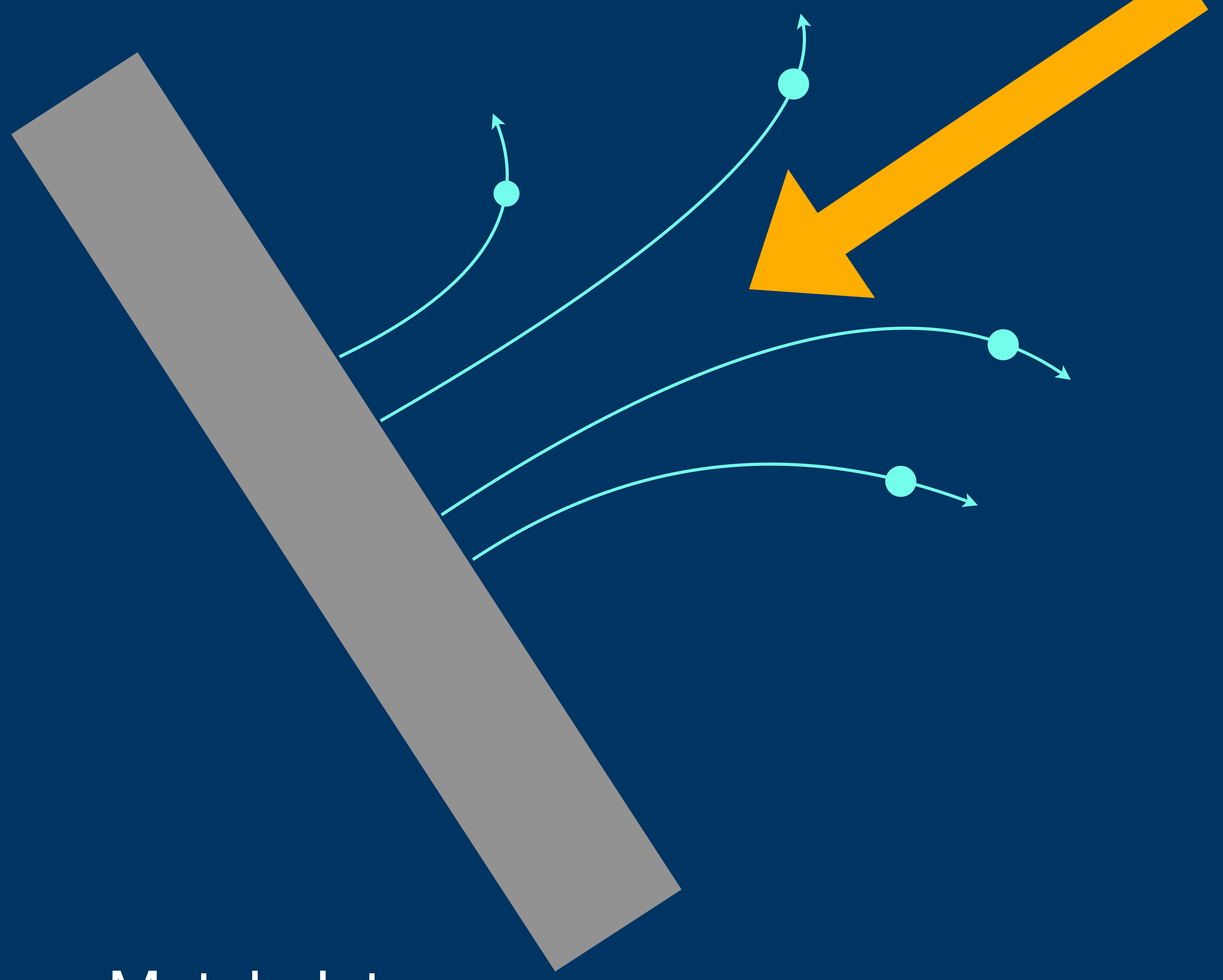
Fringe spacing



Change tack…


If we don't change direction soon, we'll end up where we're going.
— Irwin Corey —
AZ QUOTES

The photoelectric effect



Rate of emission

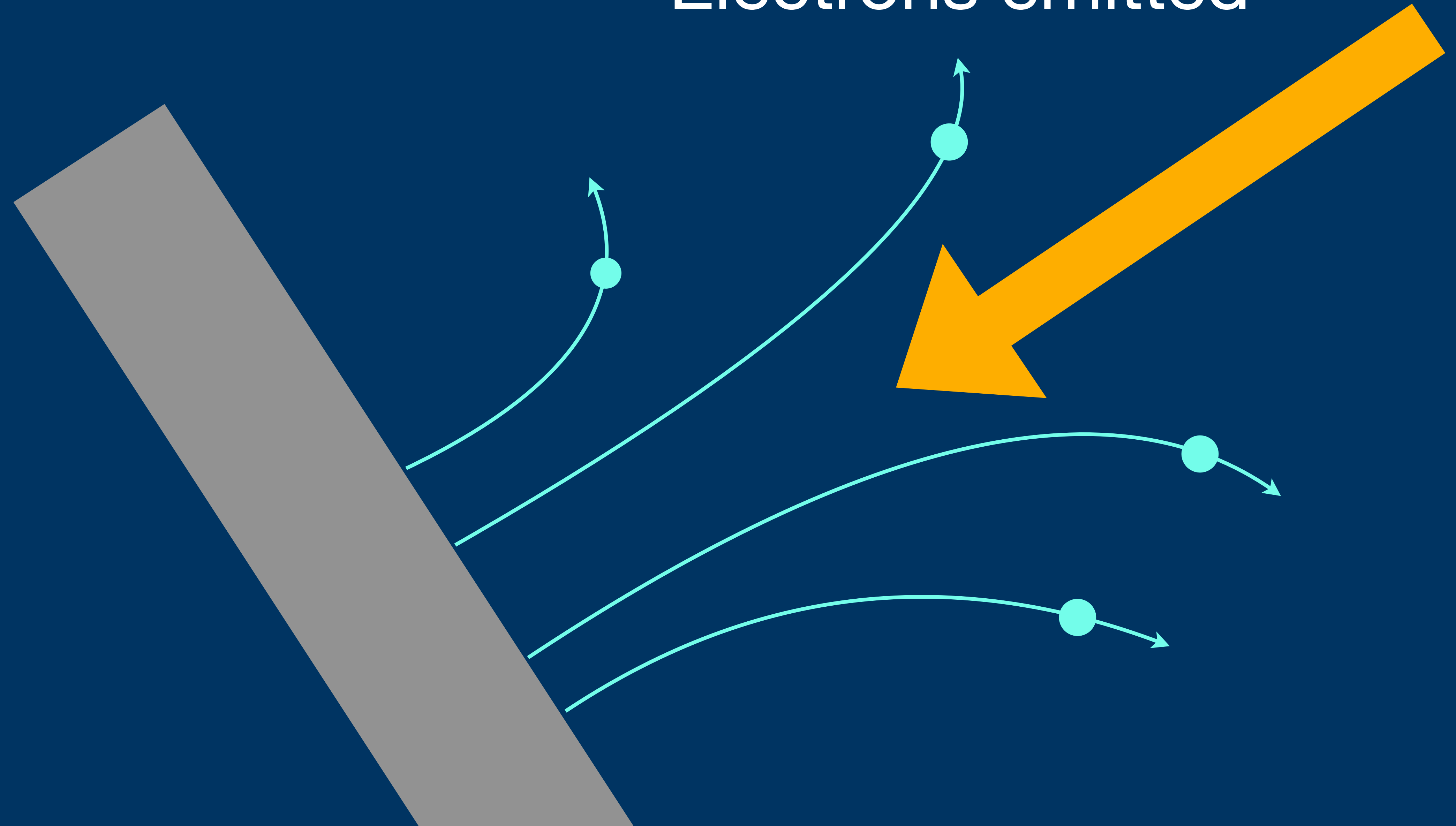
Depends on brightness of light

Energy of electrons

Depends on frequency of light

Surprise

The photoelectric effect



Rate of emission

Depends on brightness of light

Energy of electrons

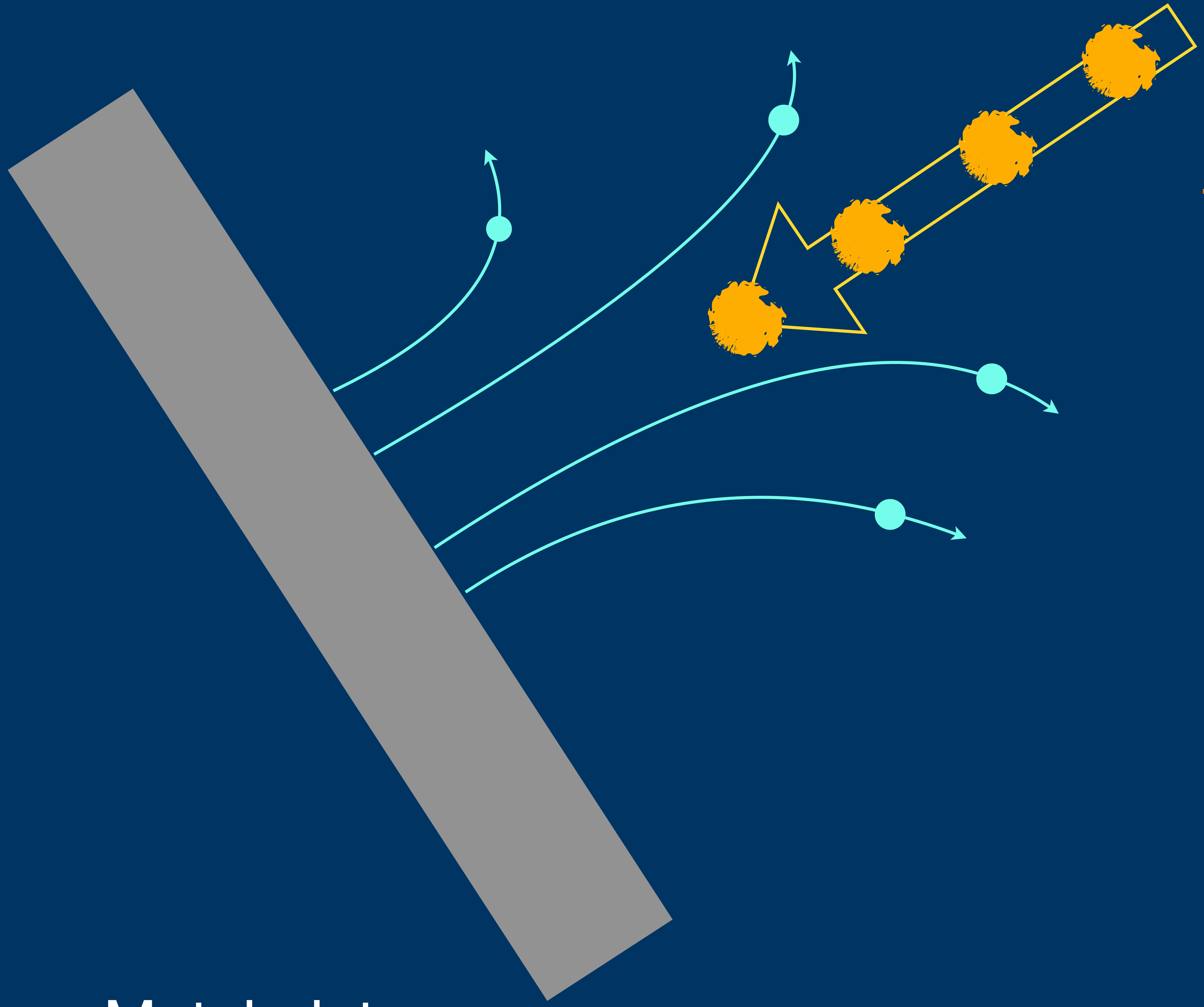
Depends on frequency of light

Surprise

For a wave, expect

Energy to depend on brightness

The photoelectric effect



Turn down the wick….

Individual photons…

Rate of emission

Drops to one electron per photon

The photoelectric effect

Metal plate

Turn down the wick….

