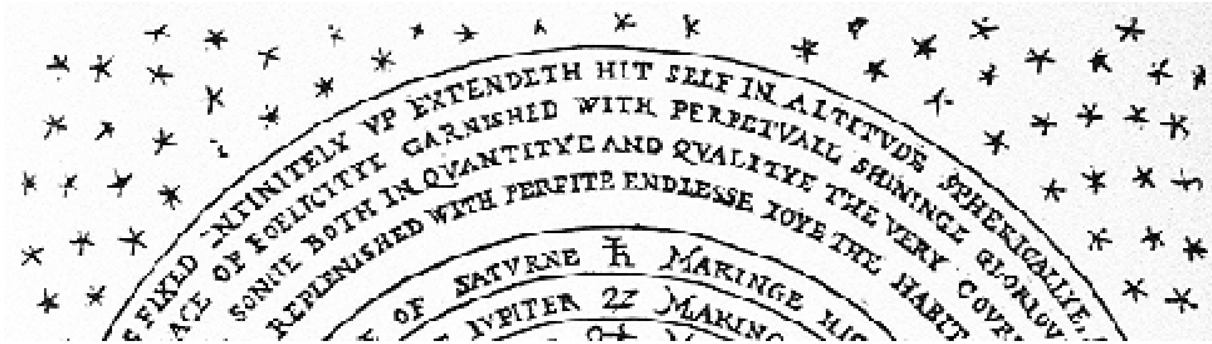


PHY1033C/HIS3931/IDH 3931 : Discovering Physics:

The Universe and Humanity's Place in It

Fall 2016

Announcements

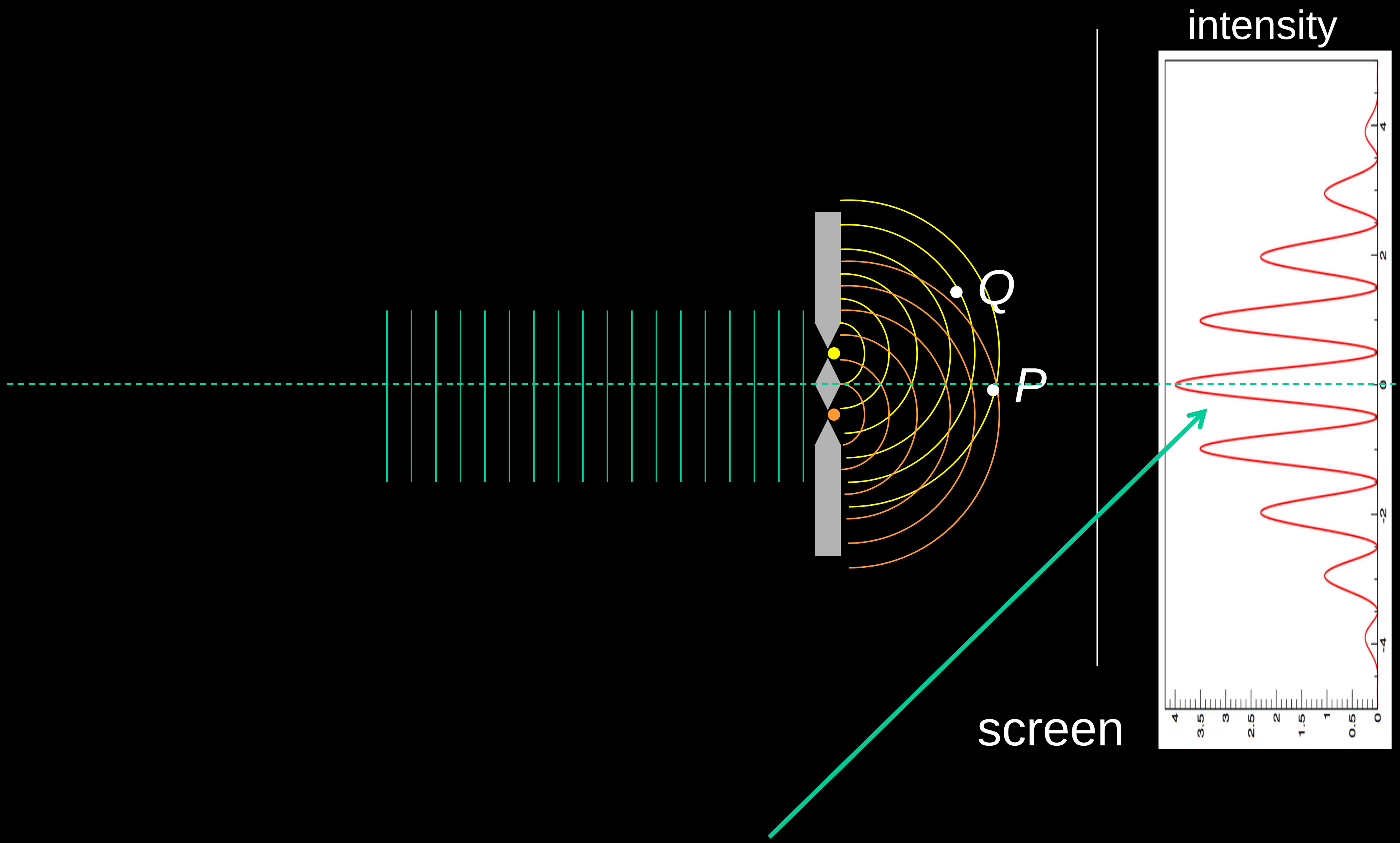
HW 9 due today HW10 posted, due Nov. 22. Put HW in Hirschfeld mailbox in manila "PHY1033C" envelope in Physics mailroom on 2nd floor outside main office.

Tues. Nov. 22 class cancelled, to be made up
Thurs. Nov. 24: Thanksgiving recess

Reading: Gregory, Chapter 21, pp. 447 to end, Chapter 25, pp. 522-24, McGrath, "In the Beginning" in the coursepack – read before Dec. 1.

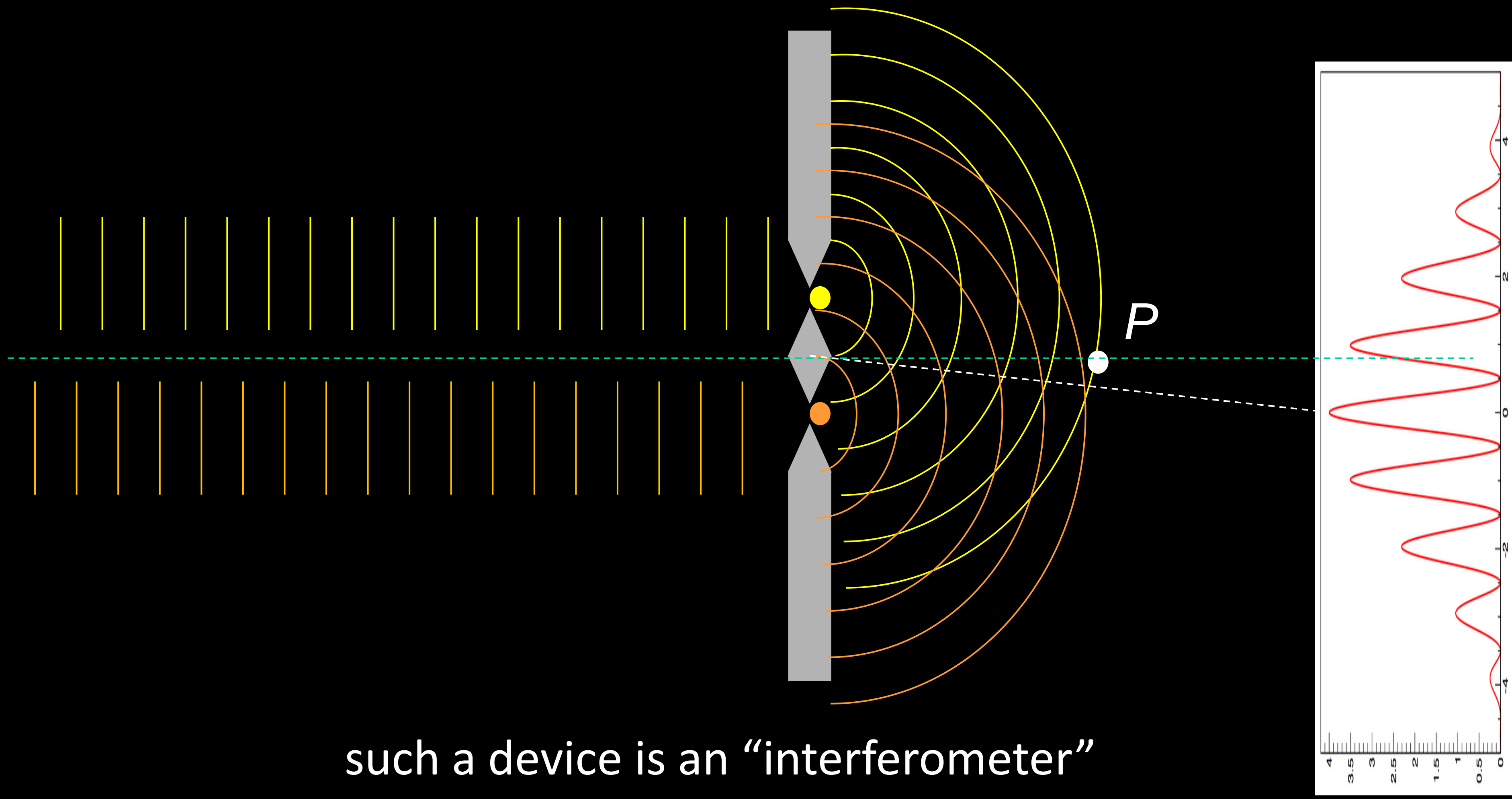
Today: quantum theory (long lecture ☹)
Thurs: Bronowski, "Knowledge or Certainty" (discuss after T'giving)

Two-slit interference pattern



maximum at
center!

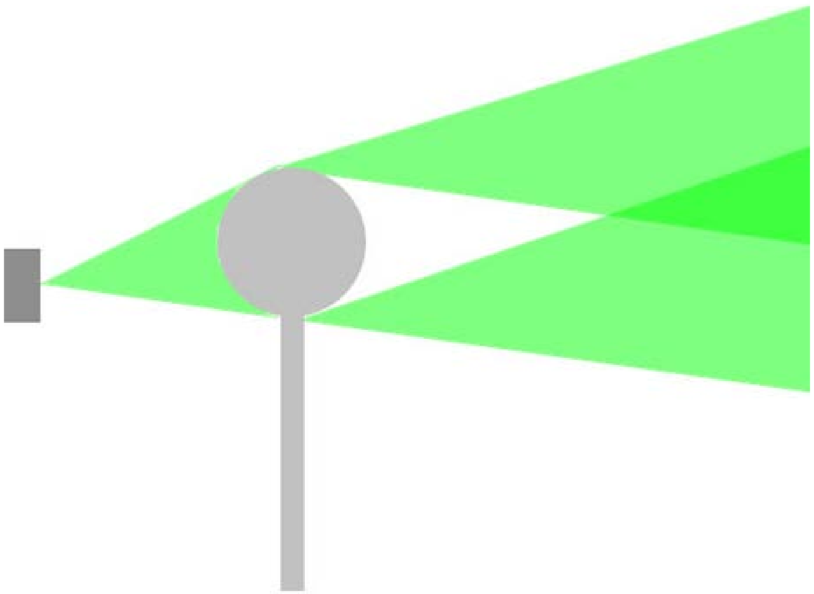
You can tell when one light beam is a little behind the other, because the pattern shifts!

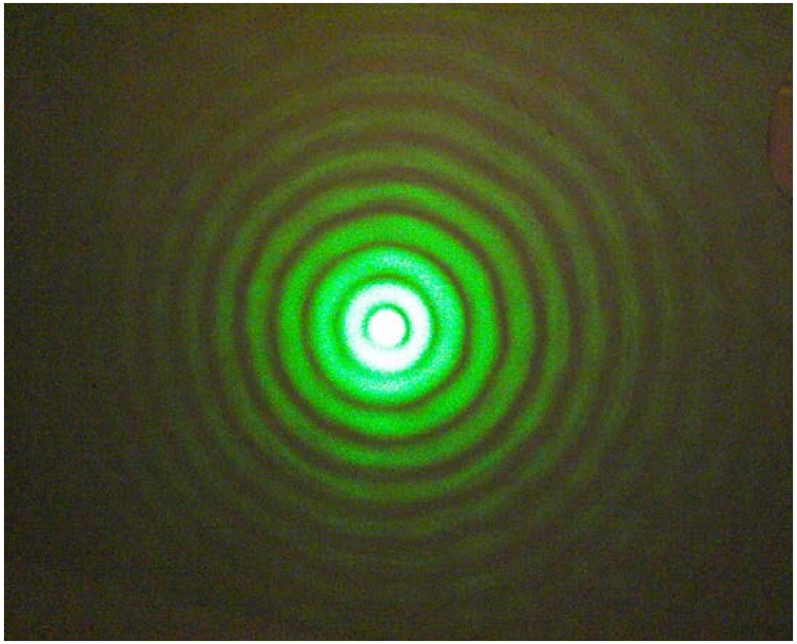


such a device is an “interferometer”

Diffraction: Poisson's (Fresnel's, Arago's) spot

Fresnel & others said light was a wave.
Poisson: "Absurde", if that were true,
there would be a bright spot behind a disk!





