Announcements

- Review: Tuesday, February 27
- All HWs and WS's will be available for pickup at the review
- Test #1: Thursday, February 29 in RH114 Closed book, closed notes. Bring a pencil and a simple calculator (no iphones or internet capable calculators)

What is luminosity?

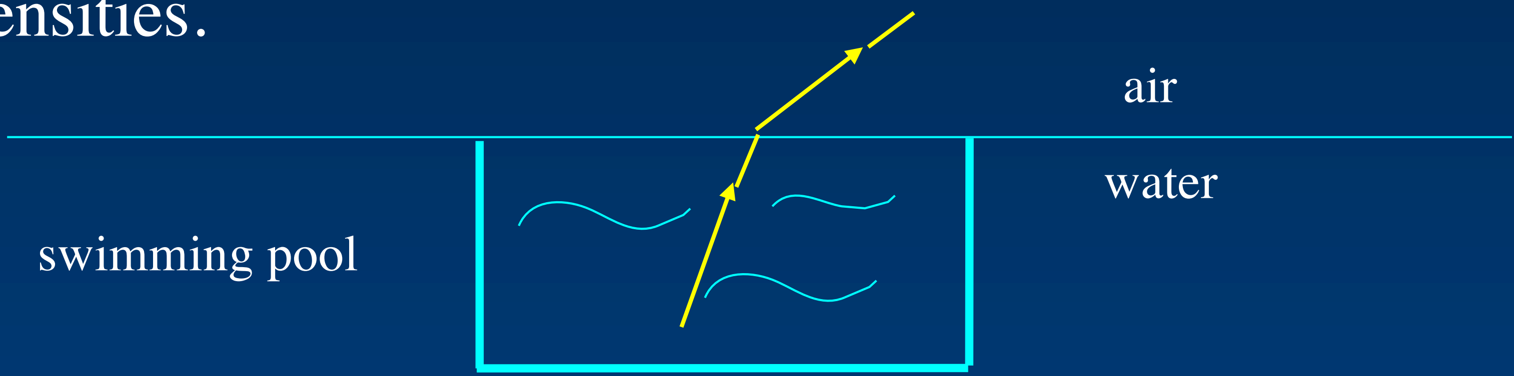
- Luminosity = total energy output from an object per second ($W = Js^{-1}$). Independent of distance - *intrinsic* property.

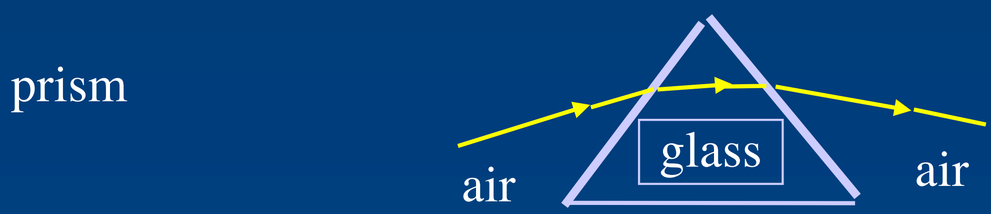
- Apparent brightness is how bright an object *appears* to be - this is what we actually measure ($Js^{-1}m^{-2}$, flux units). Depends on the distance.

Things that waves do

1. Refraction

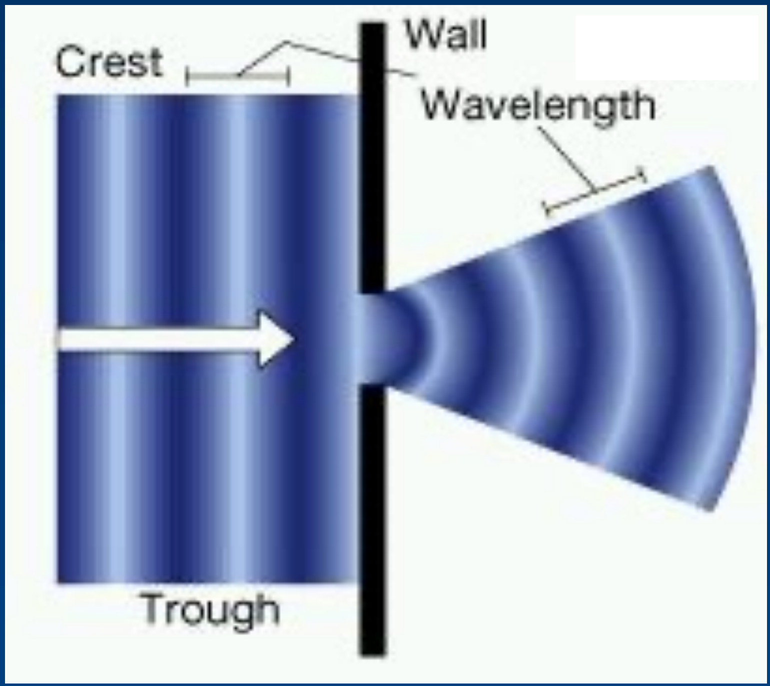
Waves bend when they pass through material of different densities.



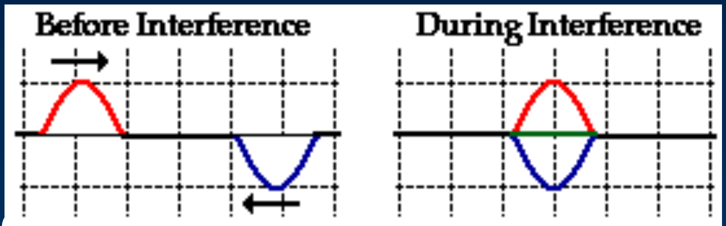


2. <u>Diffraction</u>

Waves bend when they go through a narrow gap or around a corner.

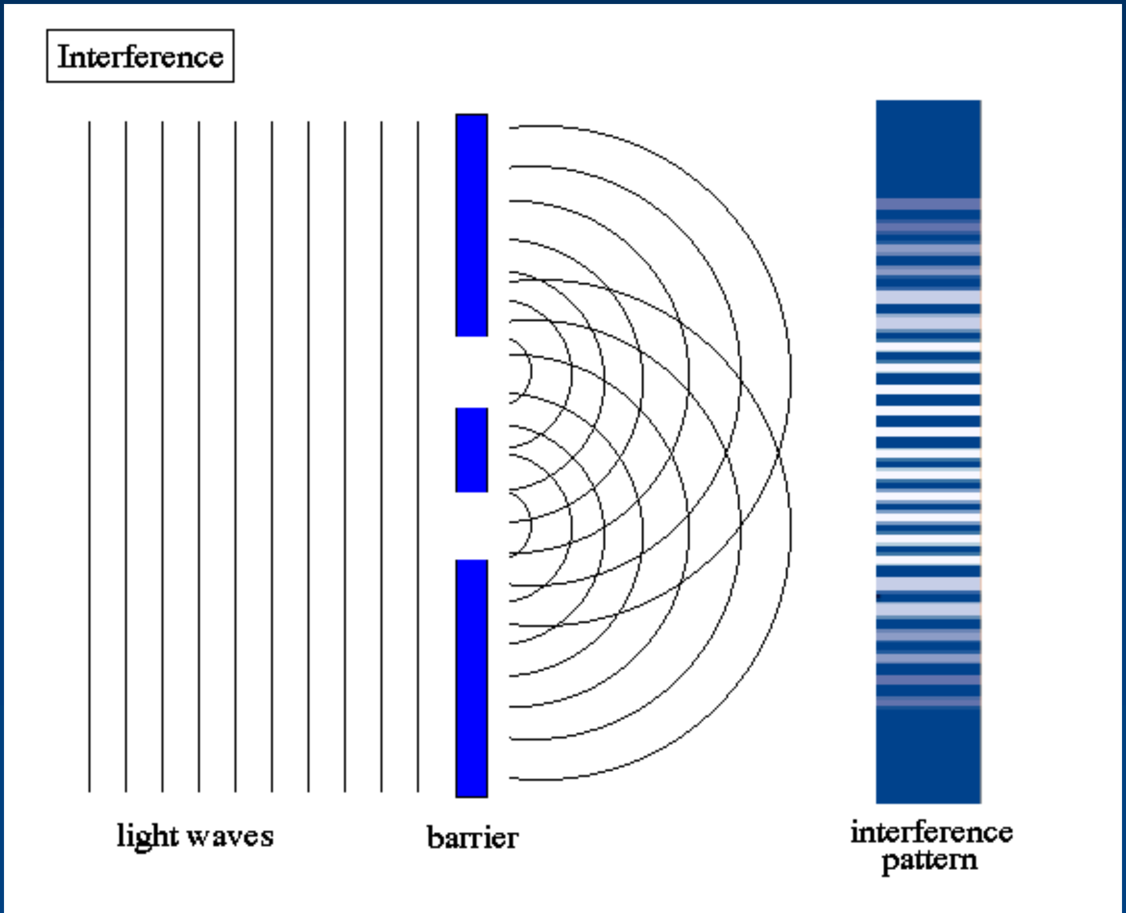


3. Interference



Waves can interfere with each other

Demo:
LASER fringes



How do radiation and matter interact?

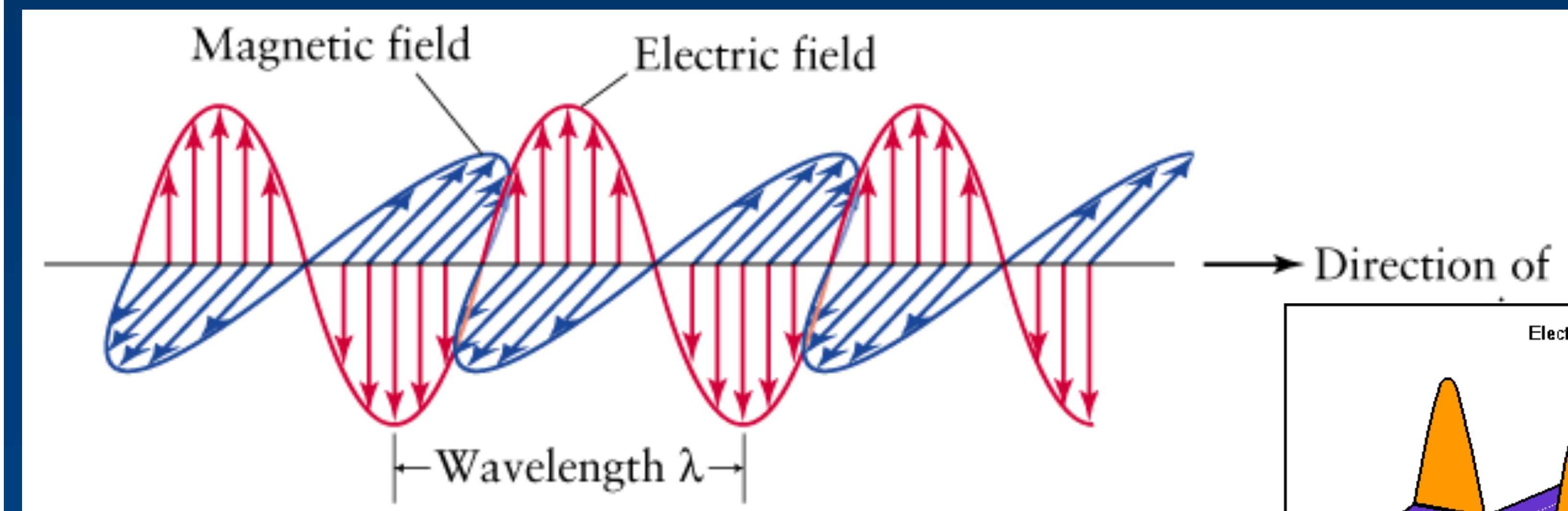
- Emission - light bulb, star
- Absorption - your skin can absorb light - the absorbed energy heats your skin
- Transmission - glass and air lets light pass through
- Reflection and scattering - light can bounce off matter leading to reflection (in one direction) or scattering (in many directions)

The Nature of Light Part II:

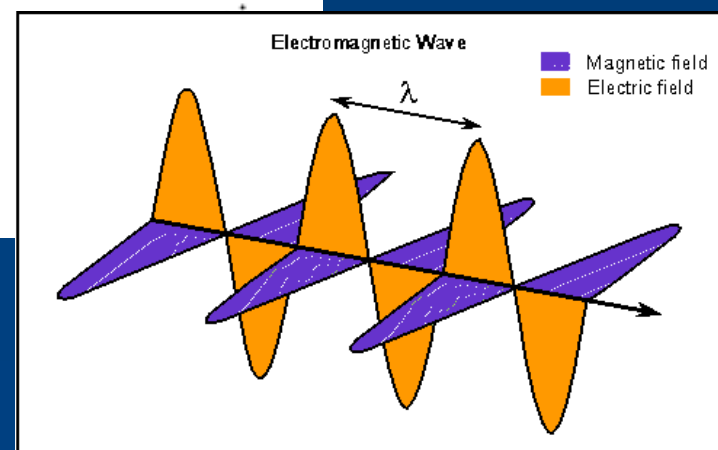
Polarization of Light
Light as a particle
Atomic Structure
Emission and Absorption Lines
Doppler Effect

