hi

Day 23, 05.04.2018

Quantum Mechanics 2

housekeeping

Gotta come to class

question about anything? I'll make a movie for you:

Quantum Mechanics:

Readings: Oerter, Cosmic Perspective, and Hobson

Hobson_QM1.pdf & Hobson_QM2.pdf are chapters 12 & 13 out of Hobson

Homework #10 is part from MasteringAstronomy and part from MasteringPhysics

honors project began

https://qstbb.pa.msu.edu/storage/Homework_Projects/honors_project_2018/

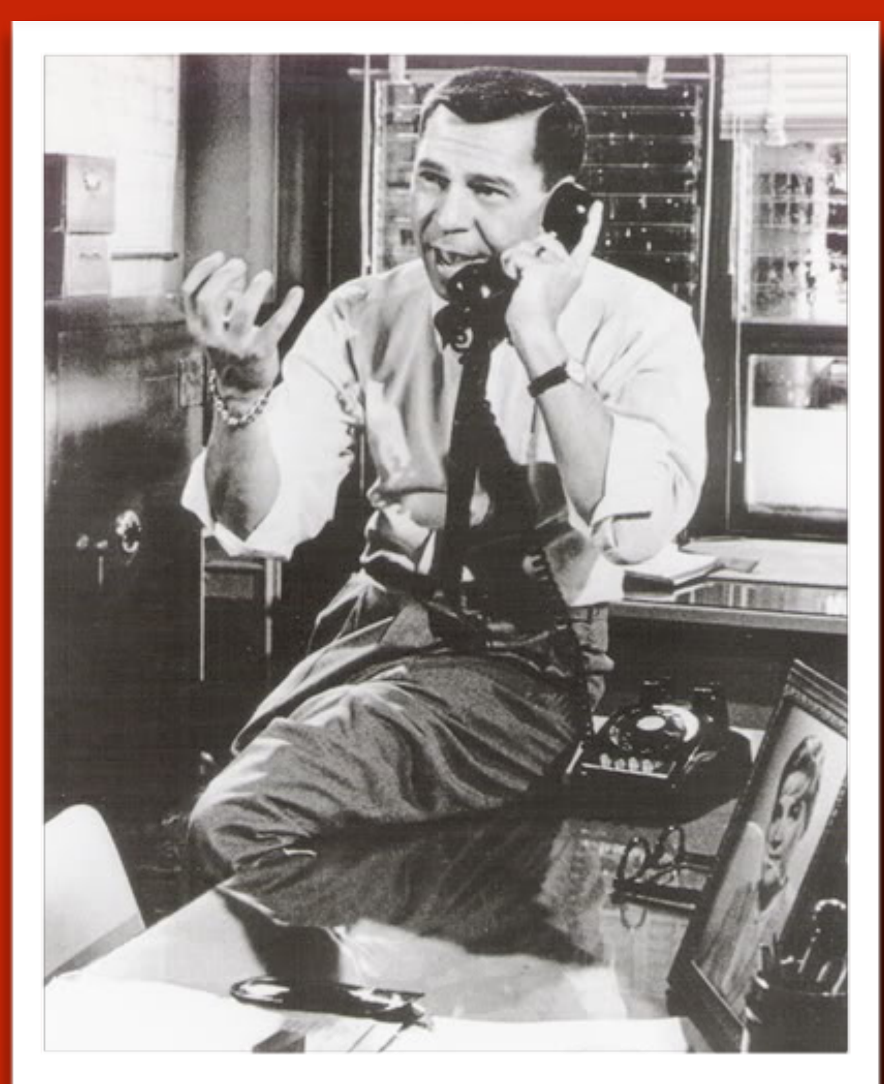
contains:

- the first instructions: the plan & tutorial
- the second instructions
- the data, assigned by name in the second instructions

dates:

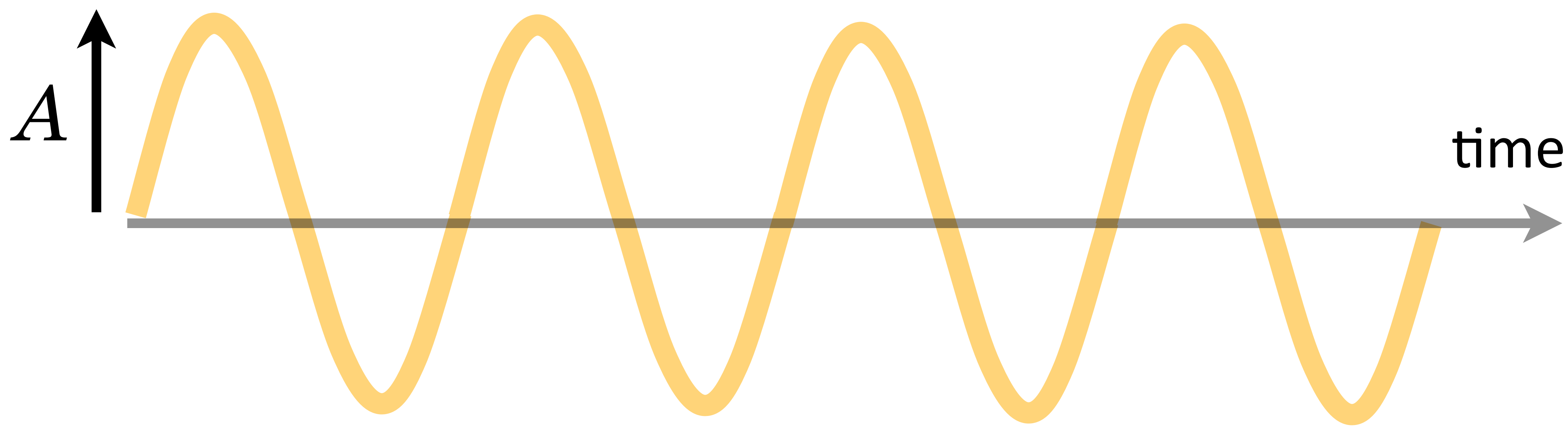
- complete first part, March 16
- analyze data and complete writeup, April 22

just some facts, Ma'am



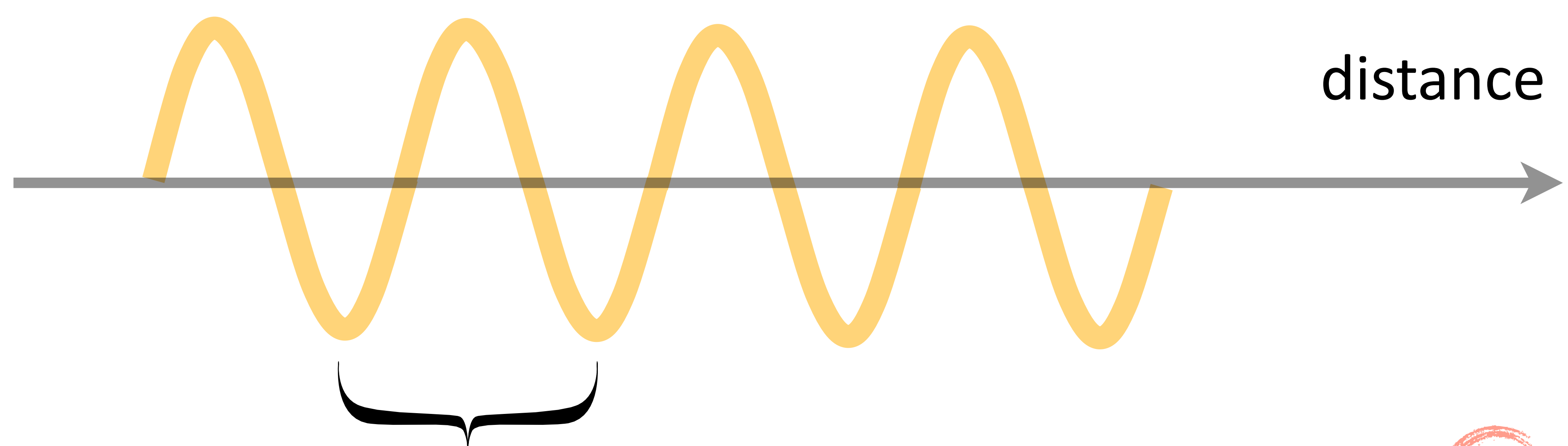
maximum height of the disturbance: "Amplitude," A.

"Intensity" is ~ A^2



time to repeat: "Period," T. seconds

rate of repetition: "Frequency," f. (Hz) $f = \frac{1}{T}$



distance through which it repeats: "Wavelength," λ m

$$v = \frac{\lambda}{T} \qquad v = \lambda f$$

wave speeds

for sound in regular room temperature air?

about 300ish m/s: so about 30 ms to hear me in the back row

for light…anywhere?

v = c = 3×10^8 m/s

$$v = \lambda f \rightarrow c = \lambda f$$

for us, two kinds

traveling waves

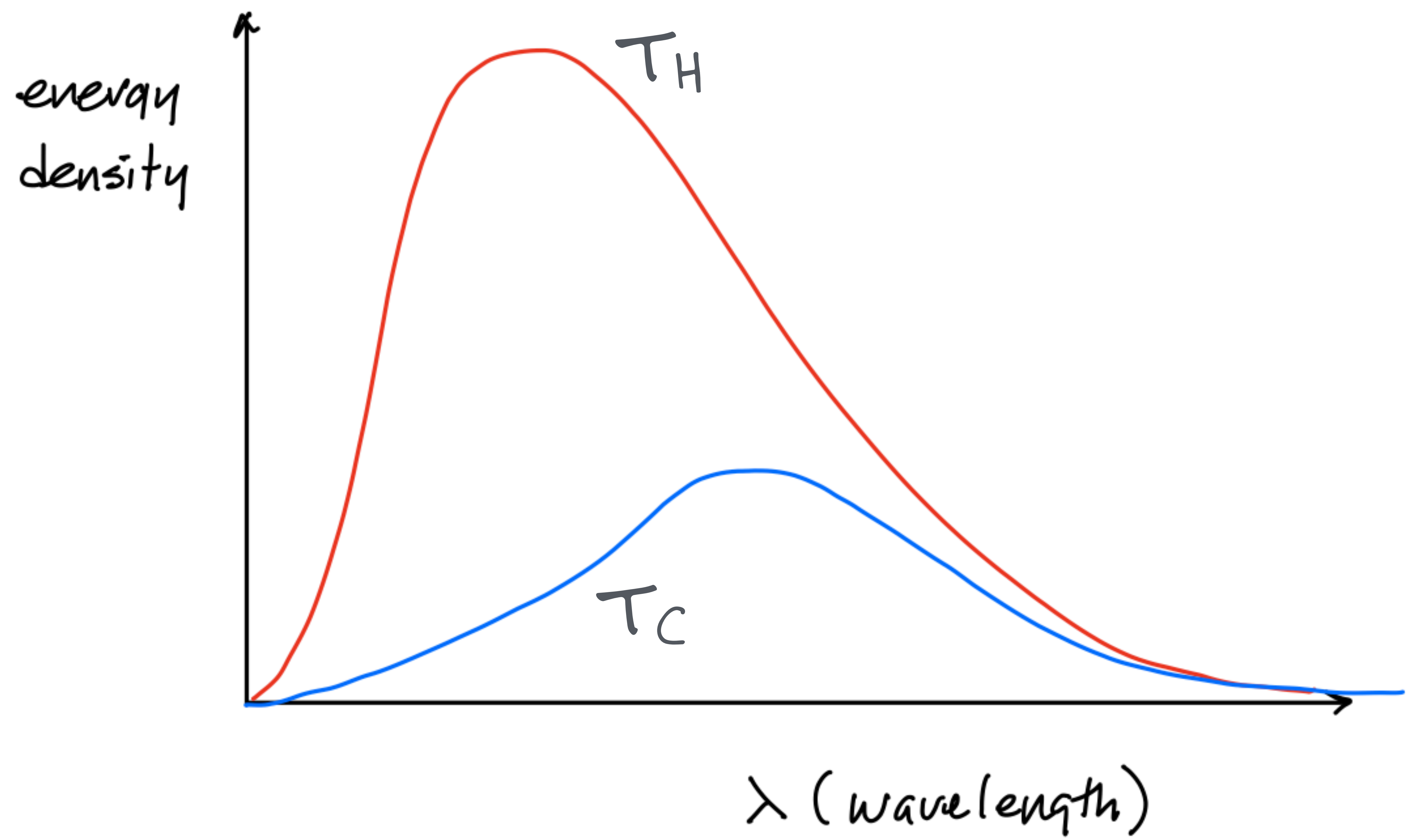
the disturbance translates

standing waves

the disturbance marches in place

Quantum Mechanics

make your fingers think



jargon alert:

Black Body Radiation

refers to:	A thermal absorber that perfectly absorbs all wavelengths of EM radiation and emits according to its temperature
entomology:	“black” in the sense of a perfect absorber...no reflection
example:	A cavity with a hole, a near-black object, a star...

relation alert: **Planck's Law**

refers to: $E = hf$

Energy of radiation comes in a discrete amount for each frequency

example: photoelectric effect

constant of nature:

Planck's Constant, h

value:	$h = 6.62606896(33)\times 10^{-34}$ J-sec
units:	Energy - time
usage:	everything at atomic and smaller sizes

Einstein said:

in that famous 1905 year

Planck's bundles are not about the walls...the radiators

It is a statement about light (electromagnetism)

Light is itself "quantized"

....as particles:

these particles are called:

"photons," γ

they have no mass

light particle energies

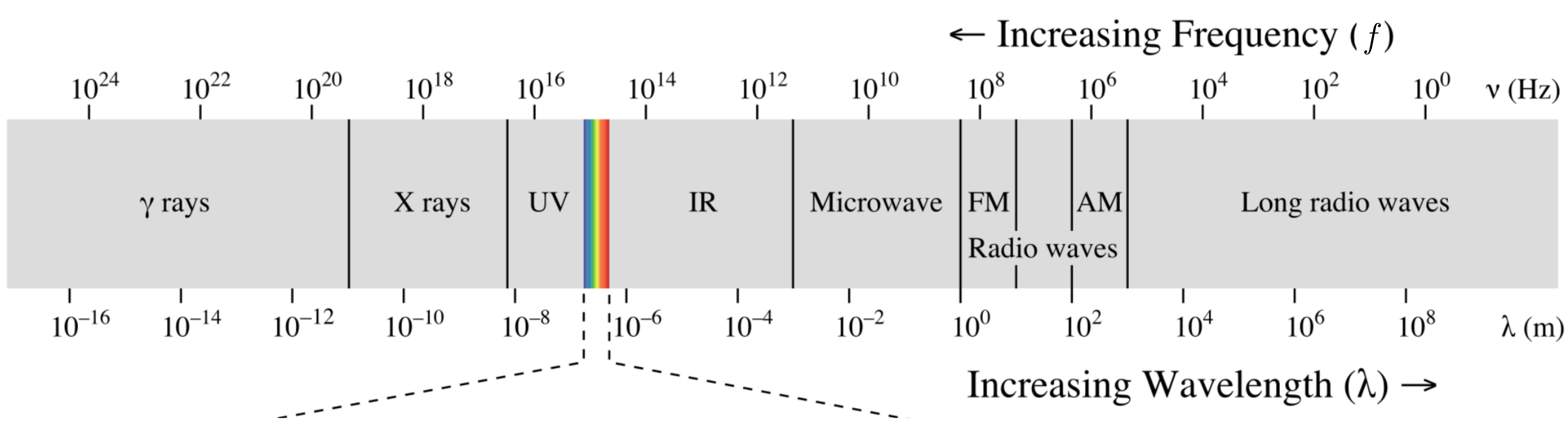
$$E = hf$$ the lower the frequency — the lower the energy

the higher the energy — the higher the frequency

$$E = \frac{hc}{\lambda}$$ the larger the wavelength — the lower the energy

the higher the energy — the smaller the wavelength

← f increase: the higher the energy



λ increase: the lower the energy →

photoelectric effect

The facts:	The light-wave expectation:
1. no electrons until a particular frequency *then, with higher frequency they come out with more energy*	huh?
2. raise the intensity...get more electrons	expect higher energy electrons

53

that's a current

everywhere:

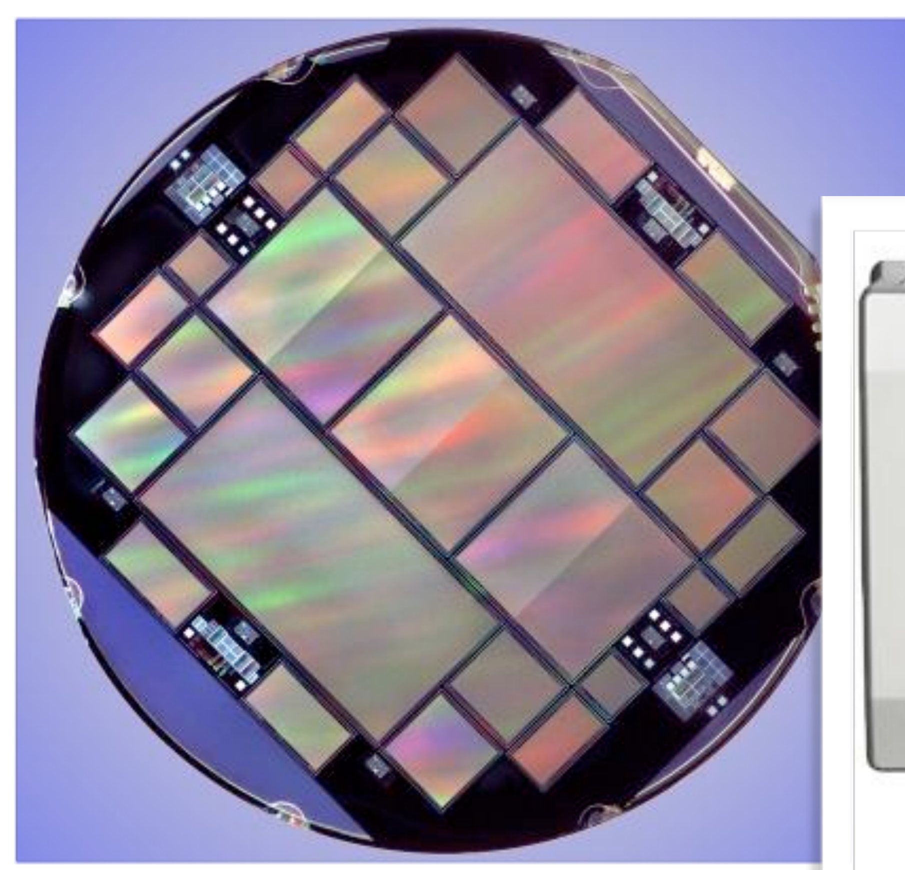
photodiodes

smoke detectors, CD players, remote controls...

photocells

packed into "pixels" and arrays of pixels:

CCDs (charged coupled devices)



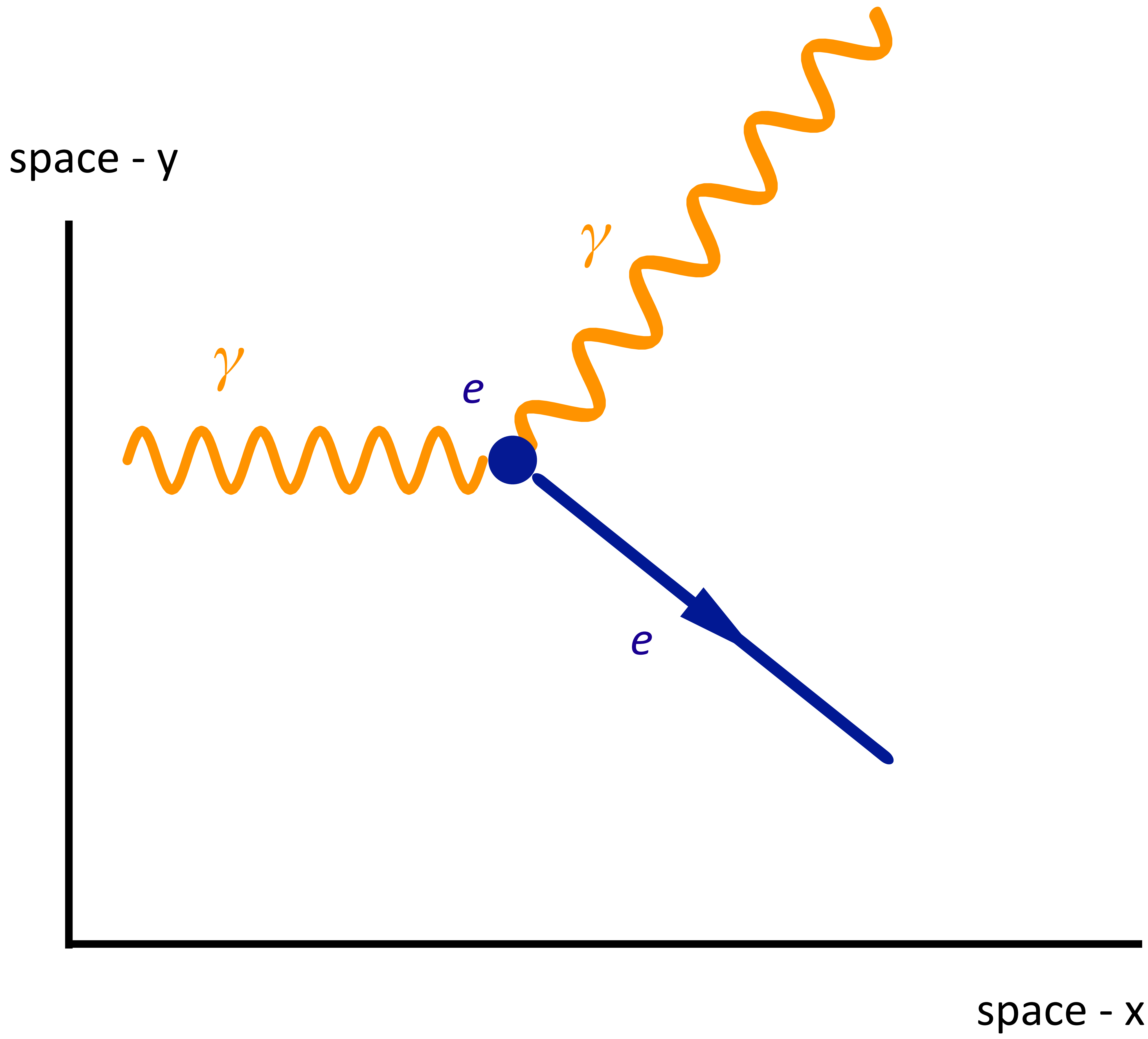
particle: **photon, γ**

symbol:	γ
charge:	0
mass:	0
spin:	1
category:	an intermediate vector boson, a messenger particle

