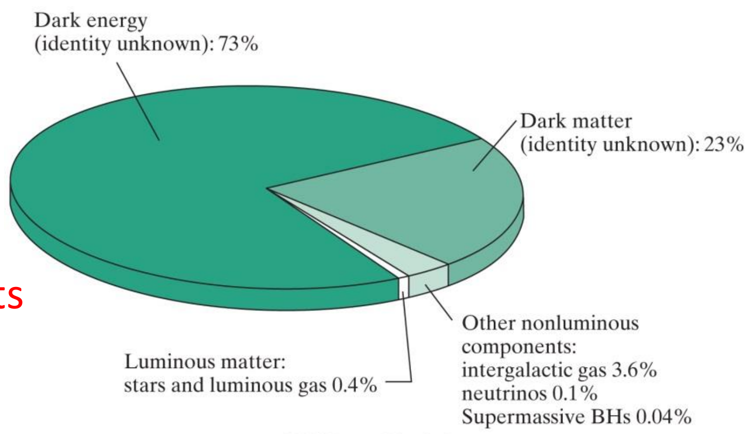
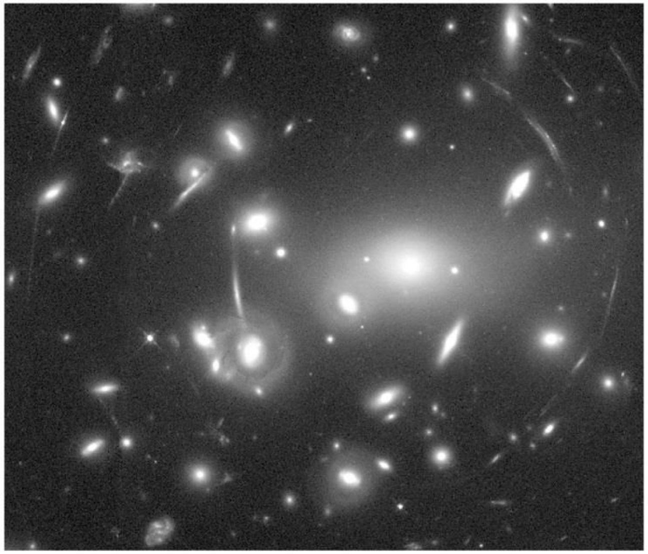
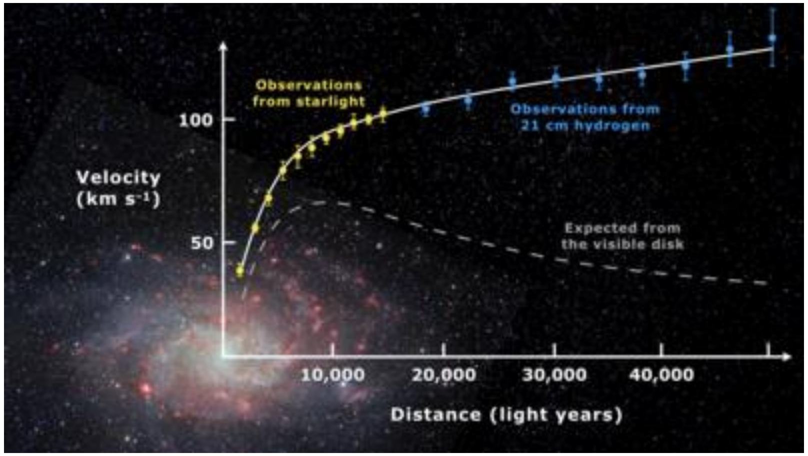
Dark Matter

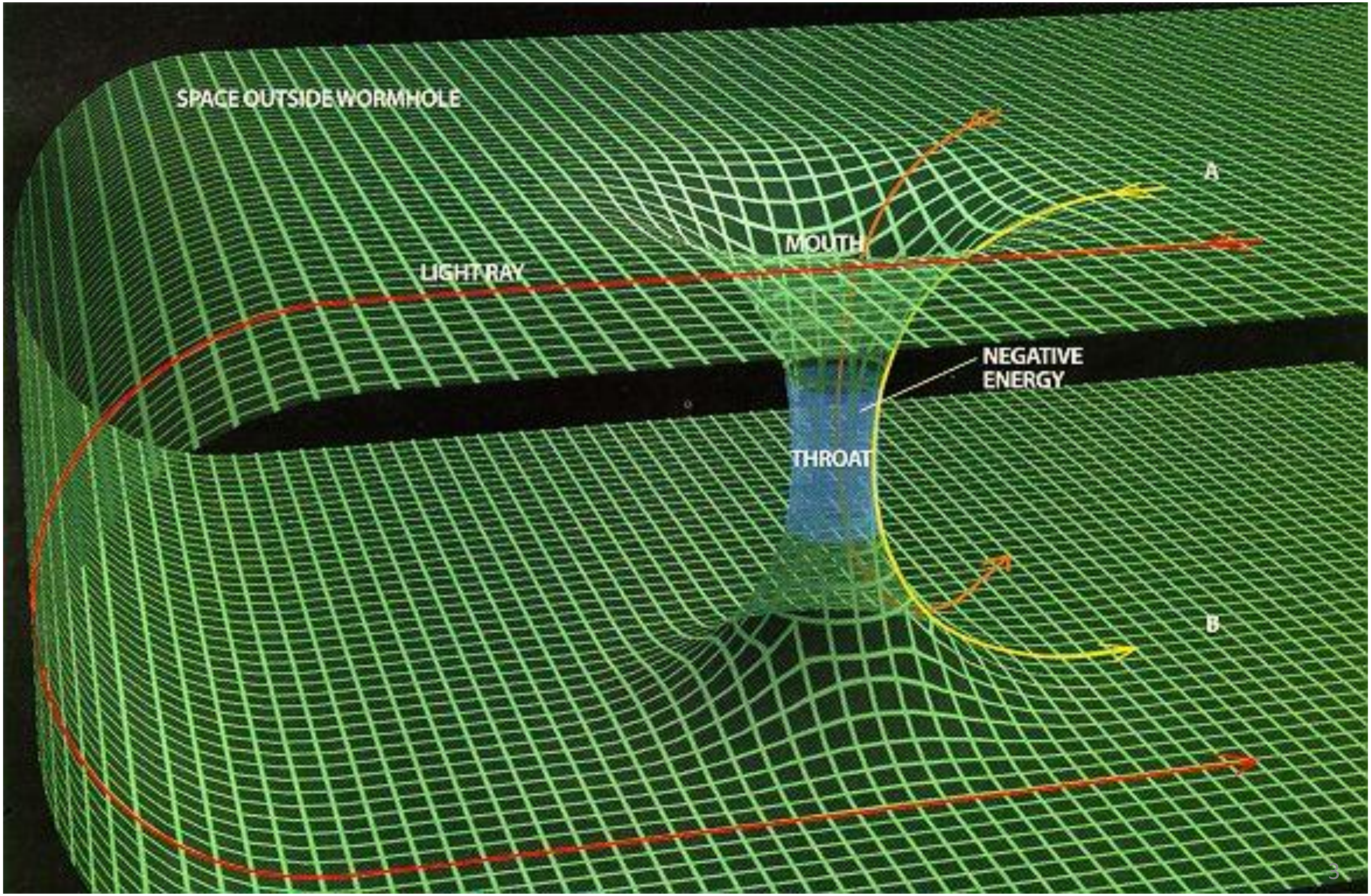
- There are many different forms of matter in the universe; besides the familiar protons, neutrons, and electrons there are neutrinos and black holes.
- But it seems that there is another form of matter, none of the above, that does not interact with electromagnetic radiation but can be detected due to its gravitational interactions. This is called dark matter.
- Dark matter, although we don't know what it is, comprises most of the mass of the universe
  - We can tell this by studying gravitational properties of galaxies.
  - Another way of detecting dark matter is by the way it distorts the light coming from distant galaxies.







Wormhole (speculation)



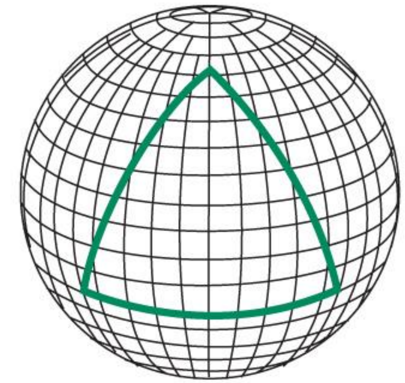
Cosmology and the Big Bang

Does the universe as a whole have a shape?

There are three possibilities for the overall geometry of the universe.

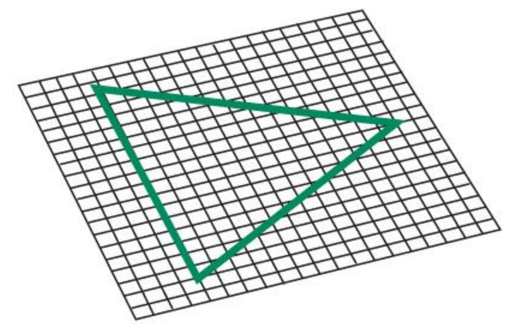
1. Closed geometry, like the surface of a sphere.
2. Flat geometry.
3. Open geometry, which can be visualized as a saddle.

Closed



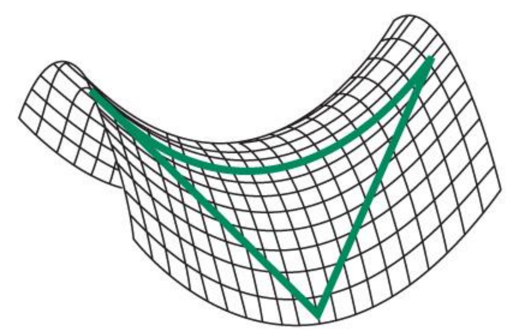
(a) Closed geometry

Flat



(b) Flat geometry

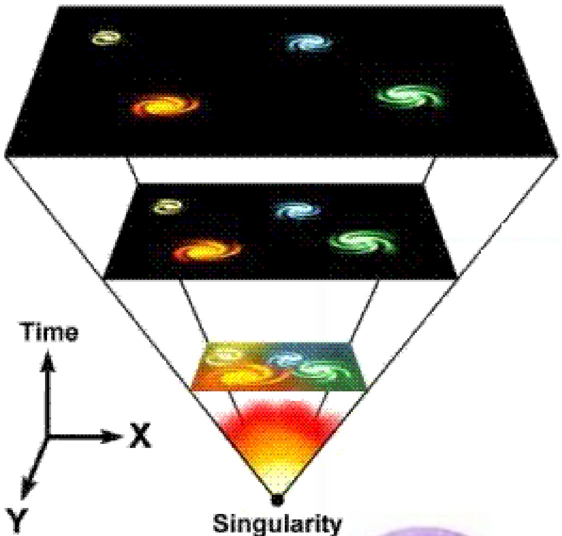
Open

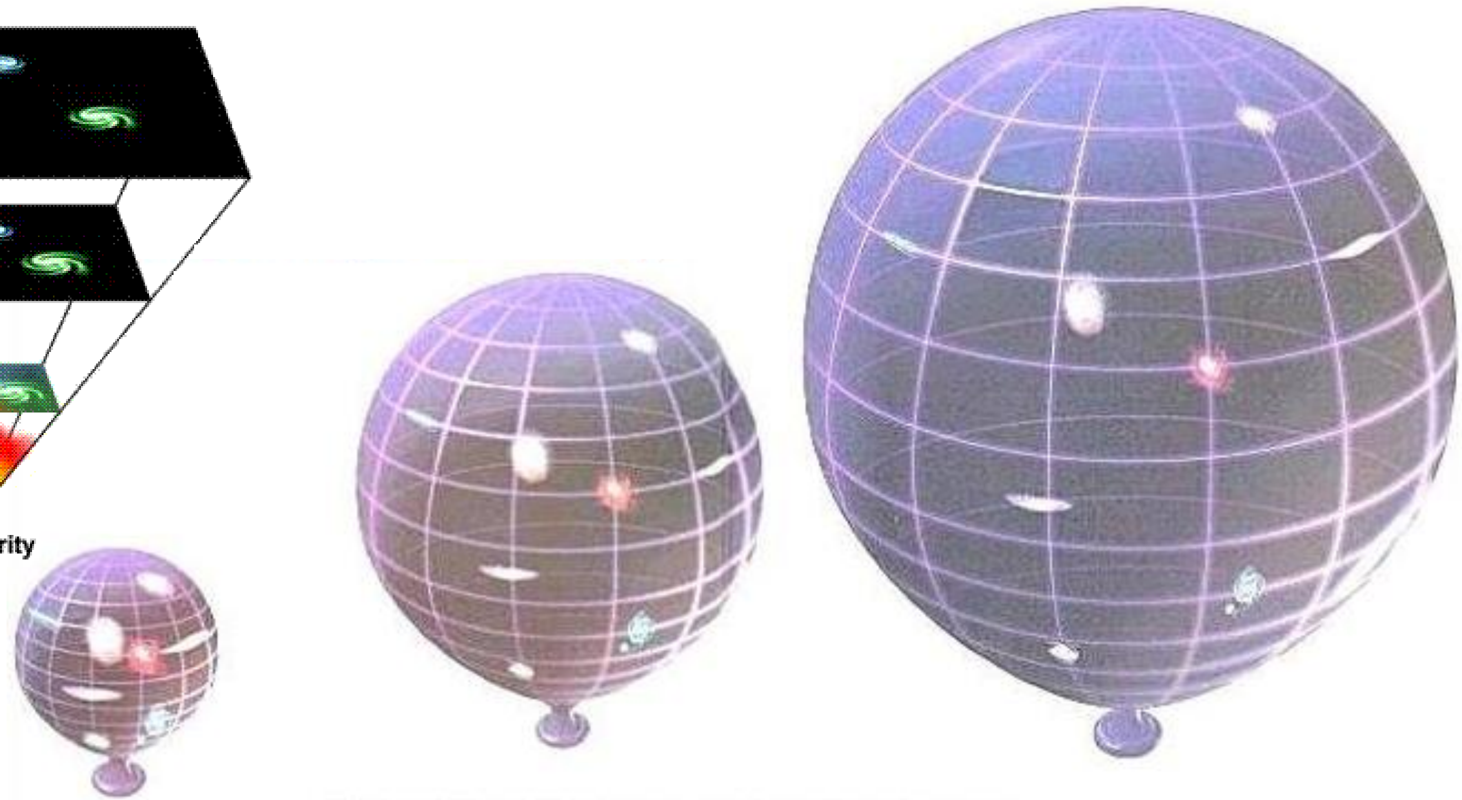


(c) Open geometry

Expanding Universe

So, which shape does our universe have?





