Quantum and Atomic Physics

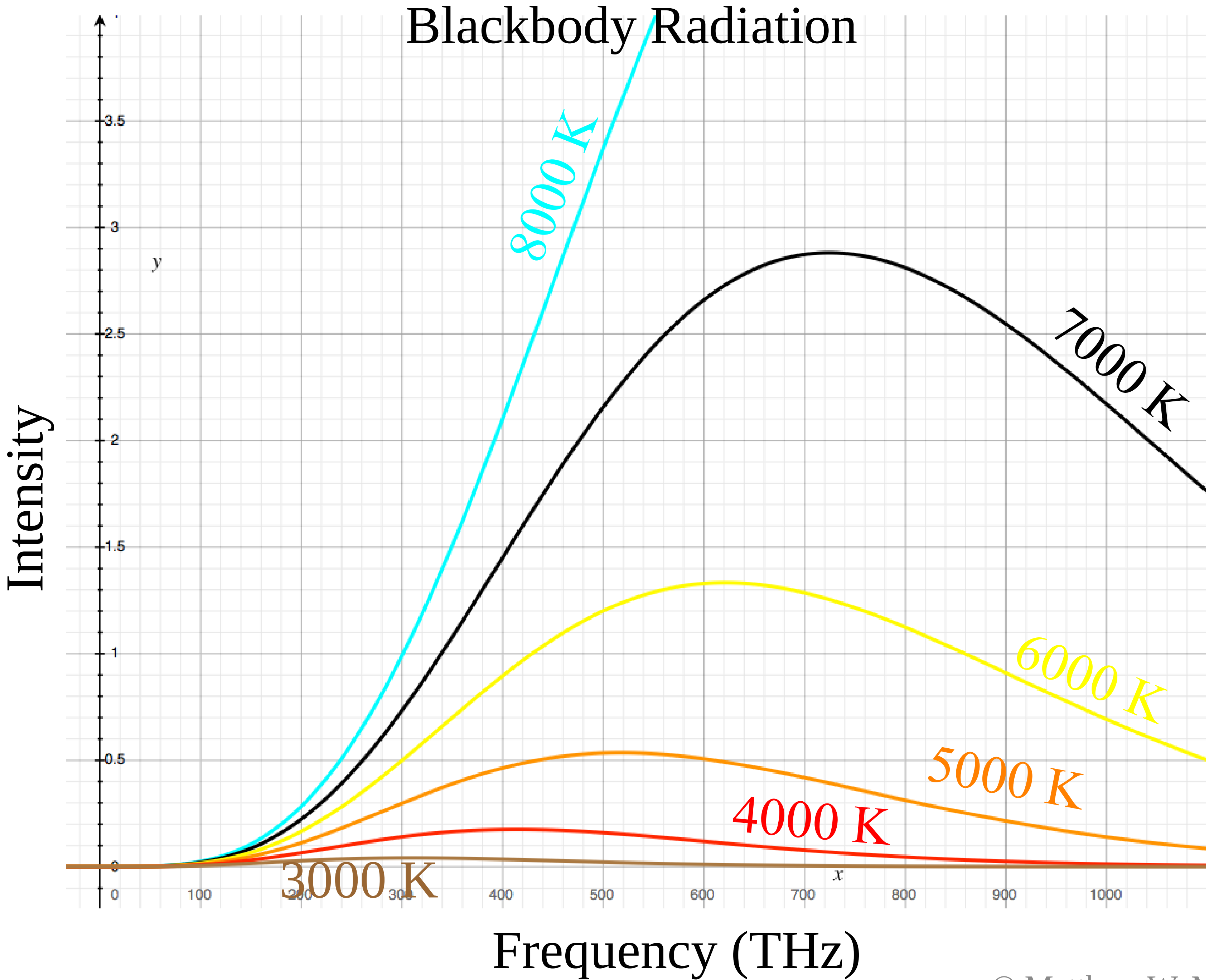
I. Wave/Particle Duality
- quantum energy, Planck's constant
- photons, photoelectric effect
- Bohr model, De Broglie wavelength
- electron diffraction, interference

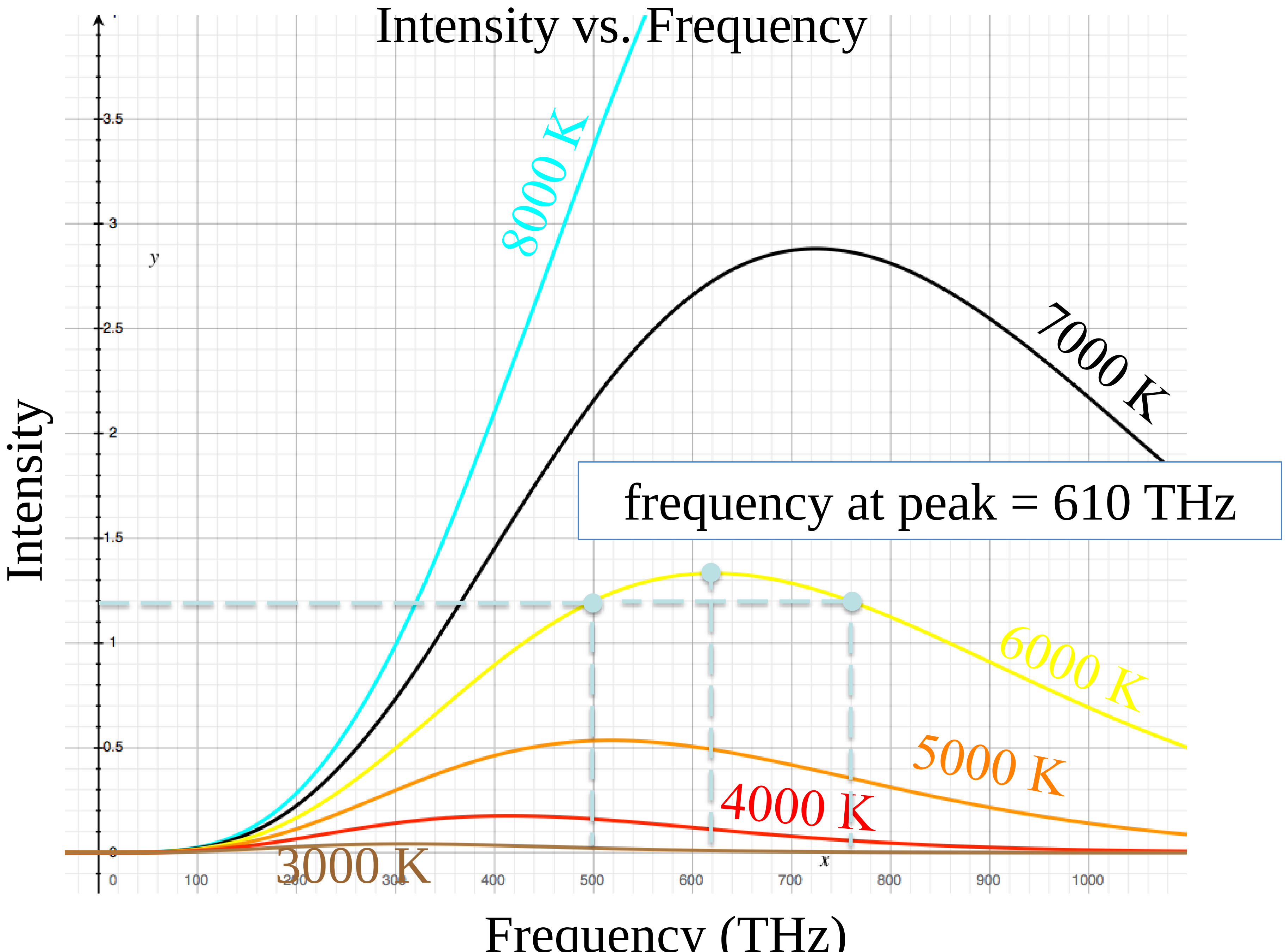
II. Special Relativity
- simultaneity, time dilation
- relativistic mass, momentum, and energy

III. Nuclear Physics
- nucleus structure, energy, strong force
- radiation/nuclear decay, weak force
- nuclear reactions

Particle Nature of Light

- Using classical physics laws of electricity and magnetism a comprehensive wave model of light was developed – light is a wave of electric and magnetic fields.
- Wave aspects of light are readily observed – for example diffraction and interference.
- However other aspects of light are not satisfactorily modeled by these ideas. In certain circumstances light exhibits characteristics more like those of particles.


Blackbody Radiation
Intensity
Frequency (THz)
8000 K
7000 K
6000 K
5000 K
4000 K
3000 K
y
x
0
0.5
1
1.5
2
2.5
3
3.5
0
100
200
300
400
500
600
700
800
900
1000



Intensity vs. Frequency
Intensity
Frequency (THz)
8000 K
7000 K
6000 K
5000 K
4000 K
3000 K
frequency at peak = 610 THz
y
x
3.5
3
2.5
2
1.5
1
0.5
0
0
100
200
300
400
500
600
700
800
900
1000
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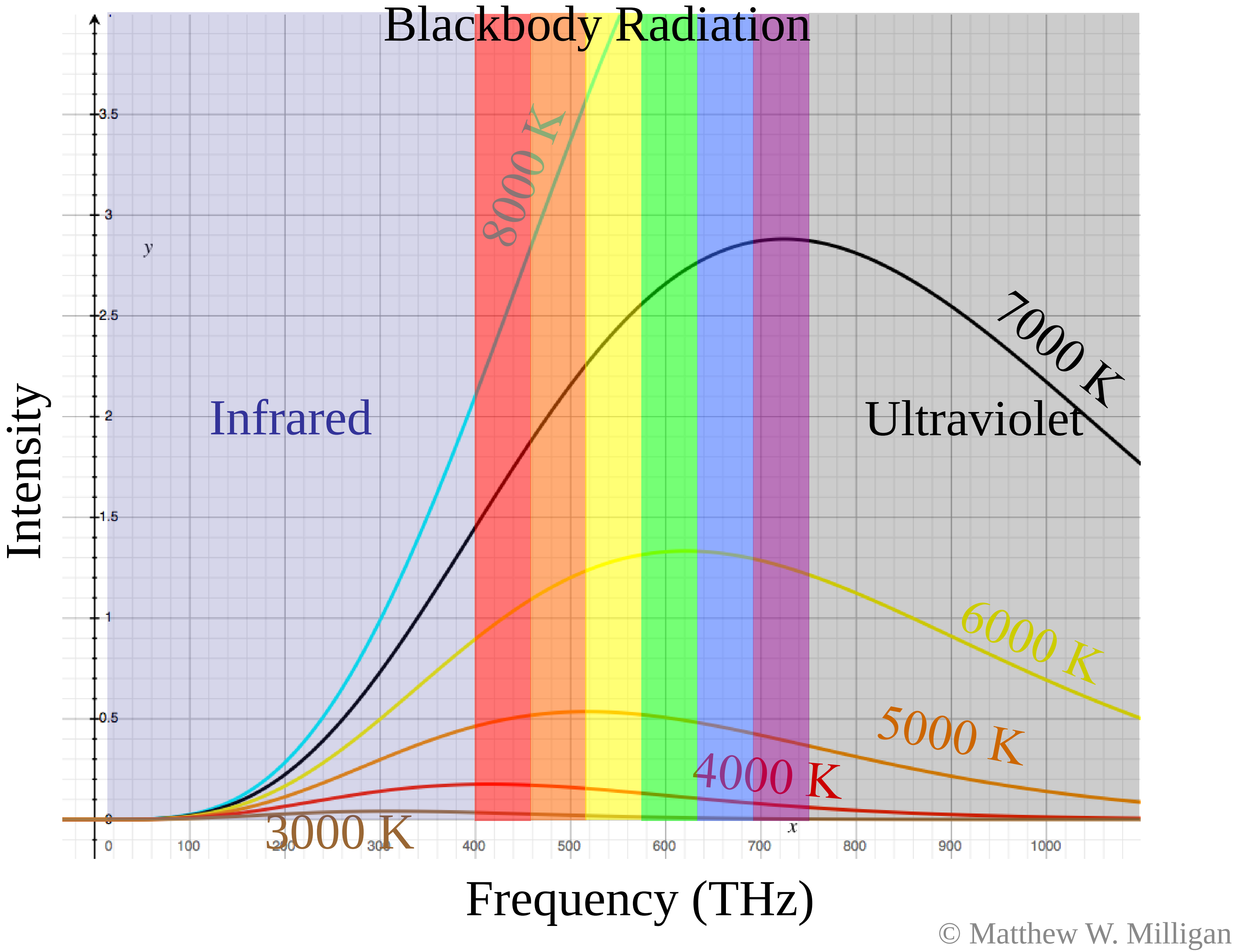