Electromagnetic waves

- EM waves: self propagating electric and magnetic fields (changes in strengths of E and M fields).
- Individual photons are polarized (direction of E field)
- Collection of photons can have a statistical polarization or be randomly oriented - DEMO



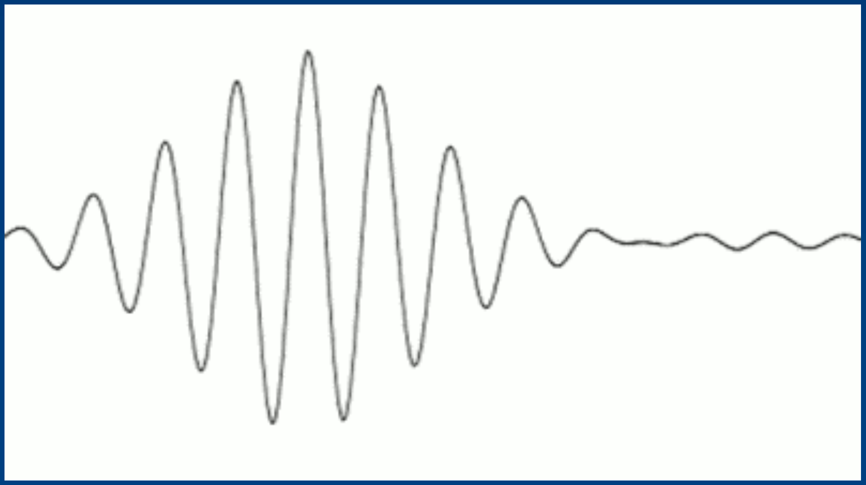
Different from other waves, since it doesn't need a medium in which to propagate!



The dual nature of light

Light often acts like a wave, but also can act like a particle – in interactions with atoms and molecules

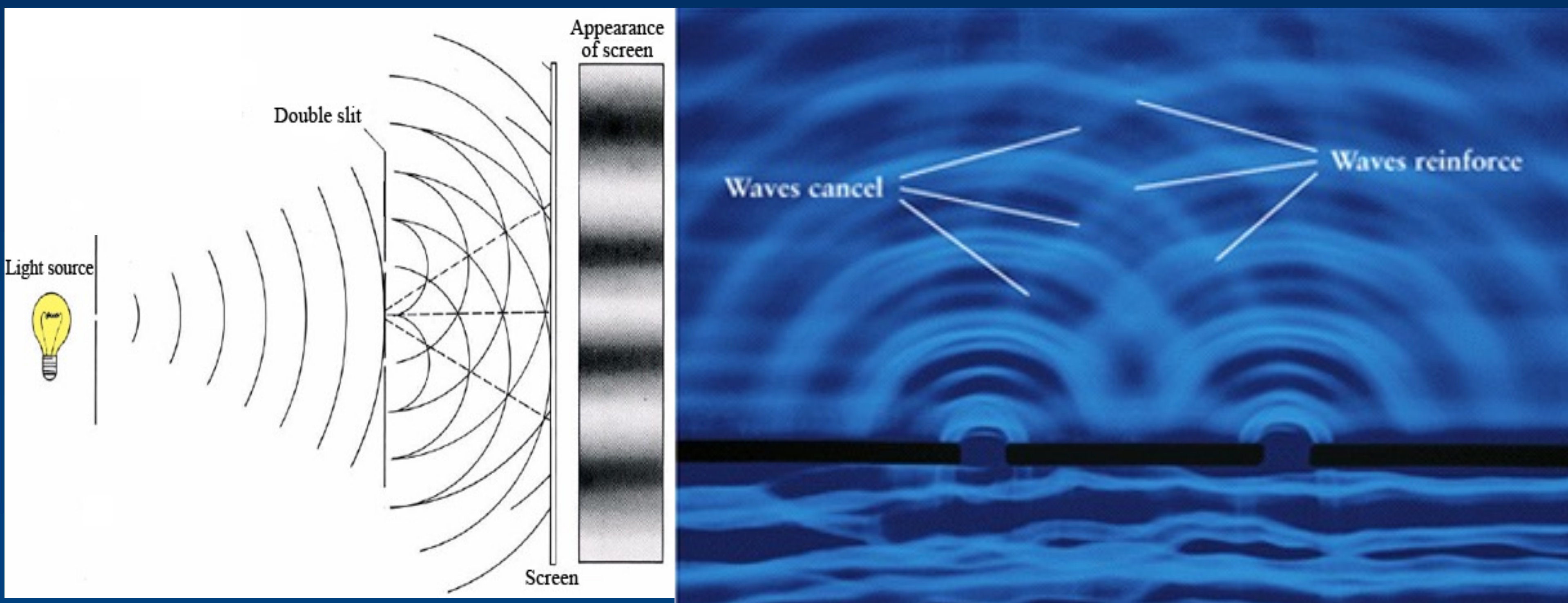
- The particles are called *photons*
- A photon is a massless particle that carries energy (and momentum) at the speed of light



Young's double slit experiment

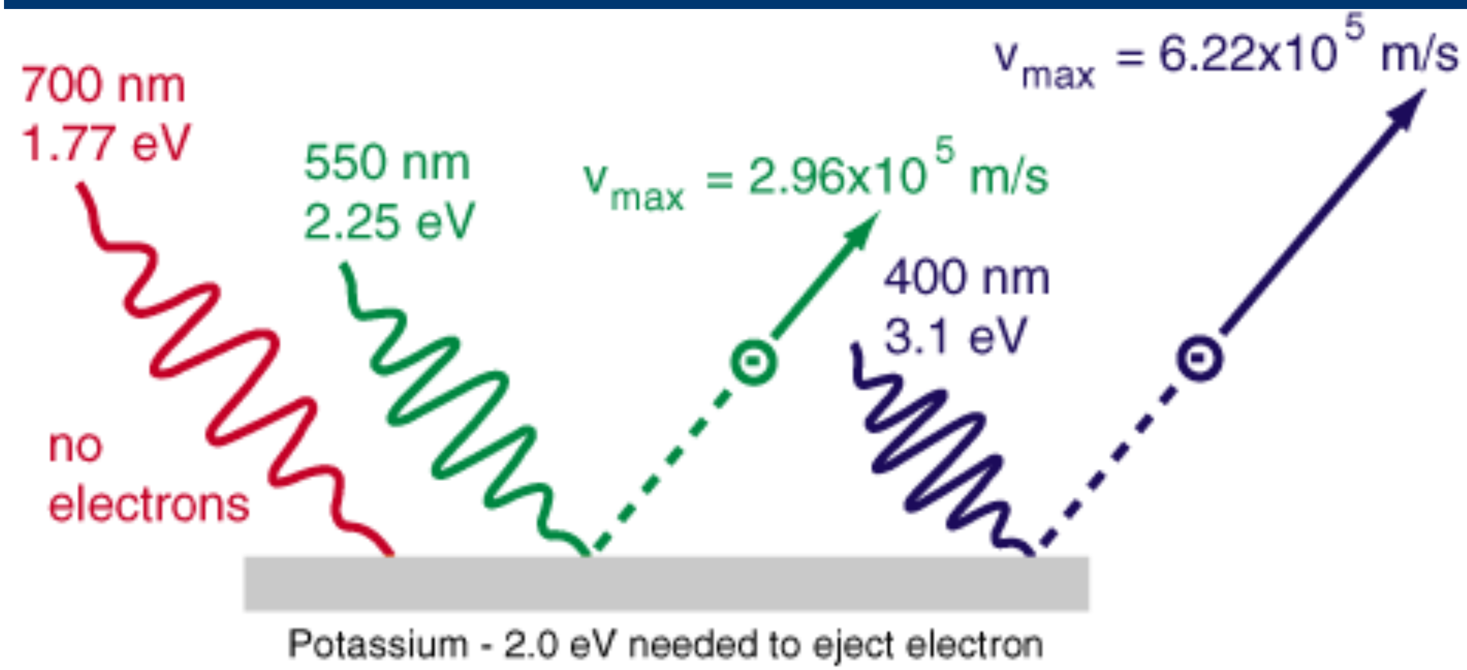
Demonstrates the wave-like nature of light:

