Schrödinger's Cat in the Particle Zoo

The Science of Space:

'A Physicists Guide to the Galaxy'

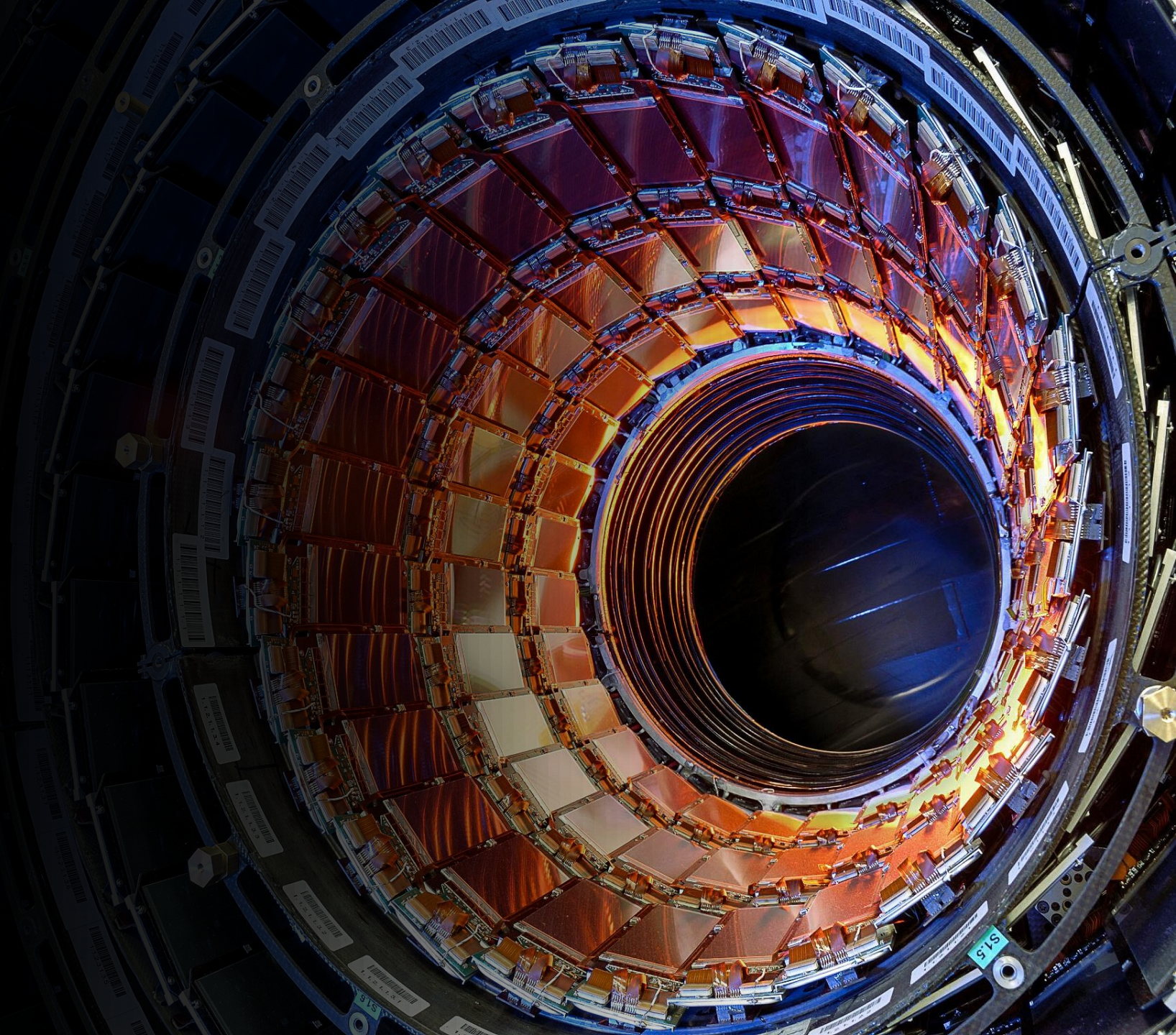
Robert Clemenson

(Sussex U & Royal Holloway UoL)

Southend Planetarium – 11.05.2025

Lecture Overview

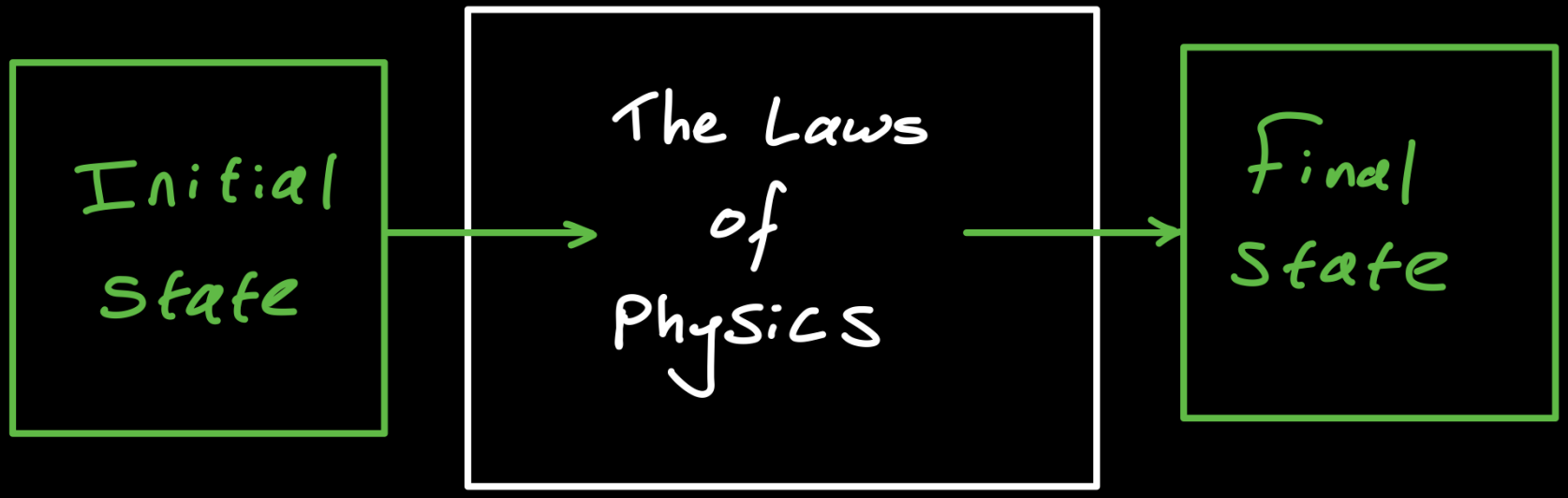
- The Death of Classical Physics
- The Birth of Quantum Mechanics
- Interpretations & the Multiverse
- The Birth of Quantum Field Theory
- The Particle Zoo
- The Standard Model
- Dark Matter
- Future Theories
- Q&A (**Questions welcome throughout the talk!**)



Classical Physics

Up until around 1926, it was believed that the laws of physics could be used in an entirely deterministic way.

This kind of physics is called Classical Physics.

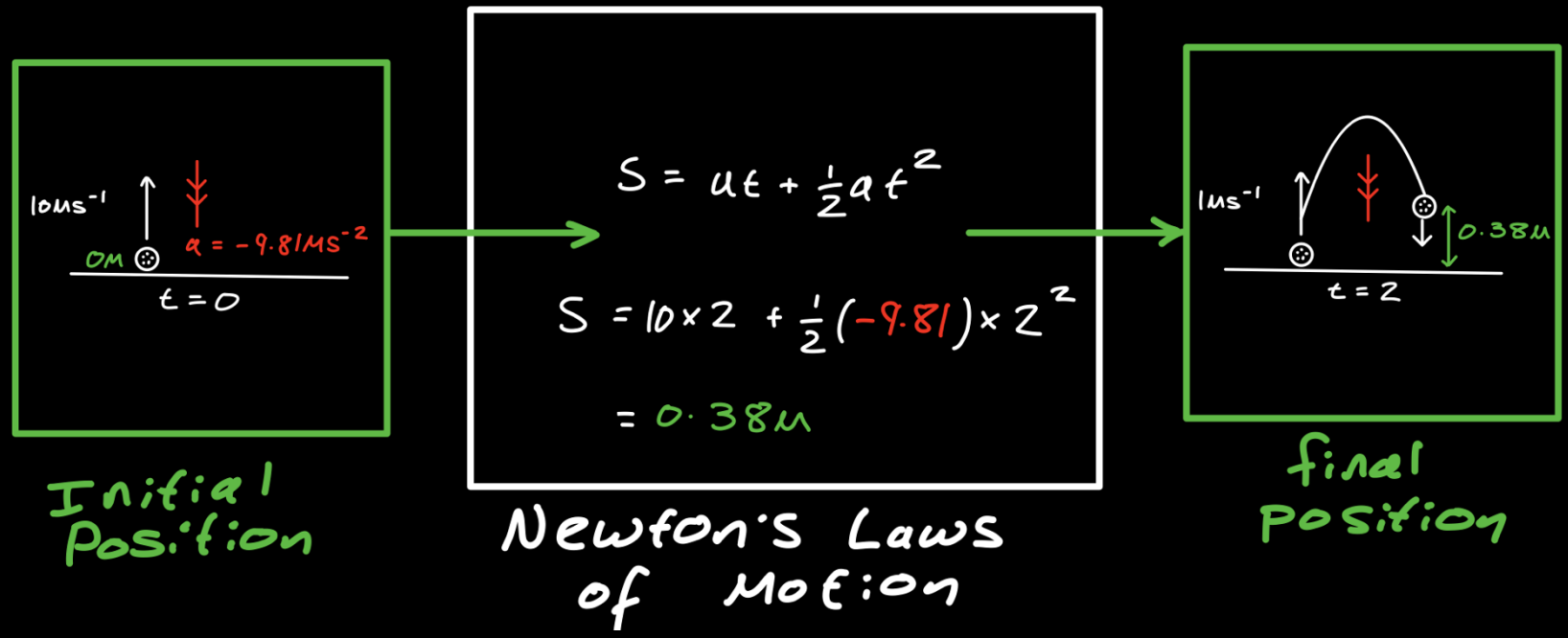


With sufficient information about the initial state of a system, sufficient knowledge of the laws of nature, and sufficient computational power (biological, or mechanical) to perform calculations: The final state of a system can always be worked out.

Classical Physics

For Example:

If we hit a golf ball vertically upwards at a certain speed, we can apply Newton's laws of motion to work out exactly where the golf ball will be and how fast it is moving some time later.



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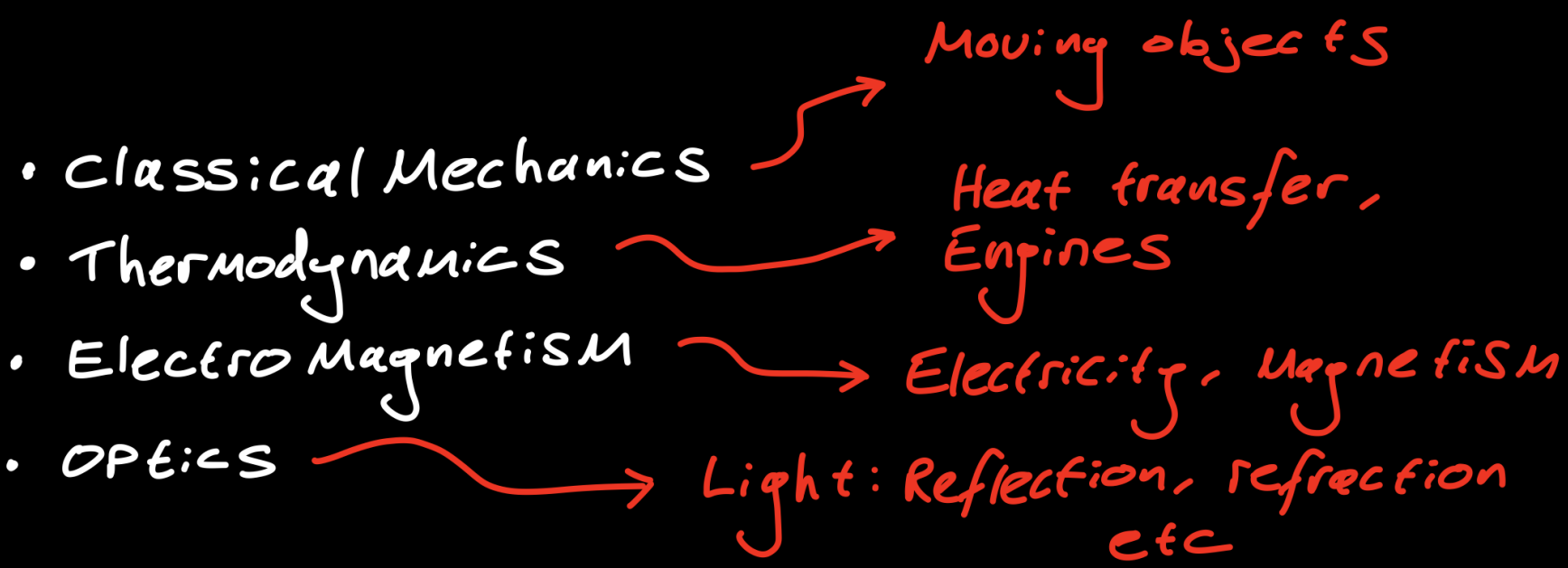
Classical Physics

Classical Physics can be broadly divided into four areas.

Classical Physics is still extremely useful today.

Classical Mechanics is what took us to the moon!



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Classical Mechanics is what took us to the moon!

Quantum Mechanics disabuses us of this notion.

With sufficient information about the initial state of a system, sufficient knowledge of the laws of nature, and sufficient computational power (biological, or mechanical) to perform calculations: The final state of a system can always be worked out.

The Ultra-Violet Catastrophe

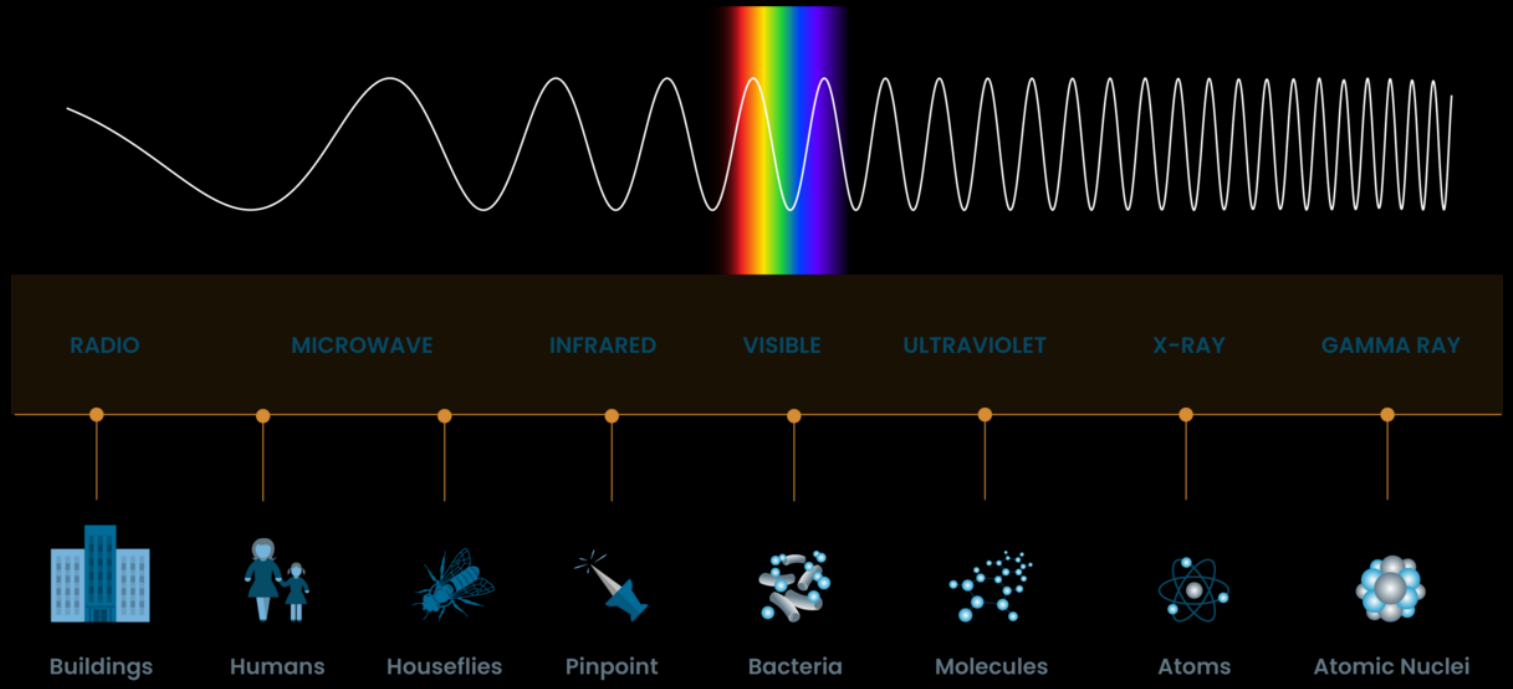
Thermal Radiation

All objects that have a temperature above absolute zero, emit thermal radiation.

This is why hot coals appear to glow orange, and how night vision cameras work (by detecting infrared light).

The thermal radiation emitted by a warm body contains a range of wavelengths of light, including other parts of the Electromagnetic Spectrum.

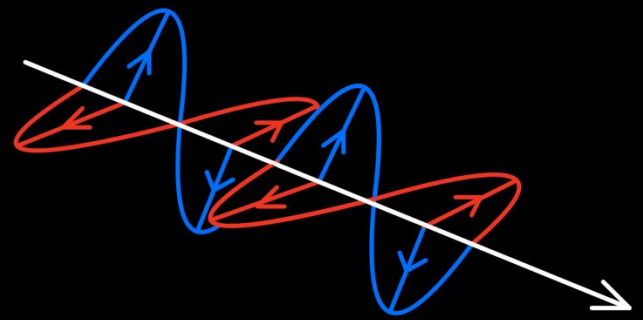
The Ultra-Violet Catastrophe



Thermal Radiation

The Electromagnetic spectrum includes the very shortest wavelengths of EM waves (gamma rays), all the way up to the very longest (radio waves).

Despite the different names, these are all the same basic phenomena, Electromagnetic Waves.



Light is an "Electro-Magnetic wave".

The Ultra-Violet Catastrophe

Thermal Radiation

The precise amount of each part of the Electromagnetic Spectrum an object emits depends on its temperature.

Hotter objects tend to appear bluer in color, as they emit more blue light (short wavelength) than red light (longer wavelength).

Objects that are not hot enough to ‘glow’ still emit thermal radiation. They just emit in the part of the EM spectrum that is outside of the sensitivity of our eyes (e.g. night vision/infrared cameras).

Compare Rigel (left), a blue supergiant star with temperature of around 12,000 Kelvin with to Betelgeuse (right) a red supergiant star with temperature of only 3,800 Kelvin.

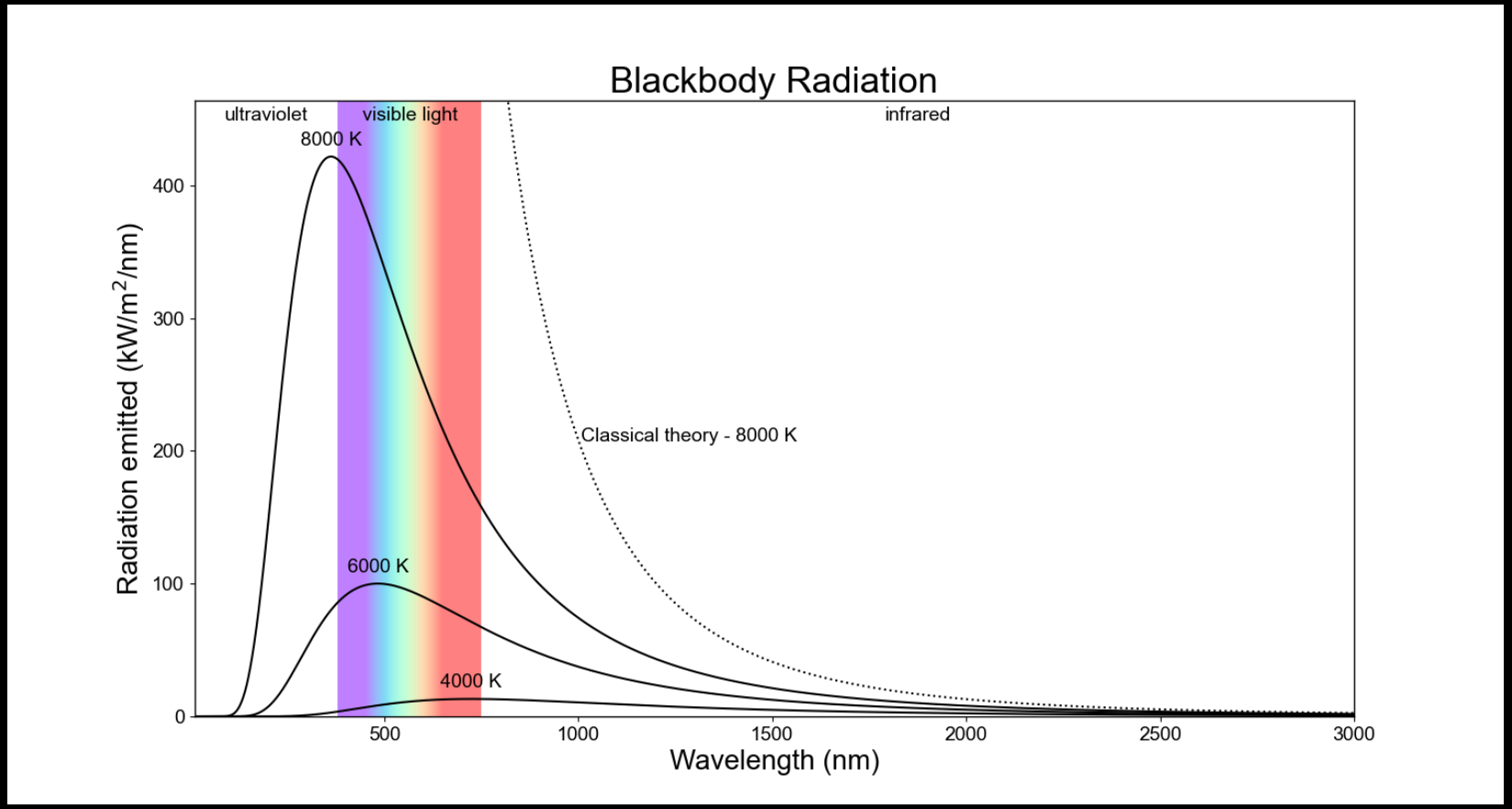
’Blue hot’ is warmer than ‘Red hot’.

The Ultra-Violet Catastrophe

In the late 1900's, physicists made observations of how much light objects with different temperatures were emitting.

When they tried to reproduce this experimental observation using the classical laws of thermodynamics known at the time, the prediction did not remotely match the observation.

This vast discrepancy is known as 'The Ultra-Violet Catastrophe'.