Video

But there is! Expt: Arago

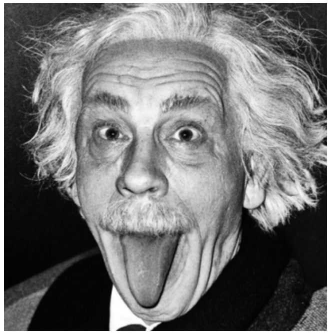
Result of the experiment(s) by Michelson

Zero. Zip. Nada.

Michelson was not happy. Problem: if there's no ether, what is waving? And with respect to what do we measure the speed of light, c?

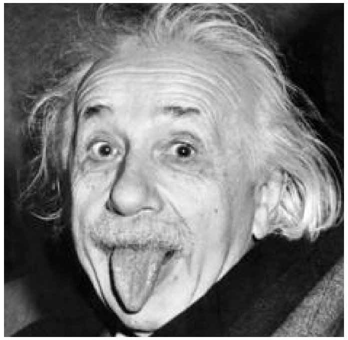
He tried for the rest of his career to refine his experiments, and never accepted that the ether did not exist.

Answers provided later by



John Malkovich

No, really by



Albert Einstein

Last time: relativity

- We restated Galilean relativity – that rest and uniform motion are equivalent states
- It's impossible to tell if one is moving from within a given frame of reference with no access to outside
- The laws of physics are the same for all observers in uniform motion
- Einstein's thought experiment: A train moving at the speed of light
  - A. Does light behave like a thrown ball?
  - B. Would he see his reflection in a mirror held out in front of him?
- 1. If no, then he'd know *from within his reference frame* that he was moving
- 2. Violating Galilean relativity not an option, therefore c is independent of reference frames
- 3. If c is constant, then space and time have to change together to accommodate it

Last time cont'd

- In Einstein's theory of special relativity,

  "Moving clocks run slower"

  "Moving objects contract"

- Amount of *time dilation* or *length contraction*

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} \quad > 1$$

- "Twin paradox" (HW): astronaut twin is younger upon return

With which of the following would Einstein agree after having formulated the special theory of relativity?

1. The laws of mechanics are the same for all observers in uniform motion, but not the laws of electromagnetism.
2. When moving at the speed of light, mass reduces to zero.
3. In a train moving at the speed of light, I will not see my own reflection
4. In order to keep the speed of light constant, space and time must change together
5. Psychedelic drugs help one visualize the effects of special relativity.

The study of light (electromagnetic radiation)at the end of the 19th century went down 3 different paths

1. The earth's motion through the ether – led to relativity

2. Strange radiation x-rays, radioactivity – led to nuclear physics, elementary particles

3. Distribution of light energies sent out by different sources – led to quantum theory

Prehistory of quantum mechanics

At the end of the 19th century, physicists were convinced they had solved all the tough problems and had learned everything there was to know about physics

There were just a few problems left…

1) Radioactivity
2) Atomic spectra
3) Black body radiation
4) Currents caused by shining light on metals (photoelectric effect)

The physicist in today’s story did not suspect that he was revolutionizing physics

Like Newton trying to solve the moon’s motion, he did not suspect that a fundamental and very general result would emerge from the very specific and particular problem he was working on

Newton was working at a time of “new science” (to borrow Galileo’s phrase)

Today’s physicist was working in a very different atmosphere

Meet Max Planck

Prehistory of quantum mechanics II

Max Planck (1900) suggested that light energy could be *quantized* in terms of *particles* called *photons*

The energy of a beam of light was simply the sum of the energies of the individual quanta of light:

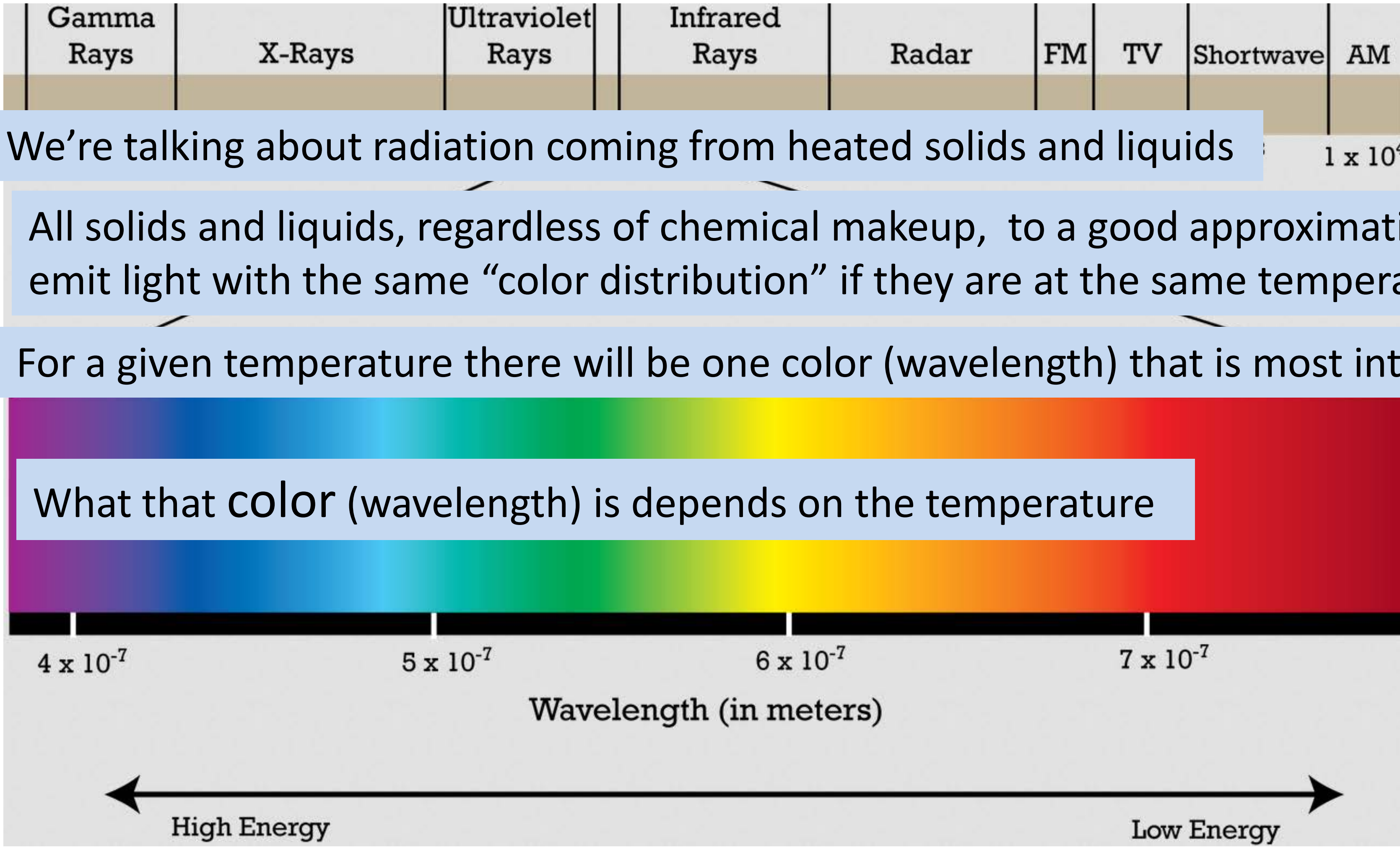
$E = hf$ for one *photon*

$E = nhf$ if there are *n photons*

h = Planck's constant = 6.6×10^{-34} J-s

This took a while to be accepted…

Planck was one of several physicists who were working on the relationship between temperature and radiation



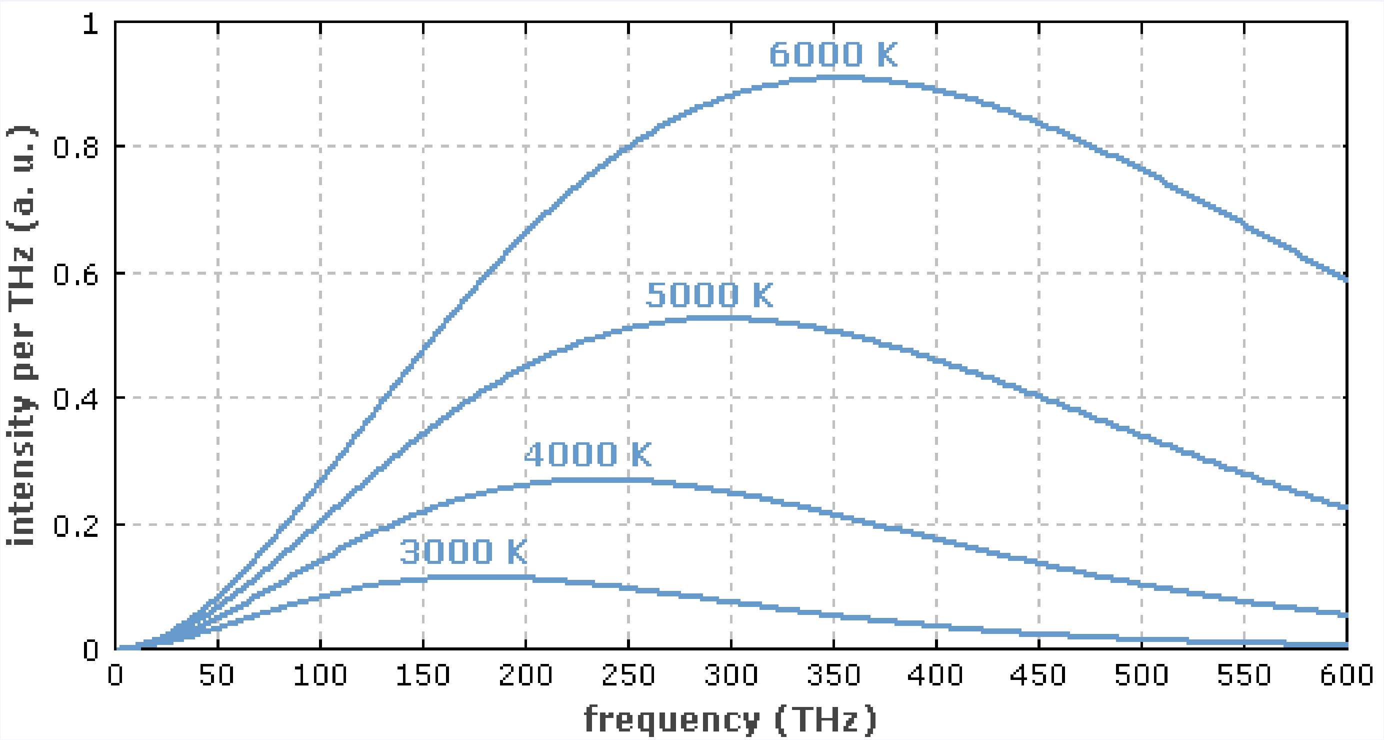
We're talking about radiation coming from heated solids and liquids

All solids and liquids, regardless of chemical makeup, to a good approximation emit light with the same "color distribution" if they are at the same temperature

For a given temperature there will be one color (wavelength) that is most intense

What that color (wavelength) is depends on the temperature

Experimental results for several temperatures: distribution of light intensity across frequency