Blackbody Radiation
Intensity
Frequency (THz)
Infrared
Ultraviolet
8000 K
7000 K
6000 K
5000 K
4000 K
3000 K
y
x
3.5
3
2.5
2
1.5
1
0.5
0
0
100
200
300
400
500
600
700
800
900
1000
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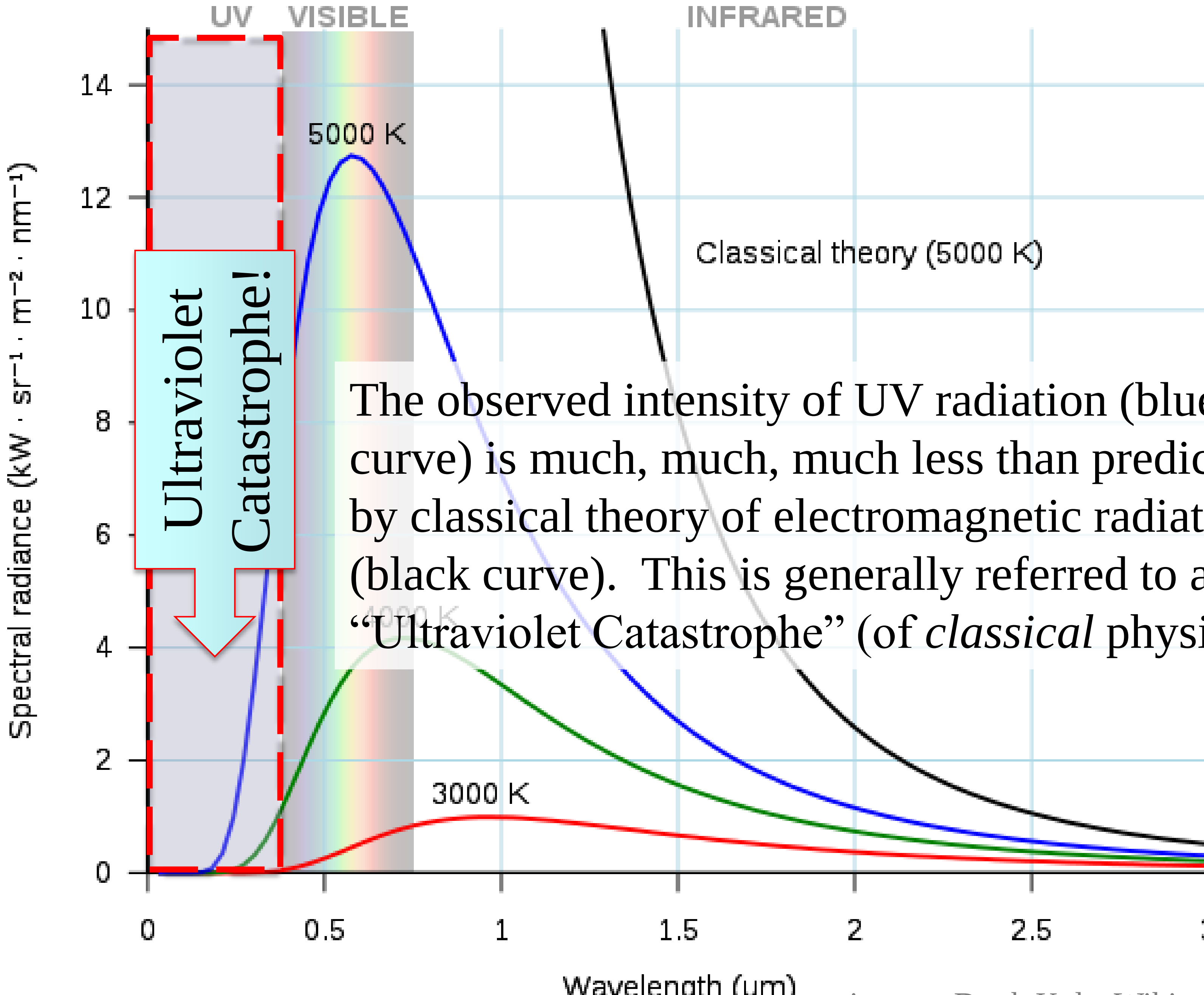

The observed intensity of UV radiation (blue curve) is much, much, much less than predicted by classical theory of electromagnetic radiation (black curve). This is generally referred to as the "Ultraviolet Catastrophe" (of *classical* physics).

image: Darth Kule, Wikipedia

Blackbody Radiation

- A blackbody curve shows intensity of radiation versus frequency for an object radiating heat at a certain temperature.
- Max Planck endeavored to understand and model this distribution of energy radiated by a substance and found a curious empirical result.
- In order to get a good match with observations he hypothesized that energy of vibrating molecules has a minimum value of $E_{min} = hf$.
- Furthermore, any greater energy of the atoms is an integer multiple of this: $E = nhf$.

Planck's constant: $h = 6.626 \times 10^{-34}\ \mathrm{J \cdot s}$

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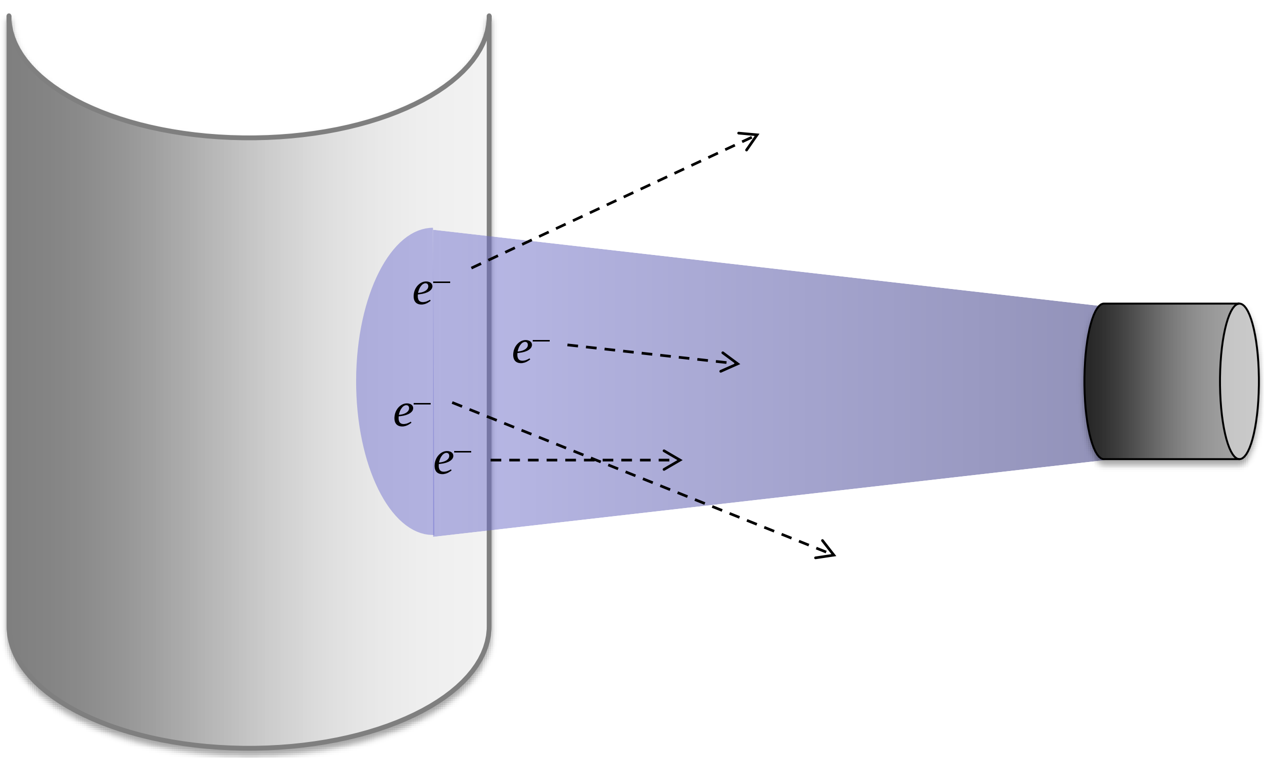


e^-
e^-
e^-
e^-

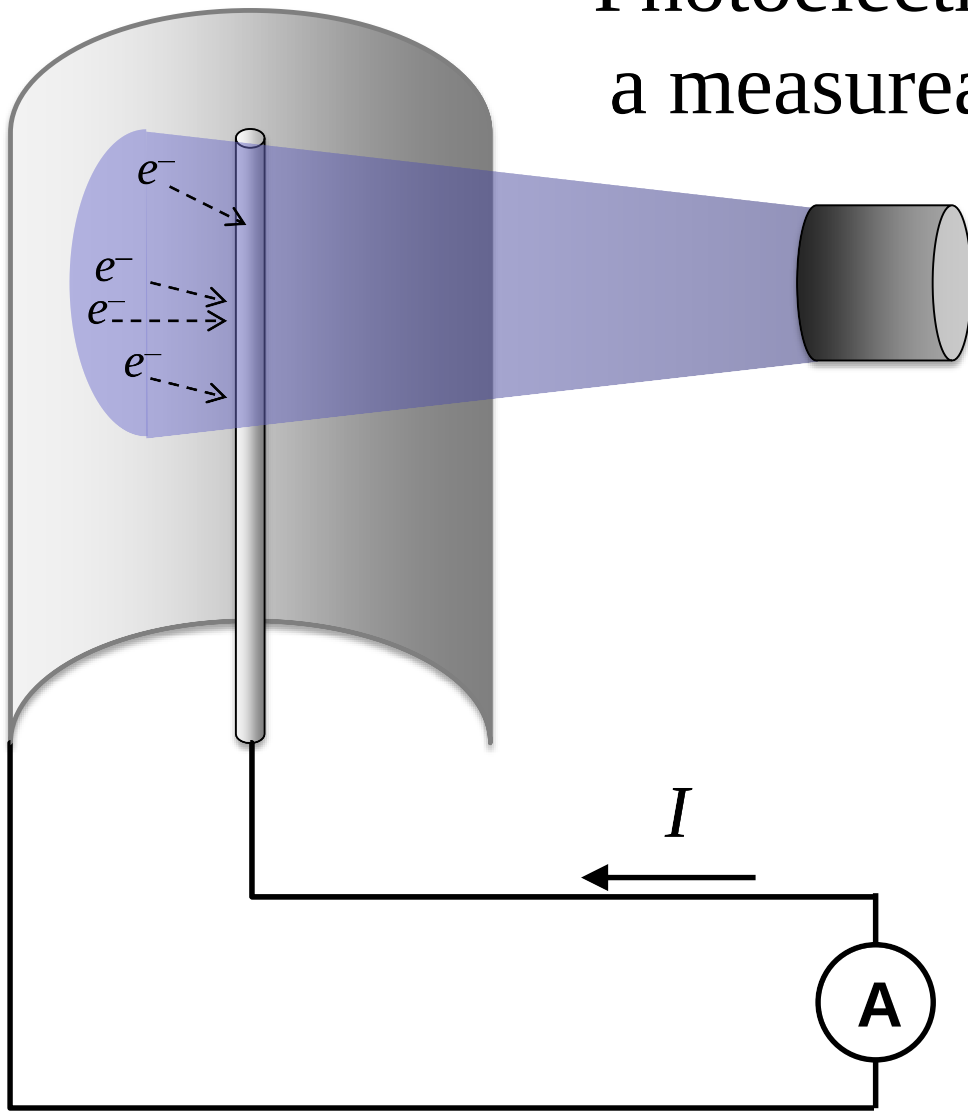
Photoelectric Effect

- Electron emission by an illuminated metal is called the photoelectric effect.
- In order to be liberated from the metal the electron must gain energy from light.
- Based on Planck's hypothesis, Einstein postulated that the energy of light itself occurs in discrete quantities given by $E = hf$.
- Einstein suggested the photoelectric effect could provide evidence to support this idea and it was confirmed in experiments conducted by Millikan (the oil drop guy!).