Like water waves (right), EM waves can interfere



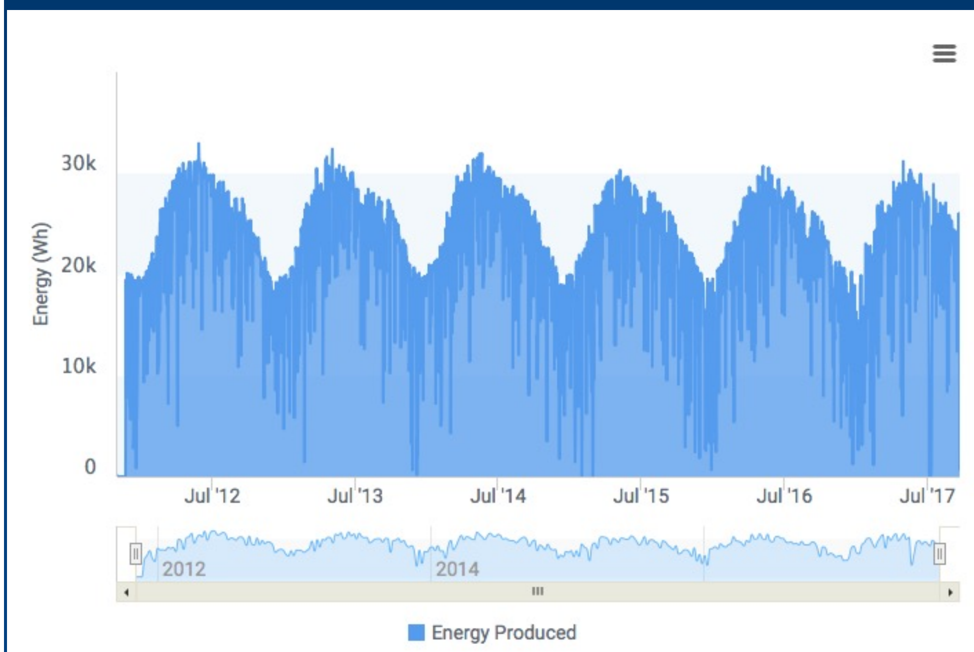
Photoelectric effect

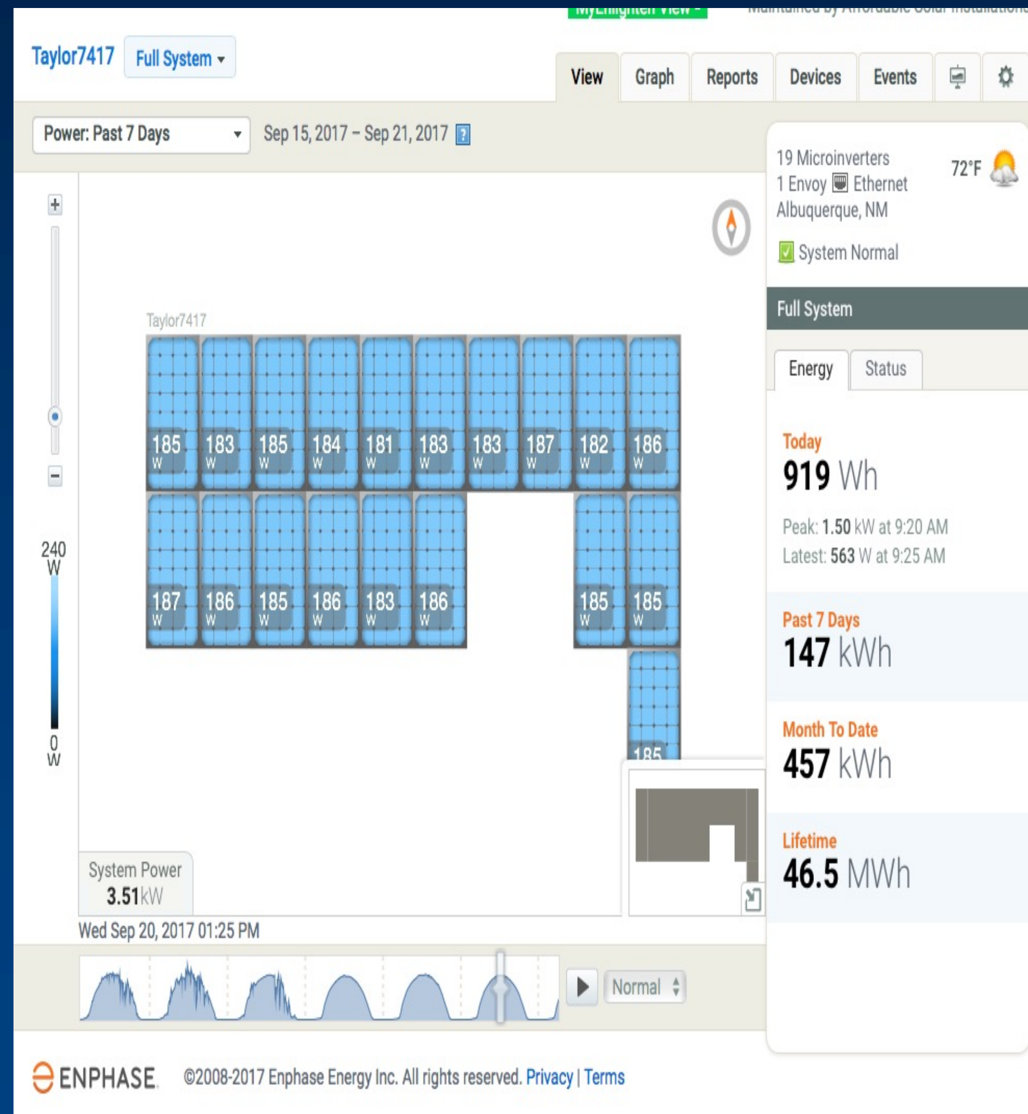
- Demonstrates particle nature of light:
  - Light hitting a metal will knock out single electrons, but only if the frequency is high enough, not the intensity
  - Energy of photoelectrons depends only on incoming light frequency, not on intensity
  - Compare energy of wave $\propto$ Amplitude^2



(1 eV = 1.6 x 10^{-19} J – energy an electron gains by accelerating through an electric potential of 1 V)

Photovoltaics





Photon energies

Explanation: can consider light as a stream of particles (photons), with energy dependent on frequency. Only photons with sufficient energy can liberate electrons from atoms.

$E = hc/\lambda$ or equivalently

$E = h\nu$

$h = 6.6 \times 10^{-34}$ J s (Planck's constant)

$h = 4.1 \times 10^{-15}$ eV s

Question: which has more energy, a photon of blue light, or of red light? UV? Radio?

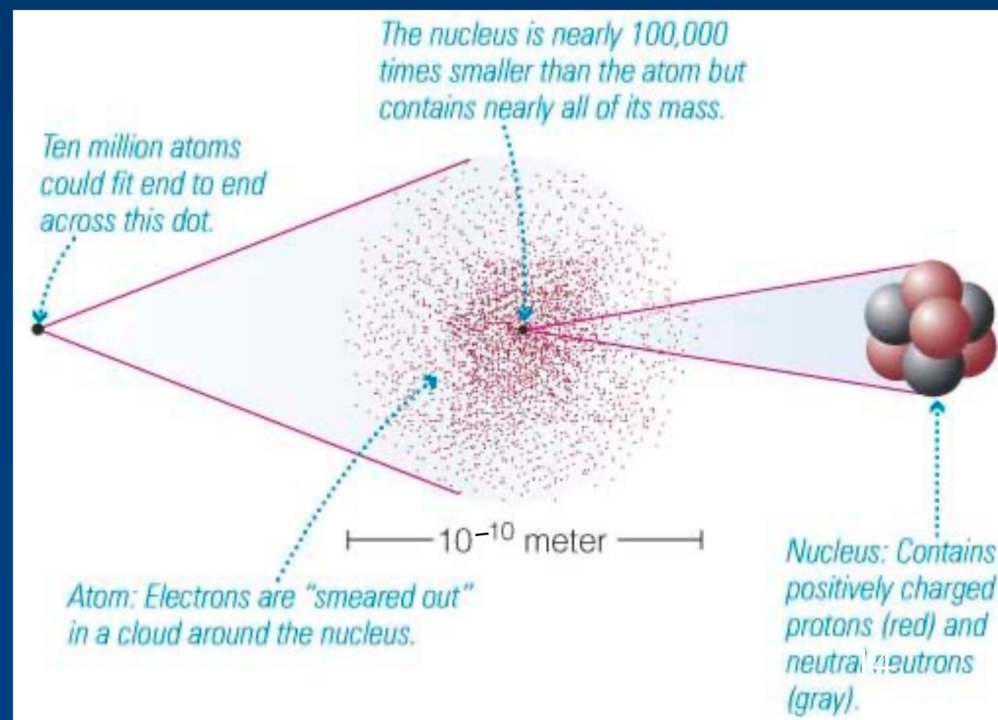
Atomic structure

Nucleus contains particles with most of atom’s mass:

Protons (positively charged)

Neutrons (uncharged)

Electrons (negatively charged) in a cloud orbiting the nucleus

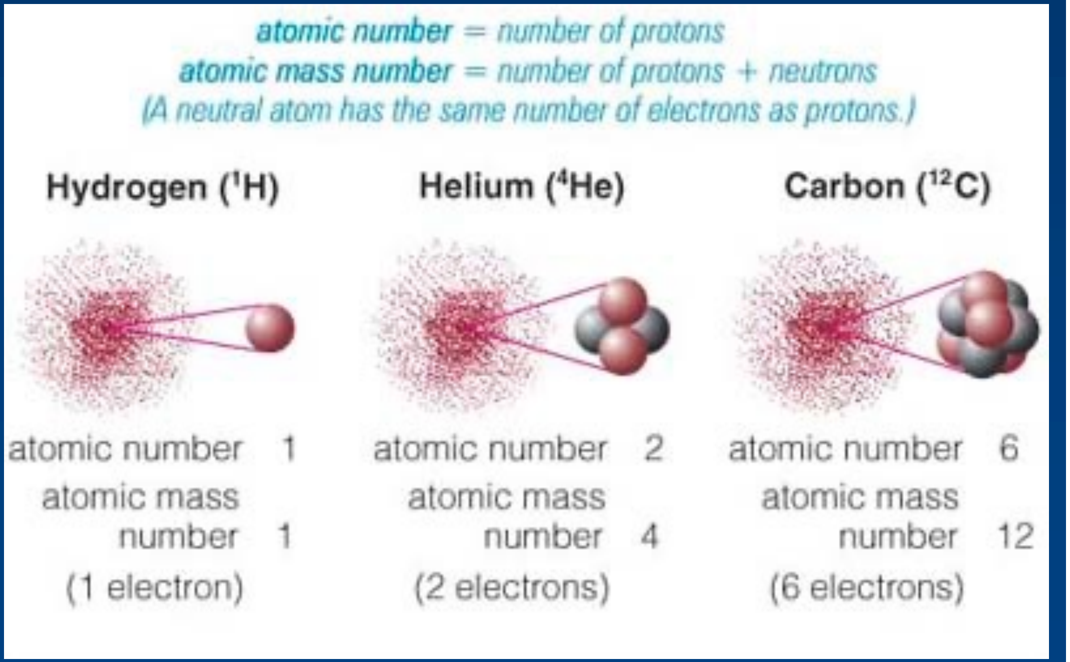


$m_p = 1.6726 \times 10^{-27}$ kg
$m_n = 1.6749 \times 10^{-27}$ kg
$m_e = 9.1094 \times 10^{-31}$ kg

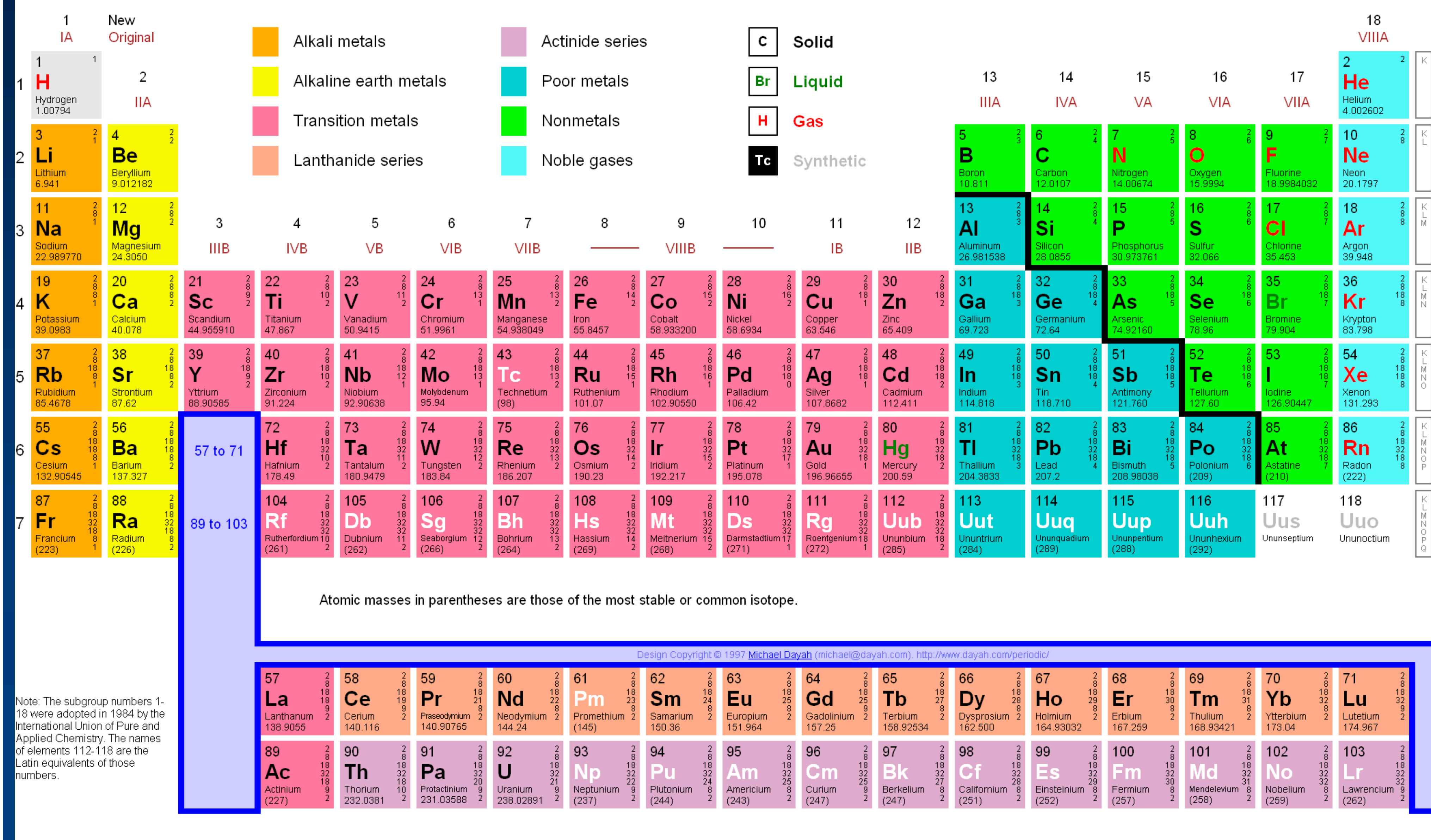
Chemical elements

- Atoms come in different *elements,* differentiated by the total number of protons in the nucleus.