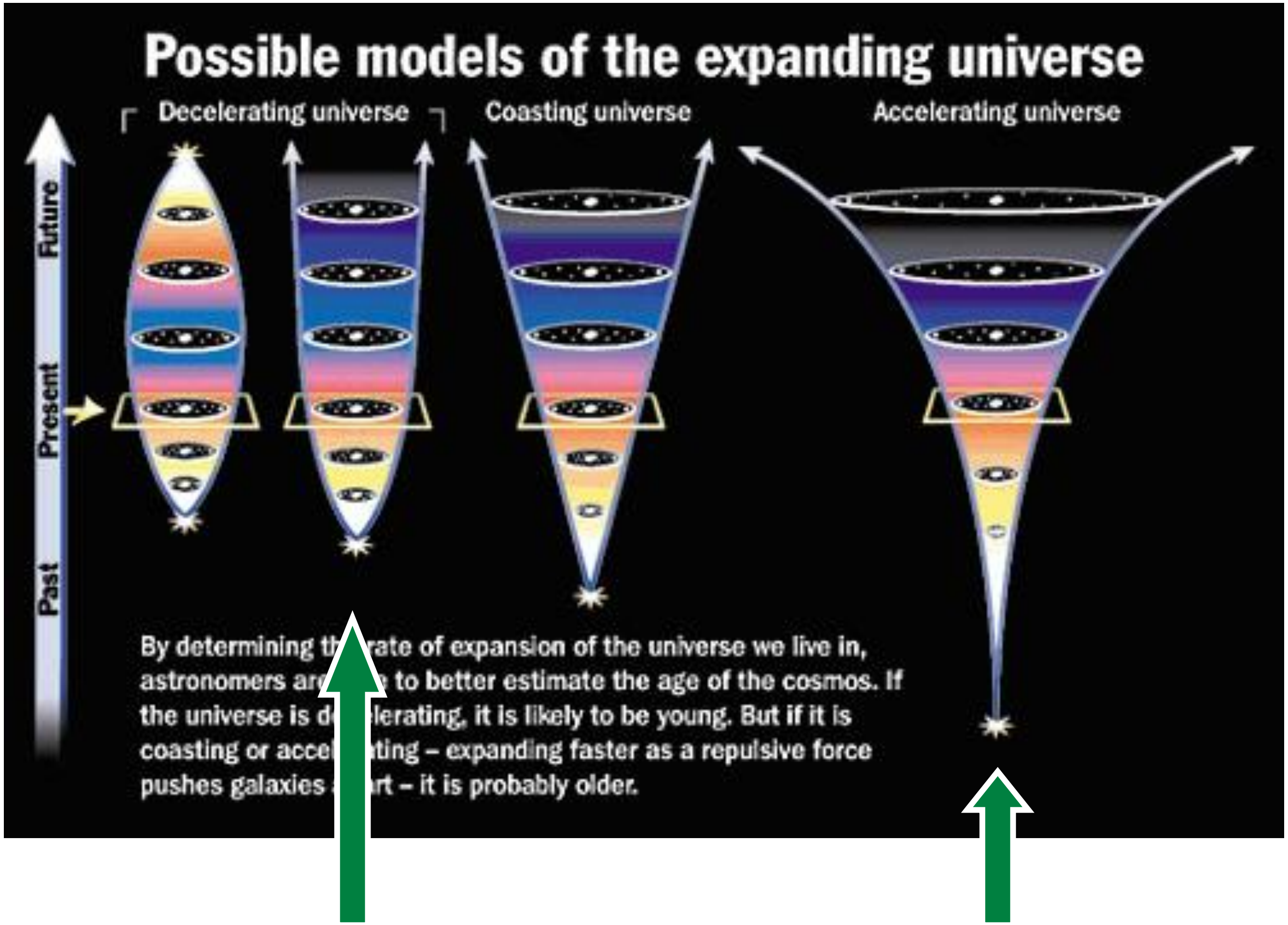
Actually, best evidence $\Rightarrow$ universe is flat

But it still expands similarly to what is shown above

And there is strong evidence that it is accelerating!

(Nobel prize in physics in 2011)

Expanding Universe



Like this in early universe

Like this more recently

Clicker

You are in a spaceship with no windows, radios, or other means to check outside. How would you determine if the spaceship is resting on the surface of a planet or using its thrusters to accelerate in outer space?

A. By determining the apparent velocity of light in the spaceship.
B. By checking your precision watch. If it's running slow, then the ship is in the gravitational field of the planet.
C. By measuring the path of a beam of light. If it bends, then you are in a gravitational field.
D. You should give up because you've taken on an impossible task.

Clicker

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D. You should give up because you’ve taken on an impossible task.

Principle of Equivalence!

Clicker

Which is true, according to the geometrical interpretation of general relativity?

A) All masses cause a warping of space and time around them.

B) All masses move according to the warping due to other masses.

C) Gravitation is not really a force - it is just the effect of the warping on the path of objects.

D) General relativity is hard to grasp intuitively because it requires you to think about warped four-dimensional space-times.

E) All of the above.

Clicker

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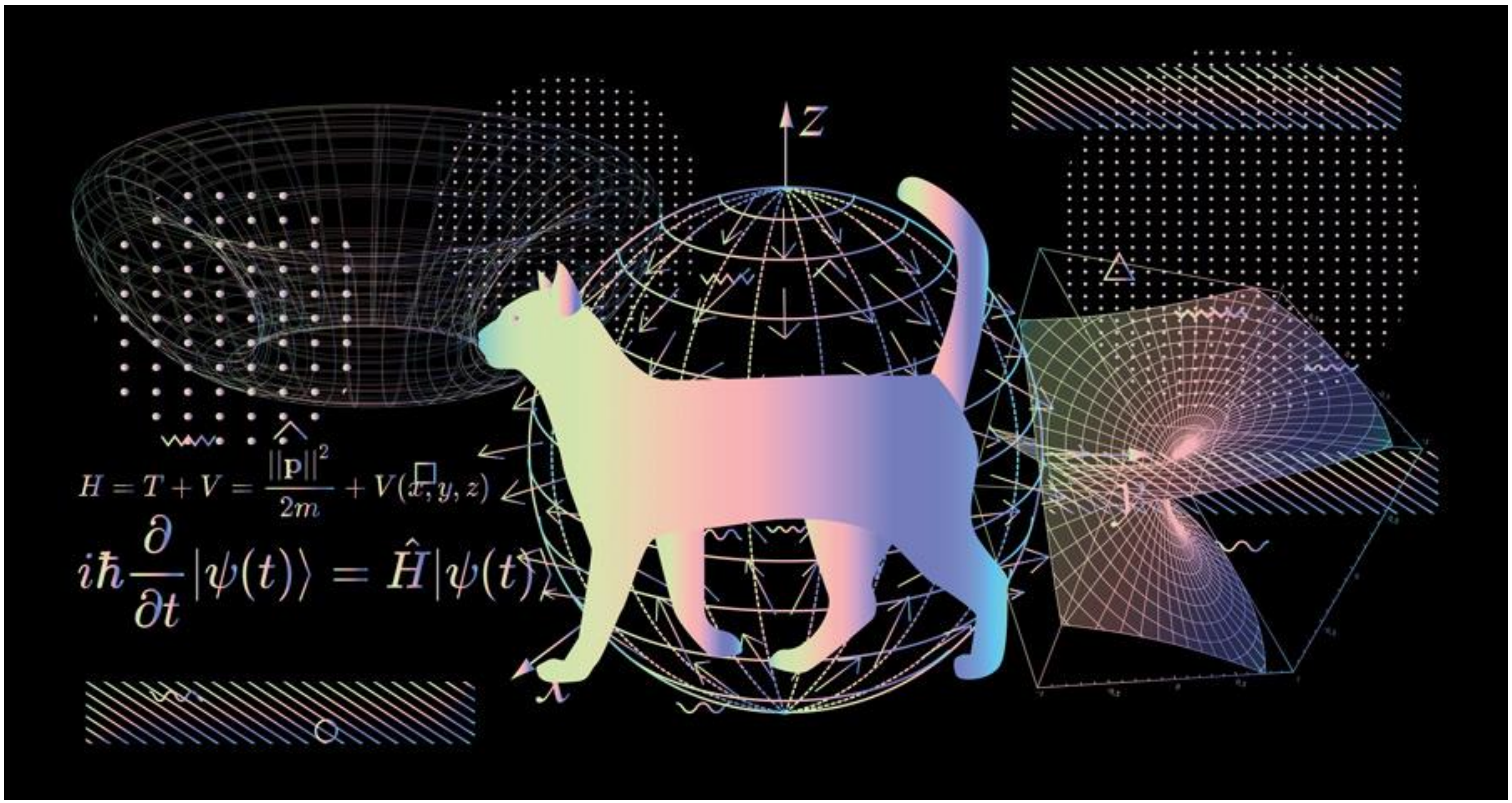
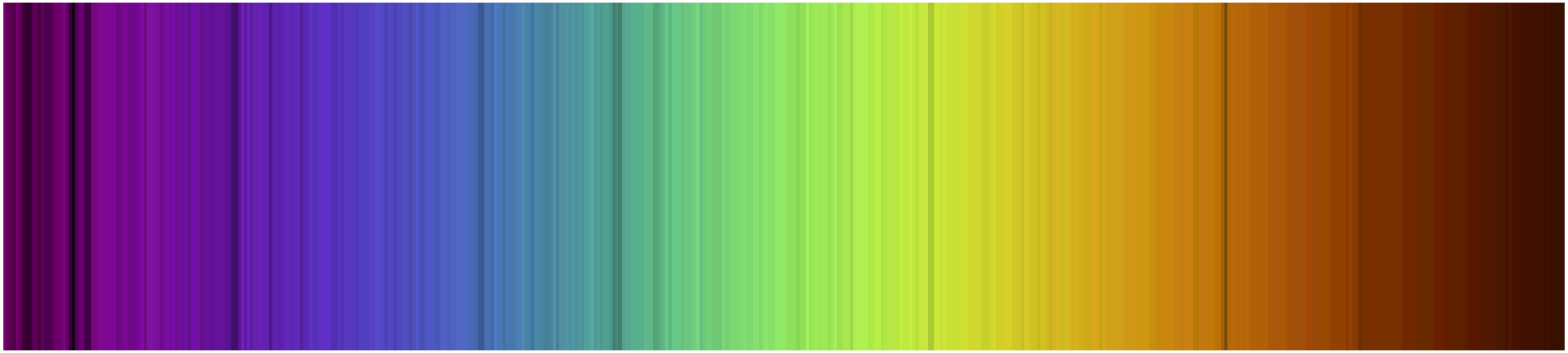
Quantum Theory