Photocells

image: Grinevitski, Wikipedia

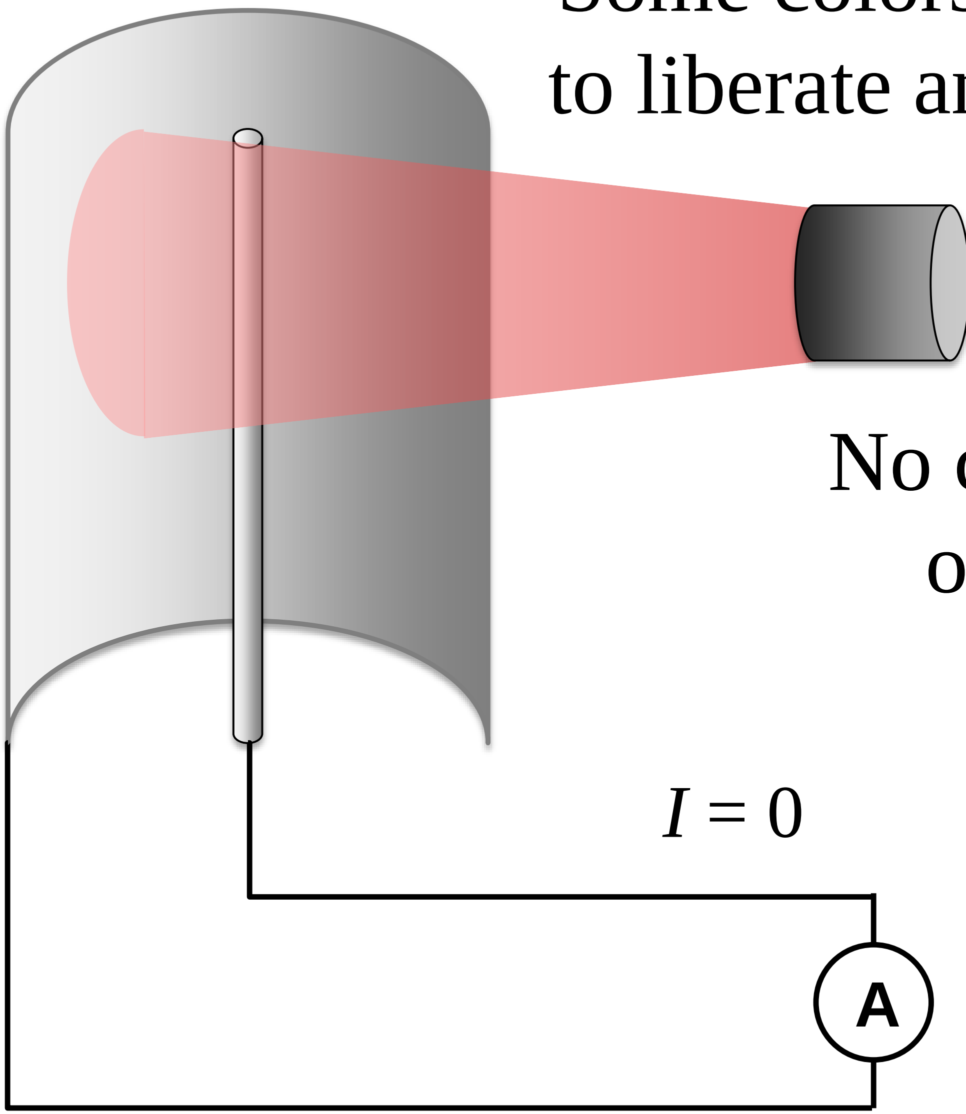
Photoelectrons produce
a measureable current.



Greater intensity
of light results in
greater current.

A brighter light
of this color
produces more
amperes current.

Some colors of light fail to liberate any electrons!

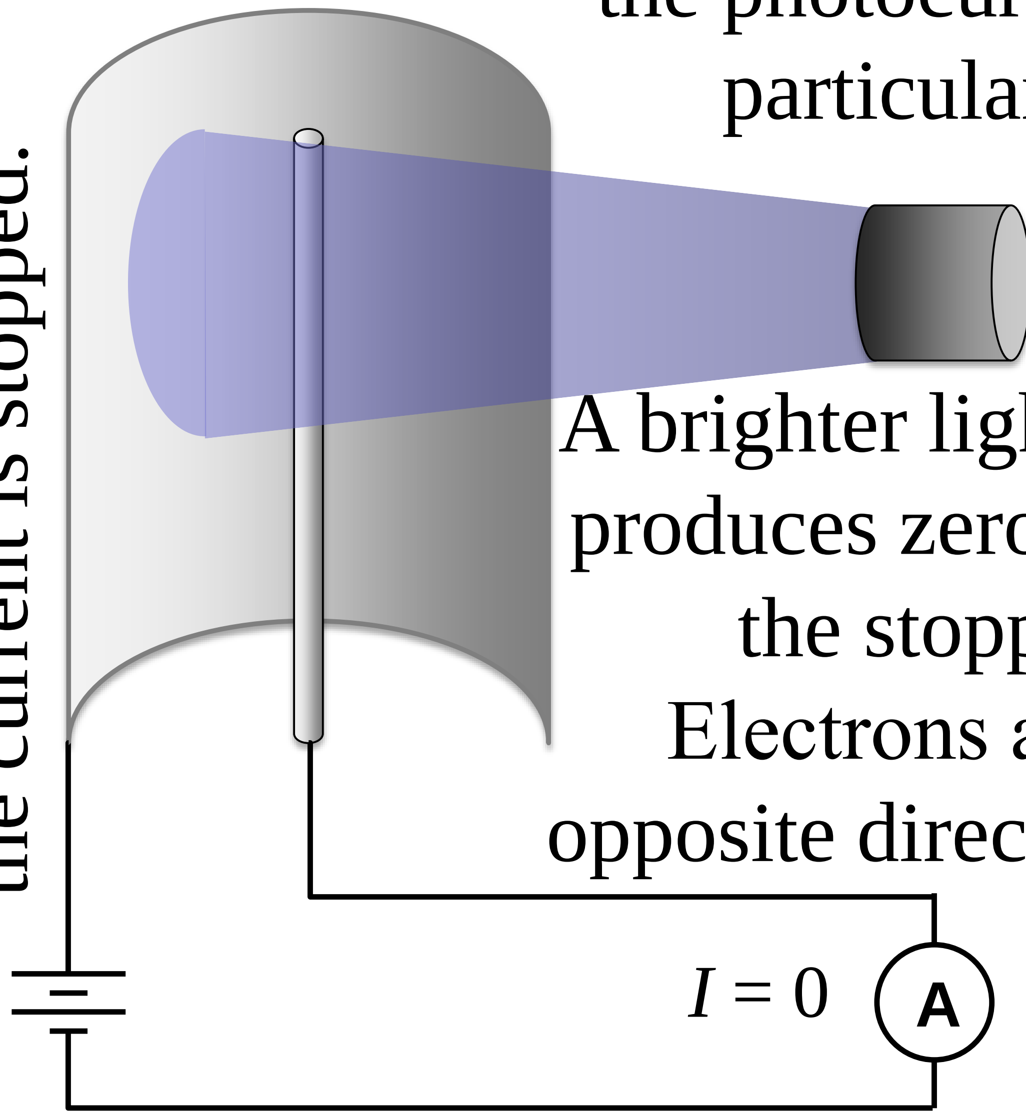


No current regardless of the intensity!

A brighter light of *this* color still produces zero current.

A voltage source can oppose the photocurrent produced by a particular color of light.

Given enough voltage the current is stopped.



A brighter light of this color still produces zero current as long as the stopping voltage exists. Electrons are "pushed" in the opposite direction by the battery.

Photoelectric Effect Experiment

The maximum kinetic energy of photoelectrons is a function of the frequency of the incident light and a the minimum work necessary to cause emission:

$$K_{max} = hf - f$$

where: K = kinetic energy

h = Planck's constant

f = frequency of light

ϕ = work function

$$h = 6.626´\ 10^{-34}\ \text{J} \times \text{s}$$

Work function and Stopping potential

Light at a certain threshold frequency is necessary to cause any photoemission and this can be related to the work function and stopping potential:

$$eV_s = hf - f$$

$$f = hf_{\min}$$

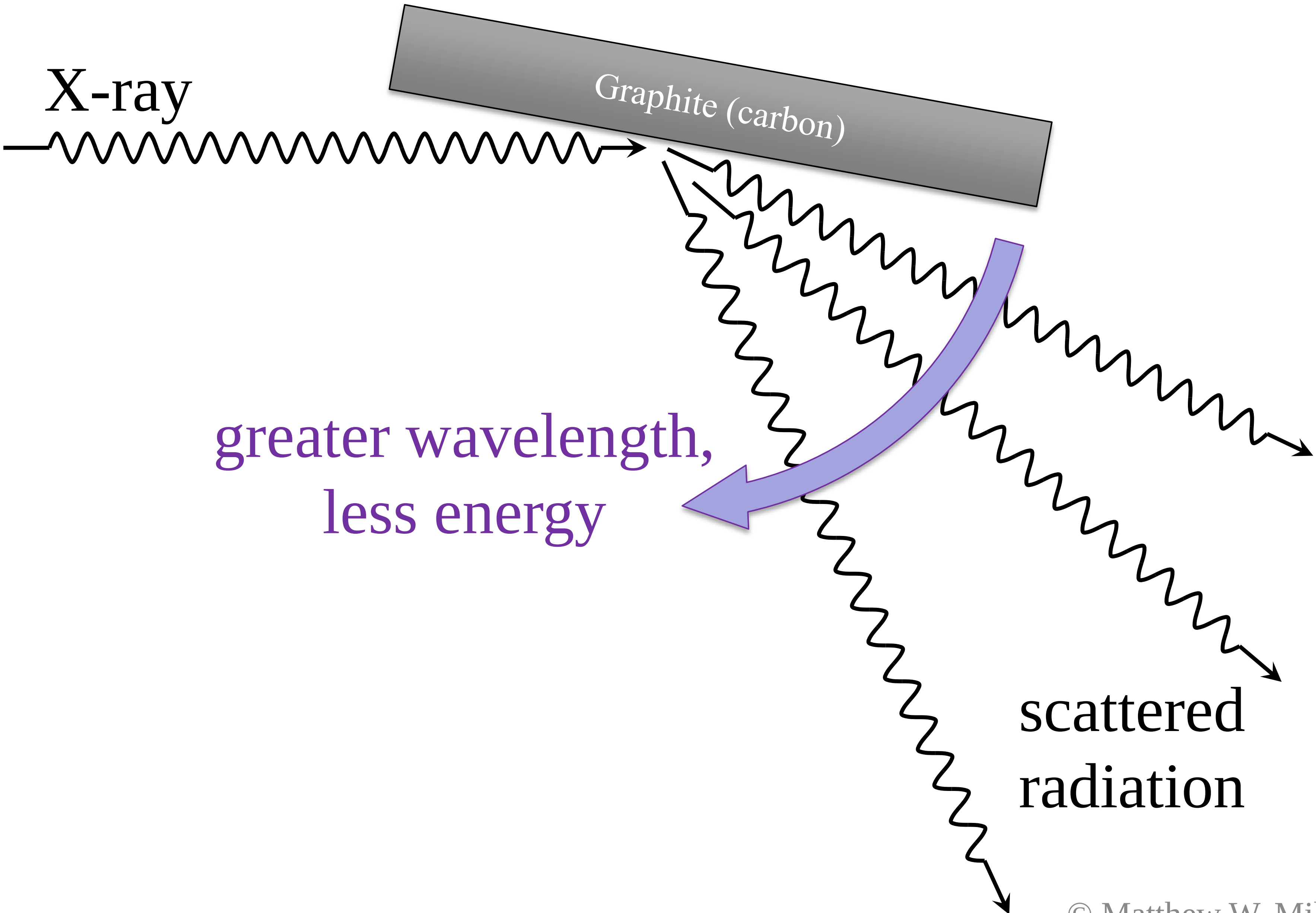
where: V_S = stopping potential

h = Planck's constant

$f_{\min}$ = threshold frequency of light

ϕ = work function

$$h = 6.626´\ 10^{-34}\ \mathrm{J} \times \mathrm{s}$$


X-ray
Graphite (carbon)
greater wavelength,
less energy
scattered
radiation

Compton Scattering

The wavelength of the scattered radiation relates to the incident wave and the angle of deflection:

$$/' = / + \frac{h}{m_0 c}\left(1 - \cos f\right)$$

where: λ = wavelength

h = Planck's constant

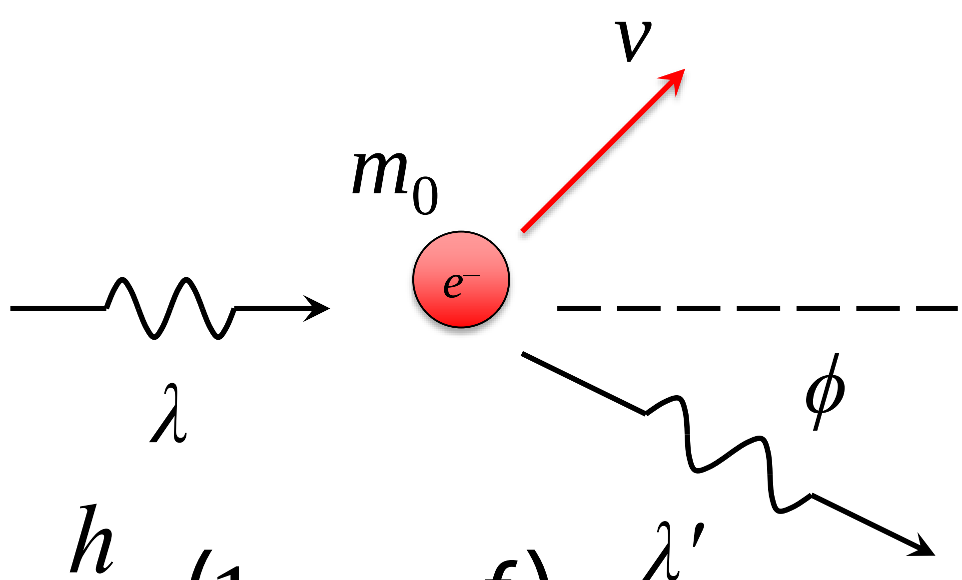
m_0 = electron mass

c = speed of light

ϕ = scattering angle

Note: this mathematical relation is *not* a tested topic for AP Physics 2.