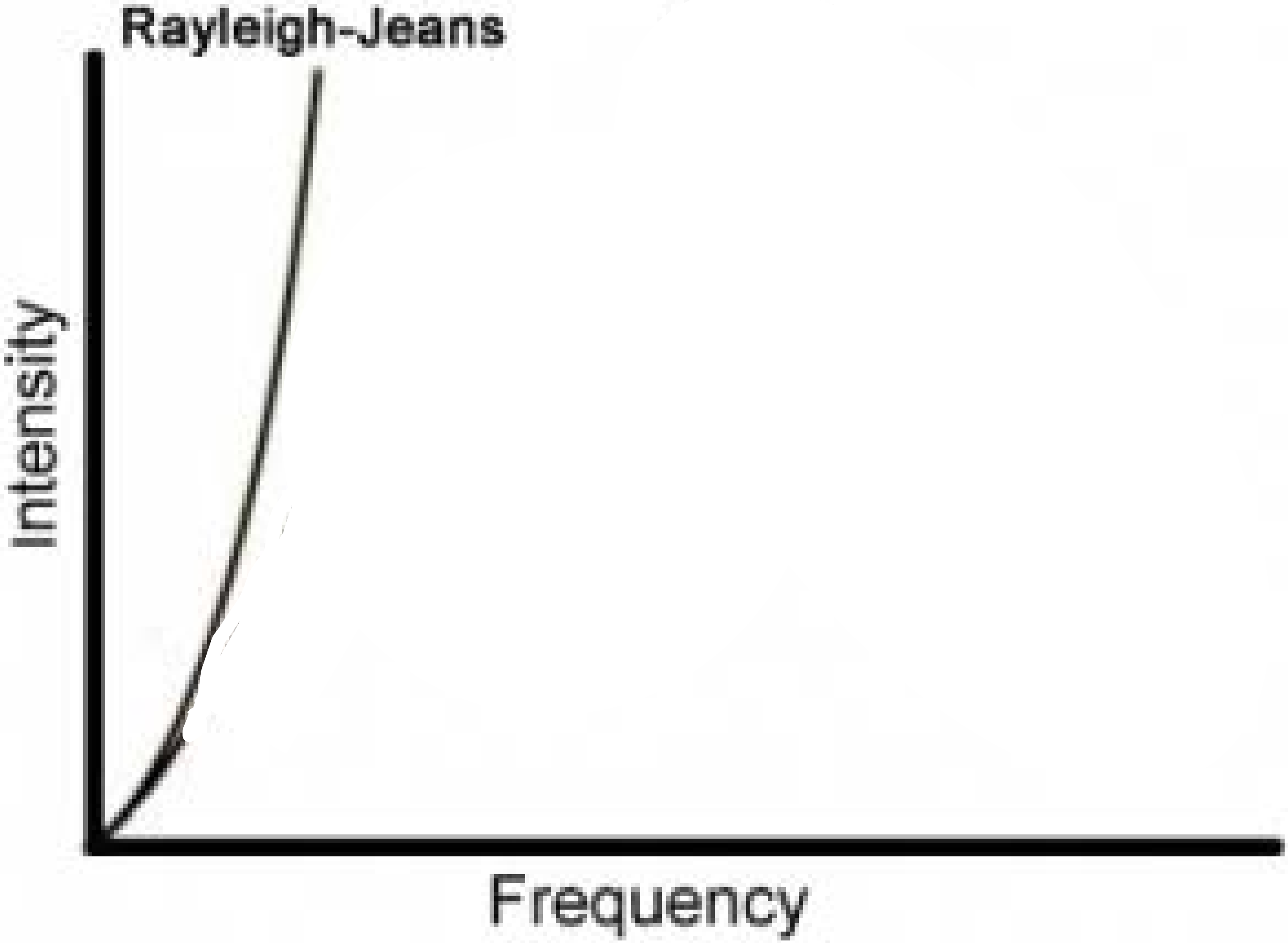


Physicists wanted a general result that would show how energy was distributed across the electromagnetic spectrum for any temperature T

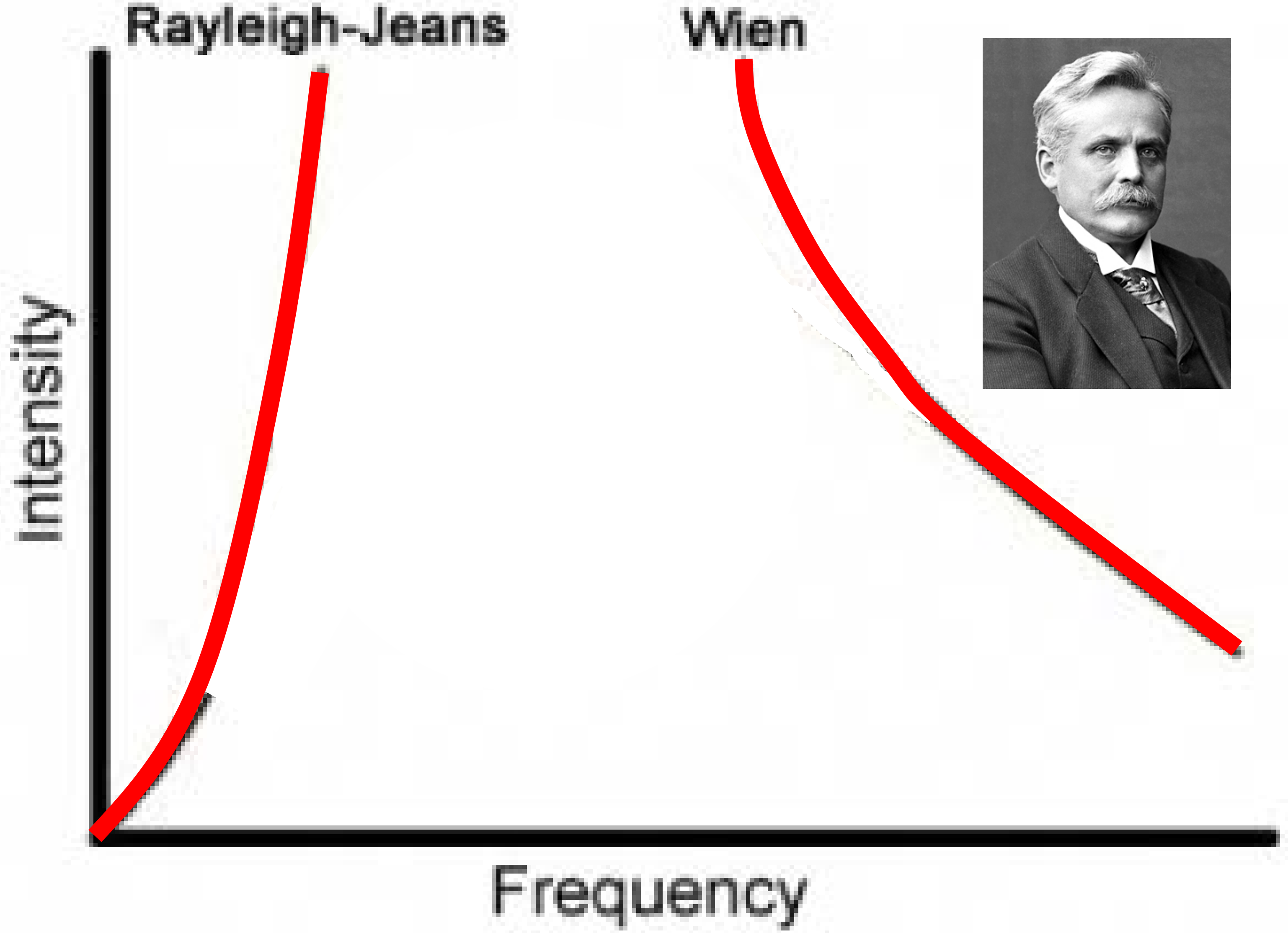
Lord Rayleigh and James Jeans came up with a curve that worked for the infra red region

Lord Rayleigh

James Jeans

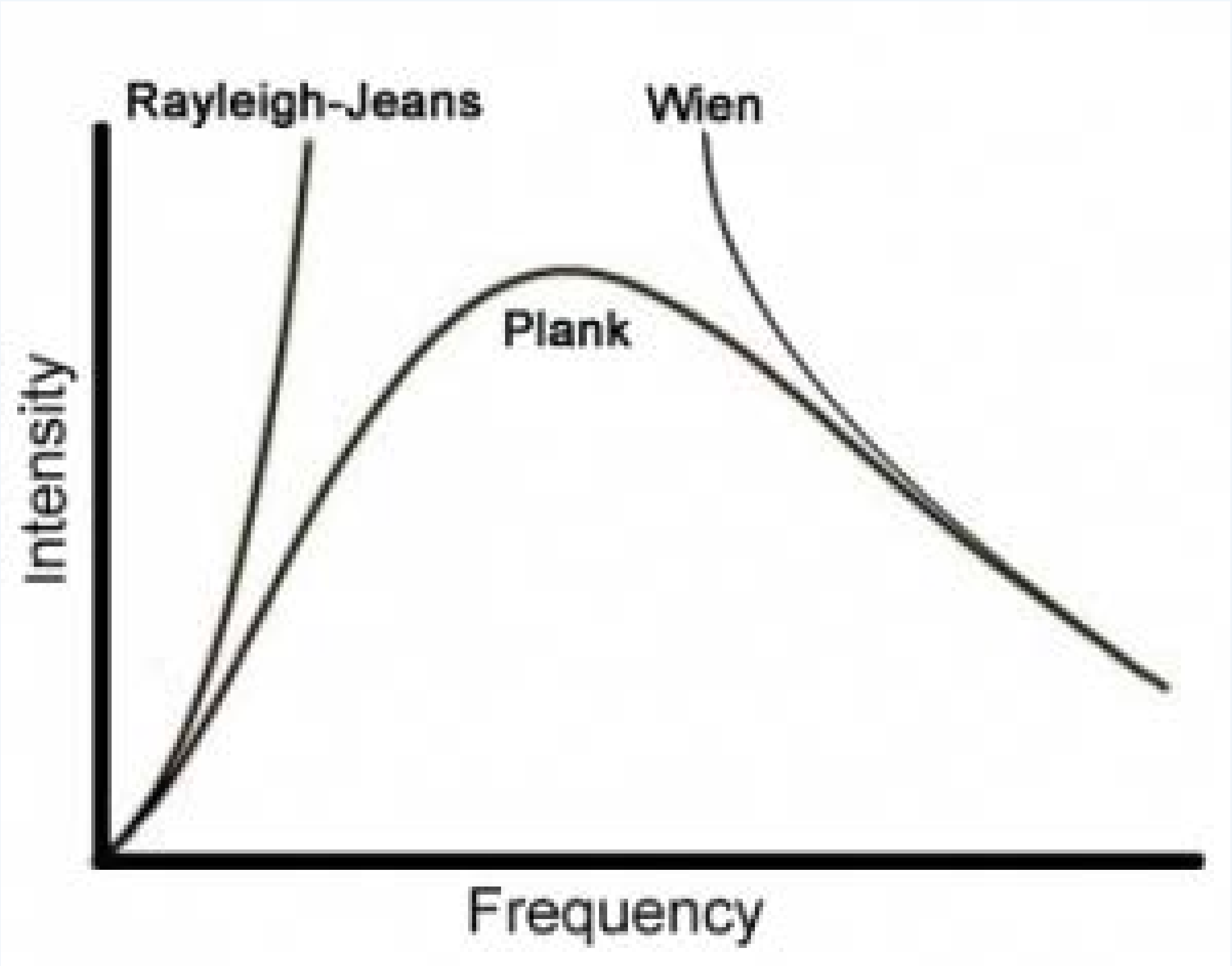


Rayleigh-Jeans
Intensity
Frequency



The German physicist Wilhelm Wien came up with a curve for the ultra-violet

By taking the best from each of these equations
Max Planck finally found a curve for the whole spectrum: $E_\lambda = C\lambda^{-5}/(e^{D/\lambda T} - 1)$