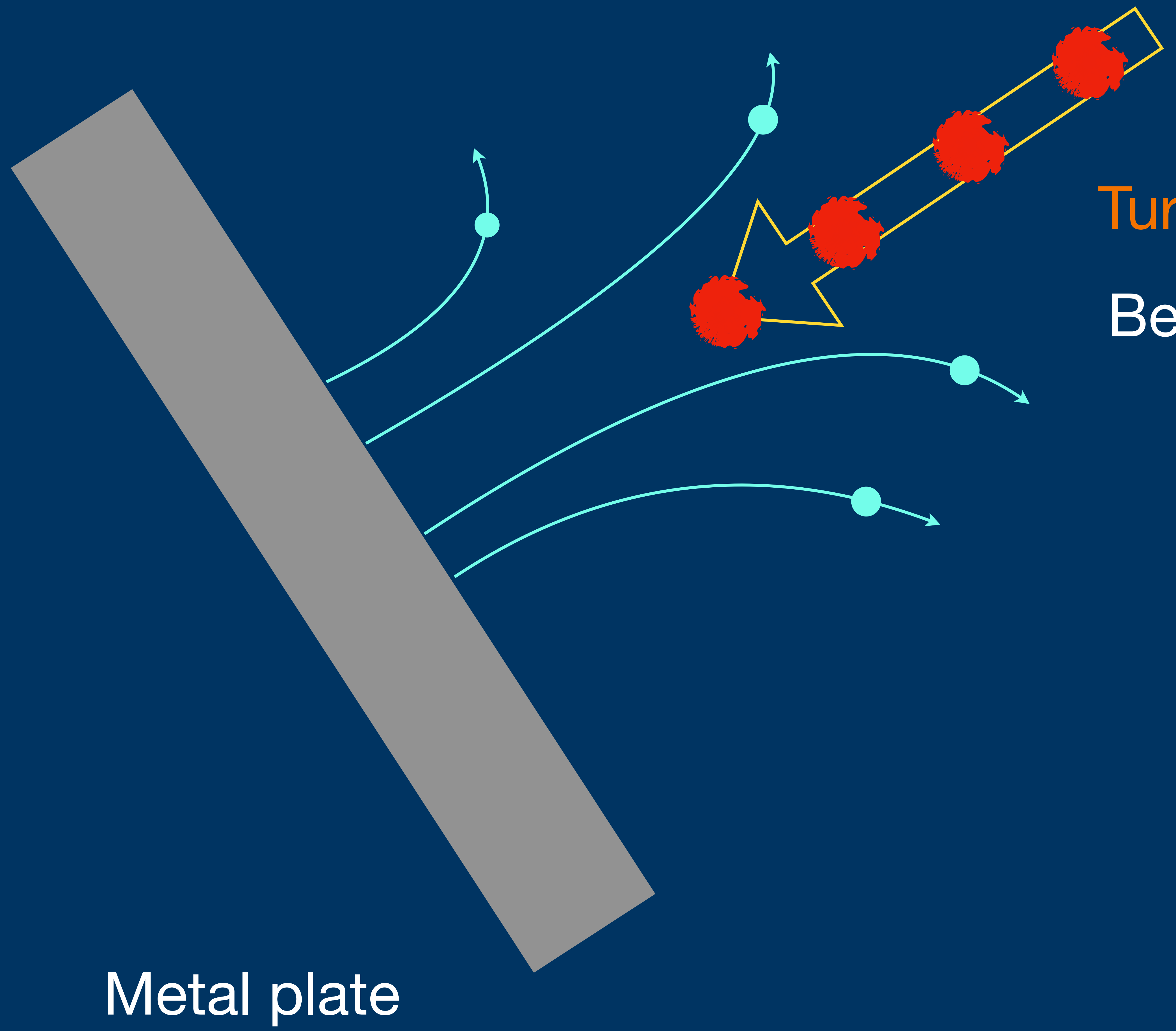
Individual photons…

Rate of emission

Drops to one electron per photon

But all of same energy…

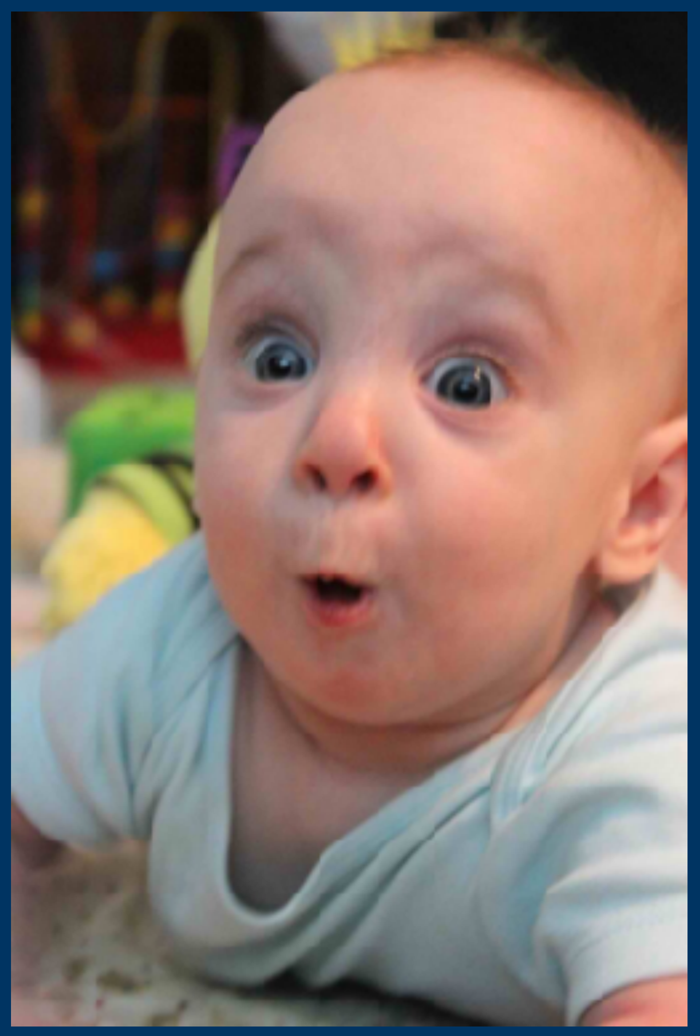
The photoelectric effect



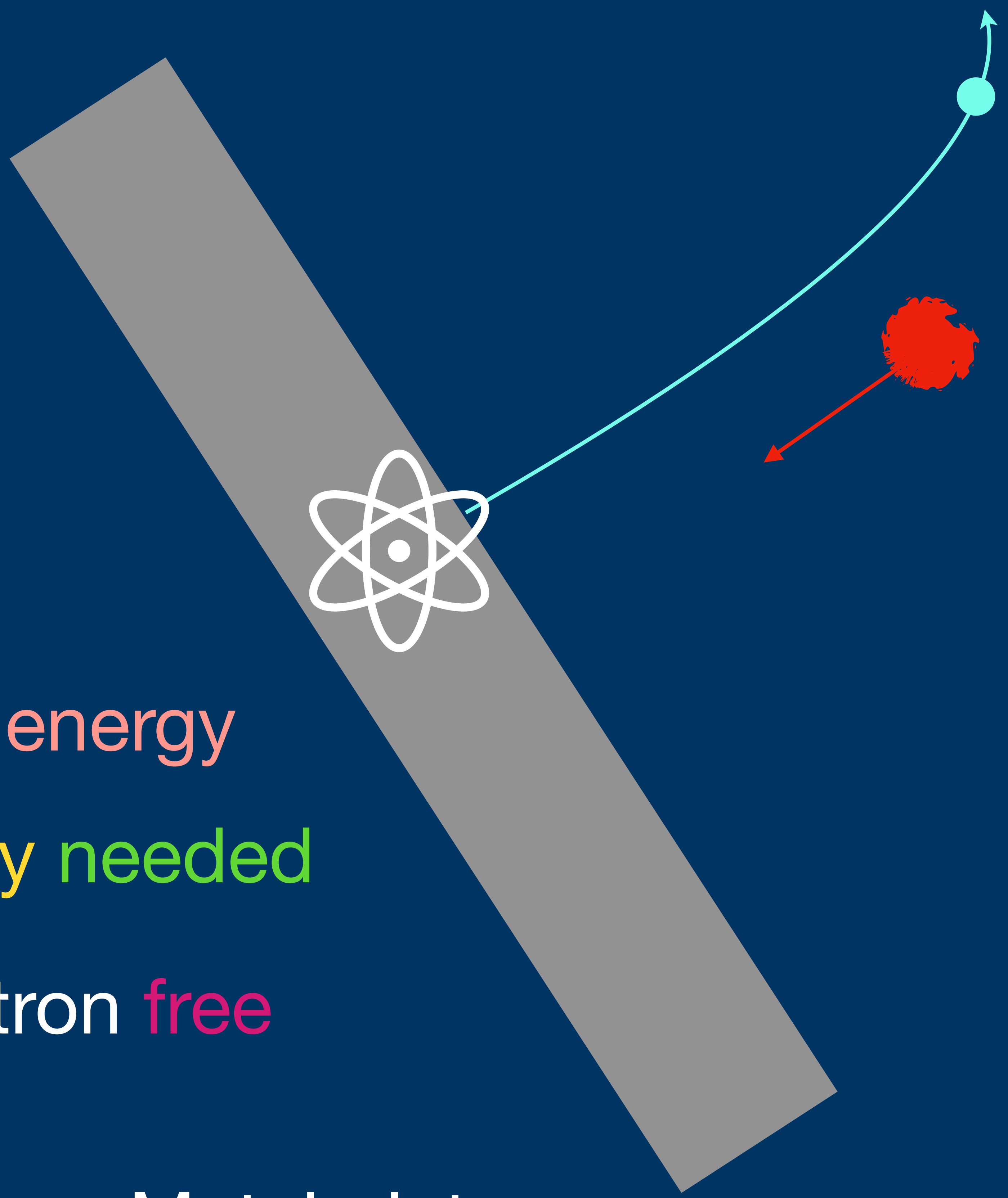
Turn down the frequency….

Below a threshold frequency

No electrons emitted



The photoelectric effect



Metal plate

Electron binding energy

Amount of energy needed

To break an electron free

Above frequency threshold

All emitted electrons have same energy

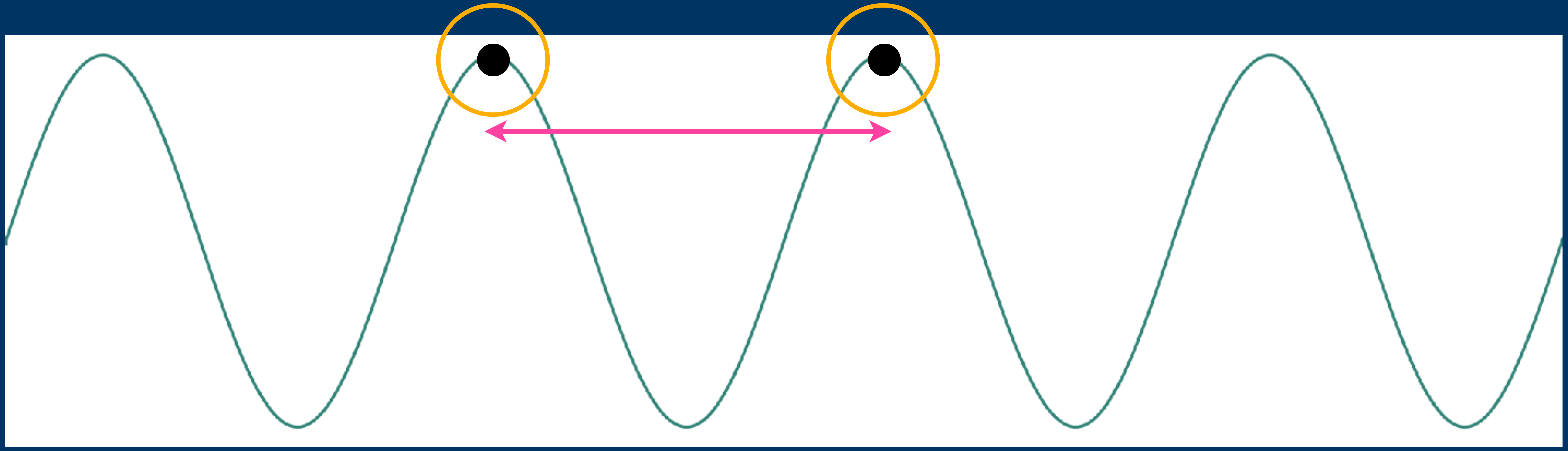
One photon breaks one electron free

Electron energy = photon energy - binding energy

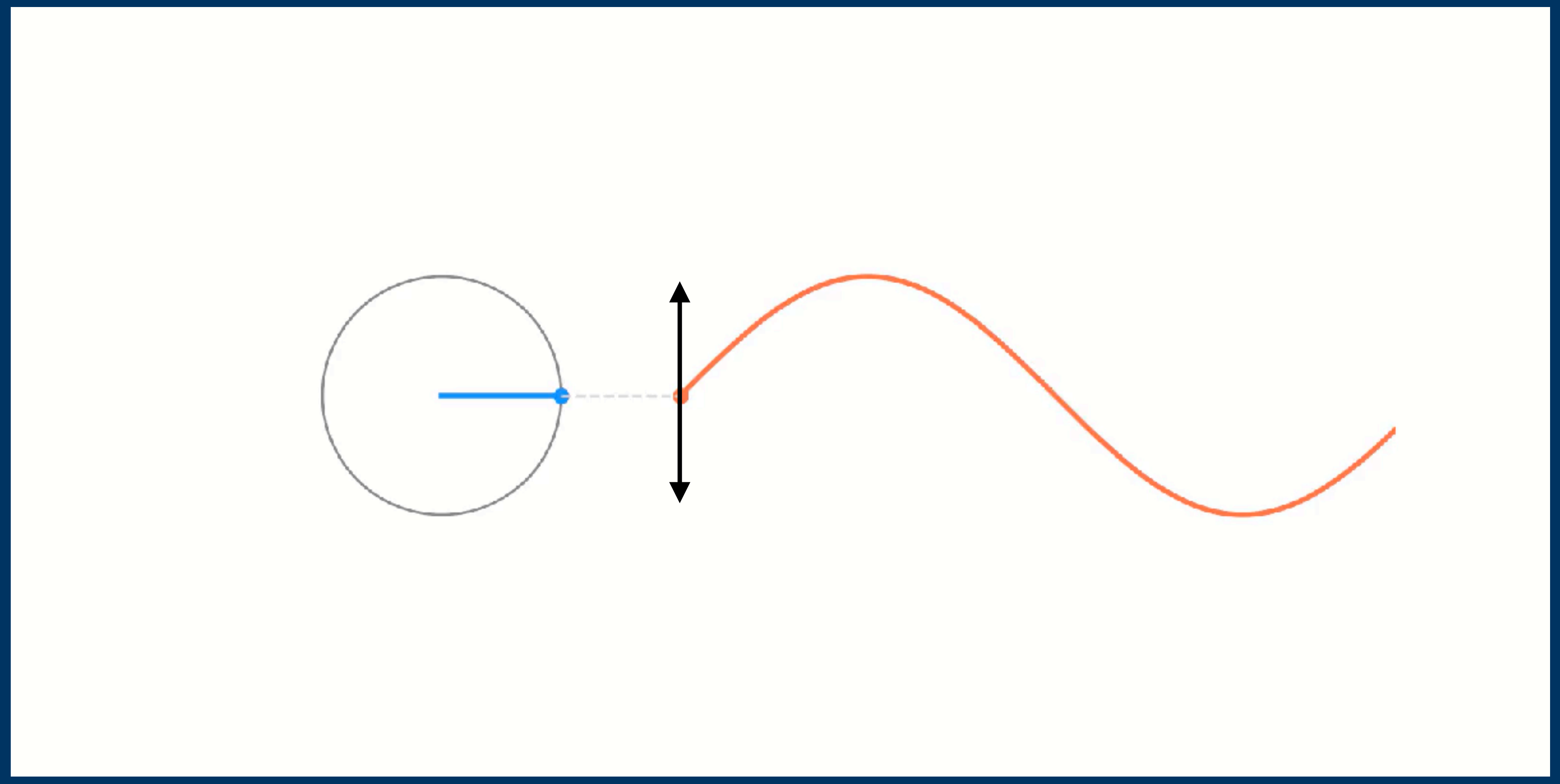
At threshold:

0 = photon energy - binding energy

So: photon energy depends on frequency



Wavelength ⟷ Momentum



Frequency ⟷ Energy

Schrödinger Equation

Classically, for a particle:

$$\text{total energy} = \text{kinetic energy} + \text{potential energy}$$

$$\frac{\text{momentum}^2}{2 \times \text{mass}}$$

Wave equation:

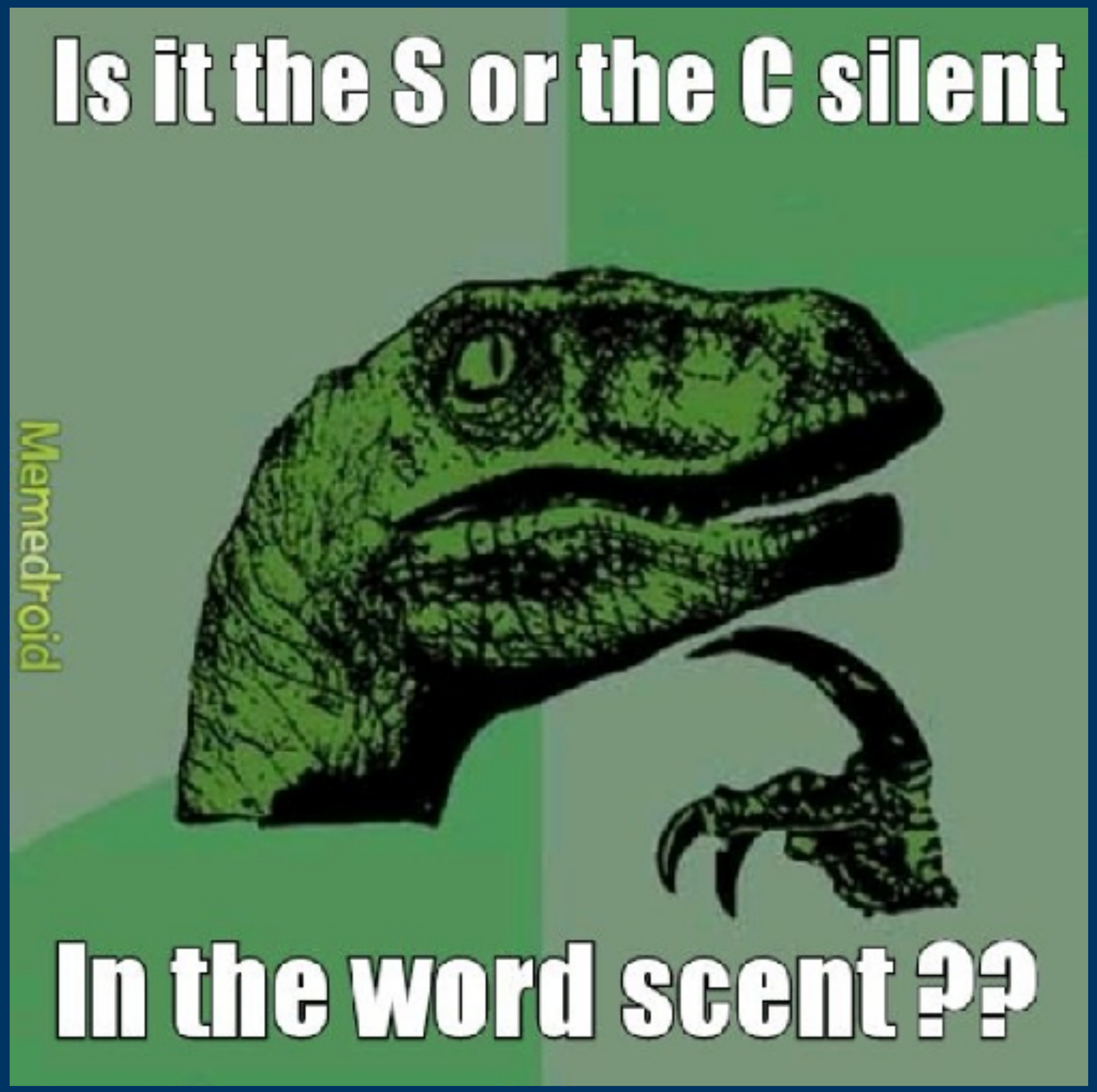
$$\text{frequency aspect} = \frac{\text{wavelength aspect}^2}{2 \times \text{mass}} + \text{potential energy}$$

