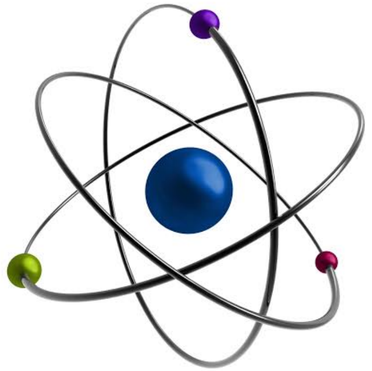
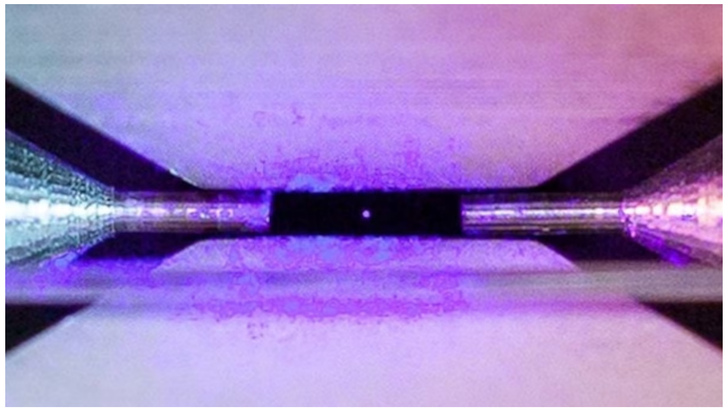
Quantum Mechanics

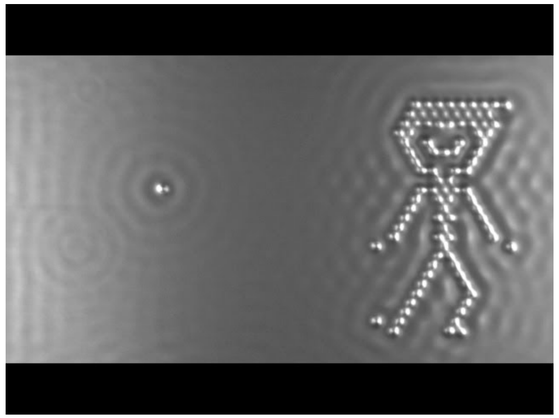
Saturday Morning Physics at Fermilab
Max Fieg

09/19/2026









Please, please, please ask questions



In a nutshell:

Quantum Mechanics is the study of the small

The world at big and small scales



Big

Small

The world at big and small scales

Big

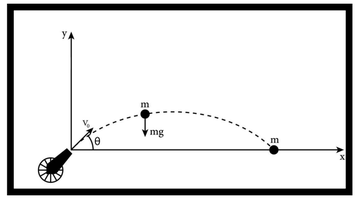
Small

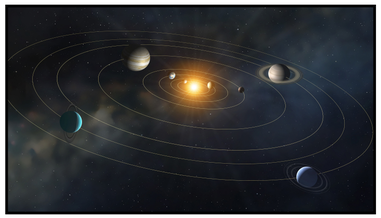
1643



Newton's **Laws**

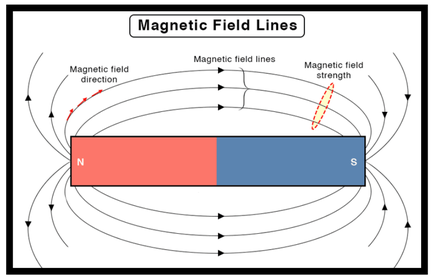
$$\overrightarrow{F} = m\vec{a}$$





1831





Maxwell's Equations

$$\nabla \cdot E = \rho/\varepsilon_0$$

Laws of thermodynamics

"…nearly all the manifold movements are caused by a most simple, magnetic, and material force, just as all motions of the clock are caused by a simple weight."
-Johannes Kepler

“Classical Mechanics” is how we describe our everyday world

Big

Newton’s **Laws**

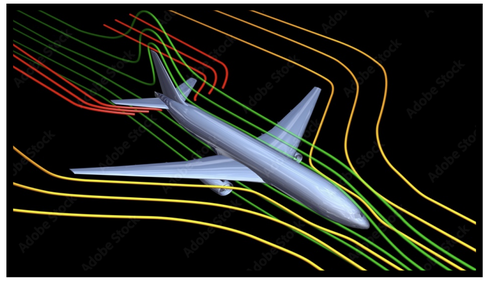




Laws of thermodynamics

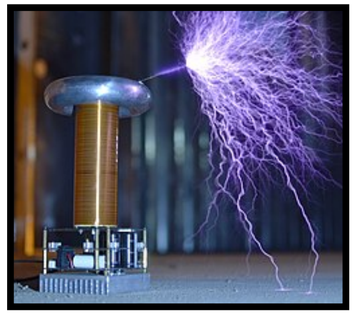






Maxwell’s Equations





Makes sense and works very well

The world at big and small scales

Big

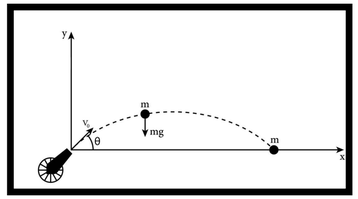
Small

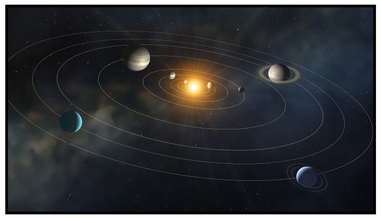
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Newton's **Laws**

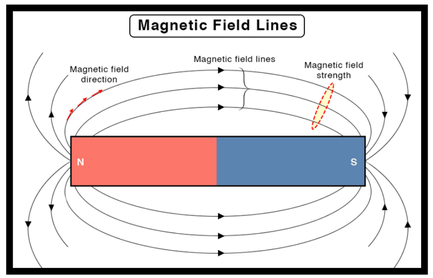
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Maxwell's Equations

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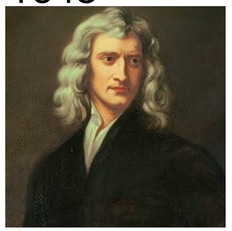
Laws of thermodynamics

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The world at big and small scales

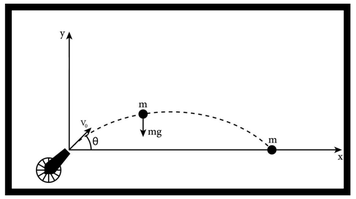
Big — Small

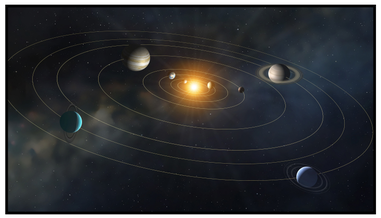
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Newton's **Laws**

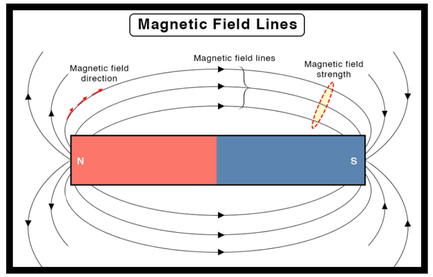
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1831





Maxwell's Equations

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Laws of thermodynamics

Classical mechanics an

incredible success!

In early 20th century, people applied the same reasoning to the small

These "laws" should also work there…right?

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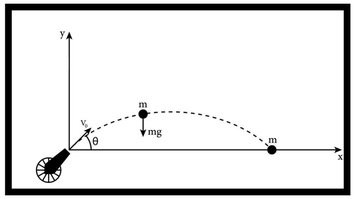
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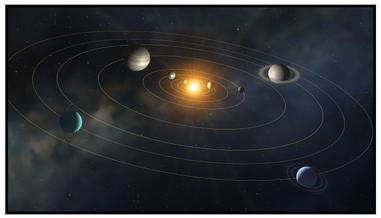
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Newton's **Laws**

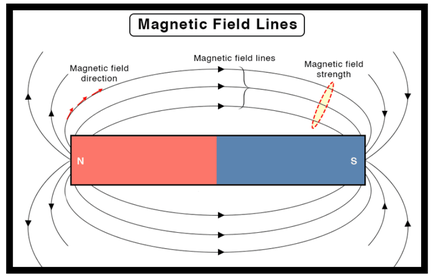
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Classical mechanics an

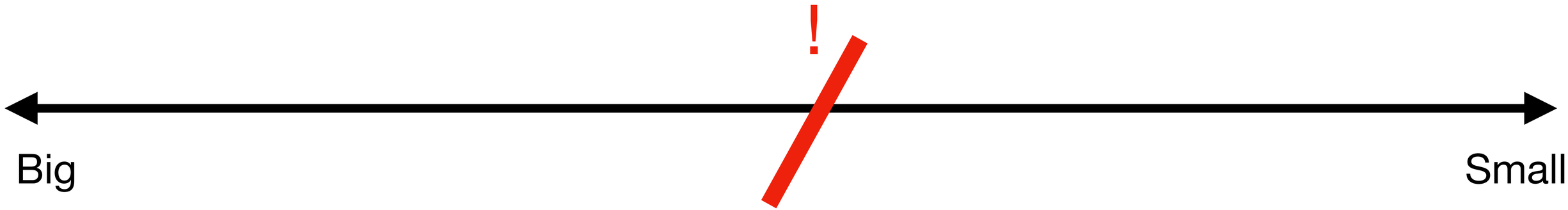
incredible success!

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No!

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Classical mechanics

Quantum mechanics

Classical mechanics completely breaks down at small scales

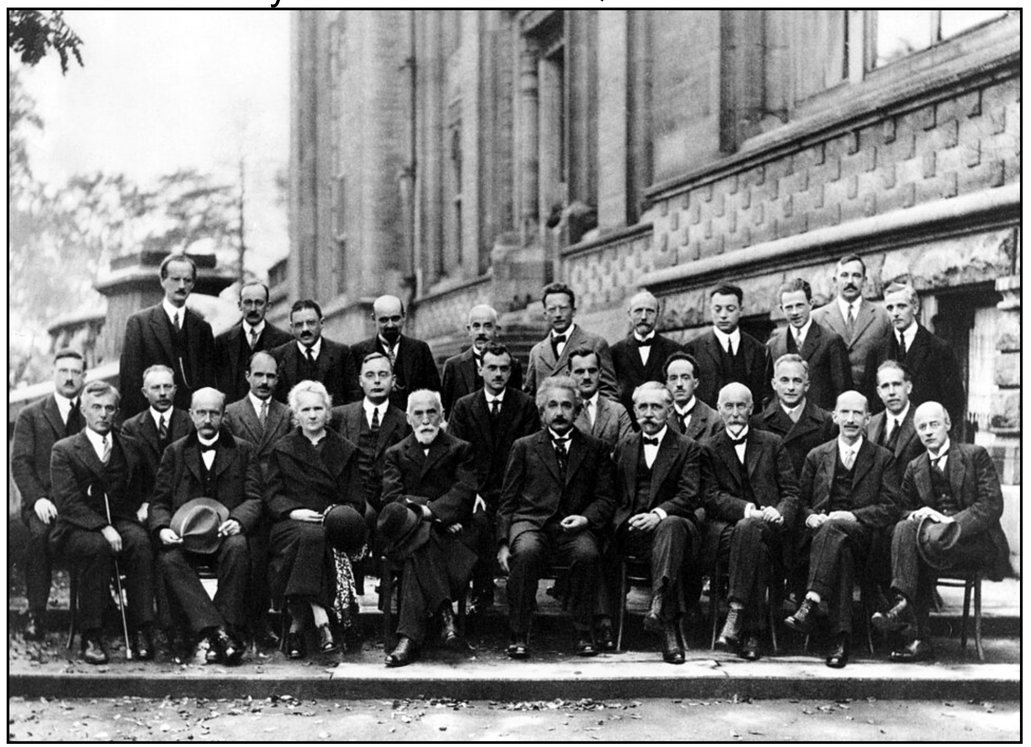
For those who are not shocked when they first come across quantum theory cannot possibly have understood it.
--Niels Bohr

I think I can safely say that nobody understands quantum mechanics.
-- Richard Feynman

Our job for today

- How did we discover quantum mechanics?
- What is it and what makes it so weird?
- How do we know it is true?

1927 Solvay Conference on Quantum Mechanics



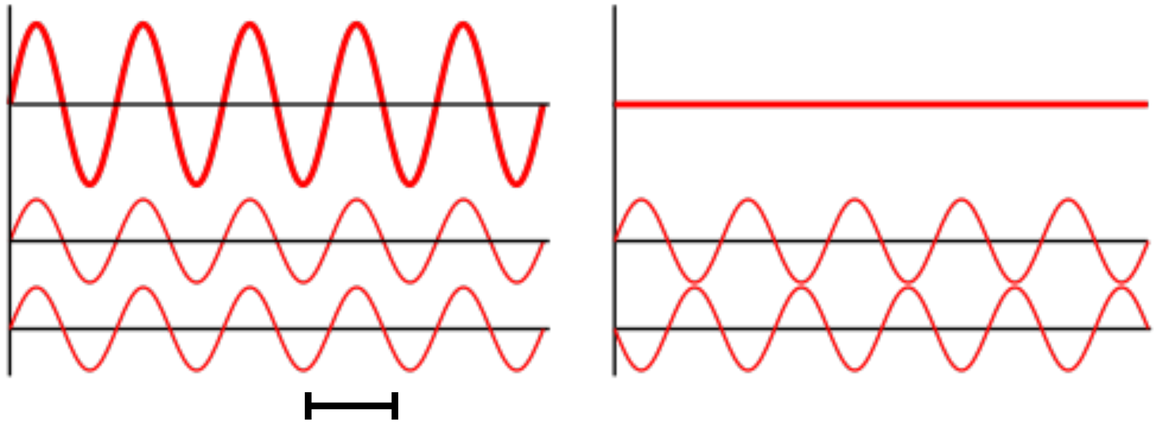
The discovery of quantum mechanics started with the study of light

Light was known to be a wave

Light as a wave

Constructive

Destructive



$$\text{wavelength} = \lambda$$

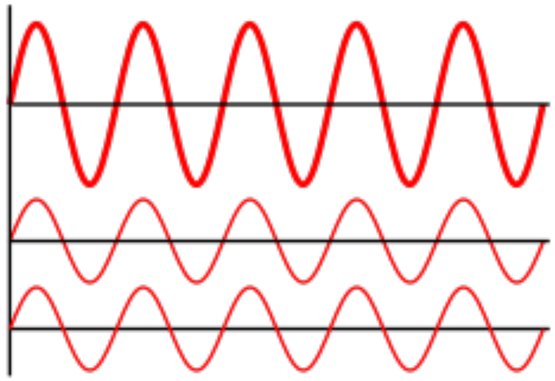
$$\text{frequency} = \nu = \frac{c}{\lambda}$$