Compton scattering can be modeled as an elastic collision between particles. The X-rays have energy *hf*.



$$\lambda' = \lambda + \frac{h}{m_0 c}\left(1 - \cos\phi\right)$$

In order for momentum to be conserved the radiation has momentum given by:

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

Photon Momentum

In certain scenarios photons are observed to have a force interaction with matter. When this occurs the photon's equivalent momentum is given by:

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

$$p = \frac{hf}{c} = \frac{E}{c}$$

where: h = Planck's constant
λ = wavelength
f = frequency
c = speed of light
E = energy per photon

Particles of Light?

- Although light can be clearly demonstrated to behave as a wave, certain experiments show it to be like a stream of particles.
- These "particles of light" are called **photons**. A photon may be thought of as a "wave packet" or a tiny burst of wave energy.
- The energy of a photon is proportional to its frequency. Higher frequency = more energy per photon.

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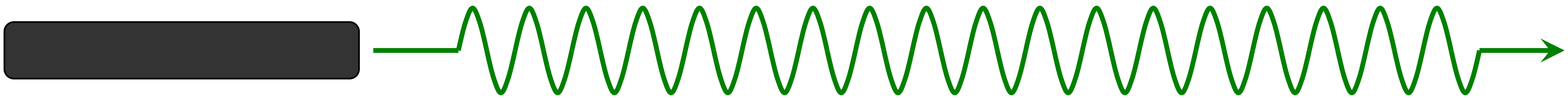
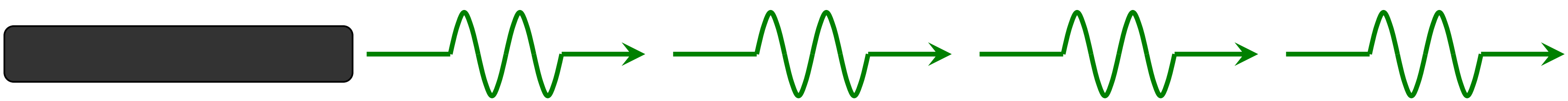
Visualizing Photons…

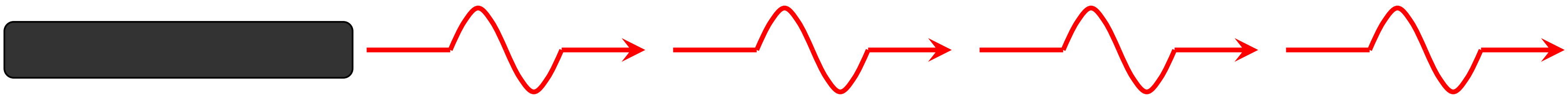


Instead of a *continuous* wave pattern in the beam of a laser pointer…

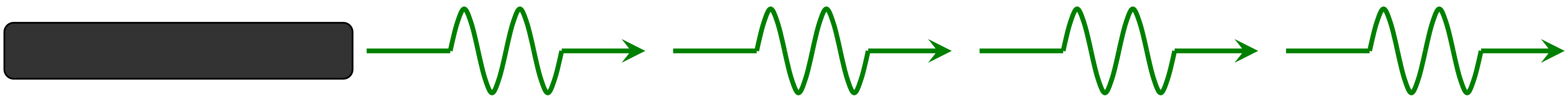


…imagine a series of "wave bursts" or *photons*, each of which has a particular frequency, wavelength, momentum, and energy.

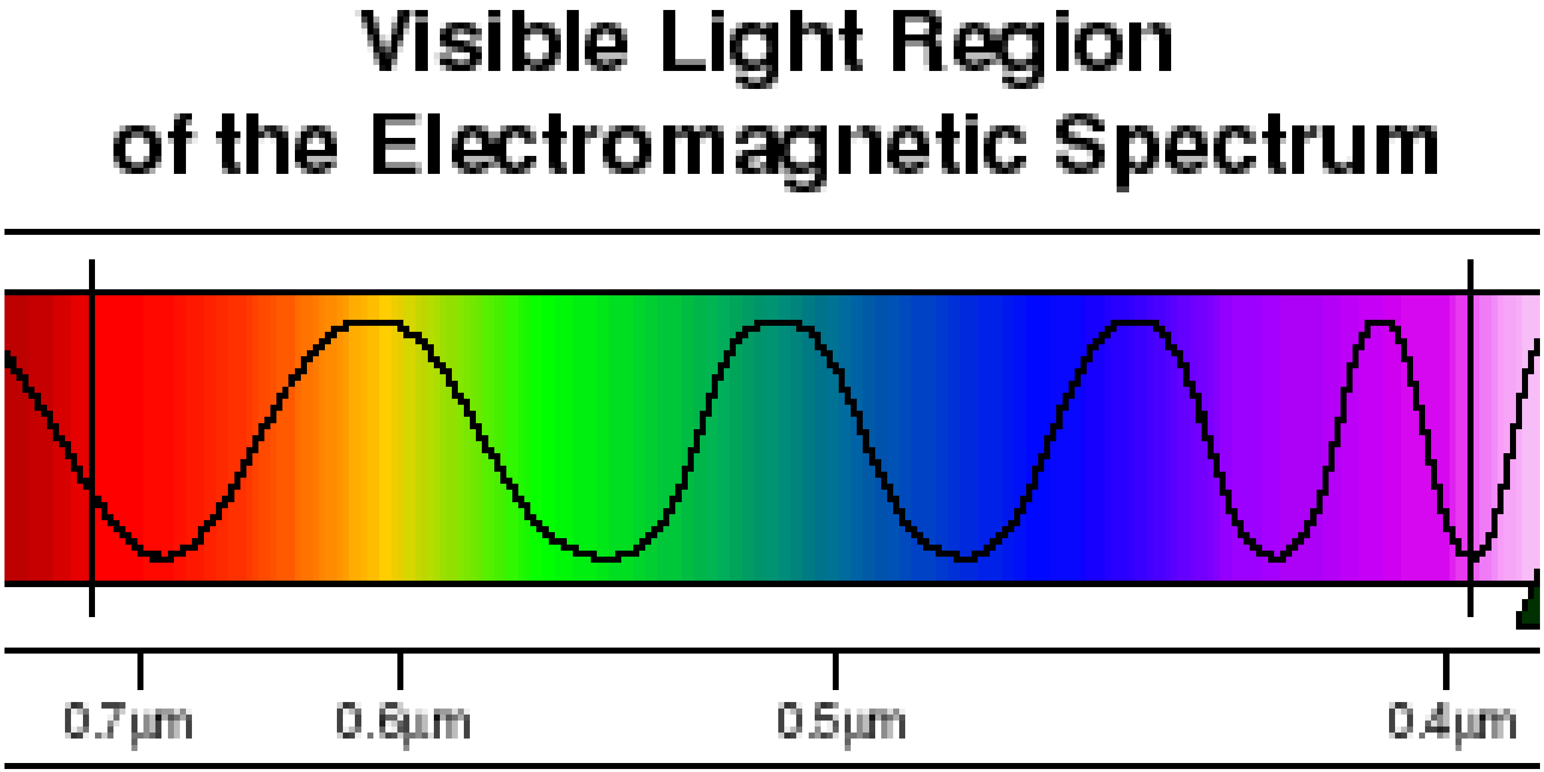
Visualizing Photons…



The red laser pointer's photons each have longer wavelength, lower frequency, less momentum, and lower energy…



…than the green laser pointer's photons, each of which have shorter wavelength, higher frequency, greater momentum, and greater energy.



increasing frequency

increasing energy per photon

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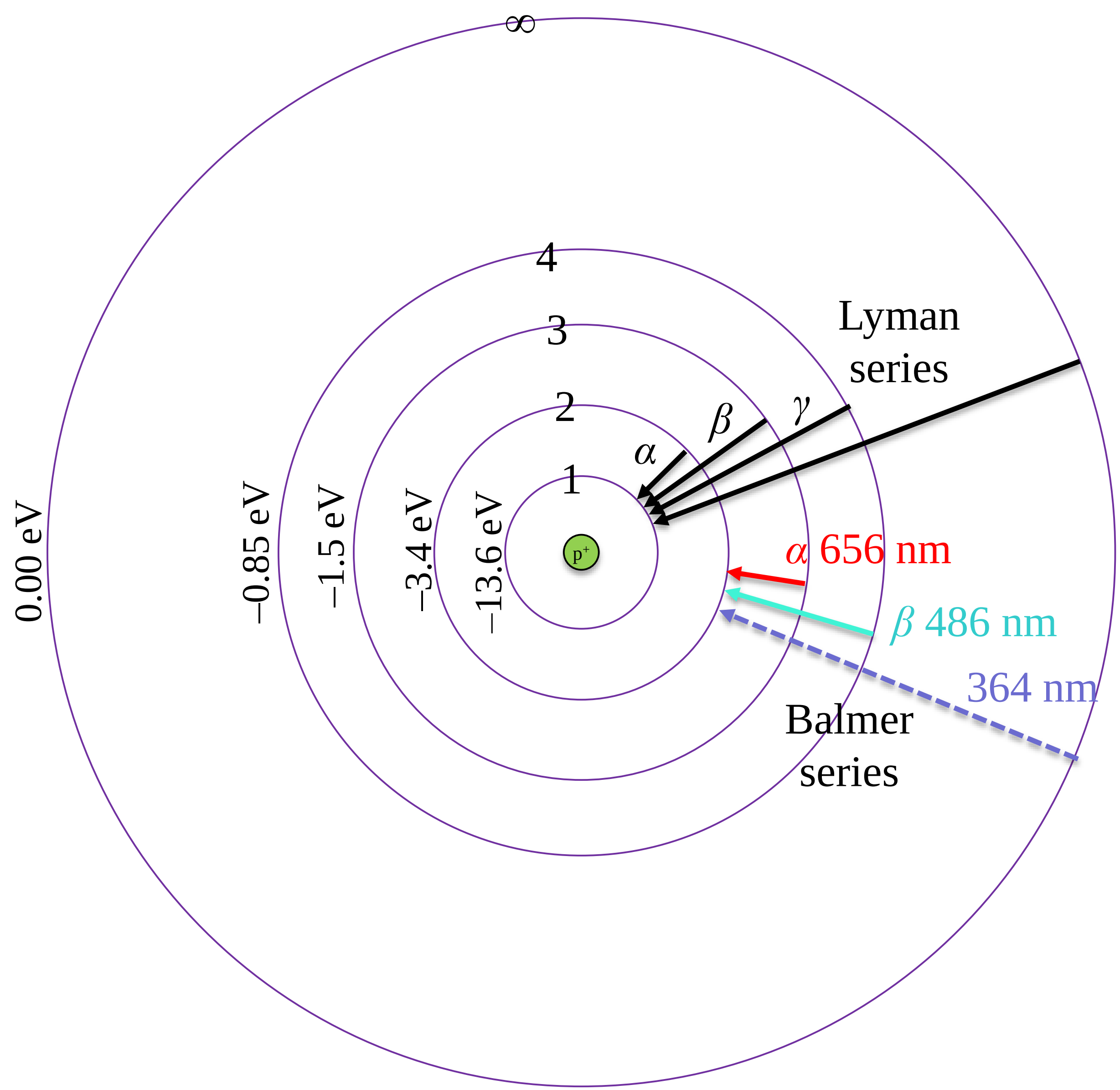
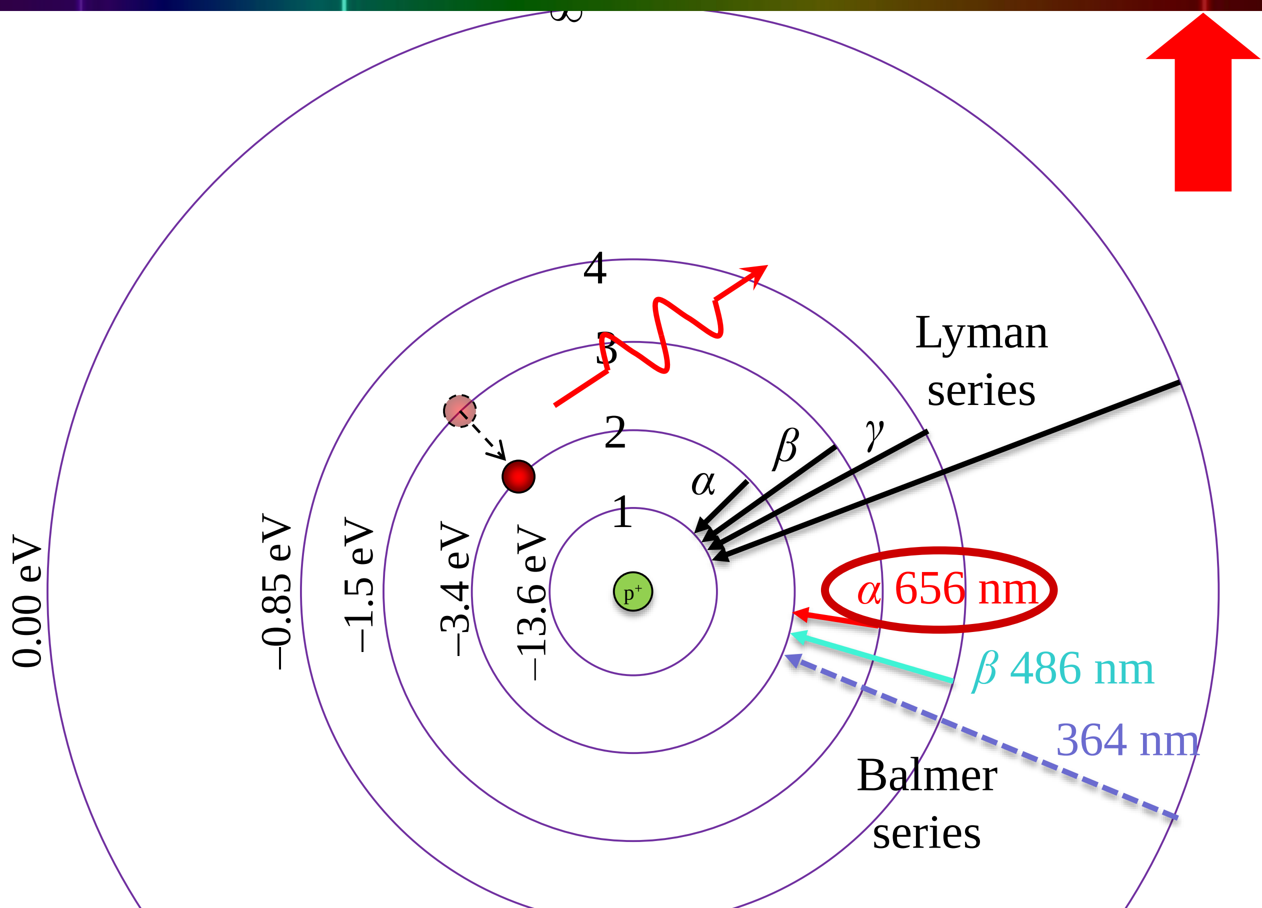
Bohr Model