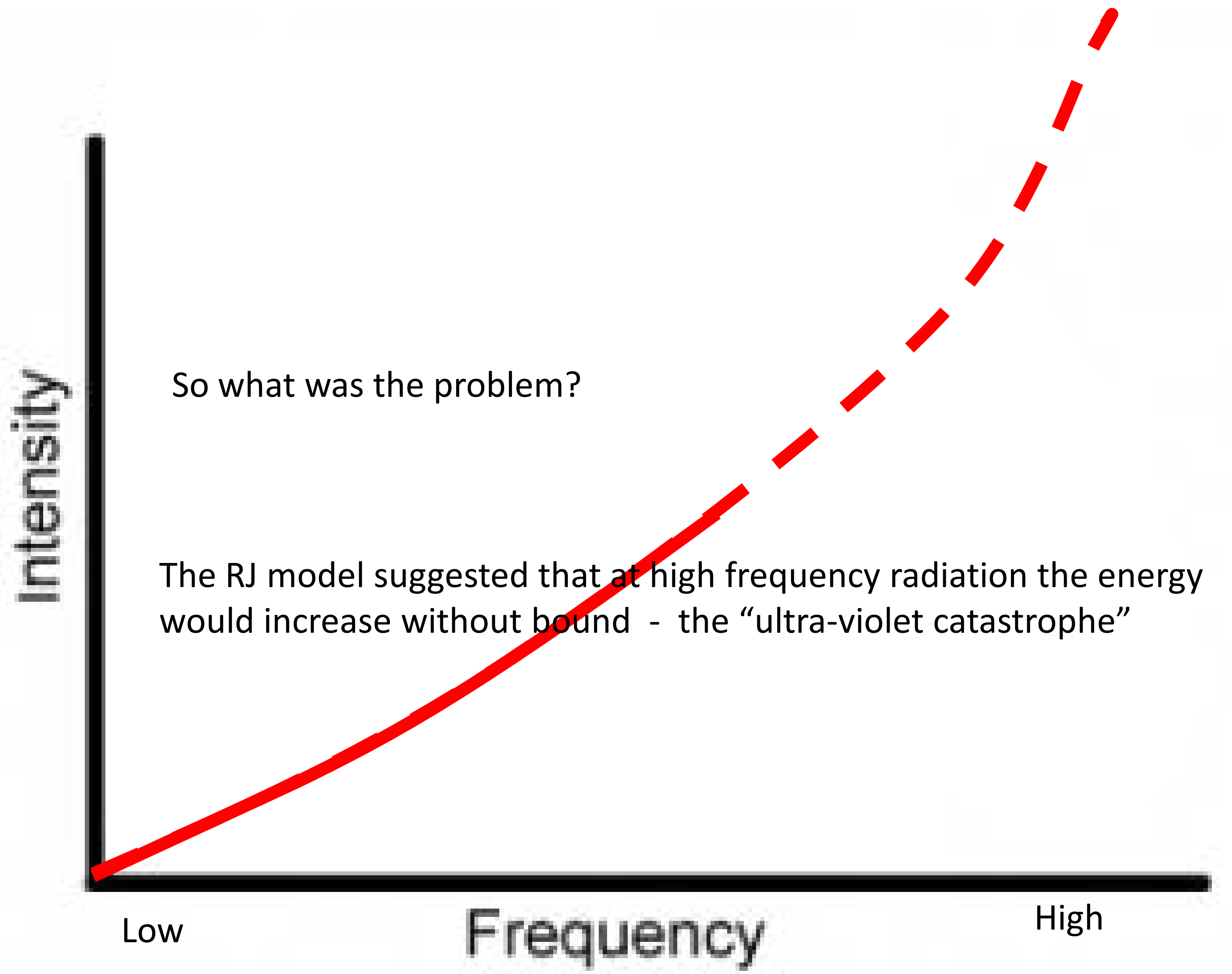
Planck and others were at a point similar to where Kepler was with his ellipses- they had a mathematical description of the results of observations, but they had no theoretical explanation

Worse than that, the model presented a major problem

Physicists at the time assumed a model of how matter produced radiation

They imagined that in the walls of the substance being heated there were vibrating electric charges (they were possibly thinking of the new “electron”)

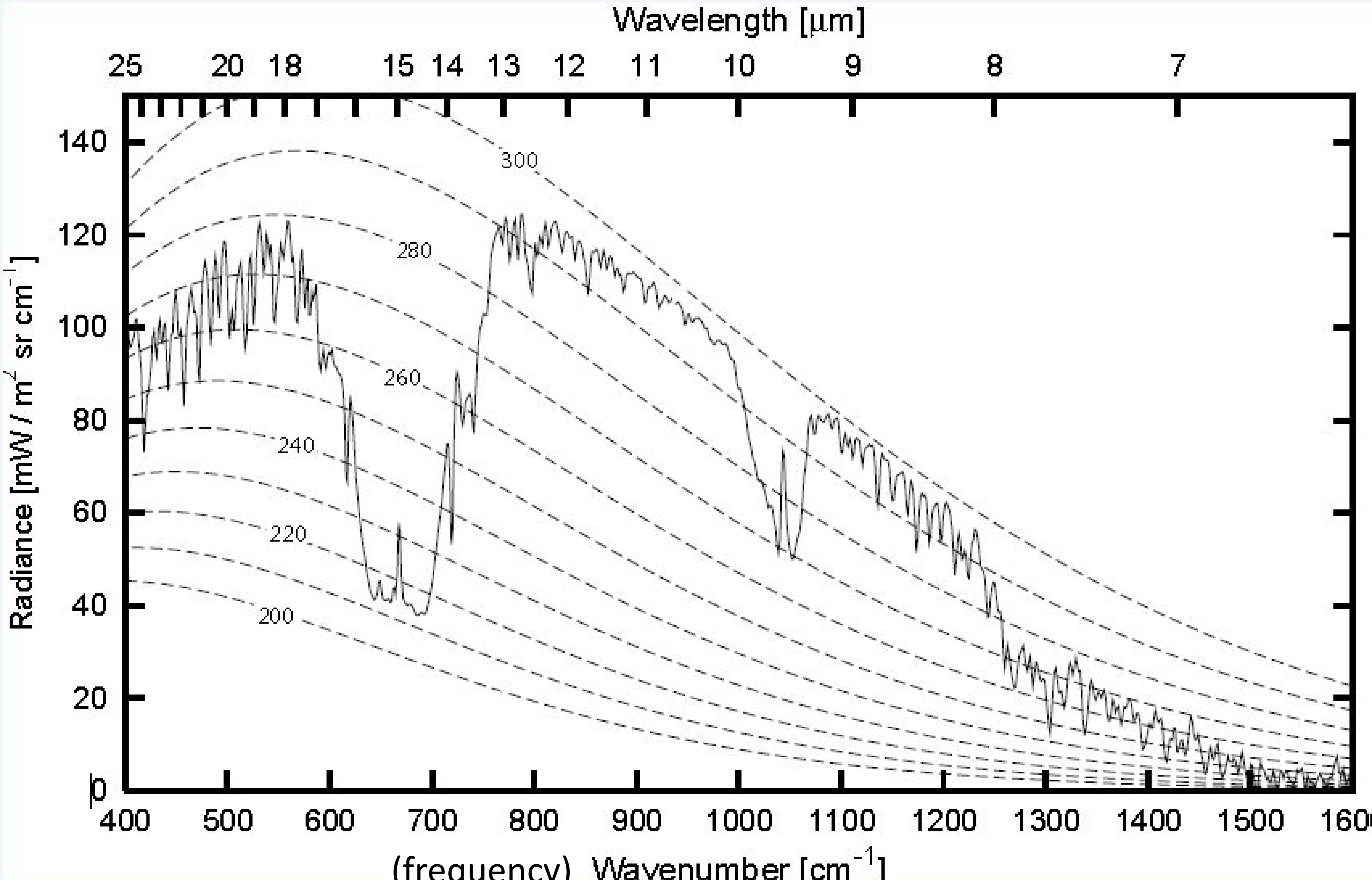
A vibrating electric charge would be a changing electric field, which would produce a changing magnetic field, which would produce a changing electric field and so on – an electromagnetic wave of radiation



So what was the problem?

The RJ model suggested that at high frequency radiation the energy would increase without bound - the “ultra-violet catastrophe”

But experimental results showed that didn’t happen



Electromagnetic radiation from the sky

Planck set out to figure out how to save the model

To do so he returned to work he had been doing in thermodynamics, convinced that a problem he had worked on there would help him in his new challenge

Planck had a long standing argument with an Austrian physicist named Ludwig Boltzmann about entropy – did it **always** increase

Boltzmann was a pioneer in statistical mechanics who saw entropy in terms of probability – entropy increase was highly probable, but it was not impossible in his view that it **could** on occasion be negative

Planck was dead set against this view - entropy **always** had to increase

Early on Planck had become convinced that the world was not so complicated that we could not figure it out

Planck’s goal was to find the absolute law governing a natural process

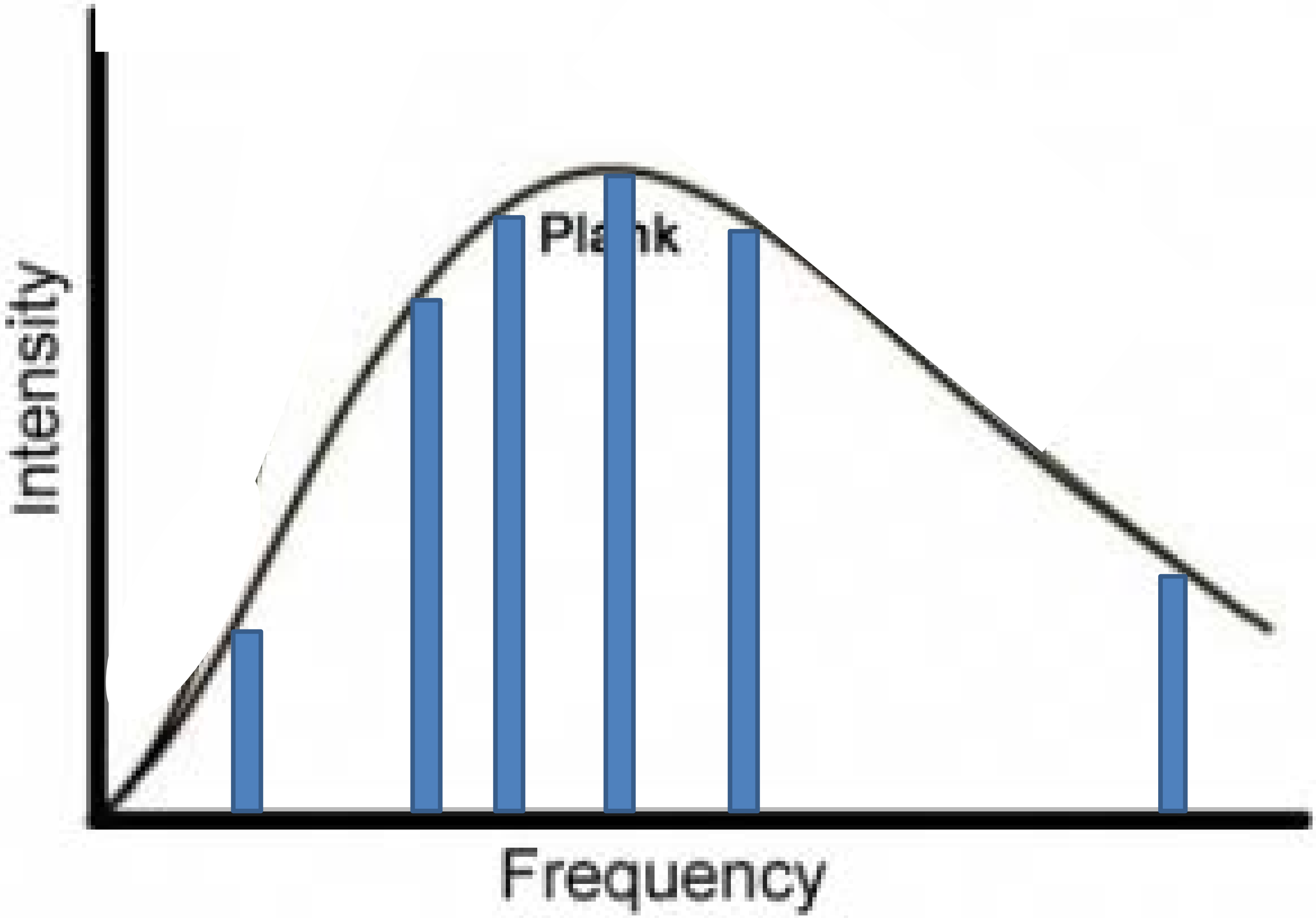
He did not like Boltzmann’s statistical approach to solving problems

But because he was getting nowhere in his attempt to save the resonator model, in desperation he tried Boltzmann’s statistical approach to his problem

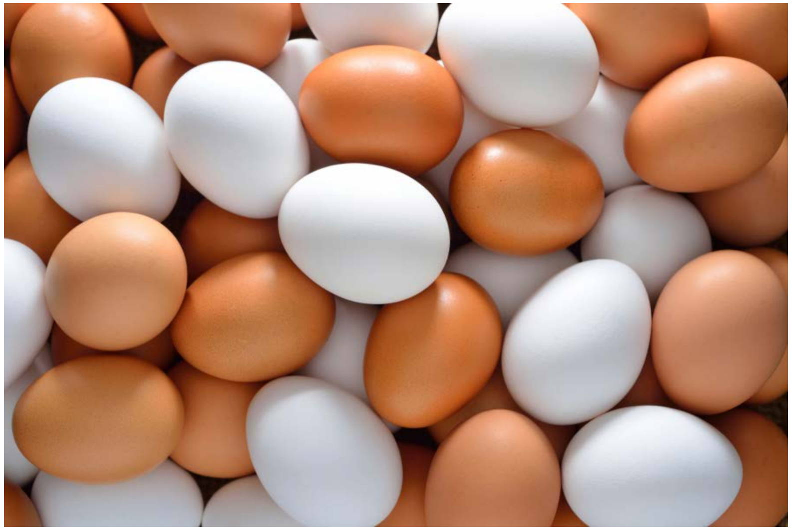
To determine a degree of probability one has to have things to count up