Wave properties

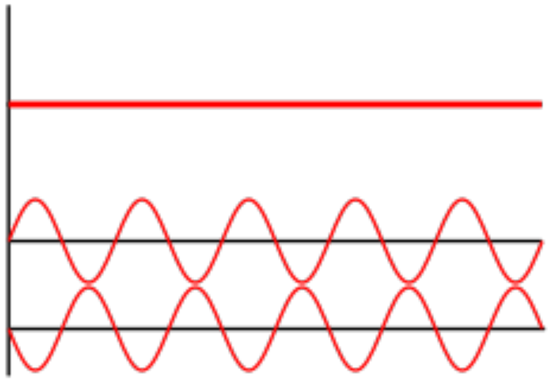


Light as a wave

Constructive

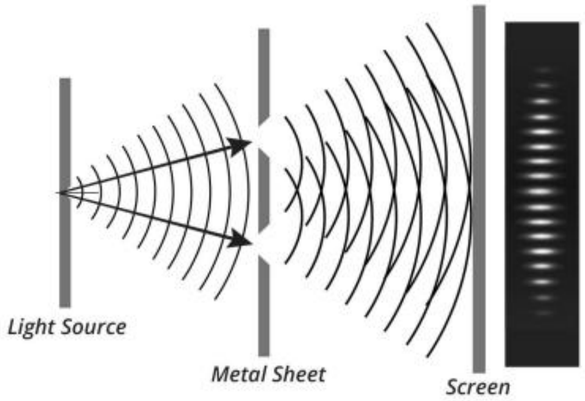


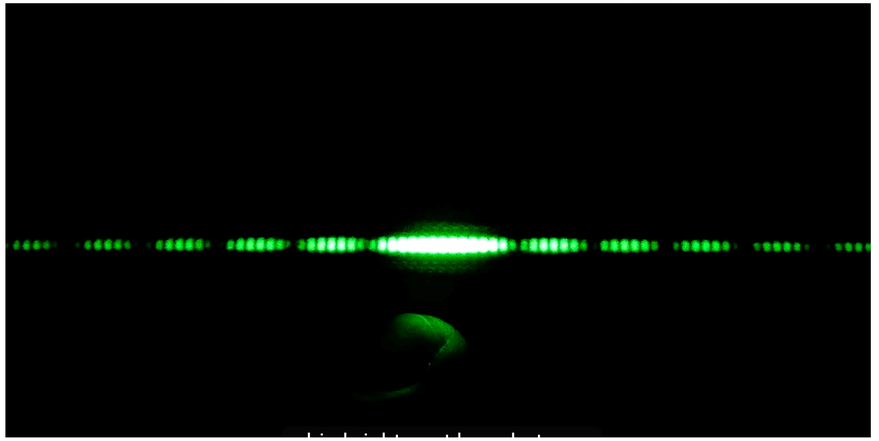
Destructive





Light waves do the same thing





The beginning of the end of classical physics

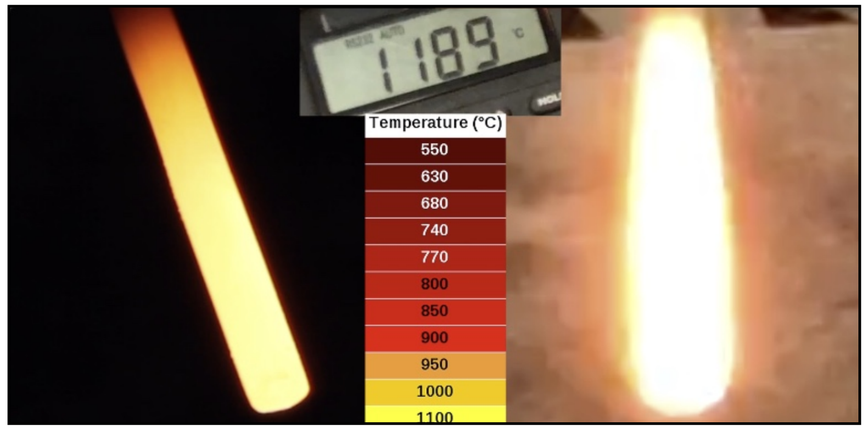


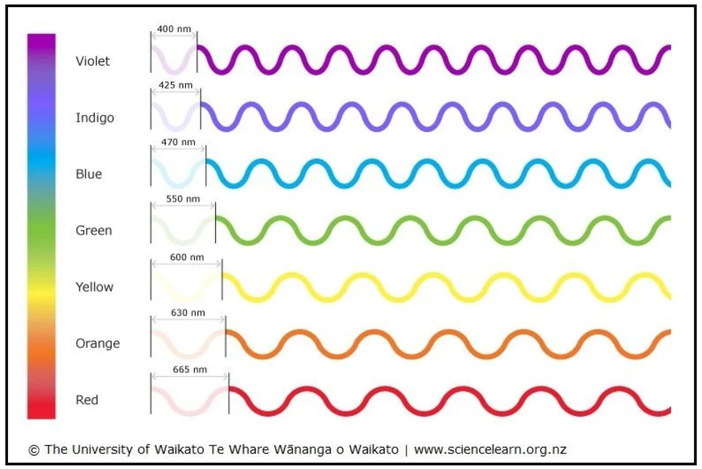
Max Planck

- Asked:

What color does a hot object glow?

Can we predict the spectrum of colors?





- At the time, light was thought to act wave where different colors have different wavelengths
    - Radio, infrared, visible, ultraviolet…

The beginning of the end of classical physics



Max Planck

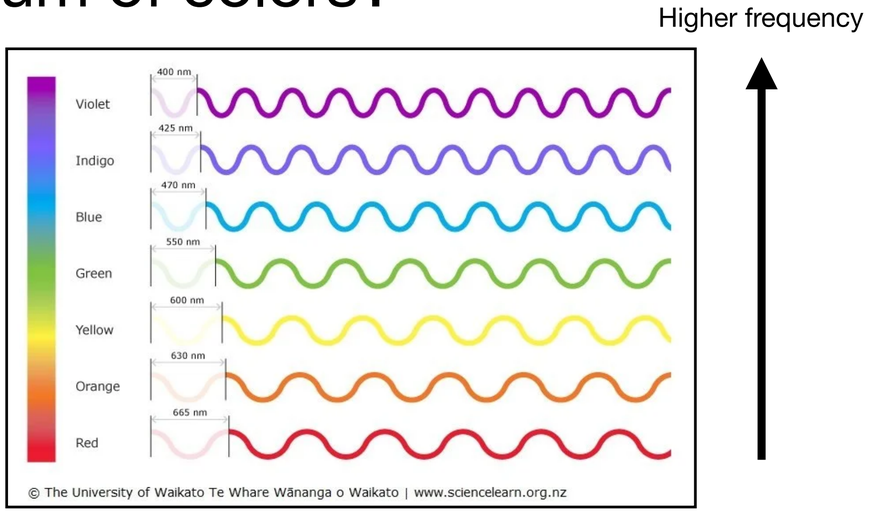
- Asked:

What color does a hot object glow?

Can we predict the spectrum of colors?

Using the laws of thermodynamics and Maxwell's equations, the reasoning goes like this:

- Heat is shared out among all the ways light can wiggle inside the hot object
- Each frequency gets the same average energy
- There are far more high-frequency light waves than low-frequency ones



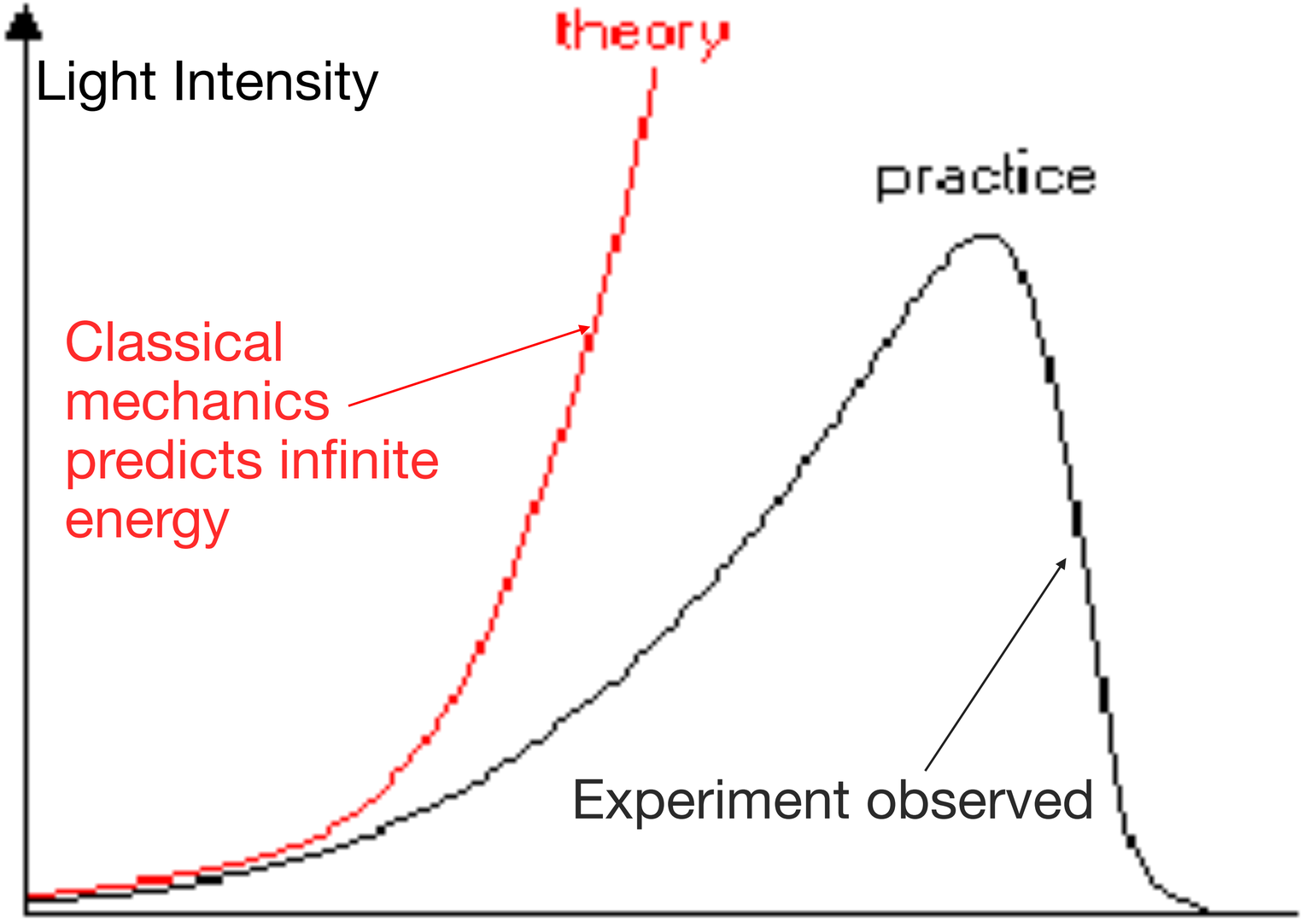
→ Hot objects should glow more with high frequency light

Known as "equipartition theorem"

The beginning of the end of classical physics



Max Planck

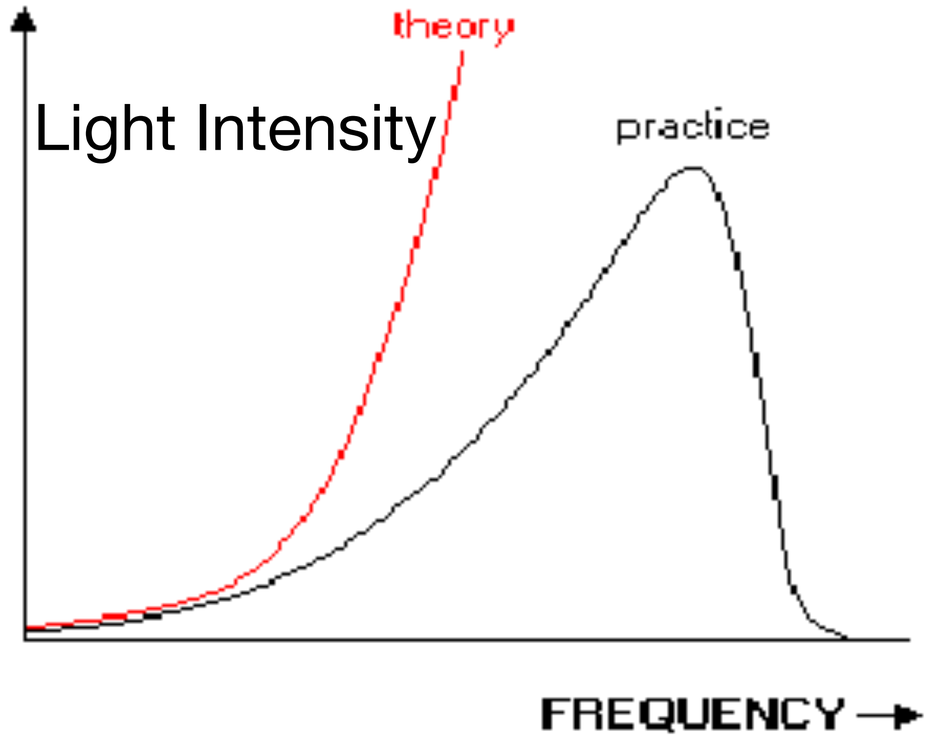




The **Ultraviolet Catastrophe**

Everyone agreed that classical mechanics was correctly applied

(and it was)



So Planck made a guess

"*What I did can be described as simply an act of desperation*"

"*…I didn't reflect much on what I was doing*"

-Max Planck



Planck's guess



Max Planck

- Light can only be emitted in discrete chunks that he called

"Quanta"

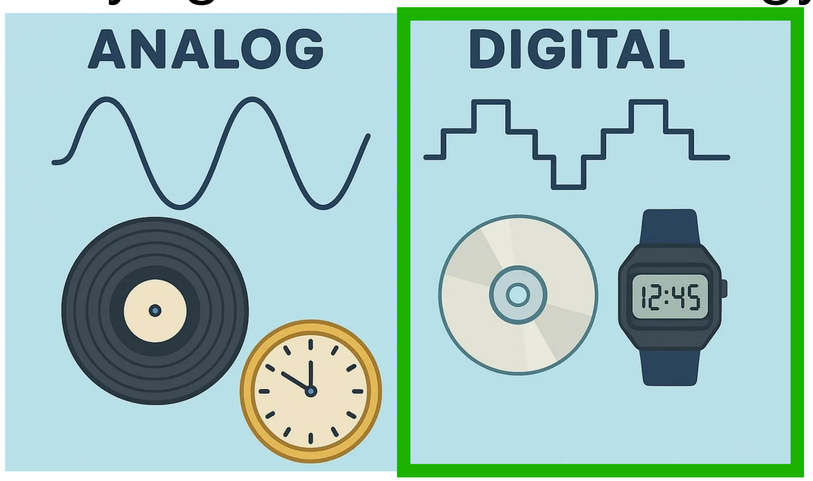
- Each quanta has a specific energy associated with it

$$\text{Energy} = h \times \text{frequency}$$

$$h = \text{Planck's contant} = 6.62 \times 10^{-34}\ \text{Joule} \cdot \text{seconds}$$