Compton scattering

Space diagram

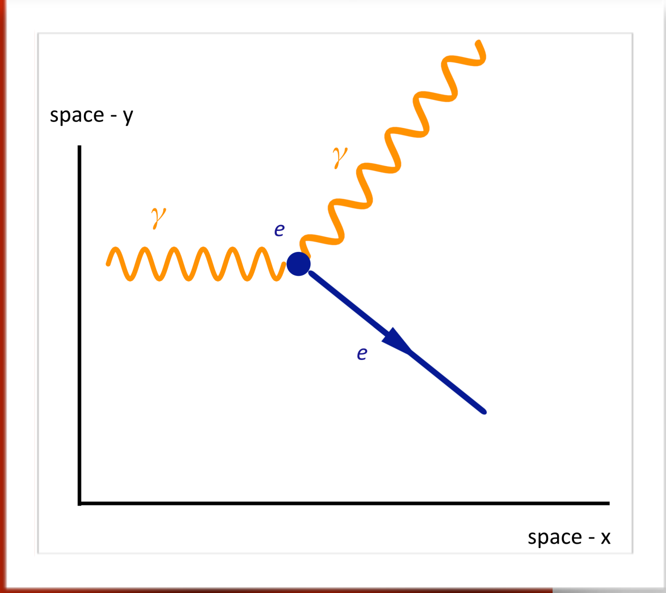
$$\gamma + e \to \gamma' + e'$$



Compton scattering

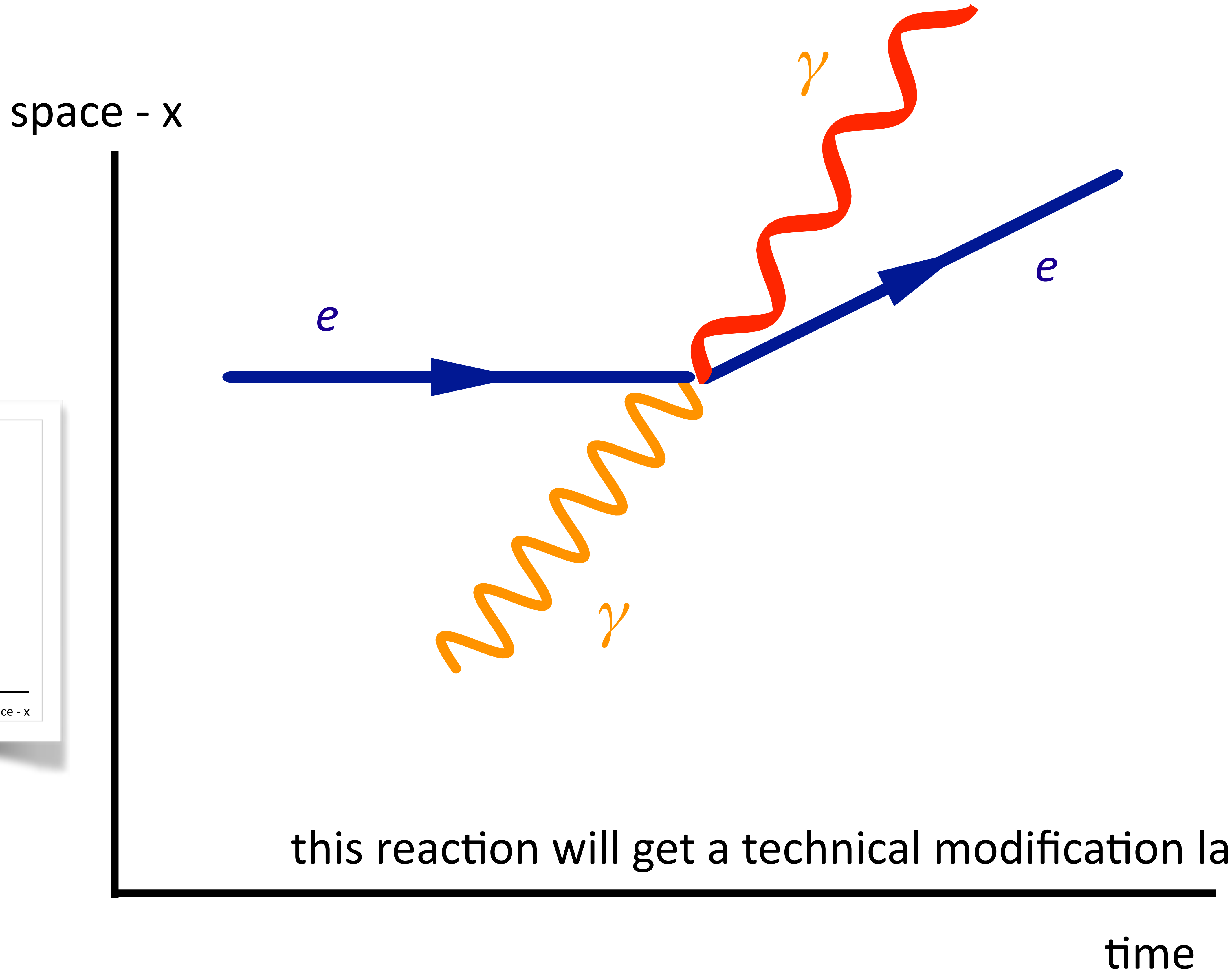
spacetime diagram

aka, *Feynman* diagram



draw the Feynman diagram for Compton Scattering

$$\gamma + e \rightarrow \gamma' + e'$$



this reaction will get a technical modification later

the definitive proof that light acts like

a particle.

How is that possible?

Particles come in whole sizes - no parts, no fractions.

Remember what "makes" a wave...

Waves interfere with one another.

What makes wave behavior in your life?

How about hearing around corners?

Stay tuned...as it will become weird.

the wavelength is the key

look at the relative sizes of openings and barriers

compared to the wavelength

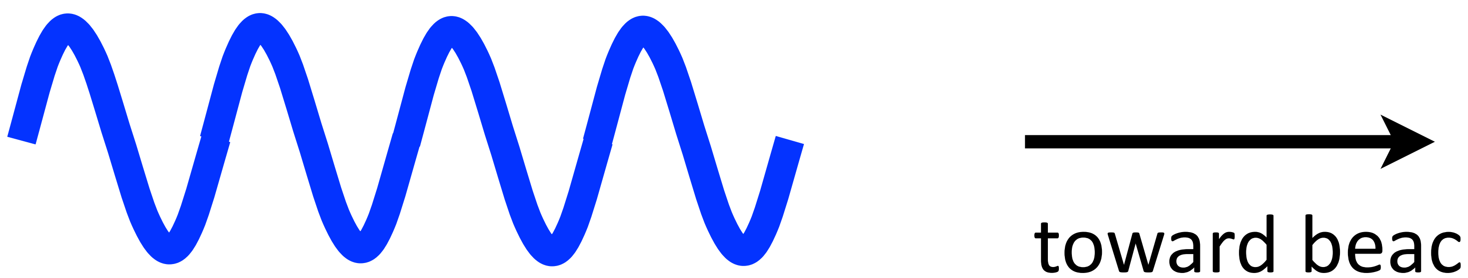
First, think about water waves, then about light waves.

imagine two shapes of waves

on water

"plane wave"

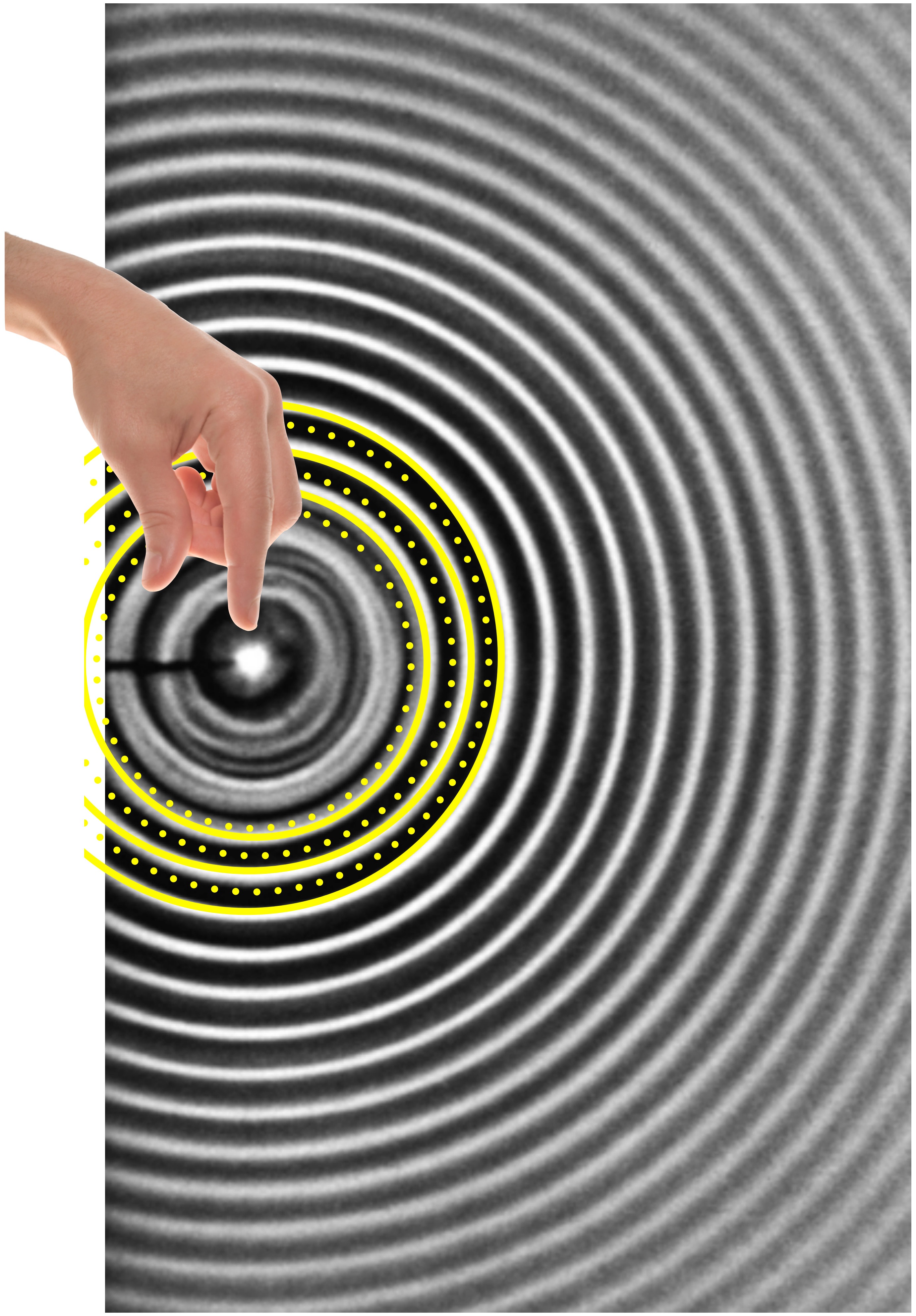
from side:



"circular wave"

waves

one tap



solid- crest
dashed - trough

interference

two taps

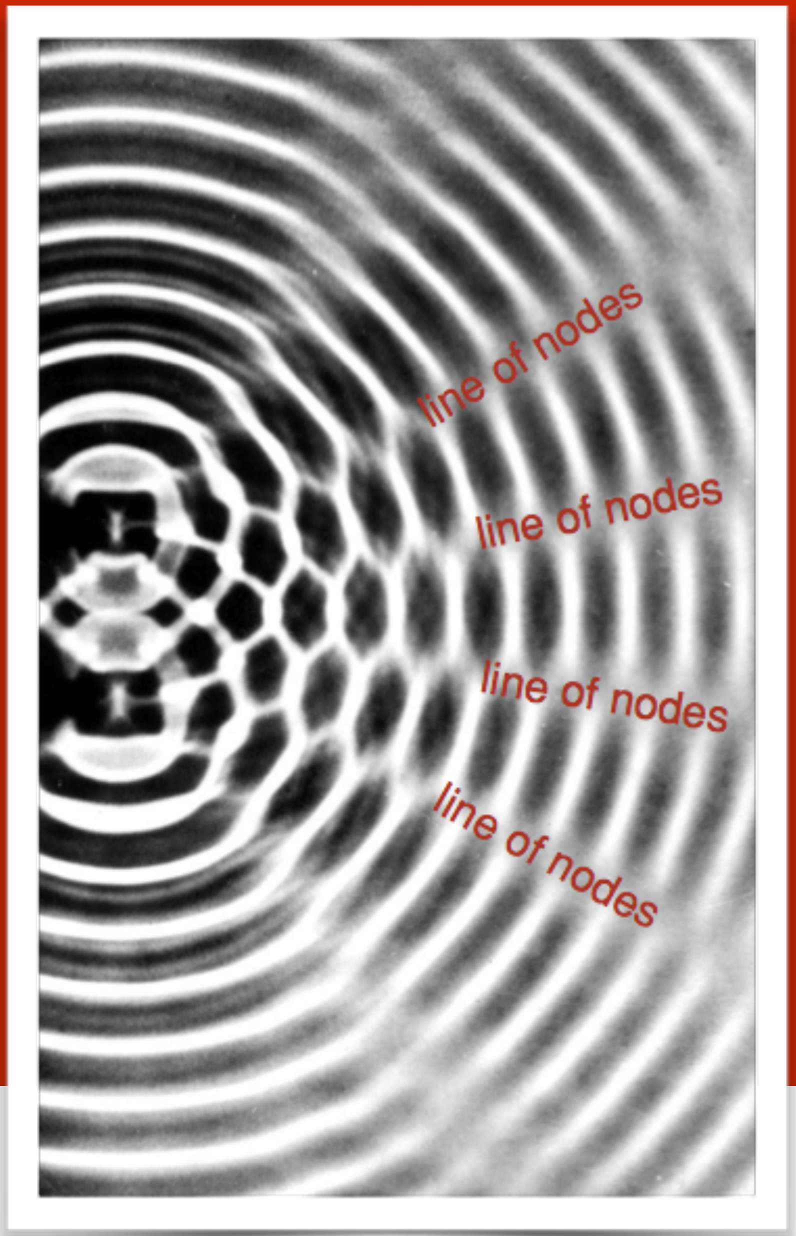
"node": a trough

"crest": a peak

solid- crest
dashed - node

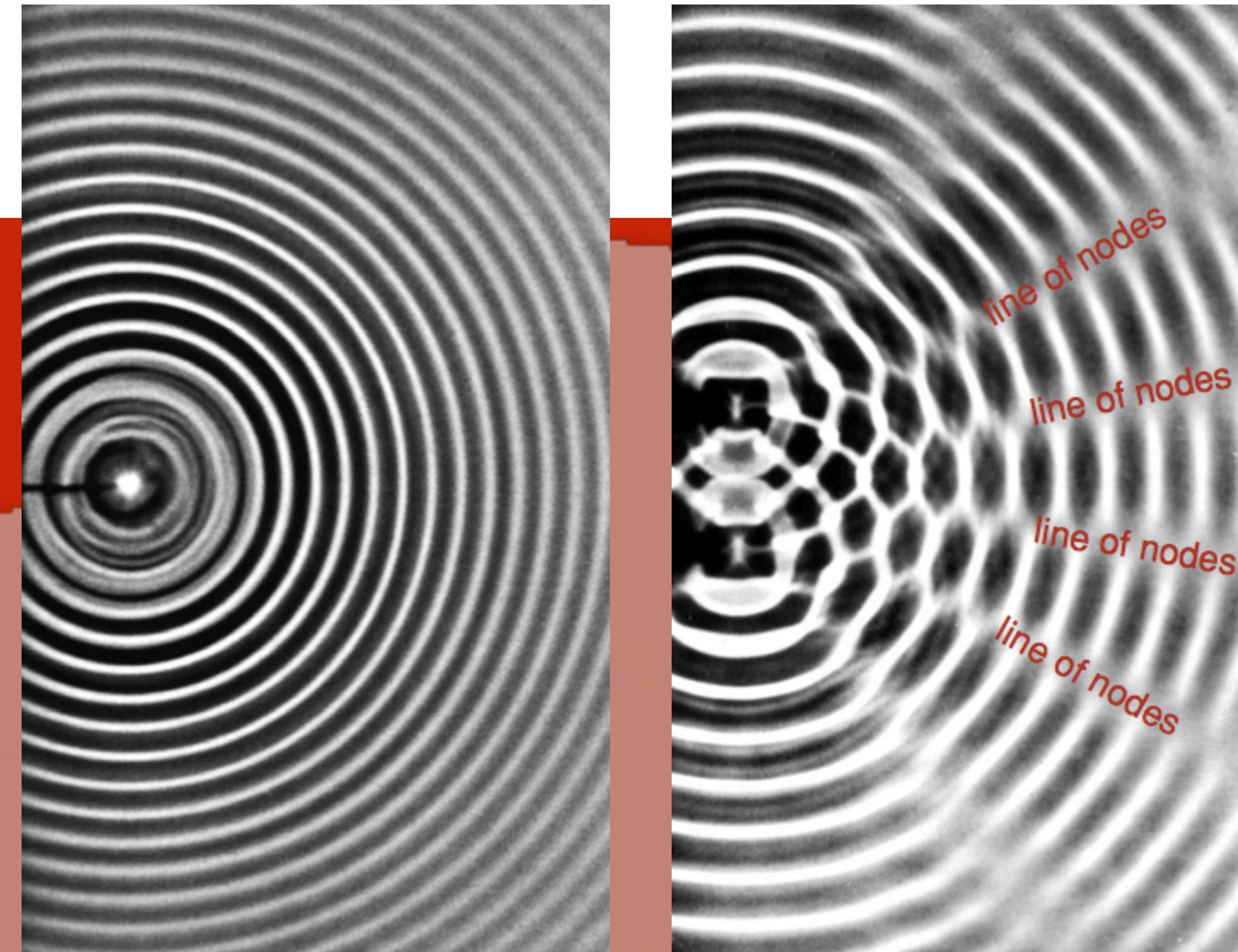
this is it

THE smoking gun of wave behavior: interference



keep those in mind

1 and 2 taps

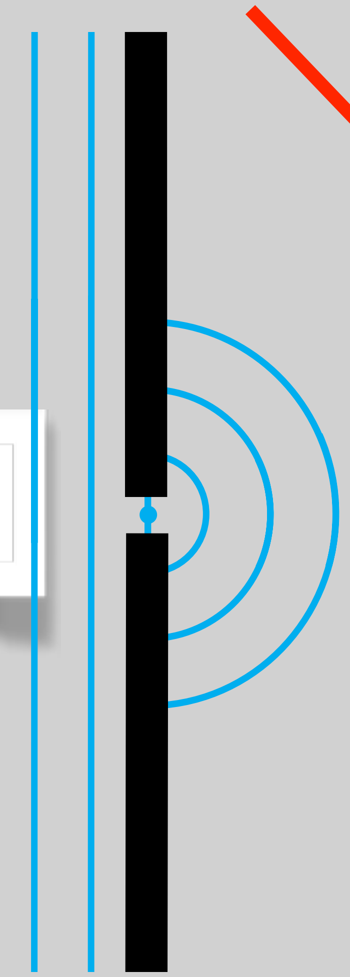


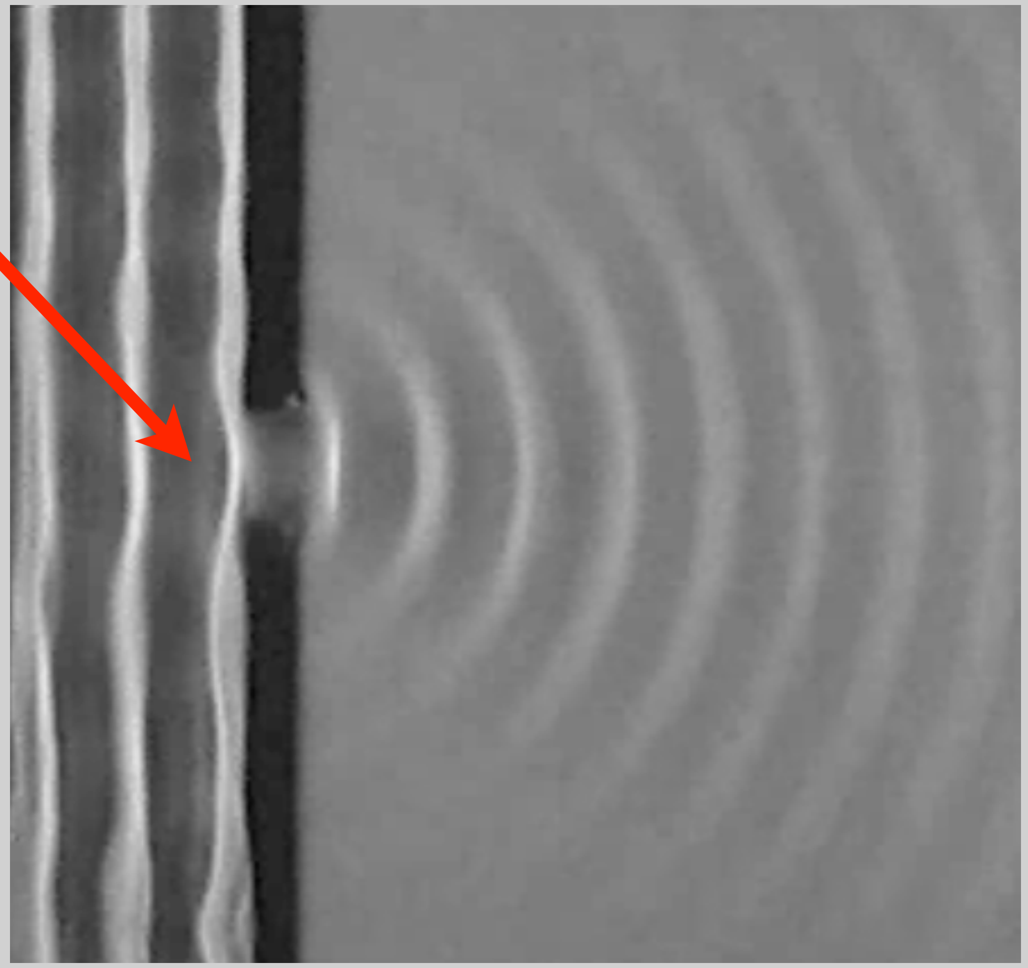
a plane wave impinging on a gap

like 1 “tap”

a gap of about a wavelength-width

plane waves





like the 1-tap image

Another smoking gun of wave-behavior (as opposed to particle behavior)

This is diffraction

...the bending of the wave around the opening.

