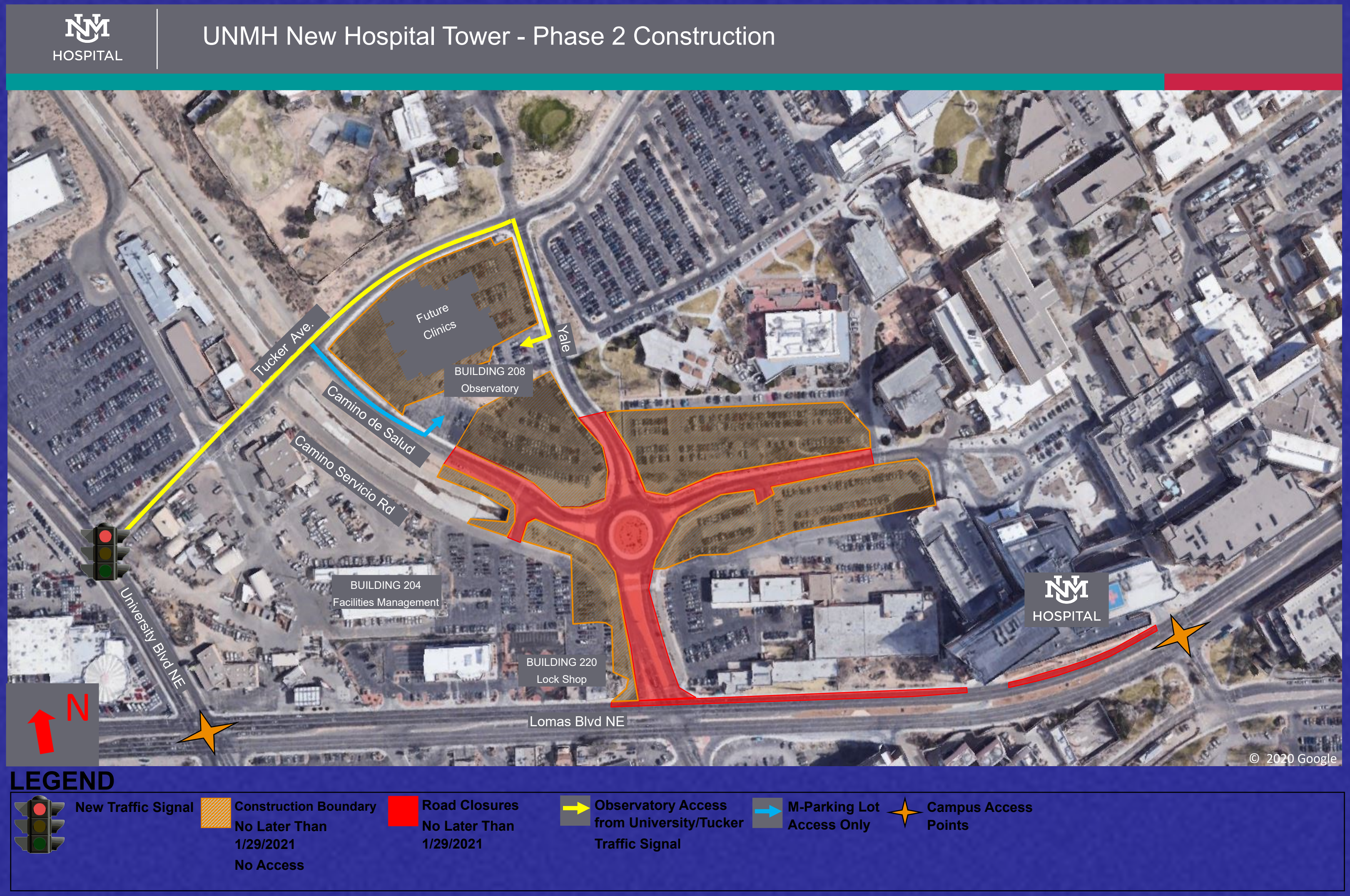
Announcements

- HW#1 is due via UNM Learn on Thursday Jan 28 by the START of CLASS
  - After 11:00am it is late and there will be a penalty of 15% (see syllabus)



Temperature

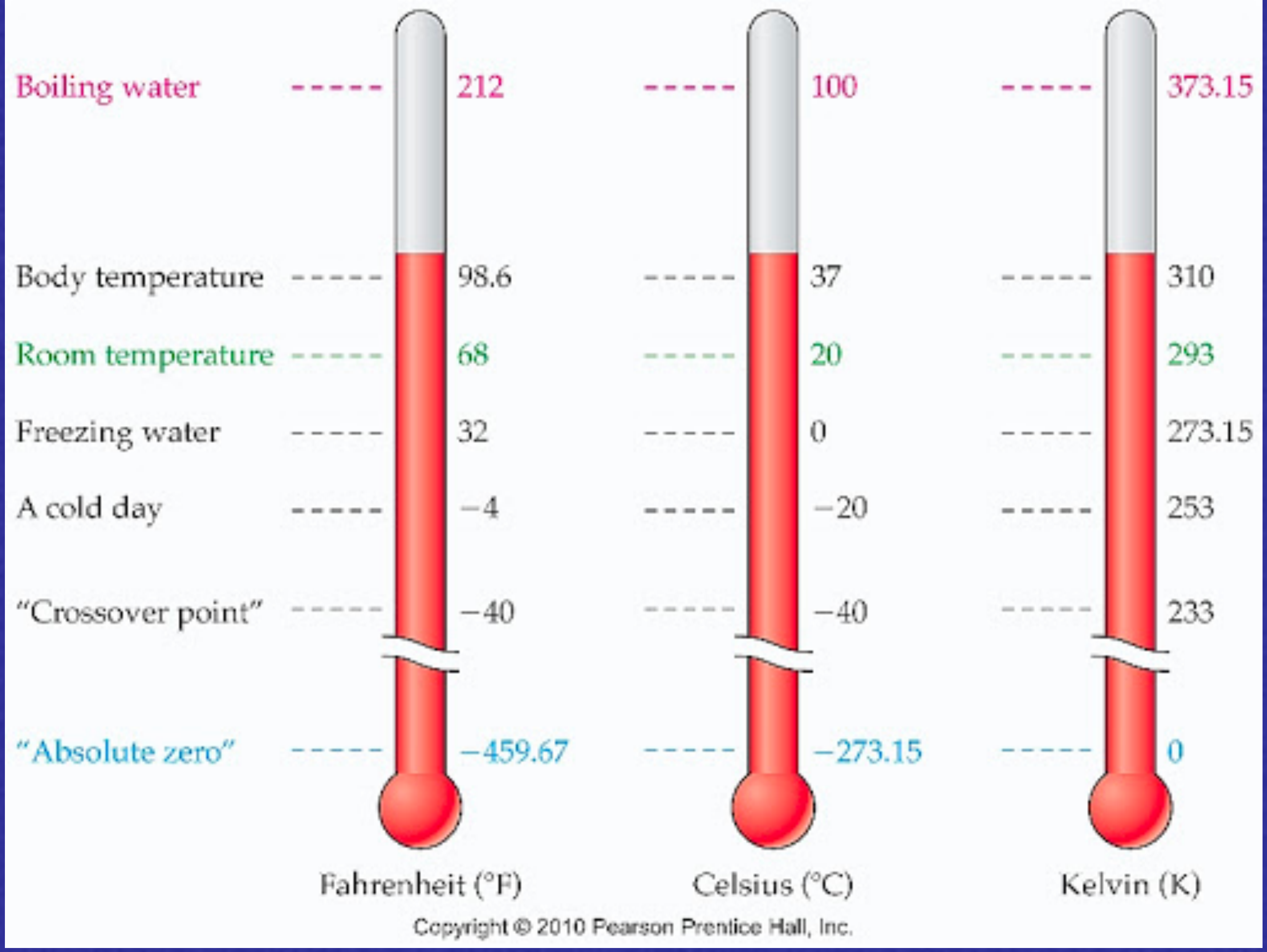
- A measurement of the internal energy content of an object.
- Solids: Higher temperature means higher average vibrational energy per atom or molecule.
- Gases: Higher temperature means more average kinetic energy (faster speeds) per atom or molecule.

Temperature

- At high temperatures atoms and molecules move quickly, and slower at lower temperatures.
- If it gets cold enough, all motion will stop.
- Corresponds to a temperature of -273° C (-459° F) - *absolute zero.*

Kelvin Temperature Scale

- An absolute temperature system in which the temperature is directly proportional to the internal energy.



– Uses the Celsius degree, but a different zero point.
– 0 K: absolute zero
– 273 K: freezing point of water
– 373 K: when water boils

Temperature conversions

– Fahrenheit, Celsius, Kelvin (absolute)
– 0 K = -273 °C $(T_K = T_C + 273)$
– Room temp about 300 K

Temperature conversions

$$T_F = \frac{9}{5} T_C + 32$$

$$T_C = \frac{5}{9}(T_F - 32)$$

$T_F =$ temperature in degrees Fahrenheit

$T_C =$ temperature in degrees Celsius

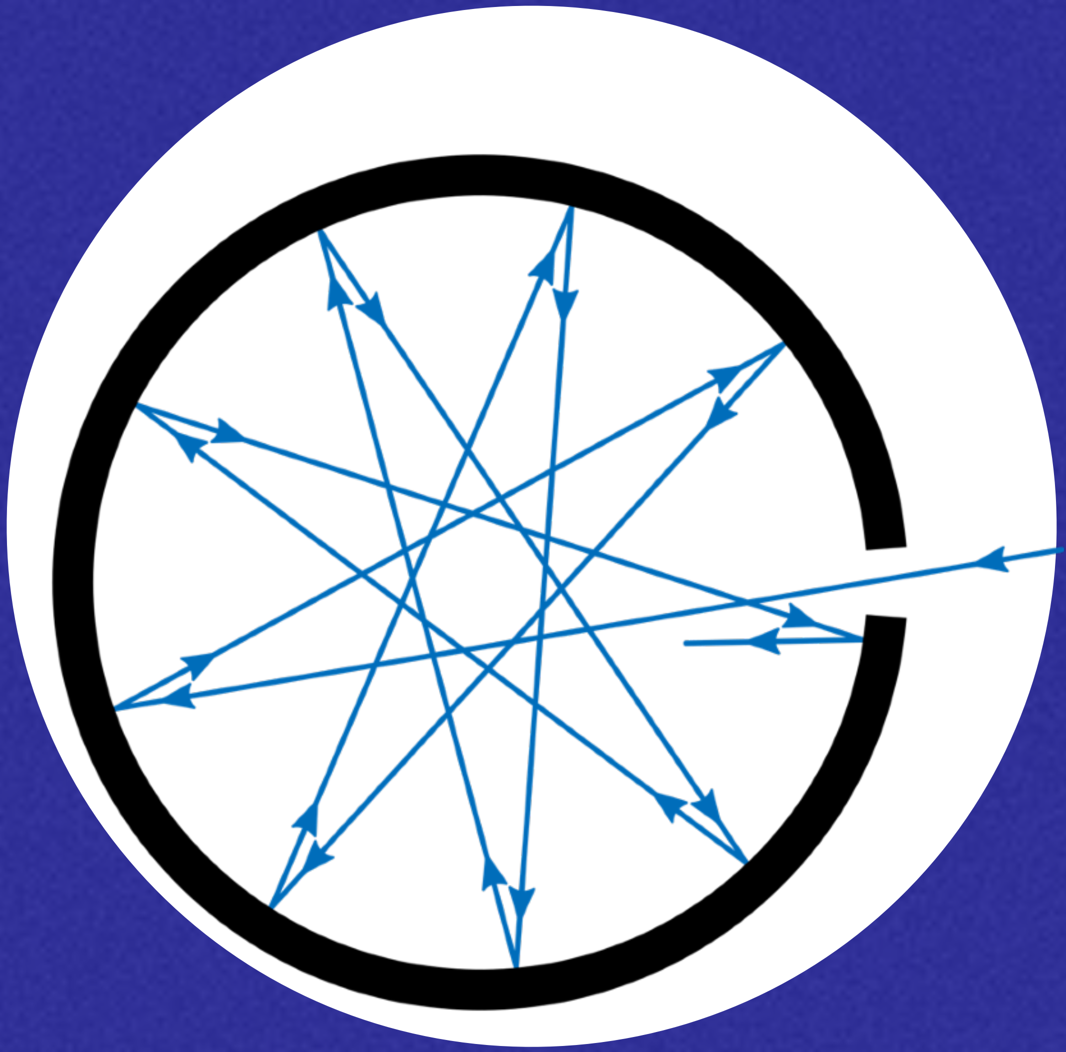
Thermal radiation

- Let's consider the concept of a "blackbody"
  - Tenuous gas: most light can pass through relatively unaffected
  - Denser matter (like a rock) will not allow light to pass as easily

- A dense body will absorb light photons over a wide range of wavelengths

- This also means the absorbed photon cannot easily escape - once reemitted it immediately interacts with another molecule

- The photons bounce around inside the body for a long time, and when they finally escapes it has randomized



A perfect absorber/emitter is called a blackbody

Blackbody (thermal) radiation

- A blackbody is an object that absorbs all light, at all wavelengths: perfect absorber
  - No reflected light
- As it absorbs the light, it will heat up
  - Characterized by its temperature
- A black body will emit light at all wavelengths (continuous spectrum): perfect emitter
  - Energy emitted depends on temperature

The radiation the blackbody emits is entirely due to its temperature.