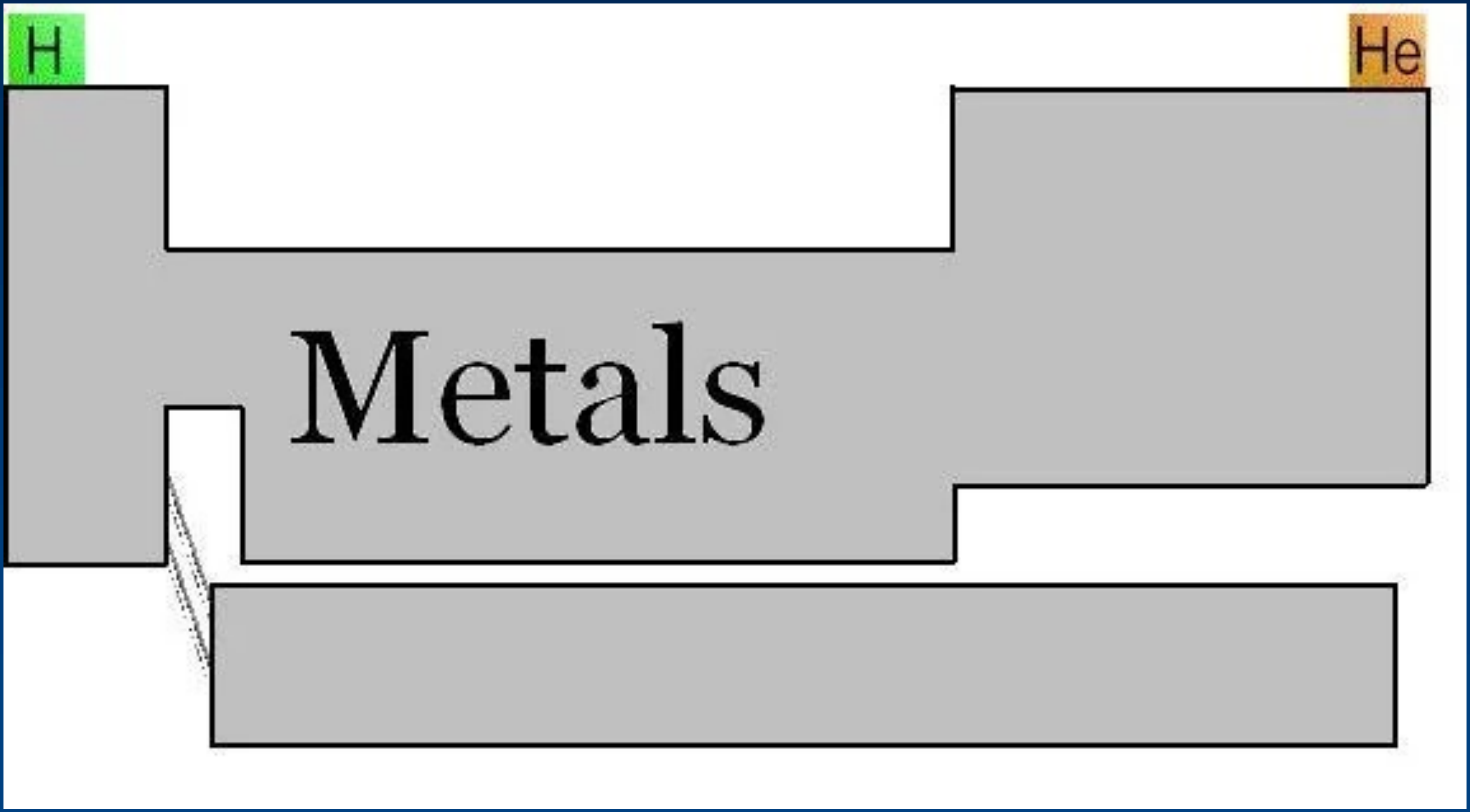
- This is called the atomic number:
  - 1 proton: Hydrogen
  - 2 protons: Helium
  - 3 protons: Lithium
  - Etc.



Periodic Table of the Elements



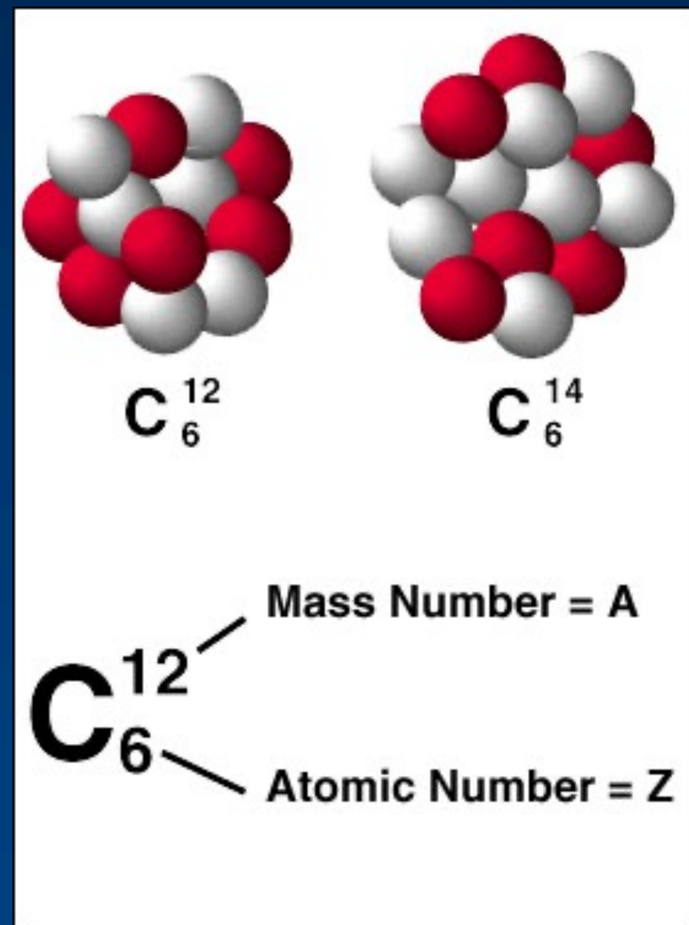
Astronomers Periodic Table



Isotopes of an element

- Same number of protons, but different number of neutrons.
- ^{12}C has 6 protons and 6 neutrons
- ^{13}C has 6 protons and 7 neutrons
- ^{14}C has 6 protons and 8 neutrons

But is unstable (half-life 5730 years)



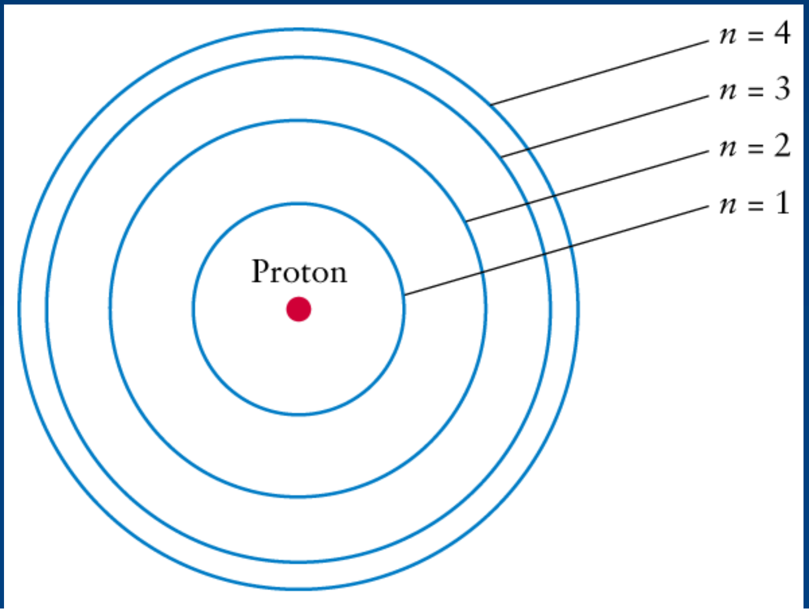
Bohr model of the H atom (1913)

- For practical purposes we can ignore fuzziness of electrons and consider them as discrete particles. Consider H:

- Proton and orbiting electron attracted. Takes energy to increase separation. Without energy, electron remains in "ground state" (n=1)

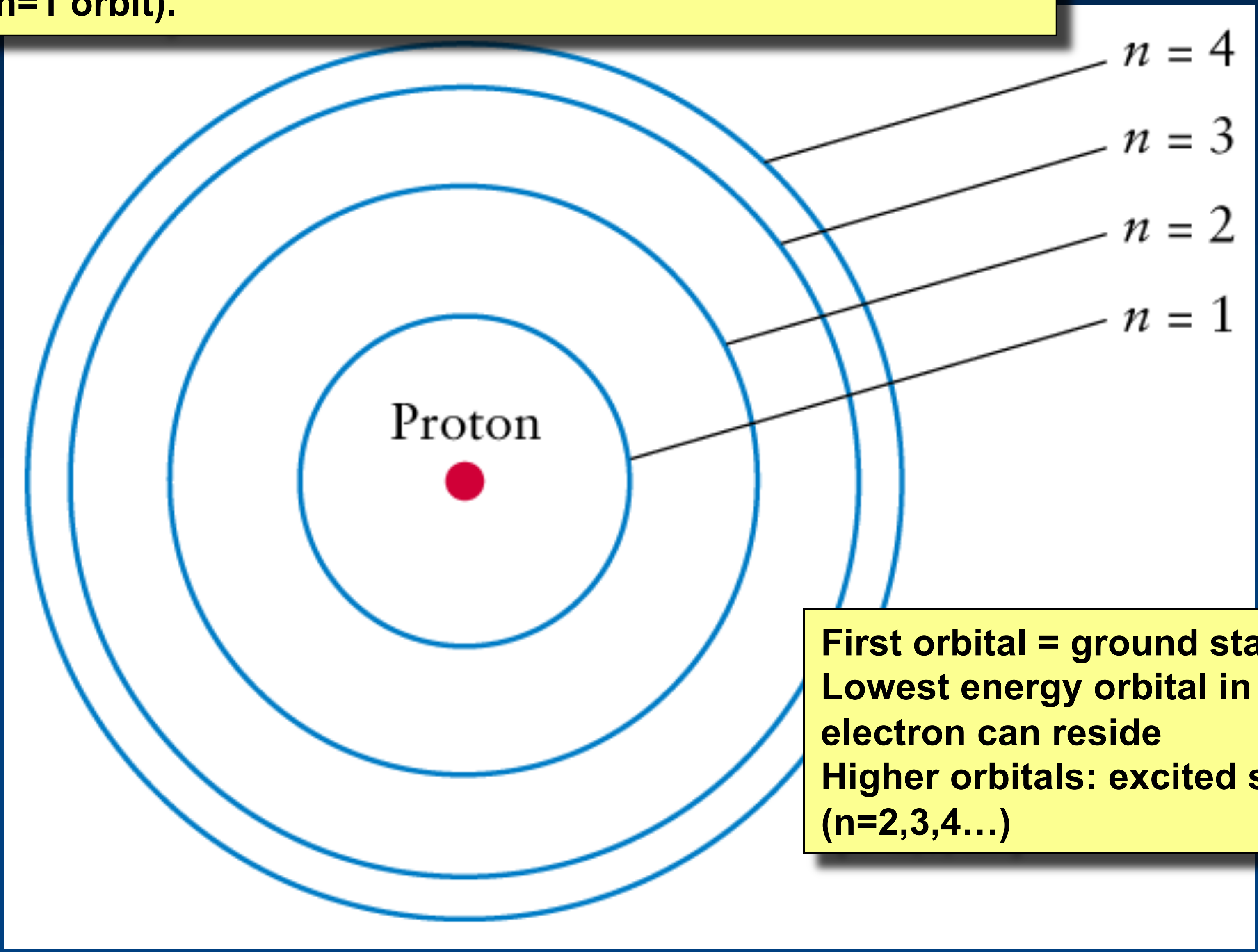
- But, only certain discrete orbitals, or energies, allowed

- Electron in "excited" state (n>1) quickly decays to lower levels.



The simple Bohr model for the hydrogen atom: a single electron orbiting a single proton (the nucleus).

The different energy levels represent allowed orbitals for electrons (not to scale, the n=2,3,4 orbits should be 4, 9 and 16 times larger than the n=1 orbit).