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \psi}{\partial x^2} + V\psi$$

ψ Wave function

But…

$$\text{frequency aspect} = \frac{\text{wavelength aspect}^2}{2 \times \text{mass}} + \text{potential energy}$$

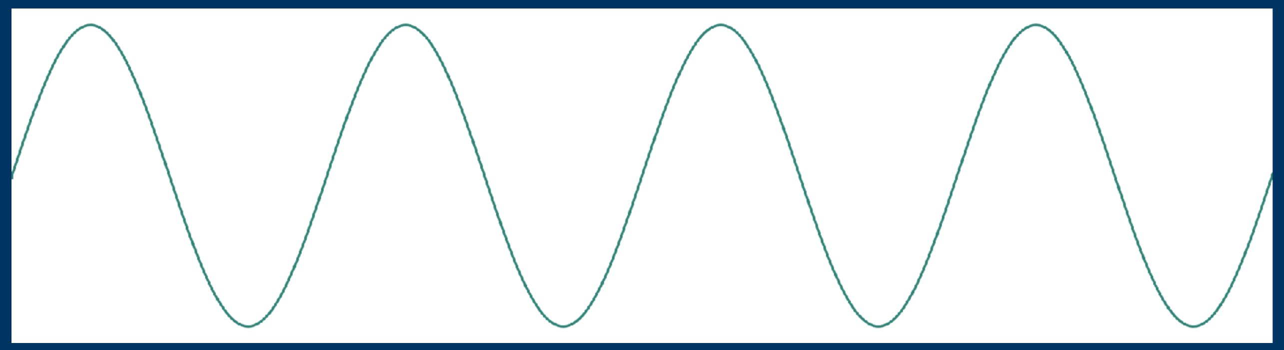


$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + V\psi$$

ψ Wave function

Not always in the form of a 'wave'

As we would recognise it…



Leaves the big question…

What is it that's waving?????

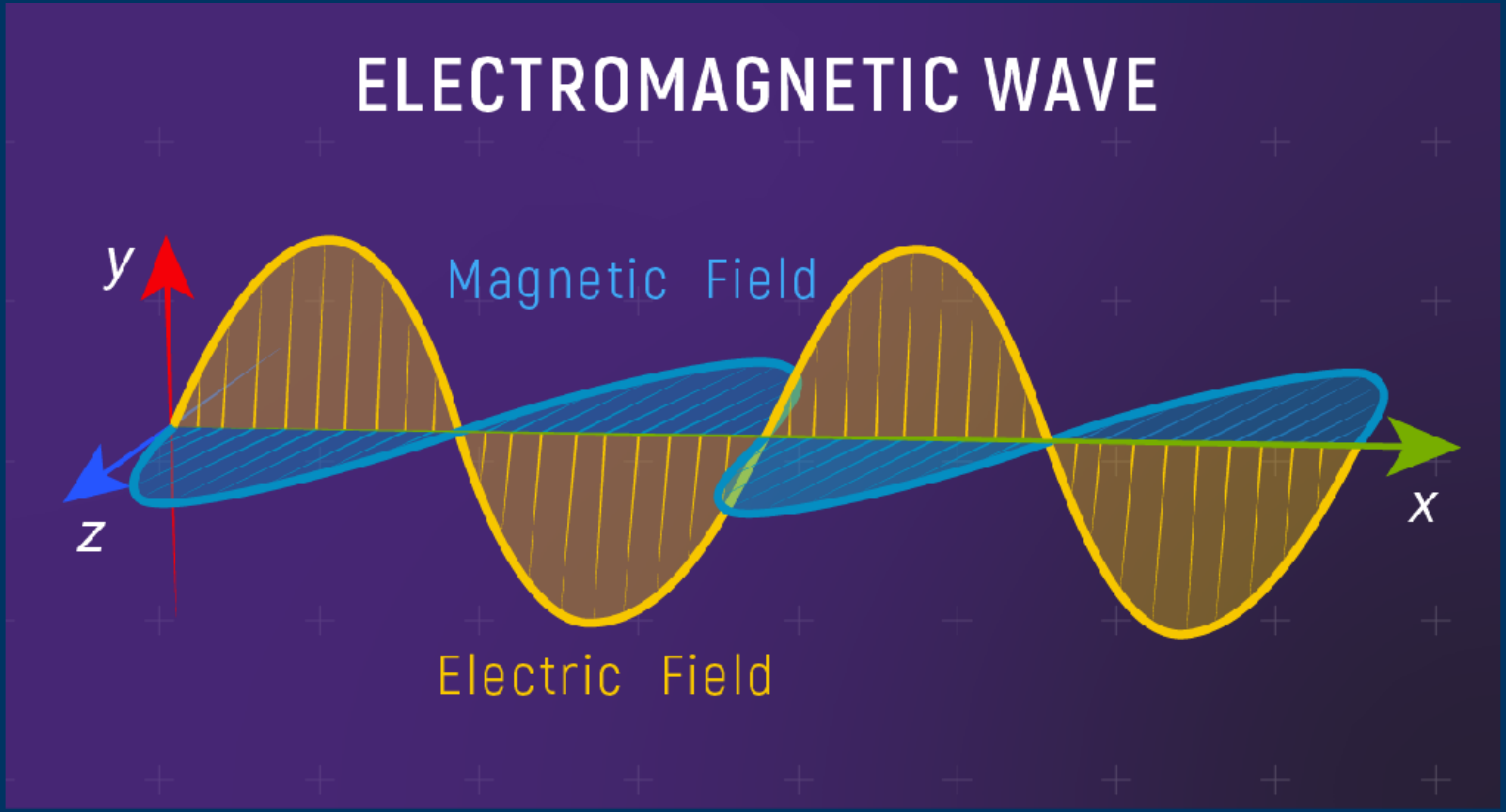
Light

An electromagnetic wave

Is physical

Just not tangible…

Variations in electric and magnetic fields



Health warning: the magnetic aspect is much weaker than shown here…

The wave function

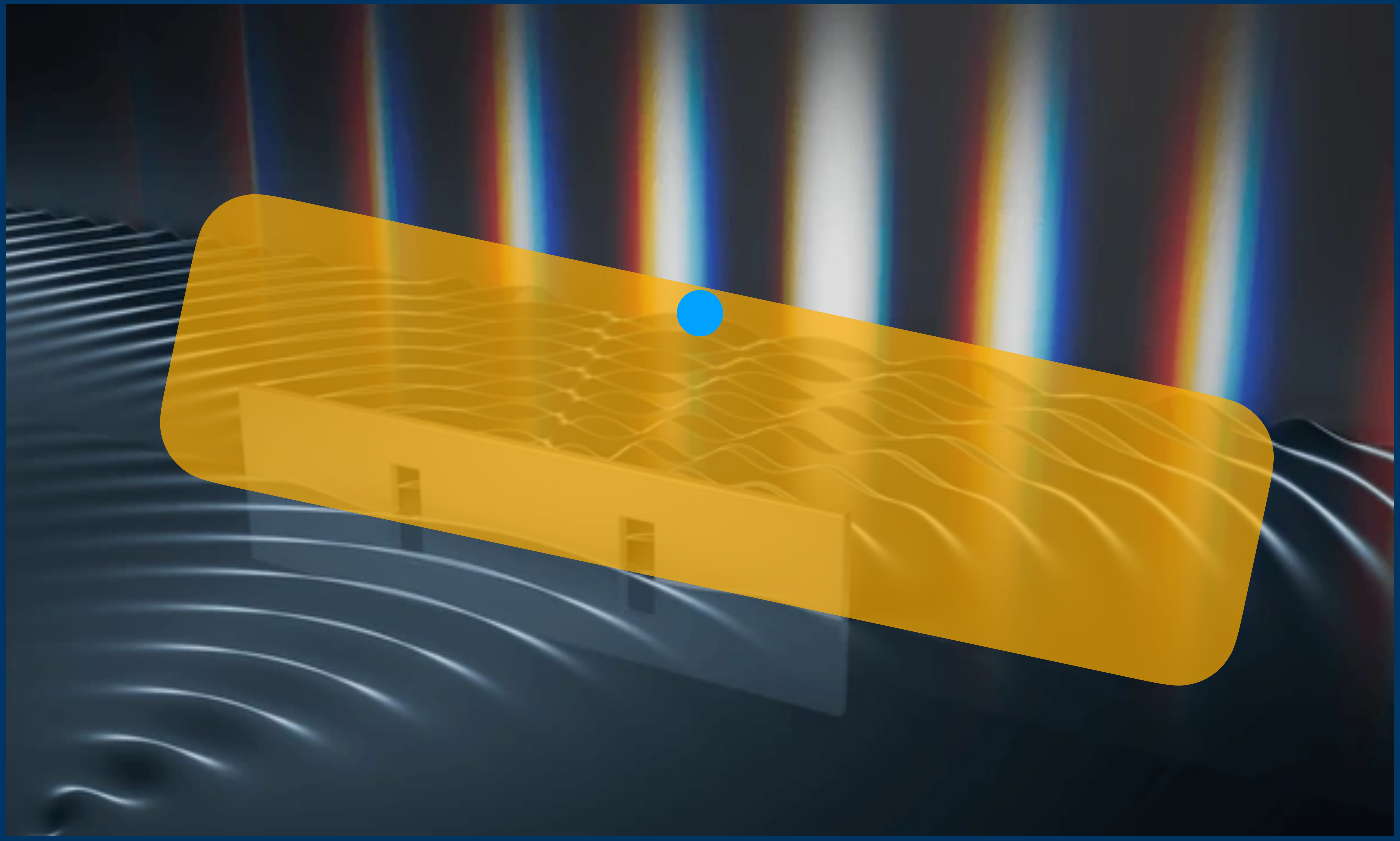
Is not in any sense ‘physical’

The intensity cannot be measured

If the electron ‘was’ the wave function

Detect a ‘spread out’ region of charge

Detect a tiny ‘dot’ of charge instead



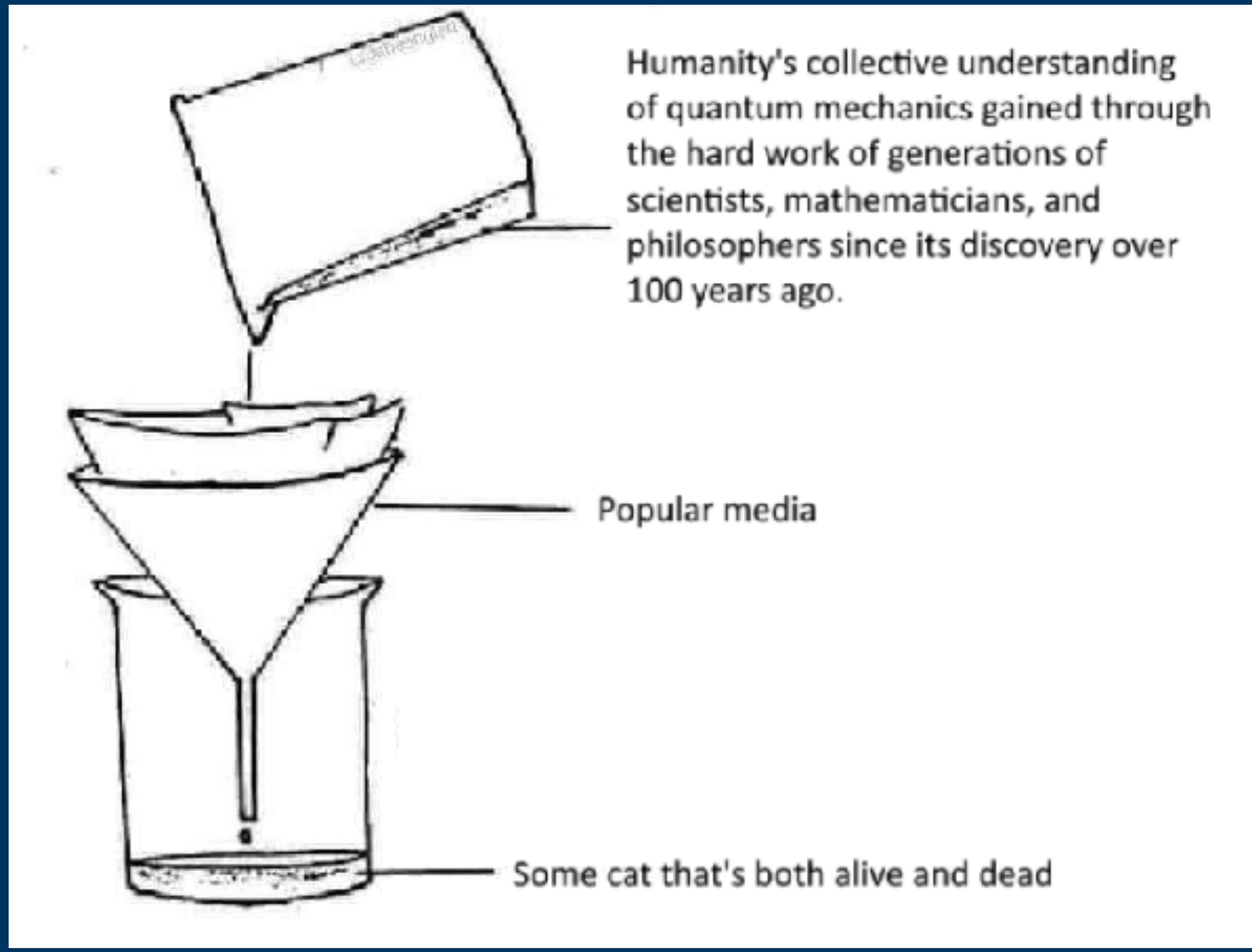
The wave function

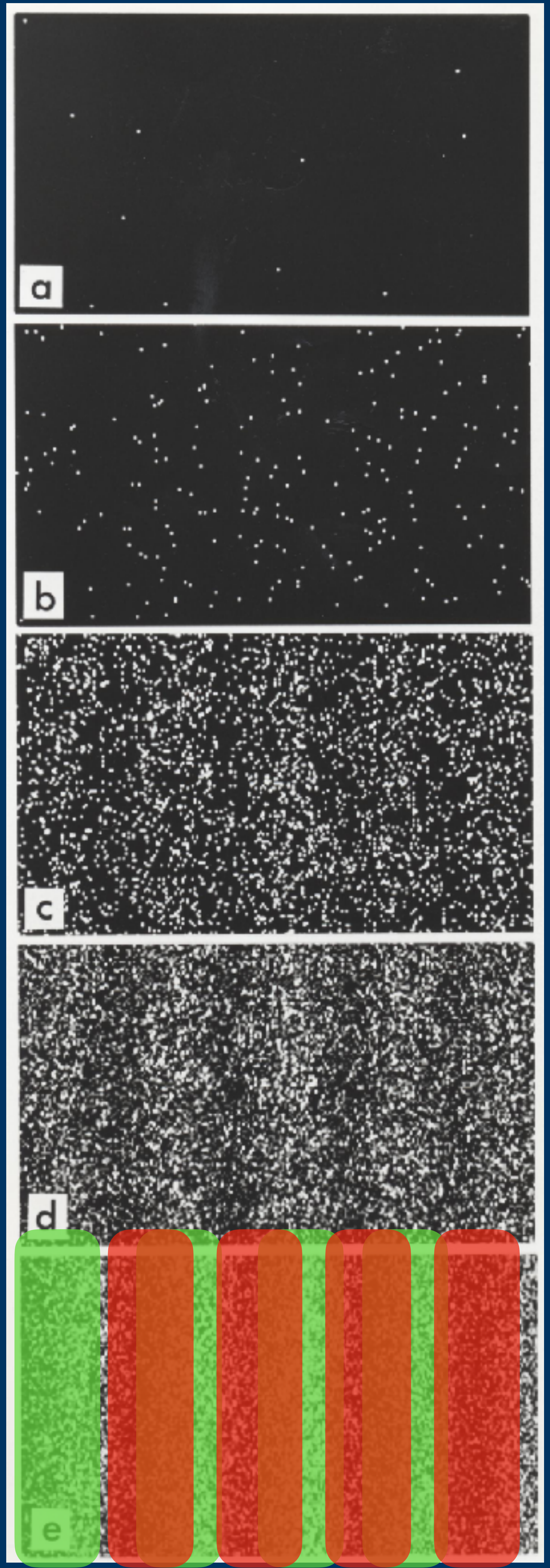
Where the wave is more intense

More likely that an electron will turn up

Where the wave is less intense

Less likely that an electron will turn up





Its a probability wave…

Whatever that means…

What is probability anyway?