Intensity, or brightness, as a function of frequency (or wavelength) is given by Planck's Law:

$$I_\nu = \frac{2h\nu^3}{c^2}\left[\frac{1}{e^{h\nu/kT} - 1}\right]$$

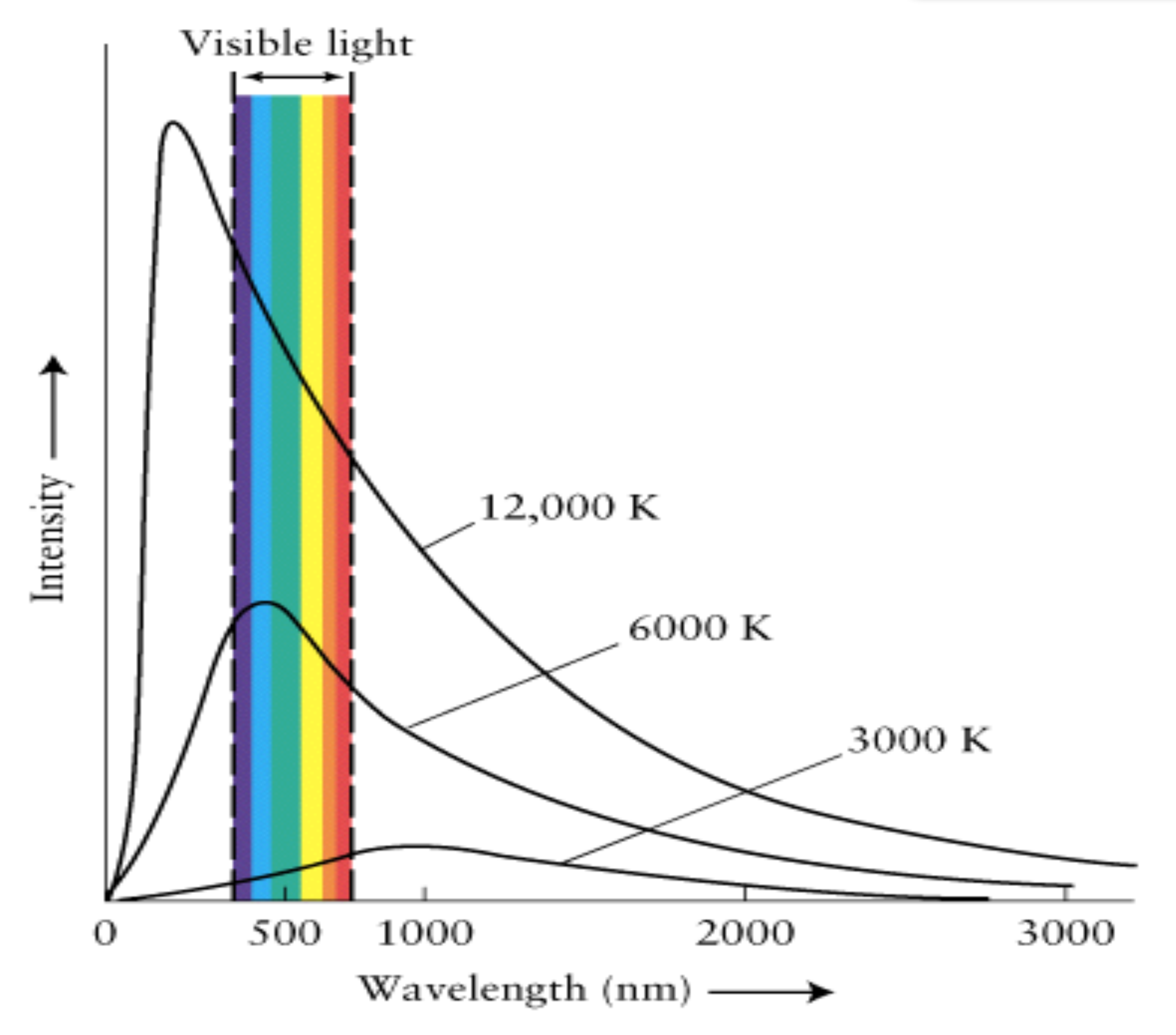
where k is Boltzmann constant = 1.38 x 10^{-23} J/K

Units: J s^{-1} m^{-2} ster $^{-1}$ Hz^{-1}

$$I_\lambda = \frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT} - 1}\right]$$

Units: J s^{-1} m^{-2} ster $^{-1}$ m^{-1} OR J s^{-1} m^{-3} ster $^{-1}$

Example: 3 blackbody (Planck curves) for 3 different temperatures.



Wien's law for a blackbody

$\lambda_{max} = 0.0029/T$

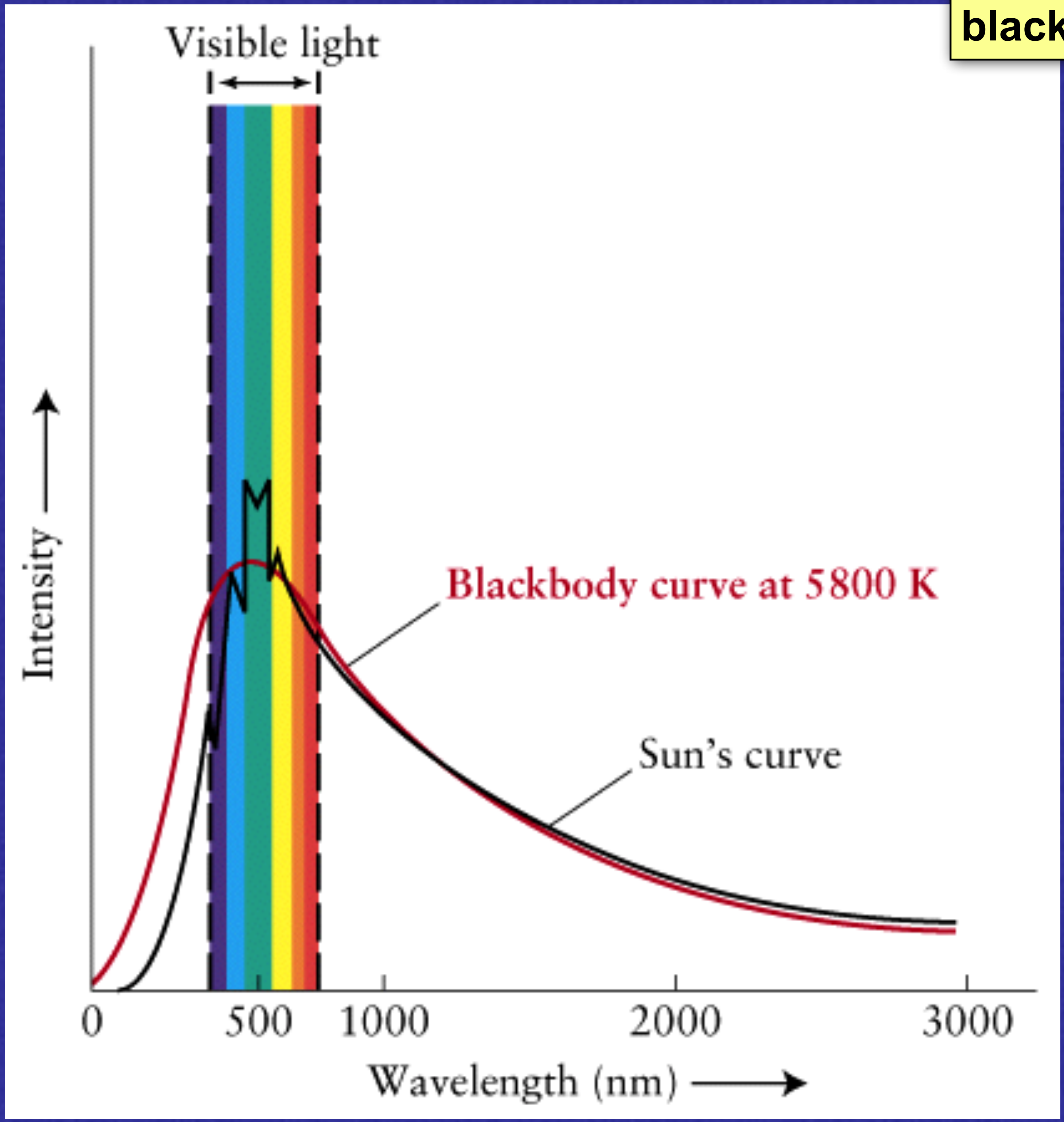
where λ_{max} is the wavelength of maximum emission of the object (in m), and T is the temperature of the object (in K).

=> The hotter the blackbody, the shorter the wavelength of maximum emission

Question: which is bluer, hotter or cooler objects?

Hotter objects are bluer, cooler objects are redder.

The spectrum of the Sun is *almost* a blackbody curve.



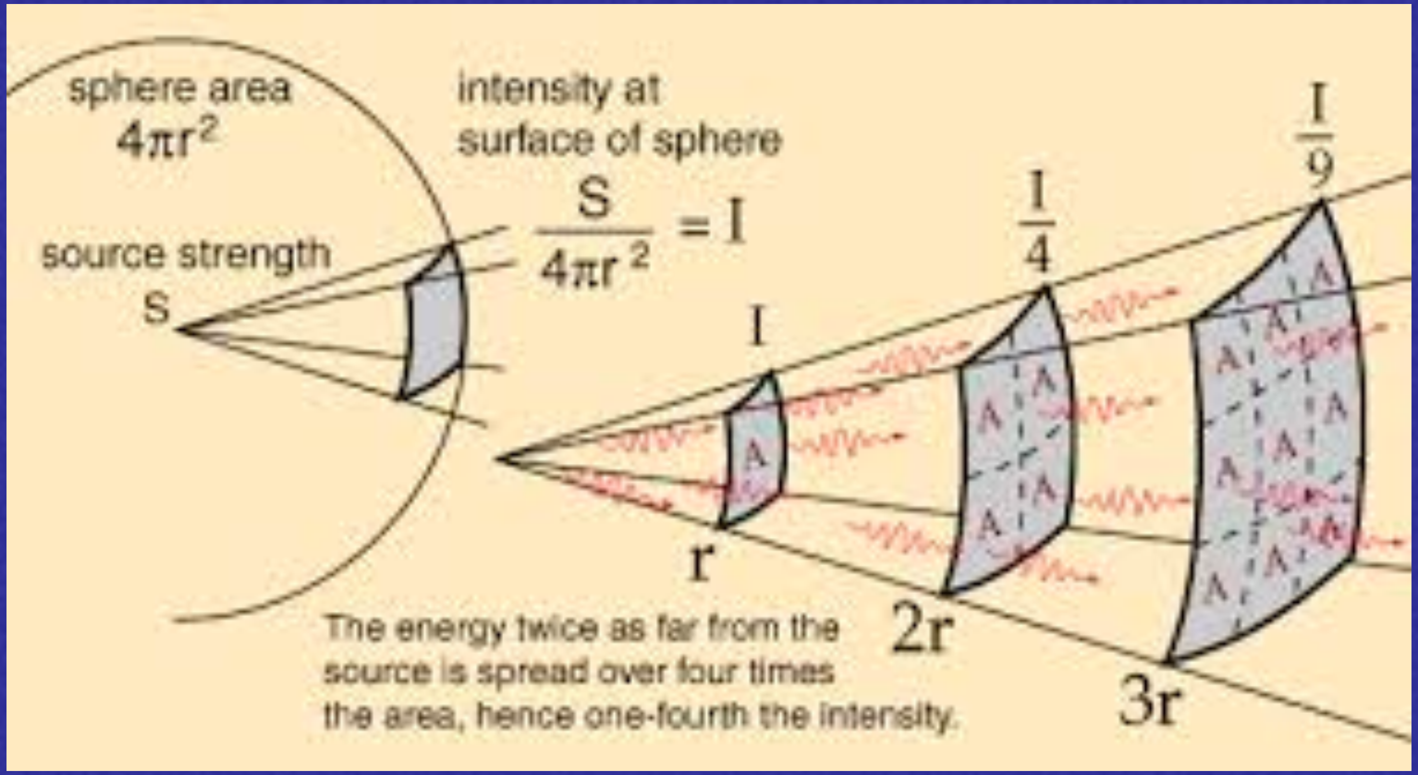
- <u>Example 1:</u> How hot is the photosphere of the Sun?
- Measure λ_{max} to be about 500 nm, so
- $T_{sun} = 0.0029/\lambda_{max} = 0.0029/5.0x10^{-7} = 5800$ K
- <u>Example 2:</u> At what wavelength would the spectrum peak for a star which is 5800/2 = 2900 K?
- For a star with T= 5800 x 2 = 11,600 K?
- What colors would these stars be?