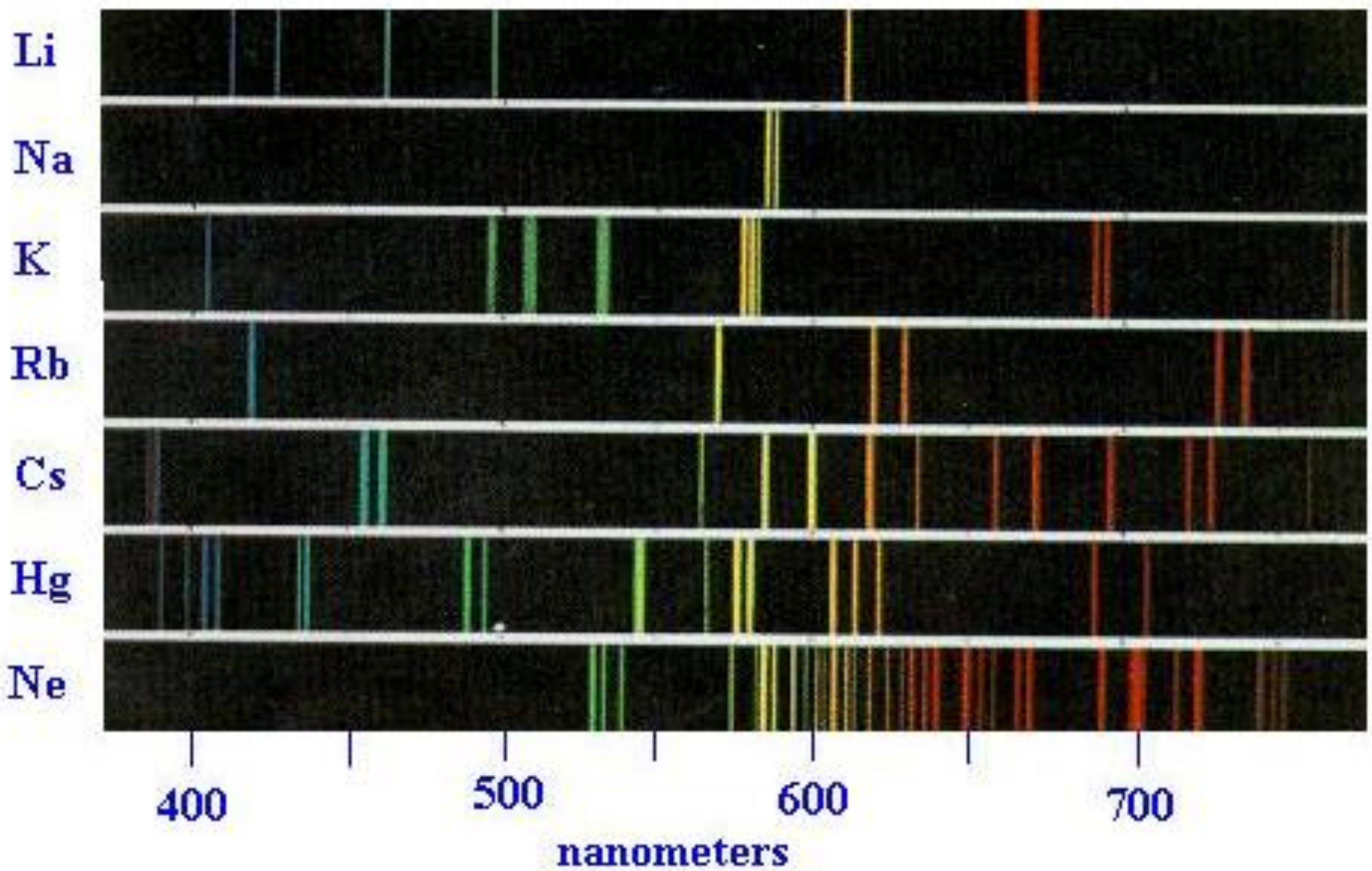


High resolution solar spectrum



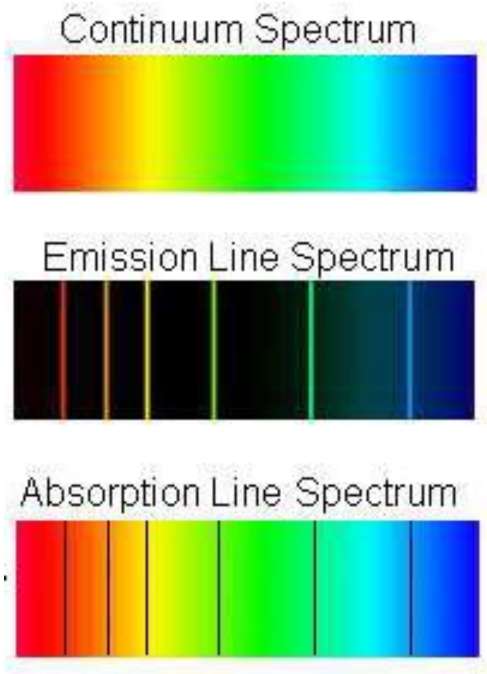
Note “absorption lines”

Light from atoms that have been excited
by an arc discharge

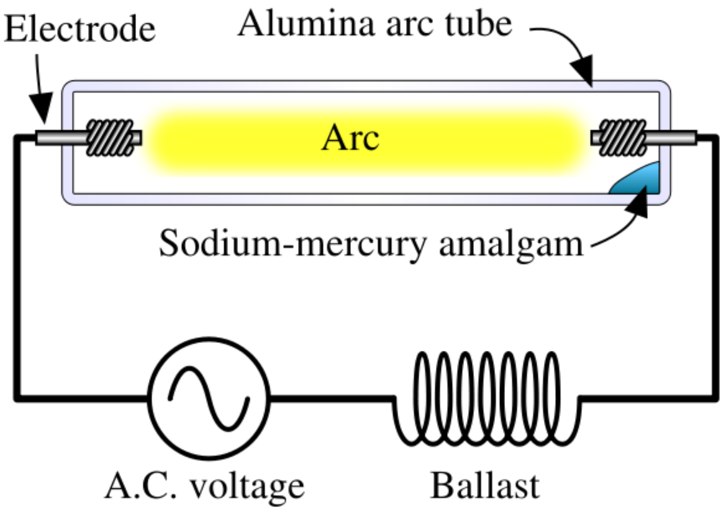


Note “emission lines”

Demo: Atomic Spectra



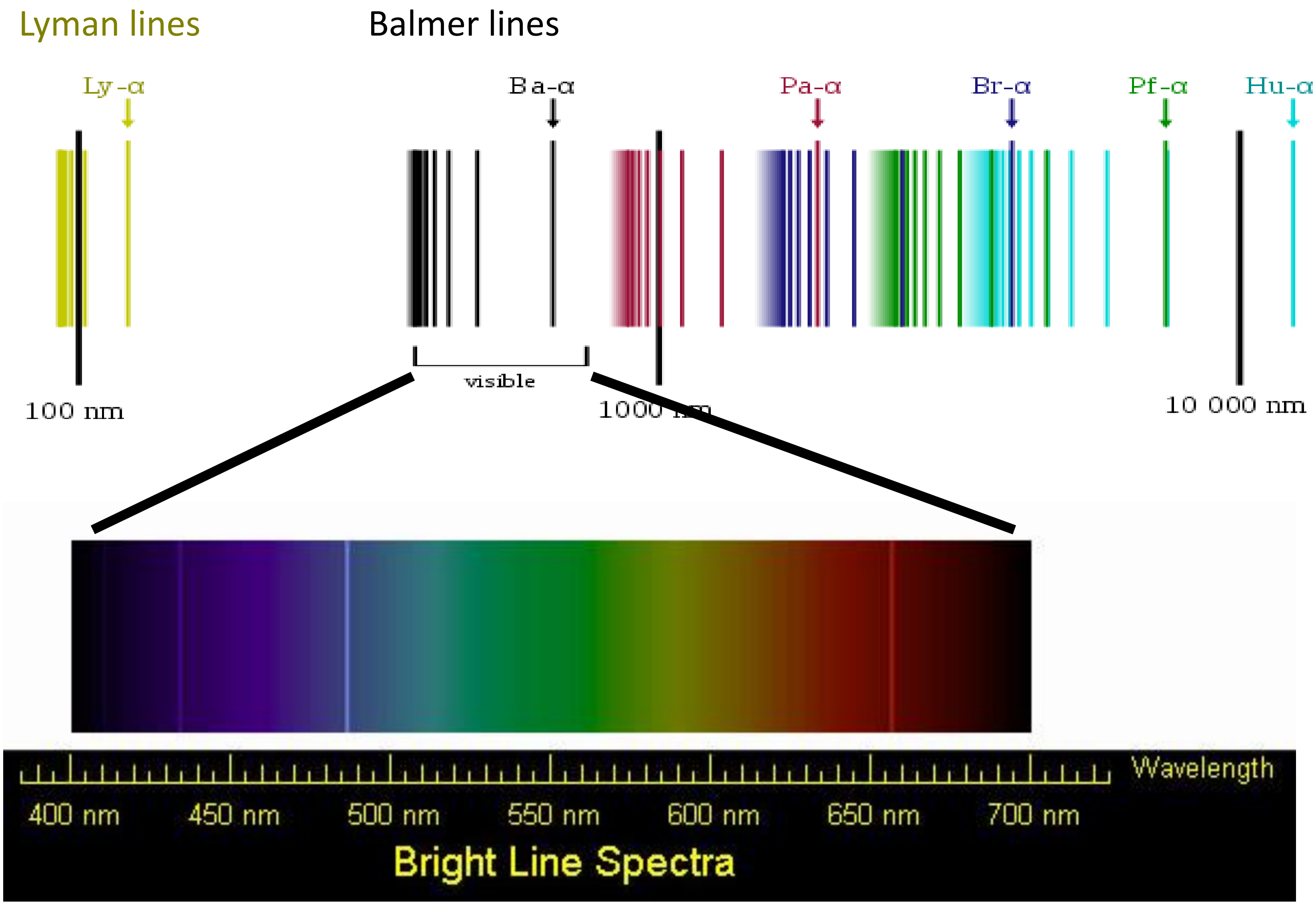
Discharge tube



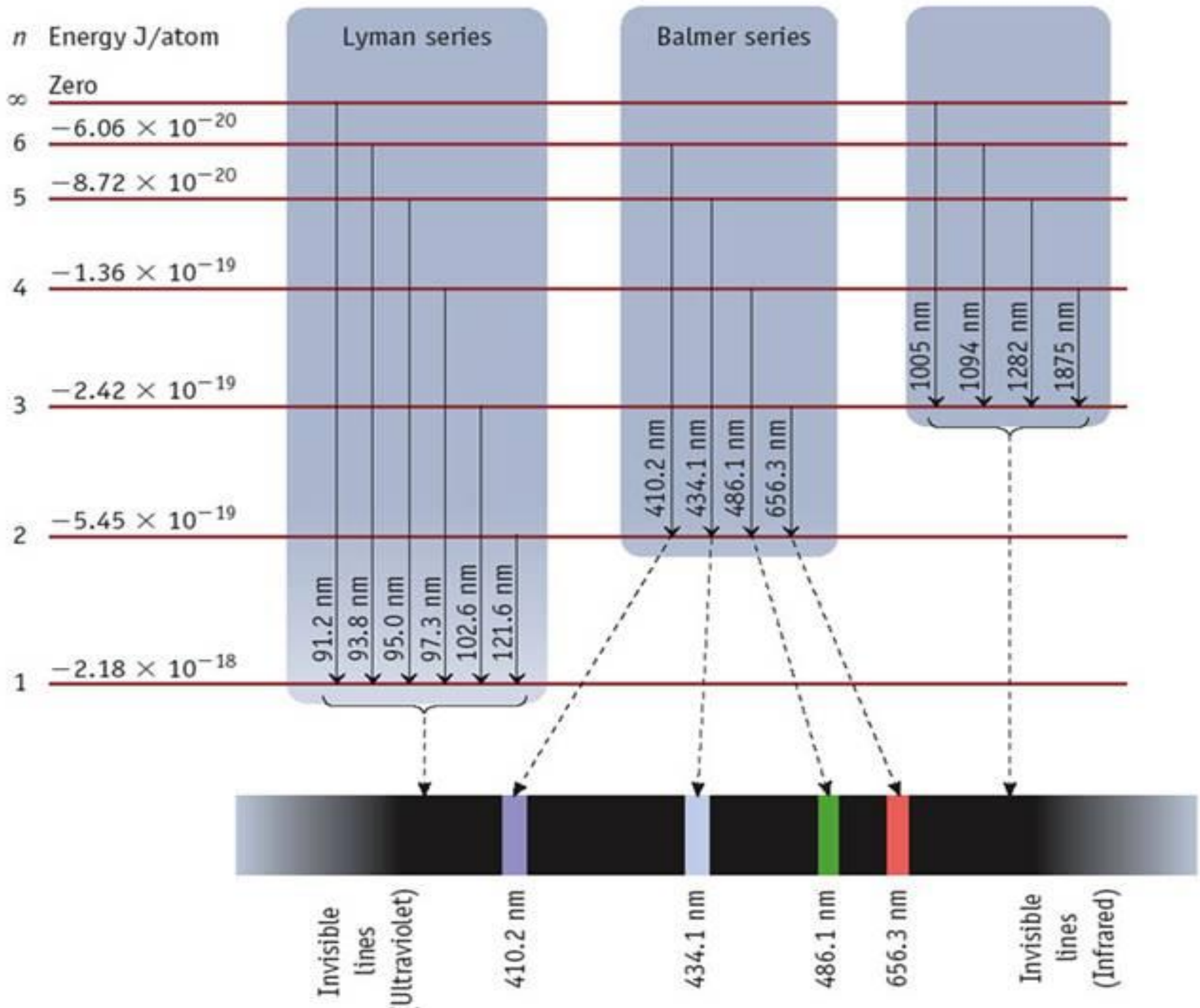
<u>Conclusion</u>: Atoms absorb and emit light of very specific wavelengths.