- High frequency light costs more energy

A fundamental constant of the universe



quantity

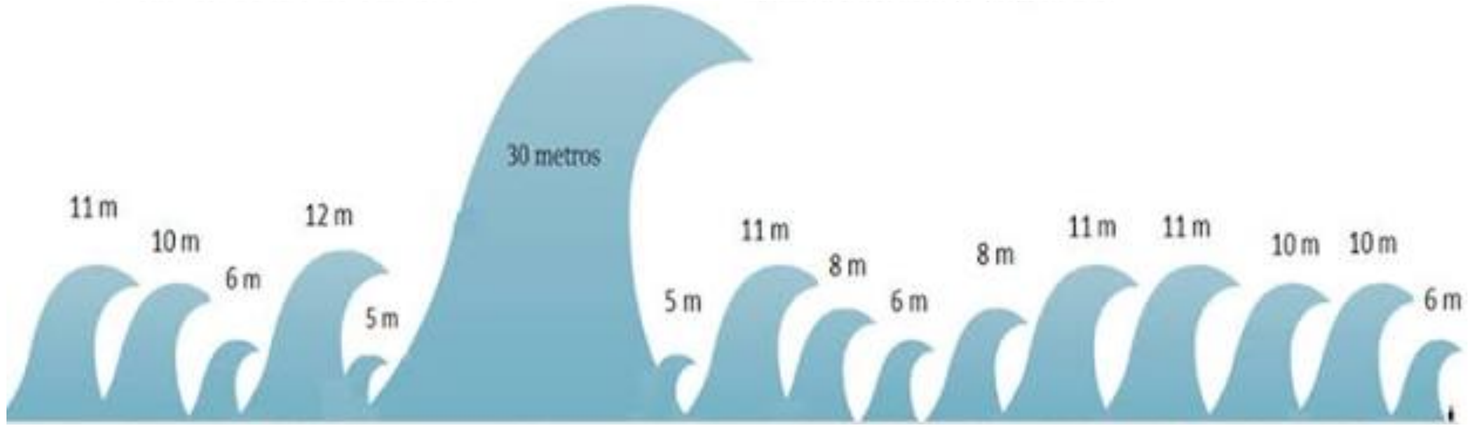
noun [C or U]

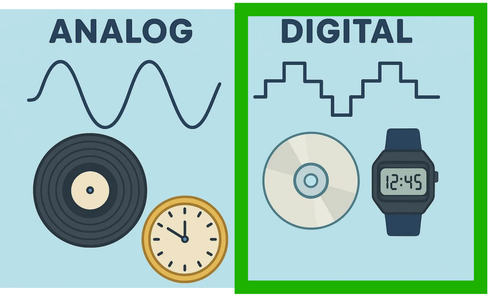
US /ˈkwɑːn.ţə.ţi/ UK /ˈkwɒn.tə.ti/

B1

the amount or number of something, especially that can be measured:

What is the height of the smallest water wave that could be made?





Planck's guess



Max Planck

- Light can only be emitted in discrete chunks that he called

"Quanta"

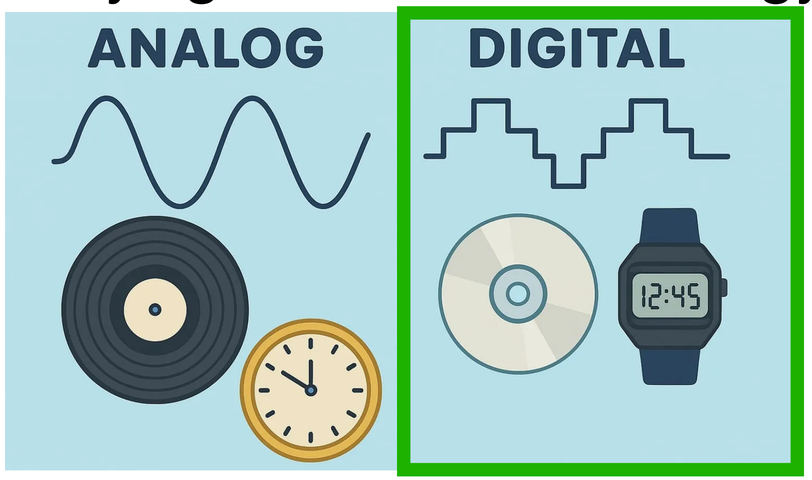
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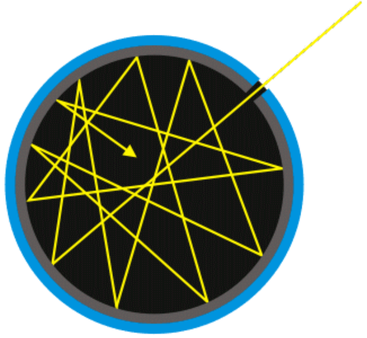
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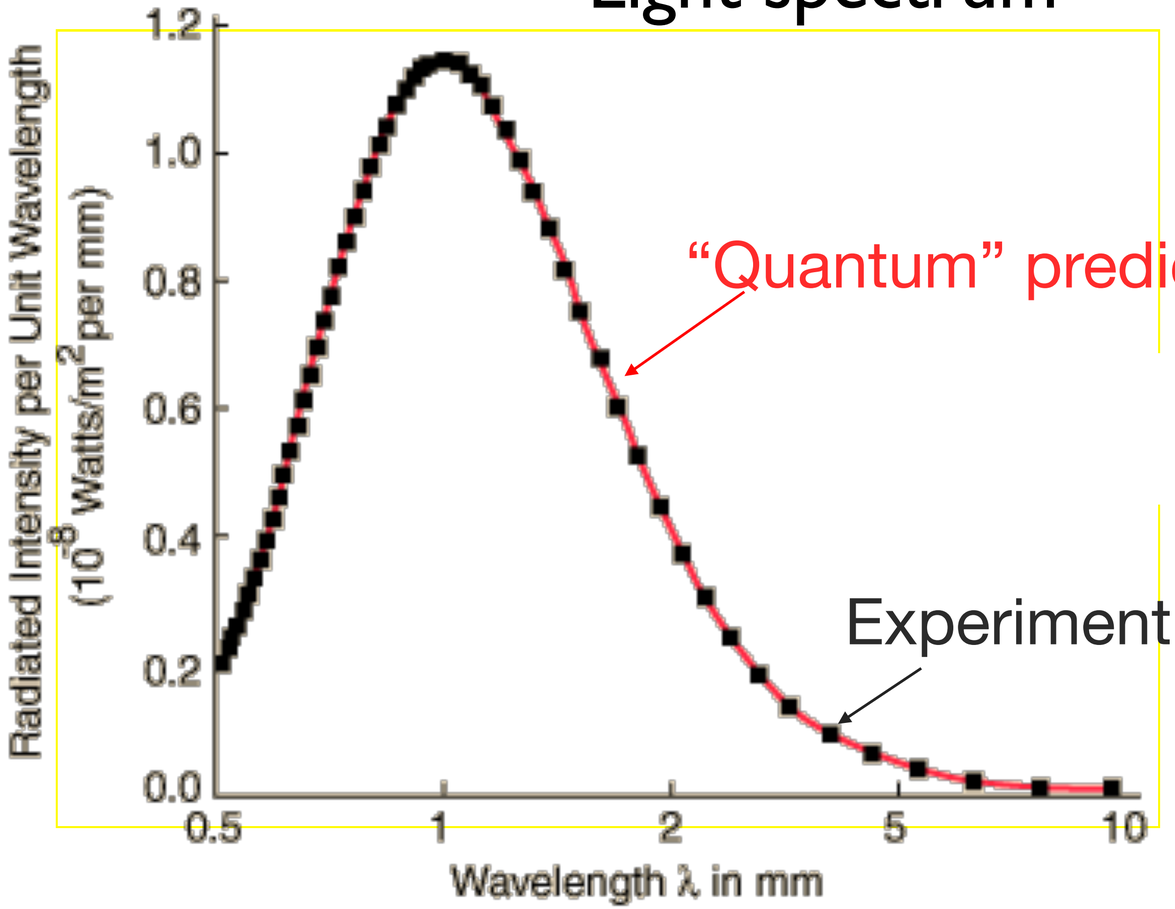
Planck's guess worked



Max Planck



Light spectrum



Light can only be emitted and absorbed in discrete units of energy, QUANTA

Why it took so long to notice quanta

How many quanta of light are emitted from the light bulb above us?

$$E = h\nu = hc/\lambda$$

$$h = 6.626068 \times 10^{-34} kg\, m^2/s = 6.62608 \times 10^{-34} Js$$

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8 m/s}{600nm} = 5 \times 10^{14} Hz$$



$$E_q = (6.6 \times 10^{-34} Js)(5 \times 10^{14} s^{-1}) = 3.3 \times 10^{-19} J$$

$$N = \frac{100 J/s}{E_q} = \frac{100 J/s}{3.3 \times 10^{-19} J} \approx 3 \times 10^{20}/s$$!!!

Why it took so long to notice quanta

How many quanta of light are emitted from the light bulb above us?

$$E = h\nu = hc/\lambda$$

Planck's constant

$$h = 6.626068 \times 10^{-34} kg\, m^2/s = 6.62608 \times 10^{-34} Js$$

Visible light frequency

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8 m/s}{600nm} = 5 \times 10^{14} Hz$$



Quanta energy

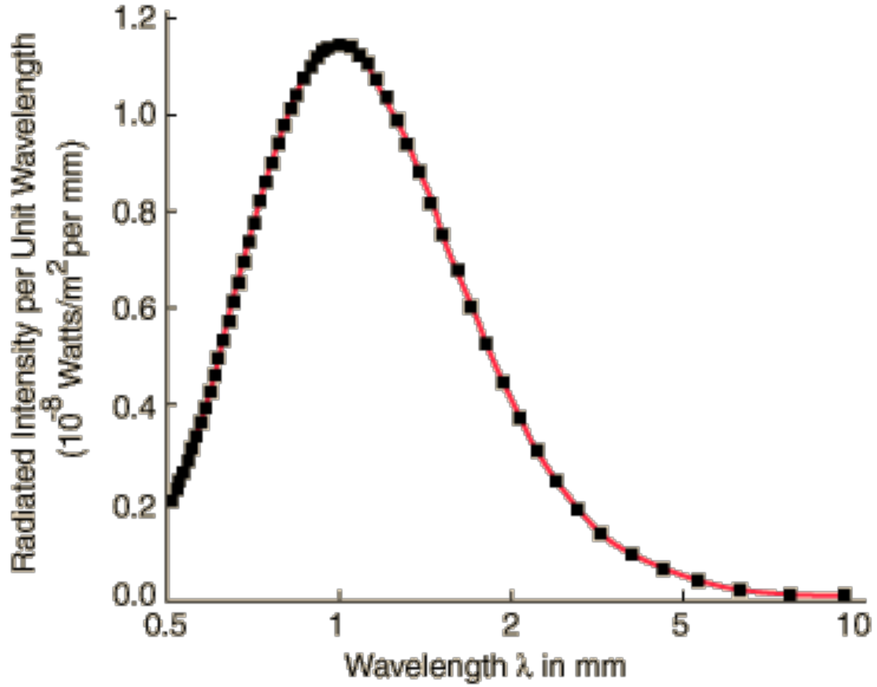
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Number of visible quanta

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Evidence #1 for Quanta:

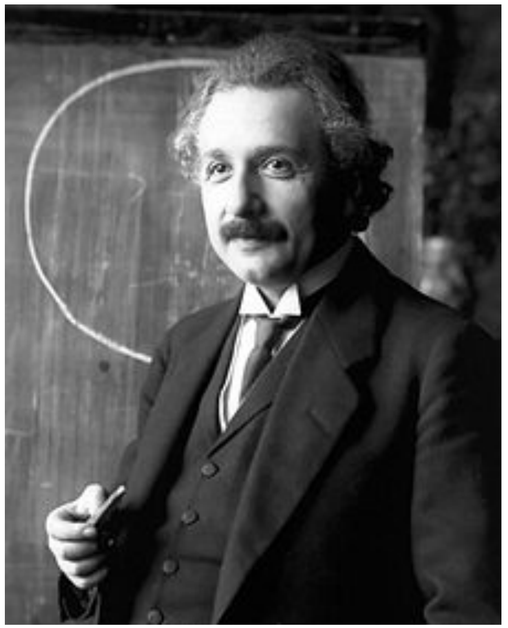
Correctly predicts the light spectrum of hot objects



Evidence # 2

The separate puzzle of…

$$E = h\nu = hc/\lambda$$



Albert Einstein



The photoelectric effect

Electrons are bound to metals

a) Shining light on metal free electrons and produces an electrical current



b) A brighter light source (more quanta) produces more current

UNLESS

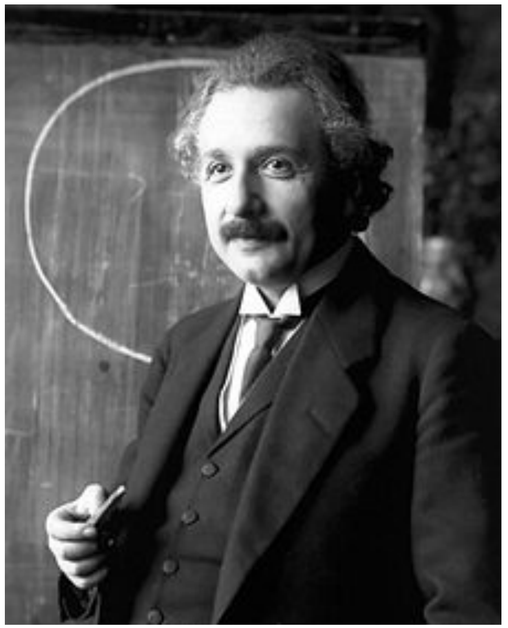
c) The light frequency is too small

- Then there is no current, no matter how bright the light is

What is the resolution?