So Planck broke up the energy distribution into pieces – differential pieces for purposes of analysis

Planck defined a rule that said how much energy portions at a given wavelength were E = hf, where h was a constant



Energy, acc. to Planck is like eggs, not milk



When energy is given off or taken on it does so in “bullets”

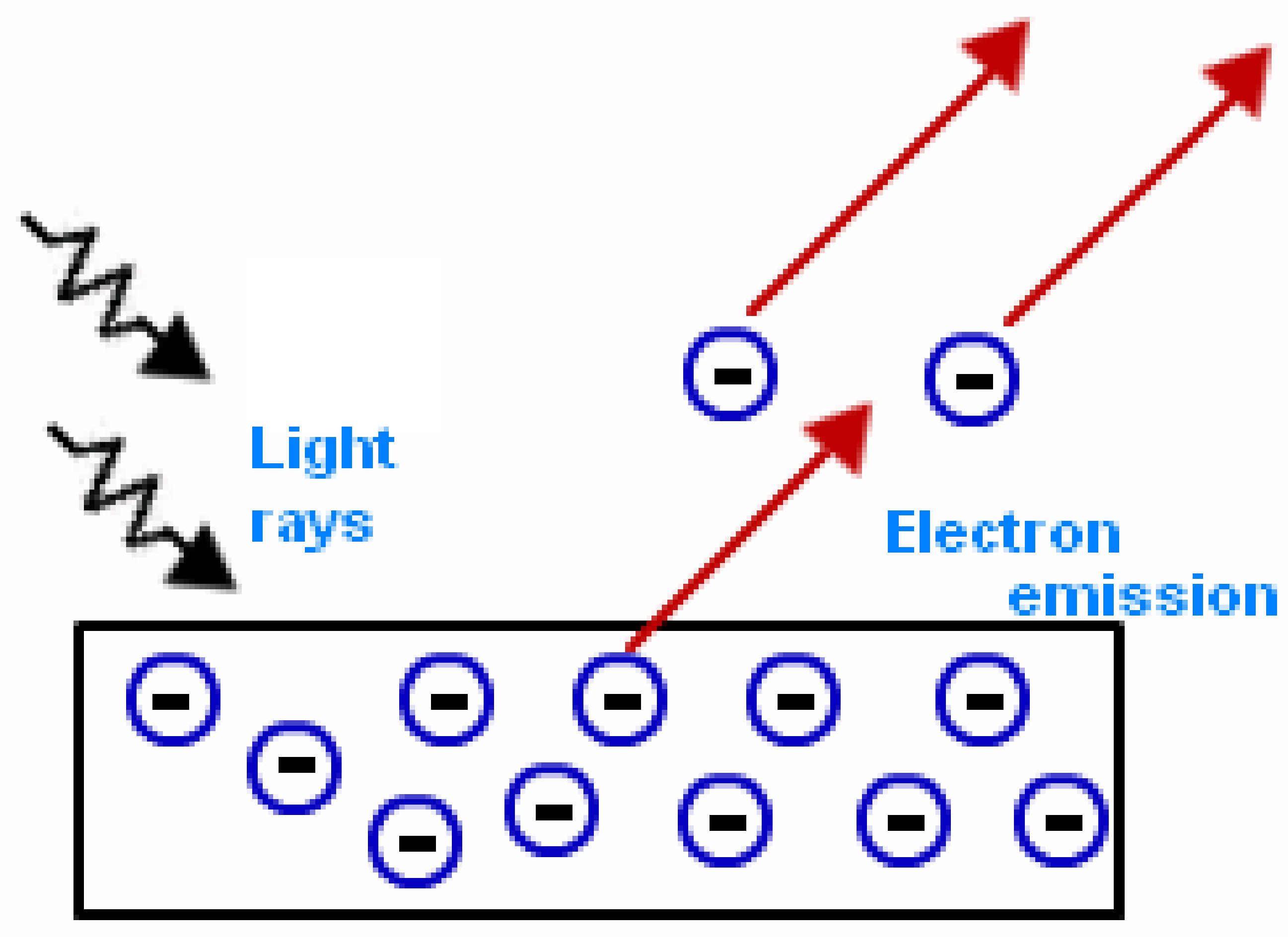
Number of “eggs”, “bullets”, or “quanta”

$$E = nhf$$

If quantizing energy were only useful in this specific context,
it would never have become so fundamental to physics

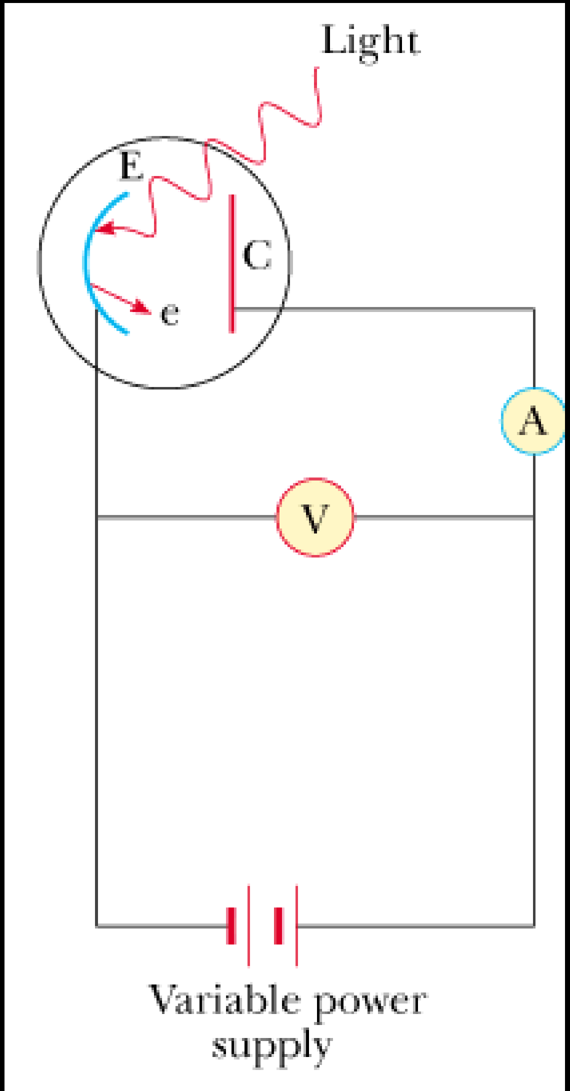
It was not long before the idea helped explain problems in other areas of physics

One was the so-called “photoelectric effect”



Light shined on certain metals produces electrical current

The Photoelectric Effect



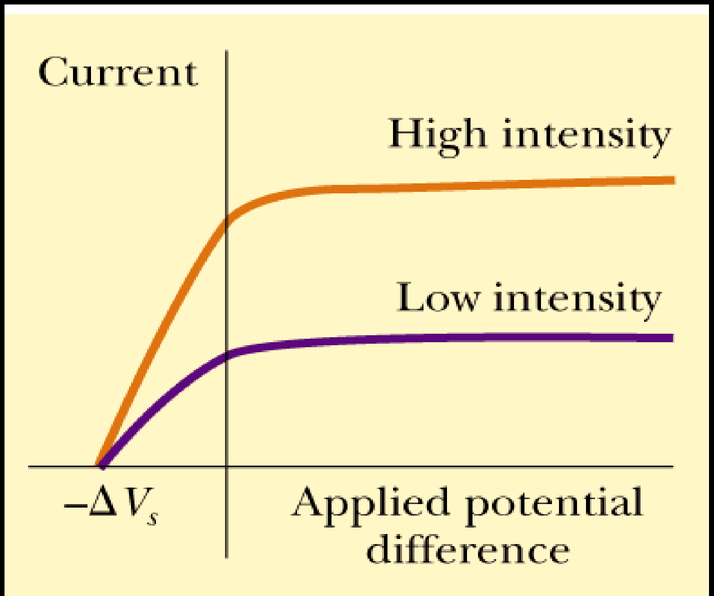
What we see:

-The current is constant for a given D*V*.

-The current increases with light *intensity*.

-No current unless frequency high enough

-max KE independent of intensity



$$K_{max} = e\Delta V_s$$

Can We Explain This?

Predictions of the Wave Model

-For high enough intensity, any wavelength of light should produce the photoelectric effect. *Not what we see.*

-The maximum kinetic energy of the photoelectrons should scale with light intensity. *Not what we see.*

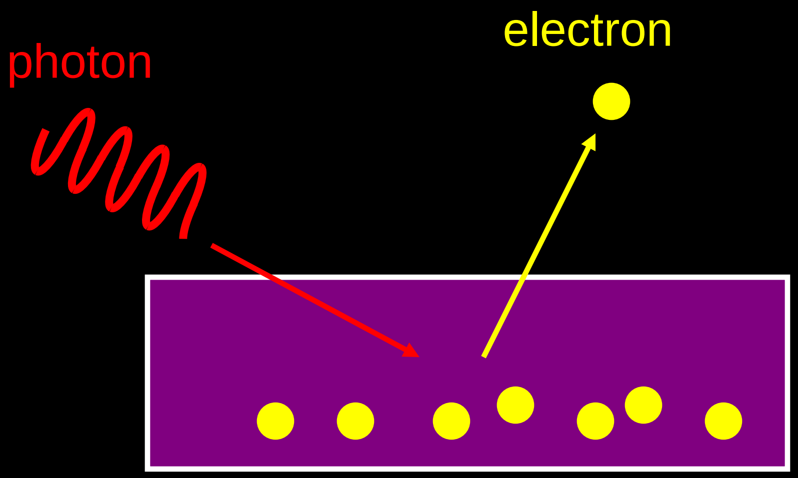
-The maximum kinetic energy should be independent of the frequency. *Not what we see.*

-The photoelectrons need a measurable amount of time to gain enough energy to be ejected. *Not what we see.*

Einstein’s Explanation

photon energy $E = hf$

electron KE $K_{\max} = hf - \varphi$

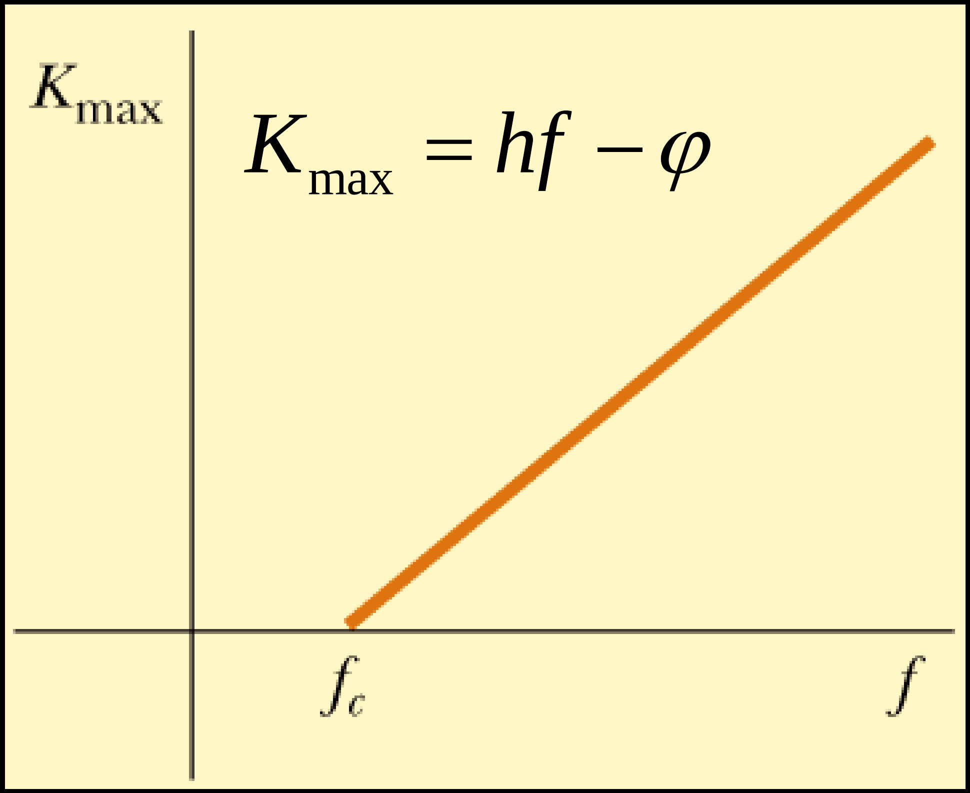


φ is work function of metal: energy necessary to remove one electron from surface

h is Planck’s constant, known from other experiments

The Photon Model correctly predicts what’s happening.