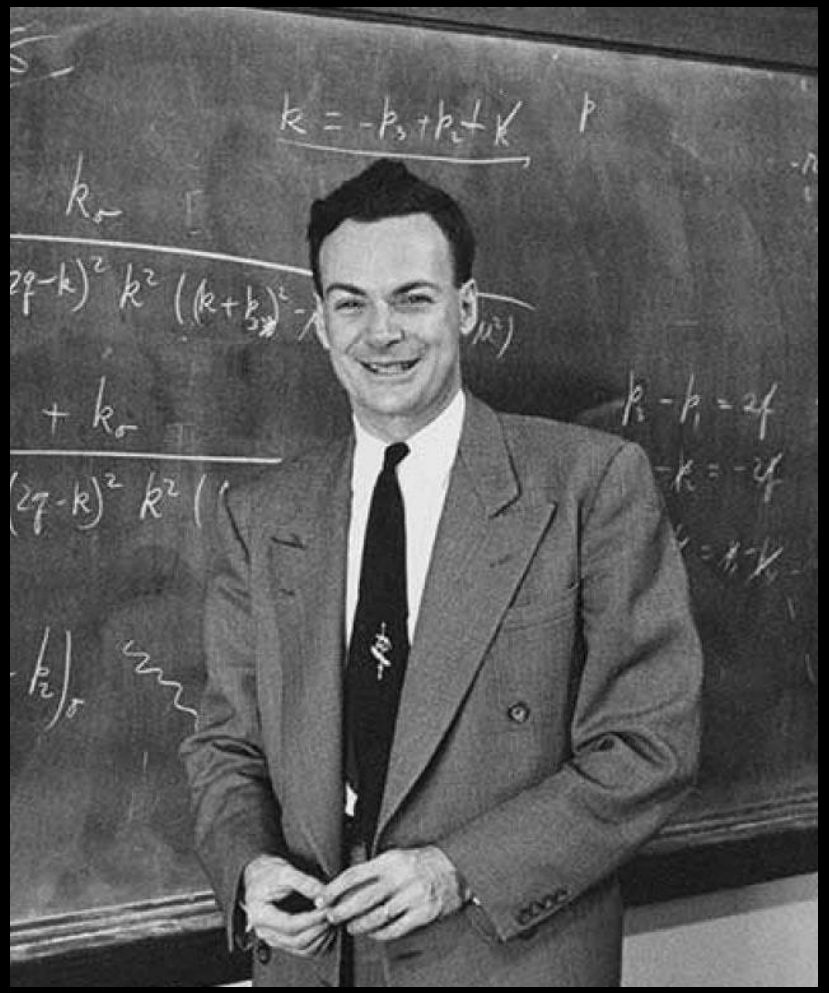


Theory vs Experiment

"In general, we look for a new law by the following process: First we guess it; then we compute the consequences of the guess to see what would be implied if this law that we guessed is right; then we compare the result of the computation to nature, with experiment or experience, compare it directly with observation, to see if it works.

*If it disagrees with experiment, it is wrong. In that simple statement is the key to science. It does not make any difference how beautiful your guess is, it does not make any difference how smart you are, who made the guess, or what his name is — **if it disagrees with experiment, it is wrong**."*

Richard Feynman



Theory vs Experiment

"If it disagrees with experiment, it is wrong." *– R.P. Feynman*

However… **Wrongness is a spectrum!**

"Absolute truth" is a challenging concept, and not one we grapple with in the sciences.

Science deals with models:

A description of a physical system that allows us to understand *some* aspects of the phenomena and make testable predictions. This does not mean that the model has to work in *all circumstances*.

Newton vs Einstein. The battle for the laws of gravity

Note: This is an AI generated image.

Theory vs Experiment

Einstein vs Newton is a good example.

Newton's theory of gravity allows us to (mostly) explain the orbits of planets in our solar system, and the dynamics of our galaxy. Newton's theory allowed us to get to the moon.

Einstein's theory of gravity (General Relativity) predicts the existence of black holes, and solves subtle problems related to the orbit of the planets that Newton's theory cannot explain.

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Newton's theory works for (relatively) small masses. Einstein's theory picks up where Newton's left off, and tells us more about larger masses and subtle (harder to observe) effects.

Theory vs Experiment

Even **Einstein's theory of gravity** (General Relativity) is not the final picture!

As we will see later today, it has flaws, and there are limits to what it can describe (i.e. the singularity of a black hole!).

Eventually, Einstein's theory of gravity will need to be replaced with a **Quantum Theory of Gravity**.

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With insufficient theory to explain experimental observations, a **new theory is needed**.

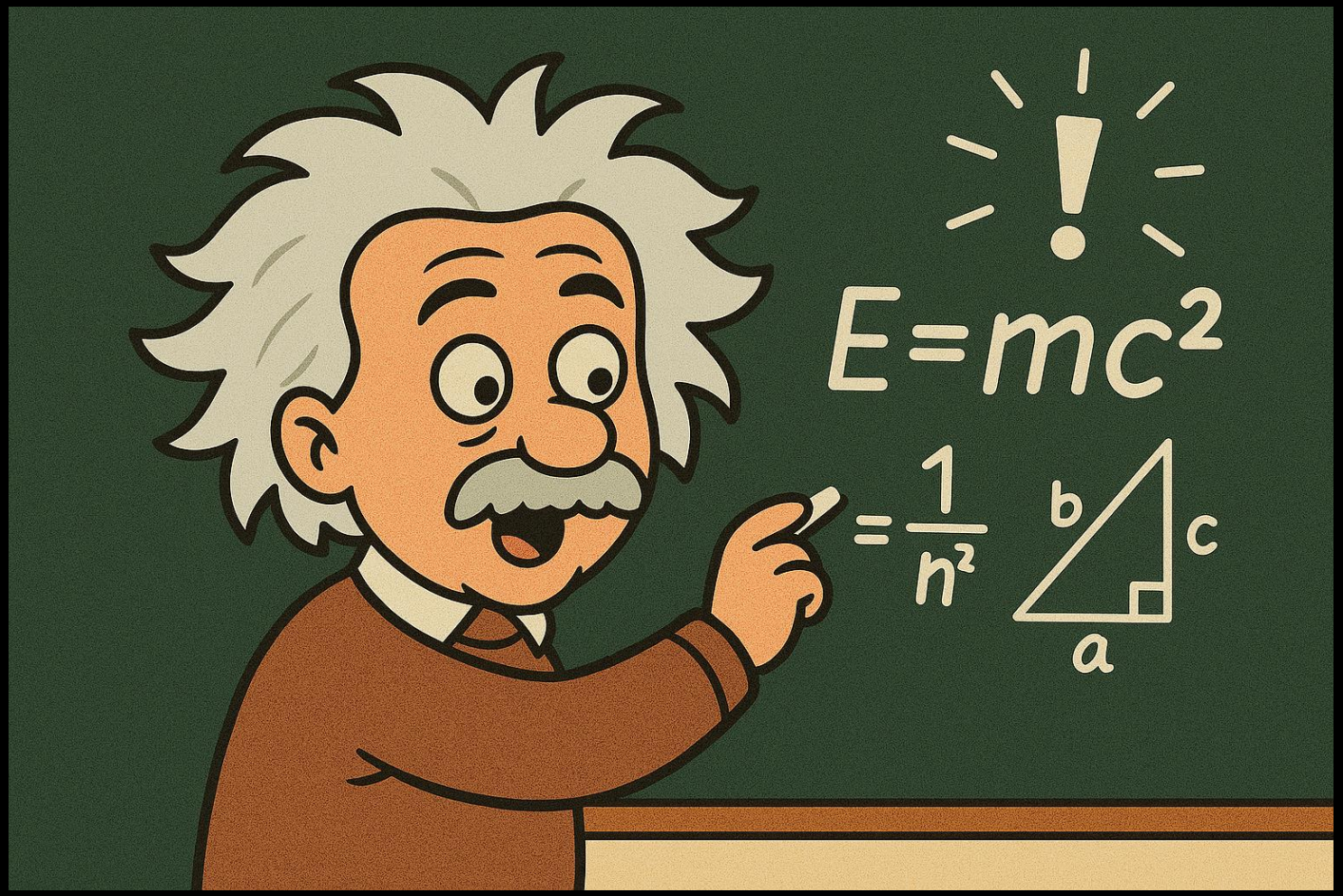
The Ultra-Violet Catastrophe

‘*Theory*’ has a much stronger meaning in science than in our everyday parlance.

A scientific theory has some strong justification, be that:

1. Experimental proof, validating the theory until contrary evidence is found.

2. ‘Theoretical evidence’ that the theory fits into the framework of existing knowledge.



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A Scientific Theory is not ‘just a guess’.

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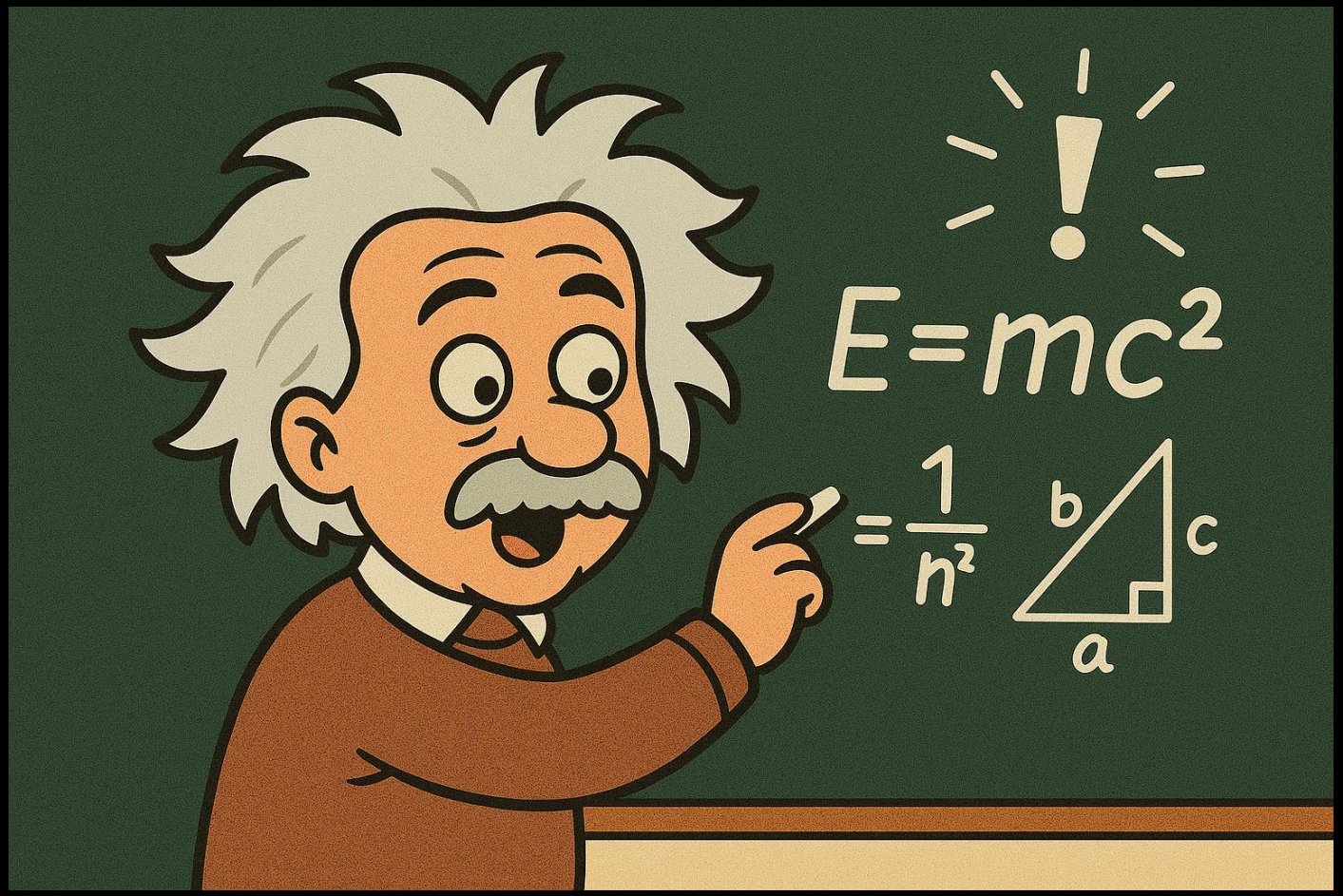

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A Scientific Theory is not 'just a guess'.

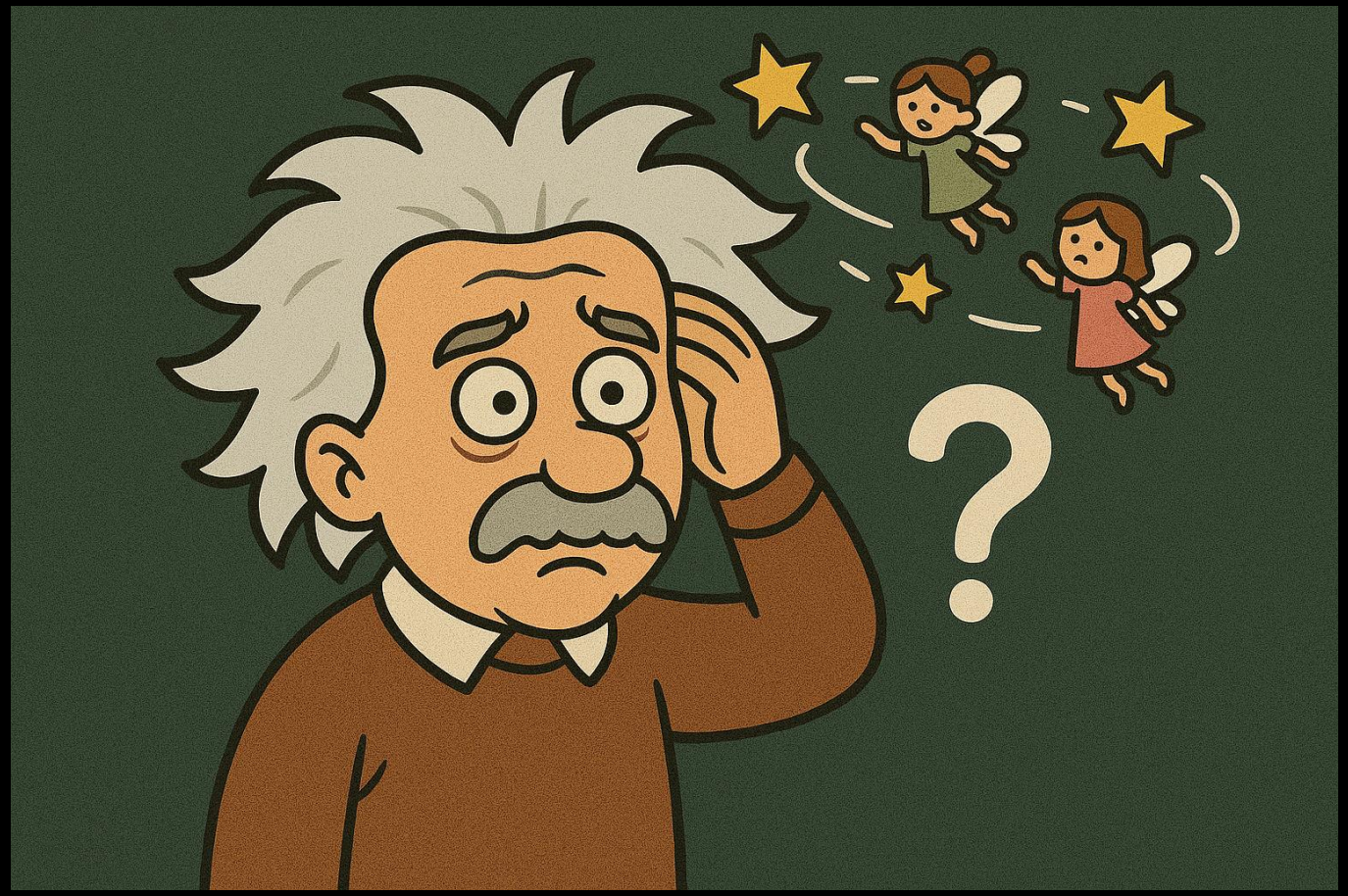
However.....

The Ultra-Violet Catastrophe

The origins of Quantum Mechanics bend the notion of '*not a guess*' to near breaking point...

But keep in mind: The wishy-washy birth of Quantum Mechanics has been complemented by **the most** intense and consistent experimental verification of *any* theory in physics.

Every time you have an MRI, use a laser, or charge anything via a solar panel – you are using something that could not have been invented without Quantum Mechanics.



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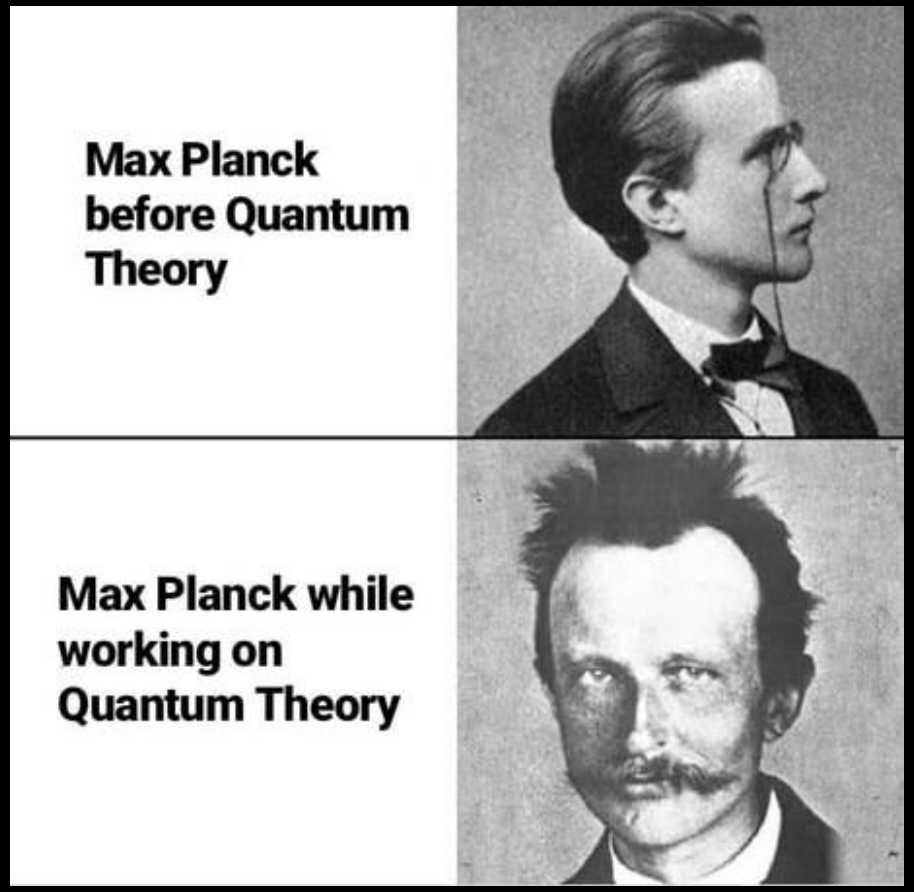
The strangest thing about Quantum Mechanics, is that it ***really is*** the way the world works.

Planck and Quanta

The solution to the UV Catastrophe comes to us from Max Planck.

In 1900, he proposed that the energy of a light ray (any any ray in the EM spectrum) is *Quantized*.

This mathematical trick was not obviously motivated… but, allowed Planck to near perfectly match his theoretical prediction, to the experimental reality.



Quantum Mechanics: Just say NO.

Quantized = Comes in a discrete packet, which cannot be divided or shared.

E.g. McDonalds Chicken Nuggets come in packets of 4, 6, 9, 20. No single intermediate values are possible.

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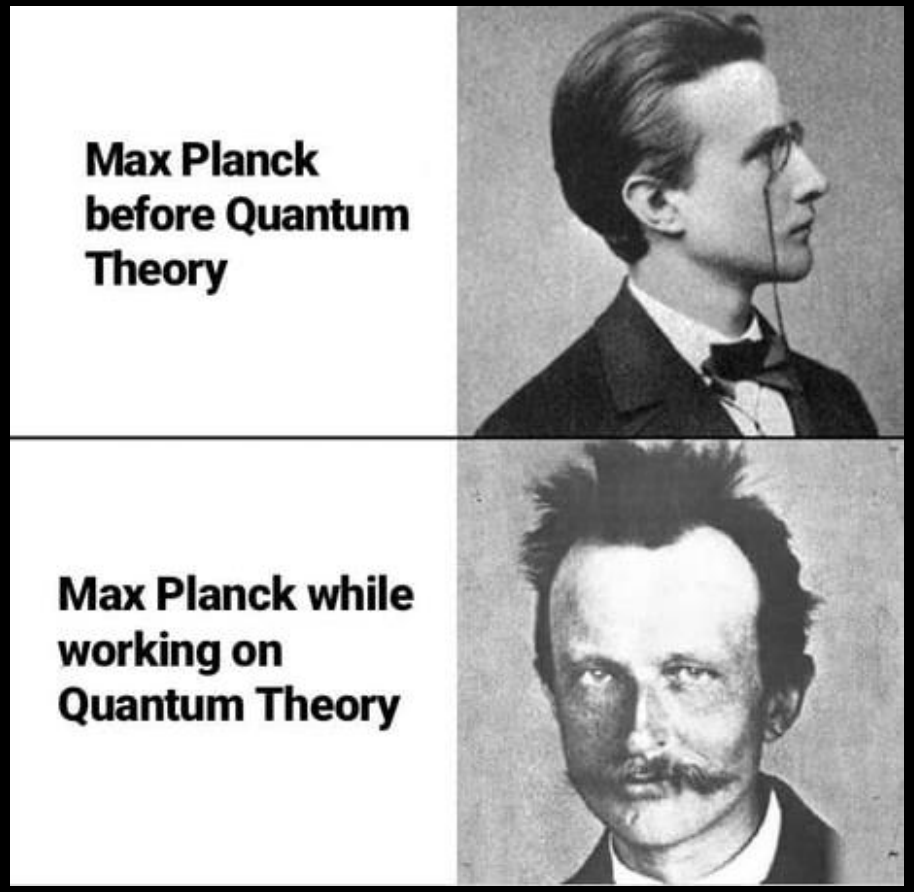
Wow!!