Why??

H atom spectrum



H atom spectrum



Atomic spectra

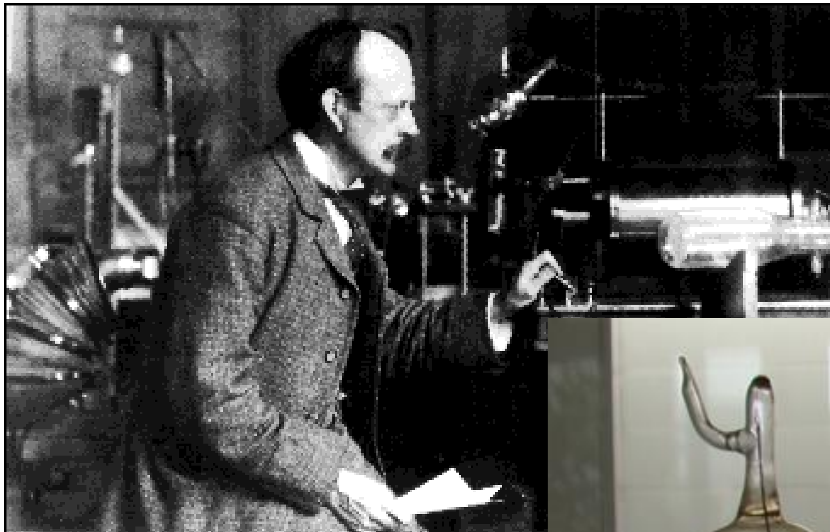
- Observed pattern: each emission or absorption corresponds to a *transition* of the atom between two *states.*
- Each state has an *energy.*
- The *frequency f* of the light is given by

(Planck's constant, called h)

(f in Hz) = (change in energy) / (6.6 x 10^{-34} Js).

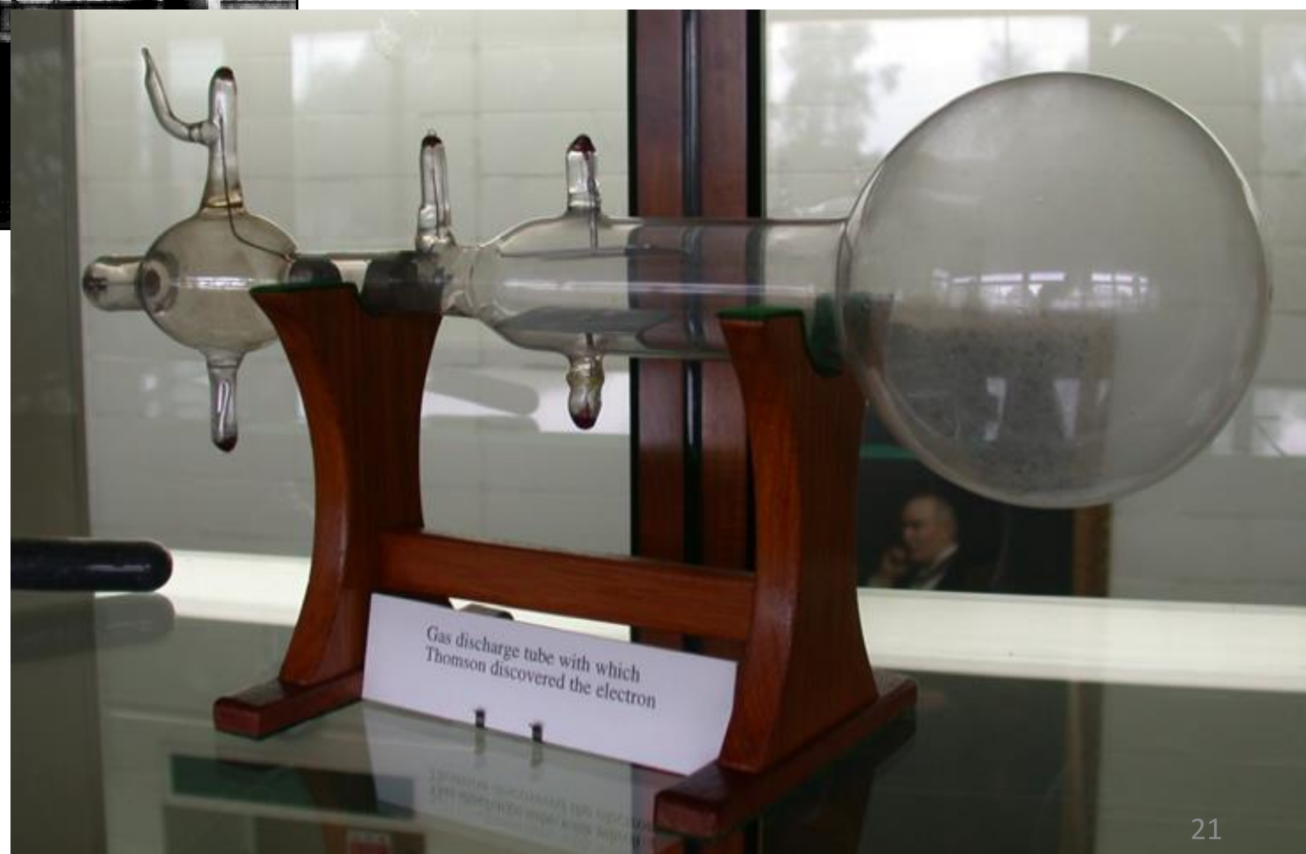
- So the *wavelength* = c / f.
- But the pattern of energies is different for every atom. How can it be explained?

Discovery of the electron

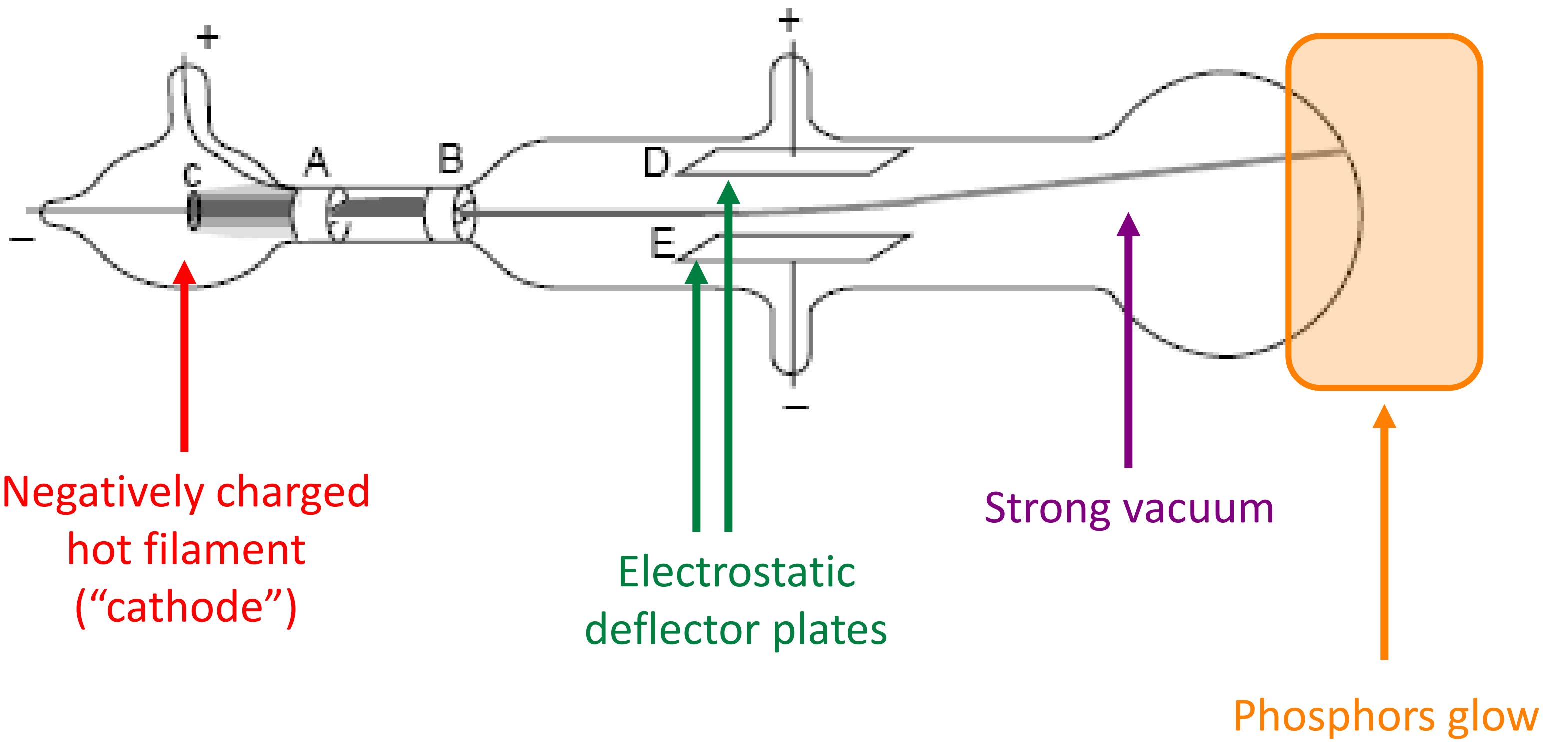


J.J. Thomson
Cambridge, England
1897

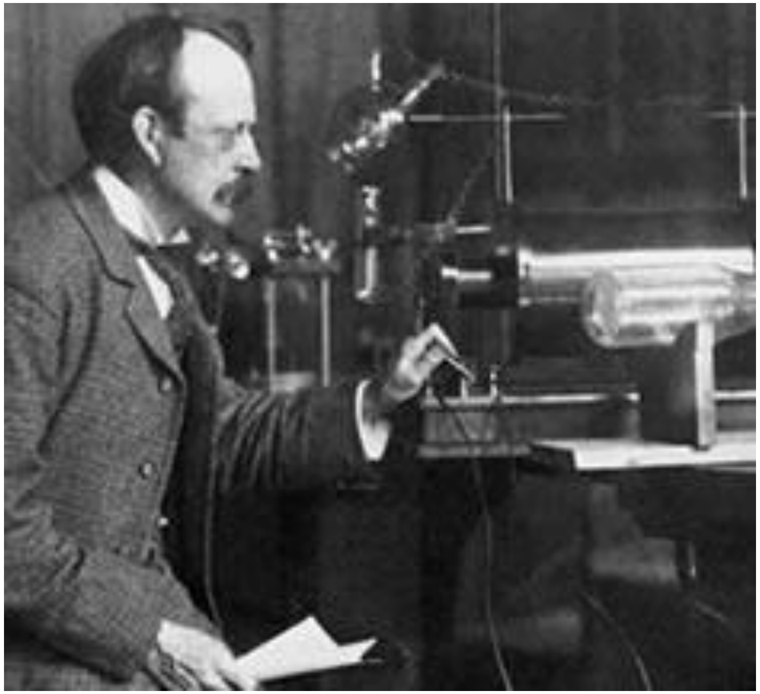
Cathode ray tube



Cathode ray tube



Discovery of the electron



J.J. Thomson
Cambridge, England
1897

“Cathode rays” are made of particles!

Thomson measured their mass and charge.

Mass turned out to be tiny!

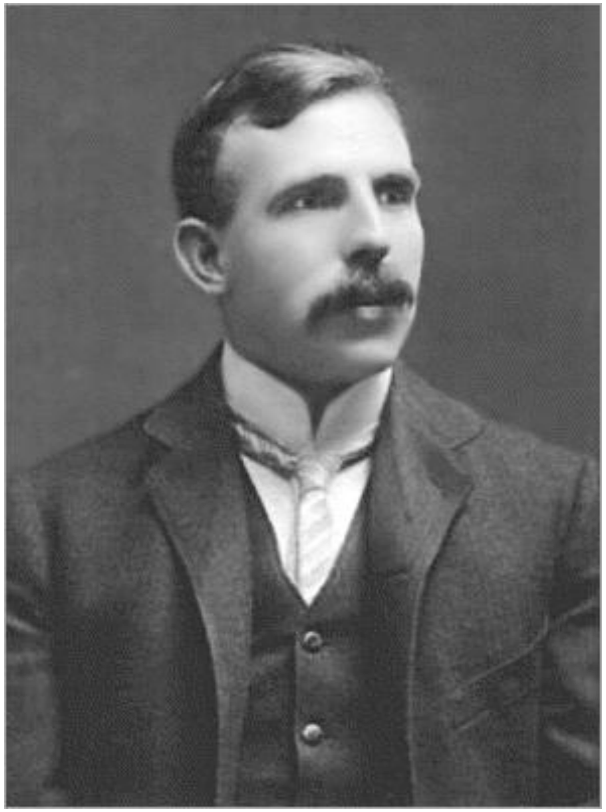
Thomson …

- Showed that electric and magnetic fields deflect the "rays" as though they are particles of mass m and charge $-e$
- Measured the ratio e/m
  - Acceleration $= F/m = Ee/m$ (electric forces)
    $= Be/m$ (magnetic forces)
- Result: e/m is more than a thousand times bigger than for H^+ ions!
- These "electrons" either have a very big charge, or else a very tiny mass!