dramatic images from oceans

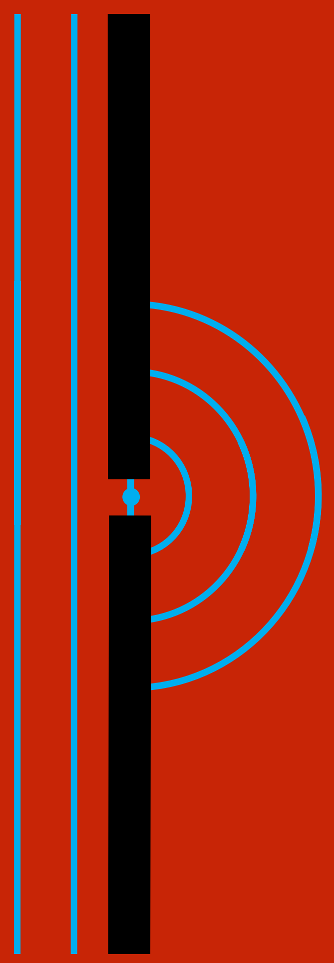
now we know the answer

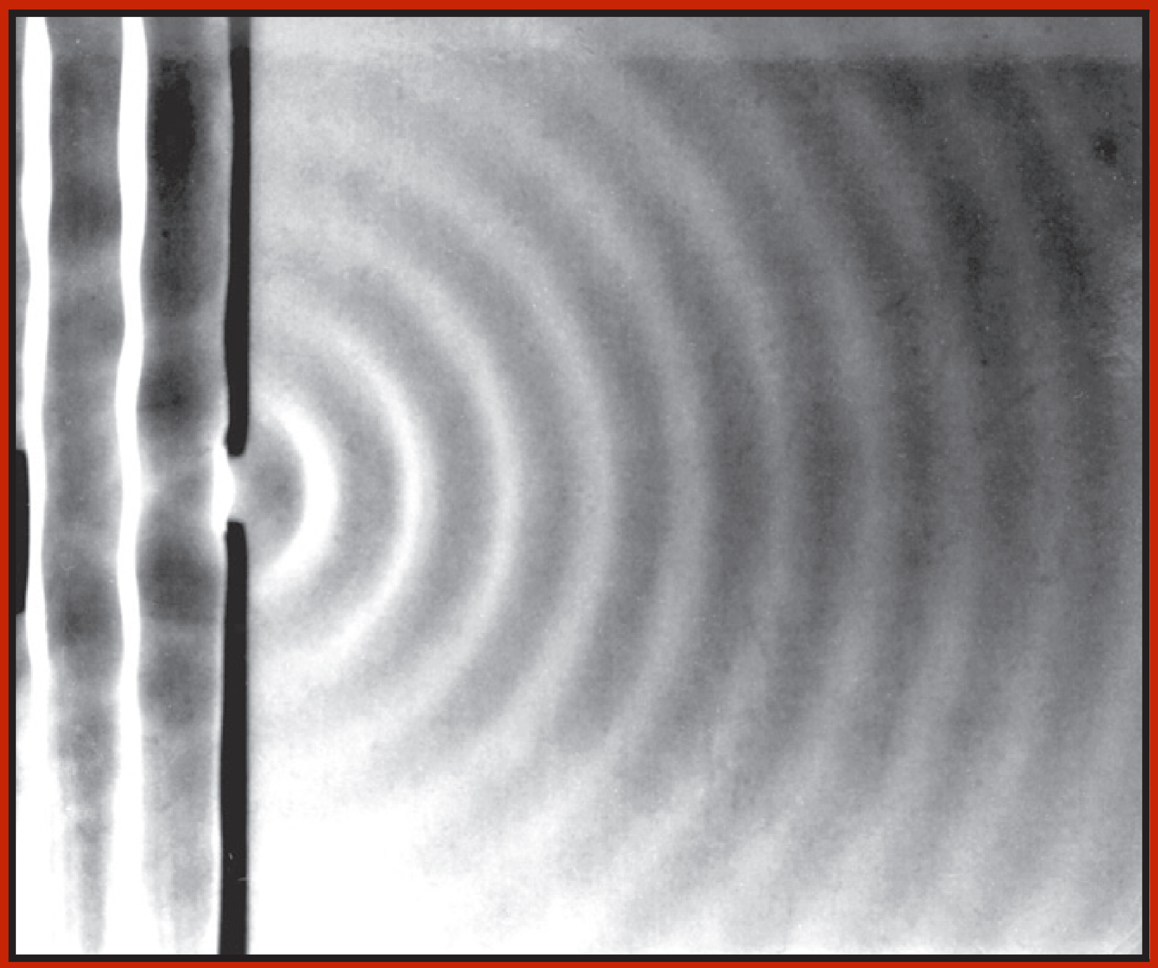
about hearing around corners

wavelength of sound? about 1m

middle C, f = 256 Hz

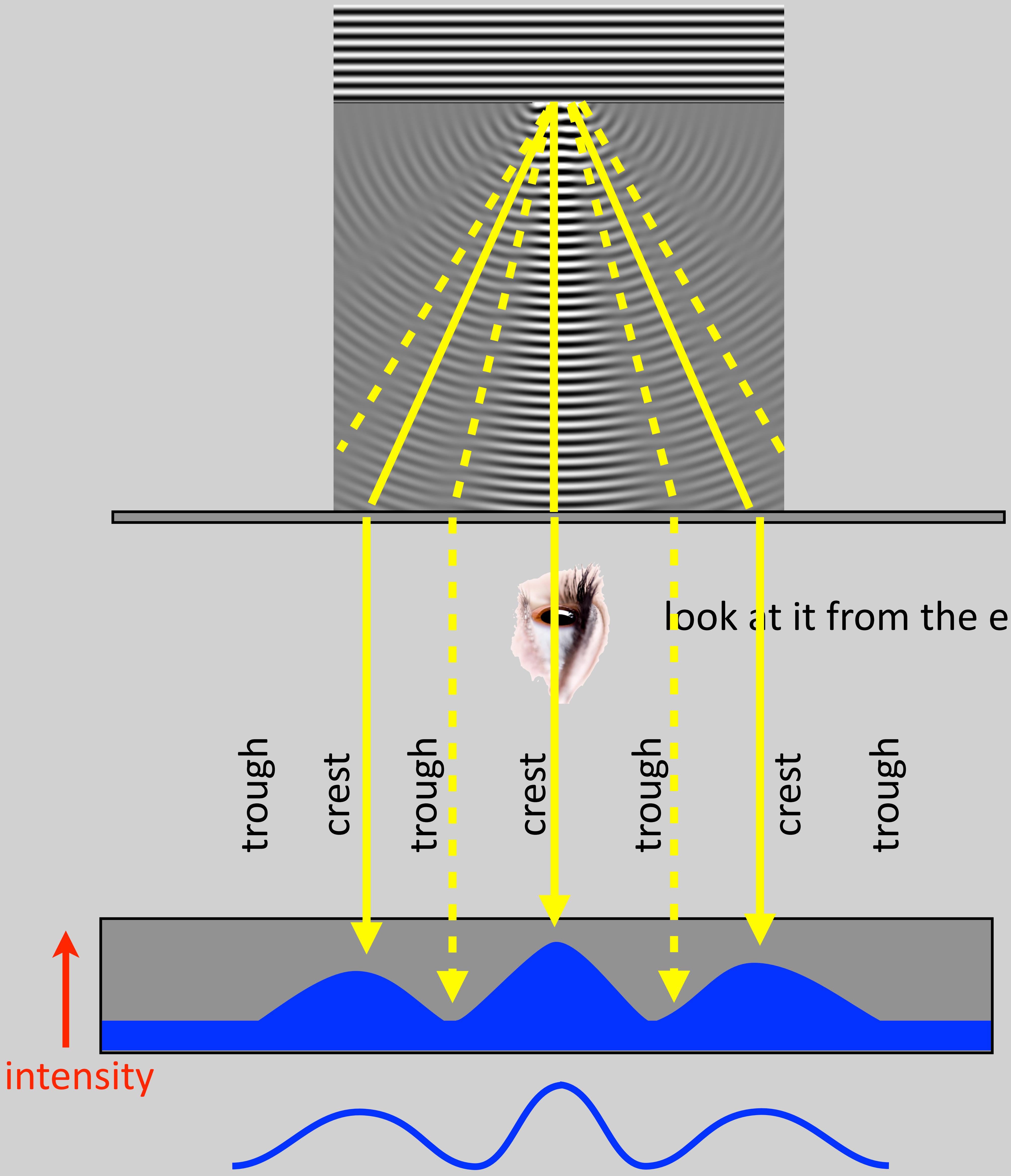
which is about door-sized





look at it from:

the side where the waves are coming at you

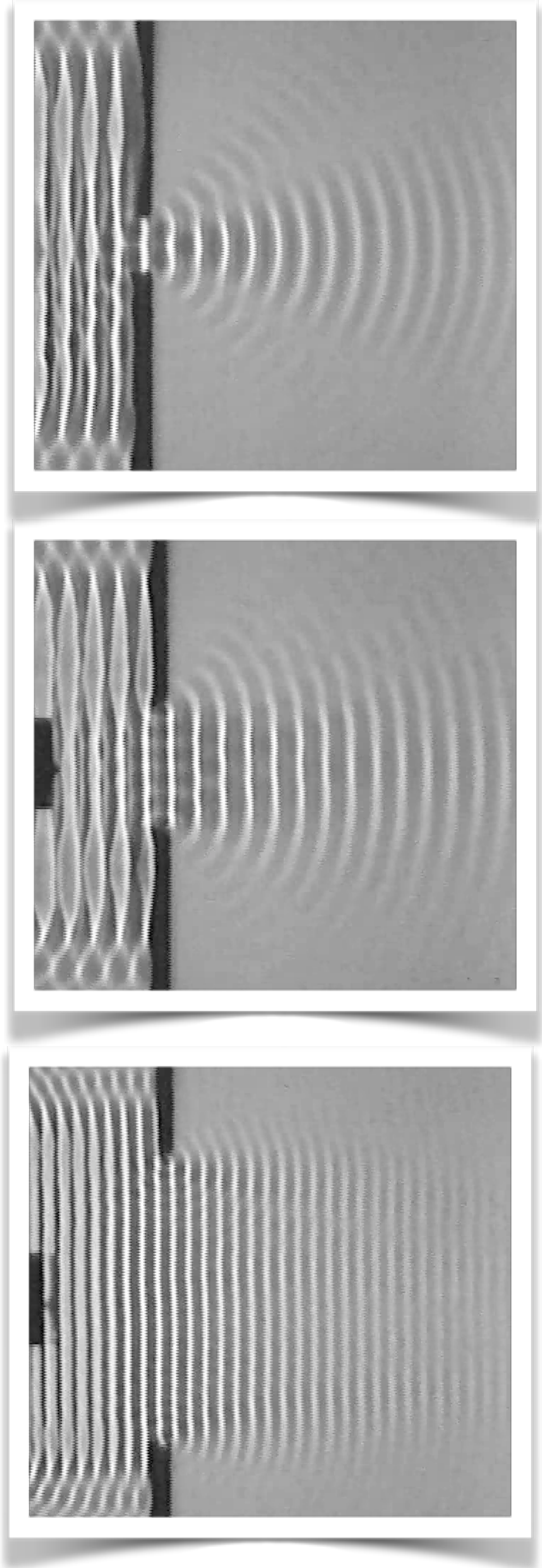


the relative size of the gap

determine the apparent diffraction amount

increasing gap relative to wavelength

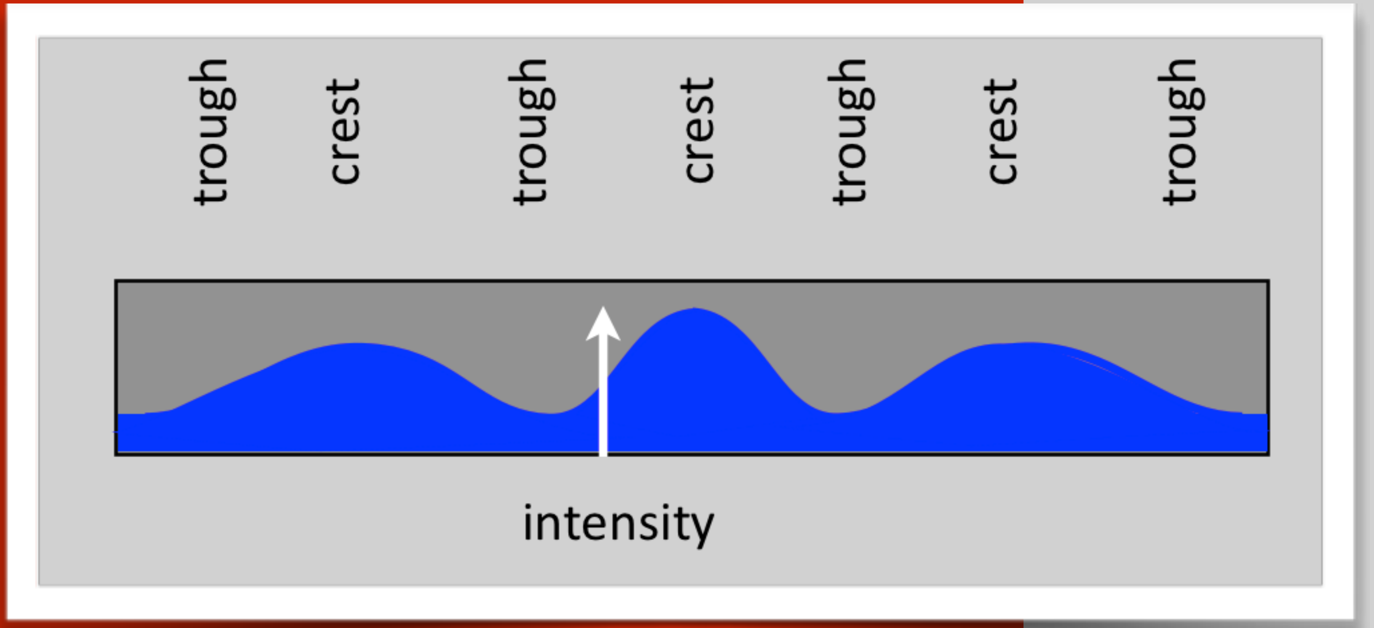
that’s why you can’t see around doors



this is for water

close to the slits

for light…many, many wavelengths away from the slits…stuff happens



diffraction

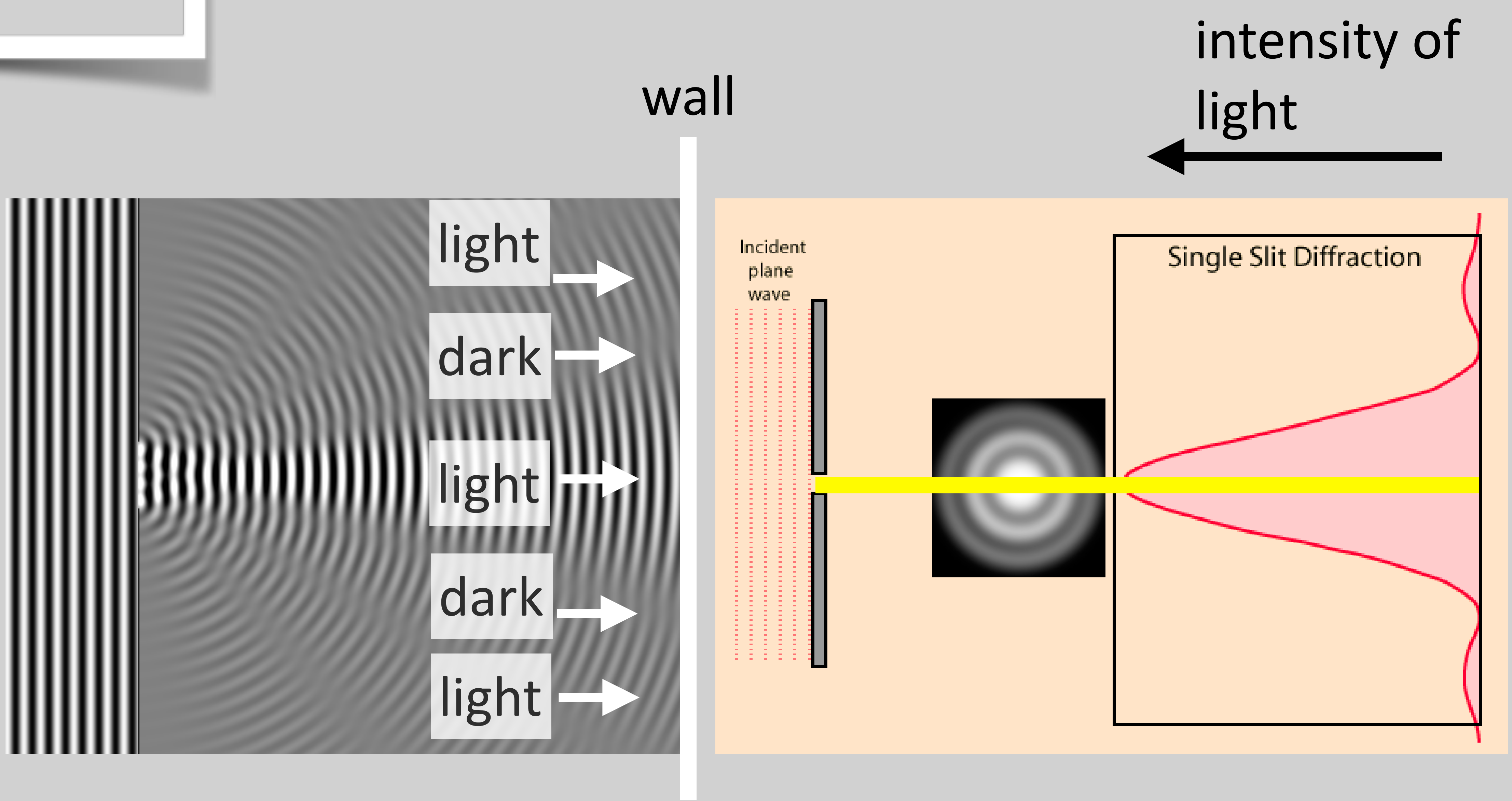
with light

like that of water

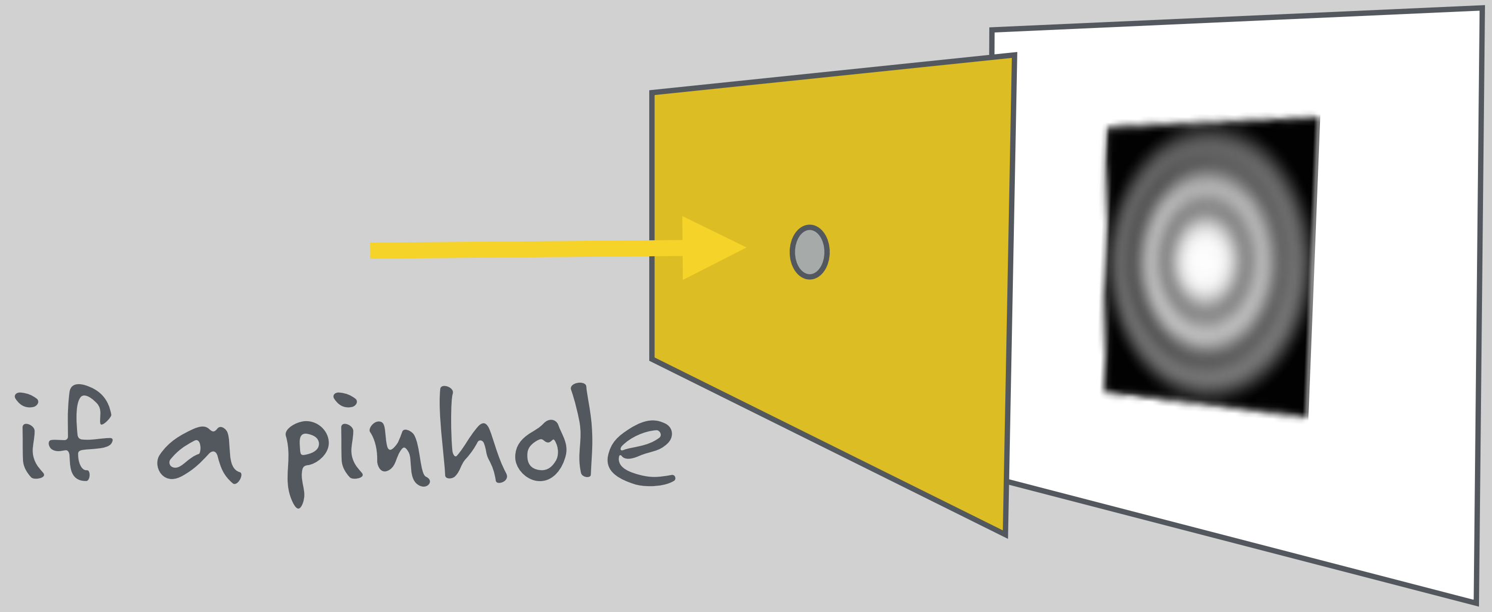
wave height like brightness

crest: bright

trough: dark



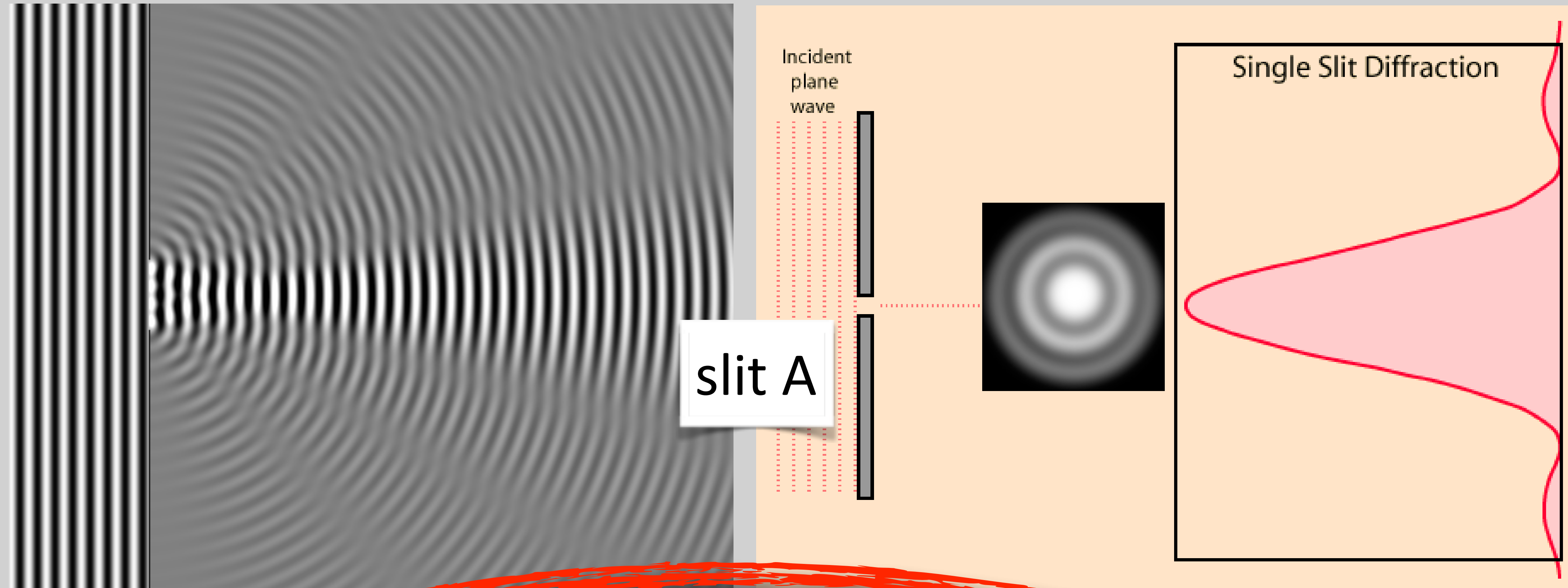
light appears all across the projected width of the gap