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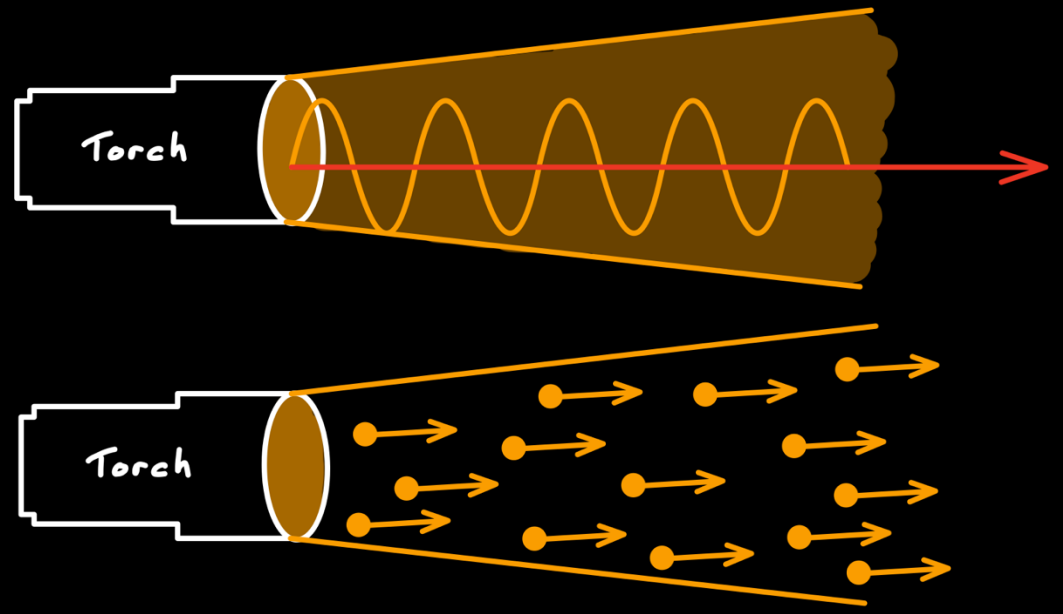
Einstein and Photons

Five years later, in 1905, Einstein fleshes out Planck's mathematical fudging.

Einstein interprets these discrete packets (quanta) of electromagnetic energy a kind of particle, the photon.

He then uses this insight, that light may behave as a particle (rather than a wave) to understand a phenomena call 'the photoelectric effect' - winning him the 1921 Nobel Prize.



Light can be understood as a stream of photons.

But wait…. If Einstein tells us that light is made out of particles (photons), why am I still calling light an Electromagnetic wave?

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It’s BOTH!

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It’s BOTH!

and NEITHER!….

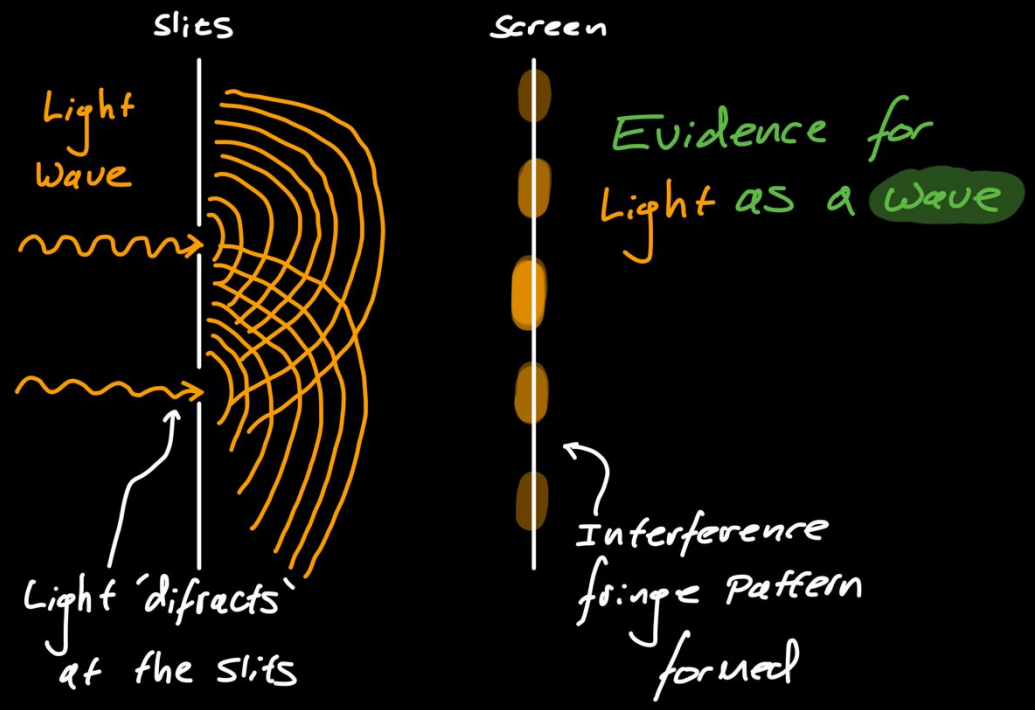
The Wave-Particle Duality

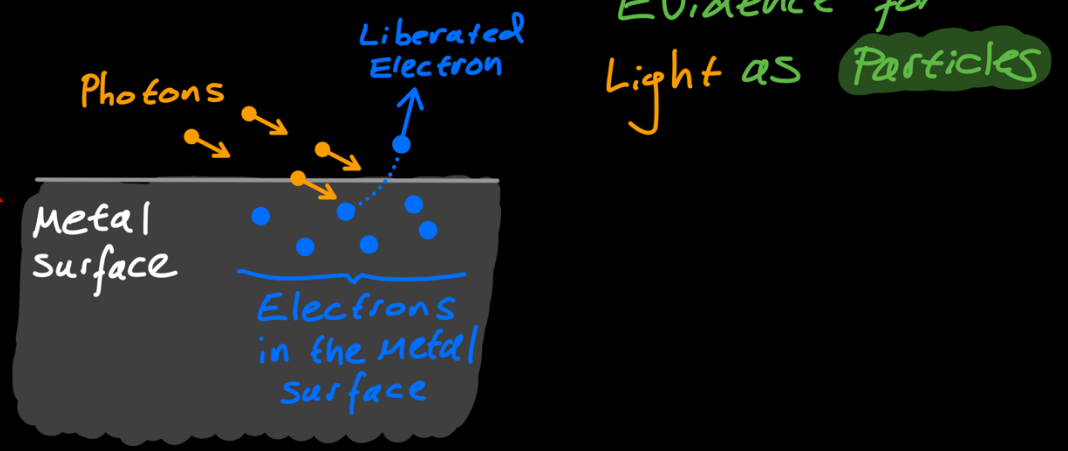
In some experiments, light acts more like a wave, and in other it acts more like a particle.

Young's Double Slit Experiment

The Photoelectric Effect Experiment

How can it be both?





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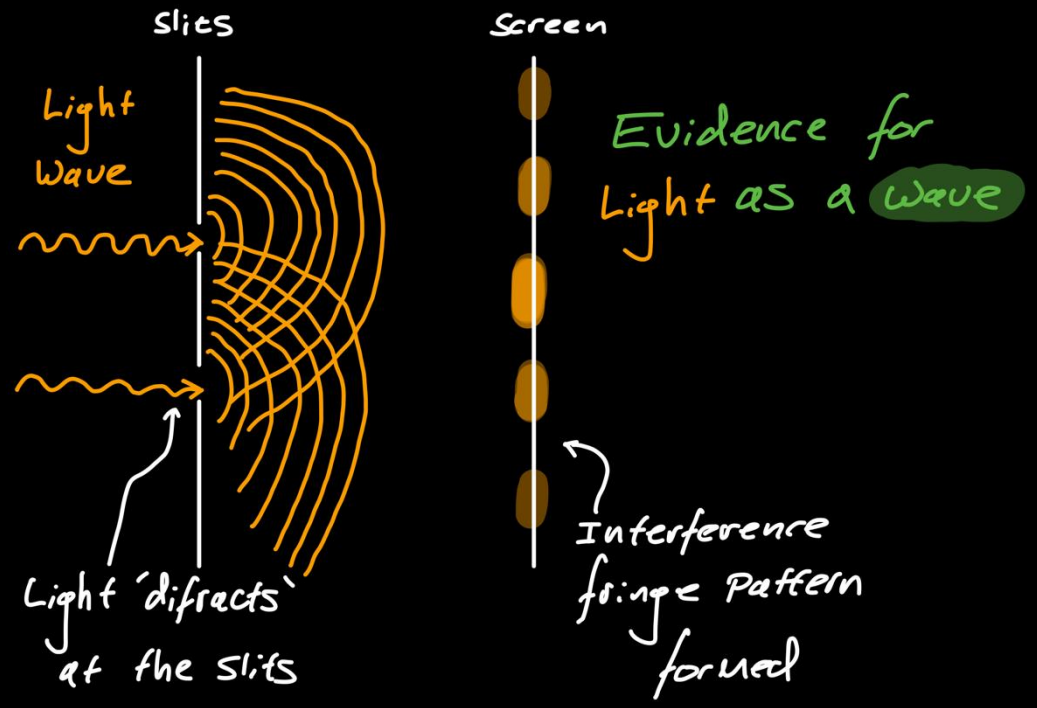
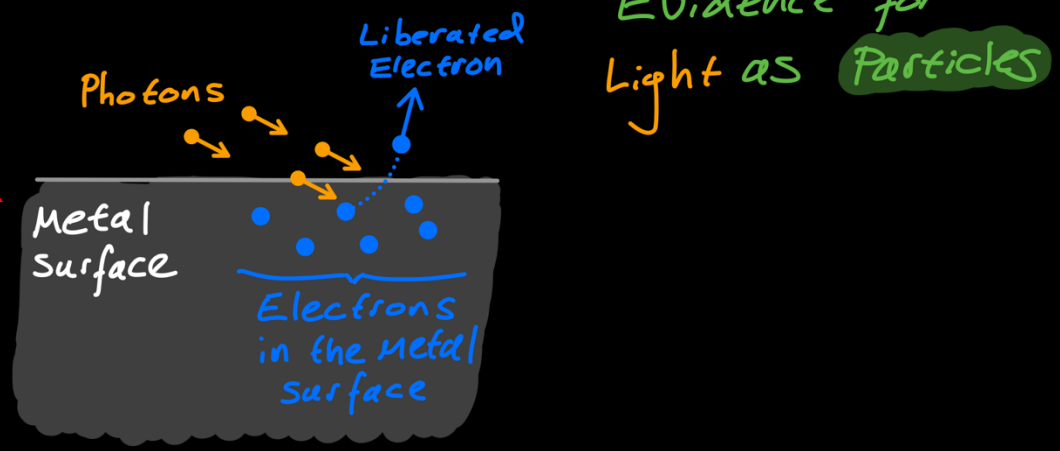
Clearly there is something strange going on.





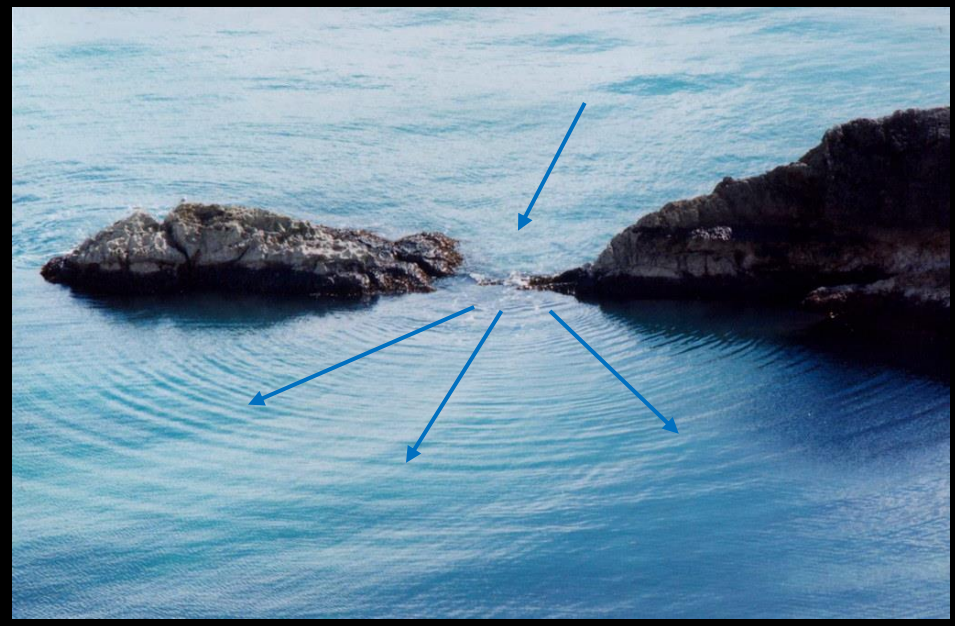
Matter Waves

It gets worse…

Light isn't the only thing to exhibit this indecisiveness.

ALL MATTER, exhibits wave-like properties!

Let's take one distinctly wave-like property as an example. Diffraction.

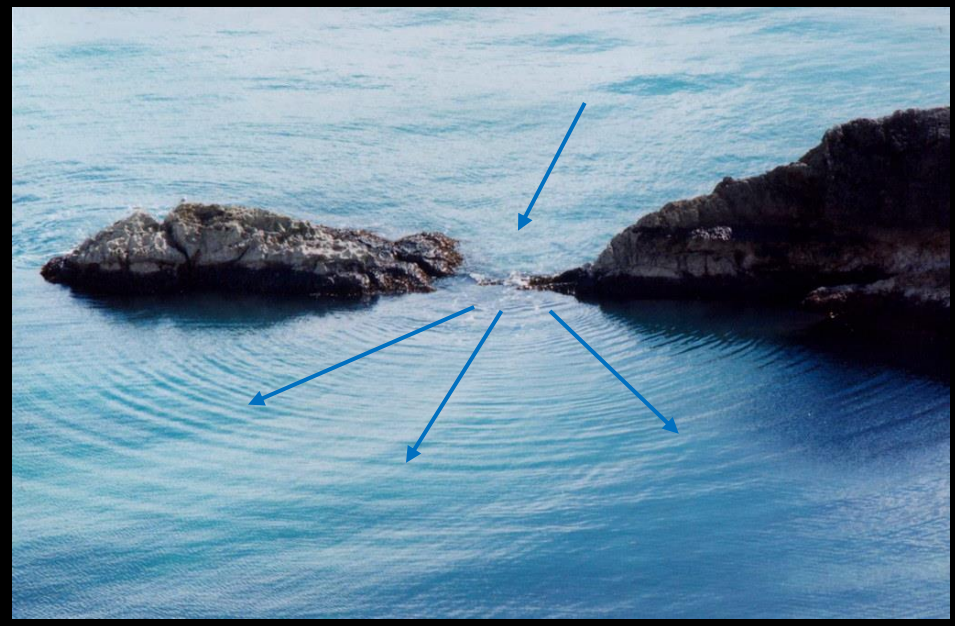


Ocean waves diffracting through a gap between two rocks.

Diffraction is the property waves exhibit, whereby they will spread out upon passing through a gap similar in size to their wavelength.

Matter Waves

Given that ***I*** am made of matter, and hence (according to Quantum Theory) exhibit wave like properties, why do I not diffract when I pass through a doorway?



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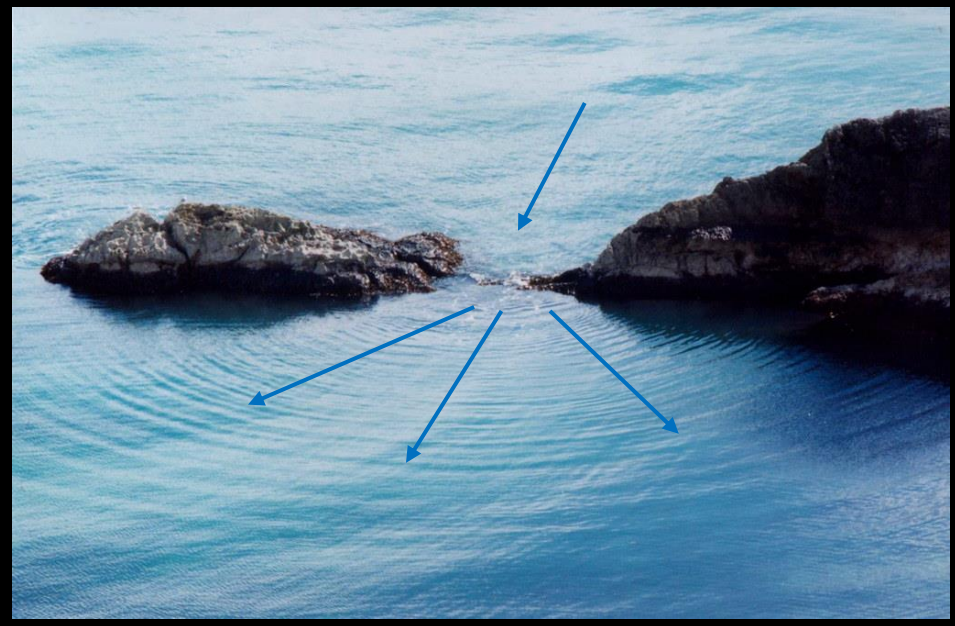
The key is in this line.

What is the wavelength of my matter wave? How does it compare to the size of a doorway?



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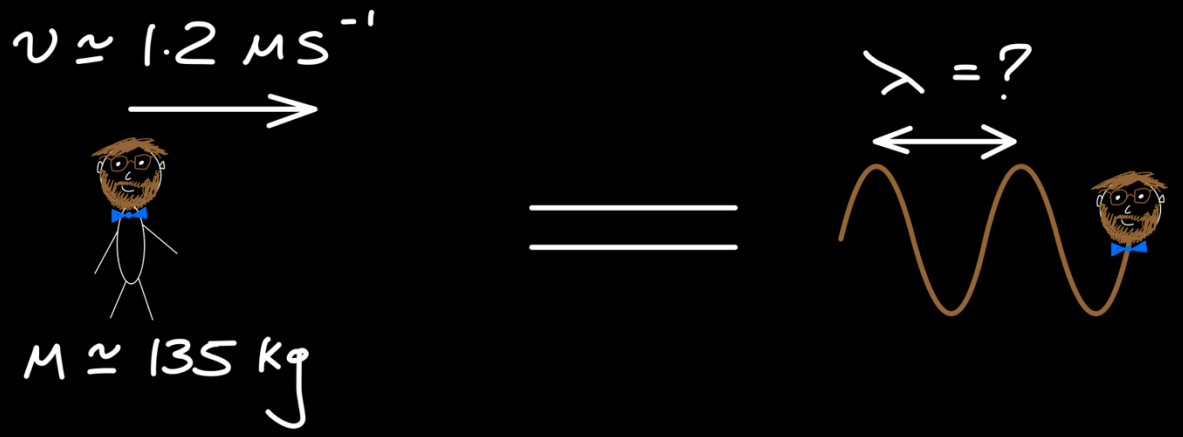

The formula for calculating the wavelength of a matter-wave comes to us from Louis de Broglie in 1924.

Planck's constant $= 6.63 \times 10^{-34}\ Js$

$$\lambda = \frac{h}{MV} = \frac{6.63 \times 10^{-34}}{135 \times 1.2} \simeq 4 \times 10^{-36}\ m$$

or...

0.000000000000000000000000000000000004 m

Applying this to myself, moving at average walking speed: The Wavelength of my matter-wave is extremely tiny.

Far FAR smaller than the width of any door. Hence, matter does not display wavelike properties on our length scale.

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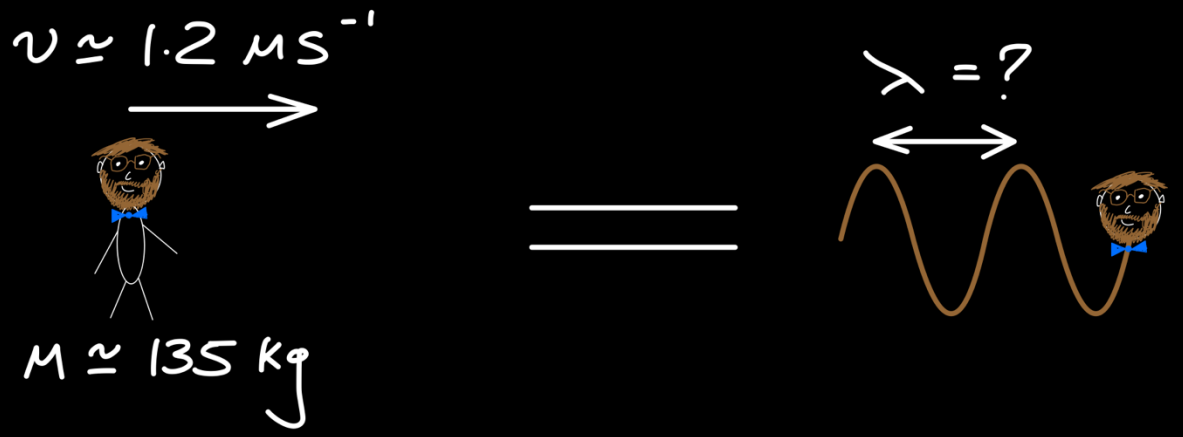
Matter Waves



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But it does, on the subatomic scale!

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The Laws of Quantum Mechanics

In 1926, Erwin Schrödinger provides us with one of the fist concrete mathematical laws of Quantum Theory, an equation which bears his name.

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2\mu} \frac{\partial^2 \Psi}{\partial t^2} + U(x)\,\Psi$$

Schrödinger's Equation.

Schrödinger’s equation is a complex valued, second order, partial differential equation.

This is usually not tackled until the second year of a physics degree!

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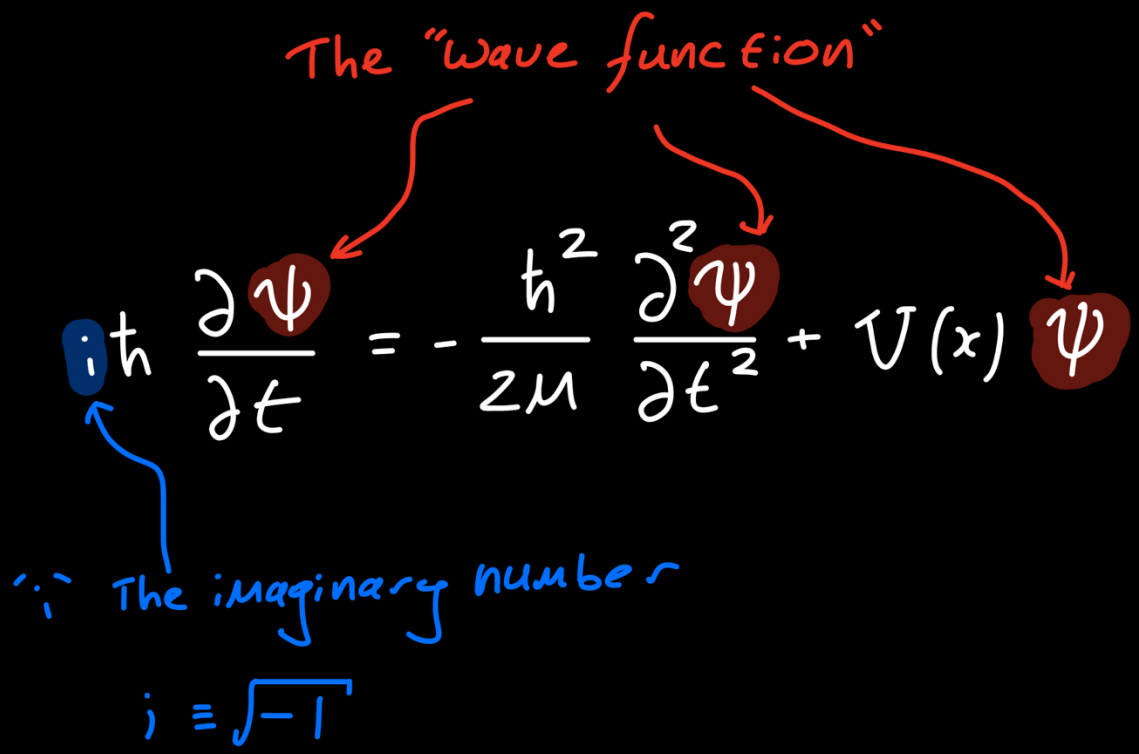

Schrödinger's Equation.