- The emission spectra of elements are unique energy signatures. Niels Bohr developed a model to understand these lines.
- Because each unique color and wavelength is a photon with a particular energy, he hypothesized that the angular momentum of orbiting electrons is quantized.
- This one assumption combined with classical physics results in a highly accurate numerical model for hydrogen or other atoms with a single electron (but not multiple electrons).

Bohr Model of Hydrogen



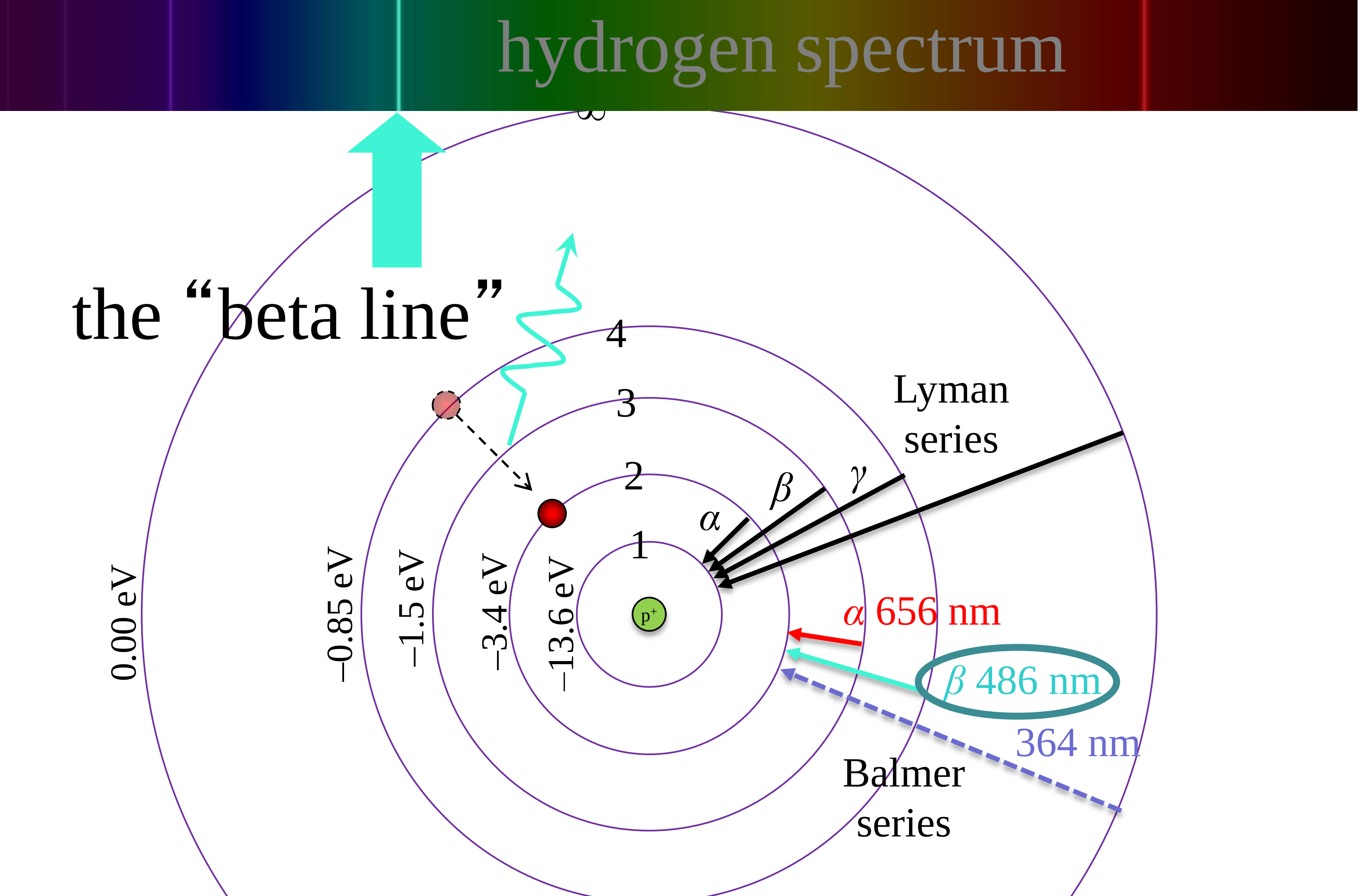
hydrogen spectrum



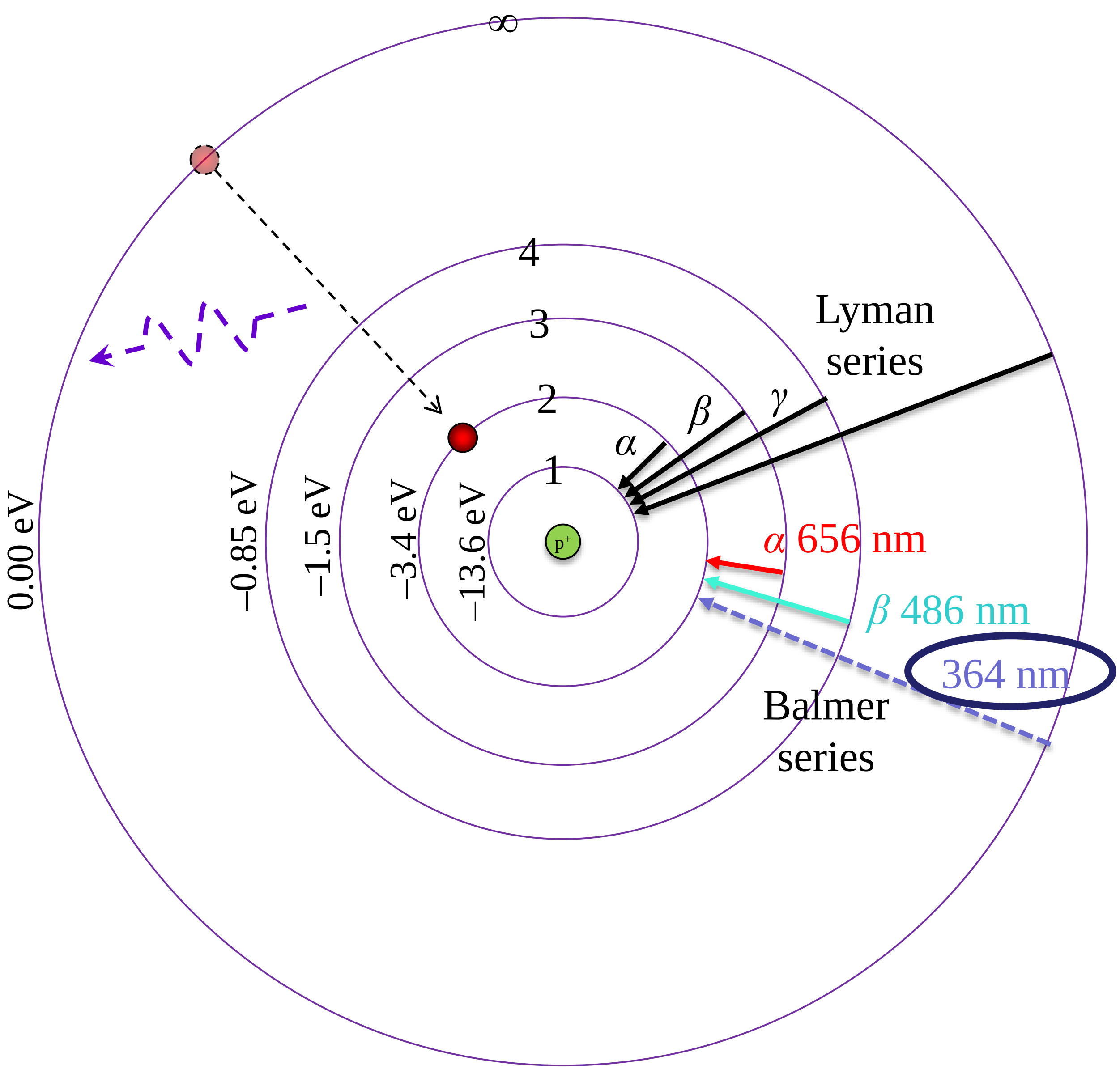
the "hydrogen alpha line"

An electron dropping to a lower orbital loses energy that becomes an emitted photon of a particular frequency and wavelength.

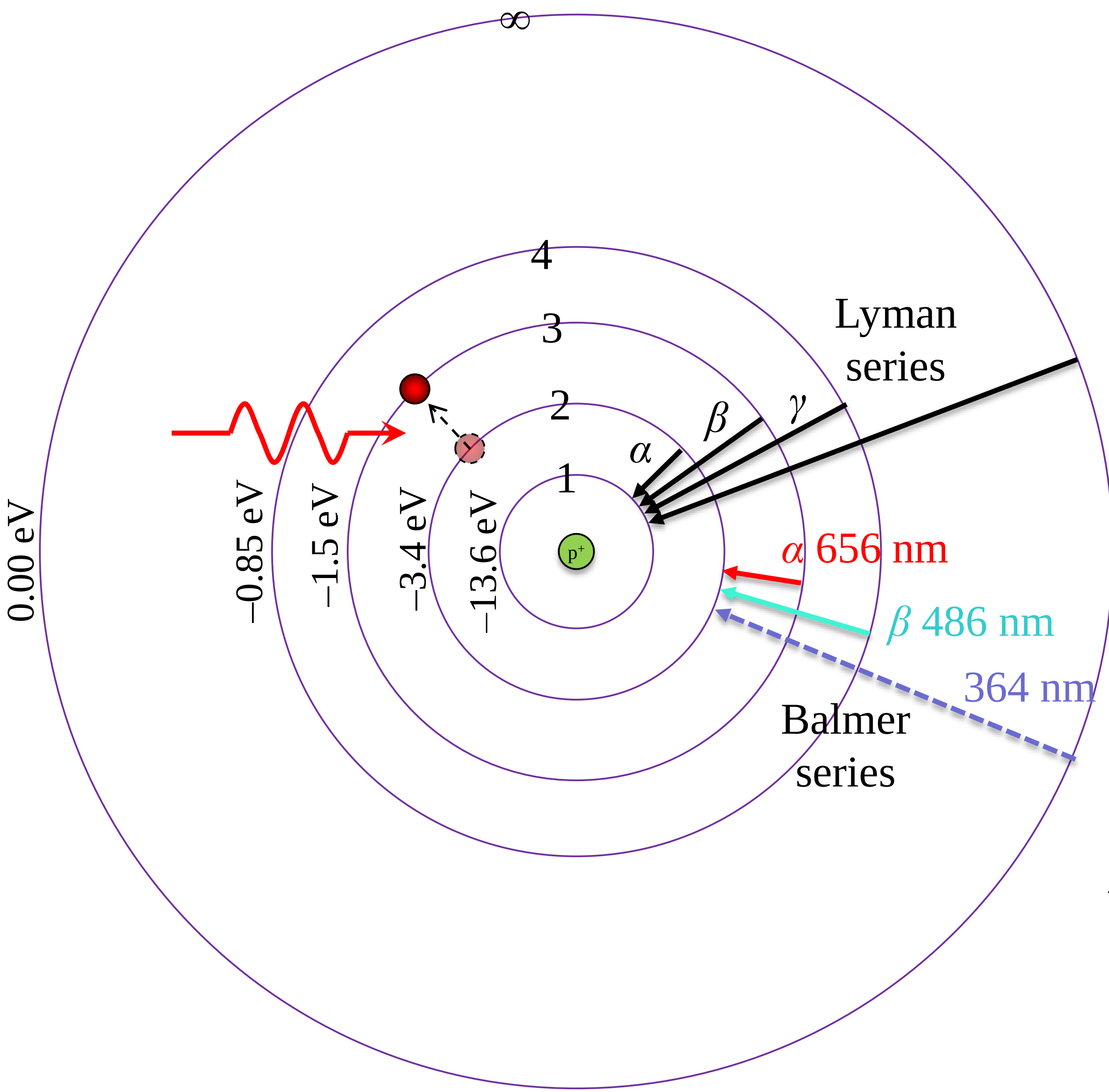
hydrogen spectrum



A greater drop in orbital energy results in an emitted photon with greater frequency and shorter wavelength.