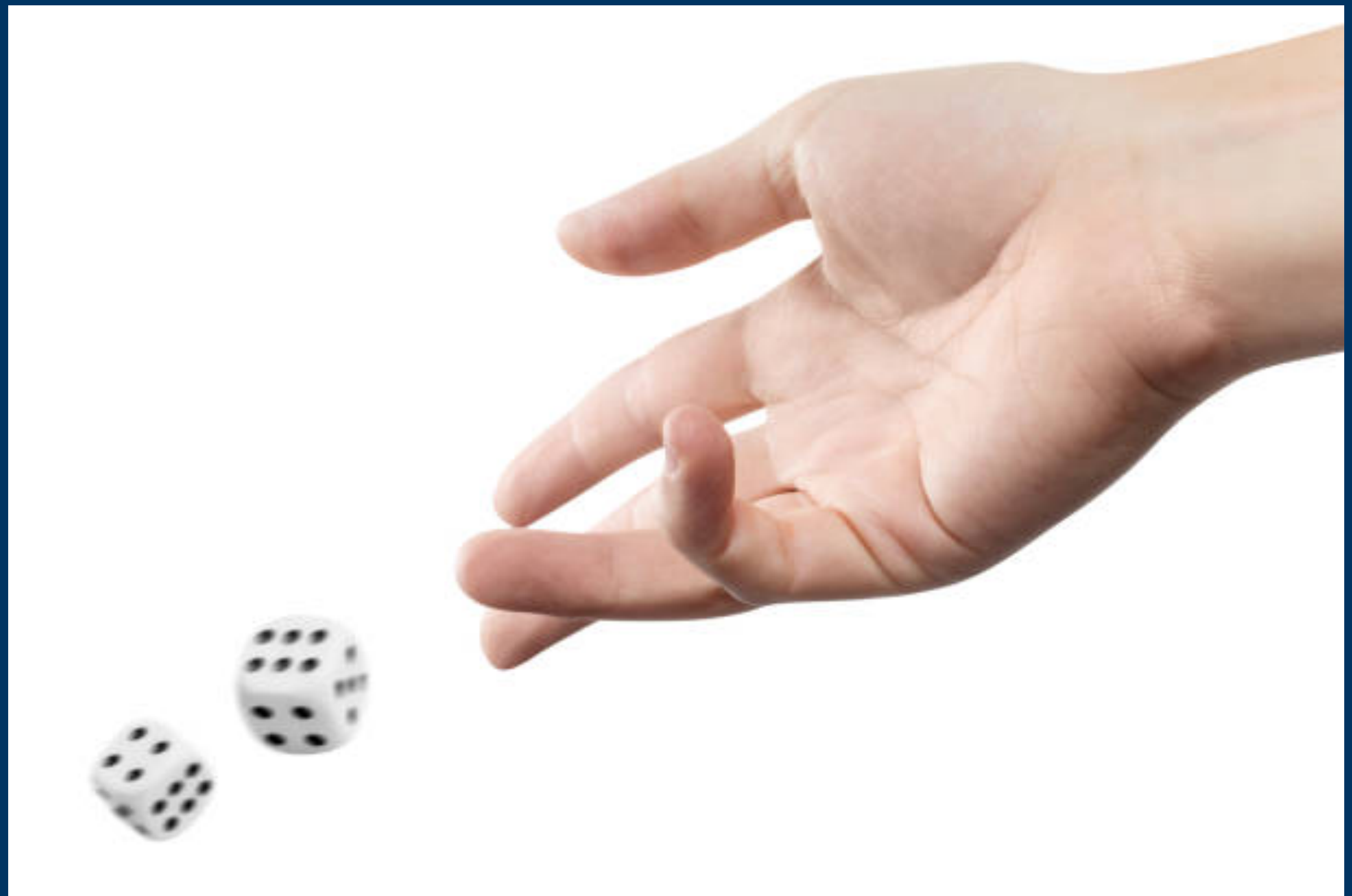
Examples:

Throwing a dice:

1 in 6 for any side

As there are 6 faces

The probability is ‘physical’



What is probability anyway?

Examples:

Horse race

Probability of a win…

More of an estimate

Charitable….more of a guess…

But physical - horse, running, other competitors…

What is probability anyway?

Examples:

Molecular speeds

Gas at a temperature

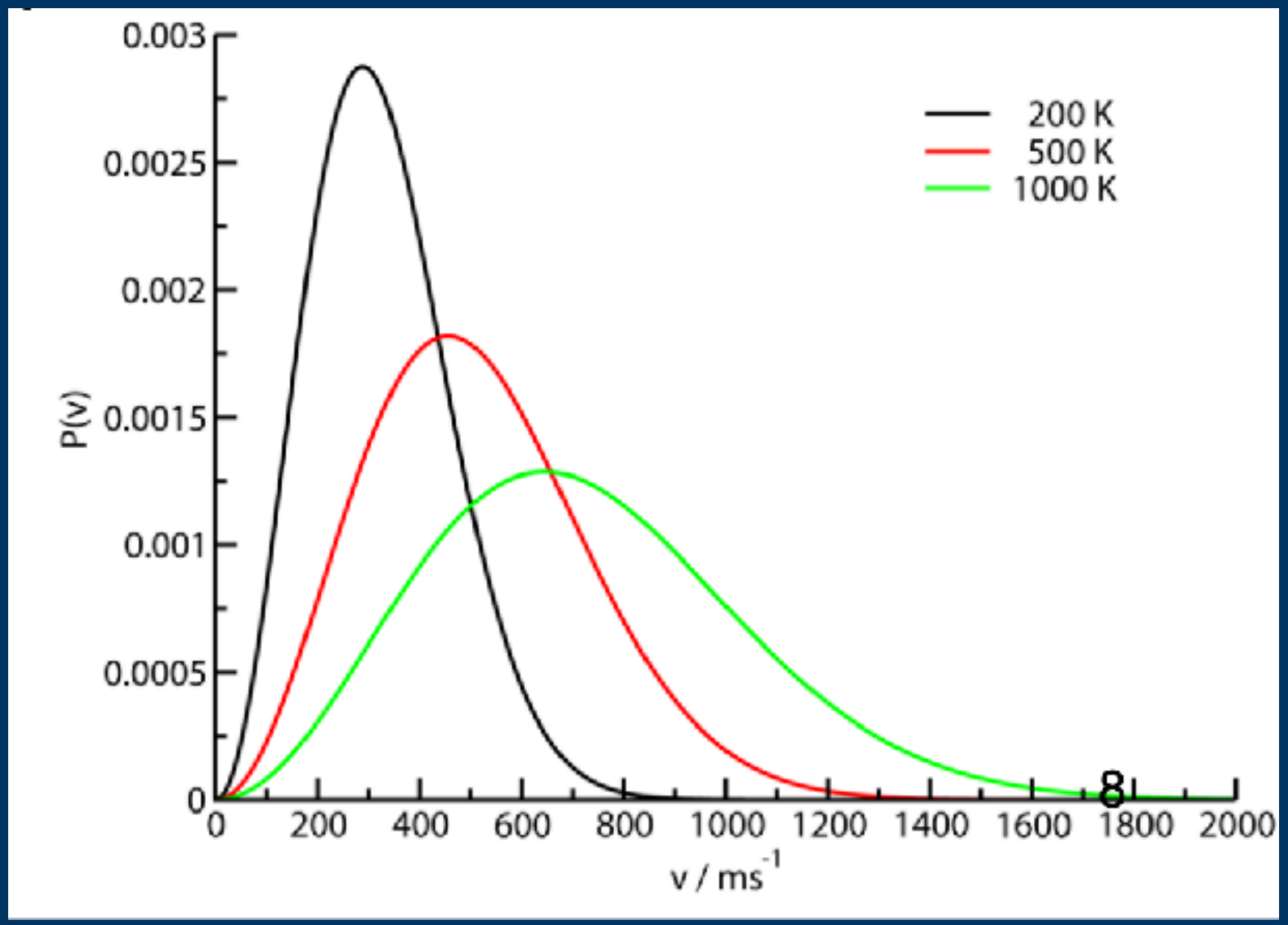
Contains molecules at different speeds

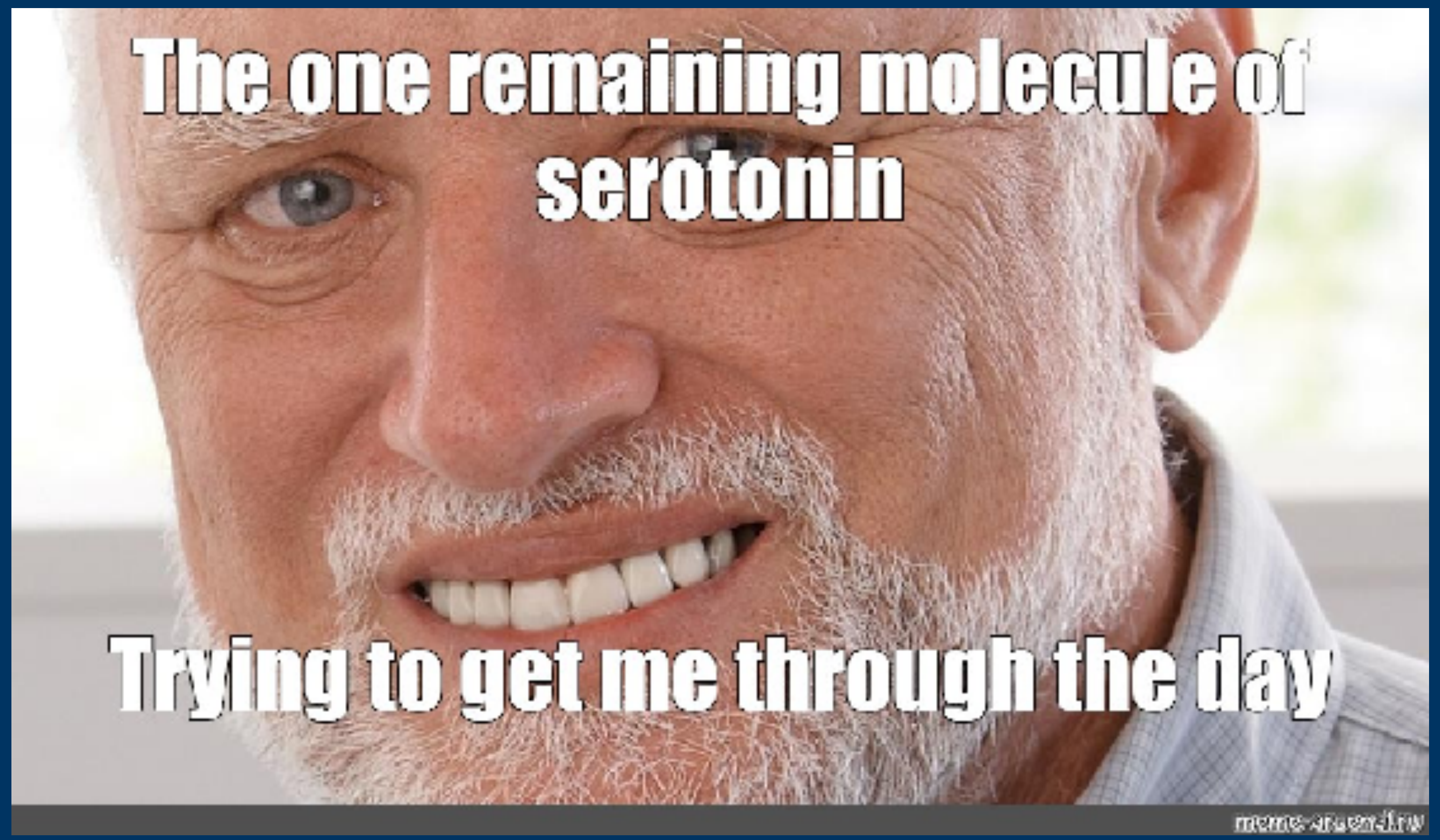
Can calculate the distribution

Does not tell you the speed of a molecule

Tells you the chance of
picking one out with a certain speed

Still arguably ‘physical’





What is probability anyway?