This equation introduces the wave-function.

A mathematical variable, which looks like a wave, but is interpreted in as a probability...

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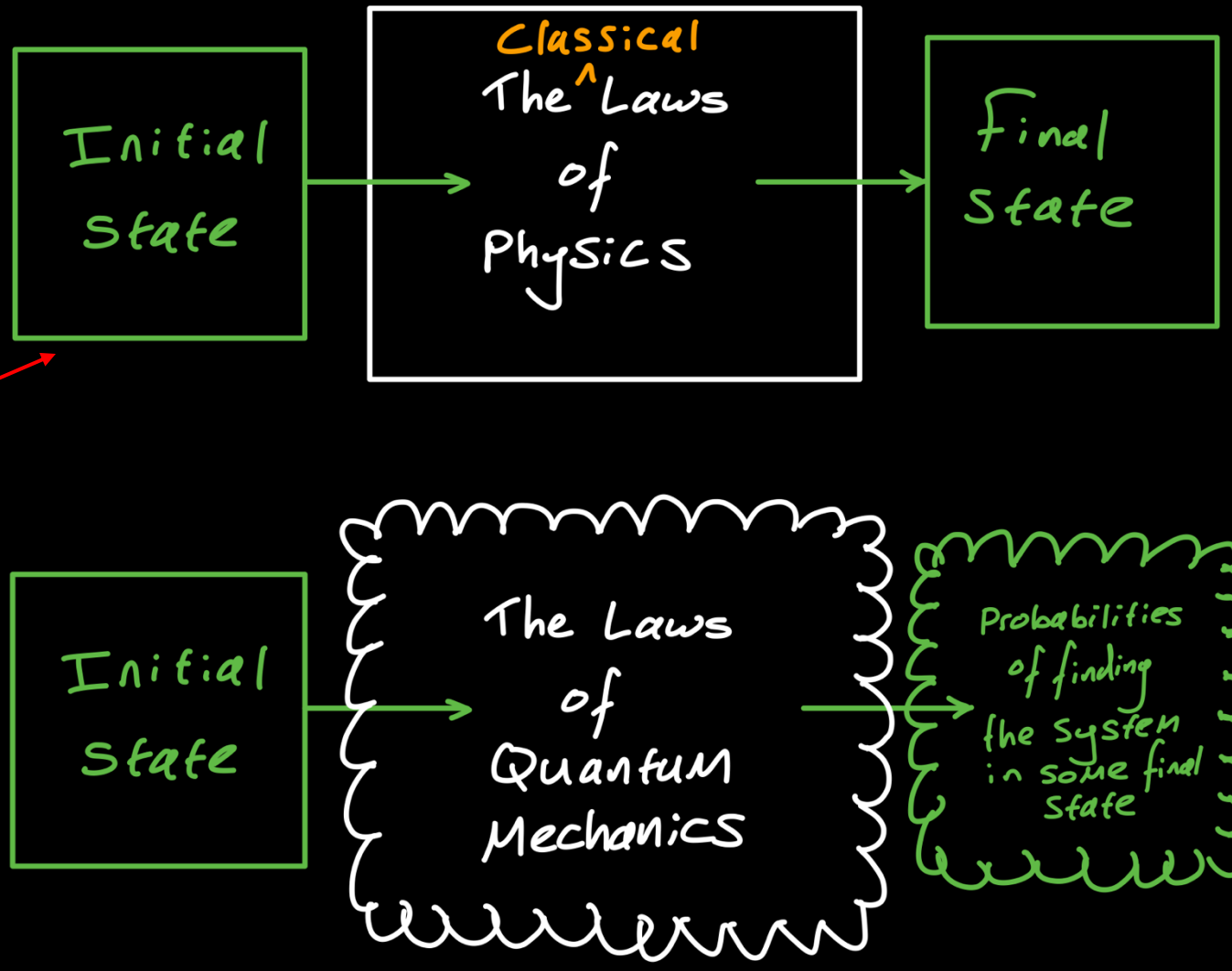
The Laws of Quantum Mechanics

'...interpreted in as a probability...'

This is the key insight into grasping the quantum mechanical description of nature.

The fully deterministic view of Classical Physics, is replaced by the probabilistic view of Quantum Physics.

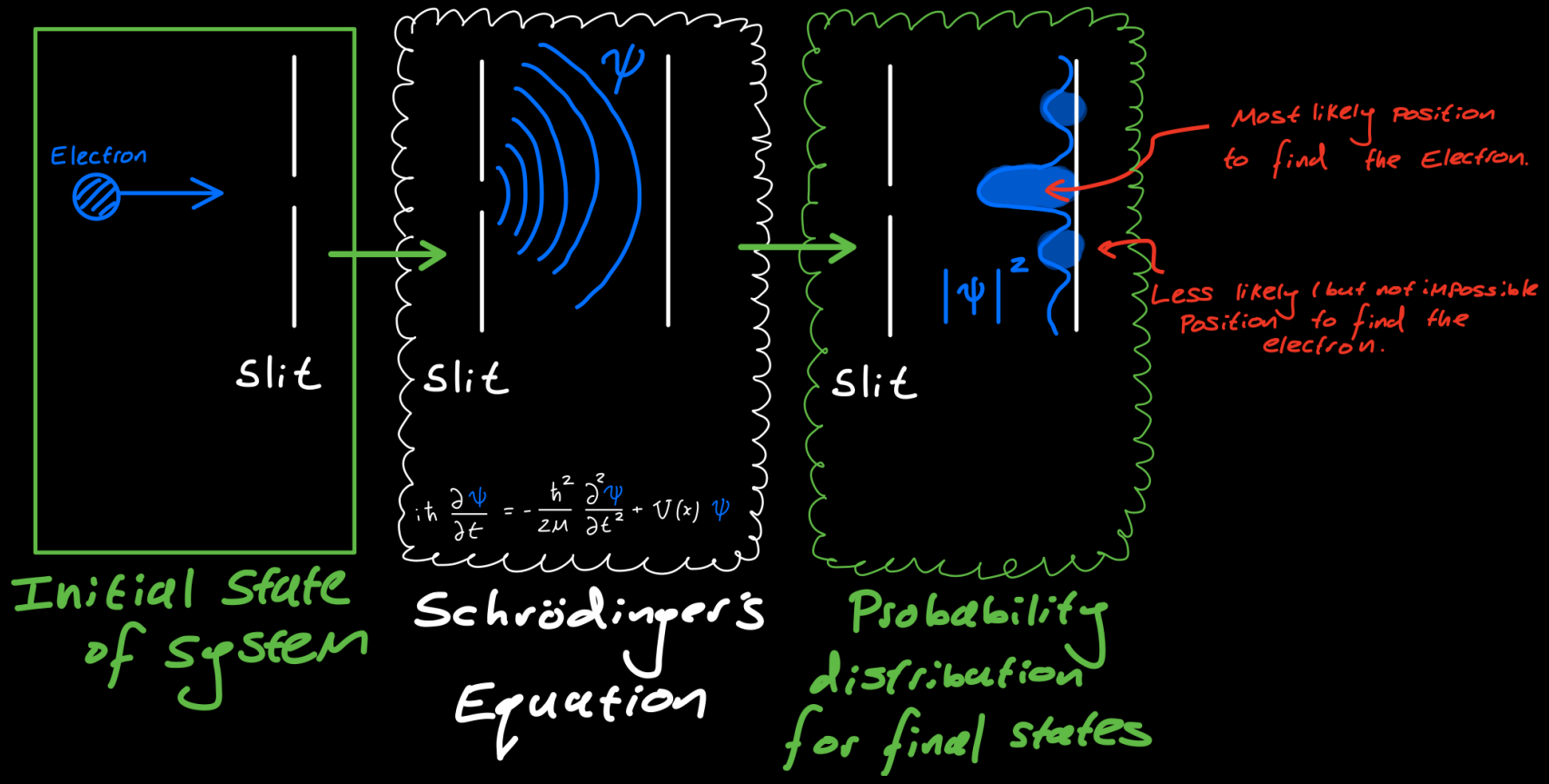
The Laws of Quantum Mechanics do not allow us to compute the exact trajectory of subatomic particles, in the way we did for a golf ball at the start of the lecture...



The Laws of Quantum Mechanics

The output of Schrödinger's equation is a probability distribution, describing the relative likelihood of the electron being found at a given location.

The greater the value of the wavefunction at a given point in space, the greater the probability of finding the electron there.



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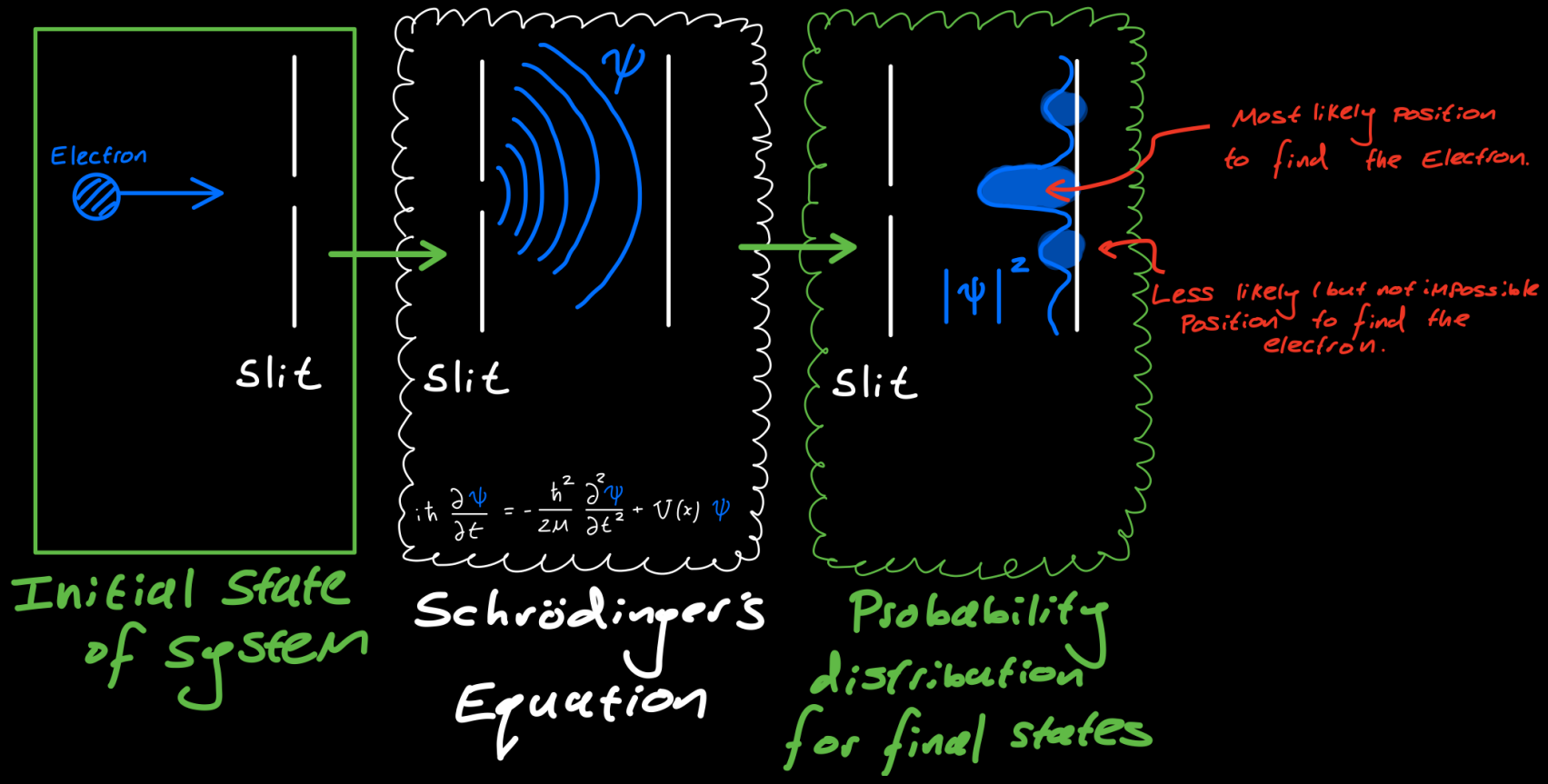

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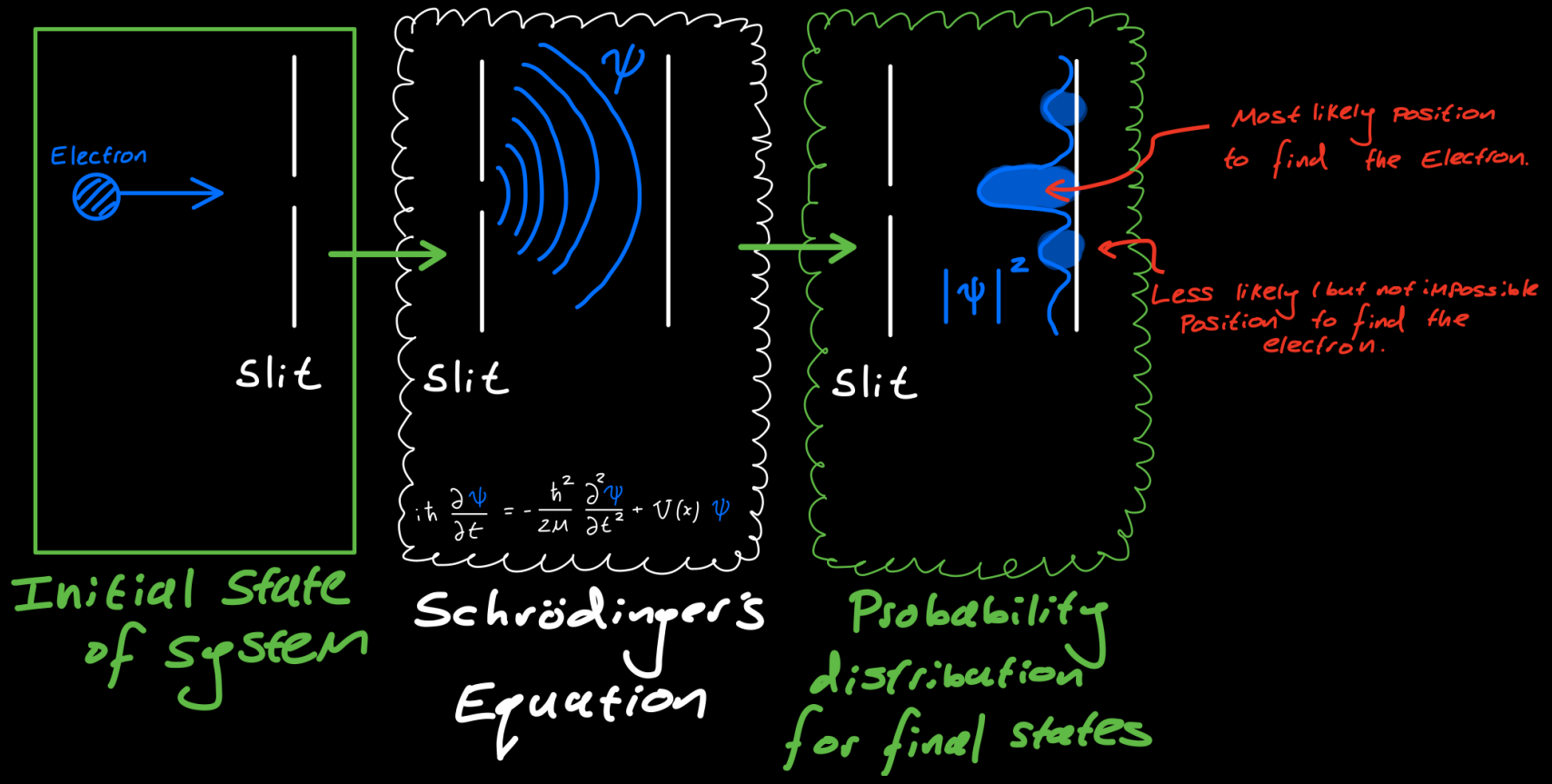

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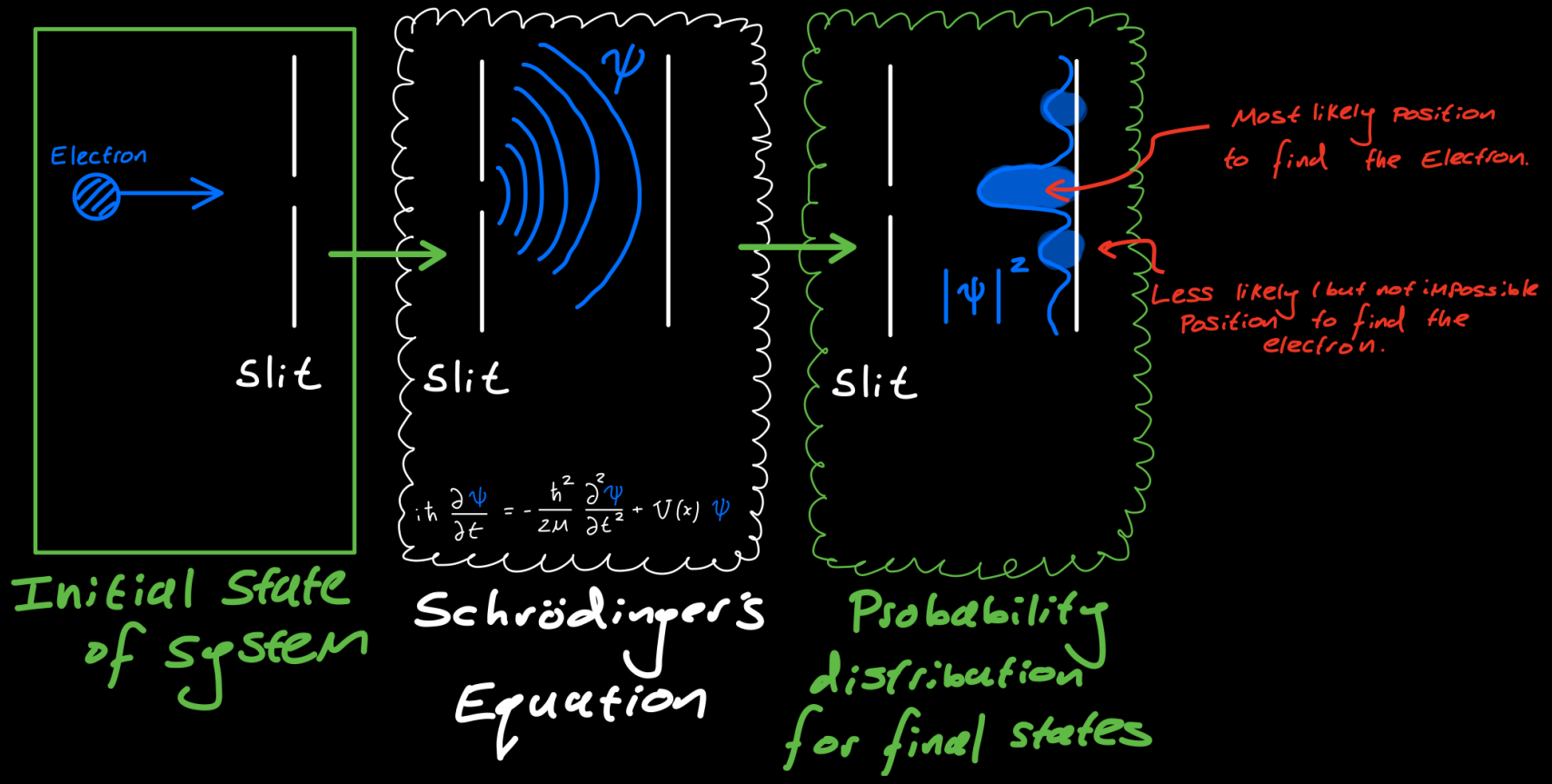


But SURELY... The electron must really be SOMEWHERE.

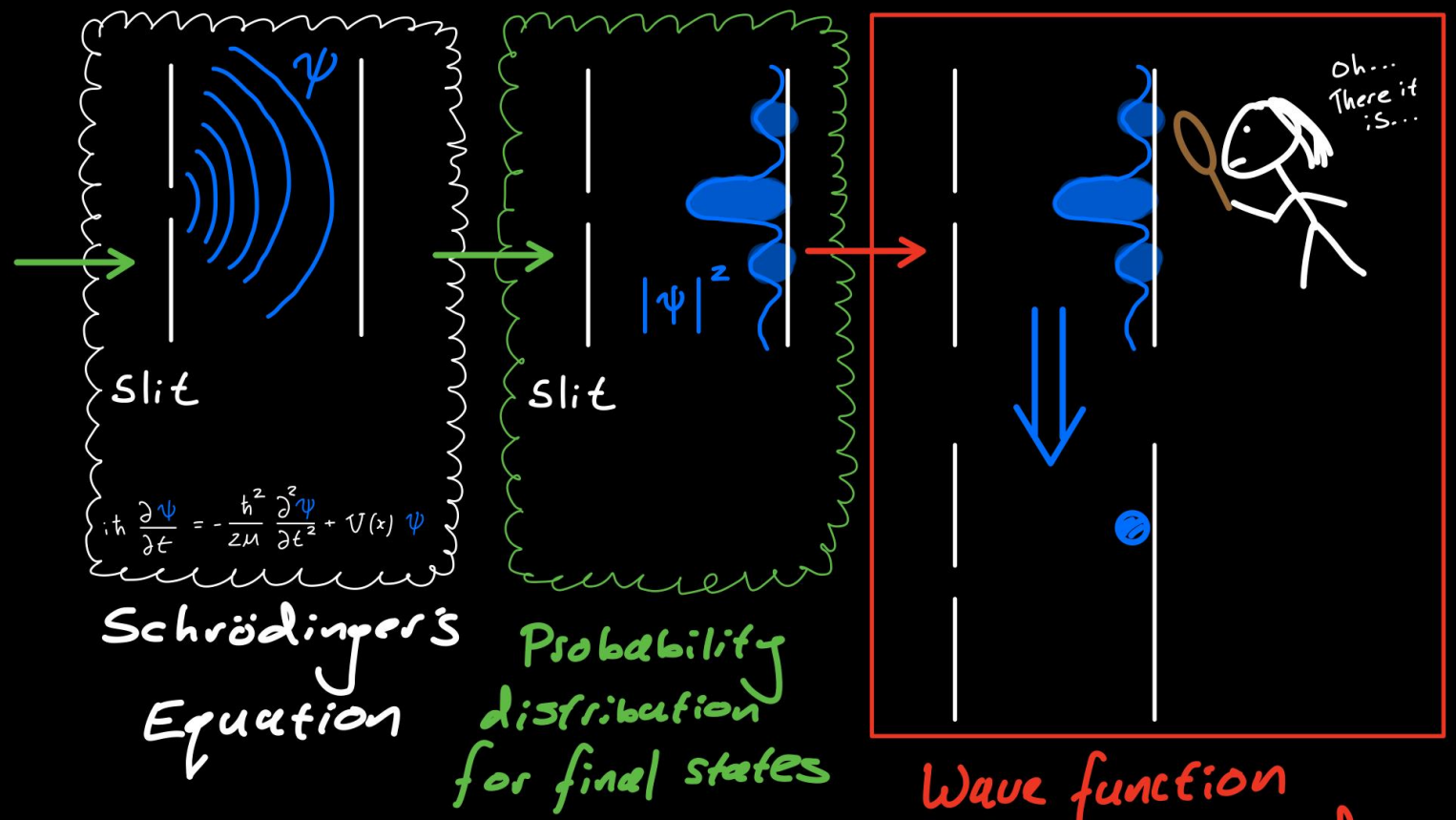
YES, AND NO

The Laws of Quantum Mechanics

There is a fourth step… Making an observation.