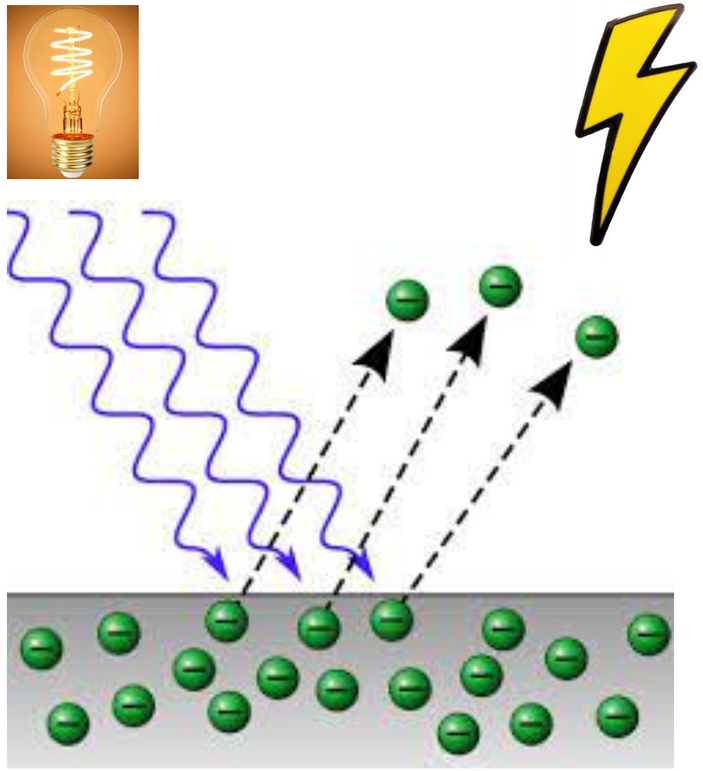
Evidence # 2: the photoelectric effect

$$E = h\nu = hc/\lambda$$

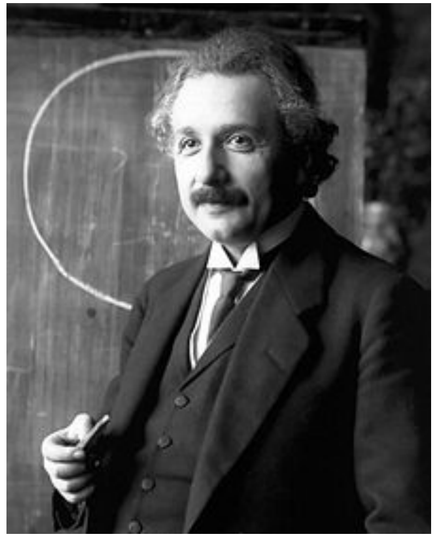


Albert Einstein 

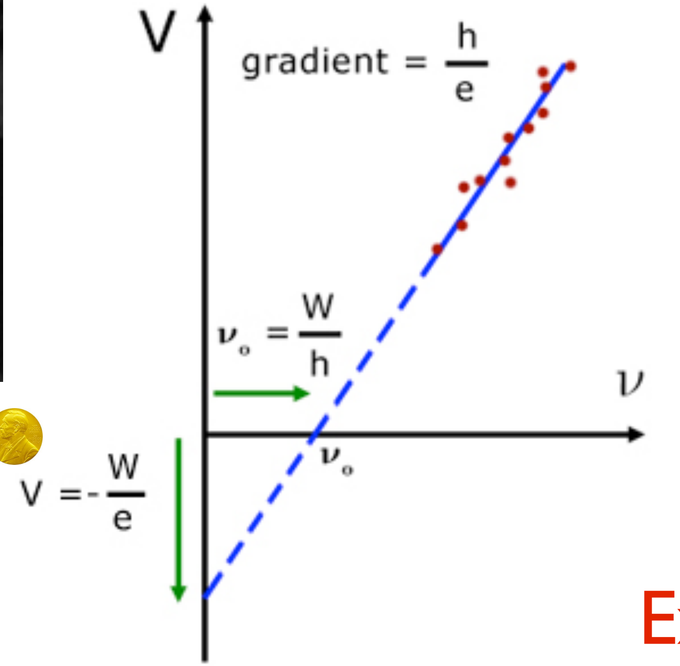
- Electrons are trapped with a certain binding energy, E_{bound}
- Quanta of light, “photons”, hit the electrons in the metal, one at a time, with energy $E = h\nu$
- If $h\nu > E_{\text{bound}}$
  - Electrons are freed. More light → more electrical current
- If $h\nu < E_{\text{bound}}$
  - Electron cannot be freed



Evidence # 2: the photoelectric effect



Albert Einstein

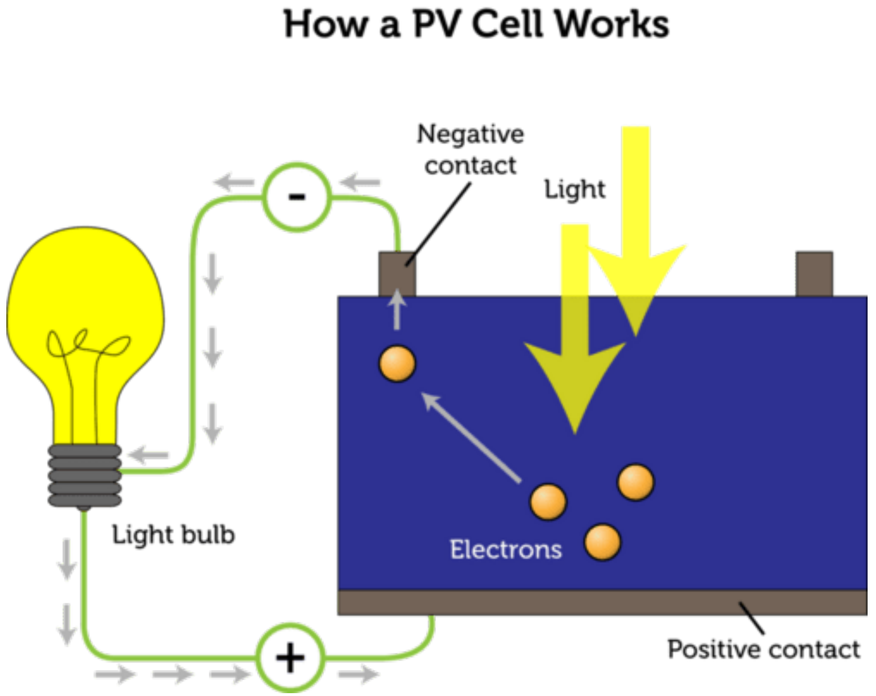


$$K.E. = E_{\text{photon}} - E_{\text{bound}}$$

$$\frac{1}{2}mv^2 = h\nu - W$$

Explains photoelectric effect
Light is a particle!

This is how solar panels work



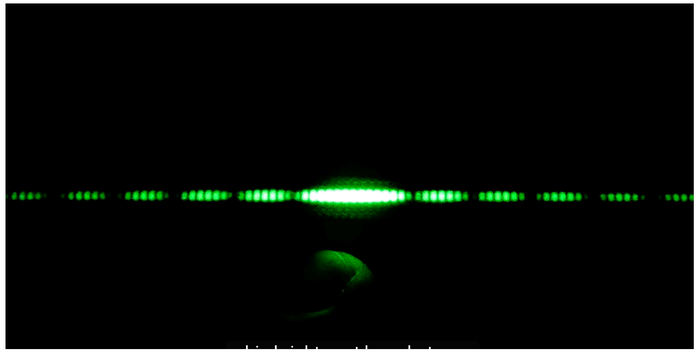
- High energy photons from the sun hit the panel, free electrons, and produce electricity

- If the light didn't come in discrete chunks, then we could use giant mirrors to focus low-energy light from the cosmos and get unlimited power



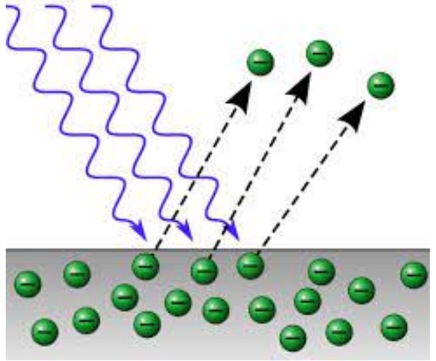


- So light is a wave



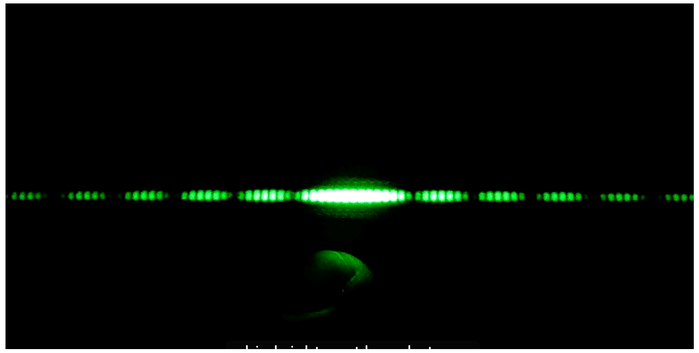
- And a quanta or “particle”

$$E = h\nu = hc/\lambda$$



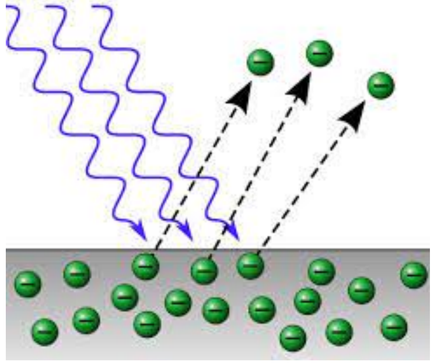
Which is it?

- So light is a wave



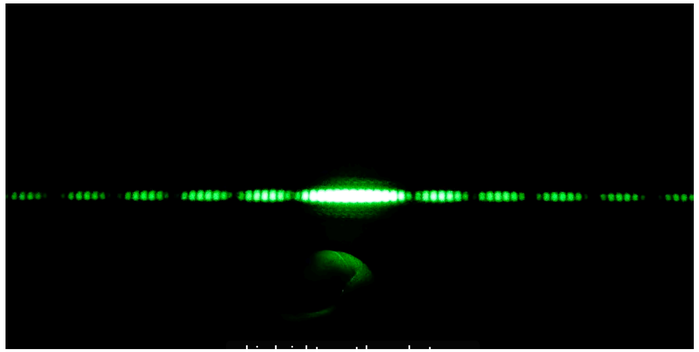
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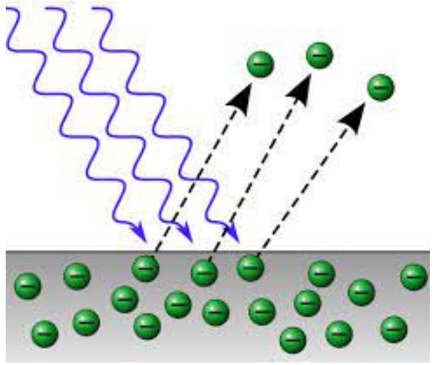


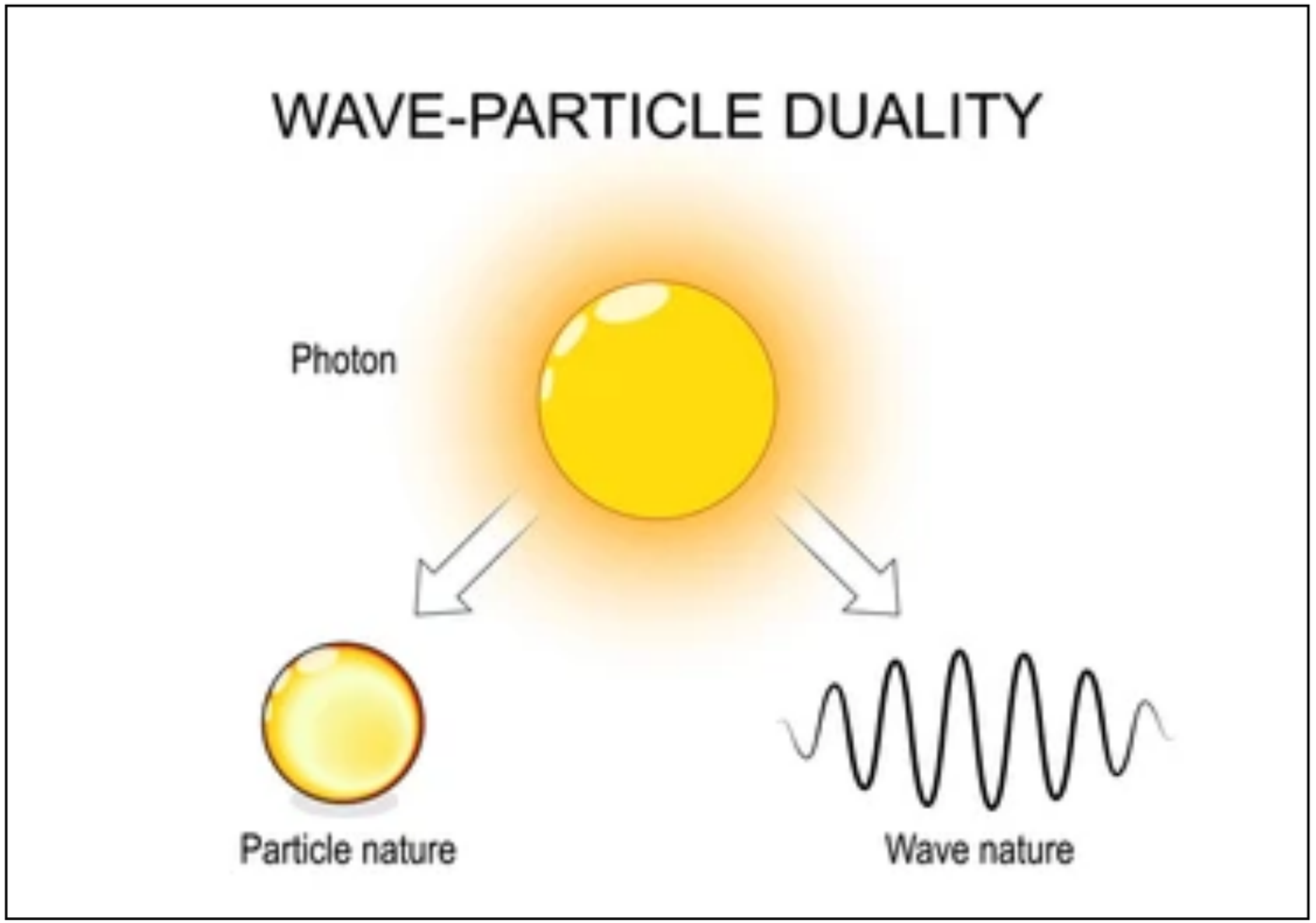
- So light is a wave



- And a quanta or “particle”

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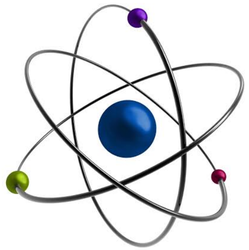
Evidence #3

Light observed sometimes as a wave, sometimes as a particle



Louis de Broglie

Electrons had been observed as particles



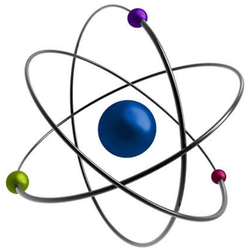
Evidence #3



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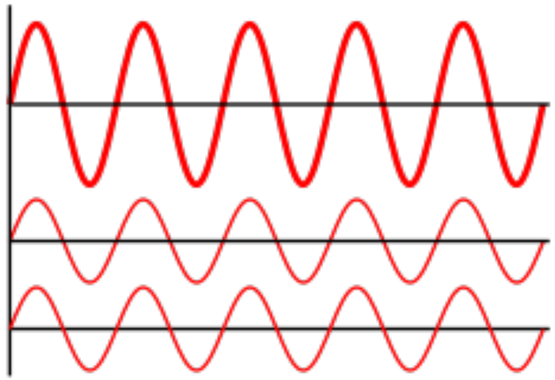
"*The electron can no longer be conceived as a single, small granule of electricity; it must be associated with a wave, and this wave is no myth; its wavelength can be measured and its [wave nature] predicted*"

- Louis de Broglie

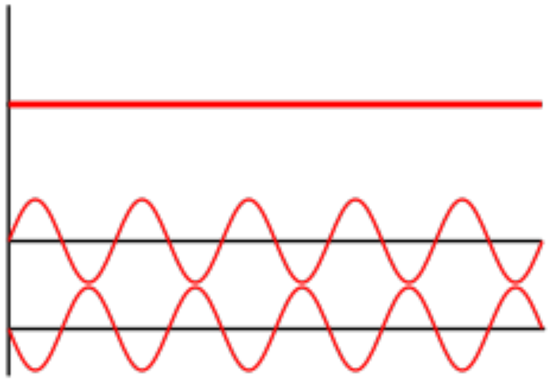
How can we test this?