First orbital = ground state (n=1). Lowest energy orbital in which the electron can reside
Higher orbitals: excited states (n=2,3,4…)

Emission and Absorption

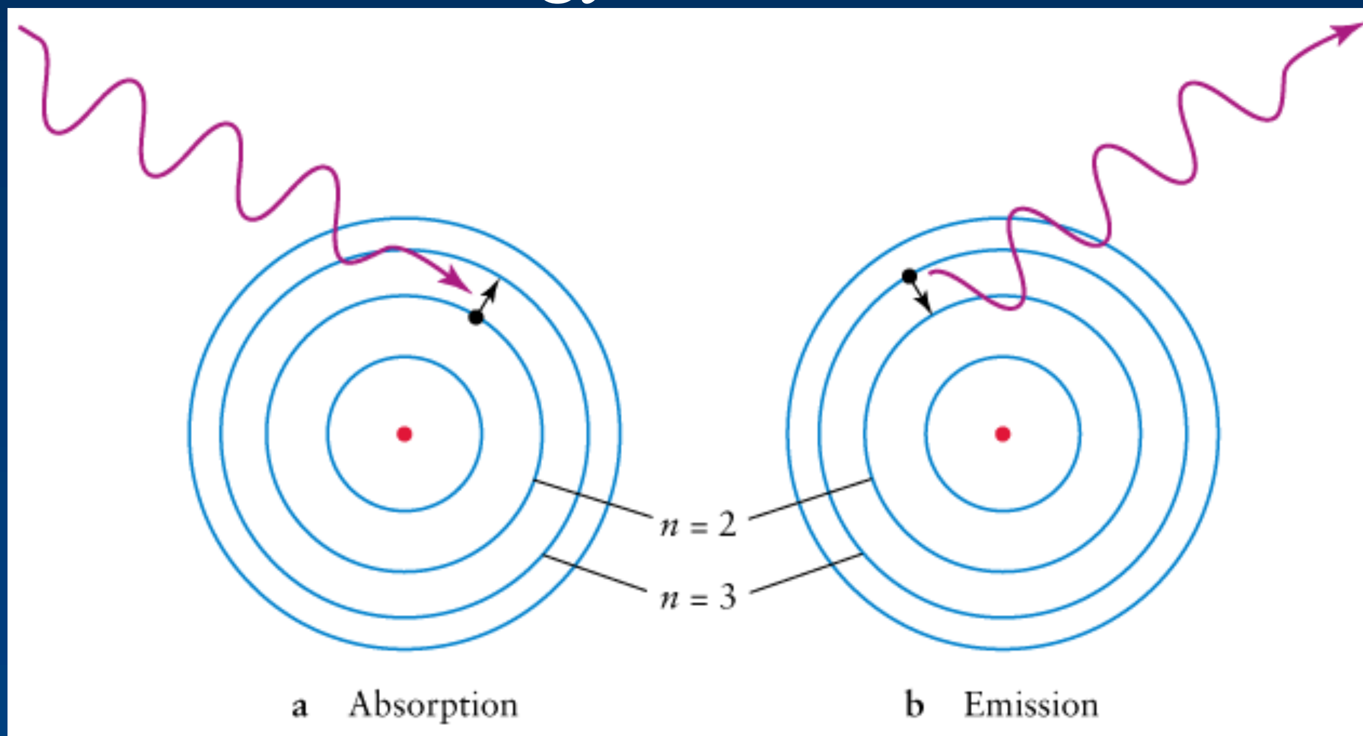
- Electrons can get into excited states by either
  - Colliding (with other atoms or free electrons)
  - Absorbing photons (of specific energy)

- Absorption: only photons with exact excitation energy are absorbed, ALL others pass through unaffected.

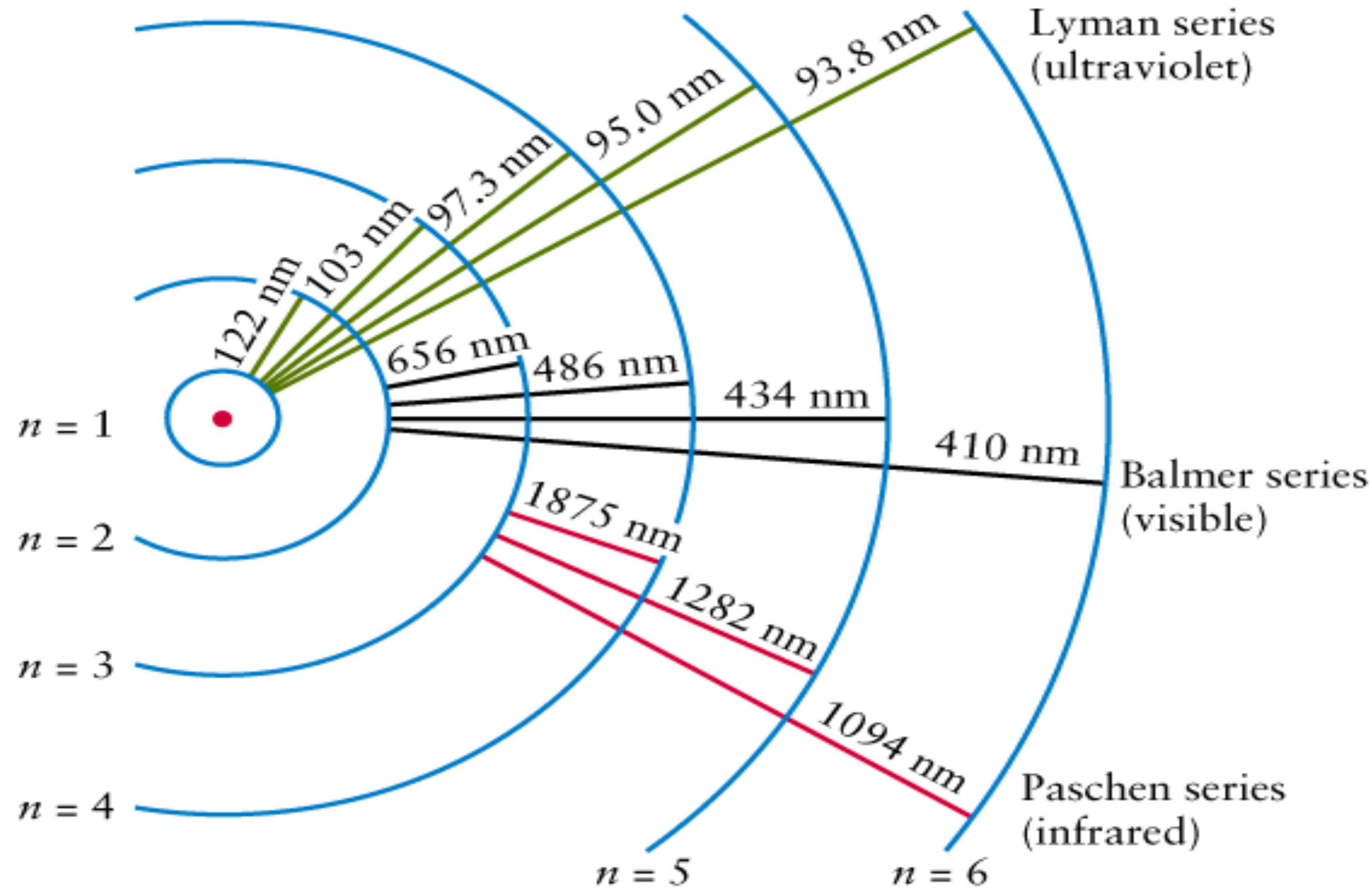
- Electrons get out of excited states by emitting photons in random directions.

- An atom can absorb a photon, causing electron to jump up to a higher energy level.

- An atom can emit a photon, as an electron falls down to a lower energy level.



- May jump more than one level, and fall back down by various paths, emitting multiple photons.



Bohr formula for hydrogen wavelengths

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

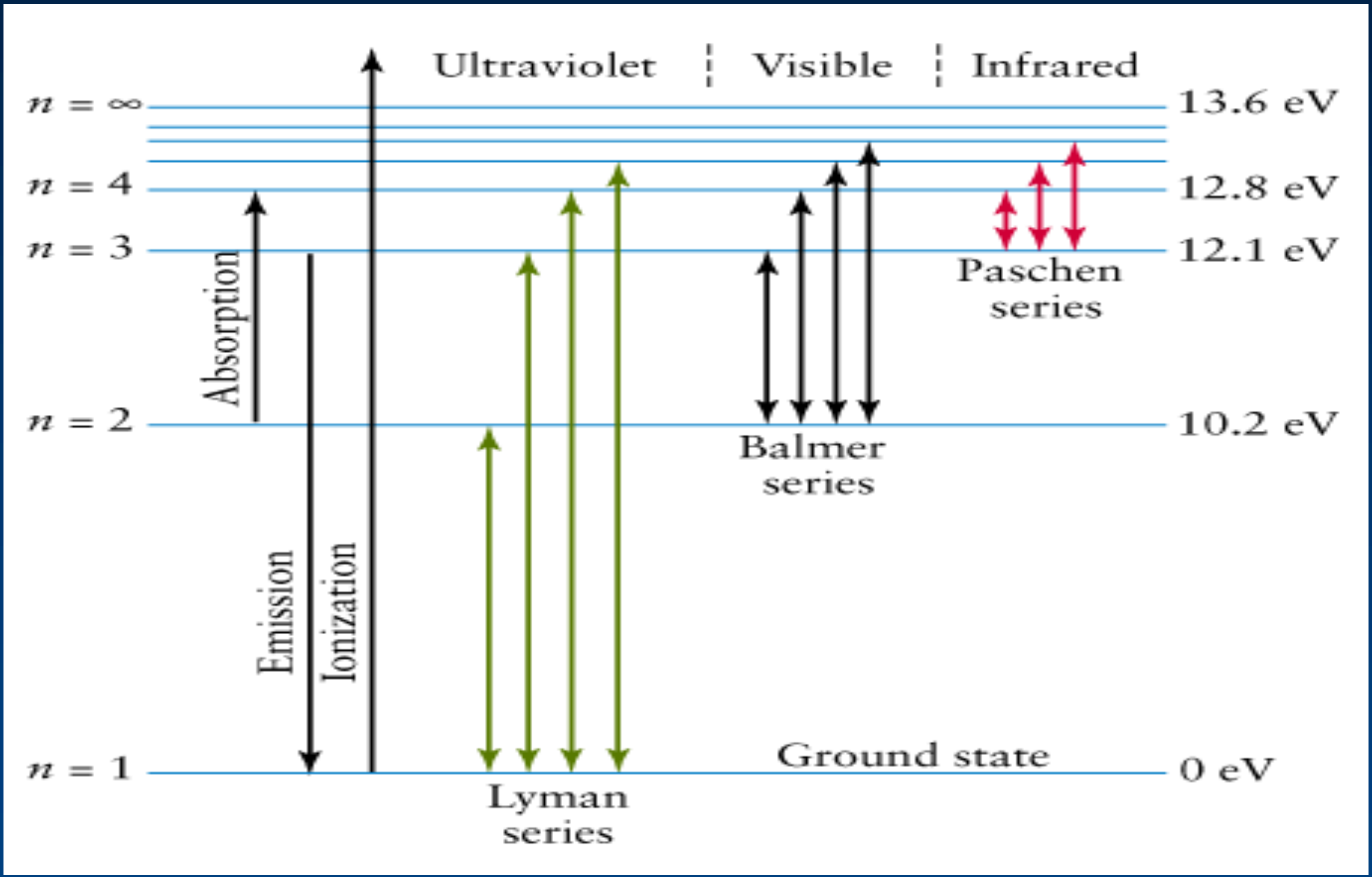
N = number of inner orbit

n = number of outer orbit

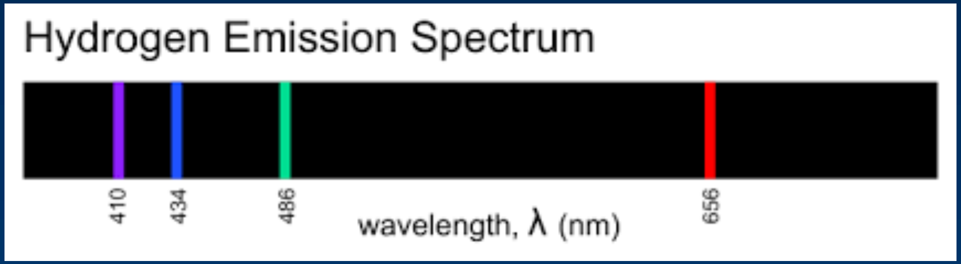
R = Rydberg constant = $1.097 \times 10^7\ \mathrm{m}^{-1}$