When the electrons position is measured (e.g. by an experiment). It's position becomes definitive.

We call this the 'collapse of the wave-function'.



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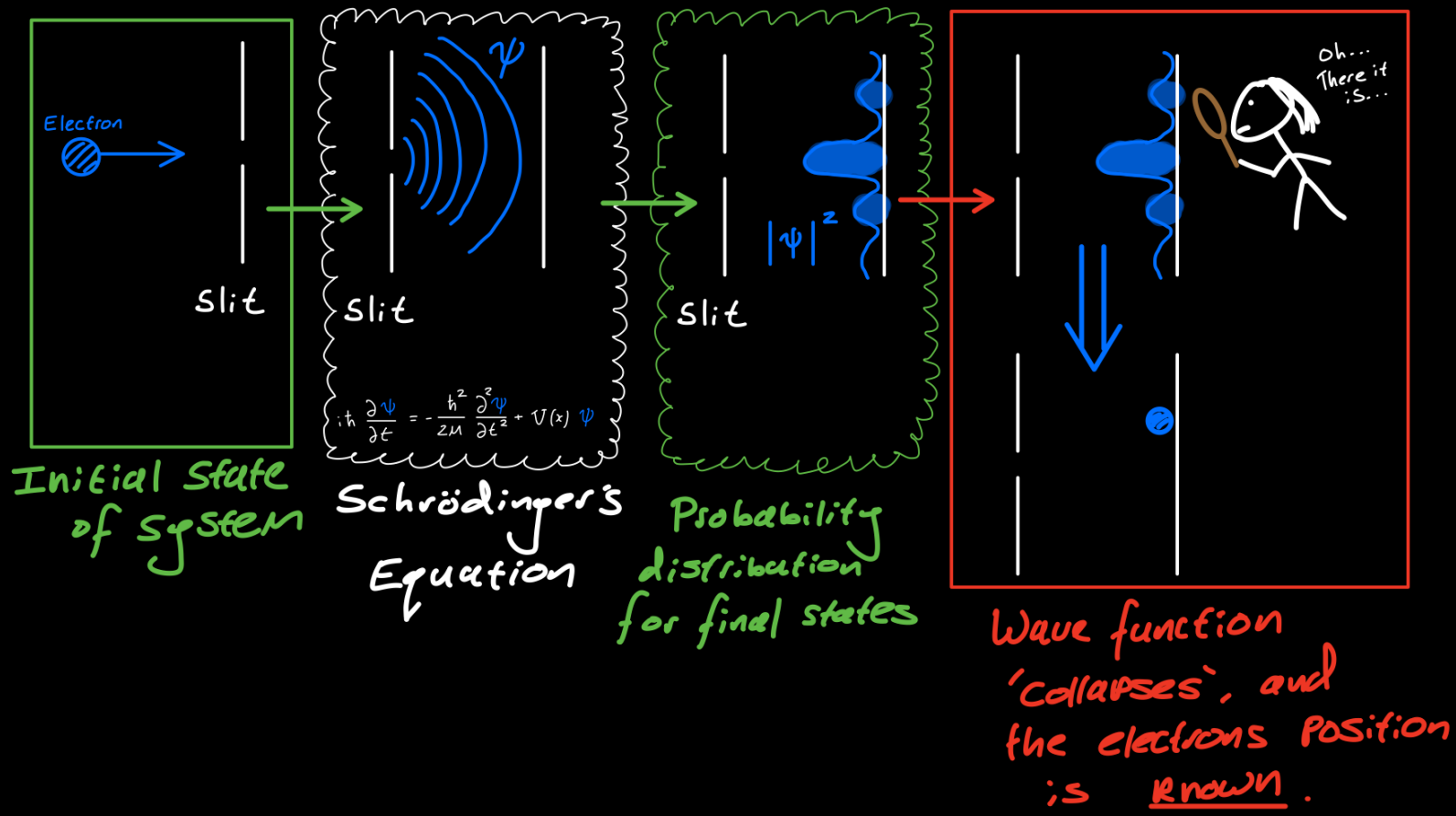
Matter behaves as a fuzzy cloud of probability (governed by Schrödinger's equation), until it is observed, then it does not.



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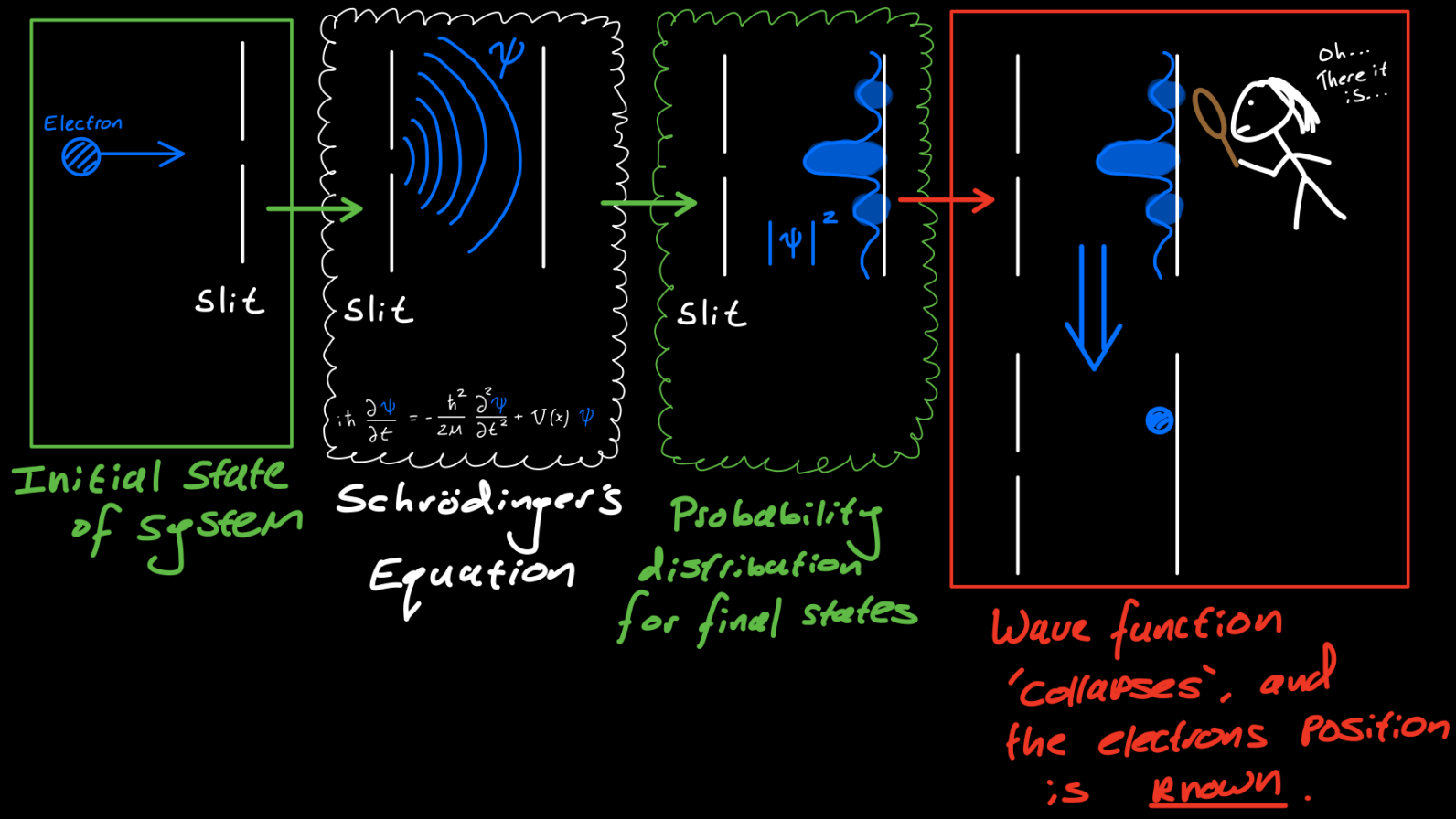
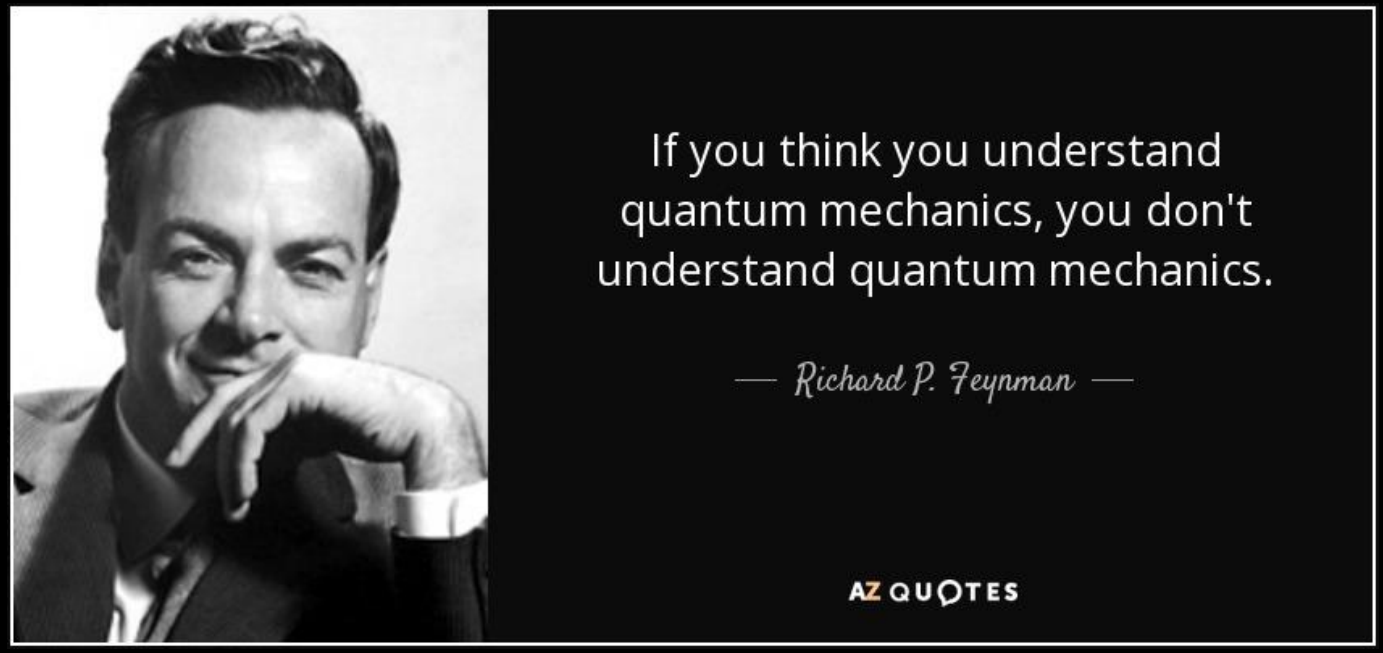
Matter behaves as a fuzzy cloud of probability (governed by Schrödinger's equation), until it is observed, then it does not.

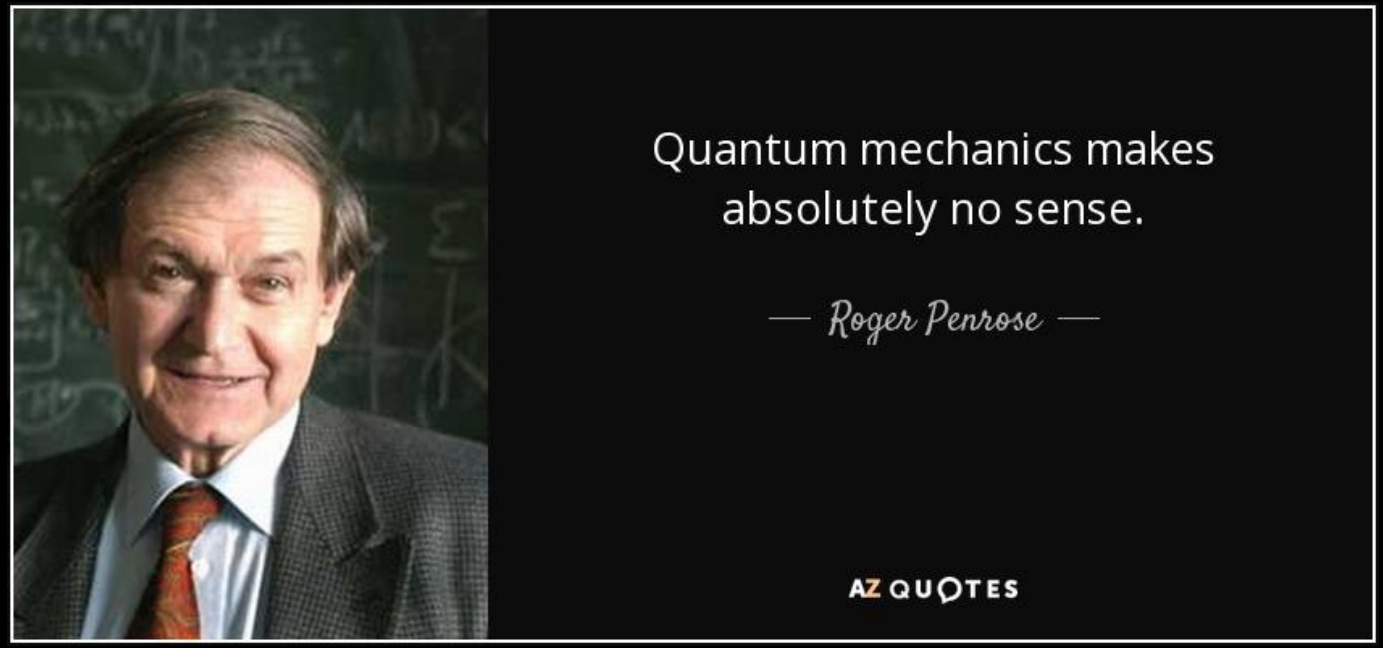
Simple, right?...



The Laws of Quantum Mechanics

Not remotely simple!....





Interpretations of Quantum Mechanics

The Copenhagen Interpretation

It really is all about probability! Get used to it and calculate!

The Many Worlds Interpretation

Every time we make a measurement with several possible outcomes, the Universe splits into multiple parallel Universes where each outcome occurs in one of the Universes.

Hidden Variables

Nature SURELY can’t be this indeterminate.. There are hidden variables we are unaware of, that makes the whole thing classical.

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Both of these interpretations are plausible, and ultimately indistinguishable.

All interpretations of Quantum Mechanics are equally valid, and equally untestable!

Except for...

Hidden variables. Which is demonstrably false, thanks to the Bell inequalities.

‘The Multiverse’

There are different kinds of **hypothetical** multiverses described by theoretical physicists, including:

Level 1: ‘Eternal Inflation Multiverse’.

A consequence of the hypothetical rapid expansion of the Universe (inflation), which leads to pockets of space causally disconnected from out own Universe. This type of Multiverse is basically just ‘more Universe’.

Level 3: The ‘Everett Multiverse’.

Named for Hugh Everett’s ‘Many Worlds Interpretation’ of quantum mechanics.

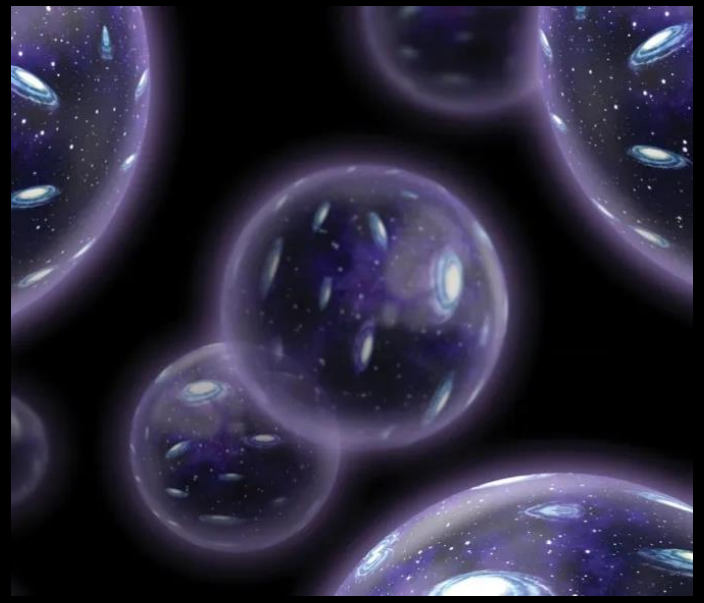
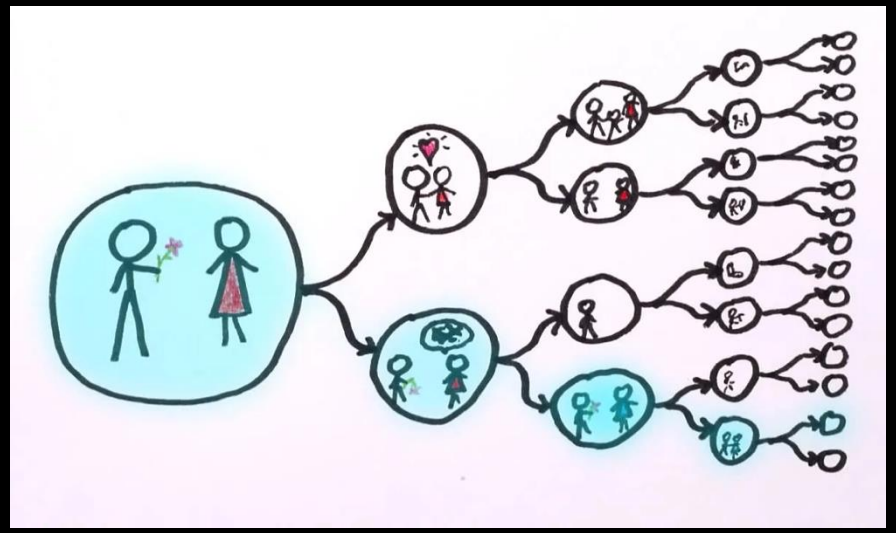


Illustration of ‘the Multiverse’.



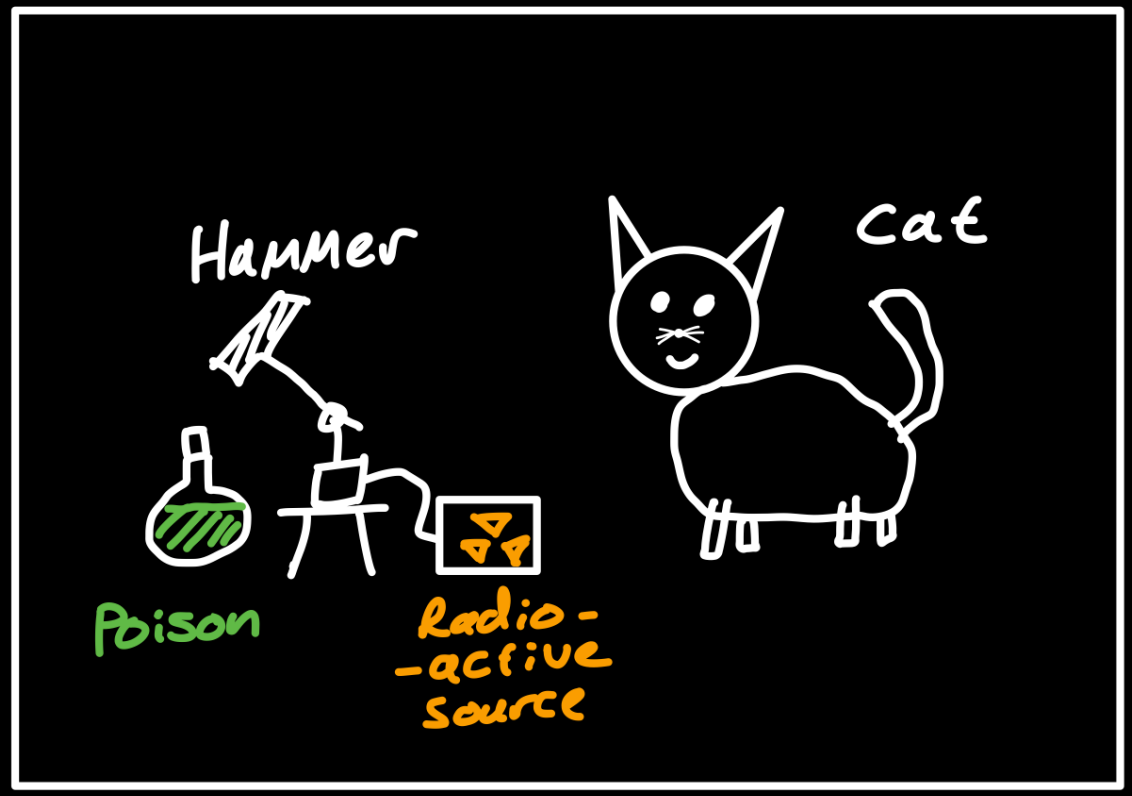
Fissioning in an Everett Multiverse.

Schrödinger’s Cat

Schrödinger's Cat is an analogy for describing the indeterminate nature of a Quantum State, prior to observation.

In this thought experiment: A cat is placed into a box, with a vial of poison, and a hammer system poised to smash the vial if a radioactive atom decays (a totally random process).

We can use this to outline both the Many Worlds, and Copenhagen interpretations.