Stefan-Boltzmann law for a blackbody

$F = \sigma T^4$

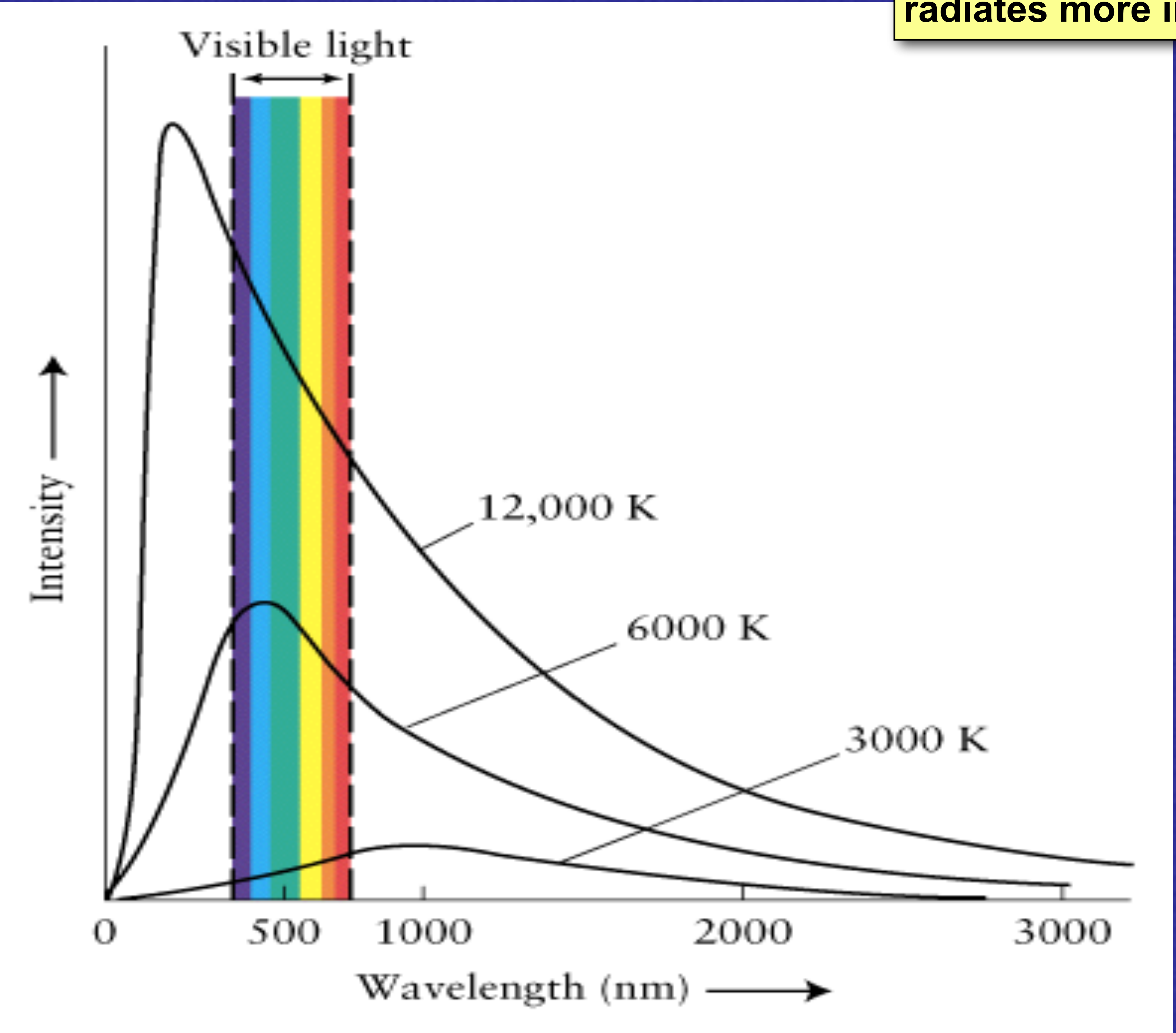
F is the energy flux, in $J\ s^{-1}\ m^{-2}$

σ is a constant = $5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$,
T is the object's temperature (in K).



The hotter the blackbody, the more radiation it gives off at all wavelengths.

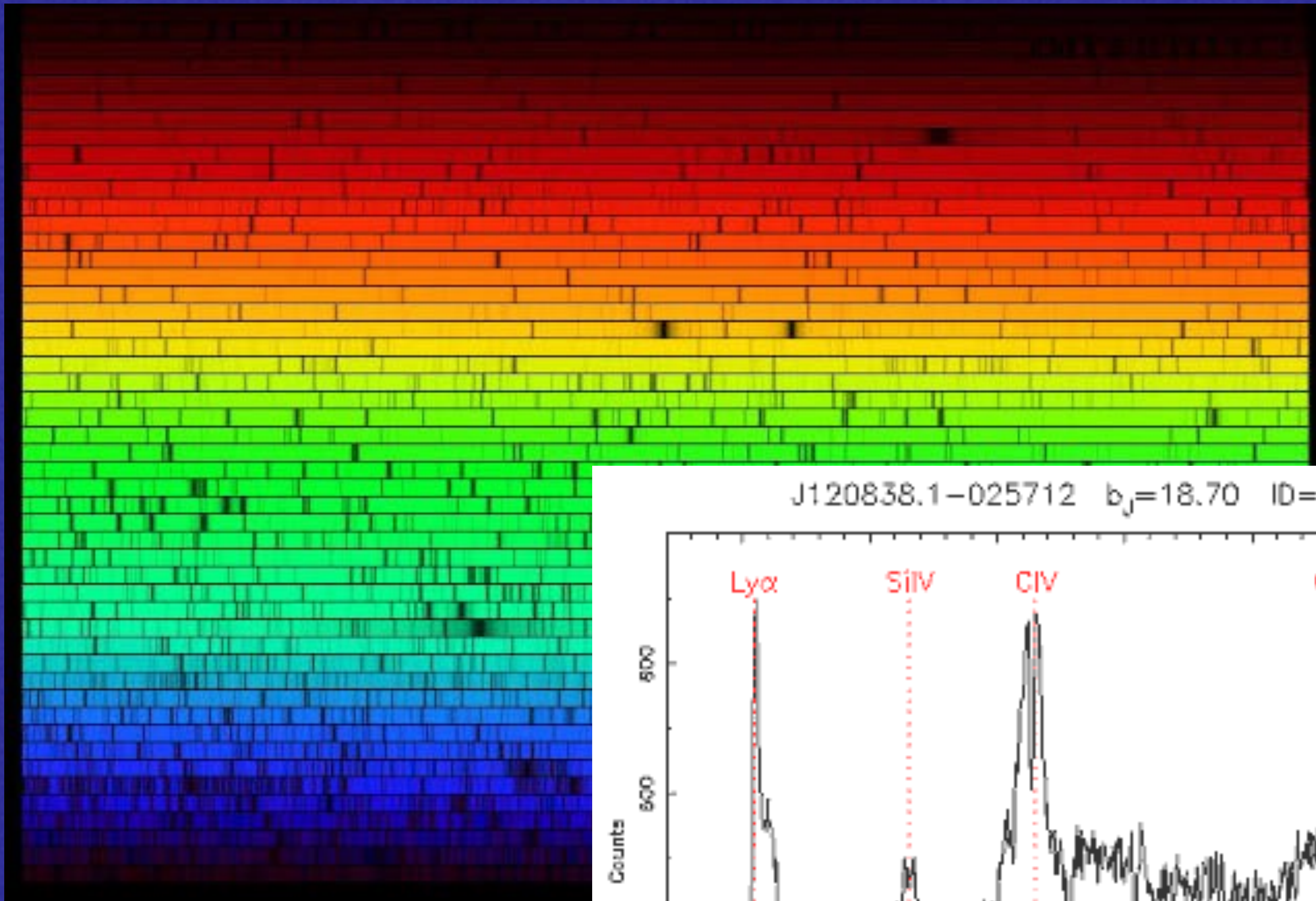
At any wavelength, a hotter body radiates more intensely.

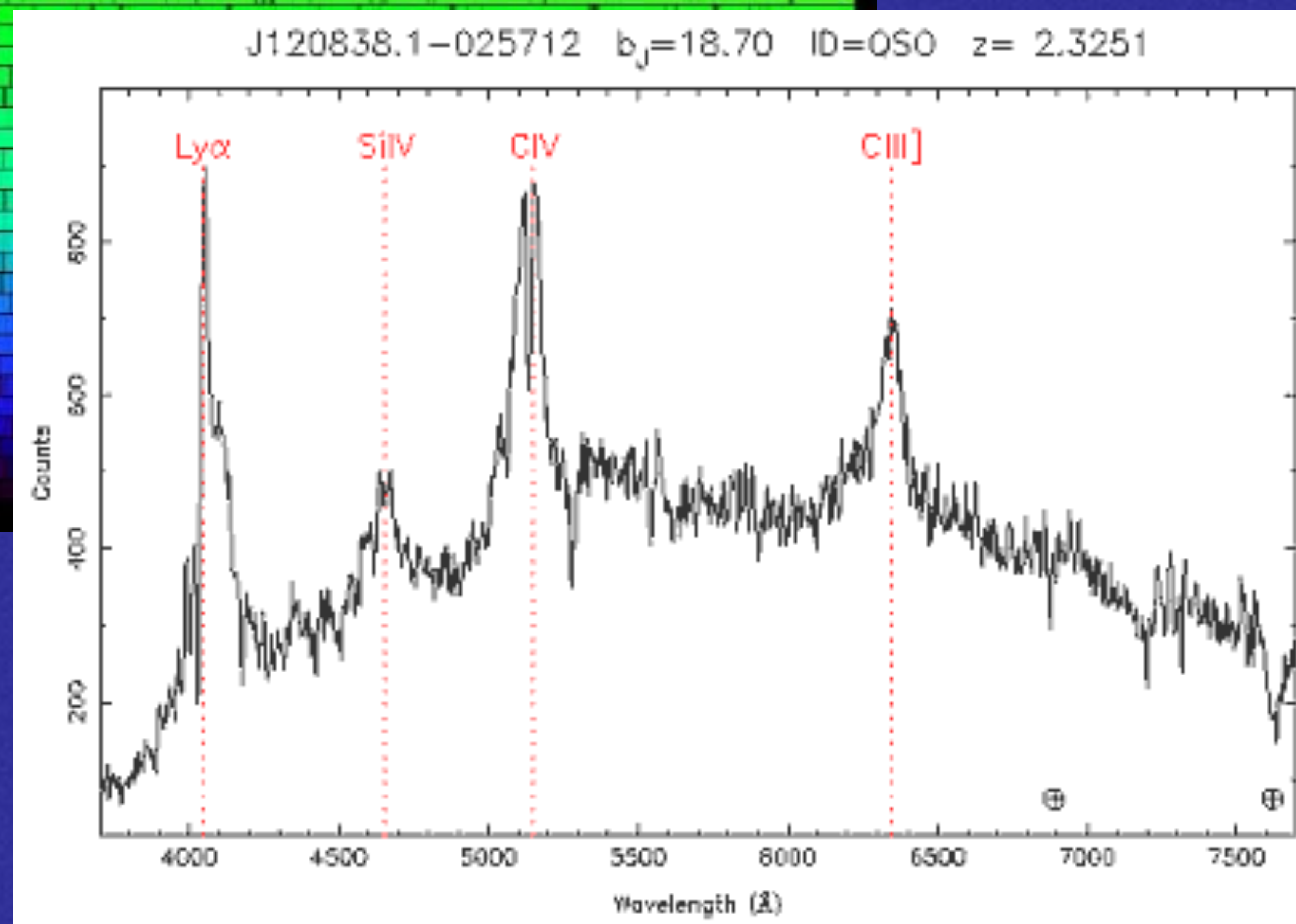


- <u>Example:</u> If the temperature of the Sun were twice what it is now, how much more energy would the Sun produce every second?