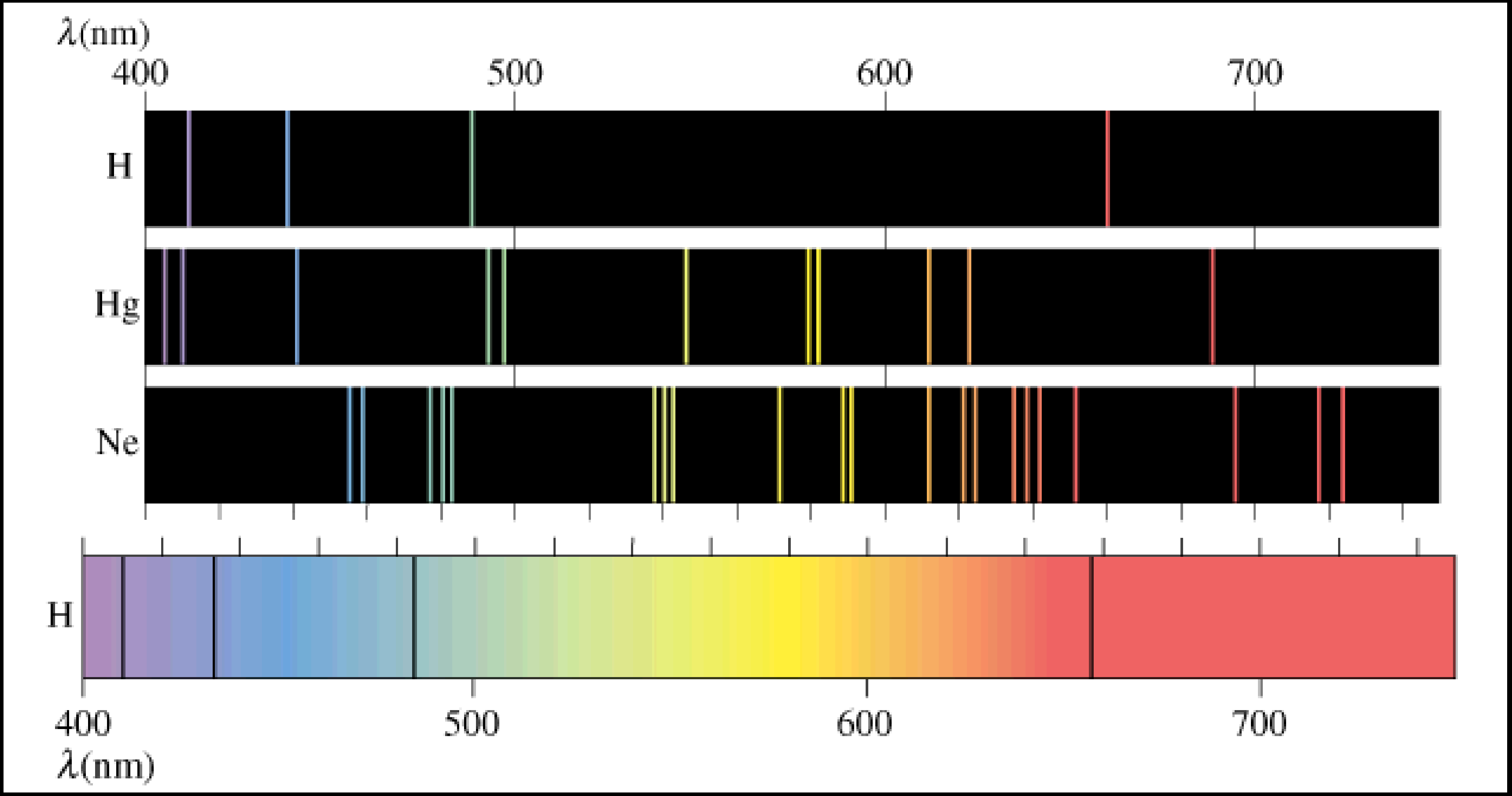
photon model explains:



minimum frequency $hf_c = \varphi$

Quantum ideas, along with relativity, presented severe challenges
To the easy notion of realism prominent in the late 19th century

Atomic Spectra



Balmer Series

Predicts the visible emission wavelengths of Hydrogen. IR and UV wavelengths are predicted by very similar rules.

$$\frac{1}{\lambda} = R_H \left(\frac{1}{2^2} - \frac{1}{n^2} \right)$$

$$R_H = 1.0973732 \times 10^{-7} \text{ m}^{-1}$$

strictly empirical formula invented by high school teacher

where does it come from?

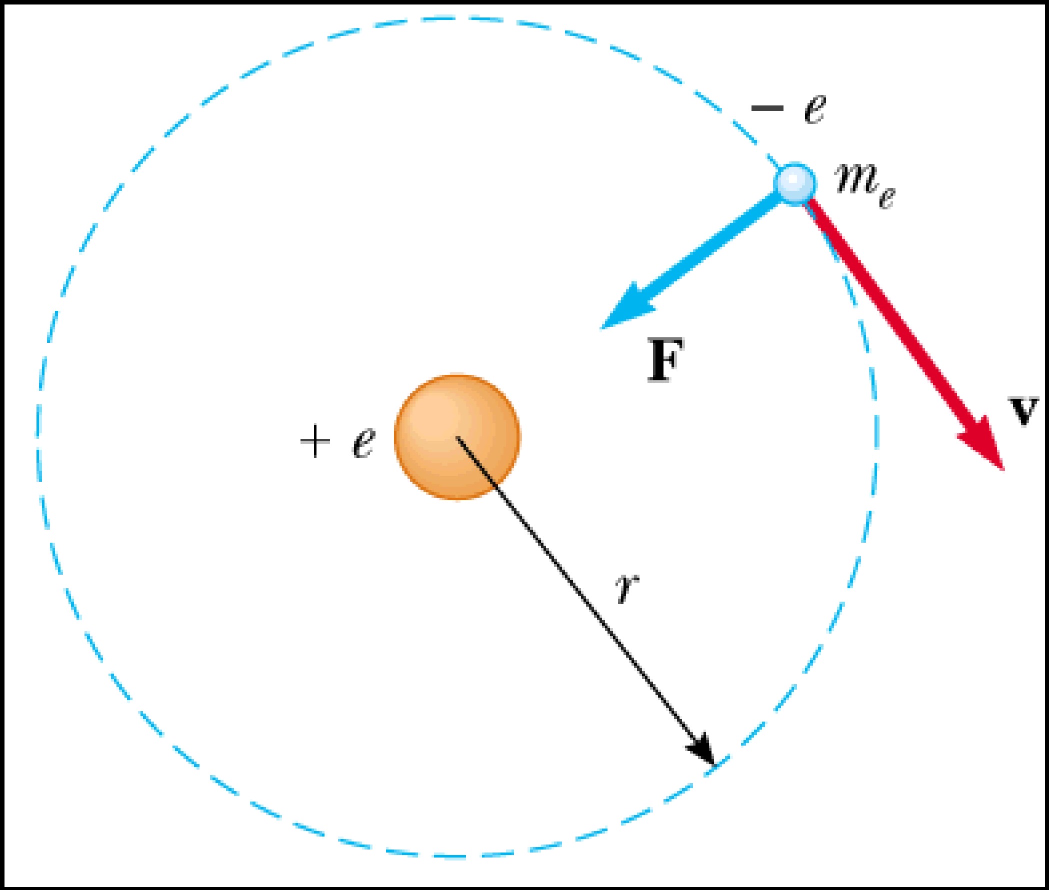
Neils Bohr

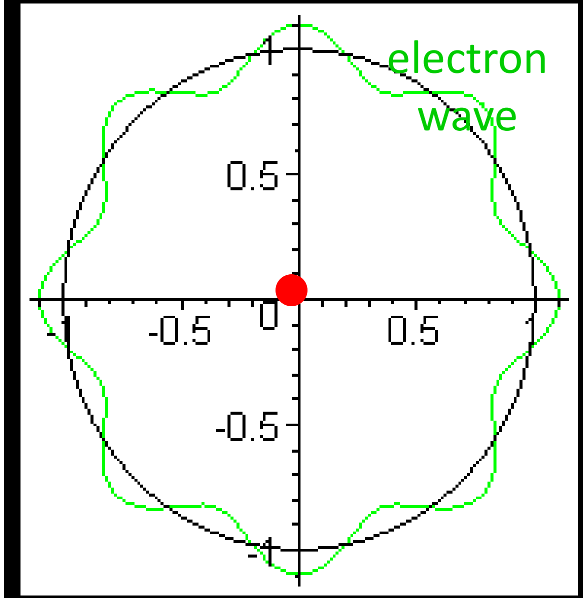
- Prof. U. Copenhagen until 2nd WW
  During war worked on atomic bomb in England,
  but argued for peaceful uses of atomic energy

- Invention of Bohr model of atom (1913)
  assuming quantized orbits for electrons

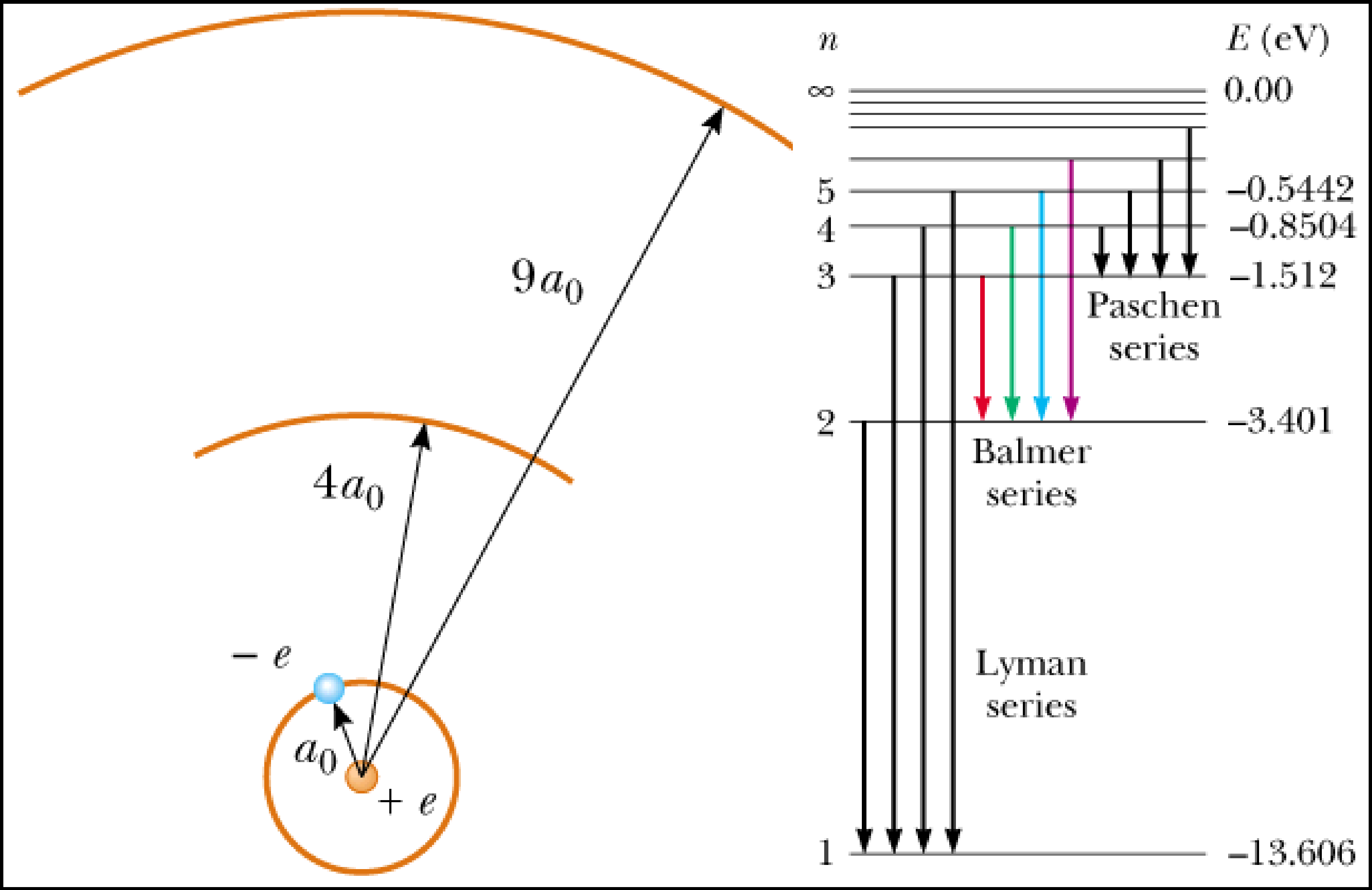
- Debates with Einstein on meaning of quantum theory

The Bohr Model of the Hydrogen Atom





Predicted Energy Levels



Louis-Victor de Broglie

- Won the Nobel Prize in Physics in 1929
  (for his 3-page PhD thesis 1924!)