J.J. Thomson

Could anything at first sight seem more impractical than a body… which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen, which itself is so small that a crowd of these atoms equal in number to the population of the whole world would be too small to have been detected by any means then known to science.

Discovery of the nucleus

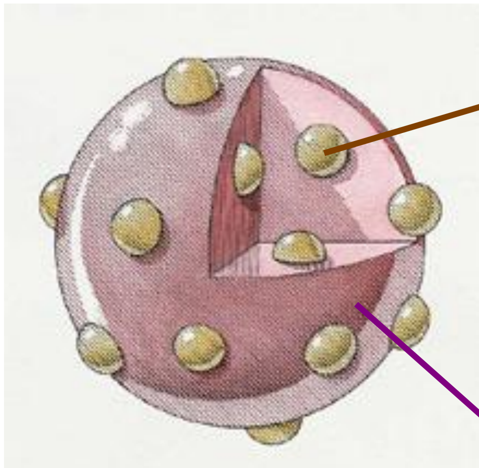


Ernest Rutherford
Cambridge, England
1909

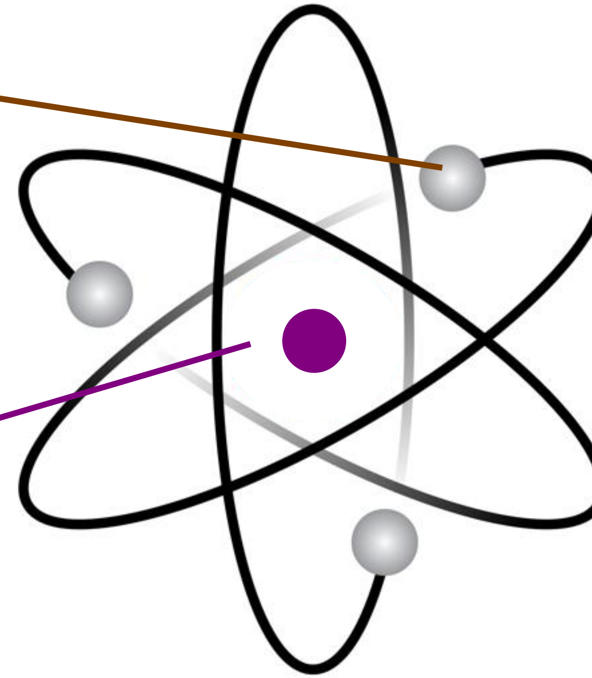
Nucleus is tiny!

What is an atom?

“Plum pudding” model



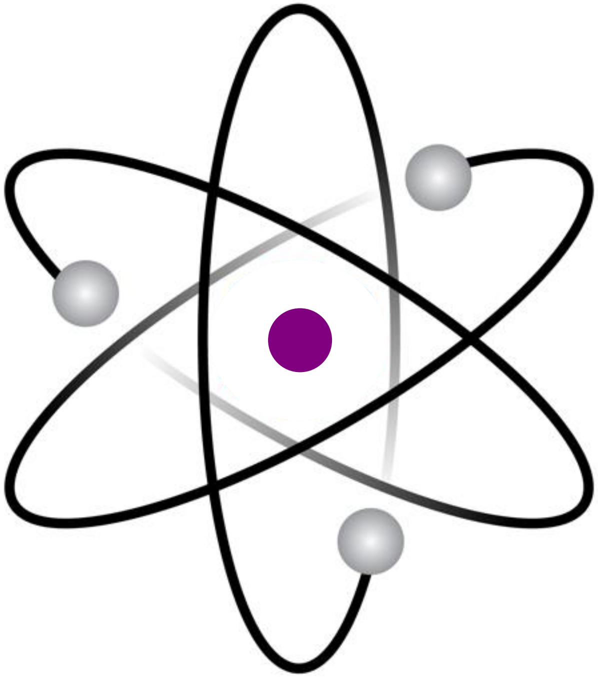
“Planetary” model



Electrons

Positive charge

“Planetary” model…



was considered unlikely, because Maxwell’s theory predicted that electrons would spiral into the nucleus

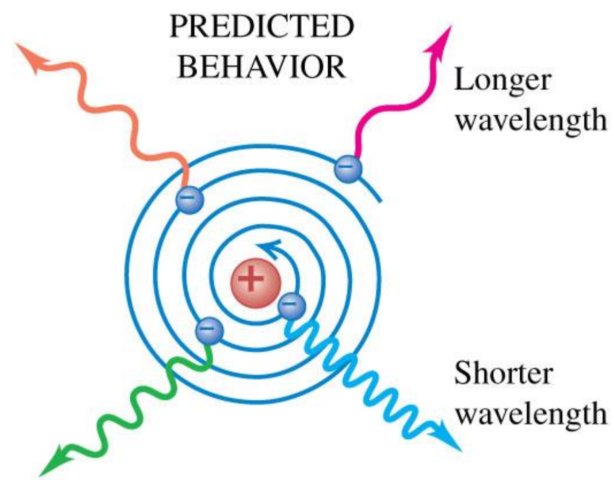
• Planetary Model of Atom

- positively charged, massive nucleus
- negatively charged, light electrons
- electrostatic attraction
- Together, these facts suggest electrons "orbiting" around the nucleus, like planets around the sun.
- Problem: The orbiting electrons would radiate light, carrying away energy
- Electrons would spiral into nucleus, atom would collapse.

ACCORDING TO CLASSICAL PHYSICS:

- An orbiting electron is accelerating, so it should radiate electromagnetic waves.
- The waves would carry away energy, so the electron should lose energy and spiral inward.
- The electron's angular speed would increase as its orbit shrank, so the frequency of the radiated waves should increase.

Thus, classical physics says that atoms should collapse within a fraction of a second and should emit light with a continuous spectrum as they do so.

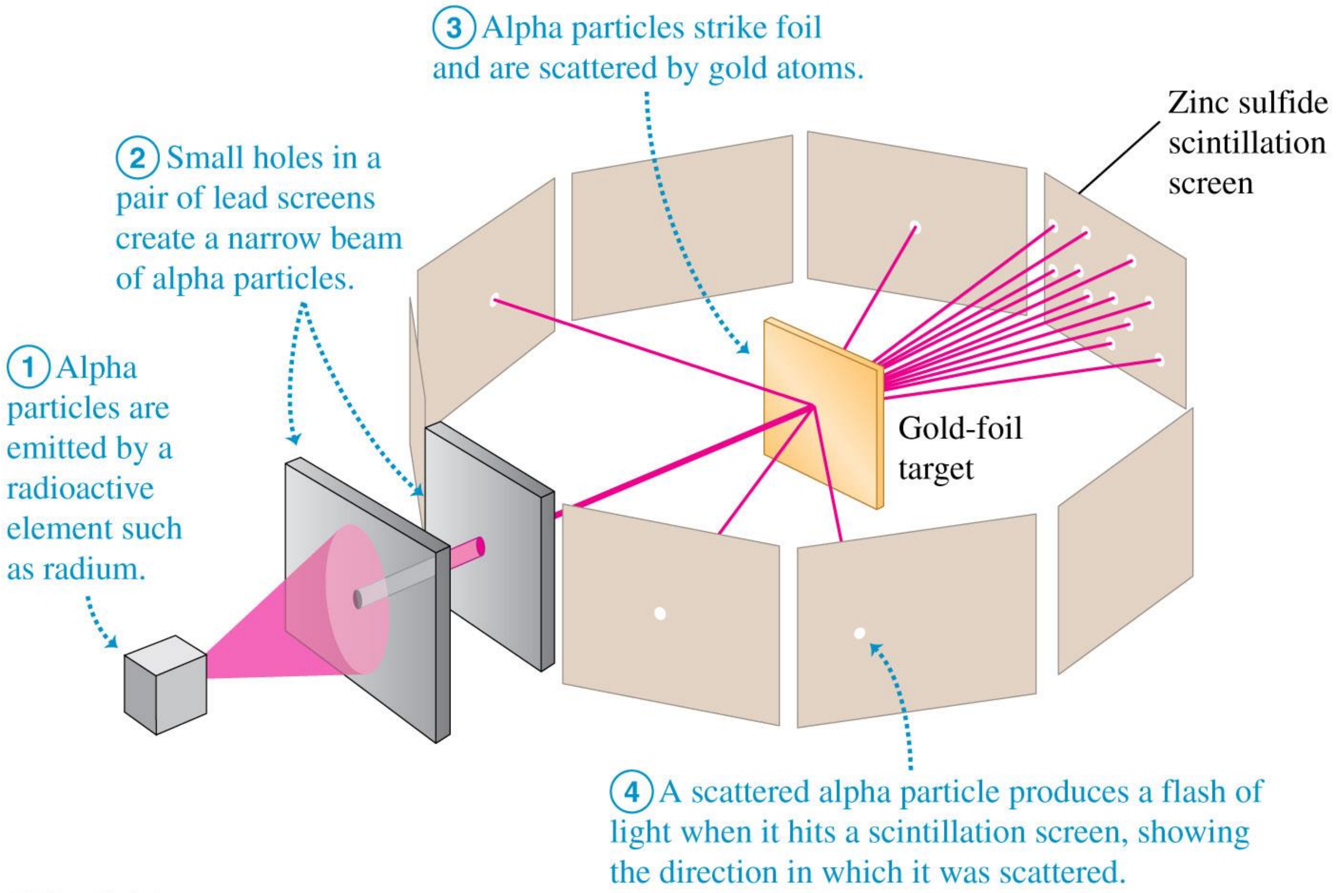


IN FACT:

- Atoms are stable.
- They emit light only when excited, and only at specific frequencies (as a line spectrum).

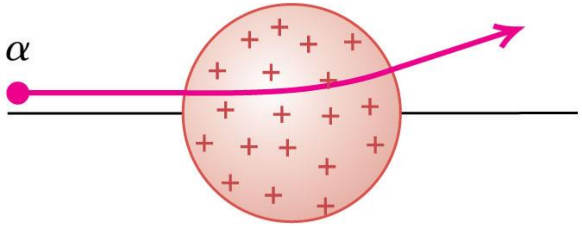
Rutherford Backscattering

In 1911, E. Rutherford led experiments scattering alpha particles (^{4}He nuclei) from gold atoms. Most of the a particles went straight through the gold foil, while a very small number were deflected at large angles:

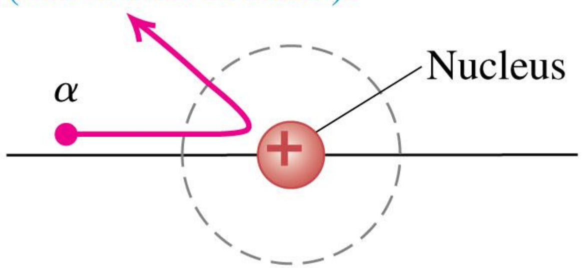


• Point-Like Nuclei

(a) Thomson's model of the atom: An alpha particle is scattered through only a small angle.

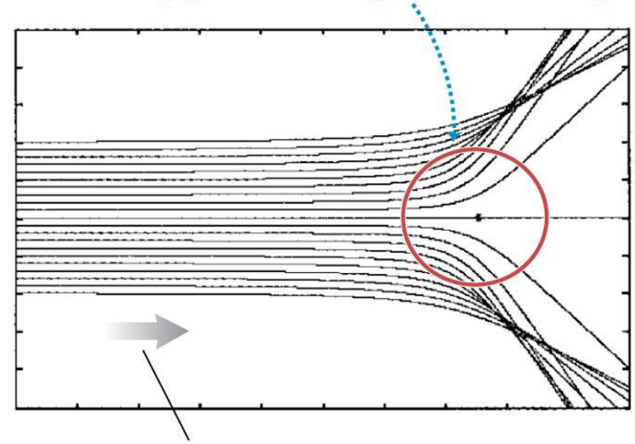


(b) Rutherford's model of the atom: An alpha particle can be scattered through a large angle by the compact, positively charged nucleus (not drawn to scale).



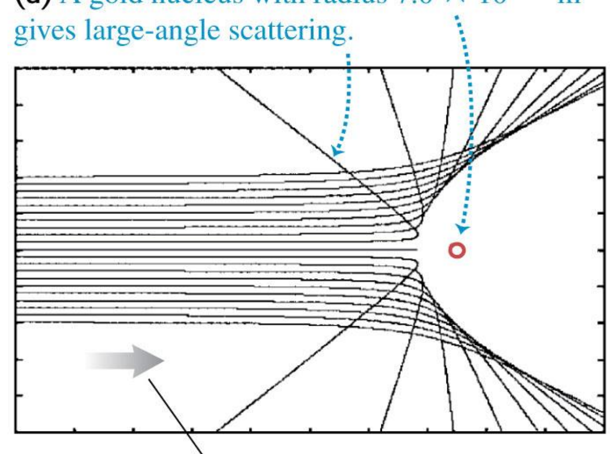
Rutherford concluded that the positive charge (and most of the mass) of the atom is concentrated in a very compact region, the atomic "nucleus".

(b) A nucleus with 10 times the radius of the nucleus in **(a)** shows *no* large-scale scattering.