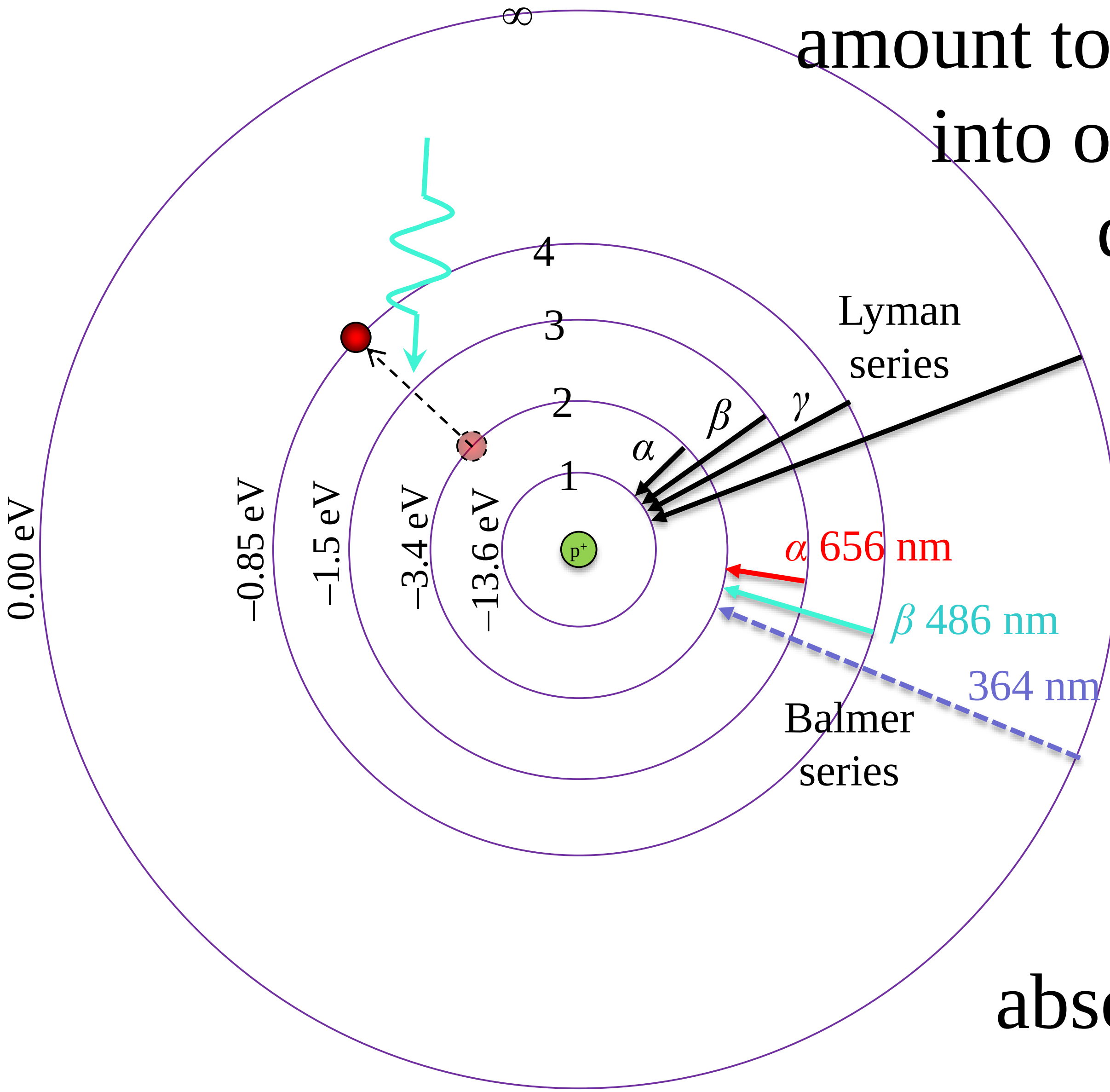


This line is ultraviolet.



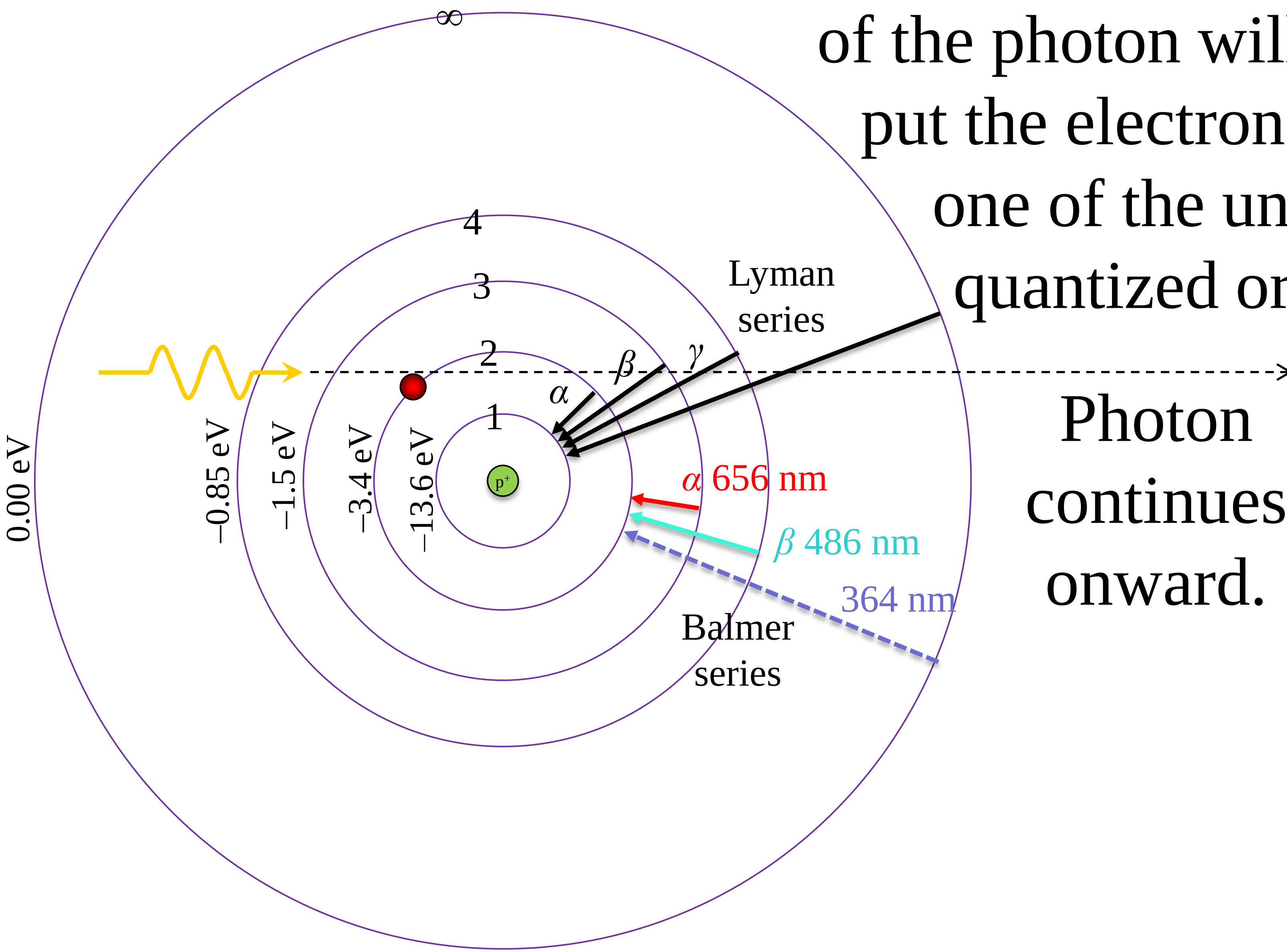
The reverse of photon emission is photon absorption. Energy of the photon goes to the electron and boosts its orbit.

Energy of the photon is the precise amount to put the electron into one of the unique quantized orbits.



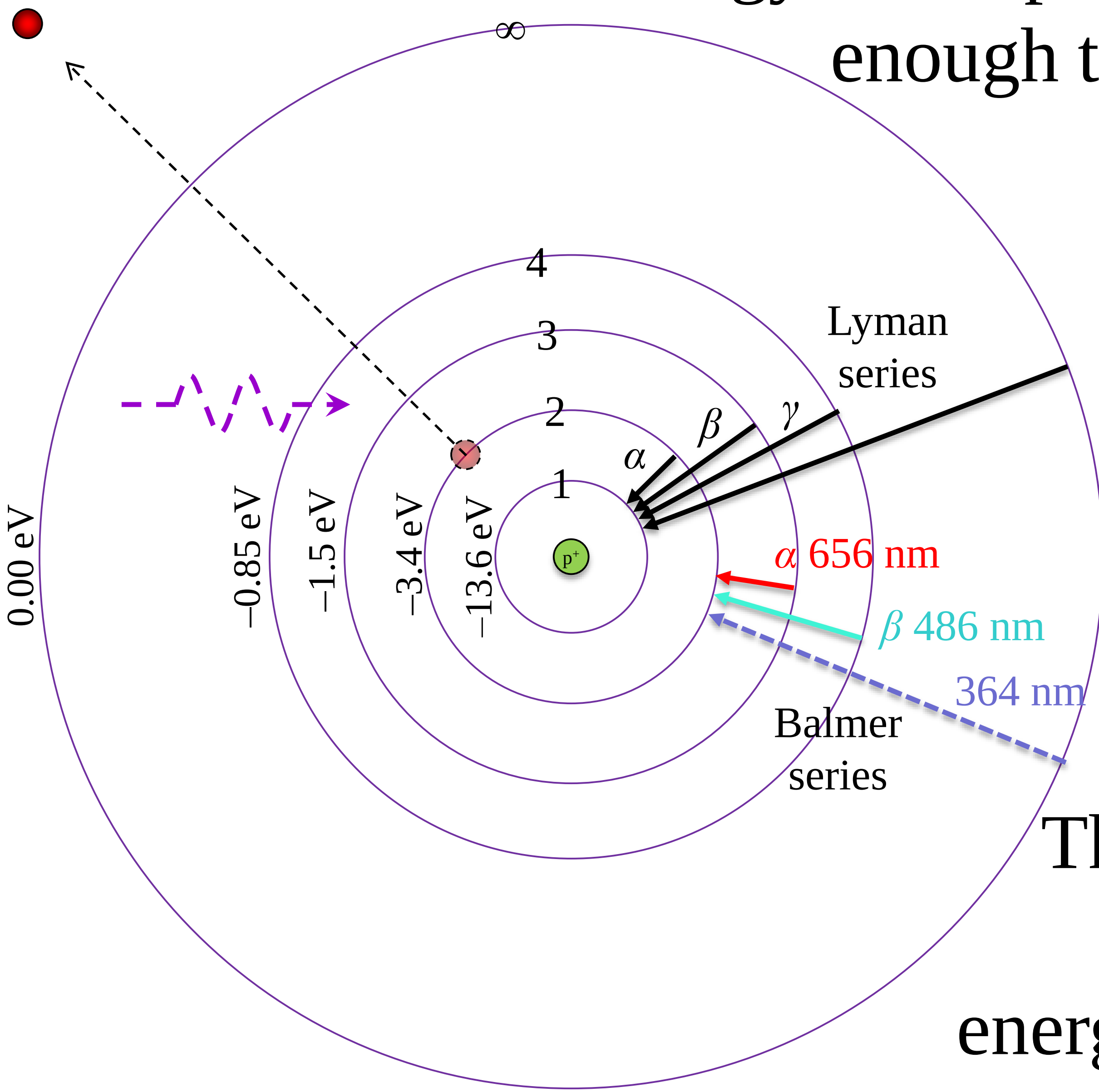
This is a requirement for absorption to occur.

No absorption occurs if energy of the photon will not put the electron into one of the unique quantized orbits.