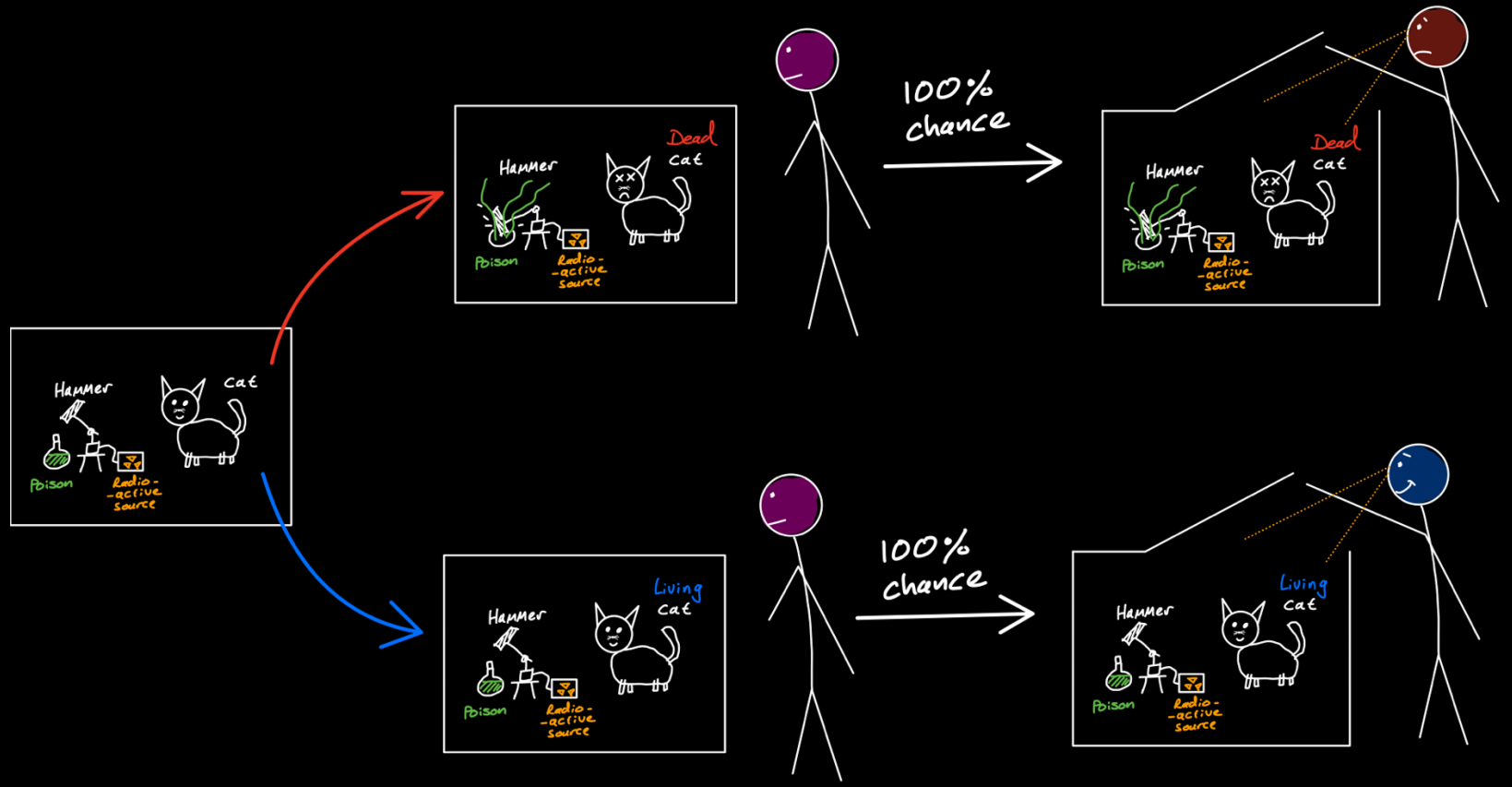
Schrödinger's Cat

<u>The Many Worlds Interpretation</u>

When the cat is placed into the box, two outcomes are possible:

1. The vial smashes and the cat dies.
2. The vial does not smash, and the cat lives.

In response to this binary choice, the Universe splits in two. One Universe where the cat lives, and one where the cat dies. We exist in one of these Universes, but we have no way of knowing which until we open the box.



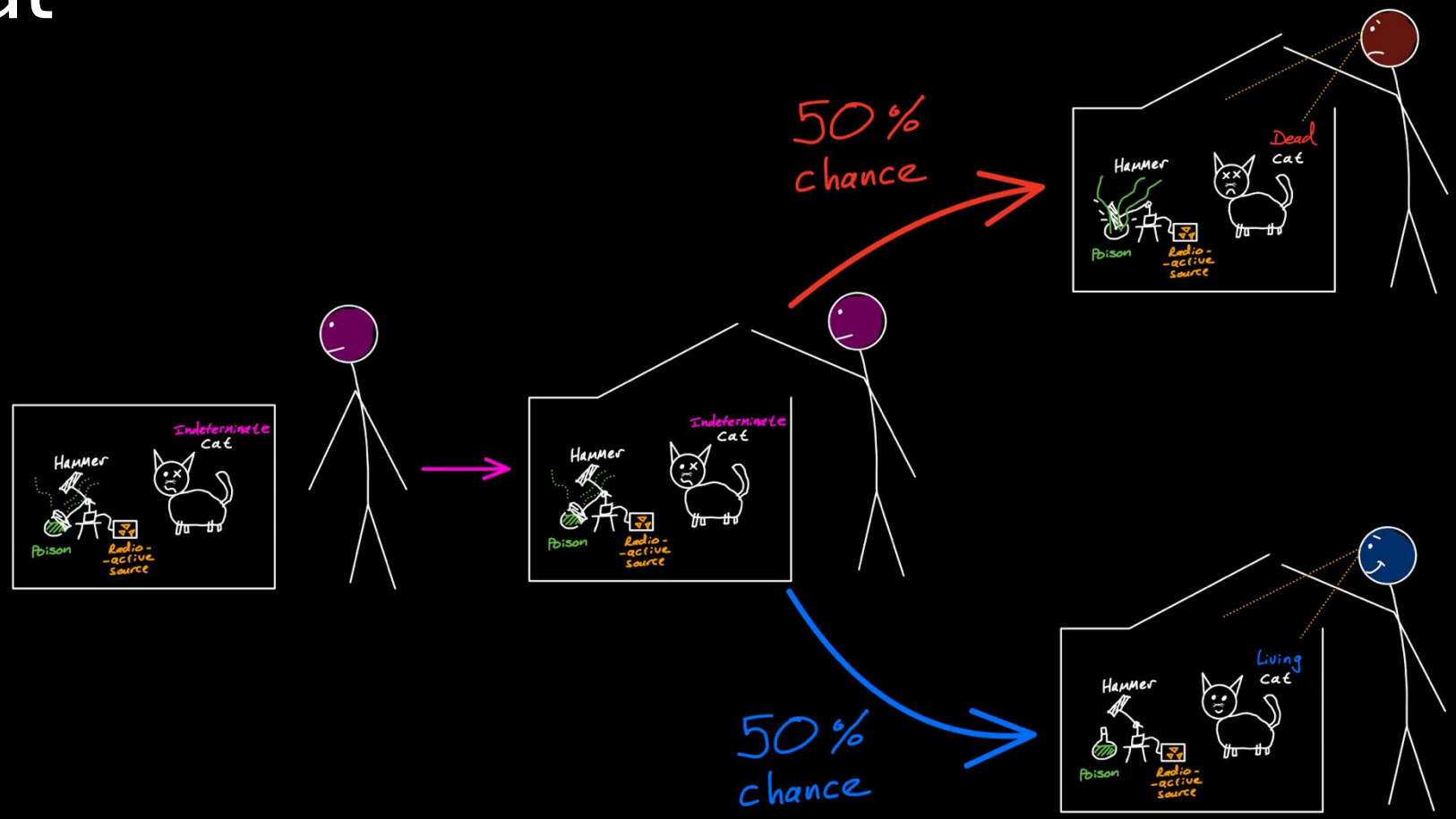
Schrödinger's Cat

<u>The Copenhagen Interpretation</u>

The cat exists in an indeterminate state (a Quantum Superposition), in which it is both dead and alive simultaneously.

It does not become one of the other until we open the box, and collapse the wave-function of it's quantum state.

Note: It *really is* indeterminate!... This is not the same as us simply not knowing... **The Universe itself does not know, until the box is opened!**



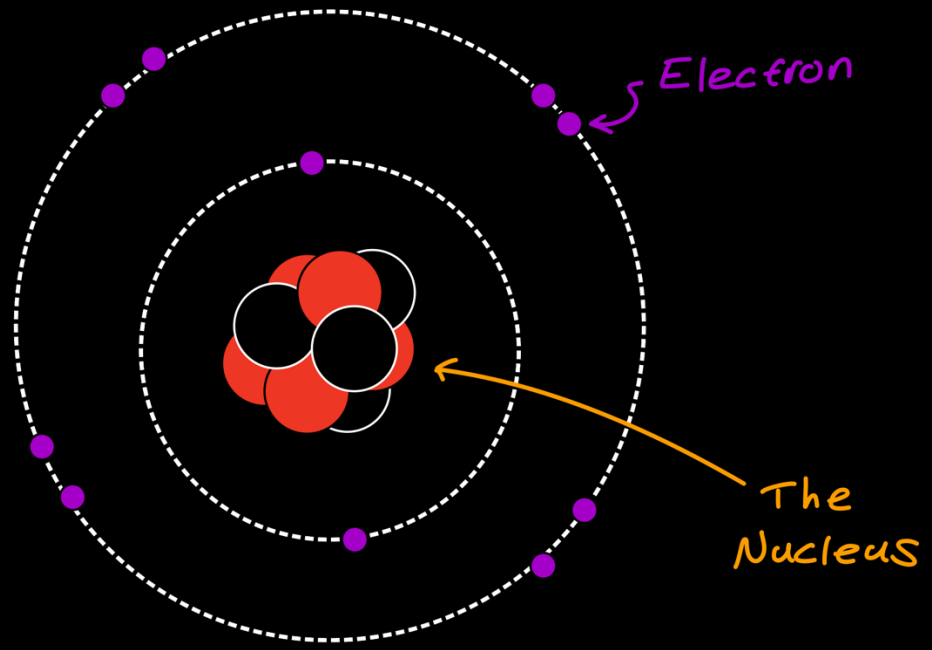
Particle Physicists Mantra

Particle Physics is the ultimate *reductionist* science.

Our Goals:

(i) To describe all matter in terms of its smallest components. fundamental particles.

(ii) To describe all forces and interactions between these matter in terms of small set of fundamental forces.



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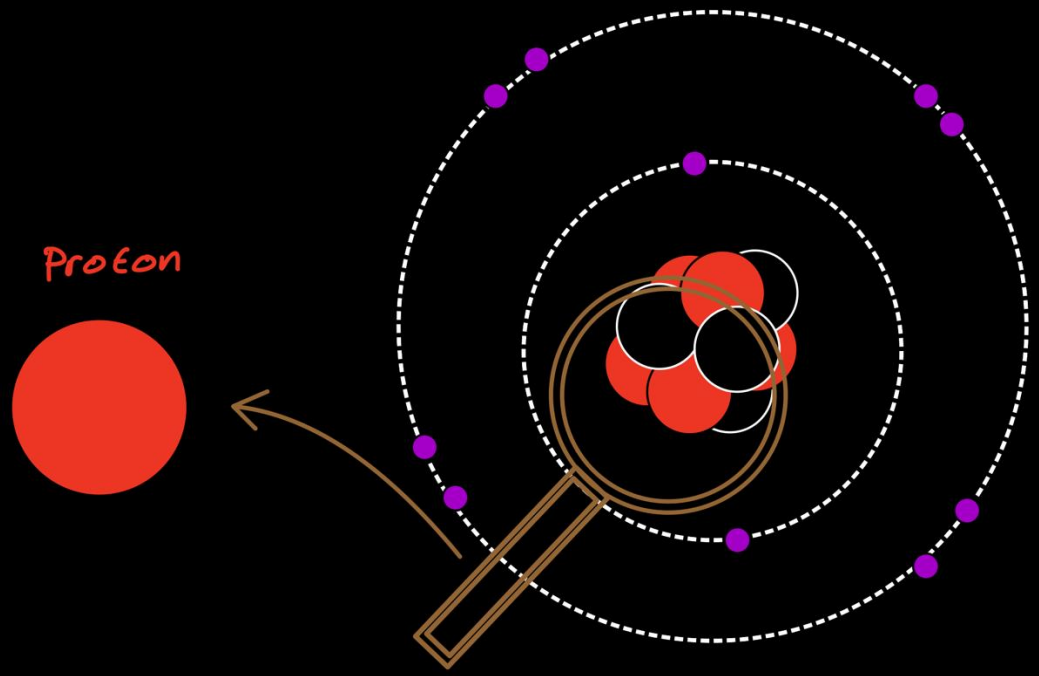

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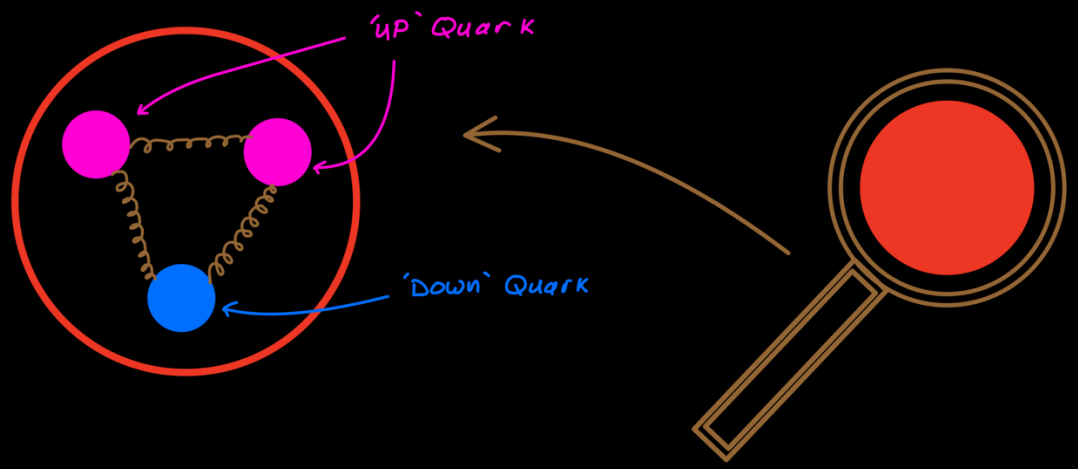

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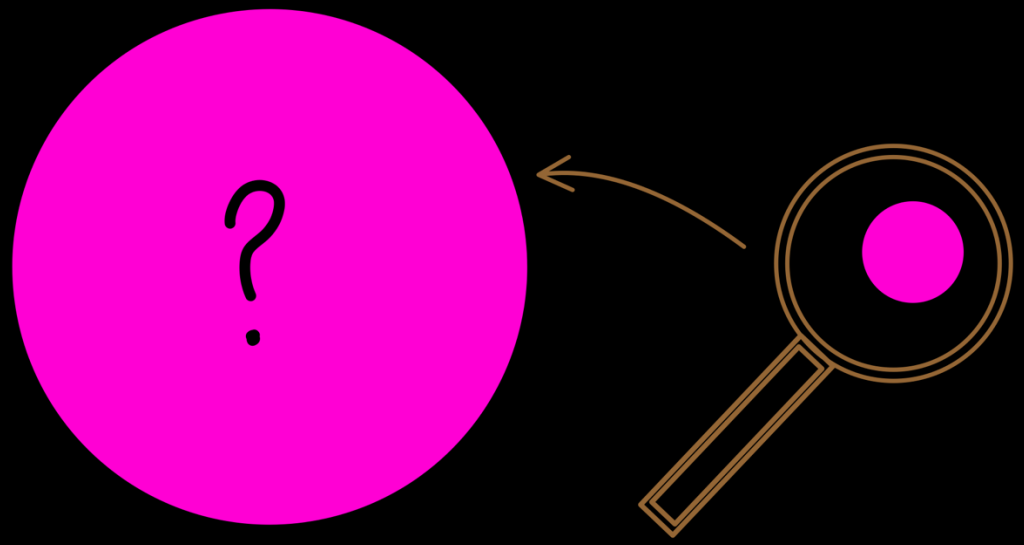

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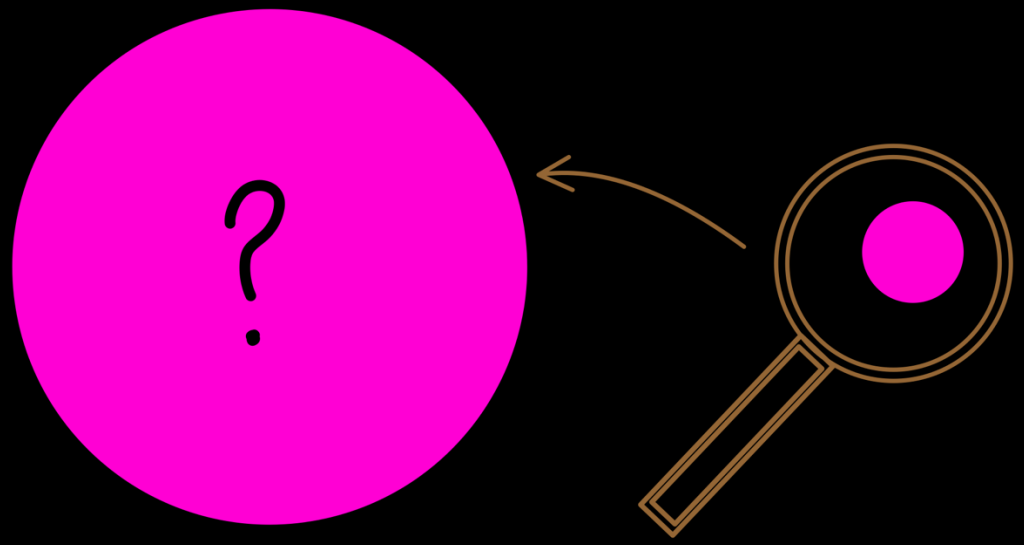
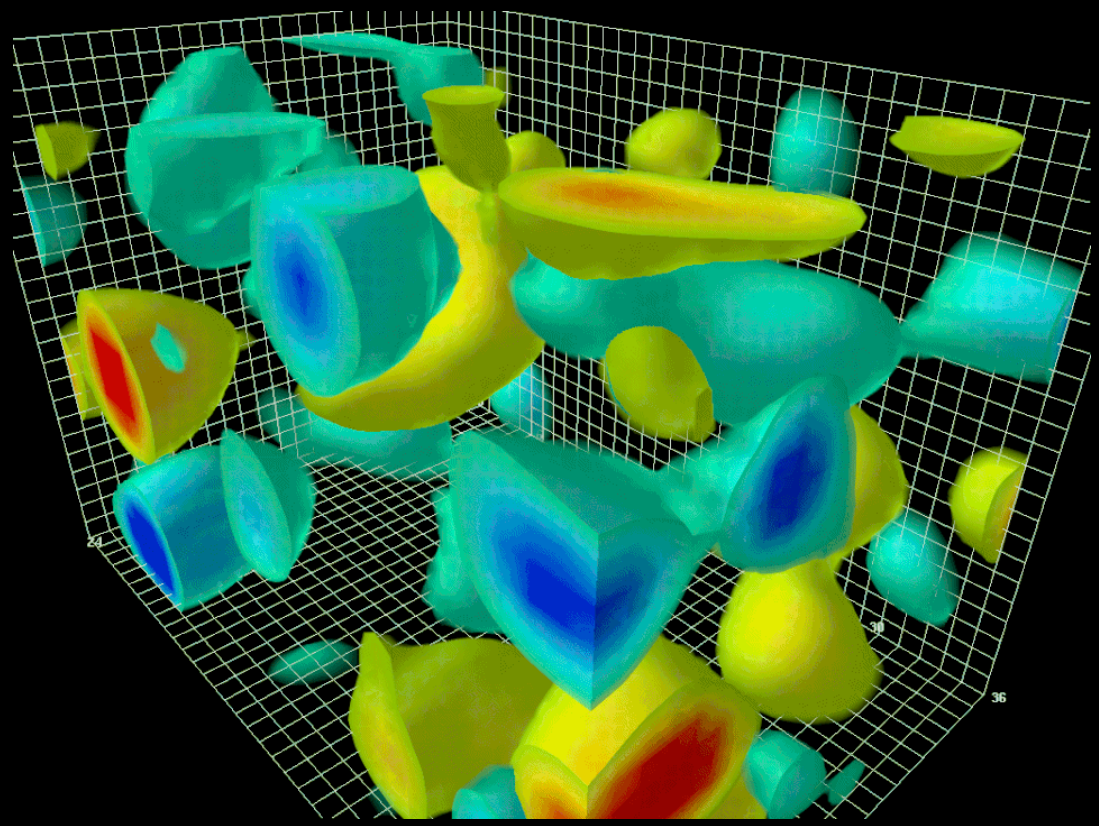


The Quark is Fundamental (to our best knowledge!).

Special Relativity
+
Quantum Mechanics



Special Relativity is Einstein's 1905 Theory of space and time (come back next week to hear more about this).

Later in 1926, efforts were being made to create a more complete quantum theory of light, which respects Special relativity.

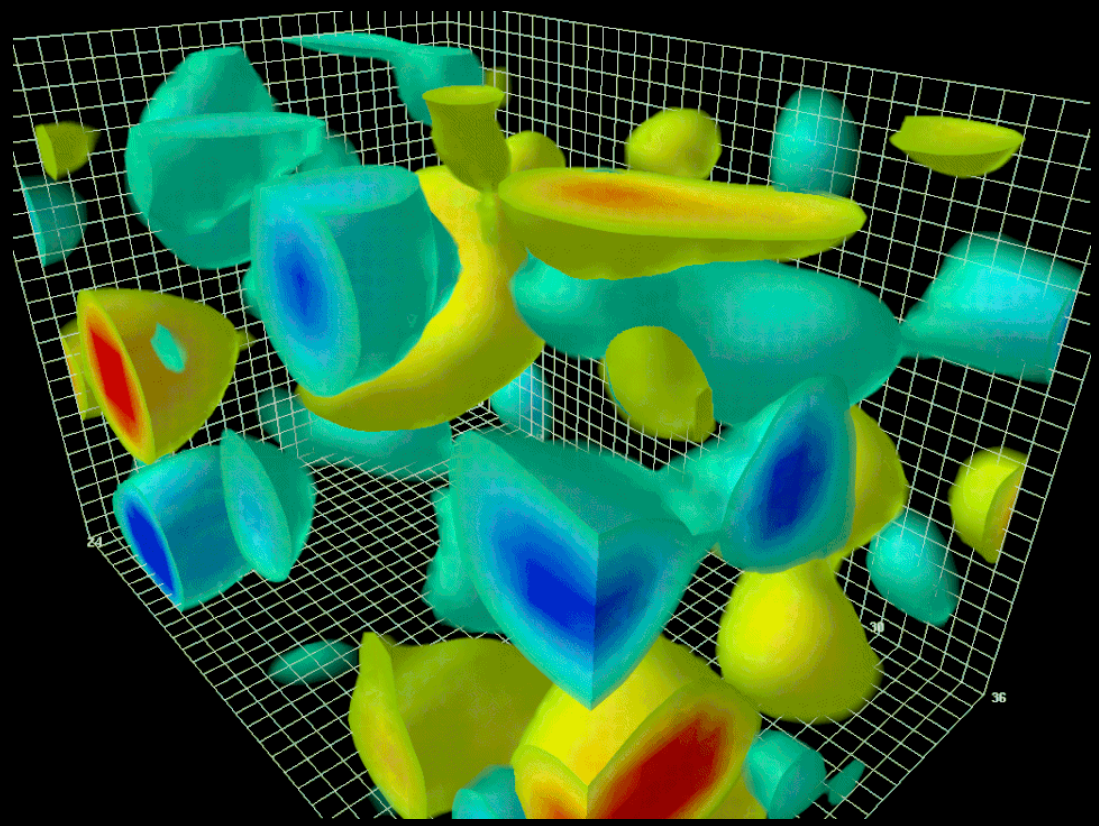
This fusion of Quantum Mechanics and Special Relativity, is called **Quantum Field Theory**.

Special Relativity
+
Quantum Mechanics

Quantum Field Theory describes matter particles, at the most fundamental level, as excitations of some undulating underlying '*Quantum Fields*'.

Particles pop into existence and dissolve back into the vacuum a short time later.

This *fizz* of of creating and annihilating particles fills the entire Universe.



So what is matter? Particle or Field?!

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It’s both!

So what is matter? Particle or Field?!

It’s both!