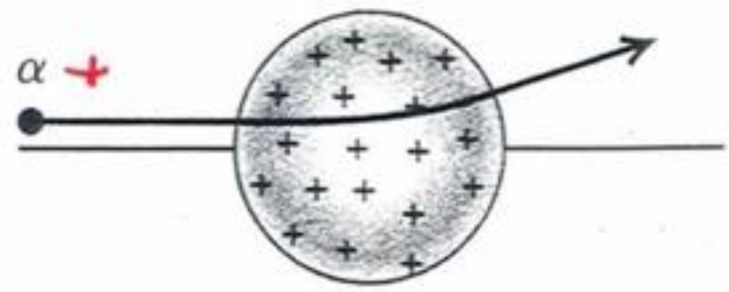
Motion of incident 5.0-MeV alpha particles

(a) A gold nucleus with radius 7.0×10^{-15} m gives large-angle scattering.

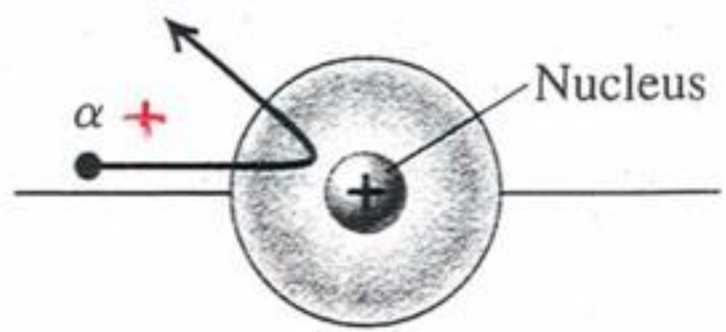


Motion of incident 5.0-MeV alpha particles

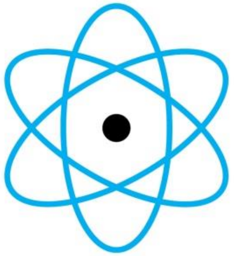
What Rutherford expected
(Thomson's model)



What Rutherford saw

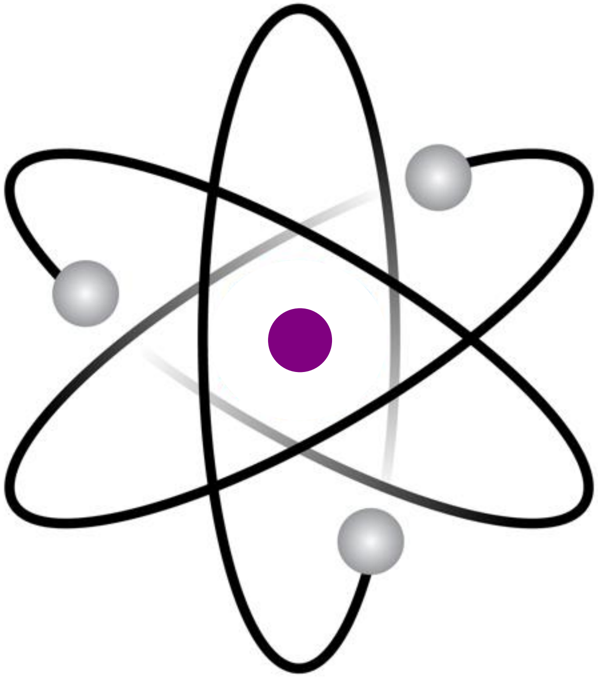


Ernest Rutherford



- “It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you. On consideration, I realized that this scattering backwards must be the result of a single collision, and when I made calculations I saw that it was impossible to get anything of that magnitude unless you took a system in which the greater part of the mass of the atom was concentrated in a minute nucleus. *It was then that I had the idea of an atom with a minute massive center carrying a charge*.”
  – Lord Rutherford, 1936

Rutherford Scattering Experiment:
Atom is small nucleus with electrons

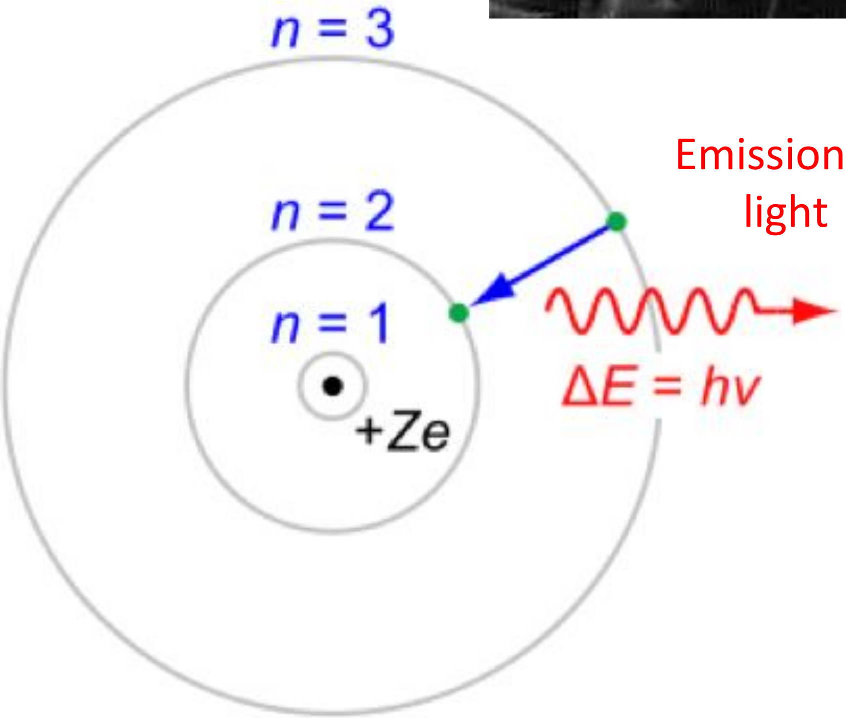


Electrons stay in orbit!
Do these orbits have special energies?

Try simplest atom first…

Bohr model of Hydrogen atom (1913)

- Electrons are in special "orbits" labeled by integers (n = 1, 2, 3, …)
- "Transitions" between orbits are responsible for emission and absorption of light



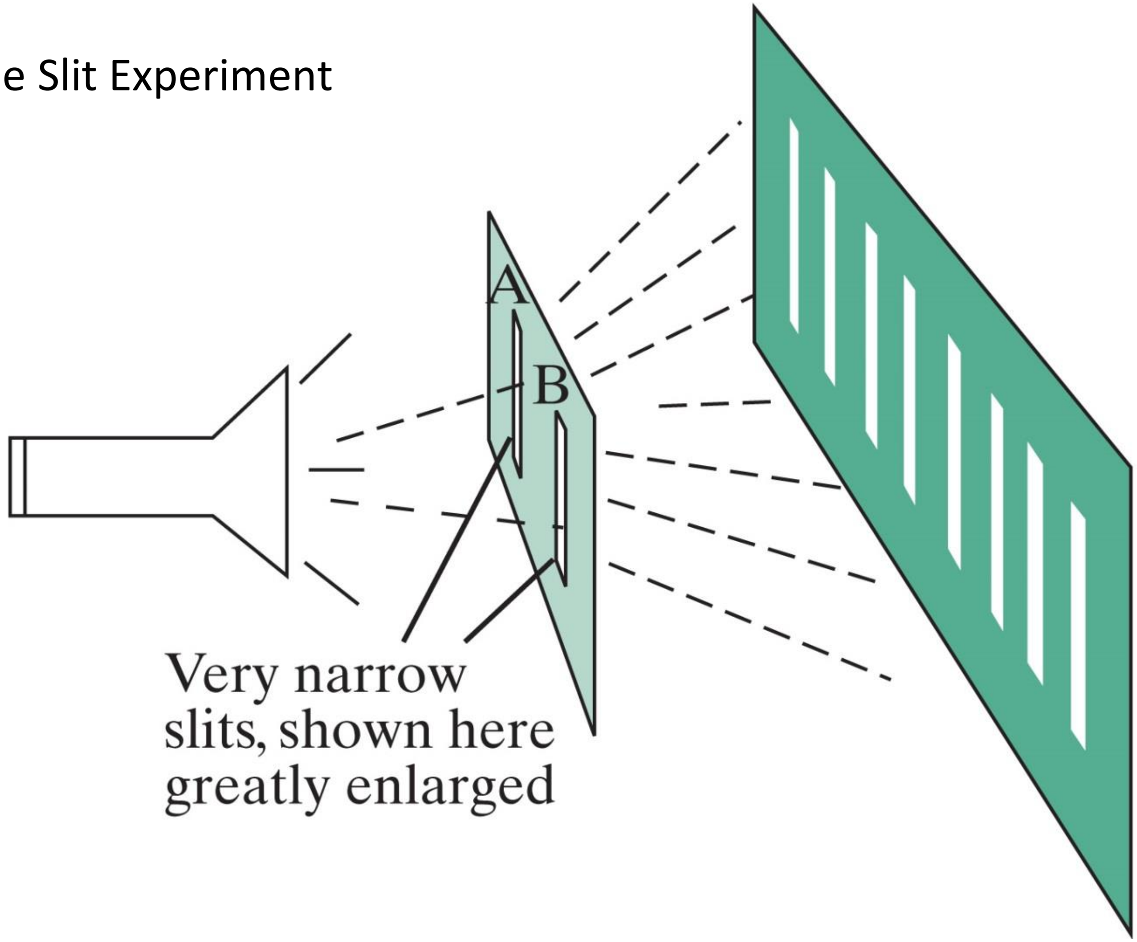
But: Many puzzling aspects…

Bohr’s “solar system” model of atom

- Works really well to explain H spectrum!
- Agrees with Rutherford’s results!
  - Small nucleus in center, electrons in orbit.
- BUT Why do electrons not radiate and lose all their energy?
  - Charged particles, undergoing acceleration…
- We need QUANTUM IDEAS.

Light waves

Double Slit Experiment



Wave Interference

Property of Waves: Interference.

- All sorts of waves show interference:
  - Water
  - Sound
  - Slinky
  - Radio Waves

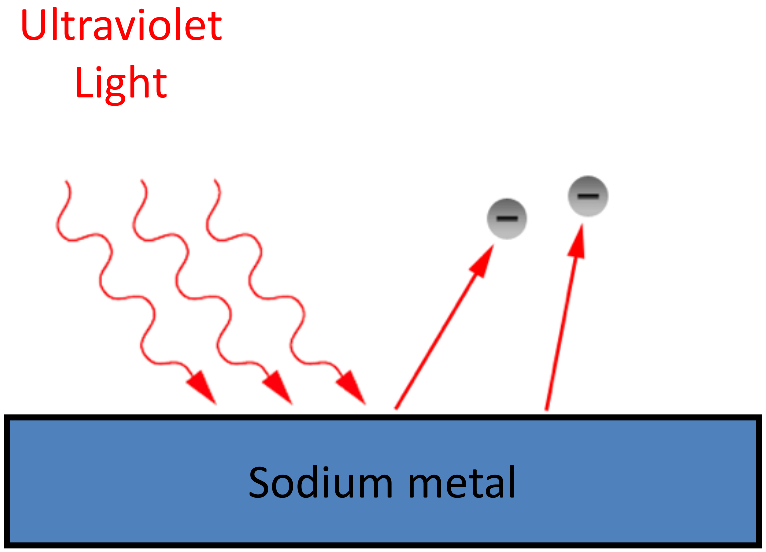
- **LIGHT shows interference.**
  - **Therefore LIGHT is a WAVE.**

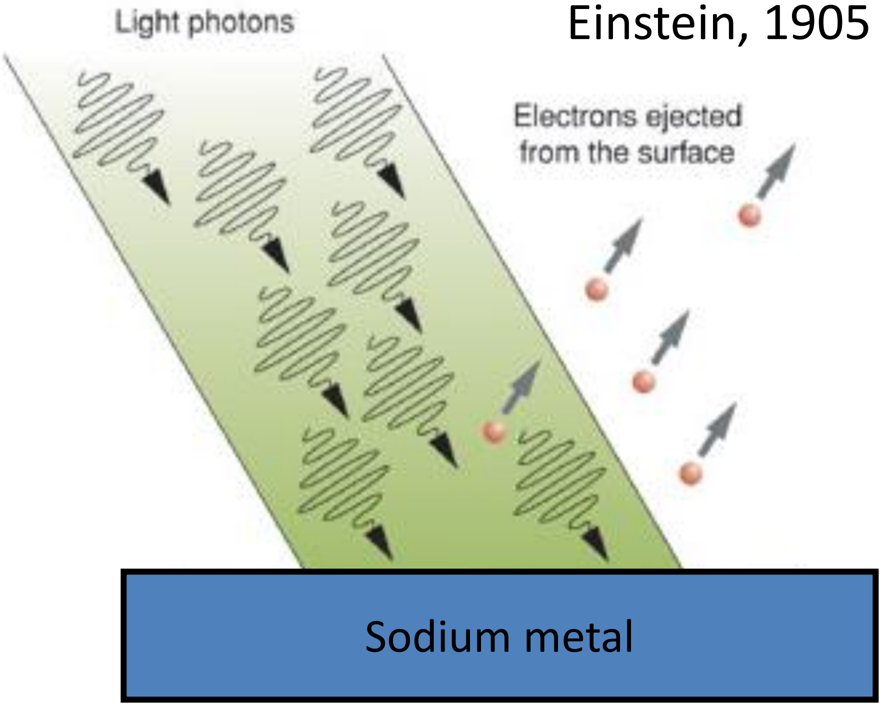
More about light: Photoelectric effect

- But: Light is ***also*** a particle.
  - Comes in quantized bunches (like bullets).