2^4 is 2*2*2*2 = 4*4 = 16 times as much energy

- See box 5-2 for more examples.





J120838.1−025712 b$_J$=18.70 ID=QSO z= 2.3251
Lyα
SiIV
CIV
CIII]
Counts
4000
4500
5000
5500
6000
6500
7000
7500
Wavelength (Å)

How are these spectra produced?

By photons interacting with matter!

Recall: we are interpreting the light collected by our telescopes.

$$E = hc/\lambda = h\nu$$

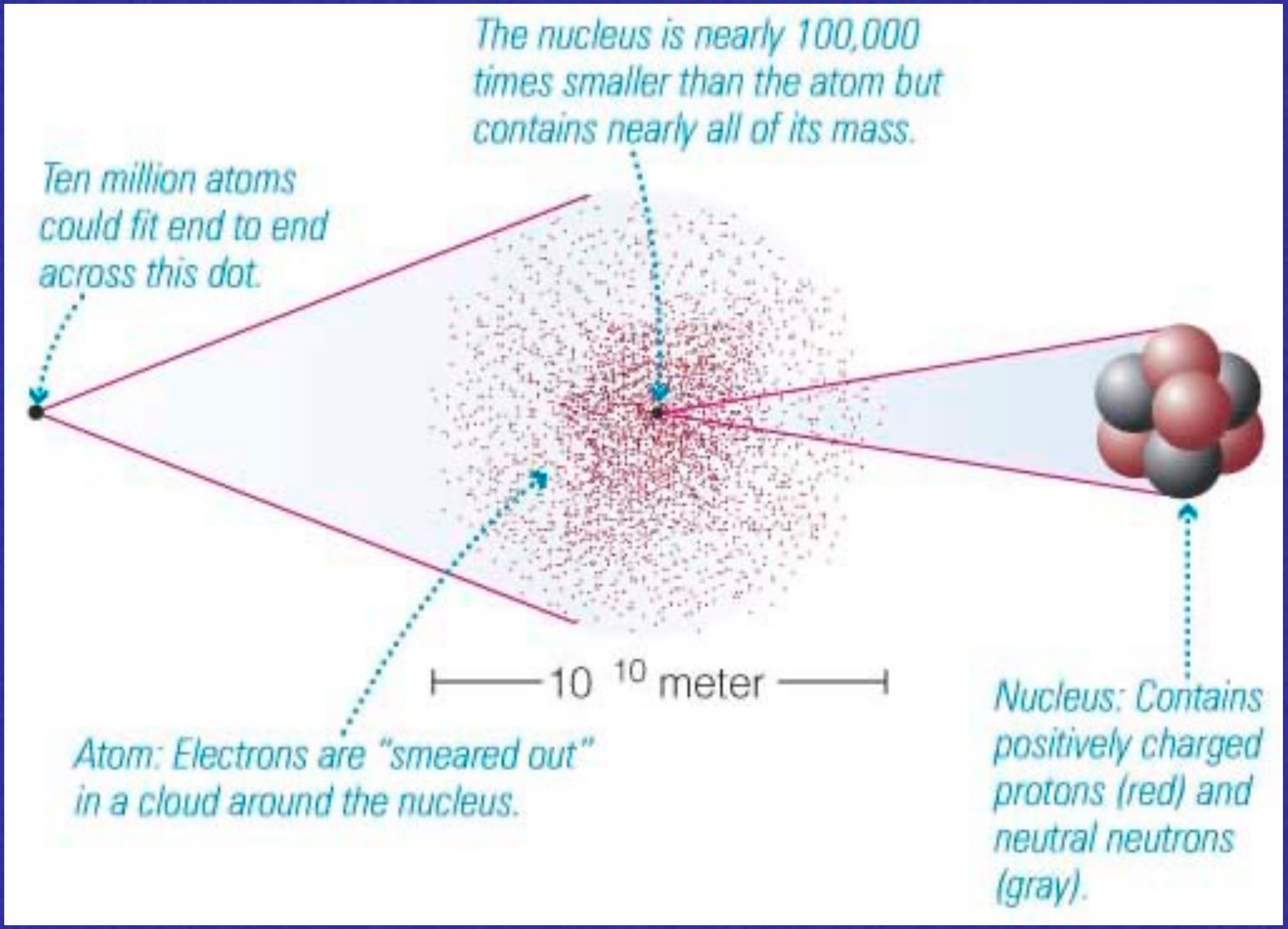
Let's look into how these interactions take place.

Atomic Structure

Nucleus contains heavy, subatomic particles:

- Protons (positively charged)
- Neutrons (uncharged)

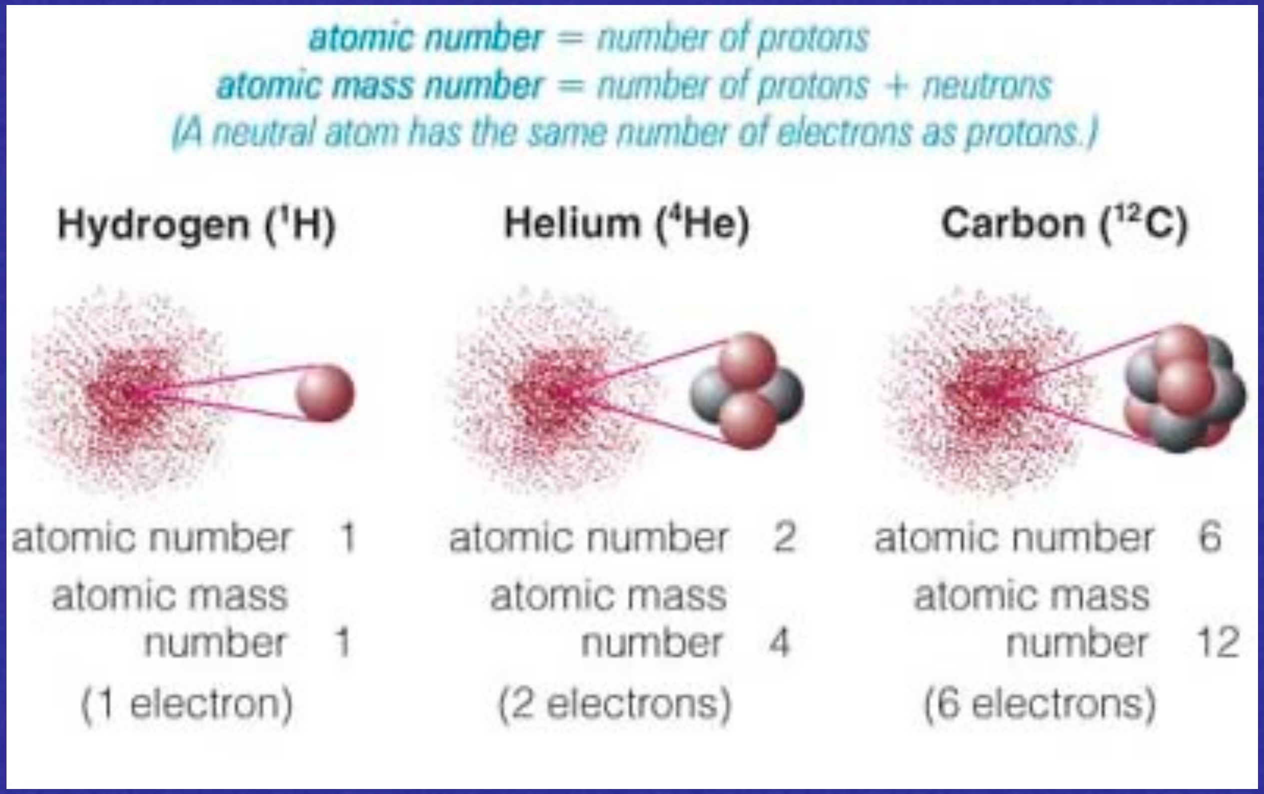
Electrons in a cloud orbiting the nucleus (negatively charged)



Chemical elements

- Atoms are distinguished into *elements* by the total number of protons in the nucleus.

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



How is energy stored in atoms?

Atoms can contain energy in three ways:

- Mass energy $E=mc^2$ (because of their mass)
- Kinetic energy (because of their motion)
- Electric potential energy (because of arrangement of electrons)

The last one is important here, because the electric potential energy is altered by EM radiation.

To understand how the atom reacts to EM radiation (and to interpret the results!) we need to know how atoms gain and release electrical potential energy.

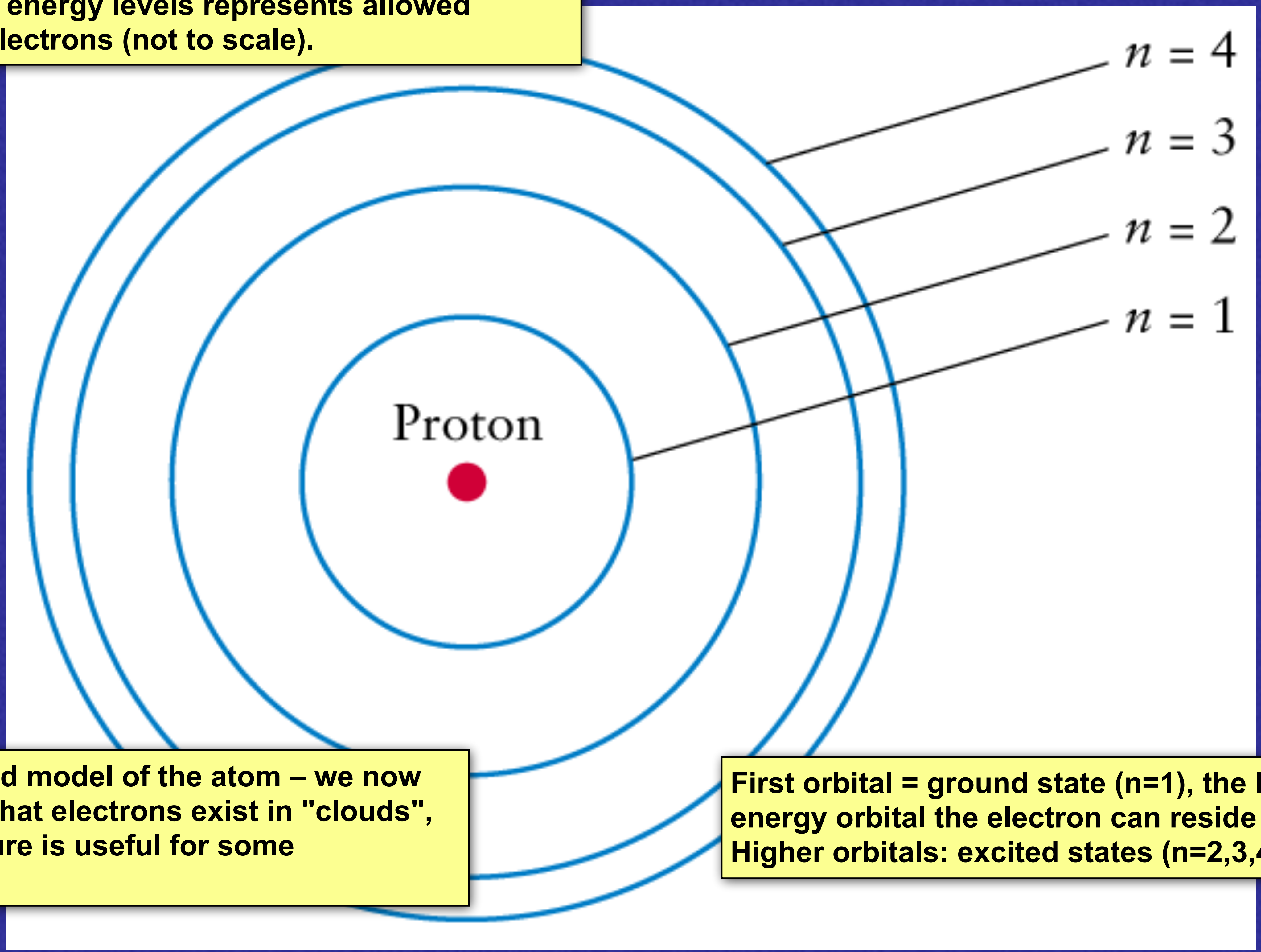
Inside the atom

Quantum mechanics determines the details:

- Electrons can only orbit the nucleus in discrete orbitals
- Each orbital corresponds to a particular energy of the orbiting electron
- The electron must have exactly the right energy - otherwise it cannot be in that orbital

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

The different energy levels represents allowed orbitals for electrons (not to scale).

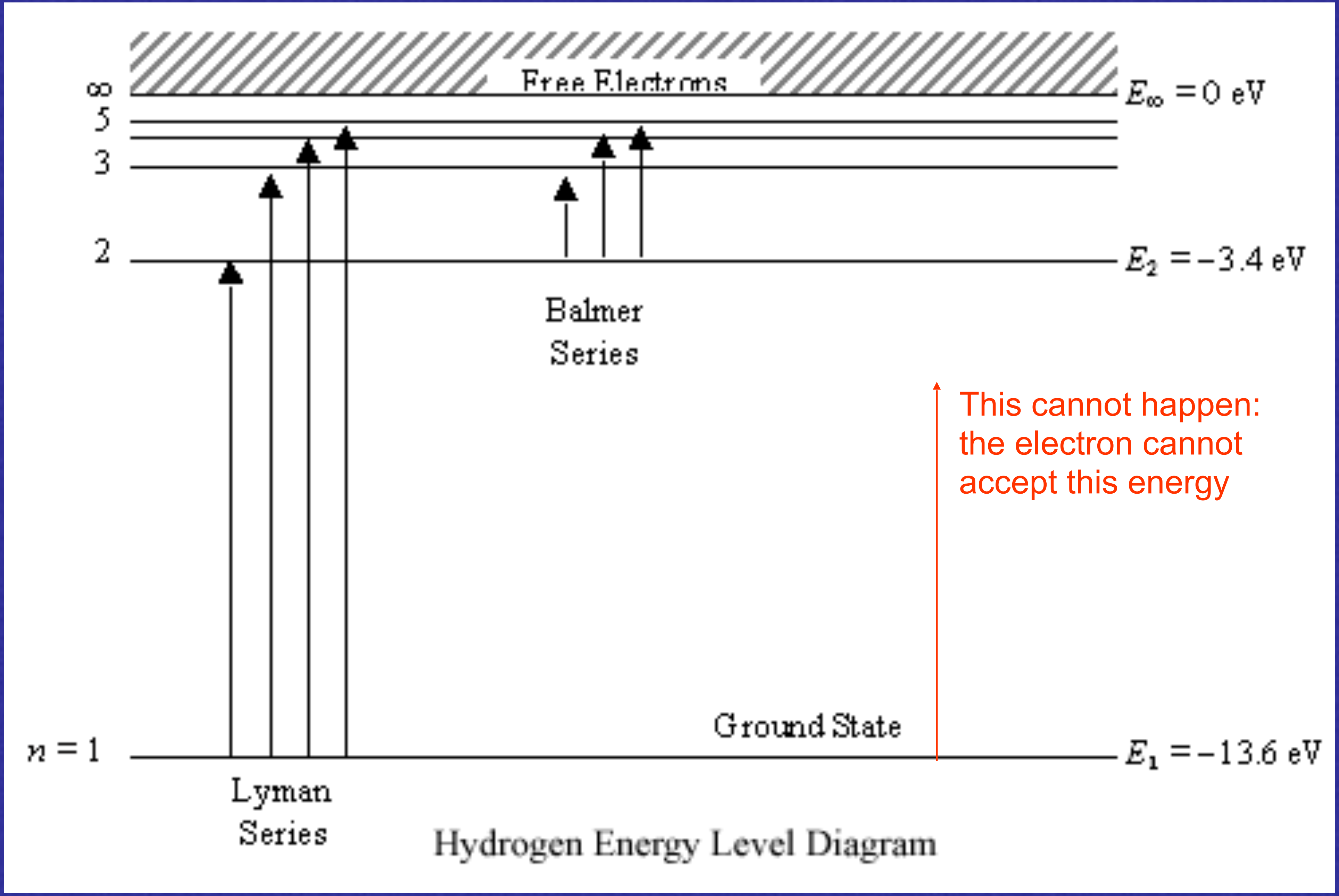


Old-fashioned model of the atom – we now understand that electrons exist in "clouds", but this picture is useful for some calculations.

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

Energy level diagram of H

Orbitals come in specific and exact energies



Emission and Absorption

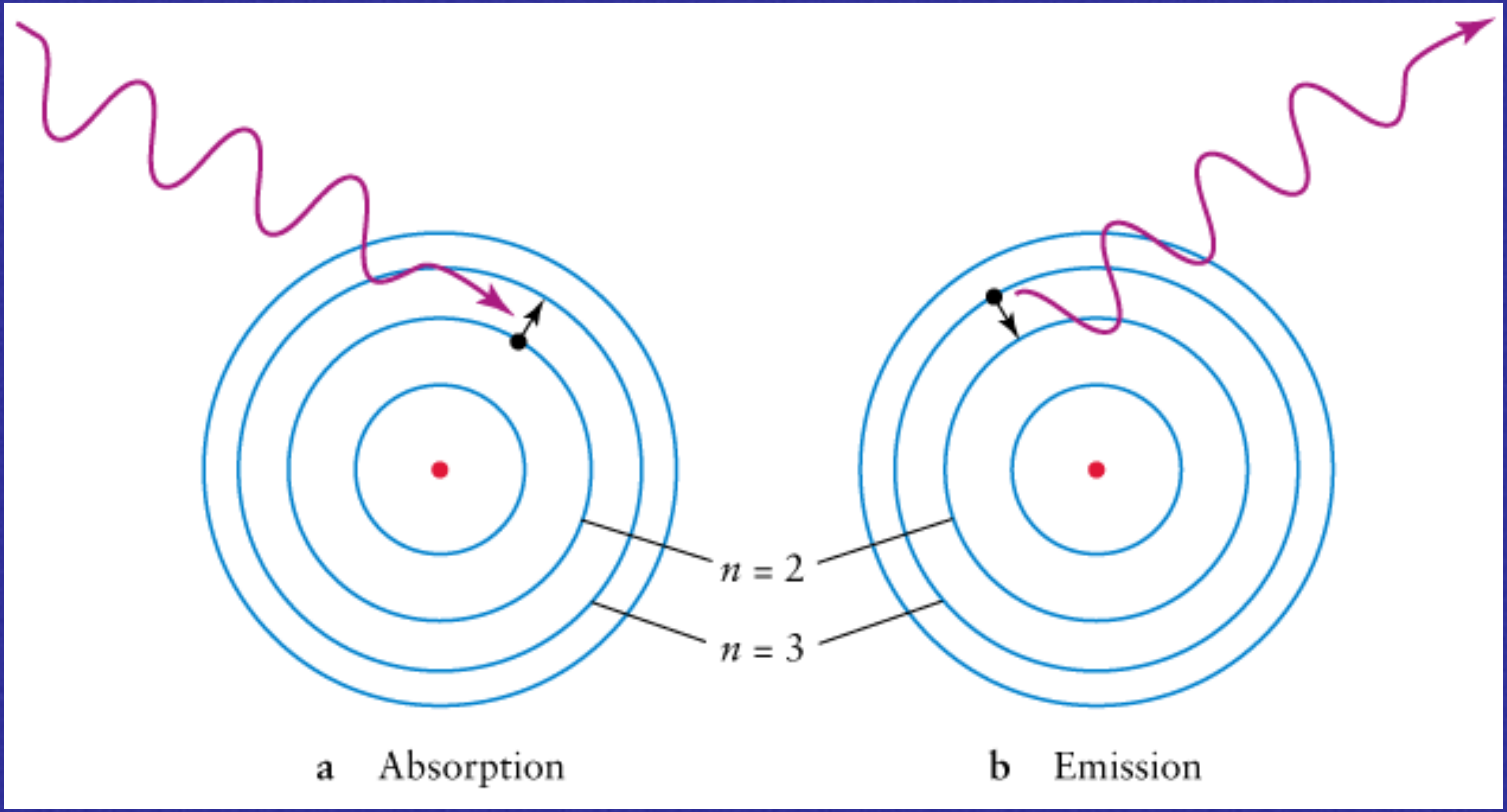
- Atoms can get into excited states by either
  - Colliding (other atoms or free electrons, higher T => higher E)
  - Absorbing photons (of specific energy)

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

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

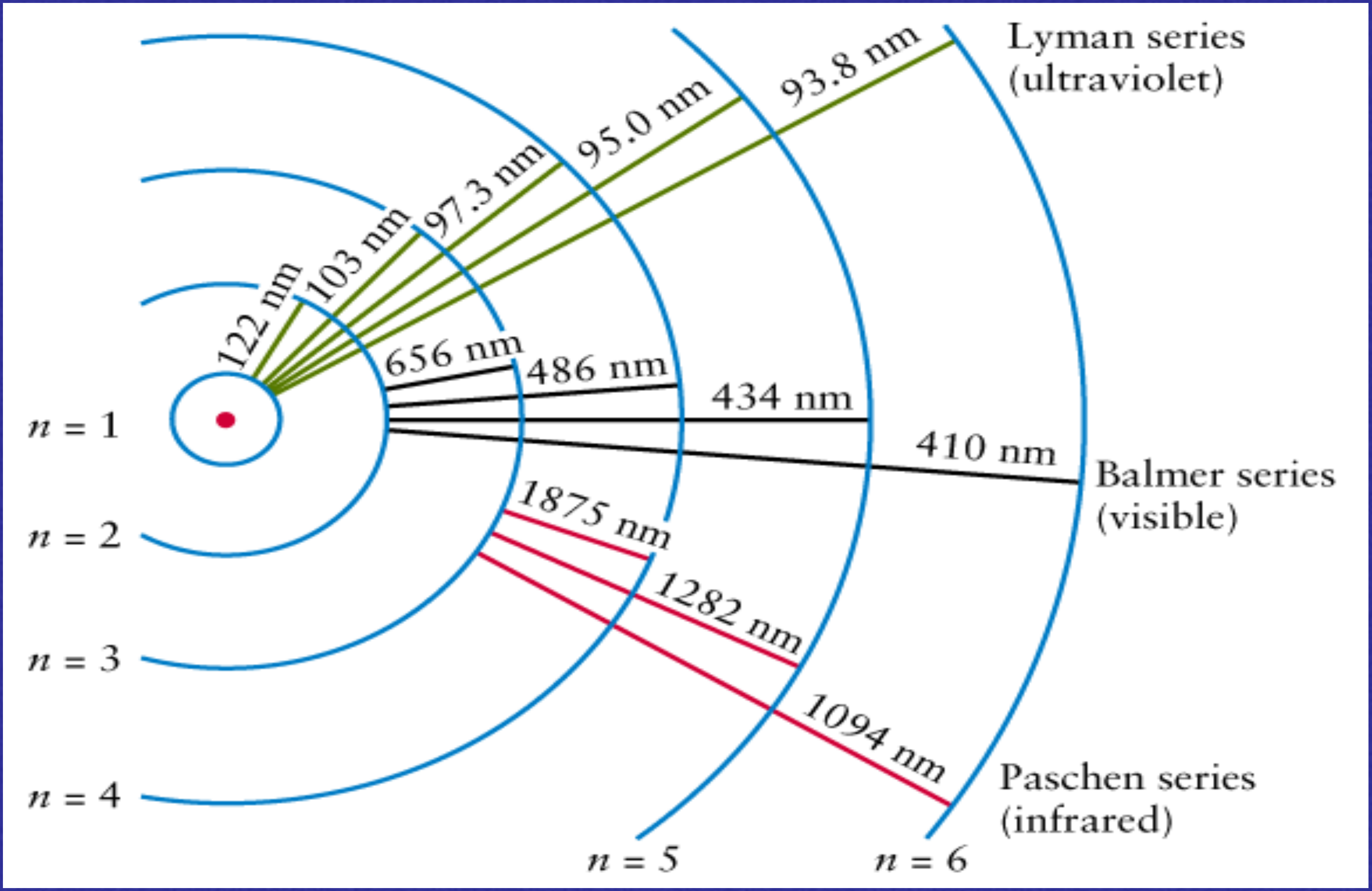
- Recall: $E = h\nu$ (a transition between energy levels correspond to a photon of a specific frequency).