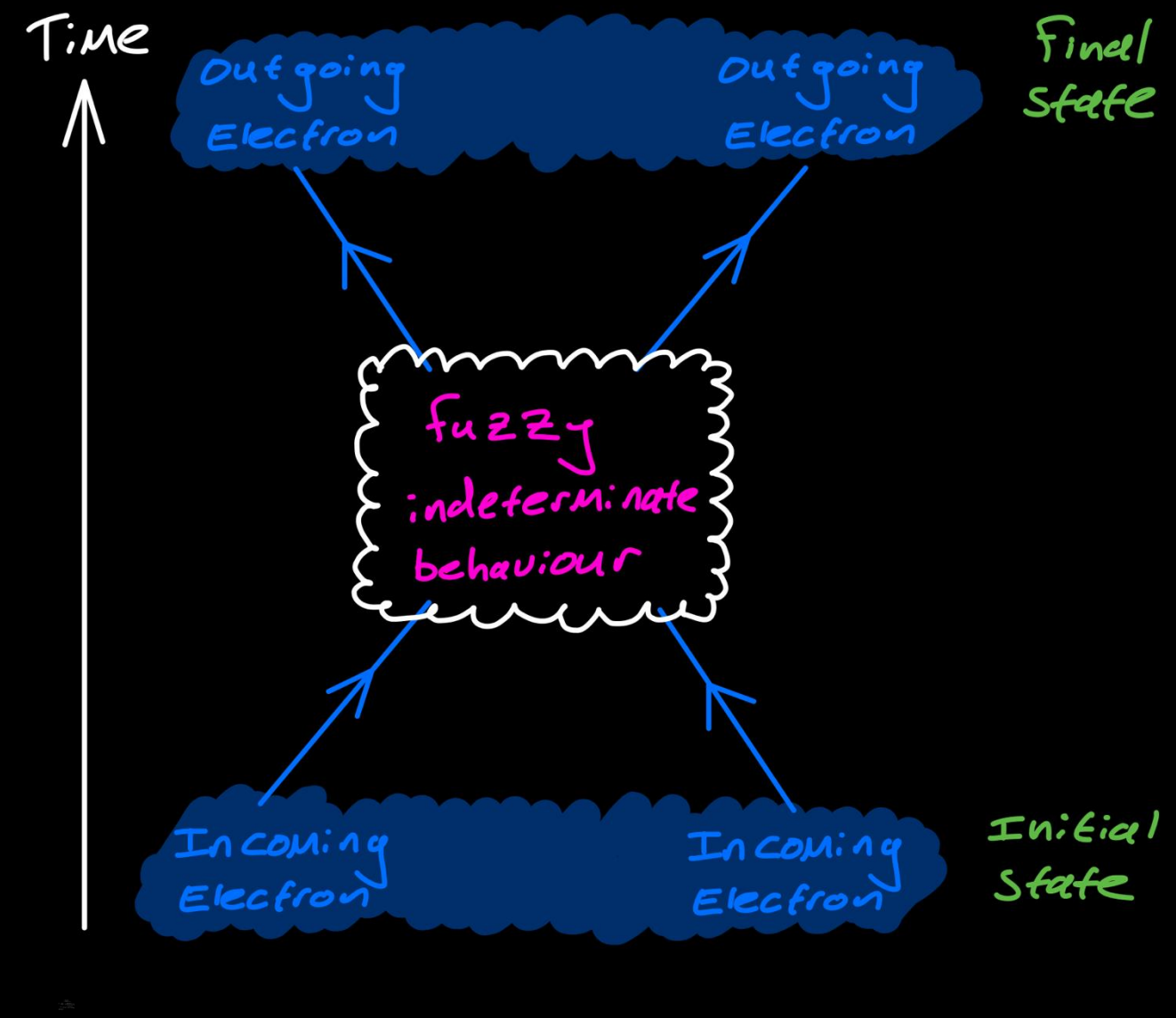
Sort of..

Electron Scattering

When we make measurements, we can observe particles at a definitive location... But what goes on in-between our observation is indeterminate.

Consider two electrons moving towards each other, and then repelling.

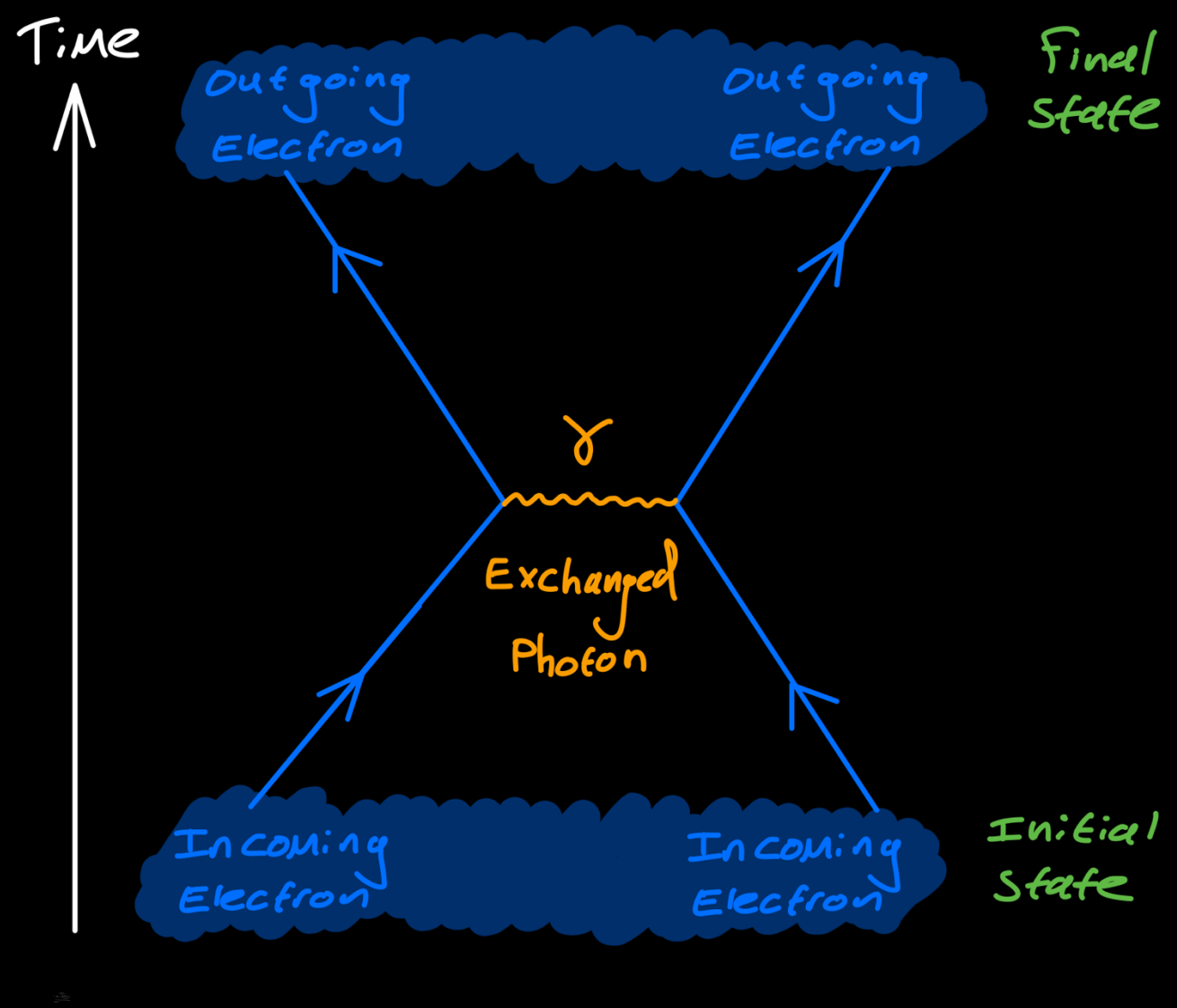
This force is controlled by the Electromagnetic Force.



Electron Scattering

In particle physics, the Electromagnetic Force is communicated by the exchange of a photon of light (the force carrying particle of the Electromagnetic Force).

The rules of Quantum Field Theory, worked out in the 1920's tell us that two electrons may exchange a single photon.



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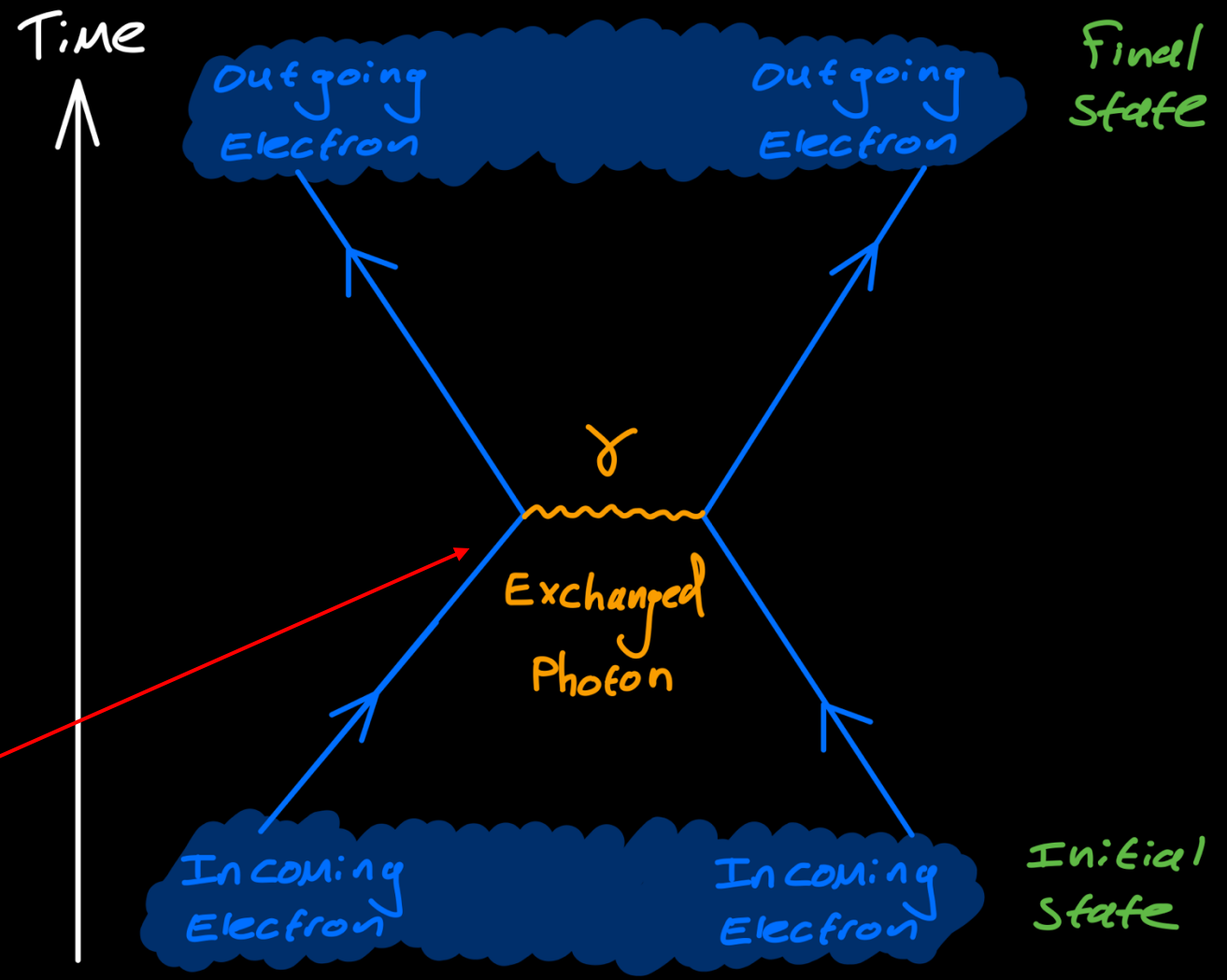

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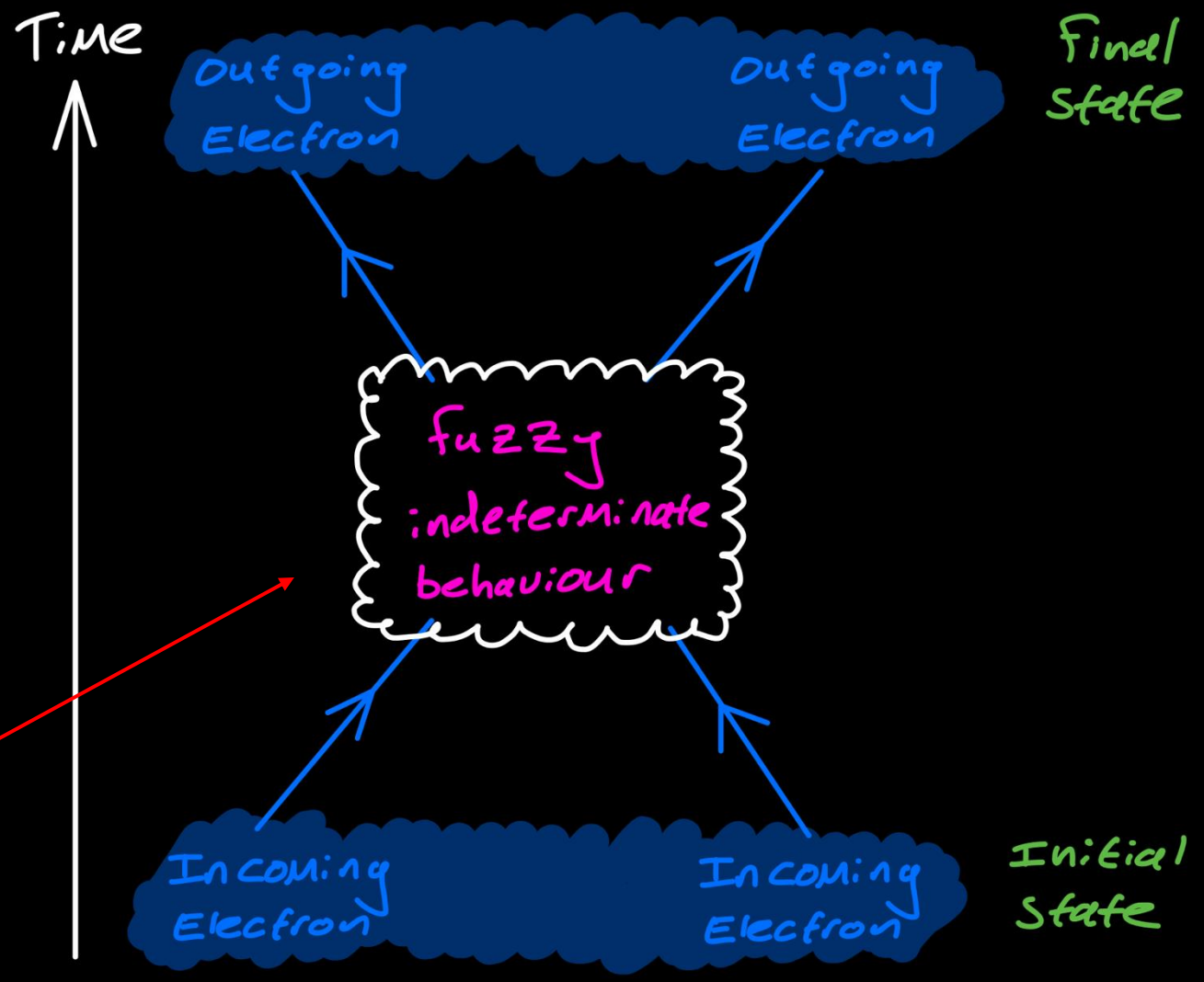
NO

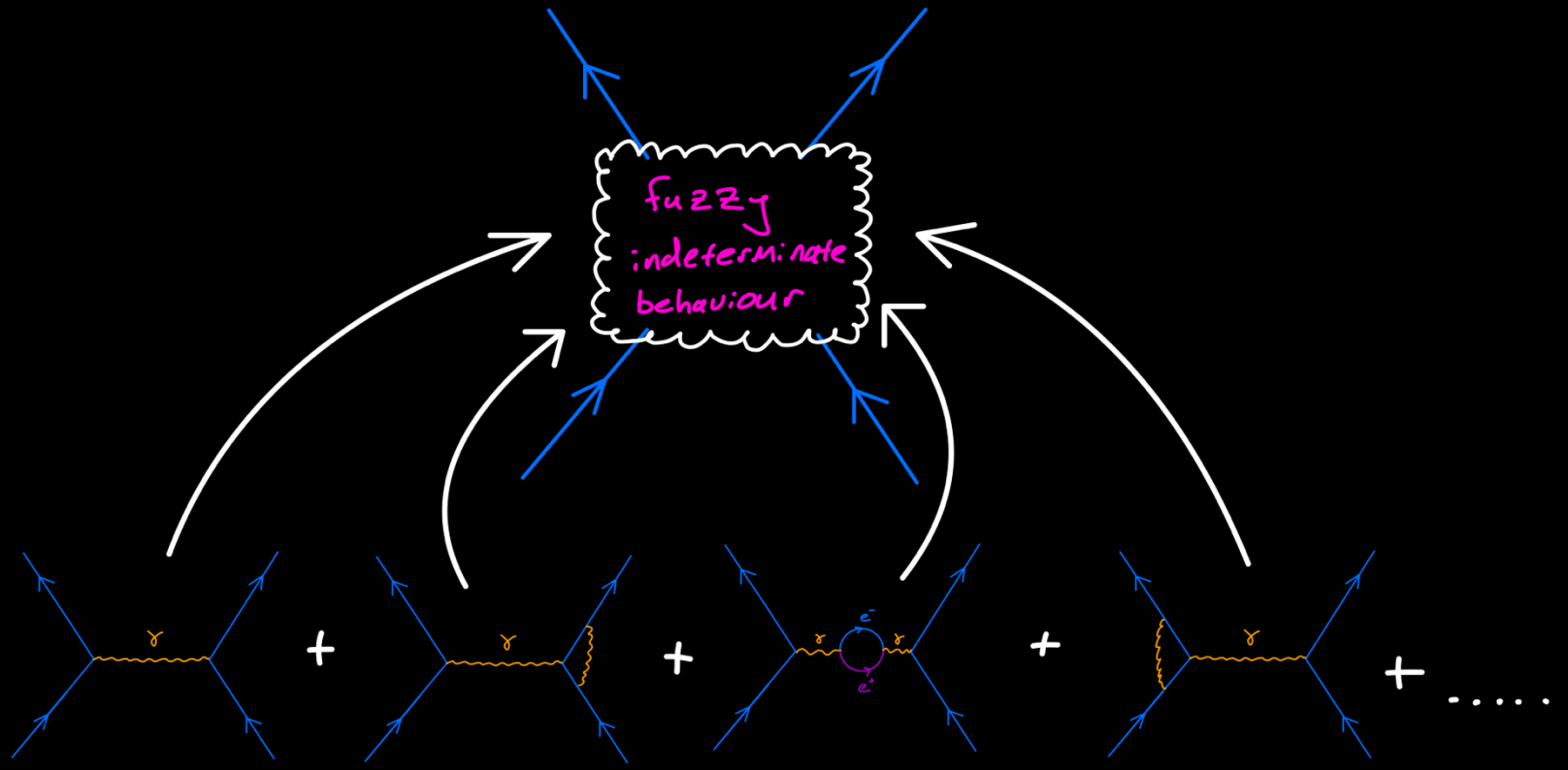


Electron Scattering

The single photon exchange we saw before is *one* possibility, of an infinitude!

To calculate the probability of this scattering interaction occurring, we have to add up the probability of all of these possible interactions!

This diagrammatic technique of representing particle interactions (and the mathematical machinery that is hidden behind them) owes itself to Richard Feynman.



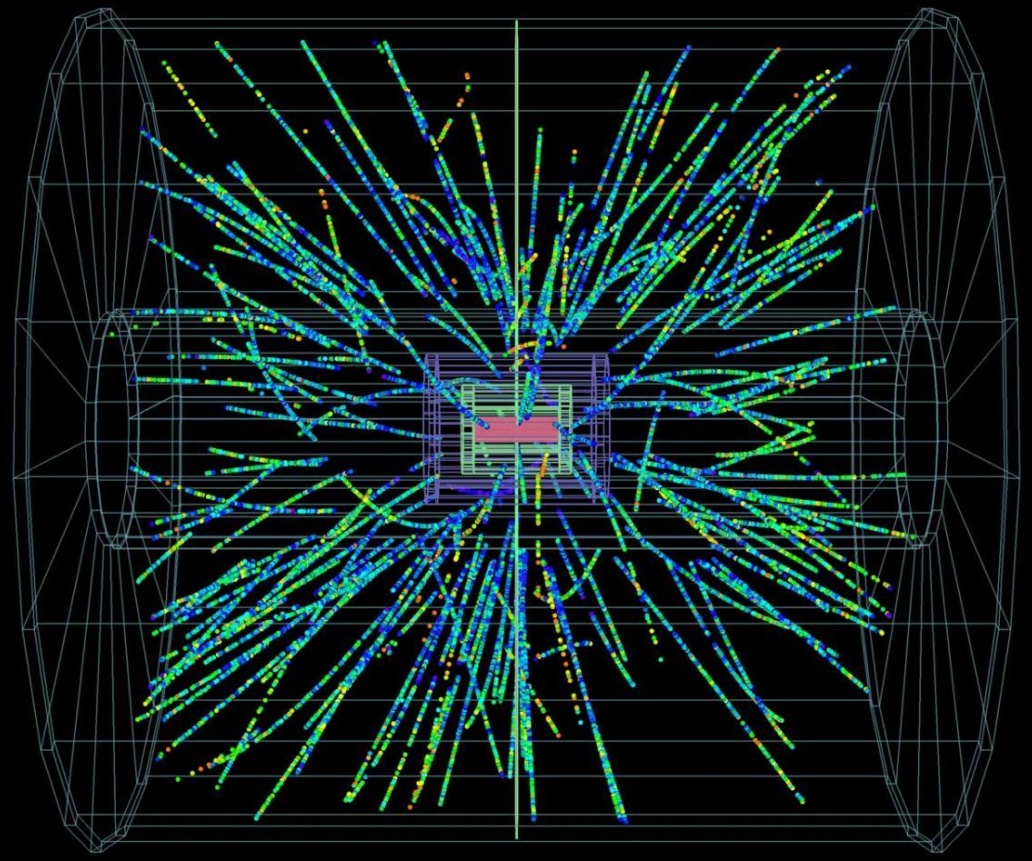
The Feynman Diagram expansion of electron scattering.

The Particle Zoo

In the 1950's advances in particle collider technology, allowed for an astonishing number of new particles to be discovered.

This was deeply unsatisfying to physicists of the day, as it was not clear how all of these particles fit together.

Were these particles *fundamental*, or *composite*?