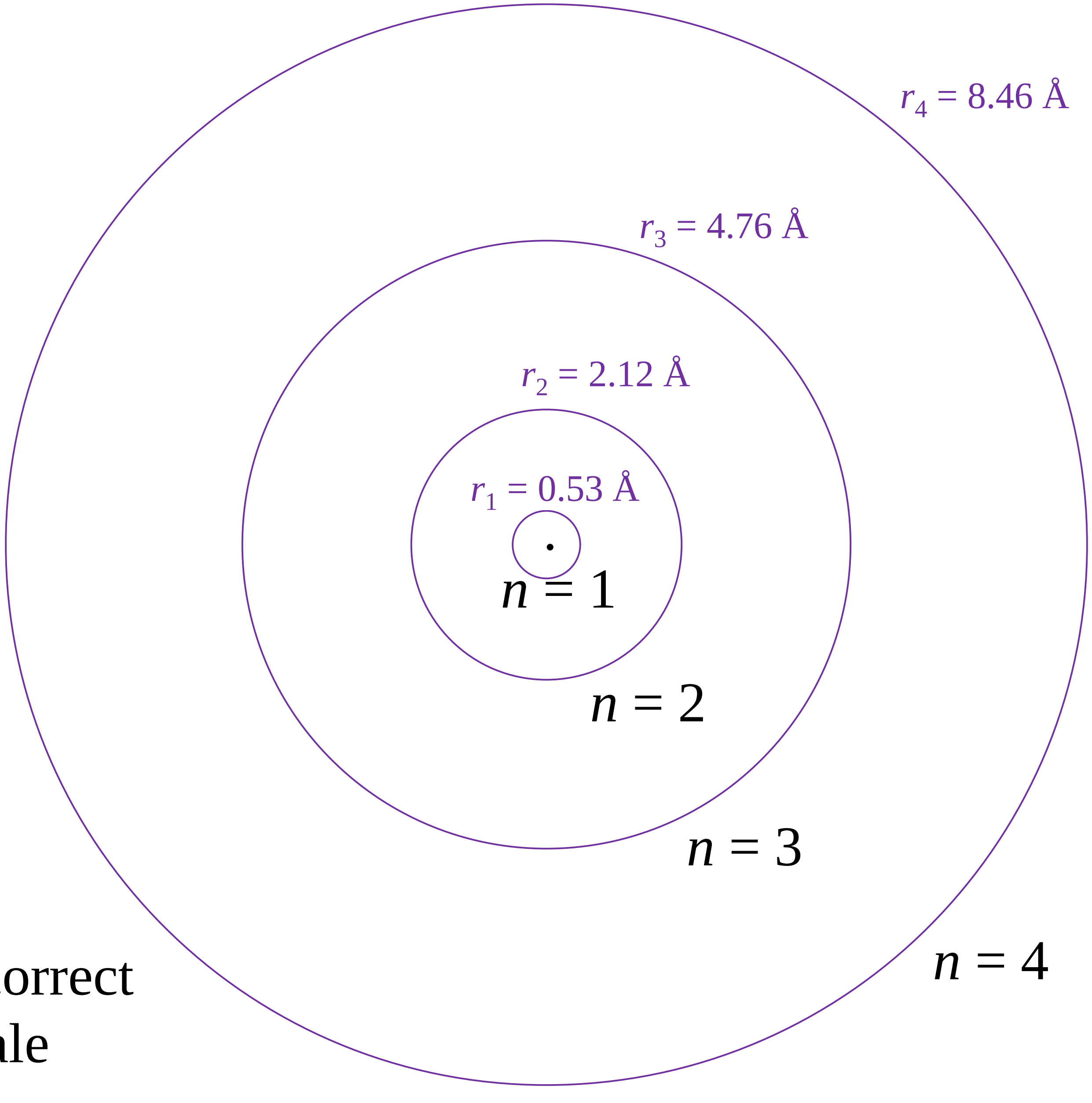


Photon continues onward.

Energy of the photon is the great enough to move electron past the highest possible orbit.

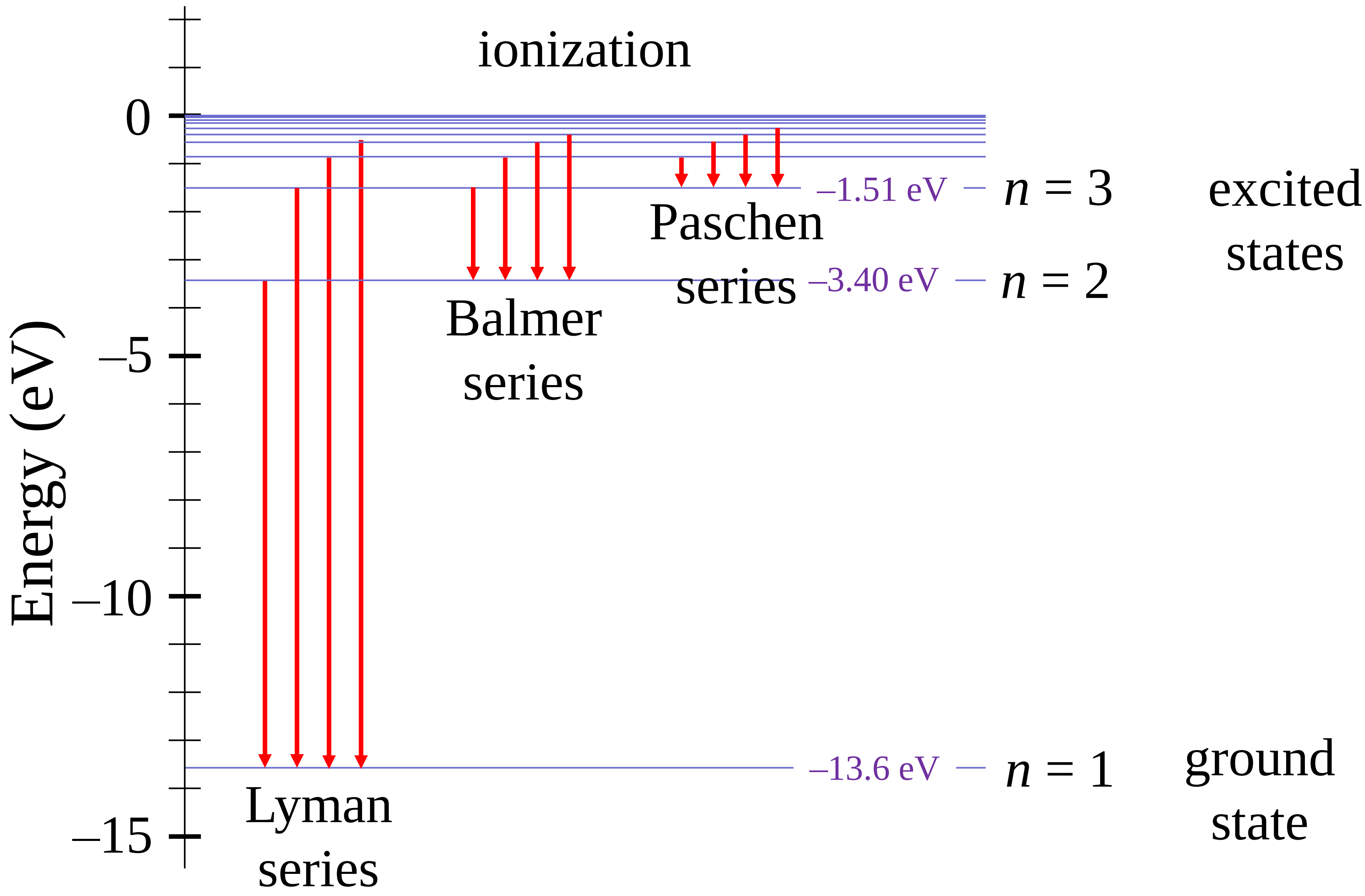


This is ionization. Any “leftover” energy of the photon becomes kinetic energy of the electron.



orbitals correct
to scale

Hydrogen Energy Levels



Bohr Model Details

Angular momentum, radius, and total energy of an electron orbiting a hydrogen nucleus:

$$L_n = n\frac{h}{2p}$$

$$r_n = n^2 r_1$$

$$E_n = \frac{E_1}{n^2}$$

where: L = angular momentum ($L = rmv$)

n = principle quantum number (1, 2, 3…)

h = Planck's constant

r = orbital radius (r_1 = 0.53 Å "Bohr radius")

E = energy (E_1 = –13.6 eV "ground state")

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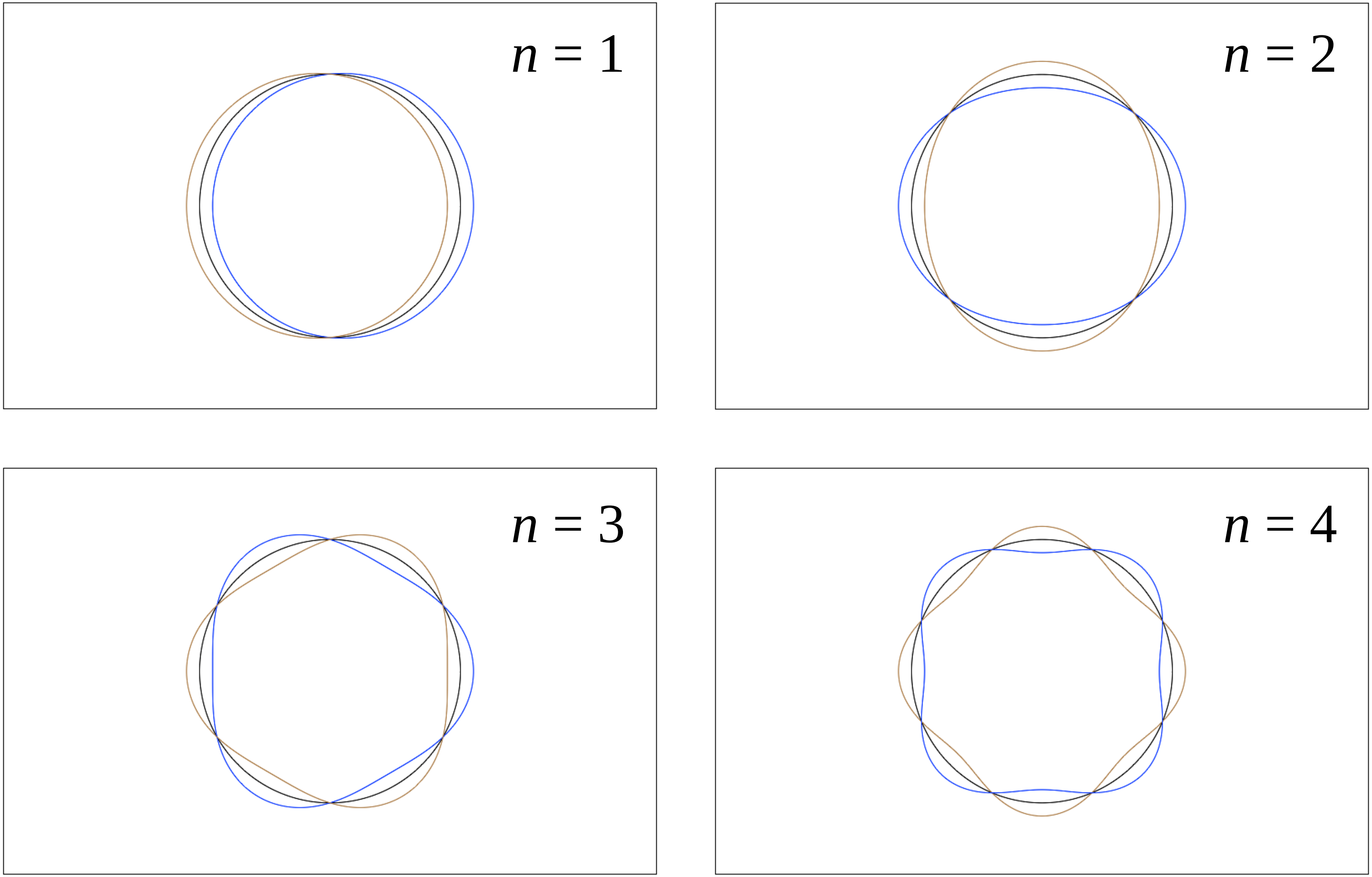
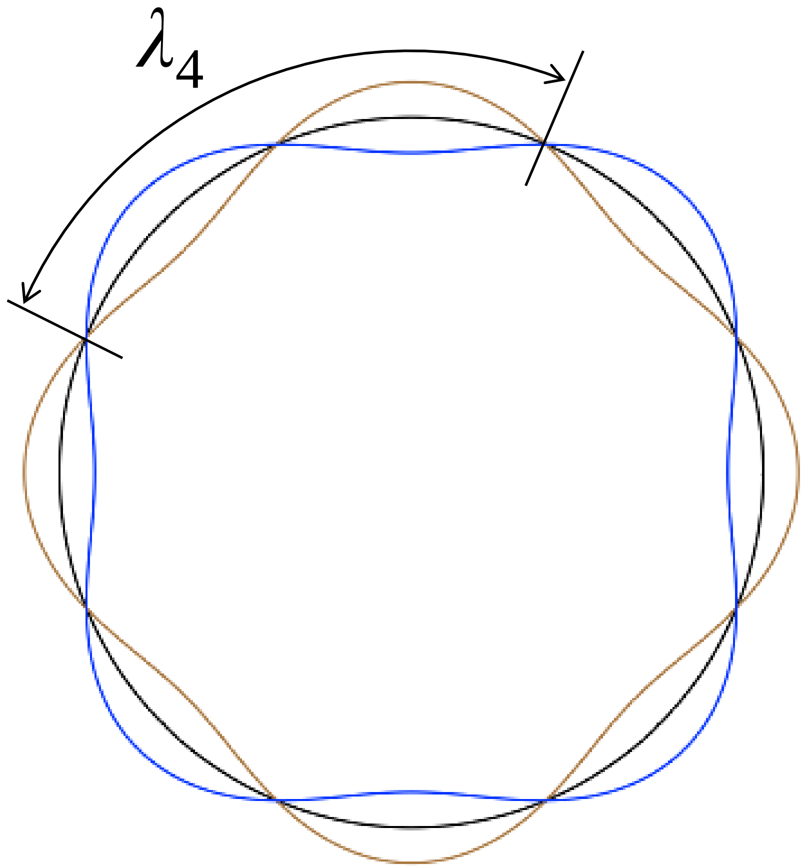
De Broglie Wavelength

- Louis De Broglie suggested that if a wave can act like a particle then a particle can act like a wave.
- If electrons can have wave-like characteristics the unique orbitals can be viewed as standing wave patterns similar to harmonics.
- The circumference of the orbit must be a multiple of the electron's wavelength in this view.
- Electrons can exhibit other wave phenomena such as diffraction and interference.