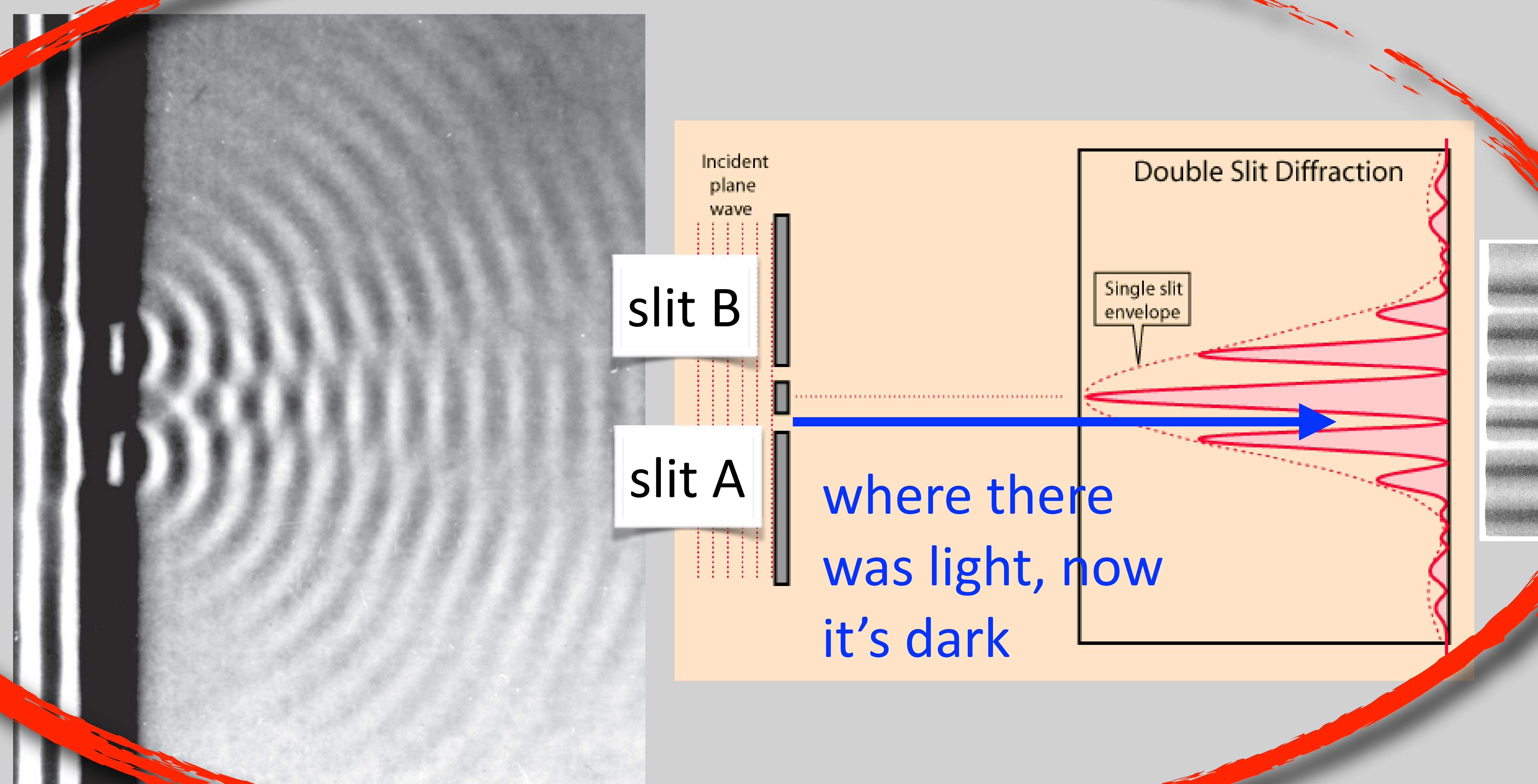
now do something strange.

add light by opening another gap

interference of light



and diffraction at the same time

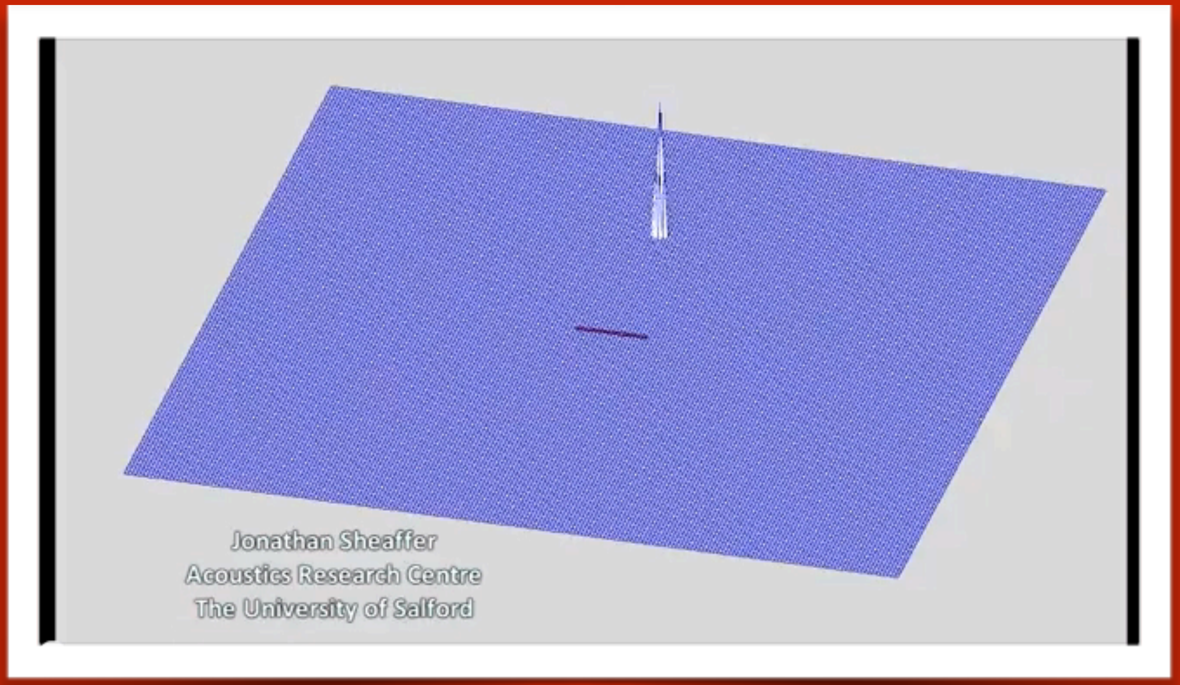


bottom line:

waves interfere...and they bend - they creep around edges

that’s diffraction

particles don’t do this!



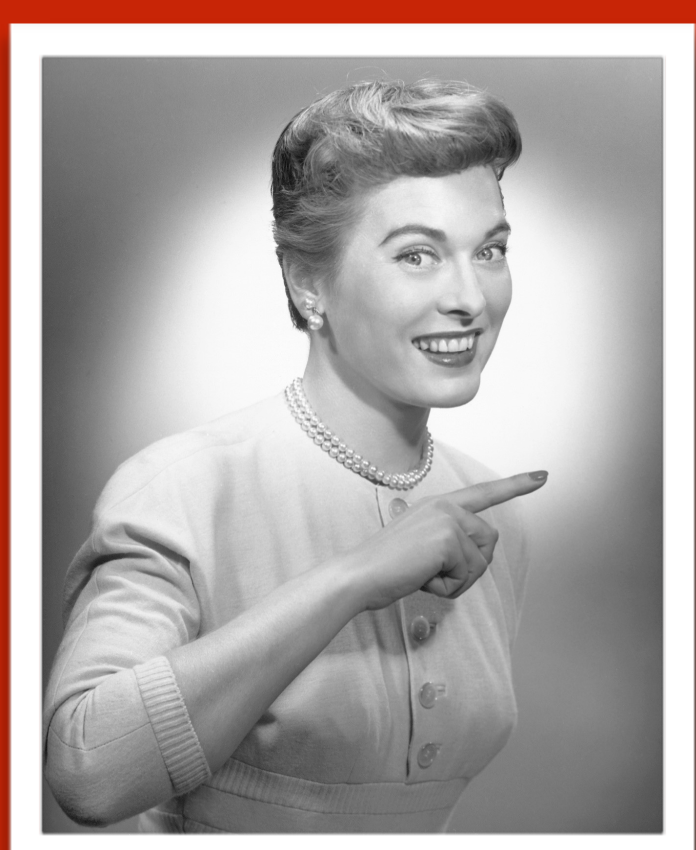
yet, Einstein suggested that waves and particles are spookily connected together in one object - a particle of light

how’s that work?

here's the connection

between the wave nature and the particle nature

of light



the wave point of view:

$$\text{Intensity} \propto |\vec{E}|^2$$

the particle point of view:

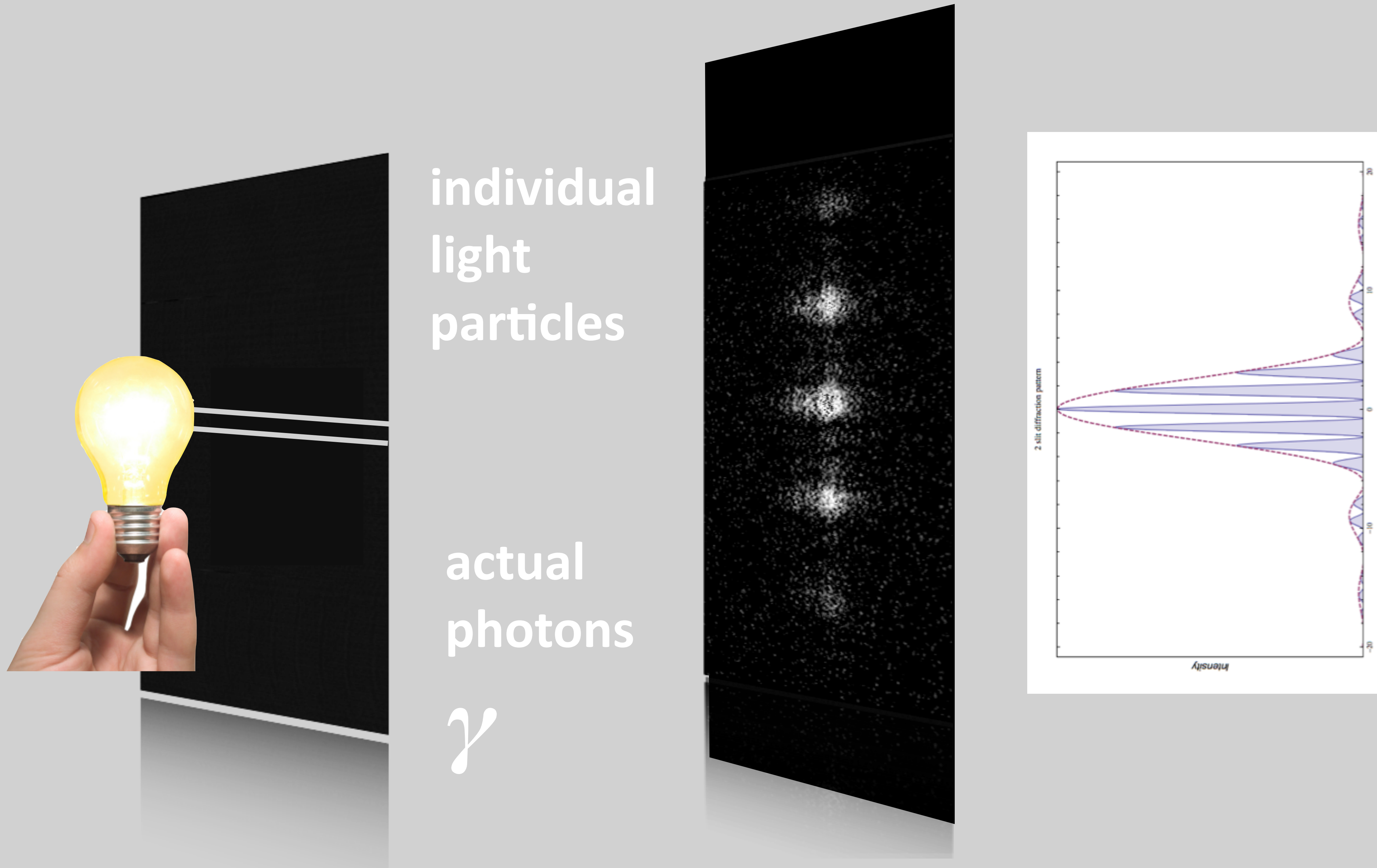
$$\text{Intensity} \propto Nhf$$

$$N \propto |\vec{E}|^2$$

intensity, or power

number of photons

here's how it works



let light go through a double slit

but sensitively count individual photons

David Dykstra, Steven Busch, Wouter Peeters, Martin vanExter, Leiden University, 2008

http://www.youtube.com/watch?v=MbLzh1Y9POQ

So, here we go.

Quantum strangeness in action.

light behaves like a wave

and light behaves like a particle

rewind a bit

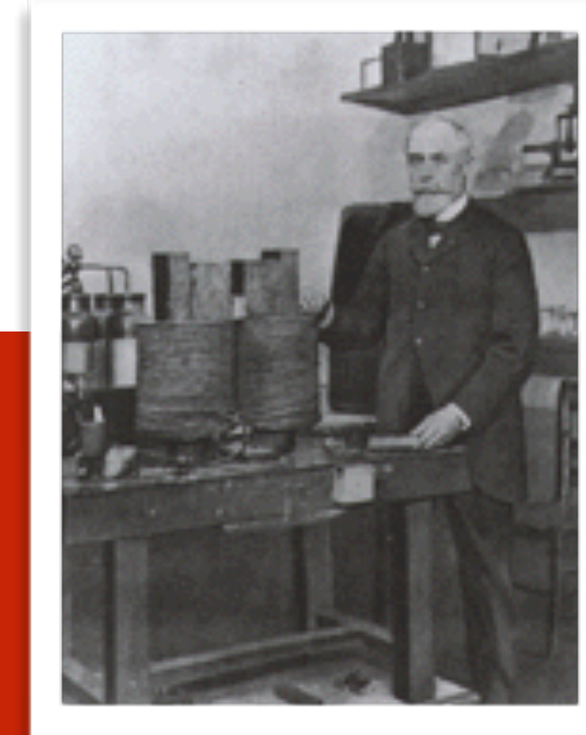
to the beginning of Nuclear Physics

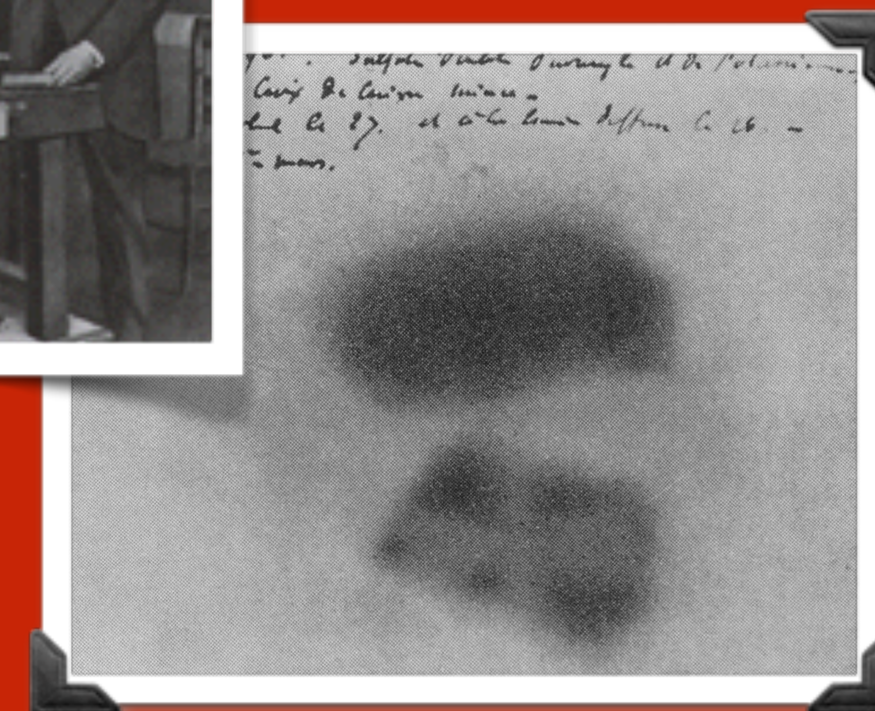
remember when we last saw the beginnings of radioactivity

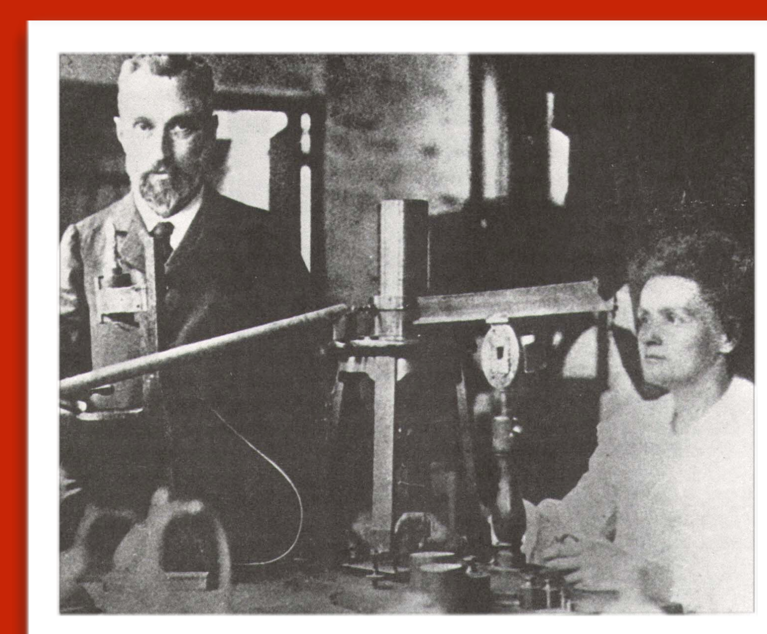
Becquerel's adventures in cloudy Paris

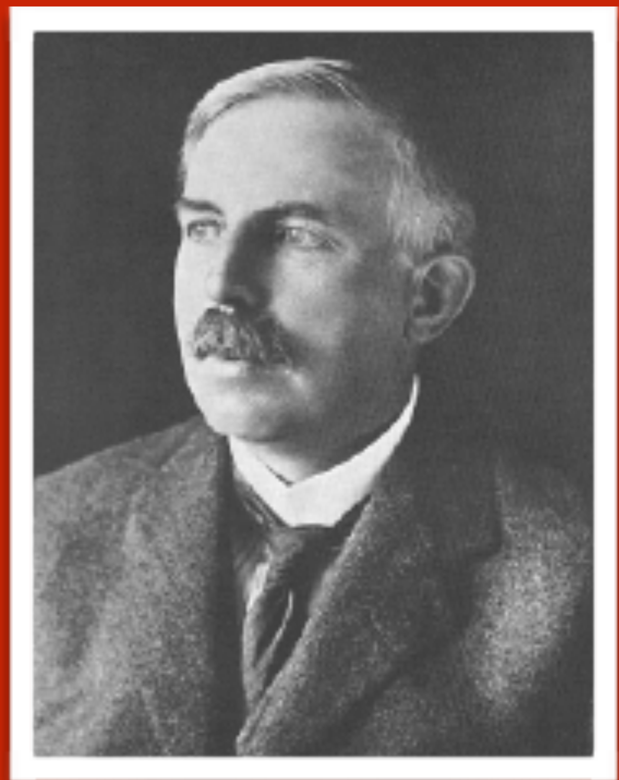
Marie and Pierre Curies' isolation of Polonium and Radium

it was clear that matter could fall apart..."decay"









1899

Ernest Rutherford

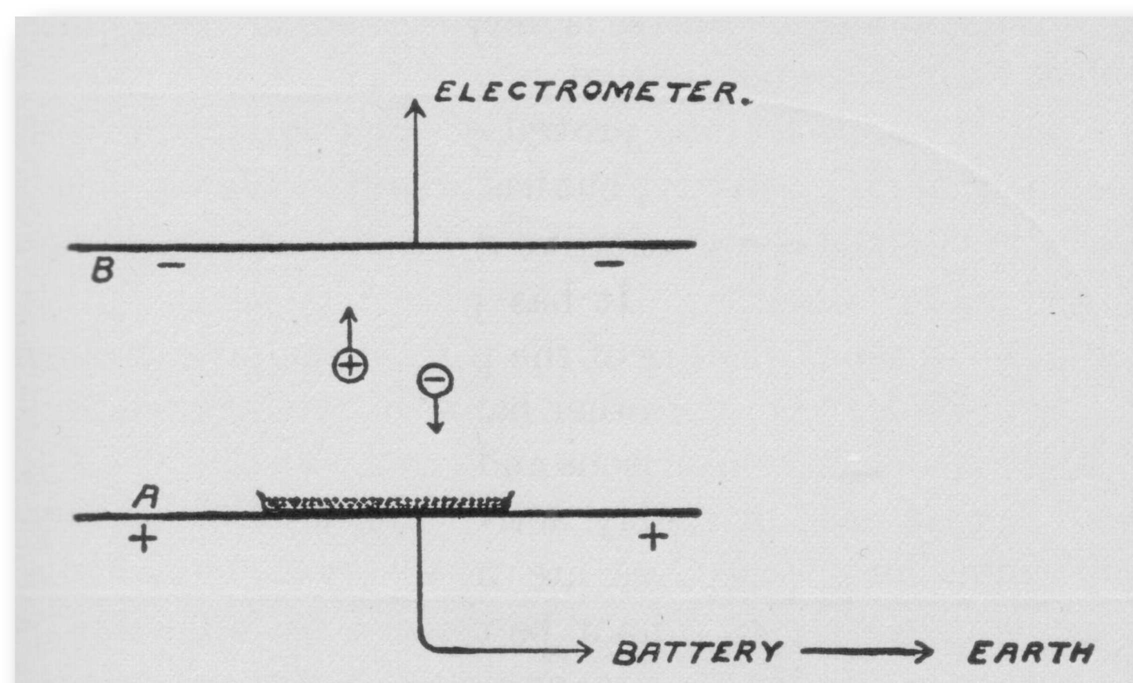
1871 – 1937

the nuclear physics' 800 lb gorrilla

> I have to keep going, as there are always people on my track. The best sprinters in this road are Becquerel and the Curies.

The epitome of the aggressive scientist...

but I mean that in a good way.



He measured the actual current from radioactive decays.