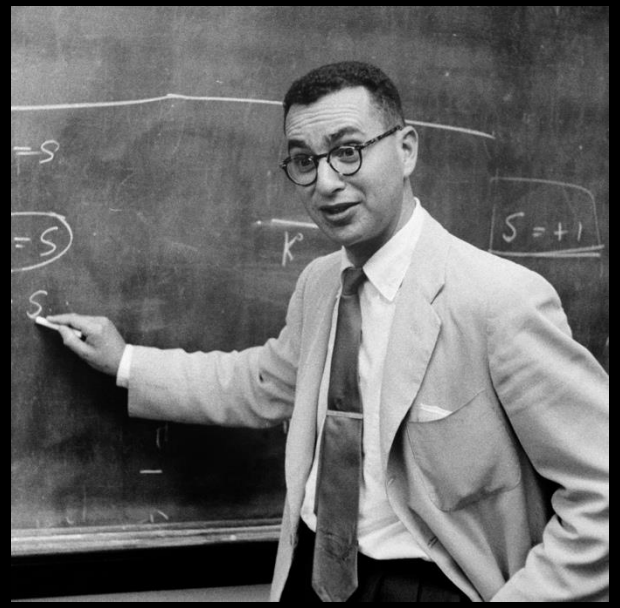


"*Maybe physicists discovering a new particle ought to be fined $10,000.*"

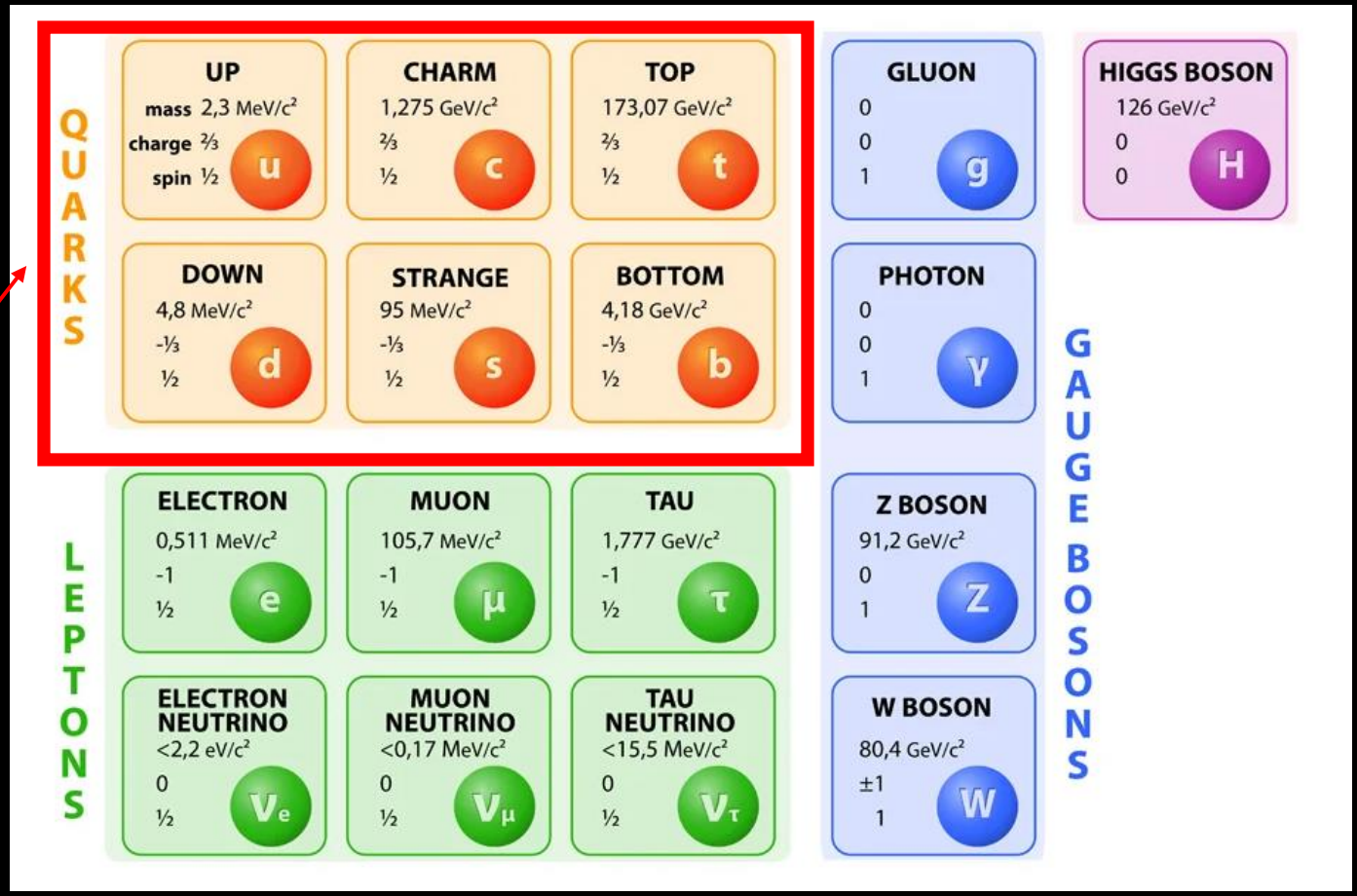
Willis Lamb in his 1955 Nobel Acceptance speech

The Eightfold Way

In 1961, Murray Gell-Mann realized, that *all* of the new particles discovered could be explained as combinations of only eight fundamental particles, the Quarks.



Gell-Man in 1956

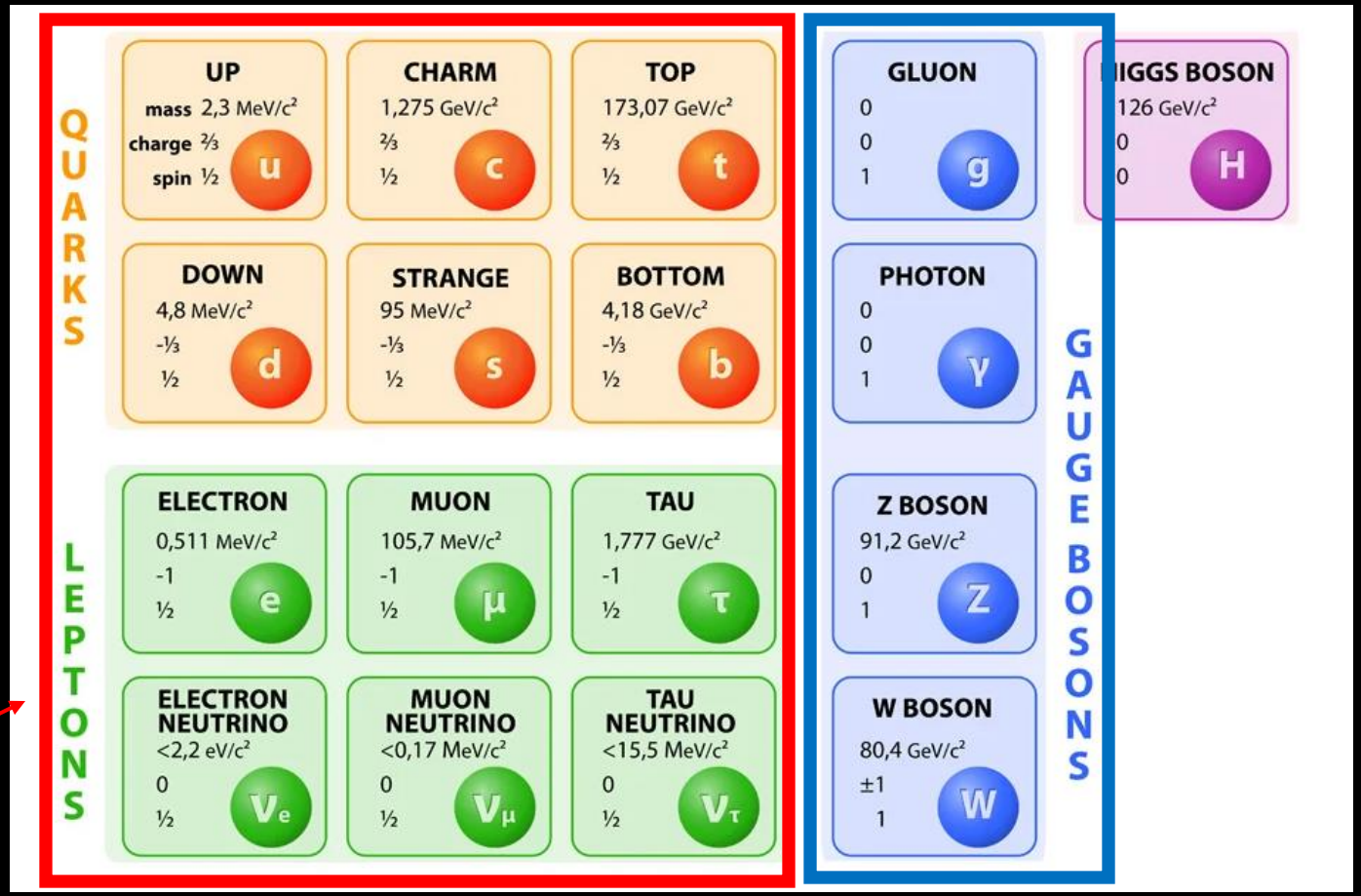


The Standard Model of Elementary Particles.

The Standard Model

This leads us to introduce the Standard Model of Elementary Particles.

This is our most complete picture of all of the matter and forces in the Universe.



The Standard Model of Elementary Particles.

All visible matter is composed of Quarks and Leptons.

Nearly all of the forces of nature, are described by force carrying particles called Gauge Bosons.

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The Standard Model of Elementary Particles.

All visible matter is composed of Quarks and Leptons.

What's going on here?...

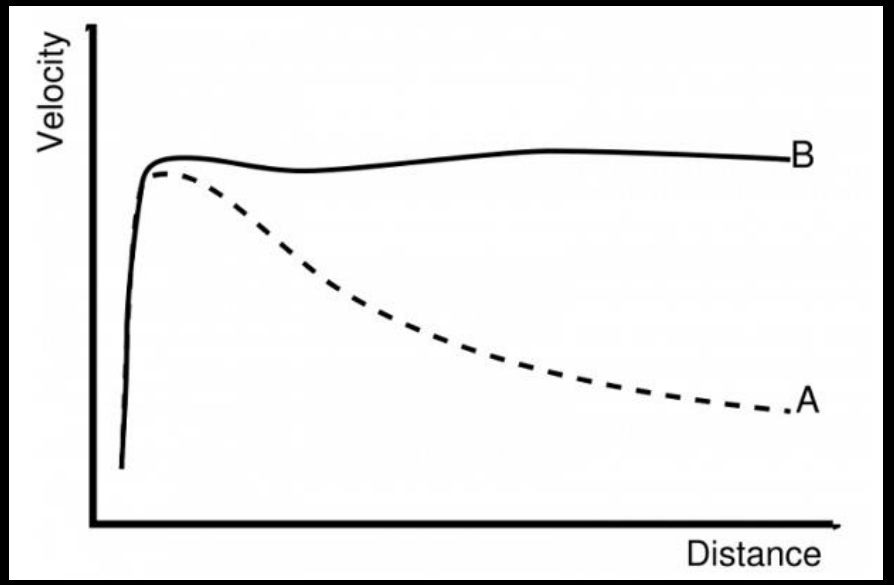
Nearly all of the forces of nature, are described by force carrying particles called Gauge Bosons.

Dark Matter

The rotation of the galaxy suggests an excess of non-visible matter, gravitationally interacting and changing the rotation of the galaxy.

If Dark Matter is not accounted for, our calculations for the rotational speeds of stars in the outer regions of the galaxy are totally wrong.

Comparing the observed rotation curves for various galaxies with the theoretical prediction, accounting for the presence of dark matter, we find that about 95% of the matter in the Universe is Dark Matter.



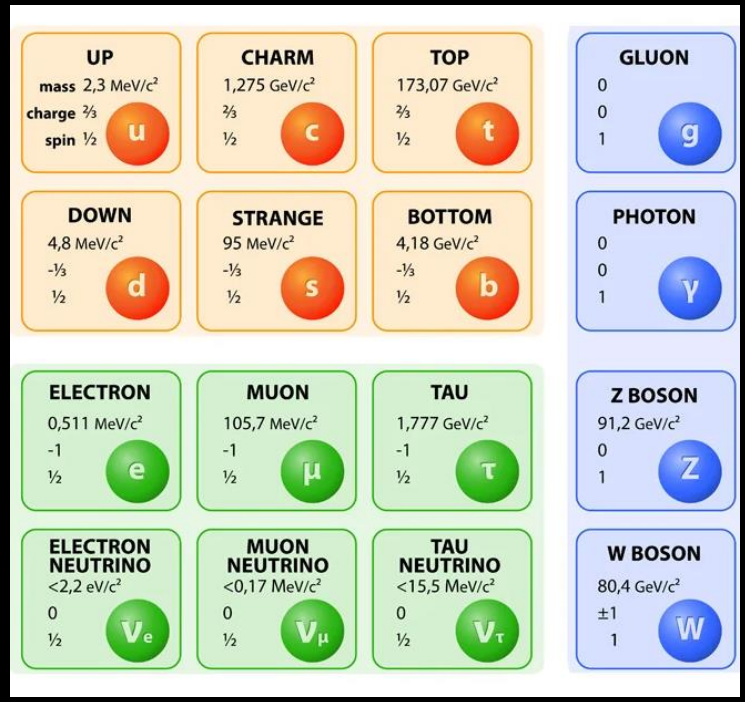
Galaxy Rotation Curves.

A: Predicted Curve. B: Observed Curve.

Dark Matter

But what is Dark Matter?

We don't know!



The standard model of particle physics describes all of the known visible matter, and most of the known forces in our Universe. It does not include DM.

Many models: including extra dimensions, WIMPs, axions, primordial black holes. Some models even doubt whether DM is a particle, instead it as a gap in our understanding of how gravity works on large scales.

Dark Matter

How are we searching for Dark Matter?

- Direct Detection Experiments:

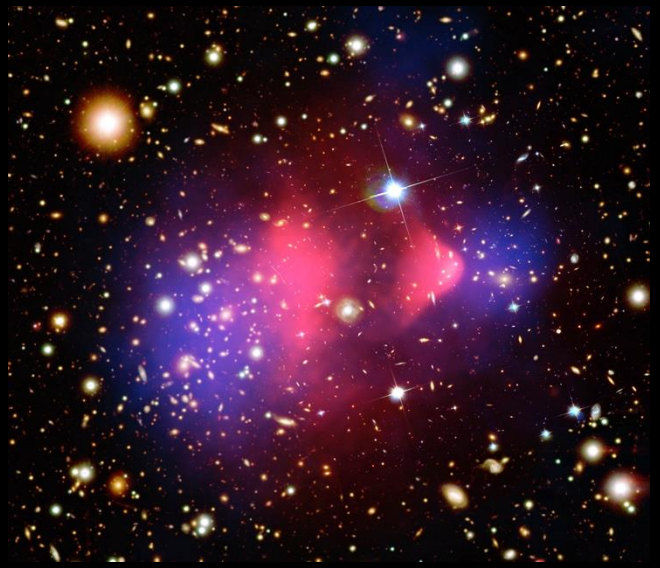
Search for instances of Dark Matter particles colliding with detectors on the Earth. Very tough, as Dark Matter only interacts gravitationally, and *perhaps* by the weak force.

- Indirect Detection Experiments:

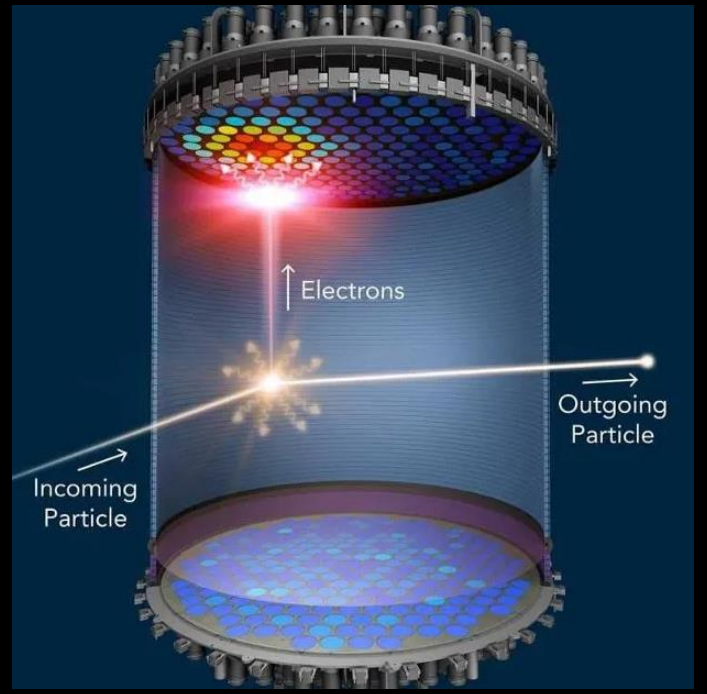
Search for the particles produced by Dark Matter particles interacting, rather than the direct interactions themselves.

- Astrophysical Detection:

Looking to the cosmos for evidence of Dark Matter. E.g. the bullet cluster.



The Bullet Cluster



The XENON experiment

Questions!

Coming Up…

The Science of Space: A Physicists Guide to the Galaxy

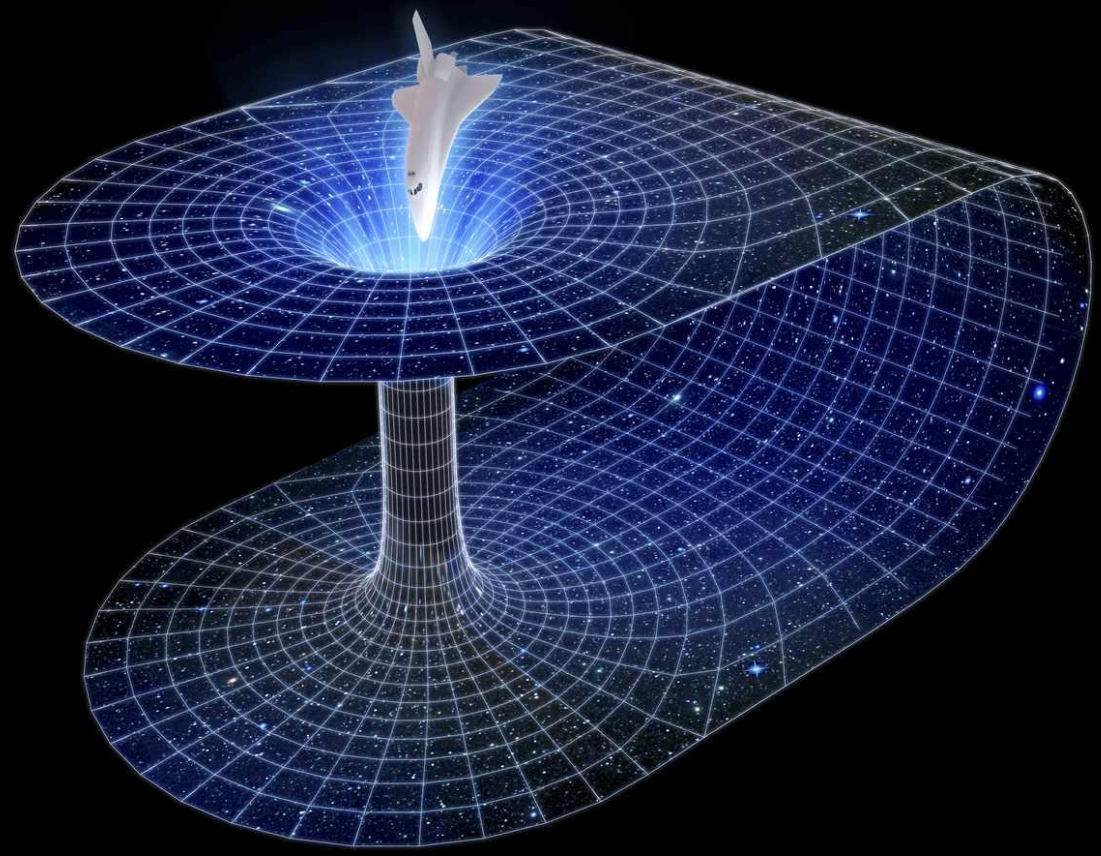
Every Sunday 11:30am in May @ The Beecroft Gallery Lecture Theatre

~~*'Our Place in the Cosmos' (04/05)*~~

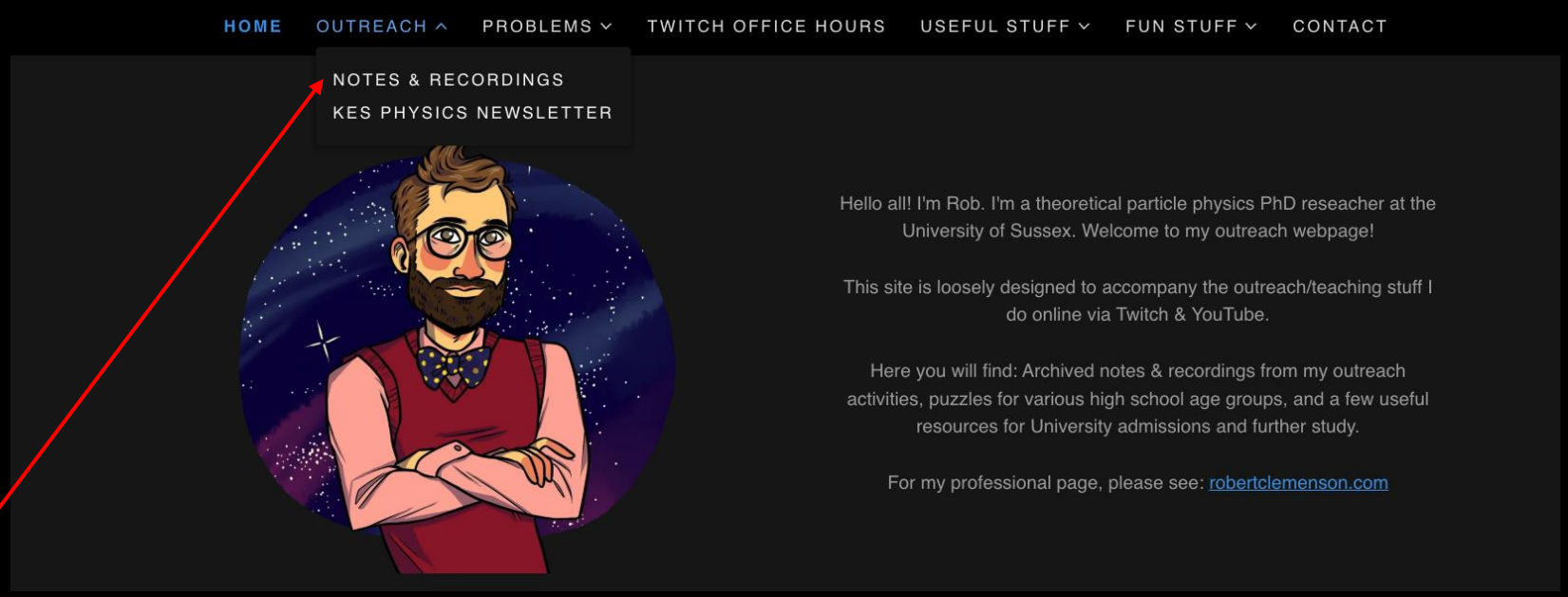
~~*'Schrodinger's Cat in the Particle Zoo' (11/05)*~~

'Time Travel 101' (18/05)

'Black Holes and Beyond' (25/05)



Lecture Slides



These lecture slides are available on my outreach website:

CosmicConundra.com