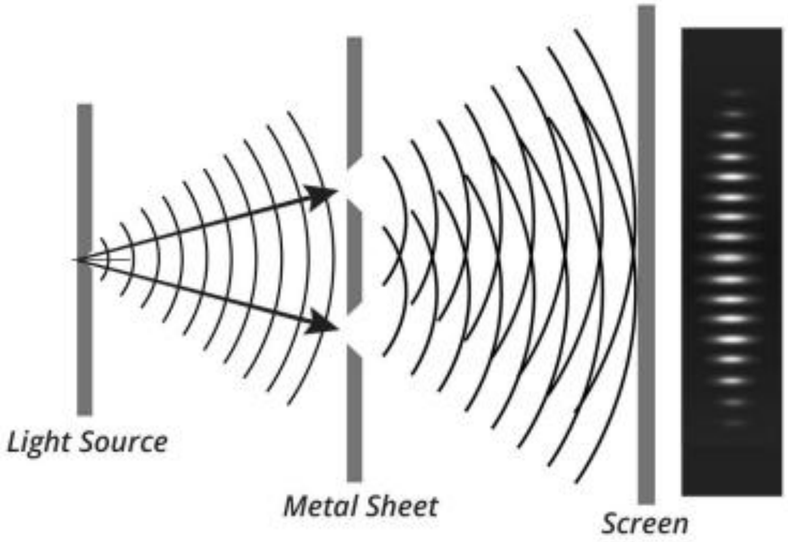
We tested the wave pattern with light

Constructive



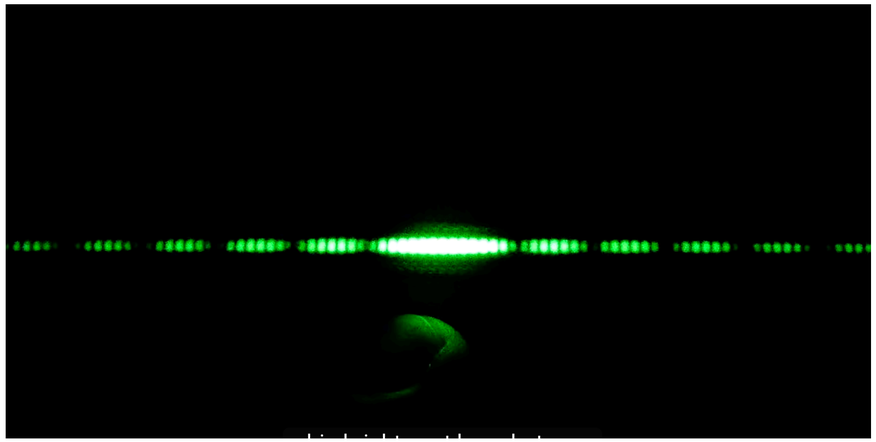
Destructive





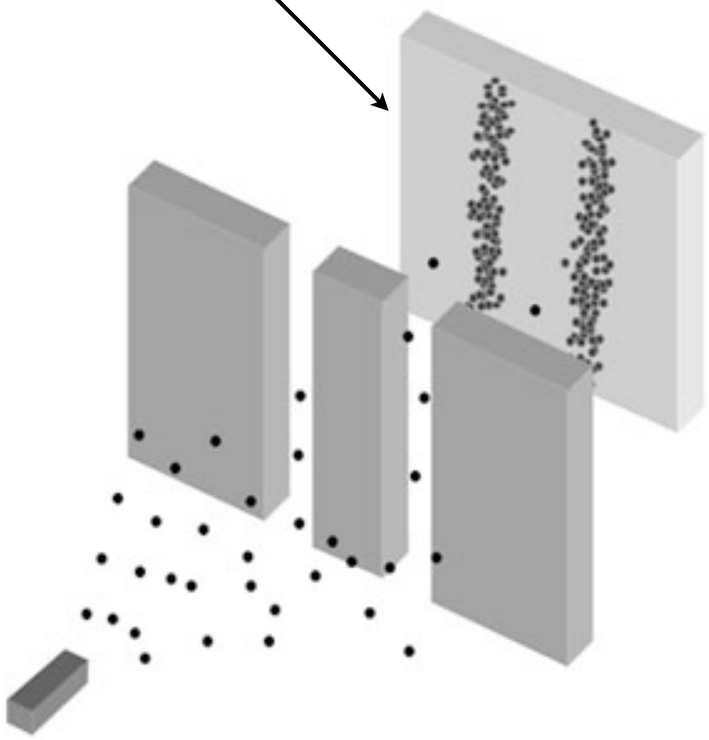
The “Double Slit” experiment

Light waves do the same thing



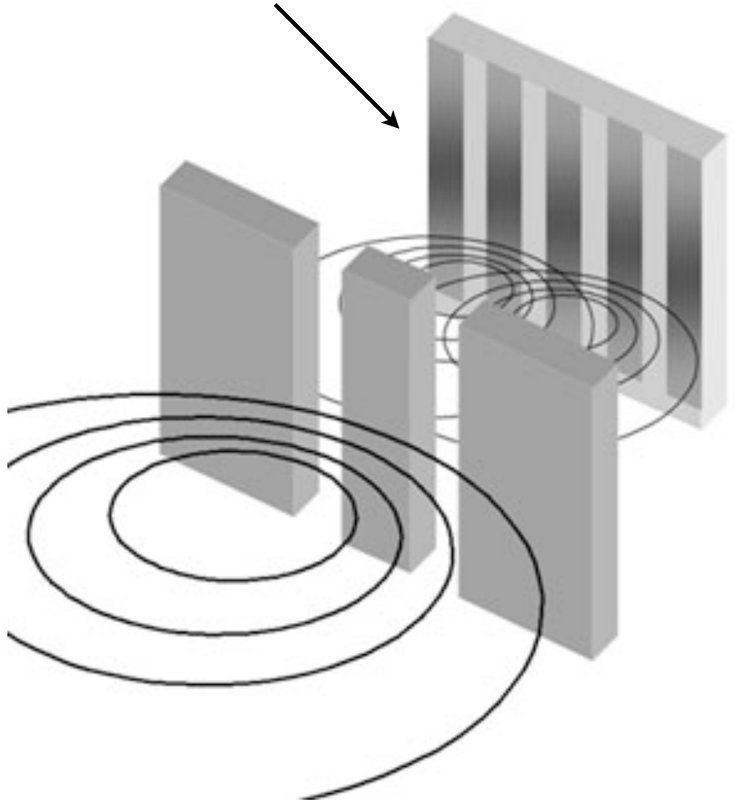
The “Double Slit” experiment

Clustered around which hole the particle went through



Classical particles, e.g. bullets

“Interference pattern”, the wave went through both slits

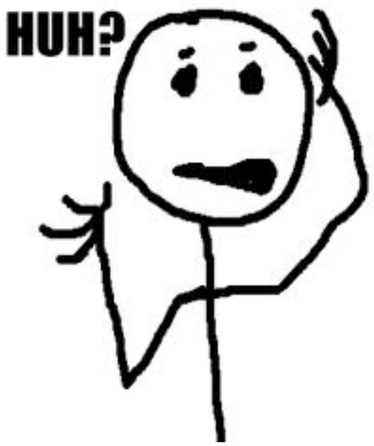


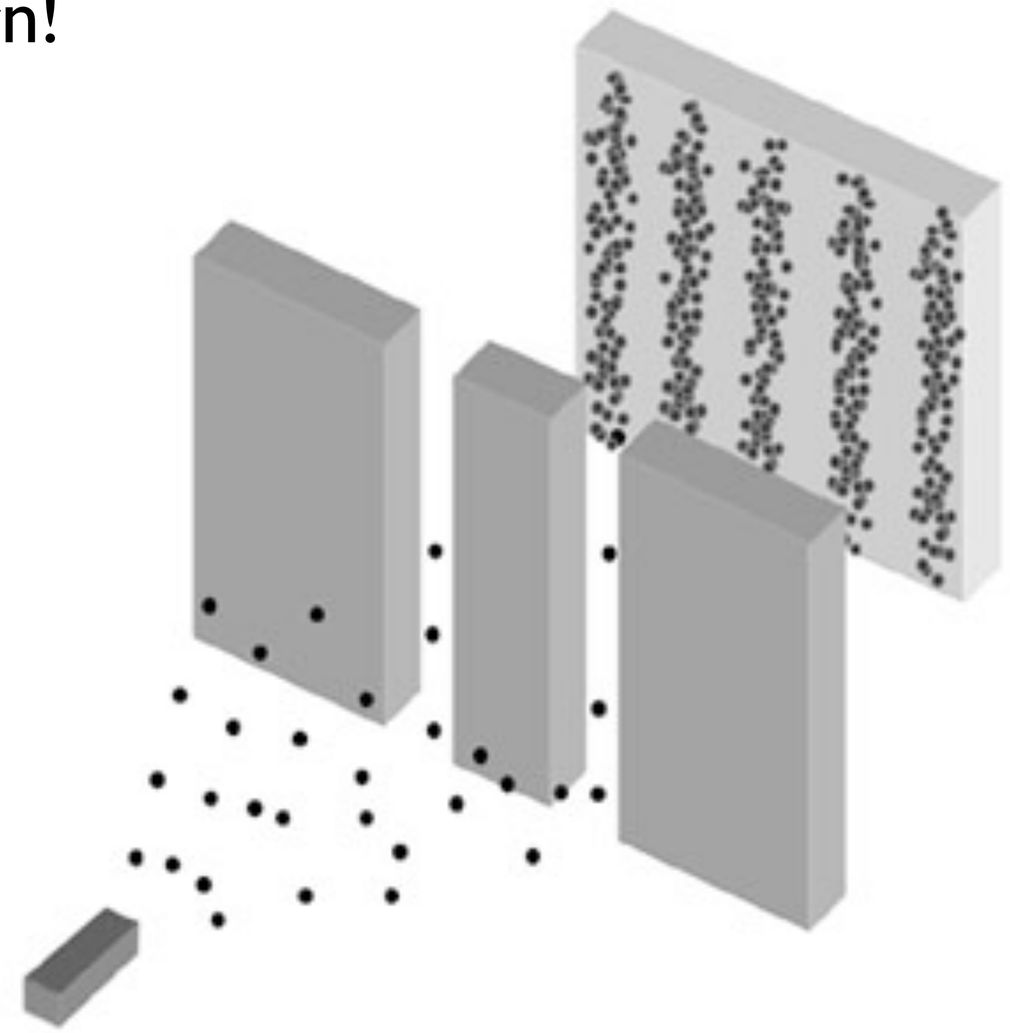
Waves, e.g. on water surface

Let’s do this with electrons

The double slit experiment with electrons

Interference pattern!
Waves of what?







So electrons, and all particles, also have some wave nature

- Waves have some wavelength
  - Or some “fuzziness”
  - The particle is “spread out”
  - For light, and particles:

$$\text{wavelength} = \frac{h}{\text{momentum}}$$

Can calculate wavelength of a human



$$\text{wavelength} = \frac{\text{h}}{\text{mass} \times \text{velocity}} = \frac{6.6 \times 10^{-34}\ \text{kgm}^2/\text{s}}{100\ \text{kg} \times 1\ \text{m/s}} \approx 10^{-34}\ m$$

Localized!

So electrons, and all particles, also have some wave nature

- Waves have some wavelength
  - Or some “fuzziness”
  - The particle is “spread out”
  - For light, and particles:

$$\text{wavelength} = \frac{h}{\text{momentum}}$$



Can calculate wavelength of a proton

$$\text{wavelength} = 10^{-15}\ m$$

What is matter/electorns a wave *of*?


INTERMISSION

What is matter a wave of?



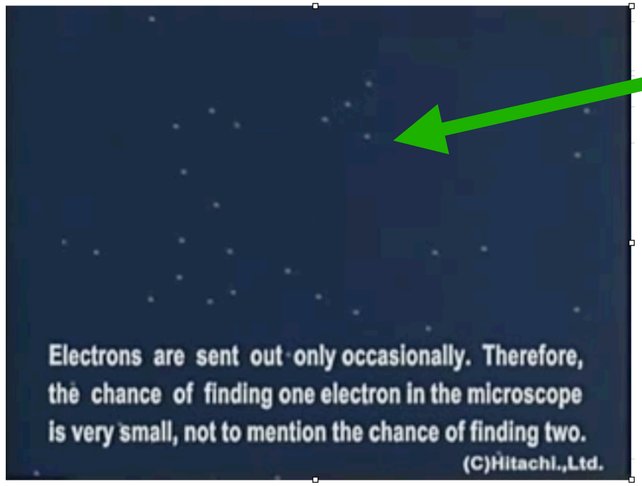
Erwin Schrödinger 

The quantum mechanical wave function

$$\Psi(x,t)$$

This is the wave that propagates

$$|\Psi(x,t)|^2$$



Cannot determine where an electron will land, only the probability that it will land somewhere

The quantum mechanical wave function

$$\Psi(x,t)$$

The probability for a particle to be at a point (x,t) is

$$|\Psi(x,t)|^2$$

Quantum mechanics is a probabilistic theory

Nature plays with dice

The quantum mechanical wave function

$$\Psi(x,t)$$

Many physicists job is to calculate this!