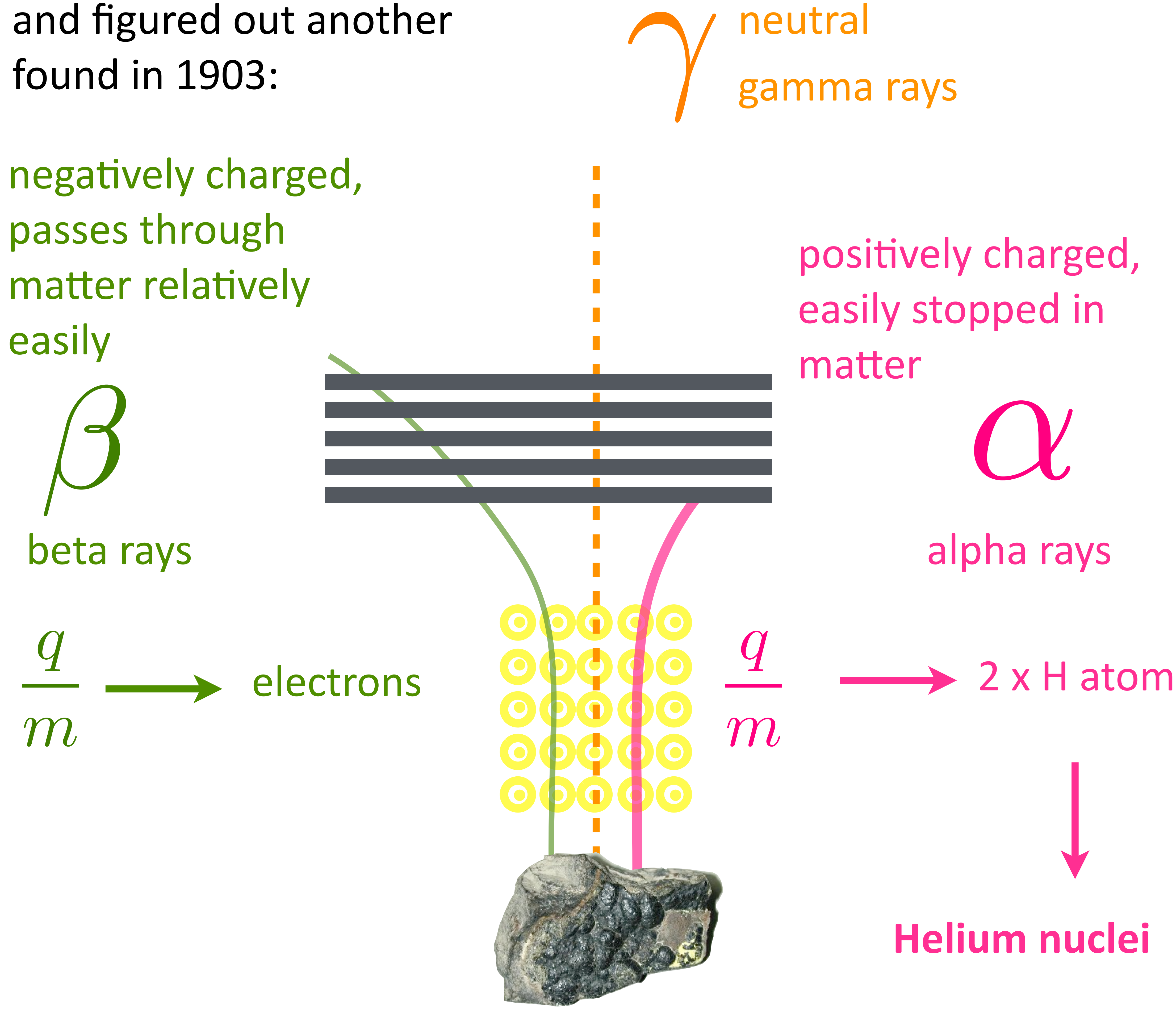
1899: he carefully isolated 2 components of radiation:

one stopped by thin aluminum

one highly penetrating

and one more

and figured out another found in 1903:



jargon alert:

beta particles,

β (old name for an electron)

refers to:	the emission of an electron in the decay of some nuclei - **beta decay**
entomology:	alpha, beta,...
example:	Carbon-14 → Nitrogen-14 + e

jargon alert:

alpha particles, α

(old name for a Helium nucleus)

refers to:	the emission of a Helium nucleus in decay of some nuclei - **alpha decay**
entomology:	alpha, beta,...
example:	Uranium-238 → Thorium-234 + e

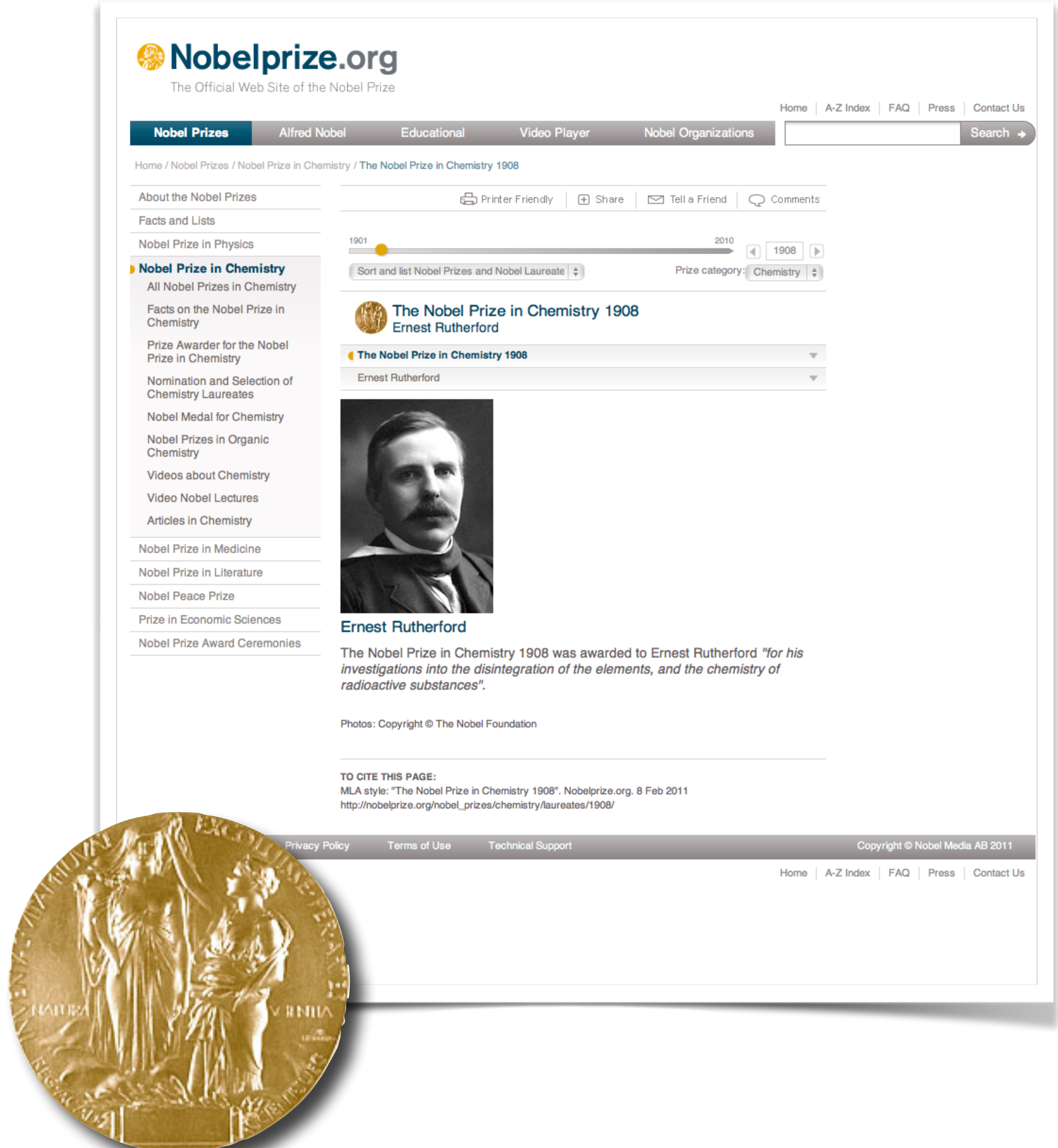
Nobel Prize in Chemistry

1908

which greatly amused him

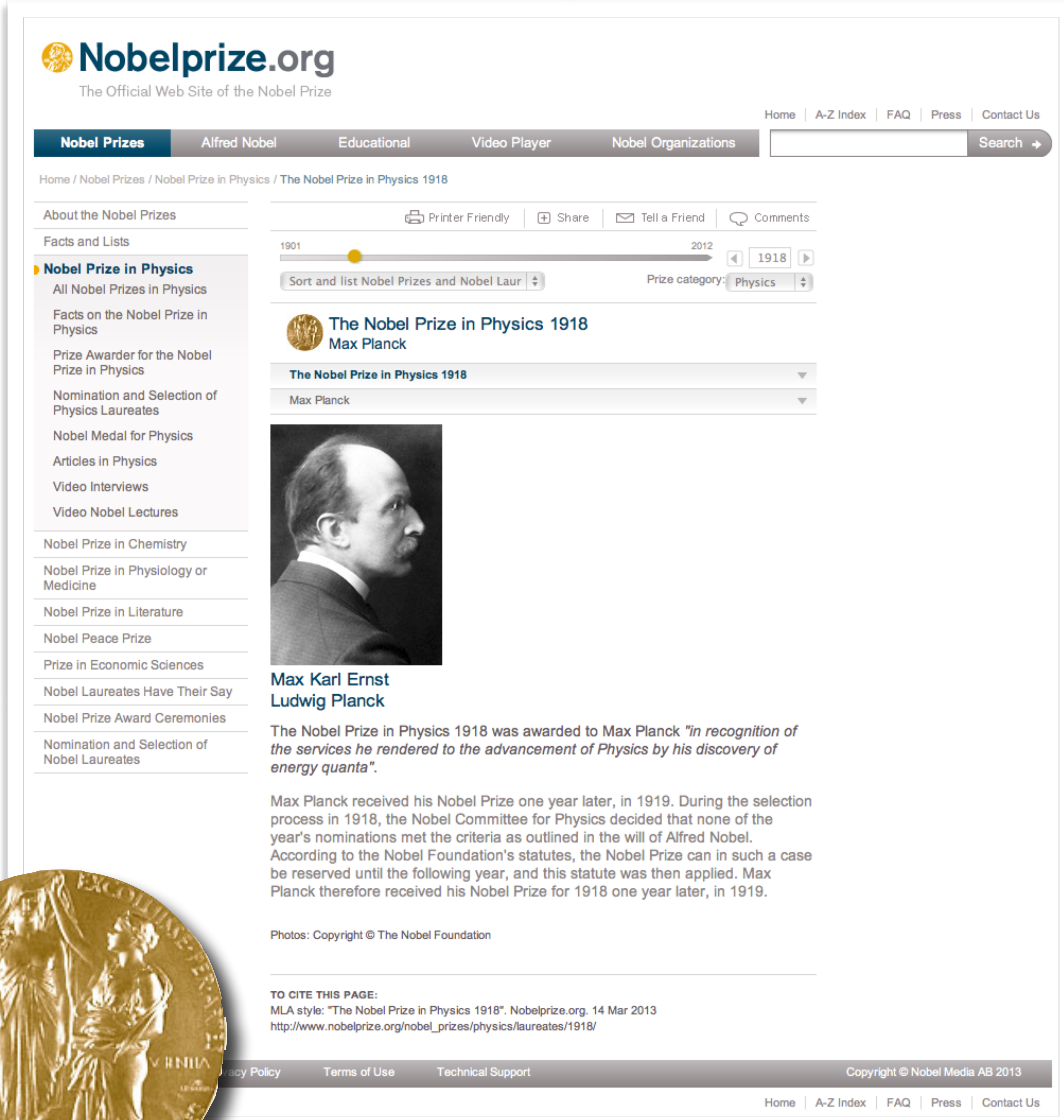
and went on

to do his best work after his Nobel...very unusual



finally, 1918

Planck got his due



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1901 2012 1918

Sort and list Nobel Prizes and Nobel Laur | Prize category: Physics

The Nobel Prize in Physics 1918
Max Planck

The Nobel Prize in Physics 1918
Max Planck

Max Karl Ernst Ludwig Planck

The Nobel Prize in Physics 1918 was awarded to Max Planck *"in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta"*.

Max Planck received his Nobel Prize one year later, in 1919. During the selection process in 1918, the Nobel Committee for Physics decided that none of the year's nominations met the criteria as outlined in the will of Alfred Nobel. According to the Nobel Foundation's statutes, the Nobel Prize can in such a case be reserved until the following year, and this statute was then applied. Max Planck therefore received his Nobel Prize for 1918 one year later, in 1919.

Photos: Copyright © The Nobel Foundation

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Max Planck, 1916

On nominating Einstein for membership in the Prussian Academy of Sciences:

"That he may sometimes have missed the mark in his speculations, as for example in his hypothesis of light quanta, cannot really be held too much against him. For it is not possible to introduce fundamentally new ideas, even in the most exact sciences, without occasionally taking a risk."

finally

the 1921 prize,
given in 1922

not the Nobel's finest hour.

so where are we, circa 1910 or so?

the electron appears to exist and so do atoms

matter is falling apart - spontaneously, and randomly

into 3 distinct kinds of “rays”

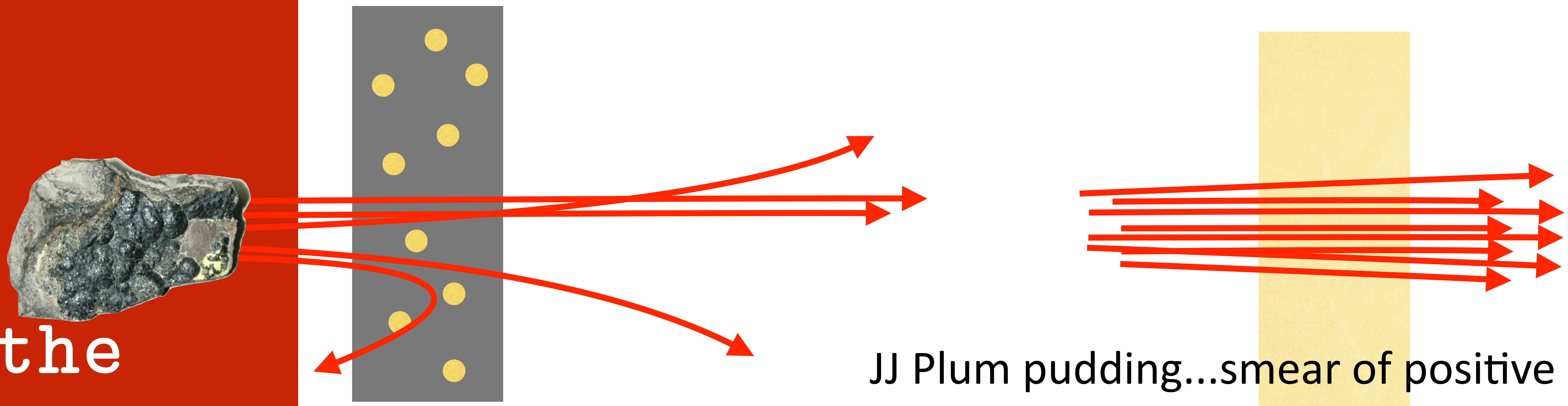
light appears to be wave-like and particle-like

He had the solution after 2 years of work

he found:

1911: that the Atomic Number was +Ze

and made a model of the atom...



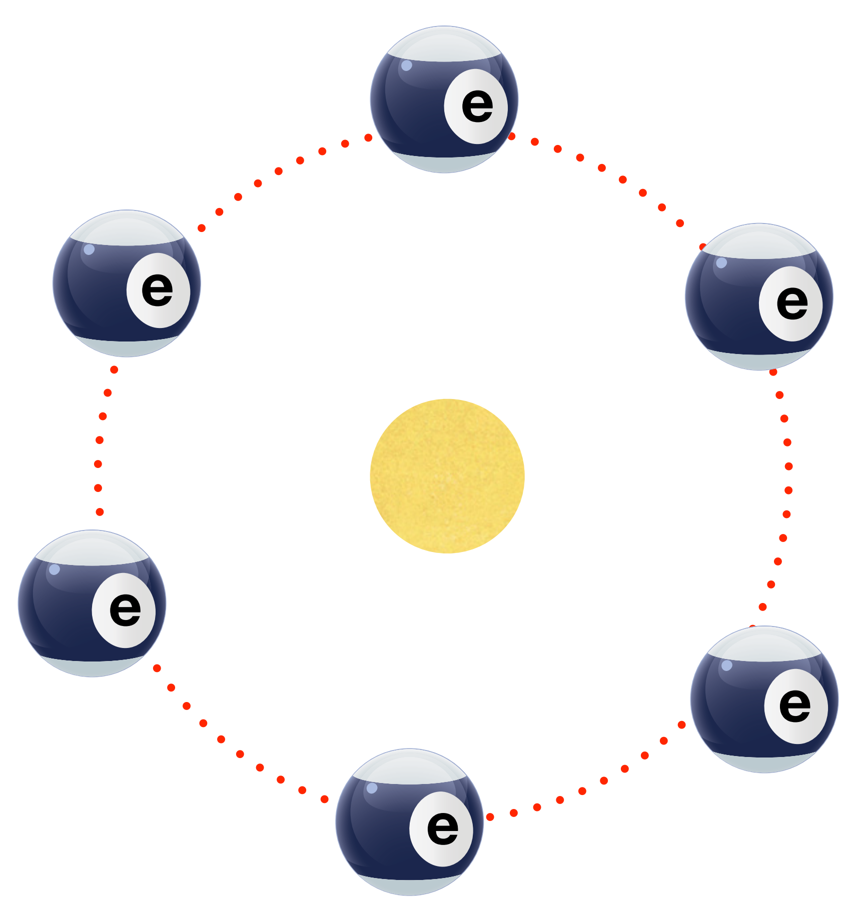
JJ Plum pudding...smear of positive charge - tiny individual deflections

the Rutherford Model of the atom:

Matter consists of **hard-cores of positive charge**.

The nucleus. This matched his alpha-scattering data.

The **electrons**? Somewhere around the outside?



That's problematic, the electrons would accelerate...and radiate.

a spiral of death.

In 1913 Bohr simply asserted

That at atomic distances...

there are electron orbits that simply don’t radiate - “stationary states”

fixed “quantized” orbital radii and orbital velocities

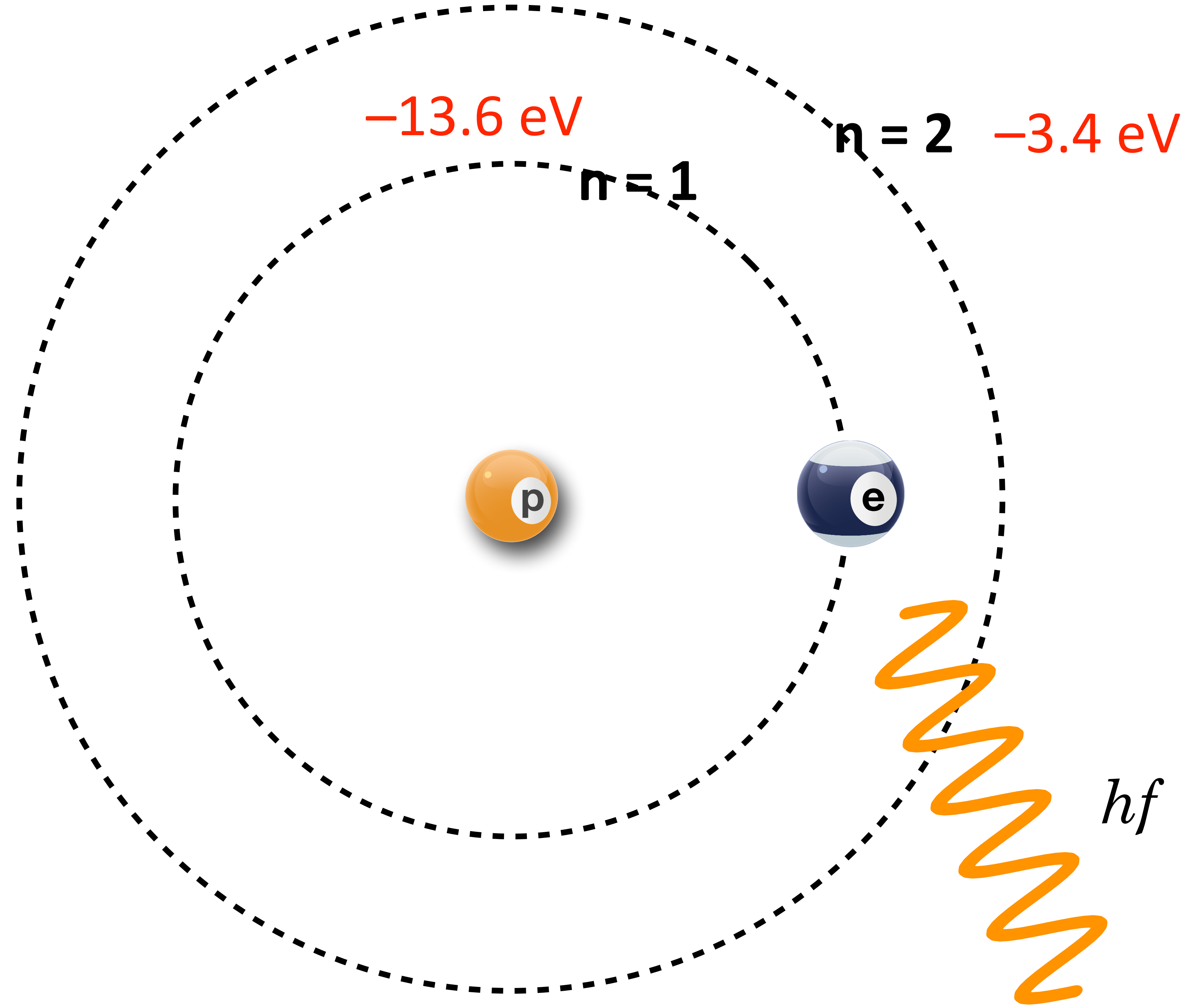
Niels Bohr

1885 – 1962

a talker.

the magic of Bohr's model:

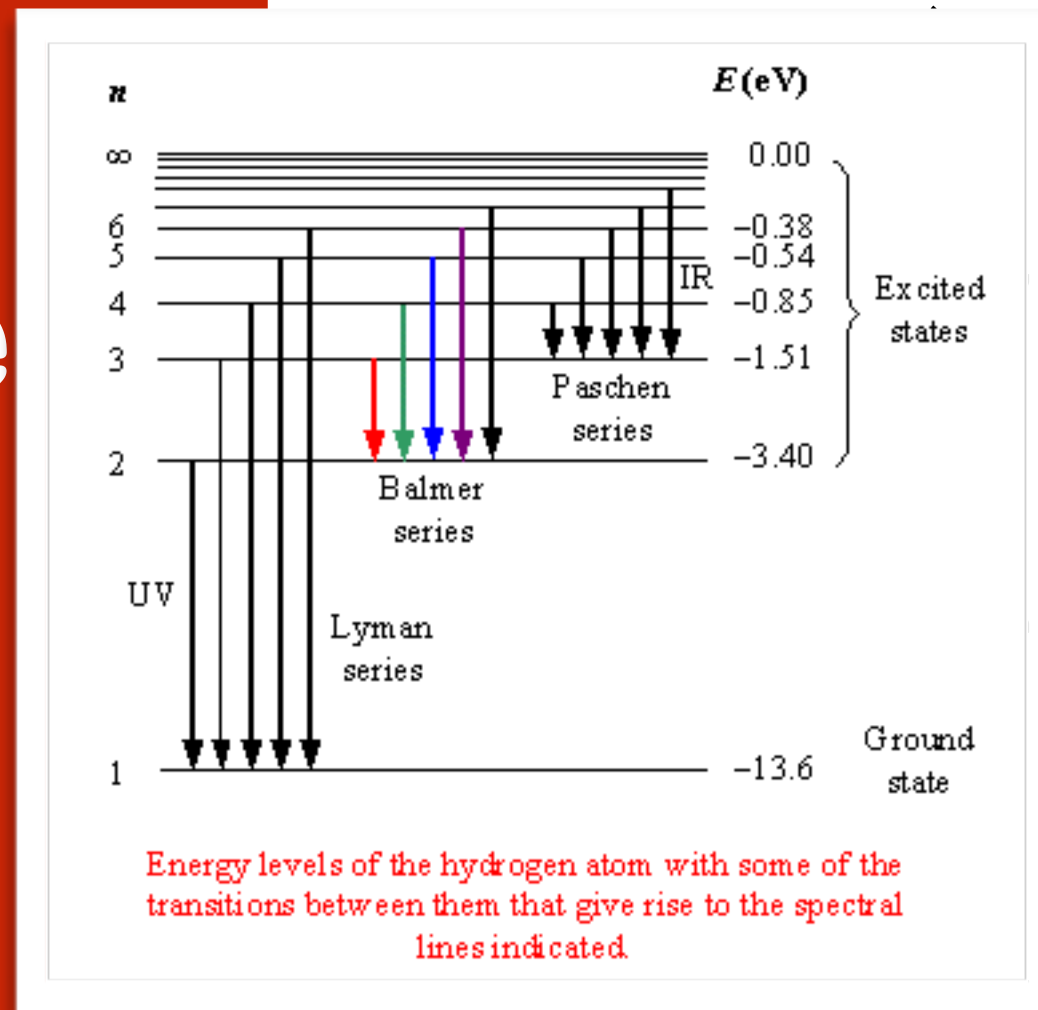
the idea of an atomic transition

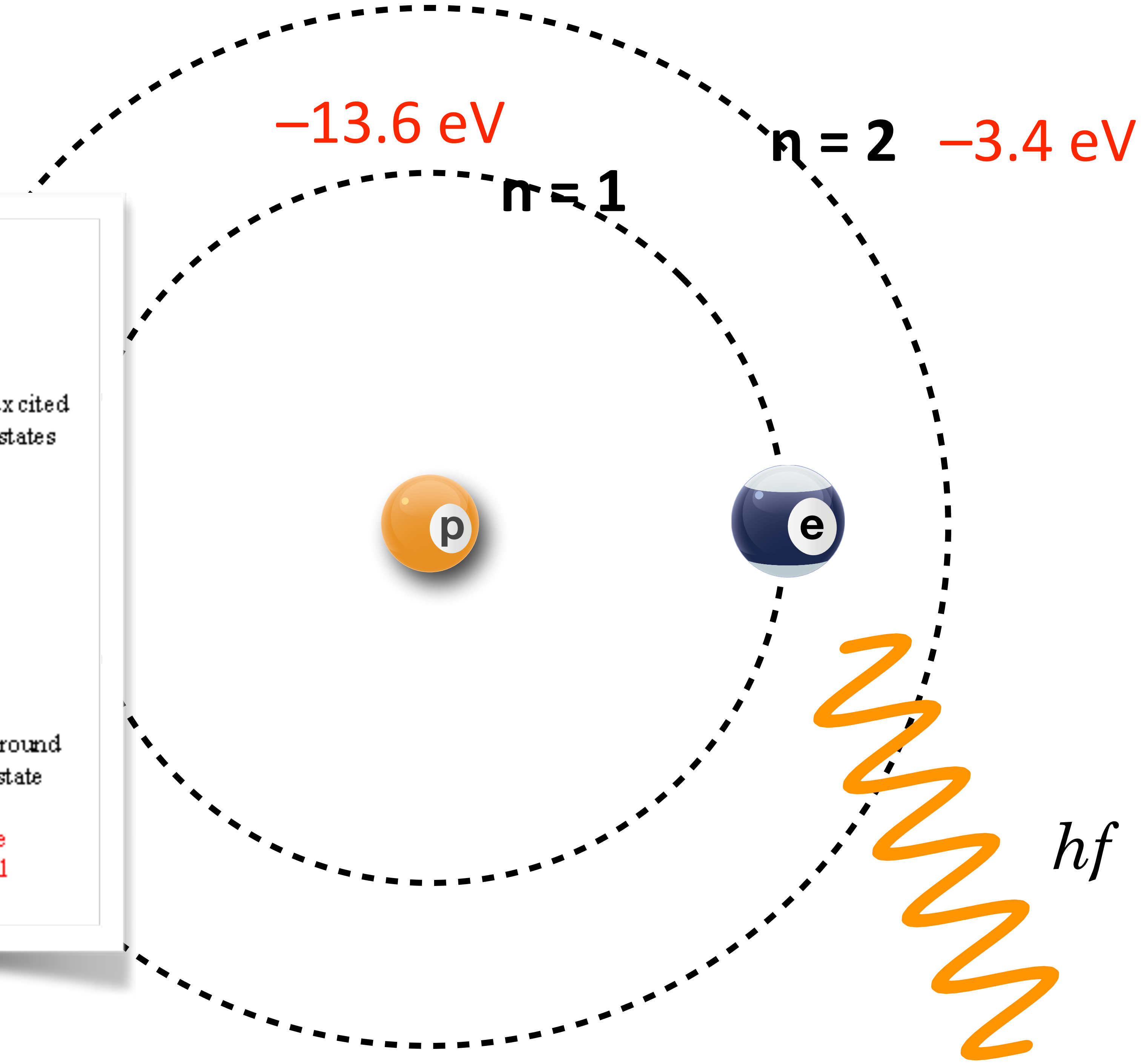


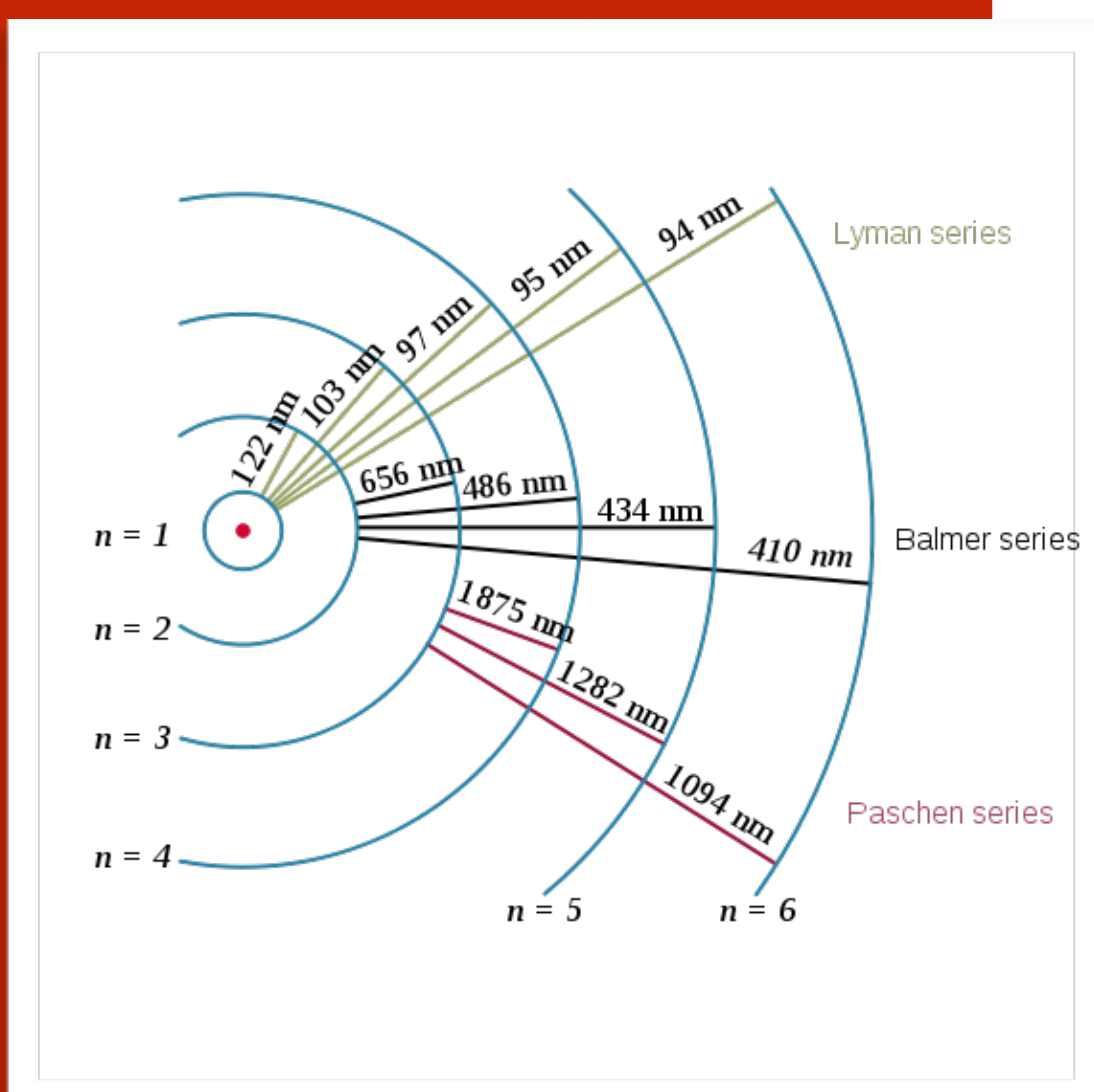
The idea: transition of electrons results in the released energy of a photon...of a particular energy

imagine his surprise

1913: his way.

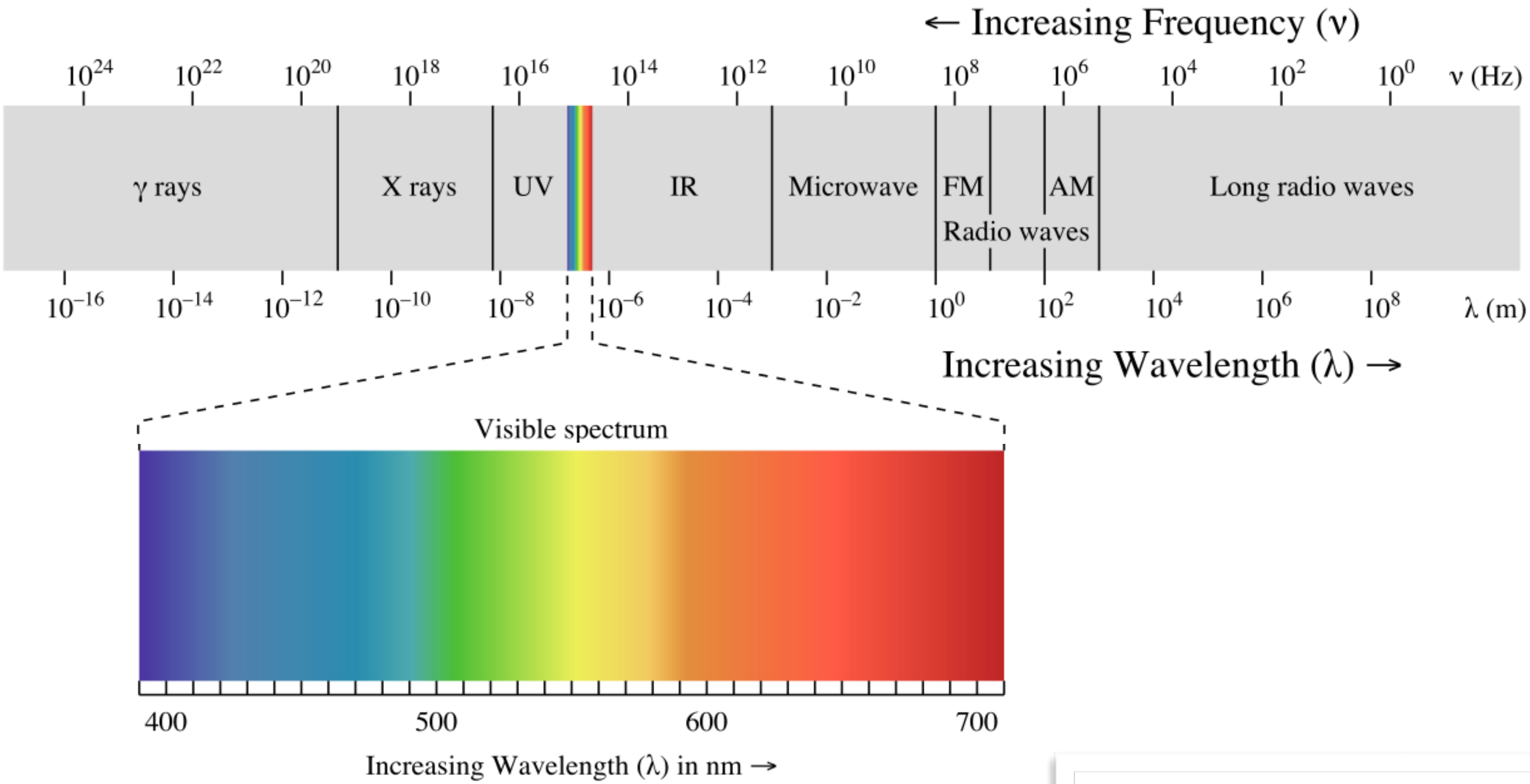






$$E_2 - E_1 = (13.6\text{ eV})\left(\frac{1}{1^2} - \frac{1}{2^2}\right) = hf$$

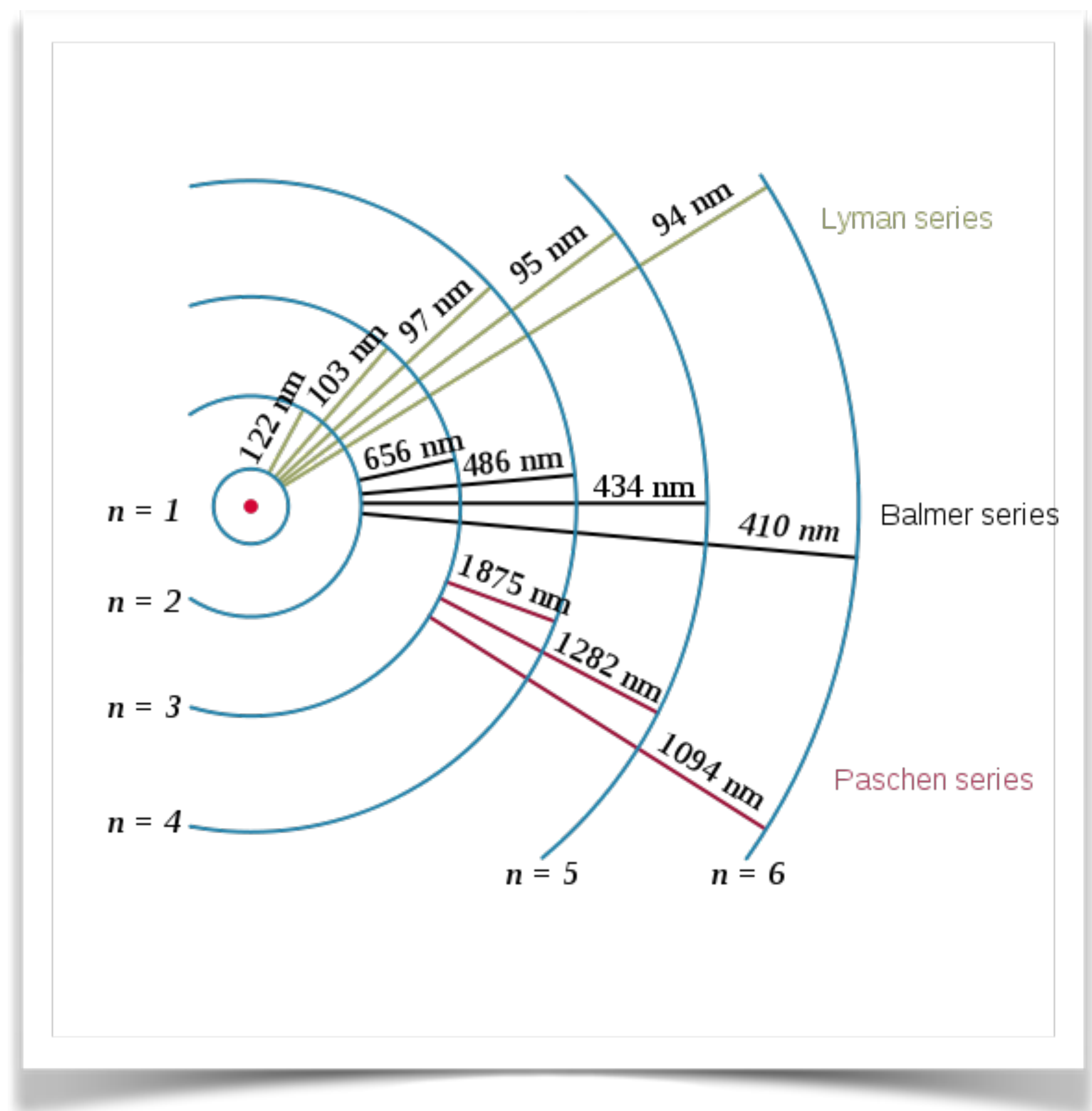
$$E_2 - E_1 = 10.1\text{ eV} \longrightarrow \lambda = 122\text{ nm}$$



410 434 486 656

nm

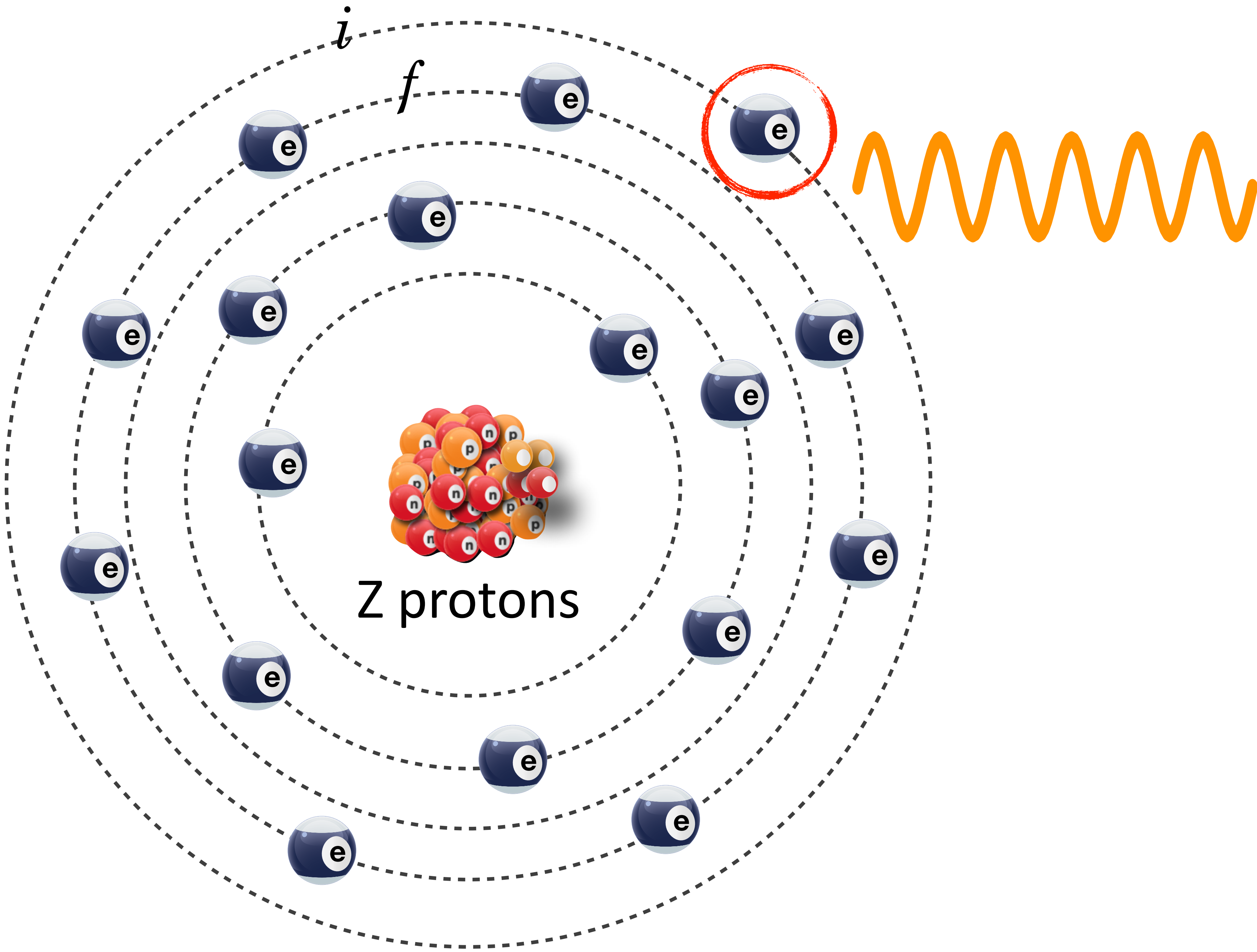
Hδ Hγ Hβ Hα

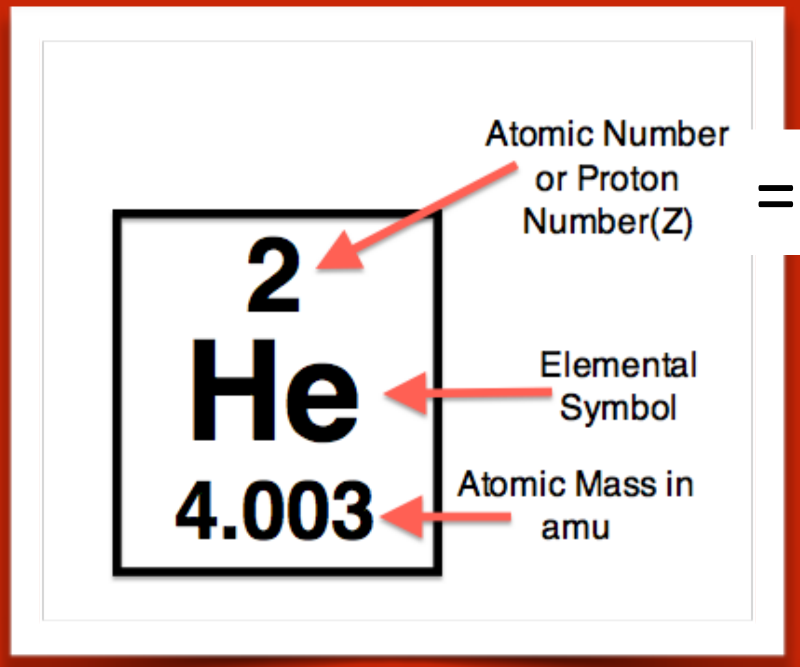


hydrogen, fine

how about more complex elements?

Higher atomic number, Z?





= # of electrons also!