- Professor at University of Paris
  Elected a member of the French Academy of Sciences 1933

- Broglie stated that all matter has a wave-like nature
  Any moving particle or object had an associated wave

- Created a new field in physics, called wave mechanics, uniting the physics of light and matter

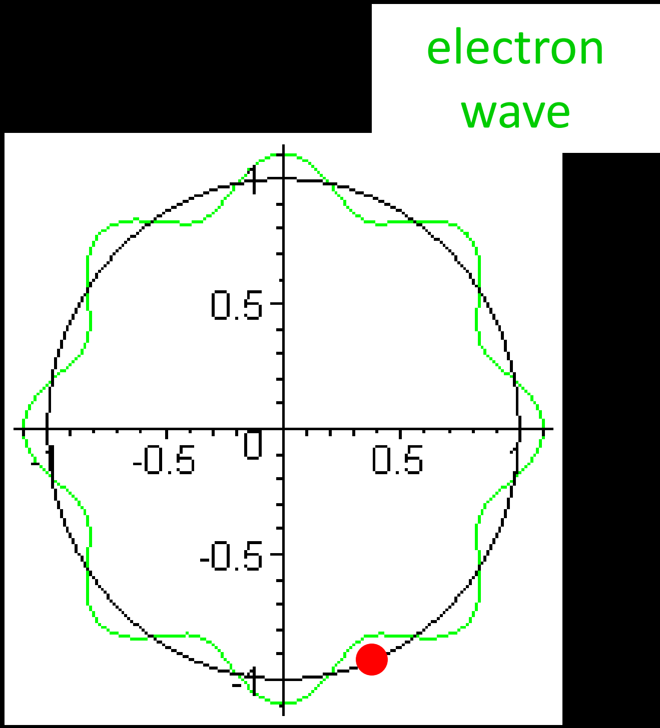
de Broglie's Equation

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

λ= particle's wavelength

h= Planck's constant

p= the particle's momentum *p=mv*



Erwin Schrödinger

- First paper has been universally celebrated as one of the most important achievements of the twentieth century, and created a revolution in quantum mechanics, and indeed of all physics and chemistry
- Nobel Prize 1933
- Schrödinger’s Cat Thought Experiment - 1935

Erwin Schrödinger

- In 1926, at the University of Zurich, published a series of 4 papers
  - Wave Mechanics & Schrodinger’s Equation
  - Compared his approaches to Werner Heisenberg (alternate “matrix mechanics”)
  - Showed how to work with *time-dependent phenomena*

Schrödinger's Equation

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

i is the $\sqrt{-1}$

$\hbar$ Planck's constant divided by 2π

$\partial/\partial t$ Derivative with respect to time

ψ(*t*) = Wave Function

H(t) = Quantum "Hamiltonian" (energy of system)

Max Born: ψ(x) is to be interpreted as the probability of finding a particle at position x

Werner Heisenberg

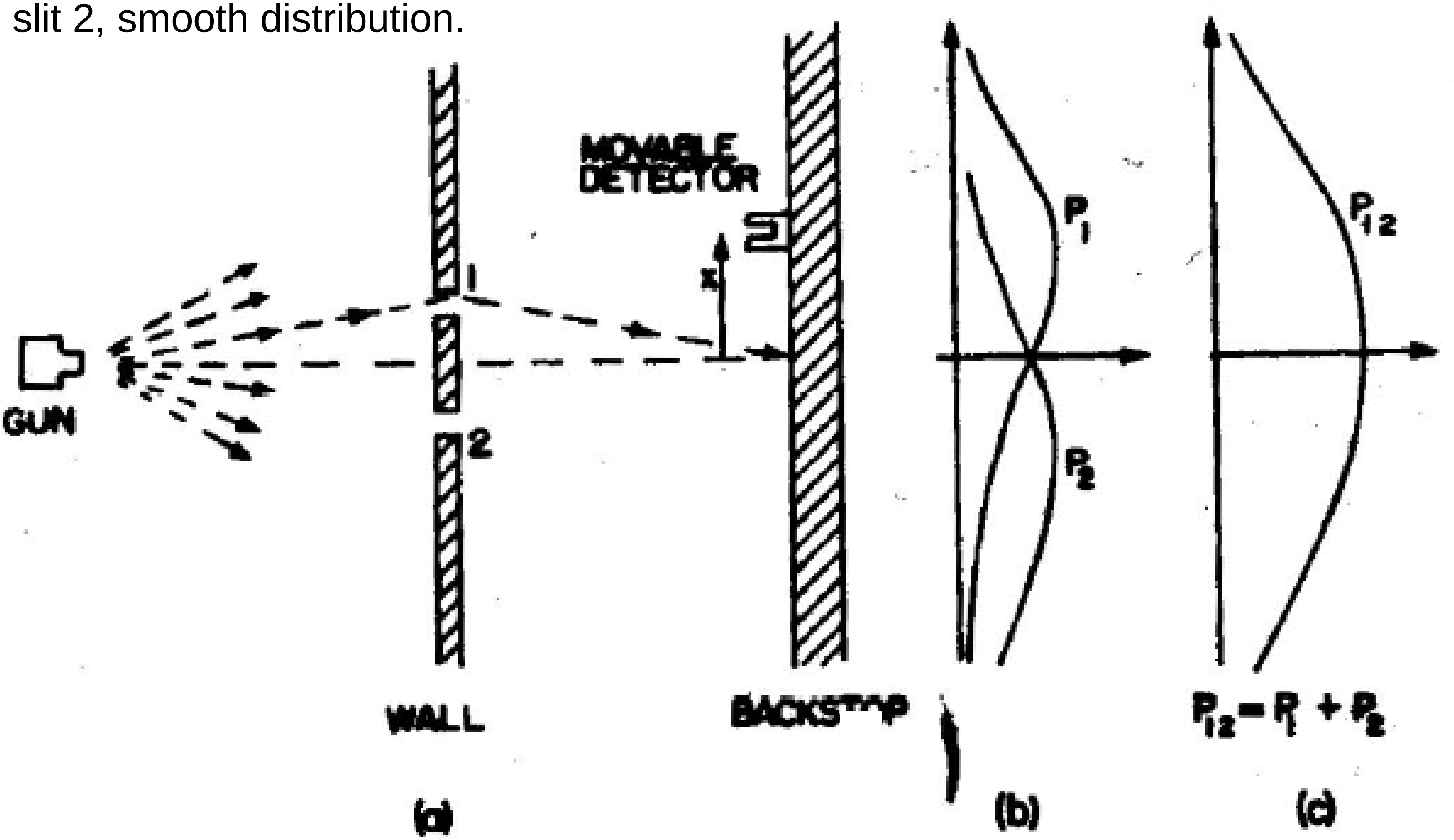
- Won Nobel Prize in 1932 in Physics "for the creation of quantum mechanics, the application of which has, inter alia, led to the discovery of the allotropic forms of hydrogen".

- Heisenberg pointed out that it is impossible to know both the exact position and the exact momentum of an object at the same time. Applying this concept to the electron we realize that in order to get a fix on an electron's position at any time, we would alter its momentum. Any attempt to study the velocity of an electron will alter its position. This concept, called the Heisenberg Uncertainty principle, effectively destroys the idea of electrons traveling around in neat orbits. Any electron that is subjected to photons will have its momentum and position affected.

Role of observer in quantum mechanics

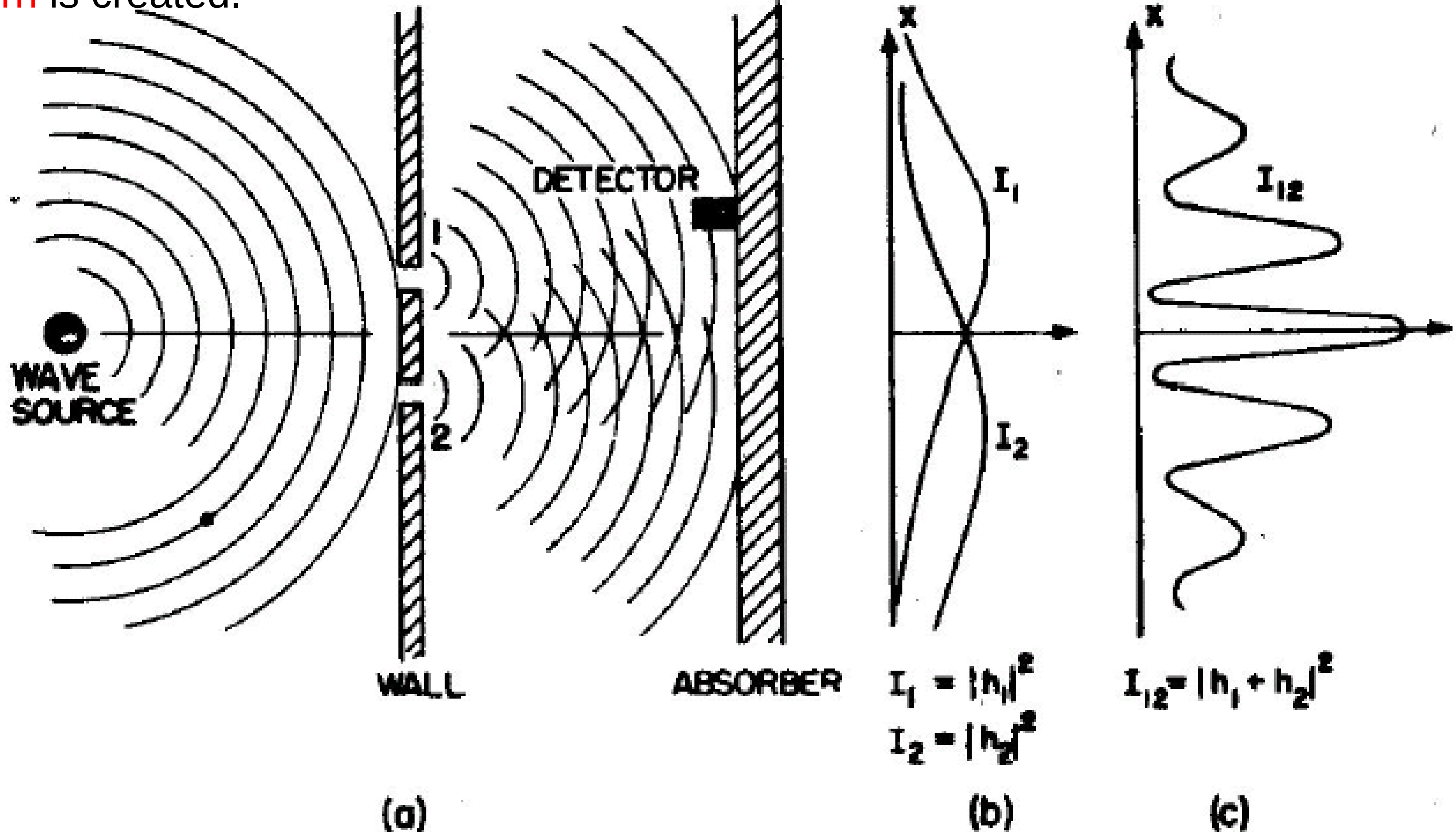
2-slit experiments with bullets (classical particles)

- Bullets always come in "lumps" -- identical size, mass particles.
- No interference: probability to arrive at screen is sum of probability to go through slit 1 and probability to go through slit 2, smooth distribution.