Examples:

Wave function

Probability of finding a particle at a certain place

Probability of the field manifesting a particle at that place

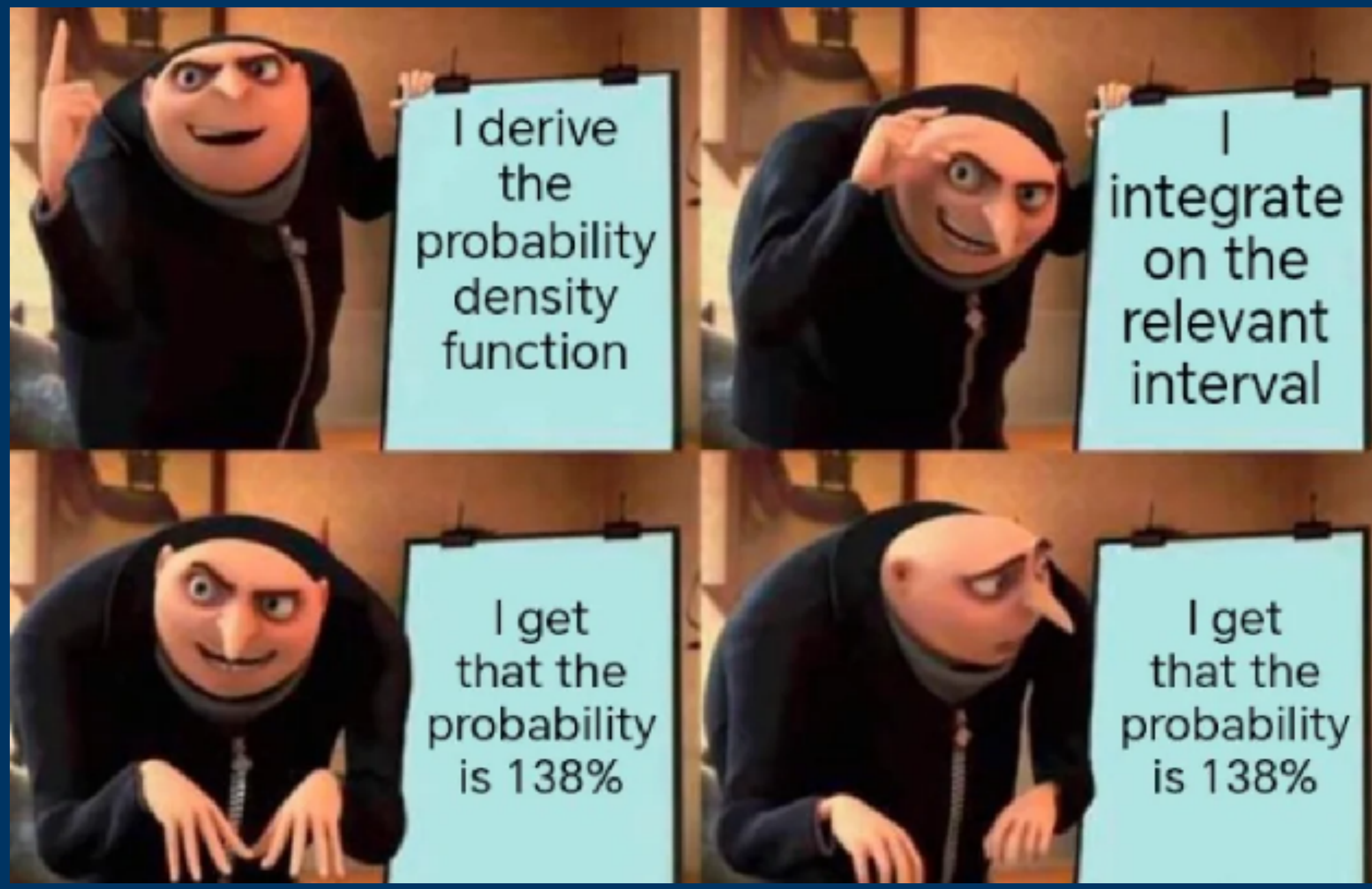
Works for a single particle…

Single particle interference

In what way is it physical???

Hidden variable distribution????

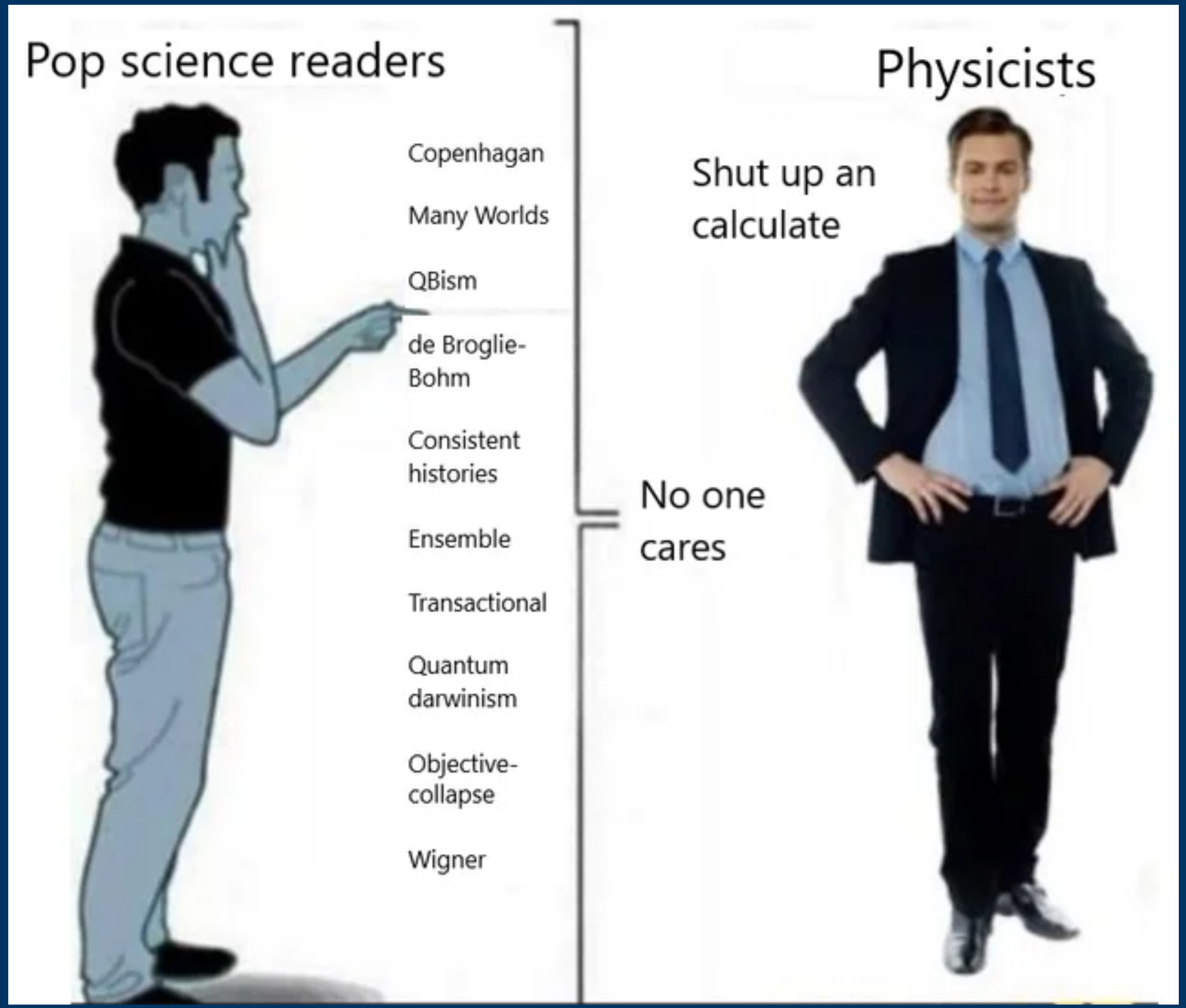
Local hidden variables ruled out



Big interpretive issue…

What is the wave function representing?

What is a quantum probability???



Heisenberg

the possibility or 'tendency' for an event to take place has a kind of reality—a certain intermediate layer of reality, halfway between the massive reality of matter and the intellectual reality of the idea or the image—this concept plays a decisive role in Aristotle's philosophy.

In modern quantum theory this concept takes on a new form; it is formulated quantitatively as probability and subjected to mathematically expressible laws of nature.

Stuart Kauffman

We thus propose a new kind of ontological duality as an alternative to the dualism of Descartes: in addition to res extensa, we suggest, with Heisenberg, what may be called res potentia. We will argue that admitting the concept of potentia into our ontology is fruitful, in that it can provide an account of the otherwise mysterious nonlocal phenomena of quantum physics and at least three other related mysteries ('wave function collapse'; loss of interference on which-way information; 'null measurement'), without requiring any change to the theory itself.

Change tack…

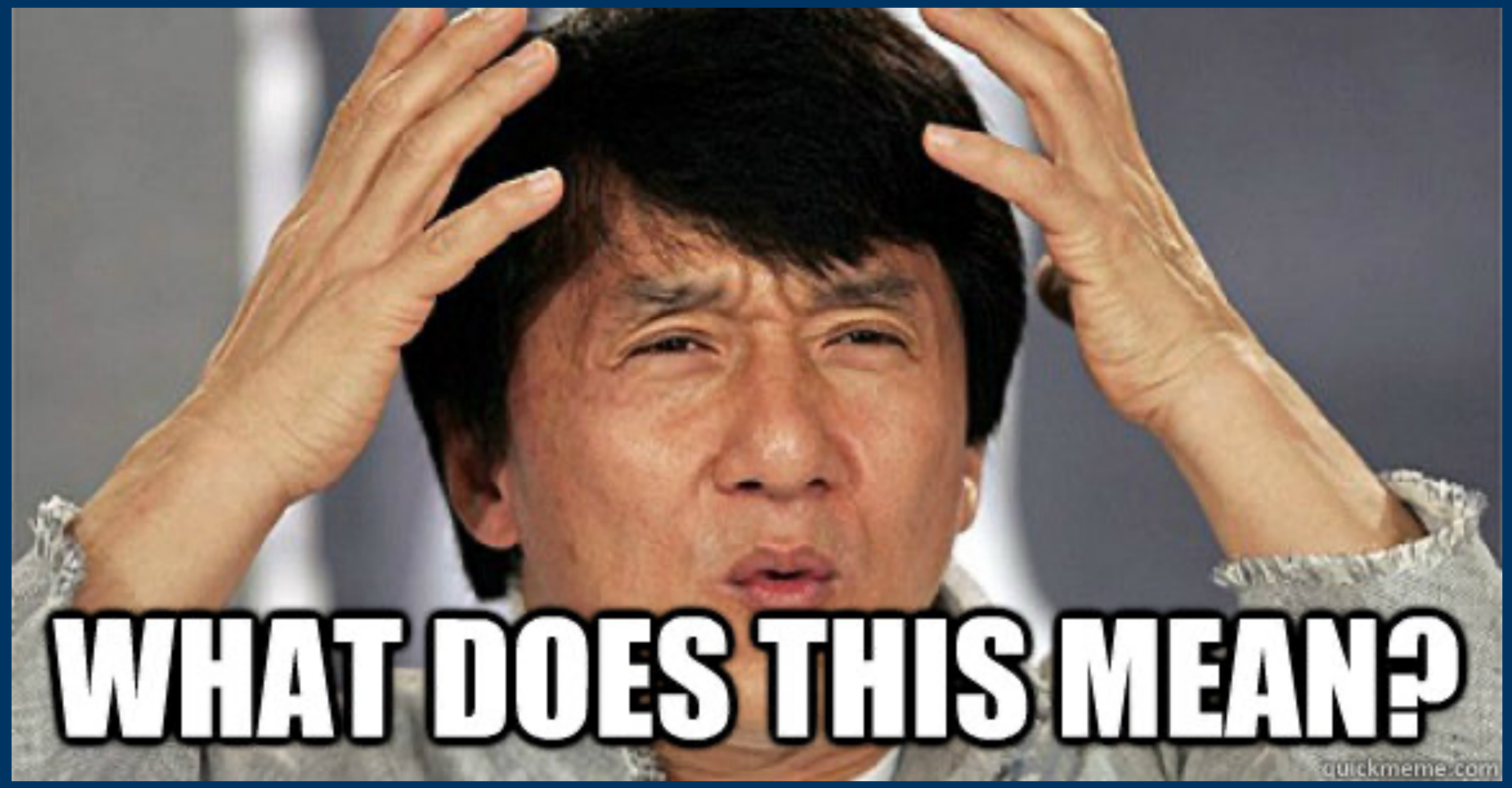
Back to Bohr

Indeed the finite interaction between object and measuring agencies conditioned by the very existence of the quantum of action entails—because of the impossibility of controlling the reaction of the object on the measuring instruments if these are to serve their purpose—the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality.

N Bohr, Can a quantum-mechanical description of physical reality be considered complete? Phys. Rev., 1935, 48

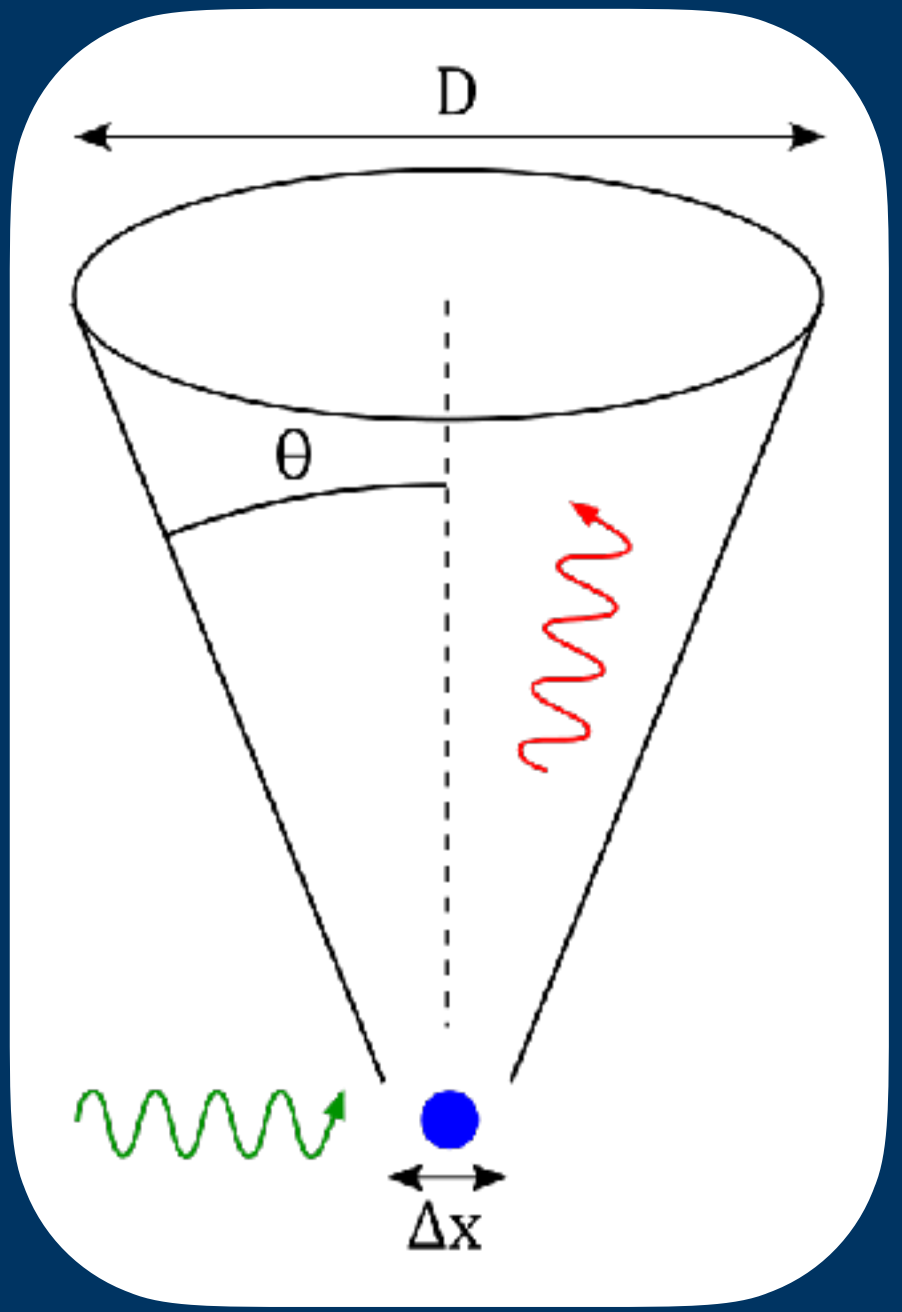
Now, the quantum postulate implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected. Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation.