λ = wavelength (in meters) of emitted or absorbed photon

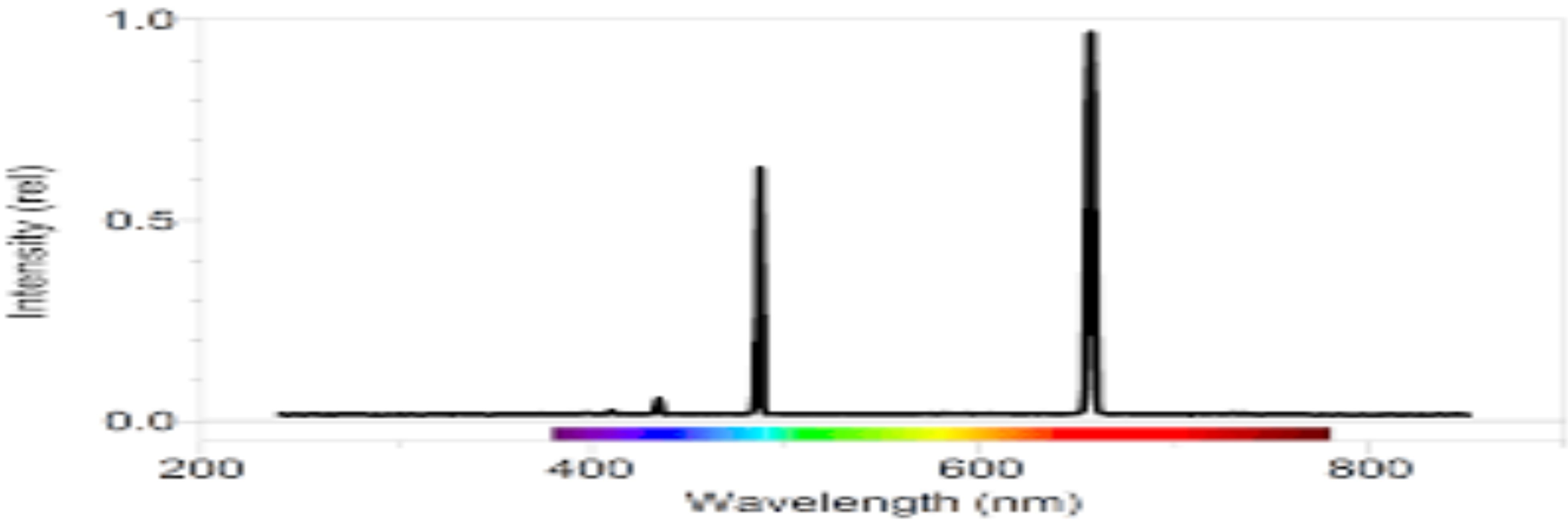
Energy level diagram for hydrogen:



Worksheet#7. Sketch the spectrum for Hydrogen in visible



Hydrogen Emission Spectrum
410
434
486
656
wavelength, λ (nm)



1.0
0.5
0.0
Intensity (rel)
200
400
600
800
Wavelength (nm)

Ionization

- If an atom or a molecule absorbs enough energy from a photon or a collision, an electron can escape the nuclear attraction => positive ion. For H, takes at least a 13.6 eV photon.

- By adding electrons, you can get a negative ion

- Each ion has its own energy levels

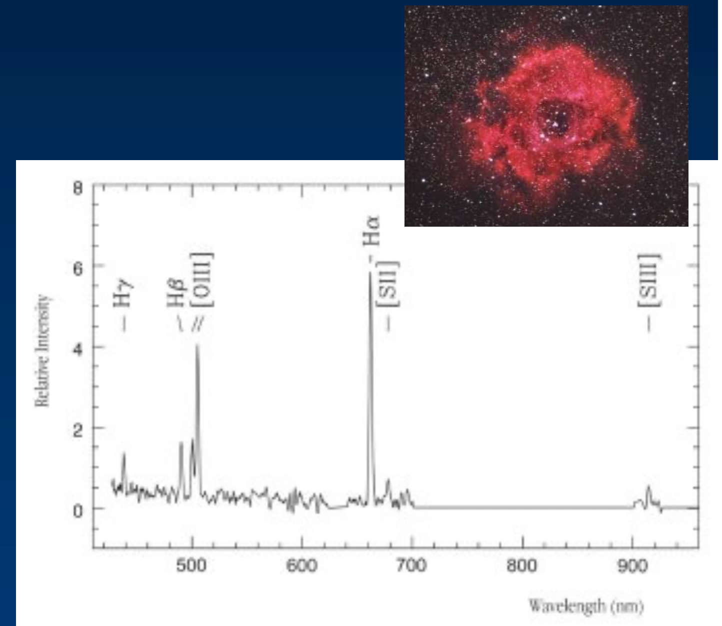
- "N II", "N III": N with one or two electrons removed. Takes higher energy photons to remove more electrons (e.g. O II: 13.6 eV, O III: 35 eV).

Fingerprints of matter

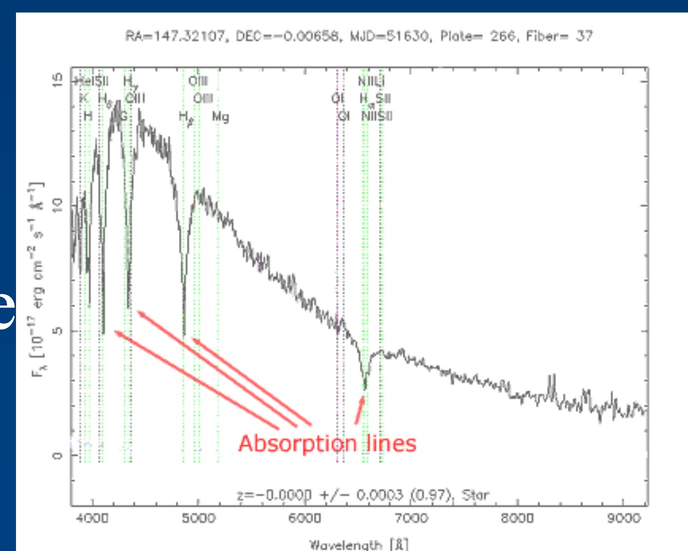
- Hydrogen has an easy orbital structure, but more complex atoms (several electrons) will have more complicated structure:
  - More energy levels and a more complex line spectrum
- Each element has a unique spectrum, reflecting the unique electron orbital structure
- Isotopes have same lines, but slightly shifted in wavelength
- Geisler tubes

Emission and absorption line spectra

- Hot, low density gas, where collisions between atoms have sufficient energy to cause electrons to move to higher levels, gives emission lines. Also gas around very hot, young stars becomes ionized, and produces emission lines as it recombines.

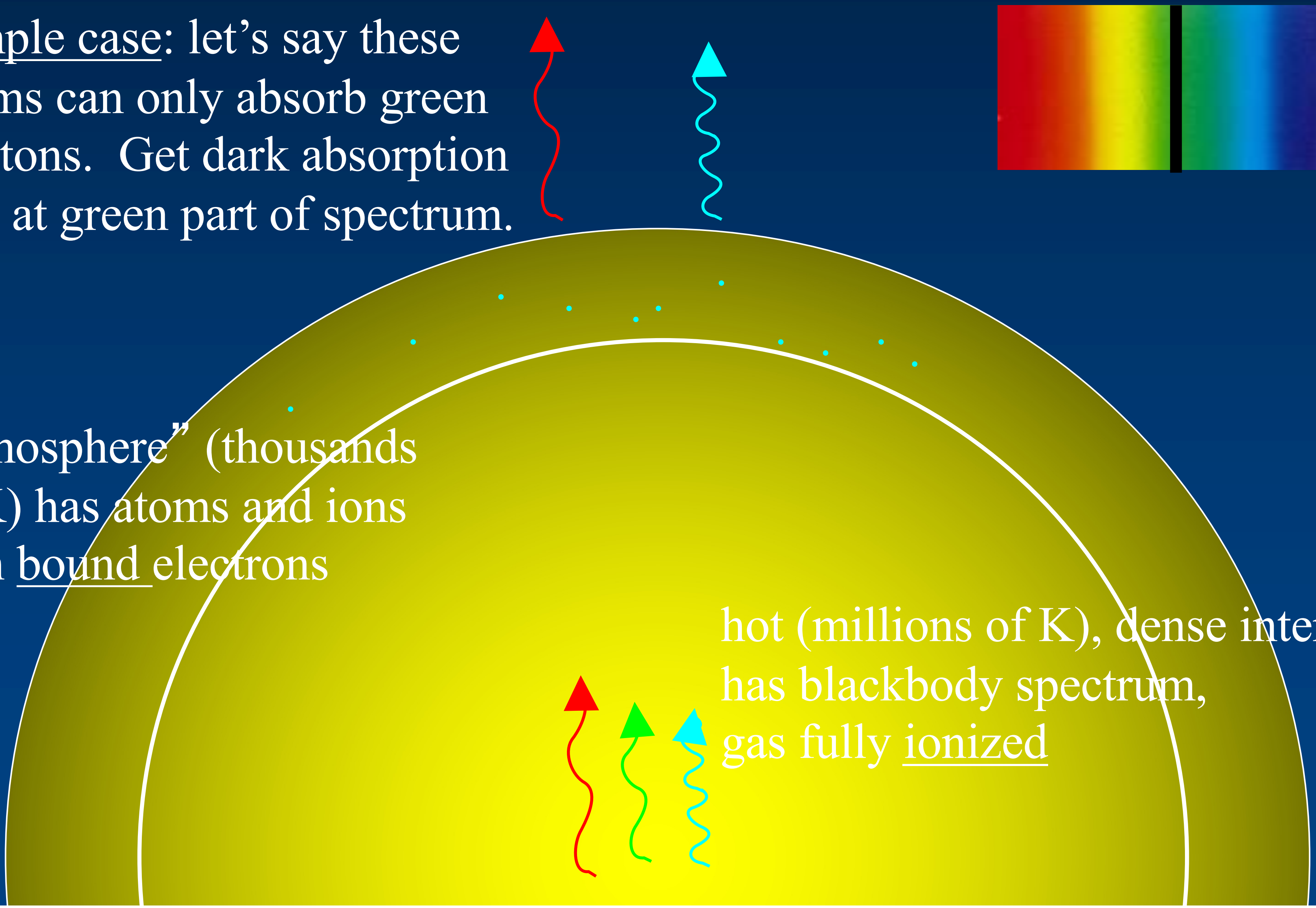


- Light from continuous spectrum through cooler gas gives absorption lines, as absorbed photons cause electrons to move to higher levels. Re-emitted photons are in random direction, so incident light in original direction much reduced.



So why do stars have absorption line spectra?

<ins>Simple case</ins>: let's say these atoms can only absorb green photons. Get dark absorption line at green part of spectrum.



"atmosphere" (thousands of K) has atoms and ions with <ins>bound </ins>electrons

hot (millions of K), dense interior has blackbody spectrum, gas fully <ins>ionized</ins>

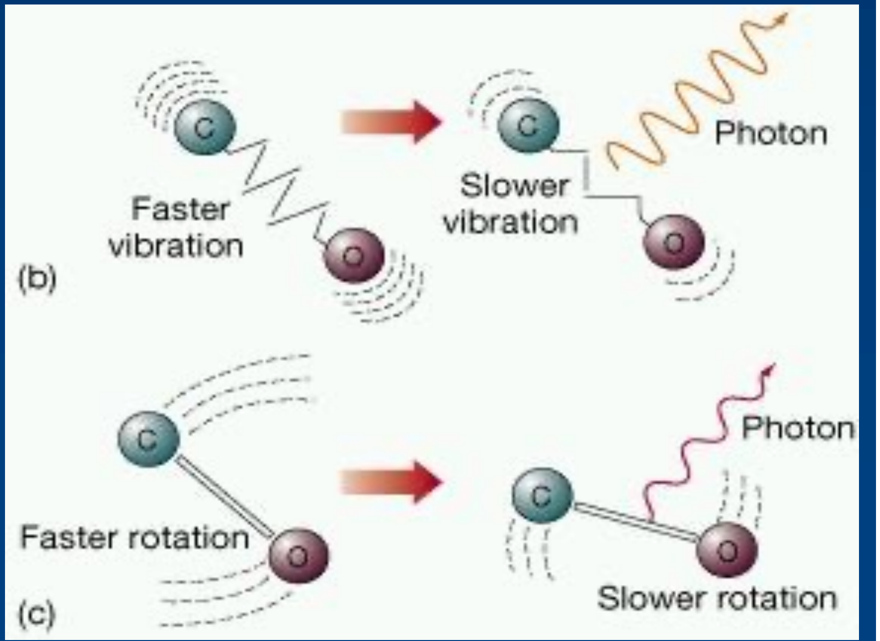
Molecules

- Even more complex - compounds of two or more atoms of same or different elements

- Share some electrons in common orbitals

- Have vibrational and rotational energy levels as well (IR, microwave, radio)

=> Very complex spectra!