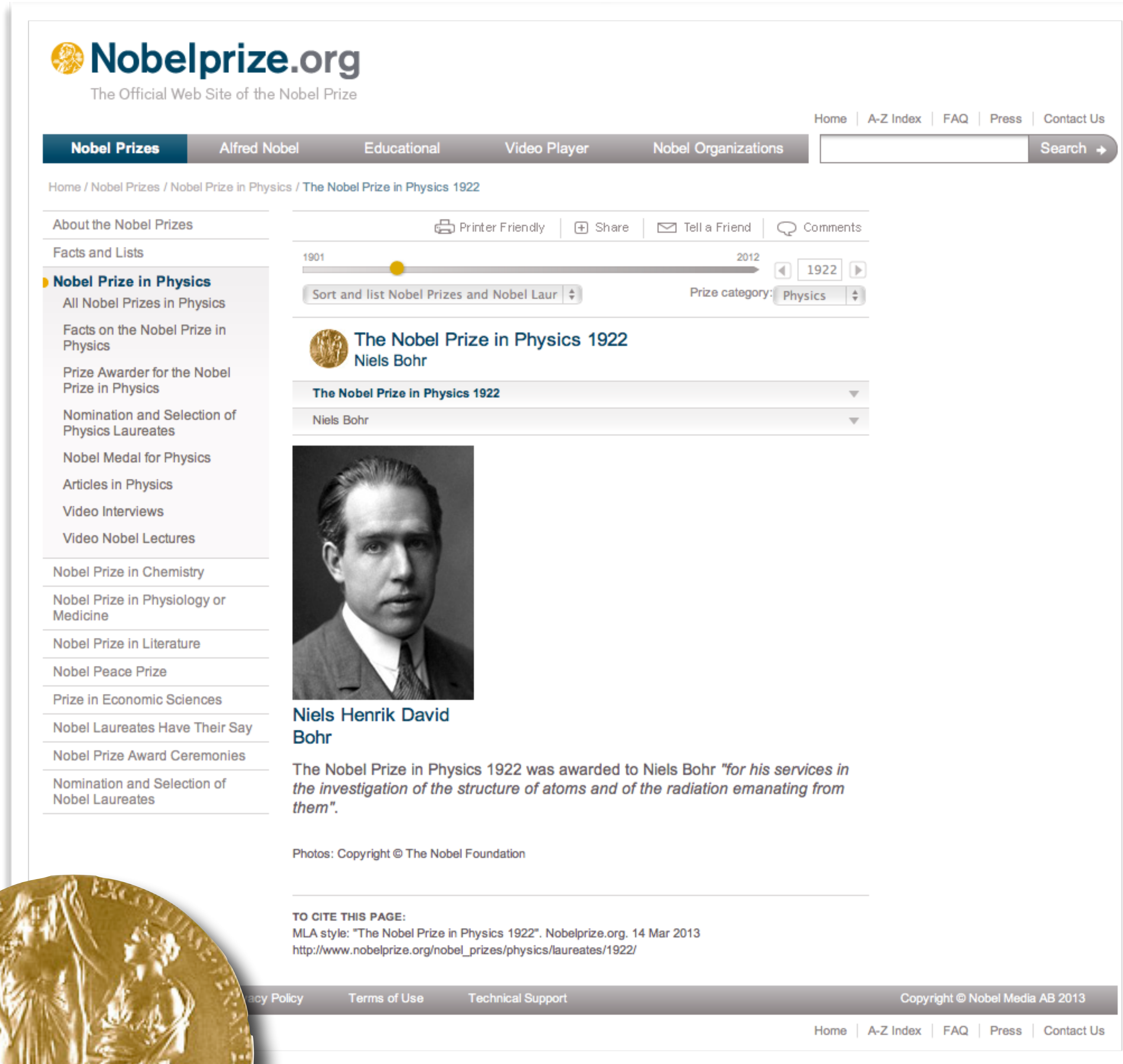
lots of electrons, but as long as there's one lone one..the Bohr Formula still works.

$$E_f - E_i = -\frac{1}{2}\frac{4\pi^2 k^2 Z^2 e^4}{h^2}\left(\frac{1}{n_i^2} - \frac{1}{n_f^2}\right) = -hf$$

Go looking for new elements....

yup, 1922

actually with Einstein's delayed prize



`then`

it got strange

quantum idea of electrons

Prince Louis de Broglie

His 1922 PhD thesis:

“The French Comedy”

must have been disconcerting

The Prince looking self-satisfied

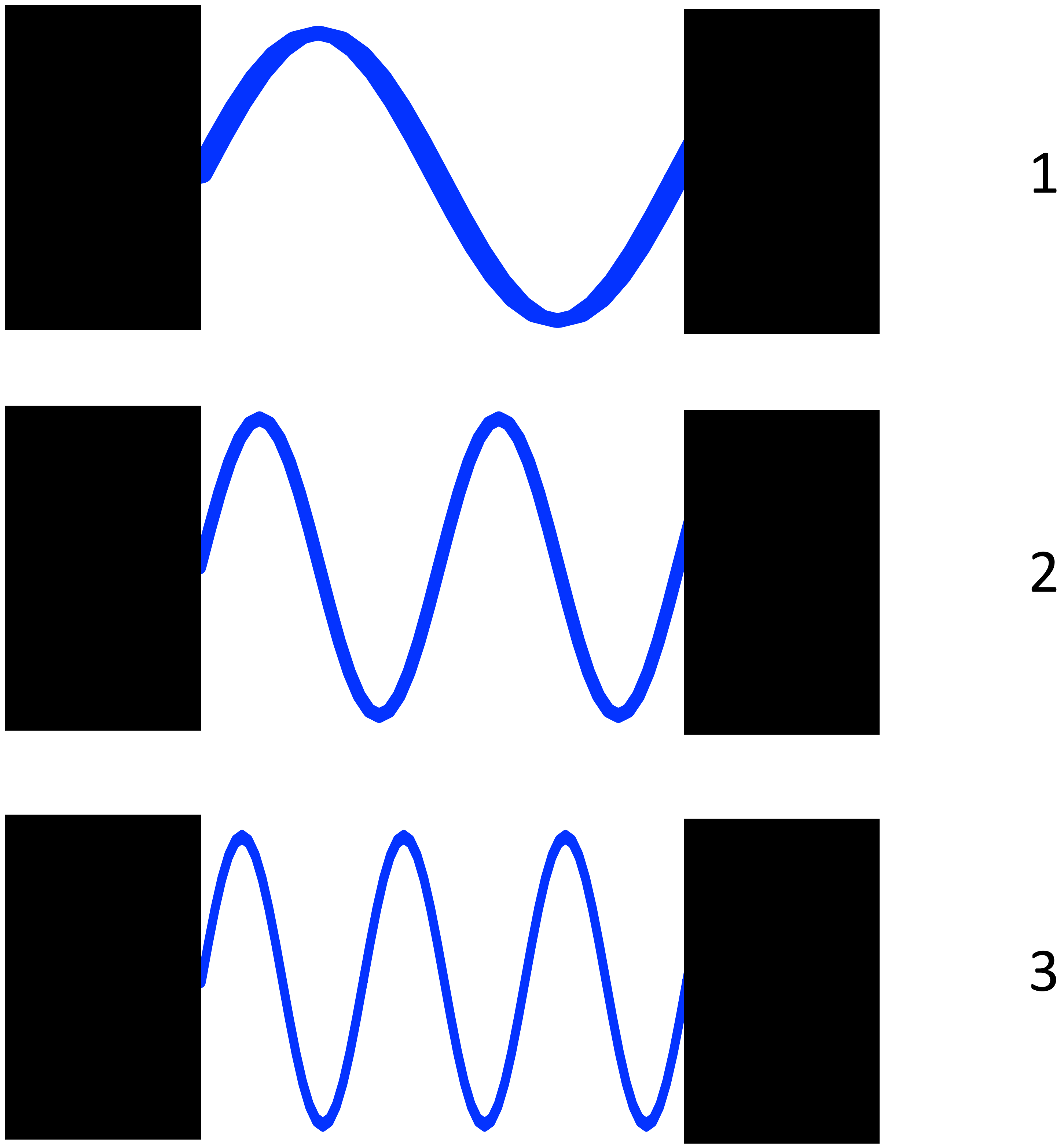
the quantum idea:

made use of **integers**

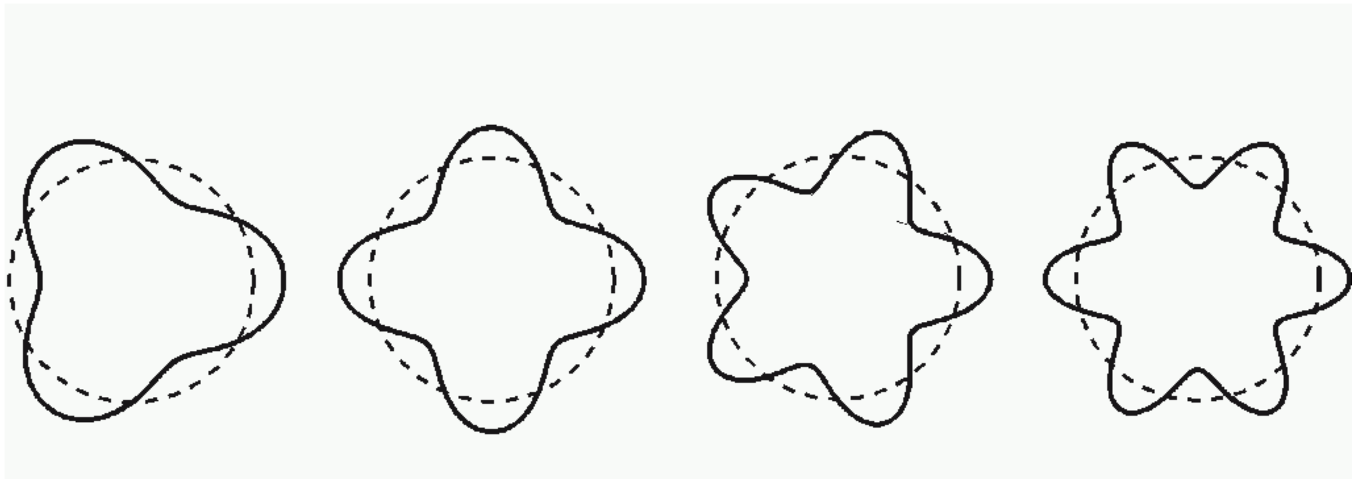
so do waves

a standing wave

uses integers



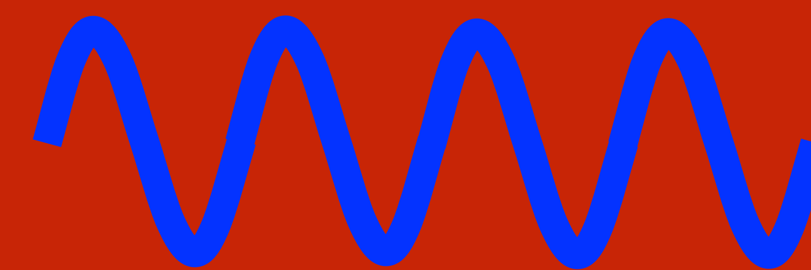
Suppose the integer's in Bohr's formula...had to do with standing waves? Wrapped around a circle?



But...you sputter...I thought the orbits were electrons?

A standing wave, wrapped around in a circle

Following Bohr:



photons

undeniably wave and particle-like

in atoms they involve integers directly.

hmmm, thought the Prince

One other thing involves integers

standing waves

well

go from photons

to matter...!

Remember the total energy relation?

$$E_T^2 = (mc^2)^2 + (pc)^2$$

In which objects with m = 0 have energy:

$$E = pc$$

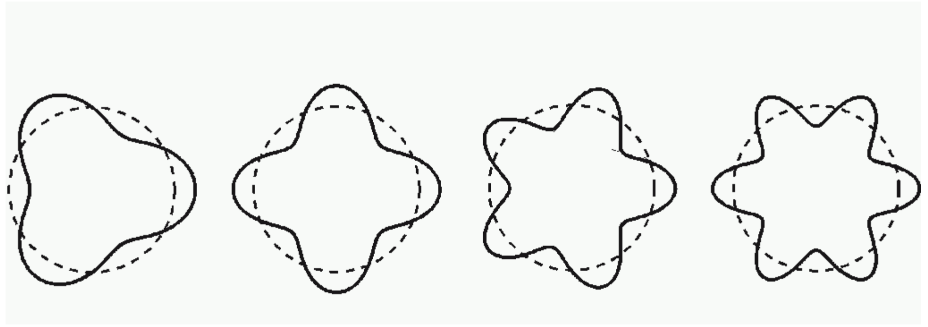
rearrange... $$p = \frac{E}{c}$$

use the Planck relation for E:

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

Pretend that this Photon-inspired, standing wave idea **works for electrons of momentum p.**

Electrons with a wavelength!



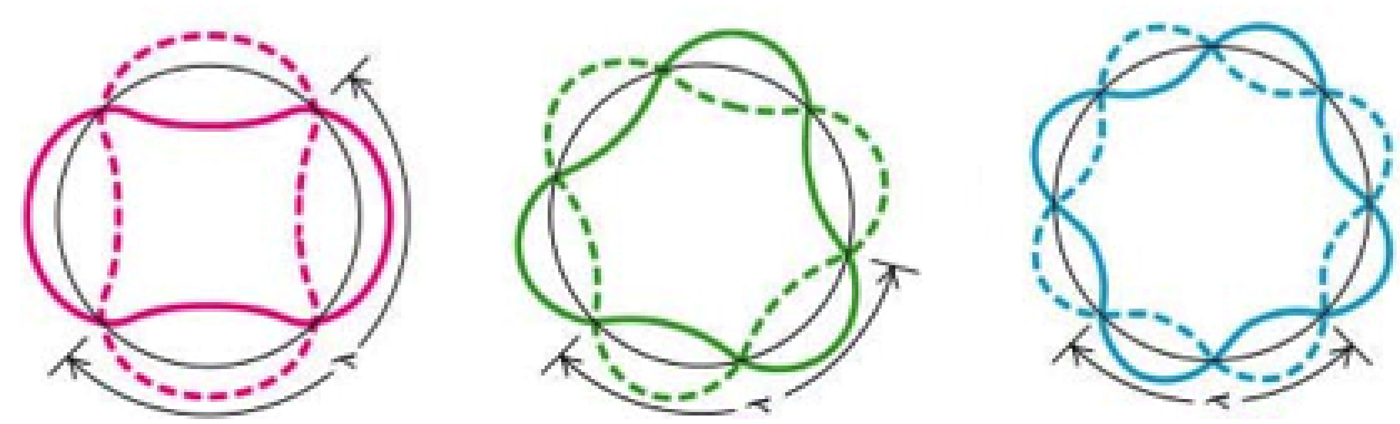
the momentum of an electron

related to the wavelength of an electron

the wavelength of an electron??

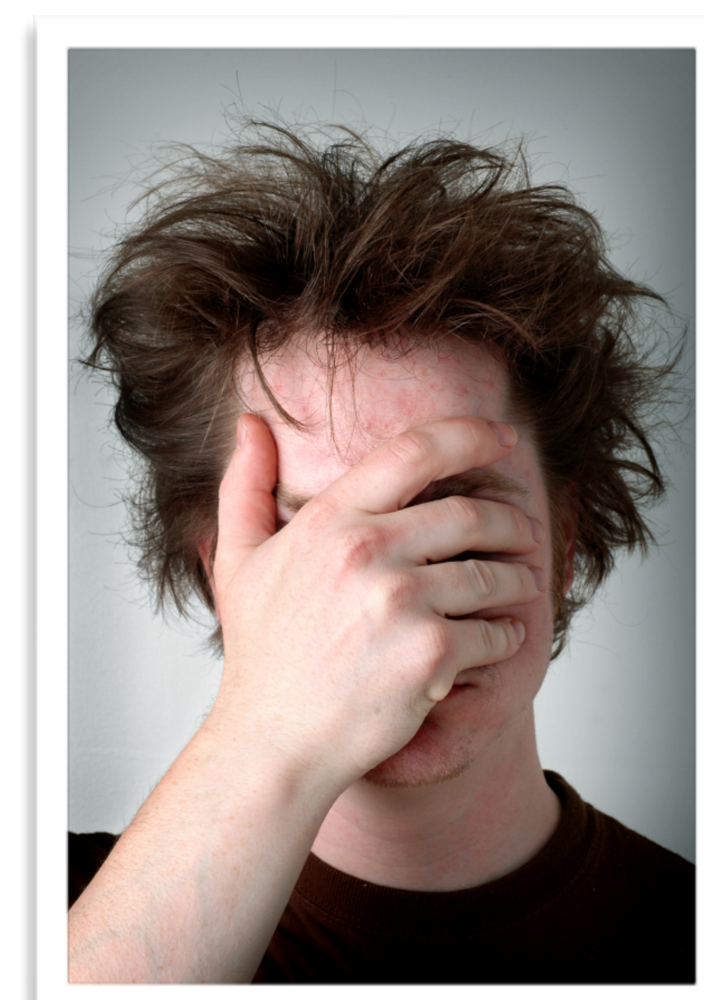
$$p = \frac{hf}{c} = \frac{h}{\lambda}$$

now, a relation for an electron!



n = 2 3 4

deBroglie guessed that the Bohr quantum number was related to the number of standing waves of the electron around the nucleus



photons:

$$\lambda_\gamma = \frac{h}{p_\gamma}$$

electrons:

$$\lambda_e = \frac{h}{p_e}$$

$$\lambda_e = \frac{h}{m_e v}$$

that was deBroglie's hypothesis

electrons are particles and waves

his PhD examination committee was so scandalized

they actually asked Einstein for advice

Who said: "sounds good to me."

this relation will be important

relating the wavelength of a quantum object

to its momentum

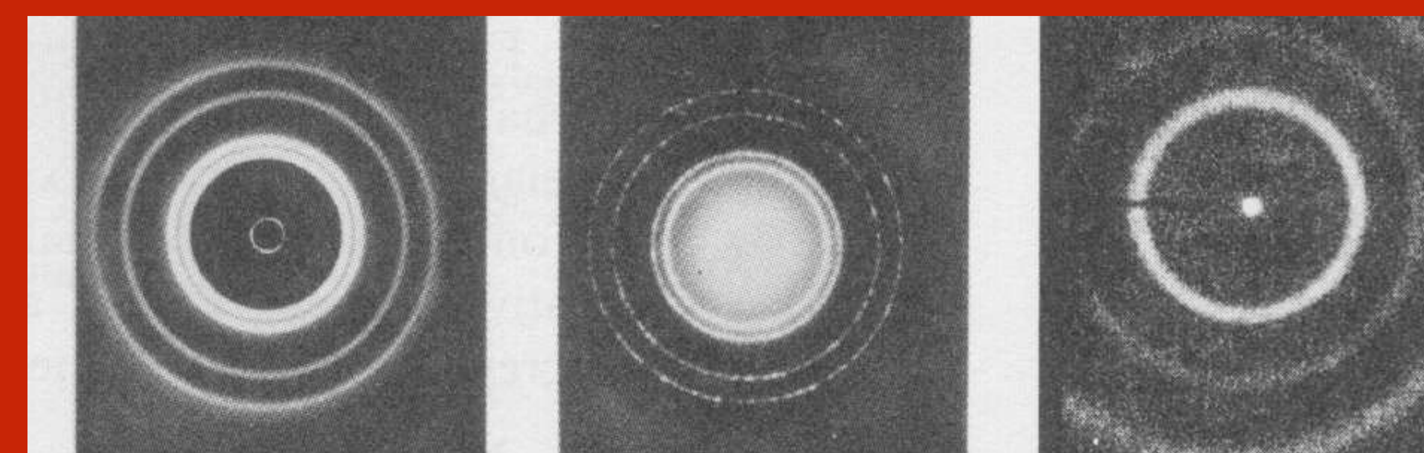
"deBroglie relation"

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

particles as waves?

deBroglie suggested how:

they should exhibit diffraction



0.071nm X-ray diffraction on a polycrystal

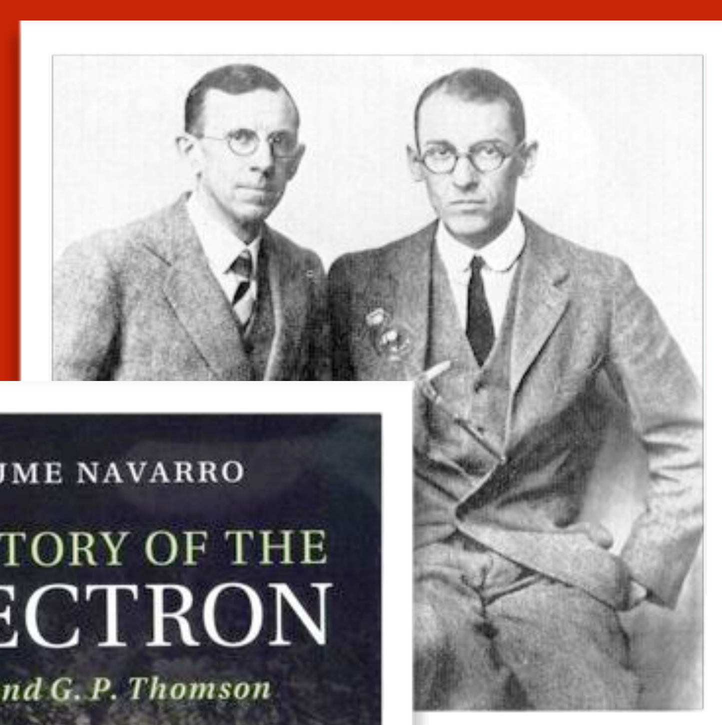
600 Ev electron diffraction on a polycrystal

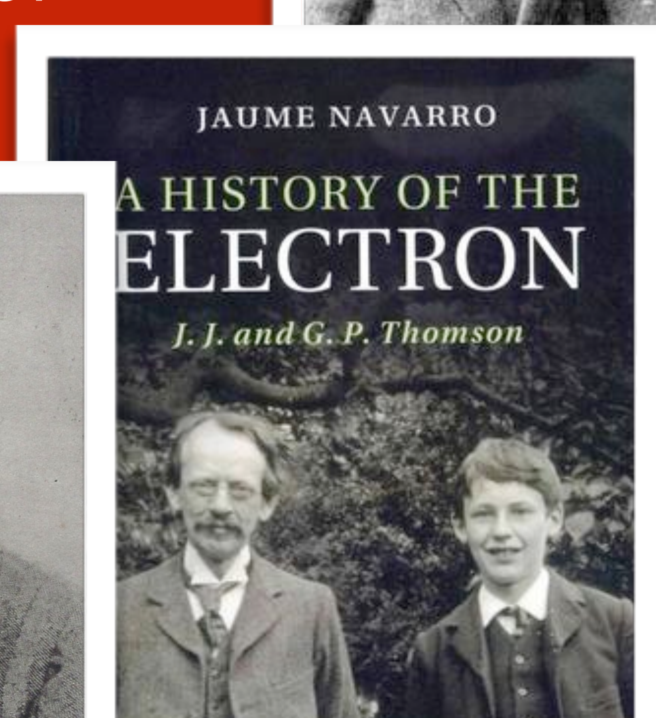
0.057 ev neutron diffraction on a polycrystal

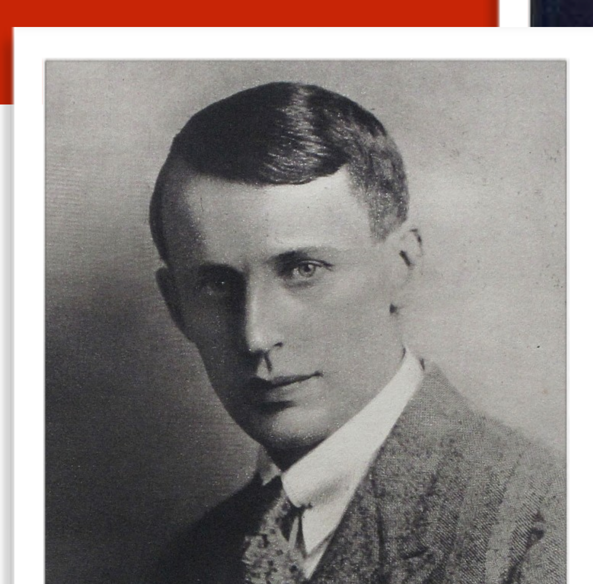
a “slit” appropriate for X-ray wavelengths