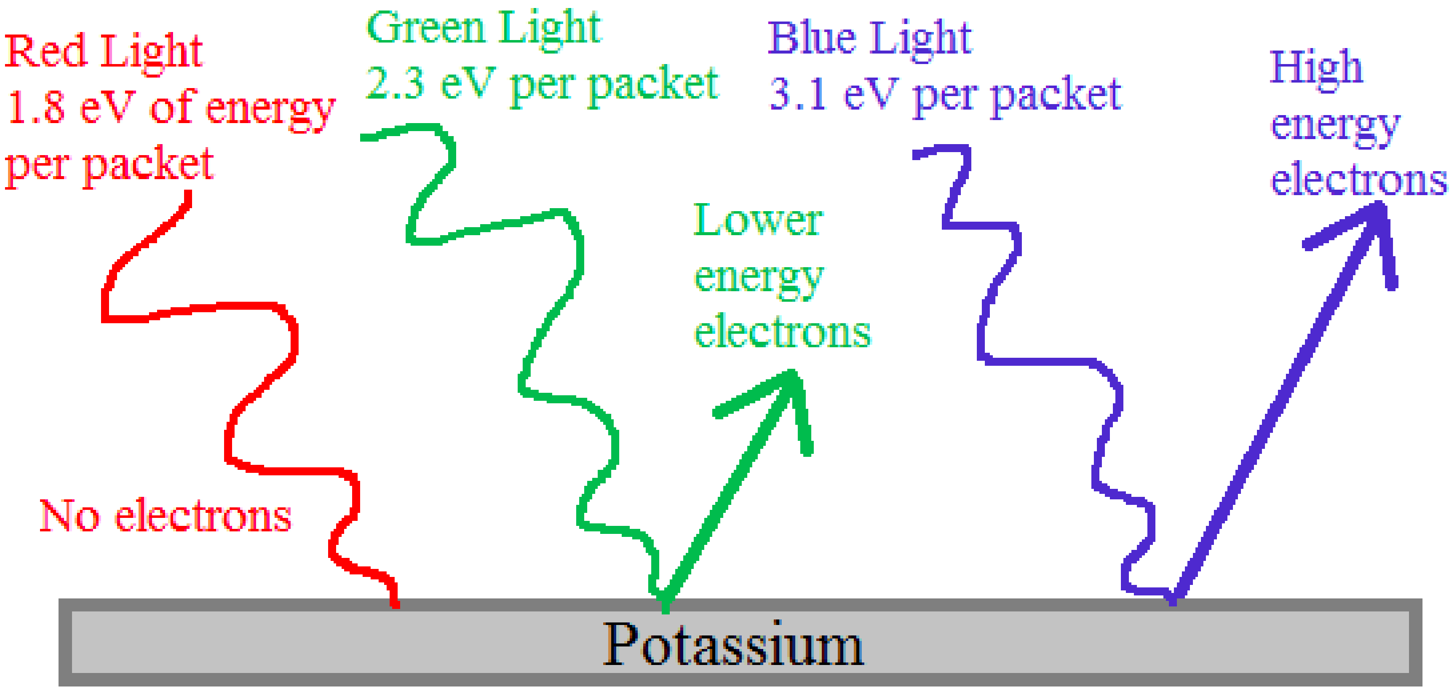
Photoelectric effect: Light as particles?

Einstein, 1905





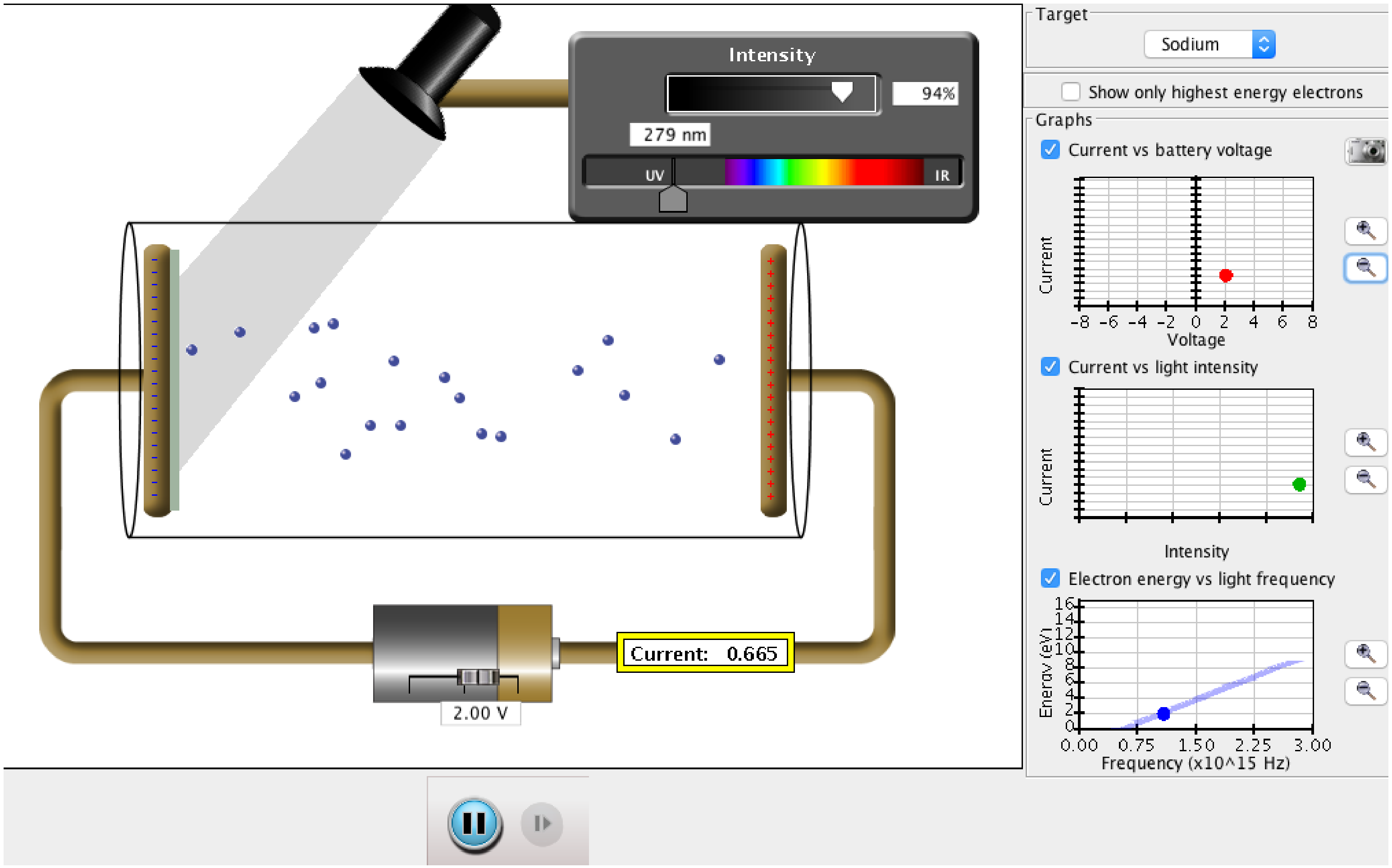
Light is a particle: Photoelectric Effect



Potassium electrons need 2 units
of energy to escape (2 eV).

PHET Demo

http://phet.colorado.edu/en/simulation/photoelectric

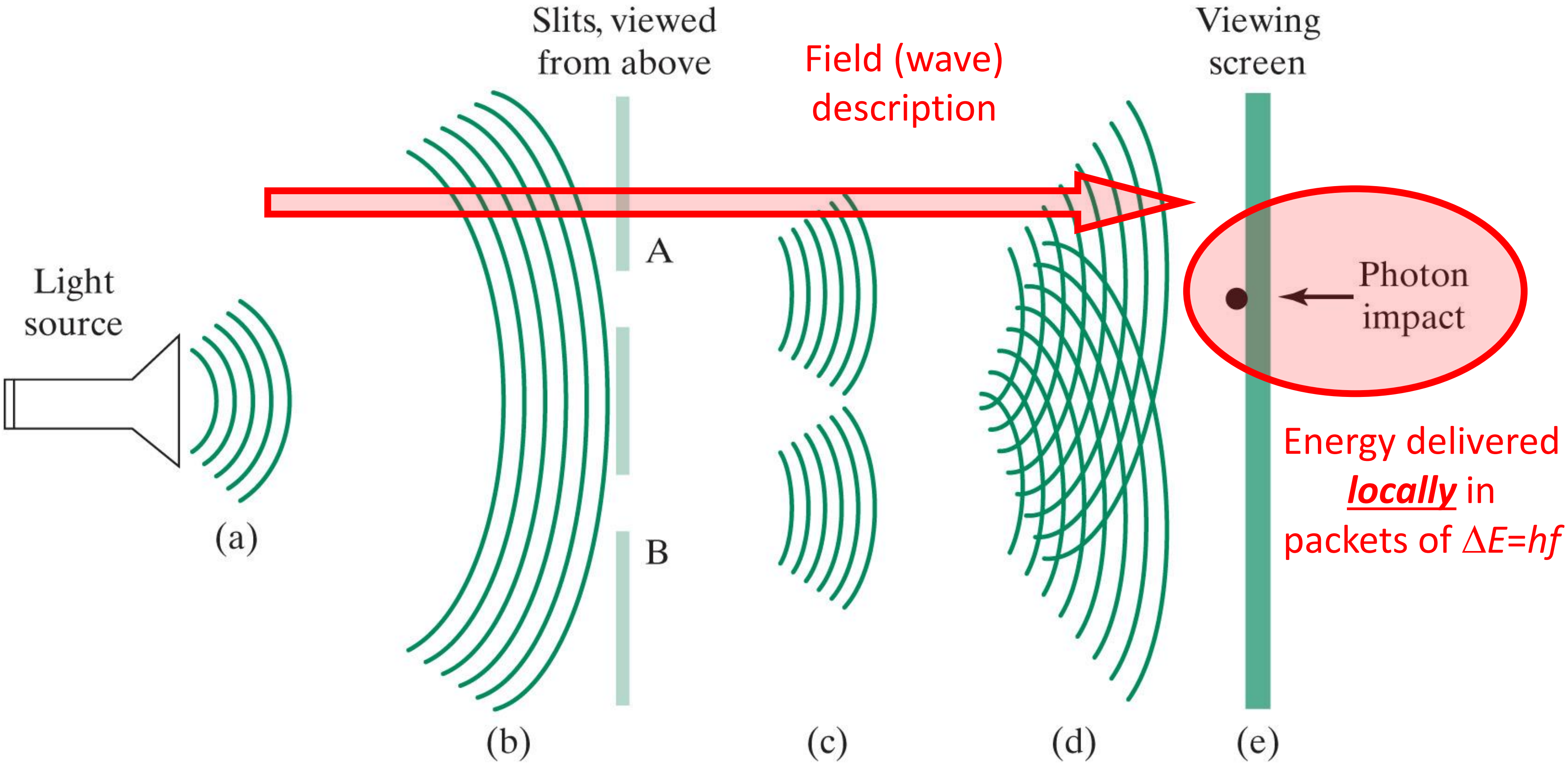


Photoelectric effect:
Light as particles?