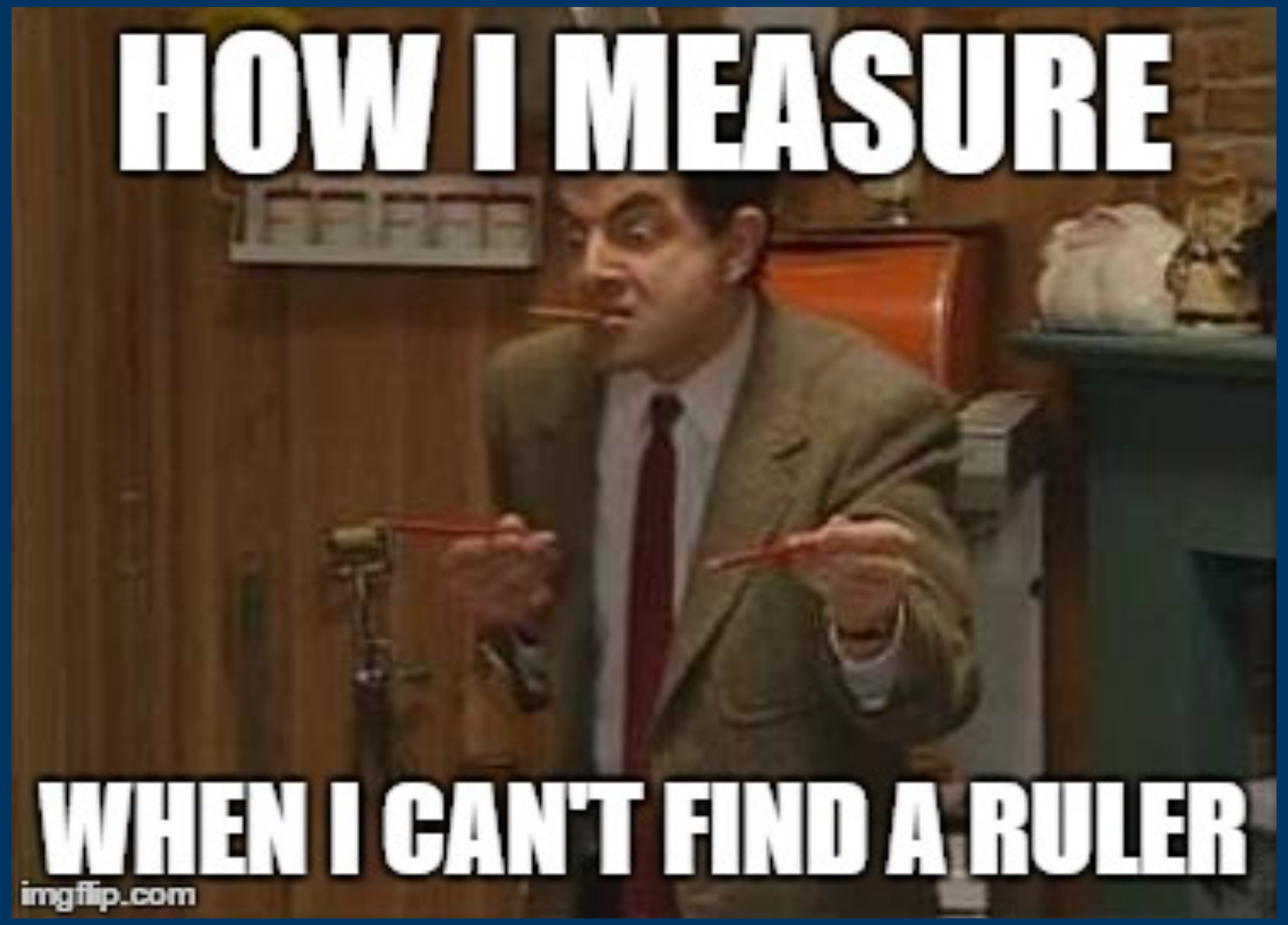
N. Bohr, Atomic Theory and the Description of Nature, Cambridge University Press, Cambridge, MA, 1934.



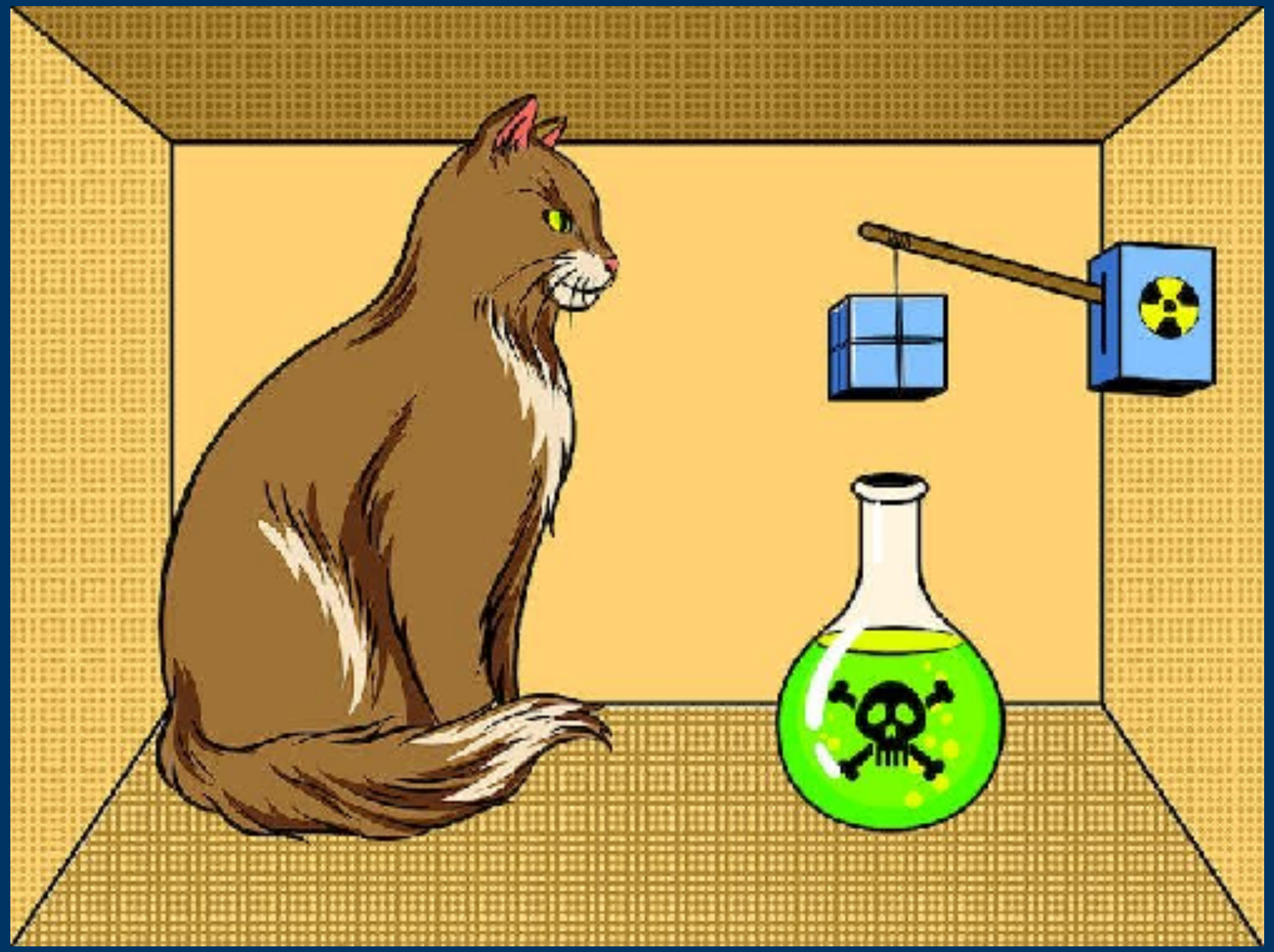
Bohr

- Every measurement
  - Involves an interaction between
    - Thing being measured
    - That doing the measurement
  - This interaction cannot be measured or controlled
    - Or we change the experiment
      - Any attempt to measure the interaction
        - Introduces a new measuring device
        - Which will interact in an uncontrollable way