The probability for a particle to be at a point (x,t) is

$$|\Psi(x,t)|^2$$

Quantum mechanics is a probabilistic theory

Nature plays with dice

The Schrödinger equation



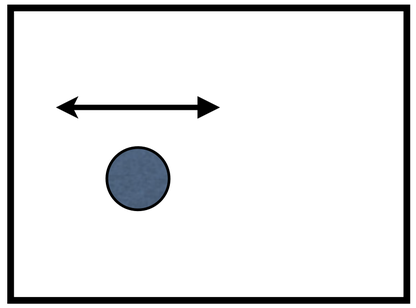
Erwin Schrödinger

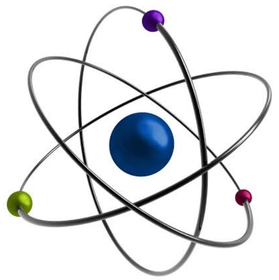
There is an equation that governs the evolution of the wavefunction

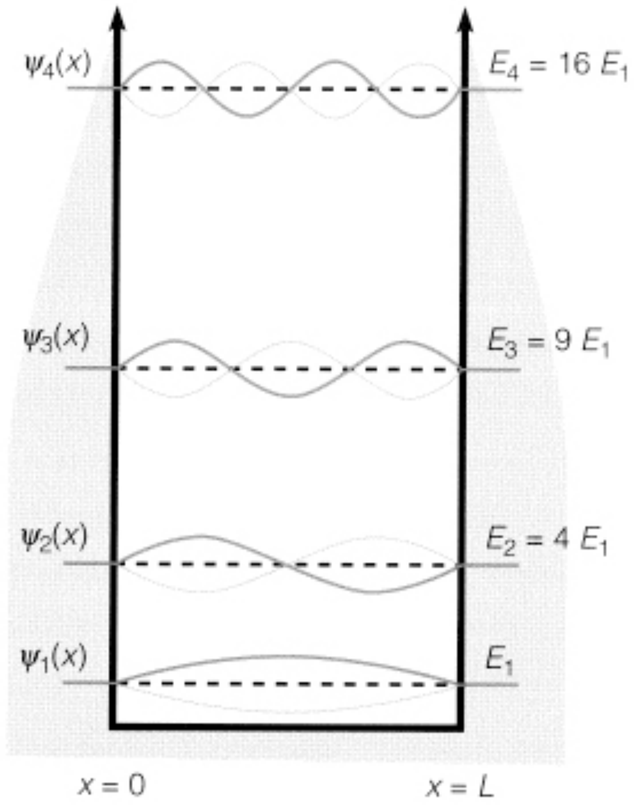
Can only ask questions like: what is the probability of seeing X?

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

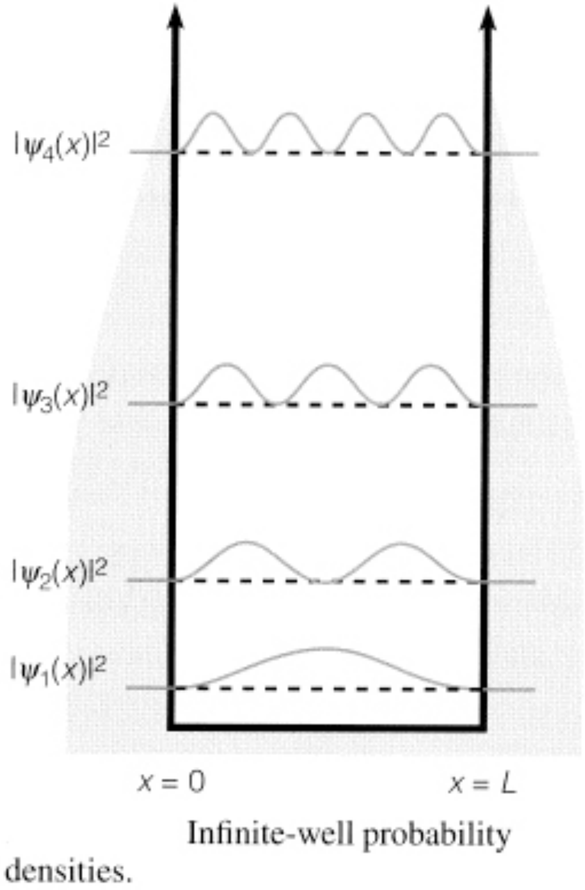
Particle trapped in a box







Infinite-well wave functions.



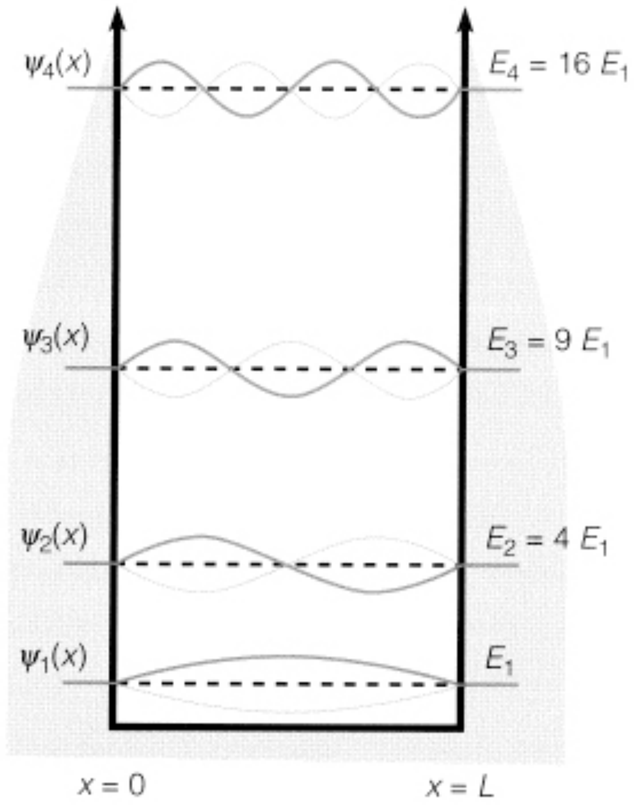
Infinite-well probability densities.

Our electrons are bound to the atoms, as if they were trapped in a box

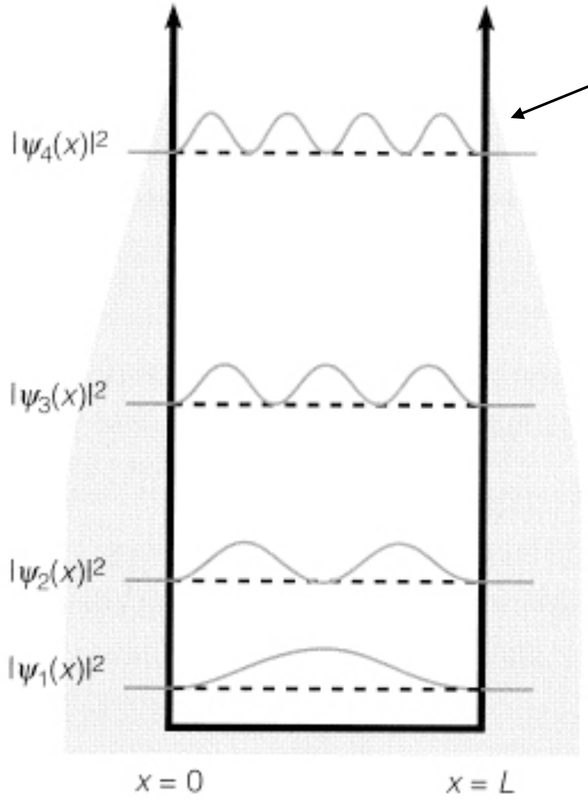
From this we can calculate where an electron is likely to be found

$$\Psi(x,t)$$

Higher frequency states



Infinite-well wave functions.



Infinite-well probability densities.

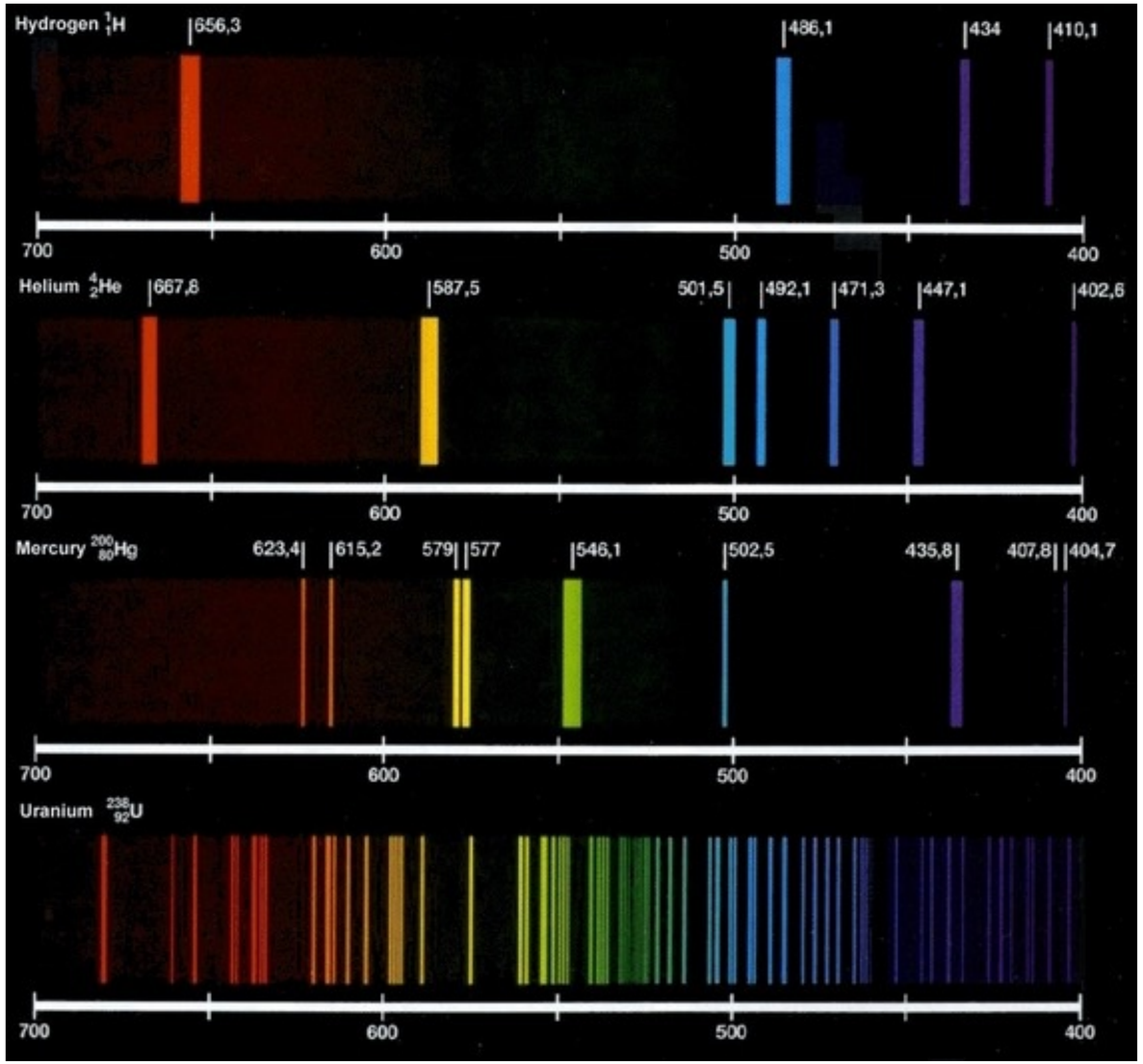
$$\Psi(x,t)$$

Another puzzle

Atoms gave off a characteristic light pattern

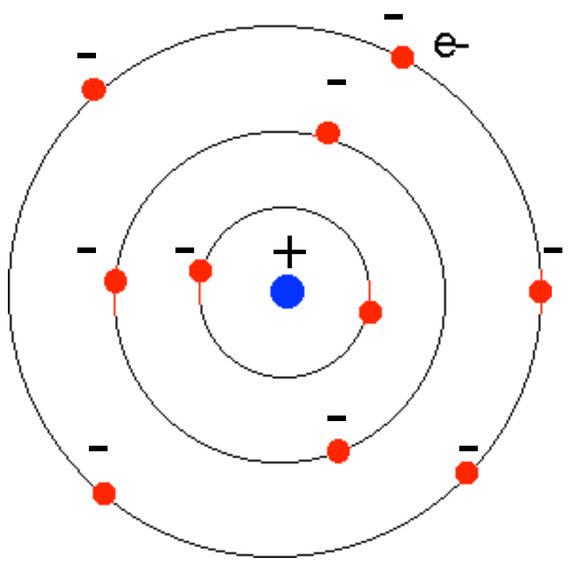
Light observed at discrete frequencies

Why?