- 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.



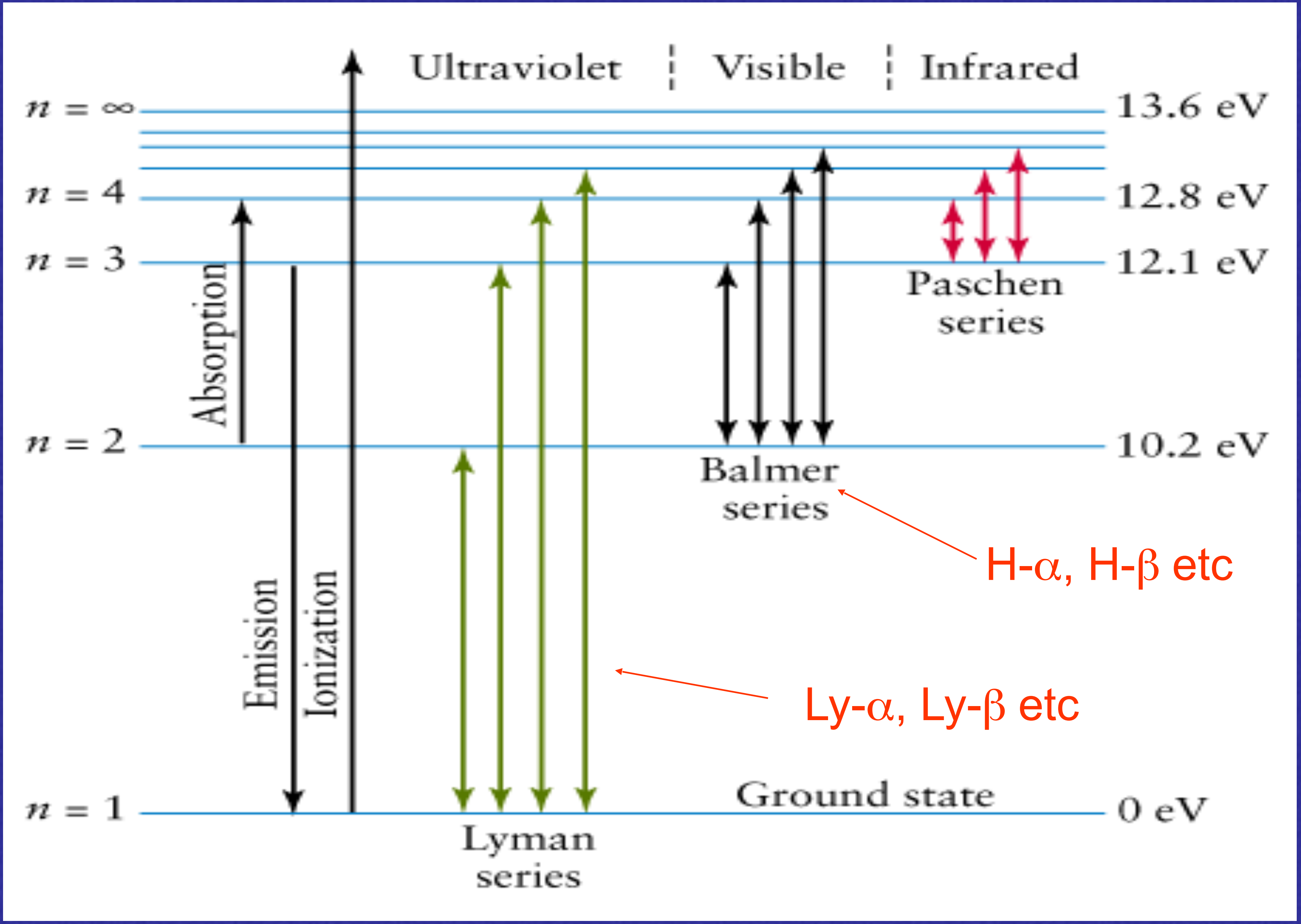
Emission and absorption line spectra

- Hot, low density gas where atoms are isolated will cause emission lines
  - Lines at specific wavelengths, dark between lines
- Light from continuous spectrum through cooler gas cause absorption lines
  - Dark regions corresponding to wavelengths of emission lines seen when the gas is hot, bright between lines



Lyman series
(ultraviolet)
93.8 nm
95.0 nm
97.3 nm
103 nm
122 nm
656 nm
486 nm
434 nm
410 nm
Balmer series
(visible)
1875 nm
1282 nm
1094 nm
Paschen series
(infrared)
$n = 1$
$n = 2$
$n = 3$
$n = 4$
$n = 5$
$n = 6$

Energy level diagram for hydrogen:



Excited, low-density hydrogen gas. Red due to “H-alpha” emission line, n = 3 to n = 2.

How is this gas is emitting light?

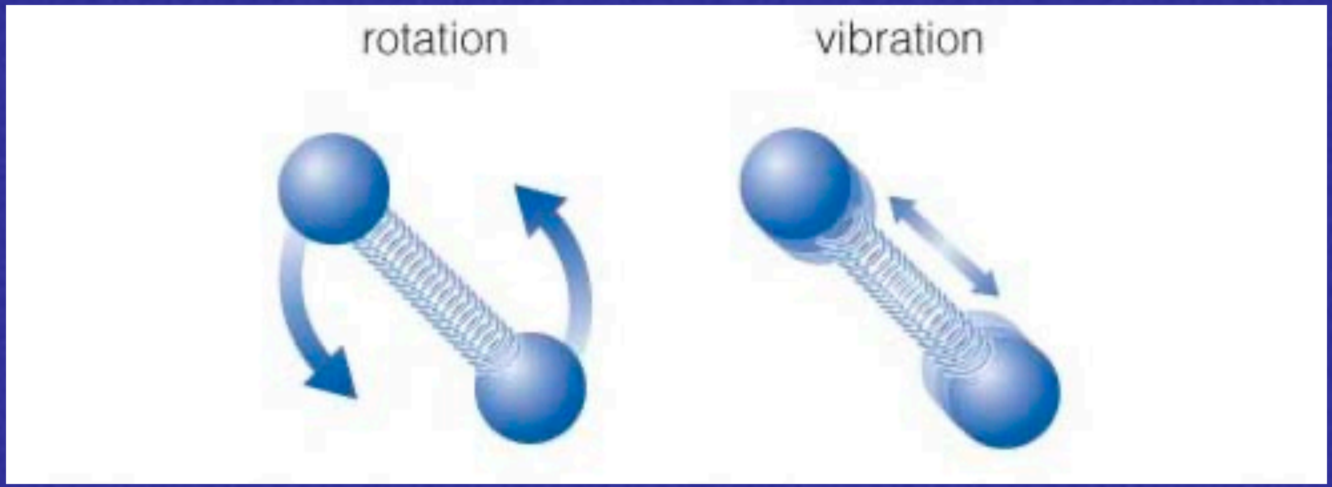
Fingerprints of matter

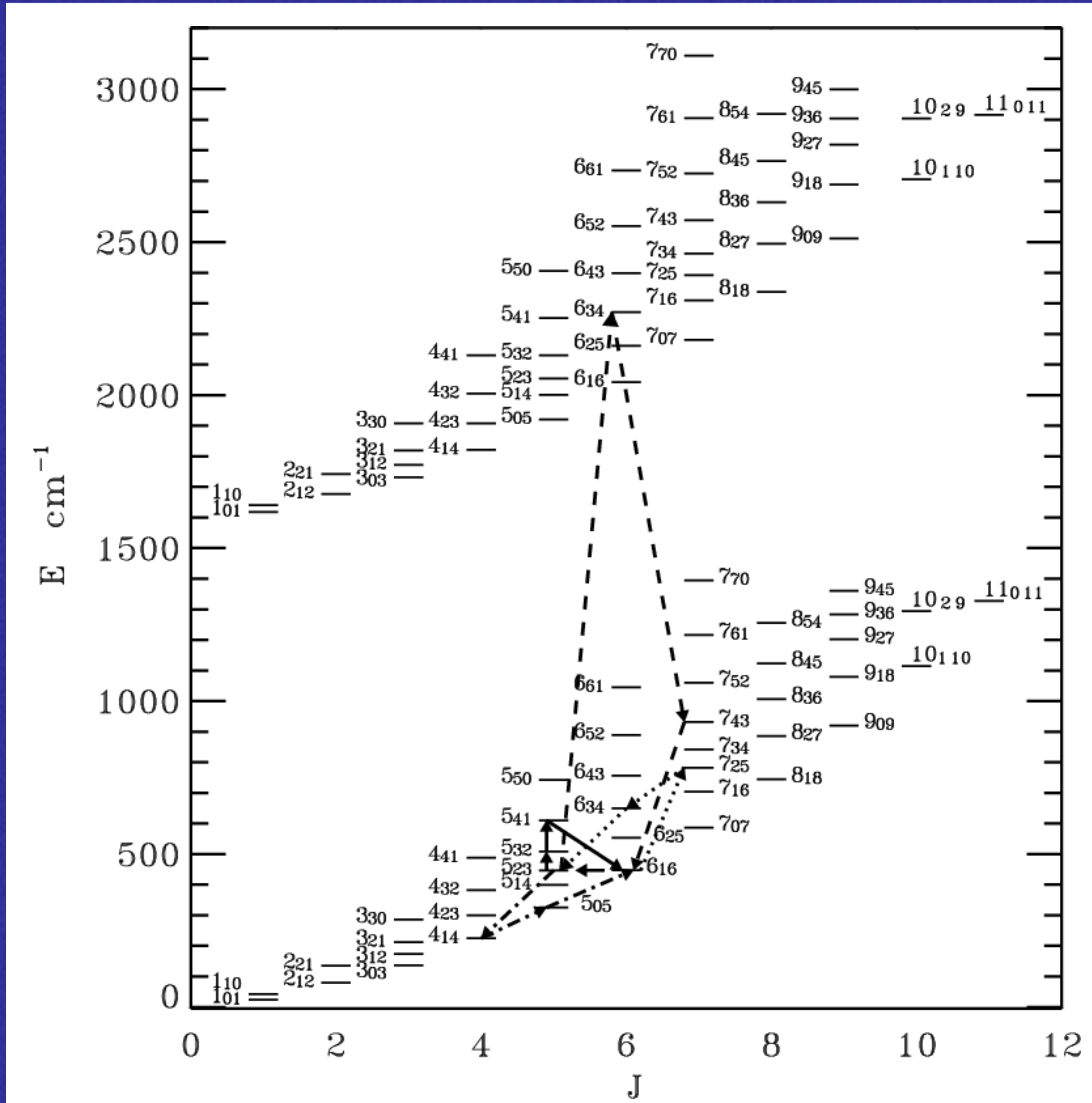
- H has an easy orbital structure, but more complex atoms (several electrons) will have more difficult structure
- This causes more energy levels and a more complex line spectra
- Each element has a unique spectrum, reflecting the unique electron orbital structure.
- Isotopes has same lines, but slightly shifted in wavelength.