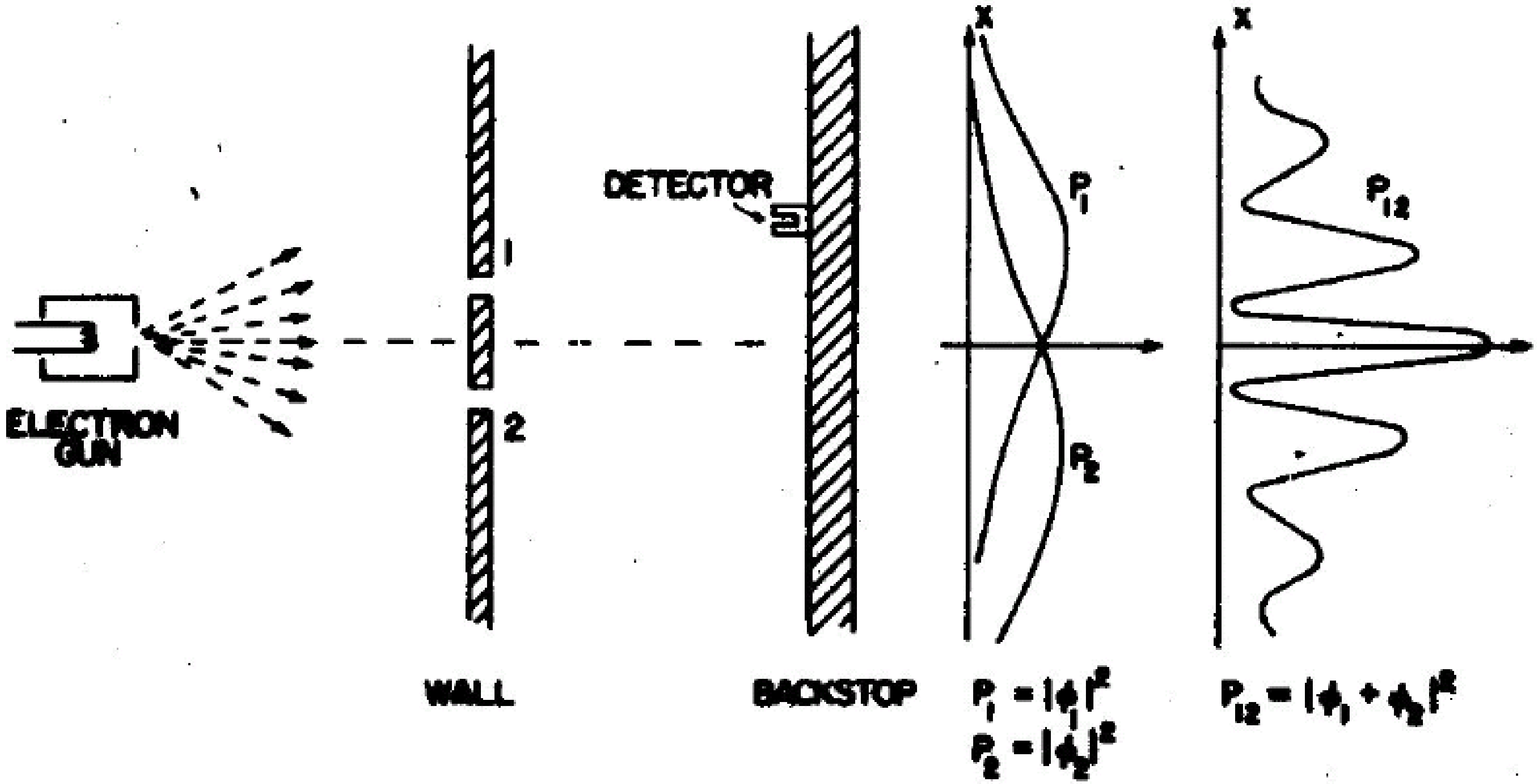
2-slit experiments with water (classical waves)

• Intensity of water waves propotional to height 2
• Intensity of waves reaching detector through slit 2 when slit 1 is closed is smooth, and vice versa.
• When two waves are allowed to pass through 1 and 2 at same time, interference pattern is created.



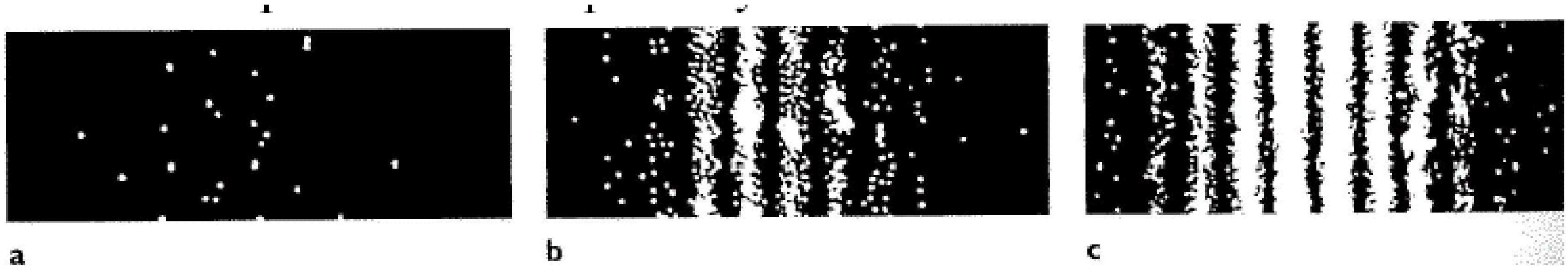
2-slit experiments with electrons
(do they behave like bullets or waves?)

- Interference pattern observed by detector at screen



So--electrons are waves?

• Wait--we can slow gun down so that only 1 electron per hour goes through. Then we expect electron goes through slit 1 or 2, right? Every hour we get a new spot on the screen.
• Interference pattern builds up slowly:

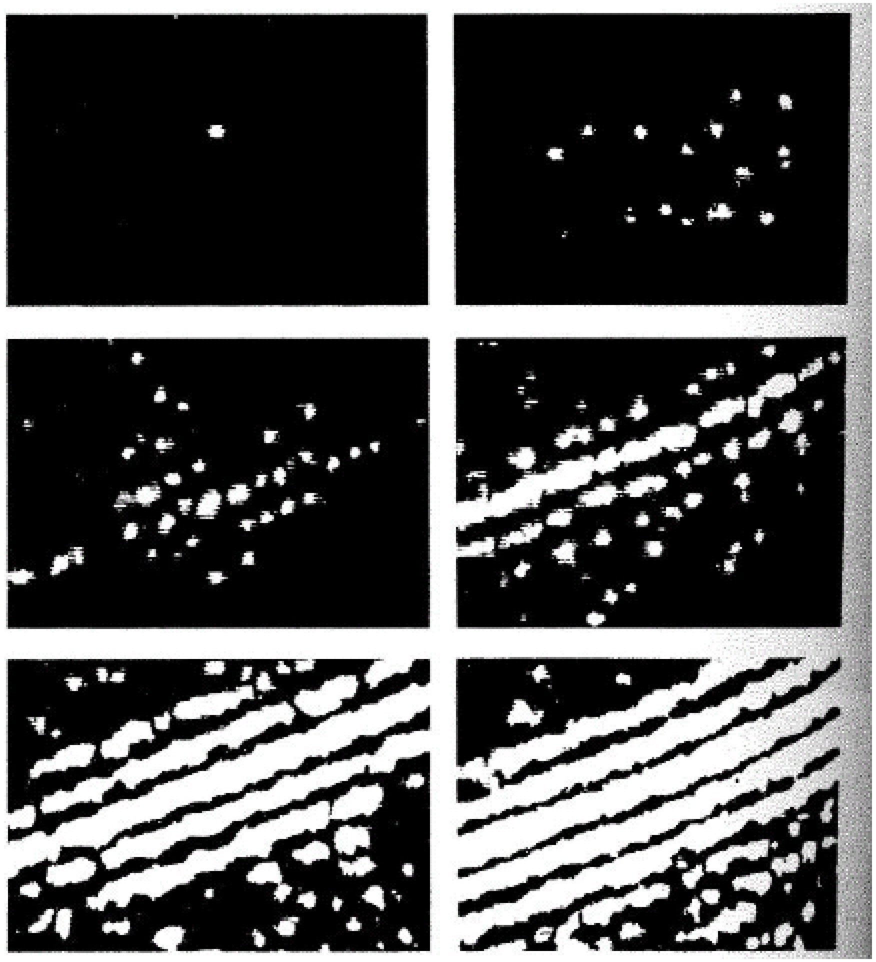


So: electrons are "particle-waves"!

They exhibit properties of classical waves *and* particles

2-slit experiments with light

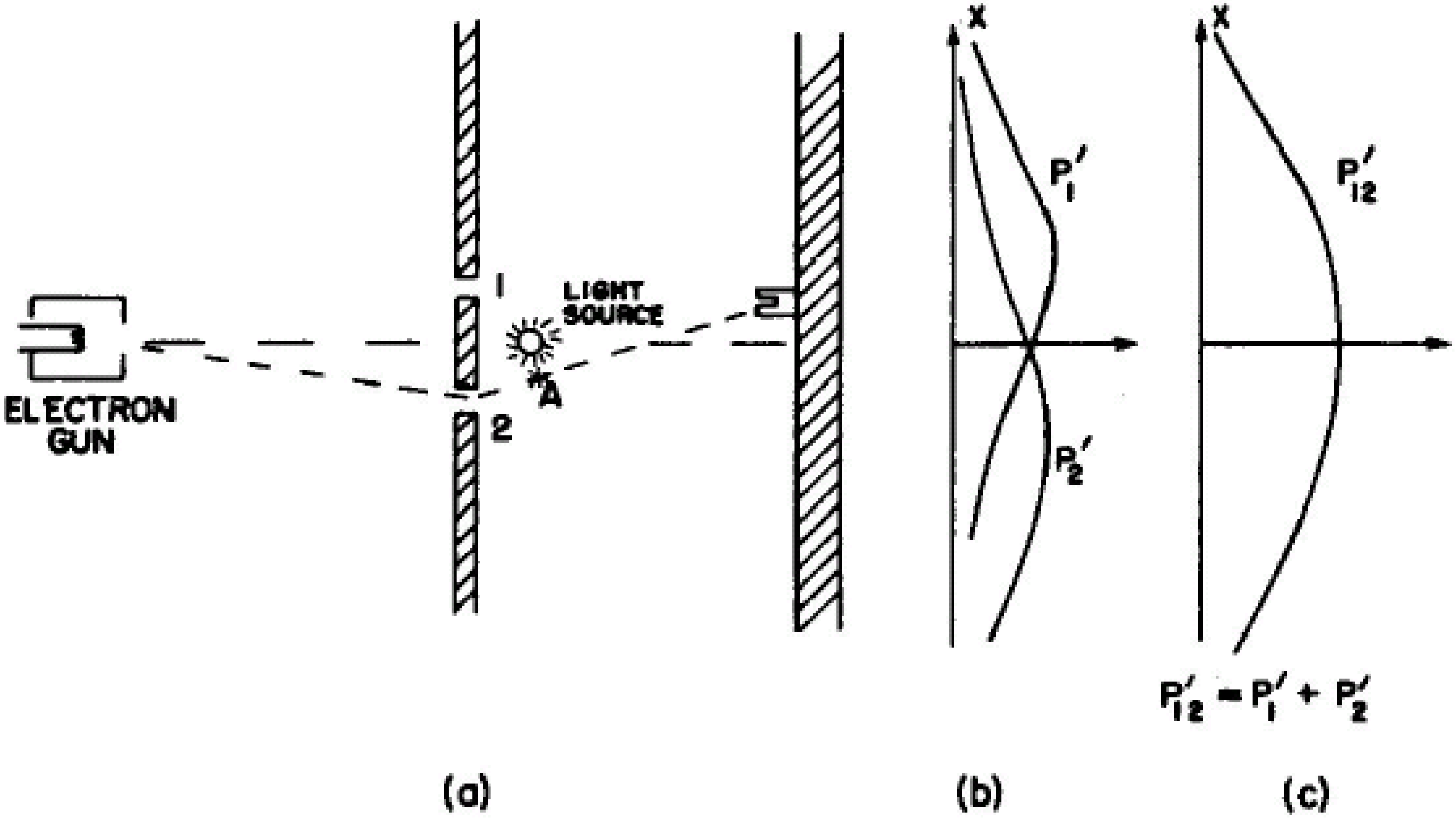
Weaken laser beam so that very few photons come out!



Light is "particle-wave" just like electrons!
(except photons move at speed of light, have no mass)

Observing which slit electrons go through I)

Wait a minute: if electrons can be seen to go through one slit or the other, how can they interfere with themselves? Let's try to determine which slit they pass through with a "camera"



Act of observation destroys interference pattern!

One way to say this: pinning down particle's position made momentum indeterminate!

Heisenberg uncertainty principle:

$$\Delta x \, \Delta p \approx \hbar$$

Planck’s const. divided by 2π

uncertainty in your measurement of particle’s *position*

uncertainty in your measurement of particle’s *momentum*

Observing which slit electrons go through II)

Wait another minute! Maybe the light we used to observe the electron bumped it somehow, destroying interference. How about if we reduce the light's intensity or frequency?

- Reduce intensity: sometimes electron isn't observed--then it contributes to interference!
- Reduce frequency: oops! Remember we said you can't resolve anything smaller than the wavelength of light? When wavelength gets bigger than distance between slits, interference pattern comes back! Heisenberg again.

Conclusions:

- at small scales physics doesn't agree with our intuition. Rules of quantum mechanics predict results of all expts. so far, even if we have no "deeper" understanding.
- Particle is described by a "probability amplitude" to be somewhere.