Neils Bohr

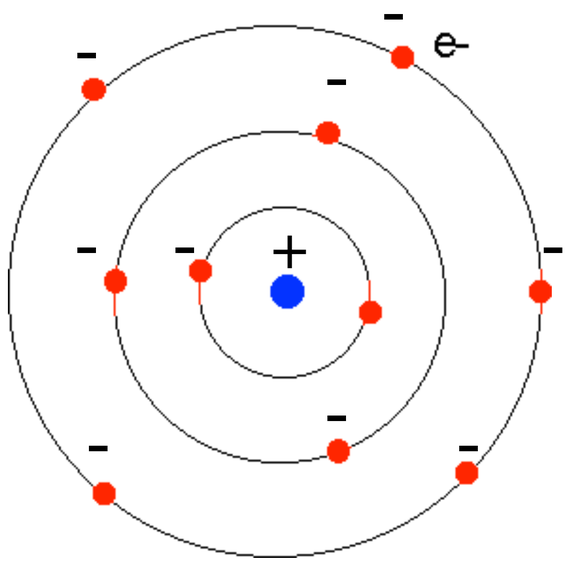


$$L \approx \text{Kinetic Energy/Radius} = n$$

"The angler momentum of electrons is quantized"

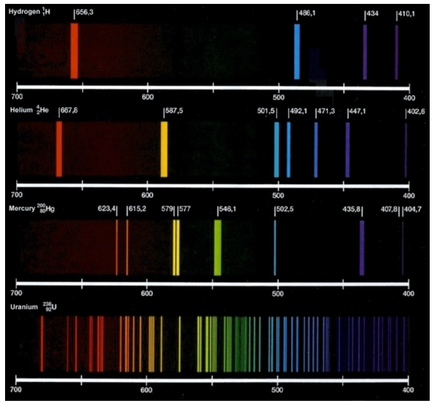


Neils Bohr



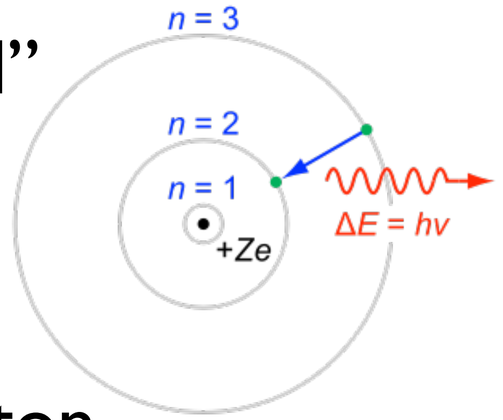
$$\nu \sim \frac{1}{n_1^2} - \frac{1}{n_2^2}$$

$$L \approx \text{Kinetic Energy/Radius} = n$$



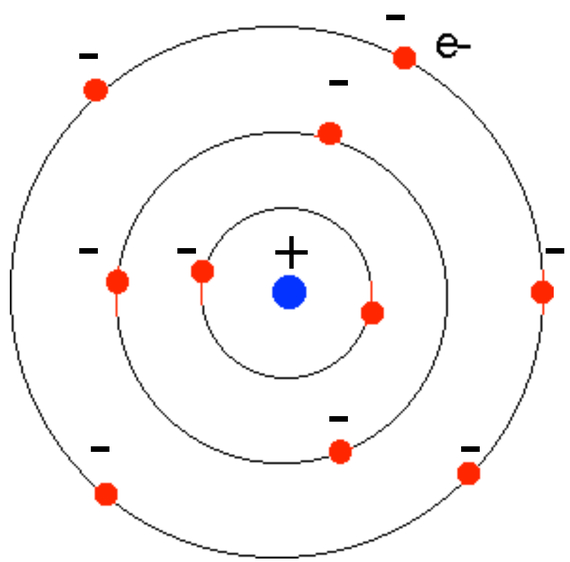
"The angler momentum of electrons is quantized"

Electrons prefer to live at discrete orbits



When they relax, they give off a characteristic photon

Why don’t electrons fall into the nucleus?



Heisenberg Uncertainty Priciple



Werner Heisenberg

$$\Delta p > \frac{\hbar}{a}$$

"The more precisely the position is determined, the less precisely the momentum is known in this instant, and vice versa."

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

HUP is an outcome of the wavelike nature of QM

Heisenberg Uncertainty Priciple



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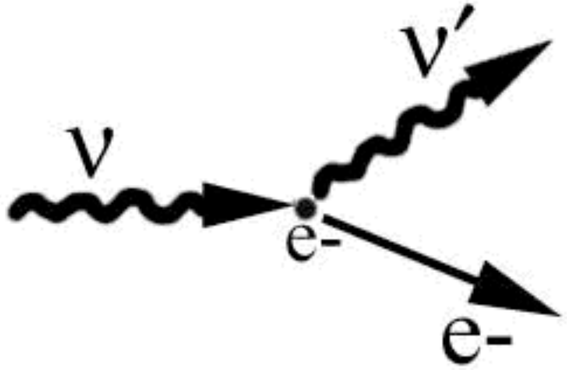
Fundamental information that we cannot know!

Try measuring a particle's position

The act of measurement disturbs the system

Use a "microscope" - shine light on an electron $\Delta x \Delta p \geq \frac{\hbar}{2}$

Shorter wavelength means better precision $\Delta x \sim \lambda$



Electron gains a momentum

$p \sim h/\lambda$

$\nu' < \nu$

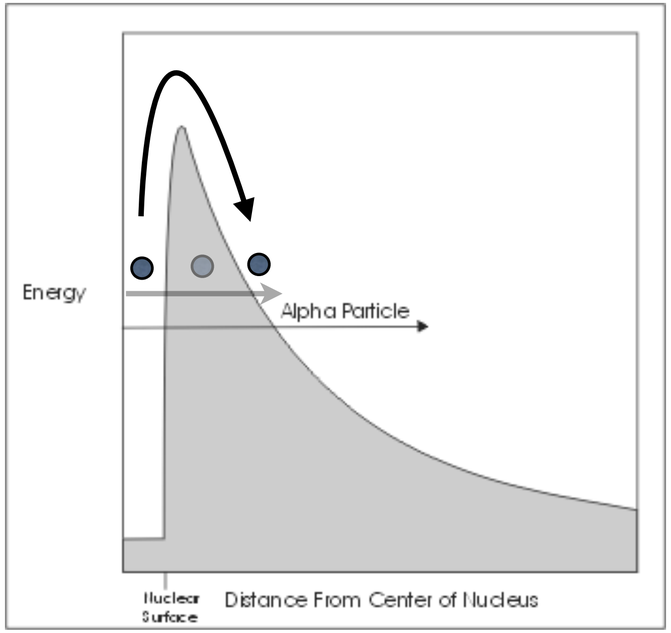
Electron is initially at rest
e- gains energy

Which enforces

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

Quantum tunneling

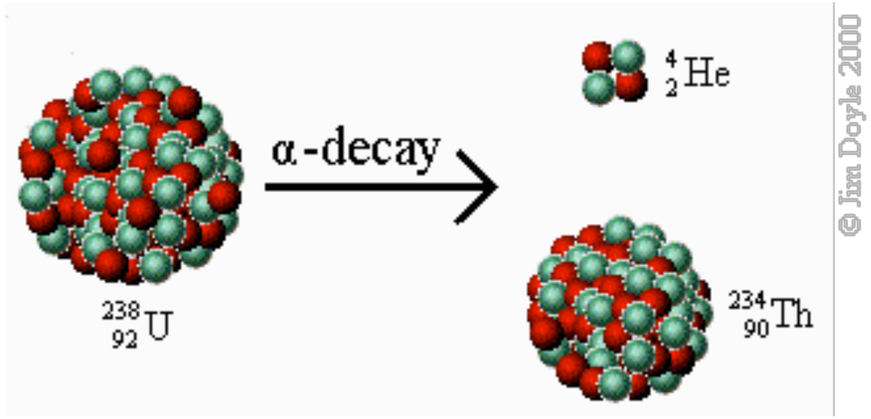
In QM the classically impossible is now just very unlikely



Classically alpha particle is trapped. Uranium cannot decay

Uncertain momentum (+Ψ) means there is a probability for it to climb over barrier can be outside…Decay!

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



How do we express Ψ mathematically?

Superpositions

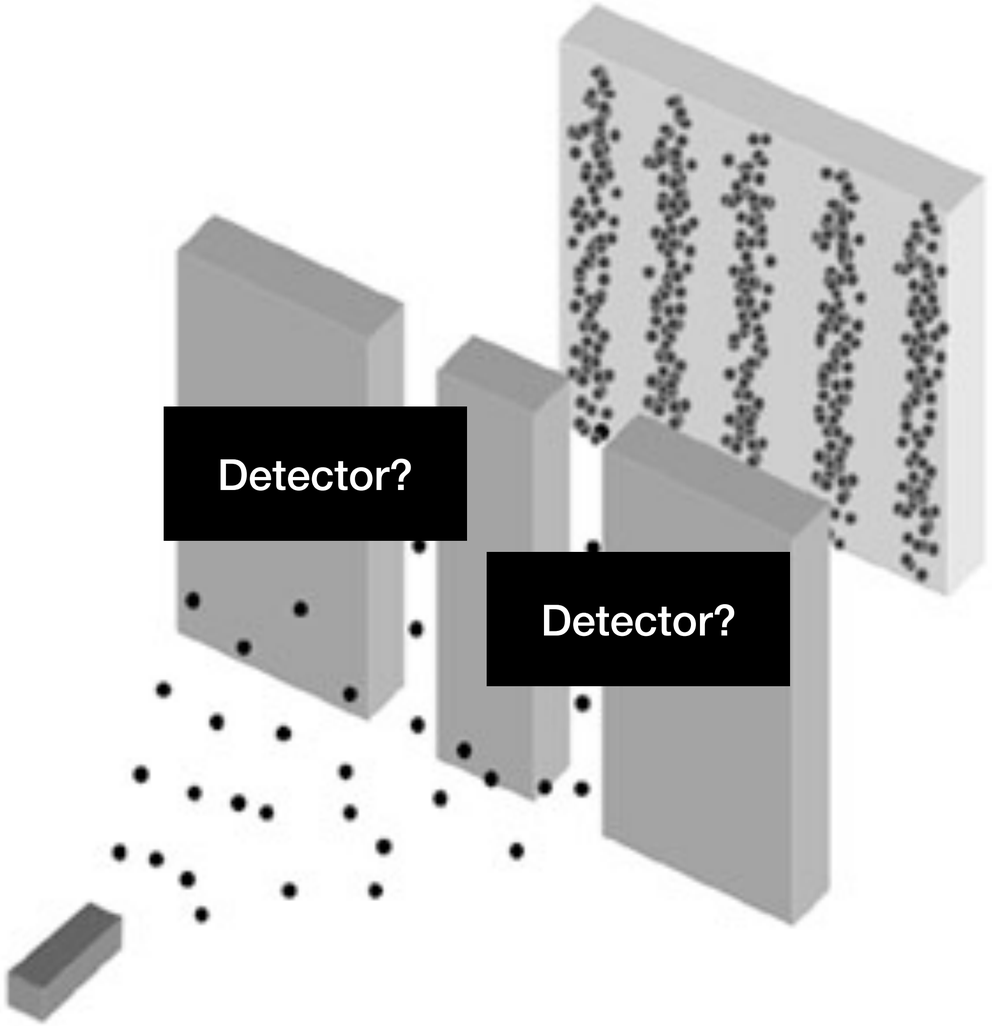
$$\Psi = \sum_i \psi_i = \psi_1 + \psi_2 + \ldots$$

Wavefunction is a superposition of all possibilities

QM predicts outcomes if expt. is repeated many times

Superpositions

$$\Psi = \psi_{\text{Left}} + \psi_{\text{Right}}$$

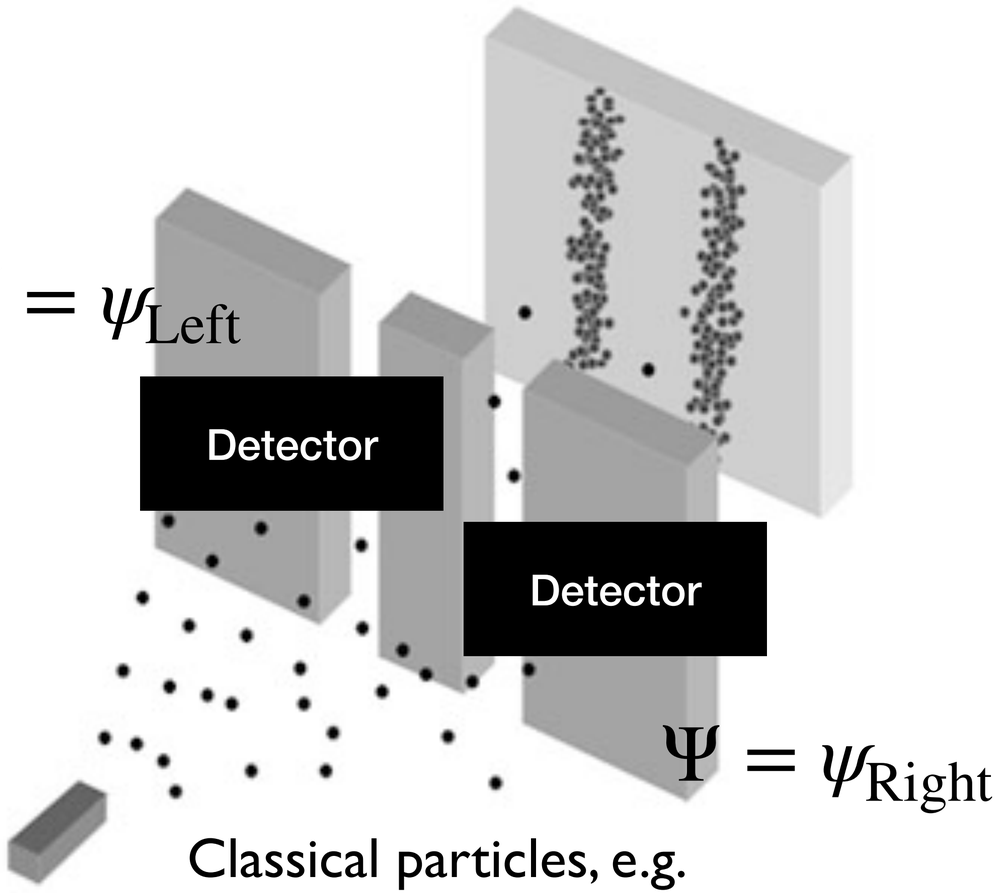


Why not just measure which slit the electron went through by placing a detector?

Surely it went through only one

Superpositions

$$\Psi = \psi_{\text{Left}} + \psi_{\text{Right}}$$



Classical particles, e.g. bullets

Why not just measure which slit the electron went through by placing a detector?

Surely it went through only one

Measuring which slit it went through collapses the wave function!

So not looking —> both slits

When looking —> Only 1

Superpositions

$$\Psi = \sum_i \psi_i = \psi_1 + \psi_2 + \ldots$$

Wavefunction is a superposition of all possibilities

QM predicts outcomes if expt. is repeated many times

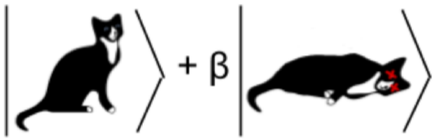
Measurement "collapses" the wavefunction
(Copenhagen Interpretation)

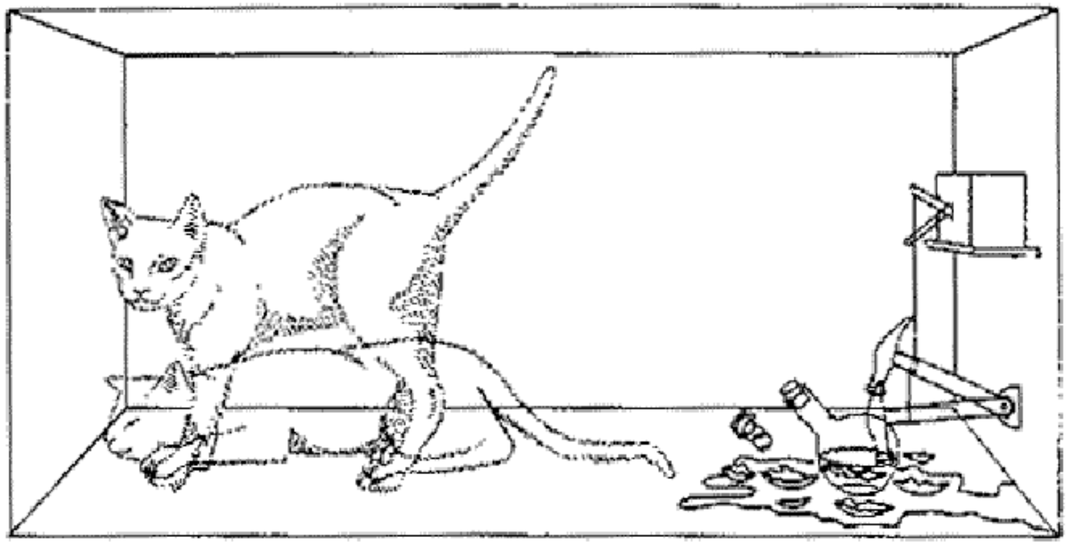
Collapse of wave function, and superposition, lead to strange results

Schrödinger's cat

Copenhagen interpretation of QM

Cat is in a superposition of alive and dead until box is opened!