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!




E cm^{-1}
0
500
1000
1500
2000
2500
3000
J
0
2
4
6
8
10
12

Ionization

- If an atom or a molecule absorbs enough energy from a photon or a collision, an electron can escape the force field => positive ion

- By adding electrons, you can get a negative ion

- Ions differ from the neutral atoms/molecules: different spectral line signatures, and different chemical properties

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)

=> Spectroscopy is a very important tool of the astronomer.

Doppler shifts: information about motion

- Happens for all wave phenomena:

  sound => change of pitch

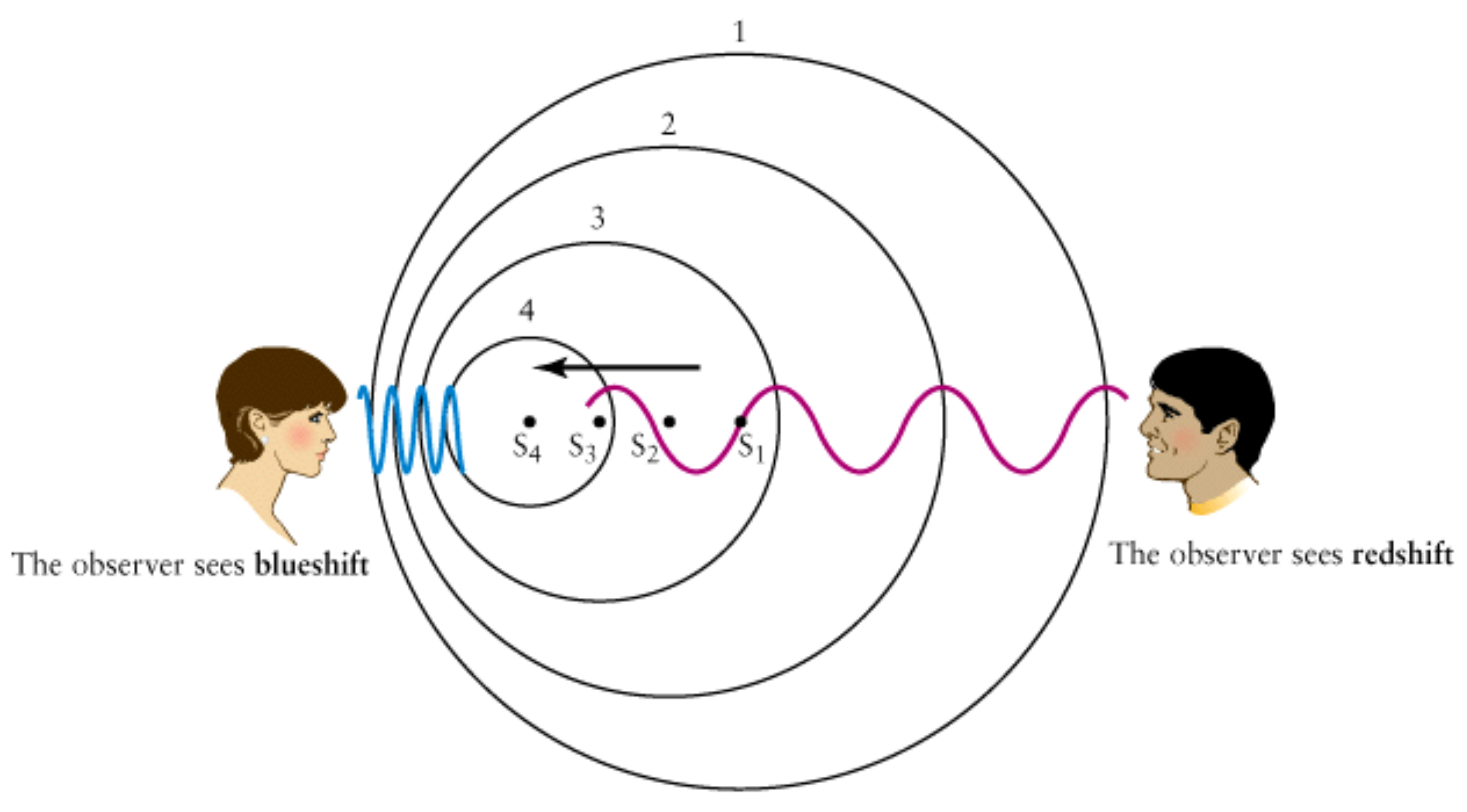
  light => change of wavelength (or color)

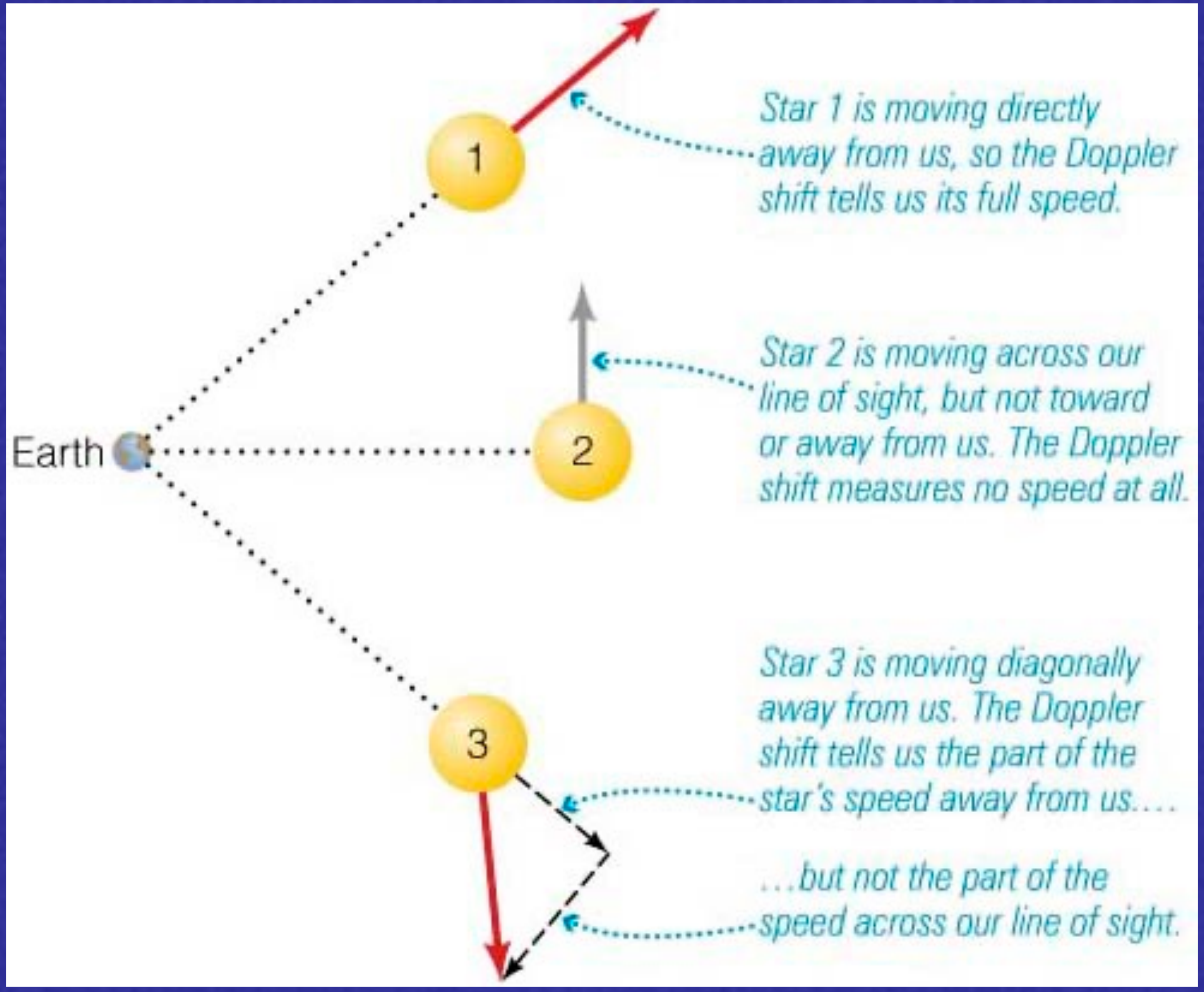
$$V_{rad} = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}} c = \frac{\Delta\lambda}{\lambda_{emitted}} c$$

where V_{rad} is the velocity of the emitting source (m/s), c is the speed of light (m/s).

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

Redshifted if receding, blueshifted (negative sign) if approaching



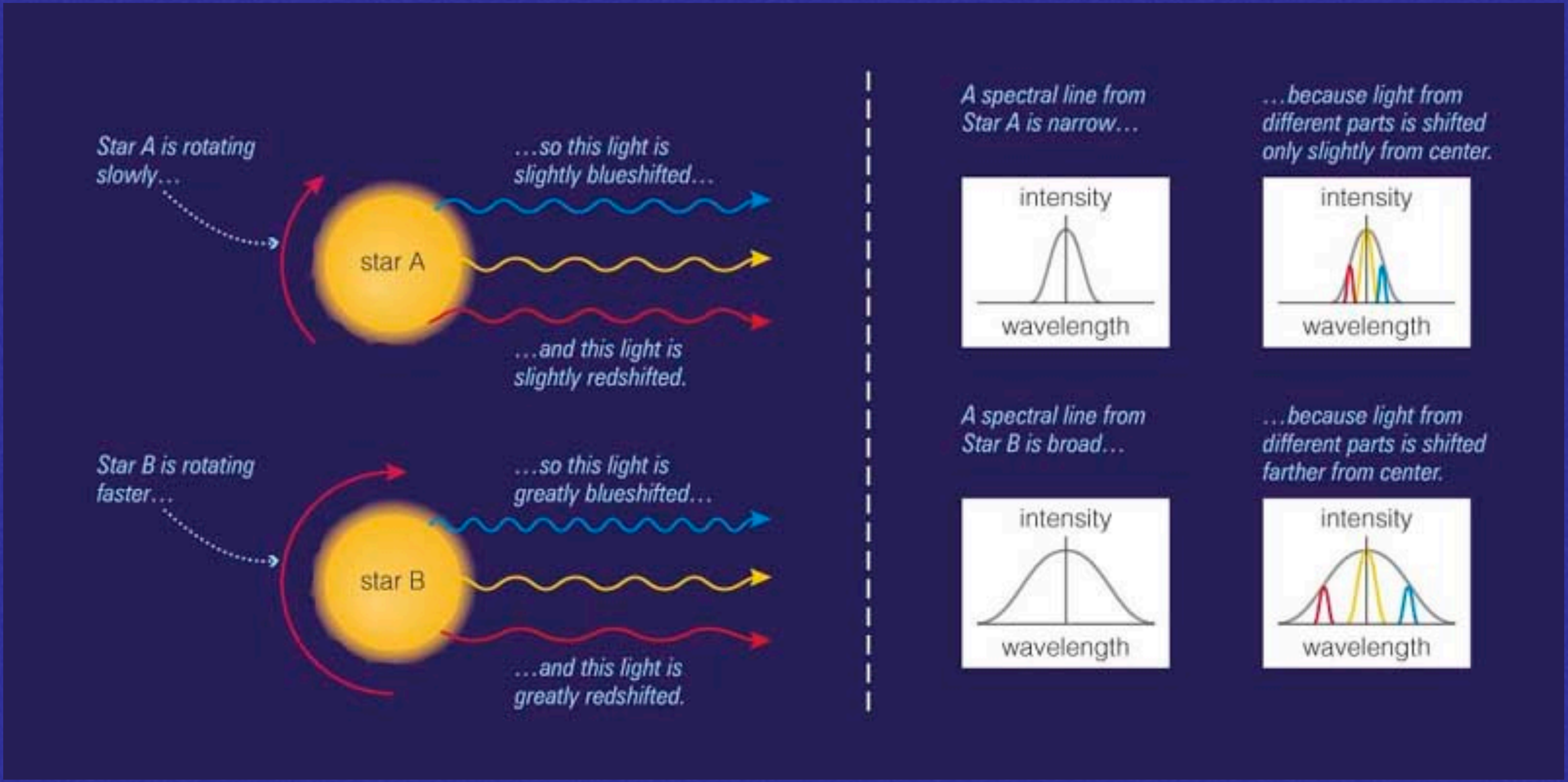


- Spectral lines provides the reference points for measuring Doppler shift

- The velocity measured is a *radial* velocity, the *tangential* part has to be measured with *proper motions*.