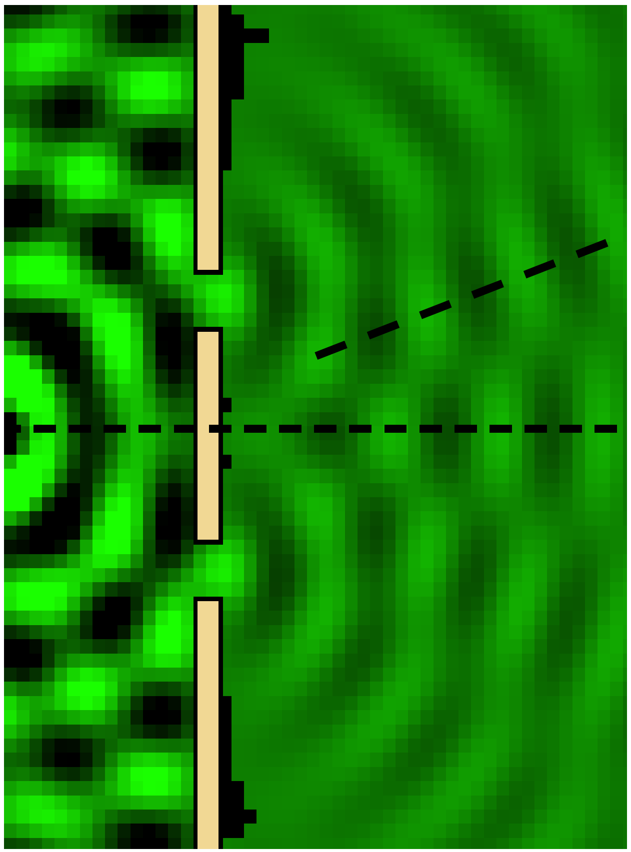
Conclusions:

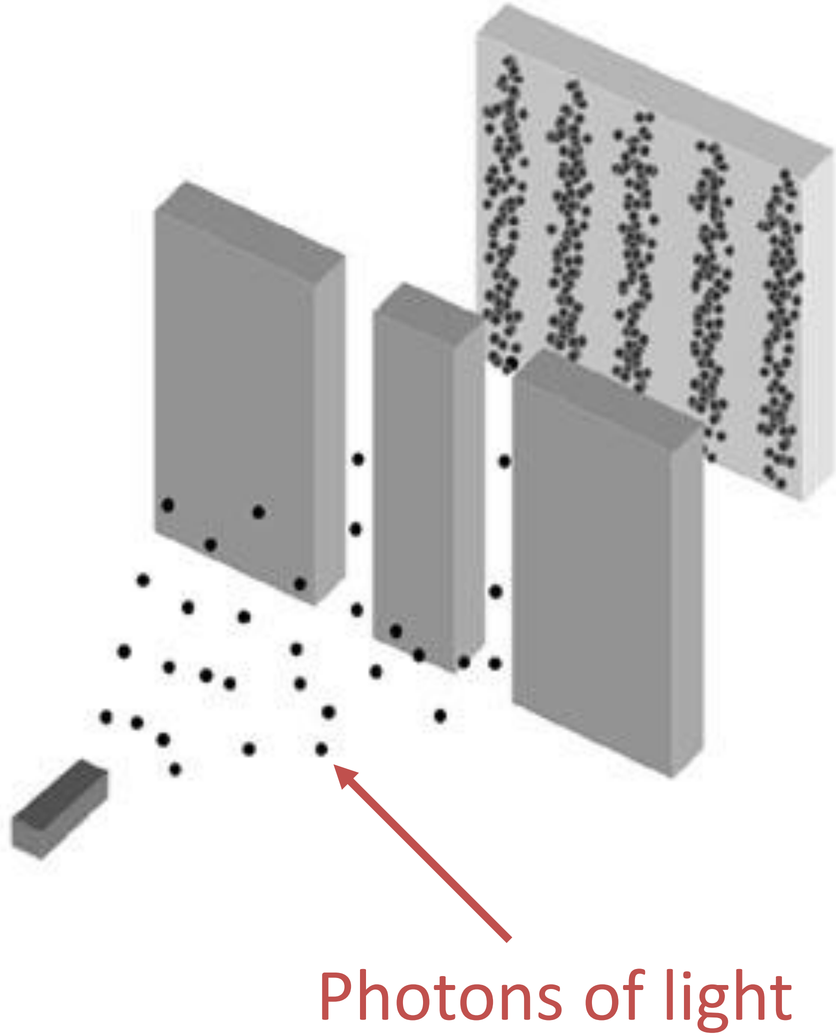
- Light delivers its energy in little packets called “quanta”
- There is a randomness to the arrival of these quanta
- The amount of energy delivered does *not* depend on the intensity of light!
- Instead, it depends on the *wavelength* (or *frequency*) of the light!

Quantization of Light



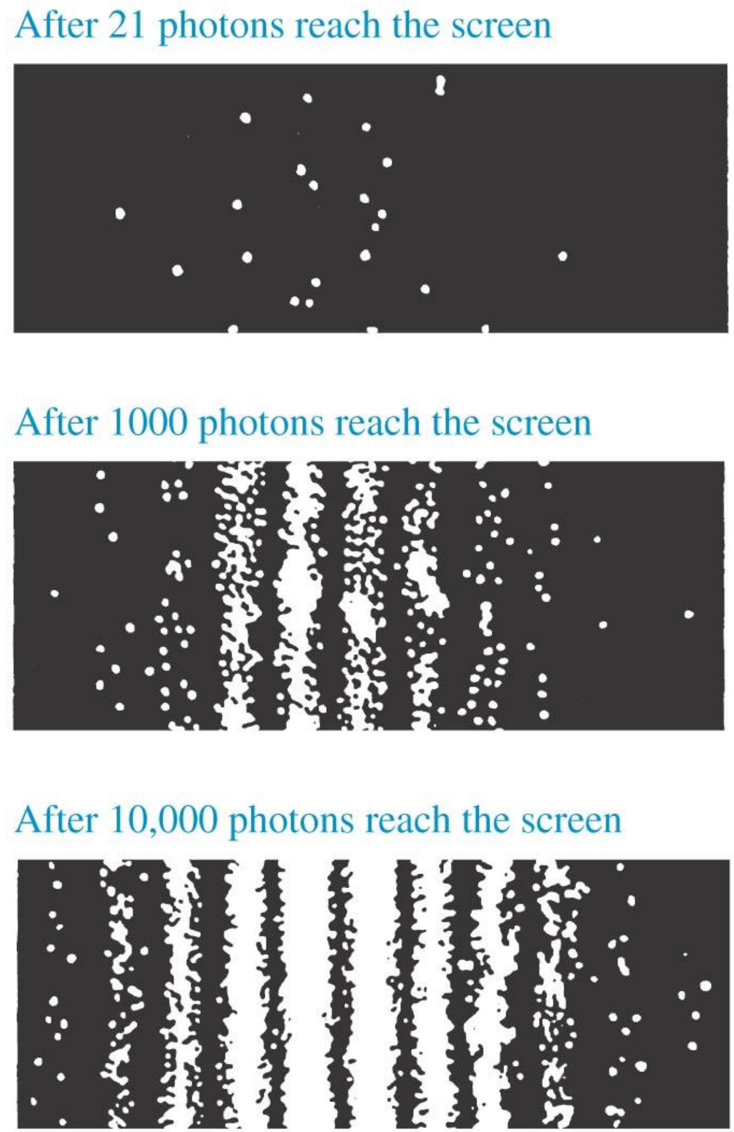
Double slit experiment





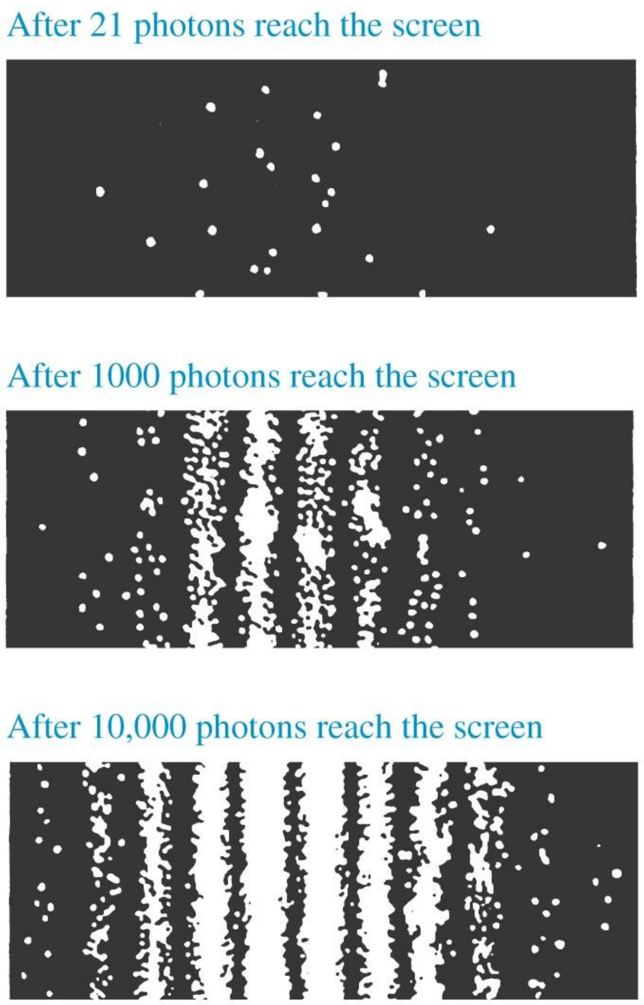
Two-Slit Interference Revisited

- As we have seen, the interference pattern is defined by the wave nature of light.
- However, with a sensitive detector, we can see individual photons appear at distinct spots.
- Does an individual photon interfere only with other photons, or with itself?
- Can a single photon produce an interference pattern?



Two-Slit Interference Revisited

- The wave and particle descriptions are complementary: Depending on what phenomena we are studying, we will use either the wave description or the particle description.
- The square of the wave amplitude at a point in space just gives the probability that a photon will show up at that point.
- The photons (particles) appear randomly according to the probability distribution predicted by the wave nature.
- Summing over lots of photons, the wave pattern appears. (simulation)
- The probability is determined by the wave nature of light, but we nonetheless detect individual photons/particles!



Quantization of Light

- Field energy comes in lumps called "quanta".
- Modern lingo: "photons"
- The energy of each quantum is

$$E = h f$$

where

f = frequency of the field wave

h = Planck's constant

$= 6.6 \times 10^{-34}$ J/Hz

Quantization of Light

- Let's put in numbers for orange light:

  $\Delta E = h\,f = (6.6\times10^{-34}\ \text{J/Hz})\ (5\times10^{14}\ \text{Hz})$

  $= 3.3 \times 10^{-19}\ \text{J}$

  Small, but enough to excite an atom!

  - Chemical energy in a donut is about 10^{6} J
  - It contains about 10^{25} atoms
  - Or about 10^{-19} J per atom

Energy and Mass of Photons

From the photoemission experiment we know that the energy of the photon is Planck's constant times the frequency:

$$E = hf$$

So what is the relativistic mass of a photon? Remember $E = m_{rel}\, c^2$:

$$m_{rel} = \frac{E}{c^2} = \frac{hf}{c^2} > 0$$

What about the rest mass of a photon? $E = m_{rel}\, c^2$
$E = \gamma\, m_0\, c^2$. Apply to photons ($v = c$):

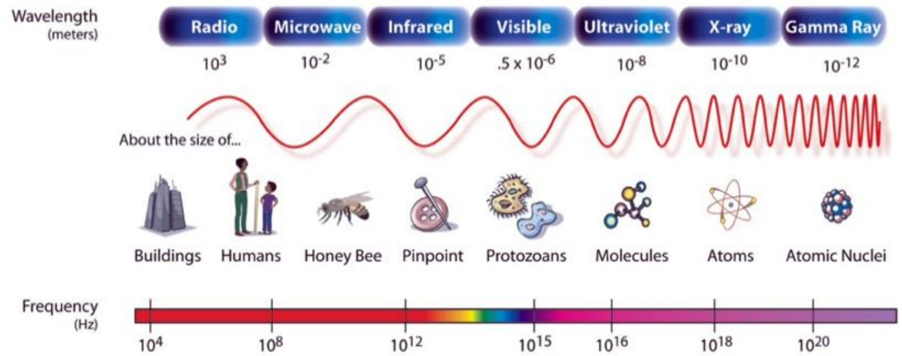
$$m_0 = \frac{E}{\gamma c^2} = \frac{E}{c^2}\sqrt{1 - \left(\frac{v}{c}\right)^2} = 0$$

The photon's "rest mass" being zero is consistent with the fact that photons cannot be brought to rest – they always travel at the speed of light!

Quantization of Light: Summary

- Light (and all EM waves) travel as waves, interfere as waves
- But are absorbed (and emitted) as "photons" having energy $E=hf$
- **Uncertainty:**
  - We cannot know where photon will hit
  - But likelihood is proportional to wave intensity!
- **Travels like a wave; interacts like a particle!**

$E = hf$



Clicker

Electromagnetic radiation made of yellow light, red light, and infrared radiation enters a camera and strikes the photographic film. Which of the three forms of radiation deposits the most energy per photon?

A) Yellow

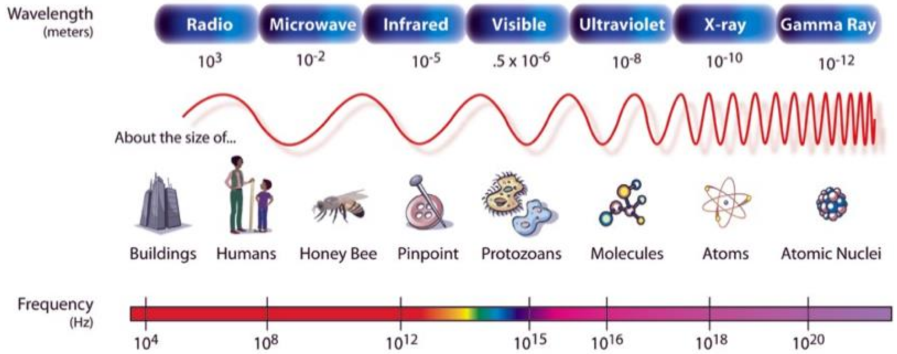
B) Red

C) Infrared

D) All deposit the same energy per photon

E) They don't deposit any energy

$E = h f$



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Yellow has the highest frequency and E=hf