$|\text{cat}\rangle = \alpha$  $+ \beta$



Entanglement

Multi-wave/particle states can become entangled, consider 2 electrons

$$\Psi = \psi_{e_1} + \psi_{e_2}$$

Their properties might depend on one another. For example their “spin”

•If e_1 is measured to be spin up, e_2 must be measured to be spin down

This correlation is somehow coordinated, even if the electrons are separated at large distances

“*Spooky action at a distance*” —Albert Einstein

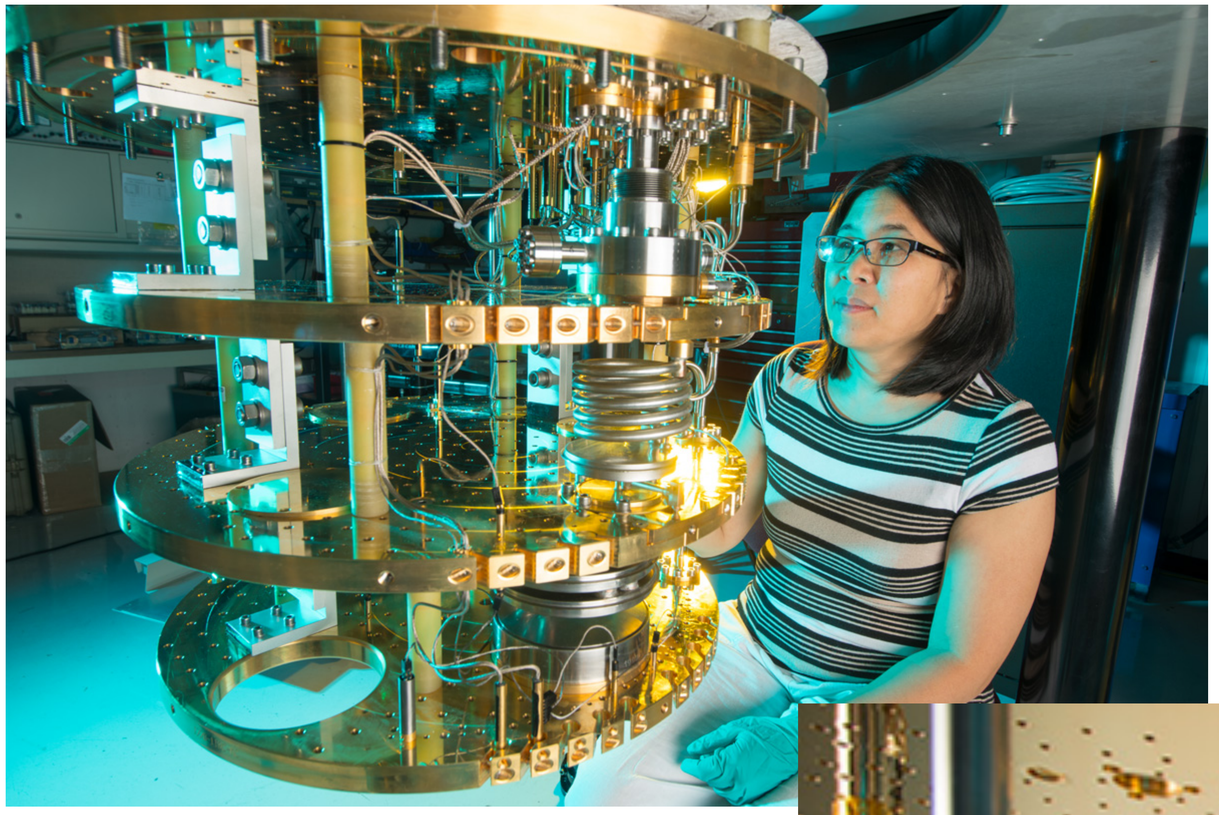
QM Interpretations

What collapses the wave function?
Why is an observer classical but the thing being observed is quantum?

Many alternatives:
Many Worlds (Everett)
Spontaneous Collapse
Hidden variable
Pilot wave
…..

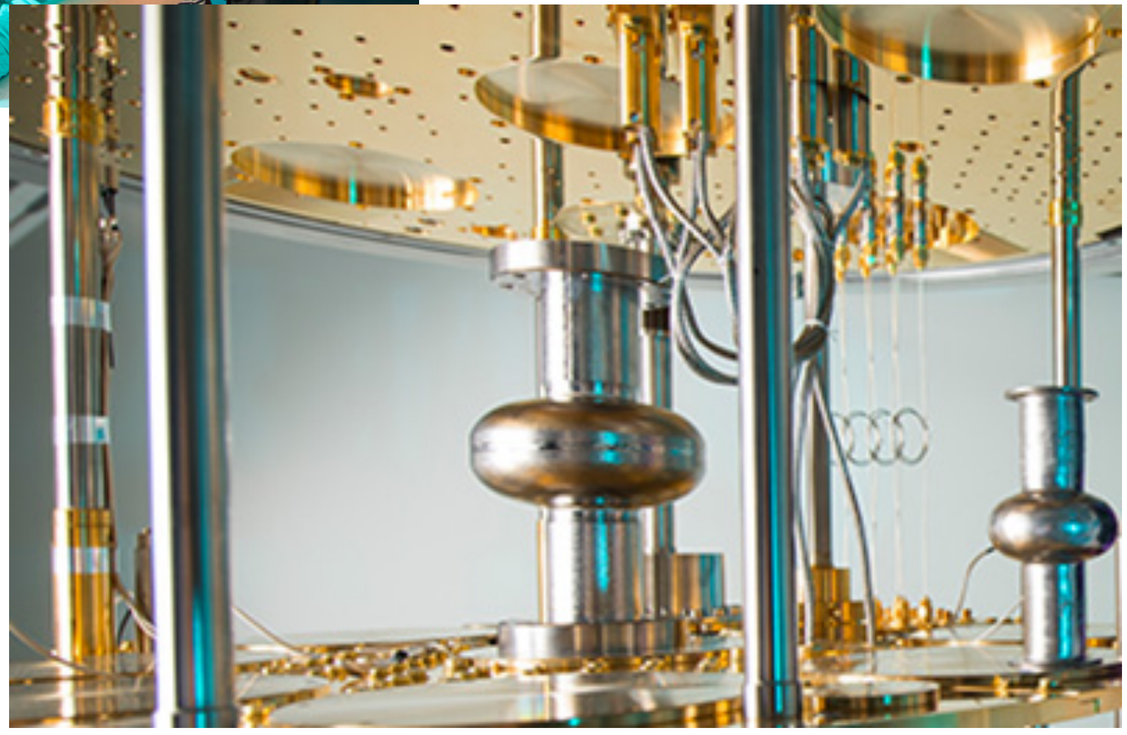
"Shut up and calculate"
--David Mermin

All predict the same outcome in experiments



New devices to search for dark matter

Developing new technologies for next generation qubits



Applications of Quantum Mechanics

The birth of QM in the early 1900's lead to a profound change in our understanding of nature at short distances

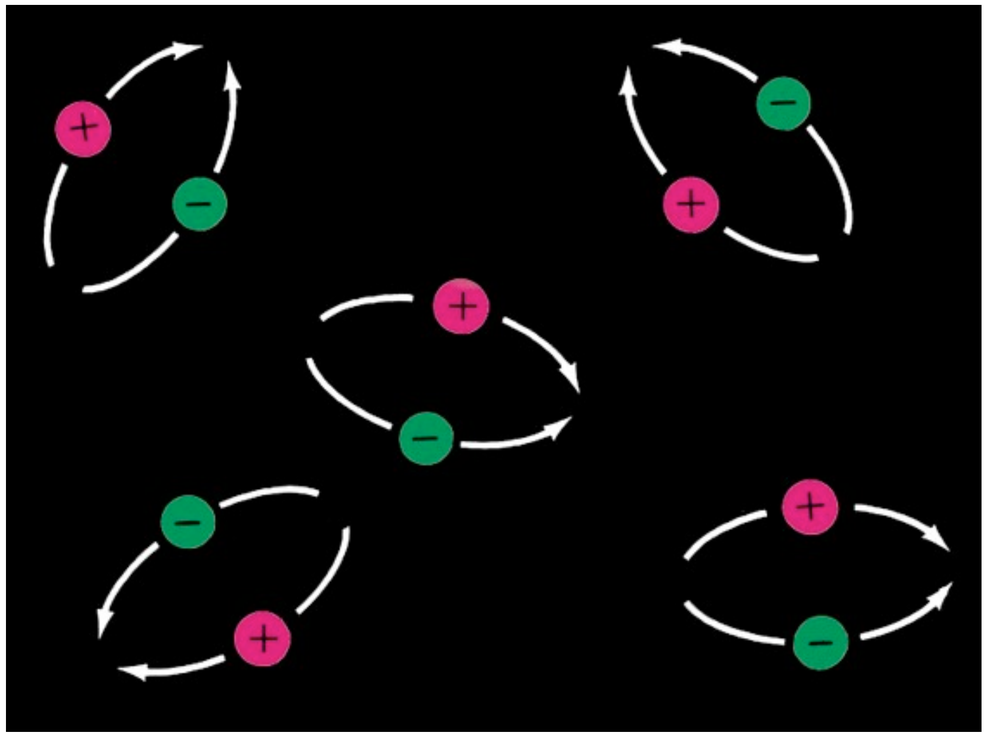
Without this understanding we would not have transistors (and all semi-conductors), lasers, medical imaging technology, superconductors,....Fermilab!

Quantum Mechanics is not the final story.....

The loss of empty space



Paul A.M. Dirac

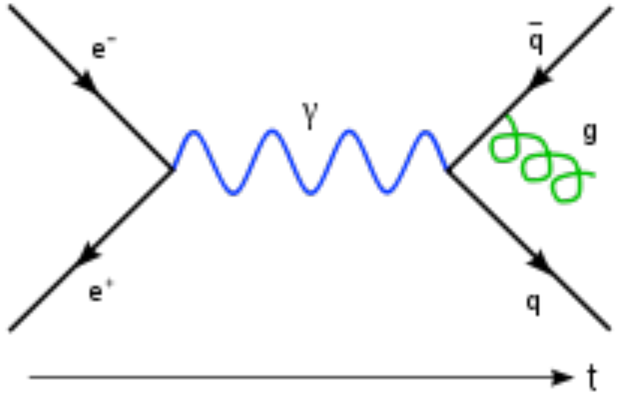


Dirac combined relativity and QM

Relativity from Dr. Patrick Fox, next time

Predicted antiparticles

Quantum Field Theory



Feynman diagrams



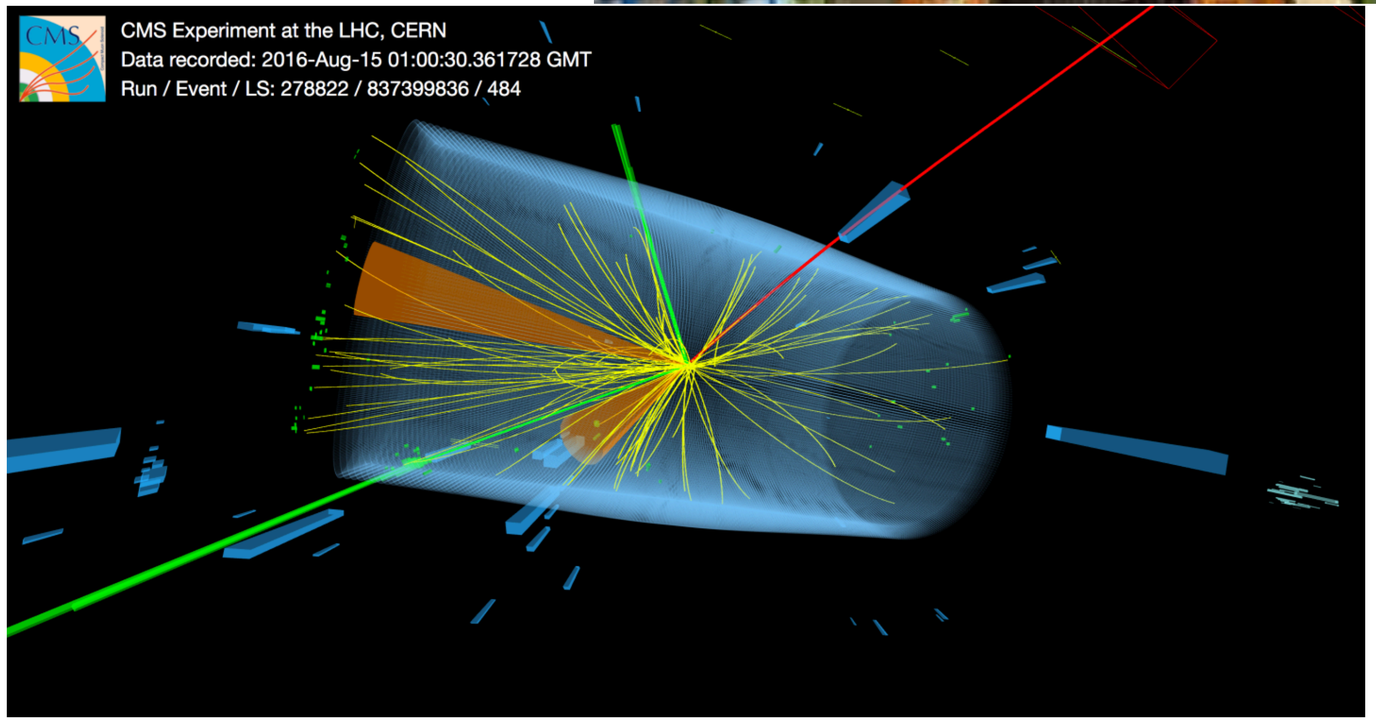
Richard Feynman

Describes physics at short distances, and high energies

Like at Fermilab






CMS Experiment at the LHC, CERN
Data recorded: 2016-Aug-15 01:00:30.361728 GMT
Run / Event / LS: 278822 / 837399836 / 484


Are there new laws governing nature at even shorter distances?