- Doppler shift can also measure rotation, and it does effect the widths of spectral lines.

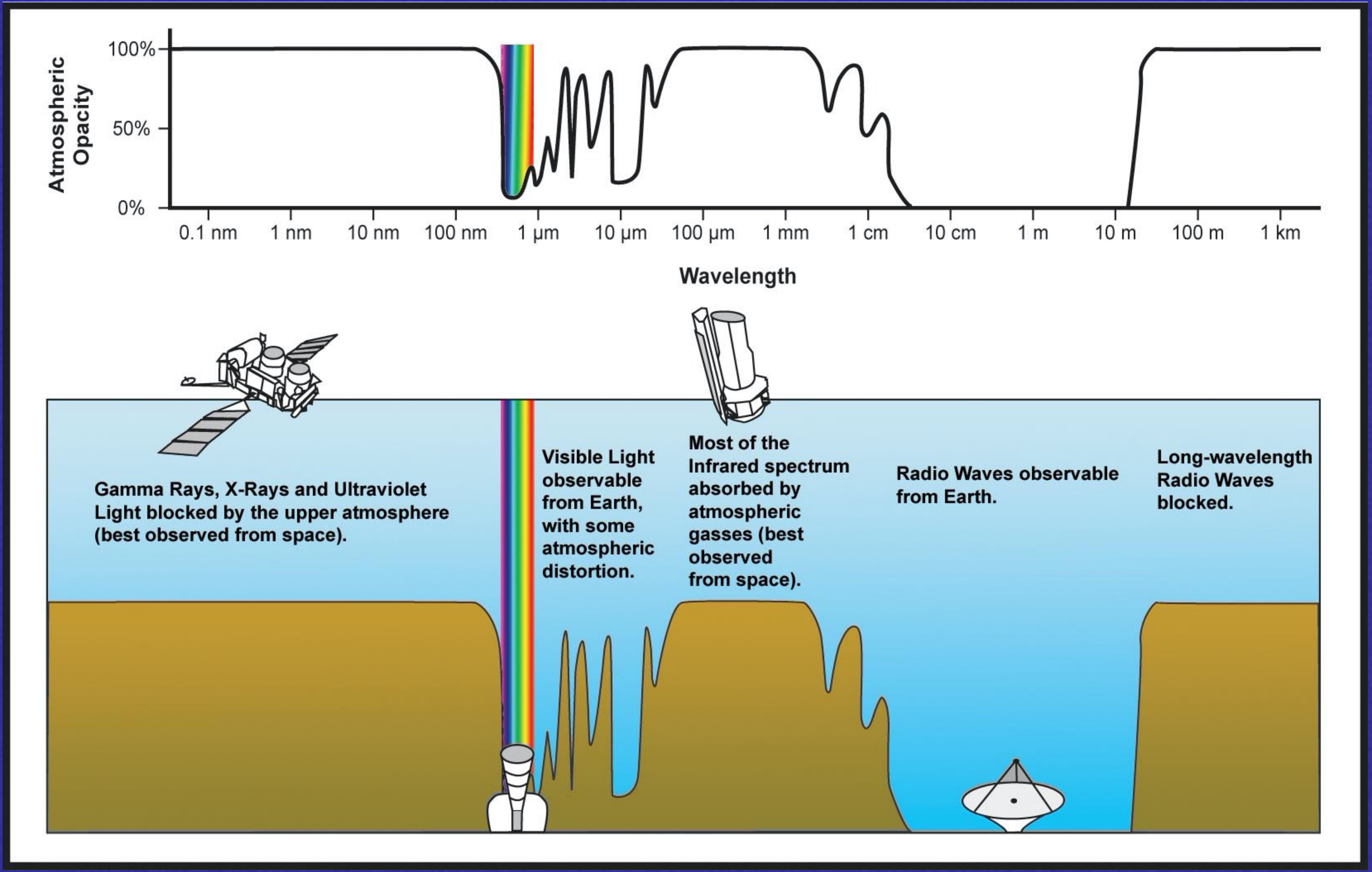
- The more 'motion' you have in an object, the broader the spectral line



Radio Astronomy

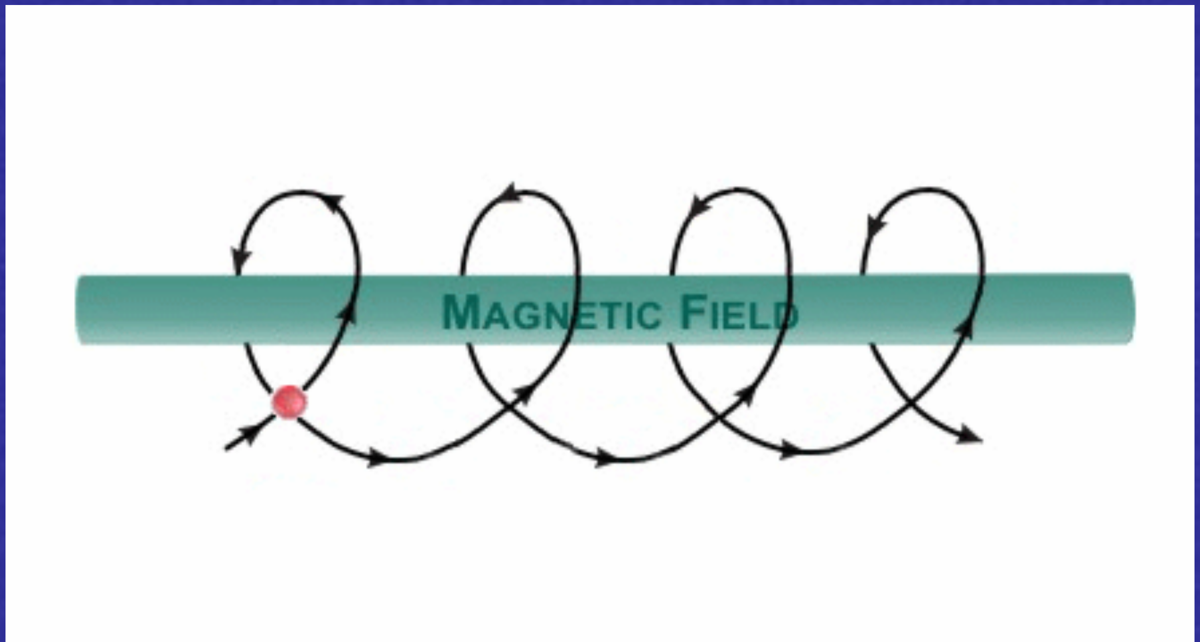
'Non-visible' wavelengths (but probing 'visible' matter).

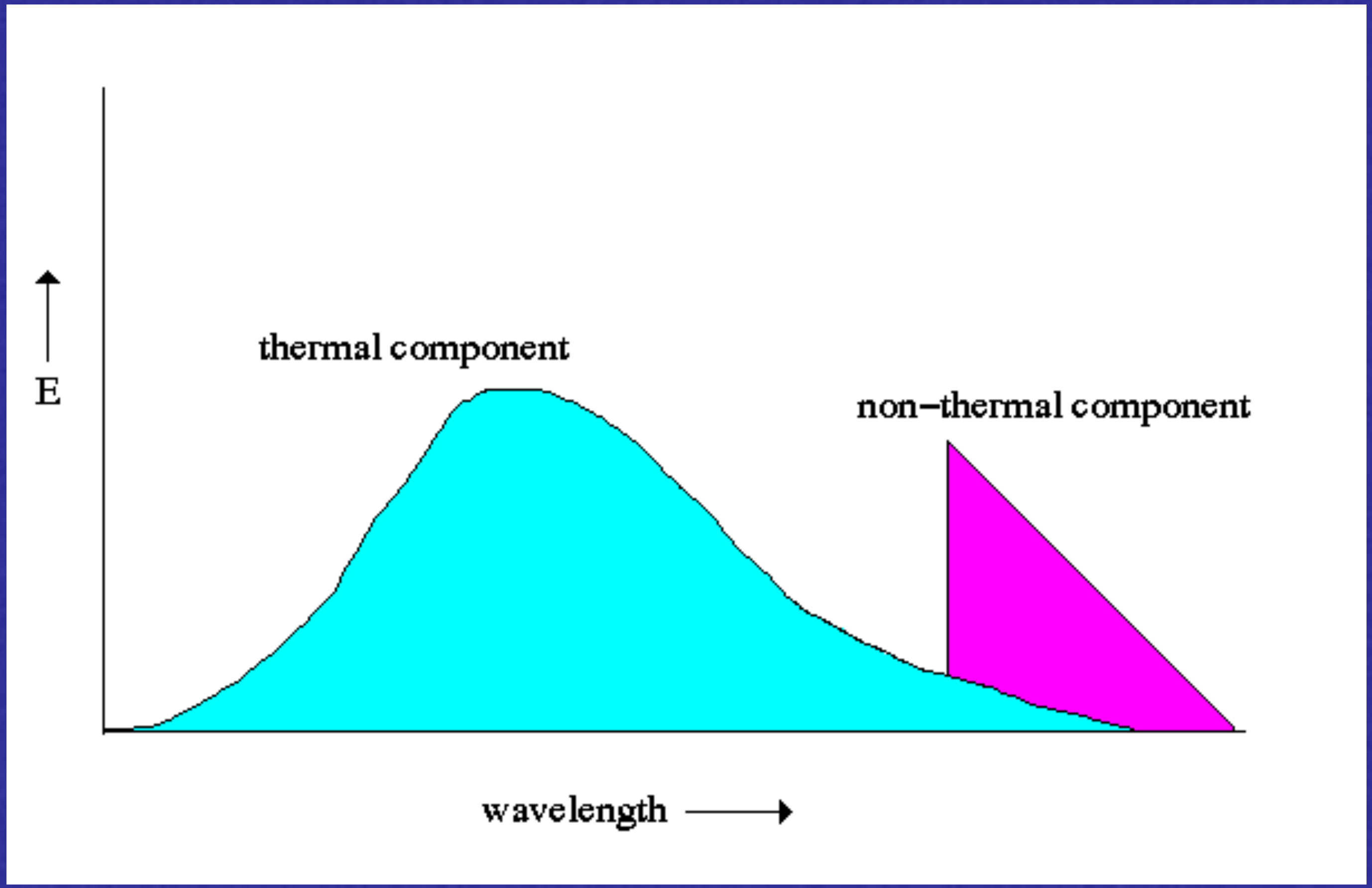
Visible matter is matter that produces EM radiation.



Synchrotron emission

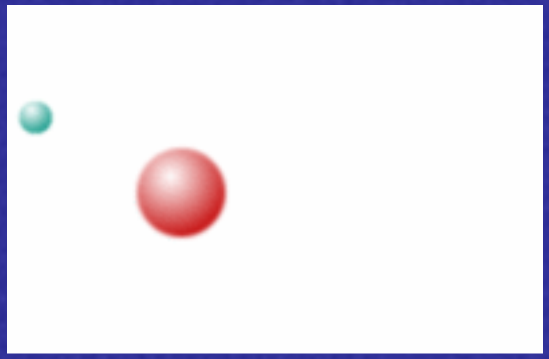
- Electrons spiraling in magnetic field
- Change of direction
  => change of acceleration
  => change in energy
  => emission of a photon





Other emission mechanisms

- Bremsstrahlung (photons deflected by charged particles)



- Atomic and molecular spectral line emission
- Thermal (blackbody) radiation from e.g. planets, stars.
- Stimulated emission of radiation (Masers)

Different emission processes occur under different physical conditions!