Kirchhoff's Laws

1. A hot, opaque body, or a hot, dense gas produces a continuous spectrum.

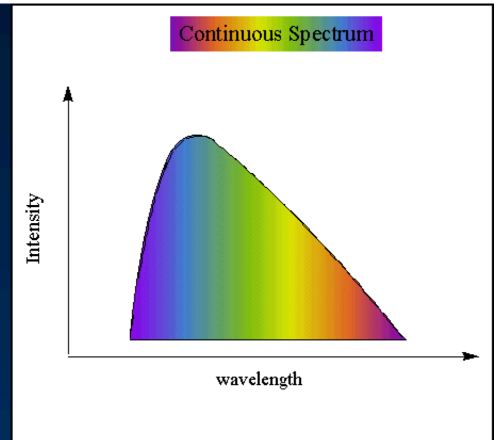
   Explained

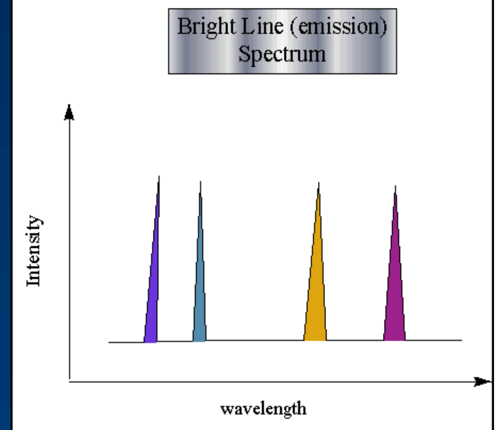
2. A hot, transparent gas produces an emission line spectrum.

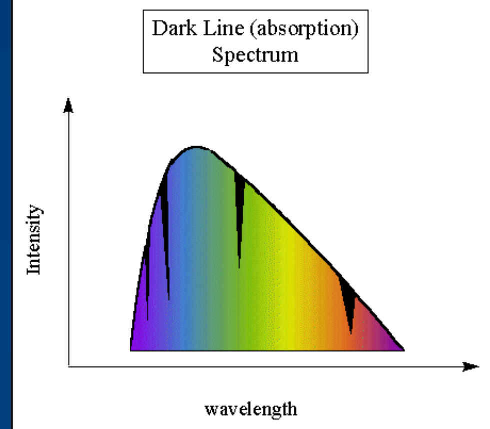
   Explained

3. A cool, transparent gas in front of a source of a continuous spectrum produces an absorption line spectrum.

   Explained







Spectroscopy

The spectrum of an objects tells us:

- Which atoms and molecules are present, and in which proportions
- Which atoms are ionized, and in which proportions
- How excited the atoms are, which tells us about the physical state (cold, hot)
- Motion of the object

⇒Spectroscopy is a very important tool of the astronomer! (invented by Gustaf Kirchoff)

(Particles emit and absorb photons in other ways, too. We'll deal with those processes as needed.)

What is brightness?

- We need to be able to quantify how bright an object is
- Wave picture: brightness corresponds to amplitude
- Particle picture: brightness corresponds to the number of photons per second from the source

The particle picture turns out to be more useful for expressing brightness.

Fundamental forces of nature

Interactions in nature are governed by four fundamental forces:

1. Gravitational force
2. Electromagnetic force
3. Strong nuclear force
4. Weak nuclear force

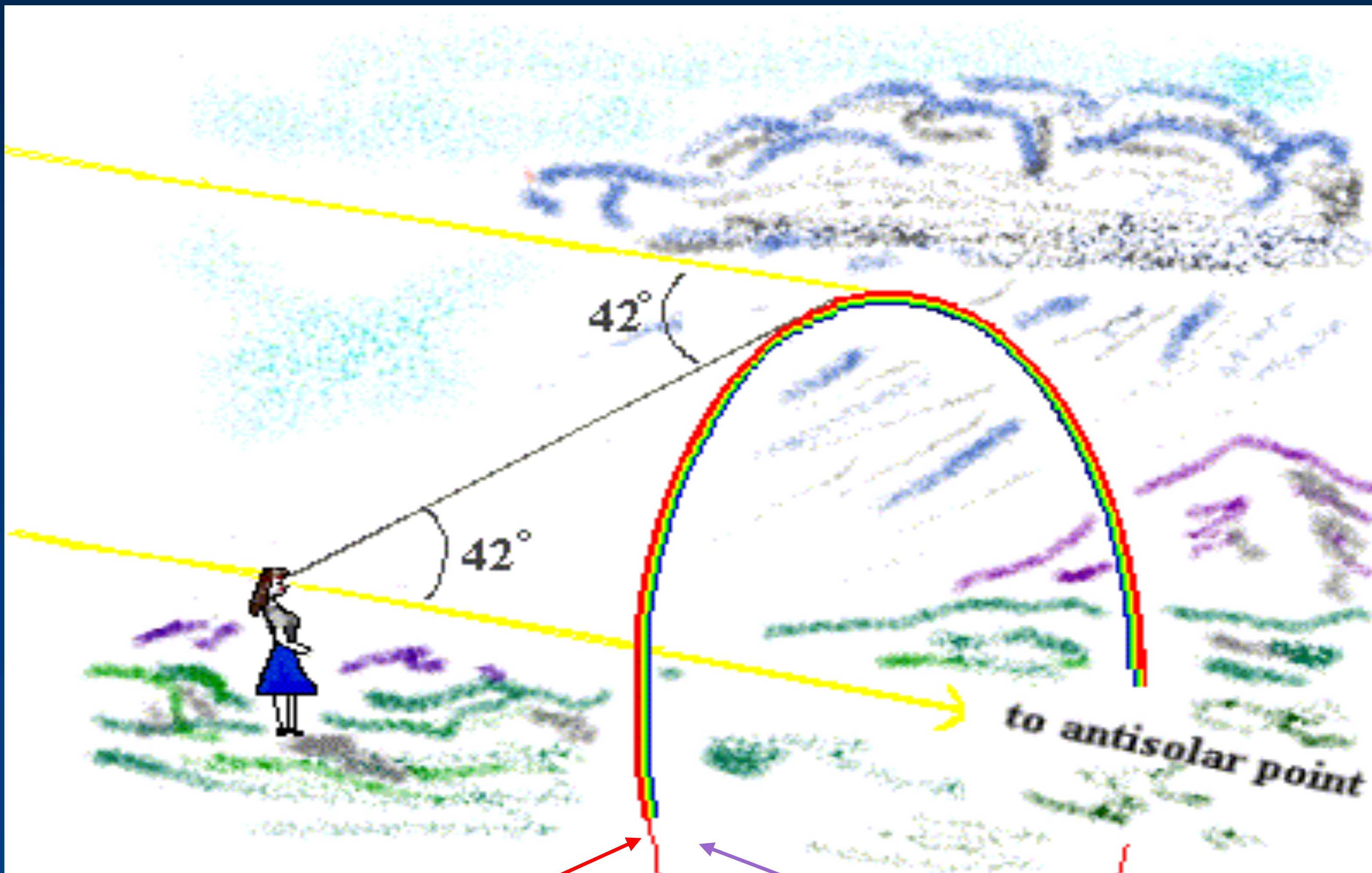
The interplay of forces

- Gravity dominates on largest scales: binds massive objects together, and mediates orbital motions
- Electromagnetism dominates on atomic scale: binds electrons to protons, atoms to molecules
- Strong and weak forces dominates on nuclear scales: binds protons to neutrons, mediates nuclear reactions

Rainbows

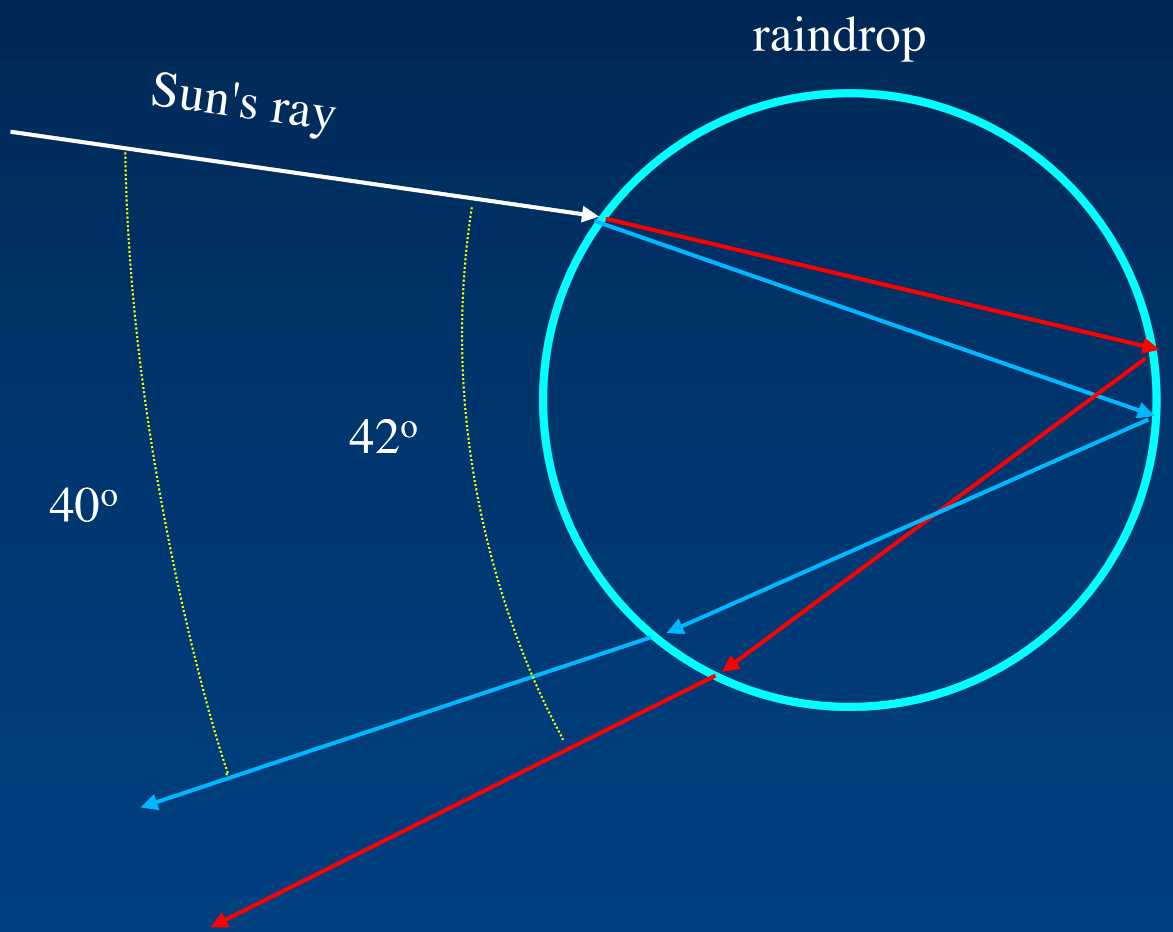
Rainbows

Rainbows

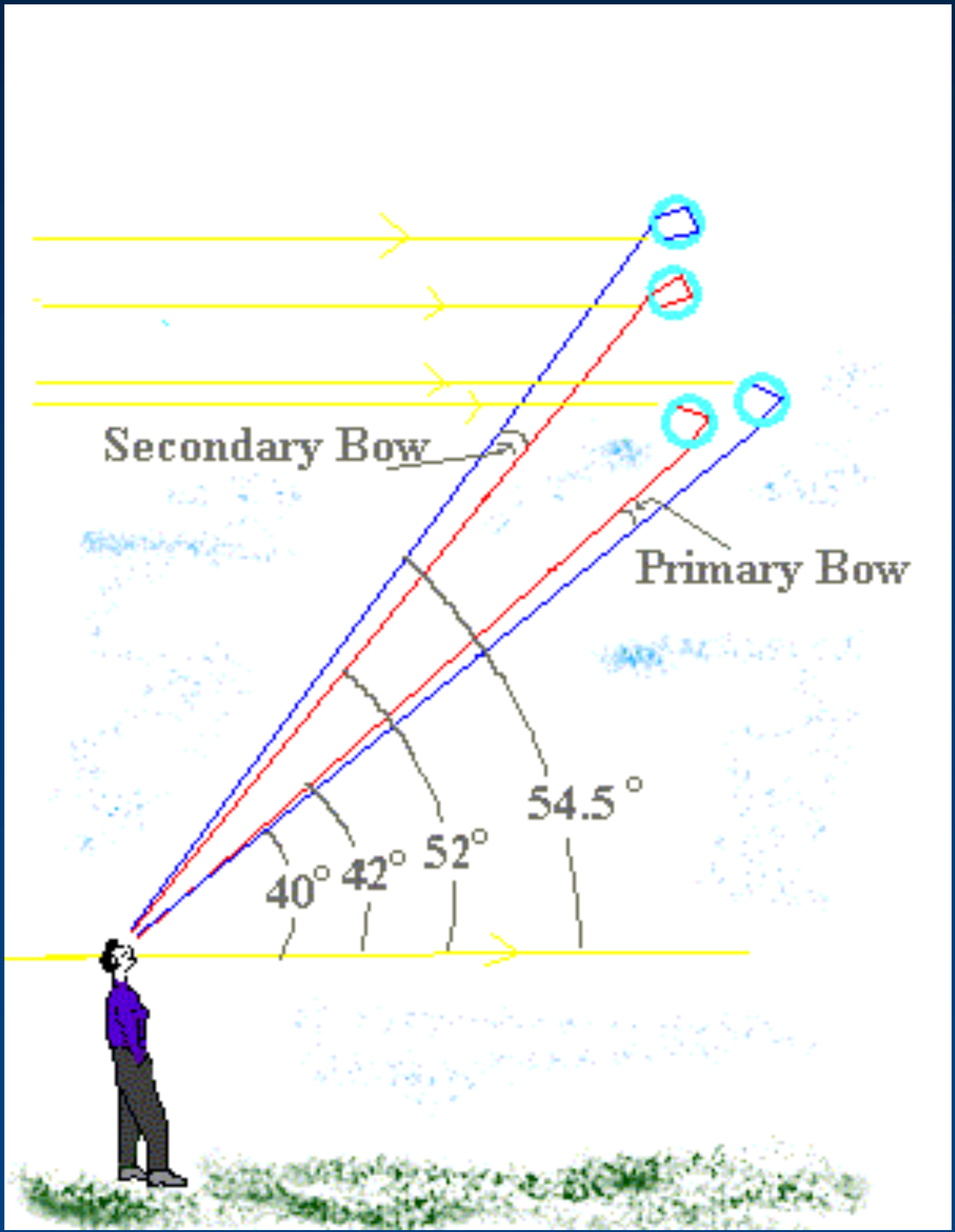


rred orange yellow green blue violet

What's happening in the cloud?