1927

Davisson & Germer







JJ's son GP

JJ got the Nobel for showing that the electron exists and is a particle

GP got the Nobel for showing that the electron is a wave

Germer lost out

Nobel rules: 3 people.

in one picture

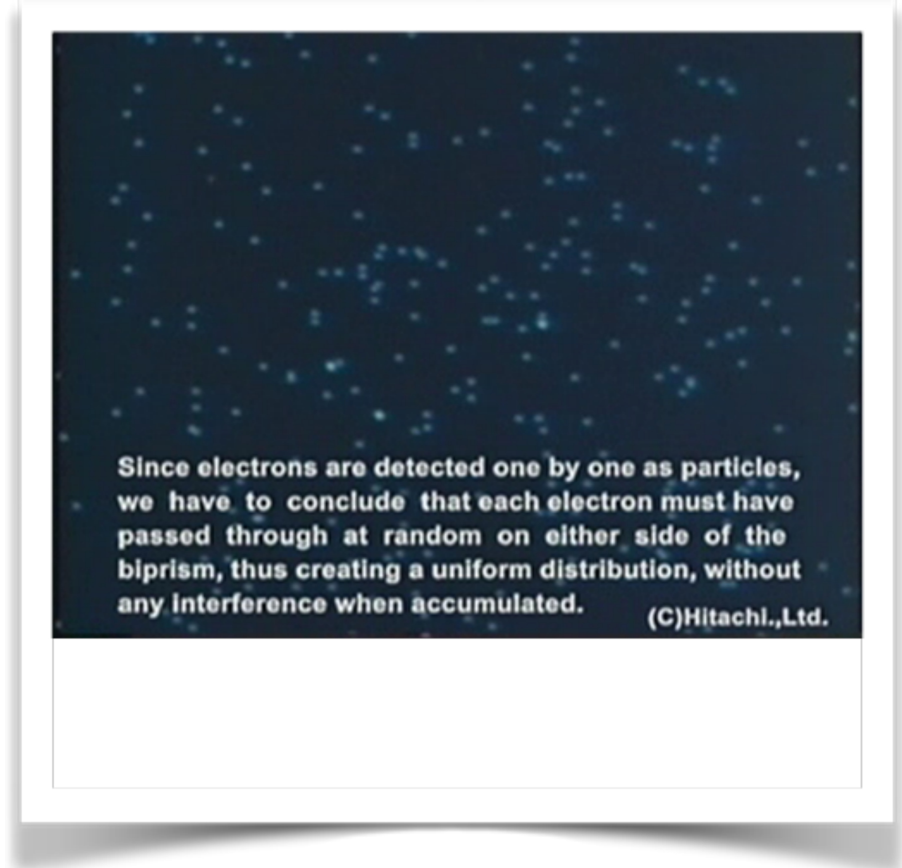
both the particle like features of electrons

the dots

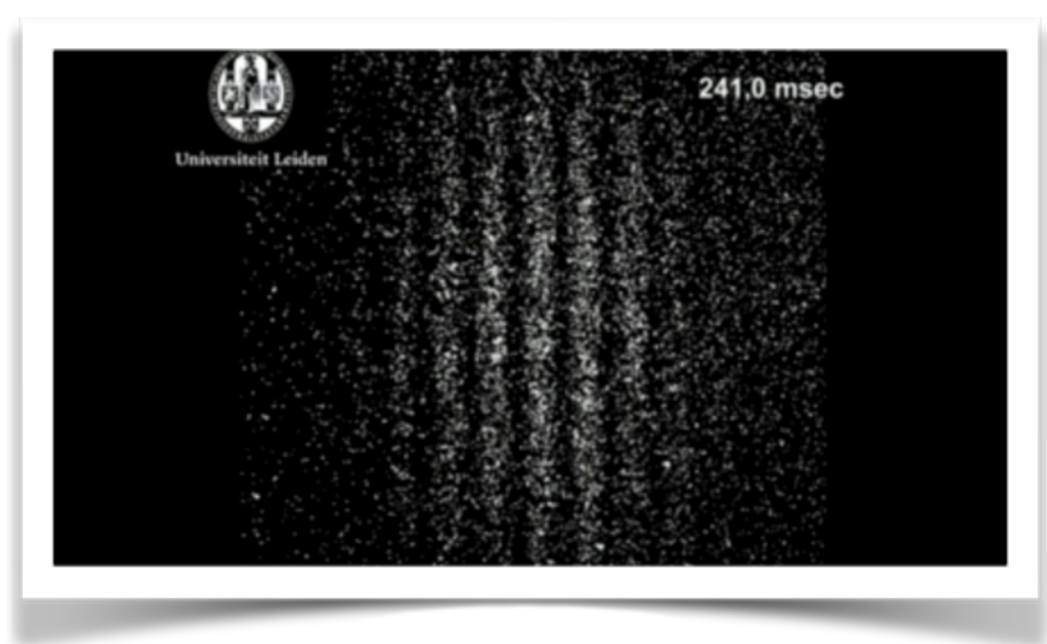
and the wavelike features of electrons

the diffraction pattern

http://www.hqrd.hitachi.co.jp/em/doubleslit.cfm



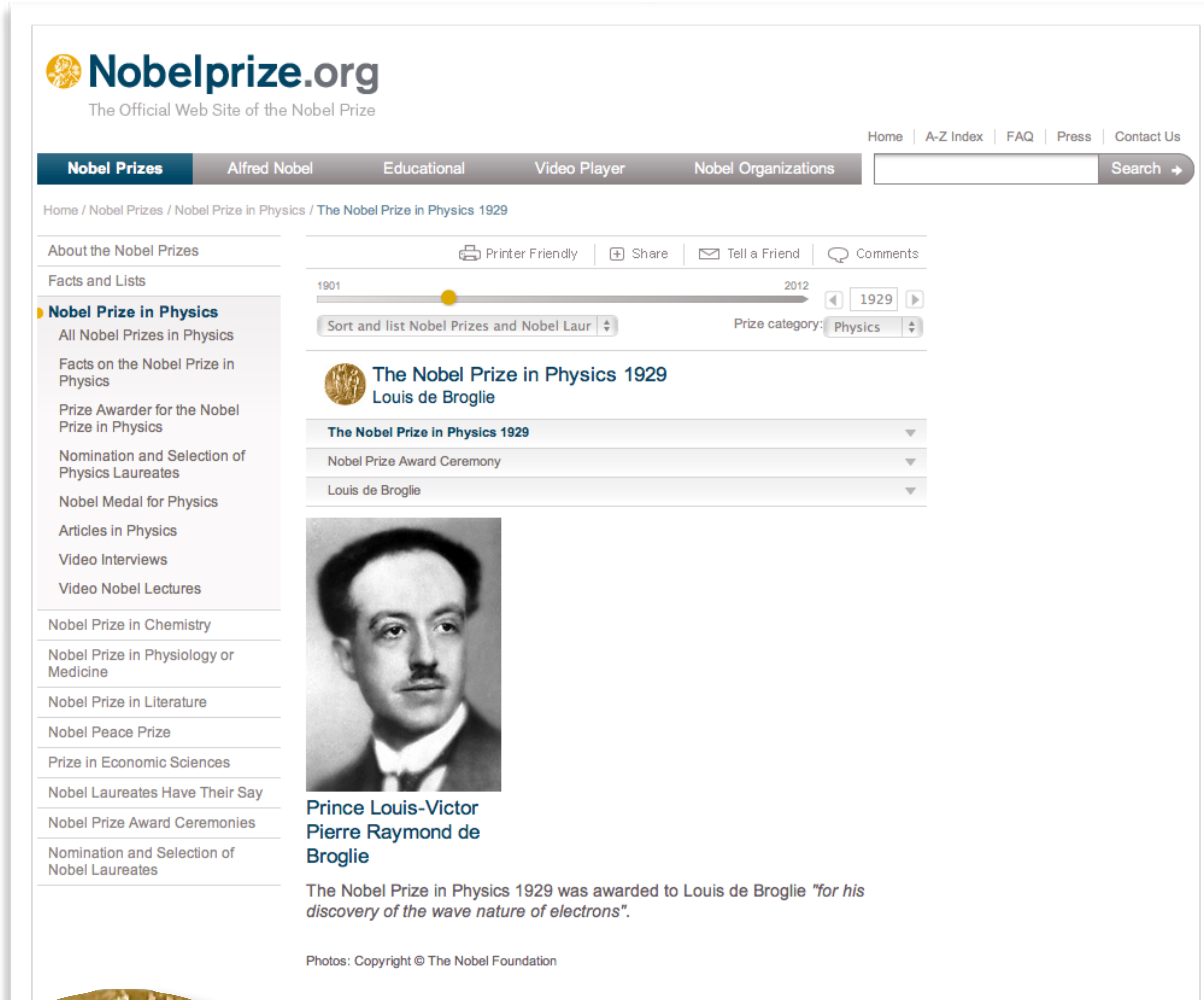
electrons!



photons!

sole winner

1929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The Nobel Prize in Physics 1929
Louis de Broglie

The Nobel Prize in Physics 1929
Nobel Prize Award Ceremony
Louis de Broglie

Prince Louis-Victor Pierre Raymond de Broglie

The Nobel Prize in Physics 1929 was awarded to Louis de Broglie *"for his discovery of the wave nature of electrons"*.

Photos: Copyright © The Nobel Foundation

get real

I weigh 200 lbs & I walk 5 mph

what's my wavelength?

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

$$\lambda = \frac{h}{mv} = 3 \times 10^{-36} \text{ m}$$

Smaller than the nucleus...My waviness doesn't show.

Why is it so small?

Two reasons:

1. My momentum is huge, downstairs
2. Planck's Constant is tiny

Quantum Mechanics born of some anxiety

the lack of radiation of Bohr's accelerating electrons was still a problem: Bohr knew it and figured there would be a more complete answer.

what in the world is an electron in deBroglie's scheme?

There was much that was ad hoc and not believable

both in Bohr's approach and deBroglie's

however, the experimental situation made it clear that the broad suppositions of both had to be a part of the truth.

Quantum Mechanics, proper was the child of 3+1 people:

Werner Heisenberg - 1925; invention #1

Erwin Schrödinger - 1926; invention #2

Paul Dirac - 1925; showed #1 and #2 are equivalent

Max Born - 1926; gave the modern interpretation

the breakthrough

from an unlikely source

Erwin Schrödinger

Erwin Schroedinger 1887-1961

where do you look for your keys in the dark?

Schroedinger was an expert

in the mathematics of waves

EM waves, material waves, fluids, elastic media, sound...

the quantum idea:

made use of **integers**

so do *complicated* waves

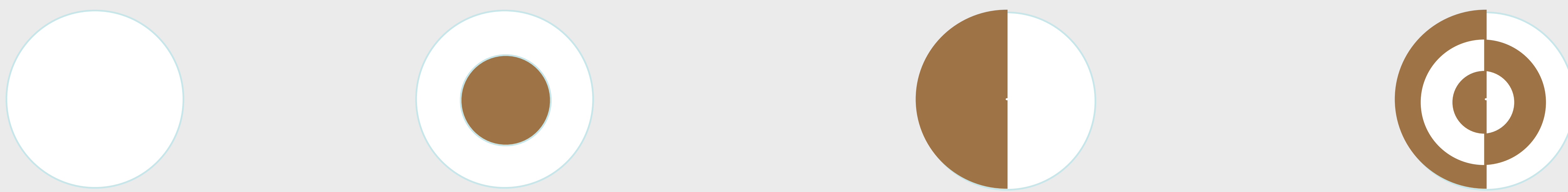
integers again

$$u(r,t) = \sum_{m=0}^{m=\infty}\sum_{k=0}^{k=\infty}[(A_{mk}\cos\omega_{mk}t + B_{mk}\sin\omega_{mk}t)\cos\theta + (A_{mk}\cos\omega_{mk}t + B_{mk}\sin\omega_{mk}t)\sin\theta]J_m(\frac{\omega_{mk}r}{v})$$

Solutions for the vibrations of a drumhead, or a violin string, or that vibrating hoop...

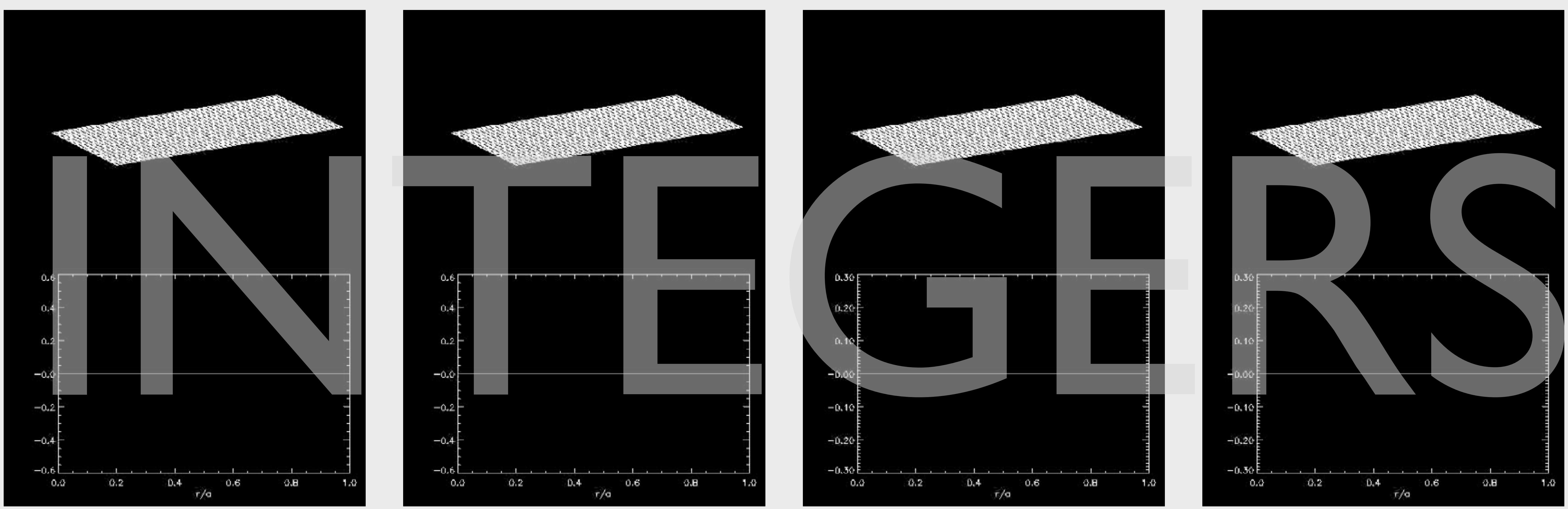
Forget the details...just notice the mixing of lots of waves...the m's and k's? **Integers**.

Here are some of these infinite modes of vibration as described by some of the functions (white and brown are moving in opposite directions (the drum is clamped down at the edges)



these are both m=0 modes

these are both m=1 modes



I found these nice movies at: http://photon.phys.clemson.edu/brad/courses.dir/movies.dir/phys841-01.dir/movies.html terrific

what’s waving???

Schroedinger “solved” a drum-head-like equation for the hydrogen atom

Discrete, vibrational modes...of a something.

However, he was in for a surprise -

Brave guy: worked in the alps over Christmas 1925 with his girlfriend while his wife stayed in Zurich.

The surprise, is that the mathematics required that the **state** of such a system had to be

imaginary!!

Solutions: the Bohr atom bang-on.
but with a twist.

the ‘‘quantum field’’

“psi”...also called the “wavefunction”

the “state” of something.

The “Schroedinger Equation”

predicts its behavior in space and time

$$\psi(x,t)$$

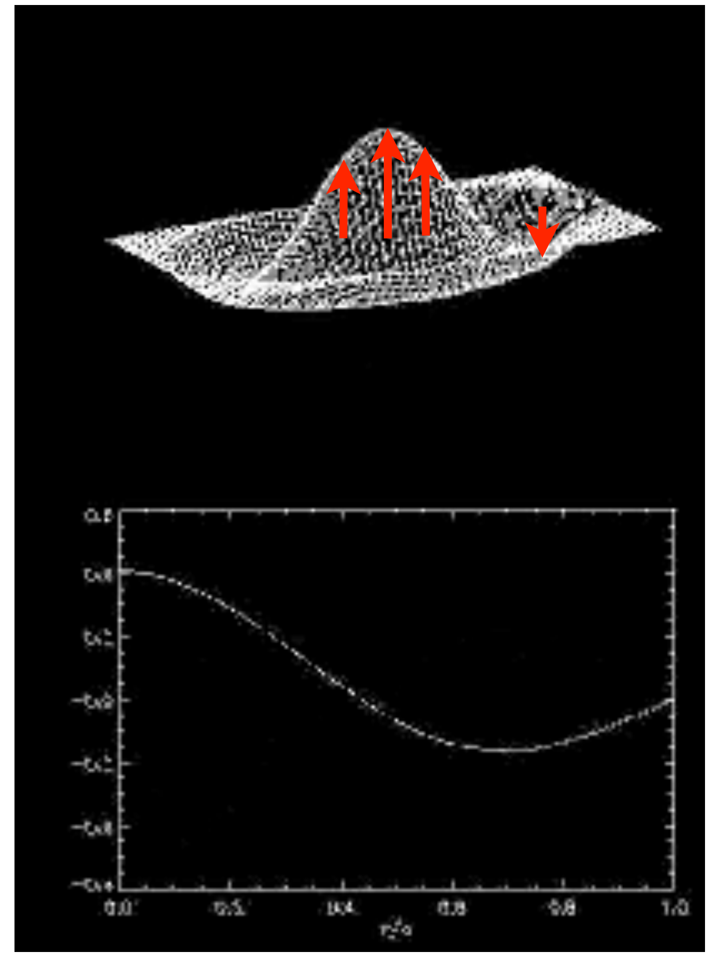
what is the ''state'' of a system

a function:

you give me a time and a position in space

I'll give you the "state" of the system

There can be classical states:

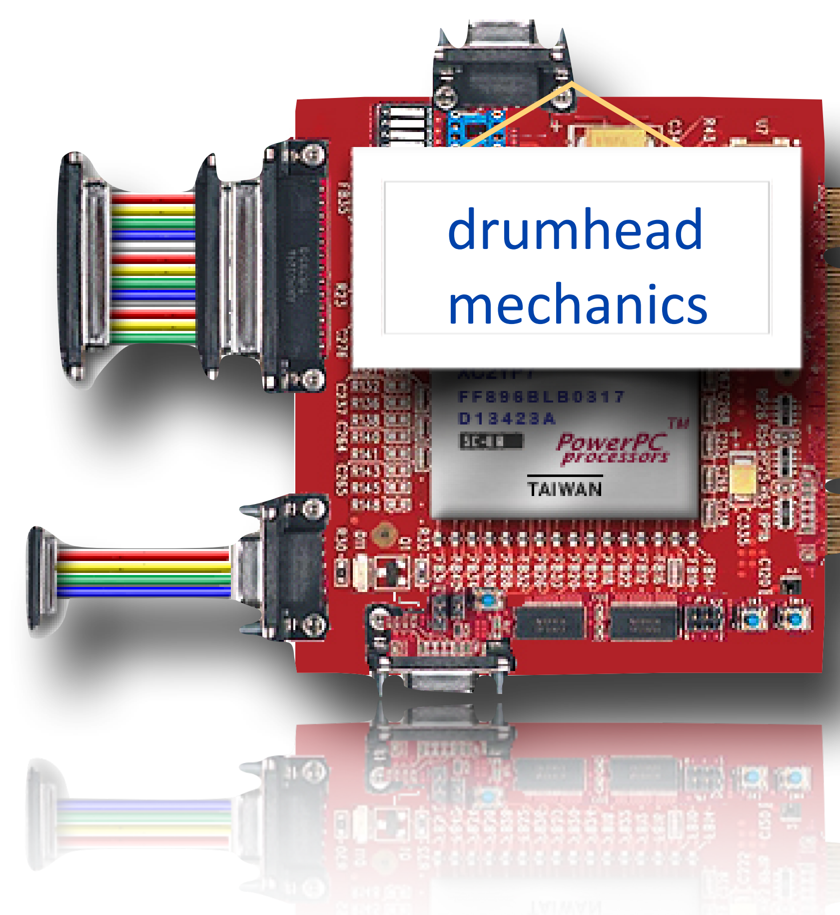


Let's call the "state" of the drumhead, S...which is a function of time and space.

The *value* of S is the height above the plane.

forces

initial state at x_0, y_0, t_0



& energy

at any time, all over the surface

what is the "state" of a system

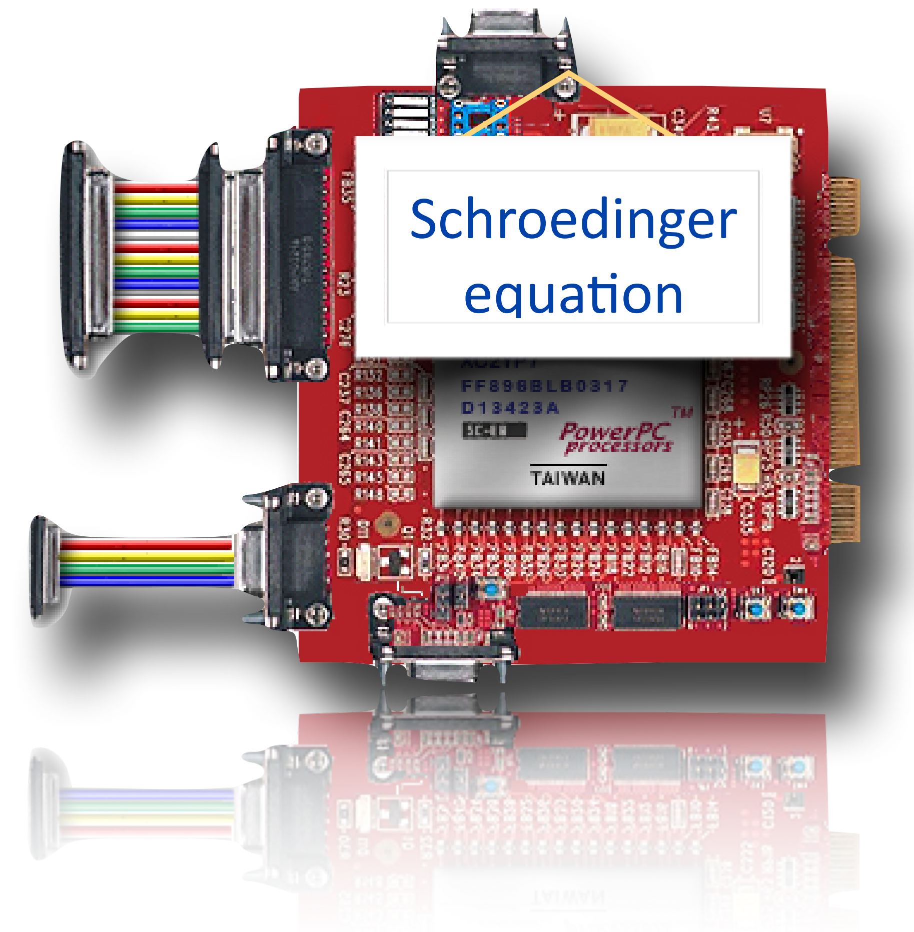
but for quantum systems?

Schroedinger didn't know what it was

but he could solve the equation

forces

initial state at x_0, y_0, t_0



& energy

at any time, all over the volume