Ok, lets talk about the cat…



Quantum state of the atom

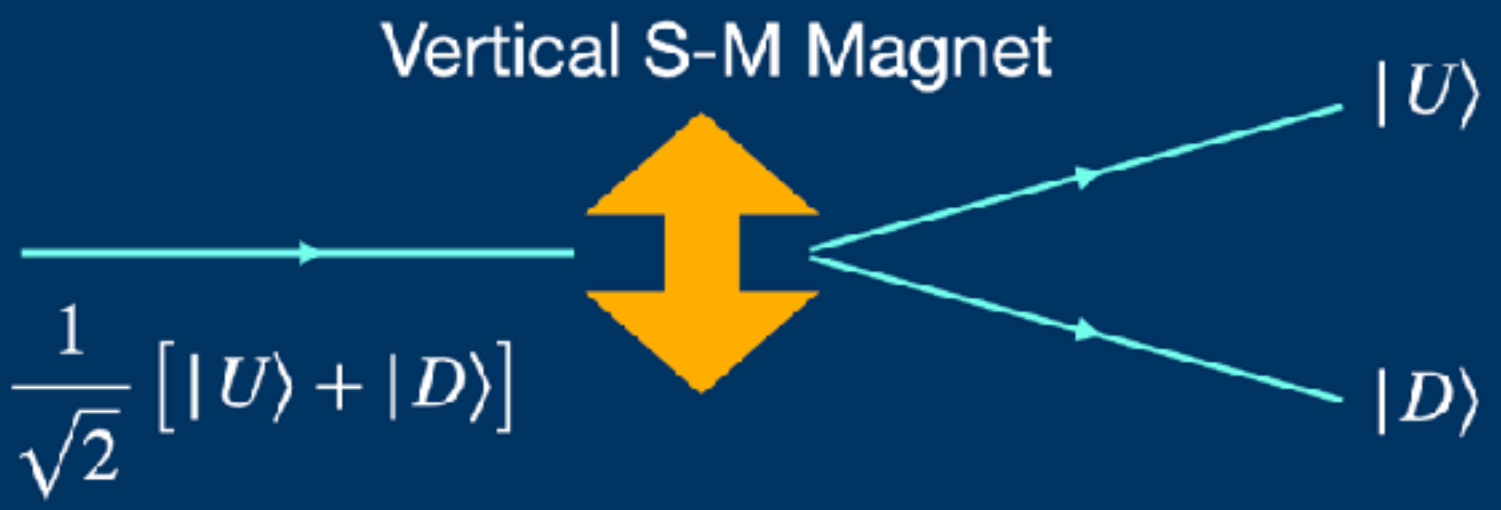
Like the paths in the interferometer

Until we measure, both at same time

Called a superposition

Atomic state a superposition of

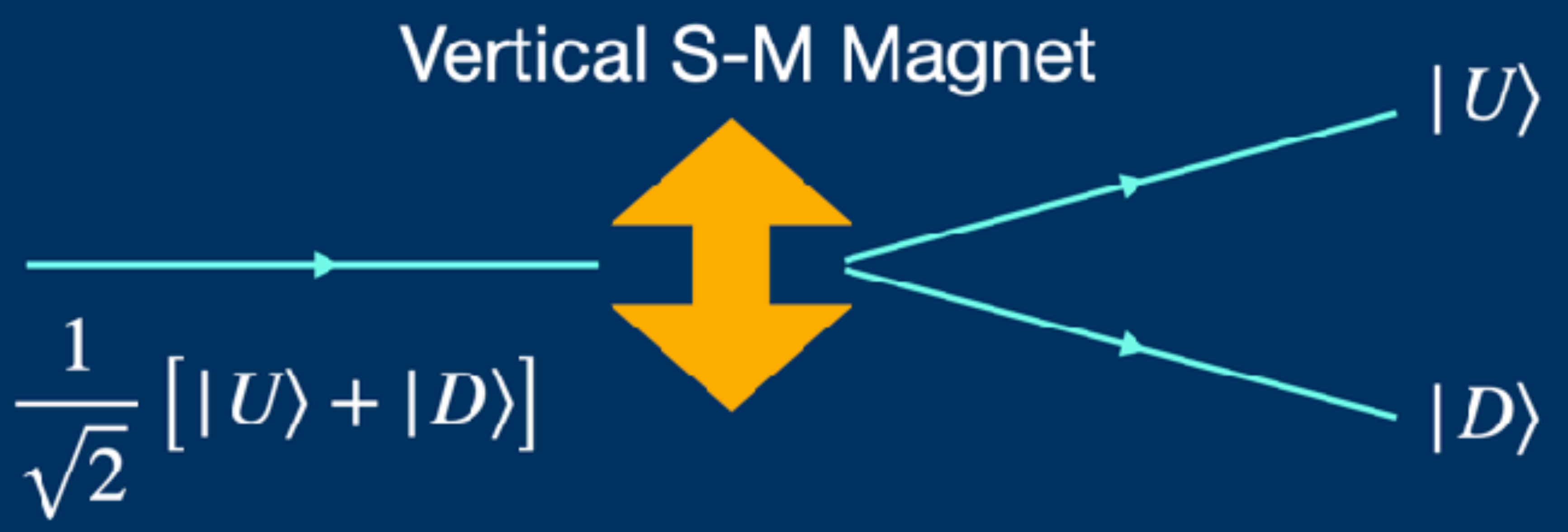
Decayed / Not decayed



Like the electron spin state…

Small aside

A superposition

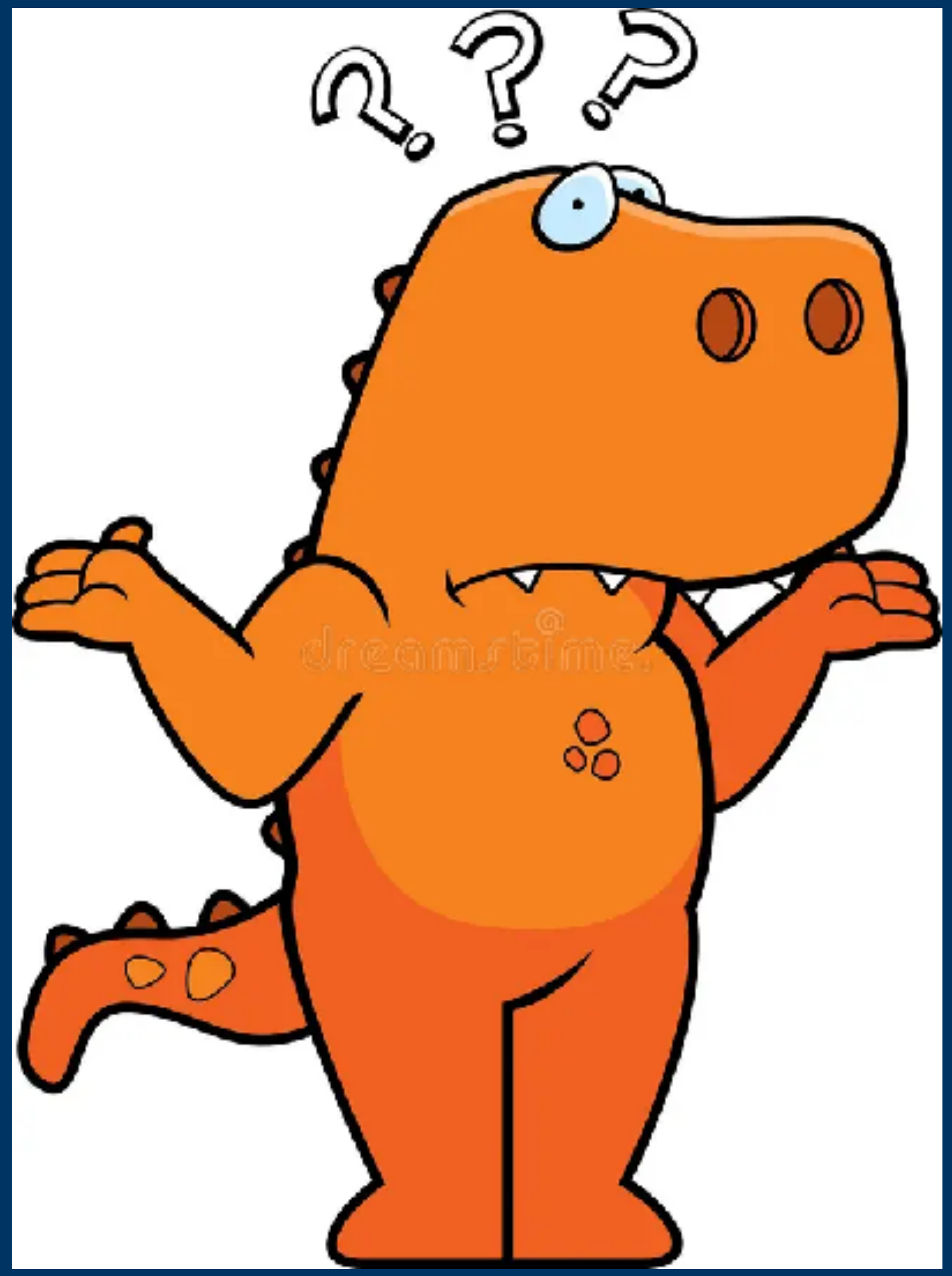


When the smoky dragon appears to be

In Several classical sates at the same time

Not possible in classical physics…

Measurement collapses it into one of the states



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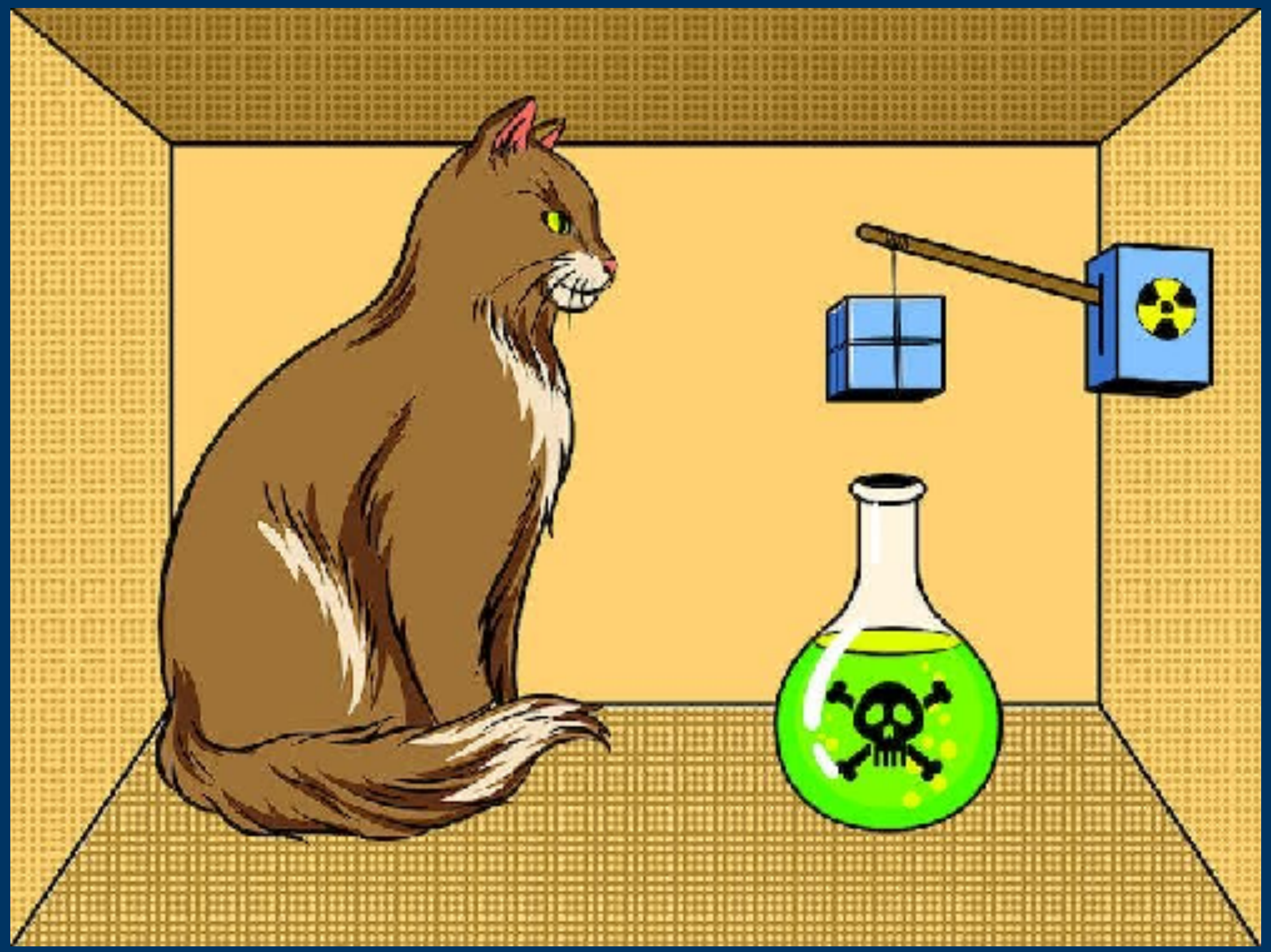


Quantum state of the poison

Like the paths in the interferometer

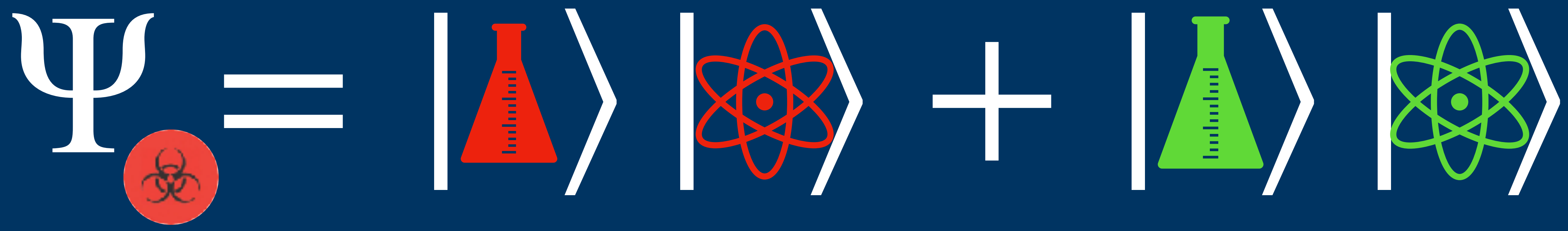
Like the electron spin state…

In superposition

As its state depends on the atom…

Entangled by the 'action' of measurement

$$\Psi = |\text{poison released}\rangle |\text{atom decayed}\rangle + |\text{poison not released}\rangle |\text{atom not decayed}\rangle$$



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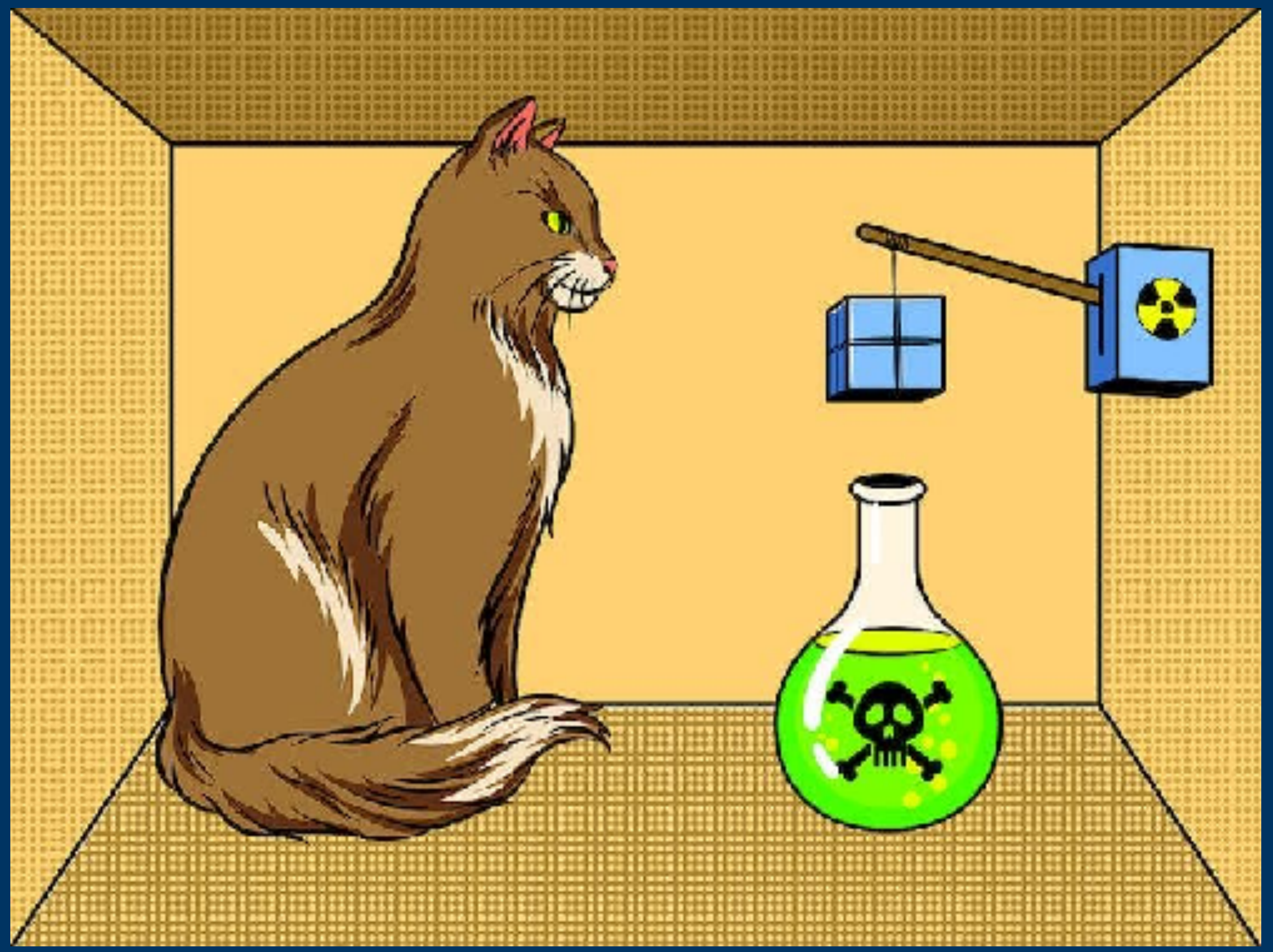


When it comes to the cat

Why would it not be described by QM?

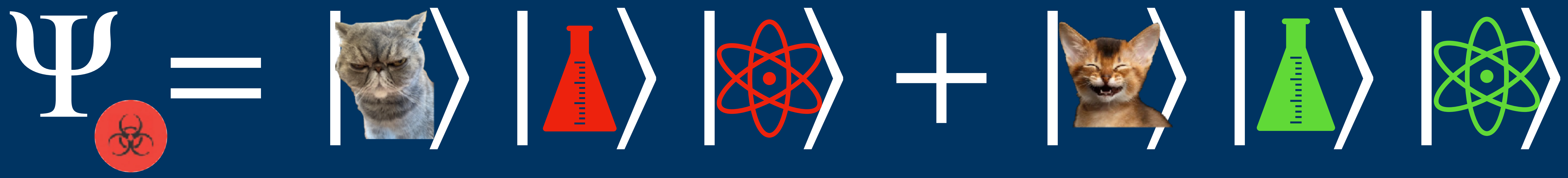
Then its state is entangled as well…

In superposition

Alive

Dead

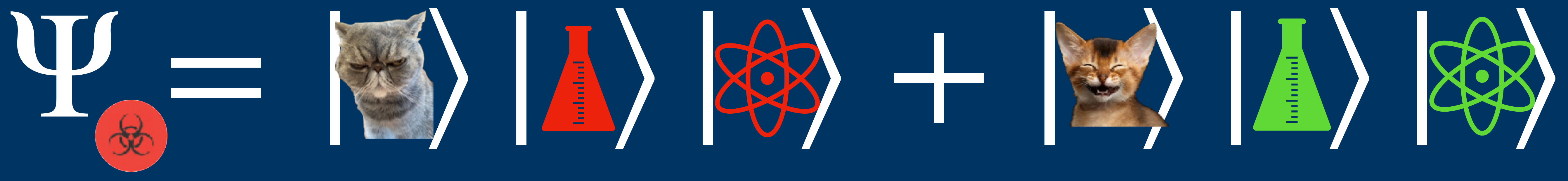
Entangled into the overall state



Schrödinger devised this fable

To demonstrate how weird QM is…

Needs someone to look inside the box…



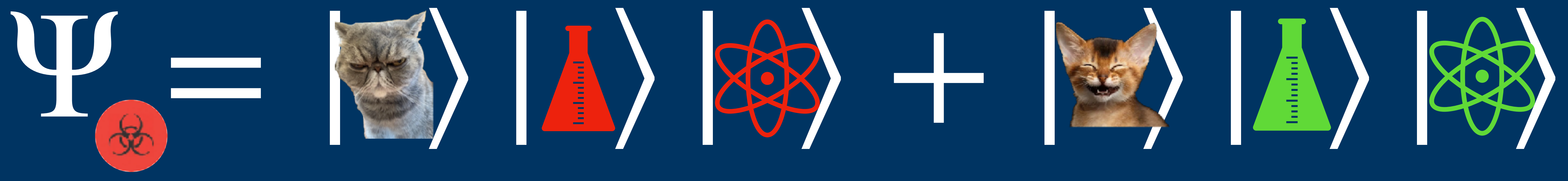
Needs someone to look inside the box…

Or how do we know???

But then according to QM…

Our observational state is entangled in as well…

When does it stop?????



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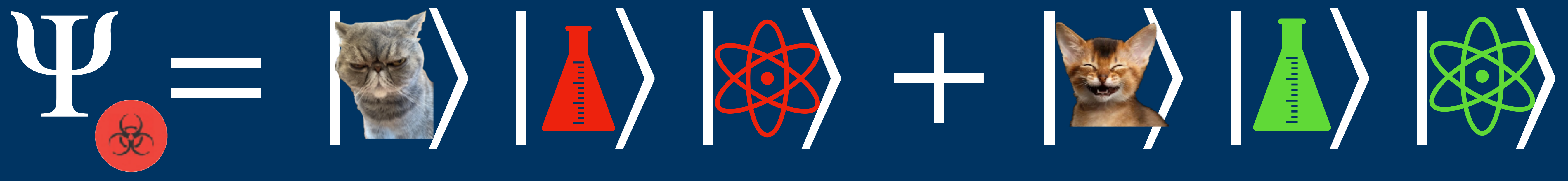


The measurement problem

Chris Isham

State Reduction

Probability

Entanglement

Measurement

What breaks the superposition?