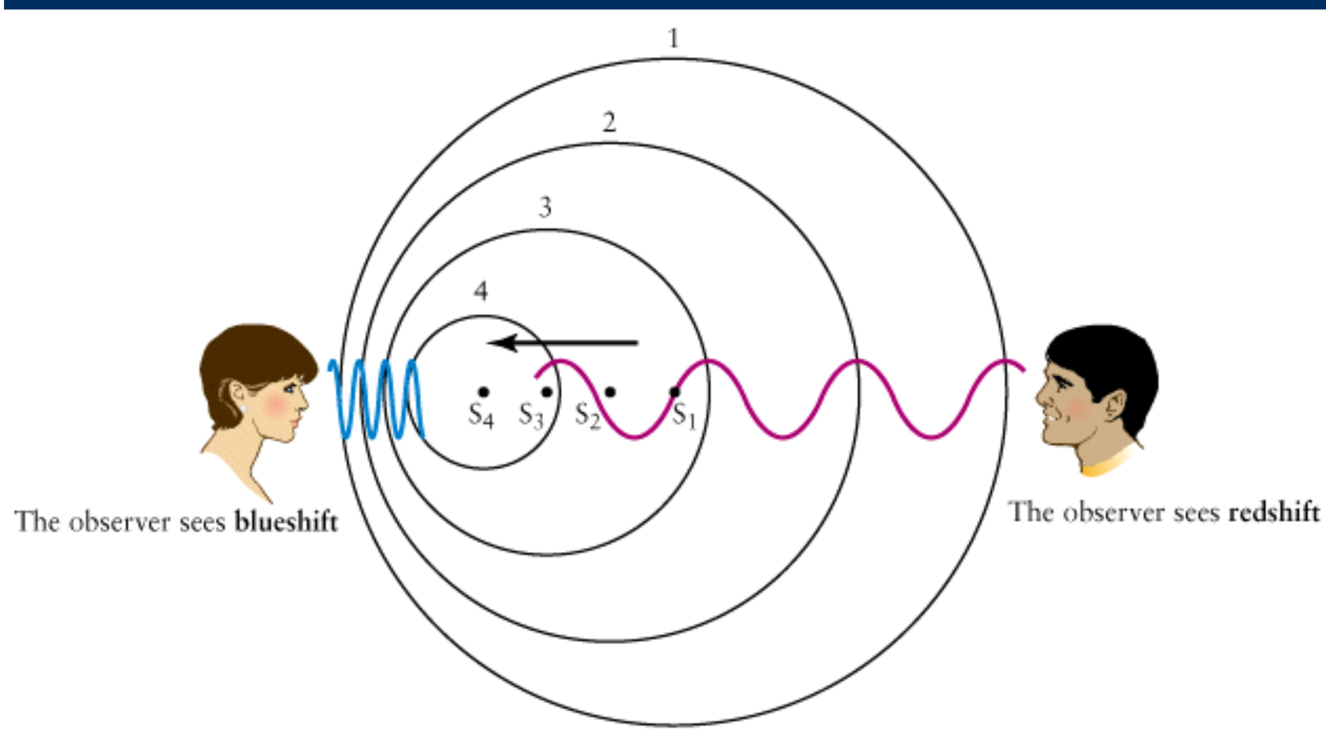
Double Rainbows

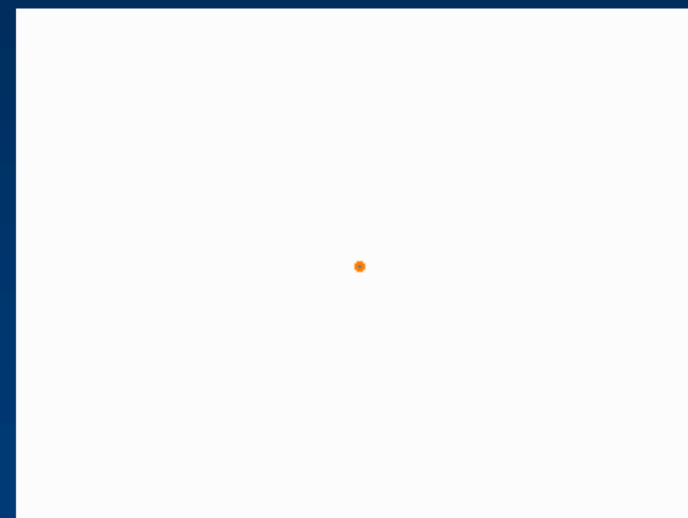


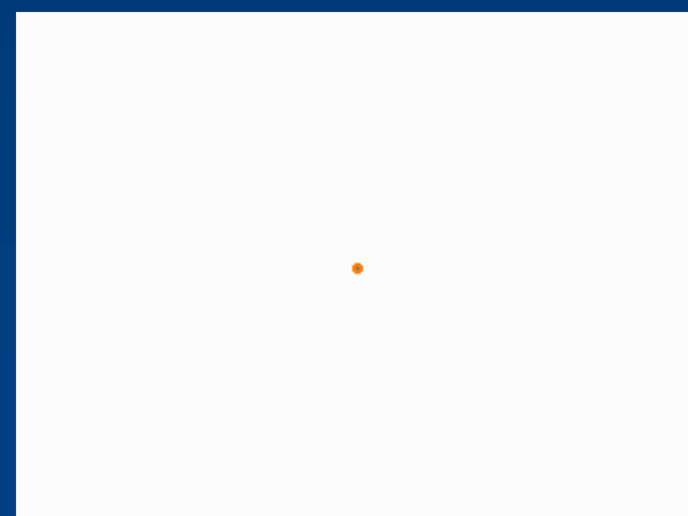
Sun Dogs and Crazy Clouds

The Doppler shift

Frequency or wavelength of a wave depends on relative motion of emitter and receiver (along the direction of wave motion).





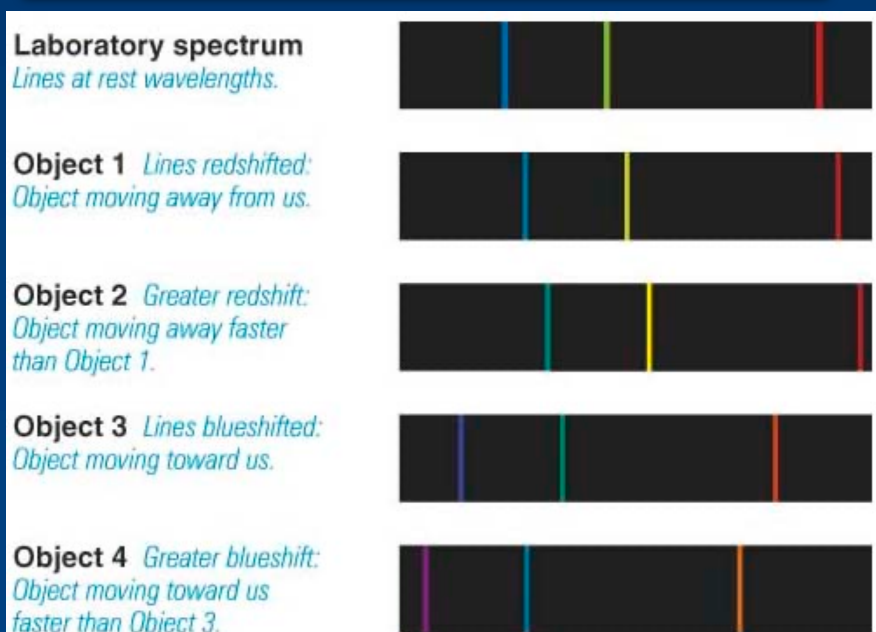


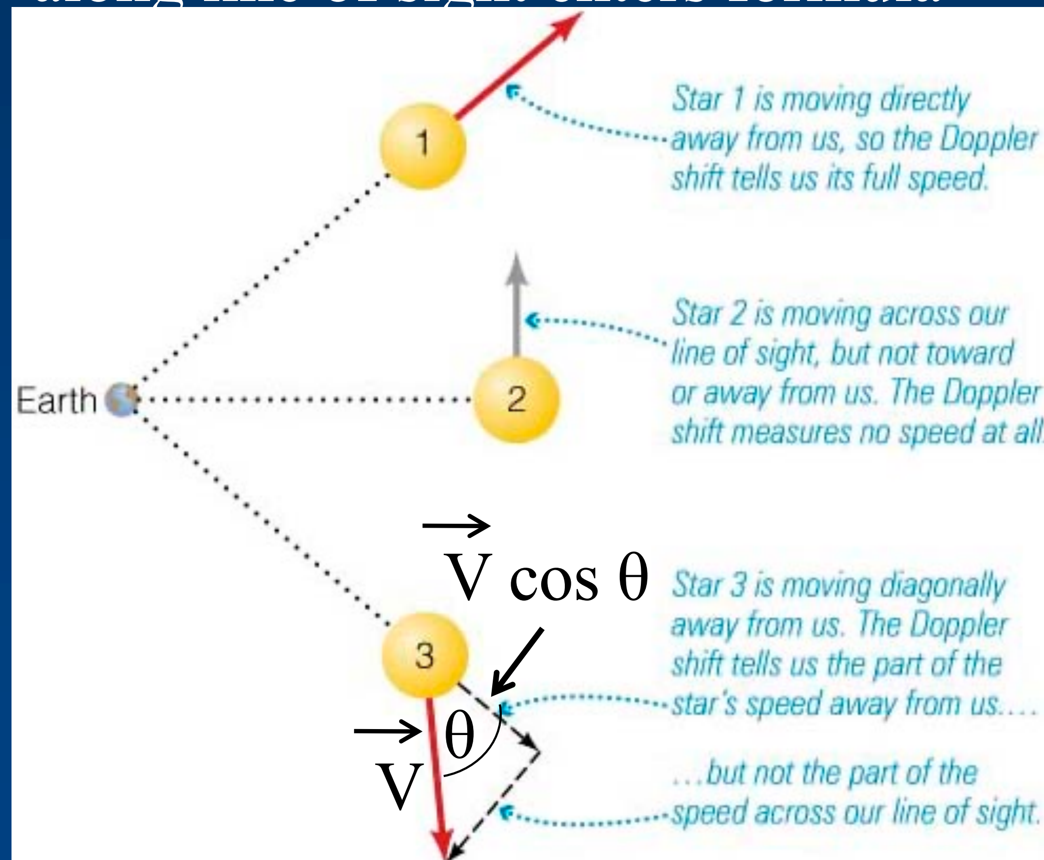
$$V = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}} c = \frac{\Delta\lambda}{\lambda_{emitted}} c$$

where V is the relative velocity along the line of sight, and c is the speed of light (both in same units, e.g. m/s).

If V is at some angle, only component along line of sight enters formula

Spectral lines are used to measure Doppler shift => gives us information about the motion of an object.





Example Doppler shift

- A spectral line normally seen at 300nm is shifted to 301nm due to relative motion of the source. What is the velocity of the source? Is it approaching or receding? "Redshift" or "blueshift"?
- What is the velocity?