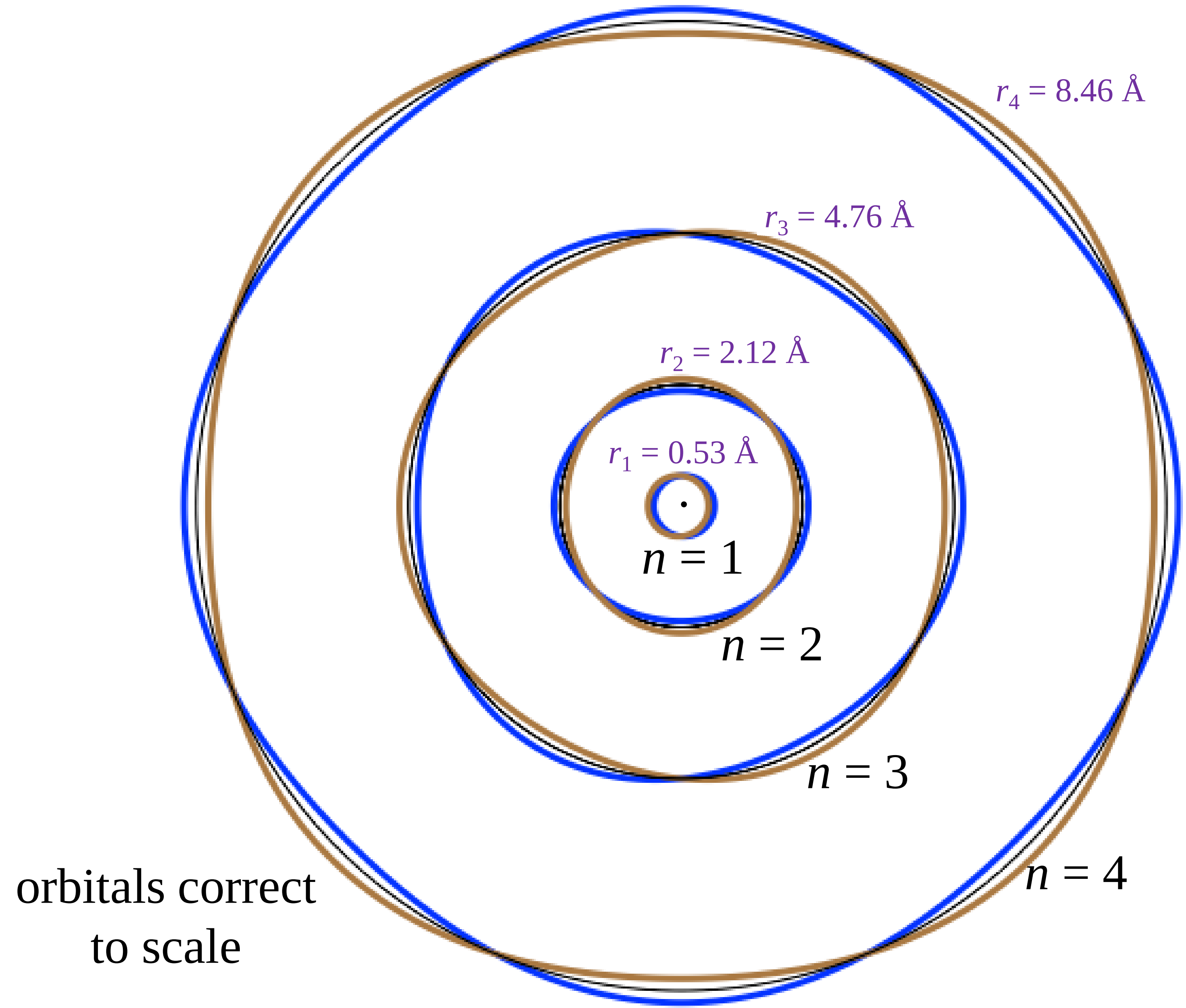


n = 1
n = 2
n = 3
n = 4



$n = 4$

The circumference of any orbital is an integer multiple of the electron's wavelength. For $n = 4$ the circumference is precisely 4 wavelengths.


r_4 = 8.46 Å
r_3 = 4.76 Å
r_2 = 2.12 Å
r_1 = 0.53 Å
n = 1
n = 2
n = 3
n = 4
orbitals correct
to scale

De Broglie Wavelength

A particle can exhibit wave-like characteristics and phenomena with a wavelength given by:

$$/ = \frac{h}{mv}$$

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

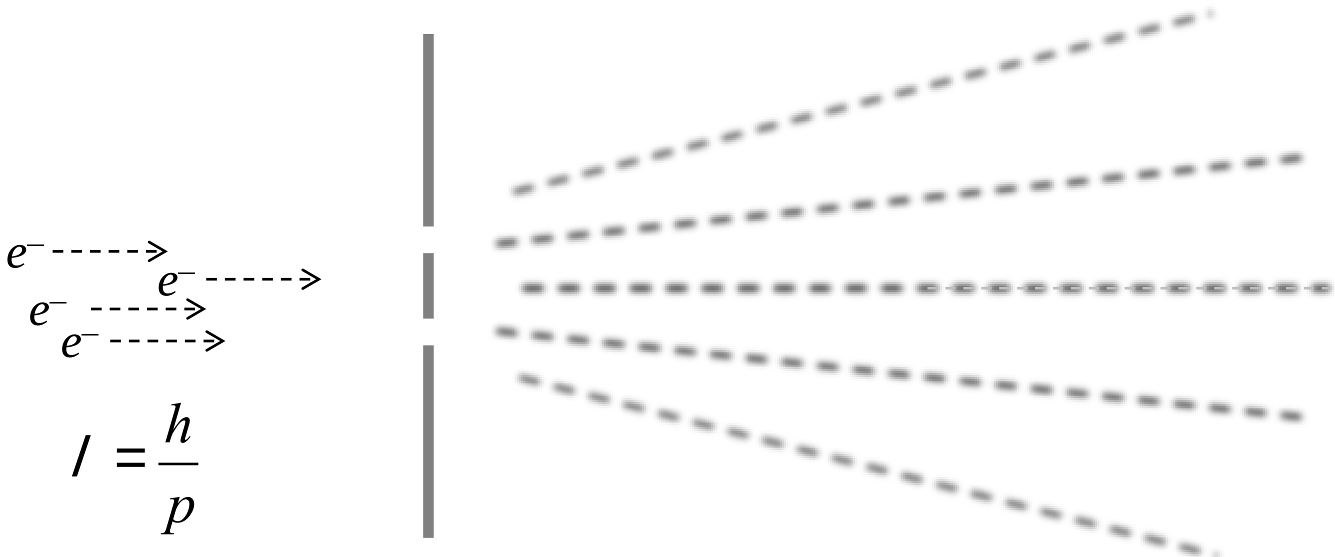
where: λ = wavelength

m = mass

v = speed

p = momentum

electron diffraction and interference



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

$$\sin \theta_n = \frac{n\lambda}{d}$$

Electrons fired through a pair of slits undergo interference just as expected for a wave. If electrons are fired *one at a time* the net result is the same – as if each single electron somehow passes through *both* slits and interferes with itself. In this situation the locations of the “bright lines” might best be described as the most probable locations the singular electrons will be observed on the other side of the slits.

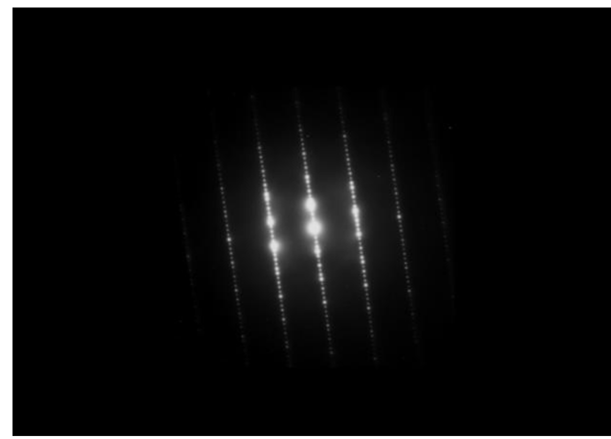


image: Oysteinp, Wikipedia

electron crystallography

The atoms in a crystalline material form a regular lattice that acts similar to a diffraction grating for electrons that pass through. The result is an interference pattern.

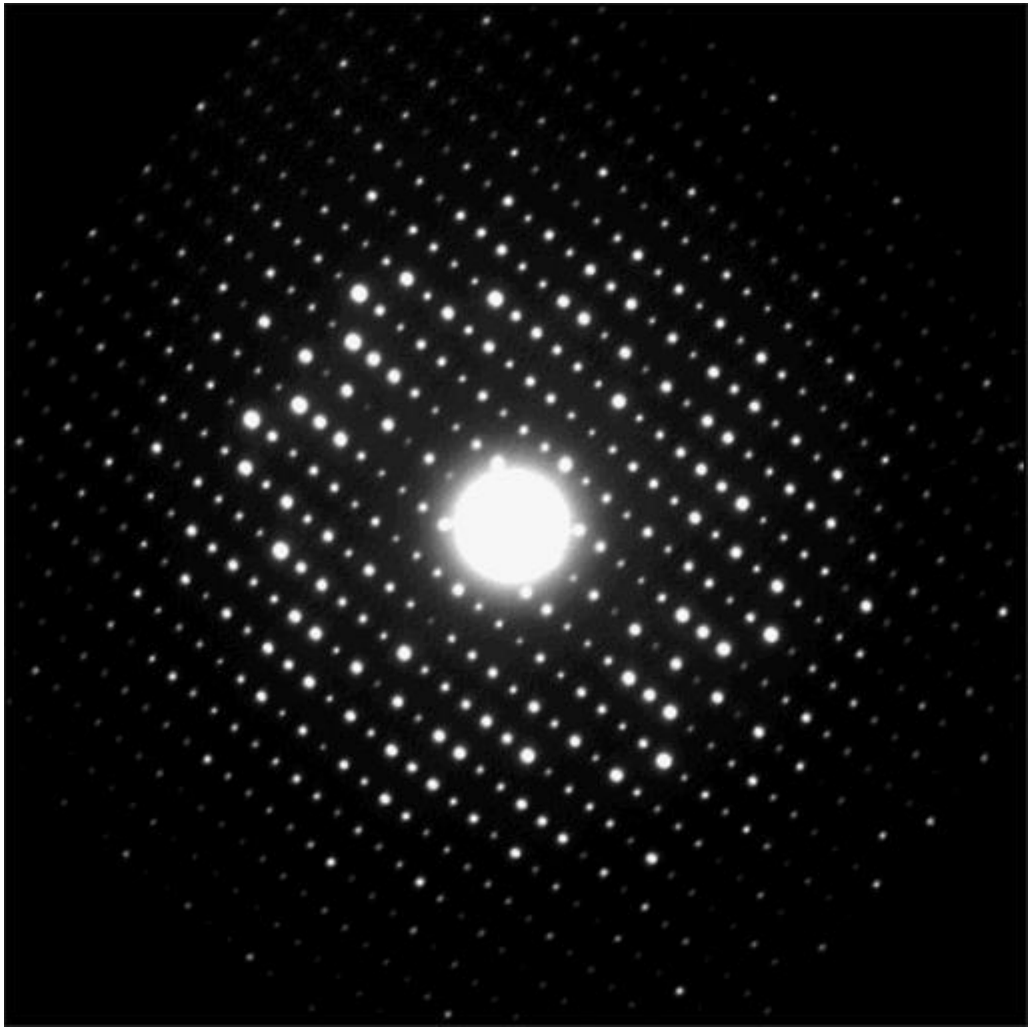


image: Sven.hovmoeller, Wikipedia