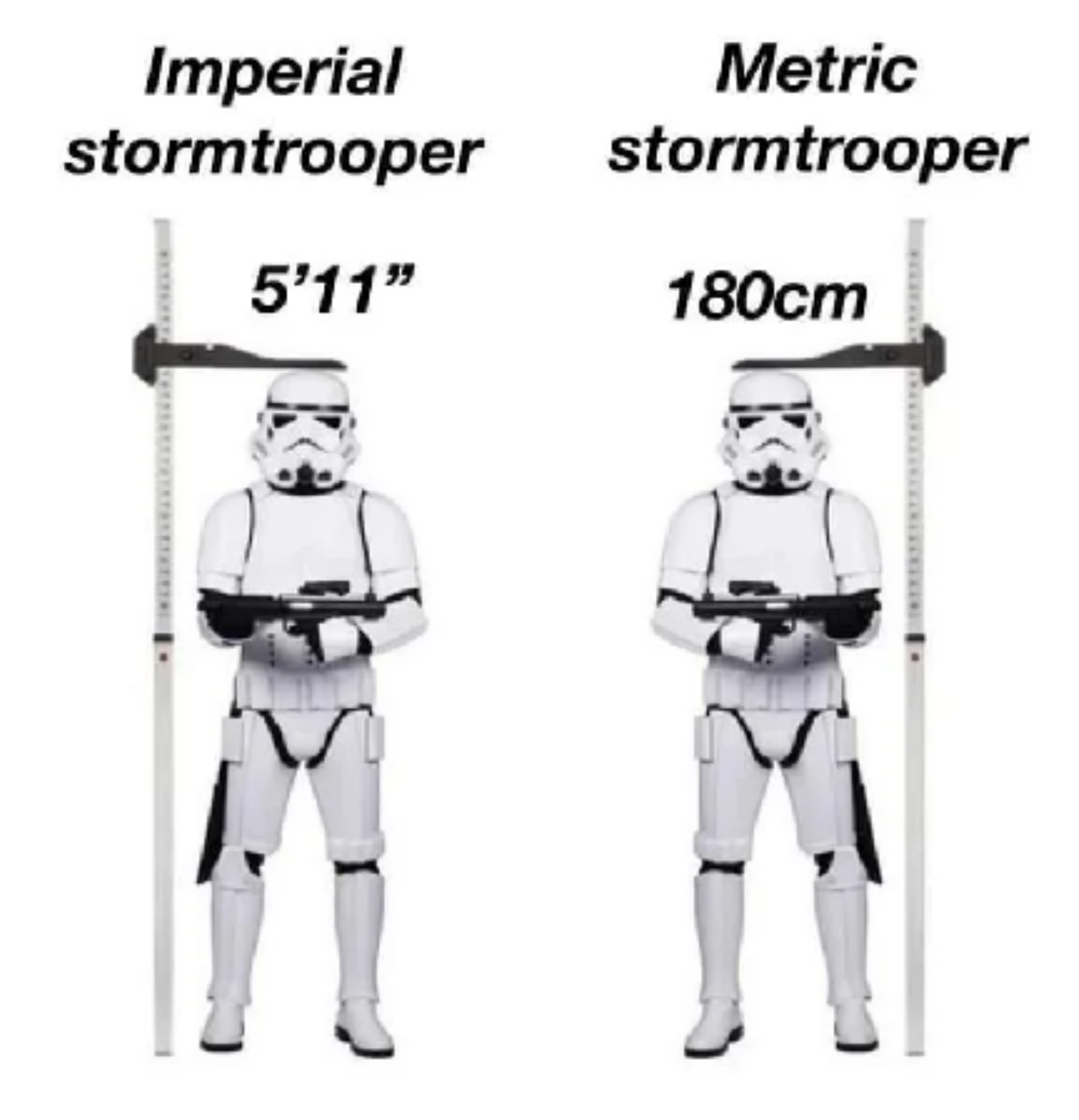
What actualises one of the options?

How do you stop entanglement spreading

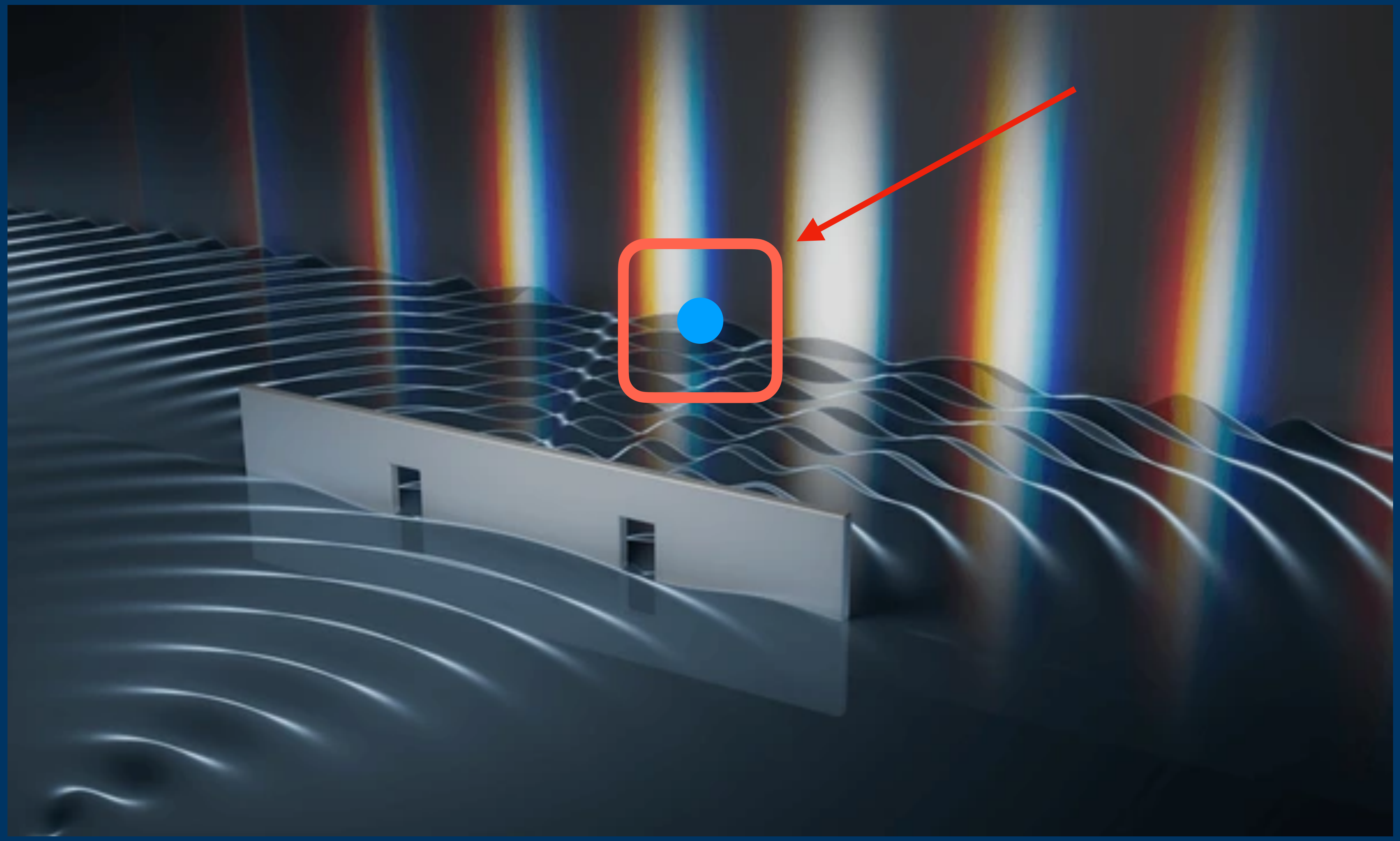
What is a quantum probability?

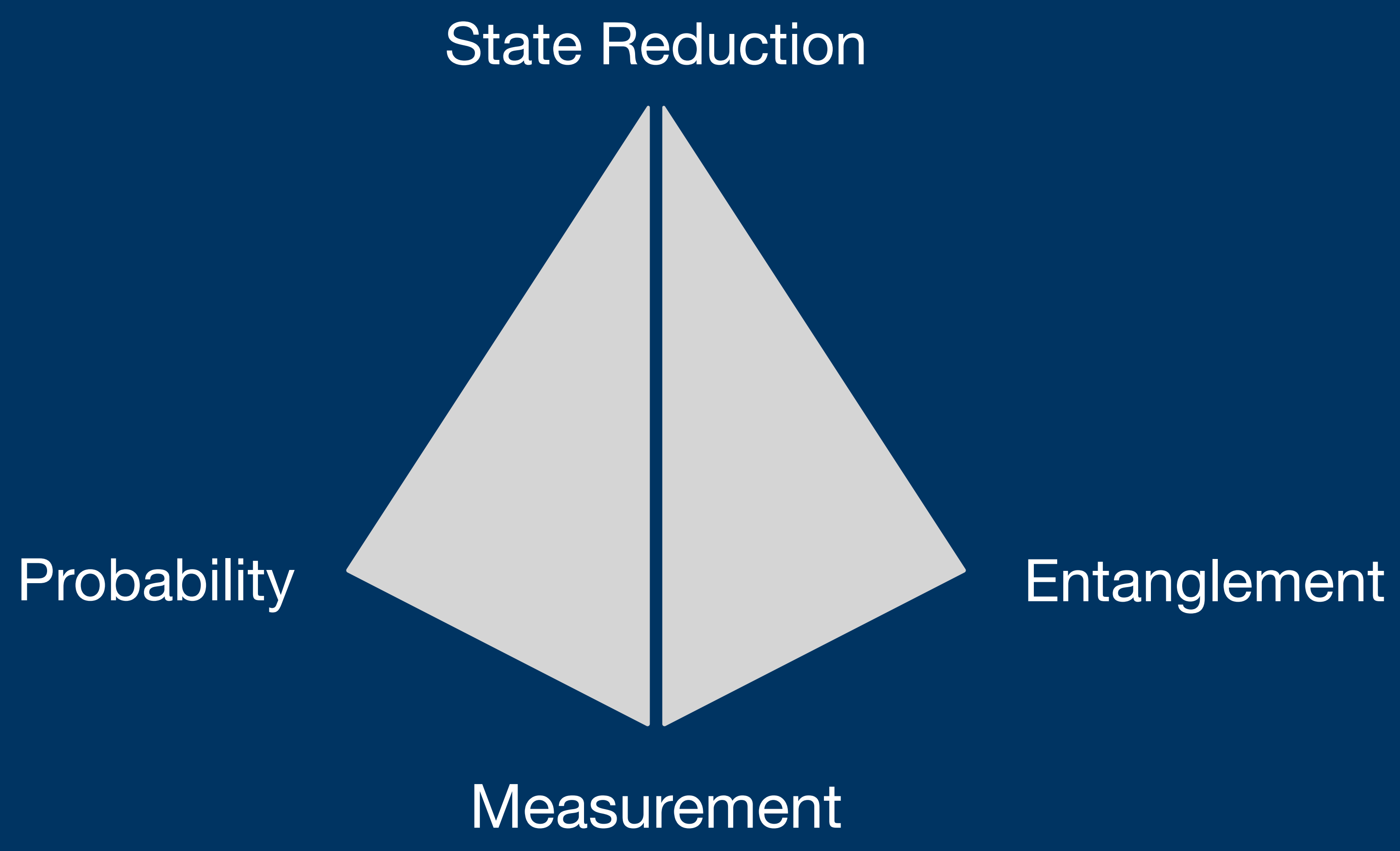
What happens in a measurement?

Why is (is it?) measurement different?



The measurement problem





State reduction

When the superposition collapses

One of the possibilities actualises

All of the others vanish…

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + V\psi$$

Not in the equations of QM…

Extra bolt-on assumption

Bohm argued that the potentialities were latent in the particle and that they could only be brought out more fully through interaction with a classical measuring apparatus.

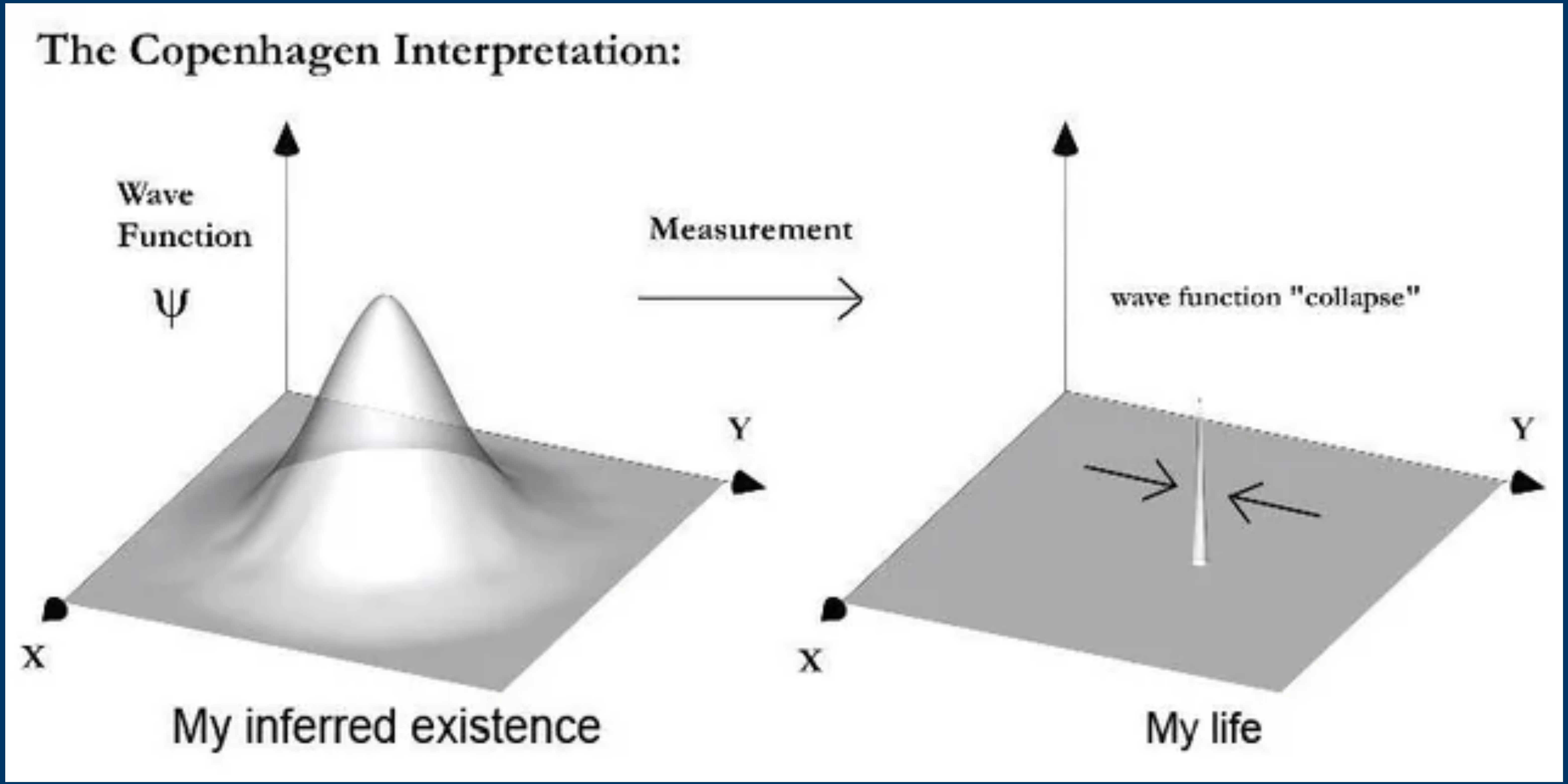
This of course is essentially the conventional view, so why did Bohm bother to make alternative proposals?

It was the complete absence of any account of the actual that troubled him.

In the quantum formalism nothing seemed to happen unless and until there was an interaction with a measuring apparatus. There was no actualisation until some form of instrument was triggered.

Surely something triggered the instrument?

Why was the measuring instrument so different? Isn't it just another collection of physical processes governed by the same laws of physics?



When my wave function collapses into my pitiful existence…